36th Annual International Symposium on Lattice Field Theory

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Book of Abstracts

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From FRIB to Lattice QCD

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The Facility for Rare Isotope Beams (FRIB) is a DOE national user facility being built at Michigan State University that will be a world leader in rare nuclear isotopes. The first part of the talk is an overview of the design and current status of the facility. The second part discusses the impact of FRIB on nuclear science, astrophysics, fundamental symmetries, and societal applications. The last part of the talk explores opportunities for lattice QCD theorists to contribute to new discoveries at FRIB.

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Lattice QCD and Nuclear Physics for BSM searches

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Low-energy tests of fundamental symmetries are extremely sensitive probes of physics beyond the Standard Model (SM), reaching scales that are comparable, if not higher, than directly accessible at the energy frontier. The interpretation of low-energy precision experiments and their connection with models of BSM physics relies on controlling the theoretical uncertainties induced by the non-perturbative nature of QCD at low energy and of the nuclear interactions.
In this talk I will discuss how the interplay of Lattice QCD and nuclear Effective Field Theories can lead to improved predictions for low-energy experiments, with controlled uncertainties. I will review recent progress in the calculation of the nucleon electric dipole moment (EDM) and of time-reversal-violating pion-nucleon couplings, and the implications for nuclear EDM experiments. I will then discuss open problems in the theory of neutrinoless double beta decay, and the important role that lattice QCD calculations in the two-nucleon sector can play to resolve these issues.

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Progress in Two-Nucleon Spectroscopy

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Anchoring the nuclear interaction in QCD is a long-outstanding problem in nuclear physics. While the lattice community has made enormous progress in mesonic physics and single nucleon physics, continuum-limit physical-point multi-nucleon physics has remained out of reach. I will review CalLat's strategy for multi-nucleon spectroscopy and our latest results.

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QCD at non-zero density and phenomenology

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In the last few years, numerical simulations of QCD on the lattice have reached a new level of accuracy. A wide range of thermodynamic quantities is now available in the continuum limit and for physical quark masses. This allows a comparison with measurements from heavy ion collisions for the first time. I will review the state-of-the-art results from lattice simulations of QCD thermodynamics and connect them to experimental measurements from RHIC and the LHC.

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Complex Langevin for Lattice QCD

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We are applying complex-Langevin simulations to lattice QCD at finite quark-number chemical potential μ and zero temperature. While we observe some improvement as we move to weaker coupling we only find agreement with the expected physics at very small and at large μ. It has been observed by others that at least part of the problem is that at small and even zero μ the gauge fields show large departures from the $SU(3)$ manifold. We are therefore quantifying how these departures depend on the size of the gauge coupling and the quark mass. It appears that these departures decrease as we move to weaker couplings and to smaller quark masses. One might ask whether this means that the complex Langevin will produce correct results in the continuum limit.
We are also extending our simulations to finite μ and temperature where it is believed that the complex Langevin should be better behaved.

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Can the complex Langevin method see the deconfinement phase transition in QCD at finite density?

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Exploring the phase diagram of QCD at finite density is a challenging problem since first-principle calculations based on standard Monte Carlo methods suffer from the sign problem. As a promising approach to this issue, the complex Langevin method (CLM) has been pursued intensively.
In this talk, we investigate the applicability of the CLM in the vicinity of the deconfinement phase transition using the four-flavor staggered fermions. A previous study on a $16^3 \times 8$ lattice showed that the CLM fails at $\beta < 5.15$ due to the excursion problem, which made the transition to the confined phase inaccessible. In this study, we employ a lattice with larger temporal size in order to make the CLM work at lower temperature. In particular, we investigate the β-dependence of the chiral condensate to look for a hysteresis which signals the expected first order phase transition.

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Stabilising complex Langevin simulations

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We present results of our technique of dynamic stabilisation (DS) applied to complex Langevin simulations of QCD in the heavy-dense limit and with staggered quarks. We show that DS is able to keep simulations stable, providing results compatible with Monte-Carlo simulations, where the latter is applicable.

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Exploring the phase diagram of finite density QCD at low temperature by the complex Langevin method

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Monte Carlo studies of QCD at finite density suffer from the notorious sign problem, which becomes easily uncontrollable as the chemical potential increases for a moderate lattice size. In this work, we attempt to approach the high density low temperature region by the complex Langevin method (CLM). Simulations are performed on an 8^3 x 16 lattice using four-flavor staggered fermions with reasonably small quark mass. Unlike previous work with a 4^3 x 8 lattice, the criterion for correct convergence is satisfied in the nuclear matter phase without using the deformation technique. In this phase the baryon number density has a plateau with respect to the chemical potential, and it starts to grow rapidly at some point.

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Investigating the Phase Structure of Large N Unitary Matrix Models using Complex Langevin Method

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Using complex Langevin method we examine the phase structure of complex unitary matrix models and compare the numerical results with analytic results found at large number of colors. The actions we consider are manifestly complex, and thus the dominant contributions to the path integral comes from the space of complexified gauge field configurations. For this reason, the eigenvalues of unitary matrices lie off the unit circle and explore out in the complex plane. One example of a complex unitary matrix model, with Polyakov line as the unitary matrix, is an effective description of a QCD at finite density and temperature, with finite number of colors and quark flavors, defined on a compact manifold. A distinct feature of this model, the occurrence of a series of Gross-Witten-Wadia transitions, as a function of the quark chemical potential, is reproduced using complex Langevin dynamics. We simulate several other observables including Polyakov lines and quark number density, for large number of colors and quark flavors, and found excellent match with the analytic results.

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Fourier acceleration, the HMC algorithm and renormalizability

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The analysis of the Hybrid Monte Carlo (HMC) algorithm developed by Luscher and Schaefer is generalized to include Fourier acceleration. We show for the ϕ^4 theory examined by Luscher and Schaefer that Fourier acceleration removes the non-renormalizable, singular behavior which they discovered and likely defines a renormalizable theory for the five-dimensional correlation functions in Euclidean space and Monte Carlo time.

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Testing a new gauge-fixed Fourier acceleration algorithm

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In hybrid Monte Carlo evolution, by imposing a physical gauge condition, simple Fourier acceleration can be used to generate conjugate momenta and potentially reduce critical slowing down. This modified gauge evolution algorithm does not change the gauge-independent properties of the resulting gauge field configurations. We describe this algorithm and present results from our first numerical experiments

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Ensemble Quasi-Newton HMC

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We present a modification of the hybrid Monte Carlo algorithm for tackling the critical slowing down of generating Markov chains of lattice gauge configurations towards the continuum limit. We propose a new method to exchange information between an ensemble of Markov Chains, and use it to construct an approximate inverse Hessian matrix of the action inspired from Quasi-Newton algorithms for optimization. The kinetic term of the molecular dynamic evolution includes the approximate Hessian for long distance couplings among the momenta. We will show the result of applying the new algorithm to the U(1) gauge theory in two dimensions, and discuss our future plans.

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Multilevel integration for meson propagators

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The computation of hadronic correlation functions in lattice QCD is severely hindered by a signal-to-noise ratio that exponentially decreases with the distance between source and sink. Recent developments for the factorization of both the fermion propagator and the fermion determinant pave the way for the implementation of multilevel Monte Carlo integration techniques, which are already known to provide a solution to this problem in pure gauge theory. In this talk, we discuss a novel strategy to compute the leading factorized contribution to connected meson propagators based on noise sources. Finally, results for vector and scalar meson propagators obtained using this technique will be presented and their numerical effectiveness will be compared to that of a standard Monte Carlo simulation.

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Multilevel integration for meson propagators: disconnected contributions

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We combine multi-level integration with a variance-reduction technique for the stochastic estimate of disconnected diagrams of various bilinear operators, and present preliminary numerical results with O(a)-improved Wilson fermions.

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Light-cone PDFs from lattice QCD

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Using the approach proposed a few years ago by X. Ji, it has become feasible to extract parton distribution functions (PDFs) from lattice QCD, a task thought to be practically impossible before Ji's proposal. In this talk, we discuss the recent progress in this approach concerning renormalization and matching and we set the stage for the following talk where results by the ETM Collaboration are presented at the physical pion mass. We also discuss the role of excited states in these computations and other systematic effects that need to be controlled to ultimately have precise determinations of PDFs.

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Quasi-PDFs from Twisted mass fermions at the physical point

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Parton distribution functions (PDFs) provide a detailed description of hadron structure and are crucial inputs in analyses of collider data. PDFs have a non-perturbative nature and Lattice QCD provides an appropriate framework of their extraction. We present results on the iso-vector quasi-quark distribution functions using an ensemble of $N_f = 2$ degenerate light quarks in the twisted mass formulation, with pion mass 130MeV, lattice spacing a=0.093 fm and lattice size $48^3 \times 96$. We discuss the non-perturbative renormalization procedure and the matching to light-cone PDFs. An overlap between lattice and phenomenological data is found for a range of Bjorken-x values.

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Matching the quasi parton distribution in a momentum subtraction scheme

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The quasi parton distribution (quasi-PDF) is an equal-time correlation of quarks along the direction the nucleon is moving at. At large but finite nucleon momentum, the quasi parton distribution can be perturbatively matched to the PDF through a factorization formula in large momentum effective theory. Following a nonperturbative renormalization of the quasi parton distribution in a regularization independent momentum subtraction scheme, we establish its matching to the MSbar PDF and calculate the non-singlet matching coefficient at next-to-leading order in perturbation theory.

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Excited state analysis in the quasi-PDF matrix elements

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The momentum smearing technique opens a new window on the lattice simulation with the large hadron momentum, while the good signals are still limited to the data with small source-sink separations. Thus whether the systematic uncertainties from the excited state contaminations can be under control with the those small separations, will be crucial for the hadron matrix element calculation in the moving frame. We will show our investigations on this topic with the quasi-PDF matrix elements.

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Lattice Calculation of Parton Distribution Function from LaMET

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We present a lattice-QCD calculation of the isovector parton distribution function (PDF) within the framework of large-momentum effective theory (LaMET). We detail the systematics that affect PDF calculations, providing guidelines to improve the precision of future lattice PDF calculations. We find our final parton distribution to be in reasonable agreement with the PDF provided by the latest phenomenological analysis.

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Neutron-antineutron oscillations from Lattice QCD at the physical point

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Fundamental symmetry tests of baryon number violation in low-energy experiments can test beyond the Standard Model explanations of the matter-antimatter asymmetry of the universe. Neutron-antineutron oscillations are predicted to be a signature of many baryogenesis mechanisms involving low-scale baryon number violation. This work presents the first complete lattice quantum chromodynamics calculation of the six-quark matrix elements needed to connect experimental

measurements of the neutron-antineutron oscillation time to constraints on beyond the Standard Model theories. Physical pion masses are used and non-perturbative renormalization is included.

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Proton decay matrix element on lattice at physical pion mass

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Proton decay is one of possible signatures of baryon number violation, which has to exist to explain the baryon asymmetry and the existence of nuclear matter. Proton decays must be mediated through effective low-energy baryon number violating operators made of three quarks and a lepton. We calculate matrix elements of these operators between an initial proton and various final pseudoscalar mesons using the three-point function method. For the first time, we use the 2+1 dynamical flavor domain wall fermions at the physical point for the calculation over the three source-sink separations.

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nEDM from BSM

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I will present an update on our calculations of nEDM due to the quark and gluon chromo-EDM operators, as well as the QCD Theta-term with which these mix. The calculations are being done by extrapolating to zero momentum transfer the F3 form factor of a vector current calculated using valence and disconnected Wilson-clover quarks on HISQ background configurations generate by the MILC collaboration.

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Non-perturbative generation of elementary fermion mass: a numerical study

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In this talk we present a numerical lattice study of a SU(3) gauge model where a SU(2) doublet of non-Abelian strongly interacting fermions is coupled to a complex scalar field doublet via a Yukawa and a Wilson-like term. Despite the presence of these two chiral breaking operators in the Lagrangian, the model enjoys an exact symmetry, acting on all fields, which prevents UV power divergent fermion mass corrections. In the phase where the scalar potential is non-degenerate and fermions are massless the bare Yukawa coupling can be set at a critical value at which

chiral fermion transformations become symmetries of the theory. Numerical simulations in the Nambu-Goldstone phase of the critical theory, for which the renormalized Yukawa coupling by construction vanishes, give evidence for non-perturbative generation of a UV finite fermion mass term in the low energy effective action.

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Towards models with an unified dynamical mechanism for elementary particle masses

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Numerical evidence for a new dynamical mechanism of elementary particle mass generation has been found by lattice simulation in a simplified SU(3) gauge model where a SU(2) doublet of strongly interacting fermions is coupled to a complex scalar field doublet via a Yukawa and a Wilson-like term. We point out that if, as a next step towards the construction of a realistic beyond-the-Standard-Model model, weak interactions are introduced, then also weak bosons get a mass by the very same non-perturbative mechanism. In this scenario (fermion) mass hierarchy can be naturally understood owing to the peculiar gauge coupling dependence of the non-perturbatively generated masses. As a consequence, if one wants to get the top-quark (or the weak bosons) mass at its phenomenological value, the RGI scale of the theory must be much larger than Λ_{QCD}. This feature hints at the existence of new strong interactions and particles at a scale Λ_T of a few TeV. In such a speculative framework the electroweak scale can be derived from the fundamental scale Λ_T and the Higgs boson should arise a bound state in the WW+ZZ channel.

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Taking the continuum limit in Lattice Quantum Gravity

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We present a study of the relative lattice spacing of different ensembles in the Euclidean dynamical triangulations approach to quantum gravity. We study the quantum fluctuations of the semiclassical backgrounds about de Sitter space following a similar analysis in causal dynamical triangulations and show how this can be used to determine the relative lattice spacing in our analysis. The agreement between this determination of the relative lattice spacing and that coming from a diffusion process lends support to the quantum gravity interpretation of our lattice formulation.

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Curvature Correlators in Lattice Quantum Gravity

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We study the curvature-curvature correlator for quantum gravity in the case of degenerate Euclidean Dynamical Triangulations, drawing on recent insights to modify the procedure for calculating connected correlation functions to reduce finite size effects. We find asymptotically a positive norm state, and a decay consistent with a power law, but cannot yet resolve what this power is in the continuum limit. Preliminary results suggest a power possibly consistent with our expectations for gravity.

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Lattice quantum gravity with scalar fields

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We consider the lattice gravity model based on Euclidean dynamical triangulations incorporating degenerate tiling with a non-trivial measure term and couple it minimally to a scalar field in the quenched approximation. Our preliminary results suggest a multiplicative renormalization for the mass of the scalar field which is consistent with the shift symmetry of the discretized lattice action. We discuss the possibility of measuring mass anomalous dimension and gravitational binding energy between two scalar test particles and argue that negative energy of the bound state would imply that this model can potentially represent gravitational attraction.

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U(1) vacuum, Chern-Simons diffusion and real-time simulations

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Non-abelian gauge theories have a complex vacuum structure which has well-known dynamical consequences. The prototypical example is given by $SU(2)$ sphalerons and their potential role in baryogenesis. Transitions between topologically inequivalent vacua can produce some irreversible net amount of chiral charge.
At a first glance, it does not seem that similar effects may be obtained with Abelian fields as they have a topologically non-degenerate vacuum. Looking more closely, one may realise that the addition of a background magnetic field changes the picture.
The aim of this talk is to present an investigation of such systems based on real-time simulations. In particular, we will give some context by presenting the numerical set up, before discussing results on the U(1) Chern-Simons diffusion rate in a constant magnetic background. We will also discuss the evolution of the chiral chemical potential.

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Renormalization on the fuzzy sphere

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We study renormalization on the fuzzy sphere. We perform Monte Carlo simulation of a scalar field theory on the fuzzy sphere, which is described by a Hermitian matrix model. We show that

correlation functions defined by using the Berezin symbol are made independent of the matrix size, which plays a role of a UV cutoff, by tuning a parameter of the theory. We also find that the theories on the phase boundary are universal. They behave as a conformal field theory at short distances, while they show an effect of the UV/IR mixing at long distances.

Vacuum Structure and Confinement / 184

Lattice Computation of the Ghost Propagator in Linear Covariant Gauges

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We discuss the subtleties concerning the lattice computation of the ghost propagator in linear covariant gauges, and present preliminary numerical results.

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Spatial structure of the color field in the SU(3) flux tube

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We report on the chromoelectric and chromomagnetic fields generated by a static quark-antiquark pair at zero temperature in pure gauge SU(3). From the spatial structure of chromoelectric field we extract its nonperturbative part and discuss its properties.

Vacuum Structure and Confinement / 30

Confinement of quarks in higher representations in view of dual superconductivity.

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Dual superconductor picture is a promising scenario for quark confinement. For quarks in the fundamental representation, we have presented a new formulation of Yang-Mills theory on the lattice, where decomposed restricted fields play the dominant role in confinement, and

demonstrated numerical evidences for the dual superconductivity. To establish this picture, we must show evidences for various situations, e.g., for quarks in higher representations.
In this talk, we investigate the Wilson loops in higher representations. By virtue of the non-Abelian Stokes theorem, we propose the suitable Wilson loop operator made of the restricted field in the fundamental representation, so that it reproduces the correct behavior of the original Wilson loop in the higher representation. We perform lattice simulations to measure the static quark potential using the Wilson loop operator in higher representations. We find that our proposed Wilson loop operators reproduce the correct behavior of the original Wilson loop average and overcome the problem that occurs in the naively Abelian-projected Wilson loop operator for higher representations.

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Linear confinement and stress-energy tensor around static quark and anti-quark pair – Lattice simulation with Yang-Mills gradient flow –

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We study the spatial distribution of the stress tensor around static quark-anti-quark pair in SU(3) lattice gauge theory. In particular, we reveal the transverse structure of the stress tensor distribution in detail by taking the continuum limit. The Yang-Mills gradient flow plays a crucial role to make the stress tensor well-defined and derivable from the numerical simulations on the lattice [1].
[1] R. Yanagihara et al., arXiv:1803.05656.

Algorithms and Machines / 256

Solving Domain Wall Dirac Equation Using Multisplitting Preconditioned Conjugate Gradient

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We show that using the multisplitting algorithm as a preconditioner for the conjugate gradient inversion of domain wall fermion Dirac operators effectively reduces the inter-node communication cost, at the expense of performing more on-node floating point operations. Compared to Schwarz domain decomposition solver algorithms our approach enforces Dirichlet boundary conditions consistently on the normal preconditioned operator. This method would be useful for lattice Monte Carlo evolutions on supercomputers with far more on-node flops than inter-node communication bandwidth.

Algorithms and Machines / 190

Communication-avoiding optimization methods for fermion matrix inverters

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The global all-to-all communications in the Krylov subspace iterative methods is one of the major performance-limiting factors on large-scale parallel machines. In this report we give a brief overview of recent algorithmic approaches to mitigate communication cost in the iterative solvers. We present several variants of communication-optimized fermion matrix inverters implemented in the QUDA library. Finally, we will discuss a few possible scenarios of utilizing exascale-ready algorithms from the Trilinos framework for LQCD applications.

Algorithms and Machines / 312

Multigrid for Wilson Clover Fermions in Grid

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With the ever-growing number of computing architectures, performance portability is an important aspect of (Lattice QCD) software. The Grid library provides a good framework for writing such code, as it thoroughly separates hardware-specific code from algorithmic functionality and already supports many modern architectures. The Regensburg group (RQCD) decided to deprecate its Xeon Phi version of the DD-αAMG multigrid solver and implement this algorithm in Grid. We describe our implementation, review the coding efforts, and summarize our experiences with the Grid library. We present the solver's features and compare its performance with other multigrid implementations.

Algorithms and Machines / 46

Three Dirac operators on two architectures

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A simple minded approach to implement three discretizations of the Dirac operator (Brillouin, Wilson, staggered) on two architectures (KNL and core_i7) is presented. The idea is to use a high-level compiler along with OpenMP parallelization and SIMD pragmas, but to stay away from cache-line optimization and/or assembly-tuning. The implementation is for Nv right-hand-sides, and this extra index is used to fill the SIMD pipeline. On one KNL node single precision performance figures for Nc=3, Nv=12 read 640 Gflop/s, 320 Gflop/s, and 520 Gflop/s for the three discretization schemes, respectively.

Nonzero Temperature and Density / 103

Towards Lefschetz thimbles regularization of heavy-dense QCD

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At finite density, lattice simulations are hindered by the well-known sign problem: for finite chemical potentials, the QCD action becomes complex and the Boltzmann weight e^-S cannot be interpreted as a probability distribution to determine expectation values by Monte Carlo techniques. Different workarounds have been devised to study the QCD phase diagram, but their application is mostly limited to the region of small chemical potentials. The Lefschetz thimbles method takes a new approach in which one complexifies the theory and deforms the integration paths. By integrating over Lefschetz thimbles,the imaginary part of the action is kept constant and can be factored out, while eˆ-Re(S) can be interpreted as a probability measure. The method has been applied in recent years to more or less difficult problems. Here we report preliminary results on Lefschetz thimbles regularization of heavy-dense QCD. While still simple, this is a very interesting problem. It is a first look at thimbles for QCD, although in a simplified, effective version. From an algorithmic point of view, it is a nice ground to test effectiveness of techniques we developed for multi thimbles simulations.

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Beyond Thimbles: Sign-Optimized Manifolds for Finite Density

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Fermionic field theories at finite density suffer from a sign problem, making lattice calculations exponentially expensive in the volume. This sign problem can be reduced or eliminated by complexifying configuration space, and integrating over a contour deformed from the real plane. We present an algorithm for determining integration contours with reduced sign problems. We give results from this algorithm for both 1+1 and 2+1 dimensional field theories at finite density.

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Deforming Path Integration Contours: Application to Finite Density Thirring Model

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Systems of fermions at finite density have complex Boltzmann weights which cause the integrand of the path integral to be highly oscillatory. As a result of these oscillations, standard integration methods require exponential precision in the spacetime volume to compute observables. However, deforming the path integration contour to a manifold which approximates a set of Lefschetz Thimbles tames phase oscillations while leaving physical observables invariant. I will describe this deformation procedure, which is achieved with the holomorphic gradient flow, then apply it to the Finite Density Thirring Model, which is a system with a sufficiently bad sign problem that standard methods fail.

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Flowing Gauge Theories: Finite-Density QED_{1+1}

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Finite-density calculations in lattice field theory are typically plagued by sign problems. A promising way to ameliorate this issue is the so-called “holomorphic flow” equations that deform the manifold of integration for the path integral to manifolds in the complex space where the

sign fluctuations are less dramatic. In this talk, We will discuss some novel features of applying the flow equations to gauge theories and present results for finite-density QED_{1+1}.

Hadron Structure / 216

Progress on parton pseudo distributions I

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In this presentation we will show theoretical developments that facilitate the better reconstruction of light cone parton distributions starting from reduced Ioffe time pseudo distributions calculated on the lattice. We also present our new results of parton distributions for the nucleon and pion from an $N_f = 2 + 1$ simulation of Wilson-clover fermions with stout smearing and tree-level tadpole improved Symanzik gauge action at two different lattice spacings. This is the first of two consecutive talks on the subject.

Hadron Structure / 272

Progress on parton pseudo distributions II

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In this presentation we will show theoretical developments that facilitate the better reconstruction of light cone parton distributions starting from reduced Ioffe time pseudo distributions calculated on the lattice. We also present our new results of parton distributions for the nucleon and pion from an $N_f = 2 + 1$ simulation of Wilson-clover fermions with stout smearing and tree-level tadpole improved Symanzik gauge action at two different lattice spacings. This is the second of two consecutive talks on the subject.

Hadron Structure / 84

Lattice QCD calculation of the nucleon hadronic tensor

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We report preliminary results on the lattice calculation of the hadronic tensor of the nucleon. Two topologically distinct connected-insertions of the Euclidean 4-point function are considered which helps to separate the connected-sea parton contribution from that of the valence. Converting the Euclidean hadronic tensor to that in the Minkowski space, which involves an inverse problem in a Laplace transform, is implemented through the maximum entropy method.

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Nucleon Structure Functions from the Feynman-Hellmann Theorem

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Better model-independent theoretical predictions and input to parton distribution functions are vital to improving our understanding of how the nucleon is formed by quarks and gluons. By using a second order extension of the Feynman-Hellmann theorem we examine the nucleon Compton form factor $F_1(\omega, Q^2)$ without the need for calculations of four-point correlators. The calculation is performed for multiple lattice spacings, volumes and a large range of Q^2 up to $9GeV^2$, allowing examination of lattice artefacts and higher twist contributions.

Hadron Spectroscopy and Interactions / 319

Gluonic structure of spin-1 meson as it becomes unstable using variationally optimized operators

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We present a first calculation of the first moments of gluon GPDs for a vector rho meson as it becomes unstable. We construct three-point functions in the forward limit using 'optimized' operators that interpolate a single state as well as a gluonic operator insertion. The two-point correlation functions have been constructed using the 'distillation' method. The correlators are calculated in anisotropic lattices and the two spin-independent and one transversity gluon distributions are extracted. We compare the distributions and the resulting gluon momentum fractions between stable and unstable meson states. We discuss finite volume effects and outline how to apply our methods to probe the gluonic structure of hybrid and exotic states.

Hadron Spectroscopy and Interactions / 318

3-body quantization condition in unitary isobar formalism

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In the isobar parametrization the three-particle states are populated via an interacting two-particle system (resonant or non-resonant), and a spectator. Using this formulation, we derive the isobar-spectator amplitude such that the three-body Unitarity is ensured exactly (arXiv:1706.06118).

Unitarity constrains the imaginary parts of such an amplitude, which determine the power-law finite-volume effects to ensure the correct 3-body quantization condition. The derivation of the latter in the present formalism (arXiv:1709.08222) as well as its subsequent application for the determination of the finite-volume energy spectrum in realistic systems will be presented in this talk.

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The Slope of Form Factors from Lattice QCD

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We present an update on the direct position-space method for calculating slopes of from factors from lattice QCD.Momentum-space derivatives of matrix elements can be related to their coordinate-space moments through the Fourier transform. We derive these expressions as a function of momentum transfer Q^2 for asymptotic in/out states consisting of a single hadron. We calculate corrections to the finite volume moments by studying the spatial dependence of the lattice correlation functions. This method permits the computation of not only the values of matrix elements at momenta accessible on the lattice, but also the momentum-space derivatives, providing a priori information about the Q^2 dependence of form factors. As a specific application we use the method, at a single lattice spacing and with unphysically heavy quarks, to directly obtain the slope of the isovector form factor at various Q^2, whence the isovector charge radius. The method has potential application in the calculation of any hadronic matrix element with momentum transfer, including those relevant to hadronic weak decays.

Hadron Spectroscopy and Interactions / 42

Constraint HMC algorithms for gauge-Higgs models

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We present the construction of constraint HMC algorithms for gauge-Higgs models in order to measure the effective Higgs potential. In particular we focus on a SU(2) Gauge-Higgs Unification model on a 5D orbifold. Previous simulations have identified a region in the Higgs phase of this model which has properties of a 4D Abelian Higgs model. We want to test this relationship by comparing the effective potential in both models.

Plenary / 326

Recent Progress on the QCD Phase Diagram

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I will review the recent progress and results on the bulk thermodynamic properties of QCD matter from Lattice. In particular I will highlight the recent calculations of the equation of state, pressure of QCD matter to the finite baryon density regime as far as μ_B/T 2.5, giving us some preliminary bounds on the location of the critical end-point. I will also stress upon the fact that

Lattice techniques are now entering into precision era where it can provide us with new insights on even the microscopic degrees of freedom in different phases of QCD. I will discuss some instances from the recent studies of of topological fluctuations and screening masses. The progress in the understanding of transport properties of the QCD matter and the effects of anomalous $U_A(1)$ symmetry on the chiral crossover transition will also be discussed.

Plenary / 325

Hints and challenges in heavy flavor physics

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Heavy flavor physics has entered a new era when the Belle II experiment observed its first collision. There are several hints found so far by BaBar, Belle, and LHCb in particular, that suggest the physics beyond the Standard Model appearing in the loop processes at short distances. They will be further tested by higher precision experiments in the coming years. The role of lattice QCD is to understand the long-distance physics quantitatively so that one can unambiguously isolate the short- distance physics from the experimental data. I'll try to summarize the status towards this goal and then look at the challenges we are facing.

Plenary / 328

Precise determinations of quark masses

Dr. KOMIJANI, Javad[1]

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We discuss the determination of quark masses using the MILC highly improved staggered-quark ensembles with four flavors of dynamical quarks. We extract quark masses from heavy-light pseudoscalar meson masses by making use of heavy quark effective theory (HQET) and continuum-QCD perturbative calculations. While heavy-light meson masses can be measured very precisely on lattice, perturbative calculations typically suffer from large truncation errors resulting in large uncertainties in final results. We present the MRS scheme, in which heavy quark masses are free from renormalon ambiguities and any renormalization scales, and we discuss how the use of the MRS scheme, as an intermediate scheme, improves the precision in our calculations. Combining our analysis with our separate determination of ratios of light-quark masses we present masses of the up, down, strange, charm, and bottom quarks. The method employed in this work also yields the matrix elements of some operators arising in HQET. Finally, we discuss and compare our results with other lattice determinations of quark masses.

Plenary / 316

Progress and prospects of lattice supersymmetry

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Supersymmetry plays prominent roles in modern theoretical physics, as a tool to improve our understanding of quantum field theory, as an ingredient in many new physics models, and as a means to study quantum gravity via holographic duality. Lattice investigations of supersymmetric field theories have a long history but often struggle due to the interplay of supersymmetry with the discretization of spacetime. I will review several areas in which these difficulties have been overcome, allowing for significant progress in recent years, and discuss important challenges that still remain.

Plenary / 231

Review on Composite Higgs Models

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Composite Higgs Models explore the possibility that the Higgs boson is an excitation of a new strongly interacting sector giving rise to electro-weak symmetry breaking. After describing how this new sector can be embedded into the Standard Model of elementary particle physics meeting experimental constraints, I will review efforts by the community to explore the physics of this new strong interactions using methods of lattice field theory. Challenges in understanding the numerical results are discussed and an outlook is given on possible future directions allowing to confirm or reject the composite Higgs hypothesis.

Weak Decays and Matrix Elements / 300

Electric Dipole Moment Results from Lattice QCD

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We utilize the gradient flow to define and calculate electric dipole moments (EDMs) induced by the strong QCD θ-term. Since the EDM is highly sensitive to the CP-violating operator induced in the action, the Euclidean time dependence of the topological charge is utilized to improve the signal to noise.
The results of the nucleon EDMs are calculated on PACS-CS gauge fields (available from the ILDG) using $N_f = 2 + 1$. These gauge fields use a renormalization-group improved gauge action and a non-perturbatively $O(a)$ improved clover quark action.
The main calculation was performed on a $32^3 \times 64$ lattice with lattice spacing $a \simeq 0.09$ fm ($\beta = 1.90$), with pion masses of $m_\pi \simeq 411, 570, 701$ MeV to perform a chiral extrapolation (with $c_{SW} = 1.715$). A second set of calculations were performed with $a \simeq 0.1215, 0.0980, 0.0685$ fm at $L \approx 1.9$ fm for continuum limit studies.

Weak Decays and Matrix Elements / 149

Towards a determination of the quark-chromo EDM with the gradient flow

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The quark-chrom EDM (qCEDM) is a dimension 5 operator parametrizing at low energy BSM contributions to a non-vanishing EDM. We discuss the implementation of the qCEDM with the

gradient flow and show preliminary results for the flow-time dependence of the CP-violating mixing angle α_N induced by the qCEDM between nucleon states. These results are computed on the $N_f = 2+1$ coarse lattice $16^3 \times 32$ with lattice spacing ($a \simeq 0.1215 fm$). We use Wilson-clover fermion with $\kappa = 0.13825$ and $c_{SW} = 1.761$.

Weak Decays and Matrix Elements / 132

Scalar, Axial and Tensor Matrix elements in light nuclei

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I will discuss recent calculations of the matrix elements of scalar, axial and tensor quark bilinear operators in light nuclei at unphysically heavy values of the quark masses. Axial matrix elements control the Gamow-Teller decays of nuclei and have potential for precision tests of the Standard Model. Tensor matrix elements determine the quark chromo-electric dipole moment and are important in the context of proposed experiments to measure nuclear EDMs. Scalar matrix elements are important for interpretation of dark matter direct detection experiments. Our calculations provide a full flavour decomposition of the matrix elements in A=1,2,3 nucleon system. Nuclear effects are resolved in most channels, with axial and tensor matrix elements modified at the percent level from naive expectations. In contrast, the scalar matrix elements in the nuclei differ at the 10% level from scaling those of the nucleon. If these effects persist at the physical quark masses and for larger, experimentally practical nuclei, their phenomenological impact would be significant.

Weak Decays and Matrix Elements / 136

Nuclear Matrix Elements for Neutrinoless Double Beta Decay from Lattice QCD

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While neutrino oscillation experiments have demonstrated that neutrinos have small, nonzero masses, much remains unknown about their properties and decay modes. One potential decay mode — neutrinoless double beta decay ($0\nu\beta\beta$) — is a particularly interesting target of experimental searches, since its observation would imply both the violation of lepton number conservation in nature as well as the existence of at least one Majorana neutrino, in addition to giving further constraints on the neutrino masses. Relating experimental constraints on $0\nu\beta\beta$ decay rates to the neutrino masses, however, requires theoretical input in the form of non-perturbative nuclear matrix elements which remain difficult to calculate reliably. In this talk we will discuss the prospects for a first-principles calculation of the relevant nuclear matrix elements using lattice QCD and effective field theory techniques, assuming neutrinoless double beta decay mediated by a light Majorana neutrino. As a proof-of-principles we will show preliminary results from a lattice calculation of the related $\pi^- \to \pi^+ e^- e^-$ transition amplitude.

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Short Range Operator Contributions to neutrinoless double beta decay from LQCD

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A strong candidate to search for new physics Beyond the Standard Model is neutrinoless double beta decay. Observation of this very rare nuclear process which violates lepton number conservation, would imply the neutrino sector has a majorana mass component and may also provide an explanation for universe's matter-antimatter asymmetry. In the case a heavy majorana neutrino is exchanged in this process, QCD contributions from short range interactions may become relevant which involve the calculation of matrix elements with four-quark operators. In this talk I will discuss the current progress on the calculation of these four-quark operators from LQCD.

Hadron Structure / 35

Calculation of Pion Valence Distribution form Hadronic Lattice Cross Sections

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Recently, it has been shown that a class of coordinate-space-separated non-local hadronic matrix elements, computable directly in lattice QCD, can be factorized into parton distribution functions with calculable coefficients, in the same manner as the hadronic cross sections measured in an experiment [Phys.Rev.Lett. 120 (2018) no.2, 022003]. The pion and kaon, the lightest pseudo scalar mesons, provide an excellent theatre in which to explore these ideas. Furthermore, the pion is of inherent theoretical interest and plays a vital role in the understanding the nucleon and in nuclear structure. In this talk, we describe progress at understanding the valence quark distribution of the pion using configuration-space separated gauge-invariant hadronic currents.

Hadron Structure / 289

Structure of pion and kaon from lattice QCD

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Direct lattice computation of the key measures of hadron structure such as the form factors, parton distribution functions, quark distribution amplitudes have always been challenging. With current enormous experimental efforts at JLab (with its 12 GeV upgrade), COMPASS in CERN, RHIC-spin and at a future EIC, it is now crucial to test and exploit the newly proposed lattice QCD ideas in hadron structure which requires increasingly high momenta. In this talk, I will discuss our recent progresses in pion/kaon structure calculations using lattice QCD. In particular, I will describe our progress at understanding the valence quark distributions of the kaon using

configuration-space separated gauge-invariant hadronic currents following a recent theoretical development [Phys.Rev.Lett. 120 (2018) no.2, 022003]. I will also briefly discuss our alternative approach using method of distillation to reach higher moemnta in simpler hadronic quantities such as pion electromagnetic form factor.

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Kaon Distribution Amplitude from Lattice QCD and the Flavor SU(3) Symmetry

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We present the first lattice-QCD calculation of the kaon distribution amplitude using the large-momentum effective theory (LaMET) approach. The momentum-smearing technique has been implemented to improve signals at large meson momenta. We subtract the power divergence due to Wilson line to high precision using multiple lattice spacings. The kaon structure clearly shows an asymmetry of the distribution amplitude around $x = 1/2$, a clear sign of its skewness. We also study the leading SU(3) flavor symmetry breaking relations for the pion, kaon and eta meson distribution amplitudes, and the results are consistent with the prediction from chiral perturbation theory.

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Moments of pion distribution amplitude using OPE on the lattice

Dr. DETMOLD, William[1] ; Dr. KANAMORI, Issaku[2] ; Prof. LIN, C.-J. David[3] ; Dr. MONDAL, Santanu[3] ; Dr. ZHAO, Yong[4]

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We will show our calculation of the moments of pion distribution amplitude using a method proposed in Phys.Rev.D73:014501(2006) [hep-lat/0507007]. Since the method requires a fine lattice, it becomes practical only recently. The procedure is based on calculating the suitable, bilocal current-current products sandwiched between a pion state and vacuum on the lattice. Then the lattice calculations of these quantities can be matched with the formulae obtained by using Euclidean operator product expansion (OPE), to calculate moments. Use of a fictitious, valance heavy quark facilitates the calculation in a number of ways. Our exploratory numerical result shows opportunities to overcome difficulties in operator mixing and renormalisation that the traditional method suffers from.

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Pion Distribution Amplitude from lattice QCD: towards the continuum limit

Dr. KORCYL, Piotr[1] ; Dr. WEIN, Philipp[2] ; Mr. HUTZLER, Fabian[3] ; Mr. GRUBER, Michael[3]

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We present the current status of a non-perturbative lattice calculation of the pion distribution amplitude by the RQCD collaboration. Our investigation is carried out using $N_f = 2{+}1$ dynamical, non-perturbatively O(a)-improved Wilson fermions on the CLS ensembles with 5 different lattice spacings and pion masses down to the physical pion mass. A combined continuum and chiral extrapolation to the physical point is performed along two independent quark mass trajectories simultaneously. We employ momentum smearing in order to decrease the contamination of excited states and increase statistical precision.

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Axial U(1) symmetry and Dirac spectra in high-temperature phase of $N_f = 2$ lattice QCD

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We investigate the axial $U(1)$ symmetry in the phase above the critical temperature in $N_f = 2$ lattice QCD, where the ensembles are generated with Mobius domain-wall fermions, and the overlap/domain-wall reweighting is applied. We show the $U(1)_A$ susceptibility extracted from the spectra of the overlap Dirac eigenmodes and discuss its temperature, quark-mass, and spatial volume dependence. The behavior of $U(1)_A$ susceptibility is compared with that of topological susceptibility and their relation is discussed.

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The fate of axial U(1) and the topological susceptibility in QCD with two light quarks

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The region of the Columbia plot with two light quark flavors is not yet conclusively understood. Non-perturbative effects, e.g. the magnitude of the anomalous U(1) axial symmetry breaking decides on the nature of the phase transition in this region. We report on our study of this region of the Columbia plot using lattice techniques. We use gauge ensembles generated within the Highly Improved Staggered Quark discretization scheme, with the strange quark mass fixed at its

physical value and the light quark mass varied such that m_l=m_s/27, m_s/40, m_s/80, where m_l=m_s/27 corresponds to the physical light quark mass. We study the eigenvalue spectrum of QCD at finite temperature around the chiral transition temperature T_c, as the light quark masses approach towards the chiral limit and infer about the fate of anomalous U(1) symmetry. We also show how the topological susceptibility of QCD at finite temperature varies as one goes towards the chiral limit.

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Topological Susceptibility in $N_f = 2$ QCD at Finite Temperature – Volume Study

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We study the topological charge in $N_f = 2$ QCD at finite temperature using Mobius domain-wall fermions with reweighting to ovelap fermions. The susceptibility χ_t of the topological charge is studied in the high temperature phase with varying quark mass. Last year, we reported on a strong suppression of the susceptibility, observed below a certain value of the quark mass on a fixed spatial volume. We extend this study by changing the volume to both smaller and larger direction. The relation with the restoration of $U_A(1)$ is discussed.

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Topological Susceptibility to High Temperatures via Reweighting

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At high temperatures, the topological susceptibility of QCD becomes relevant for the properties of axion dark matter. However, the strong suppression of non-zero topological sectors causes ordinary sampling techniques to fail, since fluctuations of the topological charge can only be measured reliably if enough tunneling events between sectors occur. We present a new method to circumvent this problem based on a combination of gradient flow and reweighting techniques. Moreover, we quote continuum extrapolated results for the topological susceptibility in the quenched approximation at 2.5 T_c and 4.1 T_c.

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Topological structures in finite temperature QCD

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We report our study on the properties of the topological structures present in the QCD medium just above the chiral crossover transition. We use dynamical domain wall fermion configurations on lattices of size 32^3x8, used earlier in [1] to calculate the crossover transition temperature Tc in QCD, and detect the topological structures through the zero modes of the overlap operator. In particular, their positions and spatial and temporal widths are measured. We explicitly show that the properties of the zero modes of the QCD Dirac operator agrees well with that of calorons with non-trivial holonomy. Different profiles of the zero modes are observed, ranging from solutions that are localized in all four spacetime dimensions, to profiles that are localized in the spatial directions, and constant along the temporal extent of the lattice. This indicates towards the presence of instanton-dyons in the hot QCD medium just above Tc, where the distance between dyons control the shape and extent of the zero modes.
[1] QCD Phase Transition with Chiral Quarks and Physical Quark Masses Phys. Rev. Lett. 113, 082001 (2014) doi:10.1103/PhysRevLett.113.082001 [arXiv:1402.5175 [hep-lat]]

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String breaking with 2+1 dynamical fermions using the stochastic LapH method

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The static potential V(r) between a static quark and a static antiquark separated by a distance r is defined as the energy of the ground state of this system. As a consequence of confinement, the energy between the quark-antiquark pair is contained inside a color flux tube, the so called string. As soon as the energy is high enough, the gluonic string connecting the quarks will break due to pair creation. String breaking is manifested as a quantum-mechanical mixing phenomenon between different states, which contain two infinitely heavy quarks acting as static color sources. We investigate this phenomenon with $N_f = 2 + 1$ flavors of dynamical Wilson fermions in the stochastic LapH framework, using an ensemble of gauge configurations generated through the CLS effort. We see the effect of the third sea-quark flavor, which results in a second mixing-phenomenon due to the formation of a strange-antistrange pair.

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Computation of hybrid static potentials from optimized trial states in SU(3) lattice gauge theory

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We compute hybrid static potentials in SU(3) lattice gauge theory using a method to automatically generate a large set of suitable creation operators from elementary building blocks. This method allows us to find a set of creation operators, which generate trial states with large ground

state overlap for several angular momentum and parity channels. We present results for the corresponding hybrid static potentials. Moreover, we study the flux tube structure using the same creation operators and show preliminary results in SU(2) lattice gauge theory.

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Confront the lattice finite-volume energy levels with chiral effective field theory

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In this talk, we will introduce the finite-volume effects in the chiral effective field theory and analyse the lattice finite-volume energy levels to extract the resonance properties with the unphysical and physical pion masses. Special attention will be paid to the a0(980) from the coupled-channel scattering of pi-eta, K-Kbar and pi-eta'. Preliminary results on the D-pi, Ds-Kbar and D-eta scattering will be also presented.
A global fit to recent lattice finite-volume energy levels from pi-eta scattering and relevant experimental data on a pi-eta event distribution and the gamma-gamma -> pi-eta cross section is performed. Both the leading and next-to-leading-order analyses lead to similar and successful descriptions of the finite-volume energy levels and the experimental data. However, these two different analyses yield different pi-eta scattering phase shifts for the physical masses for the pi, K, eta and eta' mesons. The inelasticities, the pole positions in the complex energy plane and their residues are calculated both for unphysical and physical meson masses.

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New lattice interaction and the spectrum of light and medium mass nuclei

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We present a new lattice formulation of chiral effective nuclear force with simpler decomposition into partial waves. With these new interactions the process of fitting to the empirical-observed scattering phase shifts is simplified, and the resulting lattice phase shifts are more accurate than those in precious studies. We present results for neutron-proton system up to next-to-next-to-next-to-leading order with lattice spacings of 1.97 fm, 1.64fm, 1.32fm and 0.99fm. We also present the new lattice results for the spectrum of the light and medium mass nuclei calculated with these new interactions

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Strong Decay Analysis of Bottom Mesons

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In the last decade, a significant experimental progress has been achieved in studying the heavy-light meson spectroscopy. Heavy-light mesons composed of one heavy quark Q and a light quark q are useful in understanding the strong interactions in the non perturbative regime. Experiments like LHCb, Babar etc are providing many new states which are being added to their spectroscopy.

But the information for higher excited bottom mesons is rather limited as compared to the charm mesons. In this, we study the experimentally missing radially excited (n=2) bottom mesons. We study their two body strong decays, coupling constants and branching ratios with the emission of light pseudo-scalar mesons (η,K,π) in the framework of HQET which can be confronted with the future experimental data.

Physics beyond the Standard Model / 141

Indications for infrared conformal behaviour of SU(2) gauge theory with N_f = 3/2 flavours of adjoint fermions

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We present the results of a numerical investigation of SU(2) gauge theory with $N_f = 3/2$ flavours of fermions, corresponding to 3 Majorana fermions, which transform in the adjoint representation of the gauge group. At two values of the gauge coupling, the masses of bound states are considered as a function of the PCAC quark mass. The scaling of bound states masses indicates an infrared conformal behaviour of the theory. We obtain estimates for the fixed-point value of the mass anomalous dimension γ^* from the scaling of masses and from the scaling of the mode number of the Wilson-Dirac operator.

Physics beyond the Standard Model / 186

Progress in the lattice simulations of Sp(2N) gauge theories

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We report on the status of our program to simulate Sp(2N) gauge theories on the lattice. Motivated by the potential realization of SU(4)/Sp(4) ~ SO(6)/SO(5) composite Higgs model, we first consider Sp(4) theories with two Dirac fermion flavors in the fundamental representation. Preliminary results of meson spectrum will be presented along with discussion of the lattice systematics. Toward partial top compositeness in which additional fermions carry SU(3) color quantum numbers we implement two-index antisymmetric Dirac fermions and explore the phase space of bare lattice parameters. We also present preliminary results of string tension and glueball mass spectrum in pure Sp(6) gauge theory. For all the numerical simulations we use the standard Wilson lattice gauge and fermion actions.

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Phase structure of strongly interacting four-fermion theory

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We study a four dmensional lattice model comprising four reduced staggered fermions coupled to a scalar field through an SO(4) invariant interaction. Symmetries of the lattice theory prohibit fermion mass terms. If we switch of the kinetic term for the scalar field we obtain a model with a four fermion interaction which has been the focus of several recent lattice investigations. The results of those investigations has revealed that the pure four fermi model possesses both massless and massive SO(4) symmetric phases separated by a very narrow symmetry broken phase. In this work we explore the phase diagram of the more general Yukawa model with a scalar kinetic term and present evidence that one can pass from the massless to massive phases without passing through an intermediate broken phase.

Physics beyond the Standard Model / 115

Gauge-fixing with compact lattice gauge fields

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Proper treatment of redundant gauge degrees of freedom seems necessary for gauge theories with terms that explicitly break gauge symmetry (e.g., in chiral gauge theories with manifestly local formulation of lattice fermions) since these degrees of freedom become manifestly present in such theories. There is also a no-go theorem prohibiting use of BRST formalism in theories with compact gauge fields. Results will be presented of our investigation of pure U(1) gauge theory, with higher derivative gauge-fixing term that breaks BRST, at strong gauge coupling that show that the redundant gauge degrees of freedom decouple just as seen previously in the weak coupling region. The general scheme of numerical simulation of an SU(2) gauge theory in the equivariant BRST (eBRST) formalism with dynamical ghost fields in the SU(2)/U(1) coset space will also be presented. Details of the results of the eBRST SU(2) lattice gauge theory and the theory in the reduced limit (obtained by gauge coupling taken to zero) will be covered by Mugdha Sarkar.

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eBRST SU(2) Gauge Theory on Lattice

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Equivariant BRST (eBRST) SU(2) gauge theory involves gauge fixing in the SU(2)/U(1) coset space leaving the subgroup U(1) gauge invariant. This can be taken as an alternative formulation of SU(2) lattice gauge theory that uses gauge-fixing, evading the no-go theorem by Neuberger preventing the use of standard BRST. Results will be presented for our numerical simulation of the eBRST gauge theory, generalised with addition of a mass term (for both the ghost fields and the gauge fields in the coset space) that keeps the eBRST symmetry intact. The theory in the reduced limit has also a global SU(2) symmetry which has been speculated in the literature to undergo a spontaneous breaking to U(1). Our results on this possible spontaneous symmetry breaking and its implication for possible continuum limit will be presented.

Hadron Structure / 298

Direct lattice-QCD calculation of pion valence quark distribution

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Within the large momentum effective theory framework, we present the first direct lattice-QCD calculation of the valence quark distribution in the pion. Our results are comparable quantitatively with the results extracted from experimental data as well as from Dyson-Schwinger equation. Future calculations at physical pion mass and larger momentum will be able to discern discrepancies in various existing analyses.

Hadron Structure / 277

Renormalized quasi parton distribution function of pion

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We present numerical results on the non-perturbative renormalization of the quasi-PDF operator as determined using Wilson-Clover valence fermions on HISQ ensembles at two different lattice spacings, with and without the explicit subtraction of the divergent Wilson line self-energy contribution. Then, we present some preliminary results on the renormalized pion quasi-PDF as well as the pion PDF as obtained by matching using LaMET.

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Parton Distribution Function Calculation of the Pion on a Fine Lattice

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We present numerical results on the bare quasi-PDF matric element for the pion. Our pion mass is 300 MeV using a HISQ sea and Wilson-Clover valence quarks. Our lattice spacing and volume are 0.061 fm and $48^3 \times 64$ respectivly. Large momentum calculations being necessary for reliable matching between the quasi-PDF and the light-cone PDF using LaMET, we evaluate our matrix elements for a pion with momentum 1.69(2.11) GeV, or 4(5) units on the lattice. Large momentum calculations on the lattice are notoriously contaminated with unwanted excited state contributions overlapping to our measurement. As such we also present a detailed study of pion two-point functions at large momentum, tuned using a multitude of smearing techniques to

reduce the overlap of our operators to excited states. Furthermore we HYP-smear the Wilson Line of our quasi-PDF matrix element to study the reduction of lattice artifacts in our calculation. Ioffe-Time distribution functions were also computed as an exploratory study.

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Visualizations of Centre Vortex Structure in Lattice Simulations

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This presentation examines the structure of centre vortices in Monte-Carlo generated gauge-field configurations using modern visualization techniques. We'll begin with a brief review of how centre vortices underpin dynamical chiral symmetry breaking and how their removal restores chiral symmetry.
Centre vortices are identified through gauge transformations maximizing the centre of the gauge group. Focusing on the thin vortices identified by Wilson loops having a non-trivial centre phase, the vortex structure is illustrated through renderings of oriented spatial plaquettes. Time oriented plaquettes are illustrated by identifying spatial links associated with these non-trivial plaquettes. Of particular interest is the correlation of the vortex structure and the topological-charge structure of the gauge fields, vital to dynamical chiral symmetry breaking and its associated mass generation. The results provide new insights into the role of centre vortices in underpinning non-trivial topology in gauge fields. They reveal how the removal of centre-vortices necessarily destroys non-trivial topology, immediately restoring chiral symmetry and destabilizing would-be instantons under smoothing algorithms. In contrast, vortex-only backgrounds provide gauge-field degrees of freedom sufficient to create instantons upon smoothing.
The observed correlations further strengthen the idea that centre vortices are the seeds of dynamical chiral symmetry breaking.

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Localization transition in SU(3) gauge theory

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It is known that at high temperature the lowest eigenmodes of the QCD Dirac operator become localized. Since these localized modes appear around the cross-over temperature it is natural to ask how they are related to deconfinement and chiral symmetry restoration. The simplest question one can ask in this connection is whether deconfinement and the appearance of localization happen at the same temperature. However, in QCD there is no sharply defined critical temperature since the transition is only a crossover. In contrast, having a well defined phase transition temperature, the quenched theory naturally lends itself to studying whether localization and deconfinement really happen at the same temperature. We analyze the statistics of staggered and overlap Dirac spectra on quenched SU(3) ensembles at several temperatures just above T__c. We precisely determine the temperature where localized modes appear in the Dirac spectrum and compare this temperature with that of the deconfinement transition.

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Localization and topology in high temperature QCD

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At high temperature part of the spectrum of the quark Dirac operator is known to consist of localized states. This comes about because around the cross-over temperature to the quark-gluon plasma, localized states start to appear at the low end of the spectrum and as the system is further heated, states higher up in the spectrum also get localized. Since localization and the crossover to the chirally restored phase happen around the same temperature, the question of how the two phenomena are connected naturally arises. Here we speculate on the nature of possible gauge configurations that could support localized quark eigenmodes. In particular, by analyzing eigenmodes of the staggerd and overlap Dirac operator we check whether a dilute gas of calorons or other forms of topological charge can play a major role in localization.

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Simulating Quantum Chromodynamics coupled with Quantum Electromagnetics on the lattice

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We present recent developments on our lattice simulations of fully dynamical $SU(3) \times U(1)$. Including electromagnetic effects is critical for the next level of precision in phenomenology. Examples include calculating the (higher order) QED contributions to the hadronic-vacuum-polarization contribution to the muon anomalous magnetic moment and calculating the QED contributions to meson and baryon mass splittings. We recently developed and tested a dynamical QCD+QED extension of the MILC code. We use the non-compact version of QED in this code. We discuss details of the simulation algorithms and analyze the code performance. If time permits, we will also discuss plans for exascale computing.

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Machine learning for multi-scale action matching

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Critical slowing-down of HMC algorithms presents a significant challenge in achieving LQCD calculations at fine lattice spacings. A number of methods have been proposed that circumvent this issue by acting at multiple physical length scales, including perfect actions that aim to achieve almost-continuum physics at finite lattice spacings, and multi-scale thermalisation techniques. Such approaches require careful renormalisation-group matching of the LQCD actions defined at different scales such that they describe the same long-distance physics. An essential challenge is to solve the parametric regression task: Which action parameters best represent the coarse-scale physics of an ensemble of samples generated at a finer resolution, and vice-versa? Similar parameter regression problems of LQCD ensembles arise in the context of mixed-action LQCD simulations. I will discuss the applicability of machine learning to this regression task. Deep neural networks are found to provide an efficient solution even in cases where approaches such as principal component analysis fail. The high information content and complex symmetries inherent in lattice QCD datasets require custom neural network layers to be introduced and present opportunities for further development.

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$SU(2)$ Lattice Gauge Pair Hopping Constructs Suitable for Implementation on Quantum Computers

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A traditional approach for constructing a gauge field theory on a lattice employs a basic Wilson type procedure with additional enhancements to this formulation in order to improve computational performance and accuracy. This type of lattice gauge formulation has been successfully implemented on many different high performance computing systems and has yielded useful computational results. With the recent advances in quantum computing, the question that is now being asked is whether an equivalent type of gauge invariant formulation of a field theory can be constructed on a quantum computer. Using the Quantum Link Model (QLM) plus the concept of rishons, a gauge invariant mathematical construction of a lattice field theory will be summarized. In this formulation, the number of fermionic rishons per link plays an important role in the order of the gauge group that can be constructed. Using this formulation, it may be possible to implement a simple lattice field theory on a quantum computer. This talk will specifically focus on the $SU(2)$ QLM formulation, discuss the physics that may potentially be simulated on a quantum computer with this construct, and speculate on the prospects for having quantum computers become a part of the set of hardware platforms for lattice gauge theory simulations in the future.

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Simulation of Scalar Field Theories with Complex Actions

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Many scalar field theory models with complex actions are invariant under the antilinear ($\mathcal{PT}$) symmetry operation $L^*(-\chi) = L(\chi)$. Models in this class include $i\phi^3$, the Bose gas at finite density and Polyakov loop spin models at finite density. This symmetry may be used to obtain a dual representation where weights in the functional integral are real but not necessarily positive. For a subclass of models satisfying a dual positive weight condition, the sign problem is absent; such models are easily simulated by a simple local algorithm in any number of dimensions. The existence of a positive representation is constrained by Lee-Yang zeros, and tied to the phase structure of a given model. Simulations of models in this subclass show a rich set of behaviors. Propagators may exhibit damped oscillations, indicating a clear violation of spectral positivity. Domain patterns may occur in equilibrium, with both stripe and bubble morphologies occurring. These behaviors appear to be likely in finite density QCD in the vicinity of the critical line.

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Worldline Approach to Few-Body Physics on the Lattice

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We formulate a world-line approach to study few body physics on a space-time lattice and develop a worm type algorithm to extract the low lying energy levels. We show that our formulation is efficient for studying non-relativistic spin-half fermions with both attractive and repulsive interactions and in the presence of mass imbalance, especially in one spatial dimension. Recently, such systems have been studied using the complex Langevin approach, since the traditional auxiliary field formulations suffer from sign problems. Our approach can be easily extended to higher dimensions for bosonic systems without sign problems. For fermionic systems, we study

the severity of the sign problem in our formulation as a function of the particle number with various types of interactions.

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Low temperature condensation and scattering data

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We study a complex ϕ^4 field at finite temperature and finite density using a worldline representation. In particular we focus on the low temperature regime where the particle number shows condensation steps as a function of the chemical potential. The critical values of the chemical potential, i.e., the condensation thresholds, are related to the mass and higher multi-particle energies and can be determined within a simulation. We study the first three condensation thresholds, i.e, $\mu_c^{(i)}$, $i = 1, 2, 3$, which are linked to the 2- and 3-particle energies as a function of the spatial volume L^{d-1}. The L-dependence of the multi-particle energies is described by Lüscher's formula in the 2-particle sector and by its generalization in the 3-particle case. These finite size scaling functions carry the scattering information. Finally, we cross-check the results with conventional simulations at vanishing chemical potential where we extract the mass and the 2- and 3-particle energies from the 2-, 4- and 6-point correlation functions.

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Pi_0 transition form factor in coordinate space

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We investigate the lattice calculation of pi_0 transition form factor in coordinate space, which is relevant to hadronic light-by-light (HLbL) scattering in the muon g-2. I will describe how we construct the coordinate space formulation of the pion transition form factor. I will present preliminary results for the form factor computed on a physical pion mass, 24^3, 1.0 GeV, 2+1 flavor Mobius-DWF ensemble generated by the RBC/UKQCD collaboration.

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Towards leading isospin breaking effects in mesonic masses with open boundaries

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We present an exploratory study of leading isospin breaking effects in mesonic masses using $O(a)$ improved Wilson fermions with open boundaries. Isospin symmetry is explicitly broken by distinct masses and electric charges of the up and down quarks. In order to be able to make use of existing isosymmetric QCD gauge ensembles we apply reweighting techniques. The path integral describing QCD+QED is expanded perturbatively in powers of deviations in the quark masses and the inverse strong coupling as well as the electromagnetic coupling. We have formulated

QED_L, which we use as a finite volume formulation of QED, for open boundaries. We will also give a first insight into contributions from quark disconnected diagrams.

Hadron Spectroscopy and Interactions / 210

Analysis of systematic error in hadronic vacuum polarization contribution to muon g-2

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We present a systematic study of finite size correction and cut-off effect in hadronic vacuum polarization contribution to muon g-2 with two volumes, 5.4 fm^3 and 10.8 fm^3, and two lattice cut-off, 2.33 GeV and 3.06 GeV, at the physical pion on the PACS configuration. In this analysis, using high statistics data, we compare two volumes at long-distance on the physical point to directly estimate the finite size correction, and it then makes a comparison with ChPT prediction. Using the different cut-off scales on ˜10.8 fm^3 lattice box, we try to estimate the cut-off effect with local and point-splitting operators on the two cut-off configurations.

Poster reception / 24

Meson electromagnetic form factors from lattice QCD

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Lattice QCD can provide direct determination of the electromagnetic form factors of mesons as a prediction to be compared to upcoming experiments at Jefferson Lab. At the same time we can compare to expectations from perturbative QCD, which take a very simple form at high Qˆ2. We will show recent results from HPQCD, building on the work in 1701.04250. We give predictions for pi and K mesons up to 4 GeVˆ2 that include calculations for physical u/d quarks and provide accurate predictions for Jefferson Lab. We also extend the Qˆ2 range up to 20 GeVˆ2 by studying mesons made of heavier quarks. At these values of Qˆ2, discrepancies (both in the values and the Qˆ2-dependence) with perturbative QCD raise issues of the reliability of the assumptions going in to the perturbative QCD calculations. This has wider implications also for other processes.

Poster reception / 200

Matching of Nf=2+1 CLS ensembles to a tmQCD valence sector

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We will present a detailed description of the matching of a valence Nf=2+1+1 fully-twisted tmQCD action with an Nf=2+1, non-perturbatively O(a)-improved Wilson sea. Extensive preliminary results for meson and quark masses, as well as for pseudoscalar decay constants, are available for several CLS ensembles. A comparison of the scaling behaviour of the two actions in the light and strange quark sectors, as well as various crosschecks of the solidity of the approach, will be presented.

Poster reception / 155

Inclusive decay structure function for $B \to X_c \ell\nu$: a comparison of a lattice calculation with the heavy quark expansion

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A lattice calculation of inclusive decay structure functions for $BtoX_cellnu$ is compared with the corresponding estimates based on the heavy quark expansion. Both methods are applicable in the region away from the resonances/cuts due to final charmed states, and one can test the theoretical methods employed on both sides.

Poster reception / 230

Split Grid and Block Lanczos algorithm for efficient eigenpair generation

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The increasing unbalance between computing capabilities of individual nodes and internode communication makes it highly desirable for any Lattice QCD algorithm to minimize the amount of off-node communication. One of the relatively new methods for this is the 'split-grid' or 'split-domain', where data is rearranged within the running of a single binary, so that the routines which requires significant off-node communications such as Dirac operators are run on multiple smaller partitions in parallel with a better surface to volume ratio, while other routines are run in one large partition.
While it is relatively straightforward to utilize split-grid for inverters, the typical Lanczos algorithm which has one starting vector does not render itself naturally to split-grid approach. Here we report on our investigation of Block Lanczos algorithm which allows multiple starting vectors to be concurrently. It is shown that for a moderate number of starting vectors, Block Lanczos algorithm has been implemented in Grid Data parallel C++ mathematical object library, and shown to achieve convergence comparable to normal Lanczos algorithm on DWF/Mobius ensemble with physical quark masses.

Poster reception / 183

High Precision Statistical Landau Gauge Lattice Gluon Propagator Computation

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We report on results for the Landau gauge gluon propagator computed from large statistical ensembles and look at the compatibility of the results with the Gribov-Zwanziger tree level prediction for its refined and very refined versions. Our results show that the data is well described by the tree level estimate only up to momenta p 1 GeV, while clearly favoring the so-called Refined Gribov-Zwanziger scenario. We also provide a global fit of the lattice data which interpolates between the above scenario at low momenta and the usual continuum one-loop renormalization improved perturbation theory after introducing an infrared log-regularizing term.

Poster reception / 54

Porting DDalphaAMG solver to K computer

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We port Domain-Decomposed-alpha-AMG solver to K computer. The system has 8 cores and 16 GB memory par node, of which theoretical peak is 128 GFlops (82,944 nodes in total). Its feature, as many as 256 registers par core and as large as 0.5 byte/Flop ratio, requires a different tuning from other machines. In order to use more registers, we change some of the data structure and rewrite matrix-vector operations with intrinsics. The improvement of the performance is more than factor two for twelve solves including the setup. The efficiency is still about 5% after the optimization, which is lower than a previously tuned mixed precision solver for K computer, 22%. The throughput is, however, almost three times more for a physical point configuration.

Poster reception / 302

Reweighting Lefschetz Thimbles

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One of the main challenges in simulations on Lefschetz thimbles is the computation of the relative weights of contributing thimbles. In this paper we propose a solution to that problem by means of computing those weights using a reweighting procedure. Besides we present recipes for finding parametrizations of thimbles and anti-thimbles for a given theory. Moreover, we study some approaches to combine the Lefschetz thimble method with the Complex Langevin evolution. Our numerical investigations are carried out by using toy models among which we consider a one-site z^4 model as well as a U(1) one-link model.

Poster reception / 238

On the definition of schemes for computing leading order isospin breaking corrections

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We propose a particular 'line of constant physics' (i.e., a scheme) for computing isospin breaking corrections to hadronic quantities. We show this scheme is in a class of schemes that allow for the separation of the electromagnetic and strong isospin breaking corrections at leading order, such that scheme-ambiguities are higher order in isospin breaking effects.

Poster reception / 315

Lattice calculation of neutron electric dipole moment with overlap fermions

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We report our calculation of the neutron electric dipole moment of the contribution from the θ term with overlap fermions on the 2+1-flavor RBC/UKQCD domain wall lattices 24I and 32ID. For the 24I lattice the size is 2.65 fm and the pion mass is 337 MeV and for the 32ID lattice the size is 4.58 fm and the pion mass is 171 MeV. In order to solve the large-volume problem, the cluster-decomposition error reduction (CDER) technique is utilized to improve the signal-to-noise ratio especially for the lattice with larger volume.

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Light-neutrino exchange and long-distance contributions to neutrinoless double beta decay

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Recently four experiments have demonstrated new levels of sensitivity to neutrinoless double beta ($0\nu\beta\beta$) decay. Such decay, if exists, would prove that neutrinos are Majorana fermions. The light-neutrino exchange is the most popular mechanism to explain the $0\nu\beta\beta$ decay. In this mechanism, the decay amplitude is proportional to the effective neutrino mass $m_{\beta\beta}$ and thus the detection of $0\nu\beta\beta$ decay would provide the information about the absolute neutrino mass. We report the lattice QCD calculation of the $0\nu\beta\beta$ decay amplitude, which involves light-neutrino exchange and significant long-distance contributions.

Poster reception / 61

Parity-positive Baryon Spectra on Isotropic Lattice

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We present a calculation of the low-lying spectra for the positive-parity Delta and Nucleon using the distillation approach applied on an isotropic $32^3 \times 64$ lattice at a pion mass of around 360 MeV, using a non-relativistic basis of operators together with so-called hybrid-type operators. The spectra are extracted from two-point functions using variational analysis. The results are compared with lattice calculations at higher pion masses on an anisotropic lattice, and a similar pattern emerges, including in particular the presence of hybrid states in which gluonic degrees of freedom play a manifest role, confirming the robustness of their observation. The systematic uncertainties in the calculation are explored, including in particular the effect of varying the distillation space on the spectra and a minimal number of distillation vectors is identified. The effect of varying the distillation space on the calculation is explored and to obtain a spectra with acceptable statistical error, application of a minimum number of distillation vector is proposed.

Poster reception / 63

Contribution to the anomalous magnetic moment of the muon from the disconnected hadronic vacuum polarization with four-flavors of highly-improved staggered quarks.

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We describe a computation of the contribution to the anomalous magnetic moment of the muon from the disconnected part of the hadronic vacuum polarization. We use the highly-improved staggered quark (HISQ) formulation for the current density with gauge configurations generated with four flavors of HISQ sea quarks. The computation is performed by stochastic estimation of the current density using the truncated solver method combined with deflation of low-modes. The parameters are tuned to minimize the computational cost for a given target uncertainty in the current-current correlation function. The calculation presented here is carried out on a single gauge-field ensemble of size $32^3 \times 48$ with an approximate lattice spacing of 0.15 fm and with physical sea-quark masses. We describe the methodology and the analysis procedure.

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Towards the spectrum of flavour-diagonal pseudoscalar mesons in QCD+QED

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The low-lying hadron spectrum has been of tremendous phenomenological significance in resolving the nature of quark masses in strong interaction dynamics. In particular, the pseudoscalar mesons provide the foundation of the framework of chiral perturbation theory, the low-energy effective theory of QCD. Modern lattice calculations of pure QCD now provide excellent precision in the resolution of quark masses. In order to match this theory onto the observed mass scales of the standard model at sub-percent precision, it is essential to discriminate electromagnetic effects. In this work, we explore the spectrum of the flavour-diagonal pseudoscalar mesons on dynamical QCD+QED lattices. To reduce the familiar statistical noise associated with annihilation diagrams we utilise exact colour and spin dilution with a spatial interlacing for our Z_2 noise sources.

In comparison with results from pure QCD, we make first estimates of the contribution of electromagnetic effects in the π_0–η splitting.

Poster reception / 110

Implementation of the conjugate gradient algorithm in Lattice QCD on FPGA devices

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We port the most critical part of the Lattice Quantum Chromodynamics code, the iterative solver, to modern FPGA devices. More precisely, we discuss a single-node, double precision implementation of the Conjugate Gradient algorithm and use it to invert numerically the Dirac-Wilson operator on a 4-dimensional grid on a Xilinx Zynq evaluation board. We propose a separation of software/hardware parts in which the entire multiplication by the Dirac operator is performed in hardware, and the rest of the algorithm runs on an ARM core. We find out that the FPGA implementation offers a performance comparable with that obtained modern, general purpose x86 Intel processors. Several directions of further research will be suggested.

Poster reception / 181

First Glimpse of Glue Parton Distribution Function from Lattice QCD

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Parton distribution functions (PDFs) are central to the study of the hadron scattering cross sections with(within) collinear factorization. Recently, the Large-momentum effective theory (LaMET) introduced the quasi-PDF, providing the possibility to explore the entire PDF instead of just the first few moments. Since then, a lot of studies have been done on the quark quasi-PDFs. Compared to the quark PDF, the glue PDF is less studied in theory but its contribution is dominant in the production of Higgs bosons and heavy quarkonium. Here we provide the first numerical investigation of the glue quasi-PDF on the lattice with preliminary results.

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$B \to D^{(*)}\ell\nu$ form factors from N_f=2+1 QCD with Moebius domain-wall quarks

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We report our preliminary results for the $B \to D^{(*)}\ell\nu$ semileptonic form factors at zero and nonzero recoils in 2+1 flavor QCD. The Moebius domain-wall action is employed for light, charm and bottom quarks at lattice cutoffs $a^{-1} = 2.5$ and 3.6 GeV. We take bottom quark masses up

to 2.4 times the physical charm mass to control discretization effects. We test the heavy quark scaling of the form factors for the extrapolation to the physical bottom mass.

Poster reception / 251

Relational databases for lattice data analysis

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Numerical studies in lattice gauge theory require the organization and analysis of large volumes of data. These data and analyses thereof can be viewed as a sequence of maps and reductions, a structure that can be represented naturally using relational databases. Organized in this way, the analysis of even large, heterogenous datasets is straightforward to automate. We present in abstract our methods to store, organize, and analyze lattice data, as well as an outline of a functioning implementation using PostgreSQL.

Poster reception / 308

Hyperon Axial Couplings at Physical Pion Mass

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The hyperon axial couplings are important parameters entering the low-energy effective field theory description of the octet baryons. In addition, the coupling constants appear in the non-leptonic decays of hyperons, and hyperon-hyperon and hyperon-nucleon scattering processes, which can be used in the description of neutron stars. In this poster, we present preliminary results on the Sigma-Sigma and Xi-Xi axial couplings calculated at a=0.09fm near physical pion mass with clover/HISQ actions.

Poster reception / 225

Lattice QCD on upcoming ARM architectures

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We present our experiences porting Lattice QCD code to upcoming ARM processor architectures, which will be used for future supercomputers such as QPACE 4 (University of Regensburg, Germany) and Post-K (RIKEN, Japan). These processors will support the ARM Scalable Vector Extension (SVE). SVE allows to design processor cores providing significantly higher performance compared to the cores available today.
SVE is a novel extension of the ARM instruction set architecture. It supports a vector-length agnostic (VLA) programming model that, in contrast to the traditional fixed-size SIMD instruction approach, can adapt to different vector length at run-time. The necessary hardware support for VLA helps for parallelizing applications at vector instruction level.

In this poster we present results from enabling LQCD applications SVE. More specifically, we ported the "Grid" library, which is a LQCD library optimized for processor architectures that feature wide SIMD instructions. Code correctness has been verified using emulators.
We collaborate with ARM in order to evaluate and develop key aspects of an efficient SVE toolchain, which includes SVE compiler and code profiler technology. First processors supporting SVE are expected to become available in 2020.

Poster reception / 311

Preliminary results for the confining/deconfining transition of QCD up to large \mu/T

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We perform CLE simulations both in the confining and in the deconfining phases of QCD at large temperature and in a wide chemical potential domain (up to \mu/T ~10). We show preliminary results for the deconfining transition at \beta = 5.9 for 2 flavors of Wilson fermions. Most of the data are taken at rather large quark masses (m_\pi ~ 1GeV) and small spatial volumes (8^3 and 12^3). This and the statistics do not at present permit describing the character of the transition. These limitations are mainly due to computer time availability and we hope to soon improve on them. Some further tests on the method are also discussed.

Poster reception / 179

Mass Splitting in a Linear Sigma Model

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We examine mass splittings in a linear sigma model which is an effective theory for a SU(3) gauge theory with N_1 flavors of mass m_1 and N_2 flavors of mass m_2. We discuss the consequences for current simulations done by various collaborations. We explain the relevance for BSM model building.

Poster reception / 20

Lattice QCD codes on Taihu-Light

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We are developing a code package for the supercomputer Shenwei Taihu-Light in China. There is an optimized D-slash function and some inverter functions in the code pacakge. We will show the working progress of this project.

Poster reception / 207

Lattice Calculation of the Proton Charge Radius

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The charge radius of the proton has been measured in scattering and spectroscopy experiments using both electronic and muonic probes. The electronic and muonic measurements have a currently unresolved five sigma discrepancy, giving rise to what is known as the proton radius puzzle.
Since the neutron charge radius is known, measurement of the proton charge radius on the lattice typically involves determination of the isovector form factors at various 4-momentum transfers Q^2 and then determining the slope at $Q^2 = 0$. However, due to the discretization of momentum on the lattice, there is a systematic uncertainty from extrapolation of the slope to $Q^2 = 0$. One can access negative values of Q^2 if one breaks isospin symmetry by introducing a nonzero mass splitting between the up and down quarks and then extrapolating to the limit where this splitting vanishes. We present preliminary results from this method at unphysical quark masses to determine if this method has the potential to reduce uncertainties.

Poster reception / 261

10 Years of QUDA

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This year, 2018, the QUDA library for Lattice QCD on NVIDIA GPUs celebrates its tenth birthday. QUDA has evolved from an acceleration library for solvers into an open-source framework for developing QCD simulations. It supports many different fermion discretizations, and features algorithms like adaptive multigrid, deflation and block Krylov-space methods. QUDA uses various techniques such as mixed precision and communication hiding to maximize performance. We will present the current state of QUDA and discuss performance on current hardware. We strongly encourage discussions about user requests and contributions.

Poster reception / 229

Determination of the Nf=12 step scaling function using Möbius domain wall fermions

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We calculate the step scaling function for twelve fundamental flavors nonperturbatively by determining the gradient flow coupling on gauge field configurations generated with dynamical stout smeared Möbius domain wall fermions and Symanzik gauge action. Using Zeuthen, Symanzik, and Wilson flow we measure the energy density with three different operators. Our updated analysis is now based on up to five volume pairs ranging from $L^4 = 8^4$ up to 32^4. Our new results confirm the previously observed discrepancy with results obtained from staggered fermion simulations.

Poster reception / 166

Towards a new lattice QCD code: performances and first applications

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We present a recently started project of a new implementation of a C++ code-base to perform lattice QCD calculations. As a first step, we have implemented a Multi-Hit Metropolis algorithm for generating configurations in Yang-Mills theory and a third order Runge-Kutta scheme for applying the Gradient Flow to the gauge fields. We performed tests of the autocorrelation time of the energy density and of the topological charge to find suitable parameters for the Metropolis algorithm. The scaling properties of the code have also been studied and results show that the strong scaling efficiency coefficient is $\eta_{\mathrm{S}} \approx 80\%$ for an increase in processor number of 2^4. Collectives are handled using MPI and plans of using features from the 3.0 standard are presented. The program so far has been tested on three different clusters with up to 2^{10} cores.\\ To demonstrate the capabilities of the new code-base we performed a calculation of $\Lambda_{\overline{\mathrm{MS}}}$ for pure-gauge theory using the gradient flow to define an energy scale as $q = 1/\sqrt{8t}$ finding results, through an unbiased multi-fitting procedure, consistent with the existing literature.

Poster reception / 291

Symmetric mass generation in a gauged system

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We study a model of four reduced staggered fermions transforming in the bifundamental representation of an SU(2)xSU(2) symmetry group. Single site mass terms are prohibited by this symmetry but a particular four fermi term is allowed. We gauge one of the SU(2) subgroups and examine the phase structure of the model. We find evidence that the theory forms a symmetric four fermion condensate at strong coupling. The model generalizes a SO(4) invariant four fermion model that has received recent attention.

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The properties of D1-branes from lattice super Yang–Mills theory using gauge/gravity duality

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We consider 1+1-dimensional maximally supersymmetric Yang–Mills theory (SYM) at large N and strong 't Hooft coupling which is dual to D1 branes. One can have different tori based on the expansion of the gauge links in the moduli space, which is required to target the correct continuum theory. In our previous work, we explored a special skewed torus corresponding to A2* geometry. Here, we will restrict ourselves to a rectangular torus and calculate the free energy, equation of state using some known techniques from lattice QCD. This will enable us to evaluate the speed of sound for this strongly coupled plasma. Since there is no shear viscosity in two dimensions, we comment on the expectations for the bulk viscosity from the calculations on the dual gravity side, which unlike the conformal N=4 SYM case, does not vanish and is proportional to the trace anomaly.

Poster reception / 320

Investigating volume effects for Nf=2 twisted clover fermions at the physical point

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We present a study of volume effects for Nf=2 twisted mass fermions using simulations at the physical point. The main focus will be given to nucleon quantities such as the axial charge and quark momentum fraction. The two volumes that we compare are 4.5fm and 6 fm

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Review on Lattice Muon g-2 HVP Calculation

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Recent lattice QCD results for hadron vacuum polarization (HVP) and its contribution to muon anomalous magnetic moments (g-2) will be reviewed. There currently exists tension of more than 3-sigma deviations in muon g-2 between the BNL experiment with 0.5 ppm precision and the Standard Model (SM) prediction with the QCD dispersion relation used for HVP. The lattice QCD predictions without recourse to any experimental inputs provide an independent crosscheck of the dispersive approaches and important indications for assessing the SM prediction with measurements at ongoing/forthcoming experiments at Fermilab/JPARC aiming at around 0.1 ppm uncertainty. In this regard, I overview the lattice QCD challenges for the precise HVP determination and its contribution to muon g-2. In particular, I focus on the recent progress made in controling various systematics, and compare the results by various lattice groups. I briefly discuss the lattice versus dispersive results and outlook for the per-mil-level determination of the lattice HVP muon g-2, which is required by the experiments coming years.

Plenary / 39

Leading hadronic contribution to muon g-2 from lattice QCD and the MUonE experiment

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The dominating uncertainty in the Standard Model prediction of the muon g-2 is coming from the hadronic contributions. The Muon g-2 experiment at Fermilab has started the major data collection and the aimed four-fold increase in precision will shed light on the current discrepancy between the theory prediction and the measured value. A reciprocal effort to directly measure the hadronic contributions to the running of the fine structure constant has been proposed by the MUonE experiment, which is part of the Physics Beyond Colliders program at CERN. MUonE will get a measurement of the HVP contribution from the scattering of the high-energy muons on the fixed electron target.
Lattice QCD and MUonE experiment measure high accuracy HVP in the complementary momenta ranges. Thus, a hybrid strategy including both experimental and lattice data sets is expected to give an independent check of the current dispersive results from e+e- annihilation, which dominate the current world average. In this talk, I will present a first estimate of the lattice

contribution to the hybrid HVP, which will be combined with the outcome of the MUonE experiment. Furthermore, using a physically motivated model for the I=1 vacuum polarization (Golterman et al.'13), we give the projected precision for the MUonE's measurement of the HVP in the low momentum region.

Plenary / 327

Review of Lattice Muon g-2 HLbL Calculation

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Recent lattice QCD results for hadron light-by-light scattering (HLbL) and its contribution to muon anomalous magnetic moments (g-2) will be reviewed. There are currently more than three standard deviations between the BNL experimental result and the theoretical prediction. The Fermilab/JPARC experiments will reduce the experimental uncertainty by a factor of four. The uncertainty of theory prediction needs to be reduced to a similar level. With the recent progress in the dispersive approaches and the lattice calculations in determining the hadron vacuum polarization (HVP) contribution to muon g-2, HLbL is becoming the leading source of uncertainty in the theoretical prediction. Lattice QCD provides a systematic improvable way to calculate HLbL and a result with reliable error can be eventually obtained. In this regard, I overview the recent progress in the lattice calculations of HLbL, the current status of the calculation, and the future plans. In particular, I would discuss the method for handling the finite volume errors and the discretization errors.

Plenary / 55

Hadron Spectroscopy and Resonances Review

Dr. MADANAGOPALAN, Padmanath[1]

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I review recent results on hadron spectroscopy using lattice QCD. In light of the recent discoveries in heavy baryon sector at LHCb, lattice calculations in this regard will be emphasized. Recent lattice calculations on light baryon, heavy-heavy and heavy-light meson resonances will also be discussed.

Plenary / 323

Wilson Award

Theoretical Developments / 174

Towards a Dual Representation of Lattice QCD

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Lattice QCD in a color singlet representation has been studied since decades in the limit $\beta \to 0$. In this limiting case it is possible to integrate out analytically the partition function at finite density which is then written in terms of dual, integer, degrees of freedom representing mesons and baryons. The partition function can be then sampled by means of Worm algorithms. It turned

out that within this dual representation the finite density sign problem is so mild such that the phase diagram could be established. The challenge at this point is to introduce dynamical gluons which will allow us to study the system for larger beta values in order to make the lattice finer. Having in mind the systematic inclusion of higher order correction to the strong coupling limit, we will introduce a new representation for the partition function of pure $(S)U(N_c)$ Yang-Mills theory, which is more suitable for the extension of SC-LQCD to non-zero β. We will first show how to systematically compute the gauge integrals needed to obtain such representation then possible sampling strategies of the partition function will be discussed.

Theoretical Developments / 213

Weak coupling limit of 2+1 SU(2) LGT and mass gap.

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Dual description of SU(2) lattice gauge theory in 2+1 dimensions is shown to be the theory of interacting gauge invariant 'abelian like' electric loops. The Gauss law is solved exactly to construct the Hilbert space of the gauge invariant theory using the Schwinger boson representation. This is achieved by envisaging what is called the 'splitting of a point'. Such a 'point split' lattice allows us to describe non local electric loops in terms of three independent, local, gauge invariant quantum numbers at each site satisfying triangle inequalities. The matrix elements of the Hamiltonian becomes simpler and triangle inequalities become subdominant in the weak coupling limit. The closed loop dynamics is analysed using a gauge invariant phase space path integral. In the weak coupling limit, the mean gauge invariant electric flux becomes large and small spatial electric flux loops dominate in the vacuum state leading to a mass gap.

Theoretical Developments / 26

The critical endpoint in the 2-d U(1) gauge-Higgs model at topological angle $\theta = \pi$

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We investigate the phase structure of the 2-d U(1) gauge-Higgs model at non-vanishing topological angle θ. The sign problem arising from the topological term is avoided by invoking a dual representation of the gauge-Higgs model. This allows us to observe a 1st order transition in the topological charge at the symmetrical point $\theta = \pi$. By using the Villain action to discretize the gauge field dynamics, we implement the corresponding symmetry as an exact Z_2 symmetry of the dual variables. We perform simulations to determine the critical endpoint of this transition as a function of the mass parameter and, using FSS techniques, show that it falls into the universality class of the 2-d Ising model.

Theoretical Developments / 303

Gauss' Law, Duality, and the Hamiltonian Framework of Lattice Gauge Theory

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Quantum computers have the potential to solve certain problems in lattice gauge theory that are thought to be exponentially hard for classical computers. The proposed starting point for such computations has been the Kogut-Susskind Hamiltonian supplemented by the Gauss law constraint, with a cutoff on electric field values. There are several disadvantages to this approach, including having to simulate the vast unphysical part of the Hilbert space. We consider pure U(1) gauge theory, and motivated to restrict the calculation to purely physical states, are immediately led to a duality transformation. This approach to formulating lattice gauge theory for quantum computers could have some advantages, and we speculate on how it might be extended to include matter and non-Abelian gauge groups.

Theoretical Developments / 58

Finite-size scaling of Polyakov's loop in the 2D Abelian Higgs model

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Starting with the 2D Abelian Higgs model with the quartic self-coupling taken infinitely large we study the finite-size scaling of the Polyakov loop. We find an exponential decay for large temporal extents which is dictated by the energy gap between the ground states of a system with the Polyakov loop inserted, and one without. We study this system using the tensor renormalization group, and we take the continuous-time limit to obtain a quantum Hamiltonian where gauge invariance has been maintained exactly. Comparing with numerical results from the density matrix renormalization group we find universal features of the finite-size scaling of the energy gap survive this continuous-time limit. We propose an optical-lattice ladder to quantum simulate this model, and observe the universal features of the energy gap scaling.

Hadron Structure / 21

PDFs in small boxes

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It has been recently proposed that PDFs can be studied directly using lattice QCD. Such studies require the evaluation of matrix of non-local operators. Since this was first proposed, there has been an intense investigation of all possible systematics except for the effects associated with the fact that lattice QCD is necessarily defined in a finite spacetime. In this talk, I present the first attempt to assess these systematics, and I show that these matrix elements might suffer of large finite-volume artifacts.

Hadron Structure / 290

Higher moments of parton distribution functions

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Higher moments of patron distribution functions (PDFs) have evaded lattice QCD calculations due to the well-known problem of power-divergent mixing with low-dimension operators towards the continuum limit. With a new proposal for smeared and angular-momentum projected operators presented in Phys. Rev. D 86, 054505 (2012), we obtain moments of several PDFs of the pion, including the high moments previously inaccessible to LQCD calculations, through a dedicated numerical study using a sequence of coarse to ultrafine quenched QCD ensembles generated with the proposal of Phys. Rev. D 92, 114516 (2015). Our preliminary results demonstrate the feasibility of extracting higher moments of PDFs of hadrons in future LQCD studies, complementing existing proposals for direct evaluations of quasi-PDFs.

Hadron Structure / 107

Pion distribution amplitude from Euclidean correlation functions: Universality and higher-twist effects

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We study the feasibility to extract the leading twist pion distribution amplitude (DA) and the higher twist normalization constant from suitably chosen Euclidean correlation functions with two local currents at a spacelike separation. We demonstrate the advantages of considering several correlation functions simultaneously and extracting the pion DA from a global fit. This position space approach is complementary to the calculation of the lowest moments of the DA using the Wilson operator product expansion and avoids mixing with lower dimensional local operators on the lattice. We will highlight similarities and differences to closely related methods that use quasi- or pseudo-distributions.

Hadron Structure / 219

Transverse spin structure of octet baryons

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The transverse spin structure of matter is a subject of research that has not been thoroughly explored experimentally, providing the opportunity to produce key insight from lattice QCD. We present the latest results of the transverse spin densities of the octet baryons through analysis of electromagnetic and tensor form factors. We employ $N_f = 2 + 1$ flavours of $\mathcal{O}(a)$-improved Wilson fermions, generated with the average quark mass held fixed at its physical value. By performing an SU(3) flavour-breaking expansion of the form factors, we extrapolate to physical pion mass. From this we show the spin-spin correlations and the transverse density distributions of the octet baryons.

Hadron Structure / 152

Quark orbital angular momentum in the proton evaluated using a direct derivative method

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Quark orbital angular momentum (OAM) in the proton can be calculated directly given a Wigner function encoding the simultaneous distribution of quark transverse positions and momenta. This distribution can be accessed via proton matrix elements of a quark bilocal operator (the separation in which is Fourier conjugate to the quark momentum) featuring a momentum transfer (which is Fourier conjugate to the quark position). To generate the weighting by quark transverse position needed to calculate OAM, a derivative with respect to momentum transfer is consequently required. This derivative is evaluated using a direct derivative method, i.e., a method in which the momentum derivative of a correlator is directly sampled in the lattice calculation, as opposed to extracting it a posteriori from the numerical correlator data. The method removes the bias stemming from estimating the derivative a posteriori that was seen to afflict a previous exploratory calculation. Data for Ji OAM generated on a clover ensemble at 317 MeV pion mass are seen to agree with the result obtained via the traditional Ji sum rule method. By varying the gauge connection in the quark bilocal operator, also Jaffe-Manohar OAM is extracted, and seen to be enhanced significantly compared to Ji OAM.

Hadron Spectroscopy and Interactions / 105

Nucleon-pion-state contamination in the lattice determination of the axial form factors of the nucleon

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The nucleon-pion-state ($N\pi$) contribution to QCD two- and three-point functions used in the calculation of the axial form factors of the nucleon are studied in chiral perturbation theory. For physical quark masses the $N\pi$ states are expected to dominate the excited-state contamination at large euclidean time separations. To leading order in chiral perturbation theory the results depend on two experimentally well-known low-energy constants only and the $N\pi$-state contamination can be reliably estimated. In the axial form factor $G_A(Q^2)$ it amounts to a 5 percent overestimation for source-sink separations of about 2 fm and shows essentially no dependence on the momentum transfer Q^2. In contrast, for the induced pseudo-scalar form factor $G_P(Q^2)$ the $N\pi$-state contamination shows a much stronger dependence on Q^2 and leads to a 20-40 percent underestimation of $G_P(Q^2)$ at small momentum transfers.

Hadron Spectroscopy and Interactions / 118

A new method for suppressing excited-state contaminations on the nucleon form factors

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One of the most challenging tasks in lattice calculations of hadronic form factors is the analysis and control of excited-state contaminations. Taking the isovector form factors of the nucleon as an example, a simple calculation in chiral effective field theory shows that the excited-state contributions become dominant when the axial current is spatially distant from the nucleon

source location. In this case, the distance of the propagating pions, which have been created at the source (or sink), is comparable to the distance of the equal time pion propagation, which corresponds to the ground state contribution of the form factor including the pion pole. We investigate a method on a $N_f = 2+1$ flavor CLS ensemble ($\beta = 3.55$, $a = 0.064\,\text{fm}$) with a pion mass of $m_\pi = 200\,\text{MeV}$ using Wilson fermions to address this issue.

Hadron Spectroscopy and Interactions / 208

Controlling Excited-State Contributions to Nucleon Isovector Charges using Distillation

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As all lattice calculations are subject to a trade-off between excited-state contamination at short Euclidean times and an increased signal-to-noise ratio at large Euclidean times, the need for reduced or removed excited-state effects is paramount. Perhaps the most notable in lattice calculations is that of the axial charge of the nucleon, wherein calculations have historically differed from the world average by roughly 10%. Widely used methods to tame the impact of excited states on lattice n-point functions include the Jacobi and Wuppertal smearing techniques, and the variational method. An alternative smearing algorithm called Distillation has garnered much attention in spectroscopy calculations for its utility in efficiently identifying a plethora of hadronic states across a wide range of quantum numbers, including some of hybrid nature. Distillation provides several advantages including explicit momentum projection at source and sink, and the correlation of arbitrarily complicated interpolators once a single set of modified quark propagators have been computed. That said, Distillation has as of yet seen little use in structure calculations. In this presentation we discuss the implementation of Distillation in the calculation of the nucleon isovector charges g_A, g_S and g_T. Rather than seek precise determinations of said charges, we instead highlight the demonstrable improvements achieved in calculated matrix elements by combining Distillation with the variational method. By employing a basis of several Distilled interpolators, including some of hybrid character, we demonstrate an earlier onset of a plateau region in calculated nucleon matrix elements and stability of said plateaus under variations of the source/sink interpolator separation. When compared to Jacobi smeared interpolators used in previous variational analyses, Distillation appears to afford greater statistical precision in extracted matrix elements as reliable estimates are attainable at much shorter Euclidean times. Comparisons are also made to other recent strategies seeking to control excited-state effects, and prospects are sketched for the potential efficacy of Distillation in future structure calculations, such as the many works seeking to calculate parton distribution functions.

Hadron Spectroscopy and Interactions / 204

Pion-pion scattering with physical quark masses

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We present preliminary results on the scattering of pseudoscalar, vector, and scalar mesons on a physical pion mass, 2+1 flavor mobius-DWF, ensemble with periodic boundary conditions (PBCs) generated by the RBC and UKQCD collaborations. Using all-to-all propagators, we produce thousands of correlator momentum combinations. Energy spectra and phase shifts, including excited states, are then extracted via the solutions of a generalized eigenvalue problem. Included in this talk will also be an overview of the computational strategies employed, including a discussion of split-CG matrix solvers (communication avoidance) and lattice crossing symmetry (momentum combinatorics reduction). These studies are intended to serve as groundwork for a full PBC calculation of direct CP violation in K->pipi later this year.

Hadron Spectroscopy and Interactions / 192

Calculating the ρ radiative decay width with lattice QCD

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We present the results of our lattice QCD study of the $\pi\gamma \to \pi\pi$ process, where the ρ resonance appears as an enhancement in the transition amplitude. We use Nf=2+1 clover fermions on a lattice of L=3.6 fm and a pion mass of 320 MeV. Using a combination of forward, stochastic and sequential propagators we calculate the two-point and three-point functions required in the determination of the $\pi\gamma \to \pi\pi$ amplitude and determine the $\pi\gamma \to \pi\pi$ matrix elements in a region of invariant mass s and momentum transfer q^2. To fit the q^2 and s dependence of the amplitude we are exploring a set of general models based on a Taylor expansion and their description of the data. By analytic continuation to the complex pole corresponding to the ρ resonance we determine the resonant form factors and calculate the radiative decay width of the ρ resonance.

Physics beyond the Standard Model / 245

New results on the emergent light BSM scalar as 0++ sigma-particle or dilaton

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New results are discussed on the effective field theory of the light 0++ scalar in an important near-conformal strongly coupled BSM gauge theory and its lattice simulations in the sextet fermion representation. Relevant for the composite BSM Higgs, two distinct scenarios are introduced for the emergent light scalar as the composite σ-particle of chiral symmetry breaking or the dilaton of conformal symmetry breaking. An important new method for the anomalous dimension of the chiral condensate is presented for the cross-validation of dilaton signatures in goldstone dynamics and its extensions.

Physics beyond the Standard Model / 198

Probing the composite light scalar of the sextet model for dilaton fingerprints

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The light 0++ scalar can be probed for dilaton signatures in near-conformal gauge theories. A case study is presented for the analysis of the SU(3) gauge theory with two fermions in the two-index symmetric representation (sextet model). It is shown that statistical methods which are based on Bayesian Markov Chain Monte Carlo analysis are important for robust tests of dilaton fingerprints in lattice gauge configurations.

Physics beyond the Standard Model / 98

Is SU(3) gauge theory with 13 massless flavors conformal?

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There is a long running controversy over which SU(3) gauge theories with Nf massless fermion flavors in the fundamental representation are conformal, with particular focus on Nf = 12 and 10. In our studies of both theories, we have found no evidence of conformality as shown by an infrared fixed point of the beta function, in direct contradiction to claims by other groups covering the same range of the gauge coupling and using the same beta function scheme. To complement this work, we present the current status of our beta function measurement for Nf = 13, using the gradient flow, paying particular attention to the continuum limit.

Physics beyond the Standard Model / 306

Fate of a recent conformal fixed point and beta-function in the SU(3) BSM gauge theory with ten massless flavors

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We report new results on the beta-function of an important BSM gauge theory with ten massless fermion flavors in the fundamental representation of the SU(3) color gauge group. The existence of an infrared fixed point (IRFP) was reported in [PoS LATTICE2016 (2017) 228] at $g^2 \sim 7.0$ of the renormalized gauge coupling. We find a positive and rapidly increasing beta-function in the extended gauge coupling range $5 < g^2 < 8.5$ ruling out the reported IRFP with high statistical significance. Our results also disagree at strong coupling with a much smaller and downward trending beta-function of the ten-flavor model in [EPJ Web Conf. 175 (2018) 03006] but extended only to $g^2 = 6$. It would be misguided to interpret the origin of the disagreements as non-universal staggered fermion discretization of the ten-flavor model in our work.

Physics beyond the Standard Model / 240

On two-flavor QCD(adj)

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I use the traditional and more recently discovered 1-form discrete 't Hooft anomaly matching conditions and propose a novel realization of the symmetries of SU(2) Yang-Mills theory with two massless adjoint Weyl fermions in the strongly-coupled regime. The theory has a spectrum identical to the one obtained by compactifying it on a small circle. This offers a new perspective on the lattice studies of this theory, which is among a class of models proposed to realize the electroweak symmetry breaking. I also discuss that there is a bigger class of theories that undergo no phase transition between the small-size and infinite-size circle.

Weak Decays and Matrix Elements / 294

The $K_{\ell 3}$ form factor from four-flavor lattice QCD and $|V_{us}|$

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Using HISQ $N_f = 2 + 1 + 1$ MILC ensembles at five different lattice spacings, including four ensembles with physical quark masses, we perform the most precise computation to date of the $K \to \pi \ell \nu$ vector form factor at zero momentum transfer. This is the first calculation that includes the dominant finite-volume effects, as calculated in chiral perturbation theory at next-to-leading order. Our result for the form factor provides a direct determination of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{us}|$, when combined with the corresponding experimental average. For the first time, the resulting theory error on $|V_{us}|$ is commensurate with the experimental uncertainty. We find that this determination of $|V_{us}|$ is in tension at the $2 - 2.6\sigma$ level both with determinations from leptonic decays and with the unitarity of the CKM matrix.

Weak Decays and Matrix Elements / 211

Calculation of $K \to \pi l \nu$ form factor in $N_f = 2 + 1$ QCD at physical point on $(10\mathrm{fm})^3$ volume

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We present our preliminary result of the form factor of $K \to \pi l \nu$ semileptonic decays on the large volume configuration, $L \approx 10$ fm, with the physical m_π and m_K using the stout-smearing clover quark and Iwasaki gauge actions at $a^{-1} = 2.333$ GeV. From an interpolation using the data in small momentum transfers, we determine the semileptonic decay form factors at zero momentum transfer. The result is compared with the previous lattice calculations. We also estimate the value of $|V_{us}|$ by combining our result with the experimental value of the kaon semileptonic decay.

Weak Decays and Matrix Elements / 163

Radiative corrections to decay amplitudes in lattice QCD

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The precision of lattice QCD computations of many quantities have reached such a precision that isospin breaking corrections, including electromagnetism, must be included if further progress is to be made in extracting fundamental information, such as the values of Cabibbo-Kobayashi-Maskawa matrix elements, from experimental measurements. I discuss the framework for including radiative corrections in leptonic and semileptonic decays of hadrons, including the treatment of infrared divergences. I start by briefly reviewing isospin breaking in leptonic decays and presenting the first numerical results for the ratio $\Gamma(K_{\mu2})/\Gamma(\pi_{\mu2})$ in which these corrections have been included. I will also discuss the additional theoretical issues which arise when including electromagnetic corrections to semileptonic decays, such as $K_{\ell3}$ decays.

Weak Decays and Matrix Elements / 197

QED corrections to Pion and Kaon decay constants

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Predictions for pion and kaon leptonic decay constants in Lattice QCD have reached sub-percent level precision. Since it is expected that isospin breaking corrections become important at this level of precision, further progress on the lattice requires inclusion of these effects. Given the phenomenological relevance for instance in CKM analyses this seems a worthwhile endeavour. In

this talk I present RBC/UKQCD's efforts towards the computation of isospin breaking effects to leptonic decays of light mesons using a perturbative expansion in a stochastic, gaussian EM potential. We are currently focusing our efforts to design an efficient measurement strategy using Mobius domain wall fermions at physical quark masses. Our work is based on all-to-all propagators using low mode averaging. It is implemented in Hadrons, a new workflow management system based on the Grid Library.

Weak Decays and Matrix Elements / 176

Control of SU(3) symmetry breaking effects in calculations of B meson decay constant

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Early B physics experiments have left us with a number of puzzles in heavy flavour physics. New lattice calculations and greater understanding of QCD effects in the Standard Model will be needed to support greater experimental precision in the coming years. In particular, the B meson decay constant is involved in calculations of CKM matrix elements and useful to measurements of the branching ratio B $\to \tau\nu$ expected at the Belle II Experiment.
We extend the QCDSF studies of SU(3) breaking of light decay constants into the heavy-flavour regime to examine the effects of SU(3) breaking on f_B and f_{B_s}. b-quarks are generated using an anisotropic clover-improved heavy-quark action.
The decay constants f_B and f_{B_s} will be presented for a variety of light quark masses, from the SU(3) symmetric point toward the physical quark masses. In order to focus on the SU(3) symmetry breaking effects in our extrapolation to the physical point, we choose u,d,s quark masses in each simulation such that the average quark mass, $m = m_u + m_d + m_s$, is constant and equal to its physical value. Results will be presented at a number of different lattice spacings and volumes, toward calculations of f_B and f_{B_s} at the physical point.

Chiral Symmetry / 142

The eta^prime mass on 2+1 flavor DWF lattices

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We report on measurements of the eta^prime mass on some of the 2+1 flavor DWF ensembles that have been generated by the RBC and UKQCD collaborations. We investigate the accuracy of our statistical errors, given the observed evolution of topological modes on these ensembles.

Chiral Symmetry / 292

Exploring the convergence of SU(2) HBChiPT

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By performing a simultaneous extrapolation of g_A and m_N, determined from recent lattice QCD calculations using the MDWF on gradient flowed HISQ action. We explore the convergence of SU(2) HBChiPT using expressions for g_A and m_N derived to a relatively high order.

Chiral Symmetry / 305

Baryons and Interactions in Magnetic Fields

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Motivated by lattice QCD calculations in external fields, we study the behavior of single- and few-baryon systems in large magnetic fields. The dependence of single-baryon energies on magnetic fields is explored using chiral dynamics. Lattice calculations are argued to provide a valuable diagnostic on the chiral expansion for baryons. In particular, we show the unsatisfactory state of predictions for hyperon magnetic polarizabilities. For two-body systems, lattice calculations by the NPLQCD collaboration suggest that unitary nucleon interactions may be attained by tuning the magnetic field. The possibility of such universality is investigated using effective field theory to address the modification of two-nucleon interactions in large magnetic fields.

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QCD crossover at zero and non-zero baryon densities

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We will present new state-of-the-art lattice QCD results on the chiral crossover temperature of QCD for moderately large baryon chemical potential. Firstly, we will present a more precise updated result for the QCD pseudo-critical temperature at zero baryon chemical potential, obtained from all possible second-order chiral susceptibilities that diverge in the chiral limit. Then we will present new results on the QCD pseudo-critical temperature at non-zero baryon chemical potential, computed using Taylor-expansions of chiral condensate and chiral susceptibilities up to 6th-order in the chemical potential. Finally, we will present various second-order fluctuations along the QCD crossover line to look for possible signs of increased fluctuations with increasing baryon density.

Nonzero Temperature and Density / 113

Higher order fluctuations form imaginary chemical potential

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When comparing lattice calculation to experimental data from heavy ion collision experiments, the higher order fluctuations of conserved charges are important observables. An efficient way to study these fluctuations is to derive them from simulations at a set of imaginary chemical potentials. In this talk we present results for higher order derivatives with respect to μ_B, μ_S and μ_Q determined at the physical point from simulations with staggered fermions using different imaginary values of μ_B. We then can determine several combinations that allow for a comparison to heavy ion collision experiments, and extrapolate theses observables to real baryon chemical potential.

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QCD phase diagram for finite imaginary chemical potential with HISQ fermions

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The QCD phase diagram at finite temperature and density has a very rich physical structure which can be explored with first principle lattice QCD calculations. We study the QCD phase diagram of (2+1)-flavor QCD with imaginary chemical potential using HISQ action which has reduced taste breaking effects compared to the unimproved staggered quark action and hence may allow us to get close to the continuum limit earlier. We will present results on the fate of the 2^{nd} order endpoint of the line of 1^{st} order phase transitions in the Roberge-Weiss (RW) plane. We perform calculations on lattices with temporal extend $N_t = 4$ and several spatial lattice sizes. The strange quark mass is tuned to its physical value and the degenerate light quark mass values are reduced towards the chiral limit to find the critical Goldstone pion mass at which this 2^{nd} order endpoint becomes a 1^{st} order triple point. At present we are exploring regions of pion masses $m_\pi \geq 90$ MeV.

Nonzero Temperature and Density / 214

Phase structure of three flavor QCD in external magnetic fields using HISQ fermions

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We study the phase structure of QCD with three degenerate flavors in external magnetic fields using HISQ fermions. The simulations are performed on $16^3 \times 6$ and $24^3 \times 6$ lattices. In order to investigate the quark mass dependence of the QCD transition we vary the values of quark masses from 0.015 to 0.0009375 corresponding to $m_\pi = 320$ MeV and 80 MeV in the continuum limit. We found no indication of a first order phase transition in the current window of quark masses and external magnetic fields. Unlike to the case with standard staggered fermions inverse magnetic catalysis is always observed above the critical temperature. The microscopic origin

of this phenomena as well as the volume effects are further discussed by looking into the Dirac eigenvalue spectrum.

Hadron Spectroscopy and Interactions / 297

Lattice QCD spectroscopy for hadronic CP violation

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The observed abundance of matter over anti-matter in the universe suggests the need for beyond the Standard Model sources of CP-violation. This has motivated a significant experimental effort to search for among other things, permanent electric dipole moments (EDMs) in nucleons, light and also extremely heavy nuclei. The interpretation of nuclear EDMs is clouded by large theoretical uncertainties associated with nonperturbative matrix elements. For certain nuclei, and certain classes of BSM theories, nuclear EDMs are expected to be dominated by contributions from long range, CP-violating pion-nucleon interactions. We discuss a strategy to determine these CP-violating couplings through the calculation of CP-conserving nucleon matrix elements, which are determined through a modification of the spectrum via the Feynman-Hellmann method of Bouchard et al. [arXiv:1612.06963]. We show preliminary results of LQCD calculations of these couplings.

Hadron Spectroscopy and Interactions / 268

Numerical study of QED finite-volume effects using lattice scalar QED

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Finite-volume (FV) effects are expected to be large in the presence of QED, due to the long range of the electromagnetic interaction. With large efforts under way to include QED effects in lattice calculations, it is important to understand and correct for the associated FV effects. We calculate universal QED FV effects numerically, using an efficient method for lattice simulation of scalar QED. We find good agreement with analytical calculations of power-like FV corrections to the self-energy of scalar particles in moving frames, and to the hadronic vacuum polarisation (HVP), in the widely-used QED_L scheme. We also demonstrate the method of infrared improvement, in which FV effects are suppressed by altering a subset of the photon modes.

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Towards lattice-assisted hadron physics calculations based on gauge-fixed n-point functions

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Lattice calculations of RI'(S)MOM renormalization constants typically generate lots of data for gauge-fixed n-point functions. We reuse this data and determine the full nonperturbative tensor structure of the underlying vertices. They are a crucial input for calculations of hadronic observables formulated as bound-state problems in QCD. We show first data for the simplest fermionic bilinears and confront them with solutions obtained for truncated systems of equations in the continuum.

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Bethe-Salpeter wavefunctions of hybrid charmonia

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The charmonium-like hybrid mesons with $J^{PC} = (0,1,2)^{-+}$ and $1^{-}-$ are investigated on anisotropic lattices in the quenched approximation. For these states, we construct spatially extended operators by splitting the $\bar{c}\Gamma cB$-type operators into two parts ($c\bar{c}$ and the chromomagnetic field strength B) with different spatial distances r. In the Coulomb gauge, the matrix elements of these operators between the vacuum and the corresponding states are interpreted as Bethe-Salpeter (BS) wave functions, which can be extracted by fitting the correlation functions at different r simultaneously. After disentangling from the conventional charmonium states in 0^{-+} ,2^{-+} and 1^{--} channels[U+FF0C]the spectrum and the BS wave functions of the hybrid states in the four channels are obtained. It is found that the ground state, the first excited state and even the second excited states of these channels are nearly degenerate in mass and have almost the same BS wave functions. Furthermore, the BS wave functions of the ground state, the first excited state and the second excited state have zero radial node, one radial node and two radial nodes, respectively. In the non-relativistic picture, this observation implies that the hybrid states in these four channels have similar infrastructure and the separation between the $c\bar{c}$ component and gluonic component (depicted by B operator) can be taken as a meaningful dynamical variable.

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Determination of nucleon sigma terms I

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We present recent progress in the determination of nucleon sigma terms by the BMW collaboration. In this talk the lattice setup and analysis methods are discussed.

Hadron Structure / 171

Determination of nucleon sigma terms II

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We present recent progress in the determination of nucleon sigma terms by the BMW collaboration. In this talk physical results are presented.

Hadron Structure / 44

Strange nucleon form factors with $N_f = 2+1$ O(a)-improved Wilson fermions

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We present preliminary results for strange form factors of the nucleon computed on the CLS ensembles with $N_f = 2+1$ flavours of O(a)-improved Wilson fermions. Our calculations are performed at two values of the lattice spacing ($a \in \{0.064, 0.086\}$ fm) at a pion mass of 280 MeV. The determination of strange form factors proceeds by computing quark-disconnected diagrams, for which we employ hierarchical probing in four dimensions, in order to deal with this most challenging part of the calculation. Furthermore, we investigate several source-sink separations to check on excited-state contamination.

Hadron Structure / 182

The strange quark contribution to the spin of the nucleon

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Quark line disconnected matrix elements of an operator, such as the axial current, are difficult to compute on the lattice. The standard method uses a stochastic estimator of the operator, which is very noisy. We discuss and further develop our alternative approach using the Feynman-Hellmann theorem which involves only evaluating two-point correlation functions. This is applied to computing the contribution of the quark spin to the nucleon and in particular for the strange quark.

Algorithms and Machines / 227

Clover HMC and Staggered Multigrid on Summit/Volta

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We report on recent work to integrate and optimize QUDA's adaptive multi-grid solver into Chroma RHMC Wilson-clover gauge evolution. Particular emphasis has been paid to optimization for the new Volta-powered Summit supercomputer. When combined with other recent improvements

into Chroma's molecular dynamics implementation, in moving from Titan to Summit we achieve close to an aggregate 100x improvement in throughput in gauge evolution.
Finally, we report on the ongoing project to incorporate staggered multigrid into QUDA. We have completed an initial four-dimensional implementation based on our two-dimensional algorithm and will present initial results on dynamical gauge configurations, concluding with prospects for integrating multigrid into staggered gauge evolution.

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OpenCL Library for Computing Disconnected Contributions using FPGAs

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We introduce an OpenCL library for computation of disconnected contributions for application with FPGAs and GPUs. We look at the advantages of FPGAs vs. traditional GPUs for stochastic estimation of disconnected contributions, as well as gains achieved with enhancements such as mixed precision and the truncated solver method. We also prospectively consider variance reduction algorithms and the advantages that can be provided with FPGAs.

Algorithms and Machines / 111

An AVX512 Extention to OpenQCD

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We publish an extension of openQCD-1.6 with AVX512 vector instructions using Intel intrinsics. Recent Intel processors support extended instruction sets with operations on 512-bit wide vectors, increasing both the capacity for simultaneous floating point operations and of register memory. Optimal use of the new capabilities requires a reorganisation of data and floating point operations into these wider vector units. We report on the implementation and performance of the AVX512 OpenQCD extension on clusters using Intel Knights Landing and Xeon Scalable (Skylake) CPUs. In complete HMC trajectories with physically relevant parameters we observe a performance increase of 5% to 10%.

Algorithms and Machines / 97

Simulation of dynamical (u,d,s,c) domain-wall/overlap quarks at the physical point

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We perform hybrid Monte-Carlo simulation of $N_f = 2+1+1$ lattice QCD with domain-wall/overlap quarks at the physical point. The simulation is carried out on a 64^4 lattice with lattice spacing $a \sim 0.06$ fm, using the Nvidia DGX-1 (8 Volta GPUs interconnected by the NVLink). To attain the maximal chiral symmetry for a finite extent ($N_s = 16$) in the fifth dimension, we use the optimal domain-wall fermion for the quark action, together with the exact one-flavor action for domain-wall fermion. We outline the salient features of our simulation (e.g., without topology freezing, small residual masses, etc.), and present our preliminary results of the mass spectra of mesons and baryons.

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D meson semileptonic decay form factors at $q^2 = 0$

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We calculate $D \to K l\nu, \pi l\nu$ vector form factors $f_+^{K/\pi}$ at zero-momentum transfer, using MILC's $N_f = 2+1+1$ HISQ ensembles at four lattice spacings, $a \approx 0.042, 0.06, 0.09, 0.12$ fm, and various HISQ quark masses down to the (degenerate) physical light quark mass. We use the kinematic constraint $f_+ = f_0$ at $q^2 = 0$ to determine the vector form factor from our study of the scalar current which yields f_0. We use hard pion/kaon SU(3) heavy-meson-staggered χPT and Symanzik effective theory to fit the data and extrapolate the form factors to the physical point. We improve the precision achieved in existing lattice calculations of the vector form factors at $q^2 = 0$. We also determine the CKM matrix elements $|V_{cs}|$, $|V_{cd}|$ using recent experimental results and test second row unitarity.

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Heavy-quark physics with a tmQCD valence action

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We introduce a mixed-action approach based on CLS ensembles, where a valence Nf=2+1+1 fully-twisted tmQCD action is combined with the Nf=2+1 non-perturbatively O(a)-improved Wilson sea sector. Some field-theoretical properties of this setup (unitarity, O(a) improvement, relevance of open boundary conditions) are discussed. Particular emphasis is given to the application of this setup to heavy-quark flavour physics, focusing on the developments needed to address the leading systematic effects in the charm sector.

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First results for charm physics with a tmQCD valence action

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We present first preliminary results for masses and decay constants of charmed mesons using a valence Nf=2+1+1 fully-twisted tmQCD action combined with an Nf=2+1 non-perturbatively O(a)-improved Wilson sea sector. The impact of various techniques to reduce noise and improve spectroscopic resolution is presented, and the scaling of basic observables towards the continuum limit explored in a subset of CLS ensembles.

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Charmed (and heavier) meson decay constants and heavy neutral meson mixing in the continuum limit using 2+1f of domain wall fermions

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I will present a status update of RBC/UKQCD's charm (to bottom) physics program based on ensembles with $N_f = 2 + 1$ flavours of domain wall fermions featuring physical pion masses.
After a brief review of our program, the main focus will be on mesonic decay constants and neutral meson mixing in the charm and bottom sector, where results for the bottom sector are obtained from an extrapolation from the (heavier than) charm-quark mass region to the physical b-quark mass. In particular, I will focus on the ratio of the pseudo-scalar decay constants f_{D_s}/f_D and on the extrapolation of the ratio ξ to the b-quark mass.

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Masses and decay constants of $B_c^{(*)}$ mesons with $N_f = 2+1+1$ twisted mass fermions

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We present a preliminary lattice determination of the masses and decay constants of the pseudoscalar and vector mesons B_c and B_c^*. Our analysis is based on the gauge configurations produced by the European Twisted Mass Collaboration with $N_f = 2 + 1 + 1$ flavors of dynamical quarks. We simulated at three different values of the lattice spacing and with pion masses as small as 210 MeV. Heavy-quark masses are simulated directly on the lattice up to ~ 3 times the physical charm mass. The interpolation to the physical b-quark mass is performed using the ETMC ratio method: the bottom quark point is reached using ratios of physical quantities

computed at nearby quark masses exploiting the fact that these ratios are exactly known in the static quark mass limit.

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Heavy quark scaling of $B \to \pi\ell\nu$ form factors with Mobius domain wall fermions

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We report on the progress of our calculation of form factors for the exclusive semileptonic decay of B mesons to pions on $2+1$ flavour lattices with spacings from 0.080 fm down to 0.044 fm. Using the Mobius domain wall fermion action for all quarks, we simulate pions with masses down 230 MeV over a range of momenta, and extrapolate to the bottom quark mass by utilising multiple heavy quark masses up to 2.44 times the mass of the charm quark. We discuss how the form factors depend on the pion mass, the heavy quark mass, lattice spacing, and momentum transfer.

Hadron Structure / 287

Do not measure correlated observables, but train an artificial intelligence to predict them

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In lattice QCD calculations, many different observables are measured on a gauge field, and their statistical fluctuations are correlated. By exploiting the correlation, one observable can be reconstructed from other observables, without expensive direct calculation. This idea is applied to two nucleon matrix element calculations using machine learning technique.
(1) The calculations of nucleon charges and form-factors need observables at multiple separations of nucleon source and sink in Euclidean time (t_{sep}) to remove excited state contamination. We trained a boosted decision tree regression machine learning algorithm to predict observables at $t_{sep} = 8a$ and $10a$ from the observables at $t_{sep} = 12a$ on a $a = 0.09$ fm lattice. (2) In the Schwinger source method for the quark chromo-electric dipole moment (cEDM), nucleon matrix elements are calculated from the quark propagators including CP-violating operators. We trained a machine to predict two-point correlation functions of the cEDM- and γ_5-inserted quark propagators from those of normal quark propagators without CP-violating operators.

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Nucleon EDMs and form factors on a lattice at the physical point

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Searches for the nucleon electric dipole moments (EDMs) are at the frontier of high-precision Nuclear physics. Their discovery would be evidence of CP-violation, which is necessary to explain the origin of nuclear matter and would be a signature of new non-Standard-Model interactions. CP-violation in the quark-gluon sector can be caused by the presence of the QCD θ-term or higher-order effective quark-gluon interactions. In this talk, I will present preliminary results for nucleon EDMs induced by quark-gluon chromo-electric interactions from a recent calculation with chiral-symmetric quarks at the physical point. I will also present high-statistics results for nucleon form factors from the same calculation and briefly discuss implications for the theoretic determination of the nucleon charge radius.

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Nucleon Physics with All HISQ Fermions

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A precise determination of the nucleon axial form factor will greatly reduce systematic errors for the upcoming neutrino scattering experiments. There are no foreseeable experiments to perform such measurement so lattice QCD is the best tool to accomplish the task. Such calculations are especially timely, because the uncertainty on the axial form factor is often underestimated in experimental analyses. In this talk, I will present our progress towards calculating nucleon axial form factor. Here, we use $2 + 1 + 1$ MILC HISQ action for both sea and valence quarks at the physical pion mass. First, preliminary results of the extraction of nucleon and delta masses from two-point correlators (using Bayesian fitting methodology) at three lattice spacing will be discussed. Then, I will present preliminary data of three-point correlators at both zero and non-zero momenta which will be used in the extraction of the nucleon axial charge and form factor once we have full statistics.

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Updates of Nucleon Form Factors from Clover-on-HISQ Formulation

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We update the nucleon axial, electric, and magnetic form factors obtained from Clover-on-HISQ lattice formulation. Previous results from the $2 + 1 + 1$-flavor HISQ ensembles are extended by analyzing more ensembles to cover $a \approx 0.15, 0.12, 0.09, 0.06\,\text{fm}$, $M_\pi \approx 310, 220, 130\,\text{MeV}$, and $3.3 < M_\pi L < 5.5$. All data are bias corrected with the AMA method. With higher statistics, we control excited-states contamination by including four states in two-point correlator fits and three states in three-point correlator fits. The axial and electromagnetic charge radii and the magnetic moment after chiral-continuum-finite volume extrapolation are compared with phenomenological data.

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Nucleon form factors on a (10.8fm)^4 lattice at the physical point in 2+1 flavor QCD

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We present preliminary results for nucleon form factors calculated with the plateau method varying the source-sink separation time t_s on a (10.8fm)^4 lattice at the physical point in 2+1 flavor QCD. The configurations are generated with the stout-smeared O(a)-improved Wilson quark action and the Iwasaki gauge action at beta=1.82 corresponding to the lattice spacing of 0.084 fm. We discuss the momentum dependence of the form factors in very small transfer momentum region examining a possible t_s dependence.

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Nucleon electromagnetic form factors at high momentum transfer from Wilson-clover fermions

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The electromagnetic (EM) form factors of the nucleon are fundamental quantities probing its structure. They have been precisely determined from electron scattering experiments as well as extensively studied in lattice QCD calculations. Experiments seeking to explore the behavior of the EM form factors at high momentum transfer, such as the physics program of the CEBAF at JLab which will allow measurements up to $Q^2 \sim 18$ GeV^2, further increase the motivation for a precise lattice evaluation to this high momentum transfer.
In this talk, we present high statistics results on the nucleon EM form factors at Q^2 up to 12 GeV^2. We analyze two gauge ensembles of Wilson-clover fermions with the same lattice spacing value of about $a = 0.094$ fm, pion masses $m_\pi = 270$ MeV and $m_\pi = 180$ MeV, and lattice volumes $L = 3$ fm and $L = 4.5$ fm, respectively. In our calculations we employ the momentum smearing method in order to increase the signal at high momentum transfer. Various choices of the boost momentum as well as the momentum carried by the quarks at the source and sink are tested. We consider several values of the source-sink time separation and apply a set of techniques in order to examine excited state effects. In this first study, we consider the contributions arising from only connected diagrams and compare our results with phenomenology.

Nonzero Temperature and Density / 157

Equation of state near the first order phase transition point of SU(3) gauge theory using gradient flow

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We study energy gap (latent heat) between the hot and cold phases at the first order phase transition point of the SU(3) gauge theory. Performing simulations on lattices with various spatial volumes and lattice spacings, we calculate the energy gap by a method using the Yang-Mills gradient flow and compare it with that by the conventional derivative method.

Nonzero Temperature and Density / 116

Equation of state in 2 + 1 flavor QCD at high temperatures

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We calculate the equation of state at high temperatures in 2+1 flavor QCD using the highly improved staggered quark (HISQ) action. We study the lattice spacing dependence of the pressure at high temperatures using lattices with temporal extent (N_\tau= 6,\ 8,\ 10) and (12) and perform continuum extrapolations. We also give a continuum estimate for the equation of state up to temperatures (T = 2) GeV, which are then compared with results of the weak-coupling calculations. We find a reasonably good agreement with the weak-coupling calculations at the highest temperatures.

Nonzero Temperature and Density / 165

Study of energy-momentum tensor correlation function in Nf=2+1 full QCD for QGP viscosities

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We study correlation functions of the energy-momentum (EM) tensor in Nf=2+1 full QCD for the sake of QGP viscosities. The viscosity is given by three steps on lattice: (1) calculate two point correlation functions of the energy-momentum tensor, (2) derive the spectral function from the correlation function, (3) applying the Kubo's formula the viscosity is related to the spectral function. However the first two steps have severe difficulties. By applying the gradient flow we

solve the difficulty in the first step that the EM tensor cannot be defined as a conserved current on lattice and give a non-perturbatively renormalized EM tensor. We calculate the correlation functions of the EM tensor and try to extract the shear viscosity through the spectral function.

Nonzero Temperature and Density / 22

Thermodynamics for SU(2) pure gauge theory using gradient flow

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We present lattice calculations of the equation of state of pure SU(2) gauge theory by using the gradient flow. The scale-setting of lattice parameter has been carried, and we propose a reference scale t0 satisfying t2E=0.1 for SU(2) gauge theory. This reference value is fixed by a natural scaling-down of the t0 scale for the SU(3) based on perturbative analysis. We also show the thermodynamic quantities as a function of T/Tc, which are derived by the energy-momentum tensor using the small flow-time expansion.

Nonzero Temperature and Density / 64

Topology of two-color QCD at low temperature and high density

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We study two-color QCD with nonzero chemical potential using Iwasaki gauge and Wilson fermion action. The two-color gauge theory coupled to an even number of fundamental fermions does not suffer from the sign problem because the fermion transforms in a real representation.
To perform the simulation even in high chemical potential regime, as in earlier publications, we introduce a diquark source term into the action.
In this talk, we show our results for the phase diagram in low temperature regime. Furthermore, we present the mu dependence of the topological susceptibility.

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Computing $\hat{q}$ on a quenched SU(3) lattice

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The jet transport coefficient $\hat{q}$ is the leading parameter that controls the modification of hard jets produced in heavy-ion collisions. This coefficient, like other jet coefficients is inherently non-perturbative, and hence, is challenging to compute from first principles. Currently, existing theoretical model to data comparisons require a separate normalization of $\hat{q}$ between RHIC and LHC energies, beyond the obvious T^3 scaling from dimensional arguments. This is known as the jet $\hat{q}$ puzzle. In this talk, we present a pQCD and lattice gauge theory based formulation to study

$\hat{q}$ which sheds new light on the non-perturbative nature of $\hat{q}$ and the jet puzzle. For this first attempt, we formulate $\hat{q}$ within a quenched SU(3) lattice. We consider a leading order diagram for a hard parton passing through the thermal medium. The non-perturbative part is expressed in terms of a non-local (two-point) Field-Strength-Field-Strength operator product which can be Taylor expanded after analytic continuation to the Euclidean region. Such an expansion allowed us to write $\hat{q}$ in terms of the expectation of local operators. We also carry out a perturbative analysis both on the lattice and in continuum field theory to understand the scale dependence of the jet transport coefficient.

Hadron Spectroscopy and Interactions / 138

Scattering phase shift determinations from a two-scalar field theory and resonance parameters from QCD scattering

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The two-scalar field model of Rummukainen and Gottleib is revisited, except the limit of large quartic couplings is not used and a Symanzik improved action is used. Isotropic lattices ranging from $16^3 \times 48$ to $53^3 \times 48$ are used, and the scattering phase shift is determined using a Lüscher analysis.
Results from $K\pi$ and $N\pi$ scattering will also be presented.

Hadron Spectroscopy and Interactions / 60

$K\pi$ scattering and excited meson spectroscopy using the Stocastic LapH method

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Elastic $I = 1/2$, s- and p-wave $K\pi$ scattering amplitudes are simultaneously calculated using a Lüscher style analysis on a single ensemble of dynamical Wilson-clover fermions at $m_\pi \sim 230$MeV. Partial wave mixing due the reduced rotational symmetries of the finite volume is included up to $\ell = 2$.
We also present finite-volume QCD spectra on two large anisotropic lattices ($32^3 \times 256$, $24^3 \times 128$) with $m_\pi \sim 230, 390$MeV. In each symmetry channel, a large basis of one and two hadron interpolating operators is employed with all-to-all quark propagation treated using the stochastic LapH method.

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Hadron-Hadron Interactions from N_f = 2 + 1 + 1 Lattice QCD: $\pi - K$ scattering length

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In this talk we present our recent results of the elastic scattering length in the $I_3 = \frac{3}{2}$ channel $\pi - K$ scattering. We show a new method to remove thermal effects in the interaction energy of the $\pi - K$ system, and present a careful continuum and chiral extrapolation of the scattering length.

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$K\pi$ scattering and the $K^*(892)$ resonance in 2+1 flavor QCD

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In this project, we aim to compute the form factors relevant for $B \to K^*(\to K\pi)\ell^+\ell^-$ decays. To map the finite-volume matrix elements computed on the lattice to the infinite-volume $B \to K\pi$ matrix elements, the $K\pi$ scattering amplitude needs to be determined using L\"uscher's method. Here we present preliminary results from a calculation with $2 + 1$ flavors of dynamical clover fermions, on a $32^3 \times 96$ lattice with $a = 0.1140(8)$ fm and $m_\pi = 317(3)$ MeV.

Hadron Spectroscopy and Interactions / 220

DK scattering and $D_{s0}(2317)$

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I will discuss a recent lattice QCD investigation of DK scattering relevant for near-threshold charm-strange mesons such as the enigmatic $D_{s0}(2317)$. By employing a range of techniques, we extracted finite-volume spectra in a number of different channels. These were used to map out the energy dependence of the scattering amplitudes. The resonance and bound state content was determined by studying the singularity structure of the amplitudes.

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Finite volume matrix elements of two-body states

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In this talk, I will discuss a class of observables that are experimentally inaccessible but can be accessed via lattice QCD, and how these will shed light into the nature of low-lying QCD resonances and bound states. In particular, I consider the finite-volume two-body matrix elements with one current insertion, and review the recently proposed formalism for relating these to infinite-volume amplitudes. I will place emphasis on a new set of finite volume functions that emerge.

Standard Model Parameters and Renormalization / 25

Quark mass determinations with the RI-SMOM scheme and HISQ action

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Lattice QCD provides several avenues for the high precision determination of quark masses. Using the RI-SMOM scheme applied to lattice calculations with the HISQ action, we obtain mass renormalisation factors that we use to provide strange and charm quark masses with 1% precision. The calculation involves the study of various sources of systematic uncertainty, including an analysis of possible nonperturbative (condensate) condensate contributions. These results allow a comparison of different mass determination methods of comparable precision. In particular we (HPQCD) find good agreement between RI-SMOM and current-current correlator determinations based on the same lattice QCD bare masses, providing a strong test of our understanding of systematic uncertainties.

Standard Model Parameters and Renormalization / 23

SMOM - $\overline{\mathrm{MS}}$ Matching for B_K at Two-loop Order

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The Kaon bag parameter, B_K, is a key non-perturbative ingredient in the search for new physics through CP-violation. It parameterizes the QCD hadronic matrix element of the effective weak $\Delta S = 2$ four quark operator which can only be computed non-pertubatively on the lattice. The perturbative matching of B_K between the lattice renormalization schemes and $\overline{\mathrm{MS}}$ scheme has been done before at one-loop order. In this talk I am going to present a calculation of the conversion factors for B_K between the four non-exceptional RI-SMOM schemes and the $\overline{\mathrm{MS}}$ scheme at two-loop order in pertubation theory. The calculation is performed using the loop integral solving techniques such as integration by parts and sector decomposition.

Standard Model Parameters and Renormalization / 266

Renormalization of d≤6 CP-Violating Operators in Perturbative QCD

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We use the Yang-Mills Gradient flow to study the NLO mixing of CP-violating operators in continuum QCD with special attention to Weinberg's d=6 purely gluonic operator. This method allows for a clear derivation of the Wilson coefficients of the CP-violating effective action as they pertain to the renormalization group equation. This perturbative calculation is the first step towards a high-energy matching of matrix elements involving the CP-violating operators.

Standard Model Parameters and Renormalization / 276

Towards non-perturbative renormalization of $\Delta S = 1$ four-quark operators with a position-space procedure

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We construct a concrete strategy to implement the non-perturbative renormalization of the $\Delta S = 1$ four-quark operators, which are associated with $K \to \pi\pi$ matrix elements. These non-perturbative methods can be used to determine the Wilson coefficients for the 3-flavor theory, avoiding a significant source of systematic uncertainty that arises from perturbative matching through the charm threshold. The use of an on-shell, gauge-invariant, position-space scheme is important below the charm threshold to avoid any mixing with irrelevant operators which becomes a serious problem when the RI/MOM scheme is used at low energies. In this talk, we provide a renormalization condition in the position-space procedure which is applicable even if operators mix with each other. A new treatment of discretization errors based on the idea of averaging correlators over spheres is introduced with an example of quark mass renormalization, which can be compared with our previous result from the RI/SMOM scheme.

Standard Model Parameters and Renormalization / 45

$Z_{\mathrm{S}}/Z_{\mathrm{P}}$ from three-flavour lattice QCD

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We report on advances in the non-perturbative determination of the ratio $Z_{\mathrm{S}}/Z_{\mathrm{P}}$ of the scalar to the pseudoscalar renormalization constants in three-flavour lattice QCD with Wilson-clover quarks and tree-level Symanzik improved gluons. The computations are based on the Ward identity approach, using Schrödinger functional boundary conditions. Our results for $Z_{\mathrm{S}}/Z_{\mathrm{P}}$ cover a range of couplings along a line of constant physics with lattice spacings of about $0.09\,\mathrm{fm}$ and below, relevant for phenomenological applications such as the calculation of renormalized quark masses.

Standard Model Parameters and Renormalization / 69

$\mathcal{O}(a)$ improved quark mass renormalization for a non-perturbative matching of HQET to three-flavor QCD

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The use of Heavy Quark Effective Theory (HQET) on the lattice as an approach to B-physics phenomenology is based on a non-perturbative matching of HQET to QCD in finite volume. As a first step to apply the underlying strategy in the three-flavor ($N_f = 2+1$) theory, we determine the renormalization constant and improvement coefficients relating the renormalized current and subtracted quark mass of (quenched) valence quarks in $\mathcal{O}(a)$ improved $N_f = 3$ lattice QCD. We present our strategy and first results for the relevant parameter region towards weak couplings along a line of constant physics, which corresponds to lattice resolutions $a \leq 0.02\,\mathrm{fm}$ and fixes the physical extent of the matching volume to $L \approx 0.5\,\mathrm{fm}$.

Theoretical Developments / 114

Investigation of the 1+1 dimensional Thirring model using the method of matrix product states

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We present results from our study of the 1+1 dimensional Thirring model employing the techniques of Matrix Product States. As the first step of a research programme for examining this model with the Hamiltonian formalism on the lattice, we determine the phase structure of the theory. In particular, we confirm the existence of the critical phase in the Thirring model in two dimensions. This is achieved by computing the mass gap, the chiral condensate, the entanglement entropy, as well as the fermion correlator.

Theoretical Developments / 140

Gaussian states for the variational study of (1+1)-dimensional lattice gauge models

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Gaussian states, meaning states whose density matrix can be expressed as a Gaussian function in the creation and annihilation operators, are widely used in various areas to describe fermionic as well as bosonic systems. However, in cases where both bosons and fermions are present, they cannot describe any correlations between the two species beyond mean-field. This renders them at first glance unsuitable for the description of lattice field theories with gauge and matter degrees of freedom.

In this talk, we show how to derive a set of unitary transformations for (1+1)-dimensional gauge models which allow us to disentangle the relevant degrees of freedom. The resulting formulation

can be addressed with a Gaussian variational ansatz which makes it possible to numerically investigate static and dynamical aspects of string breaking in Abelian and non-Abelian gauge models. We show that the approach captures the relevant features and reliably describes the static properties as well as the out-of-equilibrium dynamics of the phenomenon. Benchmarking our results against those obtained from Tensor Network simulations, we observe excellent agreement although the number of variational parameters in the Gaussian ansatz is much smaller.

Theoretical Developments / 146

A tensorial toolkit for quantum computing

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In most lattice simulations, the variables of integration are compact and character expansion (for instance Fourier analysis for $U(1)$ models) can be used to rewrite the partition function and average observables as discrete sums of contracted tensors. This reformulations have been used for RG blocking but they are also suitable for quantum computing. We discuss FAQ about tensorial reformulations: boundary conditions, Grassmann variables, Ward identities and manifest gauge invariance.

Theoretical Developments / 94

Tensor network study of two dimensional lattice ϕ^4 theory

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The tensor renormalization group attracts great attention as a new numerical method because it is free of the sign problem. In addition to this striking feature, it has also an attractive aspect as a coarse-graining of space-time; that is to say, the computational cost scales logarithmically with the space-time volume. This fact allows us to aggressively approach the thermodynamic limit. While taking this advantage, we study the critical coupling in the continuum limit of the two dimensional lattice ϕ^4 theory. We present the numerical results along with the extrapolation procedure to the continuum limit, and compare them with the previous ones by Monte Carlo simulations and other tensor network schemes.

Theoretical Developments / 96

Z_2 gauge theory with tensor renormalization group

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Tensor renormalization group is a new type of numerical method which does not suffer from the sign problem. We have developed the tensor renormalization group for 3-dimensional Z_2 gauge theory. We apply it to finite temperature Z_2 gauge thery in (2+1) dimensions and compare the results with those obtained by a previous Monte Carlo study.

Theoretical Developments / 14

Quantum field theory on a causal set

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Causal set theory, originally introduced by Rafael Sorkin, is a model of spacetime as a partially ordered set: an element of a set corresponds to a point in spacetime, while partial ordering corresponds to lightcone causal relation. There is no coordinate system: all of the geometry is to be deduced from partial ordering alone. Consequently, one has to rewrite Lagrangians in quantum field theory in such a way that would avoid derivative signs or anything else with Lorentz index. In my talk I will discuss some of the ways of doing so (both the ones introduced by myself and by others).

Weak Decays and Matrix Elements / 259

Kaon Matrix Elements from Coarse Lattices

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The RBC and UKQCD Collaborations have generated a number of coarse ensembles with 2+1 flavors of Mobius Domain Wall Fermions (MDWF) and physical quark masses using the Iwasaki plus Dislocation Suppressing Determinant Ratio (DSDR) action. Previous work has shown small $O(a^2)$ scaling violations for pseudoscalar decay constants, various masses and Wilson flow scales. In this talk, we present results for B_K and $\Delta I = 2$ $K \to \pi\pi$ matrix elements on these lattices and compare these to continuum limit results obtained for 2+1 flavor lattices with the Iwasaki gauge action. The scaling of these matrix elements will help to determine the utility of measuring $\Delta I = 0$ $K \to \pi\pi$ matrix elements on lattices as coarse as $1/a = 1$ GeV.

Weak Decays and Matrix Elements / 150

Studies of I=0 and 2 pi-pi scattering with physical pion mass

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We report a direct lattice calculation of both the I=0 and 2 pi-pi scattering phase shifts using G-parity boundary conditions on an ensemble of $32^3 \times 64$ gauge configurations at physical quark mass. This extends an earlier calculation of the RBC/UKQCD Collaboration by including additional operators and using non-zero center-of-mass momenta. We apply the generalized eigenvalue treatment to this set of operators in order to understand and reduce excited state contamination and to study pi-pi scattering at energies in the energy region around the kaon mass. These results are compared with results from Roy's equation.

Weak Decays and Matrix Elements / 262

Update on the improved lattice calculation of direct CP-violation in K decays

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We provide an update on the RBC & UKQCD lattice calculation of the measure of Standard Model direct CP-violation in kaon decays, \epsilon'

Weak Decays and Matrix Elements / 38

Follow-up on non-leptonic Kaon decays at large N_c

Author(s): Mr. ROMERO-LOPEZ, Fernando[1]
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In this work we present our latest results about the K $\to \pi$ matrix elements at large N_c, including the exploration of the mass dependence and the latest simulations with $N_f = 4$ dynamical fermions.

Weak Decays and Matrix Elements / 235

Progress on the study of electromagnetic corrections to $K \to \pi\pi$ decay

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In this talk, we present our progress on the study of the electromagnetic corrections to $K \to \pi\pi$ decay. To provide an accurate Standard-Model determination of direct CP violation at the precision of O(10%), it is important to include the electromagnetic corrections, as such $O(\alpha_e)$ effects could be enhanced 22 times in principle due to the isospin mixing and the $\Delta I = 1/2$ rule. On the other hand, the long-range electromagnetic interaction is inconsistent with the Luscher and the Lellouch-Luscher finite-volume formalisms. Different from the traditional infrared regulators introduced as QED_L, massive photon or C^* boundary condition, here we propose to use a truncated range as a new infrared regulator, which allows us to use the available finite-volume formalisms directly. To remove the unphysical truncation effects, we then provide the relations to connect the truncated quantities to the physical ones. Some other aspects of the electromagnetic corrections are also discussed.

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QED-corrected Lellouch-Luescher formula for K->\pi\pi decay

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A precise Standard Model prediction for the direct CP violation in the K -> \pi\pi decay process is of great importance in confronting experiments and constraining new physics. The state-of-art lattice QCD precision of this process will soon achieve a value for which QED effects can no longer be neglected. The inclusion of QED in such calculations is planned and the formalism to relate the finite-volume matrix element obtained from these calculations to the physical amplitude is underway. Here we present preliminary results on the extension of Lellouch-Luscher formula in presence of QED, therefore providing such formalism for the extraction of physical amplitudes for the K->\pi\pi process with charged initial and/or final states.

Hadron Structure / 153

Improving the Feynman-Hellmann Method

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The Feynman-Hellmann method, as implemented by Bouchard et al. [1612.06963], has recently been used successfully to determine the nucleon axial charge. A limitation of the method was the restriction to a single operator and a single momentum during the computation of each "Feynman-Hellmann" propagator. Here we discuss enhancements to the method that relax this constraint and we demonstrate the successful implementation of the improved version with a reproduction of the axial charge on a test ensemble.

Hadron Structure / 126

Pion Form Factor Calculation

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We present the form factor of pion using overlap fermion. We work on 2+1 flavor domain-wall configurations on $24^3 \times 64$ lattice with lattice spacing $a = 0.083\,\text{fm}$ and $32^3 \times 64$ lattice with lattice spacing $a = 0.083\,\text{fm}$ genterated by RBC/UKQCD collaboration. With multi–mass algorithm, we do an extrapolatiion of finite lattice spacing and varies valence quark masses to form factor at pysical pion with a range of space-like Q^2 from 0.0 to 0.6 GeV^2.

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Nucleon isovector axial charge in 2+1-flavor domain-wall QCD with physical mass

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The current status of the nucleon isovector axialvector charge calculation using a 2+1-flavor dynamical domain-wall QCD ensemble generated jointly by RBC and UKQCD Collaborations with essentially physical mass quarks and at lattice cut off of 1.730(4) GeV will be reported.

Hadron Structure / 33

Nucleon charges and quark momentum fraction with $N_f = 2 + 1$ Wilson fermions

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We present a nucleon structure analysis including the charges of isovector dimension-three operators as well as the forward matrix elements of twist-2, dimension-four operators. Computations are performed on CLS ensembles with $N_f = 2+1$ Wilson fermions, covering four values of the lattice spacing and pion masses down to $M_\pi \approx 200\,\text{MeV}$. Several source-sink separations (typically $\sim 1.0\,\text{fm}$ to $\sim 1.5\,\text{fm}$) allow us to assess excited-state contaminations. Results on each ensemble are obtained from simultaneous two-state fits including all observables and all available source-sink separations with the mass gap as a free fit parameter. Finally, the chiral and continuum extrapolation is performed to extract physical results.

Hadron Structure / 249

Neutral weak axial form factor and neutrino-nucleon scattering

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Using a combination of lattice QCD calculation of the strange-quark form factors, and experimental (anti) neutrino differential cross-section data in a regime where nuclear effects are shown to be negligible, we obtain a precise determination of the weak axial form factor in the regime $0 \leq Q^2 \leq 1\,\text{GeV}^2$, and of the corresponding weak-axial charge. We are thereby able to reproduce the MiniBooNE and BNL E734 data for the (anti) neutrino-nucleus differential cross section to high precision, showing that the nuclear corrections to the experimentally extracted cross section in this kinematic regime are very small. The calculation will play an vital role in understanding nuclear effects in neutrino-nucleus scattering.

Hadron Structure / 280

Isovector and flavor diagonal charges of the nucleon

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I will present results from the PNDME collaboration for the isovector and flavor diagonal charges of the nucleon obtained using eleven 2+1+1-flavor HISQ ensembles generated by the MILC collaboration. The talk will also cover Details of the control over excited states and the the chiral-continuum-finite volume fits leading to teh final results.

Nonzero Temperature and Density / 218

Progress on the nature of the QCD thermal transition as a function of quark flavors and masses

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We investigate to which extent we can exploit the dependence of the order of the chiral transition on the number of light degenerate flavors N_f, re-interpreted as continuous parameter in the path integral formulation, as a means to perform a controlled chiral extrapolation and deduce the order of the transition for the case $N_f = 2$, which is still under debate.

Nonzero Temperature and Density / 75

Chiral phase transition in (2 + 1)-flavor QCD

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The chiral phase transition temperature T_c is a fundamental quantity of QCD. To determine this quantity, we have performed simulations of (2 + 1)-flavor QCD using the Highly Improved Staggered Quarks (HISQ) action on $N_\tau = 6, 8, 12$ lattices and aspect ratios N_σ/N_τ ranging from 4 to 7. In our simulations, we fix the strange quark mass value to its physical value m_s^{phy}, and the values of two degenerate light quark masses m_l are varied from $m_s^{\text{phy}}/160$ to $m_s^{\text{phy}}/20$ which correspond to a Goldstone pion mass m_π ranging from 55 MeV to 160 MeV in the continuum limit. By investigating the light quark mass dependence and volume dependence of various chiral observables, e.g. chiral susceptibilities and Binder cumulants, we didn't find any evidence for a first order phase transition in our current quark mass window. By looking at the crossing point of $\chi_\sigma/\chi_\pi = m_l \chi_{tot}/\left\langle\bar{\psi}\psi\right\rangle_l$ which is the ratio of light quark mass times chiral susceptibilities and chiral condensates as a function of T and m_l, we are able to extract the value of T_c in the chiral & continuum limit without referring to critical exponents of a particular universality class. The uncertainty in the determination of T_c is also discussed.

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Chiral transition using the Banks-Casher relation

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We investigate the properties of the finite-temperature QCD transition towards the chiral limit using staggered quarks. Starting from the 2+1 flavor physical point, the limit of massless quarks is approached along two different trajectories in the Columbia-plot. Unlike in previous approaches, the chiral condensate is determined via the Banks-Casher relation. The first results of our finite size scaling analysis are presented.

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Measuring of chiral susceptibility using gradient flow

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In the lattice gauge theory with Wilson fermion, chiral symmetry is explicitly broken. A non-trivial additive correction is needed to renormalize the chiral condensate. In this study, we use gradient flow to avoid this problem. Gradient flow makes us possible to define correctly renormalized chiral susceptibility without additive renormalization. We measure not only disconnected diagram but also connected diagram for chiral susceptibility. This measurement is on finite temperature full QCD with Nf=2+1 Wilson fermion, and for temperature range 178-348 MeV.

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Continuum extrapolation of the critical endpoint in 4-flavor QCD with Wilson-Clover fermions

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We report our updated study on the critical endpoint of the finite temperature phase transition in 4-flavor QCD with Wilson-Clover fermions. Using the kurtosis intersection method, we determined the critical endpoint on lattices with $N_t = 4$, 6 and 8. Our continuum extrapolated result shows that the critical pion mass is clearly larger compared to one in 3-flavor, which suggests that the critical pion mass in 4-flavor might remain finite even in the continuum limit in contrast to the staggered quark case.

Nonzero Temperature and Density / 250

Large N Thermodynamics with Dynamical Fermions

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To date, studies of the thermodynamics of QCD in the limit of large number of colors have been limited to the quenched approximation, i.e., the behavior of pure SU(N) gauge theory at large N. We present a progress report on our investigation of the phase structure of large-N QCD in the presence of (Wilson) fermions with finite mass. We explore the light quark mass regime by simulating with two flavors of dynamical fermions in SU(3-5), and investigate the heavy quark mass regime by reweighting around $\kappa = 0$ in SU(3-7).

Hadron Spectroscopy and Interactions / 37

Progress on relativistic three-particle quantization condition

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I present an update on work extending and applying the relativistic three-particle quantization conditions of Hansen/Sharpe, and Brice\~no/Hansen/Sharpe. This is based on work done in collaboration with Tyler Blanton, Ra\'ul Brice\~no, Max Hansen and Fernando Romero-Lopez. Topics include the numerical implementation of the quantization condition in the isotropic approximation, the generalization of the formalism to include K-matrix poles, and extending the description of the three-particle divergence-free K matrix beyond the isotropic approximation.

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Relations between scattering amplitude and Bethe-Salpeter wave function in quantum field theory

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We discuss an exact relation between the two-particle scattering amplitude and the Bethe-Salpeter (BS) wave function inside the interaction range in quantum field theory. In the relation the reduced BS wave function given by the BS wave function plays an essential role. Through the relation the on-shell and half off-shell amplitudes can be calculated. We also show that the solution of Schrodinger equation with the effective potential determined from the BS wave function gives a correct on-shell scattering amplitude only at the momentum where the effective potential is calculated.

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Scattering length from BS wave function inside the interaction range

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We evaluate scattering lengths by use of a scattering amplitude calculated with the Bethe-Salpeter wave function inside the interaction range. Scattering lengths of I=2 two pions are computed by both conventional and our methods with $m_\pi = 0.52 - 0.86$ GeV in the quenched lattice QCD. The results are compared with each other to confirm consistency. Furthermore, a half off-shell amplitude is calculated.

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Roper State from Overlap Fermion

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Variational method with valence overlap fermion is employed to calculate the Roper state on the $24^3 \times 64$ domain-wall fermion lattice at a = 0.114 and 330 MeV pion mass. It is found that the results are consistent with those from the sequential empirical Bayes (SEB) method. They are about 300 MeV lower than those with the clover fermion at comparable lattice spacing and pion mass. To understand the difference, we study the would-be $\eta - \pi$ ghost state in the isovector scalar channel with the $\bar{q}q$ interpolation field in the quenched approximation for both the overlap and Wilson fermions to compare their couplings to the two hadron state with the single hadron interpolation field.

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Coupling to Multihadron States with Chiral Fermions

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Chiral symmetry is presumed to be a crucial component in the strong interaction and QCD, but its role in spectroscopy, especially for baryons, has not been fully explored. Compounding this, chiral fermions are uncommon in lattice calculations due to their expensive nature. We calculate $\eta\pi$, $K\pi$ and $N\pi$ states with $q\bar{q}$ and qqq interpolation fields at $a = 0.0114\,\mathrm{fm}$ on a $48^3 \times 96$ mixed-action lattice at physical pion mass, with domain-wall sea quarks and overlap valence quarks. We study the spectral weights of these states as a function of the valence pion mass, which ranges from $m_\pi = 115 - 665\,\mathrm{MeV}$, to be compared with results from non-chiral clover valence quarks on the same domain-wall lattice in order to examine their non-chiral effects, which are expected to decrease with the lattice spacing.

Hadron Spectroscopy and Interactions / 263

Progress towards understanding the H-dibaryon from lattice QCD

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Significant experimental and theoretical efforts to determine the existence and nature of the H-dibaryon have been underway since its prediction in 1977. Yet, conclusive evidence for such a bound state is still lacking. Results from various lattice QCD calculations show substantial disagreement for the binding energy. Since there is no conclusive evidence for or against the existence of a bound H-dibaryon, the Mainz group has joined the effort towards resolving the discrepancies. In this talk, I will first give an overview of the recent results from the Mainz group obtained in two-flavor QCD. I will then discuss work that has been done towards ensuring that the baryon-baryon operators used in the H-dibaryon studies transform irreducibly under the relevant little group. Finally, the prospects of extensions to $N_f = 2 + 1$ and the use of distillation for moving frames will be examined.

Theoretical Developments / 128

Fermions on Simplicial Lattices and their Dual Lattices

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I will show that naive and staggered fermions on simplicial lattices and their dual lattices in any dimension can be formulated about as simply as on hypercubic lattices. Point, chiral and discrete symmetry properties are however more subtle. Despite the absence of an exact chiral symmetry, there is no additive mass renormalization. There is an interesting duality between vector and axial vector currents paralleling the duality between the lattices.

Theoretical Developments / 185

Prospects for Lattice QFTs on Curved Riemann Manifolds

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Conformal or near conformal QFTs would benefit from a rigorous non-perturbative lattice formulation beyond the flat Euclidean space, R^d. Although all UV complete QFT are known to be also perturbatively renormalizable on any smooth Riemann manifold, non-perturbative realization on simplicial lattices (triangulations) encounter difficulties as the UV cut-off isremoved. We review the Quantum Finite Element (QFE) method that combines classical Finite Element and Regge Geometry with new quantum counter terms designed to address this. The construction for maximally symmetric spaces ($S^d, R \times S^{d-1}$ and AdS^{d+1}) is outlined with numerical tests on S^2 and a description of theoretical and algorithmic challenges for $d = 3, 4$ QFTs.

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A Lattice Study of Renormalons in Asymptotically Free Sigma Models

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In general, perturbative expansions of observables in quantum field theories are divergent (asymptotic) series. It is often possible to apply resummation techniques to assign a unique finite value to the asymptotic series, but a particular pattern of divergence, the so-called renormalon, gives rise to non-perturbative ambiguities. The framework of numerical stochastic perturbation theory (NSPT), based on stochastic quantisation and the Langevin equation, allows us to compute the coefficients of perturbative expansions up to very high orders (>40) on the lattice. In this talk we present first results for an NSPT study of asymptotically free sigma models and discuss possible renormalon signatures in the expansion of the energy density.

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Non perturbative physics from NSPT: renormalons, the gluon condensate and all that

Prof. DI RENZO, Francesco[1] ; Prof. DEL DEBBIO, Luigi[2] ; Mr. FILACI, Gianluca[2]

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Numerical Stochastic Perturbation Theory (NSPT) enables very high order computations in Lattice Gauge Theories. We report on the determination of the gluon condensate from lattice QCD measurements of the basic plaquette. This is a long standing problem, which was eventually solved a few years ago in pure gauge. In this context NSPT is crucial: it is actually the only tool enabling the subtraction of the power divergent contribution associated to the identity operator in the OPE for the plaquette. This subtraction is actually a delicate issue, since the perturbative expansion of the plaquette is on general ground expected to be an asymptotic one, due to renormalons. This in turns results in ambiguities and the separation of scales in the OPE does not correspond to a separation of perturbative and non-perturbative contributions. All in all, one needs to absorb the ambiguities attached to the perturbative series into the definition of the condensate itself, i.e. one needs a prescription. A possible one amounts to summing the perturbative series up to its minimal term, which means computing up to orders which only NSPT can aim at. Our computation is the first one in QCD, with massless staggered fermions. In order to remove the zero-mode of the gauge field, twisted boundary conditions are adopted for the latter, consistently coupled to fermions in the fundamental representation supplemented with smell degrees of freedom.

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Lattice N=4 three-dimensional super-Yang-Mills

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We explain our recent formulation of this theory on the lattice, and also discuss other formulations. Issues related to tuning and decoupling of auxiliary sectors are examined. The continuum limit is explored.

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Machine learning inspired analysis of the Ising model transition

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We illustrate how principal component analysis of simulation data represented as images generated from the worm algorithm, a method to sample the strong coupling contributions, can be used to identify the critical temperature Tc in the Ising model. It is shown that the eigenvalue corresponding to the first principal component of the covariance matrix obtained from pixel ensembles scales logarithmically as one approaches Tc, in a way that is similar to the specific heat. We then illustrate how to block the resulting worm configurations under renormalization group transformations. It is found that curves for the variance of the average number of bonds can be scaled appropriately to illustrate universal behavior under the renormalization group transformation, and that discrepancies can be understood as an effect of approximations.

Physics beyond the Standard Model / 148

On the calculation and use of non-zero momentum correlators in lattice simulations.

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In lattice simulations one generally projects correlators over zero spatial momentum to calculate masses and related spectral data. The sum over space lattice points, however, discards information which may be useful especially in the calculation of disconnected diagrams. I will show that, by using momentum conservation, the calculation of non-zero momentum components of disconnected diagrams and other quantities related to space convolutions can be done with little additional computational cost and I will discuss how these calculations might be useful in the analysis of disconnected correlators. (With the LSD collaboration.)

Physics beyond the Standard Model / 17

The large-mass regime of confining but nearly conformal gauge theories

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We apply a recently developed dilaton-pion effective field theory for asymptotically free gauge theories near the conformal window to the SU(3) gauge theory with $N_f = 8$ fermions in the fundamental representation. Numerical data for this theory suggests the existence of a large-mass regime, where the fermion mass is not small but nevertheless the effective theory is applicable because of the parametric proximity of the conformal window. In this regime, we find that the mass dependence of hadronic quantities is similar to that of a a mass-deformed conformal theory, so that distinguishing infrared conformality from confinement requires the study of subleading effects.

Physics beyond the Standard Model / 196

Composite phenomenology as a target for lattice QCD

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Some recent beyond Standard Model phenomenology is based on new strongly interacting dynamics of SU(N) gauge fields coupled to various numbers of fermions. When N=3 these systems are analogues of QCD, although the fermion masses are typically different from the ones of real world QCD. Many quantities needed for phenomenology from these models have been computed on the lattice. We are writing a guide for these phenomenologists, telling them about lattice results. I'll tell you what they are interested in knowing.

Physics beyond the Standard Model / 241

Updated spectroscopy for SU(3) with eight fundamental flavors

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I present updated spectroscopy results from the LSD collaboration on SU(3) gauge theory with $N_f = 8$ degenerate fermions in the fundamental representation, using nHYP-smeared staggered fermions. The new results include added statistics, a more sophisticated systematic error analysis, and the use of joint fits to stabilize estimates of the 0^{++} scalar meson mass. We find persistent evidence for a very light 0^{++} scalar, roughly degenerate with the pions and far below the rest of the spectrum. A detailed comparison with the $N_f = 4$ theory using the same lattice action is also presented.

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Baryon spectrum of SU(4) composite Higgs theory with two distinct fermion representations

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We describe our recent lattice study of the baryon spectrum of SU(4) gauge theory with fully dynamical Wilson-clover fermions in the fundamental and sextet representations. This system is closely related to a model of physics beyond the Standard Model containing a composite Higgs. The model also contains a partially composite top quark, which mixes linearly with a new baryon of SU(4) containing fermions in both representations. We will describe the overall baryon spectrum and implications for collider searches for the top quark partner.

Physics beyond the Standard Model / 188

Phase structure of multiflavor gauge theories

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A SU(3) gauge theory with 12 flavors is a model of great interest for beyond the standard model physics. Running RHMC simulations for different masses and betas we study the Fisher zeroes in the vicinity of the endpoint of a line of first order transitions. The pinching of these zeros with respect to increasing volume provide information about a possible unconventional continuum

limit. We also study the mass spectrum of a multiflavor linear sigma model with a splitting of fermion masses.

Plenary / 6

Theory Challenges in EIC Physics

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Electron-Ion Collider (EIC) is the highest priority for new construction in US nuclear science community and will likely to start physics program in about 5-10 years from now. EIC enables to make detailed studies of the parton structure of nucleons and nuclei in unprecedented accuracy and kinematic domain. How to compute the EIC observables, namely various parton distributions and fragmentations, will become a grand challenges for QCD theorists. In this talk, some recent ideas and prospects, including lattice and quantum computations are discussed.

Plenary / 275

Systematics in nucleon matrix element calculations

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The current status of calculations of simple nucleon structure observables, such as the axial charge, will be reviewed. Recent calculations have produced steadily better control over the standard sources of systematic uncertainty, and there are now multiple groups doing calculations with near-physical quark masses. A major challenge is the combination of an exponentially decaying signal-to-noise ratio and the need for large source-sink separations to eliminate excited-state contributions. There is a growing number of approaches for dealing with this problem, and an overview of them will be given.

Plenary / 57

Proton spin decomposition

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We calculate the intrinsic quark and gluon spin contribution to the total proton spin using overlap fermions on Domain-wall ensembles. We find that the total quark spin, with the axial Ward identity satisfied, is ~40%, and the glue spin contribution is ~50% if the matching procedure in LaMET is neglected.
The imperative non-perturbative renormalization to obtain the quark and glue angular momentum fractions will be also introduced in the talk.

Plenary / 49

Recent Developments in x-dependent Structure Calculations

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First principles calculations of the Bjorken-x dependence of hadron structure have been a long-standing challenge for lattice QCD. This year marks a significant milestone: the first determinations of parton distribution functions, which capture the longitudinal momentum structure of fast-moving hadrons, at physical pion masses. Moreover, there has been significant progress in our understanding of the theoretical frameworks underpinning these calculations, although not all sources of systematic uncertainty have been fully explored. I review the various approaches to extracting x-dependent hadron structure from lattice QCD and highlight recent results in both the meson and baryon sectors.

Plenary / 324

Challenges of Neutrino-Nucleus Scattering

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Plans are well underway in Japan and the US to measure neutrino mixing angles with unprecedented precision and search for CP-violating phases in the mixing. An important systematic/theory uncertainty will be that of the neutrino-nucleus cross section. In this talk I illustrate how lattice QCD calculations (combined with nuclear many-body theory and experimental data) can reduce the uncertainty on the oscillation parameters.

Standard Model Parameters and Renormalization / 244

Strange Quark Content of the Nucleon using the Yang-Mills gradient flow

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The Yang-Mills gradient flow can be used to calculate the strange quark scalar content in nucleons using Lattice QCD. Given the renormalization properties of flowed operators, the procedure promises a reduction of the uncertainties in the determination of the spin independent (SI) elastic cross section of dark matter models involving WIMP-nucleon interactions. Chiral symmetry and a small flow-time expansion relate the scalar density at zero flow time to the pseudo-scalar density at non-zero flow time which can be calculated accurately on a lattice. The pseudo-scalar density is calculated on a 32ˆ3×64 lattice using 2+1 flavor QCD gauge field configurations by PACS-CS with a spacing of a=0.0907 fm, β=1.90, m_π≅411 MeV. We show a preliminary result for the flow-time dependent vacuum to pion matrix elements and we discuss how it can be used to extract the strange quark scalar content in nucleons.

Standard Model Parameters and Renormalization / 224

Light and strange quark masses for $N_f = 2 + 1$ simulations with Wilson fermions

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We present a preliminary analysis of the u/d and s quark masses, extracted using the PCAC quark masses reported in Phys. Rev. D 95, 074504. The data is based on the CLS $N_f = 2+1$ simulations with Wilson/Clover quarks and Luescher-Weisz gauge action, at four β values (i.e. lattice spacings) and a range of quark masses. We use the Alpha results of Eur.Phys.J. C78 (2018)387 for non-perturbative quark mass renormalisation and RG-running from hadronic to electroweak scales in the Schroedinger Functional scheme. Quark masses are quoted both in the $\overline{MS}$ scheme and as RGI quantities.

Standard Model Parameters and Renormalization / 164

Test of factorization for the long-distance effects from charmonium in $B \to Kll$

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We report on a calculation of the charmonium contribution to the decay $B \to Kll$ using lattice simulations with 2+1 flavors of Mobius domain wall fermions. We focus on the region of q^2 below the J/ψ resonance and test the factorization approximation to estimate the amplitude.

Standard Model Parameters and Renormalization / 274

Scale Setting on the MDWF in Gradient Flow HISQ Action With the Omega Baryon

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We perform scale setting for the MDWF on gradient flowed HISQ action. 18 different ensembles are used to perform an extrapolation of the omega baryon to the physical point. Various schemes of defining dimensionless variables to parameterize the light and strange quark mass are used to estimate systematic uncertainties in the scale setting.

Standard Model Parameters and Renormalization / 129

Corrections to Dashen's theorem from lattice QCD and quenched QED

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We use our Nf=2+1+1 staggered lattice QCD configurations to compute the corrections to Dashen's theorem and the quark mass ratio m_u/m_d. We use quark masses around their physical values, and reach the continuum limit using 5 different lattice spacings. We use the QED_L formulation, and include the QED and u-d mass difference effects in the valence sector.

Standard Model Parameters and Renormalization / 13

Perturbative calculation of Z_q at the one-loop level using HYP-smeared staggered quarks

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We present matching factors for Z_q calculated perturbatively at the one-loop level with improved staggered quarks. We calculate Z_q with HYP-smeared staggered quarks and Symanzik-improved gluons in RI- and RI′-MOM scheme. Using the conversion factor, we also present Z_q in MSbar scheme. As a byproduct, we present the quark mass renormalization factor Z_m in MSbar scheme. We compare the result from this work with those of nonperturbative renormalization method.

Weak Decays and Matrix Elements / 19

$B_s \to D_s l\nu$ form factors using heavy HISQ quarks

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We present progress on an ongoing calculation of the $B_s \to D_s l\nu$ form factors calculated on the 2+1+1 MILC ensembles and using the Highly Improved Staggered Quark action for all valence quarks. We perform the calculation at unphysically light b quark masses and extrapolate to the physical point.

Weak Decays and Matrix Elements / 131

$B \to D^*\ell\nu$ at non-zero recoil

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We present preliminary blinded results from our analysis of the form factors for B⁻→D⋆ℓν⁻ decay at non-zero recoil. Our analysis includes 15 MILC asqtad ensembles with Nf=2+1 flavors of sea

quarks and lattice spacings ranging from a≈0.15 fm down to 0.045 fm. The valence light quarks employ the asqtad action, whereas The b and c quarks are treated using the Fermilab action. We discuss the impact that our results will have on |V_cb| and R(D*).

Weak Decays and Matrix Elements / 265

Update on $B \to D^* \ell\nu$ form factor at zero-recoil using the Oktay-Kronfeld action

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We update the calculation of $B \to D^* \ell\nu$ form factor at zero-recoil using the Oktay-Kronfeld (OK) action for bottom and charm quarks. Heavy quark action is nonperturbatively tuned. The flavor changing currents are improved to $\mathcal{O}(\lambda \approx \Lambda_{QCD}/2m_Q)$, $Q = b, c$ at tree-level in the HQET power counting. We use the HISQ action for the light spectator quark with several valence quark masses. The calculation is done on the $2+1+1$-flavor MILC HISQ ensembles at $a \approx 0.12$ and 0.09 fm with pion mass $M_\pi \approx 310$ MeV. The excited state contamination in the matrix elements is controlled by using multi-state fits on correlators with multiple source-sink separations and stabilized using an empirical Bayesian technique.

Weak Decays and Matrix Elements / 99

2018 update of ε_K with lattice QCD inputs

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We report recent progress in determining ε_K, the indirect CP violation parameter in the neutral kaon system, calculated using lattice QCD inputs including B_K, ξ_0, ξ_2, V_{us}, V_{cb}, and $m_c(m_c)$. In this report, various other input parameters such as $m_t(m_t)$ have also been updated recently.

Weak Decays and Matrix Elements / 299

Kaon mixing beyond the standard model with physical masses.

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I present an update on the calculation of beyond the standard model kaon mixing matrix elements in isospin symmetric pure QCD with $n_f = 2 + 1$ dynamical flavours calculated with data at the physical pion mass. Our analysis includes simulations with domain wall fermions and an Iwasaki gauge, at three-lattice spacings and a range of pion masses from the physical point up to 430 MeV. We perform a simultaneous chiral and continuum fit to extrapolate to the physical point continuum limit. This builds upon our earlier work, by adding the third lattice spacing and ensembles calculated directly at the physical light quark mass, improving the precision of the mass extrapolation and removal of discretisation effects.

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Results for the mass difference between the long- and short-lived K mesons for physical quark masses

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The two neutral kaon states in nature, the KL (long-lived) and KS (short-lived) mesons, are the two time-evolution eigenstates of the $K^0 - \overline{K}^0$ mixing system. The prediction of their mass difference ΔM_K based on the Standard Model is an important goal of lattice QCD. In this talk, I will present preliminary results from a calculation of ΔM_K performed on an ensemble of $64^3 \times 128$ gauge configurations with inverse lattice spacing of 2.36 GeV and physical quark masses. These new results come from twice the Monte Carlo statistics used for the result presented in last year's conference. Further discussion of the methods employed and the resulting systematic errors will be given.

Nonzero Temperature and Density / 134

Phase Fluctuations and Sign Problems

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Correlation functions for baryons, or generically systems with different U(1) charges than the vacuum, have phase fluctuations that lead to sign problems obstructing studies of finite-density matter using correlation functions. I will discuss phase fluctuations in lattice QCD and in a one-dimensional complex scalar field toy model and methods to exploit the structure of phase fluctuations to avoid or reduce sign problems. Phase reweighting correlation functions with destructively interfering phases near correlation function sources and sinks allows additional independent interpolating operators to be constructed from correlation functions in a generalization of the generalized pencil-of-functions technique that reduces the variance of the additional sources by suppressing phase fluctuations during source-creation. I will also introduce a new method in which phase unwrapping techniques from signal processing and engineering are applied to map compact random variables for which parameter inference has an exponentially severe signal-to-noise problem to non-compact random variables whose moments can be calculated without sign problems or severe signal-to-noise degradation. A cumulant expansion can be used to relate unwrapped phase moments to average correlation functions, but large phase jumps associated with heavy-tailed distributions surprisingly observed in free scalar field theory and lattice QCD can lead to significant truncation errors. I will briefly outline one-dimensional phase unwrapping results and outlook towards multi-dimensional applications where truncation errors might be better controlled.

Nonzero Temperature and Density / 135

Phase Unwrapping and One-Dimensional Sign Problems

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Lattice QCD estimates of correlation functions with non-zero U(1) baryon number suffer from a well known signal-to-noise problem at large time separations. Previous work has shown that this can be attributed to a widening phase distribution over a circular domain, where standard estimators perform exponentially poorly as the distribution approaches uniform. We present a new approach to this problem: we apply phase unwrapping from the MRI and radar domains to translate the phase circular distribution to an "unwrapped phase" distribution over the reals. Applied to the simple harmonic oscillator as a toy model, unwrapping demonstrates no exponential signal-to-noise growth in time at leading order in a convergent cumulant expansion. We explore choices of unwrapping schemes and demonstrate precise ground-state energy estimates with a good scheme choice. Truncation error in the cumulant expansion is found to be highly sensitive to the choice of unwrapping scheme, indicating that more a robust family of schemes or choice of expansion is needed to apply this technique to non-trivial models. Arguments based on topological defects suggest that multidimensional unwrapping schemes should be more robust to regions of undersampling, motivating future work with spatially-resolved correlators in higher dimensions.

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Taylor expansion and the Cauchy Residue Theorem for finite-density QCD

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The QCD pressure at non-zero chemical potential mu is typically obtained via a Taylor expansion in mu. The Taylor coefficients are traces of powers of the inverse Dirac matrices, which are computed using many noisy estimators. Here, we present an alternative based on the Cauchy Residue Theorem and discuss its merits for the Taylor coefficients.

Nonzero Temperature and Density / 15

Ab initio calculations of nuclear thermodynamics

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We present the first ab initio calculations of nuclei and nuclear matter at finite temperature. Using lattice Monte Carlo simulations and chiral effective field theory, we probe the thermal properties of nuclear systems from first principles. We find that the pinhole algorithm, initially developed for extracting nucleon densities, is well suited for computing the canonical partition function. We employ a chiral nuclear force fitted to nucleon-nucleon scattering data on the lattice and calculate a variety of thermodynamic quantities for light nuclei, dilute neutron matter, and dilute nuclear matter, such as the free energy, entropy, and specific heat. The pinhole algorithm is found to largely alleviate the sign problem, which prevented previous attempts in this direction.

Nonzero Temperature and Density / 32

The QCD Anderson transition with Nf=2+1+1 twisted mass Wilson quarks

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Chiral Random Matrix Theory has proven to describe the spectral prop- erties of low temperature QCD very well. However, at temperatures above the chiral symmetry restoring transition it can not provide a global descrip- tion. The level-spacing distribution in lower part of the spectrum of the Dirac operator is Poisson-like. The eigenmodes are localized in space-time and separated from the rest of the spectrum by a so-called mobility edge. In analogy to Anderson localization in condensed-matter systems with random disorder this has been called the QCD-Anderson transition. Here, we study the localization features of the low-lying eigenmodes of the massless overlap operator on Nf=2+1+1 twisted mass Wilson sea quarks and present results concerning the temperature dependence of the mobility edge and the mechanism of the quark-mode localization. We have used various methods to fix the spectral position of the delocalization transi- tion and verify that the mobility edge extrapolates to zero at a temperature within the chiral transition region.

Hadron Spectroscopy and Interactions / 201

Comparison between models with and without dynamical charm quarks

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We investigate the influence of dynamical charm quarks on observables with an explicit charm quark dependence, like the hyperfine splitting, quark masses and meson decay constants. For this purpose, instead of working in full QCD we study a simplified setup. We simulate two theories: $N_f = 0$ QCD and QCD with $N_f = 2$ degenerate charm quarks. The absence of light quarks allows us to reach extremely fine lattice spacings (0.02 fm < a < 0.05 fm) which are crucial for reliable continuum extrapolations. Our main result is a comparison of various quantities in the continuum limit with a precision that in some cases exceeds 0.5%.

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B_c spectroscopy using highly improved staggered quarks

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Using MILC ensembles of highly improved staggered quarks (HISQ) with lattice spacings down to a=.044 fm, we report results obtained from heavyonium and heavy-charm HISQ correlators. Using HISQ valence quarks on successively finer lattices allows us to simulate near (and in fact just beyond) the b-quark mass. In particular we focus on the Bc(2S) energy, which we compare with O(α_s)-improved non-relativistic QCD results computed on the same ensembles.

Hadron Spectroscopy and Interactions / 158

Charmed baryon spectrum in 2+1-flavor Lattice QCD

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We calculate the spectrum of charmed baryons on $32^3 \times 64$, $2+1$-flavor lattice QCD ensembles generated by the PACS-CS Collaboration. Calculations are done with almost physical light quarks, m_π ~ 156 MeV, and physical strange and charm quarks. A relativistic heavy-quark action is used for valance charm quarks to suppress the systematic errors. A two-fold variational analysis is employed in order to access the excited states by varying the interpolating operators and smearing parameters independently. In this talk, we report on the details and status of the current calculations and present some preliminary results for positive and negative parity, spin-1/2 and spin-3/2 states.

Hadron Spectroscopy and Interactions / 8

On chiral extrapolations of charmed meson masses and coupled-channel reaction dynamics

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We perform an analysis of QCD lattice data on charmed meson masses. The quark-mass dependence of the data set is used to gain information on the size of counter terms of the chiral Lagrangian formulated with open-charm states with $J^P = 0^-$ and $J^P = 1^-$ quantum numbers. Of particular interest are those counter terms that are active in the exotic flavour sextet channel. A chiral expansion scheme where physical masses enter the extrapolation formulae is developed and applied to the lattice data set. Good convergence properties are demonstrated and an accurate reproduction of the lattice data based on ensembles of PACS-CS, MILC, HPQCD, ETMC and HSC with pion and kaon masses smaller than 600 MeV is achieved. It is argued that a unique set of low-energy parameters is obtainable only if additional information from HSC on some scattering observables is included in our global fits. The elastic and inelastic s-wave πD and ηD scattering as considered by HSC is reproduced faithfully. Based on such low-energy parameters we predict 15 phase shifts and in-elasticities at physical quark masses but also for an additional HSC ensemble at smaller pion mass. In addition we find a clear signal for a member of the exotic flavour sextet states in the ηD channel, below the $\bar{K}D_s$ threshold. For the isospin violating strong decay width of the $D_{s0}(2317)$ we obtain the range $(104 - 116)$ keV.

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Coupled channel scattering of vector and scalar charmonium resonances on the lattice

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Many exotic charmonium resonances have been identified recently in experiment, however their nature and properties are mostly unknown. Algorithmic and theoretical progress in lattice calculations has enabled reliable numerical investigation of the charmonium spectrum below the strong decay threshold, while the study of resonances remain an open challenge. The main difficulty to overcome is the presence of many open decay channels which are coupled together, resulting in a complex finite volume quantization condition. We report on our recent progress towards the determination of physical scattering parameters in the scalar and vector channel on CLS ensembles. We also present an update concerning the study of the charmonium spectrum in moving frames.

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J/ψ-nucleon scattering in P_c^+ pentaquark channels

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Two pentaquarks P_c^+ were discovered by LHCb collaboration as peaks in the J/ψ-nucleon invariant mass. We performed the lattice QCD study of the scattering between J/ψ meson and nucleon in the channels with $J^P = \frac{3}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+, \frac{5}{2}^-$, where P_c^+ was discovered. Energies of the eigenstates in these channels are extracted for the first time from the lattice. We consider the single-channel approximation as a first step towards understanding these challenging channels.

Theoretical Developments / 85

Beyond Complex Langevin: a Progress Report

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Finding positive representations of complex weights still attracts a fair amount of interest. Extension of probabilistic Langevin dynamics into a complex domain works in some cases and fails in the others. For that reason some attempts were made to directly construct pairs of corresponding distributions, without invoking stochastic processes. One of such schemes, and its new theoretical and practical improvements, will be discussed in this talk.

Theoretical Developments / 191

Simulations of gaussian systems in Minkowski time

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Many research programs aiming to deal with the sign problem were proposed since the advent of lattice field theory. Several of these try to achieve this by exploiting properties of analytic functions. This is also the case for one of the approaches we're developing. There auxillary complex variables are introduced and desired weight is obtained after integrating them out. In this talk I will elucidate difficulties previously present in this method. Applications to gaussian path integrals directly in Minkowski time shall be reviewed.

Theoretical Developments / 7

Scattering in Euclidean formulations of relativistic quantum theory

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Scattering theory can be formulated given a representation of the quantum mechanical Hilbert space and a set of self-adjoint Poincar\'e generators satisfying cluster properties. These are both provided by the Osterwalder-Schrader reconstruction theorem, where the input is a collection of Euclidean-covariant reflection-positive distributions. In this representation both Hilbert space inner products and matrix elements of the generators can be expressed directly in terms of Euclidean variables, without analytic continuation. A Euclidean version of Haag-Ruelle scattering can be formulated in this representation, which leads to expressions for scattering observables as strong limits. I discuss the construction of one-particle Haag-Ruelle states in this representation and show how these states can be used to construct wave operators. I exhibit toy model calculations of sharp-momentum transition matrix elements over a wide range of energies that suggest the feasibility of formulating numerical methods to compute scattering observables in this Euclidean representation.

Theoretical Developments / 43

Bag representation for composite degrees of freedom in lattice gauge theories with fermions

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We explore new representations for lattice gauge theories with fermions, where the space time lattice is divided into dynamically fluctuating regions, inside which different types of degres of freedom are used in the path integral. The first kind of regions is a union of so-called bags, in which the dynamics is described by the free propagation of composite degrees of freedom of the original fermions. In the second region, called complementary domain, configurations of the remaining interacting degrees of freedom are used to describe the dynamics. We show that for non-abelian gauge groups at strong coupling and for abelian gauge groups at arbitrary coupling, the contribution from each bag can be computed as a determinant when the composite degrees of freedom are fermions, or as a permanent when the composite degrees of freedom are bosons.

Theoretical Developments / 36

Interacting Bosons at Finite Angular Momentum Via Complex Langevin

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Quantum field theories with a complex action suffer from a sign problem in stochastic non-perturbative treatments, making many systems of great interest - such as polarized or mass-imbalanced fermions and QCD at finite baryon density - extremely challenging to treat numerically. Another such system is that of bosons at finite angular momentum; experimentalists have successfully achieved vortex formation in supercooled bosonic atoms, and have measured quantities of interest such as the moment of inertia. However, the rotation results in a complex action, making the usual numerical treatments of the theory unusable. In this work, we use complex stochastic quantization, a method that has gained much attention in lattice QCD, to calculate basic properties of interacting bosons at finite angular momentum.

Hadron Structure / 29

Status of HVP calculation by RBC/UKQCD

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I present the current status of the HVP calculation for the muon anomalous magnetic moment by the RBC and UKQCD collaborations both for a pure lattice and a combined lattice+R-ratio calculation. I will report on our recent work [1801.07224] and on progress towards the reduction of statistical and systematic uncertainties.

Hadron Structure / 139

Exclusive Channel Study of the Muon HVP

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The Hadronic Vacuum Polarization (HVP) is a dominant contribution to the theoretical uncertainty of the muon anomalous magnetic moment. The uncertainty in lattice QCD calculations of the HVP are dominated by the long-distance contribution to the vector correlation function. With explicit studies of the exclusive channels of the HVP diagram, it is possible to reconstruct the long-distance behavior of the correlation function. This has the effect of replacing the large statistical uncertainty of the correlation function with a significantly smaller uncertainty from the reconstruction. In this talk, I will present preliminary results of an exclusive study of the vector-vector correlation function using the distillation technique. The computation is performed on 2+1 flavor Mobius Domain Wall Fermion ensembles with physical pion mass. Reconstruction of the long-distance correlation function will enable lattice-only calculations of the HVP to achieve precision similar to estimates of the HVP from the R-ratio method on the timescale of the new experimental measurements of the muon anomalous magnetic moment.

Hadron Structure / 119

Isospin breaking corrections to the HVP at the physical point

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A determination of the HVP contribution to g-2 from lattice QCD aiming at a precision of 1% requires to include isospin breaking corrections in the computation. We present a lattice calculation of the QED and strong isospin breaking corrections to the HVP with Domain Wall fermions. The results are obtained using quark masses which are tuned such that pion and kaon masses agree with their physical values including isospin breaking corrections.

Hadron Structure / 253

On isospin breaking in tau decays for (g-2) from Lattice QCD

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Hadronic spectral functions of tau decays have been used in the past to provide an alternative determination of the LO Hadronic Vacuum Polarization relevant for (g-2) of the muon. Following recent developments and results in Lattice QCD+QED calculations, we explore the possibility of studying the isospin breaking corrections of tau spectral functions for this prediction. We present preliminary results at physical pion mass based on Domain Wall Fermion ensembles generated by the RBC/UKQCD collaboration, which we compare and contrast with the previous phenomenological calculations.

Hadron Structure / 87

Anomalous magnetic moment of the muon with dynamical QCD+QED

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The QCDSF collaboration has generated an ensemble of configurations with dynamical QCD and QED fields. They are generated with the specific aim of studying flavour breaking effects arising from differences in the quark masses and charges in physical quantities. Here we study these effects in a calculation of the anomalous magnetic moment of the muon $a_\mu = (g-2)/2$ around an SU(3) symmetric point. Furthermore, by performing partially quenched simulations we are able to cover a larger range of quark masses and charges on these configurations and then fit the results to an SU(3) flavour breaking expansion. Subsequently, this allows for an extrapolation to the physical point.

Hadron Structure / 104

The leading hadronic contribution to $\sin^2\theta_W$ running and covariant coordinate-space methods

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We present a preliminary study of the leading hadronic contribution to the running of the electroweak mixing angle θ_W. The running is extracted from the correlation function of the electromagnetic current with the (vector part of the) weak neutral current using the Lorentz-covariant coordinate-space method recently introduced by Meyer. Both connected and disconnected contributions have been computed on $N_f = 2 + 1$ non-perturbatively $\mathcal{O}(a)$-improved Wilson fermions configurations. Similar covariant coordinate-space methods can be used to compute the leading hadronic contribution to the anomalous magnetic moment $g - 2$ of the muon and to the running of the QED coupling α.

Theoretical Developments / 100

The perturbative SU(N) one-loop running coupling in the twisted gradient flow scheme

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We report on our computation of the perturbative running of the 't Hooft coupling in a pure gauge SU(N) theory with twisted boundary conditions. The computation was performed using gradient flow methods in four dimensions, in the continuum, and using dimensional regularisation. The coupling is defined in terms of the energy density of the flow fields at a scale given by a particular combination of the linear size of the torus and the rank of the gauge group. We will present our strategy to regulate the divergences for a generic twist tensor, along with our results for the case of a two-dimensional non-trivial twist, analysing the dependence of the coupling with the finite size of the torus and the rank of the group, as well as the dependence on the magnetic flux induced by the twist.

Theoretical Developments / 228

Non-perturbative renormalization of operators in near-conformal systems using gradient flow

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We discuss a continuous real space renormalization group transformation based on gradient flow, allowing for a numerical study of renormalization without the need for costly ensemble matching. Applying the technique in a pilot study of SU(3) gauge theory with $N_f = 12$ fermions in the fundamental representation, we find the mass anomalous dimension to be $\gamma_m = 0.23(6)$, consistent with other perturbative and lattice estimates. We also present the first lattice calculation of the nucleon anomalous dimension in this theory, finding $\gamma_N = 0.05(5)$.

Theoretical Developments / 267

Renormalization group properties of scalar field theories using gradient flow

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Gradient flow has proved useful in the definition and measurement of renormalized quantities on the lattice. Recently, the fact that it suppresses high-modes of the field has been used to construct new, continuous RG transformations on the lattice, distinct from the usual blocking techniques in spin models and gauge theories. In this talk, we discuss two approaches to define an RG transformation which incorporate gradient flow: (1) the correlator ratio method, and (2) Langevin exact RG. We present preliminary numerical results for the critical exponents at the Wilson-Fisher fixed point of three-dimensional scalar ϕ^4 theory from both methods.

Theoretical Developments / 9

A linked cluster expansion for the Functional Renormalization Group of the Legendre effective action.

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A lattice version of the widely used Functional Renormalization Group (FRG) for the Legendre effective action is solved (exactly) in terms of a linked cluster expansion. The graph rules invoke only one-line irreducible and a new type of labeled tree graphs. Conversely, the FRG induces nonlinear flow equations governing suitable resummations of the graph expansion. The correspondence is tested on the critical line of the Luscher-Weisz solution of the phi^4 theory. An extension to QFTs on curved spacetimes with flat spatial sections is feasible.

Theoretical Developments / 106

SYM flow equation in N=1 SUSY

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In this talk, we show that the gradient flow equation is defined in $\mathcal{N} = 1$ SYM in a way that is consistent with supersymmetry in the Wess-Zumino gauge. Using the perturbation theory, we find that two-point function of flowed gauge multiplet is UV-finite at the one-loop level when four dimensional SYM is renormalized.

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Critical Point and Deconfinement in Stochastic Thermal Fields

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The critical phenomena of strongly interacting matter are studied in the random fluctuation walk model at finite temperature. The phase transitions are considered in systems where the Critical Point (CP) is a distinct singular one existence of which is dictated by the dynamics of conformal symmetry breaking. The physical approach to the effective CP is predicted through the influence fluctuations of two-particle quantum correlations to which the critical mode couples. The finite size scaling effects are used to extract the vicinity of deconfinement phase transition. We obtain the size of the particle emission source affected by the stochastic forces in thermal medium characterized by the Ginzburg-Landau parameter which is defined by the correlation length of characteristic dual gauge field. The size above mentioned blows up when the temperature approaches the critical value as correlation length becomes large enough. The results are the subject to the physical programs at accelerators to search the hadronic matter produced at extreme conditions.

Nonzero Temperature and Density / 226

Thermodynamics at strong coupling on anisotropic lattices

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Lattice QCD at strong coupling has long been studied in a dual representation to circumvent the finite baryon density sign problem. Recent results that established the non-perturbative functional dependence between the bare anisotropy and the physical anisotropy a/a_t in the chiral limit are now extended to finite quark mass. We discuss the consequences of the anisotropy callibration to the equation of state and the QCD phase diagram in the strong coupling regime.

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Temporal Correlators in the Continuous Time Formulation of Strong Coupling Lattice QCD

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We present results for lattice QCD in the limit of infinite gauge coupling on a discrete spatial but continuous Euclidean time lattice. A worm type Monte Carlo algorithm is applied in order to sample two-point functions which gives access to the measurement of mesonic temporal correlators. The continuous time limit, based on sending $N\tau \to \infty$ and the bare anistotropy to infinity while fixing the temperature in a non-perturbative setup, has various advantages: the algorithm is sign problem free, fast, and accumulates high statistics for correlation functions. Even though the measurement of temporal correlators requires the introduction of a binning in time direction, this discretization can be chosen to be by orders finer compared to discrete computations. For different spatial volumes and binnings, temporal correlators are measured at zero spatial momentum for a variety of mesonic operators. They are fitted to extract the pole masses and corresponding particles as a function of the temperature. We conclude discussing the possibility to extract transport coefficients from these correlators.

Nonzero Temperature and Density / 169

Hadronic spectrum calculations in the quark-gluon plasma

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Although the general behaviour of the crossover of QCD into the quark-gluon plasma phase at zero chemical potential is fairly well understood, the question of what exactly happens to the bound states of the theory in the crossover region is still not fully answered. In this talk the continuation of the FASTSUM collaboration's investigation of hadrons in the region of T_c will be presented. The study has been extended towards lighter quark masses with our anisotropic Gen2L ensembles with pion masses of 236 MeV. A publicly available extension of the openQCD software which incorporates anisotropic lattices and stout smearing among other improvements will also be announced.

Nonzero Temperature and Density / 284

Spectral functions from machine learning

Mr. CHEN, Shi-Yang[1] ; Dr. TOMIYA, Akio[2] ; Mr. LIU, De-Ji[1] ; Prof. DING, Heng-Tong[1]

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The spectral function is the key for understanding the in-medium hadron properties as well as the transport properties of the medium. Such as the dissociation temperatures of quarkonia, diffusion coefficients, dilepton emission rates as well as viscosities can be read-off from various corresponding spectral functions. As well-known that the spectral function is hidden in the lattice-computable correlation functions and has to be extracted from correlators, many methods, e.g. Maximum Entropy Methods and its variants, and stochastic methods have been discussed and applied to solve this ill-posed inversion problem.
Here we will present a machine learning approach to extract spectral functions from temporal correlation functions. This approach, unlike others, can build in the true answer in the algorithm. We will start discussing the applicability and advantages of this approach by showing some mock data tests mimicking the physical situation at serval temperatures below and above the transition temperature, in particular the applicability to extract transport peaks is stressed. We will then proceed to apply the method to real lattice data of temporal correlators. These correlators have been obtained on very fine isotropic lattices in quenched QCD using clover-improved Wilson fermions. The inverse lattice spacing is around 23 GeV and the spatial extent is 192 with aspect ratios ranging from 2 to 4 corresponding to the temperature region from 0.75 Tc to 1.5Tc.

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Meson correlation functions at high temperature QCD: $SU(2)_{CS}$ symmetry vs. free quarks

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We report on the progress of understanding spatial correlation functions in high temperature QCD. We study isovector meson operators in Nf=2 QCD using domain-wall fermions on lattices of Ns=32 and different quark masses. It has previously been found that at $\sim 2T_c$ these observables are not only chirally symmetric but in addition approximately $SU(2)_{CS}$ and $SU(4)$ symmetric.

In this study we increase the temperature up to $5T_c$ and can identify convergence towards an asymptotically free scenario at very high temperatures.

Hadron Spectroscopy and Interactions / 180

Towards the P-wave nucleon-pion scattering amplitude in the Δ (1232) channel: interpolating fields and spectra

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The study of strong scattering in Lattice QCD is enabled by the use of the Luescher method, which defines a mapping between the two body spectrum in the finite volume and the infinite volume scattering amplitude. It however requires full and precise knowledge of the spectrum in a given moving frame and irreducible representation. In this project we investigate the Δ (1232) resonance in the pion-nucleon system. The focus of the talk is on the group theoretical construction of single and multi hadron interpolating fields in various moving frames and irreducible representations. We construct a varied basis of interpolating fields in all of the relevant irreducible representations and determine the relevant energy levels.

Hadron Spectroscopy and Interactions / 282

Towards the P-wave nucleon-pion scattering amplitude in the Δ (1232) channel: Phase shift analysis

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The study of strong scattering in Lattice QCD is enabled by the use of the Luescher method, which defines a mapping between the two body spectrum in the finite volume and the infinite volume scattering amplitude.This talk focuses on the study of πN scattering in P-wave and $I = \frac{3}{2}$, where the Δ resonance resides. We use $N_f = 2 + 1$ flavors of tree-level improved Wilson-clover quarks corresponding to a pion mass of ~ 250 MeV with lattice size 3.7 fm, where Δ is unstable. We aim to discuss the mapping of energy levels to scattering phase shifts.

Hadron Spectroscopy and Interactions / 31

HAL QCD method and Nucleon-Omega interaction with physical quark masses

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After introducing the fundamental difficulties of the two-baryon systems in lattice QCD, we review the severe problems in the previous studies by the direct method and reliabilities of the HAL QCD method. From the HAL QCD method, we study Nucleon-Omega interaction at almost physical quark masses. A strong attractive potential without a repulsive core is found in $^5S_2$ channel, and we discuss the possibility of the dibaryon formation.

Hadron Spectroscopy and Interactions / 92

Baryon interactions at physical quark masses in Lattice QCD

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The determination of baryon interactions is of crucial importance to understand the origin of nuclei, the mechanism of supernovae and the gravitational waves emitted from the binary neutron star mergers. In this talk, we review the latest results for the first lattice QCD calculation of baryon interactions with (almost) physical quark masses (m__pi=146 MeV) obtained by the time-dependent HAL QCD method.

Hadron Spectroscopy and Interactions / 304

Three neutrons from Lattice QCD

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We present a study on ab-initio calculations of three-neutron correlators, and more generally, three-nucleon correlators, from Lattice QCD. Baryon blocks have been employed to simulate two nucleon systems in the past. We extend the method to three nucleons. In addition, we use automatic code generation to provide more flexibility and allow for easy inclusion of additional channels in the future while optimizing the evaluation of sub-expressions. We present some preliminary results of our calculations.

Hadron Spectroscopy and Interactions / 301

Charmonium-nucleon interactions from 2+1 flavor lattice QCD

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In this talk we report on the lattice QCD calculations of the interactions between a charmonium (either η_c and J/ψ) and a nucleon. We use the method introduced by the HAL QCD collaboration to compute potentials, which guarantees the interaction to be faithful to the QCD S-matrix below the open-charm threshold. Our lattice simulation is performed with $2+1$ flavor full QCD gauge configurations on a $32^3 \times 64$ lattice generated by the CP-PACS and JLQCD collaborations. The relativistic heavy quark action is employed for charm quarks. We find that both $\eta_c N$ and $J/\psi N$ are weakly attractive, but not strong enough to have a bound state.

Physics beyond the Standard Model / 11

Baryonic states in supersymmetric Yang-Mills theory

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In $\mathcal{N} = 1$ supersymmetric Yang-Mills theory the superpartner of the gluon is the gluino, which is a spin 1/2 Majorana particle in the adjoint representation of the gauge group. Combining three gluinos, it is possible to form colour neutral bound states, analogous to baryons in QCD. The correlation functions of the corresponding baryonic operators contain a contribution represented by a "sunset diagram", and in addition, unlike in QCD, another contribution represented by a "spectacle diagram". We present first results from an implementation and calculation of these objects, obtained from numerical simulations of supersymmetric Yang-Mills theory.

Physics beyond the Standard Model / 271

Investigations of N = 1 supersymmetric SU(3) Yang-Mills theory

Prof. MÜNSTER, Gernot[1] ; Dr. BERGNER, Georg[2] ; Mr. GERBER, Henning[1] ; Prof. MONTVAY, Istvan[3] ; Dr. SCIOR, Philipp[1] ; Dr. PIEMONTE, Stefano[4] ; LOPEZ, Camilo[2] ; Mr. ALI, Sajid[1]

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We summarise the current status of our numerical simulations of N = 1 supersymmetric Yang-Mills theory with gauge group SU(3). We use the formulation of Curci and Veneziano with clover-improved Wilson fermions. The masses of various bound states have been obtained at different values of the gluino mass and gauge coupling. Extrapolations to the limit of vanishing gluino mass indicate that the bound states form mass-degenerate supermultiplets.

Physics beyond the Standard Model / 76

Supersymmetric and conformal theories on the lattice: from super Yang-Mills towards super QCD

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This talk is an overview of our recent investigations of supersymmetric and near conformal gauge theories. We have studied extensively $\mathcal{N} = 1$ super Yang-Mills theory, most recently with the gauge group SU(3). In addition we have investigated theories that show indications for a conformal behaviour with an infrared fixed point. More recently we have included a mixed fundamental and adjoint fermion action setup in our studies. I will explain how this is related to the investigation of supersymmetric QCD on the lattice and present some first studies of the main obstacles that need to be addressed in the investigation of this theory.

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$\mathcal{N} = 1$ Supersymmetric $SU(3)$ Gauge Theory - Towards simulations of Super-QCD

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$\mathcal{N} = 1$ Supersymmetric QCD (SQCD) is a possible building block of theories beyond the standard model. It describes the interaction between gluons and quarks with their superpartners, gluinos and squarks. Since supersymmetry is explicitly broken by the lattice regularization, a careful fine-tuning of operators is necessary to obtain a supersymmetric continuum limit. For the pure gauge sector, $\mathcal{N} = 1$ Supersymmetric Yang-Mills theory, supersymmetry is only broken by a non-vanishing gluino mass. If we add matter fields, this is no longer true and more operators in the scalar squark sector have to be considered for fine-tuning the theory. Guided by a one-loop calculation, we show that maintaining chiral symmetry in the light sector is nevertheless an important step. Furthermore, we present first preliminary lattice results on the fine-tuning and bound-state spectrum of SQCD.

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$\mathcal{N} = 1$ Supersymmetric $SU(3)$ Gauge Theory - Pure Gauge sector with a twist

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Supersymmetric gauge theories are a popular building block of theories beyond the standard model. We investigate the pure gauge sector of Super-QCD focusing on the bound states, i.e. mesonic gluinoballs, gluino-glueballs and pure glueballs. To improve chiral symmetry as well as supersymmetry at finite lattice spacing, we introduce a deformed Super-Yang-Mills lattice action. It contains a twist term, similar to the twisted mass formulation of lattice QCD. We furthermore explore if the multigrid method (DDalphaAMG solver) applied to the gluinos (adjoint Majorana fermions) achieves similar improvements as one finds for QCD.

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Phase structure of N=1 Super Yang-Mills theory from the gradient flow

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Composite operators of bare fermion fields evolved along a trajectory on field space by means of flow equations get renormalised multiplicatively. Therefore, even in the case of Wilson fermions, the renormalization of expectation values of fermion operators can be simplified drastically on the lattice. We measure the gluino condensate in N=1 supersymmetric Yang-Mills theory at non-zero temperatures by means of the gradient flow. The non-vanishing expectation value of the gluino condensate up to a certain critical temperature is a signal of chiral symmetry breaking, in agreement with theoretical conjectures on the vacuum structure of the theory. Furthermore, the deconfinement phase transition seems to occur close to this critical temperature, meaning that in N=1 SYM the phases of broken chiral symmetry and of confinement would coincide.

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Hypercubic effects in semileptonic decays of heavy mesons, toward $B \to \pi\ell\nu$ with Nf=2+1+1 Twisted fermions

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We present a preliminary study toward a lattice determination of the vector and scalar form factors of the $B \to \pi\ell\nu$ semileptonic decays. We compute the form factors relative to the transition between pseudo-scalar heavy mesons, with masses above the D-mass, and the pion. We simulate the valence heavy quark with a mass in the range $m_c < m_h < 2m_c$. Lorentz symmetry breaking due to hypercubic effects is clearly observed in the data and included in the decomposition of the current matrix elements in terms of additional form factors. We discuss the size of this breaking as the parent-meson mass increases. Our analysis is based on the gauge configurations produced by the European Twisted Mass Collaboration with $N_f = 2 + 1 + 1$ flavors of dynamical quarks. We simulated at three different values of the lattice spacing and with pion masses as small as 210 MeV.

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$B \to \pi\ell\nu$ and $B \to \pi\ell\ell$ decays with HISQ/NRQCD valence quarks on $N_f = 2 + 1$ asqtad ensembles.

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We discuss a calculation of the form factors for the flavor-changing charged current $b \to u$ and the flavor-changing neutral current $b \to d$ semileptonic decays, $B \to \pi\ell\nu$ and $B \to \pi\ell\ell$. HISQ light and NRQCD b valence quarks are simulated on the MILC $N_f = 2+1$ asqtad ensembles, including pion momenta that cover the full kinematic range of the decay. These data are analyzed using a hard pion ChPT motivated modified z-expansion developed in previous work. Preliminary results and phenomenological implications are discussed.

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Semileptonic decays of $B_{(s)}$ mesons to light pseudoscalar mesons on four-flavor HISQ ensembles

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We report the status of an ongoing lattice-QCD calculation of form factors for exclusive semileptonic decays of B˜mesons with both charged currents ($B \to \pi\ell\nu$, $B_s \to K\ell\nu$) and neutral currents ($B \to \pi\ell^+\ell^-$, $B \to K\ell^+\ell^-$). The results are important for constraining or revealing physics beyond the Standard Model. This work uses MILC's (2+1+1)-flavor ensembles with the HISQ action for the sea and light valence quarks and the clover action in the Fermilab interpretation for the b˜quark. Simulations are carried out at three lattice spacings down to 0.088˜fm, with both physical and unphysical sea-quark masses. We present preliminary blinded results for the form factors $f_+(q^2)$, $f_0(q^2)$, and $f_T(q^2)$ (in terms of momentum transfer q^2), along with an examination of systematic errors. Our preliminary results include studies of z-expansion methods to extend the kinematic range.

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Semi-leptonic form factors for Bs -> K l nu and Bs -> Ds l nu

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We report on our determination of form factors for Bs semi-leptonic decays and extract ratios to investigate lepton flavor universality violations. Our calculation is based on RBC-UKQCD's gauge field ensembles featuring 2+1 flavors of domain-wall fermions and Iwasaki gauge action at three lattice spacing of 1/a = 1.78, 2.38, and 2.77 GeV. In the valence sector we use domain-wall light,

strange, and charm quarks and simulate physical bottom quarks using the relativistic heavy quark action. We will detail our new analysis procedure and give an outlook on future calculations.

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Determining the Efficacy of different parameterizations of the z-expansion

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We present a method of examining the efficacy of different formulations of the z-expansion in semileptonic B decays. We examine three different parameterizations of the z-expansion, the BGL, BCL and a recent Padé expansion. Our method involves fitting these parameterizations to the large momentum transfer data ($q^2 > 17\ GeV^2$) and seeing how well these parameterizations predict the low momentum transfer region ($q^2 < 17\ GeV^2$). This comparison is done using determining chiˆ2 values for the non-fitted region using the parameters found for the fitted region.

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Flavor anomalies & the lattice

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In the past few years several observables are indicating deviations from the SM amounting to a few sigmas. In view of the experimental developments on the horizon and bearing in mind recent advances in matrix elements calculations, in this talk I will discuss ways in which lattice methods may be used to improve precision in the predictions of the SM so that the experimental data can be used more effectively and reliably to test the SM.

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HISQ light quark hadronic vacuum polarization contribution to the muon anomalous magnetic moment

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We present preliminary results for the (connected) hadronic vacuum polarization (HVP) contribution to the muon anomalous magnetic moment (g-2). The HVP is computed for degenerate up and down quarks at the physical point on HISQ 2+1+1 flavor ensembles generated by the MILC collaboration. We use all mode and low mode averaging with 2000-3000 lowmodes to obtain precise statistics. Calculations performed at three lattice spacings (0.06, 0.09, and 0.12 fm) are

used to estimate the continuum limit in finite volume. Chiral perturbation theory is used to estimate the finite volume effect. We compare to other recent results.

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The hadronic vacuum polarization contribution to $(g-2)_\mu$ from $2+1$ flavours of O(a) improved Wilson quarks

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We report on our ongoing project to determine the leading-order hadronic vacuum polarisation contribution to the muon $g-2$, using ensembles with $N_f = 2+1$ flavours of O(a) improved Wilson quarks generated by the CLS effort, with pion masses down to the physical value. We employ O(a) improved versions of the local and conserved vector currents to compute the contributions of the light, strange and charm quarks to $(g-2)_\mu$, using the time-momentum representation. We perform a detailed investigation of the systematic effects arising from constraining the long-distance regime of the vector correlator. To this end we make use of auxiliary calculations in the iso-vector channel using distillation and the Lüscher formalism. Our results are corrected for finite-volume effects by computing the timelike pion form factor in finite and infinite volume. For certain parameter choices, the corrections computed in this way can also be confronted with results determined on different volumes. Currently, the overall precision of our results is limited by the uncertainties in the lattice scale.

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HVP contribution of the light quarks to the muon (g - 2) including QED corrections with Twisted-Mass fermions

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We present a preliminary lattice calculation of the Hadronic Vacuum Polarization (HVP) contribution of the light quarks to the anomalous magnetic moment of the muon including leading-order strong and electromagnetic isospin-breaking corrections. Our lattice results are obtained in an electro-quenched setup using the gauge configurations generated by the European Twisted Mass Collaboration (ETMC) with $N_f = 2+1+1$ dynamical quarks at three lattice spacings varying from 0.089 to 0.062 fm with pion masses in the range $M_\pi \simeq 220-490$ MeV. Several lattice volumes are considered in order to investigate the impact of finite-volume effects. Systematic uncertainties due to the extrapolations to the physical pion mass and to the infinite-volume and continuum limit are estimated.

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Nucleon Form factor calculation using DWQCD

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Nucleon form factors are not only interesting for understand the structure of the fundamental building blocks of nature, but they are also important input for various experiments such as neutrino facility. They are also related to the electric and axial radius of proton or nucleon, experimental results of which present some puzzles. We report form factor results on 2+1 DWQCD at physical point. We may also discuss about exploratory study on form factors using distillation.

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Nucleon form factors from Nf=2+1+1 twisted mass fermions at the physical point

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We present results on the nucleon form factors including disconnected contributions using an ensemble of Nf=2+1+1 twisted mass fermions with a clover term. The ensemble has a spatial extent of 5.12fm (64ˆ3 x128). Techniques such as the summation and the two-state fits have been employed to control possible excited states contamination.

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Public Lecture: Quantum Computing and the Entanglement Frontier

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Machines and Algorithms for Lattice QCD

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I will review recent progress in software development for lattice QCD on novel architectures and new machines. I will also report some algorithmic advancements in ensemble generation, solvers and contractions.

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Lattice QCD on modern GPU systems

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In the 10 years since the creation of the QUDA library for Lattice QCD on NVIDIA GPUs the hardware and software features of GPU systems have evolved dramatically. Not only has the raw Dslash kernel performance on a single GPU improved by more than one order of magnitude but also modern GPUs are often deployed in "Fat Nodes" with up to 8 GPUs. We report on the techniques that QUDA implements to achieve high performance on these modern GPU architecture by exploiting the features of modern NVIDIA GPUs, like Unified Memory, GPU Direct and NVLink-connections between GPUs and to IBM Power CPUs. We discuss the impact of these optimizations and present scaling results for QUDA on DGX-1 based clusters and Summit. Finally, we will give an outlook on future directions. In particular we preview strong scaling and programmability improvements by using NVSHMEM, an OpenSHMEM implementation for GPUs as well as QUDA on NVSwitch-based systems like DGX-2 with 16 fully interconnected GPUs.

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Tensor Networks and their use for Lattice Gauge Theories

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The term Tensor Network States (TNS) has become a common one in the context of numerical studies of quantum many-body problems. It refers to a number of families that represent different ansatzes for the efficient description of the state of a quantum many-body system. The first of these families, Matrix Product States (MPS), lies at the basis of Density Matrix Renormalization Group methods, which have become the most precise tool for the study of one dimensional quantum many-body systems. Their natural generalization to two or higher dimensions, the Projected Entanglement Pair States (PEPS) are good candidates to describe the physics of higher dimensional lattices. Another TNS ansatz, the MERA, has recently been connected to a discrete realization of the AdS/CFT correspondence.
TNS can be used to study equilibrium properties, as ground and and thermal states, but also dynamics. Quantum information gives us some tools to understand why these families are expected to be good ansatzes for the physically relevant states, and some of the limitations connected to the simulation algorithms.
Lattice Gauge Theories, in their Hamiltonian version, offer a challenging scenario for these techniques. While the dimensions and sizes of the systems amenable to TNS studies are still

far from those achievable by Monte Carlo simulations, Tensor Networks can be readily used for problems which more standard techniques cannot easily tackle, such as the presence of a chemical potential, or out-of-equilibrium dynamics.
The last years have seen an increasing interest in this particular application of Tensor Network methods. In this talk I will present some of the recent work in this area. In particular, using the Schwinger model as a testbench, we have shown that Matrix Product States (MPS) are suitable to approximate low energy states precisely enough to allow for accurate finite size and continuum limit extrapolations of ground state properties, mass gaps and temperature dependent quantities. The feasibility of the method has already been tested also for non-Abelian models, out-of-equilibrium scenarios, and non-vanishing chemical potential.

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Path Optimization Method with Use of Neural Network for the Sign Problem in Field Theories

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We introduce the feedforward neural network in the path optimization method (POM) to evade the sign problem in field theories. POM is based on the complexification of integral variables as in the complex Langevin method and the Lefschetz thimble method. The integration path is optimized in the complexified variable space by maximizing the average phase factor. In the last Lattice meeting [1] and in Ref.[2], we have demonstrated that POM works very well in a one-dimensional model: Setting the integration path by a simple function and optimization by the standard gradient method provide an almost perfect integration path even in the integral with a severe sign problem. In field theories, however, it is not easy to prepare and optimize the integration path in the complex space. We introduce the neural network, a kind of machine learning, in POM to investigate the sign problem in field theory [3]. As demonstrated in the last Lattice meeting [1] and followed by Alexandru et al. [4], the machine learning technique seems to be powerful in applying POM to the sign problem. We demonstrate that POM with the neural network optimization works well in $\lambda\phi^4$ theory at finite chemical potential: The average phase factor becomes well above zero and we can safely obtain the expectation value of observables [3]. The optimized path shows that the imaginary part of integration variable is strongly correlated with the real part of the nearest neighbor site, as discussed in Ref. [5]. We also plan to discuss the results of applying POM with the neural network to a gauge theory.
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