

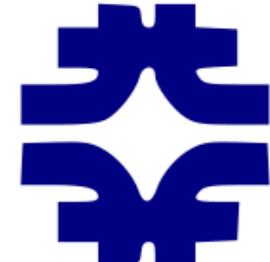
Nucleons and nuclei for BSM searches and neutrino physics

Michael Wagman

Seattle Snowmass Summer Meeting 2022

University of Washington, Seattle

July 21, 2022



Fermilab



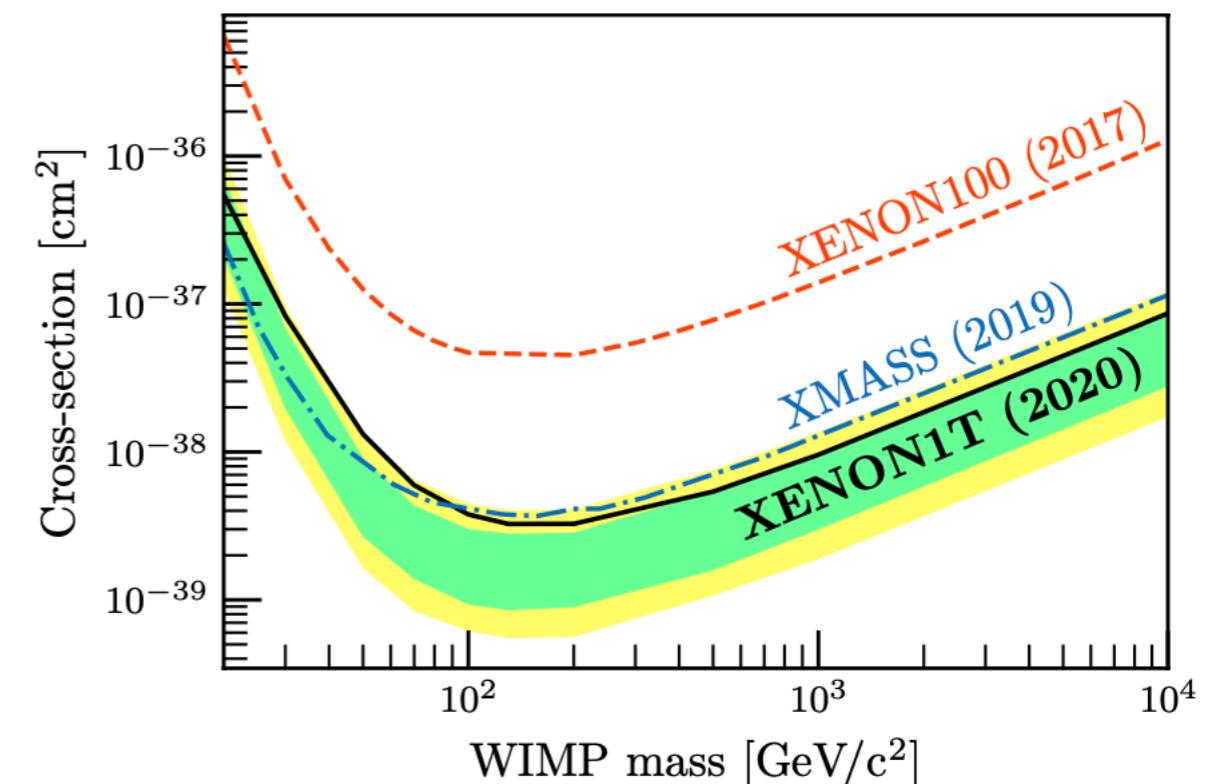
Nucleons and new physics

Nucleons and nuclei are abundant and useful experimental targets

Extracting BSM constraints from experiments involving nuclei requires:

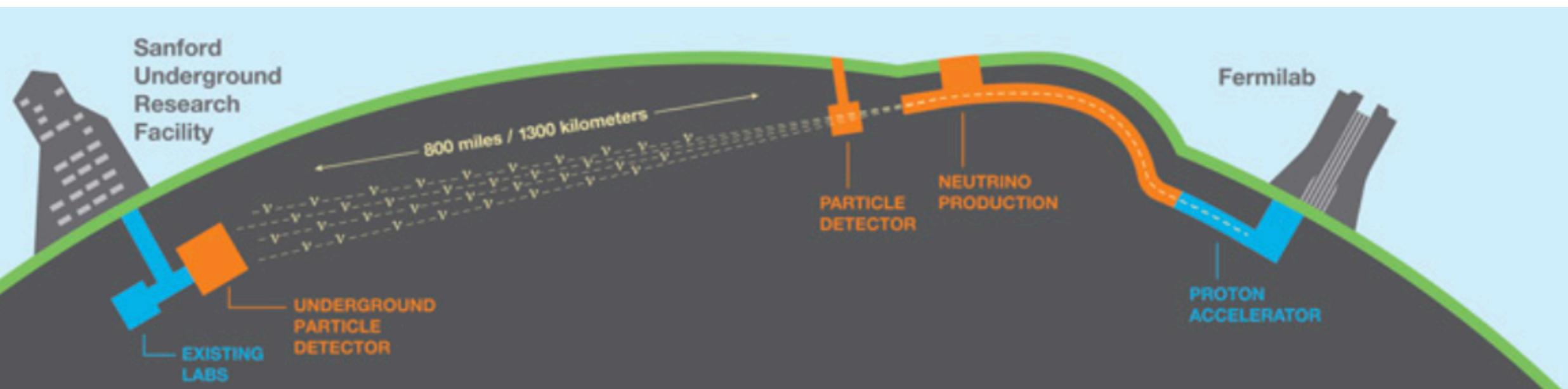
- Nuclear models (error bars?)
- Direct LQCD calculations (feasible?)
- **LQCD informed hadronic and nuclear effective theories**

Xenon1T constraint on dark matter-nucleus



Robust Standard Model predictions for nucleons and nuclei will be essential for next-generation accelerator neutrino experiments and other new physics searches

DUNE



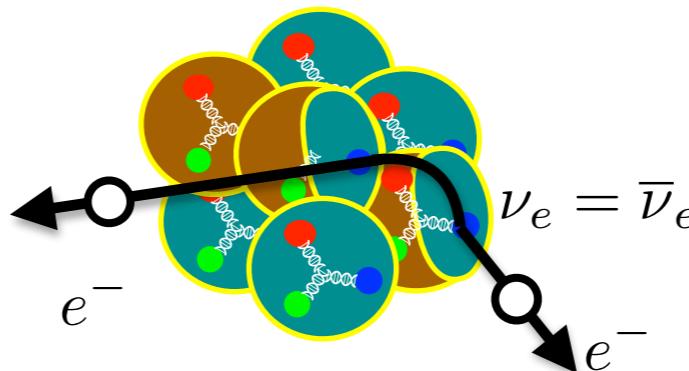
B-L Violation

BSM sources of *B-L* violation could explain matter-antimatter asymmetry

Dim 5: ***B-L* violating, *L* violating**
Majorana neutrino mass

$$\mathcal{L}_5 \sim \left(\frac{1}{\Lambda_{BSM}} \right) (H^T \ell^*) (\bar{\ell} H)$$

Also dim 7, 9, ... see Cirigliano et al JHEP 12 (2018)



Double- β decay

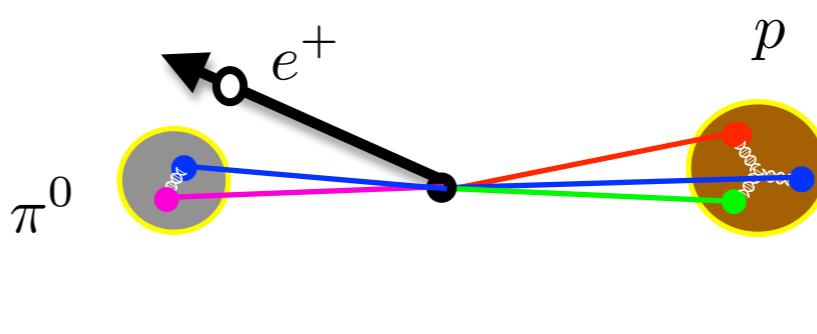
$$\Lambda_{BSM} \gtrsim 10^{10} \text{ GeV}$$



Leptogenesis

Dim 6: ***B-L* conserving, *B* violating**
proton decay operators

$$\mathcal{L}_6 \sim \left(\frac{1}{\Lambda_{BSM}^2} \right) uude + \dots$$



Proton decay

$$\Lambda_{BSM} \gtrsim 10^{16} \text{ GeV}$$

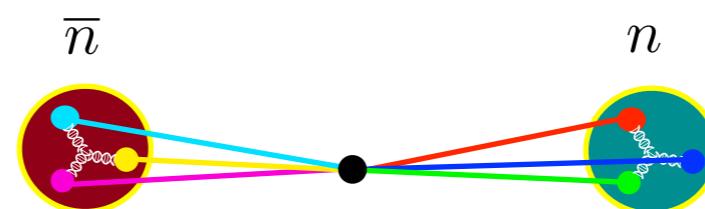


Washed out by sphalerons*

*usually, but see Heeck, Takhistov, PRD 101 (2020)

Dim 9: ***B-L* violating, *B* violating**
Majorana neutron mass

$$\mathcal{L}_9 \sim \left(\frac{1}{\Lambda_{BSM}^5} \right) uddudd + \dots$$



Neutron-antineutron oscillations

$$\Lambda_{BSM} \gtrsim 10^5 \text{ GeV}$$



Post-sphaleron baryogengesis

Neutron-Antineutron Oscillations

$n\bar{n}$ oscillation phenomenology similar to meson, neutrino oscillations

$$\mathcal{P}_{n\bar{n}} = \sin^2(t/\tau_{n\bar{n}}) e^{-\Gamma_n t}$$

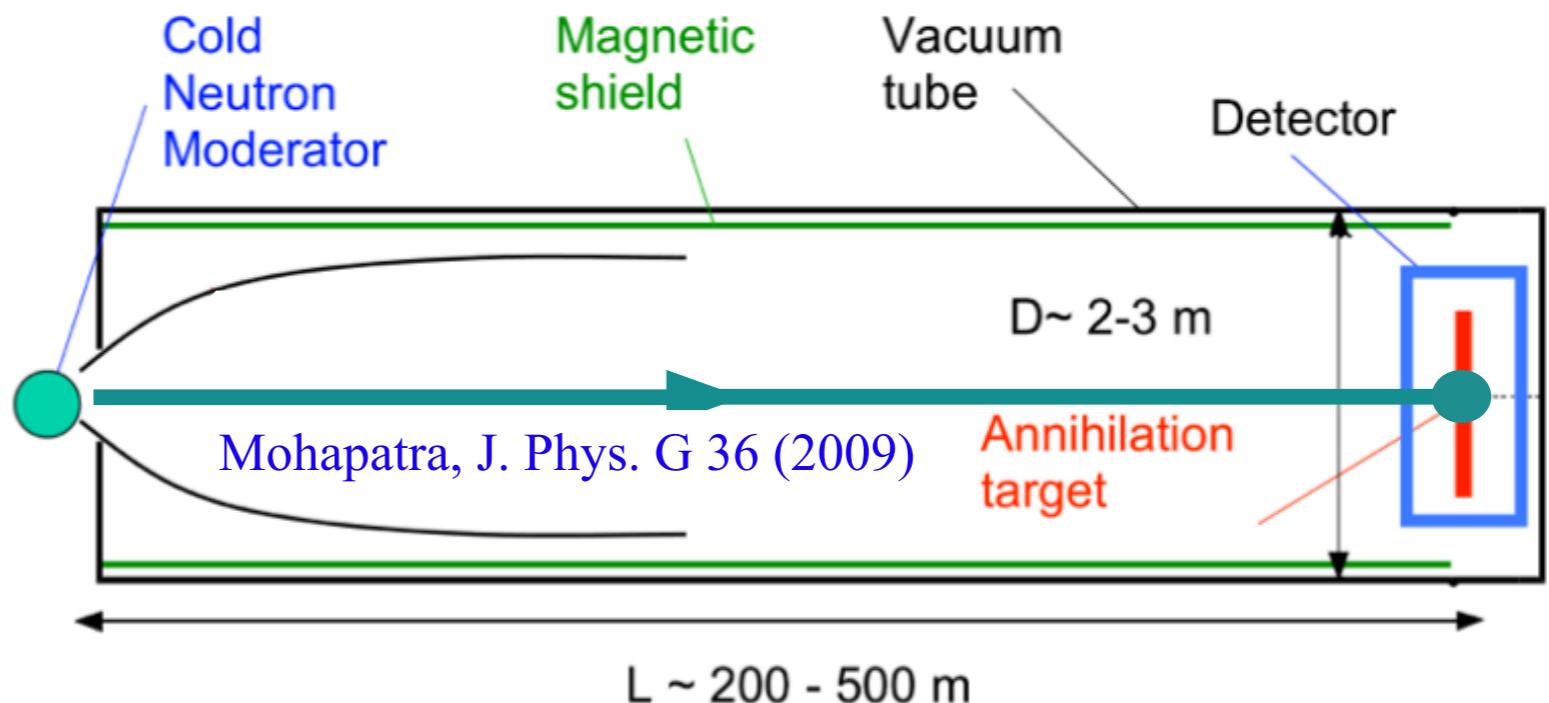
$$\tau_{n\bar{n}}^{-1} = \langle \bar{n} | H_{n\bar{n}} | n \rangle$$

In order to turn experimental constraints into BSM physics constraints, we need theory predictions of $\tau_{n\bar{n}}^{-1}$ including QCD strong interaction effects

Institut Laue-Langevin (ILL)

$$\tau_{n\bar{n}} > 0.89 \times 10^8 \text{ s}$$

Baldo-Ceolin et al, Zeitschrift für Physik C Particles and Fields (1994)



Future experiments at the European Spallation Source could increase sensitivity to by an order of magnitude

Addazi et al, J. Phys. G 48 (2021)

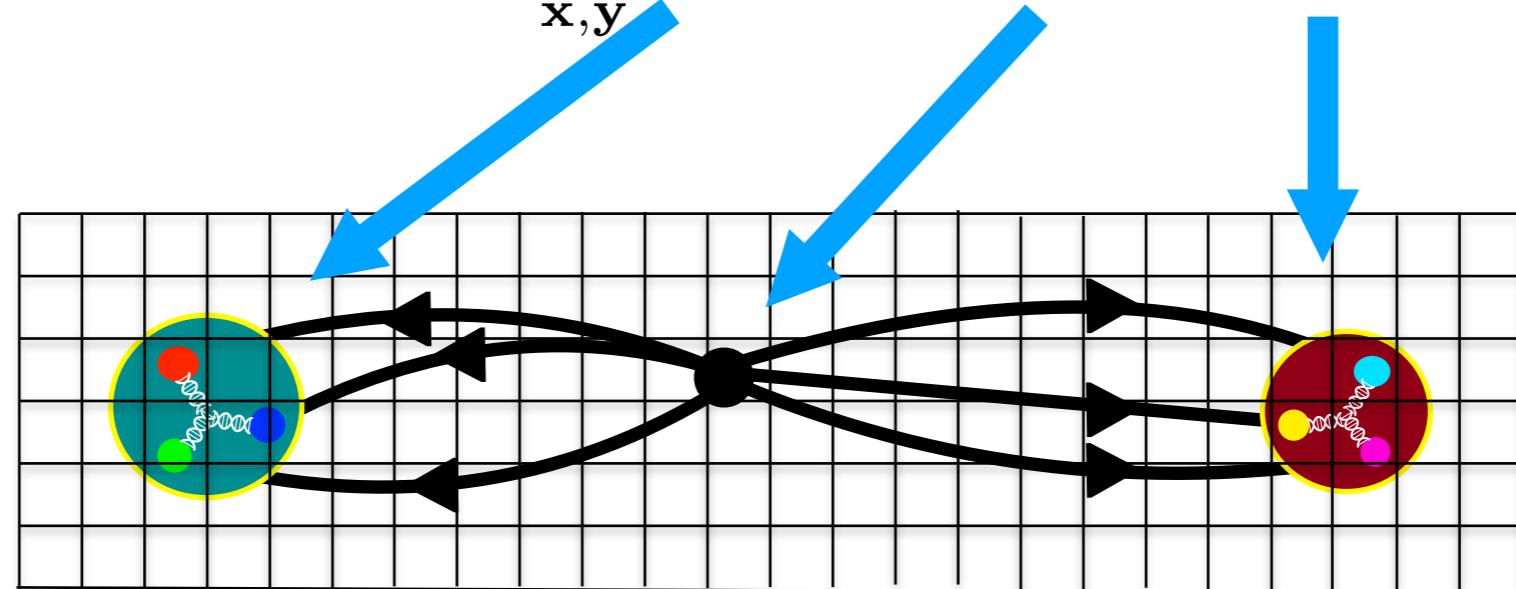
$n\bar{n}$ and LQCD

High-scale new physics can be parametrized in SM EFT:

$$\mathcal{L}_9 = \frac{1}{\Lambda_{BSM}^5} \sum_I C_I^{\overline{\text{MS}}}(\Lambda_{BSM}) Q_I^{\overline{\text{MS}}}(\Lambda_{BSM}) \quad \text{Complete basis of six-quark operators}$$

Three-point correlation functions involving Q_I computable in LQCD

$$G_I^{n\bar{n}}(t, \tau) = \int \mathcal{D}\bar{q} \mathcal{D}q \mathcal{D}U e^{-S_{QCD}} \sum_{\mathbf{x}, \mathbf{y}} n(\mathbf{x}, t - \tau) Q_I^\dagger(0) n(\mathbf{y}, -\tau)$$



Rinaldi, Srytsyn, MW et al, PRL 122 (2019)

Rinaldi, Srytsyn, MW et al, PRD 99 (2019)

Ratio of $n\bar{n}$ and neutron correlation functions gives matrix elements plus excited state effects that can be studied by e.g. two-state fits

Neutron-Antineutron Oscillations

LQCD calculations performed with

- ✓ ~physical quark masses
- ✓ nonperturbative renormalization
- ✗ 1 lattice spacing / volume

Rinaldi, Srytsyn, MW et al, PRL 122 (2019)

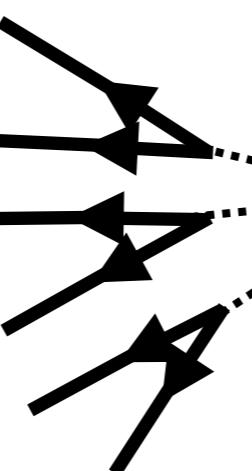
	$\mathcal{M}_I^{\overline{\text{MS}}}(700 \text{ TeV}) [10^{-5} \text{ GeV}^6]$
Q_1	-26(7)
Q_2	144(26)
Q_3	-47(11)
Q_5	-0.23(10)

Standard Model EFT:

$$\tau_{n\bar{n}}^{-1} = \frac{10^{-9} \text{ s}^{-1}}{(700 \text{ TeV})^{-5}} |4.2(1.1)\hat{C}_1^{\overline{\text{MS}}}(\mu) - 8.6(1.5)\hat{C}_2^{\overline{\text{MS}}}(\mu) + 4.5(1.1)\hat{C}_3^{\overline{\text{MS}}}(\mu) + 0.096(43)\hat{C}_5^{\overline{\text{MS}}}(\mu)|_{\mu=2 \text{ GeV}}$$

ILL:

$$\tau_{n\bar{n}} > 0.89 \times 10^8 \text{ s}$$



LR-symmetric example:

$$\frac{\Lambda_{BSM}}{(\lambda f^3 \tilde{v}_{B-L})^{1/5}} > 390 \pm 22 \text{ TeV}$$

Experimental Implications

Rinaldi, Srytsyn, MW et al, PRL 122 (2019)

Rao, Shrock, Nucl. Phys. B 232 (1984)

	$\mathcal{M}_I^{\overline{\text{MS}}}(700 \text{ TeV}) [10^{-5} \text{ GeV}^6]$	MIT Bag \times RG [10 ⁻⁵ GeV ⁶]
Q_1	$-26(7)$	$-6.4, -5.2$
Q_2	$144(26)$	$16, 19$
Q_3	$-47(11)$	$-9.1, -7.6$
Q_5	$-0.23(10)$	$-0.28, 0.15$

For fixed BSM parameters, QCD predicts experimental sensitivity is **25 - 64 times higher** than predicted using MIT bag model

$$N_{events} \propto \tau_{n\bar{n}}^{-2} \approx \left(\sum_{I=1}^3 \hat{C}_I^{\overline{\text{MS}}}(\Lambda_{BSM}) \mathcal{M}_I^{\overline{\text{MS}}}(\Lambda_{BSM}) \right)^2$$

For $SU(2)_L \times SU(2)_R \times SU(4)_C$ example, lower bound on BSM couplings from **ILL 390 TeV** instead of **290 TeV**

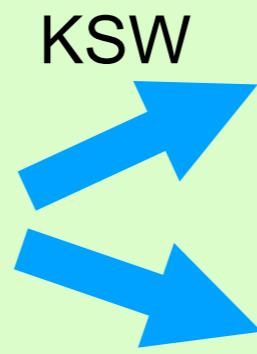
$n\bar{n}$ in nuclei

Deuteron lifetime related to $\tau_{n\bar{n}}$ in chiral EFT
....but results sensitive to choice of power counting

SNO constraint:

$$\Gamma_d^{-1} > 1.18 \times 10^{31} \text{ years}$$

Aharmin et al [SNO], PRD 96 (2017)

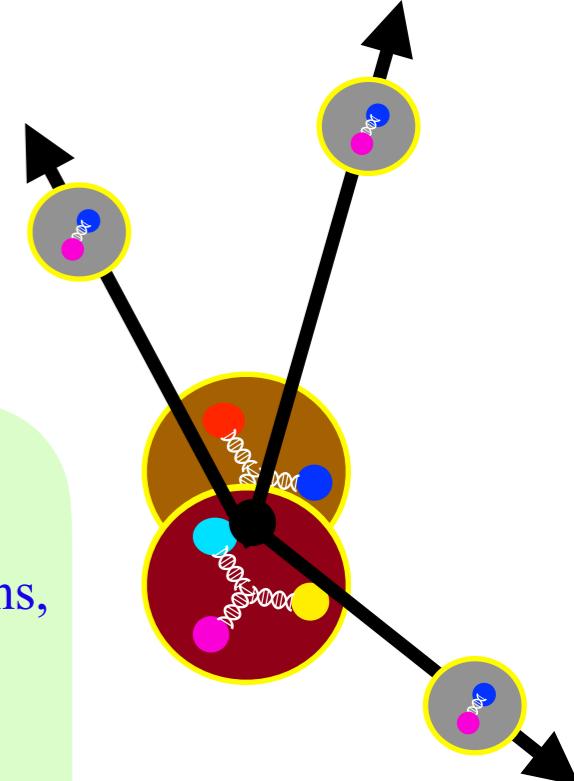


$$\tau_{n\bar{n}} > 1.6 \times 10^8 \text{ s}$$

Oosterhof, Long, de Vries, Timmermans,
van Kolck, PRL 122 (2019)

$$\tau_{n\bar{n}} > 2.6 \times 10^8 \text{ s}$$

Haidenbauer and Mei  ner,
Chinese Physics C 44 (2020)



Oxygen lifetime provides possibly stronger but more uncertain constraints

Super K constraint

$$\Gamma_{O^{16}}^{-1} > 19 \times 10^{31} \text{ years}$$

Abe et al [Super K], PRD 91 (2015)



$$\tau_{n\bar{n}} \gtrsim 2.7 \times 10^8 \text{ s}$$

State-of-the-art optical potentials:

Friedman, Gal, PRD 78 (2008)

Future argon lifetime constraints from DUNE will be even more challenging to analyze — can LQCD help benchmark the two-nucleon sector?

Proton decay

BSM theories with high-scale B violation, including some GUTs, predict that protons decay at \sim observable rates

Long history of experimental searches for decay modes with clean signatures

$$\tau/Br(p \rightarrow e^+ \pi^0) > 1.6 \times 10^{34} \text{ years}$$

Abe et al [Super K], PRD 95 (2017)

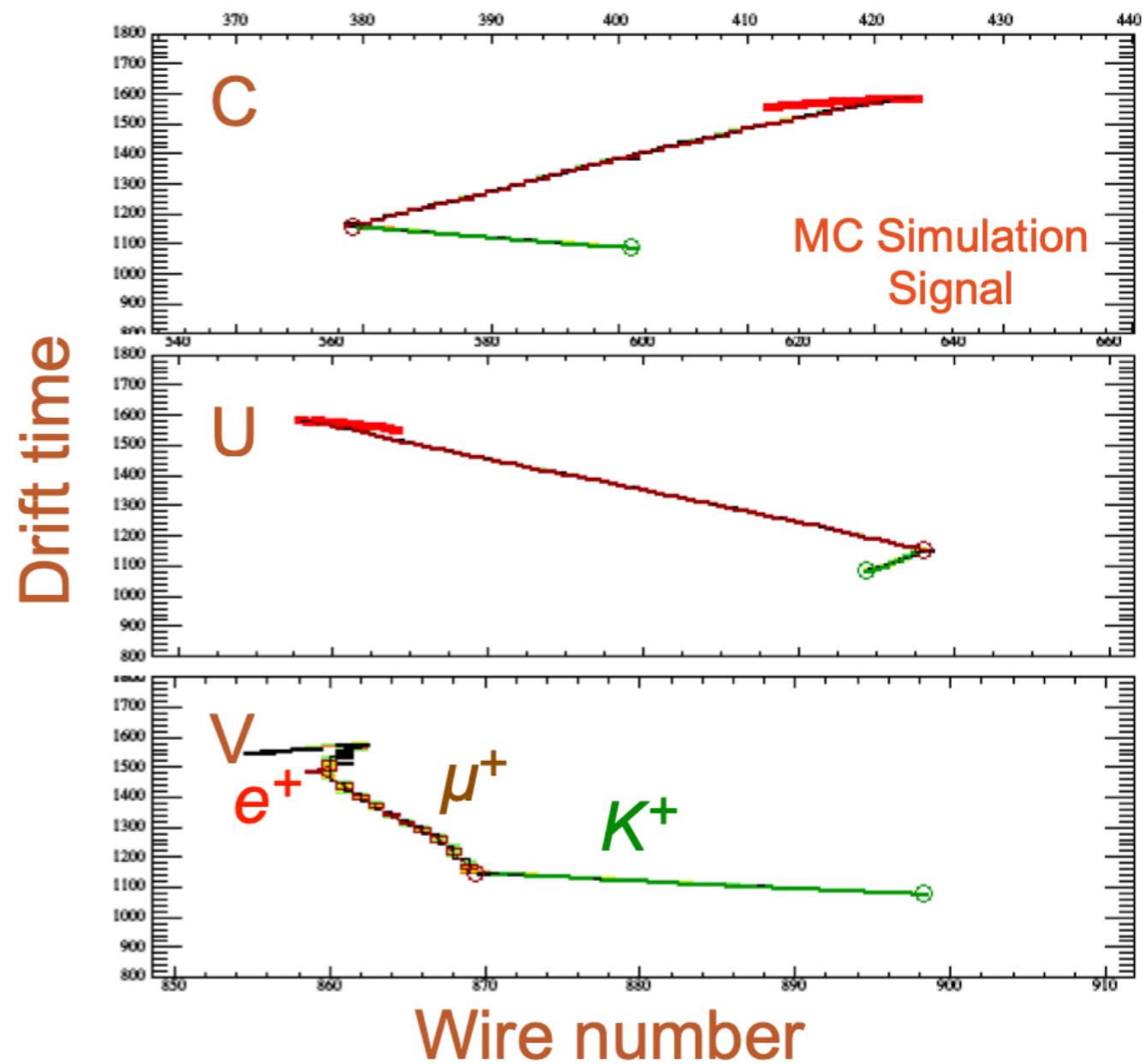
$$\tau/Br(p \rightarrow \nu K^+) > 5.9 \times 10^{33} \text{ years}$$

Abe et al [Super K], PRD 90 (2014)

Future searches at DUNE and Hyper Kamiokande could improve limits by an order of magnitude

Predictions for QCD matrix elements of dim 6 operators needed to constrain BSM models

Simulated proton decay event at DUNE



Viktor Pěč [DUNE], BLV 2019

Proton decay and LQCD

LQCD calculations relevant for proton decay pursued for 20+ years

Aoki et al [JLQCD], PRD 62 (2000)

Tensions between direct calculations and indirect calculations using χ PT relations led to concern about quark mass systematics

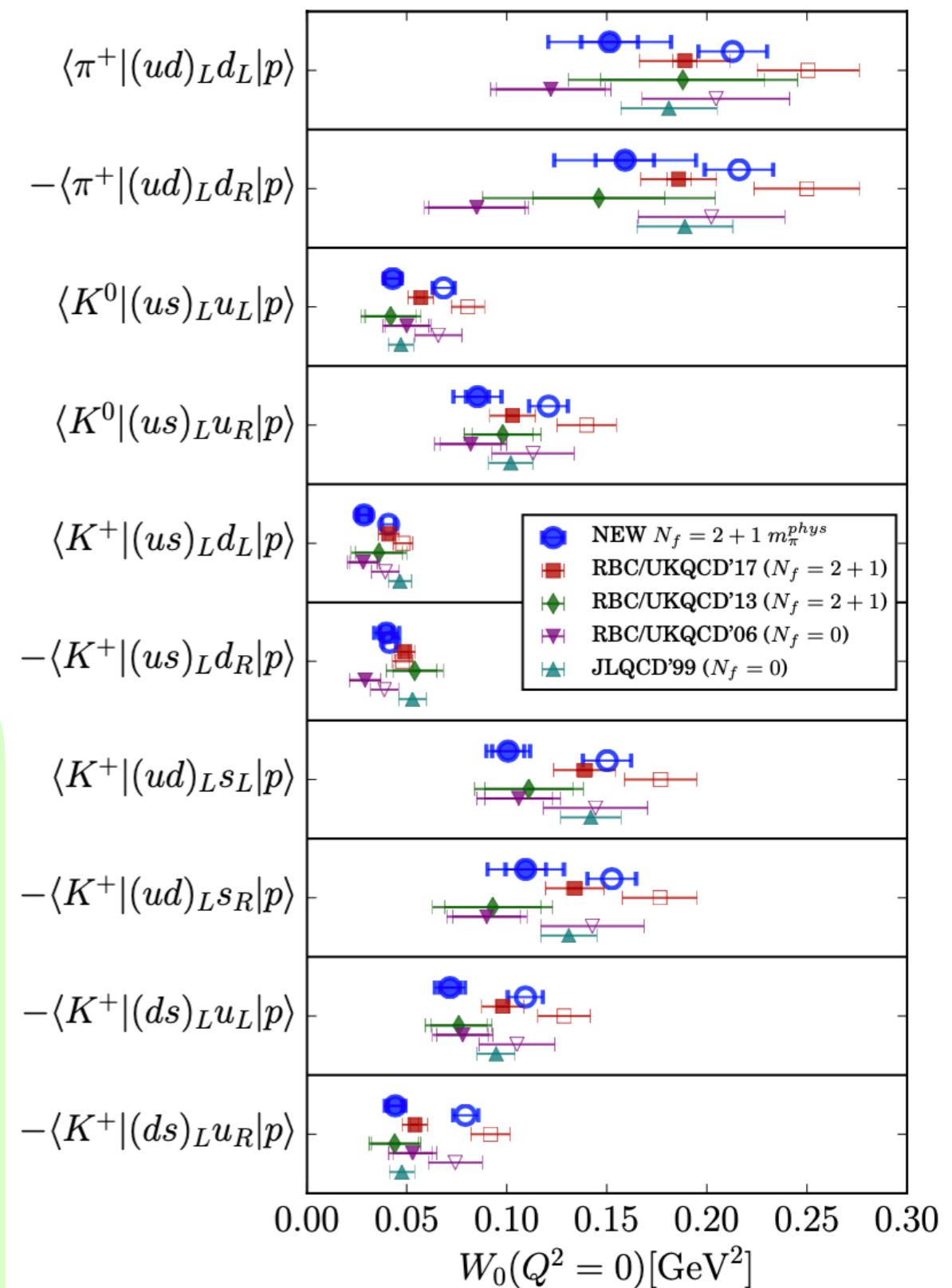
Martin and Stavins, PRD 85 (2012)

Addressed by recent LQCD calculations:

Yoo et al, PRD 105 (2022)

- ~physical quark masses
- nonperturbative renormalization
- 2 lattice spacings
- Direct and indirect methods

10-20% precision achieved, quark mass effects found to be modest



Yoo, Aoki, Boyle, Izubuchi, Soni, and Syritsyn, PRD 105 (2022)

Lepton-number violation

Experimental data on the half-lives of nuclei where double- β^- but not single- β^- decay is allowed can be used to constrain Majorana masses

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} |\mathcal{M}^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Phase space Nuclear matrix element Effective Majorana mass

Chiral EFT calculations show that a short-distance contact operator is needed for renormalizability

Cirigliano, Dekens, de Vries, Graesser, and Mereghetti PRL 120 (2018)

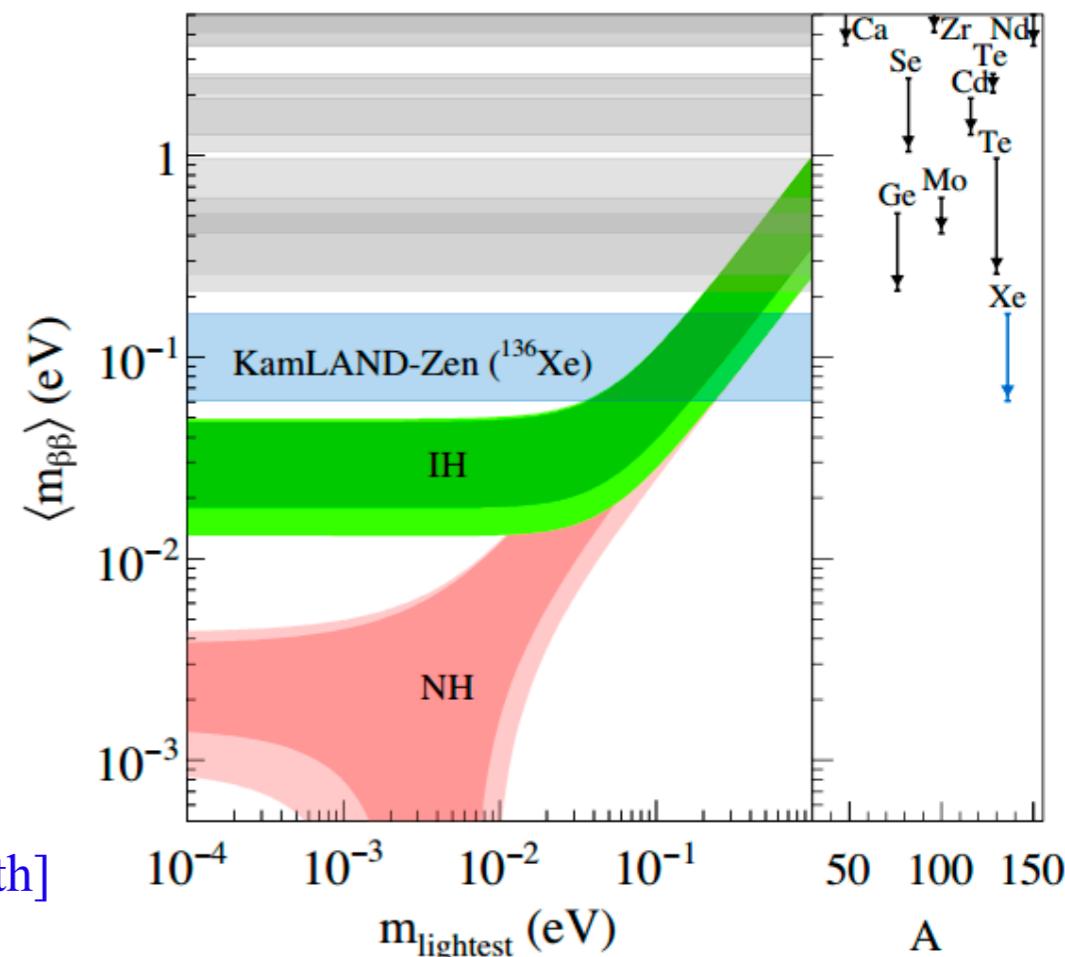
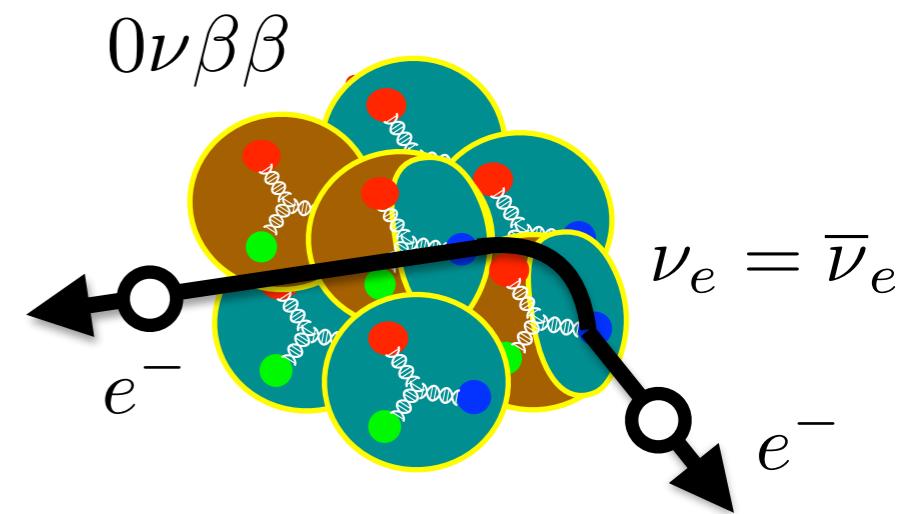
Ongoing efforts to estimate low-energy constant and study effects on nuclear matrix elements

Cirigliano, Dekens, de Vries, and Hoferichter PRL 126 (2021)

Wirth, Yao, and Hergert, PRL 127 (2021)

Weiss, Soriano, Lovato, Menedez, and Wiringa arXiv:2112.08146 [nucl-th]

...



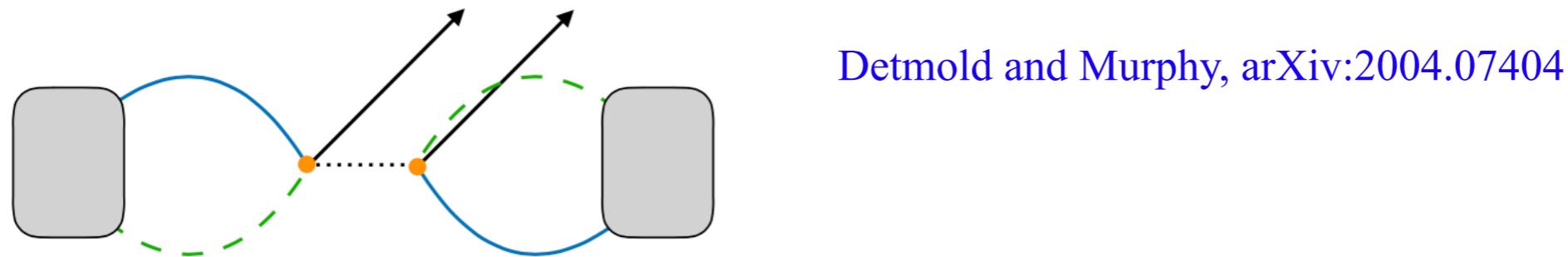
Gando et al (KamLAND-Zen) PRL 117 (2016)

$0\nu\beta\beta$ and LQCD

Pion analogs such as $\pi^- \rightarrow \pi^+ e^- e^-$ calculated with physical quark masses

Short distance Nicholson et al, PRL 121 (2018)

Long distance Feng, Jin, Tuo, PRL 122 (2019) Tuo, Feng, and Jin, PRD 100 (2019)



Detmold and Murphy, arXiv:2004.07404

Two-nucleon matrix elements for $2\nu\beta\beta$ calculated by matching LQCD and EFT

$\langle pp | A_3^+ A_3^+ | nn \rangle$ Shanahan, MW et al [NPLQCD], PRL 119 (2017)

Tiburzi, MW et al [NPLQCD], PRD 96 (2017)

Future LQCD calculations can help precisely determine contact operators appearing at LO in chiral EFT descriptions of $0\nu\beta\beta$

Formalism for relating LQCD correlation functions to physical matrix elements under active development

Briceño et al, PRD 21 (2020)

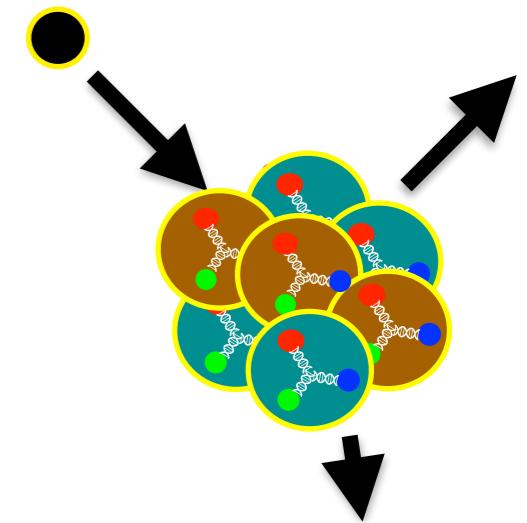
Feng, Jin, Wang, Zhang, PRD 103 (2021)

Davoudi and Kadam, PRL 126 (2021)

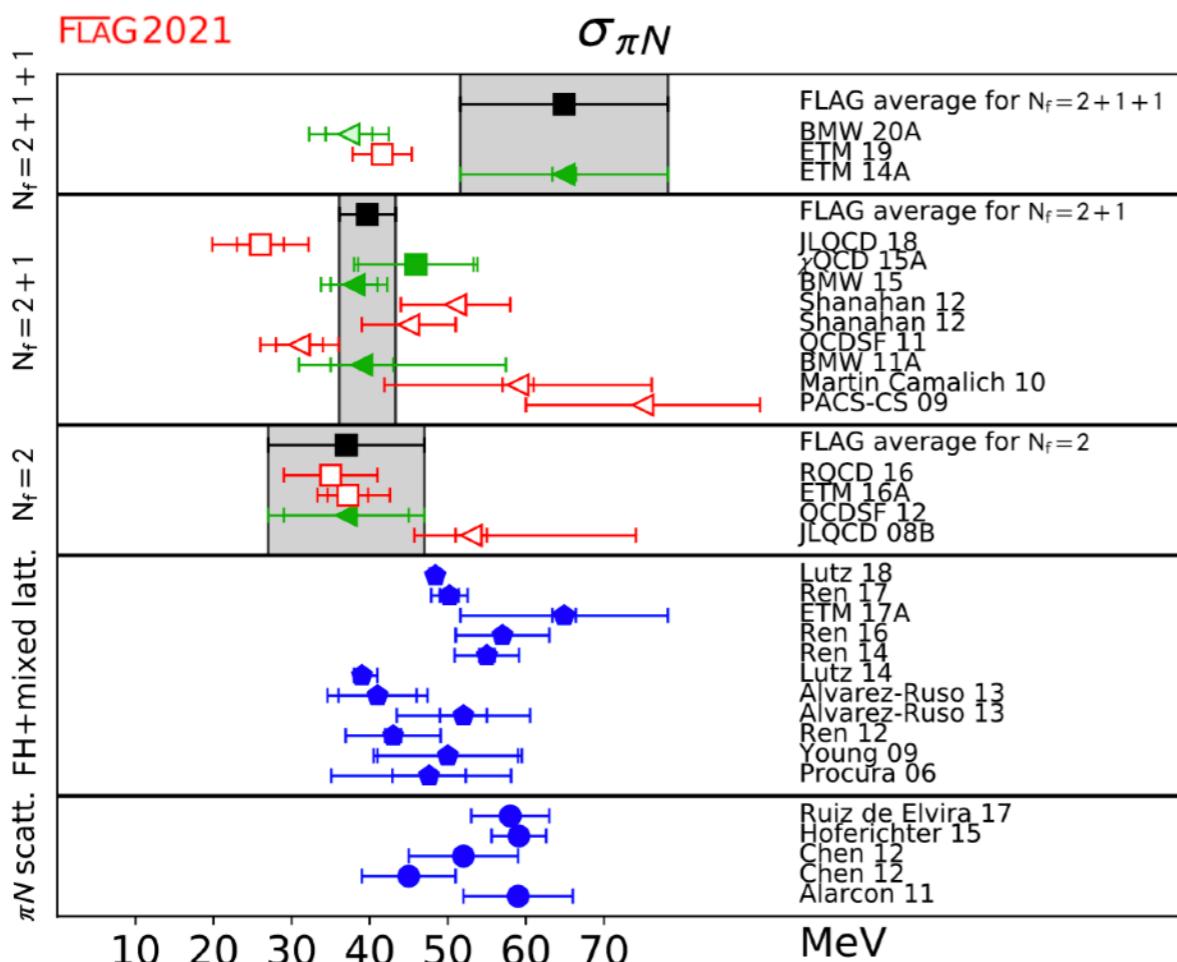
Dark Matter Direct Detection

Experiments look for nuclei recoiling from scattering with something invisible

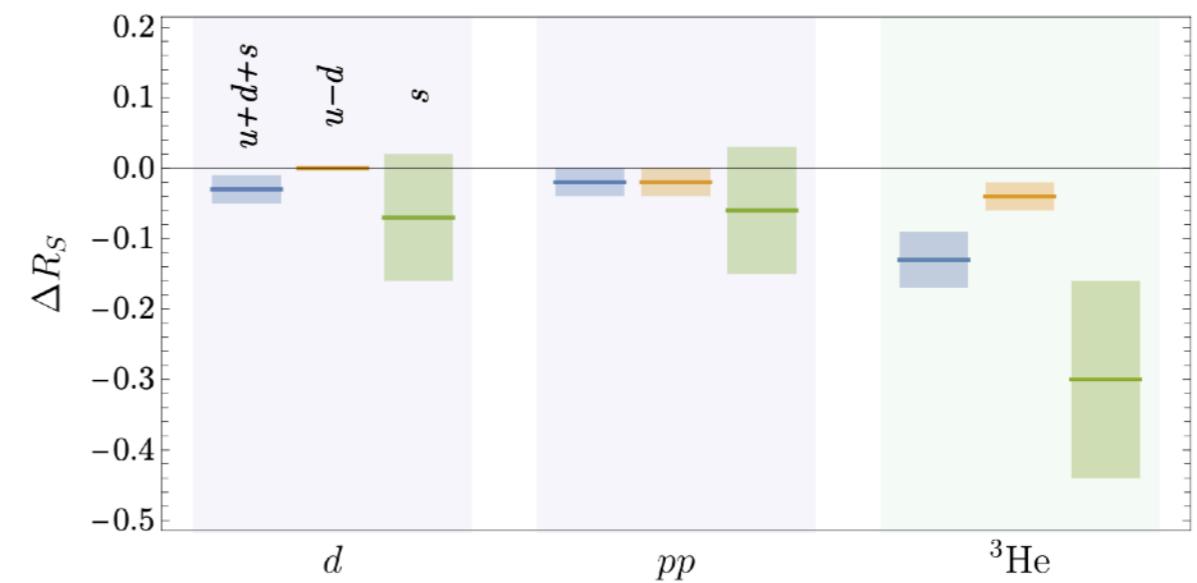
QCD needed to relate DM-nucleus and DM-nucleon cross-sections and enable comparison between different experiments



Nucleon scalar charge needed to extract BSM constraints for spin-independent direct detection studied in several LQCD calculations



Exploratory LQCD studies of nuclear effects on scalar charges at unphysical quark masses show significant effects



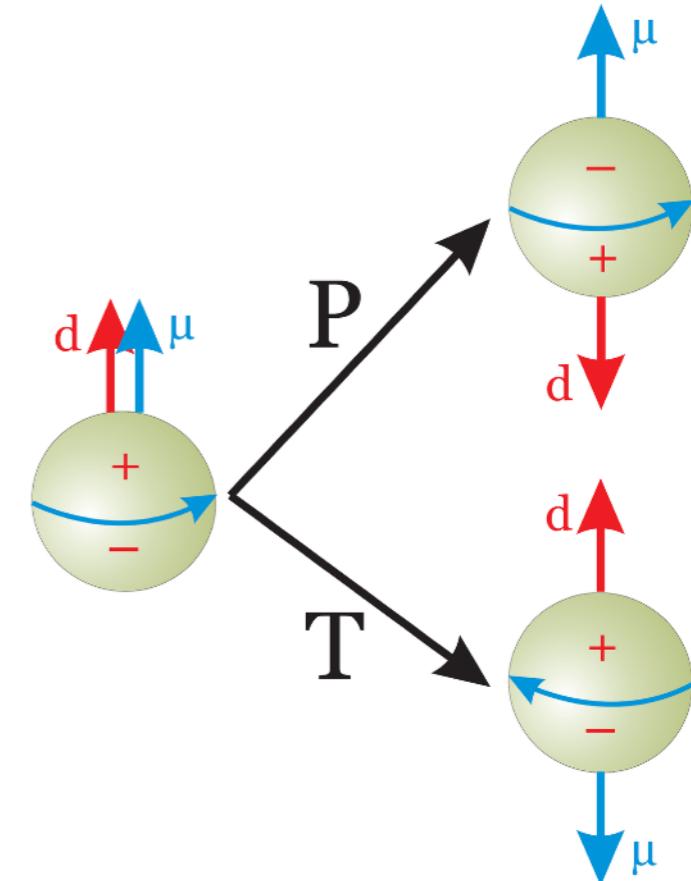
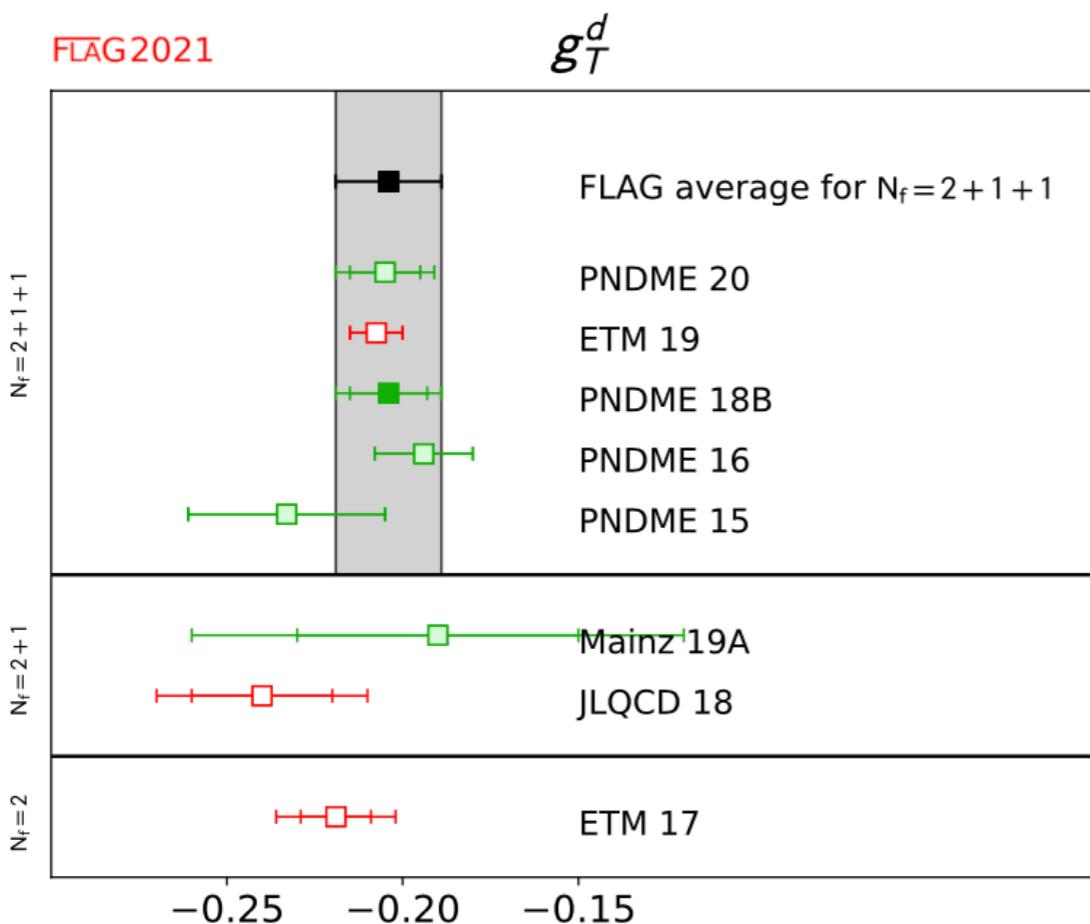
Chang, MW et al [NPLQCD], PRL 120 (2018)

CP violation

Neutron and nuclear electric dipole moments (EDMs) provide low-energy signals of CP violation

Extracting BSM physics constraints from hadronic EDMs requires QCD matrix elements

Nucleon tensor charges relating quark and nucleon EDM calculated using LQCD with complete error budgets by multiple groups



Exploratory LQCD investigations of tensor charges of A=2-3 nuclei

Chang, MW et al [NPLQCD], PRL 120 (2018)

EDM contributions from the QCD θ term are more technically challenging but under active exploration

Dragos, Luu, Shindler, de Vries, Yousif, PRC 103 (2021)

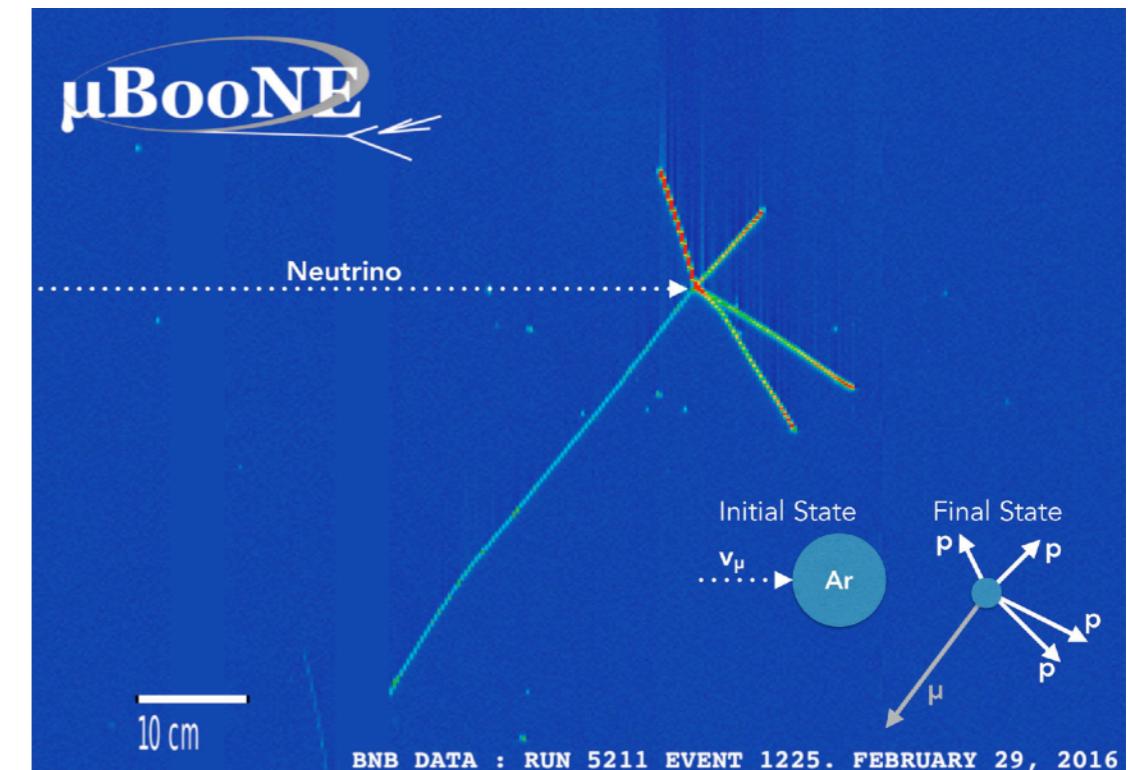
Bhattacharya, Cirigliano, Gupta, Mereghetti, Yoon, PRD 103 (2021)

Neutrinos, nuclei, and new physics

Current and future accelerator neutrino experiments search for leptonic CP violation and new physics in the neutrino sector

Inferring incident neutrino energies from measured final state event rates requires theoretical interaction model

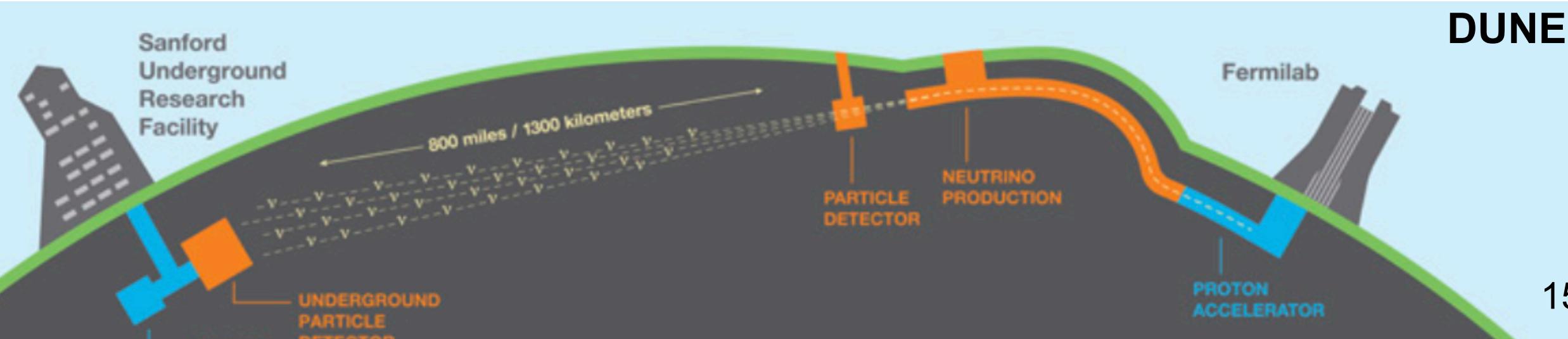
- Near detector tuning is essential but theory still needed to extrapolate to far detector kinematics, find BSM physics, ...



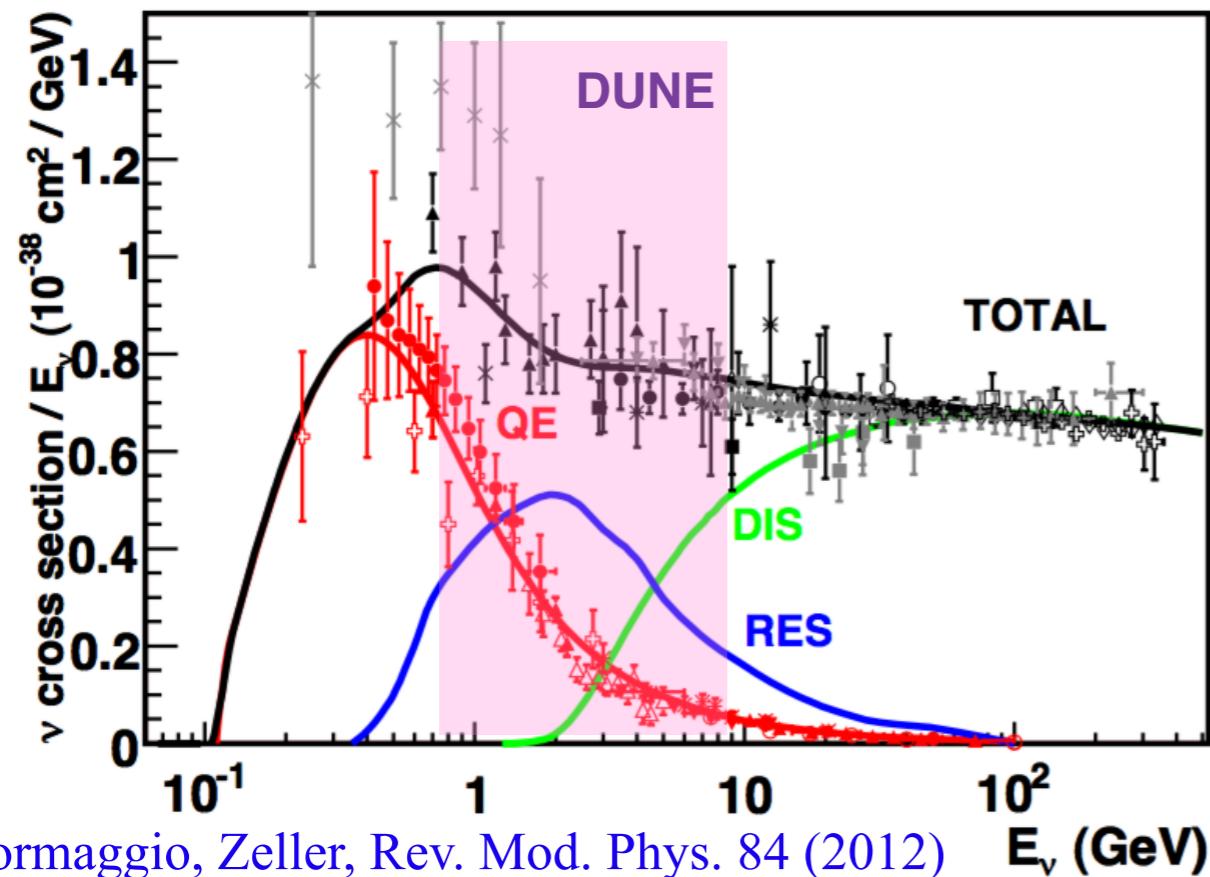
Maximizing the discovery potential of next-generation neutrino experiments will require a coordinated theory effort:

High-energy theory, nuclear many-body theory, lattice QCD, event generators, ...

See Snowmass WP: “Theoretical Tools for Neutrino Scattering” arXiv:2203.09030,
7/20 talk “Neutrino Theory and Nuclear Physics” — MW



Neutrino-nucleus scattering

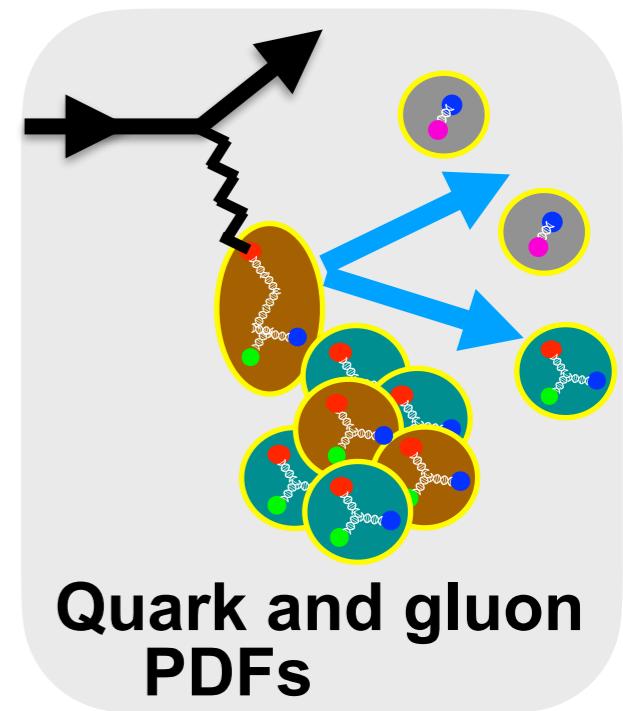
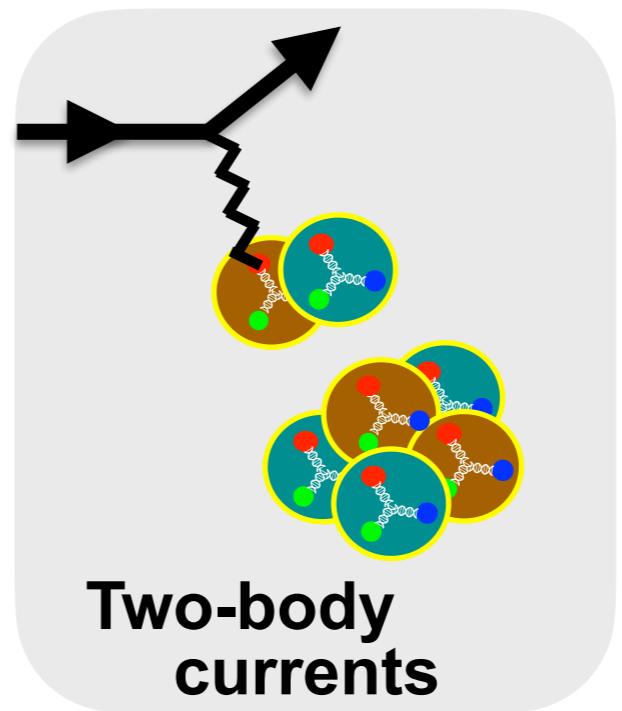
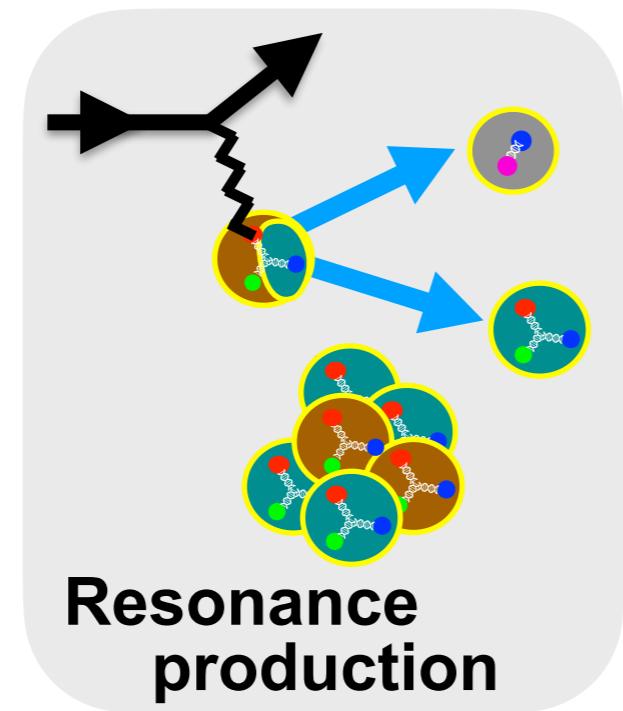
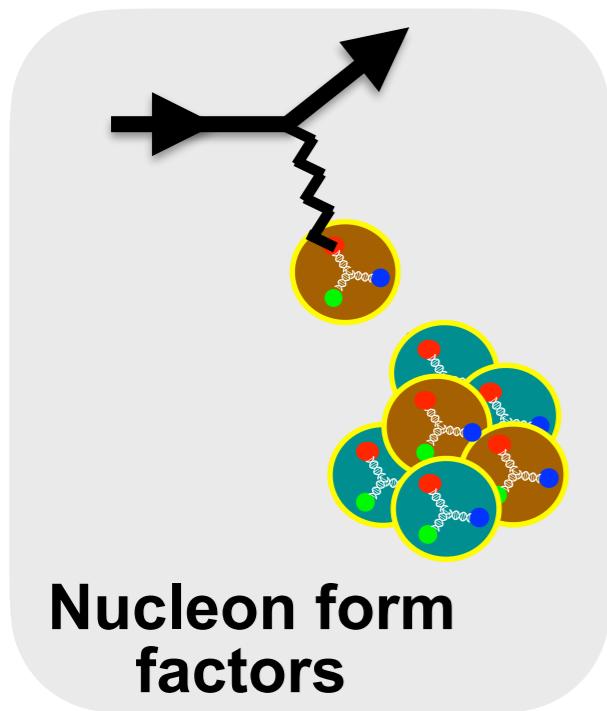


Accelerator neutrino fluxes cover a wide range of energies where different processes dominate cross-section:

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

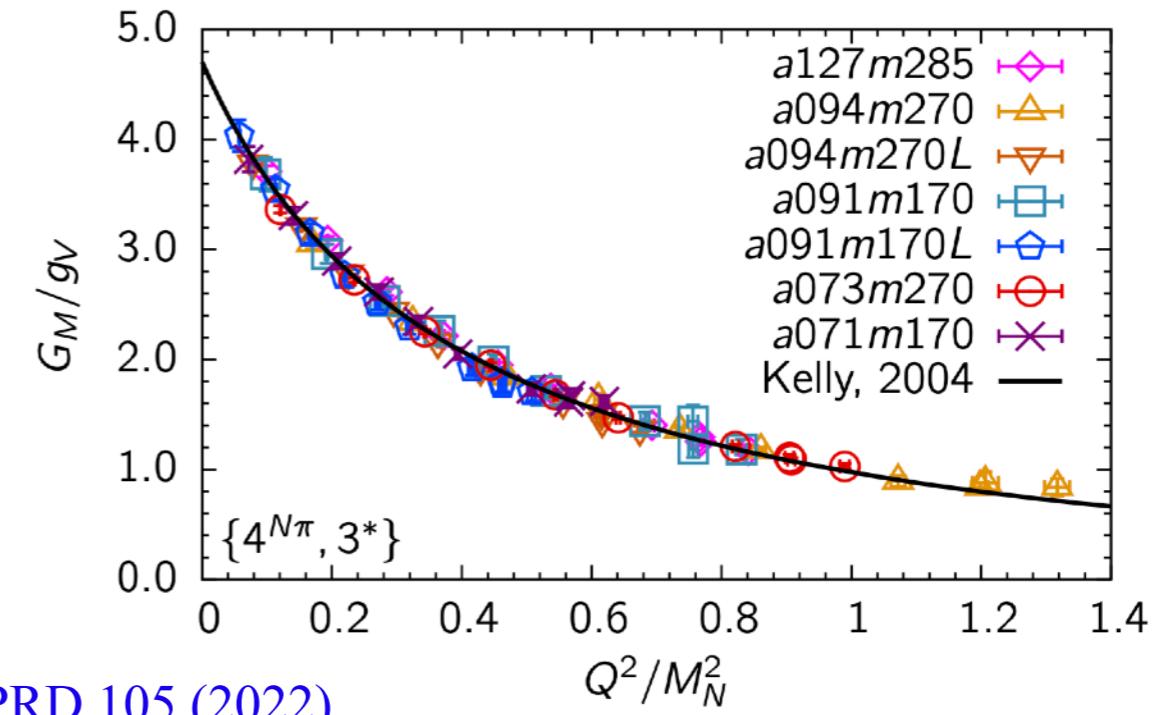
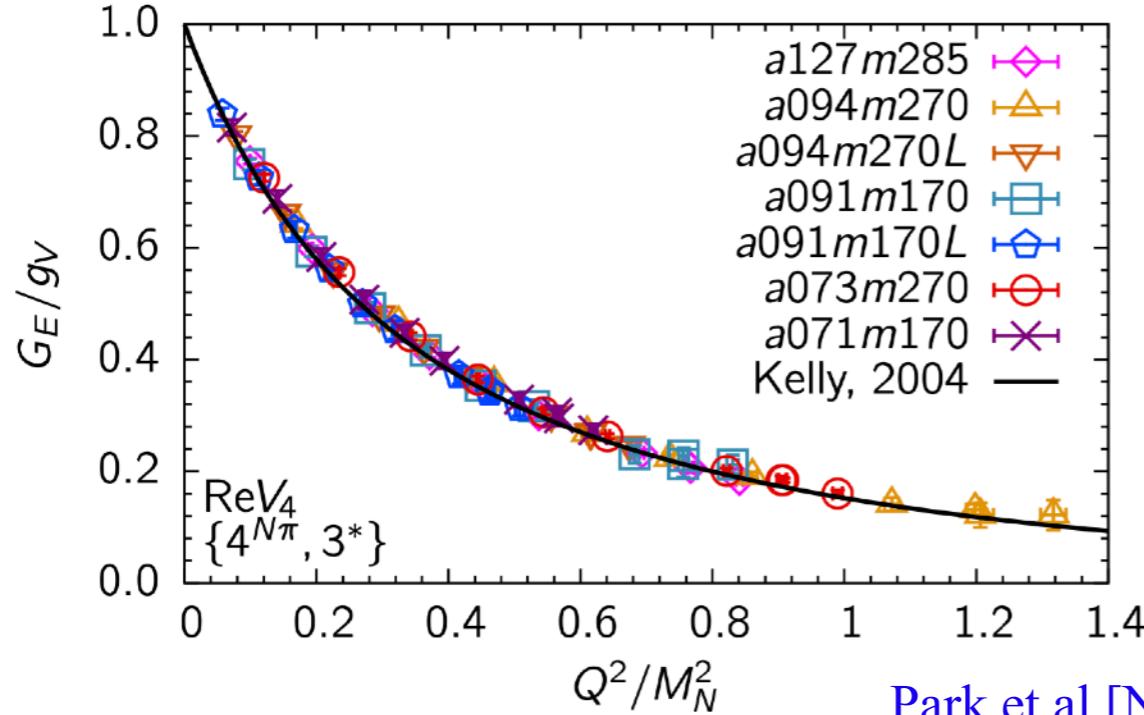
Theory input required to decompose cross section into such processes and therefore predict its energy dependence

Effective theories for different energies require different inputs



Form factors and LQCD

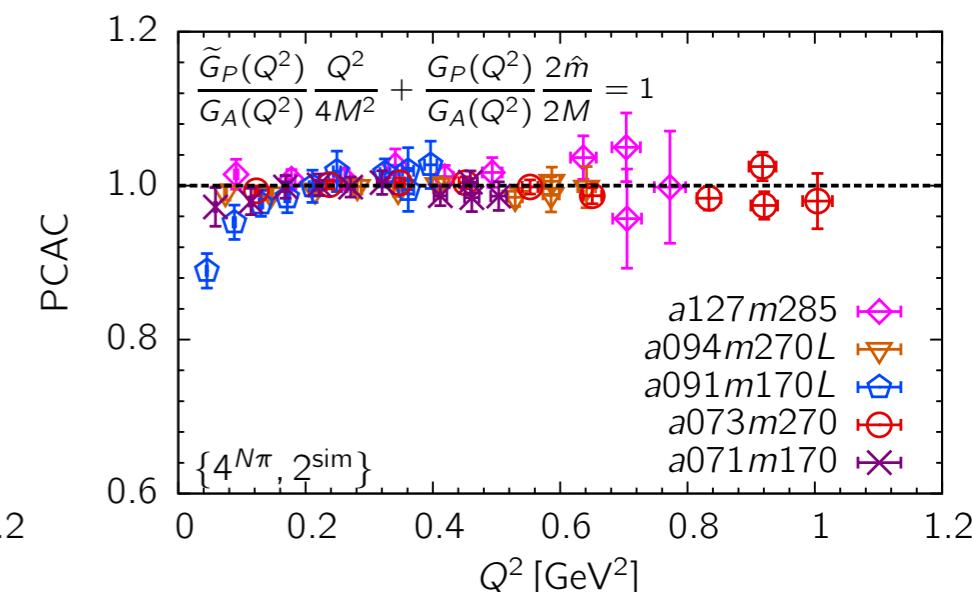
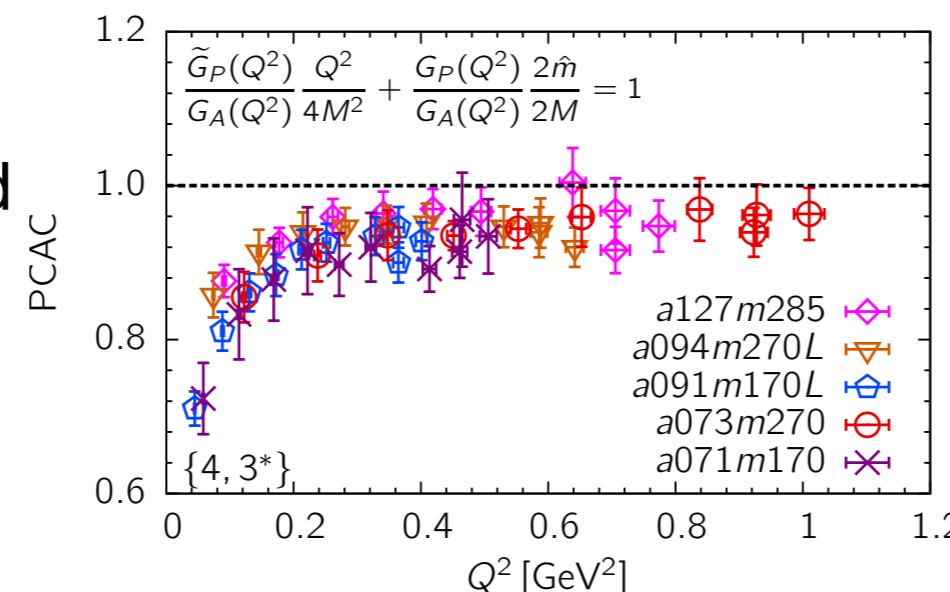
Vector and axial form factors recently calculated using nearly physical quark masses:



Park et al [NME], PRD 105 (2022)

LQCD nucleon electric and magnetic form factor results agree with phenomenological parameterizations after accounting for excited-state and discretization effects

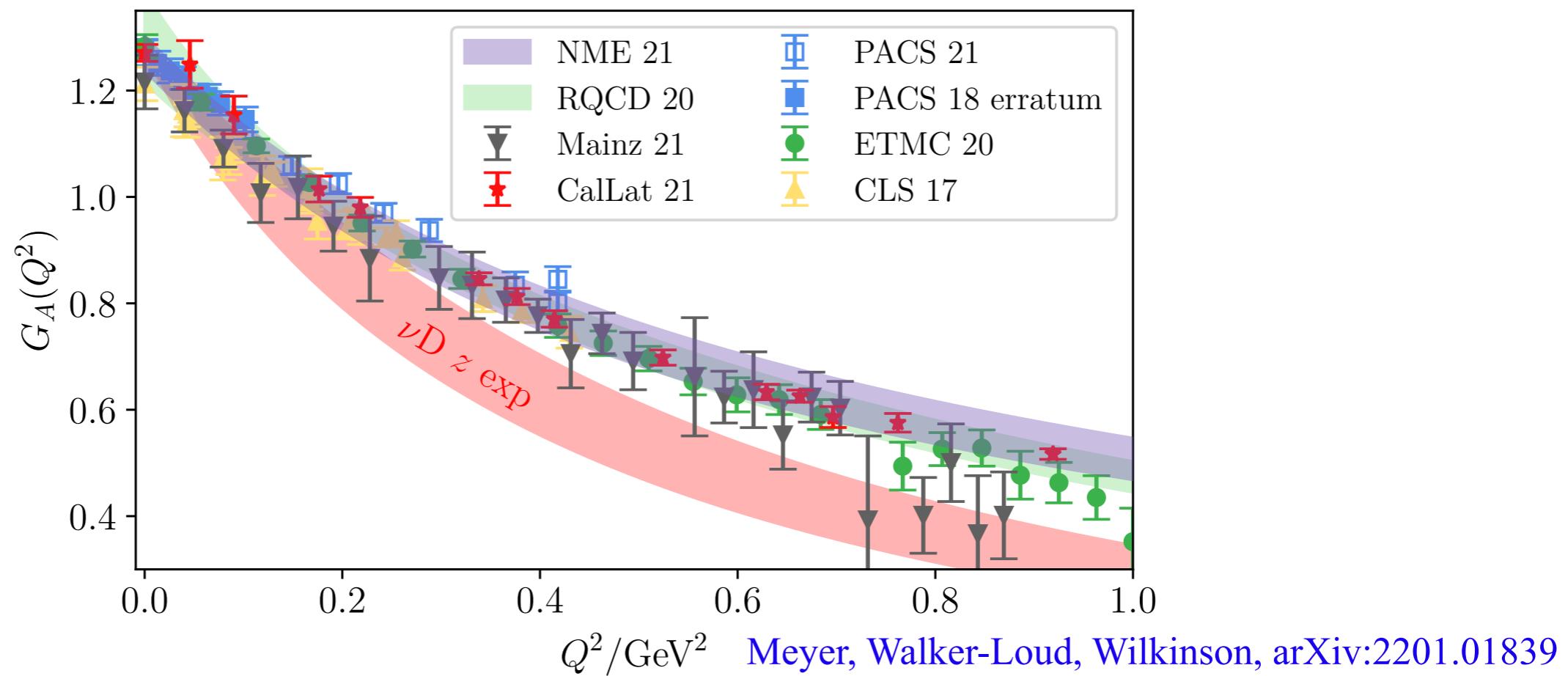
Careful treatment of $N\pi$ excited states required to reproduce consequences of axial ward identities that assume ground-state dominance



Park et al [NME], PRD 105 (2022)

Axial form factors

Recent axial form factor calculations include physical quark masses, continuum / infinite-volume extrapolations, and excited-state fits that account explicitly for $N\pi$ states



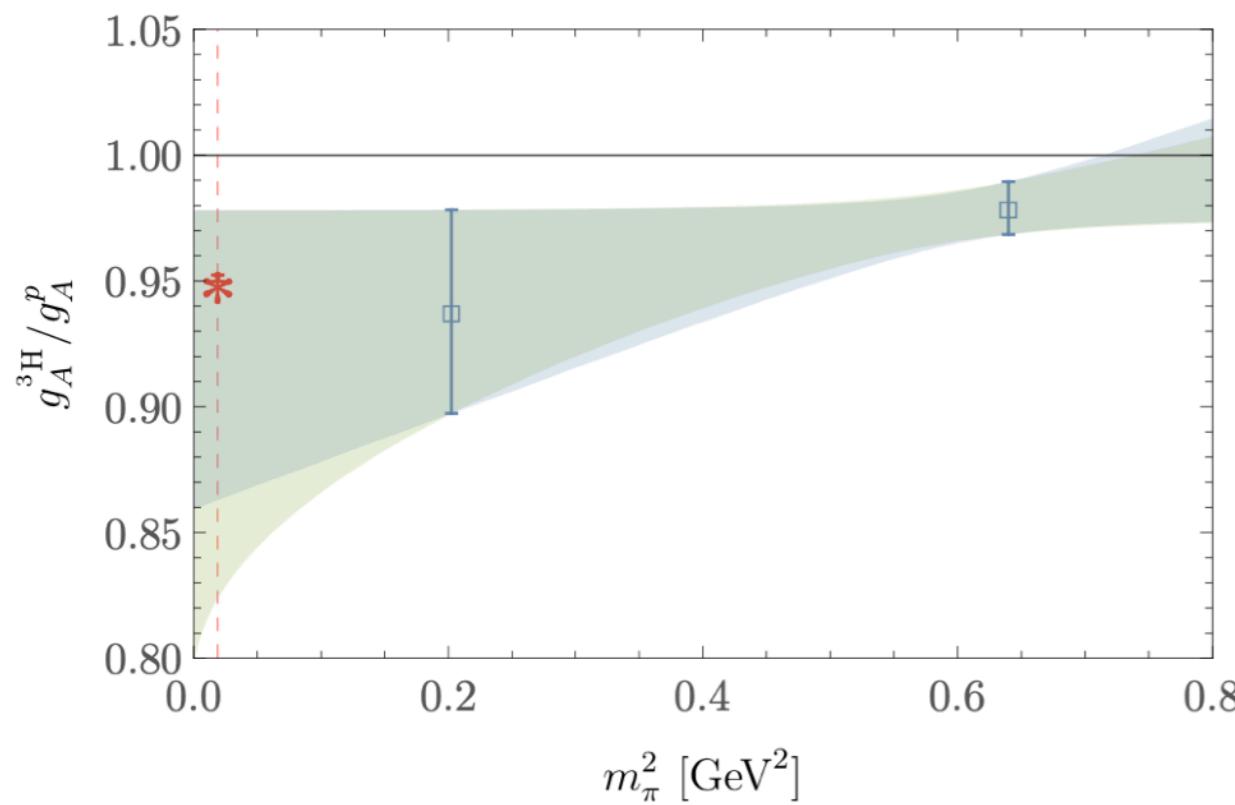
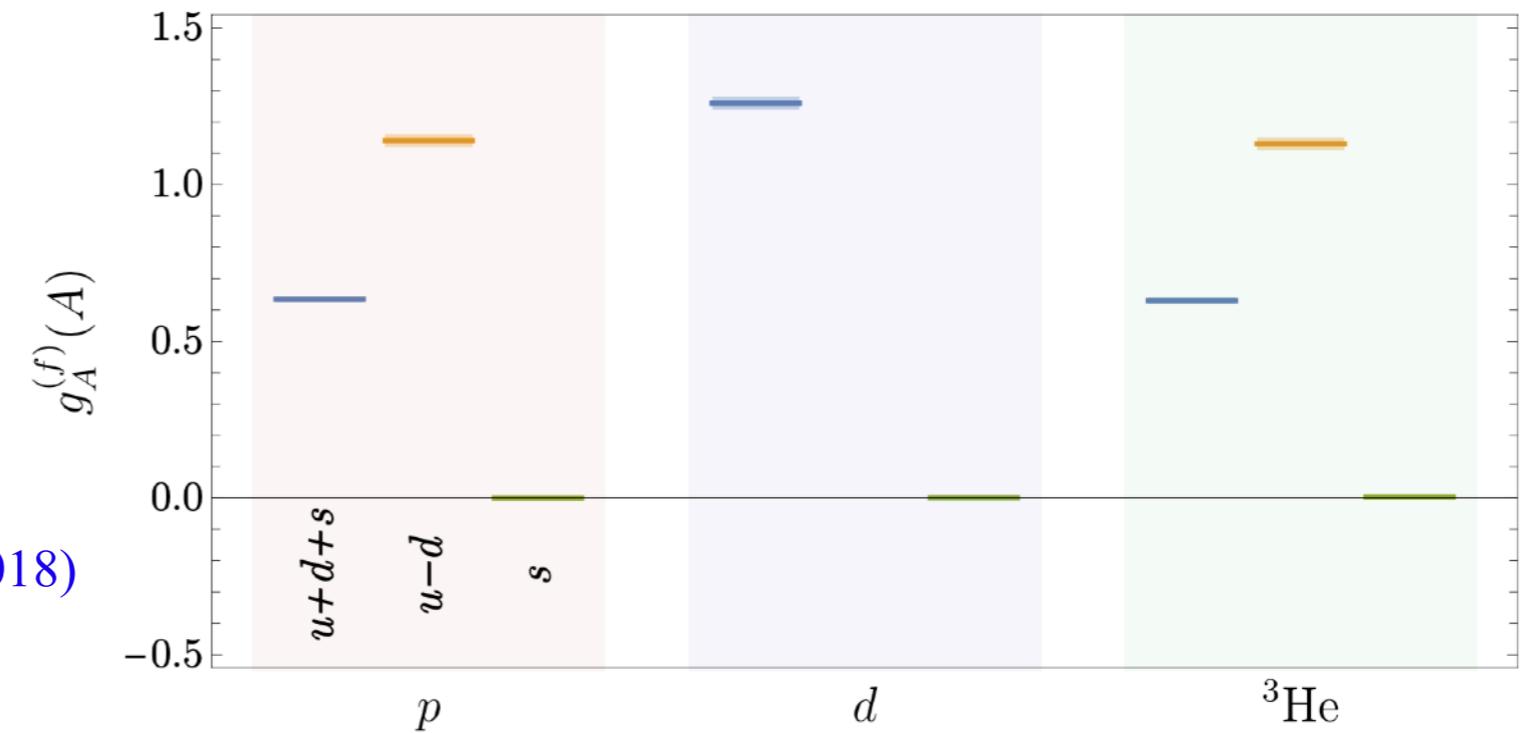
Differences between LQCD and experimental axial form factor determinations could arise from challenging LQCD systematic uncertainties (excited states, lattice spacing, ...)

Differences could also arise from underestimated uncertainties in phenomenological form factor determinations using deuterium bubble chamber data

Two-body currents in LQCD

Flavor decomposition of axial matrix elements of two and three nucleon systems computed with $m_\pi = 806$ MeV

Chang, MW et al [NPLQCD], PRL 120 (2018)



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

Axial current matrix element calculations with $m_\pi = 450$ MeV permit preliminary extrapolation of triton axial charge to physical point

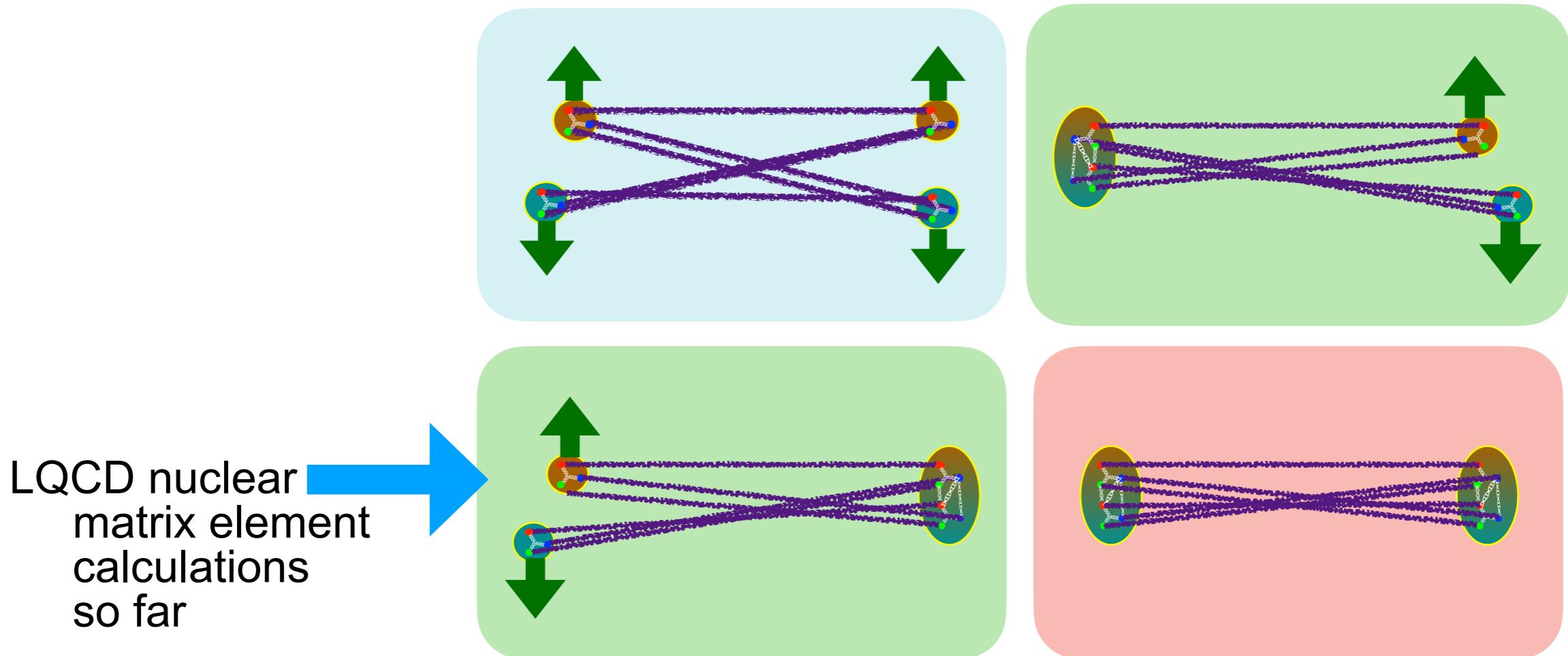
Several systematic uncertainties remain, but encouraging agreement with experiment seen

Matching to finite-volume pionless EFT used to constrain L_{1A}

Detmold and Shanahan, PRD 103 (2021)

Variational methods

Excited-state effects from unbound multi-nucleon scattering states are not effectively suppressed in computationally feasible LQCD calculations



Variational methods involving diagonalization of symmetric correlation-function matrices demonstrate that excited-state effects are significant for NN systems; provide a path towards robust future LQCD studies of multi-nucleon systems

Francis et al, PRD 99 (2019)

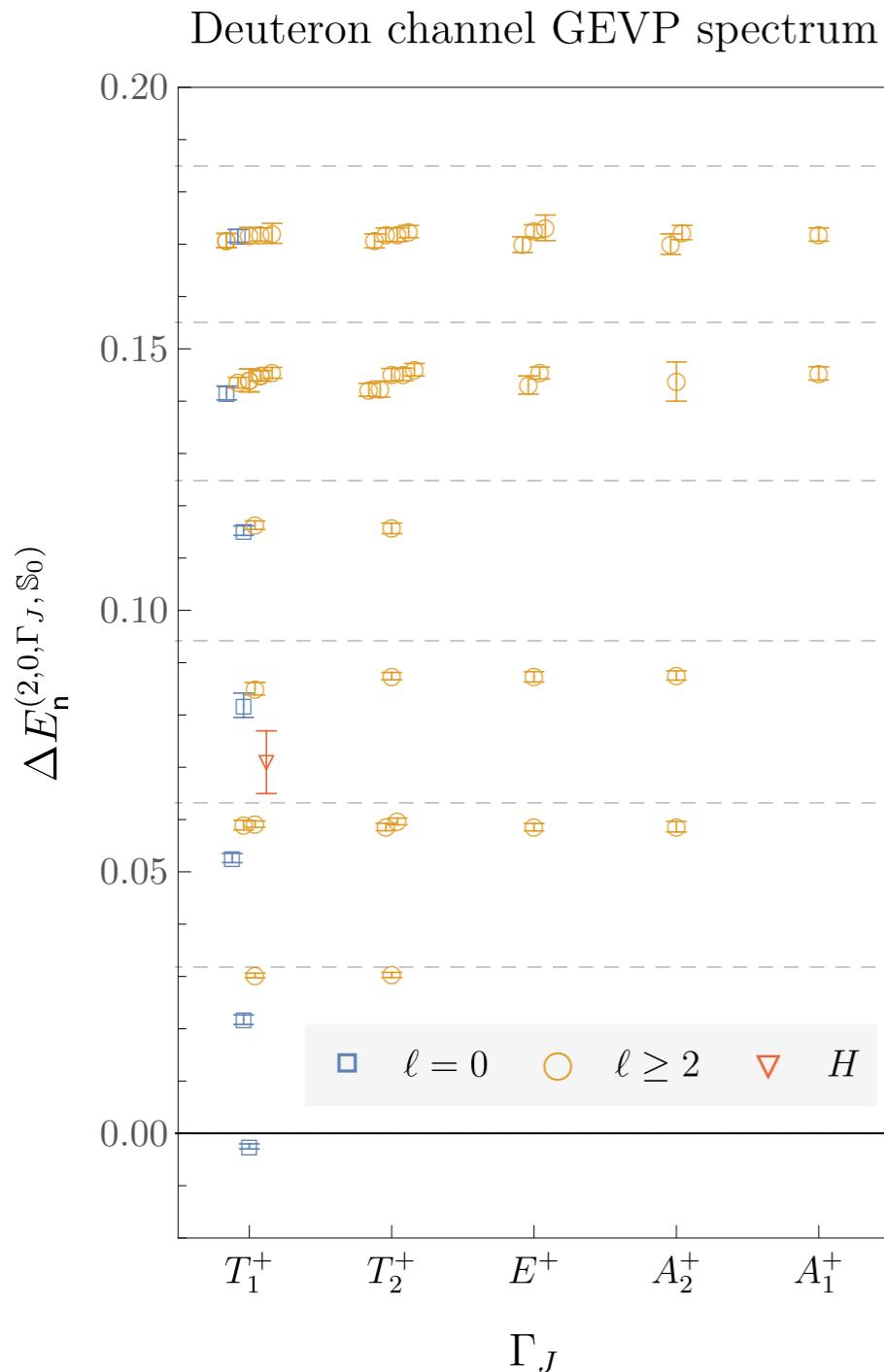
Green et al, PRL 127 (2021)

Hörz et al, PRC 103 (2021)

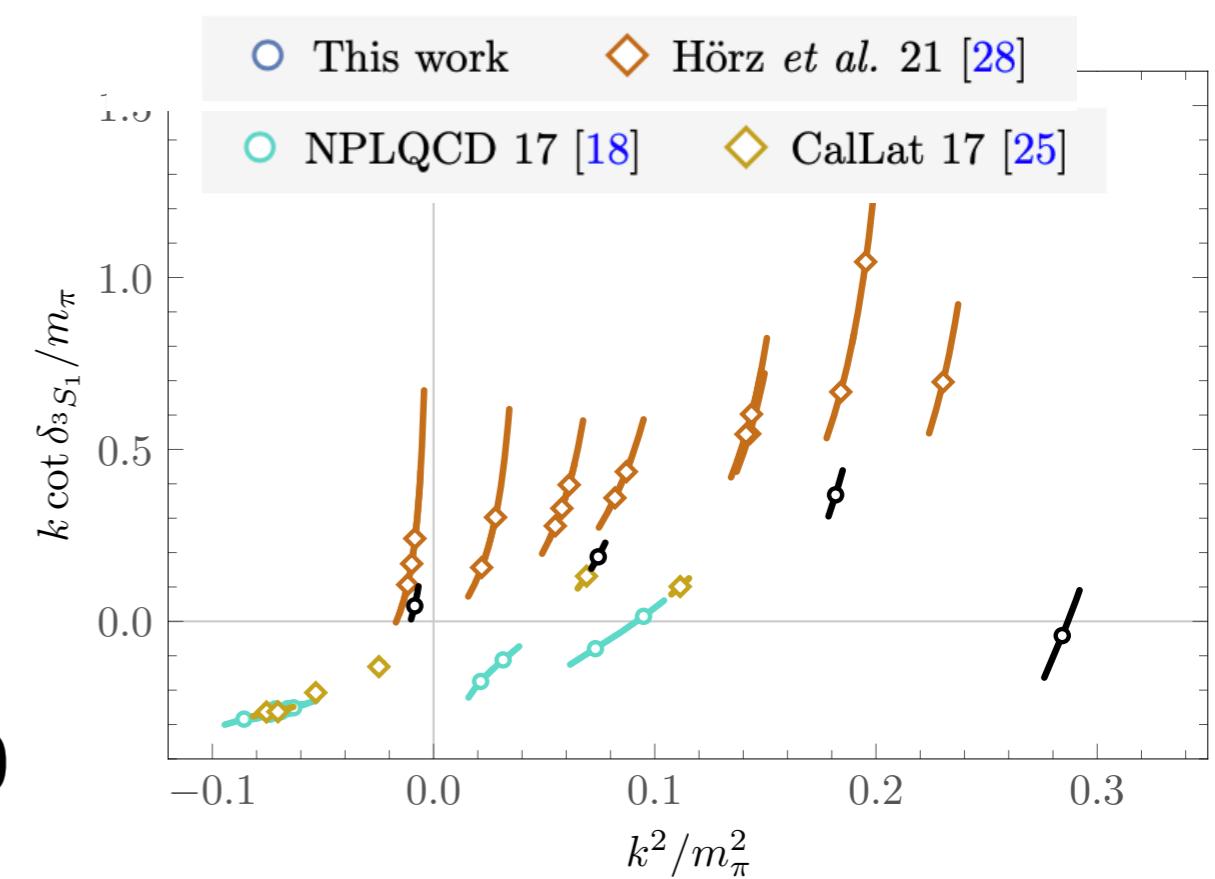
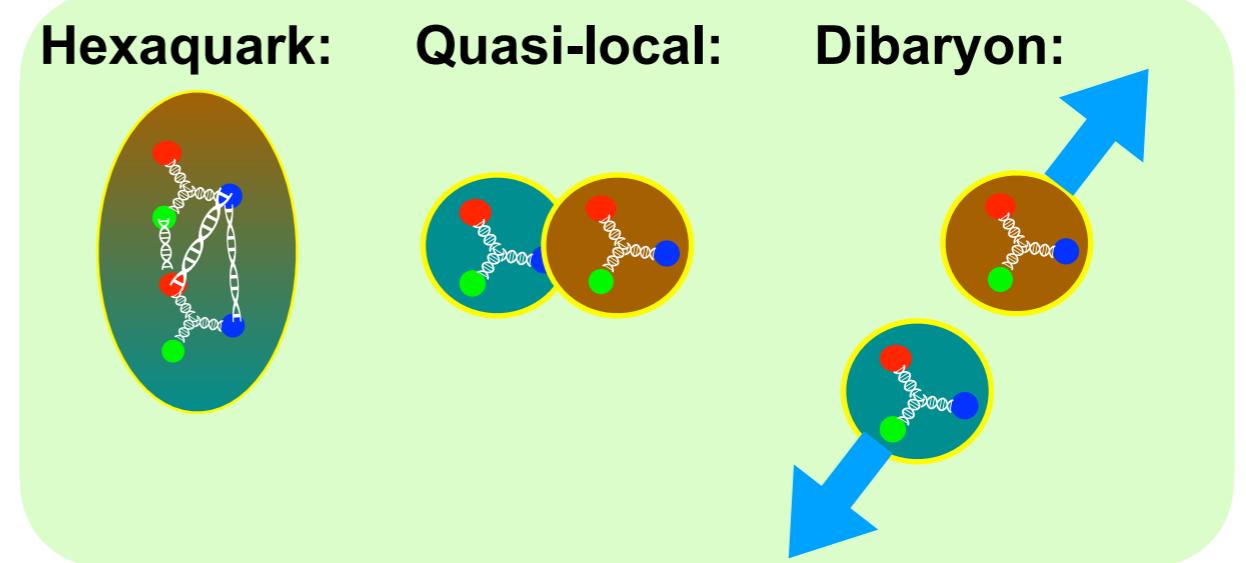
Amarasinghe, MW et al, arXiv:2108.10835

NN phase shifts

A wide range of operator structures has been used for variational studies of NN systems



Generalized Lüscher formalism
→ NN $I = 0$
s-wave
phase shift

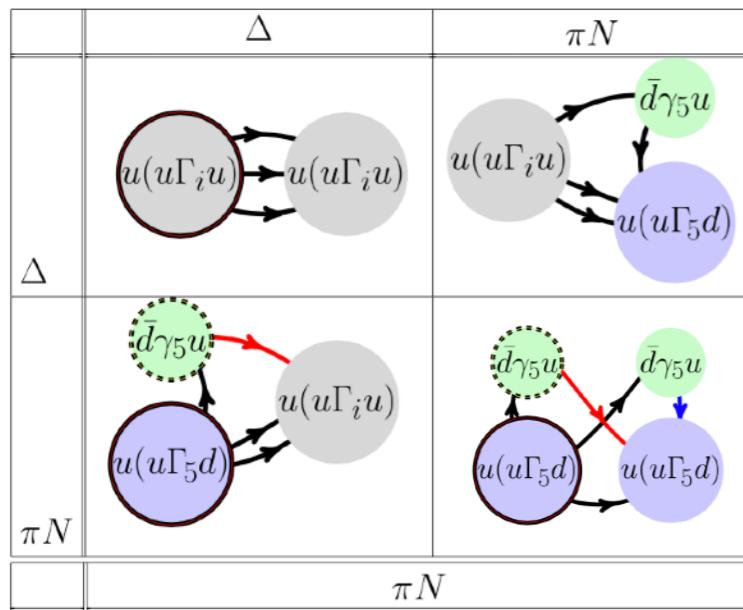


Calculations by different groups with similar interpolating operators consistent, but interpolating operator dependence significant 21

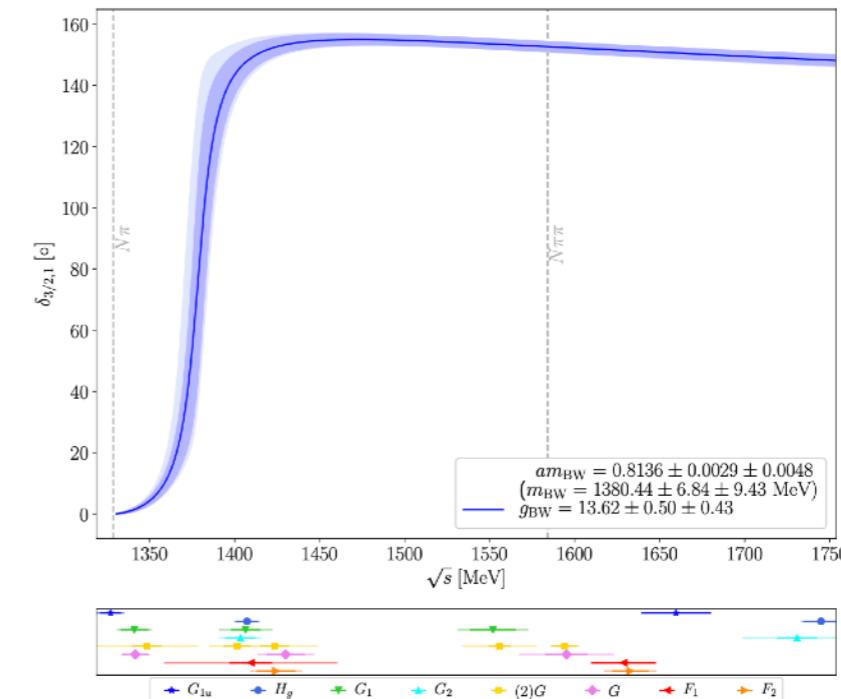
$N\pi$ systems in LQCD

Variational methods can be applied to study $N\pi$ and Δ systems in LQCD

Silvi et al, PRD 23 (2021)



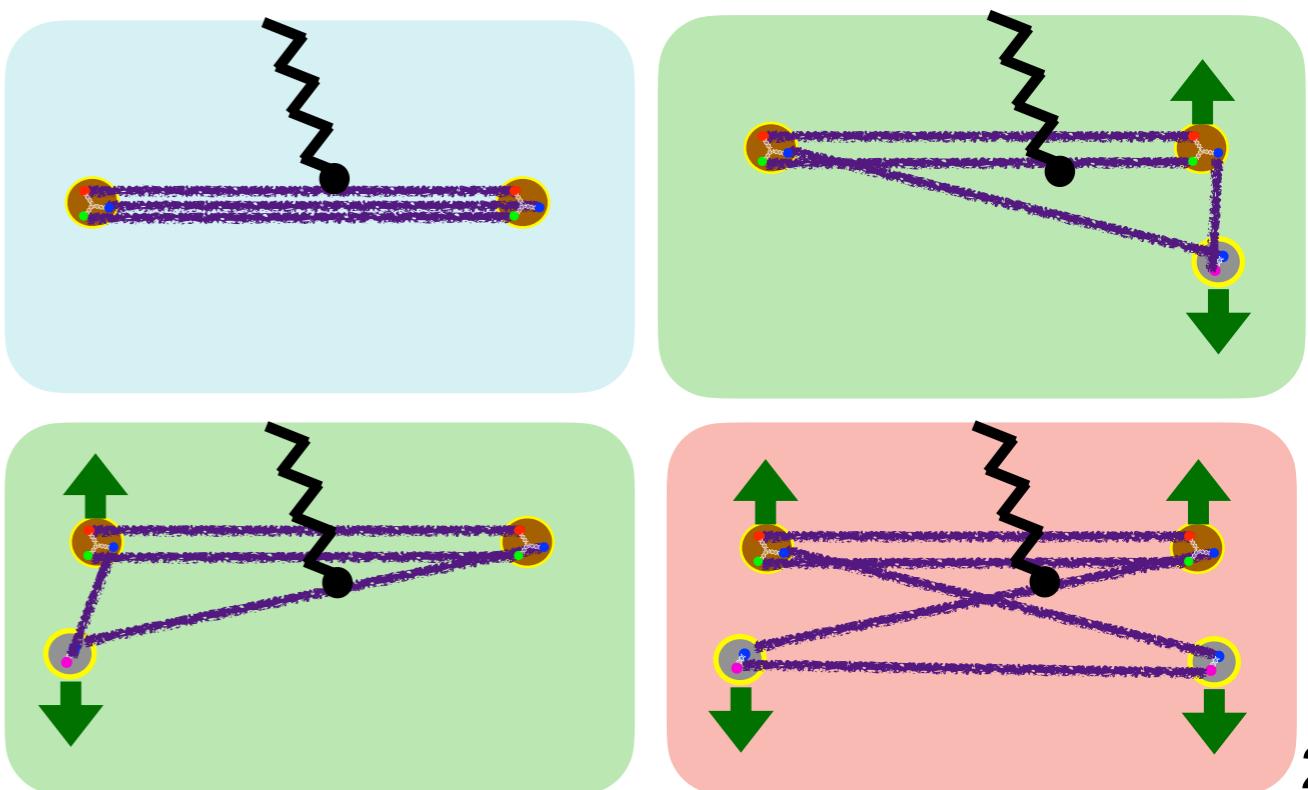
$N\pi$ p-wave
phase shift



$N \rightarrow \Delta$ transition form factors also
calculable with variational methods

Barca, Bali, and Collins, PoS LATTICE2021 (2022)

Analogous variational methods in the
nucleon sector can explicitly
remove $N\pi$ excited-state
contamination



Outlook

LQCD studies of nucleons and nuclei are needed to interpret a wide range of current and future searches for new physics

Calculations are rapidly maturing, and over the next decade LQCD results with complete error budgets should become available for many processes involving nucleons and nuclei

