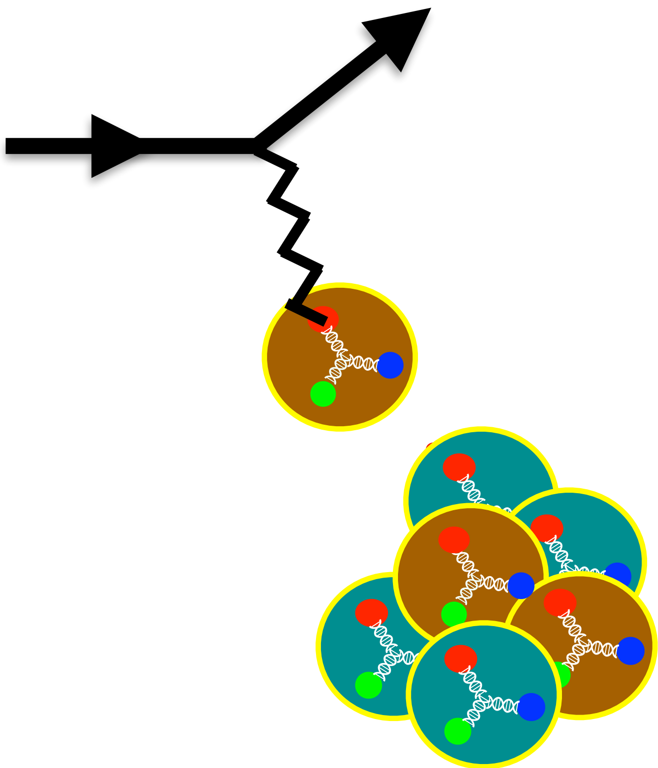
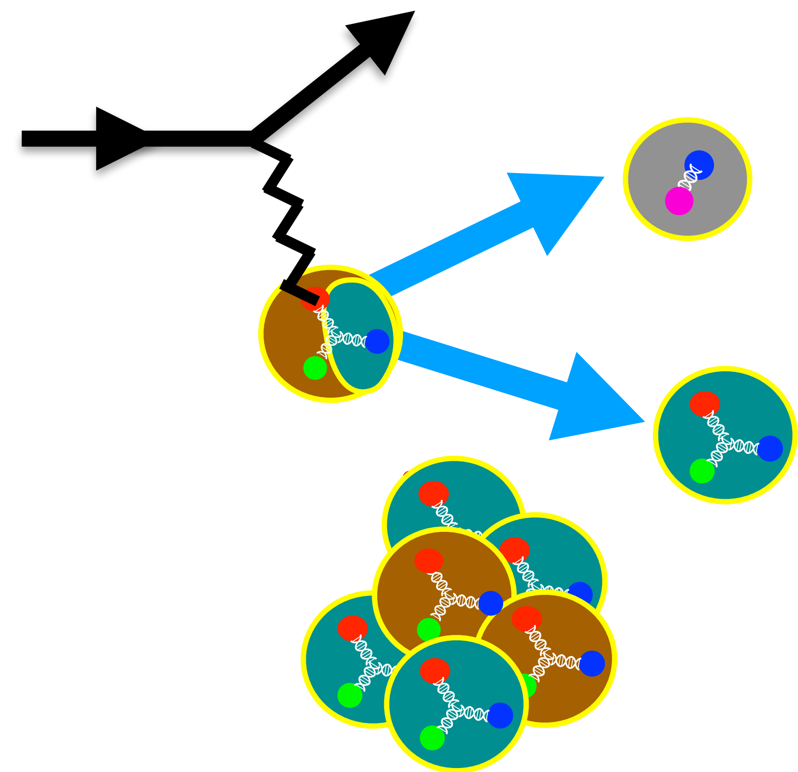
Neutrino Theory and Nuclear Physics





Michael Wagman

Seattle Snowmass Summer Meeting 2022

University of Washington, Seattle

July 20, 2022

Fermilab

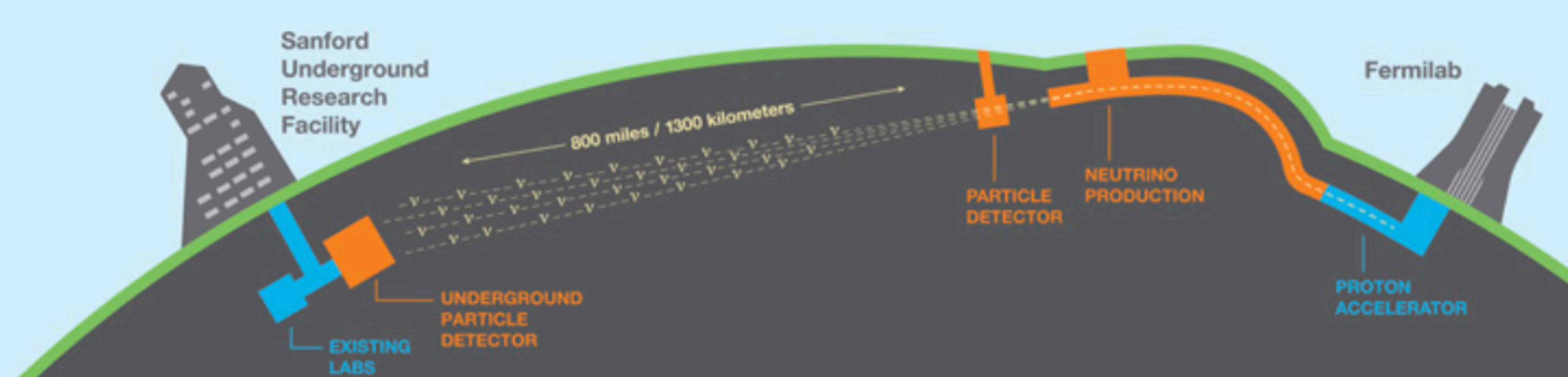
More details in Snowmass WP:
Alvarez-Ruso et al, "Theoretical Tools for Neutrino Scattering" arXiv:2203.09030

Neutrinos and new physics

Neutrino oscillations demonstrate that neutrinos have mass, but the fundamental interactions giving rise to neutrino masses are not well understood

- *CP* violation?
- Dirac or Majorana?
- Sterile neutrinos?
- Mass ordering?

Next-generation neutrino experiments will measure oscillation parameters with unprecedented accuracy to shed light on neutrino masses



DUNE

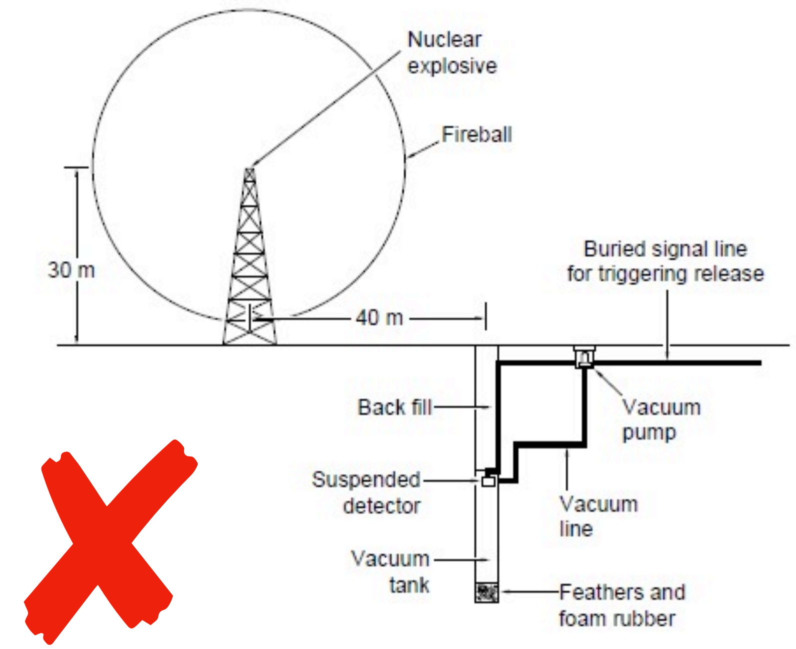
Neutrinos and nuclei

Neutrinos and nuclear physics have been intertwined since the first detection of neutrinos — emitted by a nuclear reactor

Current and future reactor neutrino experiments provide key inputs for constraining neutrino oscillation parameters

Understanding reactor neutrino fluxes requires theoretical models of complex nuclei

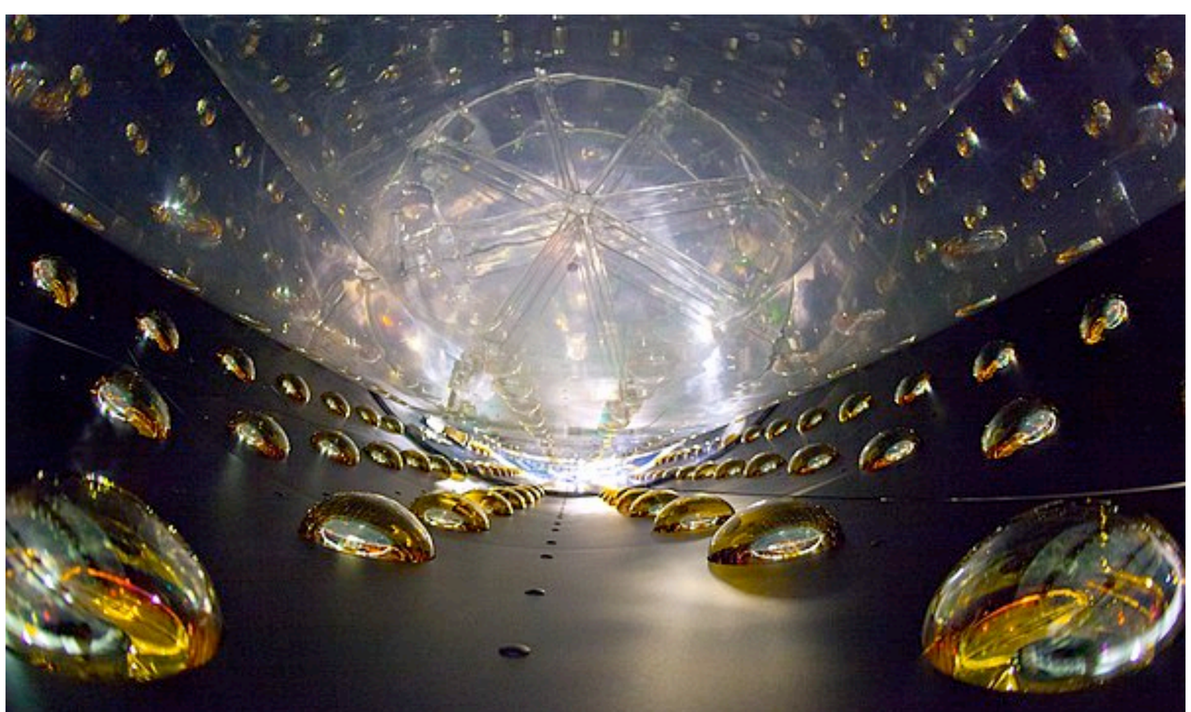
Huber, PRC 84 (2011); Berryman and Huber PRD 101 (2020); …



Los Alamos Science Number 25 1997

Site of Reines-Cowan Savannah river reactor experiment

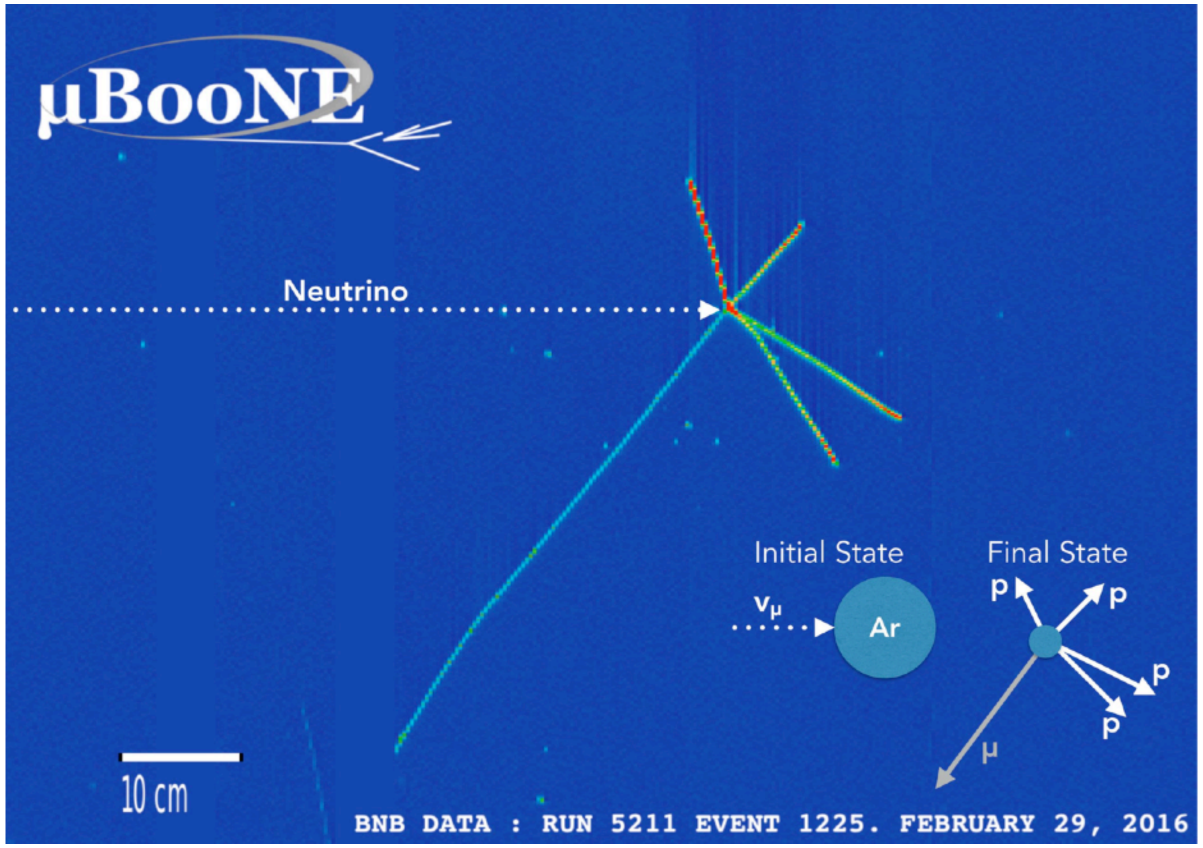
U.S. Department of Energy, Public domain, via Wikimedia Commons



Daya Bay reactor neutrino experiment

Neutrinos, nuclei, and new physics

DUNE and other accelerator neutrino experiments use nuclear targets

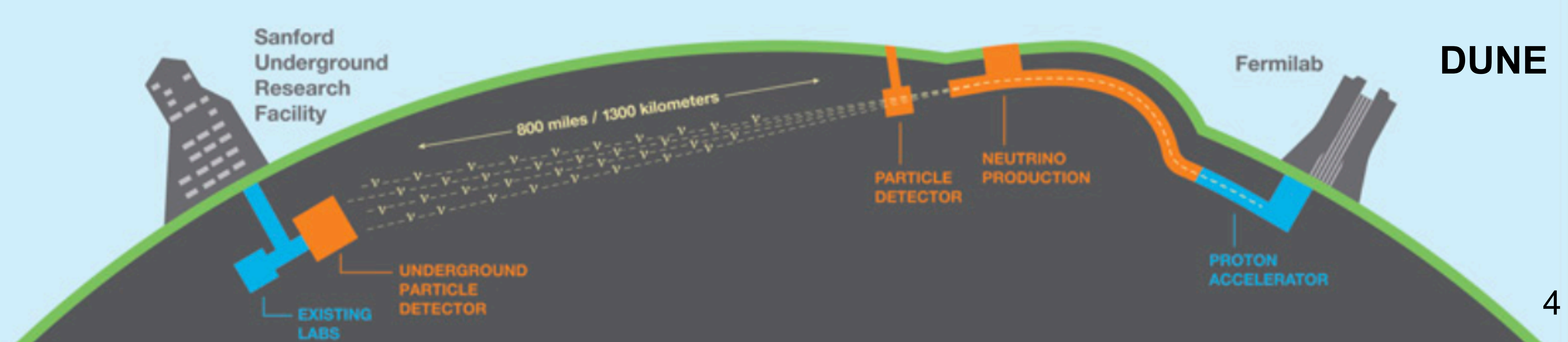


Inferring incident neutrino energies from measured final state event rates requires theoretical interaction model

- 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, …



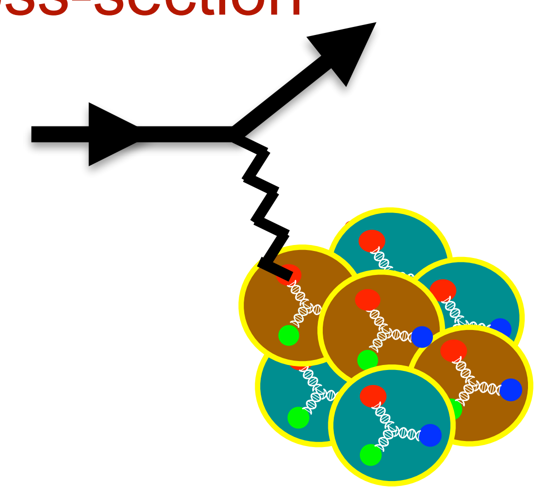
Precision neutrino physics

Relating measured final-state event rates to neutrino fluxes entering oscillation analyses requires knowledge of νA cross-section

Near-detector neutrino flux and acceptance

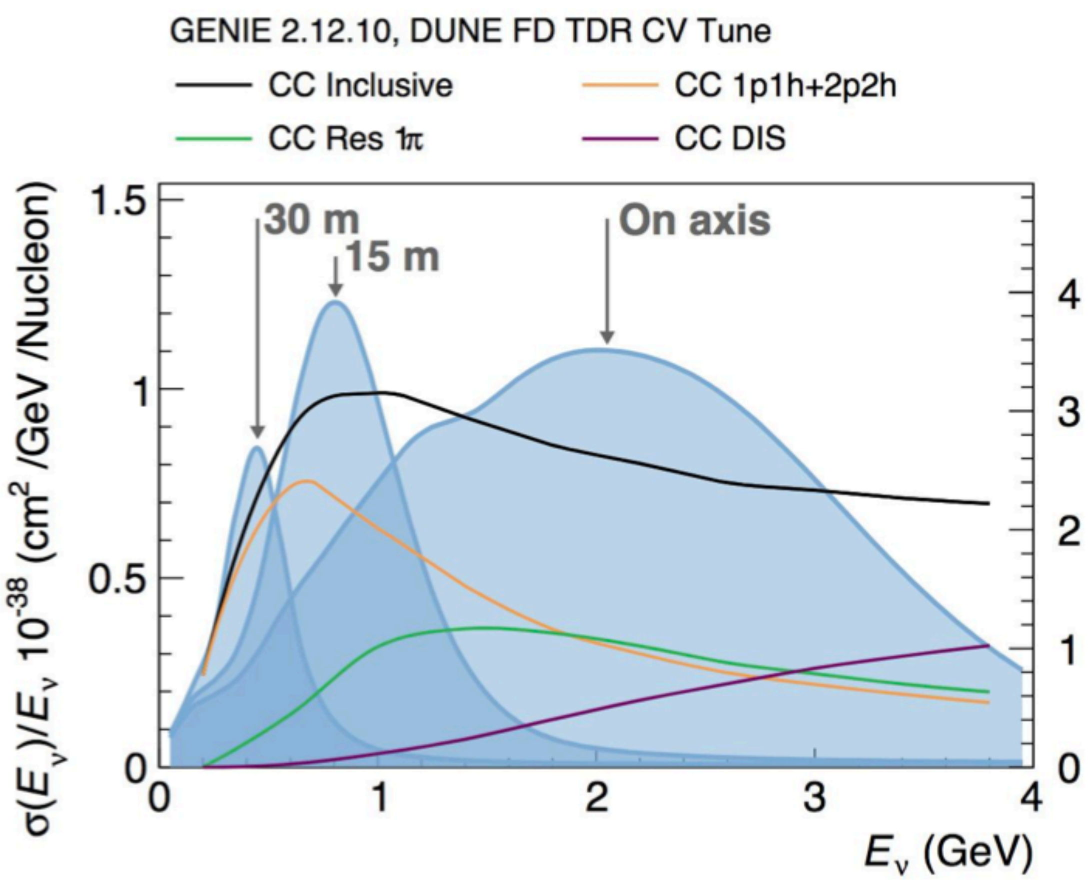
$$\frac{N_{\rm near}}{N_{\rm far}} = \frac{\int dE_\nu \Phi_{\rm near}(E_\nu)\sigma(E_\nu)}{\int dE_\nu \Phi_{\rm far}(E_\nu)\sigma(E_\nu)}$$

Cross-section



Experimentally measured event rates

Far-detector flux (depends on oscillation parameters)



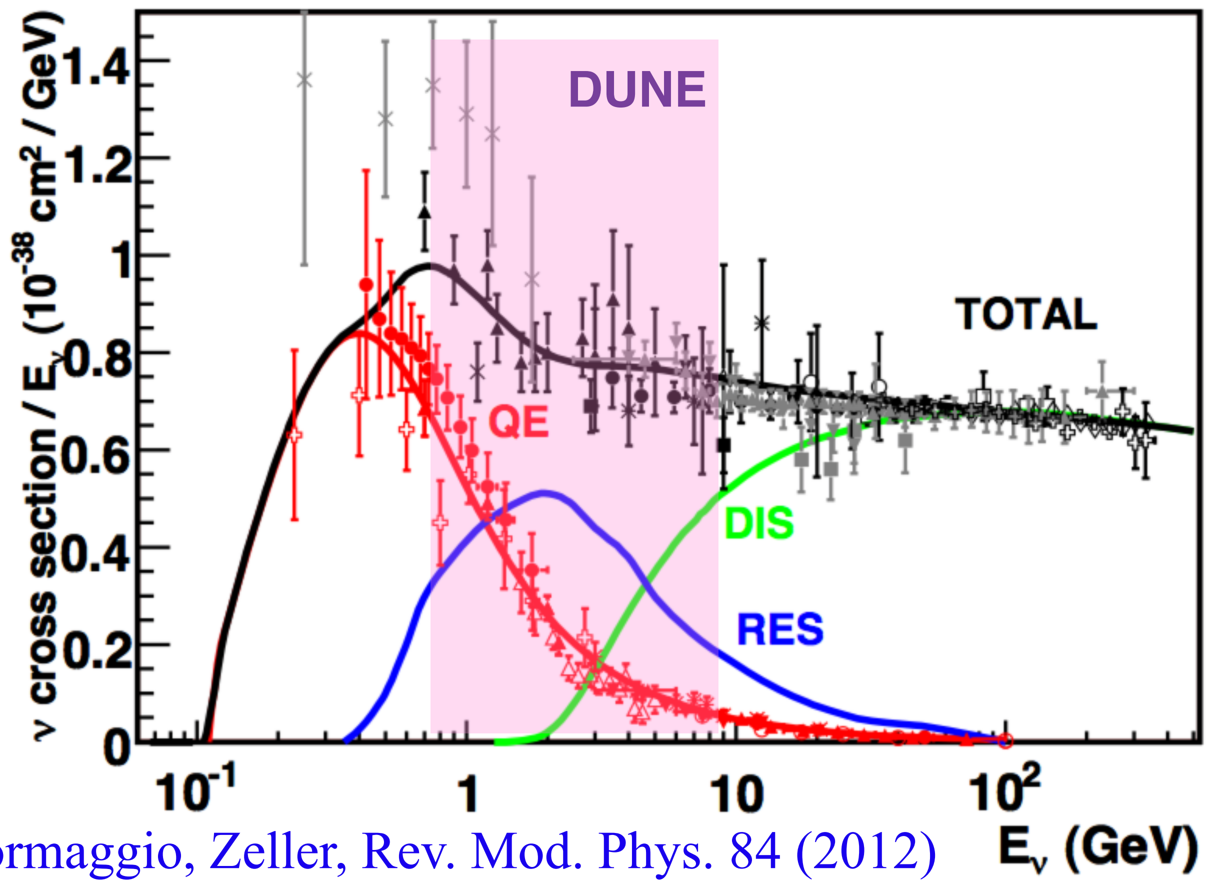
DUNE near detector CDR, arXiv:2013.13910

The DUNE near detector and especially PRISM design will provide a wealth of data for informing cross-section models

Theory input and models will also be essential:

- **BSM searches** require Standard Model predictions or else new physics will be absorbed into near detector x-sec tunes
- Neutrino energies are not directly measured, **energy reconstruction** requires a theoretical cross-section model

Neutrino-nucleus scattering



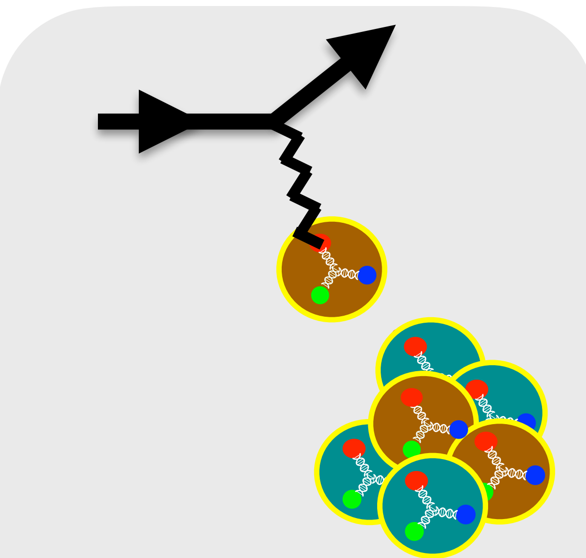
Formaggio, Zeller, Rev. Mod. Phys. 84 (2012)

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

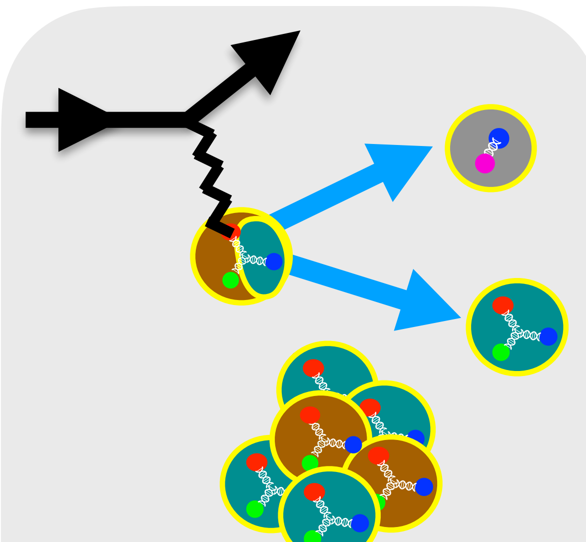
- Quasi-elastic nucleon scattering
- Resonance production
- Deep inelastic scattering

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

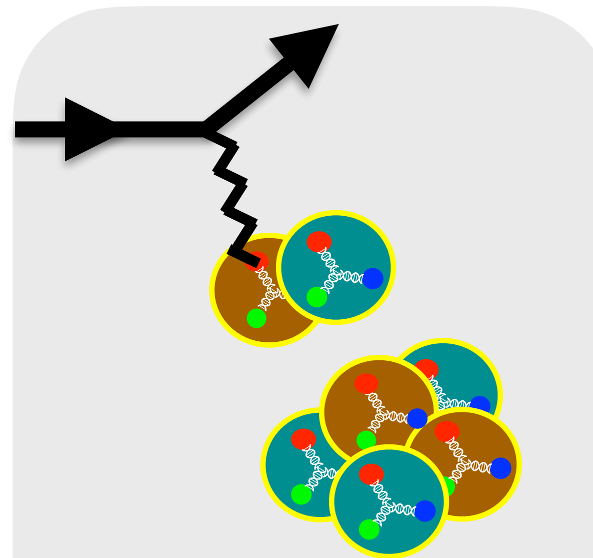
Effective theories for different energies require different inputs



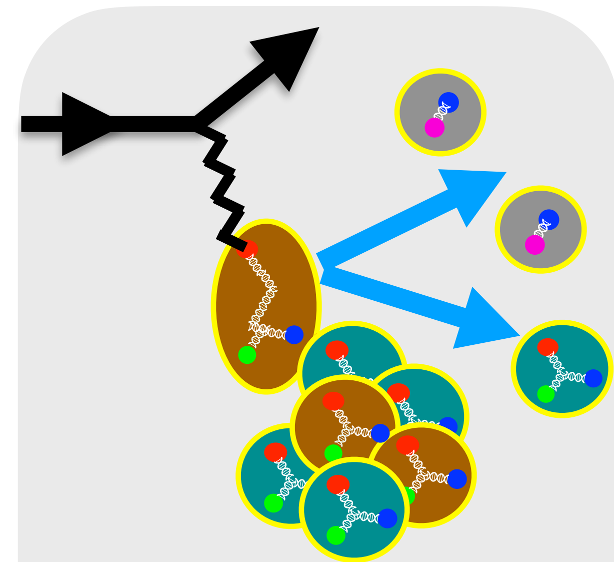
Nucleon form factors



Resonance production



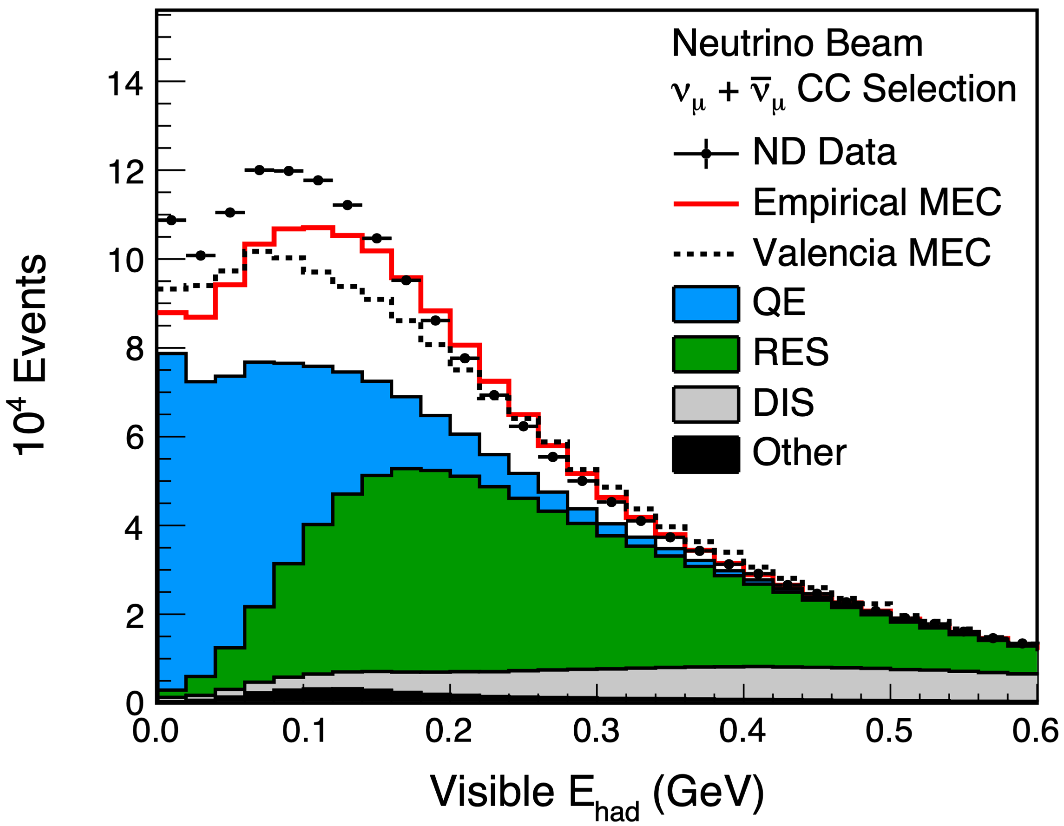
Two-body currents



Quark and gluon PDFs

Predicting νA cross-sections

Acero et al [NOvA] Eur. Phys. J. C 80 (2020)



Predictions for experimentally relevant nuclei made using **event generators** combining models for different reaction mechanisms

Snowmass WP: Campell et al, arXiv:2203.11110

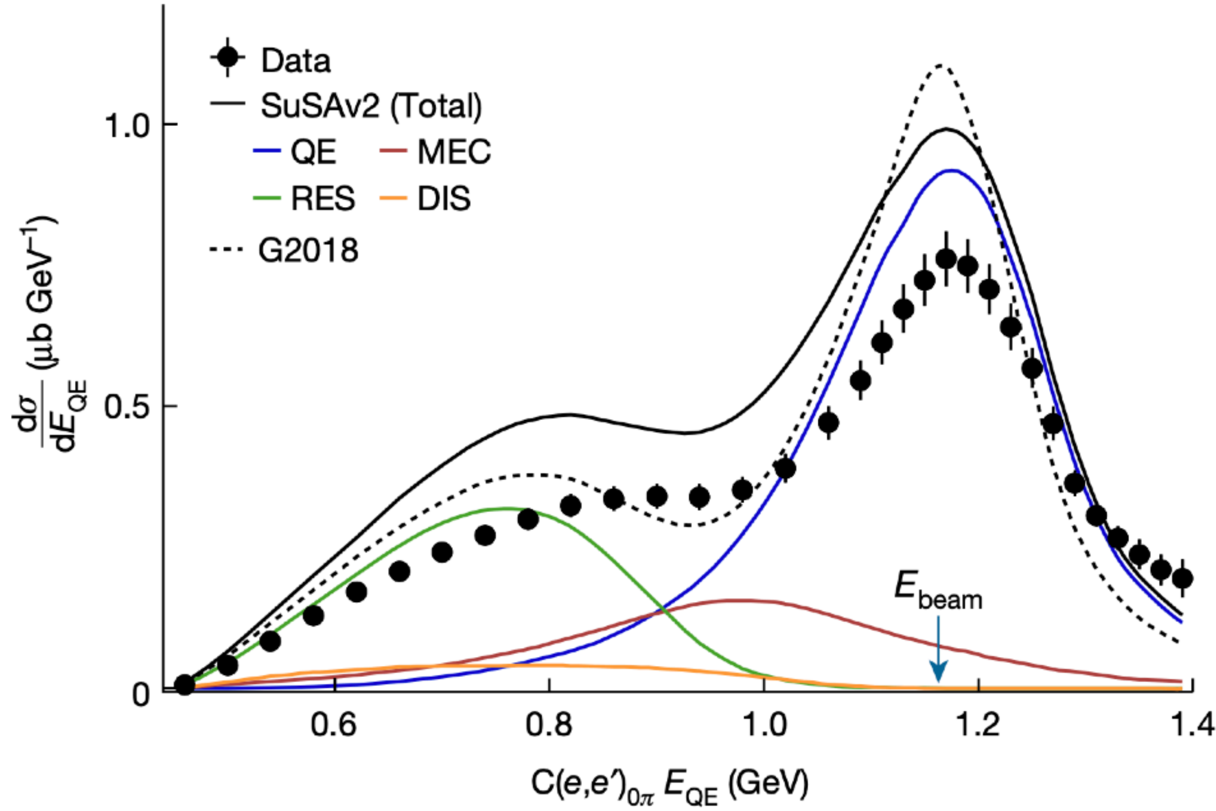
Discrepancies between generators and data often corrected by tuning an empirical model of the least well known mechanism: MEC ("meson exchange"/two-body currents)

Neutrino event generators can be validated by comparing predictions electron scattering with precise data

- Significant discrepancies presently visible
- **Tuning to reproduce one process does not mean other processes/energies will be accurately predicted**

More nice examples in talk by Kevin McFarland

- Contributions from different reaction mechanisms must be isolated



Khachatryan et al [Clas and e4v] Nature 599 (2021)

Reaction mechanisms

Process	Neutrino Energy Range	Example Final State
Coherent Elastic Scattering	$\lesssim 50$ MeV	$\nu + A$
Inelastic Scattering	$\lesssim 100$ MeV	$e + {}^{A}(Z+1)^{*}(\rightarrow {}^{A}(Z+1) + n\gamma)$
Quasi-Elastic Scattering	100 MeV–1 GeV	$l + p + X$
Two-Nucleon Emission	1 GeV	$l + 2N + X$
Resonance Production	1–3 GeV	$l + \Delta(\rightarrow N + \pi) + X$
Shallow Inelastic Scattering	3–5 GeV	$l + n\pi + X$
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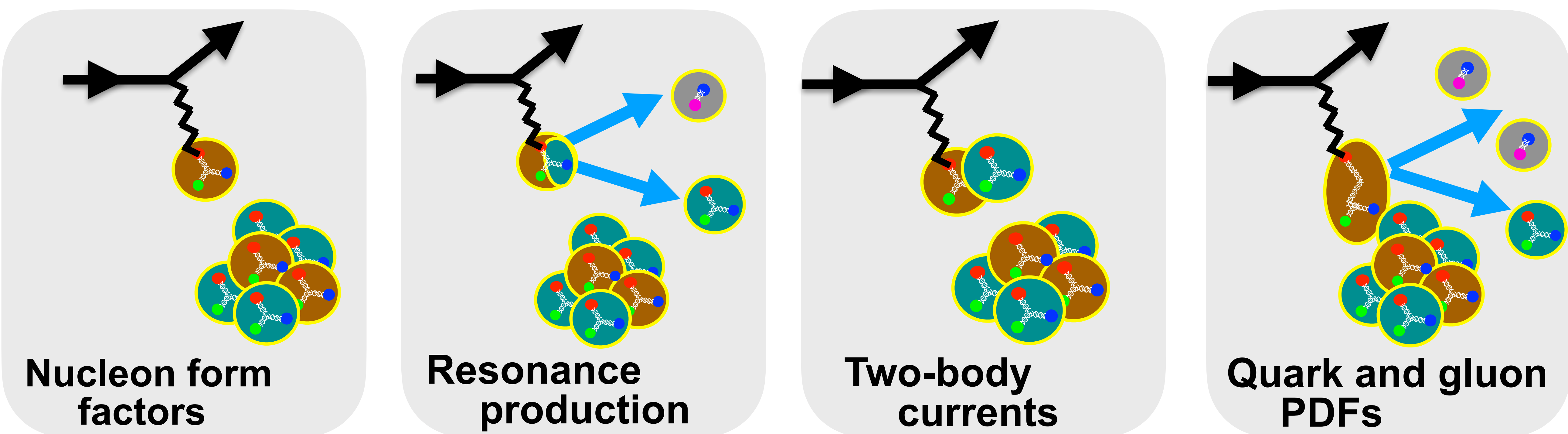

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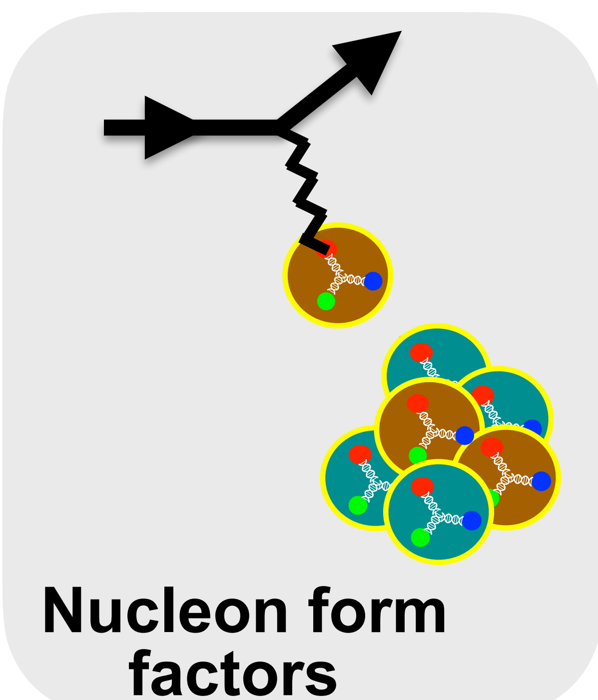
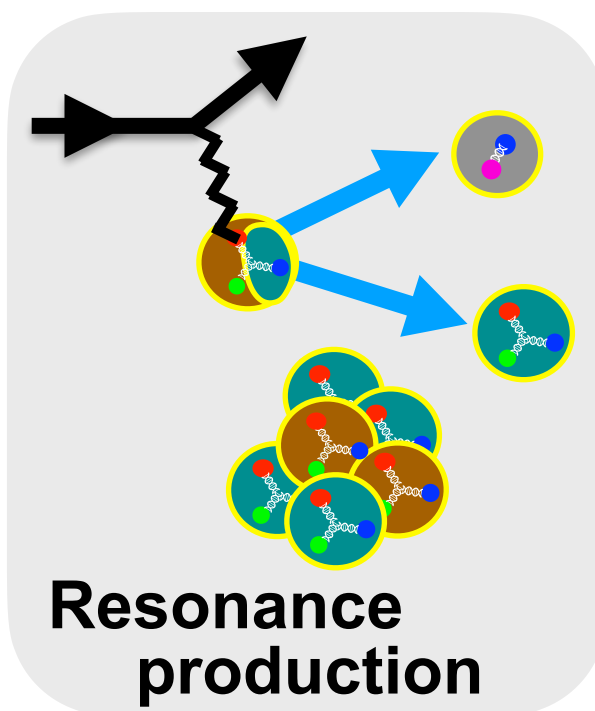
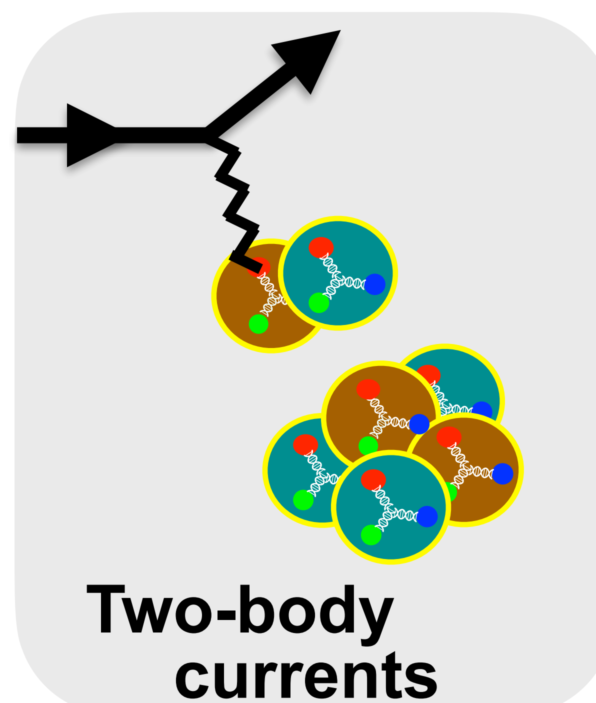
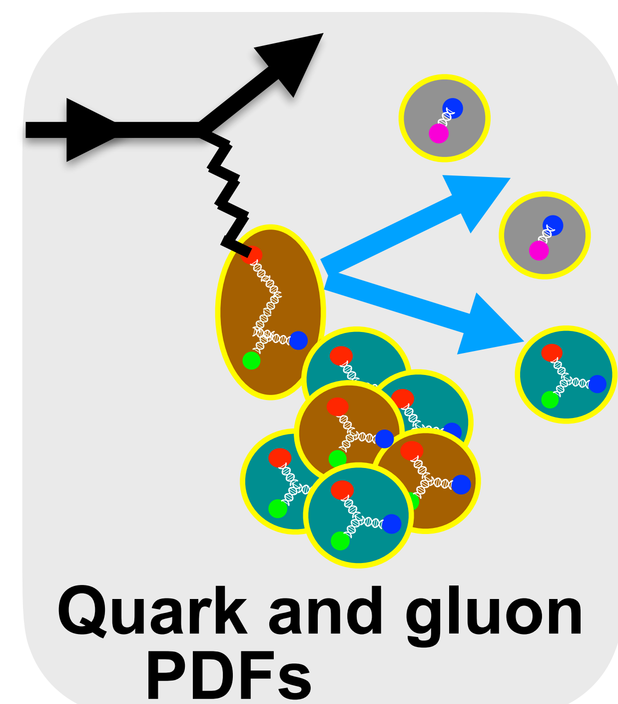








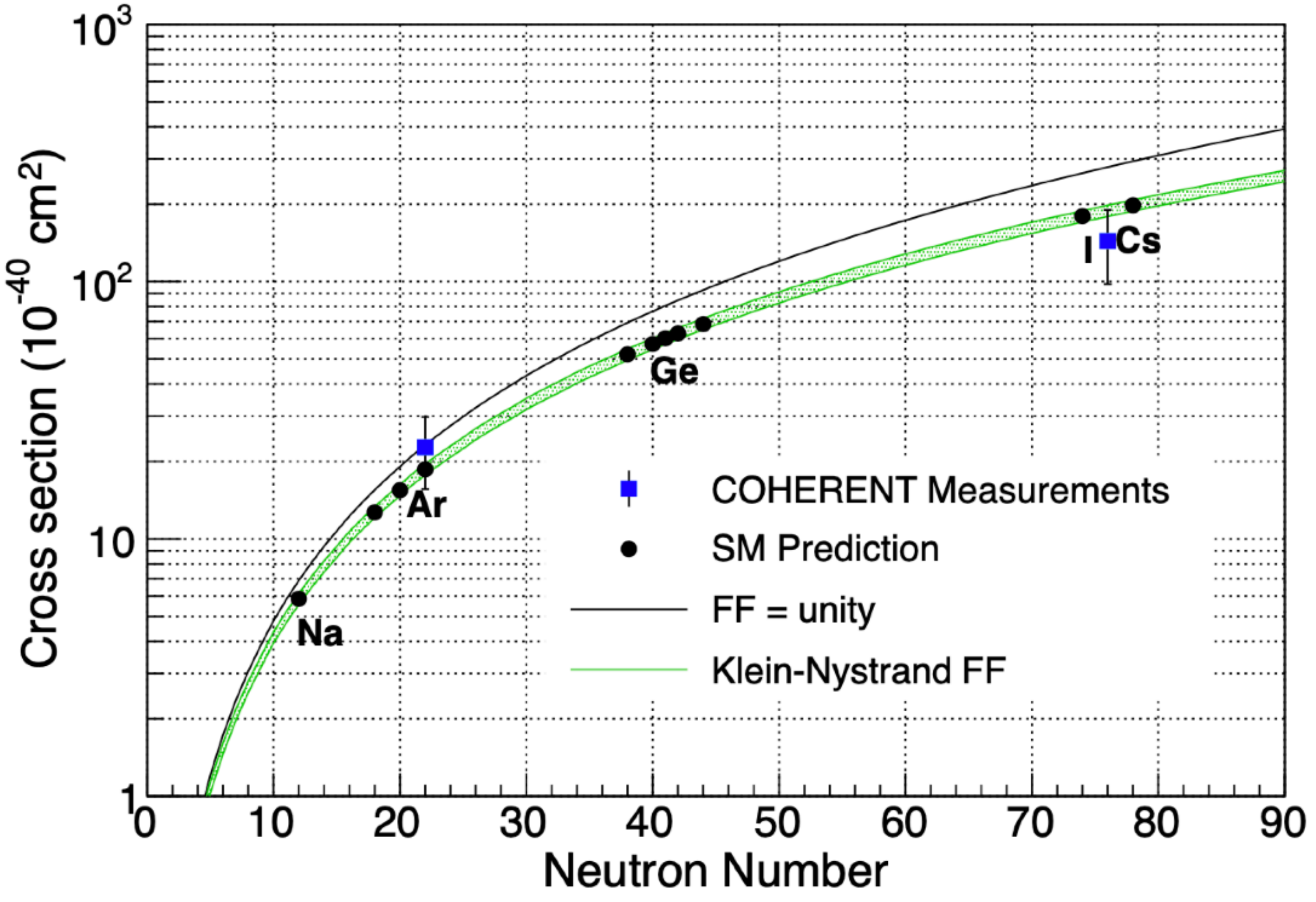
Coherent scattering

Coherent elastic neutrino-nucleus scattering (CEvNS) was first observed in 2017, now measured for cesium-iodide and argon

Ongoing efforts to improve precision of experiment and theory

Snowmass WP: Abdullah et al, arXiv:2203.07361

CEvNS cross-sections sensitive to neutron distributions that are not well constrained by electron scattering or other experiments



Comparison of CEvNS theory & experiment:

- Learn about nuclear structure probed by neutrinos (useful for e.g. argon)
- Search for BSM physics

Nuclear interactions

Standard Model effects must be reliably understood to search for new physics

Nuclei are made of quarks and gluons — but nucleons are effective degrees of freedom for quantum many-body calculations

Phenomenological hierarchy of multi-nucleon interactions: NN >> 3N >> 4N… forms the basis for nuclear effective theories

$$H = \sum_i K_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

Nucleon kinetic energy **NN potential** **3N potential**

Finding an EFT power counting for 2+ nucleon systems that preserves renormalizability order-by-order is challenging

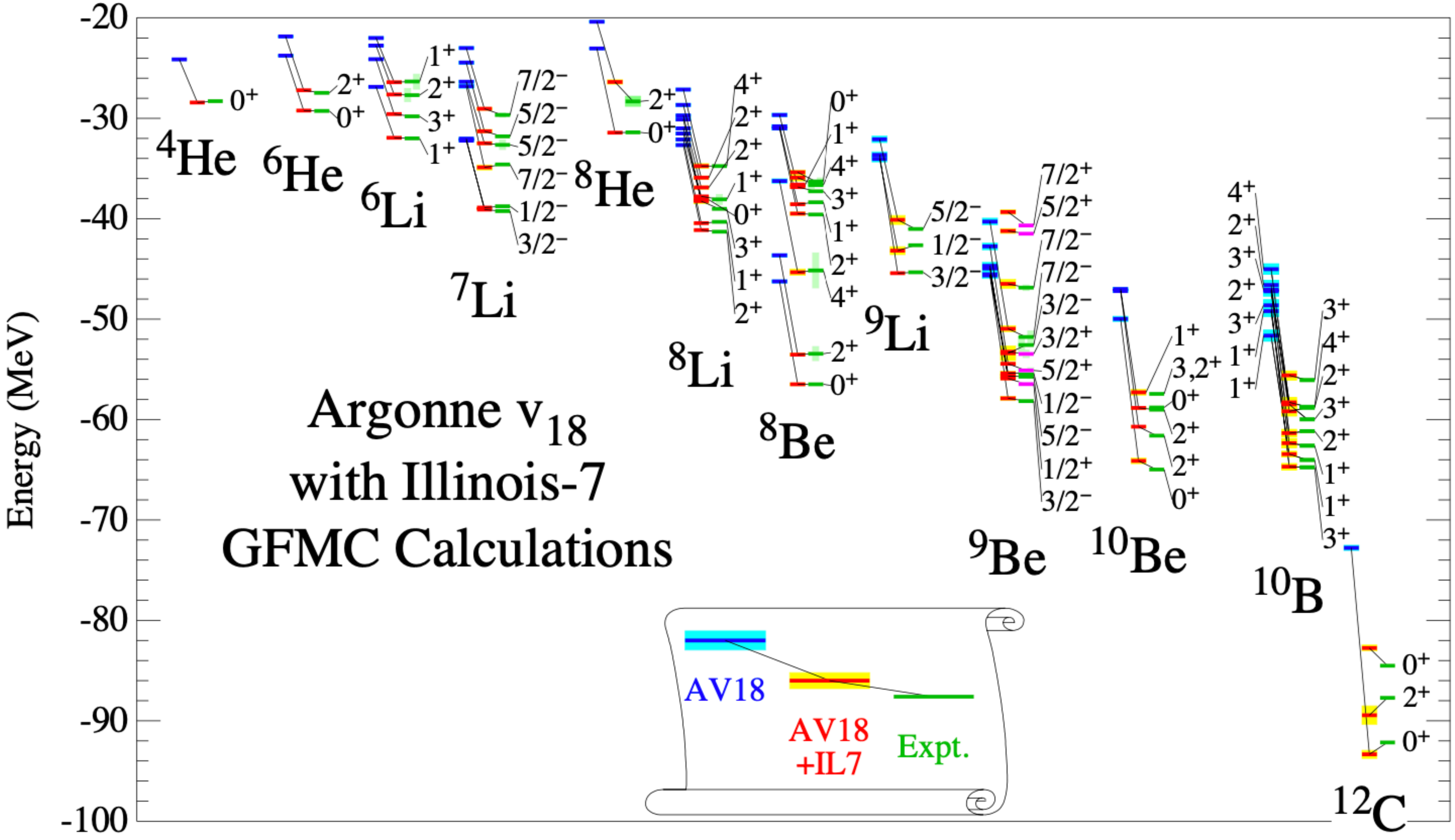
Kaplan, Savage, and Wise, Nucl. Phys. B478 (1996); Nogga, Timmermans, and van Kolck, PRC 72 (2005); …

Review: van Kolck, Front. in Phys. 8 (2020)

Nuclear effective theories

Nuclear effective theories can accurately describe light nuclei, up to $^{12}\mathrm{C}$ with Quantum Monte Carlo many-body methods and microscopic interactions:

- Phenomenological potentials such as AV18 + Illinois-7
- Chiral EFT with Weinberg power counting scheme

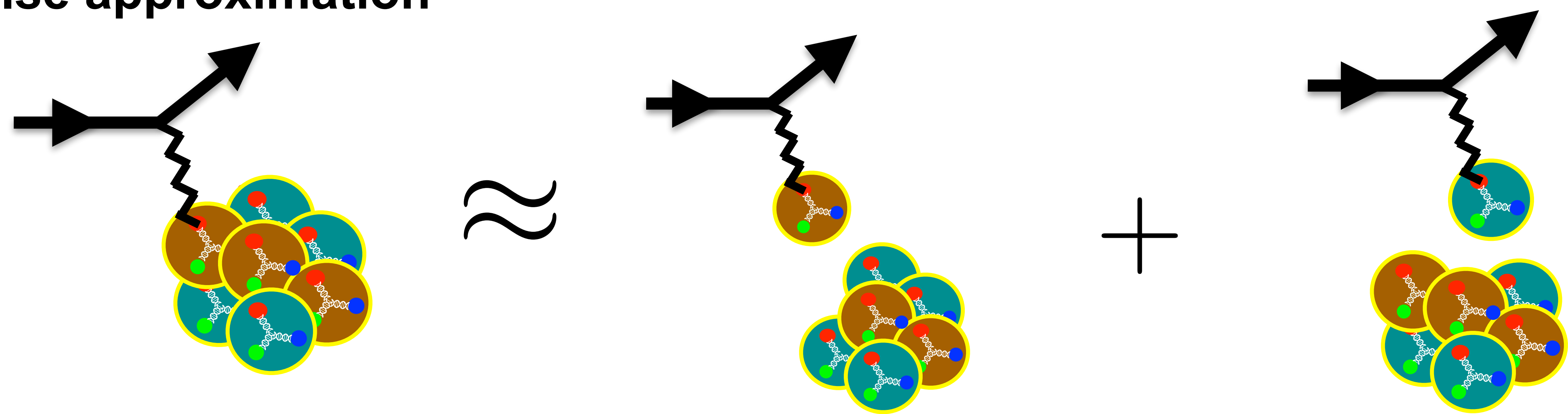


Carlson, Gandolfi, Pederiva, Pieper, Schiavilla, Schmidt, and Wiringa, Rev. Mod. Phys. 87 (2015)

Effective nuclear interactions

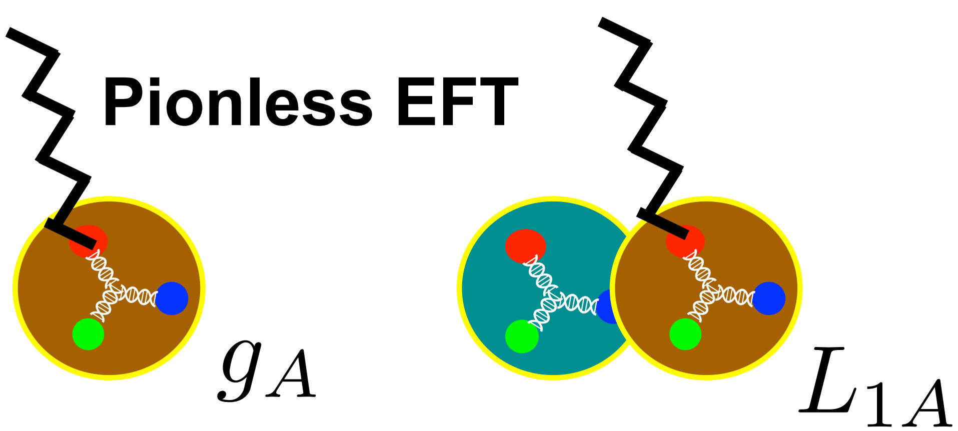
Single-nucleon currents dominate at low energies and can be used to predict nuclear response functions in EFTs of light nuclei, shell models of larger nuclei, …

Impulse approximation

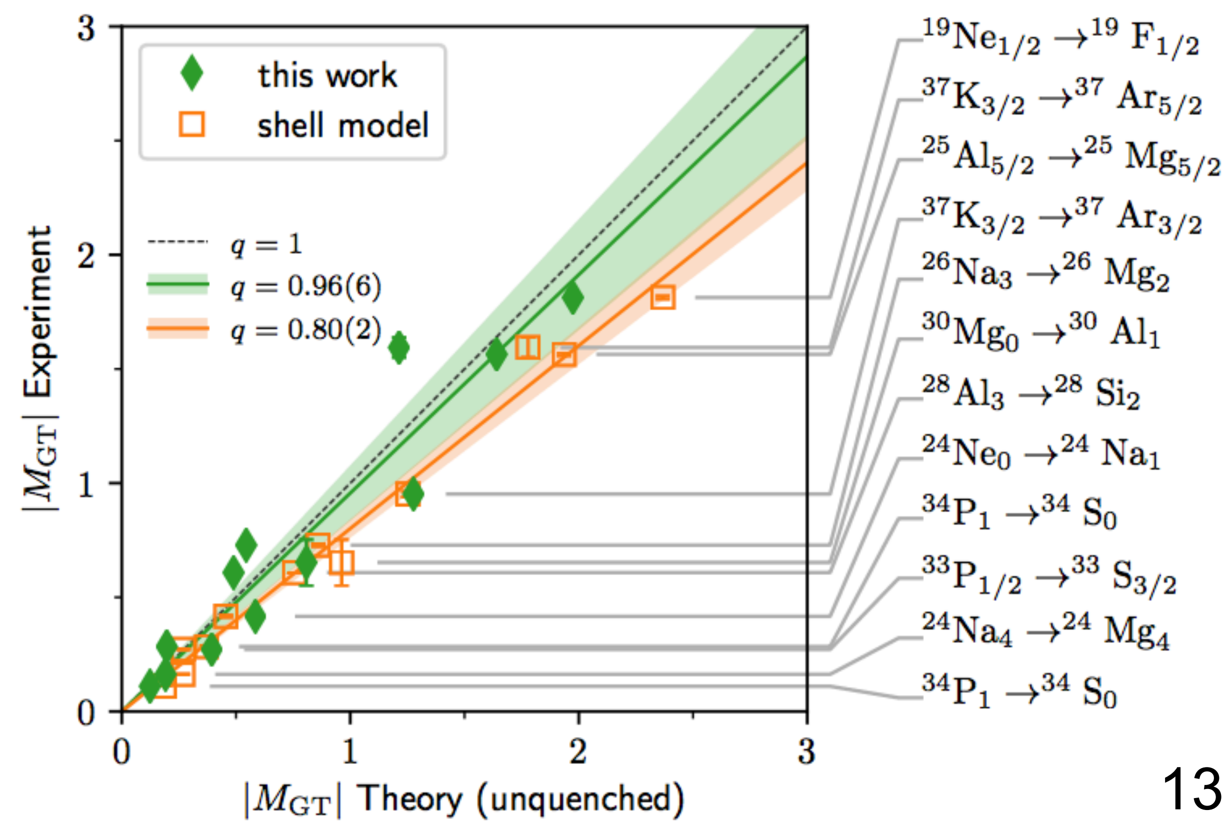


Nucleon vector and axial form factors are key inputs to nuclear EFTs / models

Two-body currents and correlations lead to significant corrections in medium-mass nuclei, 30% decrease in beta-decay rates



Gysbers et al, Nature Phys. 15 (2019)



From quarks to nuclei

To reliably search for BSM physics, we need to understand the Standard Model and how it is modified by BSM interactions

Quark level weak interactions (below electroweak scale)

$$\mathcal{L}^{\mathrm{SM}} = -\sqrt{2}G_F \sum_{q=u,d,s} \left(C_q^V \bar{\nu}\gamma^\mu P_L \nu\, \bar{q}\gamma_\mu q + C_q^A \bar{\nu}\gamma^\mu P_L \nu\, \bar{q}\gamma_\mu \gamma_5 q \right)$$

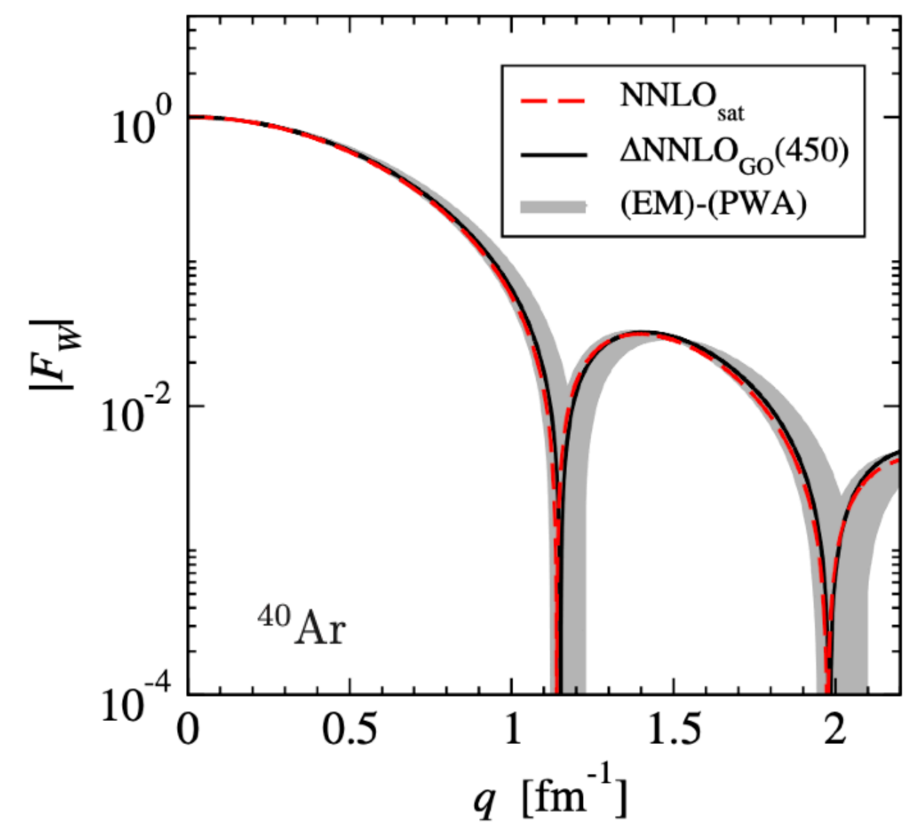
Nuclear level CEvNS

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) Q_{\mathrm{w}}^2 \left[F_{\mathrm{w}}(q^2)\right]^2$$

Nuclear weak charge and form factor

- Complicated linear combination of single-nucleon form factors integrated over distribution of nucleons in nucleus

Coupled-cluster calculation of weak form factor



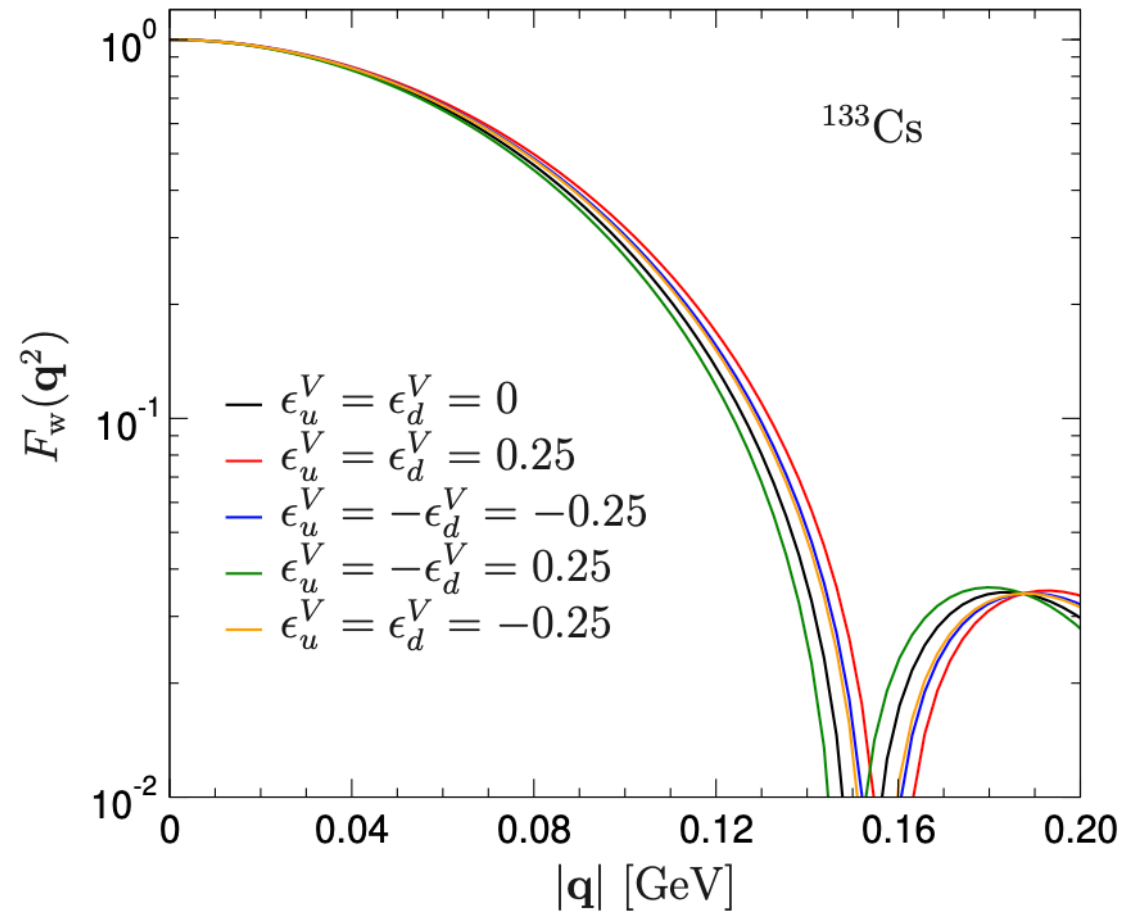
Payne, Bacca, Hagen, Jiang, and Papenbrock, PRC 100 (2019)

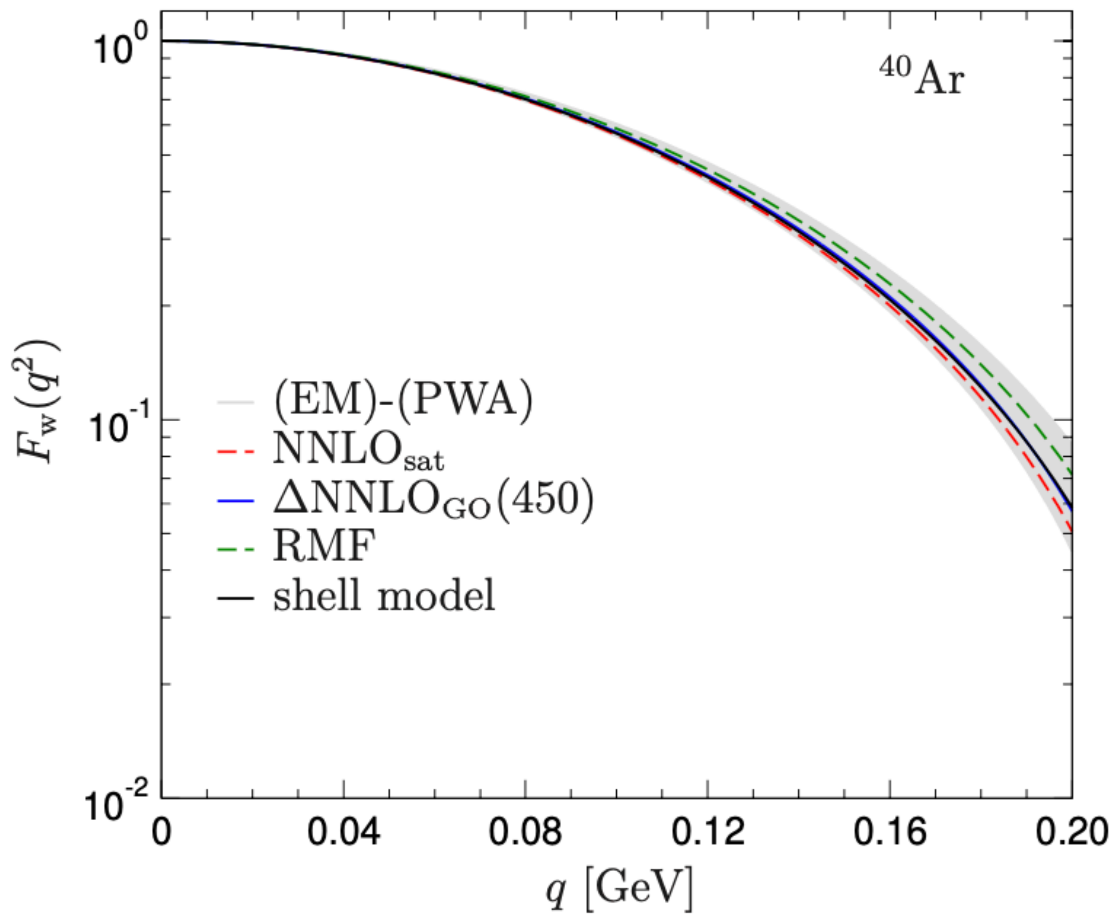
CEvNS and new physics

New physics contributions to CEvNS can be described as modifications to SM four-fermion Wilson coefficients or appearance of new operators

Nuclear and BSM physics does not simply factorize — shape of weak form factor modified by BSM contributions to four-fermion Wilson coefficients

Hofreichter, Meńendez, and Schwenk, PRD 102 (2020)





Robust understanding of nuclear weak form factors at the 10% level essential for disentangling BSM and nuclear effects in CEvNS

Reaction mechanisms

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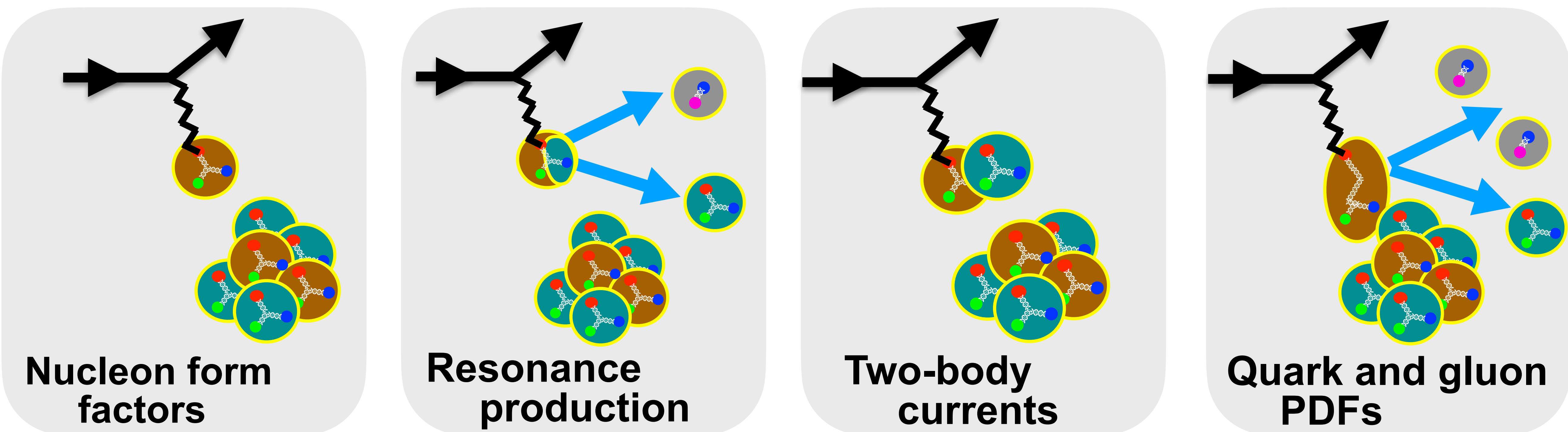
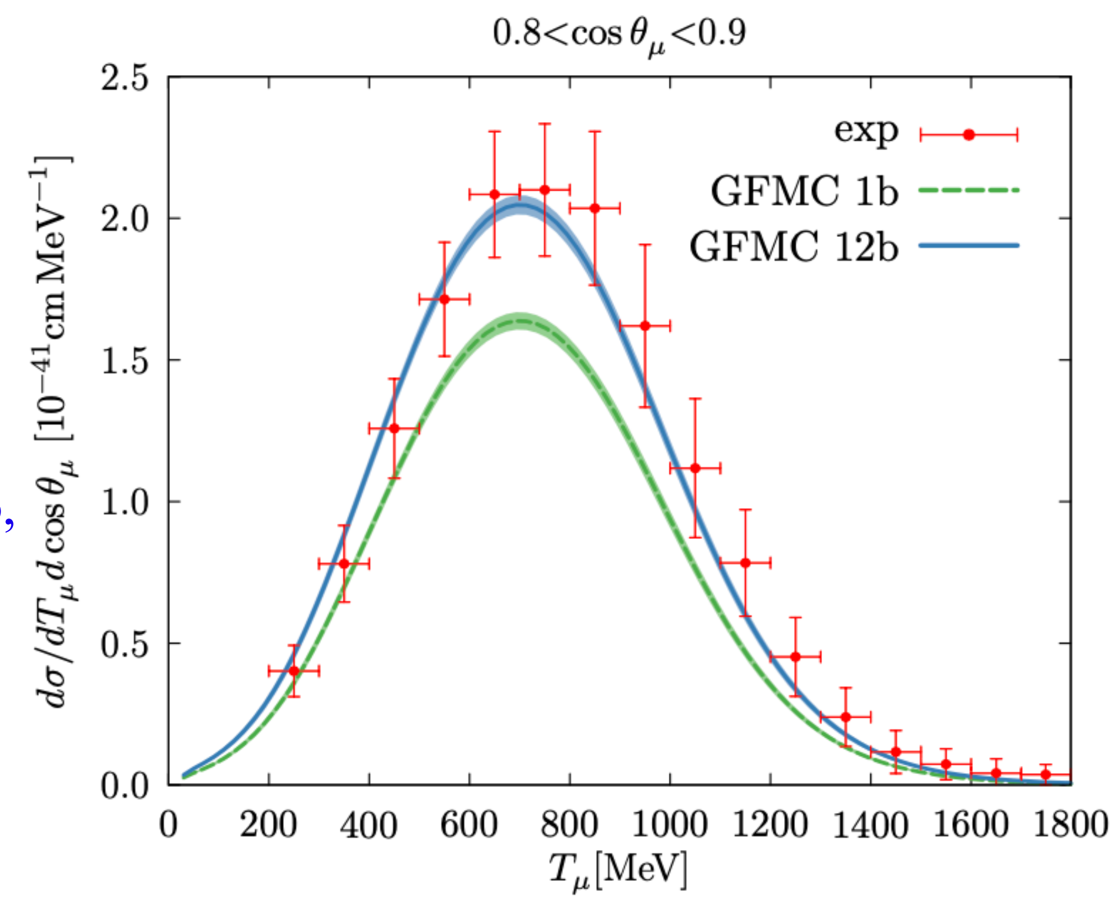


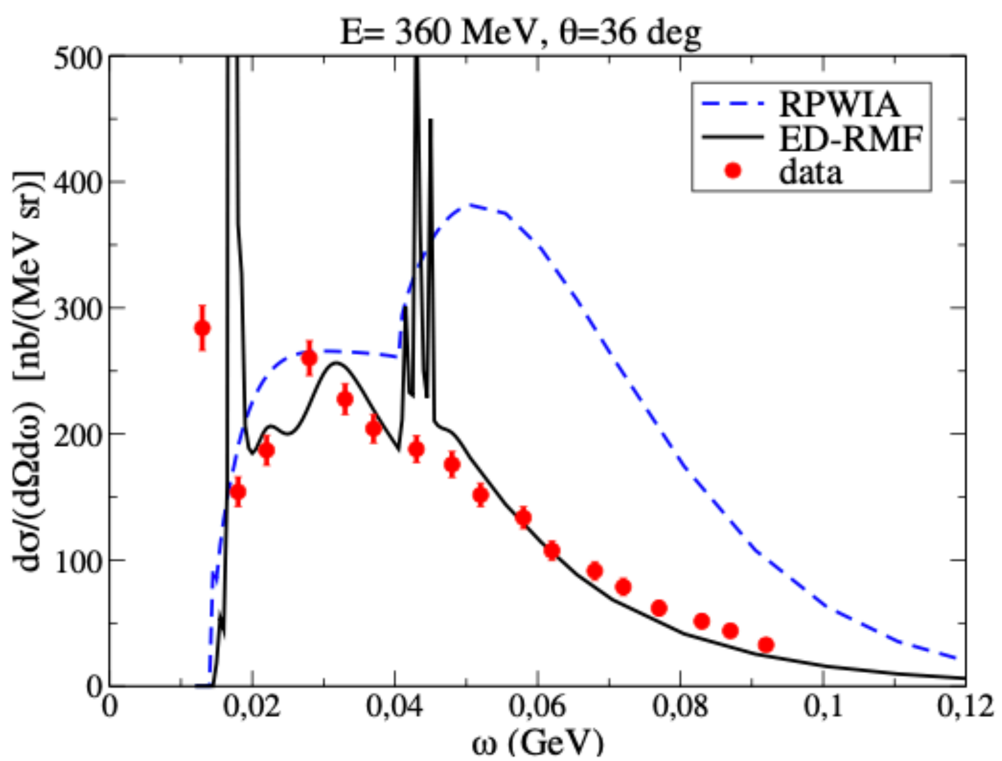
From MeV to GeV

Quasi-elastic scattering of neutrinos with a single (bound) nucleon is the dominant reaction mechanism for neutrino energies in the few hundred MeV range

Quantum Monte Carlo (GFMC) calculations can accurately describe quasi-elastic scattering for light nuclei, as well as two-body current effects present in the same energy range



Lovato, Carlson, Gandolfi, Rocco, and Schiavilla, PRX 10 (2020)

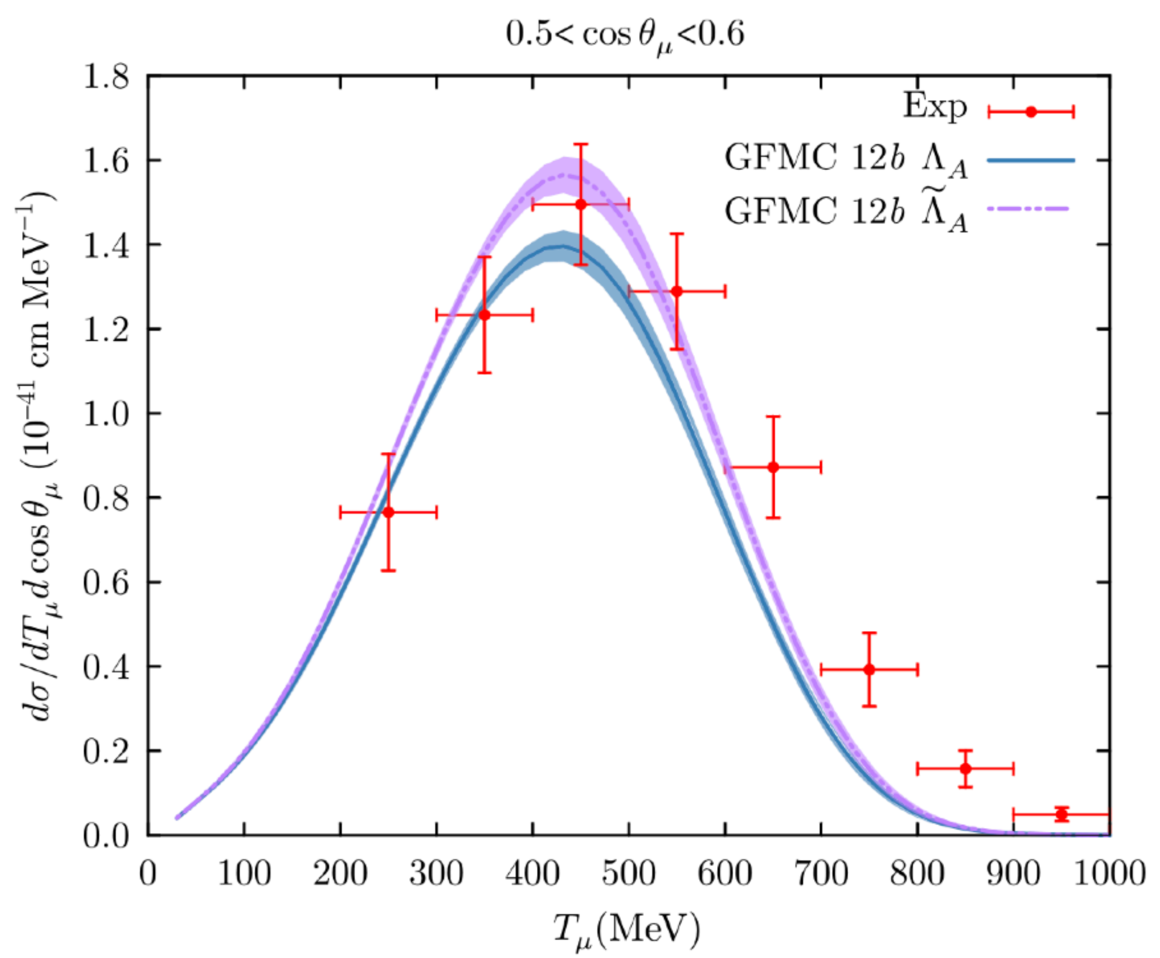


González-Jeménez, Nikolakopoulos, Jachowicz, and Udías, PRC 100 (2019)

Inelastic scattering involving low-energy nuclear excitations also contributes below ~100 MeV energies, described e.g. by mean-field + random phase approximation

Important energy range for interpreting supernovae neutrino signals at DUNE

Nuclear uncertainties



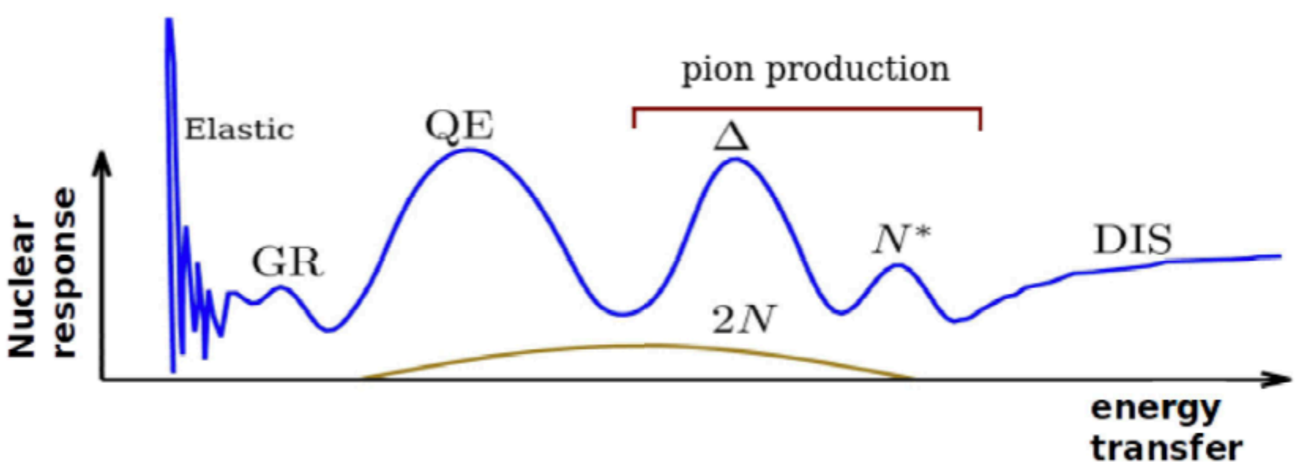
Lovato, Carlson, Gandolfi, Rocco, and Schiavilla, PRX 10 (2020)

Quasi-elastic cross-section is sensitive to nucleon axial form factors used as input

Dipole parameterization example: 15% change in axial dipole mass leads to similar change in quasi-elastic peak

Achieving few-percent cross-section uncertainties will require more precise knowledge of nucleon axial form factors

Describing the full intermediate energy regime will also require better constraints on two-body currents, resonance production, …



González-Jeménez, Nikolakopoulos, Jachowicz, and Udías, PRC 100 (2019)

Lattice QCD, EFT, and νA

LQCD can provide results for few-nucleon observables that can be matched to nuclear EFTs and models that can make predictions for larger nuclei

LQCD → Nuclear EFT and many-body → Event generators

Results provided by LQCD and experiment are complementary

Easy for LQCD:

- Axial vs vector currents
- Isovector vs isoscalar
- Pions

Hard for LQCD:

- Large baryon number
- Real-time dynamics
- Multi-hadron states
- (Light quark masses)

Lattice QCD and νA

νA scattering amplitudes factorize into leptonic and hadronic parts

$$\mathcal{M}_{\nu A \to \ell f} \propto (\overline{u}_\ell \gamma_\mu \gamma_5 u_\nu) \langle f | \, \overline{q} \gamma_\mu \gamma_5 q \, | A \rangle + \ldots$$

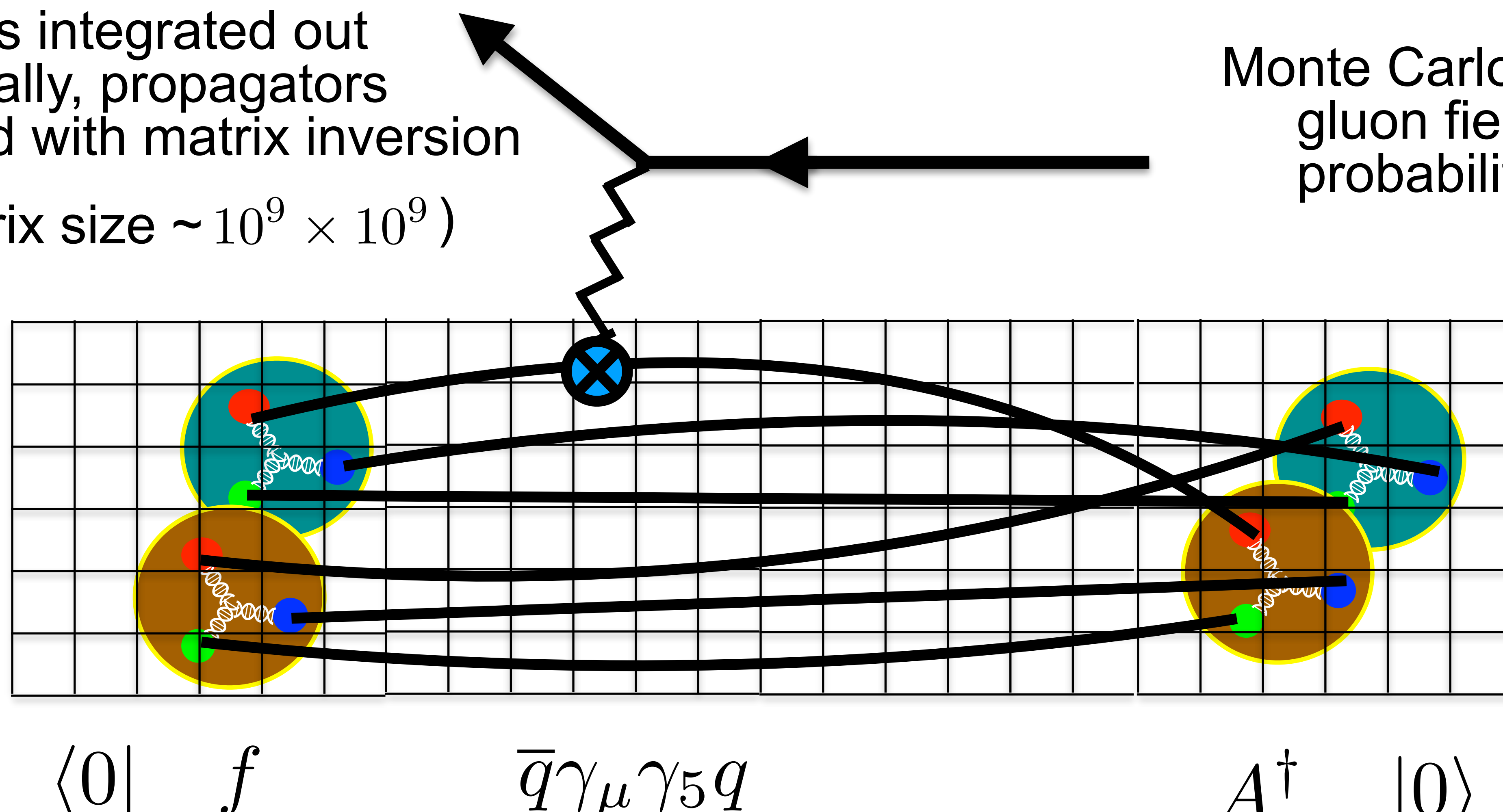
Generic Euclidean hadronic matrix elements calculable (in principle) using lattice QCD

$$\langle \mathcal{O} \rangle = \int \mathcal{D}U \mathcal{D}\overline{q} \mathcal{D}q \; e^{-S_{QCD}(U,q,\overline{q})} \; \mathcal{O}(U,q,\overline{q}) \approx \frac{1}{N_{\text{cfg}}} \sum_{i=1}^{N_{\text{cfg}}} \mathcal{O}(U_i)$$

Quark fields integrated out analytically, propagators obtained with matrix inversion

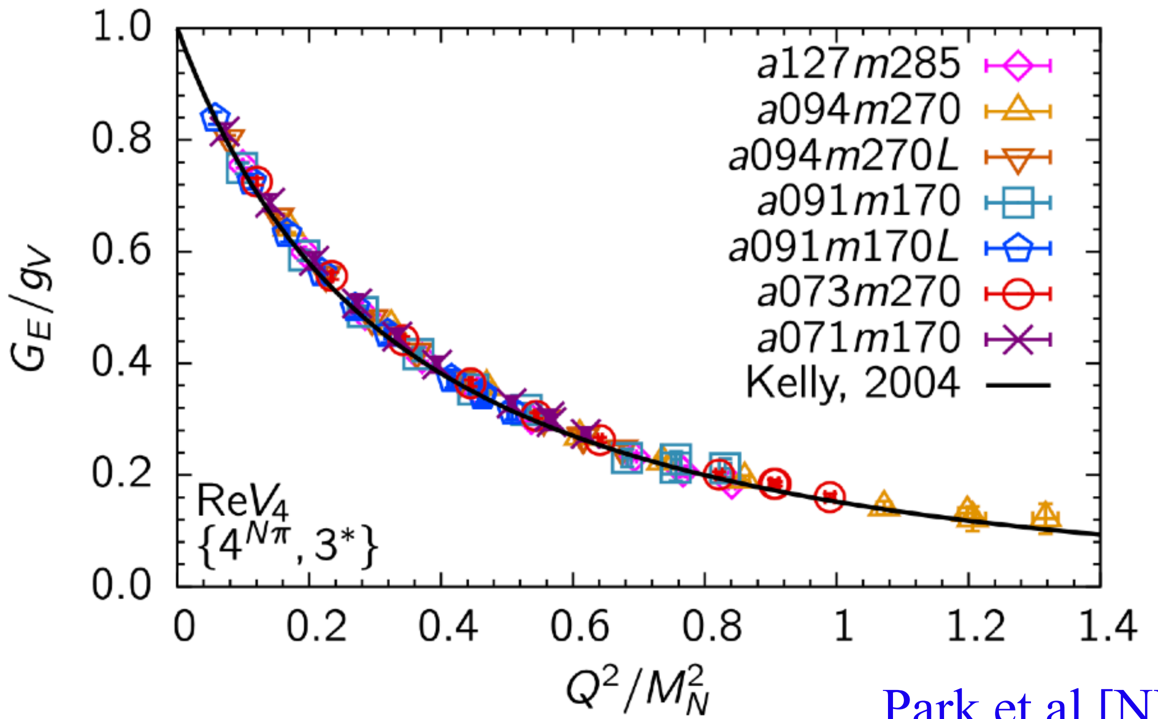
(Dirac matrix size ~ $10^9 \times 10^9$)

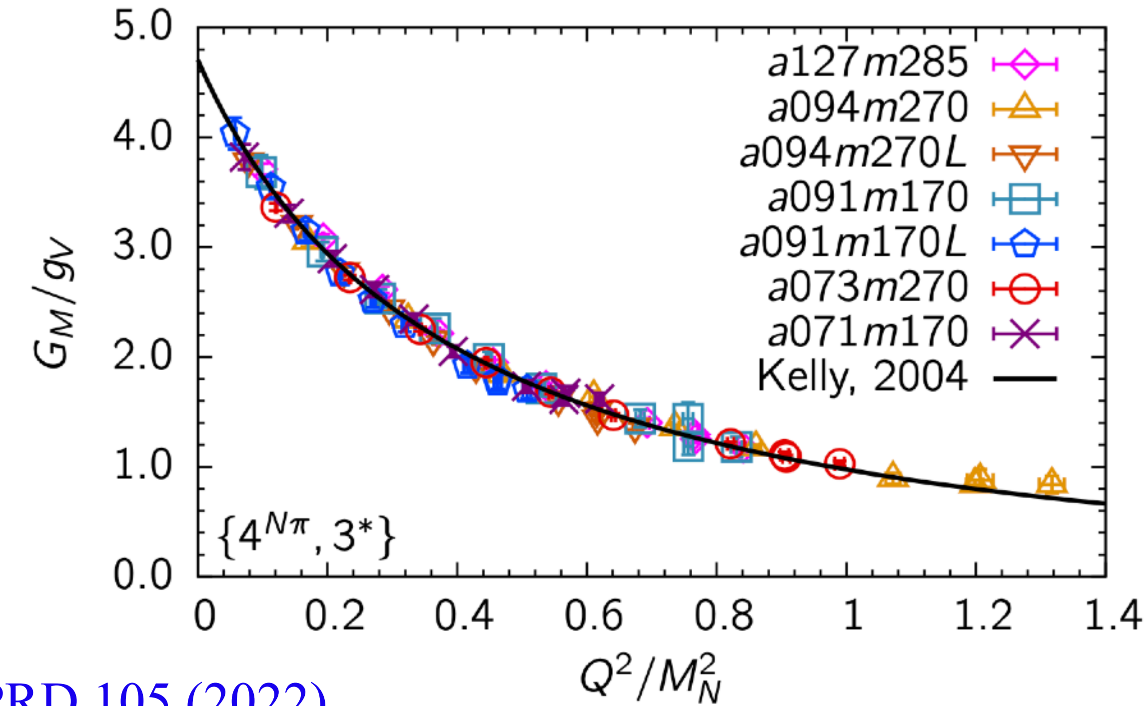
Monte Carlo sample gluon fields with probability $\propto e^{-S}$



Form factors and LQCD

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

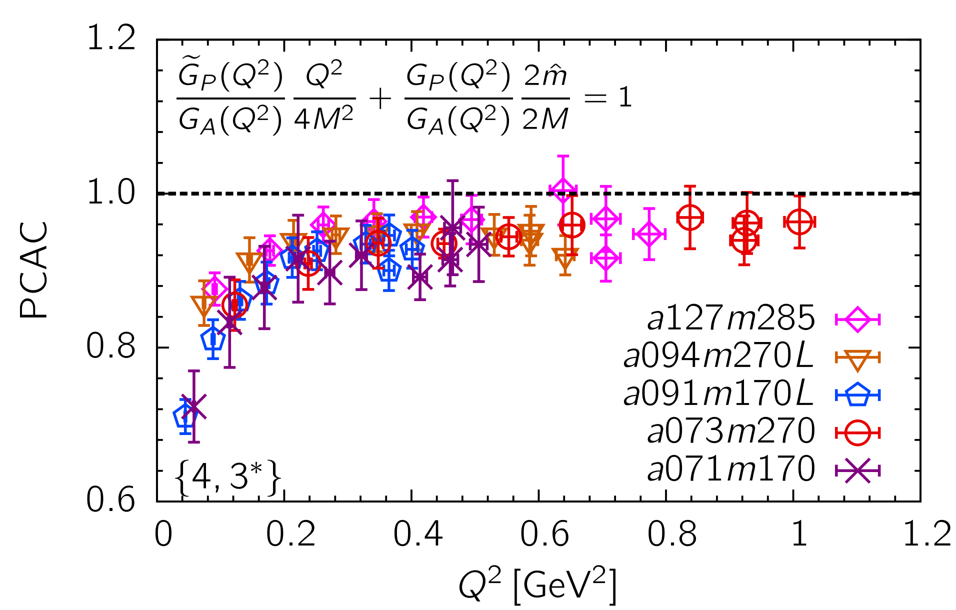


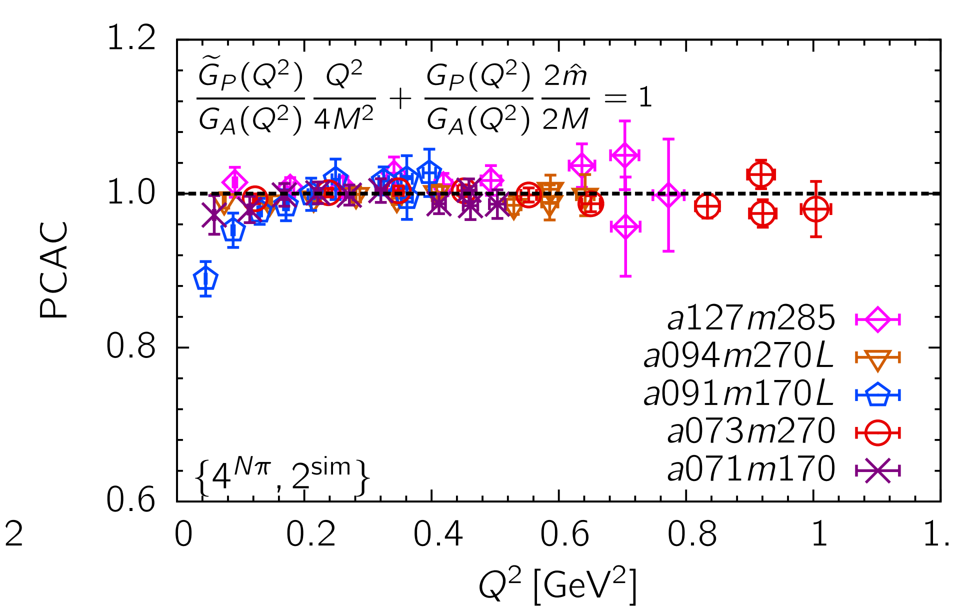


Park et al [NME], PRD 105 (2022)

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

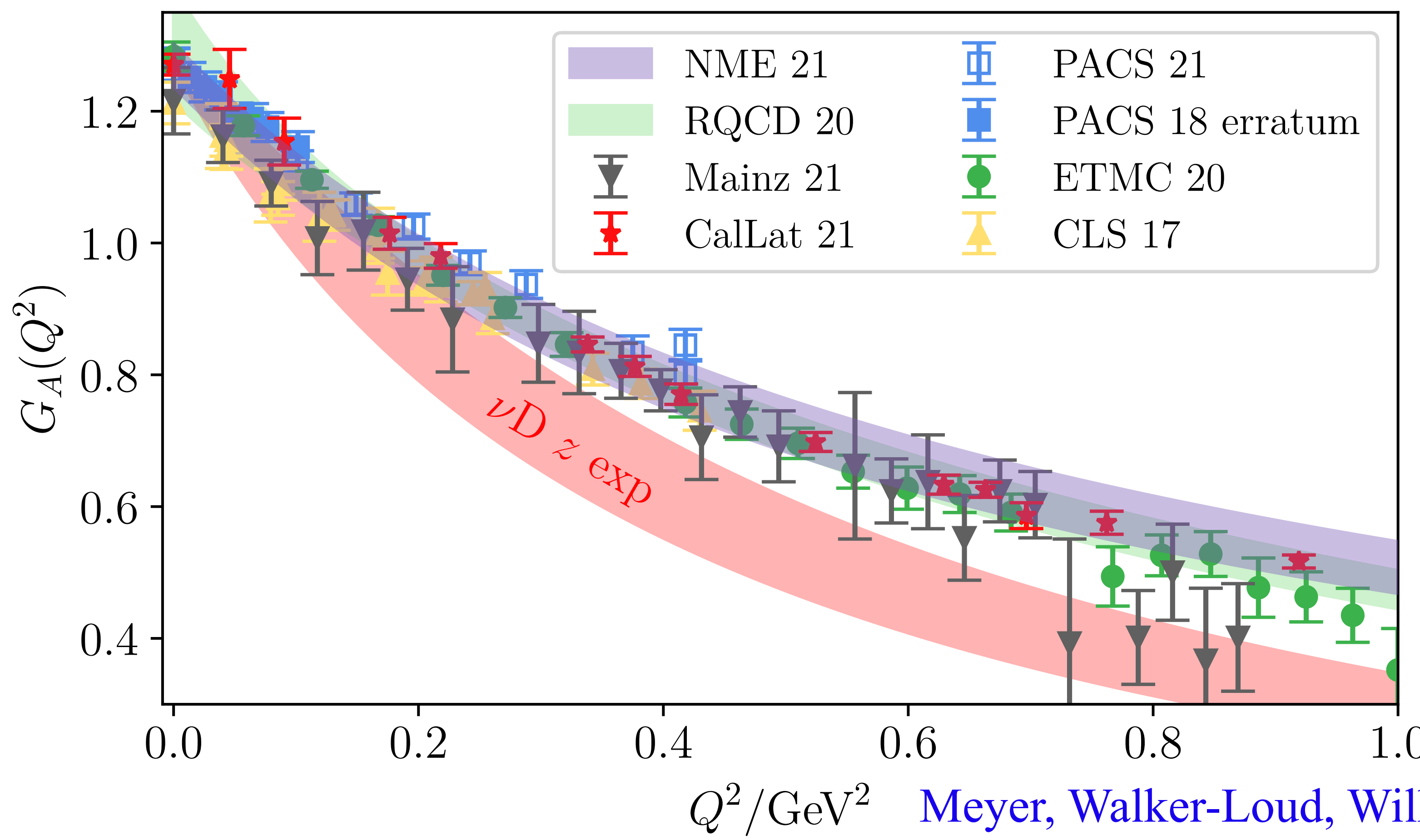




Park et al [NME], PRD 105 (2022)

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



Meyer, Walker-Loud, Wilkinson, arXiv:2201.01839

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

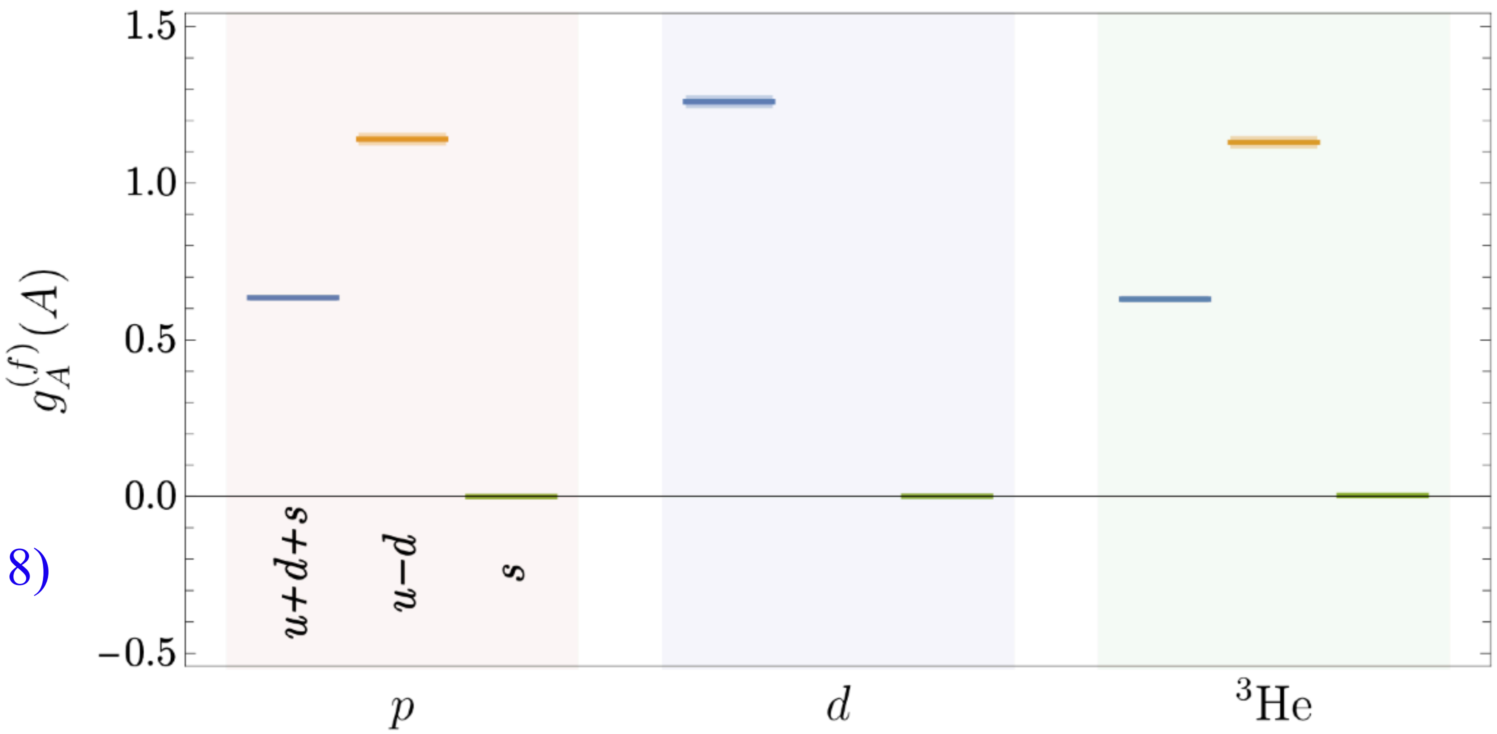
Differences could also arise from underestimated uncertainties in phenomenological form factor determinations using deuterium bubble chamber data

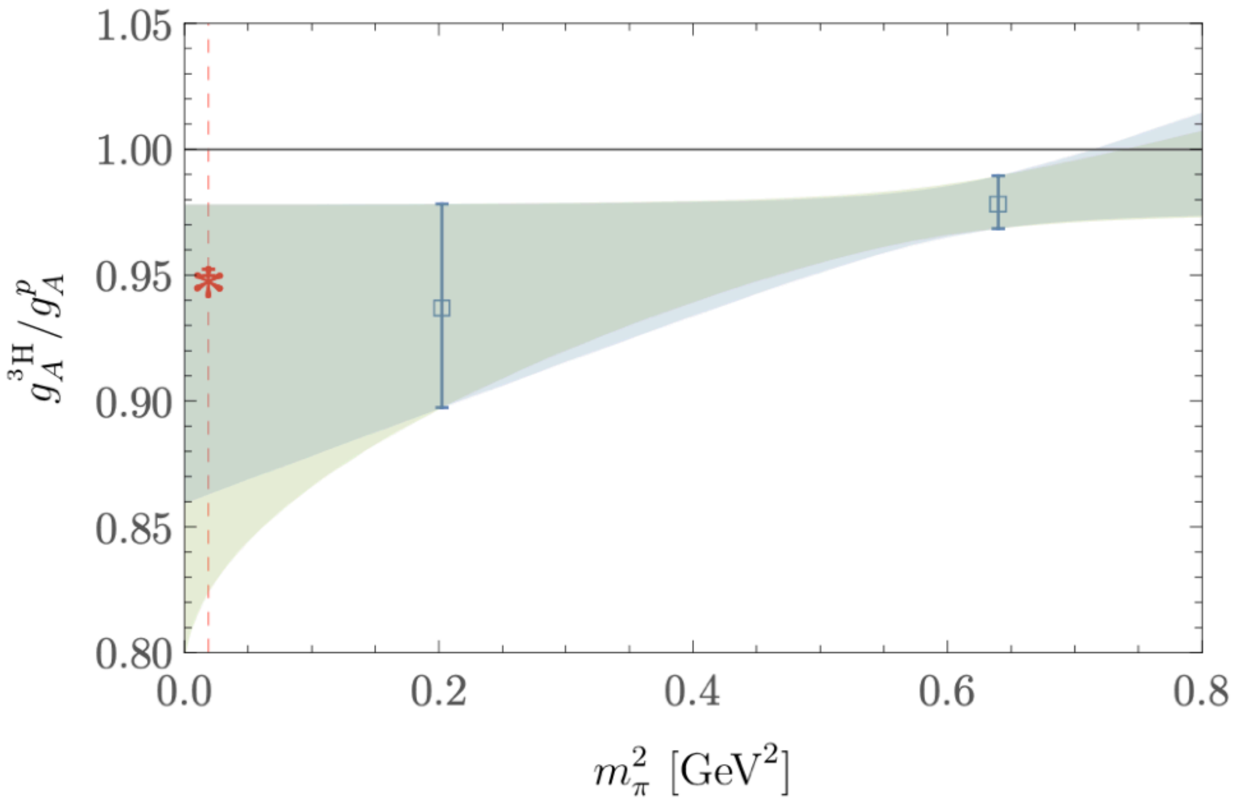
Meyer, Betancourt, Gran, and Hill, PRD 93 (2016)

Two-body currents in LQCD

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

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





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

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

Several systematic uncertainties remain, but encouraging agreement with experiment seen

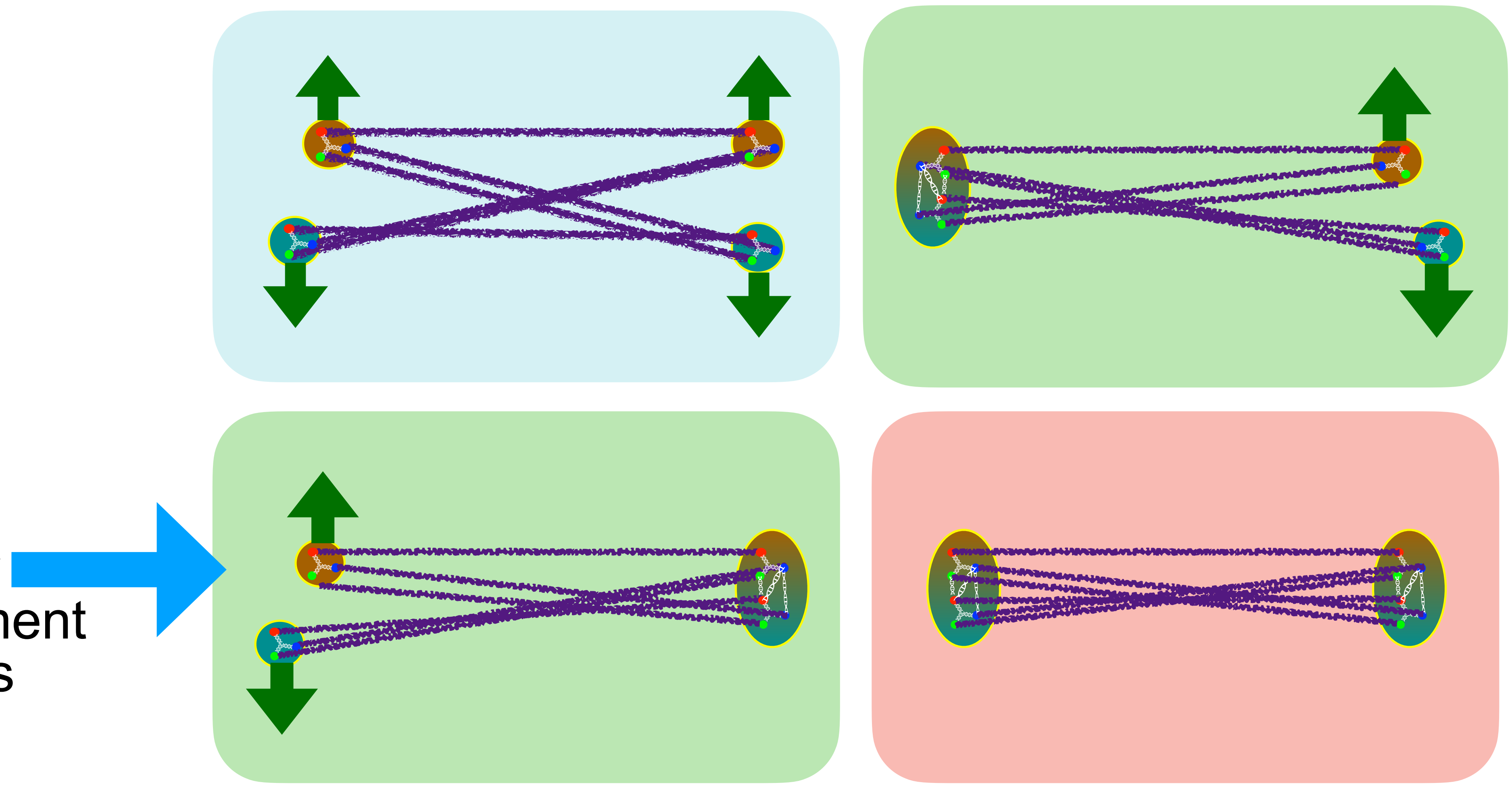
Matching to finite-volume pionless EFT used to constrain L_{1A}

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

LQCD nuclear matrix element calculations so far



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)

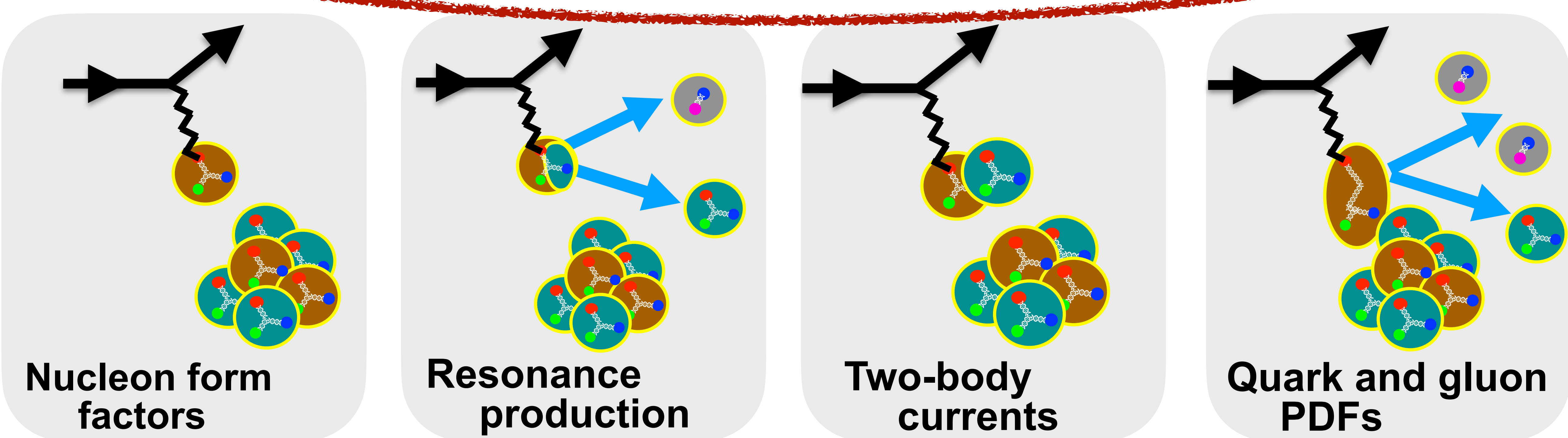
Green et al, PRL 127 (2021)

Hörz et al, PRC 103 (2021)

Amarasinghe, MW et al, arXiv:2108.10835

Reaction mechanisms

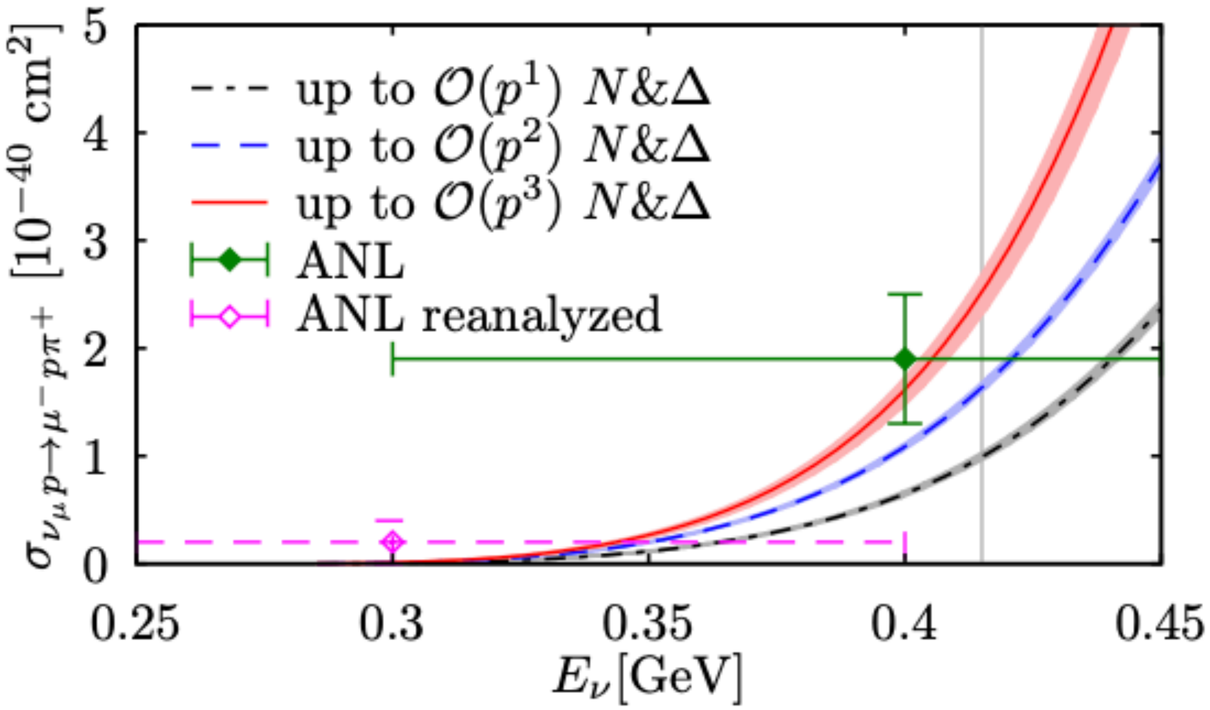
Process	Neutrino Energy Range	Example Final State
Coherent Elastic Scattering	$\lesssim 50$ MeV	$\nu + A$
Inelastic Scattering	$\lesssim 100$ MeV	$e + {}^{A}(Z+1)^{*}(\to {}^{A}(Z+1) + n\gamma)$
Quasi-Elastic Scattering	100 MeV–1 GeV	$l + p + X$
Two-Nucleon Emission	1 GeV	$l + 2N + X$
Resonance Production	1–3 GeV	$l + \Delta(\to N + \pi) + X$
Shallow Inelastic Scattering	3–5 GeV	$l + n\pi + X$
Deep Inelastic Scattering	$\gtrsim 5$ GeV	$l + n\pi + X$



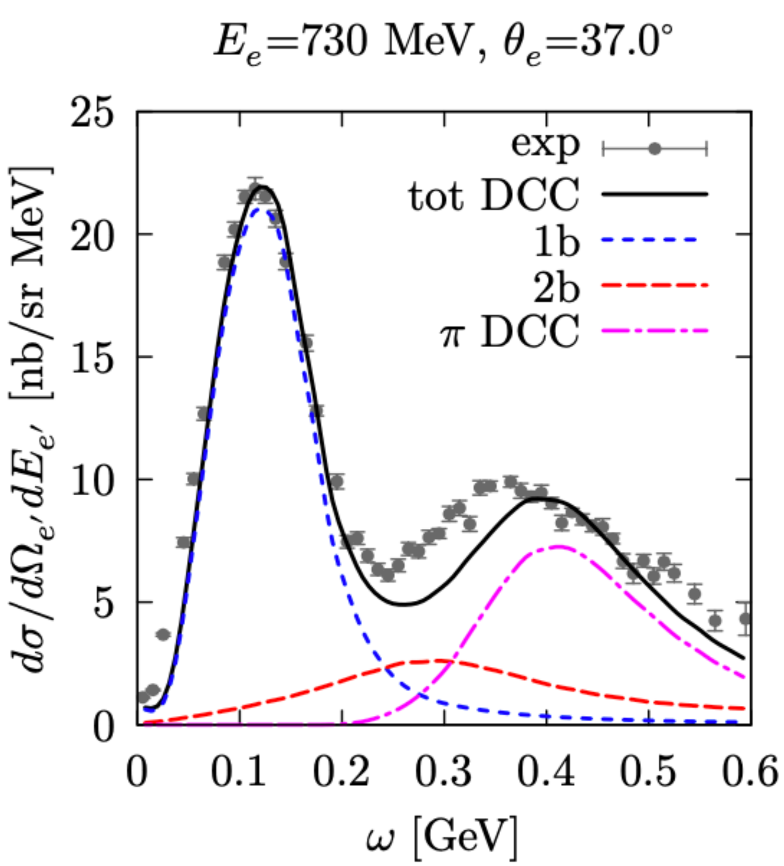
Pion production

Low-energy pion production can be described in relativistic baryon χPT including $\Delta(1232)$ degrees of freedom

- Δ resonance and nonresonant pion production both significant
- Experimental data on neutrino-induced pion production are scarce



Yao, Alvarez-Ruso, Hiller Blin, and Vicente Vacas, PRD 98 (2018)



Rocco, Nakamura, Lee, and Lovato PRC 100 (2019)

Spectral function nuclear model + dynamic coupled-channels (DCC) model of nucleon resonances can reproduce pion electroproduction data

Neutrino predictions include significant uncertainties from nuclear modifications of Δ form factors and axial contributions estimated with tree-level χPT

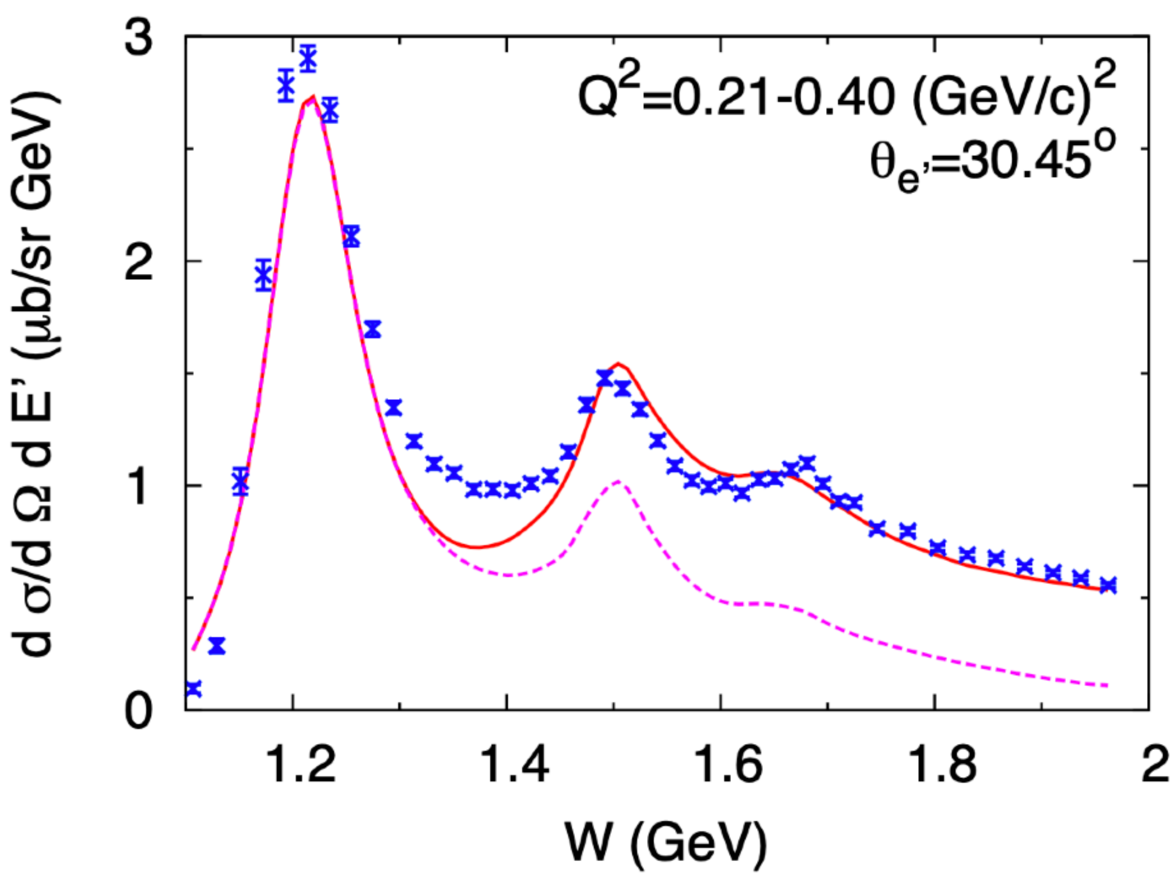
Higher-energy resonances

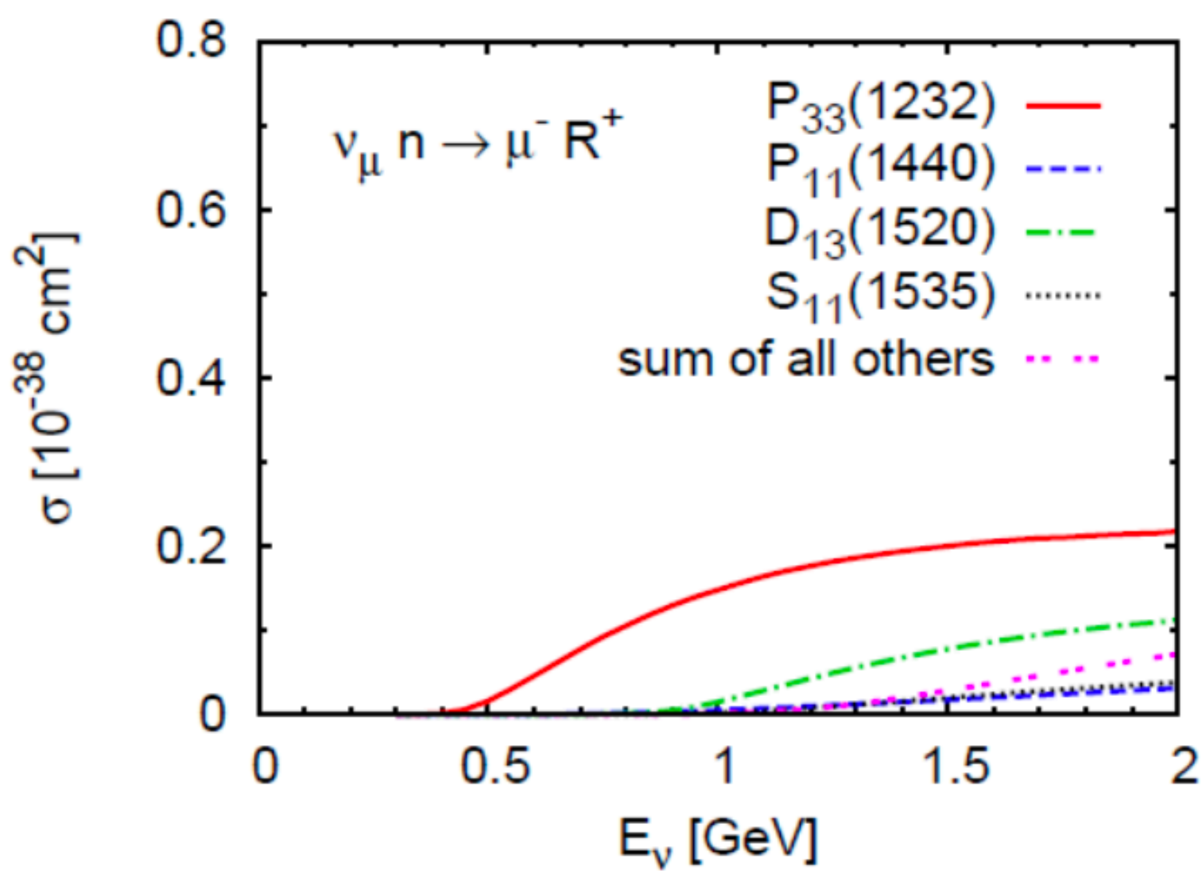
DCC model from ANL-Osaka describes nucleon resonance production by fitting to experimental data for

$$\pi N, \gamma N \;\rightarrow\; \pi N, \eta N, K\Lambda, K\Sigma$$

Same models can predict neutrino cross-sections, axial contributions constrained by πN through χPT

Nakamura, Kamano, and Sato PRD 92 (2015)





Leitner, Buss, Alvarez-Ruso, and Mosel, PRC 79 (2009)

GiBUU event generator uses detailed phenomenological resonance model

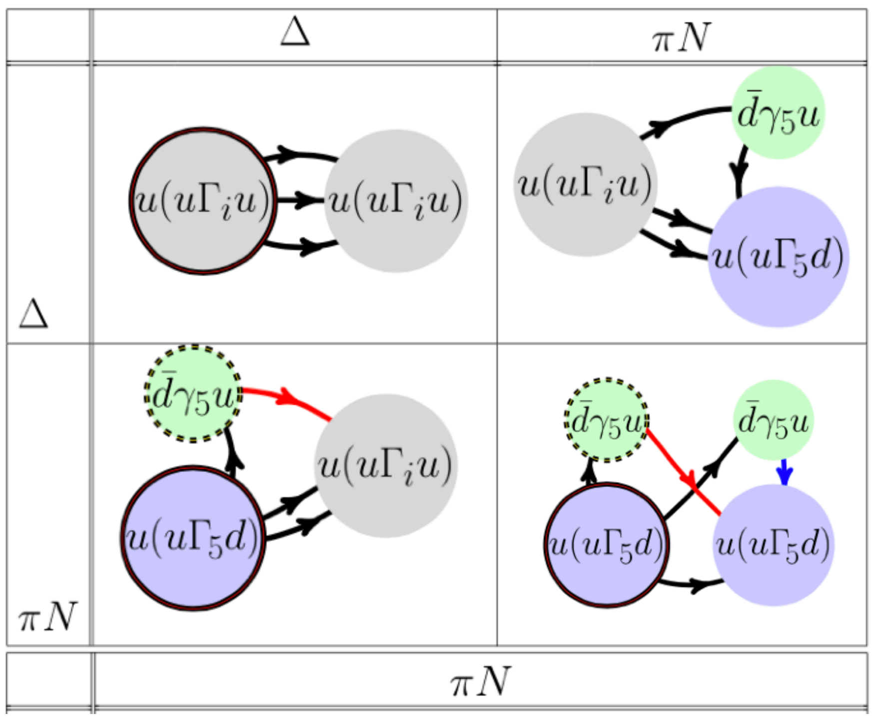
Vector-current responses taken from MAID analysis, axial-current predicted with χPT plus neutrinoproduction data for Δ

Improved constraints on N^* resonances (in nuclei!) needed to for precise predictions at DUNE energies

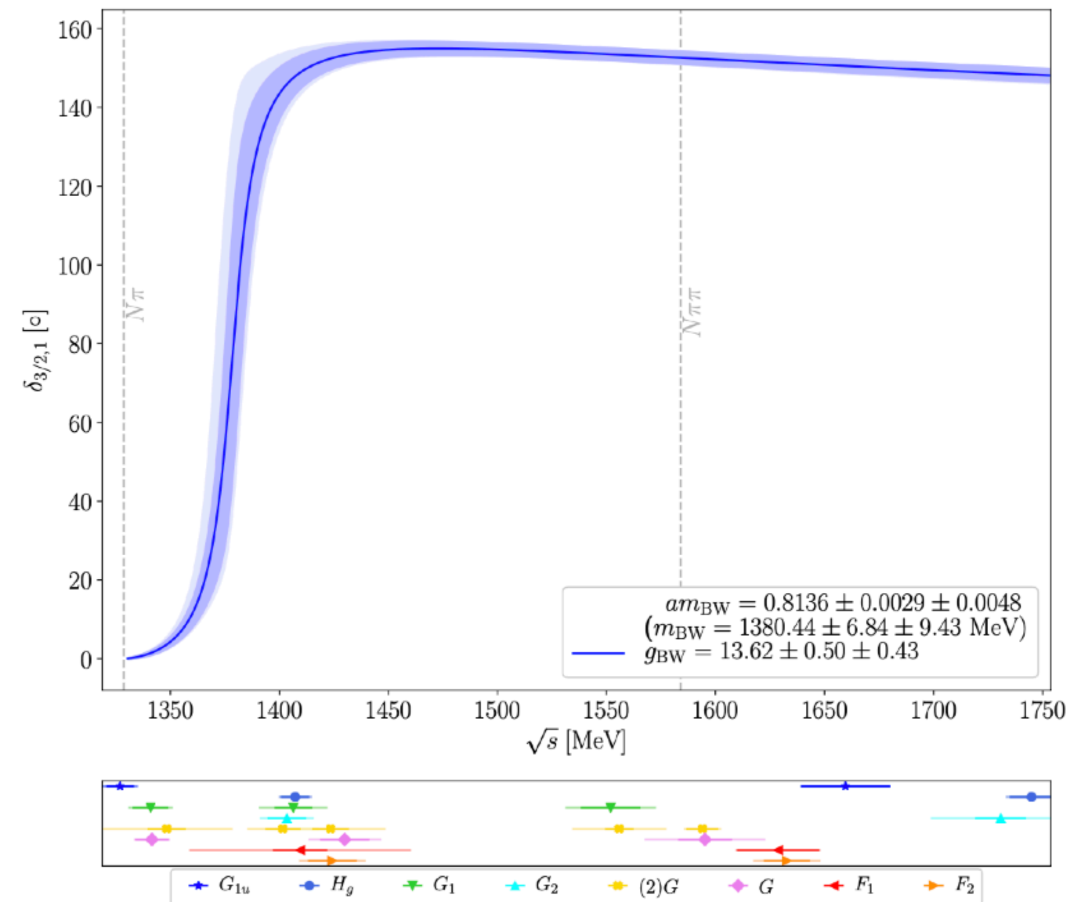
$N\pi$ systems in LQCD

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



$N \to \Delta$ transition form factors can also be calculated with variational methods

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

LQCD calculations of the nucleon hadron tensor provide an alternative route to predicting inclusive cross sections in the resonance region

Liang, Draper, Liu, Rothkopf, and Yang [χQCD] PRD 101 (2020)

Fukaya, Hashimoto, Kaneko, and Ohki, PRD 102 (2020)

Neutrino DIS

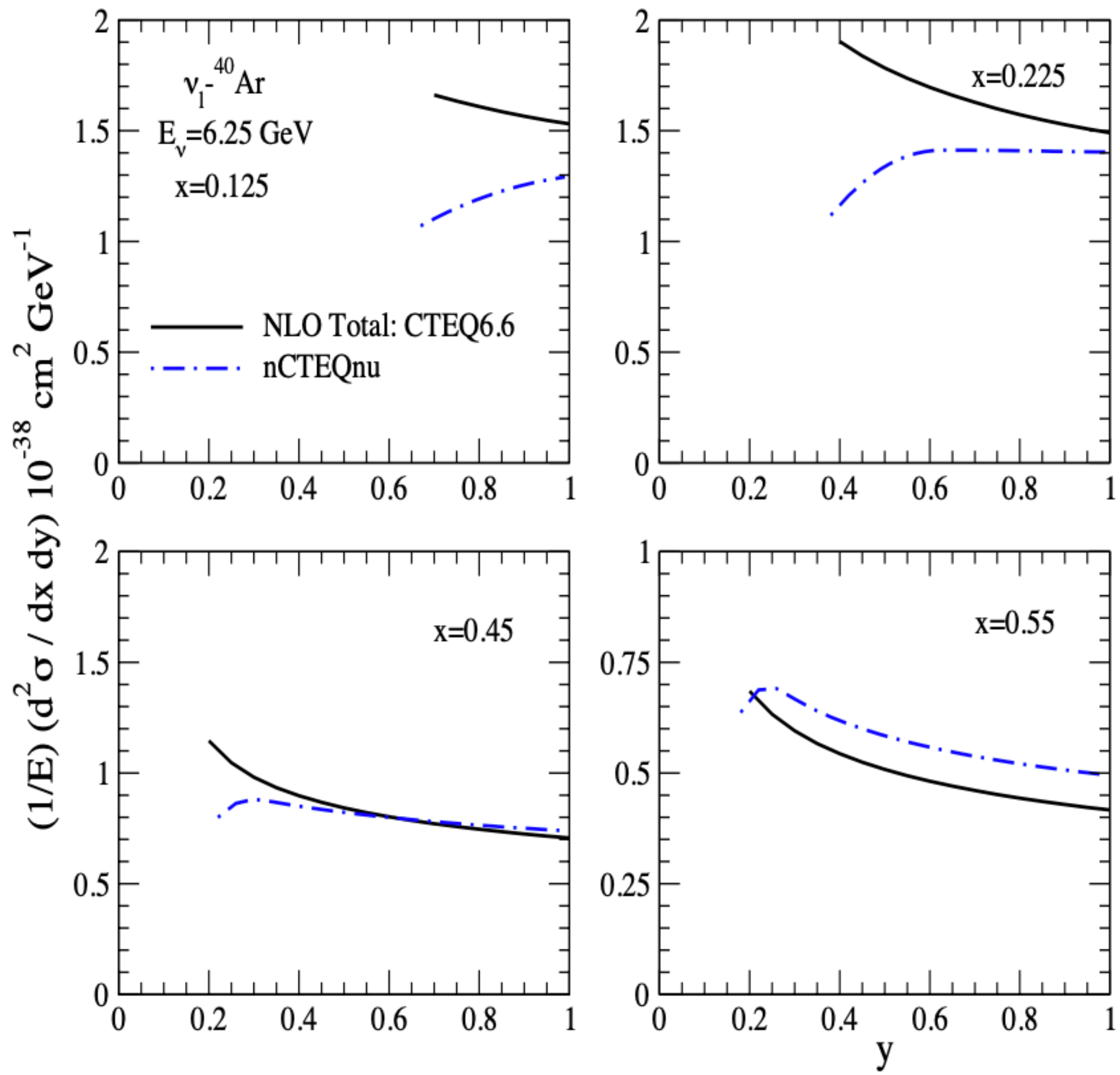
High-energy νA cross sections factorize into convolutions of hard scattering amplitudes calculable in perturbative QCD and nonperturbative PDFs

- Some PDFs appear in electron DIS and are experimentally well constrained, but others only appear in neutrino scattering

- Nuclear PDFs differ significantly from nucleon PDFs and are more uncertain

Nuclear PDFs relevant for neutrino scattering must be better constrained

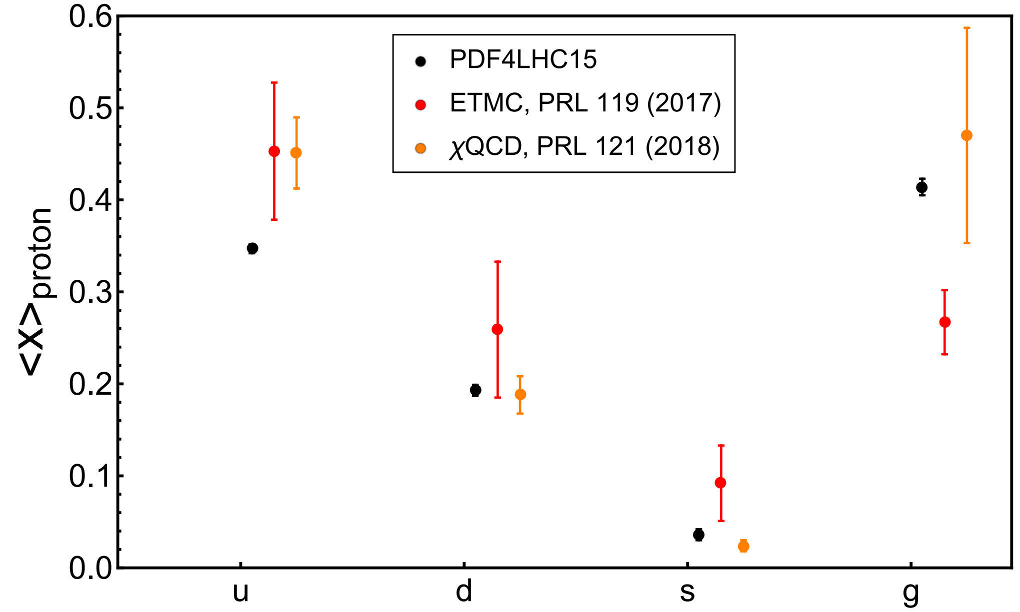
DIS models must be consistently implemented in event generators and smoothly connected to resonance region



Zaidi, Haider, Sajjad Athar, Singh, and Ruiz Simo PRD 101 (2020)

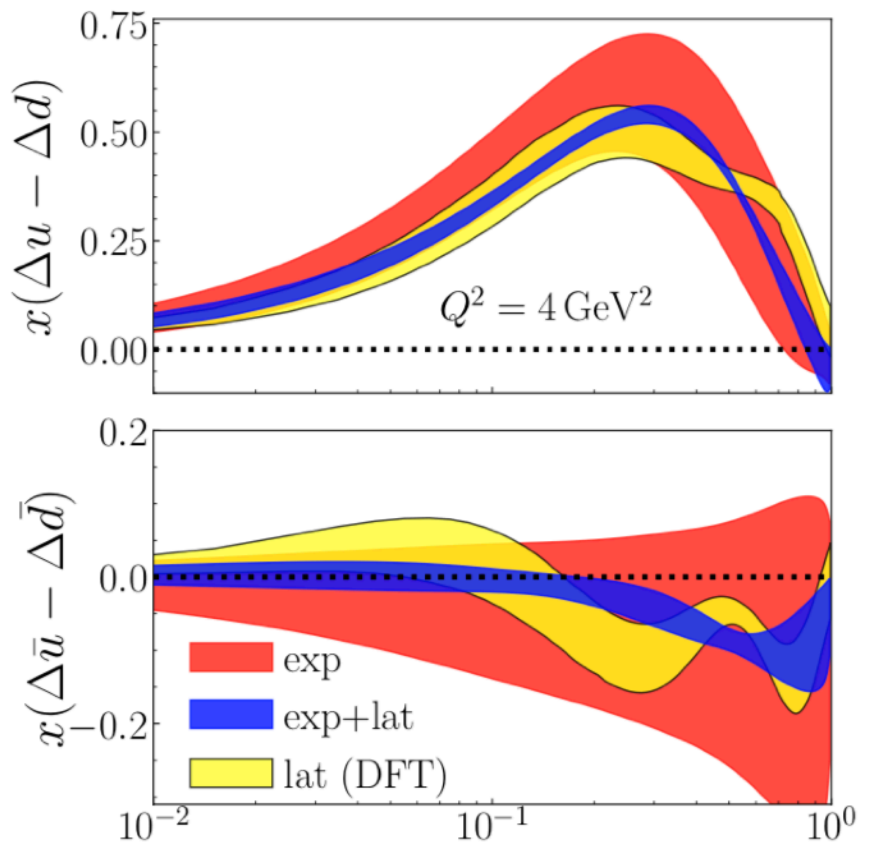
DIS and LQCD

LQCD can also compute quantities relevant to neutrino DIS



$\langle x \rangle^q_{\text{proton}}$ and $\langle x \rangle^g_{\text{proton}}$ calculated by several groups

Review: Lin et al, Prog. Part. Nucl. Phys. 100 (2018)



Bringewatt et al [JAM], PRD 103 (2021)

Large momentum effective theory connects Euclidean matrix elements to light-cone PDFs

Review: Ji et al, Rev. Mod. Phys. 93 (2021)

Current LQCD results can improve global analyses of isovector polarized PDFs that are relevant for weak interactions in neutrino DIS

Chen, Cohen, Ji, Lin, Zhang, Nucl. Phys. B 911 (2016)

Alexandrou, et al, PRL 121 (2018)   Alexandrou et al, PRL 126 (2021)

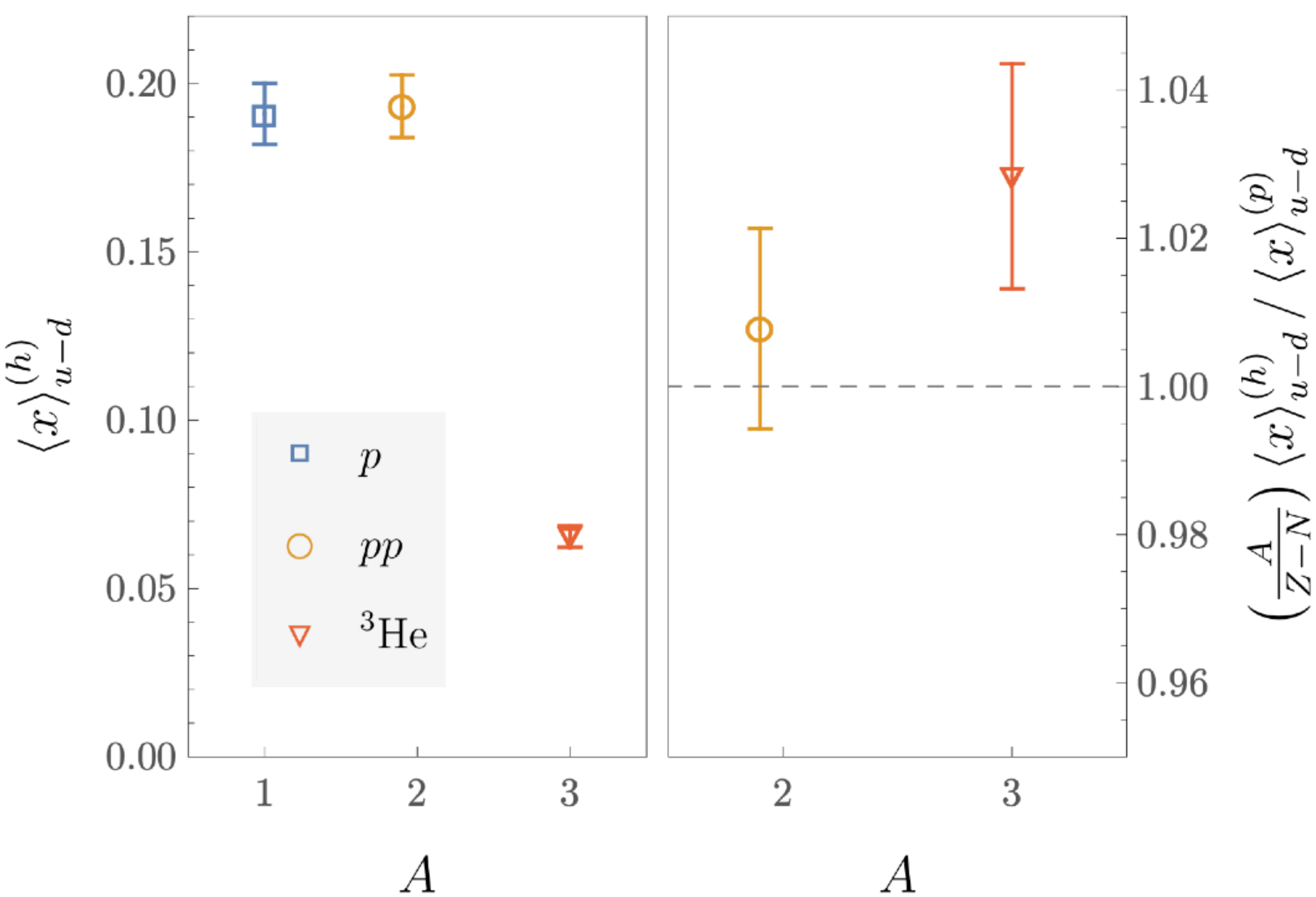
Nuclear momentum fractions

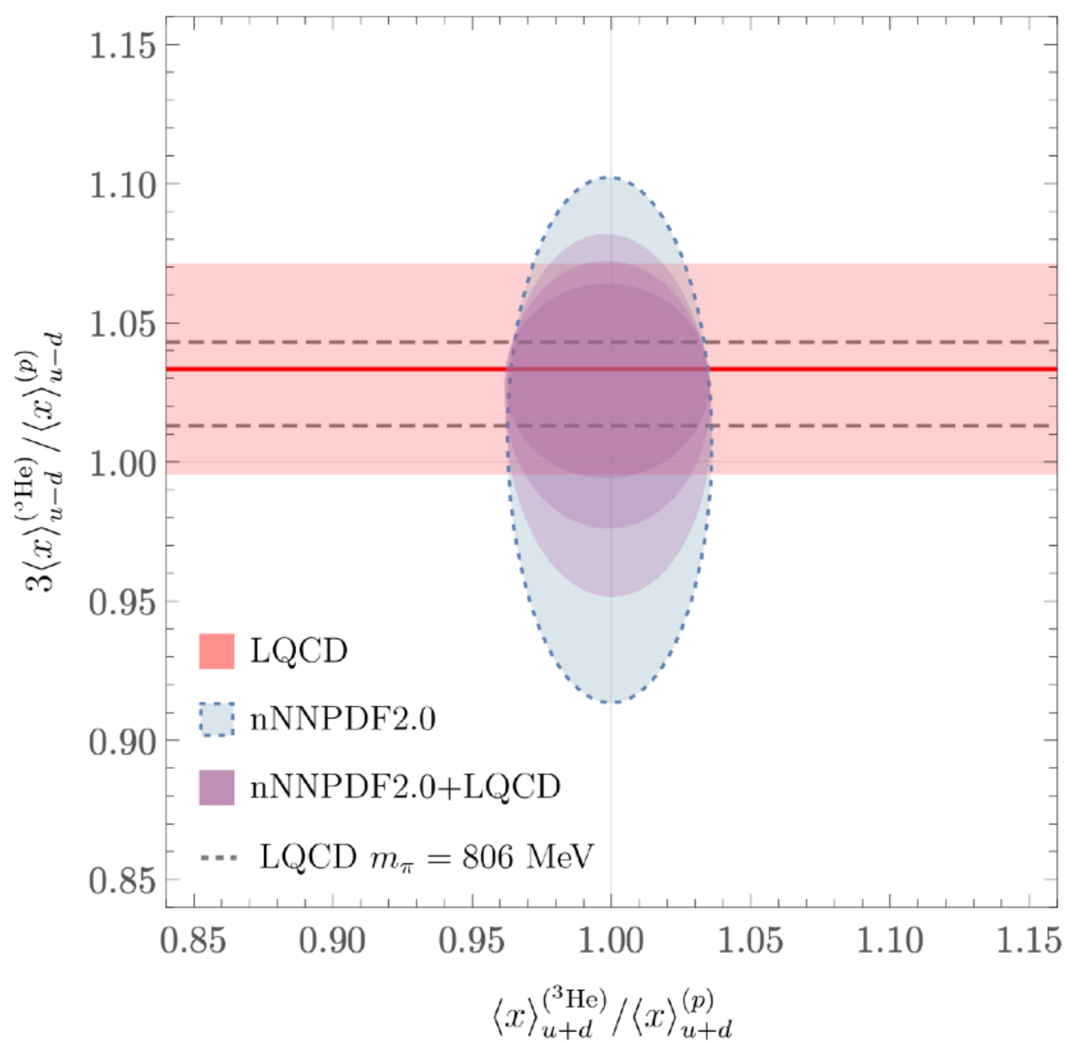
First calculations of gluon and isovector quark momentum fractions of light nuclei

Winter, MW et al [NPLQCD], PRD 96 (2017) Detmold, MW et al [NPLQCD] PRL 126 (2021)

Results matched to poinless EFT to determine two-body current operator relevant to isovector EMC effects

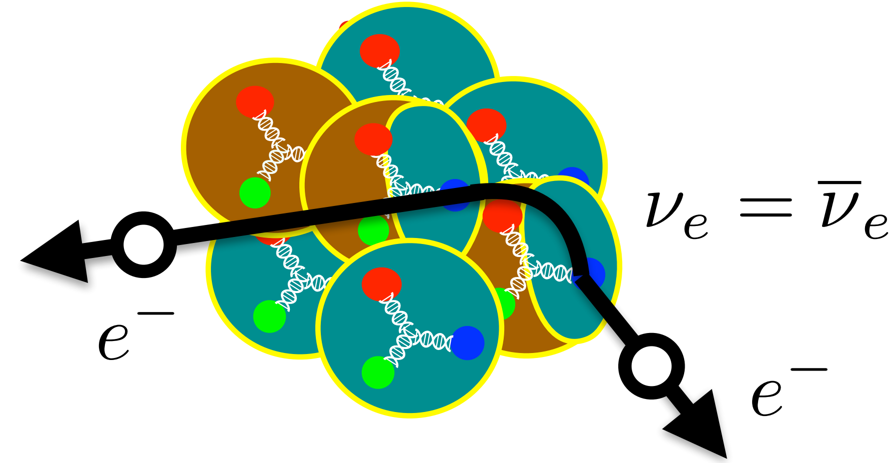
Although systematic uncertainties are not fully controlled (one lattice spacing, volume, quark mass, …) demonstrates potential for LQCD to usefully constrain nuclear PDFs





Lepton-number violation

Low-energy signature of lepton-number violation: $0\nu\beta\beta$



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

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

Phase space

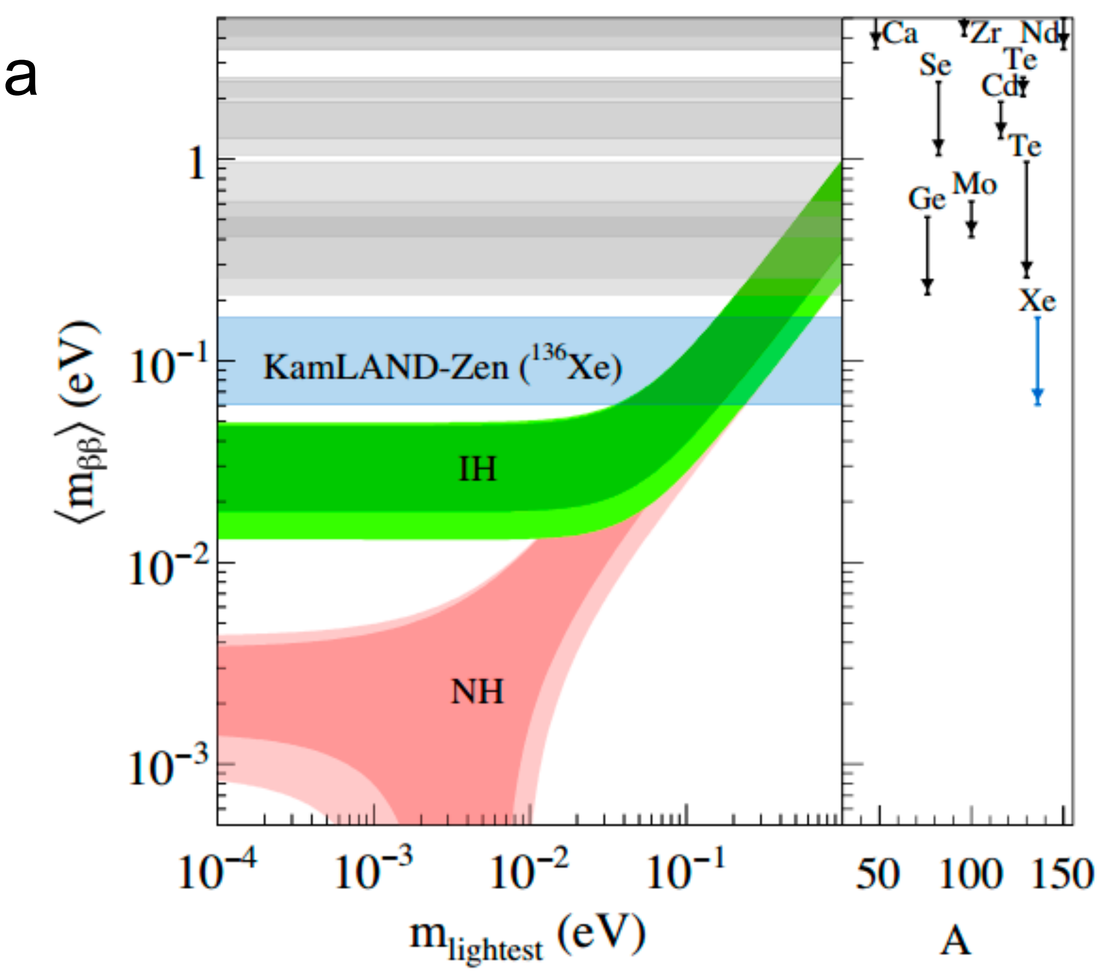
Nuclear matrix element

Effective Majorana mass

Similar theory approach: lattice QCD + effective theory + nuclear many-body methods has potential to reduce $0\nu\beta\beta$ uncertainties

Snowmass WP: Cirigliano et al arXiv:2203.12169

Synergies between νA and $0\nu\beta\beta$ theory should continue to be explored



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

Conclusions

Disentangling the νA reaction mechanisms relevant for DUNE:

- Is essential for connecting near- and far-detector measurements where fluxes differ

- Requires a robust theory pipeline from the Standard Model to event generators with cooperation between many groups: HEP / NP, theory / experiment / computing, …

LQCD → Nuclear EFT and many-body → Event generators