Lattice 2023

Monday, July 31, 2023 - Friday, August 4, 2023

Book of Abstracts

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Theoretical Developments / 2

Hamiltonian Truncation on the Lattice

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Hamiltonian truncation is a quantum variational method that approximates the ground state by minimizing the energy on a finite truncated basis of Hilbert space. A straightforward application of this method to quantum field theory would seem to be hopeless, since generic states in the Hilbert space have an exponentially small overlap with physical states. Nonetheless, this talk will present evidence that Hamiltonian truncation converges as a power law in the computational time on the lattice in finite volume. The talk will also explain why Hamiltonian truncation in the continuum is doomed for all but the simplest low-dimensional quantum field theories.

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Computation of the Kugo-Ojima function from lattice simulations

Authors: Nuno Brito[1]; Orlando Oliveira[1]; Paulo Silva[1]; Joannis Papavassiliou[2]; Maurício Ferreira[2]; Arlene Aguilar[3]

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We compute the Kugo-Ojima function $u(q^2)$ using large lattice volume simulations, study the volume dependence, and compare with analytical results from Schwinger-Dyson equations. Special attention is given to the infrared behaviour of $u(q^2)$ and the connection with confinement criteria.

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Vacuum Structure and Confinement

Particle Physics Beyond the Standard Model / 4

Scattering of pseudoscalar particles in a Sp(4)-gauge theory.

Authors: Axel Maas[1]; Fabian Zierler[1]; Yannick Dengler[1]

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In this work we consider strongly interacting dark matter candidates which are composite states of $N_f = 2$ fermions charged under a Sp(4) gauge group in the fundamental representation. We present first results from lattice calculations for the scattering properties of two pseudo-Goldstone bosons in the isospin I=2 channel. We report results for searches for bound states and resonances and compare estimates of the interaction rates to astrophysical contraints.

Topical area:

Particle Physics Beyond the Standard Model

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Non-perturbative RG β-function of 8-flavor SU(3) gauge theory

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Symmetric mass generation (SMG) is a new mechanism that leads to massive bound states without spontaneous symmetry breaking. An SMG phase could lead to a resolution of the chiral fermion problem on the lattice. Expectations from ‘t Hooft anomaly cancellation, combined with recent finite-size scaling results, indicate that the SU(3) gauge-fermion system with two sets of staggered fermions could support the existence of an SMG phase that is accessed by crossing a Berezinsky-Kosterlitz-Thouless (BKT)-like phase transition from weak to strong coupling. In this talk, we explore the β-function of this system. Using the gradient-flow-based “continuous β-function method”, our preliminary result for the continuum-extrapolated RG β-function shows signatures that are consistent with the development of a conformal fixed point.

Topical area:

Particle Physics Beyond the Standard Model

Vacuum Structure and Confinement / 6

Monopoles of the Dirac type and color confinement in QCD \\ - Study of the continuum limit -

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Non-Abelian gauge fields having a line-singularity of the Dirac type lead us to violation of the non-Abelian Bianchi identity. The violation as an operator is equivalent to violation of Abelian-like

Bianchi identities
corresponding to eight Abelian-like conserved magnetic monopole currents of the Dirac type in $SU(3)$ QCD. It is very interesting to study if these new Abelian-like monopoles are responsible for color confinement in the continuum $SU(3)$ QCD, since any reliable candidate of color magnetic monopoles is not known yet. If these new Abelian-like monopoles exist in the continuum limit, the Abelian dual Meissner effect occurs, so that the linear part of the static potential between a quark-antiquark pair is reproduced fully by those of Abelian and monopole static potentials. These phenomena are called here as perfect Abelian and monopole dominances. It is shown that the perfect Abelian dominance is reproduced fairly well, whereas the perfect monopole dominance seems to be realized for large β when use is made of the smooth lattice configurations in the maximally Abelian (MA) gauge. Making use of a block spin transformation with respect to monopoles, the scaling behaviors of the monopole density and the effective monopole action are studied. Both monopole density and the effective monopole action which are usually a two-point function of β and the number of times n of the block spin transformation are a function of $b = na(\beta)$ alone for $n = 1, 2, 3, 4, 6, 8, 12$. If the scaling behavior is seen for up to larger n, it shows the existence of the continuum limit, since $a(\beta) \to 0$ when $n \to \infty$ for fixed $b = na(\beta)$. Along with the previous results without any gauge fixing, these new results obtained in MA gauge suggest that the new Abelian-like monopoles play the role of color confinement in $SU(3)$ QCD.

Topical area:

Vacuum Structure and Confinement

Quantum Computing and Quantum Information / 7

Measurement-based quantum simulation of Abelian lattice gauge theories

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The digital quantum simulation of lattice gauge theories is expected to become a major application of quantum computers. Measurement-based quantum computation is a widely studied competitor of the standard circuit-based approach. We formulate a measurement-based scheme to perform the quantum simulation of Abelian lattice gauge theories in general dimensions. The scheme uses an entangled resource state that reflects the spacetime structure of each gauge theory. Sequential single-qubit measurements with the bases adapted according to the former measurement outcomes induce a deterministic Hamiltonian quantum simulation of the gauge theory on the boundary. Our construction includes the $(2+1)$-dimensional Abelian lattice gauge theory simulated on a 3-dimensional cluster state as an example and generalizes to the simulation of Wegner's lattice models that involve higher-form Abelian gauge fields. The resource state has a symmetry-protected topological order with respect to generalized global symmetries that are related to the symmetries of the simulated gauge theories on the boundary. We also propose a method to simulate the imaginary-time evolution with two-qubit measurements and post-selections.

Topical area:

Quantum Computing and Quantum Information

Particle Physics Beyond the Standard Model / 8

Naturalness vs Higgs masses: A comparative study within Higgs Triplet Models

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In this talk, I will focus on naturalness considerations in SM/2HDM augmented by a Triplet field, here dubbed as Higgs Triplet Models. I will show that the Veltman conditions in HTM are modified by virtue of the additional scalar charged states and that one loop quadratic divergencies can be driven to zero within the allowed respective parameter spaces, usually constrained by unitarity and boundedness from below, as well as the LHC data regarding several Higgs decay channels. In addition, the analysis will also illustrates how the naturalness condition affect drastically the heavy Higgs masses H^0, H^0, H± and H±± (when they exist).

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Particle Physics Beyond the Standard Model

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QED Corrections to Meson and Bare Quark Masses

Authors: Joshua Swaim[1]; Luchang Jin[1]

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We calculate the leading-order QED corrections to meson masses and bare quark masses. As lattice QCD calculations become more precise, these QED corrections are becoming more important. However, one of the challenges in adding QED effects to QCD calculations is avoiding power-law suppressed finite volume effects. These effects can enter calculations of many observables because QED has massless degrees of freedom. By using a recently introduced infinite-volume reconstruction method for QED, we are able to avoid this problem and perform calculations with exponentially-suppressed finite-volume effects.

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Hadronic and Nuclear Spectrum and Interactions

Theoretical Developments / 10

QED in external EM fields

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We simulate lattice QED in (strong) external electromagnetic fields using techniques developed for simulating lattice QCD. We are currently simulating lattice QED in constant external magnetic fields to observe the chiral symmetry breaking predicted by Schwinger-Dyson studies. Difficulties in extending these studies to include external electric fields are discussed.

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Mass effects on the QCD beta-function

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In this study we present lattice results on the QCD β-function in the presence of a quark mass. The β-function is calculated to three loops in perturbation theory and for improved lattice actions; it is extracted from the renormalization of the coupling constant Z_g. The background field method is used to compute Z_g, where it is simply related to the background gluon field renormalization constant Z_A. We address quark mass effects on the background gluon propagator; its dependence on the number of colors N_c, the number of fermionic flavors N_f and the quark mass, m, is shown explicitly. The perturbative results for the QCD β-function will be applied to the precise determination of the strong coupling constant, calculated by Monte Carlo simulations, removing the mass effects from the nonperturbative Green's functions.

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Hadronic and Nuclear Spectrum and Interactions

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The three-pion K-matrix at NLO in chiral perturbation theory

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The K-matrix parametrizes short-range interactions in the relativistic-field-theory finite-volume formalism. It is related to the infinite-volume scattering amplitude, thus providing a bridge between the lattice and perturbation theory, as well as a handle on finite-volume effects and the pion mass dependence. However, leading-order perturbative calculations agree very poorly with the results for systems of three interacting light mesons. I describe the calculation of the three-pion K-matrix from chiral perturbation theory at next-to-leading order, and demonstrate how this resolves most of the disagreement between perturbation theory and the lattice. Thereby, the two main tools for studying these interesting and experimentally inaccessible systems are reconciled.

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Hadronic and Nuclear Spectrum and Interactions

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The Critical Ising Model on a 2-Sphere

Author: Evan Owen[1]

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I derive a formulation of the 2-dimensional critical Ising model on non-uniform simplicial lattices. Surprisingly, the derivation leads to a set of geometric constraints that a lattice must satisfy in order for the model to have a well-defined continuum limit. I perform Monte Carlo simulations of the critical Ising model on discretizations of a 2-sphere and I show that the simulations are in agreement with the 2d Ising CFT in the continuum limit. I discuss the inherent benefits of using non-uniform simplicial lattices to study quantum field theory and how the methods developed here can potentially be generalized for use with other theories.

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Particle Physics Beyond the Standard Model

Algorithms and Artificial Intelligence / 14

From Theory to Practice: Applying Neural Networks to Simulate Real Systems with Sign Problem

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The numerical sign problem poses a seemingly insurmountable barrier to the simulation of many fascinating systems.
We apply a neural networks to deform the region of integration, mitigating the sign problem of systems with strongly correlated electrons.

In this talk we present our latest architectural developments as applied to contour deformation. We also demonstrate its applicability to real systems, namely perylene for organic solar cells.

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Algorithms and Artificial Intelligence

Algorithms and Artificial Intelligence / 15

Density of States for Observables. A derivative method.

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The density of any observable is equal to how large a volume there exist for each possible value of the observable. By considering the relative change to the volume along the direction of change of the observable, the relative change to the density of the observable can be obtained. I will show how one can calculate the change to the log of the density function rho and use this to calculate several observables, which in some cases like wilson line correlators can give errorbars 4 times smaller than standard methods.

Topical area:

Algorithms and Artificial Intelligence

Hadronic and Nuclear Spectrum and Interactions / 16

Lattice QCD studies of the Δ baryon resonance and the $K_0^*(700)$ and $a_0(980)$ meson resonances

Author: Sarah Skinner[1]

Co-authors: Andrew Hanlon [2]; Amy Nicholson [3]; Andre Walker-Loud [4]; Ben Hörz [5]; Colin Morningstar [1]; Daniel Darvish [1]; Fernando Romero-López [6]; John Bulava [7]; Pavlos Vranas [5]

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Studies of the Δ baryon resonance and the $K_0^*(700)$ and $a_0(980)$ meson resonances using $N_f = 2{+}1$ lattice QCD for pion masses near 200 MeV are presented. The role of tetraquark operators in the mesonic systems is detailed. The s-wave scattering lengths for both the $I = 1/2$ $N\pi$ and $I = 3/2$ $N\pi$ channels and properties of the Δ resonance are identified from the finite-volume energy levels of the lattice simulation.

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Triviality and negative coupling phi4 on the lattice

Author: Paul Romatschke[1]

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Triviality of phi4 theory in four dimensions can be avoided if the bare coupling constant is negative in the UV. Theories with negative coupling can be put on the lattice if the integration domain for phi(x) is contour-deformed from the real to the complex domain. In 0+1d (quantum mechanics), one can recover results from PT-symmetric quantum mechanics in this way. In this talk, I report on an attempt to put negative coupling phi4 theory in 4 dimensions on the lattice.

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QCD at Non-zero Density / 18

A New Way to Compute the Pseudoscalar Screening Mass at Finite Chemical Potential

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We present a new way of computing the pion screening mass at finite isoscalar chemical potential μ_ℓ, starting from the Taylor expansion of the screening correlator in μ_ℓ. The method derives from the known exact expression for the free theory pion screening correlator at finite μ_ℓ. As a first check of the formalism, we compare the lattice results for the free theory screening correlator and its derivatives, obtained on an $80^3 \times 8$ lattice with HISQ/tree fermions, with the corresponding theoretical expressions. We find good agreement, thus verifying our approach. We then apply our formalism to calculate the $\mathcal{O}(\mu_\ell^2)$ correction to the pion screening mass for two temperatures in the range 2 GeV $< T <$ 3 GeV, using $N_f = 2 + 1$ flavors of HISQ/tree fermions on $64^3 \times 8$ lattices. We conclude with some general remarks concerning the scope of the present study and its relation to other approaches.

Topical area:

QCD at Non-zero Density

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The two-pole nature of the $\Lambda(1405)$ from lattice QCD

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The $\Lambda(1405)$ resonance is listed in PDG as a strangeness $S = -1$ baryon with quantum numbers $I(J^P) = 0(\frac{1}{2}^-)$. However, most models based on chiral effective theory and unitary suggest two nearby overlapping resonance poles. This two-pole picture for the $\Lambda(1405)$ is disputed by recent phenomenological fits to experimental data which require only a single pole, and quark models which typically predict a single pole. In this presentation I will discuss the first lattice QCD computation of the coupled channel $\Sigma\pi$-$N\bar{K}$ scattering amplitude in the $\Lambda(1405)$ region. At a heavier-than-physical pion mass of $m_\pi = 200\,\mathrm{MeV}$, the amplitude clearly exhibits a virtual bound state below $\Sigma\pi$ threshold and an additional resonance pole just below $N\bar{K}$ threshold. These poles are identified from parametrizations of the two-channel K-matrix which are fit to the finite volume energy spectrum and analytically continued to the complex plane. Our first-principles QCD results cannot be described by a single pole and thus support the two-pole picture suggested by $SU(3)$ chiral symmetry and unitarity.

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Hadronic and Nuclear Spectrum and Interactions

Quantum Computing and Quantum Information / 20

Simulations of the Hyperbolic Ising Model

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In this talk we study the Ising model living on a discretization of two dimensional anti-de Sitter space. Our numerical work uses tensor network methods based on matrix product states (MPS) and matrix product operator (MPO) constructions. We use DMRG techniques to obtain the ground state and investigate its properties. For the time evolution of the model , we use the TEBD algorithm and show that the time evolution of the system exhibiths the expected warping effects due to the

curved background. Finally, we calculate out-of-time ordered correlators (OTOCs) for the model and evaluate the speed of information spread through the system under time evolution.

Topical area:

Quantum Computing and Quantum Information

QCD at Non-zero Temperature / 21

Baryonic screening masses in high temperature QCD

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We compute the screening masses of fields with nucleon quantum numbers for a wide range of temperatures between $T \sim 1$ GeV and $T \sim 160$ GeV. The computation has been performed by means of Monte Carlo simulations of lattice QCD with $N_f = 2+1$ flavors of $O(a)$-improved Wilson fermions: we exploit a novel strategy which has recently allowed to determine for the first time non-singlet mesonic screening masses up to extremely high temperatures. The baryonic screening masses are measured with a few per-mille precision in the continuum limit, and percent deviations from the free theory result $3\pi T$ are clearly visible even at the highest temperatures. The observed degeneracy of the positive and negative parity state's screening mass, expected from Ward identities associated to non-singlet axial transformations, provides further evidence for the restoration of chiral symmetry in the high temperature regime of QCD.

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QCD at Non-zero Temperature

Quark and Lepton Flavor Physics / 22

Using Gradient Flow to Renormalise Matrix Elements for Meson Mixing and Lifetimes

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Neutral meson mixing and meson lifetimes are theory-side parametrised in terms four-quark operators which can be determined by calculating weak decay matrix elements using lattice QCD.
While calculations of meson mixing matrix elements are standard, determinations of lifetimes typically suffer from complications in renormalisation procedures because dimension-6 four-quark operators can mix with operators of lower mass dimension and, moreover, quark-line disconnected diagrams contribute.

We present work detailing the idea to use fermionic gradient flow to non-perturbatively renormalise matrix elements describing meson mixing or lifetimes, which later is to be combined with a perturbative calculation to match to the $\overline{\mathrm{MS}}$ scheme.

Topical area:

Quark and Lepton Flavor Physics

Structure of Hadrons and Nuclei / 23

Leading Power Accuracy in Lattice Calculations of Parton Distributions

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In lattice-QCD calculations of parton distribution functions (PDFs) via large-momentum effective theory, the leading power (twist-three) correction appears as $calO(\Lambda_{\rm QCD}/P^z)$ due to the linear-divergent self-energy of Wilson line in quasi-PDF operators. For lattice data with hadron momentum P^z of a few GeV, this correction is dominant in matching, as large as 30\% or more. We show how to eliminate this uncertainty through choosing the mass renormalization parameter consistently with the resummation scheme of the infrared-renormalon series in perturbative matching coefficients. An example on the lattice pion PDF data at $P^z = 1.9$ GeV shows an improvement of matching accuracy by a factor of more than $3 \sim 5$ in the expansion region $x = 0.2 \sim 0.5$.

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Structure of Hadrons and Nuclei

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Meson-meson scattering in $N_{\rm f} = 4$ QCD

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Co-authors: Pilar Hernandez [2]; Fernando Romero-López [3]

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In this talk, we present preliminary results on $\pi\pi$ and $\rho\rho$ coupled-channel scattering with 4 degenerate light quark flavors. We focus on different scattering channels, two of which are attractive and possess the same quantum numbers as the two $X_{0,1}(2900)$ tetraquark candidates recently discovered at LHCb. Using Luscher's formalism, we investigate these resonances in the scattering amplitude. We will also discuss some ongoing study on the large $N_{\rm c}$ scaling of these scattering processes, which may shed light on the nature of such exotic states.

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Hadronic and Nuclear Spectrum and Interactions

Particle Physics Beyond the Standard Model / 25

Composite Higgs model from the lattice: Infrared fixed point and anomalous dimensions

Authors: Anna Hasenfratz[1]; Yigal Shamir[2]; Benjamin Svetitsky[2]; Ethan Neil[3]; Oliver Witzel[4]

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We use the continuous renormalization-group method, based on the gradient flow, to study a candidate theory of composite Higgs and a partially composite top. The model is an SU(4) gauge theory with four Dirac fermions in each of the fundamental and two-index antisymmetric representations. Our lattice action includes a set of Pauli-Villars fields, which decouple in the continuum limit while allowing us to reach much stronger renormalized coupling than otherwise possible. We find that the theory has an infrared fixed point at g^2□15.5 in the gradient flow scheme. The mass anomalous dimensions are large at the fixed point. On the other hand, the anomalous dimensions of top-partner operators do not exceed 0.5 at the fixed point. This disfavors the theory as a model of partial compositeness.

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Particle Physics Beyond the Standard Model

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Lattice extraction of the TMD soft function using the auxiliary field representation of the Wilson line

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The TMD soft function may be obtained by formulating the Wilson line in terms of auxiliary 1-dimensional fermion fields on the lattice. In the "timelike" region, this corresponds to the *moving* heavy quark effective theory (HQET). I present the results of the one-loop calculation of the Euclidean space analog to the soft function, and show that it must proceed in the "spacelike" region.

Finally, I present the details of an exploratory numerical study in preparation for the lattice computation.

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Particle Physics Beyond the Standard Model / 27

Lattice studies of Sp(2N) gauge theories using GRID

Author: Niccolò Forzano[1]

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Four-dimensional gauge theories based on symplectic Lie groups have been introduced as the microscopic origin for elegant proposals of several new physics models. Numerical studies pursued on the lattice can provide the quantitative information necessary for the application of such models.
To this purpose, we implemented $Sp(2N)$ gauge theories using Monte Carlo techniques within Grid, a performant framework designed for the numerical study of field theories on the lattice.
We show the first results obtained using this library in symplectic gauge theories, focusing on the $Sp(4)$ theory coupled to $N_{(as)}$ Wilson-Dirac fermions transforming in the 2-index antisymmetric representation.
Preliminary tests of the algorithm are discussed, checking the behavior of the integrators, and the implementation of the symmetries. We then study the Wilson flow as a scale setting procedure and monitor ergodicity using the topological charge.
To set the stage for future large-scale numerical studies, we vary the number of fermions in the antisymmetric representation, $N_{(as)}$, and scan the lattice parameter space, to map the critical lines of bulk phase transitions in the whole class of theories.

Topical area:

Particle Physics Beyond the Standard Model

Particle Physics Beyond the Standard Model / 28

Renormalization of the Yukawa and Quartic Couplings in $\mathcal{N} = 1$ Supersymmetric QCD

Authors: Marios Kosta[1]; Herodotos Herodotou[1]; Haralambos Panagopoulos[1]

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In this work we perform calculations in order to determine the renormalization factors and the mixing coefficients of the Yukawa and the quartic couplings in $\mathcal{N} = 1$ Supersymmetric QCD. The Yukawa couplings describe the interactions between gluino, quark and squark fields whereas the quartic couplings describe four-squark interactions. We discretize the action on a Euclidean lattice using the Wilson formulation for the gluino, quark and gluon fields; for squark fields (scalar fields) we employ naïve discretization. At the quantum level Yukawa and quartic interactions suffer from mixing with other operators which have the same transformation properties. Exploiting parity and charge conjugation symmetries of the Supersymmetric QCD action, we reduce the allowed mixing patterns. We compute, perturbatively to one-loop and to the lowest order in the lattice spacing, the relevant three-point Green's functions so as to fine tune the Yukawa couplings and the relevant four-point Green's functions to fine tune the quartic couplings. We use both dimensional and lattice regularizations as required for implementing the Modified Minimal Subtraction scheme. This work is a sequel to our earlier investigations on SCQD and completes the one-loop fine-tuning of the SQCD action on the lattice, thus paving the way for numerical simulations of SQCD.

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Particle Physics Beyond the Standard Model

Quantum Computing and Quantum Information / 29

Simulating the lattice $SU(2)$ Hamiltonian with discrete manifolds

Author: Simone Romiti[1]

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Numerical simulations of quantum Hamiltonians can be done representing the degrees of freedom as matrices acting on a truncated Hilbert space. Here we present a formulation for the lattice $SU(2)$ gauge theory in the so called "magnetic basis", where the gauge links are unitary and diagonal. The latter are obtained from a direct discretization of the group manifold, while the canonical momenta are built using an orthogonal transform on S_3. We discuss general considerations on the contraints of the spectrum of the free theory and the continuum manifold limit.

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Quantum Computing and Quantum Information

Particle Physics Beyond the Standard Model / 30

The conformal fixed point of the SU(3) gauge theory with 10 fundamental flavors

Author: Anna Hasenfratz[1]

Co-authors: Ethan Neil [2]; Yigal Shamir [3]; Benjamin Svetitsky [3]; Oliver Witzel [4]

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The SU(3) gauge theory with $N_f = 10$ fundamental flavors is thought to be close to the sill of the conformal window. I describe a recent study of this system using the continuous β function method based on the gradient flow. We use a Pauli-Villars improved gauge action and several gradient flow transformations. These features allow us to study the system at much stronger gauge couplings than previously possible. Prior lattice studies could not explore gauge couplings above $g^2 \approx 10$. We find strong evidence of a conformal infrared fixed point at $g^2 \approx 15$. The mass anomalous dimension at the conformal fixed point is $\gamma_m \approx 0.6$, indicating that the theory is well above the sill of the conformal window. Our results are consistent with those of prior studies where their domains overlap.

Topical area:

Particle Physics Beyond the Standard Model

Quantum Computing and Quantum Information / 32

Chiral fermion on quantum computers

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Quantum computation often suffers from artificial symmetry breaking. We should strive to suppress the artifact both by theoretical and technical improvements. As for chiral symmetry, there is a celebrated theoretical formalism, i.e., the overlap fermion. In this presentation, I will talk about how the overlap fermion guarantees chiral symmetry in quantum computation. I will also show that, although a drawback of the overlap fermion is its computational cost, there is a loophole in one dimension.

Topical area:

Quantum Computing and Quantum Information

QCD at Non-zero Temperature / 33

Local Polyakov-loop fluctuation and center domains in quark-gluon plasma with many colors

Author: Yuto Nakajima[1]

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The deconfinement transition in QCD is understood as the spontaneous breaking of $\mathbb{Z}_N$ symmetry at high temperatures. Accordingly, quark-gluon plasma generally includes some partial cells called center domains, each with a homogeneous Polyakov-loop. In this work, constructing an effective action describing the deconfinement vacuum of QCD with N colors, we discuss the properties of center domains.
First, we evaluate the mass of local Polyakov-loop fluctuation and demonstrate that some fluctuation becomes a Nambu-Goldstone mode in the large-N limit. We also discuss surface tension between two $\mathbb{Z}_N$ center domains. Second, we estimate the global vacuum-to-vacuum transition in a single center domain. We find that some threshold volume exists, where a domain larger than this volume is stable, and vice versa. Identifying the threshold as the lower bound of a stable center domain volume, we quantitatively argue the typical volume scale of center domains.

Topical area:

QCD at Non-zero Temperature

Structure of Hadrons and Nuclei / 34

Discretization effects on nucleon root-mean-square radii from lattice QCD at the physical point

Author: Ryutaro Tsuji[1]

Co-authors: Ken-Ichi Ishikawa [2]; Eigo Shintani [3]; Yasumichi Aoki [4]; Yoshinobu Kuramashi [3]; Shoichi Sasaki [5]; Takeshi Yamazaki [6]

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We present results of nucleon structure studies measured in 2+1 flavor QCD with the physical light quarks in a large spatial extent of about 10 fm. Our calculations are carried out with the PACS10 gauge configurations generated by the PACS Collaboration with the stout-smeared $O(a)$ improved Wilson fermions and Iwasaki gauge action at β=1.82 and 2.00 corresponding to the lattice spacings of 0.085 fm (coarser) and 0.063 fm (finer) respectively. At both lattice spacings, we evaluate nucleon form factors associated with lepton-nucleon elastic scattering measurements. In this talk, we will mainly report our preliminary results of the Root-Mean-Square radii and the discretization effects on them. In addition, the examination of the excited-states contaminations based on PCAC relation will be discussed using our data.

Topical area:

Structure of Hadrons and Nuclei

Algorithms and Artificial Intelligence / 35

Machine Learning Trivializing Flows

Author: David Albandea[1]

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The so-called trivializing flows were proposed to speed up Hybrid Monte Carlo simulations, where the Wilson flow was used as an approximation of a trivializing map, a transformation of the gauge fields which trivializes the theory. It was shown that the scaling of the computational costs towards the continuum did not change with respect to HMC. The introduction of machine learning tecniques, especially normalizing flows, for the sampling of lattice gauge theories has shed some hope on solving topology freezing in lattice QCD simulations. In this talk I will present our work using normalizing flows as trivializing flows, given its similarity with the idea of a trivializing map, and study its benefits with respect to standard HMC.

Topical area:

Algorithms and Artificial Intelligence

Theoretical Developments / 36

Lattice construction of mixed 't Hooft anomaly with higher form symmetry

Authors: Hiroshi Suzuki[1]; Motokazu Abe[2]; Okuto Morikawa[3]; Soma Onoda[4]; Yuya Tanizaki[5]

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We extend the definition of L\"uscher's lattice topological charge to the case of 4d $SU(N)$ gauge fields coupled with $\mathbb{Z}_N$ 2-form gauge fields.
This result is achieved while maintaining the locality, the $SU(N)$ gauge invariance, and $\mathbb{Z}_N$ 1-form gauge invariance, and we find that the manifest 1-form gauge invariance plays the central role in our construction.
This result gives the lattice regularized derivation of the mixed ‘t~Hooft anomaly in pure $SU(N)$ Yang–Mills theory between its $\mathbb{Z}_N$ 1-form symmetry and the θ periodicity.

Topical area:

Theoretical Developments

Particle Physics Beyond the Standard Model / 37

Hidden Conformal Symmetry from the Lattice

Authors: Andy Gasbarro[None]; Anna Hasenfratz[1]; Claudio Rebbi[2]; David Schaich[3]; Enrico Rinaldi[4]; Ethan Neil[5]; Evan Weinberg[6]; George Fleming[7]; James Ingoldby[8]; James Osborn[9]; Kimmy Cushman[None]; Oliver Witzel[10]; Pavlos Vranas[11]; Richard C. Brower[2]; Thomas Appelquist[12]; Xiaoyong Jin[9]

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We present an analysis of newly expanded and refined data from lattice studies of the SU(3) gauge theory with $N_f = 8$ light Dirac fermions, a theory which lies close to the boundary of the conformal window. We first assume that this theory is just outside the conformal window and identify a light unflavored scalar meson in this case as an approximate dilaton. We show fits of the lattice data to a dilaton effective field theory and demonstrate that it yields a good fit even at lowest order. Our fit incorporates new data for a scalar decay constant F_S. For comparison, we then assume that the theory is inside the conformal window. In this case, the fermion mass provides a deformation, triggering confinement. We employ simple scaling laws to fit the lattice data, but find that it is of lesser quality.

Topical area:

Particle Physics Beyond the Standard Model

Theoretical Developments / 38

Recent Developments of Euclidean Dynamical Triangulations with Non-Trivial Measure Term

Author: Marc Schiffer[None]

Co-authors: Mingwei Dai [1]; Jack Laiho [1]; Judah Unmuth-Yockey [2]; Walter Freeman [1]

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Dynamical Triangulations might provide a tool to discover asymptotic safety in quantum gravity. This scenario is based on scale invariance which is realized at an interacting fixed point of the renormalization group flow. In this spirit, asymptotically safe quantum gravity is a quantum field theoretic approach to quantum gravity. On the lattice, asymptotic safety would be realized as a continuous phase transition in Dynamical Triangulations. The original formulation of Euclidean Dynamical Triangulations (EDT) is known to lack a continuous phase transition in d=4 dimensions. However, recent studies suggest that a modified version of EDT, which includes a local measure term, could

exhibit a phase transition, leading to a well-behaved semi-classical limit. In this talk, I will review the current status of EDT with a non-trivial measure term and highlight emerging evidence that supports the possibility of a continuous phase transition. Finally, I will provide an outlook on ongoing research and on future studies.

Topical area:

Theoretical Developments

Quantum Computing and Quantum Information / 39

Quantum Simulation of Finite Temperature Schwinger Model via Quantum Imaginary Time Evolution

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We have studied the chiral and confinement-screening phase transitions in the Schwinger model at finite temperature and density using the quantum algorithm.
The theoretical exploration of the phase diagram for strongly interacting systems at finite temperature and density remains incomplete mainly due to the sign problem in the conventional Lattice Monte Carlo method.
However, quantum computation offers a promising solution to circumvent the sign problem as it deals with quantum field theories in the Hamiltonian formalism.
The preparation of thermal states on quantum circuits is a non-trivial challenge.
We have successfully implemented the thermal state preparation on quantum circuits using a theoretical framework known as Thermal Pure Quantum states (TPQs) and the Quantum Imaginary Time Evolution (QITE) algorithm.
The details of the algorithm, our improvements, and the results will be presented in the talk.

Topical area:

Quantum Computing and Quantum Information

Algorithms and Artificial Intelligence / 40

On the geometric convergence of HMC on Riemannian manifolds

Authors: Xinhao Yu[1]; A.D. Kennedy[1]

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We apply Harris' ergodic theorem on Markov chains to prove
the geometric convergence of Hamiltonian Monte Carlo: first on compact

Riemannian manifolds, and secondly on a large class of non-compact Riemannian manifolds by introducing an extra Metropolis step in the radial direction. We shall use ϕ^4 theory as an explicit example of the latter case.

Topical area:

Algorithms and Artificial Intelligence

Theoretical Developments / 41

Why magnetic monopole becomes dyon in topological insulators

Author: Naoto Kan[1]

Co-authors: Shoto Aoki [1]; Hidenori Fukaya [2]; Mikito Koshino [1]; Yoshiyuki Matsuki [1]

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The Witten effect predicts that a magnetic monopole acquires a fractional electric charge inside topological insulators. In this work, we give a microscopic description of this phenomenon, as well as an analogous two-dimensional system with a vortex. We solve the Dirac equation of electron field both analytically in continuum and numerically on a lattice, by adding the Wilson term and smearing the gauge field within a finite range to regularize the short-distance behavior of the system. Our results reveal that the Wilson term induces a strong positive mass shift, creating a domain-wall around the monopole/vortex. This small, yet finite-sized domain-wall localizes the chiral zero modes and ensures their stability through the Atiyah-Singer index theorem, whose cobordism invariance is crucial in explaining why the electric charge is fractional.

Topical area:

Theoretical Developments

Theoretical Developments / 42

Higher-group symmetry in lattice gauge theories with restricted topological sectors

Author: Okuto Morikawa[1]

Co-authors: Hiroki Wada [1]; Motokazu Abe [2]; Naoto Kan [1]; Soma Onoda [2]; Yuta Nagoya [1]

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We consider gauge theories on a four-dimensional torus, where the instanton number is restricted to an integral multiple of p. This theory possesses the nontrivial higher-group structure, which can be regarded as a generalization of the Green-Schwarz mechanism, between the 1-form center and $\mathbb{Z}_p$ 3-form symmetries. Following recent studies of the lattice construction of the $U(1)/\mathbb{Z}_q$ and

$SU(N)/\mathbb{Z}_N$ principal bundles, we examine how such a structure is realized on the basis of lattice regularization.

Topical area:

Theoretical Developments

Vacuum Structure and Confinement / 43

Flattening of the quantum effective potential in fermionic theories

Authors: Gergely Endrődi[1]; Tamás G. Kovács[2]; Gergely Markó[1]; Laurin Pannullo[3]

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We present mechanisms to constrain fermionic condensates on the level of the path integral, which grant access to the quantum effective potential in the infinite volume limit. In the case of a spontaneously broken symmetry this potential possesses a manifestly flat region, which is usually inaccessible to the standard approach of a double limit of volume and explicit symmetry breaking. By constraining the appropriate order parameters such as the chiral condensate, one is then able to probe the flat region. We demonstrate our method of constraining fermionic condensates in low-dimensional four-fermion models, which exhibit a spontaneously broken chiral symmetry. We show how the potential flattens in the infinite volume limit and that the flat region is dominated by inhomogeneous field configurations.

Topical area:

Vacuum Structure and Confinement

Structure of Hadrons and Nuclei / 44

Nucleon isovector form factors from domain-wall lattice QCD at physical mass

Author: Shigemi Ohta[1]

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The current status of lattice-QCD numerical calculations by joint LHP and RBC collaborations of nucleon isovector vector- and axialvector-current form factors using a 2+1-flavor dynamical domain-wall fermions lattice QCD ensemble generated jointly by RBC and UKQCD collaborations will be presented. The lattice spacing is set at about 0.1141(3) fm, and the lattice spatial extent is 48 spacings or about 5.4750(14) fm. The dynamical strange and degenerate up and down quark mass values are set at their essentially physical values to provide the physical Ω mass and a degenerate pion mass of 0.1392(2) GeV. Our nucleon mass estimate is about 0.947(6) GeV. Possible excited-state contaminations in the calculated vector- and axialvector-current form factors are hidden below larger statistical noises. The numerical details of the form-factor shape parameters, such as the mean squared radii, the anomalous magnetic moment, or the pseudoscalar coupling extracted from the form factors, will be given, along with comparisons of different approaches used to extract them.

Topical area:

Structure of Hadrons and Nuclei

Structure of Hadrons and Nuclei / **45**

Unveiling Generalized Parton Distributions through the Pseudo-Distribution Approach

Authors: Niilo Nurminen[1]; Shohini Bhattacharya[2]; Wojciech Chomicki[1]; Krzysztof Cichy[1]; Martha Constantinou[3]; Andreas Metz[3]; Fernanda Steffens[4]

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Understanding the intricate three-dimensional internal structure of the nucleon has been a long-standing challenge. The main quantitative tool to map this structure are the generalized parton distributions (GPDs). In this talk, we present the first extraction of unpolarized GPDs using the pseudo-distribution approach on the lattice. We use one ensemble of $N_f = 2 + 1 + 1$ twisted mass fermions at a non-physical pion mass of 260 MeV and a lattice spacing of 0.093 fm.

Topical area:

Structure of Hadrons and Nuclei

Quark and Lepton Flavor Physics / **46**

Status of RBC/UKQCD g-2 program

Author: Christoph Lehner[None]

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I review the status of the RBC/UKQCD g-2 program with focus on updates for the hadronic vacuum polarization.

Topical area:

Quark and Lepton Flavor Physics

Software Development and Machines / **47**

Status of the Grid Python Toolkit (GPT)

Author: Christoph Lehner[None]

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I give a status update for the Grid Python Toolkit software project.

Topical area:

Software Development and Machines

Theoretical Developments / 48

Bond-weighting method for the Grassmann tensor renormalization group

Author: Shinichiro Akiyama[1]

[1] *The University of Tokyo*

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Bond-weighted tensor renormalization group (BTRG) is a novel tensor network algorithm to improve the accuracy in calculating the partition functions of the classical spin models. We extend the BTRG to make it applicable for the fermionic system, benchmarking with the two-dimensional massless Wilson fermion. We show that the accuracy with the fixed bond dimension is improved also in the fermionic system and provide numerical evidence that the optimal choice of the hyperparameter in bond weights is not affected by whether the system is bosonic or fermionic. In addition, by monitoring the singular value spectrum, we find that the scale-invariant structure of the renormalized Grassmann tensor is successfully kept by the bond-weighting method.

Topical area:

Theoretical Developments

Quantum Computing and Quantum Information / 49

Variational ansatz inspired by quantum imaginary time evolution and its application to the Schwinger model

Author: Xiaoyang Wang[1]

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An effective way to design quantum algorithms is by heuristics. One of the representatives is Farhi et al.'s quantum approximate optimization algorithm (QAOA), which provides a powerful variational ansatz for ground state preparation. QAOA is inspired by the adiabatic evolution of a quantum system, and the ansatz can encode the real time evolution of the system Hamiltonian. In this work, we provide a guidance to design the variational ansatz, which can encode general quantum evolution, including the quantum real time evolution (QRTE) and quantum imaginary time evolution

(QITE). These heuristic variational ans\"atze preserve symmetries of the target quantum system. We construct the symmetry-preserving QITE-inspired and QRTE-inspired ans\"atze for the Schwinger model and Fermi-Hubbard model. We show the advantage of the QITE-inspired ans\"atze for the ground state preparation of these two models, compared to the one inspired by QRTE in the accuracy and efficiency. We demonstrate that the ground state and excited state properties of the Schwinger model can be studied using the QITE-inspired ansatz.

Topical area:

Quantum Computing and Quantum Information

Theoretical Developments / 50

More Minimal Renormalon Subtraction

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The minimal renormalon subtraction introduced by Komijani and used by the Fermilab Lattice, MILC, and TUMQCD Collaborations to determine quark masses is extend to other quantities. A simpler derivation of the renormalon normalization is presented, showing at the same time how it is completely general. The scale dependence of the Borel sum is investigated.

Topical area:

Theoretical Developments

Particle Physics Beyond the Standard Model / 51

The deconfinement phase transition in Sp(2N) gauge theories and the density of states method

Author: David Mason[1]

Co-authors: Biagio Lucini [1]; Maurizio Piai [1]; Davide Vadacchino [2]; Enrico Rinaldi [3]

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First order phase transitions in the early universe might produce a detectable background of gravitational waves. As these phase transitions can be generated by new physical sectors, it is important to quantify these effects. Many non-Abelian pure Yang-Mills gauge theories are known to have first order deconfinement phase transitions, with properties that can be studied with lattice simulations. Despite the recent surge of interest in Sp(2N) gauge theories as a candidate for models of physics beyond the standard model, studies of these theories at finite temperature are still very limited. In this contribution, I will present preliminary results for an ongoing numerical investigation of the thermodynamic properties of the deconfinement phase transition in Sp(4) gauge theory using the linear logarithmic relaxation algorithm. This method enables us to obtain a highly accurate determination of the density of states, allowing for a precise reconstruction of thermodynamic observables.

In particular, it gives access to otherwise difficult to determine quantities such as the free energy of the system, including its metastable and unstable branches, hence providing an additional direct observable to study the dynamics of the phase transition.

Topical area:

Particle Physics Beyond the Standard Model

Algorithms and Artificial Intelligence / **52**

Decimation map in 2D for accelrating HMC

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To conquer topological freezing in gauge systems, we develop a variant of trivializing map proposed in Luecher 2019. We in particular consider the 2D U(1) pure gauge model, which is the simplest gauge system with topology. The trivialization is divided into several stages, each of which corresponds to integrating local degrees of freedom, the decimation, which can be seen as coarse-graining. The simulation using the map has a gain in autocorrelation in wall clock time compared to conventional HMC which likely survives even in the continuum limit.

Topical area:

Algorithms and Artificial Intelligence

Hadronic and Nuclear Spectrum and Interactions / **53**

Resolving the left-hand-cut problem in lattice studies of the doubly-charmed tetraquark

Authors: Fernando Romero-López[1]; Steve Sharpe[2]; Max Hansen[3]; Zack Draper[2]

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The recently discovered I = 0, JP = 1+ doubly-charmed tetraquark Tcc(3875) is an exotic meson that is a candidate for a DD*molecule. In nature, it decays to DDπ, since the D* is unstable. It has been studied on the lattice for heavier-than-physical quark masses for which the D*is stable, so that two-particle methods can be used. However, a major drawback of this methodology is that the tentative position of the (virtual) bound state lies very close to, or even below, the left-hand cut, which is the subthreshold energy below which the two-body formalism breaks down. We present a method to overcome this limitation, in which we apply the three-particle formalism to the DDπ system and incorporate the D* as a bound state in the p-wave Dπ subsystem. Using this formalism below the three-particle threshold allows us to study the Tcc while incorporating the physics responsible for the left-hand cut. The new approach has the additional advantage of remaining valid when the quark masses are reduced into the regime where the D decays to Dπ, so that the Tcc becomes a resonance with a three-body decay.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Algorithms and Artificial Intelligence / 54

Quantum Monte Carlo for Gauge Fields and Matter without the Fermion Determinant

Authors: Debasish Banerjee[None]; Emilie Huffman[1]

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Ab-initio Monte Carlo simulations of strongly-interacting fermionic systems are plagued by the fermion sign problem, making the non-perturbative study of many interesting regimes of dense quantum matter, or of theories of odd numbers of fermion flavors, challenging. Moreover, typical fermion algorithms require the computation (or sampling) of the fermion determinant. We focus instead on the meron cluster algorithm, which can solve the fermion sign problem in a class of models without involving the determinant. We develop and benchmark new meron algorithms to simulate fermions coupled to Z2 and U(1) gauge fields to uncover potential exotic properties of matter, particularly relevant for quantum simulator experiments. We demonstrate the emergence of the Gauss' Law at low temperatures for a U(1) model in (1+1)−d

Topical area:

Algorithms and Artificial Intelligence

Particle Physics Beyond the Standard Model / 55

Running Vacuum Energy on EDT Lattice

Authors: Jack Laiho[1]; Judah Unmuth-Yockey[2]; Marc Schiffer[None]; Mingwei Dai[1]

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Euclidean Dynamical Triangulation as a lattice approach to quantum gravity has produced results that are compatible with semiclassical gravity in four dimensions. We explore the cosmological application of EDT by studying the behavior of the vacuum energy on the lattice. Although the lattice gravity calculations are broadly consistent with an emergent four-dimensional de Sitter space geometry, the calculations give corrections to a purely constant cosmological constant term. These corrections are well described by a simple model for running vacuum energy. The parameters of this model are fully determined by the lattice and can be compared with observational cosmology, which will strongly constrain this picture over the coming decade.

Topical area:

Particle Physics Beyond the Standard Model

Structure of Hadrons and Nuclei / 56

A new approach for computing GPDs from asymmetric frames

Authors: Andreas Metz[1]; Fernanda Steffens[2]; Joshua Miller[3]; Krzysztof Cichy[4]; Martha Constantinou[3]; Peter Petreczky[5]; Shohini Bhattacharya[6]; Swagato Mukherjee[6]; Xiang Gao[7]; Yong Zhao[8]

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Recently, significant progress has been made in improving the efficiency and computational speed of lattice QCD calculations associated with Generalized Parton Distributions (GPDs). These advancements are a result of employing asymmetric frames, which differ from the commonly used symmetric frames, and introducing flexibility in the distribution of transferred momentum. A key element of our approach involves utilizing a Lorentz covariant parameterization for the matrix elements in terms of Lorentz-invariant amplitudes. This enables us to establish connections between matrix elements in different frames. Furthermore, we utilize the amplitude-based approach to propose an alternative definition of quasi-GPDs. This alternative definition not only maintains frame independence but also holds the potential for reduced power corrections when matching with light-cone GPDs. We thoroughly explore the interpretations of these new definitions, carefully examining the intricacies involved, and addressing the important issue of uniqueness/non-uniqueness in their formulation. In this presentation, we discuss these theoretical advancements, focusing specifically on the axial-vector GPDs $\widetilde{H}$ and $\widetilde{E}$.

Topical area:

Structure of Hadrons and Nuclei

Hadronic and Nuclear Spectrum and Interactions / 57

Doubly charmed tetraquark T_{cc}^{+} in (2+1)-flavor lattice QCD near physical point

Authors: Sinya Aoki[1]; Yan Lyu[2]

Co-authors: Takumi Doi [3]; Tetsuo Hatsuda [3]; Yoichi Ikeda [4]; Jie Meng [2]

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The doubly charmed tetraquark T_{cc}^{+} recently discovered by the LHCb collaboration is studied on the basis of (2 + 1)-flavor lattice QCD simulations of D^*D system with nearly physical pion mass $m_\pi = 146$ MeV. The interaction of D^*D in the isoscalar and S-wave channel, derived from the

hadronic spacetime correlation by the HAL QCD method, is attractive for all distances and leads to a near-threshold virtual state with a pole position $E_{\rm pole} = -38(73)(^{+20}_{-53})$ keV and a large scattering length $1/a_0 = -0.05(5)(^{+2}_{-2})$ fm^{-1}. The virtual state is shown to evolve into a loosely bound state as m_π decreases to its physical value by using a potential modified to $m_\pi = 135$ MeV based on the pion-exchange interaction. Such a potential is found to give a semi-quantitative description of the LHCb data on the $D^0D^0\pi^+$ mass spectrum.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

QCD at Non-zero Density / 58

Speed of sound exceeding the conformal bound in dense 2-color QCD

Author: Etsuko Itou[1]

Co-author: Kei Iida [2]

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We obtain the equation of state (EoS) for two-color QCD at low temperature and high density from the lattice Monte Carlo simulation. Two-color QCD is a good toy model of a real three-color QCD. The advantage to study this model is that the sign problem is absent even in a finite density regime because of the pseudo-reality of the quark field. We find that the speed of sound exceeds the conformal bound (c_s^2/c^2=1/3) after BEC-BCS crossover in the superfluid phase. Such an excess of the sound velocity is previously unknown from any lattice calculations for QCD-like theories. This finding might have a possible relevance to the EoS of neutron star matter revealed by recent measurements of neutron star masses and radii. This talk is based on PTEP 2022 (2022) 11, 111B01 (e-Print: 2207.01253).

Topical area:

QCD at Non-zero Density

Hadronic and Nuclear Spectrum and Interactions / 59

Investigations of nucleon-pion states

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We present an analysis of the $N\pi$ contribution to the determination of the nucleon mass spectrum using constrained fits. Our study involves simultaneous fitting of $N \to N$ and $N \to N\pi$ correlation functions. The analysis is performed on a $24^3 \times 48 \times 24$ lattice with $2+1$ dynamical Domain-Wall fermions. We employ a lattice spacing of $a^{-1} = 1.74$ GeV and a pion mass of $m_\pi = 279$ MeV. Further, we will discuss our preliminary results for the computation of the nucleon axial charge.

Topical area:

Structure of Hadrons and Nuclei

QCD at Non-zero Temperature / 60

Degrees of freedom in various charm subsectors from Lattice QCD

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We establish that the charmed hadrons start dissociating at the chiral crossover temperature, $\mathrm{T_{pc}}$, leading to the appearance of charm degrees freedom carrying fractional baryon number. Our method is based on analyzing the second and fourth-order cumulants of charm (C) fluctuations, and their correlations with baryon number (B), electric charge (Q) and strangeness (S) fluctuations. First-time calculation of the QC correlations on the high statistics ($\mathrm{N}_\tau = 8$) datasets of the HotQCD Collaboration enables us to disentangle the contributions from different electrically-charged charm subsectors at and close to $\mathrm{T_{pc}}$. In particular, we see an enhancement over the PDG expectation in the fractional contribution of the $|\mathrm{Q}| = 2$ charm subsector to the total charm partial pressure for $\mathrm{T} < \mathrm{T_{pc}}$; this enhancement is in agreement with the Quark Model extended Hadron Resonance Gas (QM-HRG) model calculations. Furthermore, the agreement of QM-HRG calculations with the projections onto charmed baryonic and mesonic correlations in different charm subsectors indicates the existence of not-yet-discovered charmed hadrons in all charm subsectors below $\mathrm{T_{pc}}$.

For $\mathrm{T_{pc}} < \mathrm{T} < 240$ MeV, our data are well-described by a non-interacting gas of charmed quasi-particles composed of meson, baryon and quark-like excitations. We find no evidence for the existence of charmed diquarks above $\mathrm{T_{pc}}$. In addition to this, we find a clear agreement between three independent observables which correspond to the partial pressures of i) $\mathrm{B} = 1/3$, ii) $\mathrm{Q} = 2/3$, and iii) $\mathrm{B} = 1/3$ and $\mathrm{Q} = 2/3$ charm subsectors; this further supports the presence of charm-quark-like excitations in QGP. Moreover, similar to $\mathrm{T} < \mathrm{T_{pc}}$ regime, we conclude that for $\mathrm{T} > \mathrm{T_{pc}}$, the $|\mathrm{Q}| = 2$ charm subsector is solely composed of baryon-like states. For 240 MeV $< \mathrm{T} \leq 340$ MeV, our results approach the free charm-quark gas limit.

Topical area:

QCD at Non-zero Temperature

Quark and Lepton Flavor Physics / 61

Structure-dependent form factors in radiative leptonic decays of the D_s meson with Domain Wall fermions

Authors: Davide Giusti[1]; Christopher F. Kane[2]; Christoph Lehner[1]; Stefan Meinel[2]; Amarjit Soni[3]

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In the region of hard photon energies, radiative leptonic decays represent important probes of the internal structure of hadrons. Moreover, radiative decays can provide independent determinations of Cabibbo-Kobayashi-Maskawa matrix elements with respect to purely leptonic or semileptonic channels. Prospects for a precise determination of leptonic decay rates with emission of a hard photon are particularly interesting, especially for the decays of heavy mesons for which currently only model-dependent predictions, based on QCD factorization and sum rules, are available to compare with existing experimental data.
We present a non-perturbative lattice calculation of the structure-dependent form factors which contribute to the amplitudes for radiative leptonic decays of the D_s meson, $D_s^+ \to \ell^+ \nu_\ell \gamma$, using a domain-wall action for all quark flavors. We show how to best control two sources of systematic error inherent in the calculation, specifically the unwanted excited states created by the meson interpolating field, and unwanted exponentials in the sum over intermediate states.
With moderate statistics, thanks to the use of an infinite-volume approximation method and improved estimators, we are able to provide rather precise, first-principles results for the structure-dependent vector and axial form factors in the full kinematical (photon-energy) range. Our continuum-extrapolated lattice determinations may then be employed to compute the differential decay rate and the corresponding branching fraction and make comparisons with existing experimental data.

Topical area:

Quark and Lepton Flavor Physics

Structure of Hadrons and Nuclei / 62

Lattice QCD prediction of pion and kaon electromagnetic form factor at large Q^2 up to 10 and 28 GeV^2

Author: Qi Shi[None]

Co-authors: Heng-Tong Ding [1]; Xiang Gao [2]; Andrew Hanlon [3]; Swagato Mukherjee [4]; Philipp Scior [5]; Sergey Syritsyn [6]; Yong Zhao [7]; Peter Petreczky [8]

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The electromagnetic form factor, especially its asymptotic behavior for large momentum transfer (Q^2), of pion and kaon provides crucial insight into the partonic structure of a Nambu-Goldstone boson in the strong interaction. Studies of the electromagnetic form factor of pion and kaon up to Q^2 ~ 6 GeV^2 are underway at the ongoing JLab12 experiment and its measurements in an extended range of Q^2 ~ 10 – 40 GeV^2 are planned at the future Electron-Ion Collider (EIC). For the first time, we will

present results for the pion and kaon electromagnetic form factor in the range of $Q^2 \sim 0-10$ and 28 GeV^2, respectively, from state-of-the-art lattice QCD calculations carried out using physical values of up, down, and strange quark masses. These results will provide benchmark QCD predictions for model-based studies and the experimental measurements, in particular at the boundaries between the JLab12 and the EIC.

Topical area:

Structure of Hadrons and Nuclei

Structure of Hadrons and Nuclei / 63

Renormalization of nonlocal gluon operators in lattice perturbation theory

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In this study, we investigate renormalization of gauge-invariant nonlocal gluon operators up to one-loop in lattice perturbation theory. Our computations have been performed in both Dimensional and lattice regularizations, using the Symanzik improved gluon action, leading to the renormalization functions in the modified Minimal Subtraction ($\overline{MS}$) scheme, as well as conversion factors from the modified regularization invariant (RI') scheme to the $\overline{MS}$ scheme.

Topical area:

Structure of Hadrons and Nuclei

Quantum Computing and Quantum Information / 64

Testing importance sampling on a quantum annealer for strong coupling lattice QCD

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Quadratic Unconstrained Binary Optimization (QUBO) problems can be addressed on quantum annealing systems. We reformulate the strong coupling lattice QCD dual representation as a QUBO matrix. We confirm that importance sampling is feasible on the D-Wave Advantage quantum annealer. We describe the setup of the system and present the first results obtained on a D-wave quantum annealer for U(N) gauge group. Furthermore, we outline a strategy for going to larger volumes and tackling the SU(N) gauge theory which has the sign problem.

Topical area:

Quantum Computing and Quantum Information

Hadronic and Nuclear Spectrum and Interactions / 65

Computation of relativistic corrections to the static potential from generalized Wilson loops at finite flow time

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We present results for O(1/m) and O(1/m^2) relativistic corrections to the static potential. The potentials are computed using Wilson loops with two colour-field insertions. To renormalize the inserted fields, we applied Gradient flow to the correlator. This also leads to a significant improvement of the signal-to-noise ratio, providing access to loops with large spatial and temporal extent.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

QCD at Non-zero Density / 66

Applying the Worldvolume Hybrid Monte Carlo method to dynamical fermion systems

Authors: Masafumi Fukuma[1]; Yusuke Namekawa[2]

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The sign problem has been a major obstacle to first-principles calculations in various important physical systems. The Worldvolume Hybrid Monte Carlo (WV-HMC) method [Fukuma-Matsumoto 2020] may be a promising method towards solving the sign problem due to its versatility, reliability and low numerical cost. In this talk, I would like to report recent results on the application of the WV-HMC method to dynamical fermion systems. The emphasis will be on the Hubbard model, which is one of the simplest dynamical fermion systems that have the sign problem.

Topical area:

QCD at Non-zero Density

QCD at Non-zero Density / 67

Applying the Worldvolume Hybrid Monte Carlo method to the complex ϕ^4 theory at finite density

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The sign problem has been an obstacle to first-principles calculations based on the Monte Carlo method. The Worldvolume Hybrid Monte Carlo (WV-HMC) method [Fukuma-Matsumoto 2020] is an efficient method to reduce the sign problem with low cost. In this talk, I apply the WV-HMC to the complex ϕ^4 theory at finite density, and show that the computational cost is proportional to the degrees of freedom, N, in contrast to the N^3 scaling for other Lefschetz thimble methods.

Topical area:

QCD at Non-zero Density

QCD at Non-zero Temperature / 68

Thermal QCD phase transition with dynamical chiral fermions

Author: Andrey Kotov[None]

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We discuss the properties of Quantum Chromodynamics at finite temperature obtained by means of lattice simulations with the overlap fermion discretization. This fermion discretization preserves chiral symmetry even at finite lattice spacing. We present the details of the formulation and discuss the properties of the chiral thermal phase transition. We compare the results obtained with the chiral fermions with predictions by other fermion discretizations.

Topical area:

QCD at Non-zero Temperature

Theoretical Developments / 69

Prospects for the stout smearing as an equivalent approach to the Wilson flow

Authors: Keita Sakai[1]; Masato Nagatsuka[1]; Sasaki Shoichi[1]

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In this talk, we present the equivalence between the Wilson flow and the stout smearing. The similarity between these two methods was first pointed out by Lüscher's original paper on the Wilson flow. We first show the analytical equivalence of two methods, which indicates that the finite stout smearing parameter induces $O(a^2)$ correction. We secondly show that they remain equivalent in

numerical simulations within some numerical precision even with finite cutoffs and stout smearing parameters by directly comparing the expectation values of the action density and we shortly mention the use of the equivalence.

Topical area:

Theoretical Developments

Quark and Lepton Flavor Physics / 70

Rare K decays off and on the lattice

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Rare decays of charged and neutral Kaons will be discussed. Phenomenological works being done in collaboration with Enrico Lunghi and another one with Stefan Schacht will be discussed. Mode(s) that should be target for precision lattice study will be highlighted.

Topical area:

Quark and Lepton Flavor Physics

Algorithms and Artificial Intelligence / 71

Gauge-equivariant multigrid neural networks

Authors: Christoph Lehner[1]; Tilo Wettig[1]

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We show how multigrid preconditioners for the Wilson-clover Dirac operator can be constructed using gauge-equivariant neural networks. For the multigrid solve we employ parallel-transport convolution layers. For the multigrid setup we consider two versions: the standard construction based on the near-null space of the operator and a gauge-equivariant construction using pooling and subsampling layers. We show that both versions eliminate critical slowing down. We also show that transfer learning works and that our approach allows for communication-avoiding algorithms on large machines.

Topical area:

Algorithms and Artificial Intelligence

Theoretical Developments / 72

SymEFT predictions for local fermion bilinears

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Beyond spectral quantities, Symanzik Effective Theory (SymEFT) predictions of the asymptotic lattice-spacing dependence require the inclusion of an additional minimal basis of higher-dimensional operators for each local field involved in the matrix element of interest. Adding the proper bases for fermion bilinears of mass-dimension 3 allows to generalise previous predictions to matrix elements of those bilinears. The results should be incorporated in ansätze used in continuum extrapolations. Potential difficulties and pitfalls are being highlighted. The current work is limited to the use of Wilson or Ginsparg-Wilson quarks.

Topical area:

Theoretical Developments

Vacuum Structure and Confinement / 73

The chiral condensate at large N

Authors: Claudio Bonanno[1]; Pietro Butti[None]; Margarita Garcia-Perez[None]; Antonio Gonzalez-Arroyo[None]; Ken-Ichi Ishikawa[None]; Masanori Okawa[None]

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We present preliminary results for the large-N limit of the chiral condensate computed from twisted reduced models. We followed a two-fold strategy, one constiting in extracting the condensate from the quark-mass dependence of the pion mass, the other consisting in extracting the condensate from the mode number of the Dirac operator.

Topical area:

Vacuum Structure and Confinement

QCD at Non-zero Temperature / 74

Microscopic Encoding of Macroscopic Universality: Scaling properties of Dirac Eigenspectra near QCD Chiral Phase Transition

Authors: Heng-Tong Ding[1]; Peter Petreczky[2]; Swagato Mukherjee[3]; Wei-Ping Huang[1]

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Macroscopic properties of the strong interaction near its chiral phase transition exhibit scaling behaviors, which are the same as those observed close to the magnetic transition in a 3-dimensional classical spin system with $O(4)$ symmetry. We show the universal scaling properties of the chiral phase transition in Quantum Chromodynamics (QCD) at the macroscale are, in fact, encoded within the microscopic energy levels of its fundamental constituents, the quarks. We establish a connection between the cumulants of the chiral order parameter, i.e. the chiral condensate, and the correlations among the energy levels of quarks in the background of gluons, i.e. the eigenspectra of the massless QCD Dirac operator. This relation elucidates how the fluctuations of the chiral condensate arise from the correlations within the infrared part of the energy spectra of quarks, and naturally leads to generalizations of the Banks–Casher relation for the cumulants of the chiral condensate. Then, through (2+1)-flavor lattice QCD calculations with varying light quark masses near the QCD chiral transition, we demonstrate the correlations among the infrared part of the Dirac eigenvalue spectra exhibit same universal scaling behaviors as expected of the cumulants of the chiral condensate. We find that these universal scaling behaviors extend up to the physical values of the up and down quark masses. Our study reveals how the hidden scaling features at the microscale give rise to the macroscopic universal properties of QCD.

Topical area:

QCD at Non-zero Temperature

Standard Model Parameters / **75**

The determination of r_0 and r_1 in Nf=2+1 QCD.

Author: Tom Asmussen[1]

Co-authors: Roman Höllwieser [2]; Francesco Knechtli [1]; Tomasz Korzec [1]

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We determine the scales r_0, r_1, and the ratio r_0/r_1 for 2 + 1 flavour QCD ensembles generated by CLS. These scales are determined from an improved definition of the static force which we measure using Wilson loops and furthermore use to study the shape of the static potential. Our analysis involves various continuum and chiral extrapolations of data that covers pion masses between 130 MeV and 420 MeV and five lattice spacings down to 0.038 fm.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Theoretical Developments / **76**

A pion decay constant in the multi-flavor Schwinger model

Authors: Ivan Hip[1]; Jaime Fabián Nieto Castellanos[2]; Wolfgang Bietenholz[2]

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The pion decay constant F_π plays an important role in QCD and in Chiral Perturbation Theory. It is hardly known, however, that a corresponding constant exists in the Schwinger model with $N_f \geq 2$ degenerate fermion flavors. In this case, the "pion" does not decay and F_π is dimensionless. Still, F_π can be defined by 2d analogies to the Gell-Mann–Oakes–Renner relation, the residual "pion" mass in the δ-regime and the Witten-Veneziano formula. With suitable assumptions, simulation data inserted in these three QCD-inspired relations are all compatible with $F_\pi \simeq 1/\sqrt{2\pi}$ at zero fermion mass, and $N_f = 2, \ldots, 6$. Therefore this constant seems to be meaningful in the Schwinger model.

Topical area:

Theoretical Developments

QCD at Non-zero Density / 77

Complex control variates

Authors: Scott Lawrence[1]; Yukari Yamauchi[2]

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Contour deformation methods have succesfully tamed sign problems in low-dimensional fermionic lattice fields theories at finite density. However, one obstacle with these methods is that they do not guarantee the existence of an integration contour which solves the sign problem completely, thus making it difficult for the methods to be applied to larger and more complex systems, such as lattice QCD. In this talk, I will introduce a strict generalization of the contour deformation methods: complex control variates. In the path integral, we subtract a function from the distribution function such that the phase fluctuations in the distribution are reduced while the physics does not change. Subtraction functions which entirely remove the sign problem exist for any lattice theories, although it is difficult to find them. In practice, subtraction functions, which remove the sign problem sufficiently, can be constructed analytically or numerically with the help of machine learning. I will demonstrate this method with the classical Ising model and the 1+1-dimensional Thirring model at finite density.

Topical area:

QCD at Non-zero Density

Quark and Lepton Flavor Physics / 78

$|V_{us}|$ from kaon semileptonic form factor in $N_f = 2+1$ QCD at the physical point on (10 fm)^4

Author: Takeshi Yamazaki[1]

Co-authors: Ken-Ichi Ishikawa [2]; Naruhito Ishizuka [3]; Yoshinobu Kuramashi [3]; Yusuke Namekawa [4]; Yusuke Taniguchi [3]; naoya ukita [5]; Tomoteru Yoshie [3]

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We determine the value of $|V_{us}|$ using the kaon semileptonic form factor calculated from the PACS10 configurations, whose physical volumes are more than (10 fm)^4 at the physical point. The configurations were generated using the Iwasaki gauge action and $N_f = 2 + 1$ stout-smeared nonperturbatively $O(a)$ improved Wilson quark action at the three lattice spacings, 0.085, 0.063, and 0.041 fm. We present a preliminary result of the kaon semileptonic form factor calculated at the smallest lattice spacing. The value of $|V_{us}|$ in the continuum limit evaluated from our results including the new data is also presented. We compare our result of $|V_{us}|$ with the previous results and those through the kaon leptonic decay.

Topical area:

Quark and Lepton Flavor Physics

Structure of Hadrons and Nuclei / 79

Comparison with model-independent and dependent analyses for pion charge radius

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Traditionally, there has been a method to analyze the charge radius of the hadron based on the fits of its form factor with some model assumptions. Moreover, a completely different method has been proposed, which does not depend on the models. In this presentation, we explore several improvements to this model-independent method for analyzing the pion charge radius. Furthermore, we compare the results of the pion charge radius obtained from $N_f = 2+1$ lattice QCD data at $m_\pi = 0.51$ GeV using the three different methods: the traditional model-dependent method, the original model-independent method, and our improved model-independent method. In this comparison, we take into account systematic errors estimated in each analysis.

Topical area:

Structure of Hadrons and Nuclei

QCD at Non-zero Temperature / 80

Chiral transition via Strong Coupling expansion

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We investigate the chiral transition of $U(N)$ lattice gauge theory based on the strong coupling expansion. A generalized vertex model with vertices and weights derived from the tensor network approach of the dual representation of lattice QCD with staggered fermions is used and the configurations are sampled by the Metropolis algorithm. We study the chiral transition in the chiral limit and focus on the beta dependence of the second order chiral transition temperature T_c for different values of the gauge coupling. We compare different orders of truncations of the strong coupling expansion: $\mathcal{O}(\beta^0)$, $\mathcal{O}(\beta^1)$, and $\mathcal{O}(\beta^2)$. We comment on the prospects of extending to $SU(3)$ at finite density.

Topical area:

QCD at Non-zero Temperature

Quantum Computing and Quantum Information / 81

Three ways of calculating mass spectra for the 2-flavor Schwinger model in the Hamiltonian formalism

Author: Akira Matsumoto[1]

Co-authors: Etsuko Itou [1]; Yuya Tanizaki [1]

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We propose three independent methods to compute the hadron mass spectra of gauge theories in the Hamiltonian formalism. The determination of hadron masses is one of the key issues in QCD, which has been precisely calculated by the Monte Carlo method in the Lagrangian formalism. We confirm that the mass of hadrons can be calculated by examining correlation functions, the one-point function, or the dispersion relation in Hamiltonian formalism. These methods are suitable for quantum computation and tensor network approaches. The methods are demonstrated with the tensor network (DMRG) in the 2-flavor Schwinger model, which shares important properties with QCD. We show that the numerical results are consistent with each other and with the analytic prediction of the bosonization technique. We also discuss their efficiency and potential applications to other models.

Topical area:

Quantum Computing and Quantum Information

QCD at Non-zero Temperature / 82

Advancing real-time Yang-Mills: towards real-time observables from first principles

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The complex Langevin method shows great promise in enabling the calculation of observables for theories with complex actions. Nevertheless, real-time quantum field theories have remained largely unsolved due to the particular severity of the sign problem. In this contribution, we will discuss our recent progress in applying the complex Langevin method to SU(2) Yang-Mills theory in 3+1 dimensions. We introduce an anisotropic kernel that stabilises systems for real times longer than the inverse temperature - a first in this field. We provide explicit evidence of reproducing thermal relations among different types of propagators when the complex time path approaches the Schwinger-Keldysh contour. This method could pave the way for calculating transport coefficients and other real-time observables from first principles.

Topical area:

QCD at Non-zero Temperature

QCD at Non-zero Density / 83

The phase diagram at finite baryon and isospin densities at strong coupling

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The Hamiltonian formulation of lattice QCD with staggered fermions in the strong coupling limit can be extended to 2 flavors. It has no sign problem at non-zero baryon density and isospin densities and allows for Quantum Monte Carlo simulations. We have implemented a Quantum Monte Carlo algorithm to measure the baryon and isospin densities in the μ_B - μ_I plane in the chiral limit. We also comment on the possibility to carry out corresponding simulations on a quantum computer.

Topical area:

QCD at Non-zero Density

Quark and Lepton Flavor Physics / 84

$B_s \to K\ell\nu$ form factors from lattice QCD with domain-wall heavy quarks.

Authors: Protick Mohanta[1]; Takashi Kaneko[2]; Shoji Hashimoto[2]

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We report on our on-going study of the $B_s \to K\ell\nu$ decay in $N_f = 2+1$ lattice QCD. The M\"obius domain-wall action is employed for all quark flavors at a lattice cutoff of $a^{-1} \sim 2.5$ GeV. We present preliminary results for the relevant form factors extracted from correlator ratios by inspecting their ground state saturation.

Topical area:

Quark and Lepton Flavor Physics

Quantum Computing and Quantum Information / 85

State preparation in quantum simulations of lattice gauge theories

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State preparation is a crucial aspect of quantum simulation of quantum field theories. When aiming to simulate Standard Model physics, it is likely that fault-tolerant quantum computers will be required. In this regime, it is beneficial to consider algorithms that exhibit nearly optimal scaling with the problem parameters. Many of these algorithms rely on repeated calls to a block encoding of the Hamiltonian of interest. However, the construction of this block encoding is often a bottleneck in these algorithms, resulting in a large prefactor in the overall gate cost. To overcome this challenge, recent research has introduced several algorithms based on the Hamiltonian time evolution input model. In this approach, instead of querying the block encoding subroutine, one queries an exact time evolution circuit for some short period of time. In this talk, we will focus on one such algorithm called the Quantum Eigenvalue Transformation for Unitary Matrices (QETU). The physical system we consider is a particular formulation of U(1) lattice gauge theory in two spatial dimensions. In practice, we employ product formulas to approximate the time evolution circuit. By employing QETU, we are able to prepare the ground state of this system. Furthermore, we discuss how the gate count scales with the problem size, as well as discuss the effects of approximate implementation of time evolution via product formulas.

Topical area:

Quantum Computing and Quantum Information

Quark and Lepton Flavor Physics / 86

Status of next-generation $\Lambda_b \to p, \Lambda, \Lambda_c$ form-factor calculations

Author: Stefan Meinel[1]

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I will present preliminary results of next-generation lattice-QCD calculations of the $\Lambda_b \to p$, $\Lambda_b \to \Lambda$, and $\Lambda_b \to \Lambda_c$ form factors based on RBC/UKQCD gauge-field ensembles with 2+1 flavors of domain-wall fermions. Compared to the work published in 2015 and 2016, the new calculations include three additional ensembles (one with 139 MeV pion mass, one with 0.73 fm lattice spacing, and one with another volume) and were performed with a more accurate tuning of the charm and bottom anisotropic clover action parameters. I will also discuss a novel approach for the kinematic extrapolations of the form factors with dispersive bounds.

Topical area:

Quark and Lepton Flavor Physics

Quantum Computing and Quantum Information / 87

Investigating dynamical quantum phase transitions in the massive Thirring model using matrix product states

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Co-authors: Amit Singh [2]; Hao-Ti Hung [3]; Krzysztof Cichy [4]; Mari Carmen Banuls [5]; Ying-Jer Kao [3]

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We present our study of real-time dynamics and dynamical quantum phase transition (DQPT) in the (1+1)-dimensional massive Thirring mode using matrix product states (MPSs). Lattice regularisation of this model with Kogut-Susskind fermions corresponds to the XXZ spin chain with the presence of a constant and a staggered magnetic fields. In this work, we implement methods of variational uniform MPS and time-dependent variational principle for this spin chain. This allows us to carry out simulations directly in the thermodynamic limit. The search for DQPT is performed through examining effects of a global quantum quench on the Loschmidt echo along the real-time evolution of an initial ground state of the system. We show evidence of the connection between the occurrence of DQPT and the eigenvalue spectrum of a mixed transfer operator. Furthermore, we find that the presence of DQPT is closely related to the effective temperature of the initial state, defined as the temperature of the thermal equilibrium state with the same energy density.

Topical area:

Quantum Computing and Quantum Information

Algorithms and Artificial Intelligence / 88

Multi-Polynomial Monte Carlo for Trace Estimation in Lattice QCD

Author: Walter Wilcox[1]

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Estimating the trace of the inverse of a large matrix is an important problem in lattice quantum chromodynamics. A multilevel Monte Carlo method is proposed for this problem that uses different degree polynomials for the levels. The polynomials are developed from the GMRES algorithm for solving linear equations. To reduce orthogonalization expense, the highest degree polynomial is a composite or double polynomial found with a polynomial preconditioned GMRES iteration. Added to some of the Monte Carlo pieces is deflation of eigenvalues that reduces the variance. Deflation is also used for finding a reduced degree deflated polynomial. The new Multipolynomial Monte Carlo method can significantly improve the trace computation for matrices that have a difficult spectrum due to small eigenvalues.

Topical area:

Algorithms and Artificial Intelligence

QCD at Non-zero Temperature / 89

High temperature $U(1)_A$ restoration in the chiral limit

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We solve the long-standing problem concerning the fate of the chiral $U(1)_A$ symmetry in QCD-like theories at high temperature in the chiral limit. We introduce a simple instanton based random matrix model that precisely reproduces the properties of the lowest part of the lattice overlap Dirac spectrum. We show that in the chiral limit the instanton gas splits into a free gas component with a density proportional to m^{N_f} and a gas of instanton-antiinstanton molecules. The latter do not influence the chiral properties, but for any finite quark mass the free gas component produces a singular spectral peak at zero that dominates Banks-Casher type spectral sums. By calculating these we show that the difference of the pion and delta susceptibility vanishes only for three or more massless flavors, however the chiral condensate is zero already for two massless flavors.

Topical area:

QCD at Non-zero Temperature

Particle Physics Beyond the Standard Model / 90

Symmetric mass generation in lattice gauge theory

Author: Simon Catterall[1]

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We present results from simulations of a spin(4) lattice gauge theory in four
dimensions containing a single flavor of massless reduced staggered fermion. This model does not allow for single site gauge invariant bilinear fermion terms and instead
we show that it develops a four fermion condensate in the confining regime. The absence of symmetry breaking is consistent with the cancellation of a ‘t Hooft anomaly corresponding to a discrete Z_4 symmetry.
If the spin(4) symmetry is extended to SU(4) we argue that in the naive continuum limit the model contains the matter representations and global symmetries
of the Pati-Salam GUT model in which we can embed a single family of the Standard
Model

Topical area:

Particle Physics Beyond the Standard Model

Algorithms and Artificial Intelligence / 91

Methods for Bayesian model averaging

Author: Ethan Neil[1]

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Bayesian model averaging is a statistical method that allows for simple and methodical treatment of systematic errors due to model variation. I will summarize some recent results, including other model weights which can give more robust performance than the Akaike information criterion, as well as clarifying its use for data subset selection.

Topical area:

Algorithms and Artificial Intelligence

Software Development and Machines / 92

GPU-Enhanced Tensor Networks

Author: Abhishek Samlodia[1]

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Deep Learning Models in the Machine Learning Community relies heavily on GPU-based tensor calculations. In recent years, Tensor Networks Methods have been explored to estimate the Partition Function of a system deterministically. One of the reasons Tensor Networks have not been yet utilised to the maximum potential in the Lattice Gauge Theories is their time complexity issue of

the algorithms. Drawing motivation from these Machine Learning Models, we present a GPU-based acceleration of existing Tensor Networks Methods that reduces the simulation time.

Topical area:

Software Development and Machines

Quark and Lepton Flavor Physics / 93

Lattice Calculation of Electromagnetic Corrections to Kl3 decay

Authors: Luchang Jin[1]; Norman Christ[2]; Sachrajda Christopher[3]; Tianle Wang[4]; Xu Feng[5]

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We describe a first-principles method to apply lattice QCD to compute the order $\alpha_{\rm EM}$ corrections to $K \to \pi\ell\nu_\ell$ decay. This method formulates the calculation in infinite volume with the conventional infinite-volume, continuum treatment of QED. Infinite volume reconstruction is used to replace the QCD components of the calculation with finite-volume amplitudes which can be computed in Euclidean space using lattice QCD, introducing finite-volume errors which vanish exponentially as the volume used in the QCD calculation is increased. This approach has also been described in an appendix to the recent hep-lat posting 2304.08026.

Topical area:

Quark and Lepton Flavor Physics

Tests of Fundamental Symmetries / 94

The calculation of nucleon theta EDMs using background field method

Authors: Fangcheng He[None]; Hiroshi Ohki[None]; Michael Abramczyk[None]; Sergey Syritsyn[1]; Taku Izubuchi[2]; Thomas Blum[3]

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The measurements of nucleon Electric Dipole Moments (EDMs) are important to probe CP violation and physics beyond the Standard Model. In this talk, I will report our recent progress in calculating nucleon theta EMDs using background electric field. We extract neutron EMDs by measuring the energy shift of 2pt correlation function in the presence of background field. The gauge ensembles

are dynamical domain wall configurations with lattice spacings of a=0.11 fm and the corresponding pion mass are 340MeV and 430MeV, respectively.

Topical area:

Structure of Hadrons and Nuclei

QCD at Non-zero Density / 95

Monte Carlo study of Schwinger model without the sign problem

Author: Hiroki Ohata[1]

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In the conventional lattice formulation, conducting a Monte Carlo study of the Schwinger model (quantum electrodynamics in 1 + 1 dimensions) with a topological θ term or at finite density is almost impossible due to the sign problem. In this talk, I present the lattice formulation of the bosonized Schwinger model, which allows us to study the model using the Monte Carlo method without encountering the sign problem. I demonstrate the validity of the formulation by presenting numerical results at a finite θ angle and finite density. I also discuss possible applications of this formulation to other models.

Topical area:

QCD at Non-zero Density

Poster session / 96

New configuration set of the HAL QCD collaboration

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We report basic properties of our new configuration set.We calculated the topological charge, the mass spectra for hadrons, and so on.The lattice spacing, $a^{-1} = 2.339$[GeV], is fixed using the Omega baryon mass.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Hadronic and Nuclear Spectrum and Interactions / 97

Study on Lambda(1405) in the flavor SU(3) limit in the HAL QCD method

Authors: Kotaro Murakami[1]; Sinya Aoki[2]

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We perform a numerical study in lattice QCD on $\Lambda(1405)$, an excited Λ baryon whose existence is not well explained by the quark model. Since the previous studies using the chiral unitary model suggest that $\Lambda(1405)$ may be explained by two poles in the octet and the singlet channels of the flavor SU(3), we calculate the HAL QCD potentials for the meson-baryon systems in both channels using gauge configurations in the flavor SU(3) limit on 32^4 lattices with the meson mass $m_M \approx 670$ MeV. We successfully extract a one-parameter family of potentials in the octet channel, all of which indicate an existence of one bound state. We find that the binding energy calculated from the meson-baryon potential in the octet channel is consistent with the one estimated from the octet baryon two-point function, though errors are much larger for the former. In the singlet channel, however, an existence of a zero point in the NBS wave function leads to a singular potential, which prevents a reliable extraction of the binding energy. We briefly discuss a possible solution to overcome this difficulty in a future study.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

QCD at Non-zero Temperature / 98

Characterizing Strongly Interacting Matter at Finite Temperature: (2+1)-Flavor QCD with MDWF Fermions

Author: Jishnu Goswami[1]

Co-authors: Hidenori Fukaya [2]; Issaku Kanamori [3]; Shoji Hashimoto [4]; Sinya Aoki [5]; Takashi Kaneko [4]; Yasumichi Aoki [6]; Yoshifumi Nakamura [7]; Yu Zhang [8]

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Quantum chromodynamics (QCD) which is the theory of strong interactions describes the thermodynamics of strongly interacting matter at finite temperatures and densities. At low temperatures, chiral symmetry is broken in the QCD vacuum and as temperature increases, a transition occurs where chiral symmetry is restored, resulting in the formation of the quark gluon plasma (QGP). It is found that for the vanishing values of the light quark masses this is a
true phase transition from low to high temperatures. However, for the finite values of light quark masses, it is a smooth crossover transition from hadronic bound states to the quark gluon plasma (QGP).

In this talk, we will report our ongoing calculations of the (2+1)-flavor QCD thermodynamics with Mobius Domain Wall fermions. We consider a fifth dimension with a length of twelve, which controls the effect of the residual mass (m_{res}) reasonably well[1,2]. We will present chiral condensate and chiral susceptibilities calculated on several lattice spacings and lattice
volumes along the line of constant physics. Furthermore, we will also present preliminary results of quark number susceptibilities and conserved charge fluctuations.
[1] Thermodynamics with Möbius domain wall fermions near physical point (I), Y. Aoki, Lattice2022
[2] Thermodynamics with Möbius domain wall fermions near physical point (II), I. Kanamori, Lattice2022, PoS LATTICE2022 (2023) 176

Topical area:

QCD at Non-zero Temperature

Structure of Hadrons and Nuclei / 99

Proton and neutron electromagnetic charge radii and magnetic moments from $N_f = 2 + 1$ lattice QCD

Author: Miguel Salg[1]

Co-authors: Dalibor Djukanovic [2]; Georg von Hippel [1]; Harvey B. Meyer [3]; Konstantin Ottnad [4]; Hartmut Wittig [5]

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We present results for the electromagnetic form factors of the proton and neutron computed on the $(2+1)$-flavor Coordinated Lattice Simulations (CLS) ensembles including both quark-connected and -disconnected contributions. The Q^2-, pion-mass, lattice-spacing, and finite-volume dependence of our form factor data is fitted simultaneously to the expressions resulting from covariant chiral perturbation theory including vector mesons amended by models for lattice artefacts. From these fits, we determine the electric and magnetic charge radii and the magnetic moments of the proton and neutron. To assess the influence of systematic effects, we average over various cuts in the pion mass and the momentum transfer, as well as over different models for the lattice-spacing and finite-volume dependence, using weights derived from the Akaike Information Criterion (AIC). Our results for the magnetic moments of the proton and neutron are in good agreement with the experimental values and have a relative precision of about $2.5\,\%$ and $4\,\%$, respectively. For the electromagnetic charge radii of the proton, we achieve a $1.5\,\%$-level precision.

Topical area:

Structure of Hadrons and Nuclei

Theoretical Developments / 100

Spin-taste structure of minimally doubled fermions

Author: Johannes Heinrich Weber[1]

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Minimally doubled fermions realize one degenerate pair of Dirac fermions on the lattice. Similarities to staggered fermions exist, namely, spin and taste degrees of freedom become intertwined, and a remnant, non-singlet chiral symmetry and ultralocality are maintained. However, charge conjugation, isotropy and some space-time reflection symmetries are broken by the cutoff.
For two variants, i.e., Karsten-Wilcek (KW) or Borici-Creutz (BC) fermions, a tasted charge conjugation symmetry can be identified, and the respective representations of the spin-taste algebra can be constructed explicitly. In the case of BC fermions, the tasted symmetry indicates that amendments to the published counterterms are necessary.
The spin-taste representation on the quark level permits construction of local or extended hadron interpolating operators for any spin-taste combination, albeit with contamination by parity partners and taste-symmetry violation. The few available numerical results for KW fermions are in line with expectations.

Topical area:

Theoretical Developments

Poster session / 101

Sphaleron Rate from Lattice Gauge Theory

Author: Johannes Heinrich Weber[1]

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The "Sphaleron Rate" (imaginary linear-in-frequency part of the topological density retarded Green's function) determines the real-time relaxation rate of axial quark number for light quarks in a hot medium, and is relevant in heavy-ion collisions and electroweak baryogenesis. We recently showed how it can be determined in pure-glue QCD via standard Euclidean simulations, via a novel saddle-point method.
We extend this work to find the sphaleron rate for (2+1)-flavor QCD with $N_\tau = 8 - 16$ and HISQ action at almost physical pion masses in the temperature range $0.2 - 3$ GeV or $1.2 - 18$ times the crossover temperature T_{pc}. Similar to the pure gauge case, the QCD result is well described across the range of $1.6 - 8$ times T_{pc} as $\Gamma_s \simeq 20(\alpha_s T)^4$, where α_s is the MSbar coupling at $\overline{\mu} = 2\pi T$, determined using the gradient-flow technique.

Topical area:

QCD at Non-zero Temperature

Quantum Computing and Quantum Information / 102

Entanglement entropy from non-equilibrium lattice simulations

Authors: Andrea Bulgarelli[1]; Marco Panero[1]

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The entanglement entropy is a quantity encoding important features of strongly interacting quantum many-body systems and gauge theories, but its analytical study is still limited to systems with high level of symmetry. This motivates the search for efficient techniques to investigate this quantity numerically, by means of Monte Carlo calculations on the lattice. In this talk, we present a lattice determination of the entropic c-function using a novel algorithm based on Jarzynski's equality: an exact theorem from nonequilibrium statistical mechanics. After presenting benchmark results for the Ising model in two dimensions, where our algorithm successfully reproduces the analytical predictions from conformal field theory, we discuss its generalization to the three dimensional Ising model, for which we were able to extract universal terms beyond the area law. Finally we comment on future applications to gauge theories.

Topical area:

Quantum Computing and Quantum Information

Quark and Lepton Flavor Physics / 103

Bayesian inference for form-factor fits regulated by unitarity and analyticity

Authors: Andreas Juettner[1]; Jonathan Flynn[2]; Justus Tobias Tsang[3]

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I discuss a model-independent framework for fitting hadronic form-factor data, which is often only available at discrete kinematical points, using parameterisations based on unitarity and analyticity. The accompanying dispersive bound on the form factors (unitarity constraint) is used to regulate the ill-posed fitting problem and allow model-independent predictions over the entire physical range. Kinematical constraints, for example for the vector and scalar form factors in semileptonic meson decays, can be imposed exactly. The core formulae are straight-forward to implement with standard math libraries. I demonstrate the method for the exclusive semileptonic decay $B_s \to K\ell\nu$, an example requiring one to use a generalisation of the original Boyd~Grinstein~Lebed (BGL) unitarity constraint.

Topical area:

Quark and Lepton Flavor Physics

Quark and Lepton Flavor Physics / 104

Form factors for the charm-baryon semileptonic decay $\Xi_c \to \Xi\ell\nu$ from domain-wall lattice QCD

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Recent experimental progress measuring the branching fractions of the heavy-baryon semileptonic decays $\Xi_c \to \Xi\ell\nu$ have stimulated theoretical interest and motivate precise lattice calculations of the form factors. Here we present such a calculation using domain-wall fermions for the up, down, and strange quarks, and an anisotropic clover action for the charm quark. We use four ensembles generated by the RBC and UKQCD collaborations, with lattice spacings between 0.111 and 0.073 fm and pion masses ranging from 420 to 230 MeV. Our preliminary results for the form factors are larger in magnitude than previous lattice results.

Topical area:

Quark and Lepton Flavor Physics

Quark and Lepton Flavor Physics / 105

$K_L \to \mu^+\mu^-$ from lattice QCD

Authors: En-Hung Chao[1]; Luchang Jin[2]; Norman Christ[1]; Xu Feng[3]

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We discuss the applicability of lattice QCD to the long-distance (LD) two-photon contribution to the decay of a long-lived neutral kaon into a charged-muon pair (KL2mu). In the absence of QED, the flavor-changing neutral-current KL2mu process requires exchanging at least two W-bosons or a W- and a Z-boson, the short-distance (SD) contribution. Such a process is suppressed by two factors of the Fermi constant G_F and the appearance of loop diagrams makes it sensitive to physics at higher energy scales. Despite its rareness, the experimental KL2mu decay rate is known to 1.6 percent, which makes it an appealing precision probe of the Standard Model. With QED, the two-photon exchange contribution to KL2mu enters at O($G_F\alpha_{QED}^2$). This LD two-photon contribution is of the same order as the SD contribution predicted by electroweak perturbation theory. We demonstrate that it is possible to make a first-principles calculation of the full complex LD two-photon decay amplitude using lattice QCD; in particular, the dispersive part of the amplitude, which is inaccessible from phenomenology, can be obtained. Preliminary numerical results of the quark-connected contribution will be presented.

Topical area:

Quark and Lepton Flavor Physics

QCD at Non-zero Temperature / 107

Chiral susceptibility and axial U(1) anomaly near the (pseudo-)critical temperature

Authors: David Ward[1]; Hidenori Fukaya[1]; Issaku Kanamori[2]; Kei Suzuki[3]; Shoji Hashimoto[4]; Sinya Aoki[5]; Takashi Kaneko[4]; Yasumichi Aoki[2]; Yoshifumi Nakamura[6]

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We investigate a possible relation between the chiral susceptibility and axial U(1) anomaly in lattice QCD at high temperatures. Employing the exactly chiral symmetric Dirac operator, we can separate the purely axial U(1) breaking effect in the connected and disconnected chiral susceptibilitesin a theoretically clean manner. Preliminary results for 2 and 2+1 flavor lattice QCD near the critical temperature will be presented.

Topical area:

QCD at Non-zero Temperature

QCD at Non-zero Temperature / 108

Exploring the QCD phase diagram with three flavors of Möbius domain wall fermions

Author: Yu Zhang[1]

Co-authors: Yasumichi Aoki [2]; Shoji Hashimoto [3]; Issaku Kanamori [4]; Takashi Kaneko [3]; Yoshifumi Nakamura [5]

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The order of finite temperature QCD phase transition on the lower left corner of Columbia plot is yet to be determined, and the current studies show that the bound of critical mass has a strong cutoff and discretization scheme dependence. We present an update on the QCD phase transition with 3 flavors of Möbius domain wall fermions at zero chemical potential. We performed simulations on lattices of size $36^3 \times 12 \times 16$, $24^3 \times 12 \times 32$ and $36^3 \times 14 \times 16$ with a varity of quark masses at lattice spacing $a = 0.1361(20)$ fm. Our previous study with one volume ($24^3 \times 12 \times 16$) appeared to be consistent with a crossover at quark mass around 4 MeV ($\overline{\mathrm{MS}}$, 2 GeV) for temperature 121 MeV by investigating the Binder cumulant [1]. Now we add the larger volume ($36^3 \times 12 \times 16$) computation to investigate the volume dependence towards the thermodynamic limit for this temperature. In this talk, we will show the results of such analyses to discuss the nature of transition there. Besides that, with the newly generated lattices $24^3 \times 12 \times 32$, we will show the the effects of residual chiral symmetry breaking on the observables by using different L_s.

[1] Finite temperature QCD phase transition with 3 flavors of Möbius domain wall fermions, Yu Zhang et al., PoS LATTICE2022 (2023) 197

Topical area:

QCD at Non-zero Temperature

Quark and Lepton Flavor Physics / 109

Nonperturbative renormalization of HQET operators in position space

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Co-authors: William Detmold [1]; Stefan Meinel [2]

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Position-space schemes are very natural gauge-invariant non-perturbative renormalization schemes to implement on the lattice. The tradeoff is that the perturbative calculations required to convert to more typically used schemes such as MS are more theoretically involved. We present dimensionally regulated perturbative calculations of a set of HQET operators in position-space, allowing for conversion of bare matrix elements measured on the lattice to MS. The operators of interest include those appearing in the OPE for lifetime measurements of B-hadrons.

Topical area:

Quark and Lepton Flavor Physics

Structure of Hadrons and Nuclei / 110

The pion scalar form factor with $N_f = 2+1$ Wilson fermions

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We report preliminary results from an analysis of the pion scalar form factor computed on a set of the $\mathrm{tr}[M] = \mathrm{const}$ CLS gauge ensembles with $N_f = 2+1$ Wilson Clover-improved sea quarks. The calculations are carried out for light quarks masses corresponding to $M_\pi \approx 0.130\mathrm{MeV} \ldots 350\mathrm{MeV}$, four values of the lattic spacing $a \approx 0.050\mathrm{fm} \ldots 0.086\mathrm{fm}$ and a large range of physical volumes. A fine-grained momentum resolution is achieved by allowing for non-vanishing sink momenta and by including two particularly large and fine boxes close to physical quark masses (i.e. $T \times L^3 = 192 \times 96^3$, $M_\pi \leq 172\mathrm{MeV}$, $a \leq 0.064\mathrm{fm}$).
The pertinent quark disconnected contributions have been computed to high precision using a scheme combining 1.) the one-end trick on stochastic volume sources for the computation of differences between two quark flavors with 2.) the hopping parameter expansion and hierarchical probing to evaluate the loops for the heaviest, single quark flavor.

Topical area:

Structure of Hadrons and Nuclei

Quantum Computing and Quantum Information / 111

Improved Fermion Hamiltonians for quantum simulations

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Constructing improved Hamiltonians for gauge theories coupled to fermionic matter will be important for improving continuum limit extrapolations of quantum computations. In this talk we will present a formulation for simulating ASQTAD fermions for lattice computation and provide fault tolerant resource costs in terms of primitive operations. We additionally show tha tthe scaling of energies with respect to the lattice spacing are better than for the unimproved Hamiltonian in toy models

Topical area:

Quantum Computing and Quantum Information

Structure of Hadrons and Nuclei / 113

Parton Distributions from Boosted Fields in the Coulomb Gauge

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In this talk, we will discuss a new method to calculate parton distribution functions (PDFs) from correlations of boosted quarks and gluons in the Coulomb gauge.
Compared to the widely used quasi-PDFs defined from gauge-invariant Wilson-line operators, such correlations offer advantages including absence of linear power divergence, enhanced long-range precision, and accessibility to larger off-axis momenta. We verify the validity of this method at next-to-leading order in perturbation theory and use it to calculate the pion valence quark PDF on a lattice with spacing $a = 0.06$ fm and valence pion mass $m_\pi = 300$ MeV.
Our result agrees with that from the gauge-invariant quasi-PDF at similar precision, achieved with only half the computational cost through a large off-axis momentum $|\vec{p}| \sim 2.2$ GeV.

Topical area:

Structure of Hadrons and Nuclei

Vacuum Structure and Confinement / 114

Renyi Entropy due to the Presence of Static Quarks

Authors: Rocco Amorosso[None]; Sergey Syritsyn[1]

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We study the entanglement entropy in SU(3) pure gauge theory due to the presence of static quarks. Using a replica approach we investigate the q=2 Renyi entropy across various partitions of space A and \bar{A}. We use this to find the excess entanglement entropy induced by the presence of a quark pair in confinement, and by the presence of a single quark in deconfinement. At 4/3 Tc, we find that the entanglement entropy scales to zero, while at Tc/2, we find the entropy scales to a finite non-zero value in the continuum. In the latter case, we explore the entanglement entropy induced by the QCD string in both longitudinal and transverse directions. We also show preliminary results suggesting the entanglement entropy scales with the surface area of the region.

Topical area:

Vacuum Structure and Confinement

Particle Physics Beyond the Standard Model / 115

The f_PS / m_V and f_V / m_V ratios and the conformal window

Author: Daniel Nogradi[1]

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The mesonic f_{PS}/m_V and f_V/m_V ratios, with f the decay constant and m the meson mass, are calculated in mass perturbed conformal gauge theories to NNLO and N^{3}LO orders, respectively. Here NNLO and N^{3}LO refer to the non-relativistic effective theory expansion which is the applicable framework. The results are expanded a la Banks-Zaks in order to end up with scheme-independent predictions. These perturbative results are unambiguously reliable close to the upper end of the conformal window, $N_f = 16.5$ and it is shown that they might be reliable down to $N_f = 12$. An attempt is made to match these to previous non-perturbative lattice results in the range $2 \leq N_f \leq 10$ range. An abrupt change in the ratios is observed at around $N_f = 12 - 13$, which may signal the lower end of the conformal window.

Topical area:

Particle Physics Beyond the Standard Model

Poster session / 116

Progress report on data analysis of 2 point correlation functions for semileptonic decay $B_{(s)} \rightarrow$D_{(s)}^{(\ast)} \ell\nu$ form factors

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We report recent progress in data analysis on the two point correlation functions

which will be used to obtain form factors for the semileptonic decays $B_{(s)} \to D_{(s)}\ell\nu$.

We use a MILC HISQ ensemble ($a = 0.12fm$ and $m_\pi = 310MeV$) to produce the measurement data

using the HISQ light quarks and Oktay-Kronfeld (OK) action for the heavy quarks($N_f = 2+1+1$ flavor).

We used a sequential Bayesian method for the analysis and adopt the Newton

method to improve the fitting quality and logistics.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Quark and Lepton Flavor Physics / **117**

Semileptonic Form Factors for $B \to D^*\ell\nu$ Decays using the Oktay-Kronfeld Action

Authors: Benjamin Jaedon Choi[1]; JEONGHWAN PAK[2]; Jaehoon Leem[3]; Rajan Gupta[4]; Seungyeob Jwa[1]; Sungwoo Park[5]; Sunkyu Lee[1]; Tanmoy Bhattacharya[5]; Weonjong Lee[1]; Yong-Chull Jang[6]

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We present recent progress on the lattice calculation of semileptonic form factors for $B \to D^*\ell\nu$ decay using linear fit method. We use the Oktay-Kronfeld (OK) action for the charm and bottom valence quarks. We use results of 2pt correlator fit of B and D^* meson as input parameters to the data analysis on the 3pt correlation functions. Here, the masses of charm and bottom quark are tuned non-perturbatively. For the light spectator quarks (up, down and strange), we use HISQ action. Lattice calculation is done on a MILC HISQ ensemble ($a = 0.12\,\text{fm}$, $m_\pi = 220\,\text{MeV}$, and $N_f = 2+1+1$ flavors).

Topical area:

Standard Model Parameters

Algorithms and Artificial Intelligence / **118**

A solution for infinite variance problem of fermionic observables

Authors: Andrei Alexandru[1]; Paulo Bedaque[2]; Andrea Carosso[3]; Hyunwoo Oh[2]

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Monte Carlo simulations with continuous auxiliary fields encounter challenges when dealing with fermionic systems due to the infinite variance problem observed in fermionic observables. This issue renders the estimation of observables unreliable, even with an infinite number of samples. In this talk, I will propose an approach to address this problem by employing a reweighting method that utilizes the distribution from an extra time-slice. I will explore two strategies to compute the reweighting factor using Hubbard model: one involves truncating and analytically calculating the reweighting factor, while the other employs a secondary Monte Carlo estimation. Through our findings, I will demonstrate that utilizing the sub-Monte Carlo reweighting technique, coupled with an unbiased estimator, offers a solution that effectively mitigates the infinite variance problem at a minimal additional cost.

Topical area:

Algorithms and Artificial Intelligence

Poster session / 119

2023 update of ε_K with lattice QCD inputs

Authors: Jaehoon Leem[1]; Sunghee Kim[2]; Weonjong Lee[2]; Sungwoo Park[3]; Sunkyu Lee[2]; Yong-Chull Jang[4]

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We present recent progress in evaluatinging ε_K, the indirect CP violation parameter in the neutral kaon system, calculated using lattice QCD inputs directly from the standard model.

Topical area:

Quark and Lepton Flavor Physics

Theoretical Developments / 120

Non-equilibrium dynamics of topological defects in the 3D O(2) model

Authors: Elías Natanael Polanco Eúan[1]; Edgar López-Contreras[1]; Jaime Fabián Nieto Castellanos[2]; Wolfgang Bietenholz[1]

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We present a study of the 3D O(2) non-linear σ-model on the lattice, which manifests topological defects in the form of vortices. They tend to organize into vortex lines that bear strong analogies with global cosmic strings. Therefore, this model serves as a testbed for studying topological defects. Moreover, the model undergoes a second-order phase transition, hence it is appropriate for investigating the Kibble-Zurek mechanism for cosmic strings. We examine the persistence of topological defects as the temperature is rapidly reduced from above to below the critical temperature, leading to a cooling process that takes the system out of equilibrium. We explore a wide range of inverse cooling rates (τ_Q) and temperatures, employing several Monte Carlo algorithms. The results consistently show that the density of remaining topological defects follows a power-law in τ_Q, aligning with Zurek's proposal. However, we differ from Zurek's prediction for the exponent in this power-law.

Topical area:

Theoretical Developments

Algorithms and Artificial Intelligence / 121

Equivariant transformer is all you need

Author: Akio Tomiya[1]

Co-author: Yuki Nagai [2]

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Machine learning, deep learning, has been accelerating computational physics, which has been used to simulate systems on a lattice. Equivariance is essential to simulate a physical system because it imposes a strong induction bias for the probability distribution described by a machine learning model. However, imposing symmetry on the model sometimes occur a poor acceptance rate in self-learning Monte-Carlo (SLMC). On the other hand, Attention used in Transformers like GPT realizes a large model capacity. We introduce symmetry equivariant attention to SLMC. To evaluate our architecture, we apply it to our proposed new architecture on a spin-fermion model on a two-dimensional lattice. We find that it overcomes poor acceptance rates for linear models and observe the scaling law of the acceptance rate in machine learning. This talk is based on arXiv:2306.11527.

Topical area:

Algorithms and Artificial Intelligence

Quantum Computing and Quantum Information / 122

O(3) model in 1+1-dimensions using qumodes

Authors: Felix Ringer[1]; Raghav Jha[2]; George Siopsis[3]; Shane Thompson[3]

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We express non-linear sigma O(3) model in a form suited to continuous variable (CV) approach to quantum computing by rewriting the model in terms of boson operators in an infinite-dimensional Hilbert space. We show that it is possible to reach the scaling regime with truncation of the Fock space by considering $\mathcal{O}(10)$ photons at each site. This is an indication that it might be possible to reach the scaling regime with resources within the reach of photonics quantum hardware by the end of this decade.

Topical area:

Quantum Computing and Quantum Information

Poster session / 123

Sequential Bayesian fitting method for Pion mass spectrum with HYP-smeared staggered quarks.

Authors: Jeonghwan Pak[1]; Weonjong Lee[2]; Benjamin Jaedon Choi[2]

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We report recent progress on data analysis for 2-point correlation functions with HYP-smeared staggered quarks. We use the sequential Bayesian fitting method. We present how to obtain a good initial guess using the Newton method. We report results of fitting 2-point correlation functions, including the excited states, for $P \times P$ and $P \times A$ operators.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Quark and Lepton Flavor Physics / 124

Studies on finite-volume effects in the inclusive semi-leptonic decays of charmed mesons

Author: Ryan Kellermann[None]

Co-authors: Andreas Juettner [1]; Shoji Hashimoto [2]; Takashi Kaneko [2]; Alessandro Barone [1]

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We report on the progress in the analysis of the inclusive semi-leptonic decay of the D_s meson. This analysis is based on a pilot simulation conducted for the $D_s \to X_s \ell\nu$ process where we employed

Möbius domain-wall charm and strange quarks whose masses were tuned to be approximately physical and where we covered the whole kinematical region.
The focus of this talk is to present our progress in how the systematic error due to the presence of finite-volume effects can be estimated. Due to limitations in the available data, we construct a modelling strategy which is then used to fit to our lattice data to investigate the extrapolation to the infinite-volume limit. This procedure also includes a discussion of cut-off effects for higher energies which we encounter during the modelling stage of our data.

Topical area:

Quark and Lepton Flavor Physics

Quark and Lepton Flavor Physics / 125

Chebyshev and Backus-Gilbert reconstruction for inclusive semileptonic $B_{(s)}$-meson decays from Lattice QCD

Author: Alessandro Barone[1]

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We present a study on the nonperturbative calculation of observables for inclusive semileptonic decays of $B_{(s)}$-mesons using lattice QCD. We focus on the comparison of two different methods to analyse lattice data of Euclidean correlation functions and address inverse problems, specifically Chebyshev and Backus-Gilbert approaches. This type of computation may eventually provide new insight into the long-standing tension between the inclusive and exclusive determinations of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{cb}|$ and $|V_{ub}|$.
We report the results from a pilot lattice computation for the decay $B_s \to X_c\, l\nu_l$, where the valence quark masses are approximately tuned to their physical values using the relativistic-heavy quark action for the b quark and the domain-wall formalism for the other valence quarks. We address the computation of the total decay rate as well as leptonic and hadronic moments, discussing similarities and differences between the two analysis techniques.

Topical area:

Quark and Lepton Flavor Physics

QCD at Non-zero Temperature / 126

Critical point in heavy-quark region of QCD on fine lattices

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We perform a finite-size scaling analysis of the critical point in the heavy-quark region of QCD at nonzero temperature. Our previous analysis at $N_t = 4$ is extended to a finer lattice with $N_t = 6$ and 8. The aspect ratio is also extended up to 18 to suppress the non-singular contribution. High-precision analysis of the Binder cumulant is realized by an efficient Monte-Carlo simulation with the hopping parameter expansion (HPE). Effects of higher order terms in the HPE are incorporated by the reweighting method.

From the analysis of the Binder cumulant of the Polyakov loop, we show that the behavior of this quantity has a small but statistically-significant inconsistency with the scaling of the magnetic observable in the Z(2) universality class. We then try to construct the order parameter corresponding to the magnetic observable from the conditions between relevant observables at the critical point. It is shown that the scaling of the order parameter thus constructed reproduces the Z(2) scaling.

Topical area:

QCD at Non-zero Temperature

Hadronic and Nuclear Spectrum and Interactions / 127

Progress in generating gauge ensembles with Stabilized Wilson Fermions

Author: Anthony Francis[1]

Co-authors: Francesca Cuteri [2]; Patrick Fritzsch [3]; Giovanni Pederiva [4]; Antonio Rago [5]; Andrea Shindler [4]; Andre Walker-Loud [6]; Savvas Zafeiropoulos [7]

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The continued generation of $n_f = 2 + 1$ quark flavor gauge configurations using stabilized Wilson fermions by the open lattice initiative (OpenLat) is reported. We present the status of our ongoing production and show updates on increasing statistics at the four lattice spacings $a = 0.12, 0.094, 0.077$ and 0.064 fm. Aside from the flavor symmetric point we discuss advancements in going towards physical pion masses. We show preliminary results of the pion decay constants, extending previous results, and discuss standard hadronic and flow observables on all available ensembles.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Structure of Hadrons and Nuclei / 128

Lattice Constraints on the Fourth Mellin Moment of the Pion LCDA using the HOPE Method

Authors: Anthony Grebe[1]; C.-J. David Lin[2]; Issaku Kanamori[3]; Robert Perry[4]; William Detmold[5]; Yong Zhao[6]

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The light-cone distribution amplitude (LCDA) of the pion carries information about the parton momentum distribution and is an important theoretical input into various predictions of exclusive measurements at high energy, including the pion electromagnetic form factor. We provide constraints on the fourth Mellin moment of the LCDA using the heavy quark operator product expansion (HOPE) method.

Topical area:

Structure of Hadrons and Nuclei

Quark and Lepton Flavor Physics / 129

Structure-dependent electromagnetic finite-volume effects through order $1/L^3$

Author: Nils Hermansson Truedsson[1]

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The absence of a mass gap in QED requires handling of the zero-momentum modes of photons in finite-volume spacetimes. Once the problematic zero-momentum modes are removed using some prescription, the associated finite-volume effects in an observable typically scale with inverse powers of the spatial extent, $1/L$. In this talk, I discuss the analytical evaluation of these effects through order $1/L^3$ for pseudoscalar masses and leptonic decay amplitudes. The results depend on the internal structure of the interacting mesons, and further on the chosen prescription for the photon zero-momentum modes.

Topical area:

Quark and Lepton Flavor Physics

Theoretical Developments / 130

Hadronic Structure, Conformal Maps, and Analytic Continuation

Authors: Patrick Oare[1]; William Jay[2]; Thomas Bergamaschi[2]

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We present a method for analytic continuation of Euclidean Green functions computed using lattice QCD. The method is based on conformal maps and construction of an interpolation function which is analytic in the upper half plane. A novel aspect of our method is rigorous bounding of systematic uncertainties, which are handled by constructing the full space of interpolating functions (at each point in the upper half-plane) consistent with the given Euclidean data and the constraints of analyticity. The resulting Green function in the upper half-plane has an appealing interpretation as a smeared spectral function.

Topical area:

Theoretical Developments

Poster session / 131

Provenance model for Lattice QCD

Authors: Bertram Ludäscher[None]; Gunnar Bali[1]; Meike Klettke[None]; Simon Weishäupl[None]; Tanja Auge[None]; Tilo Wettig[2]; Wolfgang Söldner[None]

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Workflow management has become an important topic in many research communities. Here, we focus on the particular aspect of provenance tracking. We follow the W3C PROV standard and formulate a provenance model for Lattice QCD that includes the ensemble-generation and the measurement parts of the Lattice QCD workflow. Since many important provenance questions in our community require extensions of this model, we propose a multi-layered provenance approach that combines prospective and retrospective elements.

Topical area:

Structure of Hadrons and Nuclei / 132

Towards Unpolarized GPDs from Pseudo-Distributions

Authors: Anatoly Radyushkin[1]; Chris Monahan[2]; Joseph Karpie[3]; Colin Egerer[3]; David Richards[4]; Eloy Romero[5]; Kostas Orginos Orginos[6]; Robert Edwards[5]; Savvas Zafeiropoulos[7]

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Generalized Parton Distributions (GPDs) are related to one aspect of nucleon tomography, the 3D imagining the proton. In one limit, the GPD can describe both the longitudinal momentum and the transverse position of a parton. In other limits, the GPD can describe how each parton contributes to the total spin or mass of the nucleon. Nucleon tomography has sparked great interest as a goal of many experiments, including at JLab and the future EIC. In recent years, many groups have begun lattice QCD calculations of matrix elements related to GPDs. In this talk, I will present the recent calculations performed by the HadStruc collaboration to determine the pseudo-Generalized Ioffe Time Distribution and how GPDs can be extracted from them. The GPD, being a function of three momentum dependent variables, requires studying matrix elements with many combinations of initial and final momenta. This is naturally done within the distillation framework which we employed to obtain quality signal at the requisite large momenta.

Topical area:

Structure of Hadrons and Nuclei

Structure of Hadrons and Nuclei / 133

Quark orbital angular momentum in the proton from a twist-3 generalized parton distribution

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Quark orbital angular momentum in the proton is evaluated via a Lattice QCD calculation of the second Mellin moment of the twist-3 generalized parton distribution $\widetilde{E}_{2T}$ in the forward limit. The connection between this approach to quark orbital angular momentum and approaches previously utilized in Lattice QCD calculations, via generalized transverse momentum-dependent parton distributions and via Ji's sum rule, is reviewed. This connection can be given in terms of Lorentz invariance and equation of motion relations. The calculation of the second Mellin moment of $\widetilde{E}_{2T}$ proceeds via a finite-momentum proton matrix element of a quark bilocal operator with a straight-line gauge connection and separation in both the longitudinal and transverse directions. The dependence on the former component serves to extract the second Mellin moment, whereas the dependence on the latter component provides a transverse momentum cutoff for the matrix element. Furthermore, a derivative of the matrix element with respect to momentum transfer in the forward limit is required, which is obtained using a direct derivative method. The calculation utilizes a clover fermion ensemble at pion mass 317 MeV. The resulting quark orbital angular momentum is consistent with previous evaluations through alternative approaches, albeit with greater statistical uncertainty using a comparable number of samples.

Topical area:

Structure of Hadrons and Nuclei

Software Development and Machines / 134

Benchmarking portable staggered fermion kernel written in Kokkos and MPI

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In the rapidly changing hardware landscape of high performance computing (HPC), binding workforce to optimize simulation software for just a single architecture becomes a sustainability issue.

In this work I explored the feasibility of using performance portable parallel code for a staggered fermion kernel. Fusing the Kokkos C++ Performance Portability EcoSystem with MPI allows to scale on massive parallel machines while still being able to target a plentitude of different architectures with the same simple code.

Benchmarking on a range of currently deployed and recently introduced systems, including AMD EPYC 7742, AMD MI250, Fujitsu A64FX, Nvidia A100 and Nvidia H100 components, produced mostly encouraging results.

Topical area:

Software Development and Machines

Poster session / 135

”My Journey as a Physicist” Podcast

Authors: William Good[1]; Huey-Wen Lin[1]

Co-authors: Kinza Hasan [1]; Kiran Sakorikar [1]; Bryan Stanley [1]; Esther Cohen-Lin

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How and when do people become physicists? Are they always certain about their career choice? What are physicists like outside work? A team of physics students and faculty aim to answer these questions through the “My Journey as a Physicist” podcast. In each episode, a student host(s) interviews professional physicists to learn about their professional journey of how they ended up where they are today.

Guest physicists discuss their research, what got them interested in physics, obstacles they overcame, and what their typical day looks like. They also provide tips and suggestions for students who may be interested in studying physics and becoming physicists. Guests also share about their interests and hobbies outside of research; there are scoops about physicists that you only learn about in this podcast. We find that no two career paths are the same. This podcast provides insights on life as a physicist that listeners may not have otherwise learned.

Each season features physicists involved in different subfields of physics: Season 1 features physicists involved with lattice QCD (LQCD), associated with the 2021 INT Lattice Summer School [1], Season 2 features physicists involved with Snowmass [2], the US particle-physics planning community, and the latest Season 3 interviews those involved in the ongoing Nuclear Science Advisory Committee Long Range Plan (LRP) [3].

References:
[1] INT Summer School on Problem Solving in Lattice QCD https://sites.google.com/uw.edu/lqcdschool2021/home
[2] Snowmass, the US particle physics planning community https://snowmass21.org/
[3] Nuclear-Science Advisory Committee Long Range Plan (LRP) https://science.osti.gov/np/nsac

Topical area:

Structure of Hadrons and Nuclei / 136

How Gluon Pseudo-PDF Matrix Elements Depend on Gauge Smearing

Author: William Good[1]

Co-author: Huey-Wen Lin [1]

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We study effects of gauge smearing on the nucleon and meson gluon-PDF matrix elements, considering hypercubic smearing, stout smearing, and Wilson flow. The lattice calculations are carried out with $N_f = 2+1+1$ highly improved staggered quarks in ensembles generated by the MILC Collaboration. We use clover fermions for the valence action on one lattice spacing $a \approx 0.12$ fm and two pion masses $M_\pi \approx$ 310 and 690 MeV. We probe the effects of gluon matrix elements with different smearing methods at various steps. We compute and compare the resulting nucleon and meson gluon PDFs using the pseudo-PDF method when using different smearing methods.

Topical area:

Structure of Hadrons and Nuclei

Hadronic and Nuclear Spectrum and Interactions / 137

Antistatic-antistatic-light-light potentials from lattice QCD

Authors: Lasse Mueller[1]; Marc Wagner[2]; Marina Marinkovic[3]; Pedro Bicudo[4]

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We present results for the potential of two static anti-quarks in the presence of two light quarks. We improve on existing results the $\bar{b}\bar{b}ud$ tetraquark system by computing the static potential at off-axis separations, significantly increasing the number of data points in the crucial region of small distances. Moreover, we show entirely new results for the static potential of a $\bar{b}\bar{b}us$ tetraquark. Finally, we discuss phenomenologically motivated parametrizations of the potentials.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Algorithms and Artificial Intelligence / **138**

Teaching to extract spectral densities from lattice correlators to a broad audience of learning-machines

Authors: Alessandro De Santis[1]; Michele Buzzicotti[None]; Nazario Tantalo[None]

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I will present a new method, developed in collaboration with M. Buzzicotti and N. Tantalo and based on deep learning techniques, to extract hadronic spectral densities from lattice correlators. Hadronic spectral densities play a crucial role in the study of the phenomenology of strong-interacting particles and the problem of their extraction from Euclidean lattice correlators has already been approached in the literature by using machine learning techniques. In devising a new method the big challenge to be faced can be summarized in two pivotal questions: 1) is it possible to devise a model independent training strategy? 2) if such a strategy is found, is it then possible to quantify reliably, together with the statistical errors, also the unavoidable systematic uncertainties? We faced the challenge and our answers to these questions will be the subject of the talk.

Topical area:

Algorithms and Artificial Intelligence

Software Development and Machines / **139**

Status of OpenMP Target Offloading in Grid

Author: Meifeng Lin[1]

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I will give a status update of using OpenMP target offloading in the Grid library. As part of the US Exascale Computing Project, we have been investigating the possibility of using a portable programming model in Grid to support execution on different architectures. OpenMP, a directives-based programming model, supports both CPU multithreading and different GPU architectures through appropriate compilers. After some success of using OpenMP target offloading in GridMini, a reduced version of Grid, we have implemented OpenMP target offloading in the full version of Grid. I will report recent benchmark results on NVIDIA, AMD and Intel GPUs and also discuss some issues encountered.

Topical area:

Software Development and Machines

Theoretical Developments / **140**

NSPT for O(N) non-linear sigma model: the larger N the better

Authors: Francesco Di Renzo[1]; Paolo Baglioni[2]

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The $O(N)$-Nonlinear Sigma Model (NLSM) is an example of field theory on a target space with non-trivial geometry. One interesting feature of NLSM is asymptotic freedom, which makes perturbative calculations interesting.
Given the successes in Lattice Gauge Theories, Numerical Stochastic Perturbation Theory (NSPT) is a natural candidate for performing high order computations also in the case of NLSM. However, in low-dimensional systems NSPT is known to display statistical fluctuations substantially increasing for increasing orders. In this presentation, we explore how for $O(N)$ this behaviour is strongly dependent on N. As largely expected on general grounds, the larger is N, the larger is the order at which a NSPT computation can be effectively performed.

Topical area:

Theoretical Developments

Poster session / 141

Highly anisotropic lattices for Yang-Mills theory

Author: Paul Hotzy[1]

Co-authors: Denes Sexty [2]; David I. Müller [1]; Kirill Boguslavski [1]

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We examine the renormalized lattice spacing anisotropy in SU(2) Yang-Mills theory. We determine the physical anisotropy by performing anisotropic Wilson flow. Our preliminary findings indicate that, at high bare anisotropies, the physical anisotropy reaches a plateau. Further increase of the bare anisotropy results in a slight increase of the lattice spacings. Our findings can be then applied to the highly anisotropic lattices that have recently been utilised in real-time Yang-Mills simulations using the Complex Langevin method on complex time contours.

Topical area:

QCD at Non-zero Temperature

Hadronic and Nuclear Spectrum and Interactions / 142

Tcc tetraquark and the continuum limit with clover fermions

Author: Jeremy R. Green[None]

Co-authors: A. D. Hanlon ; H. Wittig ; M. Padmanath ; R. J. Hudspith ; S. Paul

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A previous calculation of baryon-baryon scattering using CLS ensembles with nonperturbatively $O(a)$-improved Wilson fermions revealed large discretization effects in the scattering amplitude. It is natural to ask whether other systems with heavy hadrons are affected. Using the same setup and adding valence charm quarks with the same action, we study DD^* scattering and the T_{cc} tetraquark. With up to six lattice spacings, we examine the dependence on a and focus on discretization effects beyond the ones that affect a single D or D^* meson.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Poster session / 143

Lattice QCD Calculation of Pion Distribution Amplitude Using Domain-Wall Fermions at Physical Pion Mass

Author: Ethan Baker[1]

Co-authors: Xiang Gao [2]; Yong Zhao [3]

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Here we present a lattice QCD determination of the first few Mellin moments of the pion distribution amplitude by analyzing the quasi-DA matrix elements using a lattice spacing of $a = 0.836$ fm. Our work differs from previous work in that we use domain-wall fermions in order to respect chiral symmetry and that calculations are performed at the physical pion mass. First, we analyze ratios of the pion-pion correlator and the pion-quasiDA correlator to determine the bare matrix elements. We then renormalize these using the double-ratio scheme. Finally, we fit these data using the leading-twist Mellin operator product expansion (OPE) to determine the Mellin moments.

Topical area:

Structure of Hadrons and Nuclei

QCD at Non-zero Temperature / 144

Complex potential at finite temperature in 2+1 flavor QCD

Authors: Alexander Rothkopf[1]; Alexei Bazavov[2]; Peter Petreczky[3]; Johannes Heinrich Weber[4]; Olaf Kaczmarek[5]; Rasmus Larsen[1]; Swagato Mukherjee[6]

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We present calculations of the complex potential at non-zero temperature in 2+1 flavor QCD. The complex potential is obtained from spectral reconstruction of the Wilson line correlators at non-zero temperature calculated on the lattice. The calculations are performed using the HISQ action at three lattice spacings, a=0.028 fm, a=0.04 fm and a=0.049 fm for temperatures in the range 130 MeV - 352 MeV. Quite surprisingly, we find that the real part of the potential is not screened and is approximately equal to the zero temperature potential, while the imaginary part of the potential increases with the temperature and distance between the static quarks.

Topical area:

QCD at Non-zero Temperature

Quark and Lepton Flavor Physics / 145

Coordinate-space calculation of isospin breaking corrections to the hadronic vacuum polarization contribution to (g-2)_\mu

Authors: En-Hung Chao[1]; Harvey B. Meyer[2]; Julian Parrino[3]

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As several lattice collaborations agree on the result for the window quantity of the hadronic vacuum polarization (HVP) contribution to (g-2)_\mu, whilst being in tension with the calculation using the dispersive approach, further effort is needed in order to pin down the cause for this difference.
Here we investigate the isospin breaking corrections to the leading order HVP. In many lattice applications, the photon propagator is treated stochastically; however, by analogy with the hadronic light-by-light contribution (HLbL) to (g-2), we apply a coordinate-space approach to the HVP at NLO. We present a calculation of the two diagrams of the (2+2) topology at unphysical pion mass, where we apply a Pauli-Villars regularization for the photon propagator in the diagram that is UV-divergent. We compare the UV-finite diagram to the pseudoscalar exchange contributions.

Topical area:

Quark and Lepton Flavor Physics

Quark and Lepton Flavor Physics / 146

New result for ε' in $K \to \pi\pi$ decay using periodic boundary conditions

Author: Masaaki Tomii[1]

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We report our recent results for $K \to \pi\pi$ matrix elements and ε', the measure of direct CP violation, released on arXiv:2306.06781. This is RBC/UKQCD's first result for ε' with periodic boundary conditions (PBC), while our earlier calculations were performed with G-parity boundary conditions, where the isospin-0 two-pion ground state corresponds to the on-shell kinematics. Using the GEVP method with multiple two-pion operators, we overcome the difficulty that PBC require us to calculate the matrix elements with excited two-pion final states to obtain the on-shell kinematics. We therefore continue measurements with more configurations and on finer lattices to improve the precision. This talk includes the report on the latest status of new calculations.

Topical area:

Quark and Lepton Flavor Physics

Plenary session / 147

Lattice QCD calculation of the invisible decay J/ψ→γνν

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Searching for the dark matter is one of the major goals of contemporary astronomy and particle physics. Many experiments have performed the searches for the J/ψ radiative decays into invisible particles, and no signal was observed. In the future, several experiments have the great potential to significantly improve the upper limit on the branching fraction of J/ψ + invisible. In this talk, we present the first lattice QCD study on J/ψ→γνν, which serving as a standard model background for this invisible decay. After a continuous extrapolation for three different lattice spacings, an exact value of the branching fraction is obtained.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Structure of Hadrons and Nuclei / 148

Lattice QCD calculation of the nucleon electromagnetic polarizability

Author: Xuan-He Wang[1]

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The electromagnetic polarizability is an import property of nucleon. It describes the reponse of a nucleon when it is placed in an external eletric or magnetic field. The polarizability can be extracted from the real or virtual Compton scattering process γN → γN. We develop a method to calculate the the Compton scattering matrix elements of nucleon from a 4-point correlation function on the lattice. Then we show that the electromagnetic polarizabilities can be extracted from the lattice data subsequently.

Topical area:

Structure of Hadrons and Nuclei

Quantum Computing and Quantum Information / 149

Scalar quantum electrodynamics with Rydberg atoms

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We review recent suggestions to quantum simulate scalar electrodynamics (the lattice Abelian Higgs model) in 1+1 dimensions with rectangular arrays of Rydberg atoms. We show that platforms made publicly available recently allow empirical explorations of the critical behavior of quantum simulators. We discuss recent progress regarding the phase diagram of two-leg ladders, effective Hamiltonian approaches and the construction of hybrid quantum algorithms targeting hadronization in collider physics event generators.

Topical area:

Quantum Computing and Quantum Information

Algorithms and Artificial Intelligence / 150

Sparse modeling approach to extract spectral functions with covariance of Euclidean-time correlators of lattice QCD

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We present our sparse modeling study to extract spectral functions from Euclidean-time correlation functions. In this study covariance between different Euclidean times of the correlation function is taken into account, which was not done in previous studies. In order to check applicability of the method, we firstly test it with mock data which imitate possible charmonium spectral functions. Then, we extract spectral functions from correlation functions obtained from lattice QCD at finite temperature.

Topical area:

Algorithms and Artificial Intelligence

Algorithms and Artificial Intelligence / **151**

Application of the projective truncation and randomized singularvalue decomposition to a higher dimension.

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We study the various tensor renormalization group (TRG), such as the Higher-order TRG (HOTRG), Anisotropic TRG (ATRG), Triad TRG, and Tensor network renormalization (TNR) with the idea of projective truncation and truncated singularvalue decomposition (SVD) such as the randomized SVD (RSVD). The details of the cost function for the isometry determine the precision, stability, and calculation time. In our study, we show calculation order improvement using RSVD. We also propose that the internal line respect for any TRG method improves the calculation without changing the order of the computational cost.

Topical area:

Algorithms and Artificial Intelligence

Software Development and Machines / **152**

SIMULATeQCD: A simple multi-GPU lattice code for QCD calculations

Authors: David A. Clarke[1]; Dennis Bollweg[2]; Lukas Mazur[3]; Olaf Kaczmarek[4]

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The rise of exascale supercomputers has fueled competition among GPU vendors, requiring lattice QCD practitioners to write code that supports multiple GPU architectures and APIs. We present SIMULATeQCD, a simple multi-GPU lattice code for large-scale QCD calculations, mainly developed and used by the HotQCD collaboration. Our open source code is built on C++ and MPI, includes CUDA and HIP back-ends and leverages modern C++ language features to provide high level data structures, objects and algorithms that allow users to express lattice QCD calculations in an intuitive way without sacrificing performance. In this talk, we explain the design strategy, discuss implementation details, and show benchmarks of performance critical kernels on recent supercomputers, including Perlmutter and Frontier.

Topical area:

Software Development and Machines

Theoretical Developments / 153

Infrared Phases of 2d QCD from Qubit Regularization

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Qubit regularization provides a framework for studying gauge theories through finite-dimensional local Hilbert spaces, presenting opportunities for digital quantum simulations. In this talk, we investigate the IR phases of 2d QCD with the $\mathrm{SU}(N)$ gauge group via qubit regularization. In the continuum, a 2d $\mathrm{SU}(N)$ gauge theory coupled to a single flavor of fundamental massless Dirac fermions can be bosonized into an $\mathrm{SO}(2N)_1/\mathrm{SU}(N)_1$ Wess-Zumino-Witten (WZW) model or a compact boson. On the lattice, utilizing a strong-coupling expansion of the qubit-regularized Kogut-Susskind Hamiltonian with the assistance of a generalized Hubbard coupling, we demonstrate that the continuum physics can be reproduced by an XXZ spin chain, together with a gapped phase. We also show the existence of a confinement/deconfinement (screening) transition. These arguments are verified numerically in the $\mathrm{SU}(2)$ case using the tensor network approach. Our numerical results reveal that the lattice model has a central charge of 1, and its spectrum can be understood as the $\mathrm{SU}(2)_1$ WZW model perturbed by a tiny marginally irrelevant operator, which can be tuned away by the Hubbard coupling. The confinement/deconfinement transition is also verified numerically by measuring the string tensions.

Topical area:

Theoretical Developments

Quantum Computing and Quantum Information / 154

Real-time dynamics of the Schwinger model via variational quantum algorithms

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In this study, we investigate the real-time dynamics in the $(1+1)$d U(1) gauge theory called the Schwinger model via variational quantum algorithms. Specifically, we simulate the quench dynamics in the presence of the external electric field.
We first prepare the ground state in the absence of the external field using variational quantum eigensolver (VQE) and then perform the real-time simulation in the presence of the external field starting from the VQE results via variational quantum simulation (VQS). We use the same ansatz in both VQE and VQS which enables us to reduce the overall circuit depth.
We test our method using a classical simulator and confirm that our simulation results agree well with the exact results.

Topical area:

Quantum Computing and Quantum Information

Poster session / 155

Towards a non-perturbative determination of b_g at small couplings

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The extraction of the QCD coupling via non-perturbative decoupling methods has been recently shown to be a compelling strategy for high-precision determinations [Eur. Phys. J. C 82 (2022) 12, 1092]. One of the key ingredients of this strategy is the determination of a (finite-volume) non-perturbative massive coupling at large values of the quark-mass, M. Robust continuum limit extrapolations for this coupling require control over potentially large $O((aM)^n)$ discretization errors. In the case of Wilson-fermions, particular care must be taken, as $O(aM)$ effects are in principle also present. Once the quark-mass has been properly renormalized and $O(a)$-improved, the remaining $O(aM)$ effects can be eliminated by the proper tuning of a single $O(aM)$-improvement coefficient, $b_g(g_0^2)$. Following a novel strategy [see S. Sint parallel talk], in this poster we present first preliminary results for $b_g(g_0^2)$ for $N_f = 3$ non-perturbatively $O(a)$-improved Wilson-fermions and Lüscher-Weisz gauge action in the range of bare couplings $g_0^2 < 1.5$.

Topical area:

Theoretical Developments

Hadronic and Nuclear Spectrum and Interactions / 156

Analytic continuation of the finite-volume three-particle amplitudes

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Many hadronic resonances, including the most intriguing ones (Roper, π_1(1600), or T_{cc}^{+}(3872)), decay into three or more particles. In principle, one can determine their properties from the multi-body version of the Luscher finite-volume scattering formalism. However, one of the obstacles in specifying their masses from Lattice QCD is the lack of developed three-body amplitude analysis techniques that would allow one to translate a finite-volume output into physically meaningful quantities. In particular, an amplitude obtained from the Lattice QCD calculation must be analytically continued to the complex energy plane, where resonances exist as pole singularities.

In the talk, I will explore the relativistic scattering of three identical scalar bosons interacting via pair-wise interactions. I will describe a general prescription for solving and analytically continuing integral equations describing the three-body process. As an illustration, I will use these techniques to analyze a system governed by a single scattering length leading to a bound state in a two-body sub-channel. I will present the resulting three-body scattering amplitudes for complex energies in the physical and unphysical Riemann sheets. In particular, I will discuss the emergence of three-particle bound states in the system under study that agrees with previous work utilizing relativistic finite-volume formalism. Finally, I will also comment on the obtained numerical evidence of the breakdown of the two-body finite-volume formalism in the vicinity of left-hand cuts.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Tests of Fundamental Symmetries / 157

The Thirring Model in 2+1d with Optimised Domain Wall Fermions

Authors: Jude Worthy[1]; Simon Hands[2]

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We present results of a study of spontaneous symmetry breaking through fermion bilinear condensation in the single flavor Thirring Model in 2+1d. Domain Wall Fermions are used to capture the symmetry breaking pattern U(2)→U(1)⊗U(1) in the limit of domain wall separation $L_s \to \infty$, with the conserved fermion current coupled to a real vector auxiliary field defined throughout the bulk. The new feature is use of both hyperbolic tangent and Zolotarev Optimal Rational Function approximations to the signum function, which enhances L_s-convergence, together with the use of both Shamir and Wilson kernel functions for the corresponding overlap operator. The results yield compatible equations of state, consistent with the existence of a unique continuum limit at a strongly-coupled UV fixed point.

Topical area:

Tests of Fundamental Symmetries

Hadronic and Nuclear Spectrum and Interactions / 158

Precision Determination of Baryon Masses including Isospin-breaking

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We give an update on an ongoing project in which we calculate the masses of octet and decuplet baryons including isospin-breaking effects. To this end, we employ single- and two-state-fits to effective masses at leading and sub-leading order in the expansion in isospin-breaking parameters. In order to remove objective bias on asymptotic masses we furthermore compute an AIC-based model-average of our fits for which we show results on ensembles at lattice spacings of 0.064 fm and 0.076 fm with corresponding pion masses ranging from 220 MeV to 360 MeV.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Hadronic and Nuclear Spectrum and Interactions / 159

Investigation of two-particle contributions to nucleon matrix elements

Authors: Constantia Alexandrou[None]; Ferenc Pittler[None]; Giannis Koutsou[None]; Marcus Petschlies[None]; Yan Li[None]

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We investigate contributions of excited states to nucleon matrix elements by studying the two- and three-point functions using nucleon and pion-nucleon interpolating fields. This study is made using twisted mass fermion ensembles with pion masses 346 MeV and 131 MeV. We compare results obtained using these two ensembles and show preliminary results for nucleon charges.

Topical area:

Structure of Hadrons and Nuclei

QCD at Non-zero Temperature / 160

Progresses on high-temperature QCD: Equation of State and energy-momentum tensor

Authors: Matteo Bresciani[1]; Mattia Dalla Brida[2]; Leonardo Giusti[3]; Michele Pepe[4]

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We present first non-perturbative results for the renormalization constants of the QCD energy momentum tensor, based on the framework of thermal QCD with shifted and twisted (for quarks only) boundary conditions in the compact direction. We also show preliminary results for the entropy density obtained with the very same numerical strategy. This opens the way to the determination of the QCD Equation of State up to very high temperatures.

Topical area:

QCD at Non-zero Temperature

Vacuum Structure and Confinement / 161

New gauge-independent transition dividing the confinement phase in the lattice gauge-adjoint scalar model

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The lattice gauge-scalar model with the scalar field in the adjoint representation of the gauge group has two completely separated confinement and Higgs phases according to the preceding studies based on numerical simulations which have been performed in the specific gauge fixing based on the conventional understanding of the Brout-Englert-Higgs mechanism.
In this talk, we re-examine this phase structure in the gauge-independent way based on the numerical simulations for the model with SU(2) gauge group performed without any gauge fixing which is motivated to confirm the recently proposed gauge-independent Brout-Englert-Higgs mechanics for the mass of the gauge field without relying on any spontaneous symmetry breaking.
For this purpose we investigate correlation functions between gauge-invariant operators obtained by combining the original adjoint scalar field and the new field called the color-direction field constructed from the gauge field based on the gauge-covariant gauge-field decomposition due to Cho-Duan-Ge-Shabanov and Faddeev-Niemi.
We reproduce gauge-independently the transition line separating confinement and Higgs phase, and discover surprisingly a new transition line that divides the confinement phase into two parts.
Finally, we discuss the physical meaning of the new transition and implications to confinement mechanism.

Topical area:

Vacuum Structure and Confinement

Hadronic and Nuclear Spectrum and Interactions / 162

Charmonium-like channels 1^{+-} and 1^{++} with isospin 1

Authors: Mitja Sadl[1]; Sara Collins[2]; M Padmanath[3]; Sasa Prelovsek[1]

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Experimentally many exotic charmonium-like mesons have already been discovered, for example, the Z_c mesons. We study the spectrum of such states with isospin 1 focusing on the $\bar{c}c\bar{q}q$ channels with $J^P = 1^+$, $C = \pm$. This is the first study of four-quark states with these quantum numbers, where the total momentum is non-zero. The simulations are performed on two $N_\mathrm{f} = 2 + 1$ CLS ensembles with different volumes and $m_\pi \simeq$ 280 MeV. We extract the finite-volume energy levels and determine the scattering amplitude assuming decoupled $D\bar{D}^*$ scattering close to the threshold using Lüscher's formalism. Additionally, one-channel $J/\psi\pi$ scattering for $C = -$ is considered, and upper bounds are put on the scattering length and $1/(p \cot \delta)$ in certain energy regions, which constrains the interaction between J/ψ and π.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Software Development and Machines / 163

Restoring Reproducibility to Lattice QCD

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The scientific method is underpinned by reproducibility, however, parallel computing often violates this through lack of associativity when summing floating point numbers. For Lattice QCD calculations this can have several undesirable effects, such as dramatic variations in solver iteration count, as well as the fundamental inability to exactly reproduce a given Monte-Carlo generated ensemble. This issue can be accentuated on a GPU, where the additional thread hierarchy results in more opportunities to violate associativity, or when comparing results across different architectures. We solve this problem through the use of the reproducible summation algorithm by Ahrens et al. In particular we adapt the algorithm for efficient enablement on clusters of GPUs, as deployed in the QUDA framework, and are able to achieve both exact reproducibility and higher accuracy with no increased cost compared to a naive parallel tree summation algorithm.

Topical area:

Software Development and Machines

Theoretical Developments / 164

Curved domain-wall fermion and its anomaly inflow

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We report on a lattice fermion formulation with
a curved domain-wall mass term to nonperturbatively
describe fermions in a gravitational background.
In our previous work in 2022, we showed in the free
fermion theory on one and two-dimensional spherical domain-walls
that the spin connection is induced on the lattice
in a consistent way with continuum theory.
In this talk we add nontrivial $U(1)$ link variables
to the spherical domain-wall fermion systems and
study the anomaly inflow between the bulk and curved edge.

We also extend our study to a Shamir type curved domain-wall fermions.
Although one domain-wall apparently admits a single Weyl fermion
on the spherical surface, we find nontrivial obstacles
in formulating chiral gauge theory.

Topical area:

Theoretical Developments

Quark and Lepton Flavor Physics / 165

Status of the exploratory calculation of the rare hyperon decay

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The rare hyperon decay $\Sigma \to p\ell^+\ell^-$ is a flavour changing neutral current process that is sensitive to new physics beyond the Standard Model.
We present the current status of the first exploratory calculation of this decay on the lattice with 340 MeV pions using domain wall fermions.

Topical area:

Quark and Lepton Flavor Physics

Algorithms and Artificial Intelligence / 166

Fixed point actions from convolutional neural networks

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Lattice gauge-equivariant convolutional neural networks (LGE-CNNs) can be used to form arbitrarily shaped Wilson loops and can approximate any gauge-covariant or gauge-invariant function on the lattice. Here we use LGE-CNNs to describe fixed point (FP) actions which are based on inverse renormalization group transformations. FP actions are classically perfect, i.e., they have no lattice artefacts on classical gauge-field configurations satisfying the equations of motion, and therefore possess scale invariant instanton solutions. FP actions are tree–level Symanzik–improved to all orders in the lattice spacing and can produce physical predictions with very small lattice artefacts even on coarse lattices. They may therefore provide a solution to circumvent critical slowing down towards the continuum limit.

Topical area:

Algorithms and Artificial Intelligence

Vacuum Structure and Confinement / 167

New gauge-independent transition separating confinement-Higgs phase in the lattice gauge-fundamental scalar model

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The lattice gauge-scalar model with the scalar field in the fundamental representation of the gauge group has a single confinement-Higgs phase which is well-known as the Fradkin-Shenker-Osterwalder-Seiler analytic continuity theorem: Confinement and Higgs regions are subregions of an analytically continued single phase and there are no thermodynamics phase transitions between them.
In this talk, however, we show that we can define new type of operators which enable to separate completely the confinement phase and the Higgs phase. In fact, they are constructed in the gauge-invariant procedure by combining the original scalar field and the so-called color-direction field which is obtained by change of field variables based on the gauge-covariant decomposition of the gauge field due to Cho-Duan-Ge-Shabanov and Faddeev-Niemi.
We perform the numerical simulations for the model with SU(2) gauge group without any gauge fixing and found a new transition line which agrees with the conventional thermodynamical transition line in the weak gauge coupling and divides the confinement-Higgs phase into two separate phases, confinement and the Higgs, in the strong gauge coupling. All results are obtained in the gauge-independent way, since no gauge fixing has been imposed in the numerical simulations.
Moreover, we give a physical interpretation for the new transition from the viewpoint of the spontaneous breaking of a global (custodial) symmetry.

Topical area:

Vacuum Structure and Confinement

Software Development and Machines / 168

First dynamical simulations with minimally doubled fermions

Authors: Attila Pasztor[1]; Chik Him Wong[2]; Daniel Godzieba[None]; Reka A. Vig[None]; Paolo Parotto[None]; Ruben Kara[2]; Szabolcs Borsanyi[None]; Zoltan Fodor[None]

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For thermodynamics studies it is desirable to simulate two degenerate flavors and retain chiral symmetry. Staggered fermions can achieve this by rooting the determinant. Rooting can be avoided using minimally doubled fermions. This discretization describes two degenerate quark flavors while explicitly breaking hypercubic symmetry, thus requiring additional counterterms. We use one particular formulation of minimally doubled fermions called the Karsten-Wilczek action and mitigate lattice artifacts by improving the spatial derivatives in the Dirac operator. In this pilot study we determine the counter terms non-perturbatively to facilitate proper dynamical simulations.

Topical area:

Software Development and Machines

QCD at Non-zero Density / 169

Staggered rooting and unphysical phases at finite baryon density

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The phase diagram at finite density is of great interest. In the literature, calculations are dominated by rooted staggered fermions. In continuum QCD at finite isospin density, there is pion condensation transition. We observe the reminants of such transition at finite lattice spacings as well at nonzero baryon density. In this talk, we discuss how this can be attributed to the ambiguity of staggered rooting at finite baryon chemical potential.

Topical area:

QCD at Non-zero Density

Particle Physics Beyond the Standard Model / 170

Continuous beta function for SU(3) with Nf fundamental flavor

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The renormalization group beta function describes the running of the renormalized coupling, connects the ultraviolet and infrared regimes of quantum field theories, and characterizes the nature of gauge-fermion systems. Using the concept of the continuous beta function and renormalized couplings obtained from the gradient flow, we present results for SU(3) gauge theories with $N_f = 2$, 4, 6, 8, 10 or 12 fundamental flavors. Our results are based on dynamical gauge field ensembles generated with three times stout-smeared Möbius domain-wall fermions and Symanzik gauge action.

Topical area:

Particle Physics Beyond the Standard Model

QCD at Non-zero Temperature / 171

Anomalous transport phenomena on the lattice

Authors: Bastian B. Brandt[1]; Eduardo Garnacho-Velasco[2]; Francesca Cuteri[3]; Gergely Endrodi[1]; Gergely Markó[1]

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We present the first continuum extrapolated results for the chiral magnetic effect (CME) and the chiral separation effect (CSE) conductivities in equilibrium with staggered fermions at physical masses. We simulate QCD in a constant magnetic background and measure respective chemical potential derivatives of the currents appearing in each effect. The conductivities are calculated as a function of relevant parameters as the temperature and the mass of the quarks. We emphasize the importance of choosing the correct discretization of the currents, which we verify by turning off gluonic interactions and comparing to analytical results; as well as by comparing to results using the Wilson fermion formulation. We also present results for the quenched theory for both staggered and Wilson fermions, where the role of the Polyakov loop for the CSE will be discussed.

Topical area:

QCD at Non-zero Temperature

Quantum Computing and Quantum Information / 172

Canonical Momenta in Digitized SU(2) Lattice Gauge Theory

Authors: Arianna Crippa[1]; marco garofalo[2]; Tobias Hartung[3]; Timo Jakobs[2]; Karl Jansen[4]; Stefan Kühn[1]; Johann Ostmeyer[5]; Dominik Rolfes[2]; Simone Romiti[2]; Carsten Urbach[2]

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Hamiltonian simulations of quantum systems require a finite-dimensional representation of the operators acting on the Hilbert space. Here we present a discretization scheme for gauge links and canonical momenta of an SU(2) gauge theory which offers the possibility to freely refine the discretisation. This is achieved by discretising SU(2) and constructing the canonical momentum using the finite element method while the matrix representation of the gauge links is diagonal. We show that the fundamental commutation relations are fulfilled up to discretisation artefacts and the spectrum of the Hamiltonian is reproduced.

Topical area:

Quantum Computing and Quantum Information

Vacuum Structure and Confinement / 173

Chiral condensate from the spectrum of the staggered Dirac operator

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The chiral condensate is computed from the mode number of the staggered Dirac operator. This result is compared with those obtained with other approaches, based on the quark mass dependence of the topological susceptibility and of the pion mass.

Topical area:

Vacuum Structure and Confinement

Algorithms and Artificial Intelligence / 174

Out-of-equilibrium simulations to fight topological freezing

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Calculations of topological observables in lattice gauge theories with traditional Monte Carlo algorithms have long been known to be a difficult task, owing to the effects of long autocorrelations times. Several mitigation strategies have been put forward, including the use of open boundary conditions and methods such as parallel tempering. In this contribution we examine a new approach based on out-of-equilibrium Monte Carlo simulations. Starting from thermalized configurations with open boundary conditions on a line defect, periodic boundary conditions are gradually switched on. A sampling of topological observables is then shown to be possible with a specific reweighting-like technique inspired by Jarzynski's equality. We discuss the efficiency of this approach using results obtained for the 2-dimensional CP^{N-1} model. Furthermore, we outline the implementation of our proposal in the context of Stochastic Normalizing Flows, as they share the same theoretical framework of the non-equilibrium transformations we perform, and can be thought of as their generalization.

Topical area:

Algorithms and Artificial Intelligence

QCD at Non-zero Density / 175

Chemical potential dependence of the endpoint of the first-order phase transition in the heavy-quark region of finite-temperature lattice QCD

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We determine the location of the critical point where the first-order deconfining transition in the heavy-quark region turns into a crossover in finite-temperature and density QCD with 2+1 flavors. Combining a hopping parameter expansion of the quark determinant with a reweighting method, we evaluate the chemical potential dependence of the critical point. By systematically calculating the coefficients of the hopping parameter expansion up to the higher order terms, it is found that the higher order terms are strongly correlated with the Polyakov loop, which is the first-order term, at each configuration. Furthermore, we find that the complex phase, which is important at finite density, is also strongly correlated with the complex phase of the Polyakov loop. Using this property, we develop a method for estimating the results incorporating high-order terms from calculations with only low-order terms. We report that the first-order phase transition region in the heavy-quark regime becomes exponentially narrower with increasing chemical potential. Since the hopping parameter at the critical point decreases exponentially with increasing density, the sign problem does not become too serious as the density increases, and the critical point can be evaluated up to a high density.

Topical area:

QCD at Non-zero Density

QCD at Non-zero Temperature / 176

QCD topology with background electromagnetic fields

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Non-orthogonal background electromagnetic fields generate a non-zero expectation value for the topological charge in QCD. For sufficiently weak fields, a linear response is expected. This linear response has been studied and related to the QCD contribution to the axion-photon coupling, for which we give preliminary results at finite lattice spacing. We also investigated the dependence of the topological susceptibility with the magnetic field around T_c. A reweighting of the fermion determinant to mimic the zero modes of the Dirac operator is shown to significantly reduce the lattice artifacts for the susceptibility. In this work we use lattice simulations with 2+1 flavors of improved staggered quarks at the physical point, including background magnetic and (imaginary) electric fields.

Topical area:

QCD at Non-zero Temperature

Software Development and Machines / 177

NeuLat: a toolbox for neural samplers in lattice field theories

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The application of normalizing flows for sampling in lattice field theory has garnered considerable attention in recent years. Despite the growing community at the intersection of machine learning and lattice field theory, there is currently a lack of a software package that facilitates efficient software development for new ideas in this field. We present the idea of NeuLat, a fully customizable software package that unifies recent advances in the fast-growing field of deep generative models for lattice field theory in a single software library. NeuLat is designed to be modular, supports a variety of lattice field theories as well as normalizing flow architectures, and is easily extensible.
We believe that NeuLat has the potential to considerably simplify the application and benchmarking of machine learning methods for lattice quantum field theories and beyond.

Topical area:

Algorithms and Artificial Intelligence

Algorithms and Artificial Intelligence / 178

Efficient computations of correlators with local distillation

Authors: Michael Peardon[1]; Nicolas Lang[2]; Robert Edwards[3]

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Distillation has been a useful tool in lattice spectroscopy calculations for more than a decade, enabling the efficient computation of hadron correlation functions. Nevertheless higher-dimensional compact operators such as baryons and tetraquarks pose a computational challenge as the time complexity of the Wick contractions grows exponentially in the number of quarks. This talk introduces a new method of performing Wick contractions efficiently in distillation space by exploiting the locality of smeared hadron sources combined with stochastic sampling procedures. The viability of the algorithm is demonstrated in a computation of Δ-baryon and nucleon correlation functions.

Topical area:

Algorithms and Artificial Intelligence

Poster session / 179

Tensor Renormalization Group Methods for Real-Time Evolution

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Ab-initio calculations of real-time evolution for lattice gauge theory have very interesting potential applications but present challenging computational aspects.
We show that tensor renormalization group methods developed in the context of Euclidean-time lattice field theory can be applied to calculation of Trotterized evolution operators at real time. We discuss the optimization of truncation procedures for various observables. We apply the numerical methods to the 1D Quantum Ising Model with an external transverse field in both the ordered and disordered phase and compare with universal quantum computing for $N_s = 4, 8$, and 16 sites.

Topical area:

Quantum Computing and Quantum Information

Particle Physics Beyond the Standard Model / 180

Exploring Composite Dark Matter with an SU(4) gauge theory with 1 fermion flavor

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Several SU(N) gauge theories have been explored as candidates for producing stable dark matter particles that can explain their relative abundance, while also evading current constraints from direct, indirect and collider searches. In this talk, I will present the confinement and spectral properties of a new model we name Hyper Stealth Dark Matter, which involves an SU(4) gauge theory with 1 quark flavor. The lightest baryon in this theory can be a potential dark matter candidate as it is protected from decay and hence can evade detection with a mass of just a few GeV. Existence of a first order confinement transition would open the possibility of potential detection of gravitational waves from such a transition at future observatories.

Topical area:

Particle Physics Beyond the Standard Model

Quark and Lepton Flavor Physics / 181

Pseudoscalar transition form factors and the hadronic light-by-light contribution to the muon $g-2$

Authors: Antoine Gérardin[None]; Willem Verplanke[1]; Gen Wang[None]

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We present the first ab-initio calculation of the π^0, η and η' transition form factors at the physical point using lattice QCD with staggered fermions on $N_f = 2+1+1$ gauge ensembles, generated by the Budapest-Marseille-Wuppertal collaboration. We compare our results with existing measurements and with other theoretical estimates. Using these transition form factors, we compute the pseudoscalar-pole contribution to the hadronic light-by-light scattering in the muon $g-2$ with a precision well below 10%, as needed for future experimental precision.

Topical area:

Particle Physics Beyond the Standard Model

Quantum Computing and Quantum Information / 182

Error mitigation strategies for simple quantum systems

Authors: Kevin Zambello[1]; Claudio Bonati[2]; Giuseppe Clemente[3]; Massimo D'Elia[2]; Lorenzo Maio[4]; Ruben Pariente[5]

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Quantum hardware in the NISQ era suffers from noise, which affects the reliability and accuracy of quantum computation. Here we present a comparison of quantum error mitigation strategies for Hamiltonian simulation and variational quantum algorithms, using as test bench some simple quantum fermionic systems and discrete gauge theories.

Topical area:

Quantum Computing and Quantum Information

Hadronic and Nuclear Spectrum and Interactions / 183

Hybrid static potentials from Laplacian eigenmodes

Authors: Francesco Knechtli[1]; Roman Höllwieser[1]; Juan Andres Urrea Nino[1]; Michael Peardon[2]; Tomasz Korzec[1]

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We present a method for computing hybrid static quark-antiquark potentials in lattice QCD based on Laplace trial states. They are formed by eigenvector components of the covariant lattice Laplace operator and their covariant derivatives. The new method does not need complicated gauge link paths between the static quarks and makes off-axis separations easily accessible. We show first results for Σ and $\Pi_{u/g}$ together with their excited states on quenched and dynamical ensembles.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

QCD at Non-zero Temperature / 184

Finite temperature effects for spin 1/2 charm baryons

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'Fit' independent methods are used to investigate temperature effects for the singly and doubly charmed spin $1/2$ baryons on the anisotropic FASTSUM 'Generation 2L' ensembles. Thereafter we determine where it is appropriate to apply standard fitting procedures in order to report the change in mass as the temperature increases. The negative parity sector is observed to be more strongly effected by temperature than the positive parity. Finally we examine the parity doubling due to the (partial) restoration of chiral symmetry and find estimates for the pseudo-critical temperature which are in good agreement with the measurement from the renormalised chiral condensate.

Topical area:

QCD at Non-zero Temperature

Quark and Lepton Flavor Physics / 185

Towards charm physics with stabilised Wilson Fermions

Authors: Fabian Joswig[1]; Jochen Heitger[2]; Justus Kuhlmann[2]; Patrick Fritzsch[3]

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We report on first computations of hadron masses and matrix elements with charm quarks in O(a) improved (2+1)-flavour lattice QCD in the framework of stabilised Wilson Fermions.
Employing SU(3)-flavour-symmetric gauge field ensembles from the OpenLAT initiative, we study two strategies how to fix the physical charm quark mass.
In a first approach, we follow the standard procedure by matching to a physical meson mass such as the D-meson mass. In our new approach we implement a massive renormalisation scheme that is designed to reduce mass-dependent cutoff effects. The latter requires the determination of certain improvement coefficients and renormalisation constants around the heavy quark mass scale which is also discussed in this contribution.

Topical area:

Quark and Lepton Flavor Physics

Poster session / 186

Bootstrap methods for digitized scalar field theory

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General positivity constraints linking various powers of observables in energy eigenstates can be used to sharply locate acceptable regions for the energy eigenvalues, provided that efficient recursive methods are available to calculate the matrix elements. These recursive methods are derived by looking at the commutation relations of the observables with the Hamiltonian. We discuss how this self-consistent (bootstrap) approach can be applied to the study of digitized scalar field theory in the harmonic basis. Using known results, we develop the method by testing on quantum systems, including the harmonic and anharmonic oscillators. We report recent numerical results for up to four coupled anharmonic oscillators. From here, we consider the possibility of using the groundwork of this method as a means of studying phase transitions in 1+1 dimensions.

Topical area:

Quantum Computing and Quantum Information

Hadronic and Nuclear Spectrum and Interactions / 187

The quenched glueball spectrum from smeared spectral densities

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Standard lattice calculations of the glueball spectrum rely on effective mass plots and asymptotic exponential fits of two-point correlators, and involve various numerical challenges.
In this work, we propose an alternative procedure to extract glueball masses, based on the computation of the smeared spectral densities that encode information about the towers of states with given quantum numbers.
While the exact calculation of spectral densities from lattice correlators is an ill-posed inverse problem, we use a recently developed numerical method, based on the Backus-Gilbert regularisation, that allows one to evaluate a smeared version of the spectral densities, without any a priori assumptions, and with controlled uncertainties.
After introducing the formalism to reconstruct the smeared spectral densities and highlighting its main strengths, we will present the novel results that we obtained for the masses of the lightest states in the glueball spectrum of the $SU(3)$ lattice gauge theory at finite values of the lattice spacing and volume. Finally, we will discuss the future steps towards a systematic investigation of the glueball spectrum using spectral-reconstruction methods.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Particle Physics Beyond the Standard Model / 188

Lattice investigation of the general 2HDM with SU(2) gauge fields

Author: Guilherme Catumba[1]

Co-authors: Alberto Ramos [2]; Karl Jansen [3]; C.-J. David Lin [4]; Mugdha Sarkar ; Atsuki Hiraguchi [5]

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In this investigation we study the most general two Higgs doublet model with SU(2) gauge fields on the lattice.
The phase space is probed through the computation of gauge-invariant global observables serving as proxies for order parameters.
In each phase, the spectrum of the theory is analysed for different combinations of bare couplings and different symmetry breaking patterns.
The scale setting and calculation of the gauge running coupling are done through the Wilson flow computation of the action density.
The computation of the renormalised gauge coupling for the Higgs theory is first tested in a single doublet model for various values of the cutoff on a line of constant physics within the Higgs phase of the theory.

Topical area:

Particle Physics Beyond the Standard Model

Algorithms and Artificial Intelligence / 189

The dependence of observables on action parameters

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Many applications in Lattice field theory require to determine the Taylor series of observables with respect to action parameters. A primary example is the determination of electromagnetic corrections to hadronic processes. We show two possible solutions to this general problem, one based on reweigting, that can be considered a generalization of the RM123 method. The other based on the ideas of Numerical Stochastic Perturbation Theory (NSPT) in the Hamiltonian formulation. We show that 1) the NSPT-based approach shows a much reduced variance in the determination of the Taylor coefficients, and 2) That both approaches are related by a change of variables. Numerical results are shown for the case of Lambda-phi^4 in 4 dimensions, but we expect these observations to be general. We conclude by commenting on the possible use of Machine Learning techniques to find similar change of variables that can potentially reduce the variance in Taylor coefficients.

Topical area:

Algorithms and Artificial Intelligence

Quantum Computing and Quantum Information / 190

Relations between Quantum Error Correction and Gauge Theory

Author: Masazumi Honda[1]

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We explore relations between quantum error correction and gauge theory. They have a conceptual similarity that quantum error correction provides a redundant description of logical qubits in terms of encoded qubits while gauge theory has a redundancy to describe physical states. Motivated by the conceptual similarity and recent demand for efficient ways to put gauge theories on quantum computers, we aim to identify precise relations between quantum error correction and gauge theory. We demonstrate that some classes of error correcting codes can be interpreted as gauge theories and vice versa.

Topical area:

Quantum Computing and Quantum Information

Quark and Lepton Flavor Physics / 191

Data-driven determination of the light-quark connected component of the intermediate-window contribution to $g_\mu - 2$.

Authors: Alexander Keshavarzi[1]; Diogo Boito[2]; Genessa Benton[3]; Maarten Golterman[3]; Kim Maltman[4]; Santiago Peris[5]

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We provide estimates for the light-quark-connected component of the RBC/UKQCD intermediate-window-hadronic contribution to the muon anomalous magnetic moment. We find significant tensions between our data-driven result,
$a_\mu^{W1,rmlqc} = 198.8(1.1) \times 10^{-10}$, and recent lattice computations.

Topical area:

Structure of Hadrons and Nuclei

Structure of Hadrons and Nuclei / 192

Gravitational form factors of the pion and the nucleon

Author: Dimitra Pefkou[1]

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The gravitational form factors (GFFs) of hadrons are related to the second Mellin moments of their generalized parton distributions. They can be extracted from matrix elements of the energy-momentum tensor of QCD. We present the gluon and quark flavor contributions to the GFFs of the pion and the nucleon in the kinematic region $0 \leq -t \leq 2$ GeV^2 on a clover improved ensemble with $a = 0.091$ fm, $N_f = 2 + 1$, and $m_\pi = 170$ MeV. The results are renormalized non-perturbatively via the RI-MOM scheme. We obtain estimates for the energy and mechanical distributions, and for the forward limit momentum fraction, spin, and D-term flavor decompositions.

Topical area:

Structure of Hadrons and Nuclei

Standard Model Parameters / 193

O(a) improved Wilson quarks and the O(am) rescaling of the bare coupling

Author: Stefan Sint[1]

Co-authors: Mattia Dalla Brida [2]; Roman Höllwieser [3]; Tomasz Korzec [4]; Francesco Knechtli [4]; Alberto Ramos [5]; Rainer Sommer [6]

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Lattice QCD with Wilson quarks near the continuum limit can be described by Symanzik's effective continuum action which contains the dimension 5 operator, $m\,tr(F_{\mu\nu}F_{\mu\nu})$. Its effect can be eliminated by an O(am) rescaling of the bare lattice coupling constant.The corresponding improvement coefficient, b_g, is currently only known to 1-loop order and the resulting uncertainty is now one of the dominant systematic errors in the recent determination of $\alpha_s(m_Z)$ with the decoupling method by the ALPHA collaboration. In this talk, I will discuss practical improvement conditions to determine b_g non-perturbatively. A perturbative test reproduces the known 1-loop result and first non-perturbative results at parameters required for the alpha_s determination will be shown in a poster by Mattia Dalla Brida.

Topical area:

Standard Model Parameters

Hadronic and Nuclear Spectrum and Interactions / 194

Charmonium spectroscopy with optimal distillation profiles

Authors: Juan Andres Urrea Nino[1]; Jacob Finkenrath[1]; Roman Höllwieser[1]; Francesco Knechtli[2]; Tomasz Korzec[2]; Michael Peardon[3]

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We use the method of optimal distillation profiles to compute the low-lying charmonium spectrum in an $N_f = 3 + 1$ ensemble at the $SU(3)$ light flavor symmetric point ($m_\pi \approx 420$ MeV), physical charm quark mass and lattice spacing $a \approx 0.0429$ fm. The spectrum and mass splittings display good agreement with their values in nature and the statistical errors are comparable, if not smaller, than those of state-of-the-art lattice calculations. We also present first results on the mixing of charmonium with glueballs and light hadrons obtained in a similar $N_f = 3 + 1$ ensemble but at larger pion mass ($m_\pi \approx 1$ GeV).

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Tests of Fundamental Symmetries / 195

Neutrinoless Double Beta Decay from Lattice QCD: The $n^0n^0 \to p^+p^+e^-e^-$ Amplitude

Authors: William Detmold[1]; Zhenghao Fu[None]; Anthony Grebe[2]; William Jay[1]; David Murphy[1]; Patrick Oare[3]; Phiala Shanahan[3]

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Neutrinoless double beta decay is a hypothetical beyond the Standard Model (BSM) process that, if observed, would imply that neutrinos are Majorana particles. Interpreting the results of double beta decay experiments requires knowledge of nuclear matrix elements that are calculable with lattice QCD. This talk presents determinations of the long-distance (mediated by a light Majorana neutrino) and short-distance (mediated by heavy BSM physics) contributions to the $n^0 n^0 \to p^+ p^+ e^- e^-$ decay through lattice QCD calculations, performed on a single ensemble at heavier-than-physical quark mass where the dineutron is assumed to be bound. These results provide proof-of-concept and can be used to compute low-energy constants in effective field theory, and we present a determination of these quantities.

Topical area:

Particle Physics Beyond the Standard Model

Quark and Lepton Flavor Physics / 196

Hadronic susceptibilities for b to c transitions from two point correlation functions

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In this talk we present a lattice determination of the hadronic susceptibilities that, as a consequence of unitarity and analyticity, constrain the form factors entering the semileptonic $b \to c$ transitions. We evaluate the longitudinal and transverse susceptibilities of the vector, axial and tensor polarization functions at zero momentum transfer from the moments of appropriate two-point correlation functions. The latter are obtained on the lattice employing gauge ensembles of the Extended Twisted Mass Collaboration (ETMC) with $N_f = 2 + 1 + 1$ flavors of Wilson-clover twisted-mass quarks with masses of all the dynamical quark flavors tuned close to their physical values. The simulations are carried out at four values of the lattice spacing, a ⊠ 0.057,0.068, 0.080, 0.091 fm, with spatial lattice sizes up to L ⊠ 7.6 fm. To allow for a smooth extrapolation to the physical b-quark mass, the heavy-quark mass is simulated directly on the lattice up to ⊠3 times the physical charm mass.

Topical area:

Quark and Lepton Flavor Physics

Quark and Lepton Flavor Physics / 197

m_b and $f_{B^{(*)}}$ of 2+1 flavor QCD from a combination of continuum limit static and relativistic results.

Authors: Alessandro Conigli[1]; Julien Frison[2]; Patrick Fritzsch[3]; Antoine Gérardin[4]; Jochen Heitger[5]; Gregorio Herdoiza[6]; Hubert Simma[2]; Simon Kuberski[7]; Carlos Pena[1]; Rainer Sommer[2]

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We present preliminary results for B-physics from a combination of non-perturbative results in the static limit with relativistic computations satisfying $am_{\mathrm{heavy}} << 1$. Relativistic computations are carried out at the physical b-quark mass using the Schrödinger Functional in a $(0.5\ \mathrm{fm})^4$ box. They are connected to large volume observables through step scaling functions that trace the mass dependence between the physical charm region and the static limit, such that B-physics results can be obtained by interpolation; the procedure is designed to exactly cancel the troublesome $\alpha_s(m_{\mathrm{heavy}})^{n+\gamma}$ corrections to large mass scaling. Large volume computations for both static and relativistic quantities use CLS $N_f = 2 + 1$ ensembles at $m_u = m_d = m_s$, and with five values of the lattice spacing down to 0.039 fm.
Our preliminary results for the b-quark mass and leptonic decay constants have competitive uncertainties, which are furthermore dominated by statistics, allowing for substantial future improvement. This talk focusses on numerical results, while the underlying strategy is discussed in detail in a companion talk.

Topical area:

Standard Model Parameters

Structure of Hadrons and Nuclei / 198

Updates on Pion and Kaon Valence-Quark and Gluon Distributions from $N_f = 2 + 1 + 1$ QCD

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We present recent updates on the lattice calculations of the valence-quark GPDs of the pion, the pion and kaon gluon PDF, and their first gluon moment in the physical-continuum limit. All these calculations are done on ensembles with $N_f = 2 + 1 + 1$ highly improved staggered quarks (HISQ), generated by the MILC Collaboration. The valence-quark GPD of the pion is done at lattice spacing 0.09~fm with physical pion masses and boosted pion momentum around 1.7~GeV with four additional nonzero transfer momenta in the Breit frame, using LaMET method with next-to-next-to-leading order perturbative matching. We update MSULat's previous meson gluon PDF calculations using pseudo-PDFs with a third lattice spacing at 0.09~fm with 310-Mev pion mass. We also present the first pion and kaon gluon moments at the continuum-physical limit with 3 pion masses and 3 lattice spacings.

Topical area:

Structure of Hadrons and Nuclei

Quark and Lepton Flavor Physics / 199

Inclusive hadronic decay rate of the τ lepton from lattice QCD

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Inclusive hadronic τ decays are very interesting from the phenomenological viewpoint since they give access to the CKM matrix elements V_{ud} and V_{us}. In this talk, exploiting flavour diagonal vector and axial two-point correlators produced with high statistics by ETMC within the muon $g-2$ HVP project, we apply the HLT method for hadronic smeared spectral densities to study the inclusive decay $\tau \to \nu + X_{ud}$ and compute its rate over $|V_{ud}|^2$. The computation avoids any recourse to OPE and/or perturbative methods, is performed in isospin symmetric $N_f = 2+1+1$ QCD, using three lattice spacings, two volumes and physical quark masses and, taking all uncertainties (apart from isospin breaking effect) into account, yields a subpercent error for $|V_{ud}|$. These findings motivate extension to the inclusive decay $\tau \to \nu + X_{us}$ and inclusion of the leading isospin-breaking effects, in order
to obtain a precise first principles determination of $|V_{us}|$ from inclusive τ decay.

Topical area:

Quark and Lepton Flavor Physics

Quantum Computing and Quantum Information / 200

Simulating the Femto-universe on a Quantum Computer

Authors: Draper Patrick[1]; Jiayu Shen[1]; Nouman Butt[1]

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We compute the low-lying spectrum of 4D SU(2) Yang-Mills in a finite volume using quantum simulations. In contrast to small-volume lattice truncations of the Hilbert space, we employ toroidal dimensional reduction to the "femtouniverse" matrix quantum mechanics model. In this limit the theory is equivalent to the quantum mechanics of three interacting particles moving inside a 3-ball with certain boundary conditions. We use the variational quantum eigensolver and quantum subspace expansion techniques to compute the string tension to glueball mass ratio near the small/large-volume transition point, finding qualitatively good agreement with large volume Euclidean lattice simulations.

Topical area:

Quantum Computing and Quantum Information

Poster session / 201

Fast Partitioning of Pauli Strings into Commuting Families for Optimal Expectation Value Measurements of Dense Operators

Authors: Andrew Lytle[1]; Nouman Butt[1]; Ben Reggio[1]; Patrick Draper[1]

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The Pauli strings appearing in the decomposition of an operator can be can be grouped into commuting families, reducing the number of quantum circuits needed to measure the expectation value of the operator. We detail an algorithm to completely partition the full set of Pauli strings acting on any number of qubits into the minimal number of sets of commuting families, and we provide python code to perform the partitioning. The partitioning method scales linearly with the size of the set of Pauli strings and it naturally provides a fast method of diagonalizing the commuting families with quantum gates. We provide a package that integrates the partitioning into Qiskit, and use this to benchmark the algorithm with dense Hamiltonians, such as those that arise in matrix quantum mechanics models, on IBM hardware. We demonstrate computational speedups close to the theoretical limit of $(3/2)^m$ relative to qubit-wise commuting groupings, for $m = 2, \ldots, 6$ qubits.

Topical area:

Quantum Computing and Quantum Information

Quantum Computing and Quantum Information / 202

Simulating Field Theories with Quantum Computers

Author: Muhammad Asaduzzaman[1]

Co-authors: Goksu Toga [2]; Yannick Meurice [3]; simon catterall [4]

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In this talk, we investigate the Trotter evolution of an initial state in the Gross-Neveu model and hyperbolic Ising model in two spacetime dimensions, leveraging quantum computers. We identify different sources of errors prevalent in various quantum processing units and discuss challenges to scale up the size of the computation. We present benchmark results obtained from some platforms and employ a range of error mitigation techniques to address incoherent noise. By comparing these mitigated outcomes with exact diagonalization results and density matrix renormalization group calculations, we assess the effectiveness of our approaches. Moreover, we demonstrate the possible implementation of an out-of-time-ordered correlators (OTOC) protocol using IBM's quantum machine, and thoroughly examine the sources of errors that emerge in the calculation. Finally, we explore the feasibility of real-time scattering calculations for a multi-flavor fermionic model using NISQ-era machines.

Topical area:

Quantum Computing and Quantum Information

QCD at Non-zero Temperature / 203

Determination of the CP restoration temperature at $\theta = \pi$ in 4D SU(2) Yang-Mills theory through simulations at imaginary θ

Author: Mitsuaki Hirasawa[1]

Co-authors: Akira Matsumoto [2]; Atis Yosprakob [3]; Jun Nishimura [4]; Kohta Hatakeyama [5]; Masazumi Honda [6]

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The 't Hooft anomaly matching condition provides constraints on the phase structure at $\theta = \pi$ in 4D SU(N) Yang-Mills theory. In particular, assuming that the CP symmetry is spontaneously broken at low temperature, it cannot be restored below the deconfining temperature at $\theta = \pi$. Here we investigate the CP restoration at $\theta = \pi$ in the 4D SU(2) case and provide numerical evidence that the CP restoration occurs at a temperature higher than the deconfining temperature unlike the known results in the large-N limit, where the CP restoration occurs precisely at the deconfining temperature. The severe sign problem at $\theta = \pi$ is avoided by focusing on the tail of the topological charge distribution at $\theta = 0$, which can be probed by performing simulations at imaginary θ. In addition to this analysis, we carry out an alternative analysis based on the analytical continuation with respect to θ and discuss the consistency of the obtained results.

Topical area:

QCD at Non-zero Temperature

Algorithms and Artificial Intelligence / 204

HISQy Business

Author: Evan Weinberg[1]

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Tackling ever more complex problems of non-perturbative dynamics requires simulations and measurements on ever increasingly large lattices at physical quark masses. In the age of the exascale, addressing the challenges of ensemble generation and measurements at such scales requires a plethora of algorithmic advances, both in theory space and in the implementation space. In this talk we will focus on tackling these issues on the largest physical-quark ensembles in active use which feature a 192^3x384 global volume and utilize the HISQ fermion discretization. We will present results from a three-pronged approach implemented in the QUDA library for GPUs: a multigrid algorithm for HISQ fermions, a refactoring and optimization of the HISQ fermion force, and a local preconditioner to the Schur-preconditioned HISQ stencil.

Topical area:

Algorithms and Artificial Intelligence

Structure of Hadrons and Nuclei / 205

Nucleon elastic and resonance structures from hadronic tensor in lattice QCD: implications for neutrino-nucleon scattering

Author: Raza Sufian[1]

Co-authors: Bigeng Wang [2]; Jian Liang ; Keh-Fei Liu [2]; Tanjib Khan ; Terrence Draper ; Yi-Bo Yang

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The excitation of nucleons to resonance structures via electromagnetic interactions is crucial for enhancing our comprehension of strong interactions within the realm of quark confinement. Additionally, accurate knowledge of neutrino-nucleon scattering is vital for neutrino oscillation experiments. In this study, we present determinations of the nucleon electric form factor ($G_E(Q^2)$), the nucleon-to-Roper transition form factor ($G_E^*(Q^2)$), and the associated longitudinal helicity amplitude ($S_{1/2}(Q^2)$) utilizing the hadronic tensor for the first time. We outline future prospects to extend this formalism for determining the nucleon's magnetic and axial structures in the elastic and resonance regions, which will provide theoretical constraints for investigating resonance structures and neutrino-nucleus scattering experiments.

Topical area:

Structure of Hadrons and Nuclei

Theoretical Developments / 206

Tensor renormalization group study of 3D principal chiral model

Authors: Shinichiro Akiyama[1]; Raghav Jha[2]; Judah Unmuth-Yockey[3]

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We study the three dimensional principal chiral model using both the triad tensor renormalization group method, and the anisotropic tensor renormalization group method. We present a tensor network formulation for the model, and compare the ability of the two methods to measure thermodynamic observables. In addition we remark upon criticality, and the possible universality class of the phase transition.

Topical area:

Theoretical Developments

Hadronic and Nuclear Spectrum and Interactions / 207

Three Relativistic Spinning Particles in a Box

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We generalize the relativistic field-theoretic (RFT) three-particle finite-volume formalism to systems of three identical, massive, spin-1/2 fermions, such as three neutrons. This allows, in principle, for the determination of the three-neutron interaction from the finite-volume spectrum of three-neutron states, which can be obtained from lattice QCD calculations.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

QCD at Non-zero Density / 208

Detecting Lee Yang/Fisher singularities by multi-point Padè

Authors: Francesco Di Renzo[1]; David A. Clarke[2]; Petros Dimopoulos[3]; Jishnu Goswami[4]; Christian Schmidt-Sonntag[5]; Simran Singh[5]; Kevin Zambello[6]

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The Bielefeld Parma Collaboration has in recent years put forward a method to probe finite density QCD by the detection of Lee Yang singularities. The location of the latter is obtained by multi-point Padè approximants, which are in turn calculated matching Taylor series results obtained from Monte Carlo computations at (a variety of values of) imaginary baryonic chemical potential. The method has been successfully applied to probe the Roberge Weiss phase transition and preliminary, interesting results are showing up in the vicinity of a possible QCD critical endpoint candidate.
In this talk we will be concerned with a couple of significant aspects in view of a more powerful application of the method. First, we will discuss the possibility of detecting finite size scaling of Lee Yang/Fisher singularities in finite density (lattice) QCD. Secondly, we will discuss our attempts at detecting both singularities in the complex chemical potential plane and singularities in the complex temperature plane. The former are obtained from rational approximations which are functions of the chemical potential at given values of the temperature; the latter are obtained from rational approximations which are functions of the temperature at given values of the chemical potential.

Topical area:

QCD at Non-zero Density

Hadronic and Nuclear Spectrum and Interactions / 209

Pion-N and Other Nucleon Excited States in Nucleon Two- and Three-point Functions

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The excited states contamination in the nucleon three-point function is one of the major systematic errors in calculating nucleon form factors. We use Bayesian Reconstruction to study the nucleon excited states in the two-point nucleon and S11 correlators which are constructed from the valence overlap fermions on DWF configurations at the physical pion mass with a lattice size of 5.5 fm. We will show the observed Roper state and discuss the non-observation of the pion-nucleon states in the nucleon positive and negative parity channels. We will discuss its consequence in the nucleon three-point functions in the context of the pion-nucleon contamination due the current-enhanced boomerang diagram for the pseudoscalar current.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Structure of Hadrons and Nuclei / 210

Extracting the Pion Distribution Amplitude from Lattice QCD through Pseudo-Distributions

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Co-authors: Kostas Orginos [1]; Anatoly Radyushkin [2]; Joseph Karpie [3]; Savvas Zafeiropoulos [4]

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The Light-Cone Distribution Amplitude (DA) encodes the non-perturbative information of the leading Fock-component of the hadron wave function, therefore required for processes including exclusive hadron production. As the Pseudo-Nambu-Goldstone boson of QCD, nonperturbative structure of the pion is of particular interest. We present a lattice QCD calculation of the pion DA on ensembles with O(a)-improved Wilson fermions on lattice spacings in the range of 0.0483fm-0.0749fm, and pion masses ranging from physical to 440MeV. The Pseudo-Distribution formalism is employed to match the Renormalization Group Invariant (RGI) matrix element to the DA.

Topical area:

Structure of Hadrons and Nuclei

QCD at Non-zero Temperature / 211

Partial deconfinement in QCD at $N = \infty$ and $N = 3$

Authors: Hidehiko Shimada[1]; Hiroki Ohata[1]; Masanori Hanada[2]; Hiromasa Watanabe[1]

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We describe how the general mechanism of partial deconfinement applies to large-N QCD and the partially-deconfined phase inevitably appears between completely-confined and completely-deconfined phases. Furthermore, we propose how the partial deconfinement can be observed in the real-world QCD with SU(3) gauge group. We propose how the Polyakov loop and chiral condensate should behave and test the proposal against lattice simulation data.

Topical area:

QCD at Non-zero Temperature

Algorithms and Artificial Intelligence / 212

Reducing the Sign Problem with simple Contour Deformation

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We apply constant imaginary offsets to the path integral for a reduction of the sign problem in the Hubbard model. These straightforward transformations enhance the quality of results from HMC calculations without compromising the speed of the algorithm. This method enables us to efficiently calculate systems that are otherwise inaccessible due to a severe sign problem. To support this claim, we present observables of the C_{20} and C_{60} fullerenes. Furthermore, we demonstrate that at a certain offset, the sign problem is completely lifted in the limit of large chemical potential.

Topical area:

Algorithms and Artificial Intelligence

Theoretical Developments / 213

From the Affine Ising model to Quantum Geometry in curved space

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A general geometrical framework is explored for quantum field theory on curved manifolds motivated by the recent map of the 2d Ising model on a triangulated grid to reproduce the integrable conformal field theory (CFT) on the modular torus ($\mathbb{T}^2$) and the Riemann sphere ($\mathbb{S}^2$). This talk will emphasize the special role of affine transformations as a bridge between Regge's simplicial Einstein gravity and simplicial lattice field theory at or near to an infrared critical point. To test and refine this geometrical framework a gradual sequence of lattice fields theories is being considered, including fermionic and gauge fields on cylindrical ($\mathbb{R} \times \mathbb{S}^{d-1}$) manifolds.

Topical area:

Theoretical Developments

Particle Physics Beyond the Standard Model / 214

Higher-Order Calculations of Anomalous Dimensions at Infrared Fixed Points in Gauge Theories and Studies of Renormalization-Group Behavior of Some Scalar Field Theories

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Speaker: Prof. Robert Shrock

Institution: Stony Brook University

Title: Higher-Order Calculations of Anomalous Dimensions at
Infrared Fixed Points in Gauge Theories and Studies of Renormalization-Group
Behavior of Some Scalar Field Theories

Abstract

We discuss higher-order calculations of anomalous dimensions of operators at an infrared fixed point in asymptotically free gauge theories with various fermion contents and compare with recent results from lattice simulations. This work is in collaboration with T. Ryttov. If time permits, we will also report on higher-order studies of the beta functions in O(N) ϕ_4^4 and ϕ_3^6 theories [R. Shrock, PRD 107, 056018 (2023); PRD 107, 096009 (2023)].

Topical area:

Particle Physics Beyond the Standard Model

QCD at Non-zero Density / 215

QCD at large isospin density: 6144 pions in a box

Authors: Fernando Romero-Lopez[1]; William Detmold[1]; Ryan Abbott[1]

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We investigate QCD at large isospin density by computing correlation functions between sources with isospin charge $n = 1, \ldots, 6144$ on two lattice volumes at quark masses corresponding to a pion mass, $m_\pi \sim 170$ MeV. By extracting the energies of the corresponding many-pion systems under the assumption of log-normality of the correlation function distributions, we determine the isospin chemical potential, the speed of sound, and related thermodynamic properties of the dense medium, extending previous work to considerably higher isospin chemical potentials, μ_I. Significant deviations from perturbative QCD are seen until $\mu_I > 10 m_\pi$ and the speed of sound is seen to significantly exceed the expectation from a free gas of quarks over a large range of isospin chemical potentials.

Topical area:

QCD at Non-zero Density

Quantum Computing and Quantum Information / 216

Gauge redundancy as approximate error correction codes for quantum simulations

Authors: Henry Lamm[1]; Wanqiang Liu[2]; Marcela Carena[1]; Ying-Ying Li[3]

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In the quantum simulation of lattice gauge theories, gauge symmetry can be either fixed or encoded as a redundancy of the digitized Hilbert space. While fixing the gauge saves the number of qubits to digitize the Hilbert space, keeping the gauge redundancy can provide space to mitigate and correct certain quantum errors by checking and restoring Gauss's law. In this talk, we treat the gauge redundancy as approximate error correction codes. I will present the correctable errors for generic finite groups and the quantum circuits to detect them, and discuss the condition when keeping the gauge redundancy is preferable to fixing it.

Topical area:

Quantum Computing and Quantum Information

QCD at Non-zero Density / 217

Universal scaling and the asymptotic behaviour of Fourier coefficients of the baryon number density

Author: Christian Schmidt[1]

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We present recent results of the Bielefeld-Parma collaboration on the baryon number density at imaginary chemical potential with (2+1)-flavors of HISQ fermions on Nt=4,6 and 8 lattices. Based on these data we calculate Fourier coefficients by means of a Filon-type quadrature. We discuss how the universal critical behavior is manifest in the asymptotic behavior of the Fourier coefficients of the baryon number density. We derive a fit ansatz for the Fourier coefficients by integrating around the Lee-Yang cut in the complex plane of the scaling function of the order parameter. Based on this formula we propose a well defined strategy to locate the position of the Lee-Yang edge singularities associated with the Roberge Weiss transition and the chiral transition in QCD. The results are in agreement with previous results of the Bielefeld-Parma Collaboration based on the multi-point Pade approach. To that extent, we also present an update of the continuum extrapolation of the Roberge-Weiss transition temperature.

Topical area:

QCD at Non-zero Density

Hadronic and Nuclear Spectrum and Interactions / 218

Exploring the anisotropic HISQ (aHISQ) action

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The fate of heavy quarkonia states in quark-gluon plasma is encoded in the temperature dependence of their spectral functions. Reconstruction of spectral functions from Euclidean lattice correlators is an ill-posed problem. Despite a variety of techniques developed recently, many questions remain unresolved. It is known that the situation may be improved using anisotropic ensembles that provide finer resolution in the temporal direction. To date, the effort focused on Wilson fermions. We report on our first study with anisotropic improved staggered quarks. To compute the spectrum of the anisotropic Highly Improved Staggered Quarks (aHISQ) we generated a library of anisotropic pure gauge ensembles. We discuss the gauge anisotropy tuning that is performed with the Symanzik gradient flow, as well as tuning of the strange quark mass and quark anisotropy with aHISQ, using spectrum measurements on quenched ensembles. Finally, we discuss the impact of anisotropy on pion taste splittings for aHISQ.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Quark and Lepton Flavor Physics / 219

Comparing phenomenological estimates of dilepton decays of pseudoscalar mesons with lattice QCD

Author: Bai-Long Hoid[1]

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Dilepton decays of the pseudoscalar mesons have been drawing particular interest, thanks to their sensitivity to both the QCD dynamics at low energy and also signals beyond the Standard model. In the first part of the talk, we present our work on an improved Standard-Model prediction for the rare decay $\pi^0 \to e^+e^-$, and compare it with the first determination on the lattice that predicted a lower $\pi^0 \to \gamma\gamma$ decay width as byproduct. In the second part, we discuss the ongoing work on $K_L \to \ell^+\ell^-$ decays and its connection to lattice QCD.

Topical area:

Quark and Lepton Flavor Physics

QCD at Non-zero Temperature / 220

Symmetries of Two-Point Spatial Correlators in $N_f = 2 + 1$ QCD above Critical Temperature

Authors: David Ward[1]; Hidenori Fukaya[1]; Issaku Kanamori[2]; Kei Suzuki[3]; Shoji Hashimoto[4]; Sinya Aoki[5]; Takashi Kaneko[4]; Yasumichi Aoki[2]; Yoshifumi Nakamura[2]

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Based on simulations of 2+1 flavor lattice QCD with M\"obius domain wall fermions at high temperatures, we use a series of recently developed spatial correlation functions to study the screened masses for quarks in meson bound states. We compare these screened masses with the symmetries of the correlators using a pair of fitting ansatz for various quark masses and lattice sizes with temperatures above the critical point. Using these spatial correlation functions we can analyze the lattices by way of standard $SU(2)_L \times SU(2)_R$ symmetry as well as examine the behaviors of the anomalous axial $U(1)_A$ symmetry above the critical point. Additionally we explore a possible and emergent chiral-spin symmetry $SU(2)_{CS}$ which we discuss at length.

Topical area:

QCD at Non-zero Temperature

Theoretical Developments / 221

Gauge field smearing and controlled continuum extrapolations

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Two popular methods to reduce discretisation effects are Symanzik improvement and gauge field smearing in the Dirac operator. Tree-level $O(a^2)$-improved Wilson fermions can be obtained from $O(a)$-improved Wilson fermions by adding one dimension-6 operator to the action. For gauge field smearing one wants to avoid the situation when too much smearing leads to uncontrolled continuum extrapolations as the short distance behaviour is mutilated. We focus on the gradient flow formalism as it allows to study both smearing and physical flow. We investigate the effect of smearing on the scaling towards the continuum limit in pure gauge theory on the example of Creutz ratios, which provide a measure of the physical forces felt by the fermions. For suitable smearing strengths we also investigate the change when the Wilson gradient flow is replaced by stout smearing.

Topical area:

Theoretical Developments

Structure of Hadrons and Nuclei / 222

Octet baryon charges with $N_f = 2 + 1$ non-perturbatively improved Wilson fermions

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The axial charge of the nucleon, g_A, has been computed extensively on the lattice. However, the axial charges for other octet baryons (hyperons) such as the Σ and Ξ baryons are less well known experimentally and theoretically.
Here we present results for the isovector axial, scalar and tensor charges, as well as for the second Mellin moments of isovector PDFs. This allows us to estimate SU(3) flavour symmetry breaking effects in the different channels. Moreover, the scalar charges are related to the difference between the physical up and down quark masses via the vector Ward identity and we determine this splitting. Our calculations are performed on a large set of $N_f = 2 + 1$ CLS ensembles of non-perturbatively $O(a)$ improved Wilson fermions with tree-level Symanzik improved gauge action. For the computation of the required three-point functions we use a stochastic technique which enables us to simultaneously compute various combinations of currents and octet baryon interpolators.

Topical area:

Structure of Hadrons and Nuclei

Quantum Computing and Quantum Information / 223

Digital Quantum Simulation for the Spectroscopy of Schwinger Model

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This talk will discuss a method for computing the energy spectra of quantum field theory utilizing digital quantum simulation. A quantum algorithm called coherent imaging spectroscopy quenches the vacuum with a time-oscillating perturbation and reads off the excited energy levels from the loss in the vacuum-to-vacuum probability following the quench. As a demonstration, we apply this algorithm to the (1+1)-dimensional quantum electrodynamics with a topological term known as the Schwinger model, where the conventional Monte Carlo approach is practically inaccessible. In particular, on a classical simulator, we prepare the vacuum of the Schwinger model on a lattice by adiabatic state preparation and then apply various types of quenches to the approximate vacuum through Suzuki-Trotter time evolution. We compare the simulation result with exact diagonalization and the continuum limit expectation. We discuss its dependence on the types of quenches as well. Furthermore, we estimate the computational complexity required to obtain physically reasonable results and conclude that the method is likely efficient in the coming era of early fault-tolerant quantum computers.

Topical area:

Quantum Computing and Quantum Information

Algorithms and Artificial Intelligence / 225

Performance of two-level methods for the glueball spectrum in pure gauge theory

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The computation of the glueball spectrum is particularly challenging due to the rapid decay of the signal-to-noise ratio of the correlation functions. To address this issue, advanced techniques such as gauge link smearing and the variational method are commonly employed to identify the spectrum before the signal diminishes significantly. However, a significant improvement in the signal-to-noise ratio can be achieved by utilising multilevel techniques. In this talk, we present a study of the glueball spectrum in pure gauge theory with a two-level algorithm. Specifically, we explore the relation between noise reduction and the various multilevel parameters, such as the width of the dynamical regions and the number of two-level configurations.

Topical area:

Algorithms and Artificial Intelligence

Poster session / 226

Domain decomposition for the propagator factorization in distillation

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Multilevel integration schemes are easy to couple with distillation, our current approach for computing highly optimized interpolating fields for hadrons. The locality of the distillation basis in the time direction can be exploited in accelerating the propagator computations with domain decomposition. Currently, we are exploring the use of asymmetric domain decomposition schemas in which the domains have only direct connections to a non-local domain. However, computing the contributions from the non-local domain may dominate the global performance of the calculation. We will show the impact on the accuracy and performance of preconditioning techniques for the resolution of linear systems with the non-local domain.

Topical area:

Algorithms and Artificial Intelligence

Hadronic and Nuclear Spectrum and Interactions / 227

Nucleon-hyperon interaction from lattice QCD on physical point

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The nucleon-hyperon interaction is important to understand the system with strange quarks, for example, the inner region of neutron stars. Although experimental study of the interaction is difficult rather than the nucleon-nucleon interaction, which is so-called nuclear force, theoretical study is possible by using the HAL QCD method in the lattice QCD. In the present contribution, we show our current results of the nucleon-hyperon interaction from the 2+1 flavor lattice QCD configuration with physical quark masses generated by the HAL QCD collaboration.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Particle Physics Beyond the Standard Model / 228

Chimera Baryon Spectrum of the Composite Higgs Model with Sp(4) gauge group

Authors: Ho Hsiao[1]; Ed Bennett[2]; Deog Ki Hong[3]; Jong-Wan Lee[4]; C.-J. David Lin[1]; Biagio Lucini[5]; Maurizio Piai[6]; Davide Vadacchino[7]

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In the context of Composite Higgs Models, where the standard model Higgs is interpreted as a pseudo Nambu–Goldstone Boson, baryons formed by matter in different representations, known as chimera baryons, could serve as top partners. The chimera baryon sharing the same quantum number as the top quark can mix with it, effectively lifting the mass of the top quark through the see-saw mechanism. We report our results of the spectrum of low-lying chimera baryons in the quenched approximation with the $Sp(4)$ gauge theory. Specifically, we investigate the chiral extrapolation of chimera baryon masses. To accomplish this, we use a fitting function inspired by QCD chiral Effective Field Theory (EFT). We employ a simplified Akaike Information Criterion (AIC) to determine the best fit among different data sets. Additionally, we conduct a sense check on the fitting procedure, confirming its validity and reliability. Last, we present the massless-continuum limit of chimera baryon masses.

Topical area:

Particle Physics Beyond the Standard Model

Quark and Lepton Flavor Physics / 229

Finite-volume collinear divergences in radiative corrections to meson leptonic decays

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In the context of radiative corrections to pseudoscalar meson leptonic decay, it is well-known that the $\mathcal{O}(\alpha_{\mathrm{em}})$ corrections to the decay amplitude logarithmically diverges when the lepton mass goes to zero, a behavior known as collinear divergences. Since leptons are not massless, this is not per se a divergence of the process, but it greatly enhances the value of the amplitude in cases where the lepton in the final state is hyper-relativistic. This occurs for example in the decay of D^+ and D_s^+ into a muon and a neutrino, relevant for CKM matrix elements determination. In an infinite volume, collinear divergences are known to be logarithmic and independent of the direction of the lepton momentum. In this talk, we demonstrate that in a finite volume, these divergences have a very complex angular dependence, likely of number theoretical nature. Although it is challenging to understand this structure analytically, we present properties obtained through numerical experiments. Finally, we conclude on the implication for lattice calculations, and possible strategies for mitigating this class of volume effects.

Topical area:

Quark and Lepton Flavor Physics

Software Development and Machines / 230

GPU computation energy-efficiency: from lattice QCD to large language model training

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In the current climate and energy crisis context, it is crucial to study and optimise the energy efficiency of scientific software used at large scale computing facilities. This supports moving toward net-zero computing targets, and reduce the negative impact of growing operational costs on the production of scientific data.
The energy efficiency of a computation is generally quantified as an amount of work performed per unit of energy spent. The study presented here was comissioned by the national UK STFC DiRAC facility, and performed on the Edinburgh "Tursa" supercomputer based on 724 NVIDIA A100 GPUs. We study how the energy efficiency of various workflows varies as we down-clock the frequency of the GPUs. From lattice QCD benchmarks (Grid & QUDA) to large language model training (GPT), we observe that lower frequencies than the default one lead to an increase of the GPU energy efficiency by 20-30%, with a reasonable impact on performances. This study led to a modification of the default GPU frequencies on Tursa in December 2022, resulting in an estimated saving to date of 60 MWh.

Topical area:

Software Development and Machines

Quark and Lepton Flavor Physics / 231

Pseudoscalar-pole contributions to HLbL at the physical point

Authors: Gurtej Kanwar[1]; Marcus Petschlies[2]; Sebastian Andreas Burri[3]; Urs Wenger[4]

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We present our computation of the pion and eta-meson transition form factors from twisted mass lattice QCD at physical quark masses. In particular, we report on the improvements we recently made in the calculation of the pion transition form factor, which finalizes the calculation with data presently available to us. We use the form factors to determine the pseudoscalar-pole contributions to the hadronic light-by-light scattering in the muon g-2, as well as the two-photon decay widths and pseudoscalar transition form factor slopes.
Our continuum estimate of the pion-pole g-2 contribution is comparable with other lattice and data-driven determinations while achieving a sub-10% precision. For the eta-pole contribution estimate at a single lattice spacing of 0.08 fm we achieve a sub-40% precision and are also compatible with other lattice and data-driven results. We further indicate the planned steps needed to achieve a continuum result for the eta-pole calculation.

Topical area:

Quark and Lepton Flavor Physics

QCD at Non-zero Temperature / 232

Axial U(1) symmetry near the pseudocritical temperature in $N_f = 2 + 1$ lattice QCD with chiral fermions

Authors: Sinya Aoki[1]; Yasumichi Aoki[2]; Hidenori Fukaya[3]; Shoji Hashimoto[4]; Issaku Kanamori[5]; Takashi Kaneko[4]; Yoshifumi Nakamura[5]; Christian Rohrhofer[6]; Kei Suzuki[7]; David Ward[8]

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We study the $U(1)_A$ anomaly at high temperatures of $N_f = 2 + 1$ lattice QCD with chiral fermions. Gauge ensembles are generated with M\"obius domain-wall (MDW) fermions, and in the measurements, the determinant is reweighted to that of overlap fermions. We report the results for the Dirac spectra, the $U(1)_A$ susceptibility, and the topological susceptibility at temperatures, T=136, 153, 175, and 204 MeV.

Topical area:

QCD at Non-zero Temperature

Poster session / 233

Charmonia distribution amplitudes

Author: Miguel Teseo San José Pérez[1]

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We present our ongoing work on the distribution amplitudes of the charmonia states $\eta_c(1s)$ and $J/\psi(1s)$. We use the so-called pseudo approach developed by A. Radyushkin in a set of three CLS $N_f = 2$ ensembles at three different lattice spacings between 0.08 fm and 0.05 fm and a pion mass around 270 MeV. The resulting momentum distributions can be studied in the region of Ioffe times $|\nu| < 4$, where we observe a non-trivial functional dependence which can be compared to the NRQCD expectation of a flat behaviour.

Topical area:

Structure of Hadrons and Nuclei

QCD at Non-zero Temperature / 234

The thermal photon emissivity at the QCD chiral crossover from imaginary momentum correlators

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The thermal photon emissivity at the QCD chiral crossover is investigated using imaginary momentum correlators. These have been measured on a newly generated 20×96^3 lattice-QCD ensemble with $\mathrm{O}(a)$-improved Wilson quarks and physical up, down and strange quark masses at a temperature $T = 154$ MeV near the pseudo-critical temperature. In order to realize the photon on-shell condition, the spatially transverse Euclidean correlators have to be evaluated at imaginary spatial momenta.
Employing a bounding method, we present a preliminary result on the quantity $H_E(\omega_1)$, which corresponds to an energy-moment of the photon spectral function $\sigma(\omega)$.

Topical area:

QCD at Non-zero Temperature

Poster session / 235

The $\Lambda(1405)$ from lattice QCD: Something about determining the finite-volume spectra

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Hadronic scattering amplitudes determined in Lattice QCD using Lüscher's formalism depend crucially on the finite-volume energy spectrum. This work presents some of the technical details of the determination of such spectra within the study of the two-poles nature of the $\Lambda(1405)$ from Lattice QCD. Starting with the extraction of energy states from correlation functions, the GEVP technique has shown to be a useful tool to investigate the desired states, and two independent analyses were done in parallel, the so-called: Single Pivot and Rolling Pivot. This procedure was followed by a detailed analysis of the fits to ratios of correlators, which results in the energy difference of a certain level to the close-by energies of non-interacting mesons. The final results were in good agreement between both implementations and were ultimately used as input for the computation of the scattering amplitude.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

QCD at Non-zero Density / 236

Analysis on phases in the Gross-Neveu Model on the lattice with shape-based clustering method

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In low temperature and high density region possible interesting phases are discussed from effective theories which exhibit the same symmetries as QCD, chiral symmetry.
They are pion condensation, color super conducting phases and inhomogeneous chiral condensation.
For spatial dependence of inhomogeneous chiral condensation, various kinds of structures are discussed; chiral density wave, kinks as solitonic solutions. Usually the investigations are limited to specific ansatz such as a selected set of Fourier modes. One of pioneering works is carried out without using ansatz for spatial structure of chiral condensation. Also, lattice calculation of the 1+1 dimensional Gross-Neveu model is performed. Here, we apply a shape-based clustering method, which is unsupervised learning, to estimate the spatial dependence of chiral condensation in configurations of the 1+1 dimensional Gross-Neveu model on the lattice. Furthermore we demonstrate to classify the phases of the 1+1 dimensional Gross-Neveu model on $T-\mu$ plane, using the shape-based clustering method.

Topical area:

QCD at Non-zero Density

Hadronic and Nuclear Spectrum and Interactions / 237

Timelike pion form factor from lattice QCD

Author: Felipe Ortega Gama[None]

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We perform a lattice QCD calculation to study the behavior of the electromagnetic form factor of the pion, both in the spacelike and timelike region. At the heavier than physical pion mass of 284 MeV of this lattice, the rho meson is a narrow resonance that drives the pion-pion P-wave elastic interaction. As a preamble for future work studying the timelike form factor in the coupled channel energy region, we also extract the scattering amplitude in the inelastic region containing the isovector kaon-kaon channel. In part, this work aims to test finite volume correction techniques that are needed to calculate the electroweak response of hadronic resonances. This will yield a quantitative description of their structure and further insight into their nature.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Algorithms and Artificial Intelligence / 238

Three simple tricks for better Trotterization

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Suzuki-Trotter decompositions of exponential operators like exp(Ht) are required in almost every branch of numerical physics. Often the exponent under consideration has to be split into more than two operators, for instance as local gates on quantum computers.
In this talk, I will demonstrate how highly optimised schemes originally derived for exactly two operators can be applied to such generic Suzuki-Trotter decompositions.
After this first trick, I will explain what makes an efficient decomposition and how to choose from the large variety available.
Furthermore I will demonstrate that many problems for which a Suzuki-Trotter decomposition might appear to be the canonical ansatz, are better approached with different methods like Taylor expansions.

Topical area:

Algorithms and Artificial Intelligence

Algorithms and Artificial Intelligence / 239

Neural network contour deformation for 3d SU(2) gauge theory

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I present our results on exponential variance reduction of Wilson loops on 3d SU(2) gauge theory using the contour deformation technique. Previous studies focused on gauge theories in two dimensions with open boundary conditions that are analytically tractable. In this study, we extend

the formalism to three dimensions with periodic boundary conditions, and show how gauge fixing, U-net convolutional neural networks, and transfer learning are used to exponentially suppress the Wilson loop variance.

Topical area:

Algorithms and Artificial Intelligence

Poster session / **240**

Staggered nucleon axial charge and form factors

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In this poster, I present preliminary results from the Fermilab Lattice and MILC collaborations on the nucleon axial charge and nucleon axial and vector form factors with the HISQ action for both valence and 2+1+1 sea quarks. For the nucleon axial charge, we compute correlators across four physical mass ensembles with approximate lattice spacings of 0.15, 0.12, 0.09, and 0.06 fm, and perform continuum extrapolation; for the nucleon form factors, we compute correlators on a 300 MeV pion-mass ensemble with the approximate lattice spacing of 0.12 fm and demonstrate the method to extract nucleon form factors with staggered action.

Topical area:

Structure of Hadrons and Nuclei

Poster session / **241**

Optimal smearing for heavy-light mesons in motion

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This work presents a study of Wuppertal smearing, comparing different mesons and kinematic configurations.
We propose a parametrization of the optimal smearing radius in terms of the reduced masses of the mesons, giving, at the same time, an estimate of the efficiency of the smearing in suppressing the excited states.

The relation between Momentum Smearing and ordinary Wuppertal smearing with Twisted Boundary conditions is discussed and the two are found to be substantially equivalent.
These results will lay the ground for future calculations of the form factors for heavy-light to heavy-light semileptonic decays, where the smearing will be fundamental to extracting physical quantities from regions with better signal-to-noise ratios.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Quark and Lepton Flavor Physics / 242

Status update: $\pi^0 \to \gamma^*\gamma^*$ transition form factor on CLS ensembles

Authors: Antoine Gérardin[None]; Jonna Koponen[1]; Georg von Hippel[2]; Harvey B. Meyer[3]; Konstantin Ottnad[4]

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We present the status of the Mainz group's lattice QCD calculation of the transition form factor $\mathcal{F}_{\pi^0\gamma^*\gamma^*}$, which describes the interaction of an on-shell pion with two off-shell photons. This form factor is the main ingredient in the calculation of the pion-pole contribution to hadronic light-by-light scattering in the muon $g-2$, $a^{\mathrm{HLbL};\pi^0}$.

We use the $N_f = 2+1$ CLS gauge ensembles, and we update our previous work by including a physical pion mass ensemble (E250). We compute the transition form factor in a moving frame as well as in the pion rest frame in order to have access to a wider range of photon virtualities. In addition to the quark-line connected correlator we also compute the quark-line disconnected diagrams that contribute to the form factor.

At the final stage of the analysis, the result on E250 will be combined with the previous work published in 2019 to extrapolate the form factor to the continuum and to physical quark masses.

Topical area:

Structure of Hadrons and Nuclei

Particle Physics Beyond the Standard Model / 243

2-flavour $SU(2)$ gauge theory with exponential clover Wilson fermions

Author: Laurence Sebastian Bowes[1]

Co-authors: Vincent Drach [1]; Patrick Fritzsch [2]; Antonio Rago [3]; Fernando Romero-López [4]

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Composite Higgs models are a class of models proposed to address the hierarchy and naturalness problems associated with the Standard Model fundamental scalar Higgs. $SU(2)$ with two fundamental flavours is a minimal model for the composite Higgs sector which is not yet ruled out by experimental data. We present lattice results for $SU(2)$ with two fundamental mass degenerate flavours. For the fermion action we use the new exponential clover Wilson fermion action, which offers $O(a)$ improvement via a parameter C_{SW} which must be tuned separately. We discuss tuning the C_{SW} parameter through Schrodinger functional simulations, the scale setting of the ensembles using the Wilson gauge flow, and the low energy spectroscopy of the theory including the masses of the π and the ρ.

Topical area:

Particle Physics Beyond the Standard Model

Quark and Lepton Flavor Physics / 244

Semileptonic form factors for exclusive $B_s \to K\ell\nu$ decays

Authors: Ryan Hill[1]; Jonathan Flynn[2]; Andreas Juettner[2]; amarjit soni[3]; Justus Tobias Tsang[4]; Oliver Witzel[5]

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Heavy-light semileptonic decays provide an important channel to perform high-energy precision tests of the standard model, determine $|V_{ub}|$, and test lepton flavour universality. In this talk, the current status of exclusive $B_s \to K\ell\nu$ semileptonic decays within the RBC-UKQCD Relativistic Heavy Quark (RHQ) project will be presented. We will present recently-published form factor results for $B_s \to K\ell\nu$ and discuss key findings. Combining our results with experimental data yields $|V_{ub}| = 3.8(6) \times 10^{-3}$, which is dominated by experimental error. The next phase of this work is the inclusion of a physical-point ensemble to more strongly constrain the chiral-continuum behaviour, which will also be particularly important for improving our analysis of $B \to \pi\ell\nu$. Additionally, a modified form factor fit ansatz will be presented, which potentially gives stronger constraints on excited-state contributions.

Topical area:

Quark and Lepton Flavor Physics

Structure of Hadrons and Nuclei / 245

Trace anomaly form factor of the pion and the nucleon from lattice QCD

Author: Bigeng Wang[1]

Co-authors: Fangcheng He ; Gen Wang ; Jian Liang ; Keh-Fei Liu [1]; Terrence Draper ; Yi-Bo Yang

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The trace of the energy momentum tensor (ETM) in the hadron gives the hadron mass. The trace anomaly due to the conformal symmetry breaking is believed to be an important ingredient for confinement. In this talk, I will show the trace anomaly form factors of the pion, nucleon and ρ meson as functions of the squared momentum transfer Q^2 up to $\sim 4.3\ \mathrm{GeV}^2$ which are calculated on a domain wall fermion (DWF) ensemble with overlap valence quarks at $m_\pi = 340$ MeV. We found a sign change behavior of the trace anomaly form factor of the pion. This is consistent with the sign change of the radial distribution of the trace anomaly matrix element in a recent lattice calculation.

Topical area:

Structure of Hadrons and Nuclei

Quark and Lepton Flavor Physics / 246

Investigation of the hadronic light-by-light contribution to the muon $g-2$ using staggered fermions

Author: Christian Zimmermann[1]

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Hadronic contributions dominate the uncertainty of the standard model prediction for the anomalous magnetic moment of the muon. In this talk, we will describe an ongoing lattice calculation of the hadronic, light-by-light, four-point function, performed with staggered fermions. The presence of quarks with different tastes complicates the analysis of this position-space correlation function. We present a suitable adaption of the "Mainz method". As a first numerical test, we reproduce the well-known lepton-loop contribution. Results at a single lattice spacing for the light quark contribution, using several volumes from 3 to 6 fm, will then be discussed. Our study of the long distance behavior and finite-volume effects is supplemented by considering the contribution of the light pseudoscalar-pole. The corresponding transition form factors have been evaluated in previous simulations on the same ensembles.

Topical area:

Particle Physics Beyond the Standard Model

Poster session / 247

Calculation Of Observables At Finite Temperature using Normalizing Flows

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Normalizing flow based methods for sampling lattice gauge theories has shown some recent progress. Here, we present rudimentary results for observables with finite temperature on small lattices in 2+1 dimensions.

Topical area:

Algorithms and Artificial Intelligence

Poster session / 248

Flow-based sampling of CP^{N-1} models: how important is equivariance?

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Numerous studies have demonstrated that the rapid decline in the efficiency of traditional sampling algorithms caused by Critical Slowing Down can be alleviated or even sidestepped completely using flow-based sampling. Such approaches trade off a reduction in autocorrelation times with an increase in the cost of generating new field configurations and an up-front training cost. The two-dimensional CP^{N-1} models exhibit severe Critical Slowing Down in their topological observables, making them good candidates for testing flow-based sampling in a more challenging setting without invoking the full complexity of QCD.

Part of the difficulty with the flow-based approach is in identifying suitable ways of parametrising families of invertible transformations, which need to balance expressivity with efficiency in computing the Jacobian determinant. Equivariance with respect to known symmetries of the action is widely understood to be desirable, or even crucial, depending on which theory is being studied. Here we consider parametrisations of flows based on coupling layers (pointwise transformations with triangular Jacobian), and look at the effect of enforcing equivariance under $\mathrm{U}(1)$ transformations.

Topical area:

Algorithms and Artificial Intelligence

Quark and Lepton Flavor Physics / 250

Operator mixing and non-perturbative running of ΔF=2 four-fermion operators

Author: Riccardo Marinelli[1]

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We compute non perturbatively the RG running of the complete basis of $\Delta F = 2$ four fermion operators in the chirally rotated Schrödinger Functional in the region of energies between the W mass and the switching scale (4GeV).

Topical area:

Particle Physics Beyond the Standard Model

Algorithms and Artificial Intelligence / 251

A Neural Network Approach to Lattice Field Theory

Author: Andy Sheng[1]

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Upon taking a bosonic quantum field theory in the Hamiltonian formalism and discretizing the field on a lattice, the theory becomes equivalent to a non-relativistic many-body problem. Neural networks have recently been proposed as effective wavefunction parametrizations in numerical searches for ground state solutions of quantum many-body problems using variational Monte Carlo. We introduce a novel way of enforcing Bose-symmetric neural network functions and apply them to study several non-relativistic quantum systems as well as 1+1d ϕ^4 theory non-perturbatively.

Topical area:

Algorithms and Artificial Intelligence

Theoretical Developments / 252

Generalized Hall current on a finite lattice

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Gapped fermion theories with gapless boundary fermions can exist in any number of dimensions.
When the boundary has even space-time dimensions and hosts chiral fermions, a quantum Hall current
flows from the bulk to the boundary in a background electric field. This current compensate for the boundary chiral anomaly. Such a current inflow picture is absent when the boundary theory is odd dimensional. However, in recent work, the idea of quantum Hall current has been generalized to describe odd dimensional boundary theories in continuous Euclidean space-time dimension of infinite

volume. In this talk we extend this idea to a lattice regulated finite volume theory of 1+1 dimensional Wilson-Dirac fermions. This fermion theory with a domain wall in fermion mass can host gapless modes on the wall. The number of gapless fermions is equal to the integral of the divergence of the lattice generalized Hall current.

Topical area:

Theoretical Developments

Poster session / 253

Study of the phase diagram of 1+1d Z(N) multi-flavor gauge theory at finite density using Tensor Networks and Quantum Simulations

Authors: Adrien Florio[1]; Semeon Valgushev[2]; Andreas Weichselbaum[3]; Rob Pisarski[3]

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The phase diagram of QCD at finite density remains largely unknown due to the sign problem. We propose a 1+1 dimensional model which mimics some of the features of QCD in order to study how quantum computers can avoid the sign problem and allow computations at the finite density. The model is a Z(3) gauge theory coupled to 3 flavors of staggered fermions, and it features baryon-like excitations in addition to meson-like bound states. We present the study of the phase diagram of this model using tensor networks.

Topical area:

Quantum Computing and Quantum Information

Quantum Computing and Quantum Information / 254

How many quantum gates do gauge theories require?

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We discuss implementations of lattice gauge theories on digital quantum computers. In particular, we investigate the number of gates required to simulate the time time evolution. Using state-of-the art methods with our own augmentation, we find that the cost of simulating a single time step evolution of an elementary plaquette is prohibitive in the current era of quantum hardware. Moreover, we

observe that such a cost is highly sensitive to the scheme adopted in deriving lattice gauge theories Hamiltonians, emphasizing the need for low-dimensional formulations of lattice gauge theories in the same universality class as the desired continuum theories.

Topical area:

Quantum Computing and Quantum Information

QCD at Non-zero Density / 255

Searching for the QCD critical point using Lee-Yang edge singularities

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Using $N_f = 2 + 1$ QCD calculations at physical quark mass and purely imaginary baryon chemical potential, we locate Lee-Yang edge singularities in the complex chemical potential plane. These singularities have been obtained by the multi-point Padé approach applied to the net baryon number density. We recently used this approach to extract the correct scaling of singularities near the Roberge-Weiss transition. Now we study the universal scaling of these singularities in the vicinity of the QCD critical endpoint. Making use of an appropriate scaling ansatz, we extrapolate these singularities on $N_\tau = 6$ and $N_\tau = 8$ lattices towards the real axis to estimate the position of a possible QCD critical point. We find an apparent approach toward the real axis with decreasing temperature. We compare this estimate with a HotQCD estimate obtained from poles of a single-point, $[4, 4]$-Padé resummation of the eighth-order Taylor expansion of the QCD pressure.

Topical area:

QCD at Non-zero Density

Quark and Lepton Flavor Physics / 256

Light meson decay constants from Möbius domain-wall fermions on gradient flowed HISQ ensembles

Authors: Amy Nicholson[1]; Andre Walker-Loud[2]; Dean Howarth[2]; Henry Monge-Camacho[3]; Kate Clark[4]; Nolan Miller[5]; Pavlos Vranas[6]; Zack Hall[7]

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We update our previous results and also determine F_K and F_π separately using Möbius domain-wall fermions computed on gradient-flowed N_f = 2 + 1 + 1 highly-improved staggered sea-quark ensembles. We use five values of the pion mass ranging from 130 $\leq m_\pi \leq$ 400 MeV, four lattice spacings of a $\sim$ 0.15, 0.12, 0.09, 0.06 fm and multiple lattice volumes. The physical point, continuum, and finite-volume extrapolations are performed with relevant mixed-action effective field theory expressions.

Topical area:

Quark and Lepton Flavor Physics

Quantum Computing and Quantum Information / 257

Fuzzy Qubitization of Gauge Theories

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Formulating bosonic field theories for quantum simulation is a subtle task. Ideally, one wants the smallest truncation of the bosonic Hilbert space that simultaneously exhibits a high degree of universality. But many of the most straight-forward truncations probably do not exhibit much universality. Meanwhile, recent work on the so-called “fuzzy” sigma model has shown promise as a very efficient qubitization of the 1+1d sigma model, with only a 4-dimensional 1-site Hilbert space. In this talk we discuss the generalization of the fuzzy strategy to non-abelian gauge theories. We argue that a promising gauge theory can be constructed based on the Orland-Rohrlich gauge magnet, and we contrast this “fuzzy” gauge theory with the traditional Laplacian truncation strategy.

Topical area:

Quantum Computing and Quantum Information

Quantum Computing and Quantum Information / 258

Qubitization strategies for bosonic field theories

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Simulations of bosonic field theories on quantum computers demand a truncation in field space to "fit" the theory onto limited quantum registers. We examine two different truncations preserving the same symmetries as the 1+1-dimensional $O(3)$ non-linear σ-model - one truncating the Hilbert space of functions on the unit sphere by setting an angular momentum cutoff and a fuzzy sphere truncation inspired by non-commutative geometry. We find evidence that the angular-momentum truncation fails to reproduce behavior of the σ-model, while the anti-ferromagnetic fuzzy model agrees with the full theory. These lessons will inform how we qubitize lattice gauge theories.

Topical area:

Quantum Computing and Quantum Information

Structure of Hadrons and Nuclei / 259

Generalized form factors of the pion and kaon using twisted mass fermions

Authors: Constantia Alexandrou[None]; Joseph Delmar[1]; Giannis Koutsou[None]; Ian Cloet[2]; Martha Constantinou[1]; Simone Bacchio[3]

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We present an update on our lattice calculations of the Mellin moments of PDFs and GPDs for the pion and kaon, using momentum-boosted meson states. In particular, we focus on the calculation of the scalar and tensor local operators, as well as the vector operator with up to three-covariant derivatives. The corresponding matrix elements allow us to extract the scalar and tensor charges, as well as $\langle x^n \rangle$ with $n = 1, 2, 3$. In addition, we introduce momentum transfer between the initial and final meson state that leads to the scalar, vector, and tensor form factors, and the generalized form factors up to three covariant derivatives. The above results are obtained using two ensembles of maximally twisted mass fermions with clover improvement with two degenerate light, a strange, and a charm quark $(N_f = 2 + 1 + 1)$ at lattice spacings of 0.093 fm and 0.081 fm. The pion mass of the ensembles is about 260 MeV. We study excited-states effects by analyzing four values of the source-sink time separation (1.12 - 1.67 fm). We also examine discretization and volume effects. The lattice data are renormalized non-perturbatively, and the results are presented in the MS scheme at a scale of 2 GeV.

Topical area:

Structure of Hadrons and Nuclei

Quantum Computing and Quantum Information / 260

Symmetry Breaking and Clock Model Interpolation in 2D Classical O(2) Spin Systems

Authors: Leon Hostetler[1]; Ryo Sakai[2]; Jin Zhang[3]; Alexei Bazavov[1]; Yannick Meurice[3]

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Motivated by attempts to quantum simulate lattice models with continuous Abelian symmetries using discrete approximations, we study an extended-O(2) model that differs from the ordinary O(2) model by the addition of an explicit symmetry breaking term. Its coupling allows to smoothly interpolate between the O(2) model (zero coupling) and a q-state clock model (infinite coupling). In the latter case, a q-state clock model can also be defined for non-integer values of q. Thus, such a limit can also be considered as an analytic continuation of an ordinary q-state clock model to non-integer q. In previous work, we established the phase diagram of the model in the infinite coupling limit. We showed that for non-integer q, there is a second-order phase transition at low temperature and a crossover at high temperature. In this work, we establish the phase diagram at finite values of the coupling using Monte Carlo and tensor methods. We show that for non-integer q, the second-order phase transition at low temperature and crossover at high temperature persist to finite coupling. For integer $q = 2, 3, 4$, there is a second-order phase transition at infinite coupling (i.e. the clock models). At intermediate coupling, there are second-order phase transitions, but the critical exponents vary with the coupling. At small coupling, the second-order phase transitions may turn into BKT transitions.

Topical area:

Quantum Computing and Quantum Information

Tests of Fundamental Symmetries / 261

Taming power divergences with the gradient flow

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When calculating hadronic matrix elements using a lattice regulator,
the presence of power divergences in the lattice spacing poses a significant challenge.
Non-perturbatively subtracting these power divergences presents
both theoretical and numerical difficulties.
The gradient flow offers a theoretically sound and numerically robust approach
for renormalizing power divergences.
We demonstrate how to establish a connection between flowed and physical (unflowed)
hadronic matrix elements, focusing specifically on the quark content of the nucleon and
CP-odd local operators as illustrative examples.

Topical area:

Tests of Fundamental Symmetries

Hadronic and Nuclear Spectrum and Interactions / 262

Testing formalism for $\gamma^\star \to 3\pi$ and $K \to 3\pi$

Author: Raul Briceno[1]

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Recently, formalism has been derived for obtaining the physical amplitudes for $\gamma^\star \to 3\pi$, $K \to 3\pi$, and other electroweak three-body decays, from finite-volume matrix elements, which can be obtained from lattice QCD calculations of three-point correlation functions. The relation between the finite-volume quantities and the desired infinite-volume amplitudes requires solving integral equations of singular functions. In this work, we provide some non-trivial tests on the aforementioned formalism. In particular, we consider a limit where the three-body final state supports a bound state. For kinematics below the three-body threshold, we demonstrate that the finite-volume matrix elements are accurately described by the well-known formalism for two-body systems.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Algorithms and Artificial Intelligence / 263

Fourier Acceleration of SU(3) Pure Gauge Theory at Weak Coupling

Authors: Yikai Huo[1]; Norman Christ[1]

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In the hybrid Monte Carlo simulation of $\mathrm{SU}(3)$ pure gauge theory, we explore a Fourier acceleration algorithm to reduce critical slowing down. By introducing a soft-gauge-fixing term in the action, we can identify the eigenmodes in the weak-coupling expansion of the action and eliminate the differences in their evolution frequencies. A special unit-link boundary, in which the links lying in the boundary faces are fixed to be unit matrices, is also proposed to eliminate the $\mathbb{Z}_3$ symmetry and the tunneling between $\mathbb{Z}_3$ phases in which is not of interest here. We present the theoretical details and the numerical implementation of this algorithm, compare the autocorrelation times of certain observables with the usual hybrid Monte Carlo algorithm to show its acceleration effect for weak coupling and examine its potential application to physically relevant lattice spacings.

Topical area:

Algorithms and Artificial Intelligence

Software Development and Machines / 264

Renormalization of Karsten-Wilczek Quarks on a Staggered Background

Authors: Daniel Godzieba[1]; Szabolcs Borsanyi[None]; Paolo Parotto[None]; Chik Him Wong[2]; Reka A. Vig[None]; Zoltan Fodor[None]

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The Karsten-Wilczek action is a formulation of minimally doubled fermions on the lattice which explicitly breaks hypercubic symmetry and introduces three counterterms with respective bare parameters. We present a tuning of the bare parameters of the Karsten-Wilczek action on 4-stout configurations at the physical point.

Topical area:

Software Development and Machines

Algorithms and Artificial Intelligence / 265

Trivializing Flow in 2D-O(3) model

Author: Christopher Chamness[1]

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The 2D O(3) model has been widely used as a toy model for quantum chromodynamics and ferromagnetism. It shares fundamental features with quantum chromodynamics, such as being asymptotically free. It is possible to define a trivializing map, a field transformation from a given theory to trivial variables, through a gradient flow. An analytic solution to this trivializing flow may be obtained by a perturbative expansion in the flow parameter. Utilizing this solution allows for new approaches to be considered when proposing updates for a Markov Chain algorithm.

Topical area:

Algorithms and Artificial Intelligence

Structure of Hadrons and Nuclei / 266

Toward a precision calculation of generalized parton distribution functions.

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Generalized parton distribution functions (GPDs) describe the longitudinal momentum distribution within a hadron among its constituent partons as well as information about the momentum in the transverse direction. We calculate unpolarized and helicity GPDs using 2+1+1 flavors of highly improved staggered quarks in ensembles generated by the MILC collaboration at a=0.09 fm with a physical pion mass using the method of large-momentum effective theory (LaMET). We use boosting momentum ~ 1.7 GeV for multiple $\xi = 0$ and $\xi = 0.25$ with multiple transfer momenta renormalized in the hybrid scheme. In addition, we study the effects of systematic errors by applying leading renormalon resummation and renormalization group resummation in the matching process.

Topical area:

Structure of Hadrons and Nuclei

Hadronic and Nuclear Spectrum and Interactions / 267

Search for isoscalar axialvector $bc\bar{u}\bar{d}$ tetraquark bound states

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The study of doubly heavy tetraquarks has gained substantial topical interest, primarily boosted by the recent discovery of doubly charmed tetraquark T_{cc} and by its phenomenological prospects. While T_{cc}^+ is observed to be ~0.4 MeV below the DD^* threshold, multiple lattice calculations point to a deep binding ($\mathcal{O}(100MeV)$) in T_{bb}. However, the predictions for the binding in T_{bc} are scattered. We report a lattice study of DB^*-BD^* scattering in the isoscalar axial-vector channel with the explicitly exotic flavor $bc\bar{u}\bar{d}$. The simulation is performed on four $N_f = 2+1+1$ MILC gauge ensembles with different lattice spacings and volumes. The DB^* scattering amplitudes are extracted from the low-lying finite-volume spectra following the amplitude analysis {\it \'a la} L\"uscher. The light quark mass ($m_{u/d}$) dependence of the continuum extrapolated amplitudes is analyzed to determine the fate of the $bc\bar{u}\bar{d}$ at the physical $m_{u/d}$. We find strong evidence for a bound $bc\bar{u}\bar{d}$ tetraquark at physical $m_{u/d}$ in this channel. We also determine the critical $m_{u/d}$ at which such a state becomes unbound.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Plenary session / 268

Flow-based sampling for lattice field theories

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Critical slowing down and topological freezing severely hinder Monte Carlo sampling of lattice field theories as the continuum limit is approached. Recently, significant progress has been made in

applying a class of generative machine learning models, known as "flow-based" samplers, to combat these issues. These generative samplers also enable promising practical improvements in Monte Carlo sampling, such as fully parallelized configuration generation. In this talk, I will discuss the progress towards this goal and future prospects of the method.

Topical area:

Algorithms and Artificial Intelligence

Theoretical Developments / 269

A staggered U(1) gauge theory inspired by self-adjoint extensions

Authors: Aditya Banerjee[1]; Alessandro Mariani[2]; Debasish Banerjee[None]; Gurtej Kanwar[3]; Tobias Rindlisbacher[2]; Uwe-Jens Wiese[2]

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Novel regularizations of lattice gauge theories can potentially enable faster classical or quantum simulation, but the landscape of available regularizations and their continuum limits is not fully understood. Our recent work adds a point to this landscape by introducing a generalization of U(1) lattice gauge theory obtained by applying a boundary condition in group space with a twist angle Θ, motivated by a self-adjoint extension of the electric field operator. The "staggered" choice $\Theta = \pi$ is of particular interest, as it preserves almost all of the original symmetries of the theory. In this talk, I will discuss a numerical study of the staggered theory in three dimensions, which demonstrates confinement, as in the ordinary $\Theta = 0$ theory, and more exotic phenomena including spontaneous $\mathbb{Z}_2$ symmetry breaking and fractionalization of the confining string.

Topical area:

Theoretical Developments

Particle Physics Beyond the Standard Model / 270

Exploring the large-N_c limit of one-flavour $SU(N_c)$

Authors: Benjamin Jaeger[1]; Michele Della Morte[2]; Sofie Martins[2]; Felix P. G. Ziegler[3]; Justus Tobias Tsang[4]; Steffen Ulrik Jensen[2]

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We are examining one-flavour $SU(N_c)$ gauge theories with one fermion in the antisymmetric representation as a candidate to approximate $\mathcal{N} = 1$ SYM due to their equivalence in the large-N_c limit.

Summarising results on spectral evaluations of $N_c = 3$, we will report on the progress of dynamical calculations for $N_c > 3$. Here we will discuss cutoff effects and challenges in configuration generation.

Topical area:

Particle Physics Beyond the Standard Model

Algorithms and Artificial Intelligence / 271

Constructing approximate semi-analytic and machine-learned trivializing maps for lattice gauge theory

Authors: Daniel Hackett[1]; Julian Urban[1]; Denis Boyda[2]; Fernando Romero-López[1]; Phiala Shanahan[3]; Ryan Abbott[1]

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While approximations of trivializing field transformations for lattice path integrals were considered already by early practitioners, more recent efforts aimed at ergodicity restoration and thermodynamic integration formulate trivialization as a variational generative modeling problem. This enables the application of modern machine learning algorithms for optimization over expressive parametric function classes, such as deep neural networks. After a brief review of the historical origins of this research program, I will focus on spectral coupling flows as a particular parameterization of gauge-covariant field diffeomorphisms. The concept will be introduced by explicitly constructing a systematically improvable semi-analytic solution for SU(3) gauge theory in (1+1)d, followed by a discussion and outlook on recent results in (3+1)d from a proof-of-principle application of machine-learned flow maps.

Topical area:

Algorithms and Artificial Intelligence

Structure of Hadrons and Nuclei / 273

Perturbative study of renormalization and mixing for asymmetric staple-shaped Wilson-line operators on the lattice

Authors: Gregoris Spanoudes[1]; Haralambos Panagopoulos[1]; Martha Constantinou[2]

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We present one-loop perturbative results of the renormalization functions for a complete set of nonlocal quark bilinear operators containing an asymmetric staple-shaped Wilson line, using a family of improved lattice actions. This study is relevant for the nonperturbative investigations regarding the renormalization of the unpolarized, helicity and transversity transverse-momentum dependent parton distribution functions (TMDPDFs) in lattice QCD. We employ a number of different versions of regularization-independent (RI′) renormalization prescriptions which address the power and logarithmic divergences of such non-local operators, the pinch-pole singularities at infinite Wilson-line lengths, as well as the mixing among operators of different Dirac structures, as dictated by discrete symmetries. All cancelations of divergences and admixtures are confirmed by our results at one-loop level. We compare all the different prescriptions and we provide the conversion matrices at one-loop order which relate the matrix elements of the staple operators in RI′ to the reference scheme $\overline{\mathrm{MS}}$.

Topical area:

Structure of Hadrons and Nuclei

Theoretical Developments / 274

Confining Strings as Integrable Spin Chains in Large N Lattice Yang-Mills Theory

Authors: Hiroki Kawai[1]; David Berenstein[2]

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We present a novel approach to construct effective descriptions of a confining string. We consider a string pinned with heavy quark-antiquark endpoints on the lattice Yang-Mills theory (Kogut-Susskind Hamiltonian) as background with $SU(N_c)$ gauge symmetry with large N_c. Our approach describes the dynamics of the confining string as two different spin chains, which are both integrable. In the talk, I will demonstrate it in 2+1-D as the simplest example, but it is also applicable for gauge theories in higher dimensions.

Topical area:

Theoretical Developments

Theoretical Developments / 275

Study of 3-dimensional SU(2) gauge theory with adjoint Higgs as a model for cuprate superconductors

Authors: Alberto Ramos[1]; C.-J. David Lin[2]; Atsuki Hiraguchi[3]; George Wei-Shu Hou[4]; Guilherme Catumba[5]; Karl Jansen[6]; Mugdha Sarkar[7]; Ying-Jer Kao[8]

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We study a 3-dimensional SU(2) gauge theory with 4 Higgs fields which transform under the adjoint representation of the gauge group, that has been recently proposed by Sachdev et al. to explain the physics of cuprate superconductors near optimal doping. The symmetric confining phase of the theory corresponds to the usual Fermi-liquid phase while the broken (Higgs) phase is associated with the interesting pseudogap phase of cuprates. We employ the Hybrid Monte-Carlo algorithm to study the phase diagram of the theory. We find the existence of a variety of broken phases in accordance with earlier mean-field predictions and discuss their role in cuprates.

Topical area:

Hadronic and Nuclear Spectrum and Interactions / 276

Doubly charm tetraquark using meson-meson and diquark-antidiquark interpolators

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We perform a lattice simulation to investigate the doubly charm tetraquark T_{cc}^{+} observed by the LHCb collaboration with flavor content $cc\bar{u}\bar{d}$, isospin-0, and only 0.4 MeV below the $D^{*+}D^0$ threshold. We implement two-meson interpolators, and additionally also diquark-antidiquark interpolators. This is the first extraction of the scattering amplitude from correlators based on both types of operators. The simulation is performed on $N_f = 2{+}1$ CLS ensembles in the lattice spacing with $m_\pi \simeq 280$ MeV and $a \simeq 0.086$ fm. The main aim of this work is to determine the impact of the diquark-antidiquark operators on the eigenenergies and the scattering amplitude.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Algorithms and Artificial Intelligence / 277

Bayesian interpretation of Backus-Gilbert methods

Author: Alessandro Lupo[1]

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The problem of extracting spectral densities from Euclidean correlators
evaluated on the lattice has been receiving increasing attention.
Spectral densities provide a way to access quantities of crucial
importance in hadronic physics, such as inclusive decay rates,
scattering amplitudes, finite-volume energies, as well as transport
coefficients at finite temperature. Many approaches have been developed
to tackle this challenging problem. In this talk, we review how
Backus-Gilbert methods can be interpreted in the Bayesian framework,
focusing on the systematics of the two approaches.

Topical area:

Algorithms and Artificial Intelligence

Particle Physics Beyond the Standard Model / 278

SU(4) Stealth Dark Matter Baryons using LapH

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The LSD collaboration is studying Stealth Dark Matter, an SU(4) gauge theory, whose ground state spin-0 baryon is the dark matter candidate. We are investigating Stealth Dark Matter with two fermions in the fundamental representation using the quenched approximation. I will discuss our baryon operator construction using LapH and lattice octahedral group irreps. Then I will present the latest results of the meson and baryon spectrum.

Topical area:

Particle Physics Beyond the Standard Model

Vacuum Structure and Confinement / 279

Asymptotic scaling in Yang-Mills theory at large-N_c

Authors: Antonio González-Arroyo[1]; Pietro Butti[1]

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TEK reduction is a well established technique that allows single-site simulations of Yang-Mills theory in the large-N_c limit by exploiting volume reduction induced by twisted boundary conditions. We performed simulations for $SU(841)$ for several gauge couplings and applied standard Wilson flow techniques combined with a tree-level improvement methodology to set the lattice scale. The wide range of gauge couplings covered by our simulations allows us to explore a region in the coupling space where our data exhibits asymptotic scaling, and perturbation theory could be used to analyze the behavior of the β-function. In this talk I will review the methodology used and go thorugh the main results we obtained, including a determination of the Λ-parameter of Yang-Mills theory at large-N_c in $\overline{\text{MS}}$-scheme.

Topical area:

Vacuum Structure and Confinement

Hadronic and Nuclear Spectrum and Interactions / 280

Optimized Distillation Profiles for Heavy-Light Spectroscopy

Authors: Jan Neuendorf[1]; Giulia Egbring[2]; Jochen Heitger[1]; Roman Höllwieser[3]; Francesco Knechtli[3]; Tomasz Korzec[3]; Juan Andrés Urrea-Niño[3]

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It has been demonstrated that distillation profiles can be employed
to build optimized quarkonium interpolators for spectroscopy calculations
in lattice QCD. We test their usefulness for heavy-light systems on
(3+1)-flavor ensembles with mass-degenerate light and a charm quark in
the sea in preparation for a future DDbar-scattering analysis.
The additional cost of light inversions naturally leads to the question
if knowledge of optimal profiles can be used to avoid superfluous
computations. We show such optimal profiles for different lattice sizes and pion masses and discuss general trends.
Furthermore, we discuss the handling of momenta in this framework.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Vacuum Structure and Confinement / 281

Extracting Yang-Mills topological structures with adjoint modes

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We report on how adjoint zero modes can be used to filter out the topological structures of gauge configurations from the UV fluctuations. The techniques presented here look promising to investigate regimes relevant to recent studies based on semiclassical methods. A particularly interesting application is to test whether the dynamics of fractional instantons can explain properties of the Yang-Mills vacuum like the string tension and finite topological susceptibility.

Topical area:

Vacuum Structure and Confinement

Algorithms and Artificial Intelligence / 282

Sampling Nambu-Goto theory using Normalizing Flows

Author: Elia Cellini[1]

Co-authors: Michele Caselle [2]; Alessandro Nada [3]

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Effective String Theory (EST) is a non-perturbative framework used to describe confinement in Yang-Mills theory through the modeling of the interquark potential in terms of vibrating strings. An efficient numerical method to simulate such theories where analytical studies are not possible is still lacking. However, in recent years a new class of deep generative models called Normalizing Flows (NFs) has been proposed to sample lattice field theories more efficiently than traditional Monte Carlo methods. In this talk, we show a proof of concept of the application of NFs to EST regularized on the lattice. Namely, we use as case study the Nambu-Goto string in order to use the well-known analytical results of this theory as a benchmark for our methods.

Topical area:

Algorithms and Artificial Intelligence

Hadronic and Nuclear Spectrum and Interactions / 283

Towards a high-precision description of the ρ and K^* resonances

Author: Nelson Lachini[1]

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We present preliminary results for the $\rho(770)$ and $K^*(892)$ resonances using the Lüscher method. This work employs distillation on an RBC-UKQCD $N_f = 2 + 1$ domain-wall fermion lattice with a physical pion mass. We consider irreducible representations with only leading $P-$wave contributions and extract the associated low-lying energy levels. These are used to parametrise the scattering phase shifts. We study systematic errors resulting from the choice of fit ranges through a model-averaging technique.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

QCD at Non-zero Temperature / 284

Sphaleron rate as an inverse problem: a novel lattice approach

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We compute the sphaleron rate on the lattice. We adopt a novel strategy based on the extraction of the spectral density via a modified version of the Backus-Gilbert method from finite-lattice-spacing and finite-smoothing-radius Euclidean topological charge density correlators. The physical sphaleron rate is computed by performing controlled continuum limit and zero-smoothing extrapolations.

Topical area:

QCD at Non-zero Temperature

Poster session / 285

Three-particle scattering in the (1+1)-dimensional O(3) non-linear sigma model

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We present results on three-particle scattering in the (1+1)-dimensional O(3) non-linear sigma model using lattice-determined finite-volume energies and the relativistic-field-theory (RFT) finite-volume formalism. We focus on the isospin-3 and isospin-2 three-particle channels, and perform lattice computations for four different volumes with three values of the lattice spacing each. The continuum-extrapolated finite-volume energies are compared to the RFT formalism predictions assuming a zero three-particle divergence-free K-matrix, $K_{\text{df},3} = 0$. We study the effect of changing the cutoff function appearing in the quantization condition. Finally, the numerical results are used to constrain the value of $K_{\text{df},3}$. The eventual aim is to match the results for $K_{\text{df},3}$ to the analytically known three-to-three S-matrix, to build experience and confidence in the formalism, as it is also applied to three-hadron QCD calculations.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Software Development and Machines / 286

Optimizing Staggered All-to-All for GPUs

Author: Michael Lynch[1]

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We present our implementation of the all-to-all meson field and low mode averaging (LMA) calculations, built on the Grid and Hadrons libraries. We discuss code optimizations made for staggered fermions and GPU offloading, as well as benchmark comparisons on leadership-class resources. We conclude with the statistical gains achieved using LMA for vector-current two-point functions relevant for computing the HVP contribution to muon $g-2$. The calculation is performed on 2+1+1 HISQ ensembles at physical pion mass and lattice spacings as small as 0.06 fm. We discuss the effect of this low-mode–improved data set on long-distance noise and the results of combining our new data with our previous high-statistics data.

Topical area:

Software Development and Machines

Theoretical Developments / **287**

Methods for lattice QCD calculations of hadronic observables using stochastic locality

Author: Marco Cè[1]

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Stochastic locality, arising from the mass gap of QCD, allows for independent fluctuations in distant regions of lattice gauge field configurations.
This can be used to increase statistics and, in the extreme case of the master-field approach, obtain an error estimate from a single configuration.
However, spatially-separated samples at moderate distances show residual correlation that needs to be taken into account.
Focusing on hadronic observables, we adapt variance estimation methods for autocorrelated Monte Carlo samples to account for correlated spatially-separated samples.
These techniques can be applied to a wide range of observables, including momentum-projected and position-space correlators, and can be combined with standard blocking and bootstrap or jackknife.
Our numerical studies show that, depending on the observable, an effective integrated correlation volume can be estimated already on moderately large ensembles.

Topical area:

Theoretical Developments

Quark and Lepton Flavor Physics / 288

A status update of Fermilab/HPQCD/MILC Collaborations muon g-2 project

Authors: HPQCD, MILC collaboration Fermilab Lattice[None]; Shaun Lahert[1]

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We present an update, from the Fermilab Lattice, HPQCD, and MILC collaborations, of our results for the hadronic vacuum polarization contribution to the muon's anomalous magnetic moment. Preliminary results for light-quark-connected contributions to the intermediate and long-distance window quantities employ new, low-mode-improved, data sets on our finest ensembles. We also present updated results for sub-leading contributions. The calculations are performed on 2+1+1 highly-improved staggered quark (HISQ) ensembles with physical pion mass at a range of lattice spacings (0.15fm-0.06fm).

Topical area:

Quark and Lepton Flavor Physics

Structure of Hadrons and Nuclei / 289

Nucleon Axial Form Factor from Domain Wall on HISQ

Author: Aaron Meyer[1]

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The Deep Underground Neutrino Experiment (DUNE) is an upcoming neutrino oscillation experiment that is poised to answer key questions about the nature of the neutrino. Lattice QCD has the ability to make significant impact upon DUNE by computing the interaction of a nucleon to a weak current. Nucleon amplitudes involving the axial form factor are part of the primary signal measurement process for DUNE, and precise calculations from LQCD can significantly reduce the uncertainty for inputs into Monte Carlo generators. Recent calculations of the nucleon axial charge have demonstrated that sub-percent precision is possible on this vital quantity. In this talk, I will discuss results for the Callat collaboration's calculation of the axial form factor of the nucleon. These computations are performed with M\"obius domain wall valence quarks on HISQ sea quark ensembles generated by the MILC and Callat collaborations. Preliminary results will be shown with a single ensemble at physical pion mass.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Poster session / 290

Use of Inverse Methods for Reconstructing the Hadronic Tensor from Euclidean Correlators

Author: Douglas Stewart[1]

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While Wick rotation to Euclidean spacetime is necessary for lattice QCD calculations, the subsequent rotation back to Minkowski spacetime from discrete correlator data is an ill-posed problem. In this proof-of-concept calculation, we compute correlation functions necessary for computing the hadronic tensor of the pion using existing ensembles generated by the MILC collaboration and $N_f = 2 + 1 + 1$ dynamical HISQ-like fermions at the physical point. Using a modification of the Backus-Gilbert method developed by Hansen, Lupo, and Tantalo (HLT), we apply the HLT method to the Euclidean lattice correlators to extract smeared finite-volume spectral functions. Our future goal is to apply these techniques to more complicated systems such as the nucleon.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Vacuum Structure and Confinement / 291

Confining strings and glueballs in Z_N gauge theories

Authors: Andreas Athenedorou[1]; Sergei Dubovsky[2]; Conghuan Luo[2]; Michael Teper[3]

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Effective string theory has shown its universal power in the prediction of the spectrum of low-lying excited states of confining strings. In these works we focus on 3d Ising gauge model and vector Z_N gauge theories. We have computed the low-lying confining flux tube spectrum in 3d Ising gauge model and shown that they agree with the prediction of the Nambu-Goto spectrum. Moreover, we observe a massive resonance on the string, which turns out to be the glueball mixing with flux tubes. In the vector Z_N gauge theories (dual to clock spin models), we observe a continuous phase transition for $N \geq 4$, while for $N > 5$ it is governed by O(2) universality class. Also for these cases we observe that they approach the glueball spectrum of U(1) gauge theory.

Topical area:

Vacuum Structure and Confinement

Standard Model Parameters / 292

Charm quark mass using a massive nonperturbative renormalisation scheme

Author: Rajnandini Mukherjee[1]

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We present a first numerical implementation of a massive nonperturbative renormalisation scheme, RI/mSMOM, in the study of heavy quarks using the domain-wall fermion action. In particular, we calculate renormalisation constants for fermion bilinears at non-vanishing heavy quark masses and compare the approach to the continuum of the renormalised charm quark mass with that from a mass-independent scheme.

Topical area:

Quark and Lepton Flavor Physics

Structure of Hadrons and Nuclei / 293

On the Baryon Octet: Sigma Terms in the continuum limit from $N_\mathrm{f} = 2 + 1$ QCD with Wilson fermions

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A lot of progress has been made in the direct determination of nucleon sigma terms. Using similar methods we consider the sigma terms of the other octet baryons as well. These are determined on CLS gauge field ensembles employing the Lüscher-Weisz gluon action and the Sheikholeslami-Wohlert fermion action with $N_\mathrm{f} = 2 + 1$. The ensembles analysed here have pion masses ranging from $410\,\mathrm{MeV}$ down to $216\,\mathrm{MeV}$ and lattice spacings covering a range between $0.039\,\mathrm{fm}$ and $0.098\,\mathrm{fm}$.
To tackle the well-known problem of excited state contamination we have studied the effect of different multi-state fits on the sigma terms. In order to investigate the systematic error arising from the varied treatment of the excited states we carry out the full analysis for different choices of multi-state fits. In the end, the sigma terms of the baryon octet are simultaneously extrapolated to the physical point taking the quark mass dependence and lattice spacing effects into account.

Topical area:

Structure of Hadrons and Nuclei

Theoretical Developments / 294

The twisted gradient flow strong coupling with parallel tempering on boundary conditions

Authors: Andrea Giorgieri[1]; Claudio Bonanno[2]; Jorge Luis Dasilva Golán[3]; Margarita Garcia-Perez[None]; Massimo D'Elia[4]

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We present a proposal for calculating the running of the coupling constant of the $SU(3)$ pure gauge theory, which combines the Twisted Gradient Flow (TGF) renormalization scheme with Parallel Tempering on Boundary Conditions (PTBC). The TGF is a gradient flow-based renormalization scheme formulated in an asymmetric lattice with twisted boundary conditions. Combined with step scaling, it has been successfully used to calculate the SU(3) Λ parameter. As with all gradient flow-based schemes, the coupling constant is highly correlated with the topological charge and affected by topology freezing, an issue addressed by projecting the determination of the coupling onto the zero topological sector. As an alternative to the zero charge projection, we combine TGF with PTBC, we combine TGF with PTBC by replicating multiple copies of the same lattice, interpolating between periodic and open boundary conditions in a parallel-tempered manner. We present a first exploration of these ideas by analyzing specific ensembles of $SU(3)$ lattices with and without PTBC.

Topical area:

Theoretical Developments

Algorithms and Artificial Intelligence / 295

Hutch++ and XTrace to improve stochastic trace estimation

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We present the analysis of two recently proposed noise reduction techniques, *Hutch++*[1] and *XTrace*[2], both based on inexact deflation. These methods were proven to have a better asymptotic convergence to the solution than the classical *Hutchinson stochastic method.* We applied these methods to the computation of the trace of the inverse of the Dirac operator with $O(a)$ improved Wilson fermions on the QCD ensemble generated by the RC* collaboration with $m_{\pi} \approx 400$ MeV and $V = 64 \times 32^3$. Unfortunately, we see no noise reduction with a moderate number of sources, and we attempt an explanation of why this is the case.
This study was part of the effort to evaluate Isospin Breaking effects using the RM123 with C* boundary conditions in an unquenched set-up.

References:

1. arXiv:2010.09649
2. arXiv:2301.07825

Topical area:

Algorithms and Artificial Intelligence

QCD at Non-zero Temperature / 296

Fluctuations of conserved charges in strong magnetic fields in (2+1)-flavor QCD

Authors: Heng-Tong Ding[1]; Jin-Biao Gu[1]; Jun-Hong Liu[1]; Sheng-Tai Li[1]

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We present the first lattice QCD results of the second order fluctuations of and correlations among net baryon number, electric charge and strangeness in (2+1)-flavor lattice QCD in the presence of a background magnetic field with physical pion mass m_π = 135 MeV. To mimic the magnetic field strength produced in the early stage of heavy-ion collision experiments we use 6 different values of the magnetic field strength up to ~10 m_π^2. The simulations were performed using the Highly Improved Staggered Quarks with physical pion mass on $N_\tau = 8$ and 12 lattices. By comparing lattice QCD results to results from the hadron resonance gas model, possible proxies are proposed to study the imprints of magnetic fields in high-energy heavy ion collision experiments.

Topical area:

QCD at Non-zero Temperature

Tests of Fundamental Symmetries / 297

Exploiting hidden symmetries to accelerate the lattice calculation of $K \to \pi\pi$ decays with G-parity boundary conditions

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The RBC & UKQCD collaborations have successfully employed G-parity boundary conditions in the measurement of $K \to \pi\pi$ decays to obtain a physical decay with the two-pion ground state, at the cost of a significant increase in computational expense. We report on new theoretical/algorithmic developments based upon the properties of the Dirac operator under complex conjugation that have been exploited to achieve highly significant computational cost reductions, and explain their impact on our ongoing effort to repeat the calculation on finer lattices.

Topical area:

Tests of Fundamental Symmetries

Quantum Computing and Quantum Information / 298

Exploring lattice supersymmetry with variational quantum deflation

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Lattice studies of spontaneous supersymmetry breaking suffer from a sign problem that in principle can be evaded through novel methods enabled by quantum computing. I will present ongoing work exploring ways quantum computing could be used to study spontaneous supersymmetry breaking in lower-dimensional lattice systems including the (1+1)d N=1 Wess–Zumino model. A particularly promising recent development is to apply the variational quantum deflation algorithm, which generalizes the variational quantum eigensolver so as to resolve multiple low-energy states.

Topical area:

Quantum Computing and Quantum Information

Standard Model Parameters / 299

Update on the gradient flow scale on the 2+1+1 HISQ ensembles

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Co-authors: Aida El-Khadra [2]; Andreas Kronfeld [3]; Carleton DeTar [4]; Claude Bernard [5]; Elvira Gamiz [6]; Steven Gottlieb [7]; Urs Heller [8]; William Jay [9]; Yin Lin

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We report on the ongoing effort of improving the determination of the gradient flow scale on the 2+1+1 HISQ ensembles generated by the MILC collaboration. We measure the t_0 and w_0 scales with the Wilson and Symanzik flow using three discretizations for the action density: clover, Wilson and tree-level Symanzik-improved. For the absolute scale setting we intend to employ the Omega baryon mass but are also using the pion decay constant while the Omega-mass calculations are in progress.

Topical area:

Standard Model Parameters

Standard Model Parameters / 300

The static force with gradient flow

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We measure the static force directly by inserting chromo electric fields into the Wilson loop. We use the gradient flow to improve the signal-to-noise ratio, and to renormalize the field components. Furthermore, we can perform the continuum and zero flow time limit, obtaining a first direct determination of the QCD static force.
By comparing the lattice result with a perturbative calculation of the force, we can aim at a precise extraction of Λ_0. Additionally, we obtain a determination of the scales r_1, and r_0.

Topical area:

Standard Model Parameters

QCD at Non-zero Temperature / 301

Moment of inertia and instability of rotating gluodynamics

Authors: Victor Braguta[1]; Maxim Chernodub[2]; Ilya Kudrov[3]; Artem Roenko[1]; Dmitrii Sychev[1]

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Using numerical lattice simulations, we analyze the influence of uniform rotation on the equation of state of gluodynamics. For a sufficiently slow rotation, the free energy of the system can be expanded into a series of powers of angular velocity. We calculate the moment of inertia given by the quadratic coefficient of this expansion and determine its dependence on the temperature We find that the moment of inertia unexpectedly takes a negative value below the "supervortical temperature" ~ 1.5, vanishes at $=$, and becomes a positive quantity at higher temperatures. The negative moment of inertia indicates a thermodynamic instability of plasma with respect to rigid rotation, which resembles the rotational instability of spinning Kerr black holes. We discuss how this instability is related to the scale anomaly and the magnetic gluon condensate. We argue that our results are in qualitative agreement with previous lattice calculations indicating that the rigid rotation increases the critical temperature in gluodynamics.

Topical area:

QCD at Non-zero Temperature

Structure of Hadrons and Nuclei / 302

Magnetic polarizability of a charged pion from four-point functions

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We explore a general method based on four-point functions in lattice QCD. The electric polarizability (α_E) of a charged pion has been determined from the method in a previous simulation. Here we focus on the magnetic polarizability (β_M) using the same quenched Wilson action on a $24^3 \times 48$ lattice at $\beta = 6.0$ with pion mass from 1100 to 370 MeV. The results from the connected diagrams show a large cancellation between the elastic and inelastic contributions, leading to a relatively small and negative value for β_M consistent with chiral perturbation theory.

Topical area:

Structure of Hadrons and Nuclei

Theoretical Developments / 303

Fermi Gases in Two Dimensions

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Laboratory setups and astrophysical circumstances may confine fermions to two spatial dimensions. Leading-order nonrelativistic pionless EFT in 2D has an anomalously broken conformal symmetry, and exhibits BKT phase transition. We use classic tools from lattice field theory to make predictions about this strongly correlated system.

Topical area:

Theoretical Developments / 304

Extracting OPE Coefficients of the 3d Ising CFT from the Four-Point Function

Author: Anna-Maria Elisabeth Glück[1]

Co-authors: George Fleming [2]; Richard C. Brower [3]; Venkitesh Ayyar [3]; Evan Owen [3]; Timothy Raben [4]; Chung-I Tan [5]

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At its critical point, the three-dimensional Ising model is described by a conformal field theory (CFT), the 3d Ising CFT. While the critical exponents of the Ising model, which are related to the scaling dimensions of certain primary operators of the CFT, have been well-investigated in lattice calculations over the past few decades, the theory's operator product expansion (OPE) coefficients have not been accessible with traditional Monte Carlo methods. If, however, instead of carrying out simulations on Euclidean lattices we use the Quantum Finite Elements method to radially quantize critical ϕ^4-theory on simplicial lattices approaching $\mathbb{R} \times \mathbb{S}^2$, we show in this work that not only the scaling dimensions but also the OPE coefficients of the 3d Ising CFT can be extracted from the four-point function. We obtain these quantities by measuring the four-point function of identical scalars in a special antipodal frame on $\mathbb{R} \times \mathbb{S}^2$ at different lattice refinements, fitting the data with expectations from the OPE in radial quantization, and extrapolating to the continuum. Having already shown preliminary findings at LATTICE 2022, we present our final results for the scaling dimensions Δ_ϵ, Δ_T and the OPE coefficients $f_{\sigma\sigma\epsilon}$, $f_{\sigma\sigma T}$ of the first spin-0 and spin-2 primary operators ϵ and T, from which also the central charge of the theory can be calculated, and compare to values obtained with the conformal bootstrap and Hamiltonian methods on the fuzzy sphere.

Topical area:

Theoretical Developments

Standard Model Parameters / 305

Determination of the gradient flow scale t_0 from a Mixed Action with Wilson Twisted Mass Valence Quarks.

Author: Alejandro Saez-Gonzalvo[1]

Co-authors: Alessandro Conigli [1]; Julien Frison [2]; Gregorio Herdoiza [3]; Carlos Pena [1]

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We carry out a scale setting procedure of a mixed action setup consisting of valence Wilson twisted mass fermions at maximal twist on CLS ensembles with $N_f = 2 + 1$ flavours of $O(a)$-improved Wilson sea quarks. We determine the gradient flow scale t_0 using pion and kaon isoQCD masses and decay constants as external input. We employ model variation techniques to probe the systematic uncertainties in the extraction of the ground state signals of lattice observables, as well as for the continuum-chiral extrapolations used to compute t_0 at the physical point.

Topical area:

Quark and Lepton Flavor Physics

Quantum Computing and Quantum Information / 306

Finite-group Laplacian and the physical Hilbert space of finite-group gauge theories

Author: Alessandro Mariani[1]

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One possible approach to the quantum simulation of gauge theories involves replacing the gauge group, a compact Lie group, with one of its discrete finite subgroups. We show how the electric Hamiltonian may be interpreted as a Laplacian operator on the finite group and how this is related to the degeneracy of the electric ground state. Moreover, we discuss the dimension of the physical, gauge-invariant subspace, which is an important question for resource estimation. We give an exact formula for the dimension of the physical subspace of pure gauge theories with an arbitrary finite group on an arbitrary lattice and comment on the case of matter fields.

Topical area:

Quantum Computing and Quantum Information

Plenary session / 307

Overview of hadron structure form lattice QCD

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Topical area:

Plenary session / 308

Welcome to Lattice 2023

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Plenary session / 309

Representation and diversity within physics

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Plenary session / 310

Outreach, Education, and DEI in Lattice QCD

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Topical area:

Plenary session / 311

Advances in algorithms for solvers and gauge generation

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Plenary session / 312

Phase diagram at non-zero temperature and density

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Plenary session / 313

Isospin-breaking and electromagnetic corrections to weak decays

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Plenary session / 314

Quantum simulations of lattice field thoeries

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Plenary session / 315

Qudit-based quantum computing with SRF cavities at Fermilab

Plenary session / 316

Theory needs of neutrino experiments

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Plenary session / 318

Hadron spectroscopy and few-body dynamics

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Plenary session / 319

Transport and connection to heavy-ion collisions

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Plenary session / 321

Renormalons in the renormalization of quasi-PDF matrix elements

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Quark and Lepton Flavor Physics / 323

B-meson semileptonic decays from highly improved staggered quarks

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We present an update for results on B-meson semileptonic decays using the highly improved staggered quark (HISQ) action for both valence and 2+1+1 sea quarks. The use of the highly improved action, combined with the MILC collaboration's gauge ensembles with lattice spacings down to ~0.03 fm, allows the b quark to be treated with the same discretization as the lighter quarks. The talk will focus on updated results for $B_{(s)} \to D_{(s)}$, $B_{(s)} \to K$ scalar and vector form factors.

Topical area:

Quark and Lepton Flavor Physics

Quark and Lepton Flavor Physics / 324

Radiative Electroweak box correction to pion, kaon and Nucleon β decay

Authors: Boram Yoon[1]; Jun-sik Yoo[2]; Rajan Gupta[3]; Tanmoy Bhattacharya[1]

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Recent investigations of tests of unitarity of the first row of the CKM matrix report roughly 3σ tension. Nonperturbative calculations of the radiative corrections (RC) are needed to reduce the theory uncertainty in CKM matrix elements. Here we present the electroweak box contribution to the pion, kaon and neutron decays. For pion and kaon case, we present published results from eight $N_f = 2+1+1$ HISQ- ensembles analyzed using Clover fermions. Our results after extrapolation to the physical point are
$square^{VA}_{\gamma W}|_{\pi} = 2.810(26) \times 10^{-3}$ and
$square^{VA}_{\gamma W}|_{K} = 2.389(17) \times 10^{-3}$. We also present first results for RC to neutron decay from three $N_f = 2+1+1$ HISQ ensembles.

Topical area:

Standard Model Parameters

Theoretical Developments / 325

Towards space-time symmetry preserving lattice discretisation schemes

Authors: Alexander Rothkopf[1]; Jan Nordström[2]

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The conventional discretisation of space-time entails a breaking of continuum symmetries and spoils the conservation of the associated Noether charges with ramifications for particle spectra and the renormalisation of central quantities, such as the Energy Momentum Tensor on the lattice.
In this work 1 we take first steps towards discretizing classical actions, while retaining its continuum space-time symmetries. Our proof-of-principle for a point particle in (1+1)d adopts the action formalism from general relativity, where both space $x(\gamma)$ and time $t(\gamma)$ are dependent variables of a worldline parameter γ. Discretizing in γ, leaves the values of both x and t continuous and thus the invariance under infinitesimal translations in (1+1)d remains intact. Building upon our previous work on solving initial values on the level of the system action 2, we show that the new relativistic approach allows to compute numerically the classical trajectory of a particle under an arbitrary

bounded potential, while conserving the relativistic Noether charge for time translation symmetry *exactly and at its continuum value* in the interior of the simulated domain.

1 A. Rothkopf, J. Nordström, (in preparation)
2 A. Rothkopf, J. Nordström, J.Comput.Phys. 477 (2023) 111942 (2205.14028)

Topical area:

Theoretical Developments

Plenary session / 326

Quark flavor physics with lattice QCD

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Plenary session / 327

The International Lattice Data Grid (ILDG)

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Plenary session / 328

Hadronic contributions to the anomalous magnetic moment of the muon

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Kenneth Wilson Award for Excellence in Lattice Field Theory

Plenary session / 329

Electroweak transitions involving resonances

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Poster session / 330

The four-gluon vertex in Landau gauge

Authors: Manuel Colaço[1]; Orlando Oliveira[1]; Paulo Silva[1]; Joannis Papavassiliou[2]; Maurício Ferreira[2]; Arlene Aguilar[3]; Leonardo Santos[3]

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The Landau gauge four-gluon vertex is studied using high
statistical lattice simulations for several momentum configurations.
Furthermore, the outcome of the lattice QCD simulations are compared
with calculations performed with continuum Schwinger-Dyson equations.

Topical area:

Vacuum Structure and Confinement

Poster session / 331

Machine learning estimator for the trace of inverse Dirac operator

Authors: Hiroshi Ohno[1]; Takayuki Sumimoto[1]

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In lattice QCD calculations, the trace of operator products involving the inverse Dirac operator is often necessary for evaluating various observables, such as cumulants of the chiral order parameter and conserved charge fluctuations. Since the Dirac operator is represented by a large sparse matrix on the lattice, the exact calculation of the trace is typically impractical. Instead, it is commonly estimated by solving systems of linear equations for stochastic sources, which remains computationally demanding, particularly when dealing with numerous sources.
As an alternative approach to trace estimation, we explore a method of adapting a regression algorithm that enables us to predict the relationship between variables. By successfully capturing the correlation between the traces and other observables, it is anticipated that the desired quantity can be inferred without solving linear equations.
In this poster, we present our preliminary results of utilizing the boosting tree algorithm to predict the trace of a power of the inverse Dirac operator. Additionally, we discuss the effectiveness of this method in computing observables, comparing it to the conventional approach.

Topical area:

Algorithms and Artificial Intelligence

Structure of Hadrons and Nuclei / 332

Twist-3 axial GPDs of the proton from lattice QCD

Authors: Martha Constantinou[1]; Shohini Bhattacharya[2]; Krzysztof Cichy[3]; Jack Dodson[1]; Andreas Metz[4]; Aurora Scapellato[None]; Fernanda Steffens[5]

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We present the first lattice calculation of the four twist-3 axial quark GPDs for the proton in the $N_f = 2+1+1$ twisted-mass formulation with a clover improvement. The ensemble has a volume $32^3 \times 64$, lattice spacing 0.0934 fm, and corresponds to a pion mass of 260 MeV. The calculation used the quasi-GPDs approach, which requires matrix elements with momentum-boosted proton states coupled to non-local operators. Here, we use three values of the proton momentum, namely 0.83, 1.25, and 1.67 GeV. The light-cone GPDs are defined in the symmetric frame, which we implement here with a (negative) 4-momentum transfer squared of 0.69, 1.38, and 2.76 GeV2, all at zero skewness. We also conduct several consistency checks, including assessing the local limit of the twist-3 GPDs and examining the Burkhardt-Cottingham-type as well as Efremov-Teryaev-Leader-type sum rules.

Topical area:

Structure of Hadrons and Nuclei

Quark and Lepton Flavor Physics / 333

Towards hadronic D decays at the SU(3) flavour symmetric point

Authors: Antonin Portelli[1]; Fabian Joswig[1]; Maxwell Hansen[None]; Felix Erben[None]; Nelson Pitanga Lachini[1]; SRIJIT PAUL[2]

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We present progress towards extracting multi-hadron D decay amplitudes, such as $D \to \pi\pi$, in a pilot study using three ensembles of stabilised Wilson fermions at the SU(3) flavour symmetric point, with $M_\pi = 410$ MeV. As the three ensembles differ only in the lattice spacing, with well matched physical volumes, it is possible to perform a continuum limit for finite-volume energies (and eventually weak-decay matrix elements) at fixed physical volume. The talk will summarise the work-flow and challenges of the ongoing calculation with a focus on results for the a^2-dependence and continuum limit of the two-to-two pseudoscalar S-wave scattering amplitude, determined via the GEVP+Lüscher approach in an exact distillation setup implemented in the Grid and Hadrons software libraries.

Topical area:

Quark and Lepton Flavor Physics

Algorithms and Artificial Intelligence / 334

MLMC: Machine Learning Monte Carlo for Lattice Gauge Theory

Authors: James Osborn[1]; Sam Foreman[2]; Xiaoyong Jin[1]

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We present a trainable framework for efficiently generating gauge configurations, and discuss ongoing work in this direction. In particular, we consider the problem of sampling configurations from a 4D $SU(3)$ lattice gauge theory, and consider a generalized leapfrog integrator in the molecular dynamics update that can be trained to improve sampling efficiency.

Topical area:

Algorithms and Artificial Intelligence

Algorithms and Artificial Intelligence / 335

Scalar content of nucleon with the gradient flow using machine learning

Authors: Giovanni Pederiva[1]; Andrea Shindler[2]; Jangho Kim[3]

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We present the results of our determination of the scalar content of the nucleon using various techniques to address the large computational cost of a direct calculation. The gradient flow is employed to improve the signal, combined with the stochastic calculation of the all-to-all propagator using the standard Hutchinson trace method. By using supervised machine learning, decision trees in our case, we further reduce the numerical cost by having the ML algorithm model the correlations between different flow times, allowing us to compute the flow only on a small subset of the whole ensemble. Our results are validated against the ”traditional” result and against established comparable results from FLAG.

Topical area:

Algorithms and Artificial Intelligence

Hadronic and Nuclear Spectrum and Interactions / 336

To bind or not to bind, a question of various two-nucleon interpolators

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I discuss our progress in studying the two-nucleon spectrum at heavy pion mass using various types of interpolating operators to create the correlation functions. These include momentum-space creation and annihilation operators using the stochastic Laplacian Heaviside method both with and

without local hexa-quark interpolators, local hexa-quark creation operators and momentum space annihilation operators, as well as the HAL QCD Potential method. We compare and contrast the spectrum from these various methods and discuss potential unresolved systematic uncertainties.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Algorithms and Artificial Intelligence / 337

Lattice real-time simulations with machine learned optimal kernels

Authors: Alexander Rothkopf[1]; Daniel Alvestad[None]; Denes Sexty[2]; Nina Lampl[2]

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Direct simulations of real-time dynamics of strongly correlated quantum fields are affected by the NP-hard sign sign-problem, which requires system-specific solution strategies 1.
Here we present novel results on the real-time dynamics of scalar field theory in 1+1d based on our recently developed machine-learning assisted kernelled complex Langevin approach 2. By using simple field independent kernels and an improved optimization functional [3] we manage to extend the validity of the simulations to a real-time extent twice the current community benchmark (which was based on contour deformations). Due to the favourable numerical cost of our CL approach we are able to avoid discretisation artefacts that plagues previous simulations.

1 M. Troyer, U.-J. Wiese Phys.Rev.Lett. 94 (2005) 170201 (cond-mat/0408370)
2 D. Alvestad, R. Larsen, A. Rothkopf, JHEP 04 (2023) 057 (2211.15625)
[3] D. Alvestad, A. Rothkopf, N. Lampl, D. Sexty (in preparation)

Topical area:

Algorithms and Artificial Intelligence

Particle Physics Beyond the Standard Model / 338

Studying gauged Yukawa models and their supersymmetric limit on the lattice

Authors: Georg Bergner[1]; Stefano Piemonte[2]

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We present our lattice simulations of gauge theories coupled to fermions and scalar fields in adjoint and fundamental representation. Supersymmetric gauge theories emerge as specific limiting cases within this theory space. We discuss our efforts to tune the parameters towards the supersymmetric limit.

Topical area:

Particle Physics Beyond the Standard Model

Poster session / 339

Glueballs in $N_f = 1$ QCD

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We present an evaluation of the glueball spectrum for configurations produced with $N_f = 1$ dynamical fermions as a function of the m_{PCAC} mass. We obtained masses of states that fall into the irreducible representations of the octagonal group of rotations in combination with the quantum numbers of charge conjugation C and parity P. Due to the low signal to noise ratio, practically, we can only extract masses for the irreducible representations A_1^{++}, E^{++}, T_2^{++} as well as A_1^{-+}. We make use of the Generalized Eigenvalue Problem (GEVP) with a basis operators consisting only of gluonic operators. Throughout this work we are aiming towards the identification of the effects of light dynamical quarks on the glueball spectrum and how this compares to the statistically more precise spectrum of $SU(3)$ pure gauge theory. We used large gauge ensembles which consist of $\sim calO(10\mathrm{K})$ configurations. Our findings demonstrate that the low lying spectrum of the scalar, tensor as well as pseudo-scalar glueballs receive negligible contributions from the inclusion of $N_f = 1$ dynamical fermions.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Quark and Lepton Flavor Physics / 340

B(s)-mixing parameters from all-domain-wall-fermion simulations

Authors: Justus Tobias Tsang[1]; Felix Erben[None]; Takashi Kaneko[2]; Rajnandini Mukherjee[3]

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We present an update of the study of bag parameters of neutral $B_{(s)}$-meson mixing, which constrains the Standard Model as well as BSM scenarios. Our calculations use an all-domain-wall-fermion approach. We combine three lattice spacings ($1.7\mathrm{GeV} \leq a^{-1} \leq 2.7\mathrm{GeV}$) including 2 physical pion mass ensembles generated by RBC/UKQCD with ensembles with three finer lattice spacings ($2.5\,\mathrm{GeV} \leq a^{-1} \leq 4.5\,\mathrm{GeV}$) generated by the JLQCD collaboration. We will show preliminary non-perturbatively renormalised results for bag parameters and demonstrate that all required limits are controlled.

Topical area:

Quark and Lepton Flavor Physics

Poster session / 341

Normalizing flows for gauge theories: towards finite temperature simulations

Authors: Christopher Kirwan[1]; Sinéad Ryan[2]

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Normalizing flow based methods for efficient sampling in lattice gauge theories have shown impressive progress. We have extended these methods to generate ensembles for SU(3) in 2+1 dimensions at a range of temporal extents. Preliminary results for observables are presented and future prospectives for finite temperature simulations are discussed

Topical area:

Algorithms and Artificial Intelligence

Quark and Lepton Flavor Physics / 342

The mixing of two-pion and vector-meson states using staggered fermions

Author: Fabian Justus Frech[1]

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In this study we employ staggered fermions to calculate the two-pion taste singlet states at rest. Leveraging the Clebsch-Gordan coefficients of the symmetry group associated with staggered fermions, we effectively compute the $\pi\pi$ contributions to the resting ρ-meson. To discern the distinct energy states involved, we adopt a generalized eigenvalue problem-solving approach. This work will provide insight into the important role played by the two-pion contribution to the anomalous magnetic moment of the muon.

In this talk, we present our group theoretic considerations and preliminary results on the contribution of two-pion states to the rho meson.

Topical area:

Quark and Lepton Flavor Physics

Structure of Hadrons and Nuclei / 343

Helicity GPD for the proton using an asymmetric kinematic setup

Authors: Joshua Miller[None]; Shohini Bhattacharya[1]; Krzysztof Cichy[2]; Martha Constantinou[3]; Jack Dodson[3]; Xiang Gao[4]; Andreas Metz[5]; Swagato Mukherjee[1]; Peter Petreczky[6]; Aurora Scapellato[None]; Fernanda Steffens[7]; Yong Zhao[8]

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First lattice QCD calculations of x-dependent GPD have been performed in the Breit frame, where the momentum transfer is evenly divided between the initial and final hadron states. Employing the asymmetric frame proposed in PRD 106 (2022) 11, 114512, we are able to obtain proton GPDs for multiple momentum transfers in a computationally efficient setup. In this presentation, we focus on the helicity twist-2 GPD at zero skewness that gives access to the $\widetilde{H}$ GPD. We will cover the implementation of the asymmetric frame, its comparison to the Breit Frame, and the dependence of the GPD on the four-vector momentum transfer squared. The calculation is performed on an $N_f = 2 + 1 + 1$ ensemble of twisted mass fermions with a clover improvement. The mass of the pion for this ensemble is roughly 260 MeV.

Topical area:

Structure of Hadrons and Nuclei

QCD at Non-zero Temperature / 344

Finite volume effects near the chiral crossover

Authors: Attila Pasztor[1]; Chik Him Wong[2]; Jana N. Guenther[3]; Paolo Parotto[None]; Ruben Kara[2]; Szabolcs Borsanyi[None]; Zoltan Fodor[None]

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The effect of a finite volume presents itself both in heavy ion experiments as well as in recent model calculations. The magnitude is sensitive to the proximity of a nearby critical point. We calculate the finite volume effects at finite temperature in continuum QCD using lattice simulations. We focus on the vicinity of the chiral crossover. We investigate the impact of finite volumes at zero and small chemical potentials on the QCD transition though the chiral observables.

Topical area:

QCD at Non-zero Temperature

Structure of Hadrons and Nuclei / 345

Nucleon electromagnetic form factors at large momentum from Lattice QCD

Authors: Andrew Pochinsky[1]; John Negele Negele[1]; Sergey Syritsyn[2]; Jeremy Green[3]; Michael Engelhardt[4]; Stefan Krieg[5]; Stefan Meinel[6]

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Proton and neutron electric and magnetic form factors are the primary characteristics of their spatial structure and have been studied extensively over the past half-century. At large values of the momentum transfer Q^2 they should reveal transition from nonperturbative to perturbative QCD dynamics and effects of quark orbital angular momenta and diquark correlations. Currently, these form factors are being measured at JLab at momentum transfer up to $Q^2 = 18$ GeV^2 for the proton and up to 14 GeV^2 for the neutron. We will report theoretical study of these form factors using nonperturbative QCD on the lattice, including G_E and G_M nucleon form factors with momenta up to $Q^2 = 12$ GeV^2, pion masses down to the almost-physical m_π=170 MeV, several lattice spacings down to $a = 0.073$ fm, and high $O(10^5)$ statistics. Specifically, we study the G_E/G_M ratios, asymptotic behavior of the F_2/F_1 ratios, and flavor dependence of contributions to the form factors. We observe qualitative agreement of our ab initio theory calculations with experiment. Comparison of our calculations and upcoming JLab experimental results will be an important test of nonperturbative QCD methods in the almost-perturbative regime.

Topical area:

Structure of Hadrons and Nuclei

Theoretical Developments / 346

Euclidean, Weak-Field General Relativity on the Lattice

Author: Christopher Bouchard[1]

[1] *University of Glasgow*

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I will discuss a discretization of Euclidean, weak-field General Relativity allowing the generation of a Markov chain of dynamic, pure gravity spacetimes at non-zero temperature via Metropolis algorithm with importance sampling. A positive action conjecture is implemented on the lattice, ensuring a probabilistic interpretation of exp(-S) and that dS=0 yields the Einstein field equations. Preliminary results demonstrating discretization and finite volume systematic effects will be presented and the coupling of dynamic spacetime to the QCD vacuum will be discussed.

Topical area:

Theoretical Developments

Algorithms and Artificial Intelligence / 347

Bayesian Inference for Contemporary Lattice Quantum Field Theory

Author: Julien Frison[1]

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Bayesian inference provides a rigorous framework to encapsulate our knowledge and uncertainty regarding various physical quantities in a well-defined and self-contained manner. Utilising modern tools, such Bayesian models can be constructed with a remarkable flexibility, leaving us totally free to carefully choose which assumption should be strictly enforced and which should on the contrary be relaxed. The practical evaluation of these assumptions, together with the data-driven selection or averaging of models, also appears in a very natural way.
In this presentation, I will discuss its application in the context of lattice QCD and its common statistical problems. As a concrete illustration, I will present a few parametric and non-parametric hierarchical models applied to actual correlator data.

Topical area:

Algorithms and Artificial Intelligence

Hadronic and Nuclear Spectrum and Interactions / 348

Spectroscopy of heavy-light mesons

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Co-authors: David J. Wilson [2]; Luke Gayer [1]

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We present updated results of the excited and exotic spectra of B, B_s and B_c mesons. The calculations are performed on dynamical, anisotropic lattices with relativistic heavy quarks. A first look at finite volume effects and next steps are also discussed.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Poster session / 349

Affordable low mode averaging

Authors: Marina Marinkovic[1]; Roman Gruber[2]

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We present a new take on low-mode averaging, where the dimension of the low-mode subspace is multiplied by exploiting local coherence of low modes. The fraction of the quark propagator captured by this subspace can easily be volume averaged or sampled excessively and reaches gauge variance with lower computational cost than the traditional methods. The remainder piece can be sampled stochastically by solving the Dirac equation to low precision without compromising the correctness of the solution.

Topical area:

Algorithms and Artificial Intelligence

Structure of Hadrons and Nuclei / 350

Renormalization of transverse-momentum-dependent parton distribution on the lattice

Authors: Kuan Zhang[None]; Xiangdong Ji[1]; Yibo Yang[2]; Jianhui Zhang[3]; Fei Yao[None]

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To calculate the transverse-momentum-dependent parton distribution functions (TMDPDFs) from lattice QCD, an important goal yet to be realized, it is crucial to establish a viable nonperturbative renormalization approach for linear divergences in the corresponding Euclidean quasi-TMDPDF correlators in large-momentum effective theory. We perform a first systematic study of the renormalization property of the quasi-TMDPDFs by calculating the relevant matrix elements in a pion state at 5 lattice spacings ranging from 0.03 fm to 0.12 fm. We demonstrate that the square root of the Wilson loop combined with the short distance hadron matrix element provides a successful method to remove all ultraviolet divergences of the quasi-TMD operator, and thus provide the necessary justification to perform a continuum limit calculation of TMDPDFs. In contrast, the popular RI/MOM renormalization scheme fails to eliminate all linear divergences.

Topical area:

Structure of Hadrons and Nuclei

Hadronic and Nuclear Spectrum and Interactions / 351

Variational study of NN systems and the H dibaryon

Authors: Phiala Shanahan[1]; Zohreh Davoudi[2]; William Detmold[3]; Marc Illa Subina[4]; William Jay[3]; Assumpta Parreno[5]; Robert Perry[6]; Michael Wagman[7]

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I will present updated results from the NPLQCD collaboration including a variational study of NN systems at $m_\pi \sim 800$MeV on two lattice volumes, using a set of interpolating operators that includes non-local products of plane-wave baryons as well as operators spanning the full Hilbert space of local six-quark operators. I will also show a first glance at the results of the same analysis at $m_\pi \sim 170$MeV. In addition, I will discuss an analysis of the isospin singlet, strangeness -2 sector relevant for the H-dibaryon at $m_\pi \sim 800$MeV on two volumes.

Topical area:

Structure of Hadrons and Nuclei

Software Development and Machines / 352

Exploiting Modern C++ for Portable Parallel Programming in Lattice QCD Applications

Author: Alexei Strelchenko[1]

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In this presentation, we will discuss the application of recent and emerging C++ features, with a focus on portable parallel programming in lattice QCD. Specifically, the discussion will center around certain key features introduced in the C++17, C++20, and C++23 standards, as well as an exploration of some experimental features currently under development.
A primary emphasis will be placed on accelerator programming, aiming to highlight the potential of these modern C++ features in achieving highly efficient and portable solutions to enhance and streamline the programming of complex LQCD applications.

Topical area:

Software Development and Machines

Plenary session / 353

Lattice QCD input for neutrino-nucleus scattering

Author: Rajan Gupta[1]

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In this review, I will cover the status of the calculations of quantities that are needed in the analysis of neutrinos off nuclear targets. These include the axial charge and the form factors of the nucleon. A discussion of systematics—removing excited state contributions and obtaining results at the physical point will be included. Looking ahead, I will conclude with prospects of calculating transition matrix elements.

Topical area:

Structure of Hadrons and Nuclei

Quark and Lepton Flavor Physics / 354

Computing hadronic vacuum polarization on 0.048 fm lattices with GPUs

Author: Gen Wang[None]

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I will present ongoing efforts, by the Budapest-Marseille-Wuppertal collaboration, concerning the staggered-fermion computation of the HVP two-point function, on new 0.048 fm lattices. In particular, I will focus on aspects of our GPU determination of the Omega baryon mass, used for scale setting, and that of the connected, light-quark contribution to the muon g-2.

Topical area:

Quark and Lepton Flavor Physics

Algorithms and Artificial Intelligence / 355

Multiscale Normalizing Flows for Gauge Theories

Authors: Daniel Hackett[1]; Julian Urban[1]; Phiala Shanahan[2]; Ryan Abbott[1]; Denis Boyda[3]; Fernando Romero-Lopez[1]

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Scale separation is an important physical principle that has previously enabled algorithmic advances such as multigrid. Previous work on normalizing flows has been able to utilize scale separation in the context of scalar field theories, but mostly not in the context of gauge theories. In this talk, I will give an overview of a new method for generating gauge fields using heirarchical normalizing flow models. This method builds gauge fields from the outside in, allowing different parts of the model to focus on different scales of the problem. In addition I will present numerical results for U(1) and SU(3) gauge theories in 2, 3, and 4 spatial dimensions.

Topical area:

Algorithms and Artificial Intelligence

Theoretical Developments / 356

A qubit regularization of asymptotic freedom without fine-tuning

Authors: Sandip Maiti[1]; Debasish Banerjee[1]; Shailesh Chandrasekharan[2]; Marina Marinkovic[3]

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Other than the commonly used Wilson's regularization of quantum field theories (QFTs), there is a growing interest in regularizations that explore lattice models with a strictly finite local Hilbert space, in anticipation of the upcoming era of quantum simulations of QFTs. A notable example is Euclidean qubit regularization, which provides a natural way to recover continuum QFTs that emerge via infrared fixed points of lattice theories. A non-trivial question is whether such regularizations can also capture the physics of ultraviolet fixed points. Specifically, can we recover massive continuum QFTs which are free in the UV but contain a marginally relevant coupling?

In this talk, I will discuss a novel regularization of the asymptotically free massive continuum QFT that emerges at the BKT transition through a hard core loop-gas model. Our proposed model offers several advantages compared to traditional regularizations. Firstly, without the need for fine-tuning, it can reproduce the universal step-scaling function of the classical lattice XY model in the massive phase as we approach the phase transition. Secondly, our approach exhibits reduced finite size effects for certain universal quantities at the BKT transition compared to the traditional XY model. Lastly, our model serves as a prime example of Euclidean qubit regularization of an asymptotically free massive QFT and helps understand the emergence of asymptotic freedom as a relevant perturbation at a decoupled fixed point without fine-tuning.

Topical area:

Theoretical Developments

Vacuum Structure and Confinement / 357

Adjoint chromoelectric and chromomagnetic correlators with gradient flow

Author: Viljami Leino[1]

Co-author: TUMQCD collaboration

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When QCD is described by a non-relativistic EFT, operators consisting of gluonic correlators of two chromoelectric or -magnetic fields will often appear in descriptions of quarkonium physics. At zero T, these correlators give the masses of gluelumps and the moments of these correlators can be used to understand the inclusive P-wave decay of quarkonium. At finite T these correlators definite the diffusion of the heavy quarkonium. However, these correlators come with a divergent term in lattice spacing which needs to be taken care of. We inspect these correlators in pure gauge theory with gradient flow smearing, which should allow us to reduce and remove the divergence more carefully. At this talk we focus on the effect of gradient flow to these correlators and the reduction of this divergence.

Topical area:

Vacuum Structure and Confinement

Quark and Lepton Flavor Physics / 358

Hadronic vacuum polarization: comparing lattice QCD and data-driven results in systematically improvable ways

Author: Laurent Lellouch[1]

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Significant tensions are observed between the dispersive and the lattice QCD results for hadronic vacuum polarization (HVP). We will present a general framework that allows to compare the two approaches and to combine them, if they can be reconciled. We have applied this framework to determine the distance or energy scales that could be responsible for the observed tensions and we will present the ensuing results. We will also discuss the limits in the information that can be extracted from a finite set of moment integrals of the R-ratio.

Topical area:

Quark and Lepton Flavor Physics

Hadronic and Nuclear Spectrum and Interactions / 359

Finite-volume scattering on the left-hand cut

Authors: Andre Baiao Raposo[1]; Maxwell Hansen[None]

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The Lüscher formalism is a well-known and widely used method for extracting scattering amplitudes from the finite-volume spectrum. Recent lattice QCD calculations involving systems where a lighter particle couples to heavier scattering particles (e.g. baryon-baryon scattering) have highlighted the limitations of the standard formalism below threshold. This is due to the presence of left-hand cuts in the partial-wave-projected scattering amplitudes. In this talk, we describe an extension of the existing framework to the left-hand cut, summarising the complete procedure including the solving of integral equations to extract physical observables. We further describe first numerical tests on mock data, and explicitly show the equivalence between our method and the familiar formalism in the regime where both are valid.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Tests of Fundamental Symmetries / 360

Neutron Electric Dipole Moment from Isovector Quark Chromo-Electric Dipole Moment

Author: Tanmoy Bhattacharya[1]

Co-authors: Boram Yoon [2]; Emanuele Mereghetti [1]; Jun-sik Yoo [3]; Rajan Gupta [4]; Vincenzo Cirigliano [5]

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We present results from our lattice QCD study of the contribution of the isovector quark chromo-electric dipole moment (qcEDM) operator to the nucleon electric dipole moments (nEDM). The calculation was carried out on four 2+1+1-flavor of highly improved staggered quark (HISQ) ensembles using Wilson-clover quarks to construct correlation functions. We use the non-singlet axial Ward identity including corrections up to O(a) to show how to control the power-divergent mixing of the isovector qcEDM operator with the lower dimensional pseudoscalar operator. Results for the nEDM are presented after conversion to the MSbar scheme at the leading-log order.

Topical area:

Particle Physics Beyond the Standard Model

Algorithms and Artificial Intelligence / 361

Practical applications of machine-learned flows on gauge fields

Authors: Daniel Hackett[1]; Denis Boyda[2]; Fernando Romero-Lopez[1]; Julian Urban[1]; Phiala Shanahan[3]; Ryan Abbott[1]

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Normalizing flows are machine-learned maps between different lattice theories which can be used as components in exact sampling and inference schemes. Ongoing work yields increasingly expressive flows on gauge fields, but it remains an open question how flows can improve lattice QCD at state-of-the-art scales. This talk discusses and demonstrates several useful applications which are viable with presently available flows, highlighting replica exchange sampling and a new approach to Feynman-Hellmann calculations.

Topical area:

Algorithms and Artificial Intelligence

QCD at Non-zero Density / 362

QCD equation of state in the presence of magnetic fields at low density

Authors: Adeilton Dean Marques Valois[1]; Bastian B. Brandt[2]; Gergely Endrodi[2]; Jana Guenther[3]; Ruben Kara[3]; Szabolcs Borsanyi[None]

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Peripheral heavy-ion collisions are expected to exhibit magnetic fields with magnitudes comparable to the QCD scale, as well as non-zero baryon densities. Whereas lattice QCD at finite magnetic field can be simulated directly with standard algorithms, an implementation of real chemical potentials is hindered by the infamous sign problem. Aiming to shed light on the QCD transition and on the EoS in that regime, we carry out lattice QCD simulations with 2+1+1 staggered quarks with physical masses at finite magnetic field, and imaginary chemical potential to circumvent the sign problem. We present the leading coefficient of Taylor expansion calculated at non-zero magnetic field and discuss the impact of the field on the strangeness neutrality condition.

Topical area:

QCD at Non-zero Density

Algorithms and Artificial Intelligence / **363**

Fine grinding localized updates via gauge equivariant flows in the 2D Schwinger model

Author: Jacob Finkenrath[1]

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State-of-the-art simulations of discrete gauge theories are based on Markov chains with local changes in the field space, which however at very fine lattice spacings are notoriously difficult due to separated topological sectors of the gauge field resulting in very long autocorrelation times.

An approach, which can overcome long autocorrelation times, is based on trivializing maps, where a new gauge proposal is given by mapping a configuration from a trivial space to the target one, distributed via the associated Boltzmann factor. Using gauge equivariant coupling layers, the map can be approximated via machine learning techniques. However the deviations between exact distribution and approximated one scales with the volume in case of local theories, rendering a global update unfeasible for realistic box sizes.

In the talk, we will discuss the potential of localized updates in case of the 2D Schwinger Model. Using gauge-equivariant flow maps, a local update can be fine grained towards finer lattice spacing. Based on this we will present results on simulating the 2D Schwinger Model with dynamical Nf=2 Wilson fermions at fine lattice spacings with global correction steps and compare the performance to the HMC.

Topical area:

Algorithms and Artificial Intelligence

Algorithms and Artificial Intelligence / **364**

Neural Network Gauge Field Transformation for 4D SU(3) gauge fields

Author: Xiaoyong Jin[1]

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We construct neural networks that work for any Lie group and maintain gauge covariance, allowing smooth and invertible transformations of gauge fields. We implement the transformations for 4D SU(3) lattice gauge fields, and explore their use in HMC. Our current research develops various loss functions and optimizes field transformation accordingly. We show the effect of these transformations on HMC's molecular dynamics evolution and discuss the scalability of this approach.

Topical area:

Algorithms and Artificial Intelligence

Algorithms and Artificial Intelligence / 365

Unfreezing topology with nested sampling

Author: Daniel Hoying[1]

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We introduce nested sampling as a generic simulation technique to integrate over the space of lattice field configurations and to obtain the density of states. In particular, we apply it as a tool for performing integrations in systems with ergodicity problems due to non-efficient tunneling, e.g., in case of topological freezing or when computing first order phase transitions. As a proof of principle, we show how this technique avoids topological freezing in 2D U(1), allowing us to compute topological charge and susceptibility for a range of usually inaccessible values of β.

Topical area:

Algorithms and Artificial Intelligence

Quantum Computing and Quantum Information / 366

Simulating Z2 lattice gauge theory on a quantum computer

Authors: Clement Charles[None]; Erik Gustafson[1]; Henry Lamm[2]; Florian Herren[2]; Judah Unmuth-Yockey[2]; Michael Wagman[2]; Norman Hogan[None]; Ruth Van de Water[2]; Sara Starecheski[None]

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Quantum simulations of lattice gauge theories are currently limited by the noisiness of the physical hardware. Various error mitigation strategies exist to extend the use of quantum computers. We

perform quantum simulations to compute two-point correlation functions of the 1 + 1d Z2 gauge theory with matter to determine the mass gap for this theory. These simulations are used as a laboratory for investigating the efficacy and interplay of different error mitigation methods: readout error mitigation, randomized compiling, rescaling, and dynamical decoupling. We find interesting synergies between these methods and that their combined application increase the simulation times at a given level of accuracy by a factor of six or more compared to unmitigated results

Topical area:

Quantum Computing and Quantum Information

Structure of Hadrons and Nuclei / 367

Flavor diagonal nucleon charges from clover fermions on MILC HISQ ensembles.

Authors: Tanmoy Bhattacharya[1]; Rajan Gupta[2]; Huey-Wen Lin[3]; Santanu Mondal[4]; Sungwoo Park[5]; Boram Yoon[6]

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We update our calculation of flavor diagonal nucleon axial, scalar and tensor charges on eight 2+1+1-flavor MILC HISQ ensembles using Wilson-clover fermions. We discuss the signal in the sum of the connected and disconnected contributions for the up, down and strange quarks, control over fits to remove excited state contamination, the simultaneous chiral-continuum fit used to extract the charges. We calculate the renormalization including mixing between flavors nonperturbatively using RI-sMOM. We compare two different determinations of Z_ψ, one from the quark propagator and the other from the nucleon vector charge and the vector Ward identity, and consider the resulting difference in the renormalized flavor diagonal charges.

Topical area:

Structure of Hadrons and Nuclei

Poster session / 368

Beyond Generalized Eigenvalues

Author: George Fleming[1]

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Two analysis techniques, the *generalized eigenvalue method* (GEM) or *Prony's method* (PM), are commonly used to analyze statistical estimates of correlation functions produced in lattice quantum field

theory calculations. GEM takes full advantage of the matrix structure of correlation functions but only considers individual pairs of time separations when much more data exists. PM can be applied to many time separations and many individual matrix elements simultaneously but does not fully exploit the matrix structure of the correlation function. We combine both these methods into a single framework based on *matrix polynomials* which we call *block Prony method* (BPM).

Topical area:

Algorithms and Artificial Intelligence

Algorithms and Artificial Intelligence / 369

Meron-Cluster Algorithms for Quantum Link Models

Author: Joao Carlos Pinto Barros[1]

Co-authors: Marina Marinkovic [2]; Thea Budde [2]

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State-of-the-art algorithms for simulating fermions coupled to gauge fields often rely on integrating fermion degrees of freedom. While successful in simulating QCD at zero chemical potential, at finite density these approaches are hindered by the sign problem, for example, leading to extensive research on alternative formulations suitable, inter alia, for simulations of gauge theories on quantum devices.

In this talk, we will discuss the simulation of lattice gauge theories in the Hamiltonian formalism and present an efficient generalized meron-cluster algorithm for the simulation of the Schwinger Model. A key feature of this algorithm is the ability to satisfy Gauss' law exactly during cluster flips, allowing for non-local updates while remaining within the physical subspace. Not only this enables the study of models directly relevant to current quantum simulators, but it also presents a promising first step toward constructing new efficient algorithms for more complicated gauge theories.

Topical area:

Algorithms and Artificial Intelligence

Hadronic and Nuclear Spectrum and Interactions / 370

Spectroscopy of Nucleon-Pion Systems using Sparsened Interpolators

Authors: Anthony Grebe[1]; Michael Wagman[1]

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Neutrino oscillation experiments require accurate reconstructions of neutrino energies, which depend in part on a theoretical understanding of the axial $N \to \Delta$ transition form factors. A lattice QCD study of this transition will require construction of all hadronic states with energies up to m_Δ, which at the physical point includes $N\pi$ and $N\pi\pi$. Building interpolating operators from sparse

grids at the source and sink is a versatile method that allows construction of a wide range of diagram topologies and has successfully been used in other multi-hadron calculations. We will discuss application of this method to nucleon-pion systems and present preliminary results.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Quantum Computing and Quantum Information / 371

Thermodynamics of non-Abelian D_4 lattice gauge theory via Quantum Metropolis Sampling

Authors: Edoardo Ballini[1]; Giuseppe Clemente[2]; Lorenzo Maio[3]; Kevin Zambello[4]; Massimo D'Elia[5]

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The possibility to use fault-tolerant Quantum Computers in the "Beyond the NISQ era" is a promising perspective: it could bring the implementation of Markov Chain Monte Carlo (MCMC) quantum algorithms on real machines. Then, it would be possible to exploit the quantum properties of such devices to study the thermodynamic properties of the system. This also allows us to avoid the infamous sign problem, which plagues classical Monte Carlo simulations of several interesting systems - such as the QCD in the presence of an external electric field or a finite chemical potential. In this work, we discuss the effectiveness of Quantum Metropolis Sampling in the study of thermodynamic properties of a non-Abelian gauge theory, based on the discrete D_4 symmetry group. This is the first study of a non-Abelian Lattice Gauge Theory by means of a quantum MCMC algorithm: we simulate the behavior of an ideal quantum Computer, aiming to demonstrate the feasibility of such simulations.

Topical area:

Quantum Computing and Quantum Information

Poster session / 372

Streamlined data analysis in Python

Authors: David Clarke[1]; Hauke Sandmeyer[None]; Jishnu Goswami[2]

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Python is a particularly appealing language to carry out data analysis, owing in part to its user-friendly character as well as its access to well maintained and powerful libraries like NumPy and

SciPy. Still, for the purpose of analyzing data in a lattice QCD context, some desirable functionality is missing from these libraries. Moreover, scripting languages tend to be slower than compiled ones. To help address these points we present the LatticeToolbox, a collection of Python modules to facilitate lattice QCD data analysis. Some highlighted features include general-purpose jackknife and bootstrap routines; modules for reading in and storing gauge configurations; a module to carry out hadron resonance gas model calculations; and convenience wrappers for SciPy integration, curve fitting, and splines. These features are sped up behind the scenes using Numba and concurrent.futures.

Topical area:

Software Development and Machines

Quantum Computing and Quantum Information / 373

Hybrid Quantum Estimation of Thermal Averages via Partial Mixed States Preparation

Author: Giuseppe Clemente[1]

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In this talk we introduce a novel quantum algorithm for the estimation of thermal averages
in the NISQ-era through an iterative combination of Variational Quantum Eigensolver techniques and reweighting.
We discuss the details of the algorithm and the scaling of resources and systematical errors,
showing some results of the application to compelling test cases.

Topical area:

Quantum Computing and Quantum Information

Algorithms and Artificial Intelligence / 374

Riemannian manifold HMC with fermions

Authors: Chulwoo Jung[1]; Norman Christ[2]

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We report on the study of a version of the Riemannian Manifold HMC (RMHMC) algorithm, where the mass term is replaced by rational functions of the SU(3) gauge covariant Laplace operater.
RMHMC on a 2+1+1-flavor ensemble with near physical masses is compared against HMC, where increased rate of change in Wilson flow scales per fermion Molculardynamics step is observed.

Topical area:

Algorithms and Artificial Intelligence

Hadronic and Nuclear Spectrum and Interactions / 375

Breakdown of Lüscher Formalism near Left Hand Cuts

Authors: Md Habib E Islam[1]; Sebastian Dawid[2]; Raul Briceno[3]

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Understanding three-body dynamics is crucial in comprehending the behavior of hadronic states that decay into three or more particles under strong interactions. Recent advances in Lattice QCD techniques allow us to calculate three-particle interactions from QCD and access finite volume energies. Connecting these energies to physical observables involves multiple steps. Firstly, we use the Lüscher formalism and its extensions to map these energies to intermediate quantities in infinite volume. These quantities serve as input in a set of integral equations, yielding the three-body scattering amplitude. Before applying this method to actual Lattice QCD calculations, we must verify its consistency with various toy models. In this study, we numerically solve relativistic three-body integral equations for a toy model of three identical scalar bosons. The model's two-body sub-channel, defined by scattering length, permits bound states. Our results for a bound-state+particle system are compared to established results using Lüscher formalism for the same toy model. We discuss methods of solving the integral equations above the bound-state+particle threshold and provide a prescription for analytically continuing solutions below threshold. Although our solutions agree well with previous results, we find evidence of Lüscher formalism breaking down near the left-hand cut resulting from exchange particle interactions. This talk primarily focuses on our solution techniques and the breakdown of the finite volume formalism.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Quark and Lepton Flavor Physics / 376

Form factors for semileptonic B-decays with HISQ light quarks and clover b-quarks in Fermilab interpretation

Authors: Aida El-Khadra[1]; Alejandro Vaquero[2]; Andreas Kronfeld[3]; Andrew Lytle[1]; Carleton DeTar[2]; Elvira Gamiz[4]; Hwancheol Jeong[5]; Steven Gottlieb[6]; William Jay[7]; Zechariah Gelzer[8]

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We compute the complete set of form factors for the $B \to \pi$, $B \to K$, and $B_s \to K$ amplitudes, which are needed to describe semileptonic B-meson decay rates for both the charged and neutral current cases. We use the highly improved staggered quark (HISQ) action for the sea and light valence quarks. The b quark is described by the Wilson-clover action in the Fermilab interpretation.

Simulations are carried out on $N_f = 2+1+1$ MILC HISQ ensembles at approximate lattice spacings from 0.15 fm down to 0.057 fm. We present preliminary results for the form factors.

Topical area:

Quark and Lepton Flavor Physics

Algorithms and Artificial Intelligence / 377

Enhancing Expressivity in Machine Learning: Application of Normalizing Flows in lattice QCD Simulations

Authors: Daniel Hackett[1]; Denis Boyda[2]; Fernando Romero-López[1]; Julian Urban[1]; Phiala Shanahan[3]; Ryan Abbott[1]

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I will highlight existing limitations of the current architecture of Normalizing flows as applied to the generation of lqcd samples. From the Geometric Deep Learning perspective, existing architecture utilized the most basic features - invariant quantities that correspond to isotropic filters. In order to establish an expressive flow model transforming base distribution to target, I will formulate an equation and demonstrate the necessity of incorporating equivariant features. Furthermore, I will delve into the algorithm that enables us to identify approximate solutions and approach analytic trivialization. The limitations associated with coupling transformations will be discussed, emphasizing the need for a hierarchical model to attain an exact solution. Lastly, I will elucidate how the analysis of flow equation leads us to consider geometry. From a geometric standpoint, it is argued that trivializing 2D SU(3) gauge theory is relatively straightforward, while the presence of geometrical "defects" in 3D and 4D scenarios significantly complicates the process of trivialization.

Topical area:

Algorithms and Artificial Intelligence

Vacuum Structure and Confinement / 378

Extracting Instantons from the Lattice

Author: Falk Zimmermann[1]

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In this talk, I summarize phenomenological results on topology, in particular the extraction of distinct topological sectors that resemble instantons, and support the picture of the QCD vacuum being filled with highly localized topological excitations.
Combining the identification of topological sectors (connected regions of either left- or right-handed winding in $n_f = 2+1+1$ configurations) with a simple charge gradient approach increases the number of instanton sectors found. Such sectors deviate from the background by a distinct charge-volume behavior and, in addition, by a high degree of self-duality.

Defining the topological charge density with an improved $O(a^6)$ field strength removes leading UV lattice artifacts that would otherwise contribute to the multiplicative renormalization constant. As a result, we find that the total charge of the configurations Q is very close to integers and the charge content of the instanton sectors is close to ± 1.

In addition, I show that the topological charge density contains a wave standing in the simulation box and present evidence for a physical phenomenon as well as hints in favor of a link to the (auto)correlation oscillations introduced by the HMC 1.

1 https://pos.sissa.it/430/045/pdf

Topical area:

Vacuum Structure and Confinement

Structure of Hadrons and Nuclei / 379

The parity-odd structure function of nucleon from Compton amplitude

Author: K. Utku Can[None]

Co-authors: Roger Horsley ; Yoshifumi Nakamura ; Holger Perlt ; Paul Rakow ; Gerrit Schierholz ; Hinnerk Stüben ; Ross Young ; James Zanotti

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The dominant contribution to the theoretical uncertainty in the extracted weak parameters of the Standard Model comes from the hadronic uncertainties in the electroweak boxes, i.e. $\gamma - W^{\pm}/Z$ exchange diagrams. A dispersive analysis relates the box diagrams to the parity-odd structure function, F_3, for which the experimental data either do not exist or belong to a separate isospin channel. Therefore a first-principles calculation of F_3 is highly desirable.

In this contribution, we report on the QCDSF/UKQCD Collaboration's progress in calculating the moments of the $F_3^{\gamma Z}$ structure function from the forward Compton amplitude at the SU(3) symmetric point. We extract the moments for a range of Q^2 values. A comparison to the Gross-Llewellyn Smith sum rule is given. Additionally, we estimate the power corrections by studying the Q^2 dependence of the moments.

Topical area:

Structure of Hadrons and Nuclei

Algorithms and Artificial Intelligence / 380

Tuning HMC parameters with gradients

Author: James Osborn[1]

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We will investigate the effectiveness of tuning HMC parameters using information from the gradients of the HMC acceptance probability with respect to the parameters. In particular, the optimization of the

trajectory length and parameters for higher order integrators will be studied in the context of pure gauge and dynamical fermion actions.

Topical area:

Algorithms and Artificial Intelligence

Hadronic and Nuclear Spectrum and Interactions / 381

Quark masses and low energy constants in the continuum from the tadpole improved clover ensembles

Authors: Zhicheng Hu[None]; Bolun Hu[None]; Jihao Wang[None]; Ming Gong[None]; Liuming Liu[None]; Peng Sun[None]; Wei Sun[None]; Wei Wang[None]; Yibo Yang[None]

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We present a study of lattice quantum chromodynamics (QCD) calculations in 2+1 flavor full QCD ensembles with the stout smeared clover fermion action and Symanzik gauge action, at three lattice spacings in the range of a ∈ [0.05, 0.11] fm, three volume size and three pion masses down to the physical one. We determine lattice spacings by applying Wilson flow to all 11 ensembles, which is essential for comparing lattice results with experimental data. We conduct a joint fit of pion two-point correlation function, the partially conserved axial current (PCAC) relation, and a ratio of two two-point correlation functions for each valance quark mass in each ensemble, incorporating proper renormalization constants. Pion masses, quark masses, and decay constants are then extracted across ensembles. A global fit of squared pion masses (m2π) and pion decay constants (Fπ) across various quark masses according to next-to-leading order (NLO) partially quenched chiral perturbation theory equations is conducted, yielding the pion decay constant in the chiral limit, the chiral condensate, and a set of low-energy constants. Extrapolating to infinite volume and zero lattice spacing limits, our results show a light quark mass of mud = 3.375(79) MeV, considering the physical pion mass of 134.98 MeV. This result agrees with the FLAG 2019 average value for 2+1 flavor mud = 3.364(41) MeV. This study offers a detailed and precise determination of quark masses and will serve as the foundation of future study of these ensembles, enhancing our understanding of hadronic physics and the Standard Model.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Structure of Hadrons and Nuclei / 382

Flavour-breaking effecting in the Hyperon charges

Author: James Zanotti[1]

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We present results from the QCDSF/UKQCD/CSSM collaboration for the charges g_T, g_A and g_S of the baryon octet, obtained through the use of Feynman-Hellmann techniques. We use a flavour symmetry breaking method to systematically approach the physical quark mass using ensembles that span five lattice spacings and multiple volumes. We extend this existing flavour breaking expansion to also account for lattice spacing and finite volume effects in order to quantify all systematic uncertainties.

Topical area:

Structure of Hadrons and Nuclei

QCD at Non-zero Density / 384

The magnetized Gross-Neveu model at finite chemical potential

Author: Michael Mandl[None]

Co-authors: Julian Lenz [1]; Andreas Wipf

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Relativistic fermionic theories with four-Fermi interactions have a broad range of applications, e.g., as toy models for QCD as well as in condensed-matter physics. We study the simplest such theory, the so-called Gross-Neveu model, exposed to a background magnetic field in 2+1 dimensions. In the mean-field limit the model exhibits a rich phase structure when the magnetic field and the chemical potential are both non-zero. We investigate the phase diagram of the full (i.e., beyond-mean-field) Gross-Neveu model on the lattice, using overlap fermions, and find that it is much simpler than in the mean-field limit.

Topical area:

QCD at Non-zero Density

Quark and Lepton Flavor Physics / 385

A strategy for B-physics observables in the continuum limit

Authors: Alessandro Conigli[1]; Rainer Sommer[2]; Antoine Gérardin[None]; Carlos Pena[1]; Gregorio Herdoiza[3]; Hubert Simma[None]; Julien Frison[4]; Patrick Fritzsch[None]; Simon Kuberski[5]

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In a not well known paper [JHEP01(2008)076] it was shown how to perform interpolations between relativistic and static computations in order to obtain results for heavy-light observables for masses from (say) m_{charm} to m_{bottom}. All quantities are first continuum extrapolated and then interpolated in $1/m = 1/m_{\mathrm{heavy}}$. Large volume computations are combined with finite volume ones where a relativistic bottom quark is accessible with small am. We discuss how this strategy is extended to semileptonic form factors and other quantities of phenomenological interest. The essential point is to form quantities which cancel all $alpha_s(m)^(n+\gamma)$ perturbative corrections to large mass scaling. We also point out how such an approach can help to control systematics in semileptonic decays with just large volume data. First numerical results with $N_f = 2 + 1$ and lattice spacings down to 0.039 fm are presented in a companion talk.

Topical area:

Standard Model Parameters

Plenary session / 386

Speed of sound exceeding the conformal bound in dense 2-color QCD

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Plenary session / 387

Lattice quantum field theories beyond the Standard Model

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Plenary session / 388

Exascale computing panel

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Topical area:

Plenary session / 389

Future Lattice announcements

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Topical area:

Plenary session / 390

Muon g−2: Status of the Fermilab experiment and of the dispersive approach

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Plenary session / 391

Muon g-2: Lattice calculations of the hadronic vacuum polarization

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Plenary session / 393

Introducing the Lattice Virtual Academy (LaVA)

Author: Claudio Bonanno[1]

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Topical area:

Hadronic and Nuclear Spectrum and Interactions / 394

Isospin-$\frac{1}{2}$, $\frac{3}{2}$ $D^{(*)}\pi$ scattering and the D_0^* resonance

Authors: Chuan Liu[1]; Haobo Yan[1]; Hanyang Xing[None]; Liuming Liu[None]

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We present preliminary results of lattice QCD calculations for $D\pi$ scattering with isospin-$\frac{1}{2}$ and $\frac{3}{2}$. Using newly generated $N_f = 2+1$ Wilson-Clover configurations by the CLQCD collaboration, we examine two volume extents ($L^3 \times T = 32^3 \times 96$ and $48^3 \times 96$) at the same lattice spacing ($a = 0.080$ fm) with a pion mass of $m_\pi \approx 290$ MeV. Employing various operators in both the rest and the moving frame, we determine S-wave scattering phase shifts from finite-volume spectra, assuming negligible contributions from higher partial waves. We identify a virtual state associated with the D_0^* in these ensembles. Ongoing investigations aim to determine higher partial waves and explore the m_π dependence and the continuum limit.

Topical area:

Hadronic and Nuclear Spectrum and Interactions

Particle Physics Beyond the Standard Model / 395

The infinite volume based beta-function from the gradient flow with applications

Author: Julius Kuti[1]

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The origin of the infinite volume based beta-function from the gradient flow is discussed with its technical implementations. Recent applications include the new beta function with ten massless fermion flavors in the SU(3) color representation and the new effort to calculate with high precision the QCD running coupling at the Z~pole.

Topical area:

Particle Physics Beyond the Standard Model

Particle Physics Beyond the Standard Model / 396

Dynamical dark energy from lattice quantum gravity

Author: Jack Laiho[1]

[1] *Syracuse University*

Euclidean Dynamical Triangulation (EDT) is a lattice approach to quantum gravity that has produced results compatible with semiclassical gravity in four dimensions. Although the lattice gravity calculations are broadly consistent with an emergent four-dimensional de Sitter space geometry, the calculations give corrections to a purely constant cosmological constant term. These corrections are well described by a simple model for running vacuum energy. A determination of the parameters of the model from the lattice is presented, along with a discussion of the implications for cosmology.

Topical area:

Particle Physics Beyond the Standard Model

Poster session / 397

Constrained curve fitting with Bayesian neural networks

Author: Curtis Peterson[1]

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Common to many analysis pipelines in lattice field theory is the need to fit data to a model that is determined partially by a finite number of model parameters. Familiar examples include analyses of finite-size scaling and ground state spectroscopy. We propose a Bayesian fit method that utilizes a neural network to approximate the component of such models that is a priori unknown. The viability of our method is tested on a number of finite-size scaling problems with increasing complexity.

Topical area:

Structure of Hadrons and Nuclei / 398

Collins-Soper kernel from lattice QCD at the physical pion mass

Author: Artur Avkhadiev[1]

Co-authors: Michael Wagman [2]; Phiala Shanahan [3]; Yong Zhao [4]

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This work presents a determination of the quark Collins-Soper kernel, which relates transverse-momentum-dependent parton distributions (TMDs) at different rapidity scales, using lattice quantum chromodynamics (QCD). This is the first lattice QCD calculation of the kernel at quark masses corresponding to a close-to-physical value of the pion mass, with next-to-next-leading logarithmic matching to TMDs from the corresponding lattice-calculable distributions, and includes a complete analysis of systematic uncertainties arising from operator mixing. The kernel is extracted at transverse momentum scales $240\,\text{MeV} <\sim q_T <\sim 1.6\,\text{GeV}$ with a precision sufficient to begin to discriminate between different phenomenological models in the non-perturbative region.

Topical area:

Poster session / 399

AdS/CFT Correspondence for Scalar Field Theory in Lattice AdS$_2$, AdS$_3$

Author: Cameron Cogburn[None]

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We use a regular tessellation of AdS$_2$ based on the (2,3,7) triangle group, with an extension to Euclidean AdS$_3$, to study the AdS/CFT correspondence. Perturbative calculations are verified and initial tests of monte carlo calculations for non-perturbative ^{4} theory exhibit critical phenomena on the boundary.

Topical area:

Poster session / 400

LDIC Survey 2023: Feeling Welcome in the Community

Authors: Bipasha Chakraborty[1]; Christopher Aubin[2]; Finn Stokes[None]; Liuming Liu[None]; Luigi Del Debbio[3]; Nilmani Mathur[4]; Sofie Martins[5]; Tereza Mendes[None]; William Detmold[6]

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We review the level of welcomeness that members of the lattice field theory community feel based on the results of a survey performed in May and June 2023. While respondents reported generally high levels of feeling welcome at the lattice conference, women and people with diverse gender identities, sexual orientations, ethnic backgrounds and religious affiliations feel less included and have more negative experiences at the lattice conference than their peers. Respondents report that they are actively informing themselves about inequities in the community, however a large fraction of survey participants underestimate the severity of the problem, as was found in previous surveys. The survey data indicate that this situation can be most effectively improved by organizing talks and events about issues of diversity and inclusion within the lattice community. Respondents also reported that individual readings of scientific papers on equity and inclusion are effective in giving people agency in making a change and hence it may be helpful to collate a collection of important articles on these topics.