Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Fermilab Theory Broad Overview

Michael Wagman

Tues. June 14, 2022

Fermilab Theory

What we do:

- Identify and support theory needs of experiments at Fermilab
- Connect Fermilab with the global theoretical physics community
- Train HEP theorists developing deep connections to the experimental community

Fermilab theory plays a leading role in many HEP community-wide efforts:

- Neutrino Theory Network
- QuantISED Theory Consortium
- Muon g-2 Theory Initiative
- Exascale Computing
- …

Theory Division
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P. Fox, Deputy Head
R. Carrara, FFM

(C. Armstrong, HR Partner)
(K. Swanson, DSO, ESH)

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O. Vizcarra, Div. Support
M. Martinez, Admin

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B. Assi, RA
E. Bernreuther, RA
V. Brdar, RA/JA
J. Campbell
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N. Coyle, GS
D. Danielson, GS
A. Dev, RA
B. Dobrescu
(P. Fox)
W. Giele
(R. Harnik)
S. Hoeche
F. Herren, HF
(T. Hobbs, SCD)
A. Ireland, GS
J. Isaacson, RA
S. Li, RA
Y-Y. Li, RA
(J. Lykken, DO)
P. Machado
(S. Mrenna, SCD)
A. Nikolakopolous, RA
S. Parke
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(A. Strelchenko, SCD)
(J. Simone, SCD)
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(P. Fox)
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(R. Harnik)
C. Hogan, JA
G. Krnjaic
(Y-Y. Li, RA)
(S. Li, RA)
S. McDermott, SF
E. Pinetti, RA
A. Sokolenko, JA
A. Stebbins

Quantum Theory Department
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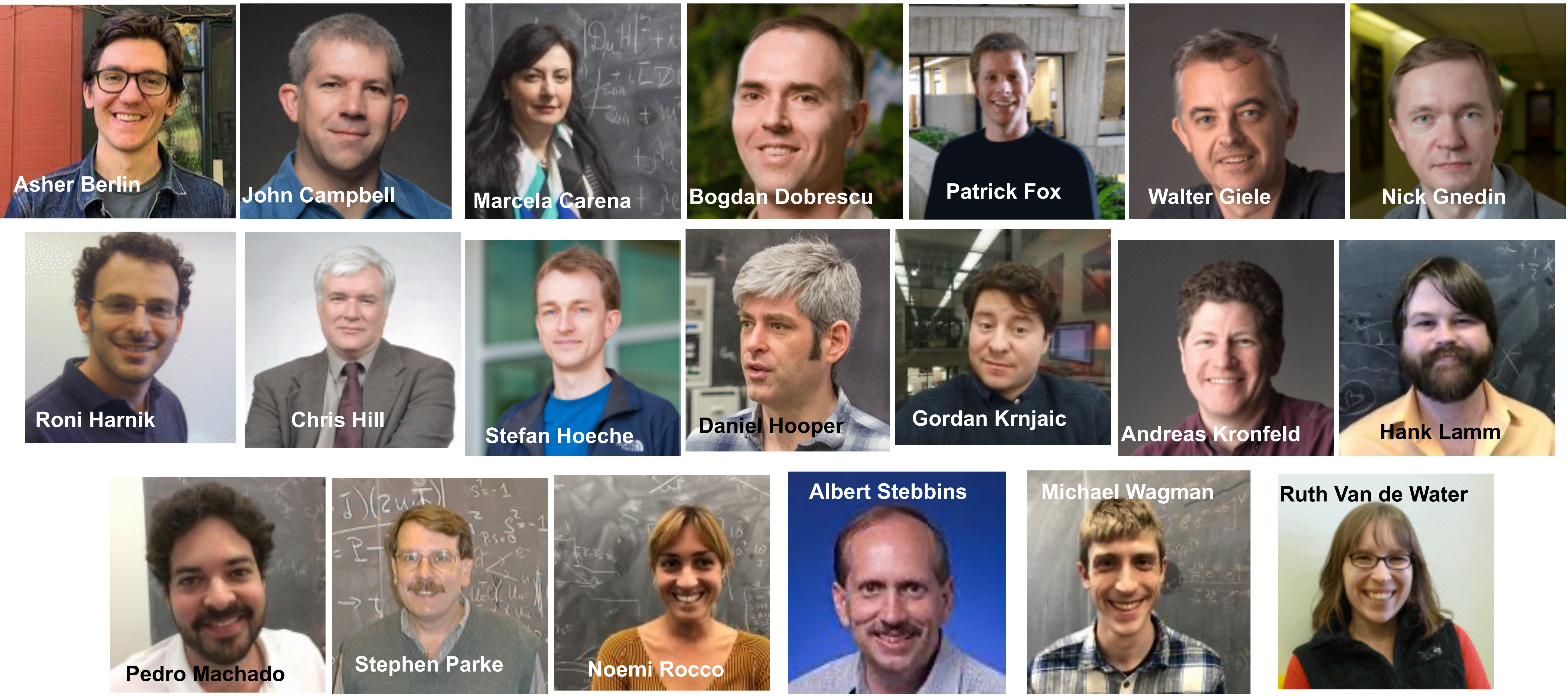
Y. Gao, JA
E. Gustafson, RA
R. Janish, RA
(G. Krnjaic)
(D. Kurkcuoglu, FQI/SQMS)
H. Lamm
(A. Li, FQI/SQMS)
(Y-Y. Li, RA)
(A. Macridin, FQI/SQMS)
T. Ou, GS
(B. Ozguler, FQI/SQMS)
(G. Perdue, FQI/SQMS)
(P. Shyamsundar, FQI)
J. Unmuth-Yockey, RA
W. Liu, GS

Scientists Emeritus
W. Bardeen
E. Eichten
C. Hill
B. Kayser
P. Mackenzie
C. Quigg

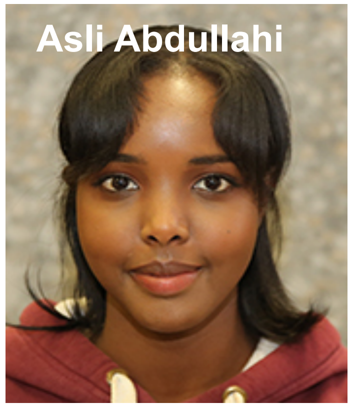
Scientists

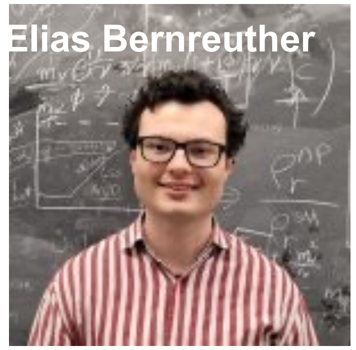


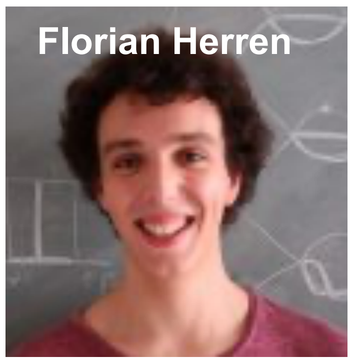
Broad interests:

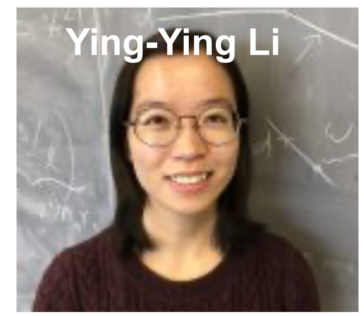
- Astrophysics/cosmology
- Dark matter/dark sectors
- Higgs physics
- Lattice QCD
- Neutrino physics
- Perturbative QCD
- Phenomenology
- QIS and QFT simulation
- QIS and quantum sensors

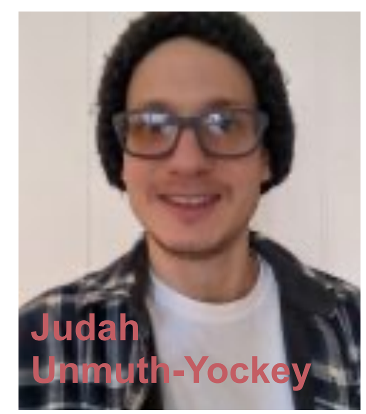
Postdocs











Vibrant postdoc cohort essential for success of Fermilab theory

Growing efforts to collaborate with graduate students (connections with Chicagoland universities, URA Fellowships, …) and undergraduates (SULI, SIST, new theory-led Quantum Computing Internship for Physics Undergraduates)

Recent highlights from Fermilab theory

Illustrative, not exhaustive

One (biased) perspective

Muon $g-2$

Fermilab *g-2* experiment has published its first results

Abi *et al.* [Muon *g-2* Collaboration], PRL 126 (2021)

4.2σ discrepancy between experiment and Standard Model prediction as of 2020 white paper

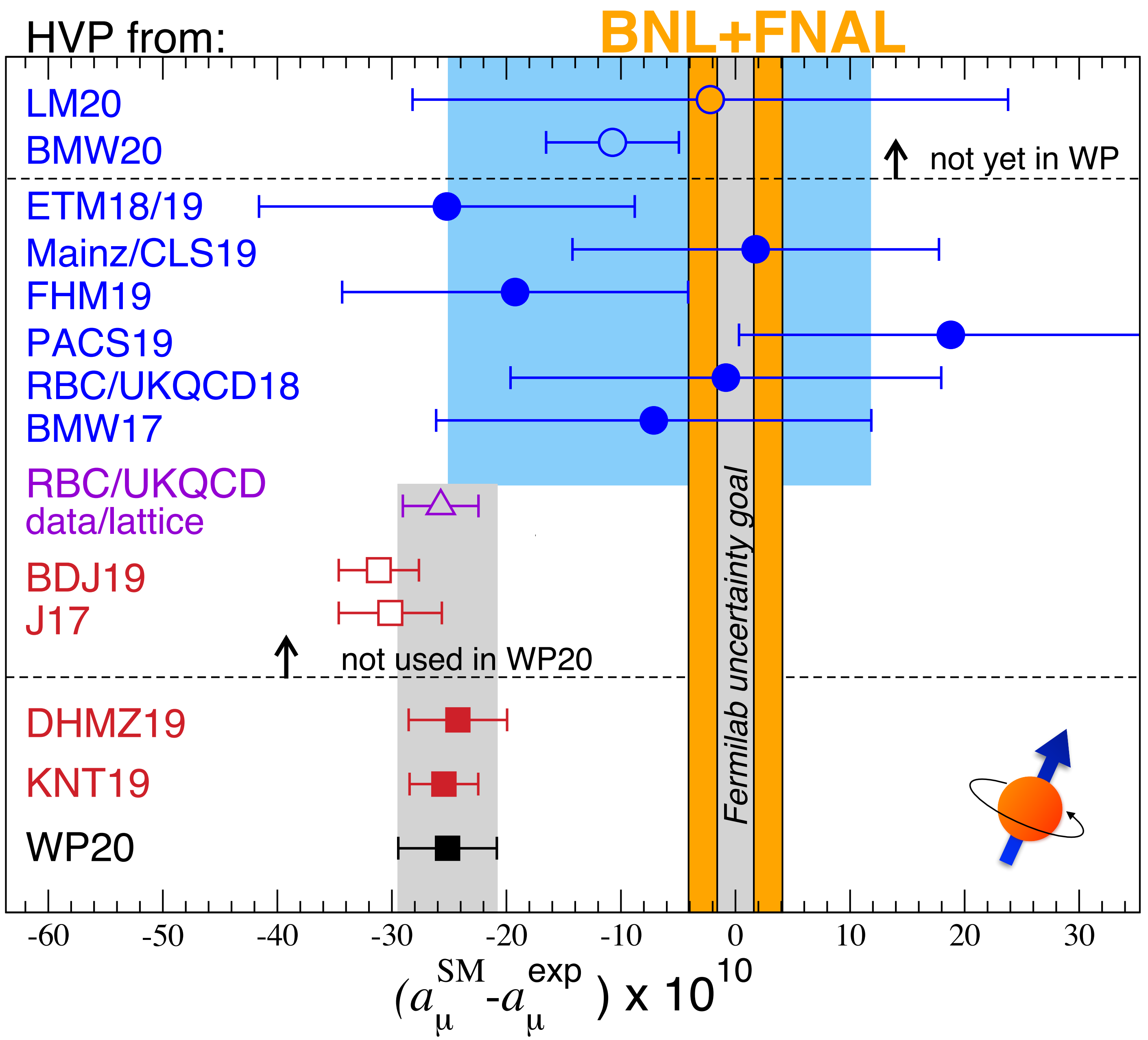
Aoyama *et al.* Phys. Rept. 887 (2020)

Many BSM explanations have been proposed (including by Fermilab theorists)

Baum, Carena, Shah, and Wagner, JEHP 01 (2022)

Holst, Hooper, Krnjaic, PRL 128 (2022)

…



The most precise Standard Model predictions use data-driven dispersive approaches to determine the hadronic vacuum polarization (HVP) contribution and combine dispersive and lattice QCD (LQCD) results for light-by-light scattering

Recent LQCD calculation by BMWc with 0.8% precision shows tension with dispersive results

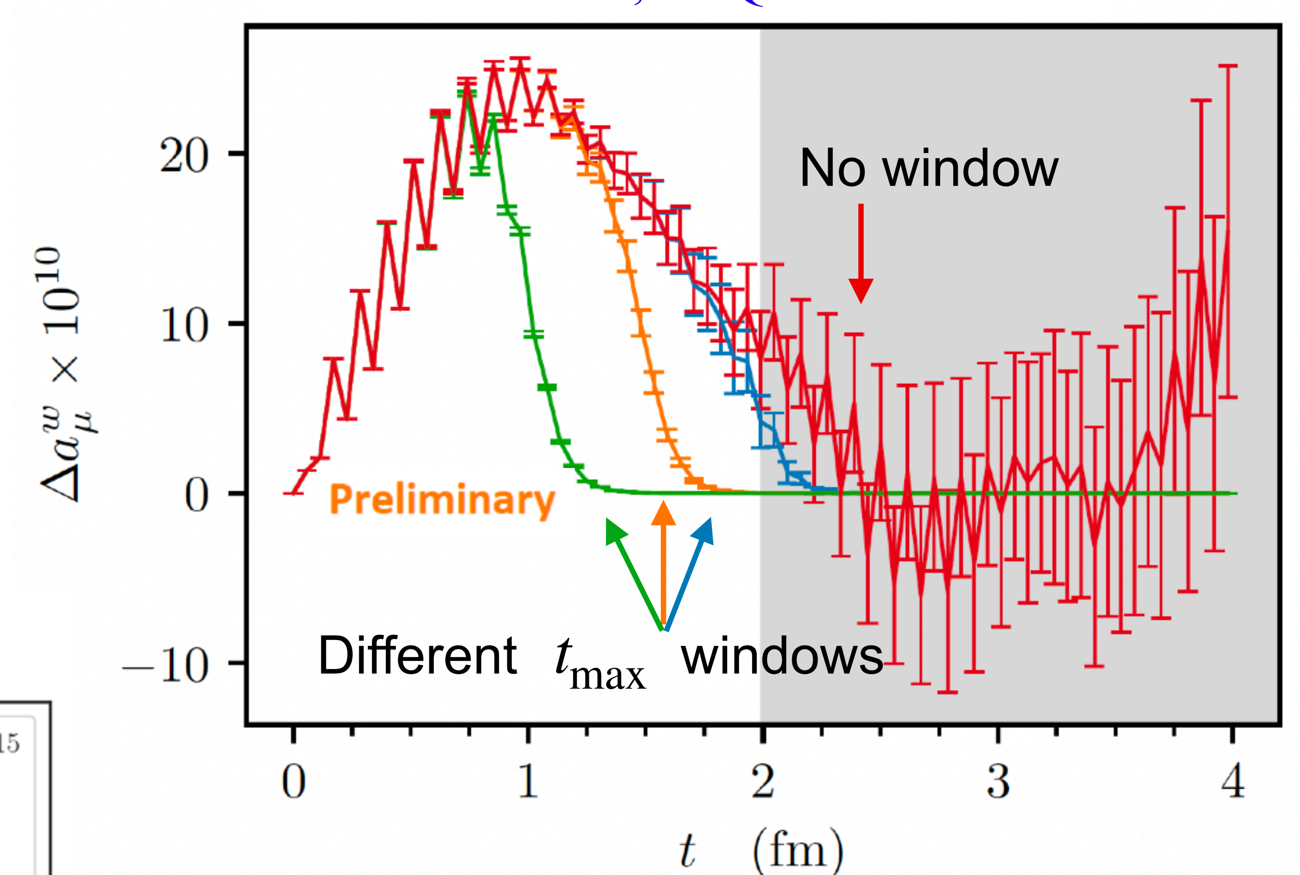
Lattice QCD and $g-2$

Ongoing efforts will improve precision of LQCD results for LO HVP and illuminate tensions with dispersive approaches

- Comparisons using different "window functions" isolate regions where different systematics dominate

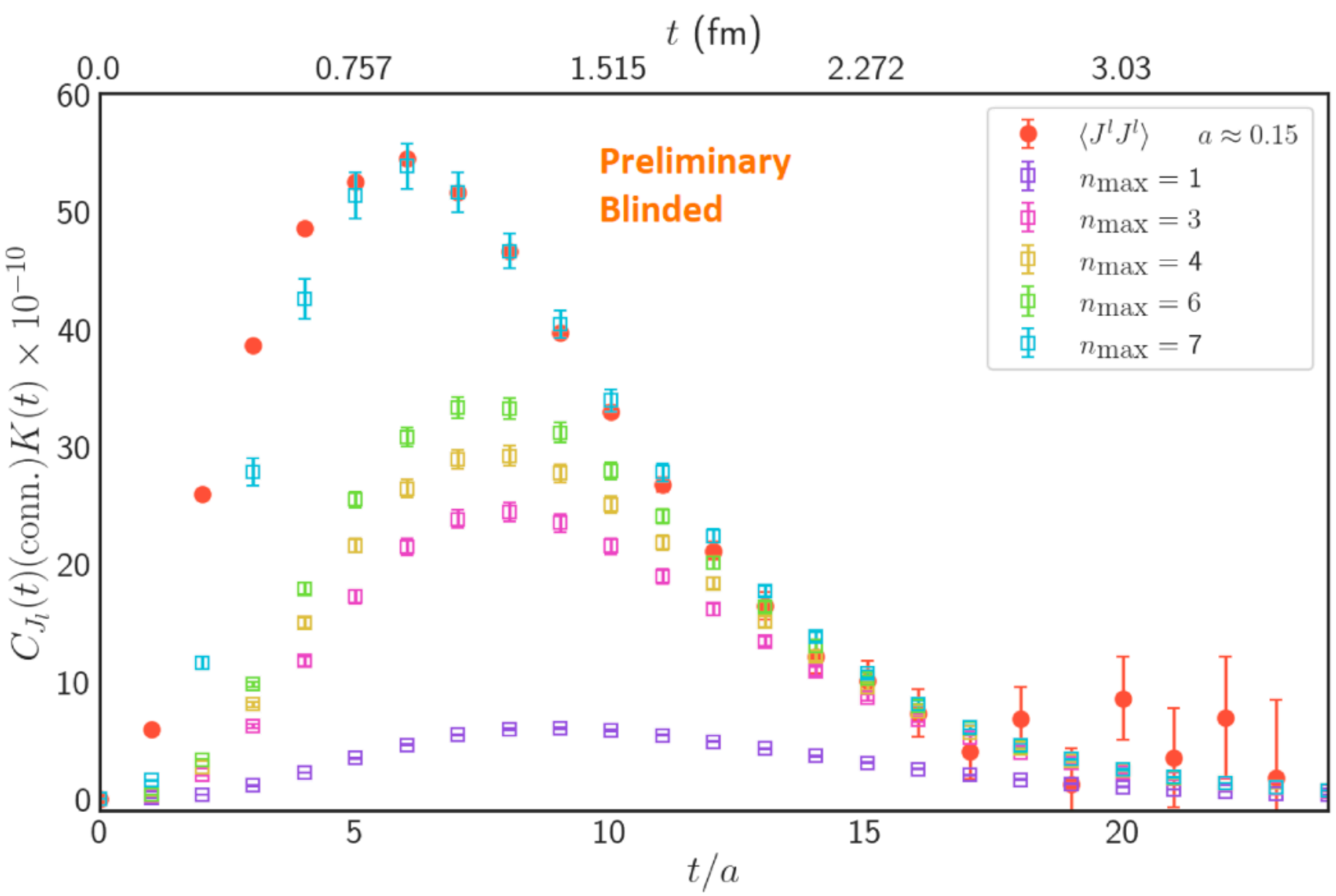
Window comparison

Fermilab Lattice, HPQCD and MILC



Data from: Davies *et al.* [Fermilab Lattice, HPQCD and MILC], Phys. Rev. D 101 (2020)

Direct calculation of $\pi\pi$ contribution



Lahert *et al.* [Fermilab Lattice, HPQCD and MILC], Lattice 2021, arXiv:2112.11647

- Calculations of $\pi\pi$ correlation functions using variational methods allow improved precision at large t

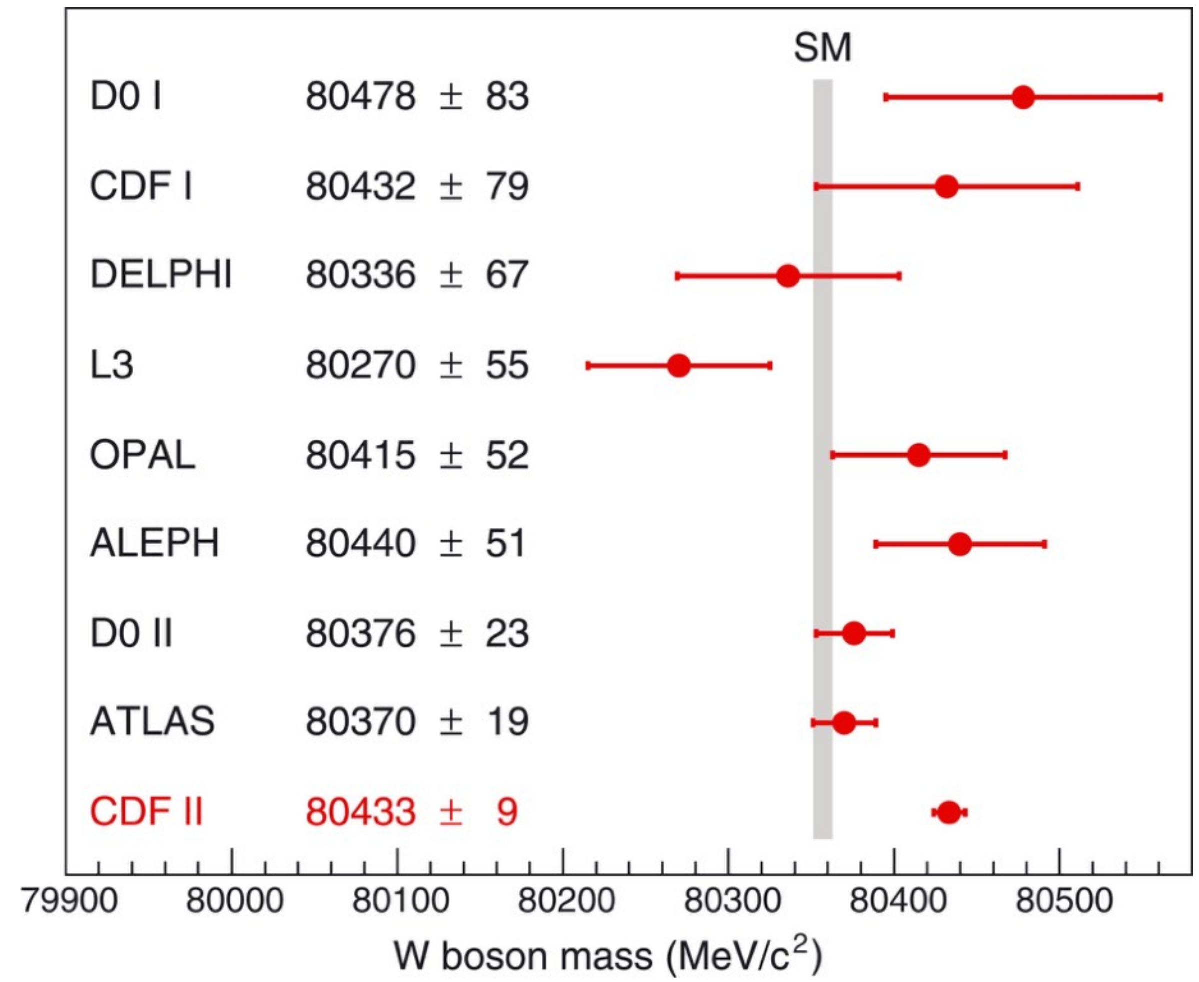
Stay tuned for percent-level LO HVP predictions from Fermilab Lattice/ HPQCD/MILC Collaborations

The W boson mass

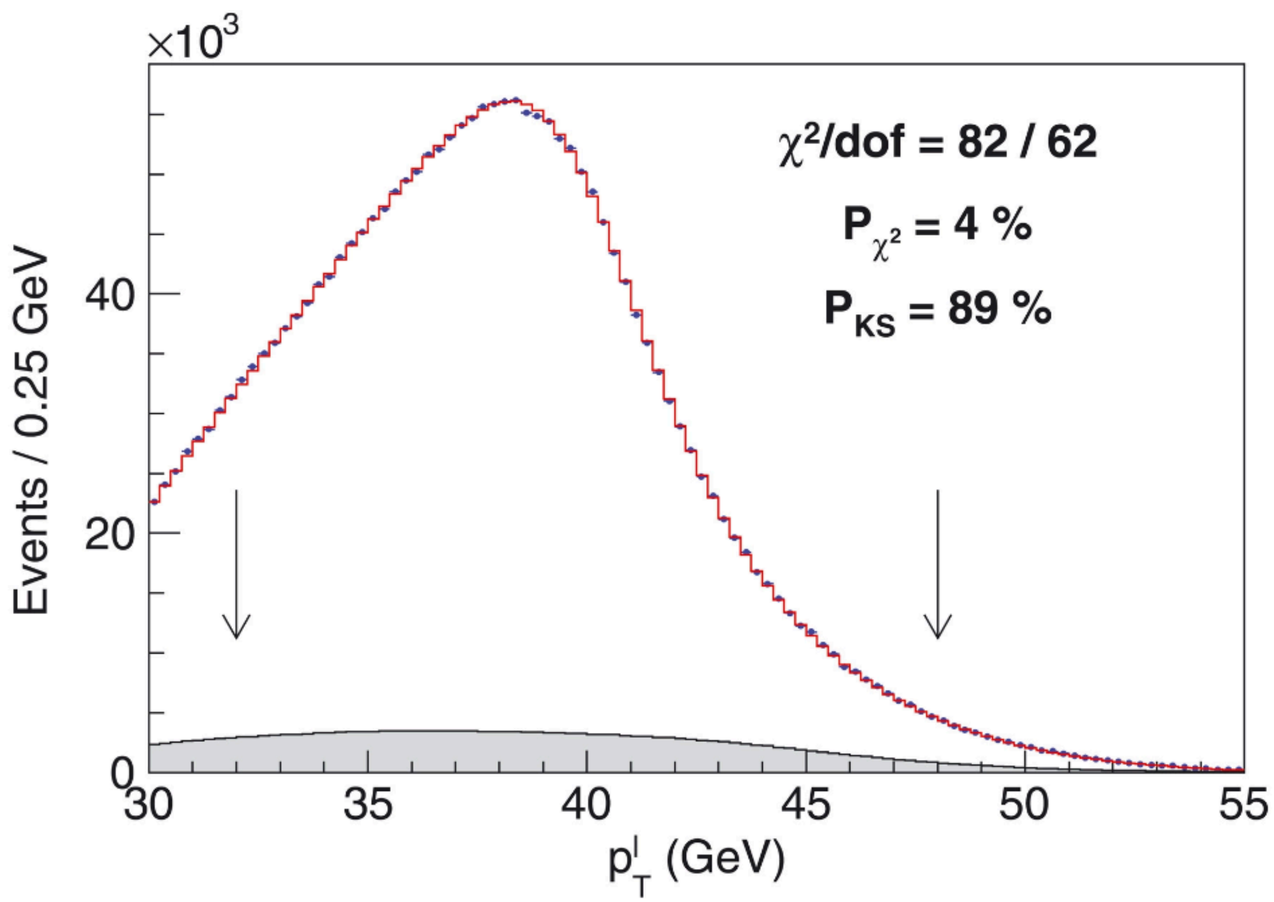
Precise measurement of M_W from CDF disagrees at 7 sigma with M_W obtained from electroweak precision fits

New physics?

- Robust understanding of all theory uncertainties essential
- Implications for particular new physics models must be understood



Aaltonen et al [CDF], Science 376 (2022)

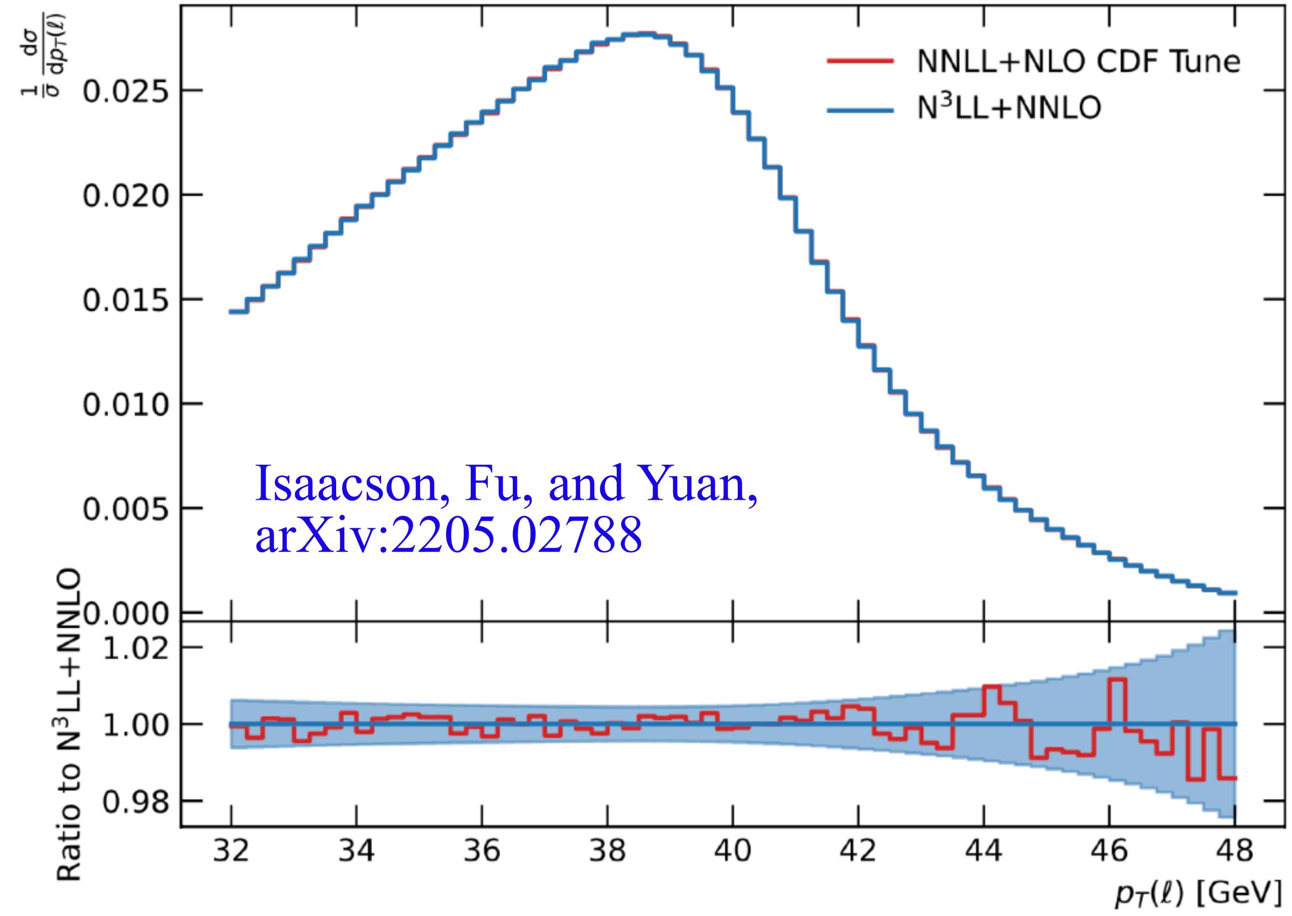


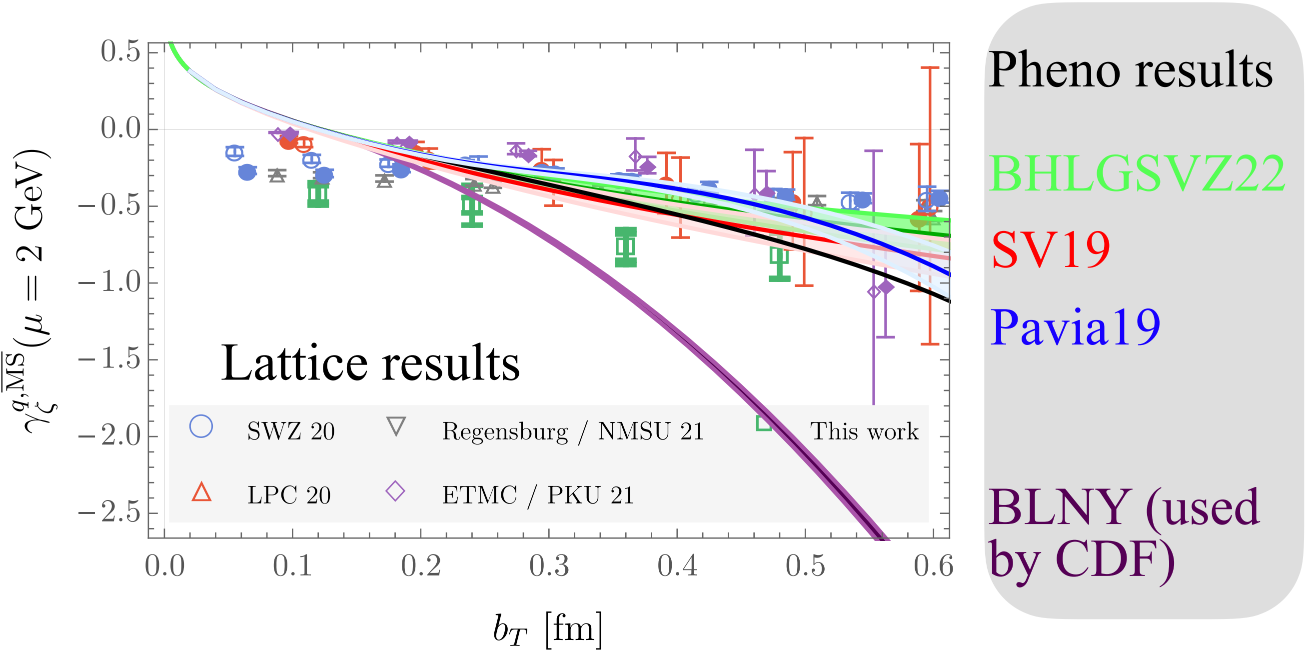
Measurement made by fitting shapes of transverse momentum distributions to theory predictions including perturbative, resumed and nonperturbative QCD effects

M_W and QCD

CDF made cross-section predictions by convolving perturbative QCD amplitudes and nonperturbative PDFs / Transverse-Momentum Dependent PDFs (TMDPDFs) with *Resbos* code

Isaacson *et al* verified that higher-order perturbative QCD effects included in *Resbos2* do not significantly affect CDF data-driven M_W result





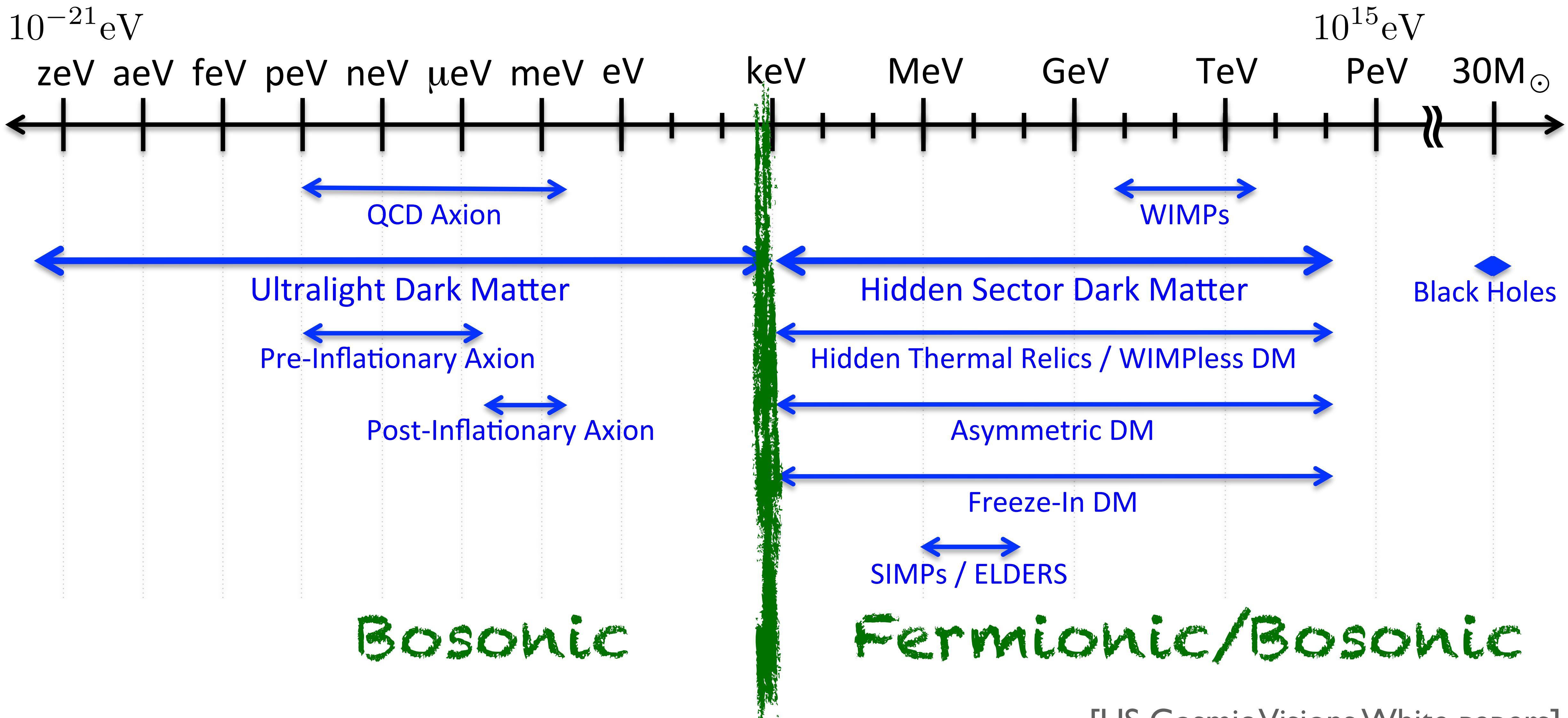
Distribution shapes are sensitive to some nonperturbative QCD effects: TMDPDF evolution and flavor dependence

Work in progress to understand impact on M_W of differences in TMDPDF evolution between BLNY and recent pheno/LQCD results

adapted from Shanahan, MW, Zhao, PRD 104 (2021)

Isaacson and MW, *in preparation*

Searching for dark matter



[US Cosmic Visions White papers]

With such a broad range of possibilities we need an equally broad-based search strategy

Detector	Xenon 1T	Borexino	SNO	DUNE	IceCube
Mass (ton)	1	300	10^3	3×10^4	10^7
Threshold (MeV)	10^{-3}	0.15	1	$1 - 10$	10^4

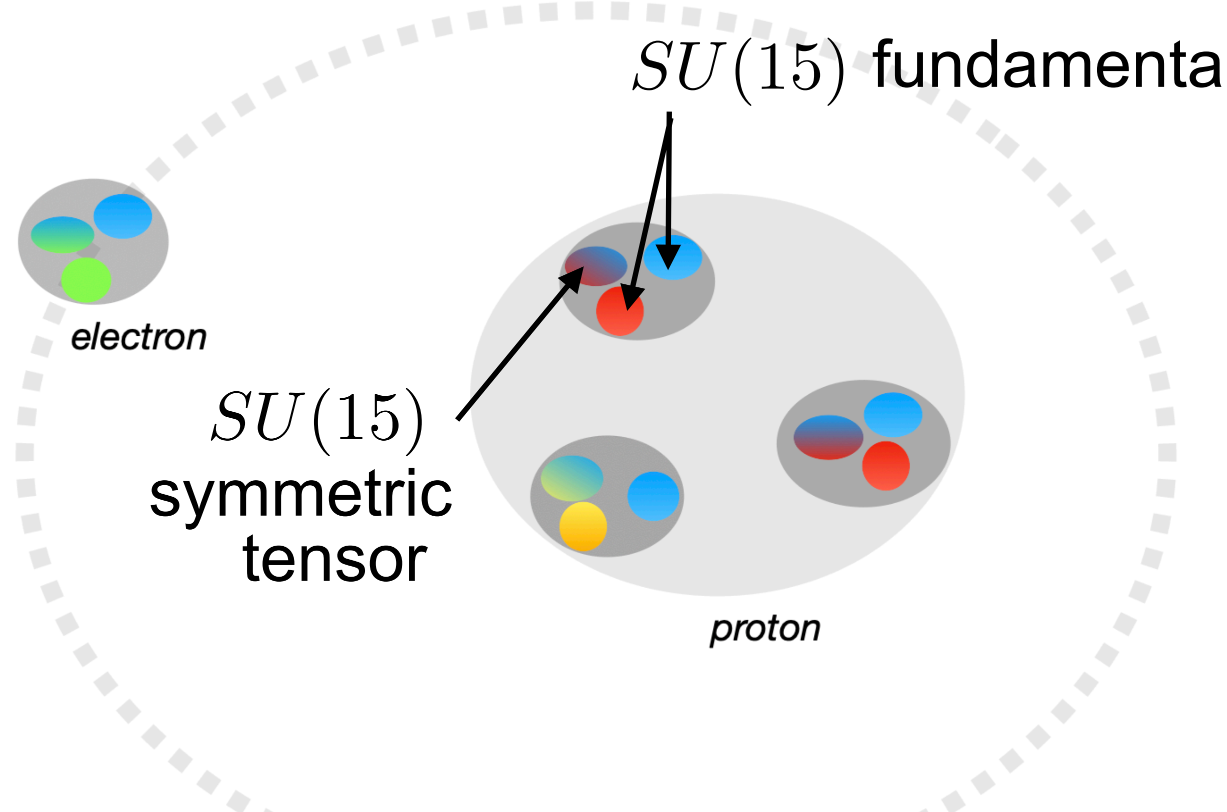
Strongly-coupled new physics

Strongly coupled gauge theories — interesting BSM candidates with hidden sectors

$SU(15)$ is a phenomenologically viable theory of composite quarks and leptons

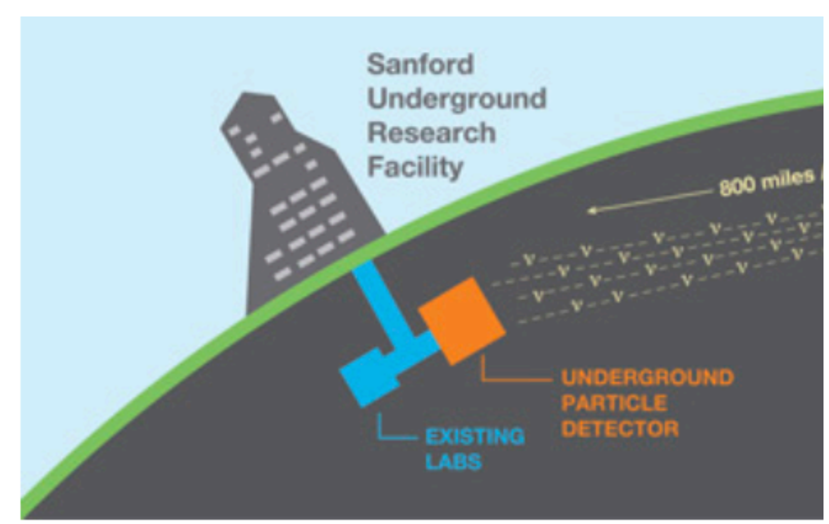
Dobrescu, arXiv:2112.15132

Assi and Dobrescu, *in preparation*



- 3 generations of SM required by anomaly cancellation
- Realistic quark, lepton, and Majorana neutrino masses can be generated
- Proton decay rates are suppressed in $SU(15) \times SO(10)$ UV completion

Complementary constraints arise from direct LHC searches and proton decay searches — future discoveries possible at Hyper-Kamiokande and DUNE

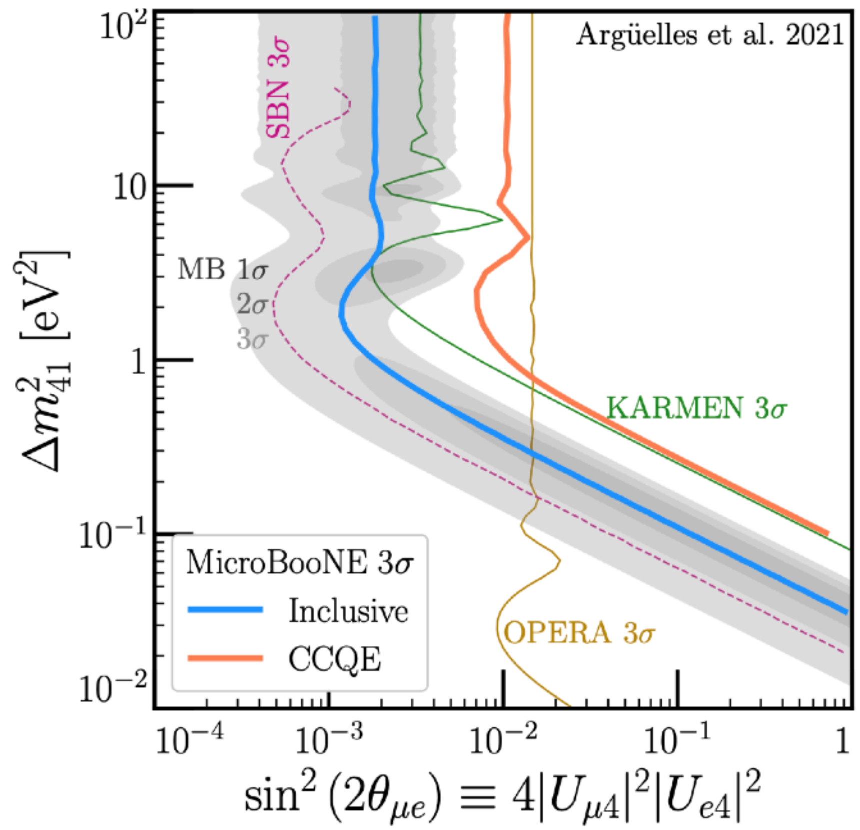


Neutrinos and new physics

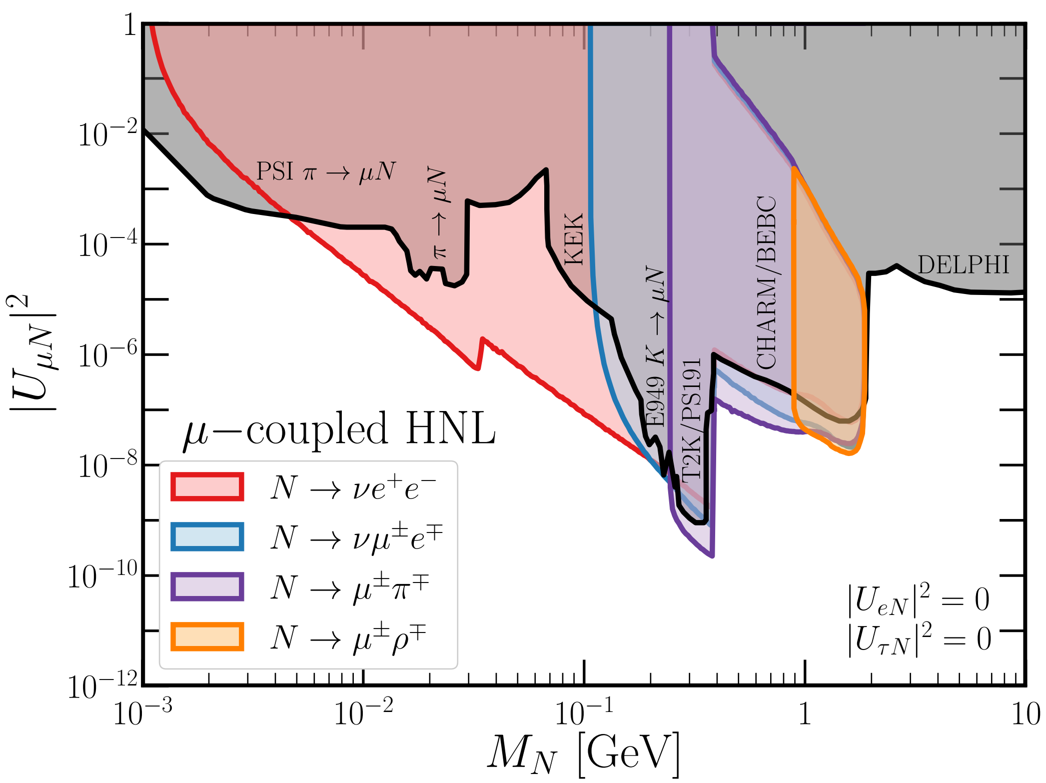
New results from MicroBooNE can be used to better understand the MiniBooNE low-energy excess

Detailed analysis shows that MicroBooNE results disfavor the central value of a fit to the MiniBooNE excess, but probe only part of sterile neutrino parameter space after taking systematic uncertainties into account

Arguelles, Esteban, Hostert, Kelly, Kopp, Machado, Martinez-Soler, Perez-Gonzalez, arXiv:2111.10359



Berryman, de Gouvea, Fox, Kayser, Kelly, Raaf, JHEP 02 (2020)



New physics searches at the DUNE near detector can constrain a variety of scenarios:

- Heavy neutral leptons (neutrino portal)
- Dark scalars (Higgs portal)
- Dark photons (gauge boson portals)

Novel signatures can probe dark sector properties like Dirac vs Majorana heavy neutral leptons

Precision neutrino physics

Comparisons of near + far detector neutrino fluxes can be used to precisely determine oscillation parameters, discover neutrino *CP* violation, …

Relating measured final-state event rates to incoming neutrino flux requires precise knowledge of νA cross-section

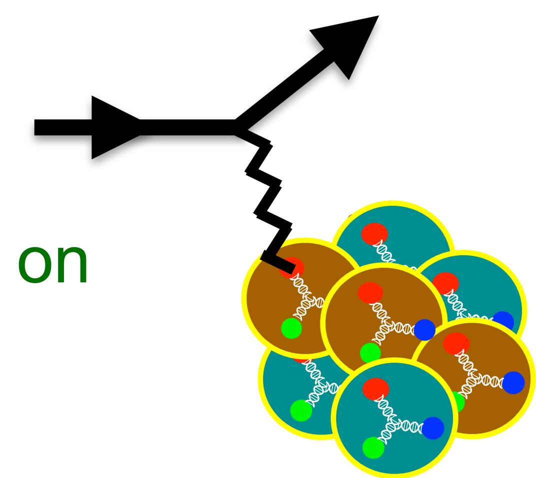
Near-detector neutrino flux

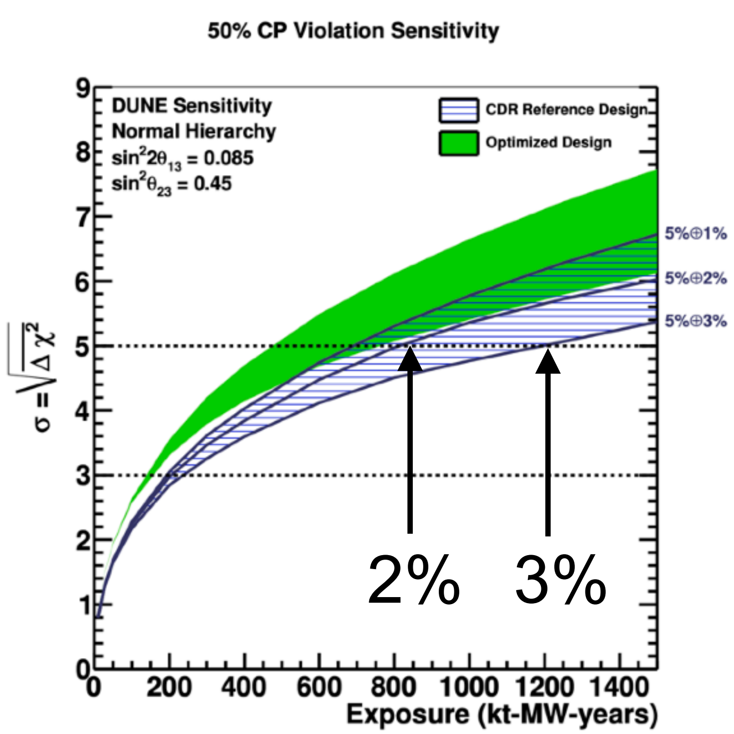
$$\frac{N_{\text{near}}}{N_{\text{far}}} = \frac{\int dE_\nu \Phi_{\text{near}}(E_\nu)\sigma(E_\nu)}{\int dE_\nu \Phi_{\text{far}}(E_\nu)\sigma(E_\nu)}$$

Cross-section

Experimentally measured event rates

Far-detector flux (depends on oscillation parameters)



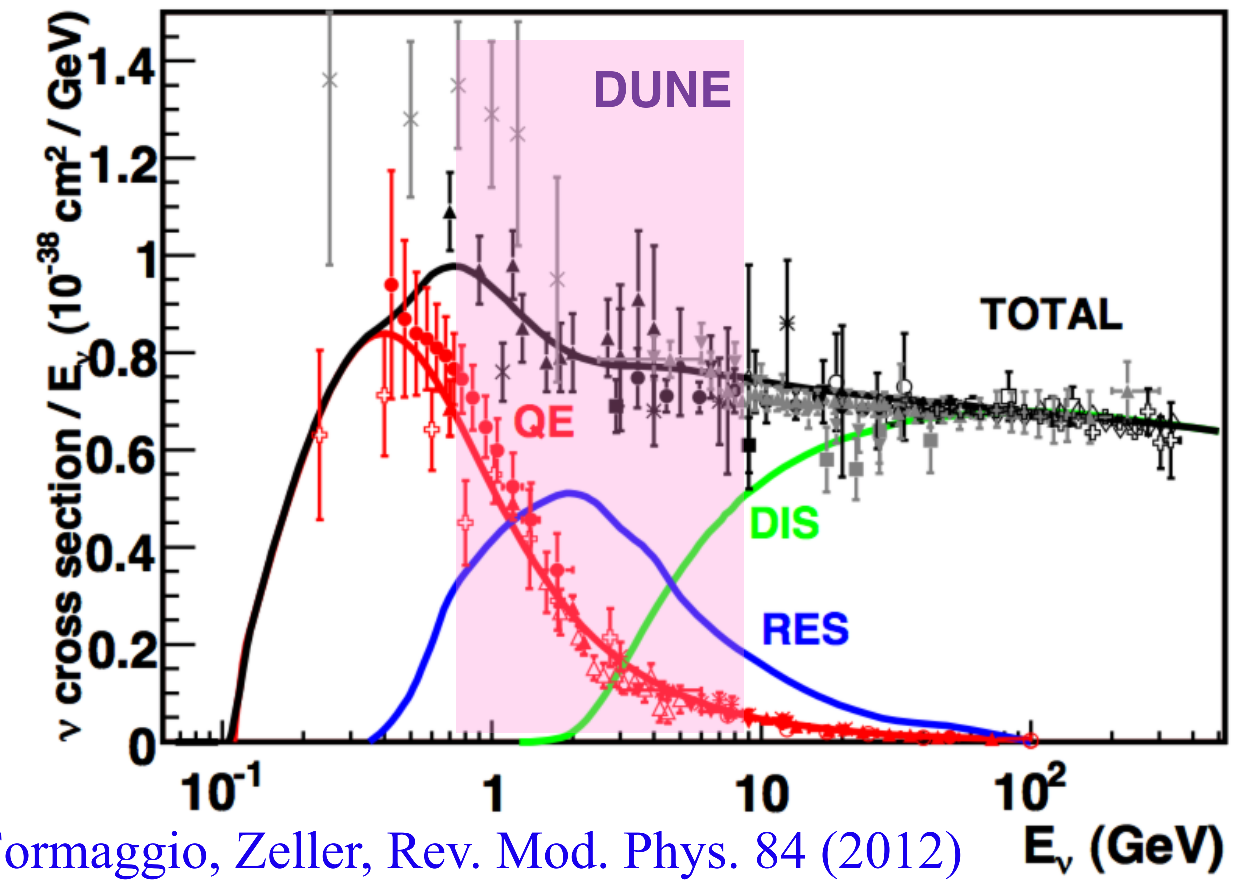


DUNE aims to have few-percent cross-section uncertainty

- 2% vs 3% cross-section uncertainty estimated to change exposure required to discover *CP* violation by 50%

Acciarri et al (DUNE) arXiv 1512.06148

Neutrino-nucleus scattering



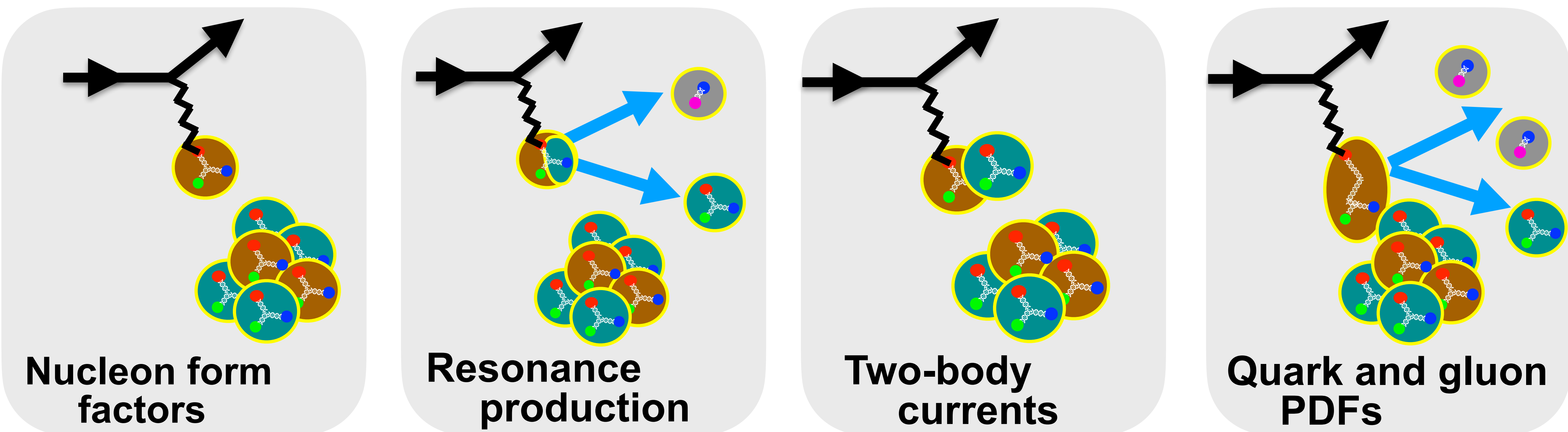
Formaggio, Zeller, Rev. Mod. Phys. 84 (2012)

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

- Quasi-elastic nucleon scattering
- Resonance production
- Deep inelastic scattering

Theory input required to decompose cross section into such processes and therefore predict its energy dependence

Effective theories for different energies require different inputs

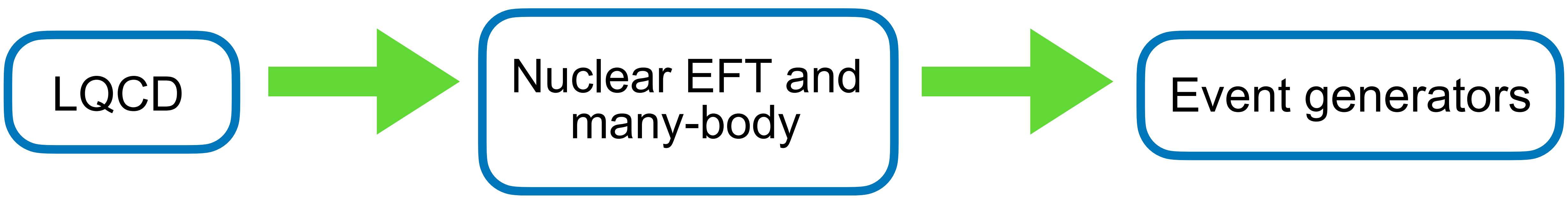


From quarks to nuclei

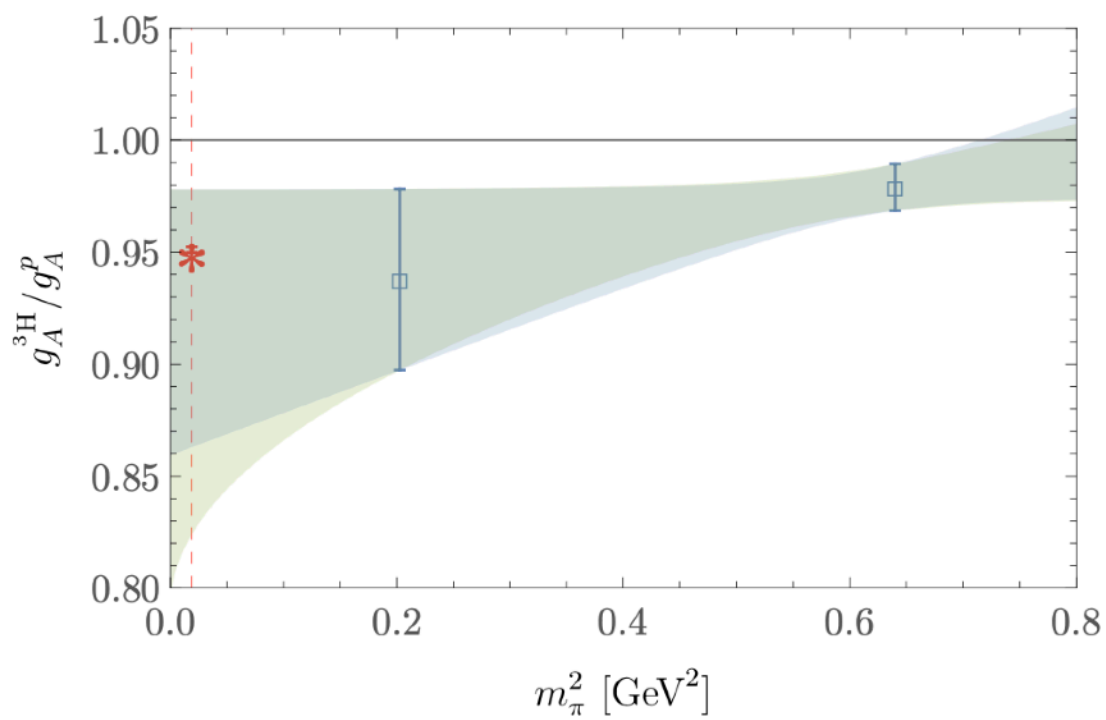
Current and future LQCD calculations could provide precise constraints on

- Nucleon axial + pseudoscalar form factors
- Nucleon pion production
- Two-body axial currents in nuclei

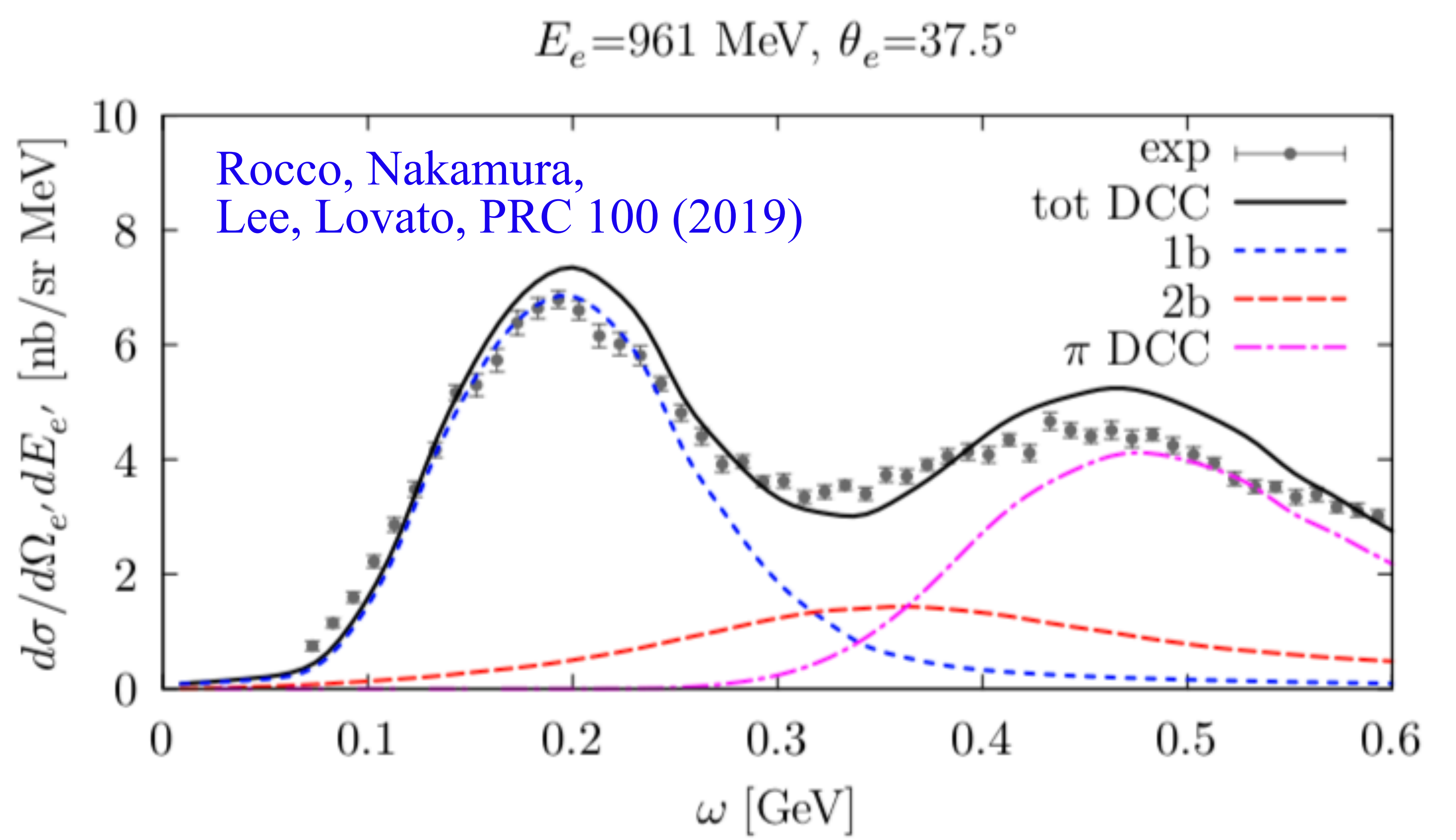
that can be matched to nuclear EFTs and event generators to make predictions for experimentally relevant nuclei such as carbon and argon



See Snowmass Whitepaper - Alvarez-Ruso et al "Theoretical Tools for Neutrino Scattering" arXiv:2203.09030



Parreño, MW et al [NPLQCD] PRD 103 (2021)



Event generators

In order to leverage the discovery potential of precise experiments, theory predictions for event rates need to achieve comparable precision

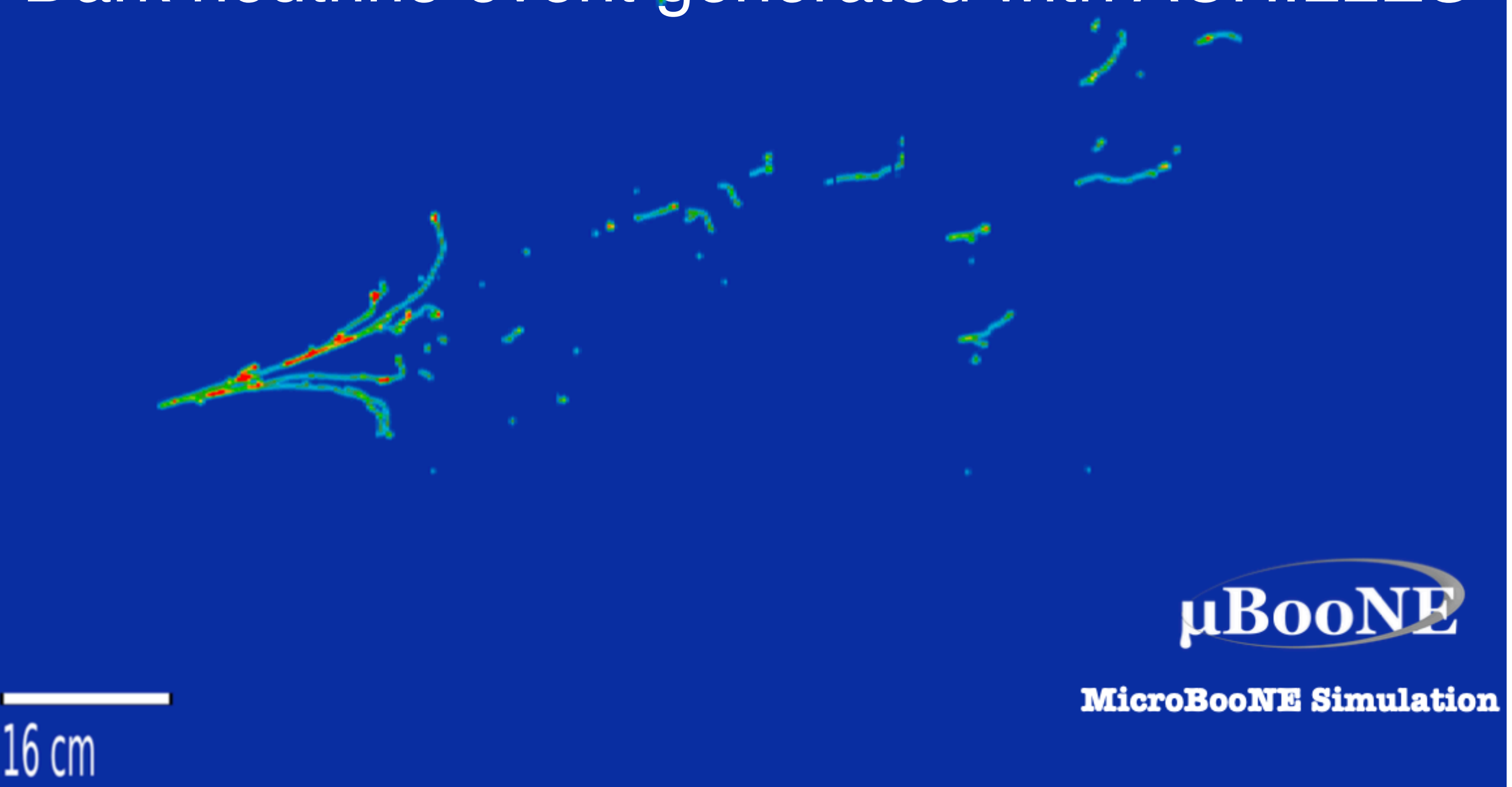
Monte Carlo event generators are a key tool for bridging theory + experiment

See Snowmass Whitepaper - Campbell et al "Event Generators for High-Energy Physics Experiments" arXiv:2203.09030

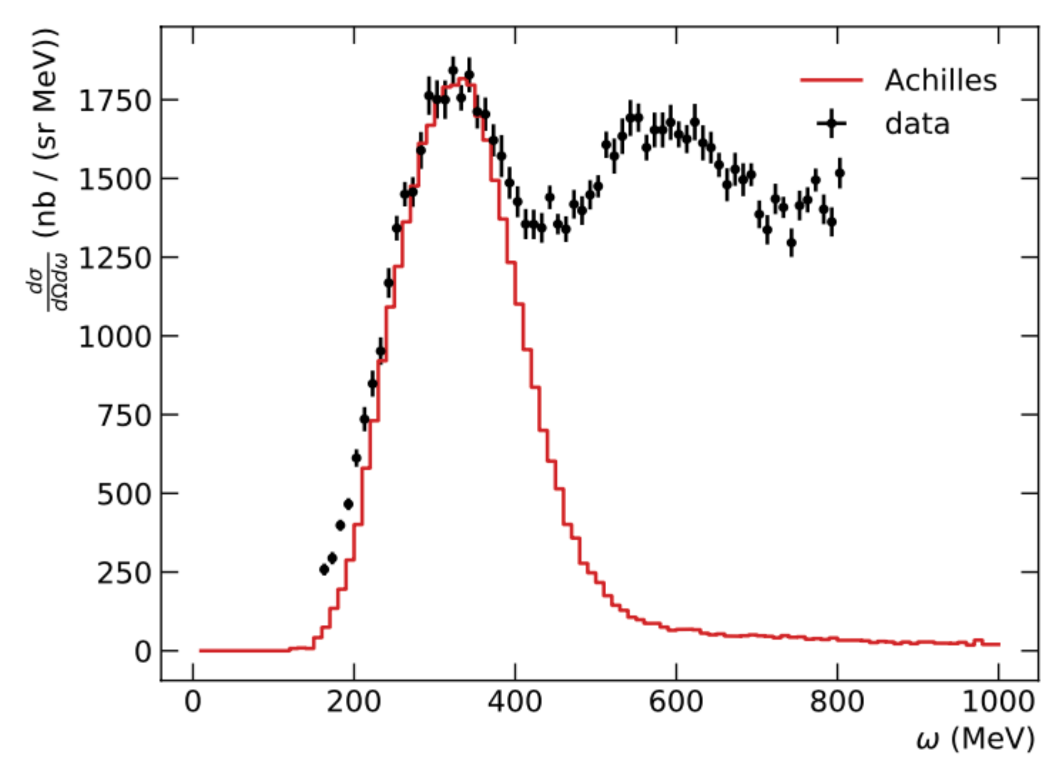
Ongoing Fermilab efforts to improve the theoretical models used in neutrino event generators - "Joint Meeting Between Theorists and Experimentalists"

New event generator ACHILLES - "A CHIcagoLand Lepton Event Simulator" aims for modular design and leveraging of existing LHC event generator tools

Dark neutrino event generated with ACHILLES



Isaacson, Jay, Lovato, Machado, Rocco, arXiv:2110.15319



Quantum sensing

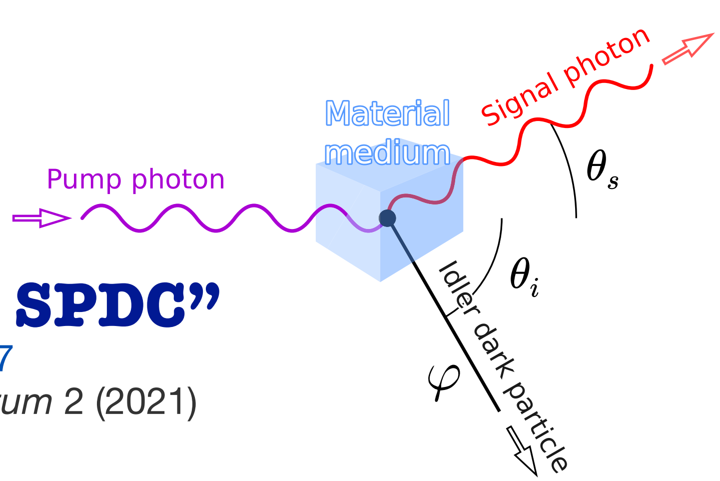
Dark SRF

Probing fundamental physics with quantum systems. For example:

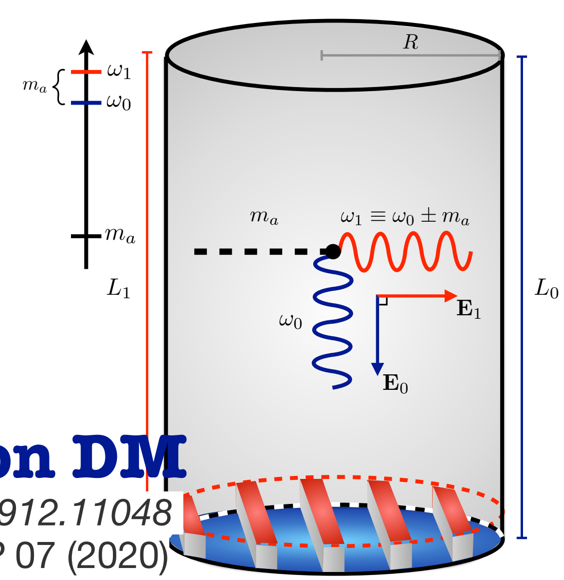
- Dark matter searches (axion, dark photons, B-L, …)
- New particles and forces (millicharges, axions, dark photons, …)
- Gravitational waves

Technologies we think about [and some related Fermilab efforts]:

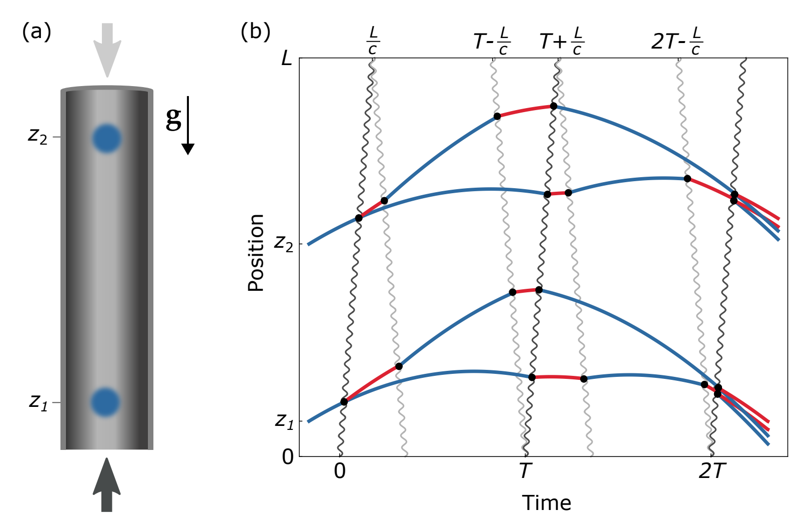
- Superconducting cavities and qubits [**Dark SRF** (light-shining-thru-wall), the **SQMS center**]
- Atom interferometry [Fermilab **MAGIS-100** experiment for GW and DM]
- Opto-mechanical systems



“Dark SPDC”
2012.04707
PRX Quantum 2 (2021)



Axion DM
1912.11048
JHEP 07 (2020)



MAGIS-100

2104.02835
Quantum Sci.Technol. 6 (2021)

Machine learning for HEP

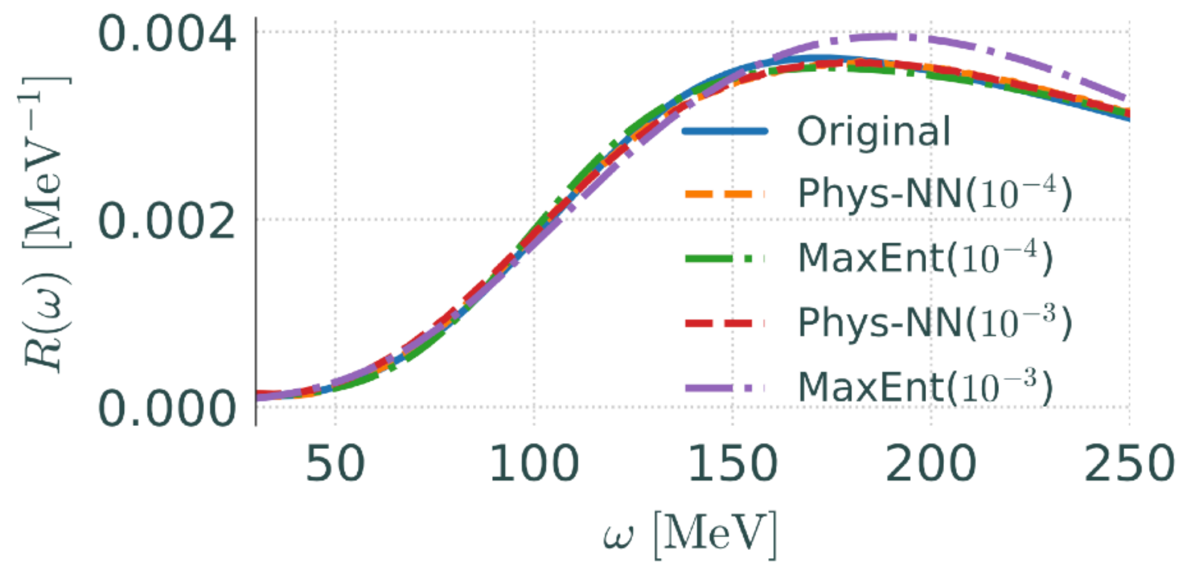
Fermilab theorists are using new machine learning tools to solve problems appearing throughout high-energy physics

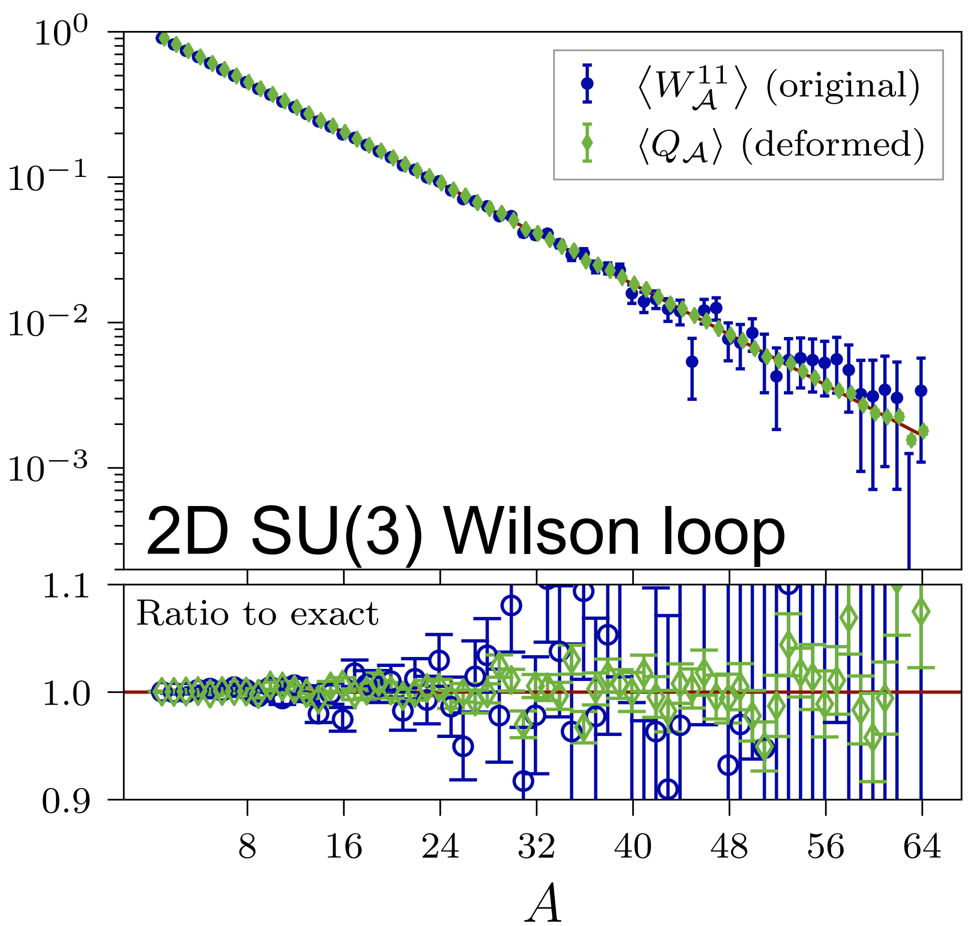
- Calculating phase space integrals for LHC cross sections

Gao, Isaacson, Krause, Mach. Learn. Sci. Tech. 1 (2020)

- Solving inverse Laplace transforms to predict cross sections with nuclear effective theories

Raghavan, Balaprakash, Lovato, Rocco, and Wild, PRC 23 (2021)





- Improving signal-to-noise problems in lattice QCD calculations using path integral contour deformation

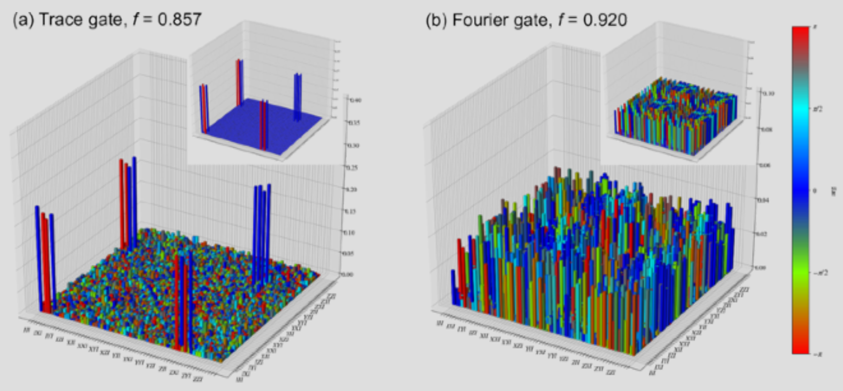
Detmold, Kanwar, Lamm, MW, Warrington, PRD 103 (2021)

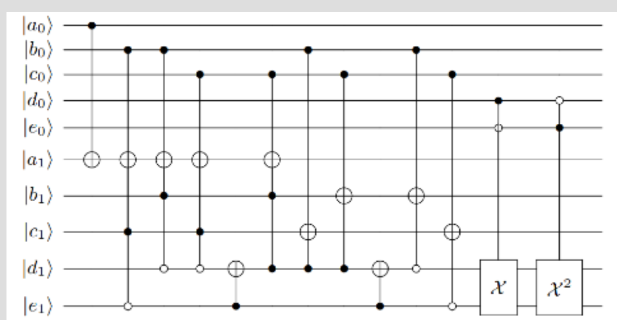
Real-time QCD? Kanwar, MW, PRD 104 (2021)

Growing efforts to build collaborations between Fermilab theory and AI divisions

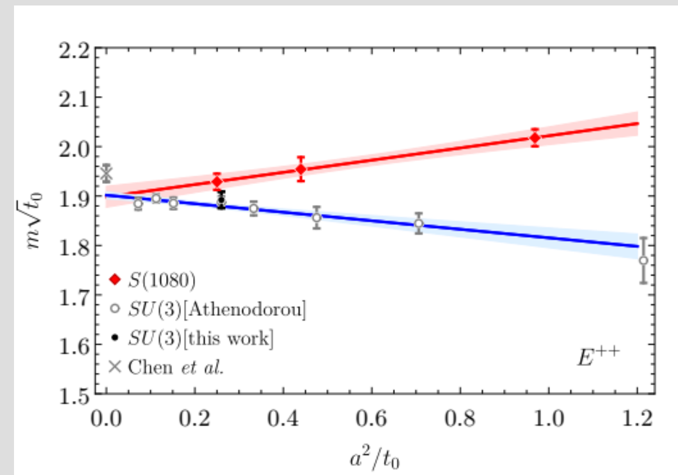
Quantum simulation

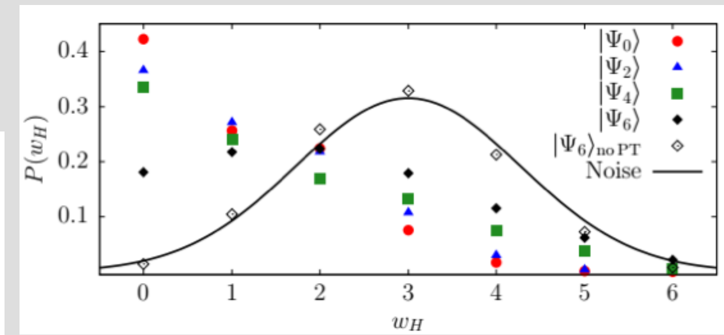
Primitive Gates for Nonabelien Gauge Theories

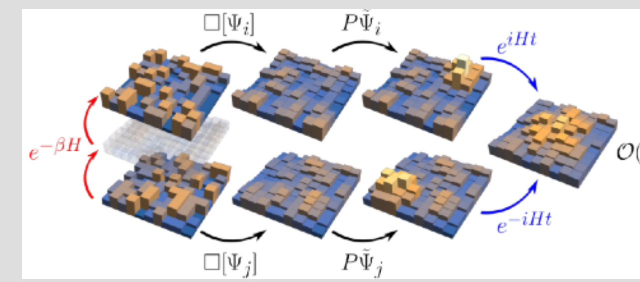




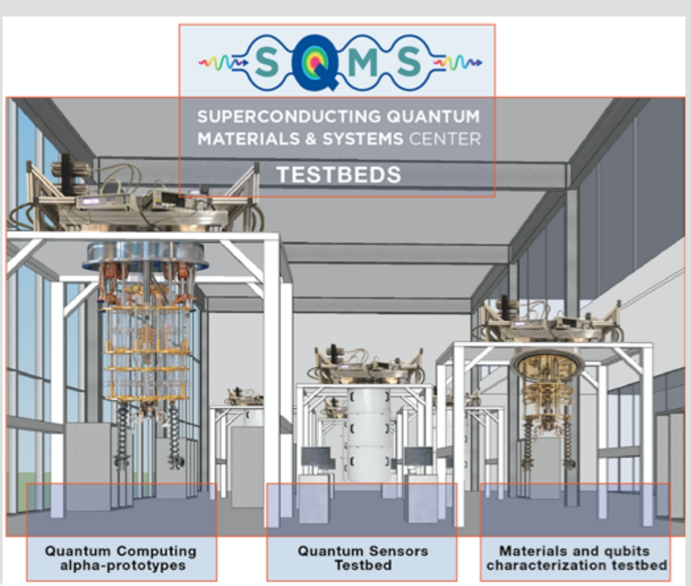
Reducing Resources via Classical Methods

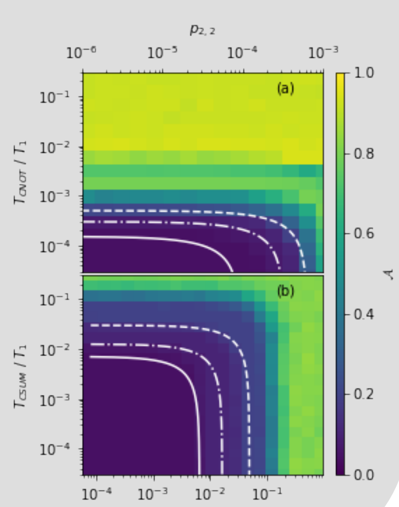




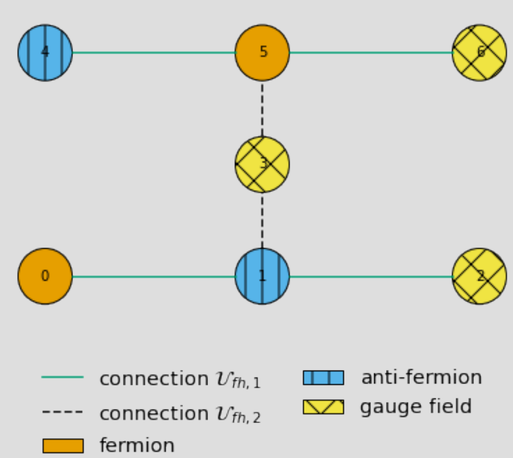


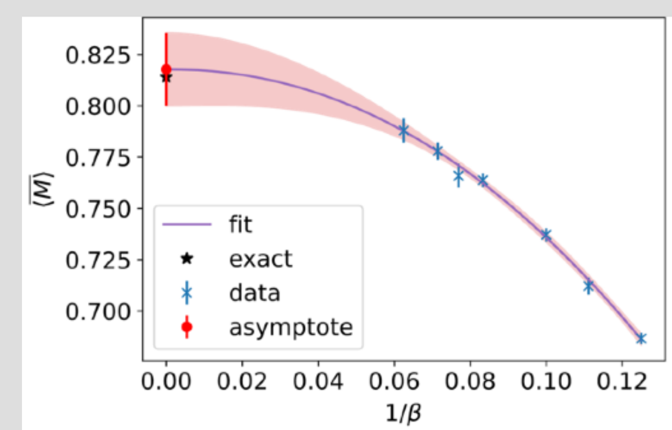
Qudit Algorithm design for HEP





Algorithm and Error Mitigation for NISQ-era Simulations





Next-generation quantum

Fermilab Theory Division organized the first Quantum Computing Internship for Undergraduates (QCIPU) at Fermilab last summer (Year 2 starting soon!)

- 17 undergraduate student interns went from the basics of quantum computing to simulating real-time gauge theory dynamics over a 3 week summer school
- 5 continued doing quantum simulation research as Theory Division interns this year

Other theory group members involved in student mentoring through SULI/SIST

Questions

Fermilab Theory Division