Theory at Fermilab

Marcela Carena
PAC, June 7, 2023

Overview of the theoretical physics program at the laboratory

Charge to the PAC:

- review the theoretical physics program at the laboratory
- review the readiness of the laboratory for the upcoming DOE Comparative Review.
- review the status of the recommendations from previous reviews:

➢ The PAC recommends that the Lab provides the Theory Division with the requested support.

➢ The Lab and the Theory Division should maintain close connections to the University community

➢ and ensure that the programs it is offering are welcomed by the community, as opposed to being seen as securing a larger piece of a small pie.

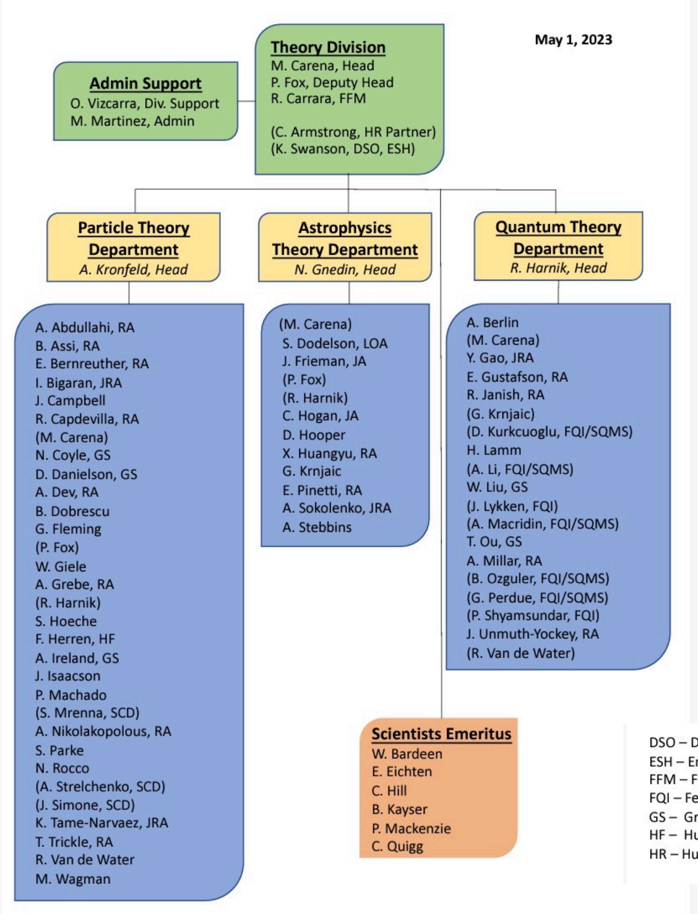
Mission of Fermilab Theory Program

- Conduct world-leading theoretical particle physics, cosmology/astrophysics, and quantum science research.
- Focus effort and core strength in key research areas directly related to the U.S. and worldwide experimental programs.
- Lead and support national and international theory consortia and networks focused on areas of special importance to the DOE HEP program.
- Influence and motivate the design of experiments, data analyses, and their interpretation.
- Train the next generation of theorists in data-rich environment
- Provide a national resource for university physicists.
- Foster an intellectually vibrant atmosphere at the lab.
- Promote an inclusive, equitable and diverse work environment at the lab

Theory Division

3 Departments

with cross-department activities and overlap in research areas

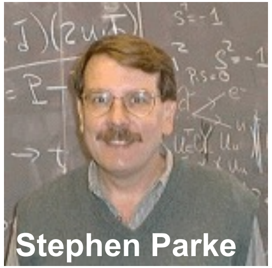


DSO – Division Safety Officer
ESH – Environmental, Safety & Health
FFM – Field Financial Manager
FQI – Fermilab Quantum Institute
GS – Graduate Student
HF – Humboldt Fellow
HR – Human Resources
JA – Joint Appointment
JRA – Joint Research Associate
LOA – Leave of Absence
RA – Research Associate
SCD – Scientific Computing Division
SF – Schramm Fellow
SQMS – Superconducting Quantum Materials and Systems

Theory Division Scientists reviewed in 2018 and here today

Particle theory dept.:

Distinguished Scientists:



Scientists and Senior Scientists:

Theory Division Scientists reviewed in 2018 and here today

Astro theory dept.:

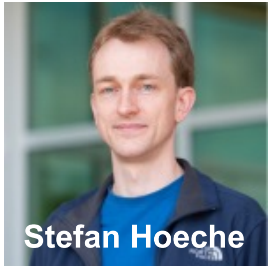
Distinguished Scientists:

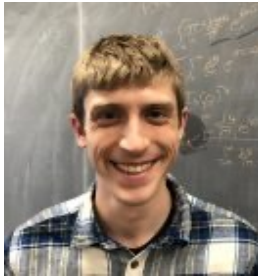
Senior Scientists:

Scientist new additions since 2018:

Particle theory dept.:

vs three retirements and one departure




Michael Wagman


George Fleming

Quantum theory dept.:

Astro theory dept.:

vs one departure and
one LOA: Scott Dodelson

Areas of expertise: from theory to theoretical tools to experiments

- **Colliders and BSM theories**
  [Campbell, Carena, Dobrescu, Fox, Hoeche, Giele, Harnik, Fleming, Krnjaic]

- **Neutrinos**
  [Rocco, Machado, Wagman, Parke, Hoeche, Giele, Hooper, Krnjaic, Harnik]

- **Lattice Gauge Theories** (including g-2, R_D, and BSM)
  [Wagman, Van de Water, Kronfeld, Lamm, Simone(SCD), Fleming]

- **Quantum Simulations for QFT** [Lamm, Carena, Van de Water, Wagman]

- **Dark sectors/Dark Matter** (including quantum sensors and accelerator-based expts.)
  [Hooper, Krnjaic, Fox, Machado, Harnik, Fleming, Berlin, Carena]

- **Cosmological probes, phase transitions, neutrino astrophysics, gravity waves**
  [Hooper, Gnedin, Stebbins, Krnjaic, Carena, Harnik, Berlin, Fleming]

Associated Staff and Long-Term Visitors

Josh Isaacson
(Application Physicist)

James Simone

Josh Frieman

Richard Hill

Long-term visitors 2023:

Pavel Nadolsky, Susan Gardner, Peter Vander Grind (RA), Felix Yu, Ulrich Nierste

Renew visitor summer program 2023: about 35 visitors in June through September

European Network visitors 2023: about 20 for one to two months

Many visiting students, summer and beyond, from Brazil, Germany, Italy, France

Postdocs: the lifeblood of the Division

Postdocs work broadly across all Departments and topics

Large International component due to our standing in field

Supported by DOE Theory base funding

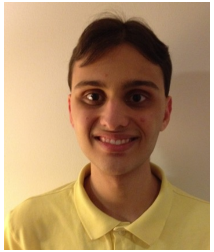

Benoit Assi


Elias Bernreuther


Abhish Dev


Tanner Trickle


Sandra Robles


Anthony Grebe


Alexis Nikolakopoulos

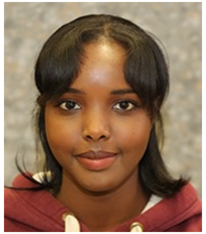

Elena Pinetti

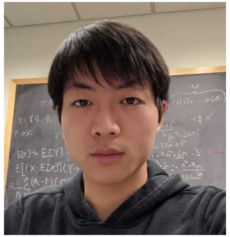

Rodolfo Capdevilla

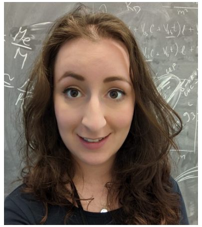
Postdocs: the lifeblood of the Division

Leveraging limited resources through JRA/other funding

University Funding, Early Career Award, Humboldt Foundation, Office of Science Distinguished Fellowship program, QuantISED grant, SQMS Center


Asli Abdullahi


Huangyu Xiao


Ines Bigaran (JRA)


Christina Gao (JRA)


Florian Herren (HF)


Karla Tames Narvaez (JRA)


Alex Millar


Ryan Janish


Anastasia Sokolenko (JRA)


Judah Unmuth-Yockey

Connection with UChicago, Physics and Astronomy depts, EFI and KICP

4 Joint Appointments at the faculty level: Carena, Gnedin, Hooper, Krnjaic

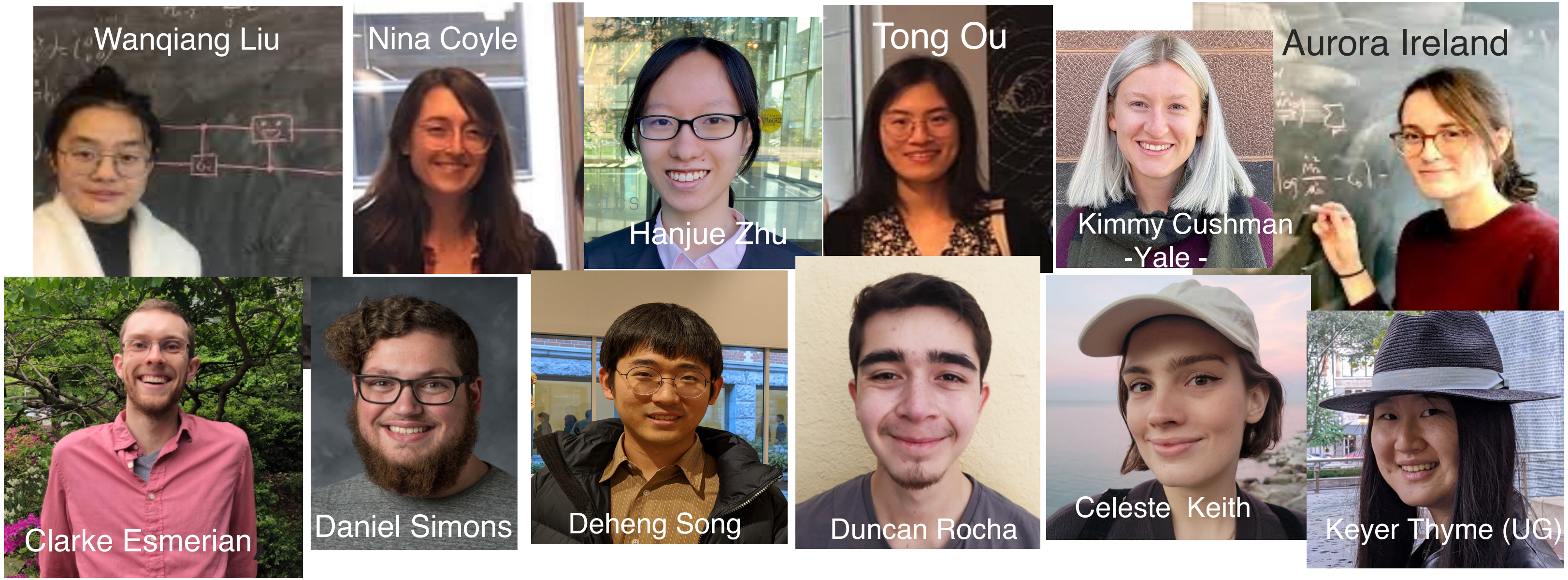
1 Joint Appointment at the Postdoctoral level (JRA's) (Sokolenko) plus
2 additional ones about to start (Bodas, Liu)

Many UChicago students working with Fermilab scientists (see attached)

There is interest to enhance these connections to include other areas in THD, eg, neutrinos, colliders, pQCD, …

Students (current)

(UChicago GS: supported by URA, SCGSR program, QuantISED grant, DOE Office of Science Distinguish Fellow award, NASA (TCAN) - No Theory DOE direct funding for students -



Other Students: Julian Mayer-Steudte (TUM), David Robinson (Michigan), Gustavo Alves (USP), Antonio Ferreira (USP), Ian Holst (UChicago), Stacie Moltner (UT Austin), Bashi Mandava (Caltech), Diana Forbes (UIUC), 9 Undergrads (QuantiSED interns), 2 SULI Undergrads, 1 Undergrad in SQMS

Quantum scientists of tomorrow

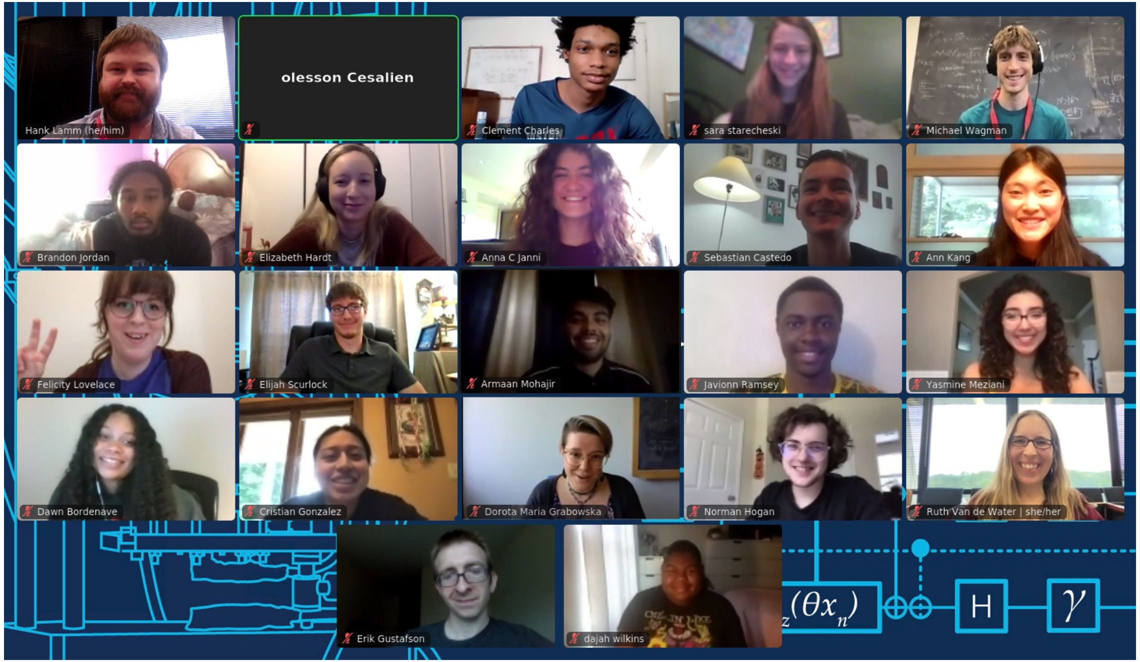
THD hosting 3rd annual Quantum Computing for Physics Undergraduates internship

https://internships.fnal.gov/quantum-computing-internship-for-physics-undergraduates-program/

- 34 summer interns and 12 semester/full-year interns in years 1-2
- 3 students pursuing PhD's in quantum computing so far…
- 5 students on papers published or submitted + more in progress

Charles, Gustafson, **Hardt**, Herren, **Hogan**, Lamm, **Starecheski**, Van de Water, Wagman, arXiv:2305.02361

Gustafson, Lamm, **Lovelace**, Musk, PRD 106 (2022)



Plan is to apply and merge with RENEW

Fermilab

Big Questions

Evolution of Early Universe
Matter-Antimatter Asymmetry
Nature of Dark Matter
Origin of Neutrino Mass
Origin of EW Scale
Origin of Flavor

Exploring the Unknown

A few Highlights from work at the THD from the recent past

More info in the Looking Ahead of Snowmass Series Theory presentations by Ruth, Gordan, Dan, Bogdan, Stefan and Mike https://indico.fnal.gov/event/59904/ https://indico.fnal.gov/event/59564/ and Fermilab P5 town Hall meeting talks by Noemi and Pedro https://indico.fnal.gov/event/58272/

Neutrinos

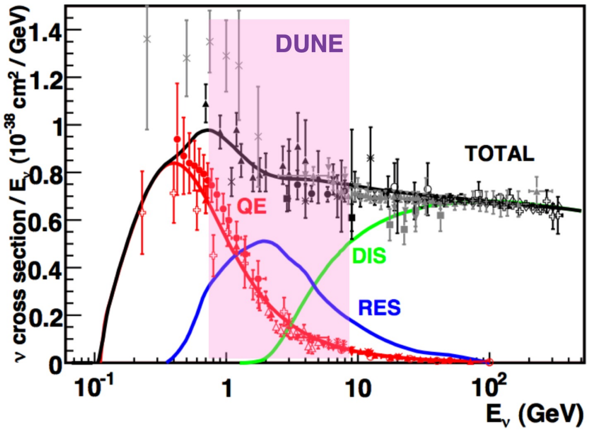
We need a precision physics program to go well beyond neutrino properties, to explore the unknown through the lens of neutrinos

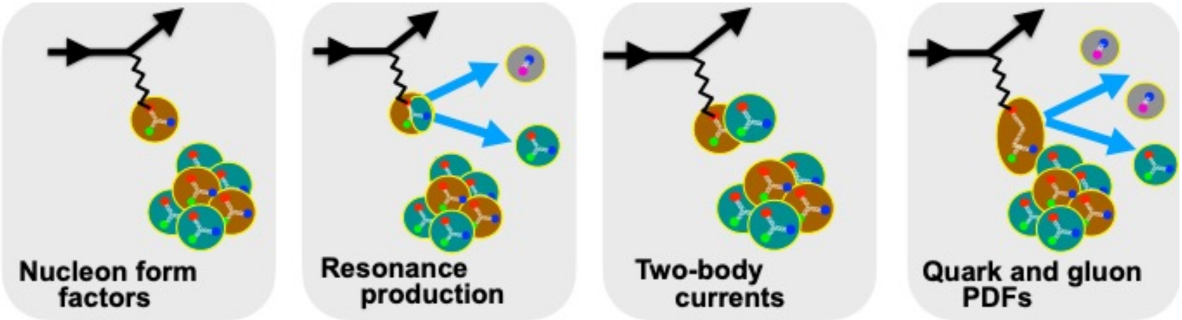
We need precise determination of σ(E) – evaluation of neutrino interactions and nuclear models is critical

Accelerator neutrino fluxes cover a wide range of energies where different processes dominate the cross-section

Lattice QCD can provide few-nucleon inputs to nuclear many-body calculations

Strong complementary between lattice QCD and experiment (e.g. electron scattering)





Fermilab

A critical ingredient of the νA cross section: the axial form factors

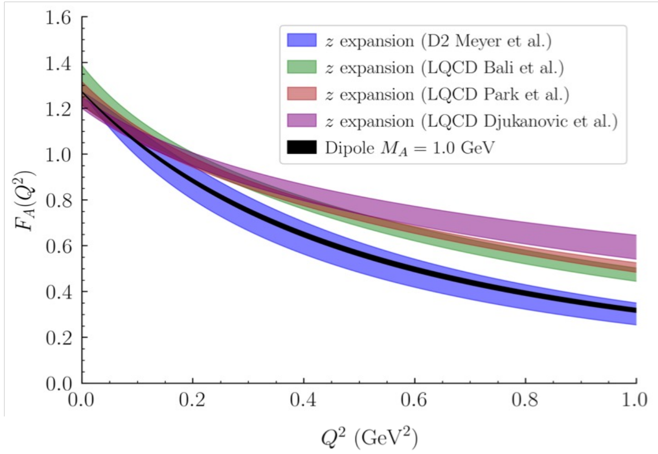
The first steps towards getting few-% cross-section uncertainties are understanding what input parameters we will need and what precision we will need them at.

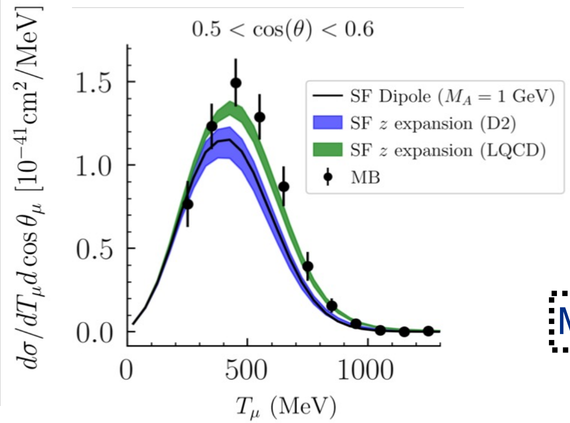
Recent study on cross section dependence from axial form factor

D.Simons, et al incl., **N Rocco and M. Wagman**
arXiv:2210.02455

Different determinations of nucleon axial form factor including LQCD predictions

Axial form factor ➔ input in state-of-the-art microscopic approaches to predict neutrino-nucleus cross sections





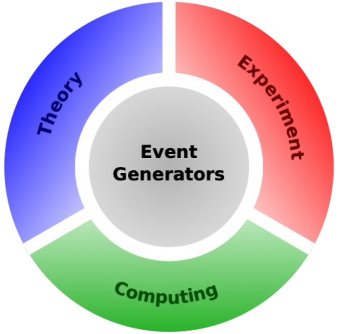
MiniBooNE data

Using different axial form factors leads to ~ 20% difference in the cross section at the peak

Event Generation and Simulation: for SM and BSM

The propagation of **hadrons** through the **nuclear medium** is crucial in the analysis of neutrino oscillation experiments.

Event generators are used to predict **signal**, **backgrounds** and **efficiency**



Event Generators for HEP Experiments, 2022 Snowmass Summer Study

They typically involve a number of unknown model parameters that must be tuned to experimental data, while maintaining the integrity of the underlying physics models.

Next-generation: **uncertainty quantification** will permit a **better understanding** of how to **tune** models to experiment.

Different Monte Carlo event generators

ACHILLES is a novel and unique effort carried out at Fermilab THD

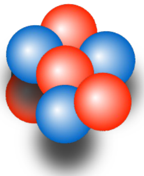
[Isaacson, Hoeche, Rocco, Gutierrez] arXiv:2110.15319
[Isaacson, Jay, Lovato, Machado, Rocco] arXiv:2205.06378

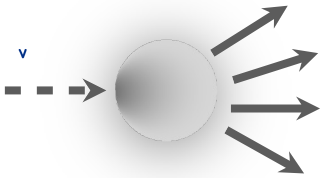
Developing and maintaining EGs requires tight collaboration between theory, experiment, and computing science

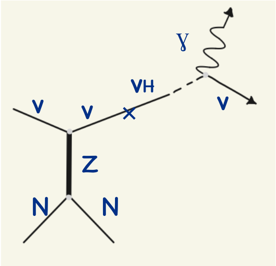
Summary of Neutrinos @ Fermilab THD efforts

Support for efforts aimed at strengthening the US neutrino community and its impact on the US neutrino experimental program:

Nuclear Physics:

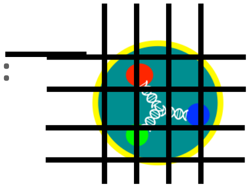






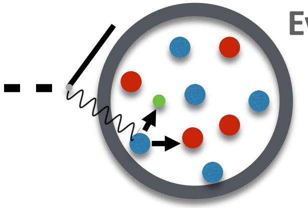
BSM

Lattice QCD :



Simulate neutrino-nucleus cross sections to untangle neutrino oscillations from the measured interactions

Event Generator



Neutrino Theory Network initiative of the DOE supporting the neutrino theory community

New Initiative: Accelerating lattice QCD and neutrino-nucleus scattering with AI

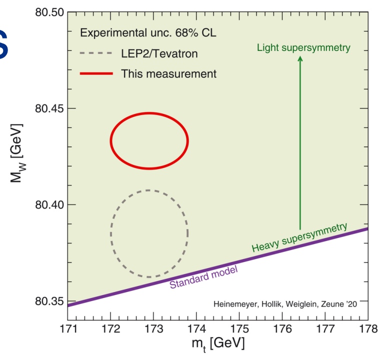
Event Generators for SM and BSM Phenomenology

Enabled by decades of experience developing Event Generators by the collider physics community (e.g. FeynRules+UFO) [Hoeche, Issacson et al.] arXiv:2304.09883

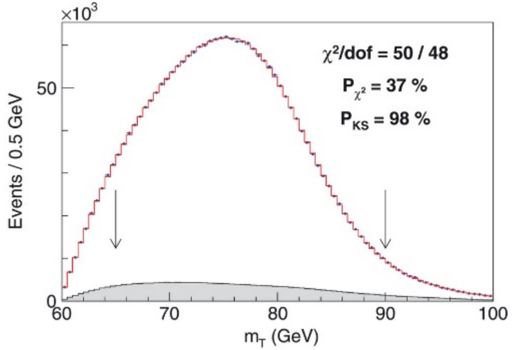
Ideal workflow for SM and specially for BSM exploration
Quantum Field Theory Lagrangian ➡ Simulation (Generator) ➡ Analysis (data)

Generators for Precision Measurements

E.g.: CDF's measurement of the W-boson mass emphasizes importance of precision calculations for extraction of SM parameters at colliders



[CDF Collaboration]
Science, 376, 6589, 170-176



Fermilab theorists provides two of the most important tools for predictions of the p_T spectrum: MCFM and ResBos

- ResBos2 – N2LO fixed order, N3LL resummed [Isaacson et al.]
- MCFM – N3LO fixed order, N4LL resummed [Campbell et al.]

Generators for Exploring the Unknown at Colliders

- Higgs self interaction is key to understanding the EW sector
- Measurement will require careful combination of many analyses with full HL-LHC data set
- Heavy flavor channels needed for high statistical significance

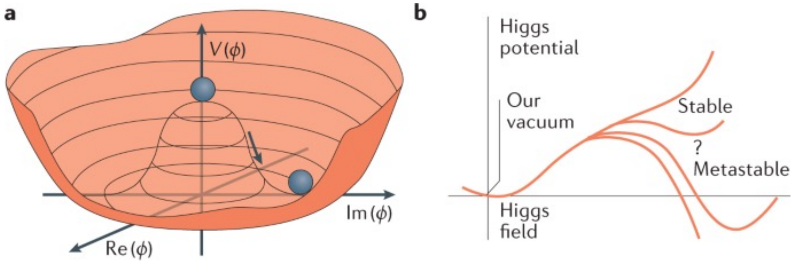
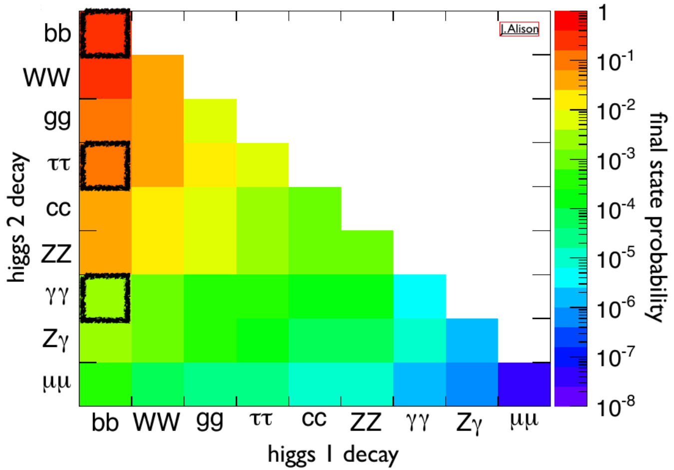


Image Credit: *Nat Rev Phys* **3**, 608–624 (2021)



- Predictions for heavy quark production as part of inclusive heavy plus light flavor jets difficult to obtain at high precision
- Multiple approaches co-developed at Fermilab & implemented in simulations
  - **MCFM** [Campbell et al.]   - **Sherpa** [Höche et al.]
- Estimation of matching scheme uncertainties crucial for reliable extraction of triple Higgs coupling

Beyond the Standard Model at Colliders

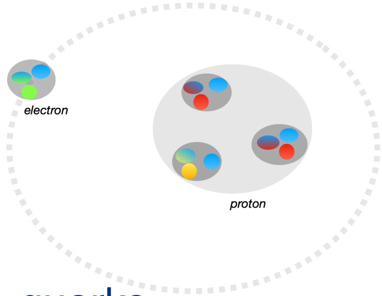
Tough questions which could eventually be answered by experiments at high-energy colliders:

- *Do the SM particles have substructure?*
- *Why is the weak scale much smaller than the Planck scale?*
- *Can deviations from quantum field theory be measured?*

More tractable questions addressed by CMS & ATLAS:

- *Is the gauge symmetry larger than* $SU(3) \times SU(2) \times U(1)$ *?*
- *Do vectorlike quarks or leptons exist?*
- *Are there 'elementary' spin-0 particles other than* h^0*?*

A model of quark and lepton compositeness

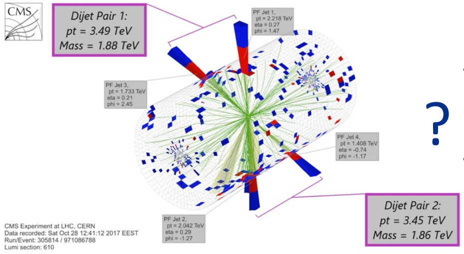


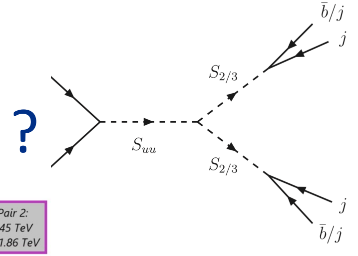
Dobrescu, PRL 2022

⋆ composite vectorlike quarks
– at pp colliders from gluon initial states.
⋆ composite vectorlike leptons
– at a $\mu^+\mu^-$ collider via an off-shell γ or Z
⋆ light composite pseudoscalars
– at e+e– colliders through $h_0 \rightarrow A_0 A_0$

New channels not yet constrained by other searches
e.g. an ultraheavy resonance: an 8 TeV diquark or coloron that can decay into a pair of ~ 2 TeV vector-like quarks, not LHC reach, yet.

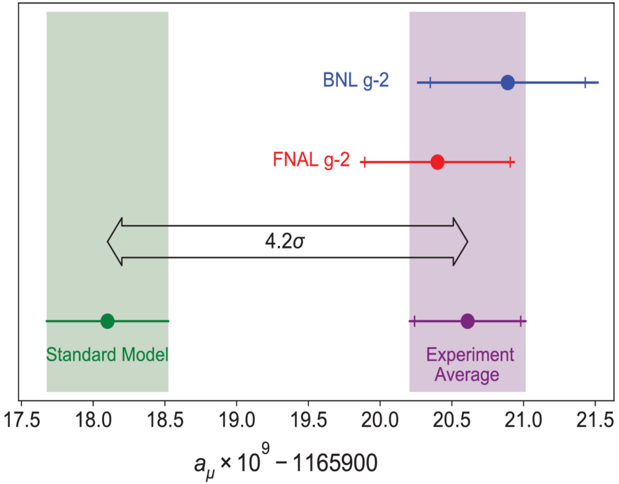
Dobrescu, Harris, Isaacson



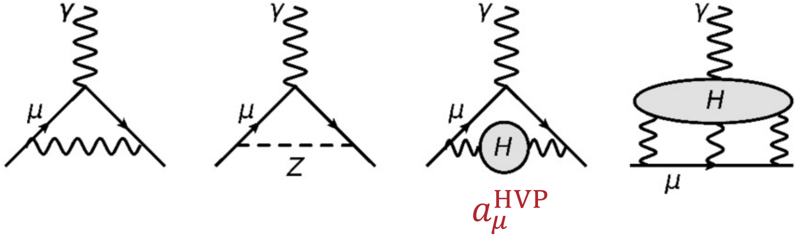


Muon's anomalous magnetic moment

The conclusive interpretation of the $(g-2)_\mu$ measurements as evidence for or against new physics hinges on the availability of a *reliable* & *equally precise* Standard-Model (SM) theory value.



Dominant uncertainty in SM theory value stems from **hadronic vacuum polarization (HVP) contribution,** $a_\mu^{\rm HVP}$:



Presently obtained via data-driven approach using measured $\sigma(e^+e^- \to \text{hadrons})$ + dispersion relations, but significant disagreements between experimental inputs

Can be computed from QCD first principles with controlled uncertainties via numerical lattice simulations

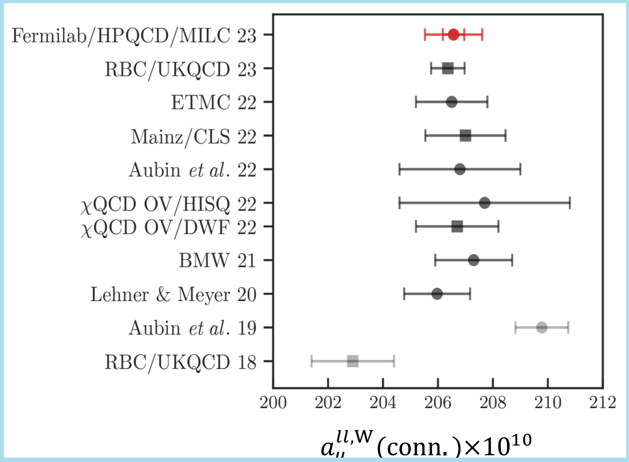
Muon's anomalous magnetic moment

The conclusive interpretation of the $(g-2)_\mu$ measurements as evidence for or against new physics hinges on the availability of a *reliable* & *equally precise* Standard-Model (SM) theory value.

Together, the Fermilab Lattice, HPQCD, & MILC Collaborations (FHM) are undertaking a multi-year, multi-pronged effort to compute a_μ^{HVP} in lattice QCD to sub-percent precision.

This year FHM computed the dominant piece of the ``intermediate window" — a benchmark quantity that comprises around 30% of a_μ^{HVP} — to 0.5% precision.

Set new "gold standard" for lattice-QCD HVP calculations



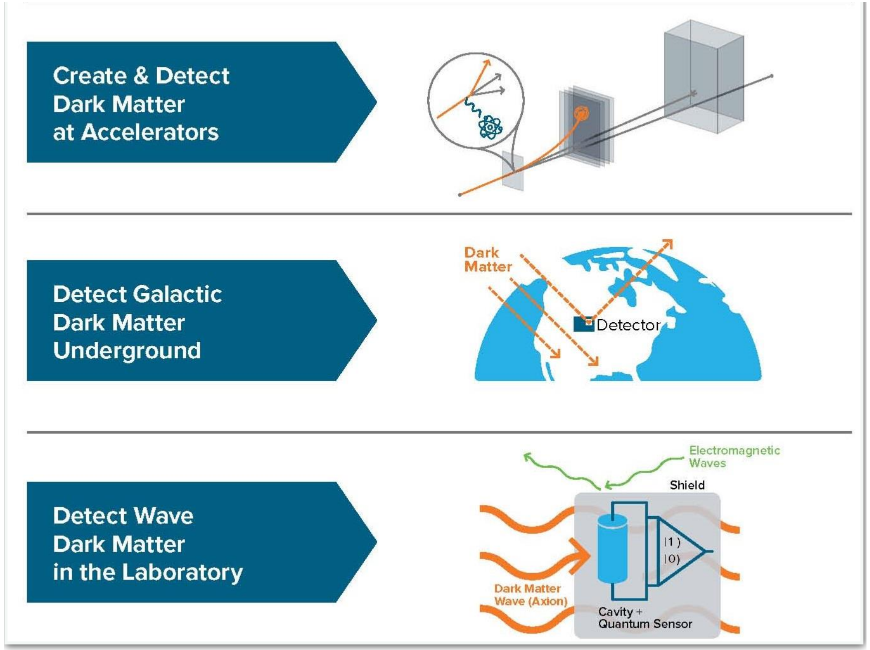
FHM is computing all ingredients to a_μ^{HVP} and anticipates updating total with increased statistics and finer lattice spacings late this year.

Fermilab

The Nature of Dark Matter:

- Huge range of possibilities:

Three priority research directions



FNAL BRN report: Chou, Estrada, **Harnik, Krnjaic**,Tran

+ Indirect dark matter detection

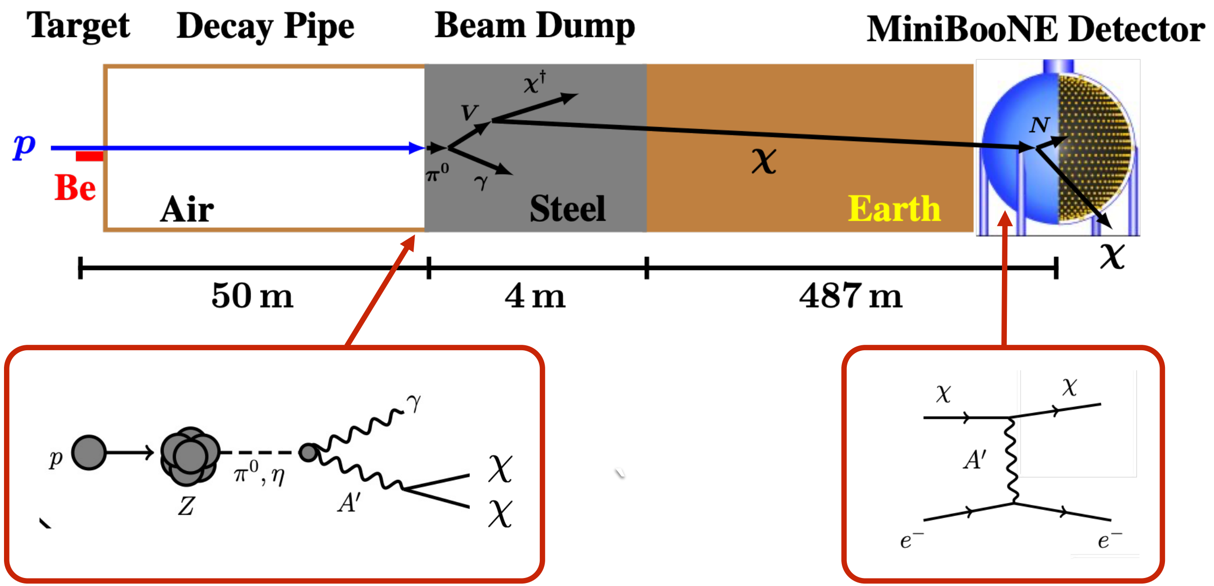
+ learning Dark Matter physics from astrophysical measurements of DM halos

Casting a wide net in the search for dark matter

- Numerous studies on indirect searches for DM (Hooper, Krnjaic, Pinetti, Sokolenko, Fox)
- Long standing program to use the Lyman-Alpha Forest to constrain DM (Gnedin)
- Constraints on charged DM from large-scale Galactic magnetic fields (Stebbins, Krnjaic)
- DM distribution studies on small-scales in scenarios of an early matter dominated era (Blinov, Stebbins, Hooper)
- DM pheno/model building/production mechanisms (Krnjaic, Hooper, Sokolenko, Xiao, Fox, Berlin, Dev, Robles, Trickle)
- DM Connections with muon g-2 (Krnjaic, Hooper; Janish; Carena)
- DM models with electroweak baryogenesis, new forces & dark CPV (Carena, Ou, Li)
- and more

Dark Matter/Dark Sectors production at proton beam facilities

Fermilab theory has led effort to develop light dark matter searches at neutrino facilities



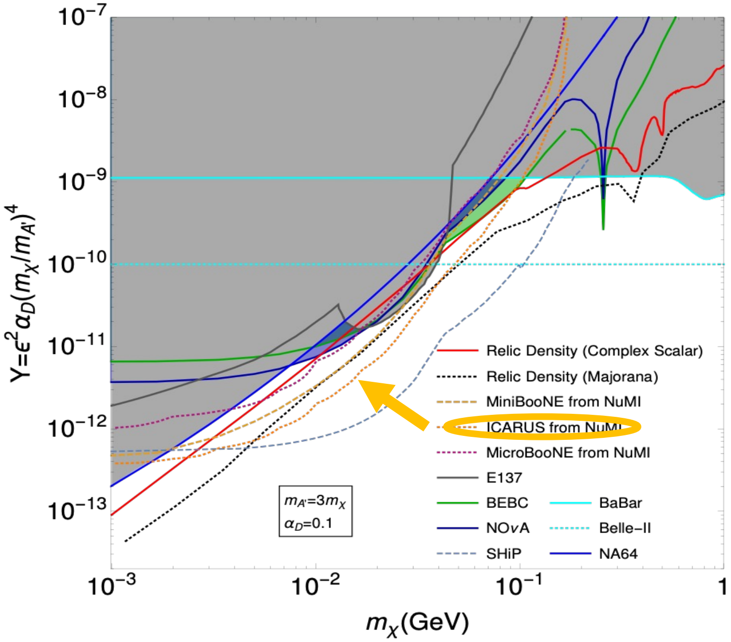
Batell, Pospelov, Ritz 0903.0363

Dobrescu, Friuguele 1410.1566
Kahn, **Krnjaic**, Thaler, Toups 1411.1055
Berlin, Kling 1810.01879

Izaguirre, **Kahn**, Krnjaic, Moschella 1703.06881
De Gouvea, **Fox, Harnik, Kelly**, Zhang 1809.06388
De Niverville, **Tsai**, Liu 1908.07525

Dark Matter Reach @ FNAL Neutrino Experiments

- Look for light dark matter particles (mass <~ 100 MeV) that could be produced in the NuMI beam
- They can scatter off electrons in a target
- ICARUS, for example, has interesting sensitivity to this kind of DM with parameters giving the expected relic density
- Neutrinos are just an annoying background for this kind of search



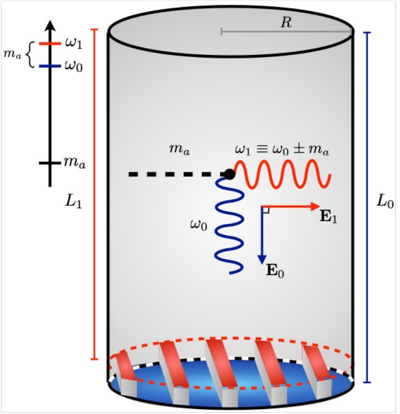
Buonocore, **Frugiuele**, deNiverville 1912.09346

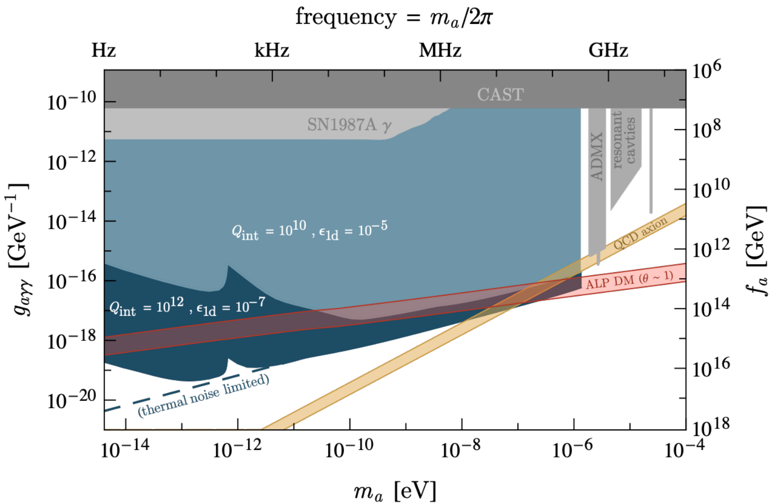
see also Izaguirre, Kahn, **Krnjaic**, Moschella 1703.06881

Batell, Berger, Darme, **Frugiuele**, 2106.04584

Fermilab

Axion Detection w/ SRF Cavities





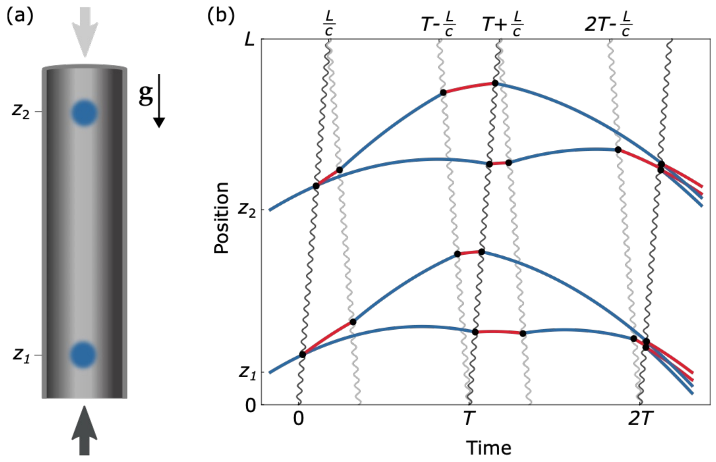
Berlin et al 1912.11048

Superconducting RF cavity with applied B field "eats" DM axions. Usually match axion mass to the cavity frequency

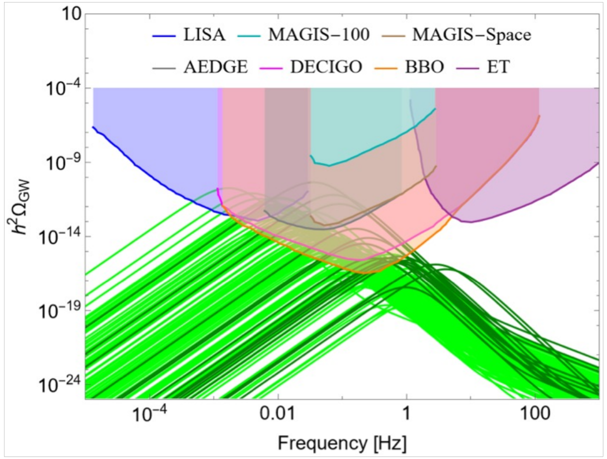
New concept: tune nearby cavity modes to be on resonance with axion mass in presence of variant B field → Enables sensitivity to much lower axion mass values (prototype cavity in production)

THD working with SQMS experts in many experiments involving SRF cavities..

THD bringing Magis-100 Atom Interferometry @ FNAL



Abe, **Harnik, Lykken** et al 2021 Quantum Sci. Technol. **6** 044003



Carena, Li, Ou, Wang 2210.14352

Single baseline atom interferometer search for DM, gravity waves, tests of QM

Split/recombine matter waves of atomic gas with laser pulses

BSM affects observed interference pattern of atomic clouds in free fall

We are also exploring theories with early phase transitions that can be tested in MAGIS-100.

Cosmic History: Inflation, Dark Energy, and Beyond

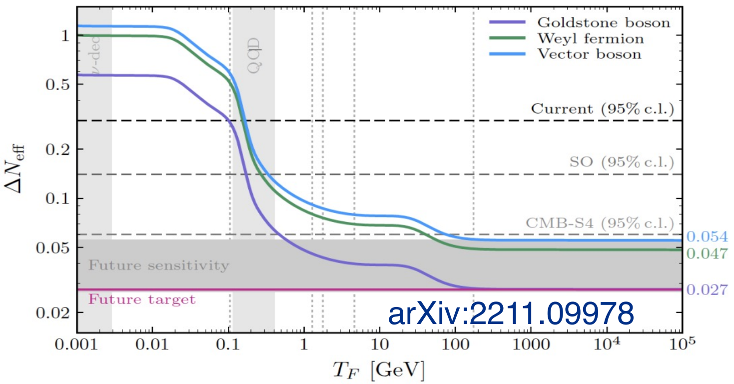
- ΔNeff, Sensitive to wide range of BSM – discovery channel for Stage IV CMB

  Contributions to ΔN_{eff} e.g. from

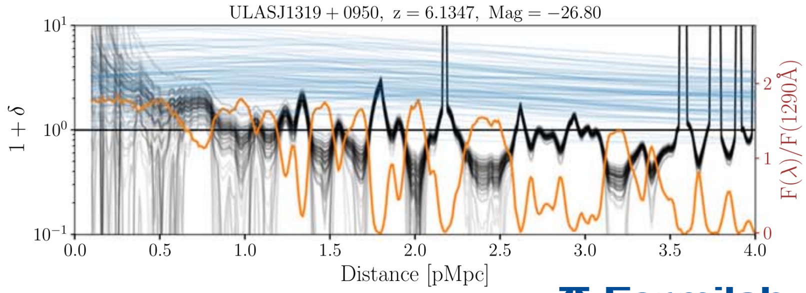
  primordial black holes (Krnjaic, McDermott, Hooper)

  inflationary fluctuations (Krnjaic)

  light gauge bosons (Krnjaic, Hooper)



- Progress in understanding the process of galaxy formation (Gnedin)
- Exploring connections between dark matter and inflation (Krnjaic, McDermott, Hooper)
- Proposals to address Hubble tension between CMB and local H_0 measurements (Blinov, Krnjaic, Li; Blinov, Kelly, Krnjaic, McDermott; Blinov, Hooper; Berlin)
- Early galaxies as probes of fundamental physics (Gnedin et al. 2101.11627, 2110.13917, 2208.13787)
- Looking to the future: 21-cm cosmology (Stebbins)



Quantum simulations for High Energy Physics

[PRX Quantum 4 (2023) 2, 027001]

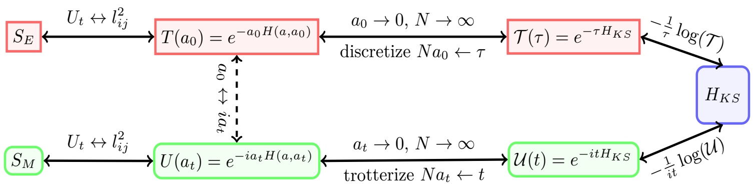
Quantum Simulation for High Energy Physics

Christian W. Bauer,[1,a] Zohreh Davoudi,[2,b] A. Baha Balantekin,[3] Tanmoy Bhattacharya,[4] Marcela Carena,[5,6,7,8] Wibe A. de Jong,[1] Patrick Draper,[9] Aida El-Khadra,[9] Nate Gemelke,[10] Masanori Hanada,[11] Dmitri Kharzeev,[12,13] Henry Lamm,[5] Ying-Ying Li,[5] Junyu Liu,[14,15] Mikhail Lukin,[16] Yannick Meurice,[17] Christopher Monroe,[18,19,20,21] Benjamin Nachman,[1] Guido Pagano,[22] John Preskill,[23] Enrico Rinaldi,[24,25,26] Alessandro Roggero,[27,28] David I. Santiago,[29,30] Martin J. Savage,[31] Irfan Siddiqi,[29,30,32] George Siopsis,[33] David Van Zanten,[5] Nathan Wiebe,[34,35] Yukari Yamauchi,[2] Kübra Yeter-Aydeniz,[36] and Silvia Zorzetti[5]

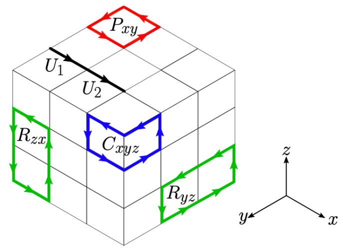
Real time strong dynamics, out-of-equilibrium and quantum interference processes → induce sign problems or rare events that have exponential-scaling of the complexity

Quantum simulations can provide a new tool to enable HEP discoveries

Decades of lattice field theory experience with classical computers can provide insight on renormalization, scale setting, discretization effects, and other aspects of quantum simulations

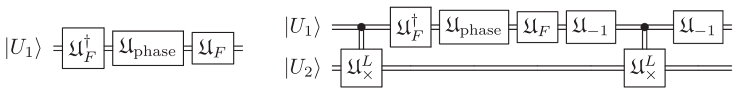


Carena, Lamm, Li, and Liu; and Gustafson, PRDs 104 (2021)



Original Hamiltonian

Improved Hamiltonian



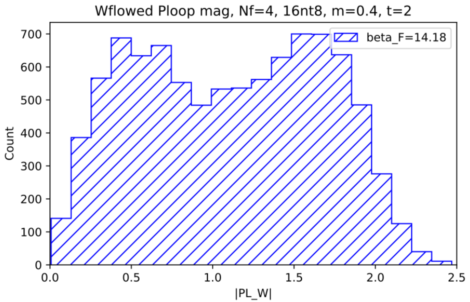
Lattice gauge theory Hamiltonians are not uniquely defined at the lattice scale

Carena, Lamm, Li, Liu, PRL 129 (2022)

Improved Hamiltonians can accelerate the approach to the continuum limit where universal gauge theory results are achieved

Lattice strong dynamics: composite BSM physics (new THD scope)

- Non-perturbative lattice calculations to investigate the finite-temperature confinement transition of stealth dark matter: strong 1st order + GW signal

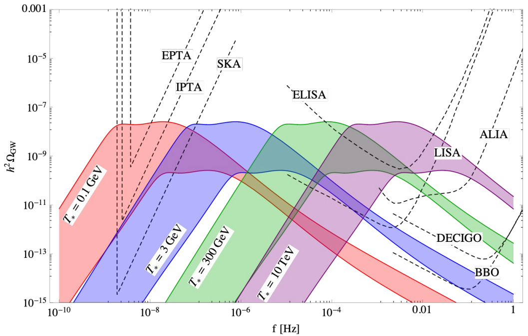


Double peak implies strong 1st order PT

Fleming et al, Phys.Rev.D 103 (2021) 1, 014505

Confining SU(N) gauge theories can produce dark matter particles over wide range of mass scales.

1st order phase transitions in early universe can produce detectible gravitational wave signatures.



Gravitational Waves from a Dark PT

- Composite Higgs: Could explain new W mass measurement
- Non perturbative QFT in curved manifolds

Fleming et al: arXiv:2006.15636

Realization of non-perturbative radial quantization now possible. Enables direct calculation of Critical Field Theory OPE coefficients from four-point function.

Snowmass Contributions

Topical Group Conveners:

- Fox: Theory Frontier: BSM Model Building (TF08)
- Harnik: Theory Frontier: Quantum Information Science (TF10)
- Hoeche: Energy Frontier: Precision QCD (EF05)
- Machado: Neutrino Physics Frontier: Understanding Experimental Neutrino Anomalies (NF02)

30+ Snowmass white papers co-authored by ThD scientists.

About half the ThD scientists were present in Seattle

Snowmass Contributions

Examples of the 30+ Snowmass white papers co-authored by ThD scientists

- Physics Opportunities for the Fermilab Booster Replacement (Harnik, Krnjaic, Machado)
- Neutrinos and lattice QCD (Wagman)
- Quantum simulation of QFT's (Lamm, Carena)
- Computational needs for lattice field theory (Kronfeld)
- Probing the Electroweak Phase Transition with Exotic Higgs Decays (Carena)
- Report on the Snowmass 2021 TG on Lattice gauge Theory (Kronfeld, Van De Water, Wagman)
- Future prospects for parton showers (Hoeche)
- Puzzling Excesses in Dark Matter Searches and How to Resolve Them (Hooper)
- DarkQuest: A dark sector upgrade to SpinQuest at the 120 GeV Fermilab Main Injector (Berlin)
- Snowmass Neutrino Frontier:DUNE Physics Summary(Machado, Parke)
- Light Sterile Neutrino Searches and Related Phenomenology (Machado)
- Event Generators for High-Energy Physics Experiments (Campbell, Hobbs, Hoeche, Isaacson, Rocco)

Fermilab Theory and National/International Initiatives

- **Neutrino Theory Network**: 14 universities and 6 labs participating. Managed by Fermilab Theory but almost all funds go out the door. New, highly competitive NTN postdoctoral fellow program aim at strengthening the theoretical neutrino physics research effort in the US and its impact on the experimental programs.

- Two fellows per year for 3 years each since FY21. Info @https://ntn.fnal.gov

Zahra Tabrizi
(Northwestern)

Bijaya Acharya
(ORNL)

Ryan Plestid
(Caltech)

Payel Mukhopadhyay
(Berkeley)

Aaron Meyer
(LLNL)

Matheus Hostert
(Harvard)

Fermilab Theory and National/International Initiatives

- **QuantISED Theory Consortium**:
  National Consortium launched 2018 , Carena PI, with Caltech and U. Wash, renewed in 2020 adding QuantISED pilot PIs from UIUC, MIT, and Purdue. Other Universities expressed interest in joining, JHU is in the process.

  Possibly moving forward to base funding in FY24

Fermilab Theory and National/International Initiatives

- **Muon g-2 Theory Initiative**

Outgrowth of the Distinguished Scholar Program, supporting the Muon *g*–2 Experiment

In anticipation of Fermilab E989's measurement, Fermilab theorists helped launch the Muon g-2 Theory Initiative:

It highlights Fermilab role as a hub.

It continues to contribute substantially to theory-initiative workshops, reviews, and white papers.

- **Lattice QCD**:

Active leadership of the USQCD Collaboration, which is the national framework of lattice infrastructure, including Kronfeld, Fleming and Simone as member of the USQCD Executive Committee (Kronfeld served as Chair until 9/20/2021)

Kronfeld PI of the Exascale Computing Project for lattice QCD

Kronfeld co-PI of SciDAC5 (ASCR+HEP) project for lattice gauge theory

Close collaboration with the LQCD extension III computing program (managed in SCD).

Other Fermilab Theory Initiatives

- **Postdoc Joint Appointments:**

In past 5 years: Northwestern(5), U. Chicago (2 + 2 (FY24)),
plus one at each of the following institutions:
U. Maryland, U. Kentucky, IIT, UIUC, ANL, Notre Dame, UIC (FY24)

Pursuing structured initiatives: Kadanoff Institute at UChicago (quantum).

- **Distinguished Fermilab Scholars**

Rotating multi-year appointments for U.S. theorists at Fermilab, with at least one-month residence per year (bring postdocs/students). This program strengthens the connections between lab & university theory and increases the local expertise supporting Fermilab exp.

Other Fermilab Theory Initiatives

- **Cross-division cross-fertilization for experiments (examples):**

BSM programs for DUNE, SBN, and MiniBooNE; millicharged/HNL/ALP@ArgoNeuT

Seeded and continue to participate in LDMX

Develop AI/ML based tracking algorithms with potential for HL-LHC

Expand focus/reach/ideas with Skipper CCDs (SENSEI, OSCURE, quantum imaging, DarkNESS, vIOLETA)

Leadership role in SQMS

Quantum experiments underway (brought MAGIS-100 to FNAL; proposed Dark SRF, Axion SRF)

Muon Missing Momentum (M^3);

SpinQuest; …

Strong connections with LPC, CPC, NPC (TH/EXP liaisons)

Fermilab

Theory output in numbers:

149 papers with 590 citations in the past year in key research areas directly related to the U.S. and worldwide experimental programs

Special emphasis on restoring pre-pandemic level of activities in-person at the lab: seminars, visitors, schools and conferences - important challenges related to site-access-

Grants and Awards

- Exascale Computing Project (ECP) for Lattice QCD - U.S.'s largest federally funded scientific computing project ever.- PI: A. Kronfeld (FY2018-FY2023)
- HEP SciDAC-5 Project. Neu-Col: Next-Generation Precision for Neutrino and Collider Computations. PI: N. Rocco (FNAL), co-Pis from FNAL: Campbell, Hoeche, Isaacson. (FY2023-2027)
- DOE INCITE Leadership Computing program for supercomputer resources on leadership-class machines at Argonne and Oak Ridge PI: A Kronfeld. (FY 2021 – FY2023 and continuing)

- HEP-ASCR SciDAC 5 Project. (FY2023-FY2027) Co-PI form FNAL: Kronfeld (FY 2023-2027)
- STREAMLINE Collaboration: Machine Learning for Nuclear Many-Body Systems. PI: D. Lee (MSU), co-Pi from FNAL: Rocco. (FY 2024-25)
- Accelerating Simulations for LQCD and neutrino-nucleus scattering using AI. PI: R. Gupta (LANL), co-PI from FNAL: Rocco, Wagman. (FY24-26)
- Nuclear Theory for New Physics (NTNP) topical collab. PI: V. Cirigliano (UW), co-Pi from FNAL: Rocco. (FY26-28)

- Early Career Award 2019: Pedro Machado
- DOE Office of Science Distinguished Scientist Fellows 2022: Marcela Carena
- Technical University Munich Ambassador 2022: Andreas Kronfeld

Quantum Theory Department

- Provides a single home for lab theorists working in Quantum
- Involvement from other division scientists and postdocs.
- Pursuing an expanding area at the interface of HEP and quantum science.
- Strong efforts in quantum simulation and in quantum sensing.
- Latest hires: Hank Lamm (quantum simulation of HEP-QFT - March 2021) and Asher Berlin (quantum sensing – November 2021) strong additions to the program
- Synergy with SQMS (via SQMS science thrust lead Harnik) and FQI
- Supported fully by **non-base** funding:

QuantISED DOE grant (PI Carena) and SQMS Center

Moving towards base funding with an ongoing FWP

Important to keep its identity within the lab and its agility to explore new research directions as a vibrant department within the Theory Division

Astrophysics Theory Department

- Well integrated with the Fermilab Cosmic Program
- Absence of Scott Dodelson (LOA) and Josh Frieman (now only 2 months/yr Fermilab) leaves major gaps in scientific expertise and leadership that we need to fill
- Latest Hire: Gordan Krnjaic (Dark Matter and Neutrino Cosmology, December 2018) strong addition to the program
- Want to build/leverage on our strong connections to the Kavli Institute and Astronomy Dept. at U. Chicago
- Similarly for our connections to the CIERA astrophysics center at Northwestern

Particle Theory Department

- Well integrated with the Fermilab LPC, Muon and Neutrino Programs
- Latest hires: Noemi Rocco (neutrino nuclear – October 2020) and Mike Wagman (lattice neutrinos and QFT – December 2019) strong additions to the program
- Successful efforts of leveraging through SciDAC, ECA, Exascale and International connections such as European Networks and Humboldt Foundation
- Strong connections with colleagues at US Universities and abroad that attract

  students and postdocs to come to Fermilab

Review the status of the recommendations from previous reviews

- The PAC recommends that the Lab provides the Theory Division with the requested support.

  We have adequate program support
  We are still waiting for any support to maintain and reconfigure our space

- The Lab and the Theory Division should maintain close connections to the University community.

  We have multiple strong connections/collaborations but are suffering a lot from site access issues and resulting negative feelings
  [see recent example on following slide]

Review the status of the recommendations from previous reviews

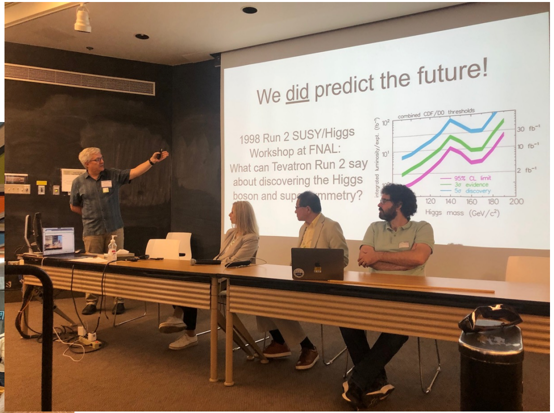
- and ensure that the programs it is offering are welcomed by the community, as opposed to being seen as securing a larger piece of a small pie.

  NTN and quantum simulation consortium are highly valued by the community

  Restoring pre-pandemic levels of visitor program, including Fermilab Distinguished Fellows program, and on-site meetings would be key, but this is undermined by current site access difficulties and concomitant reputational damage.

Beyond the SM from Colliders to the Early Universe, 5/27-30, 2023

- Recent Theory symposium
- First 2 days @U. Chicago, 3rd day @FNAL



Scientifically the meeting was a big success

But due to sit access many barriers, it is questionable how many participants will be choosing to sign up for any future meetings at Fermilab

We are worried about 2 upcoming international events: Lattice 2023 (August) and SM@LHC (July)

Thank you