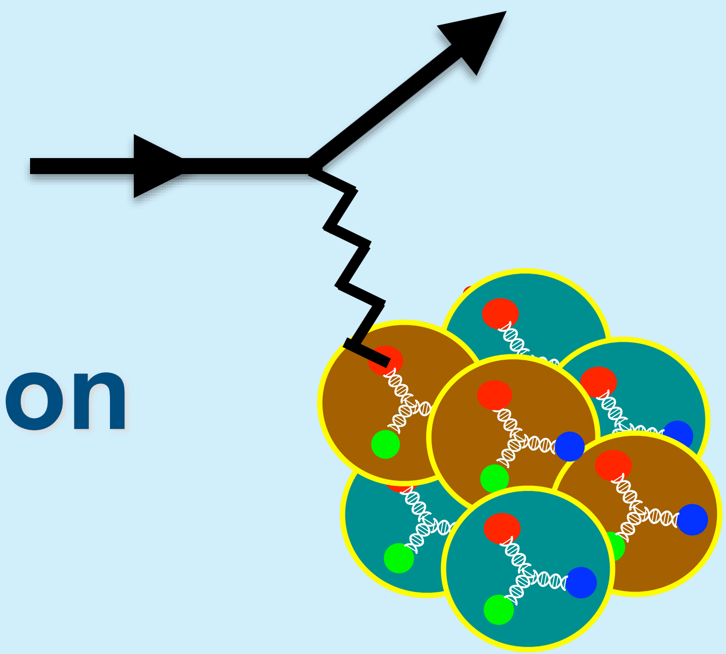
FERMILAB-SLIDES-20-704-T

Connecting QCD to neutrino-nucleus scattering



Michael Wagman

Snowmass Mini-Workshop on Neutrino Theory

Sep 23, 2020

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Connecting QCD to neutrino-nucleus scattering LOI link

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The precision era of ν physics

Next-generation oscillation experiments can answer fundamental questions about the neutrino mass ordering, size of leptonic *CP* violation, and more

Discovering new physics with ν experiments requires control of all the Standard Model physics in the detector

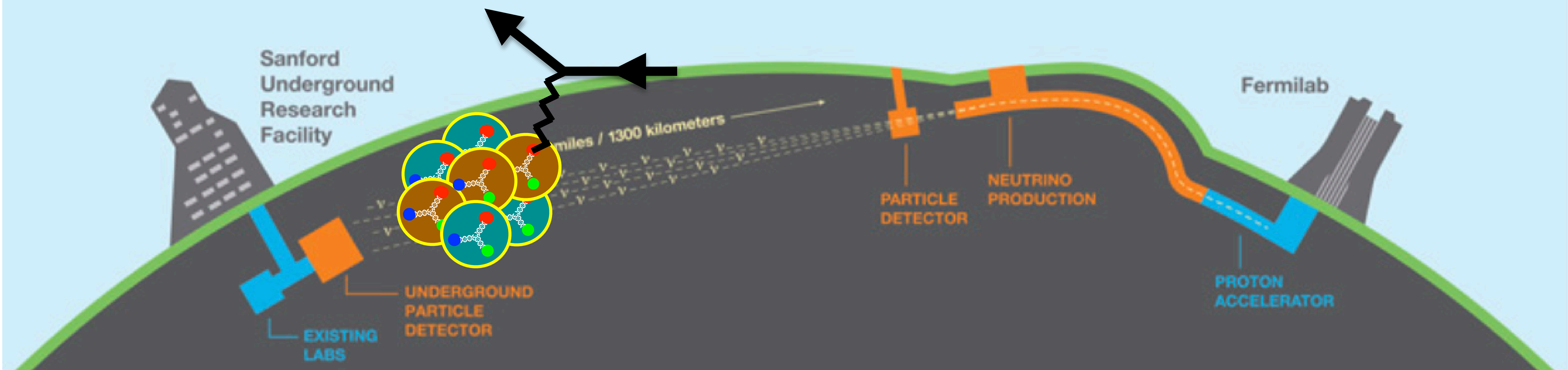
Acciarri et al (DUNE) arXiv 1512.06148

$$N_{\rm FD}^{expected}(\nu_e) = N_{\rm ND}^{data}(\nu_\mu) \otimes \frac{\Phi_{\rm FD}(\nu_\mu)}{\Phi_{\rm ND}(\nu_\mu)} \otimes P(\nu_\mu \to \nu_e) \otimes \frac{\varepsilon_{\rm FD}(\nu_e)}{\varepsilon_{\rm ND}(\nu_\mu)} \otimes \frac{\sigma_{\rm FD}(\nu_e)}{\sigma_{\rm ND}(\nu_\mu)}$$

Measured Goal νA cross-section

Exclusive νA cross-sections required for event-by-event reconstruction of incident neutrino energy

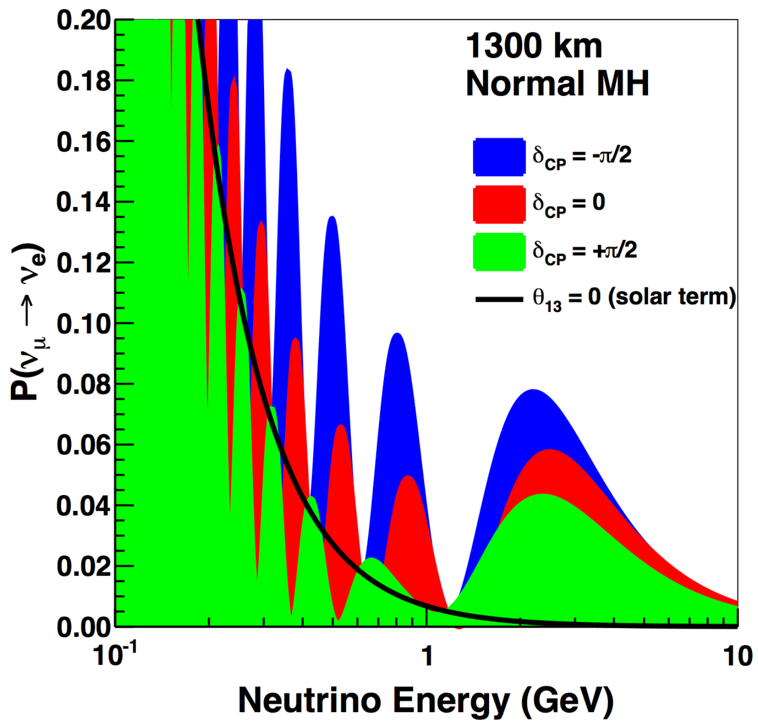
See talks by Shirley Li, Will Jay, Josh Barrow, Kajetan Niewczas

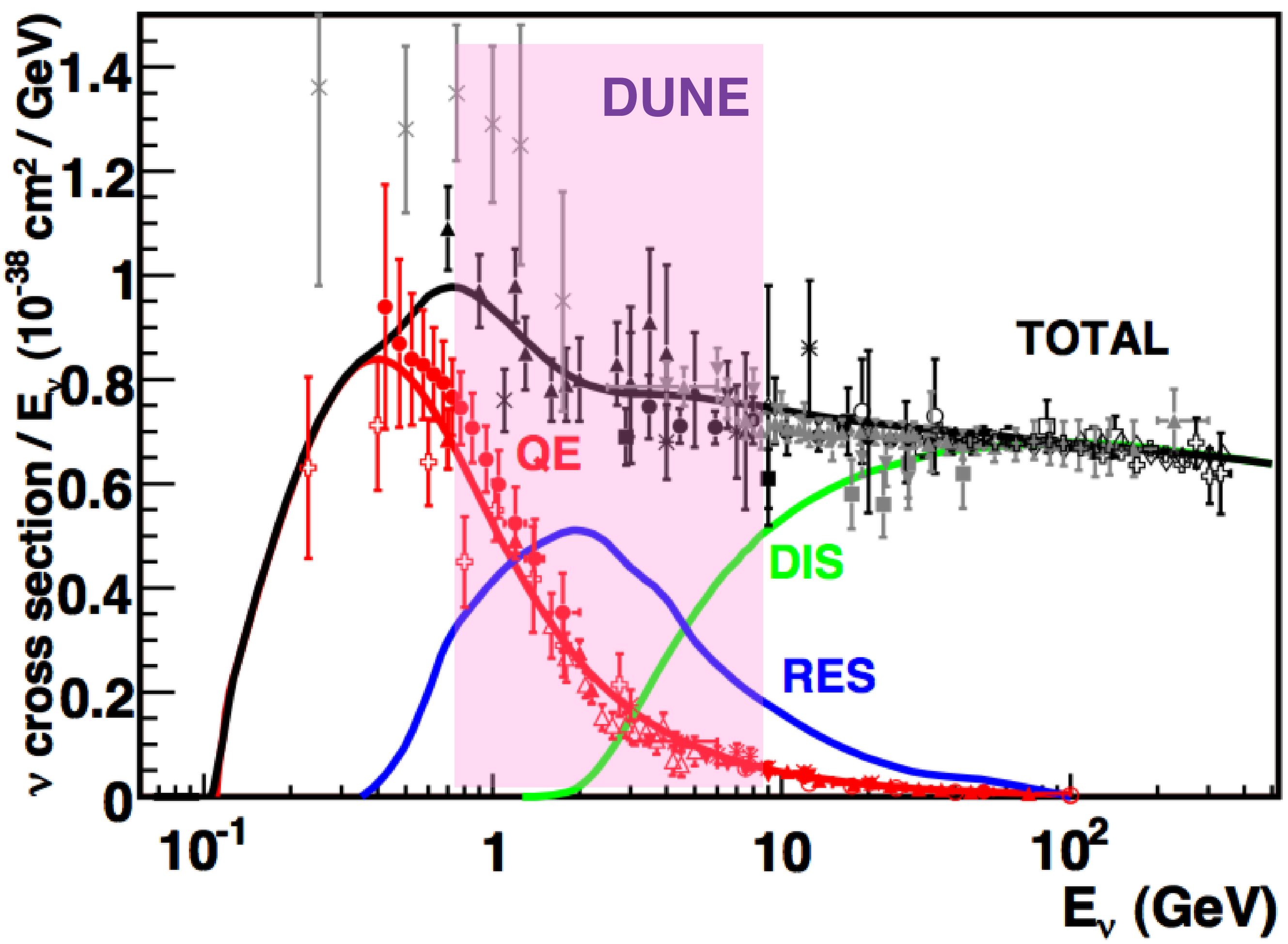


Challenges of νA

Neutrino-argon cross-sections with few percent-level accuracy required to achieve design sensitivity to *CP* violation at DUNE

Acciarri et al (DUNE) arXiv 1512.06148





Accelerator neutrino flux covers a wide range of energies with different dominant physics processes:

- Quasi-elastic
- Resonance production
- Two-body currents
- Deep inelastic scattering

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

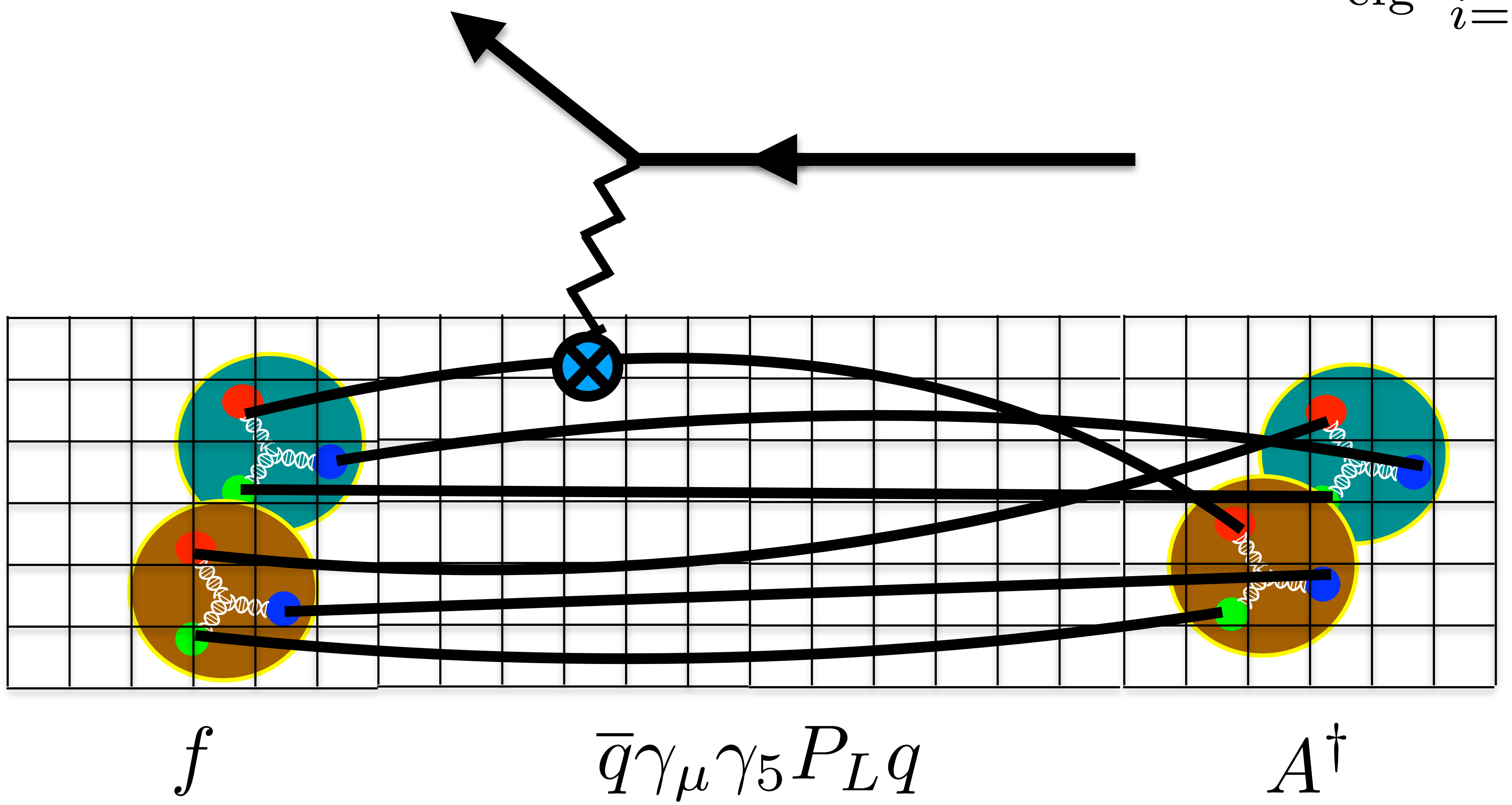
Lattice QCD and νA

νA scattering amplitudes factorize into leptonic and hadronic parts

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

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

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

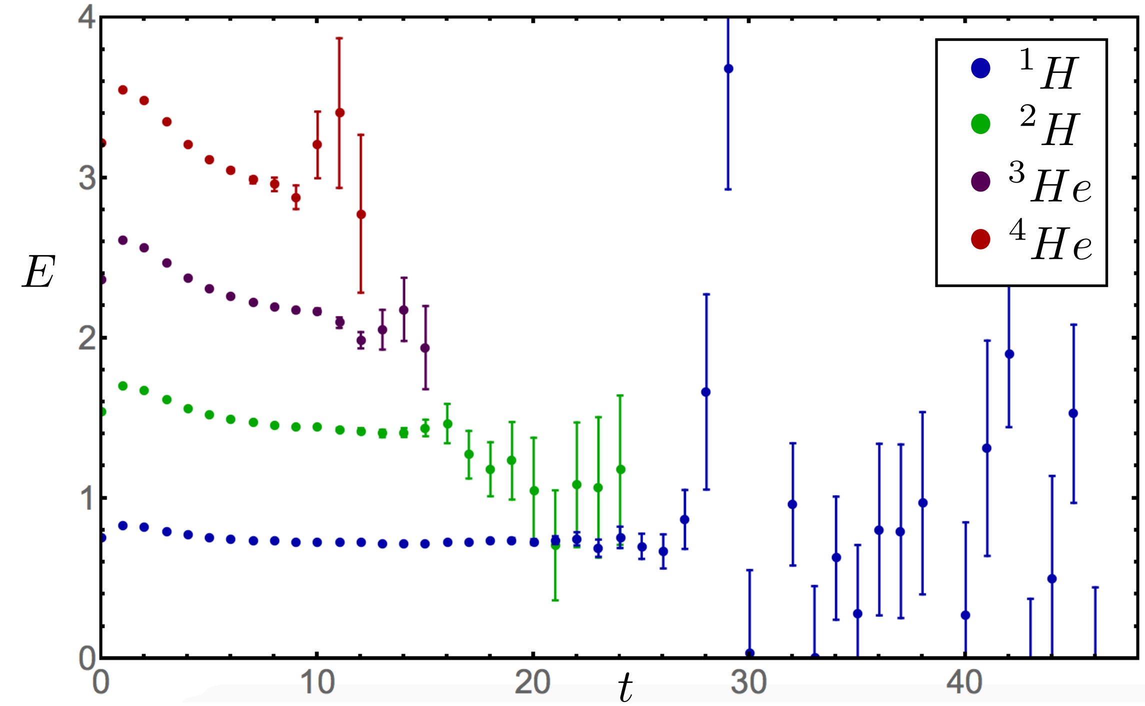


Lattice QCD, EFT, and νA

Lattice QCD simulations of nuclei face several practice challenges:

- Exponential signal-to-noise degradation
- Small gaps to finite-volume excited states
- Rapid growth in number of Wick contractions

NPLQCD Collaboration



Matrix element studies so far limited to $A \leq 3$ with unphysical quark masses

Review: Davoudi, Detmold, Orginos, Parreño, Savage, Shanahan, MW arXiv:2008.11160

Nuclear many-body methods are capable of efficiently describing larger nuclei, but require accurate inputs that are not all known from experiment

See talk by Noemi Rocco

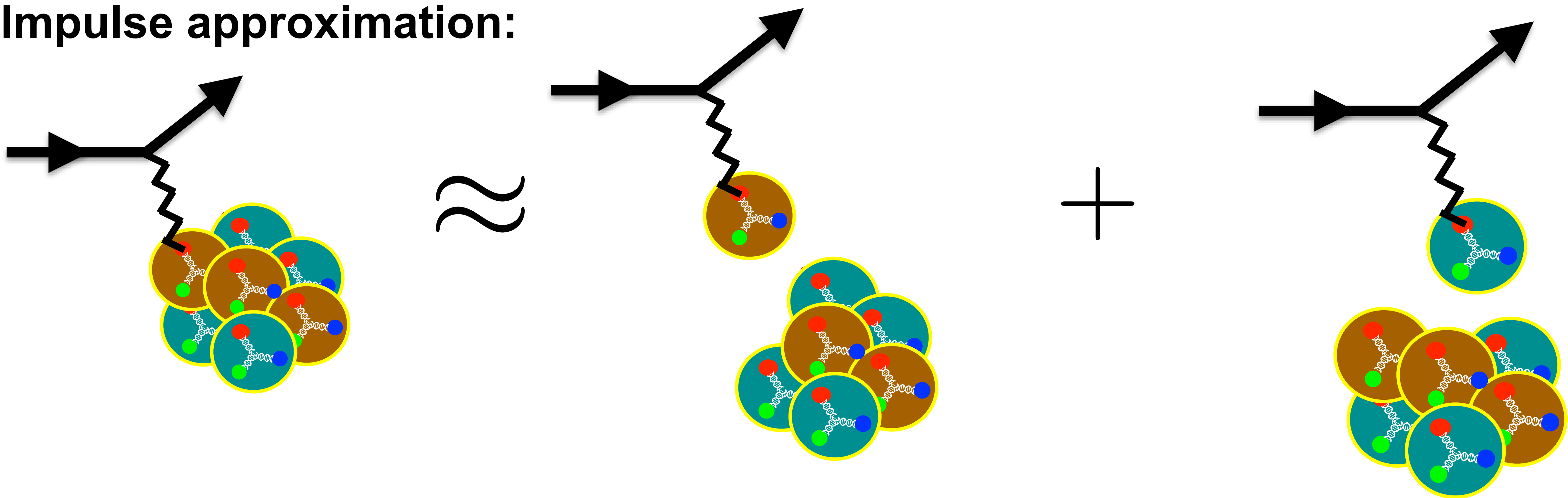
Strategy outlined in USQCD νA white paper: Kronfeld et al Eur. Phys. J. A 55 (2019)

Quasi-elastic region

Nucleons are effective degrees of freedom for nuclei at low energies

Currents dominantly couple to single-nucleon operators

Impulse approximation:



Cross-section in this region controlled by single-nucleon form factors

Vector current form factors are constrained by electron scattering, axial current form factors are less well-known

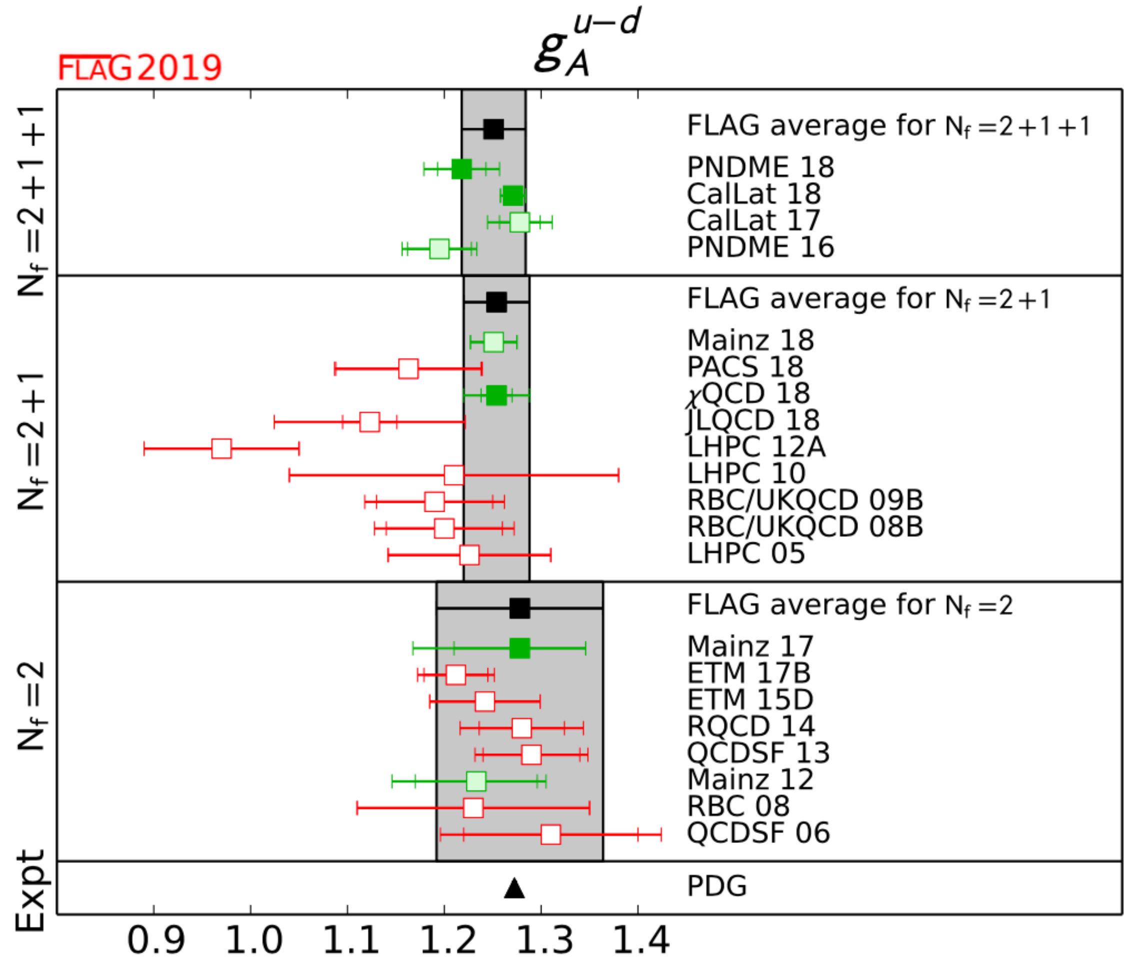
Single-nucleon QCD input

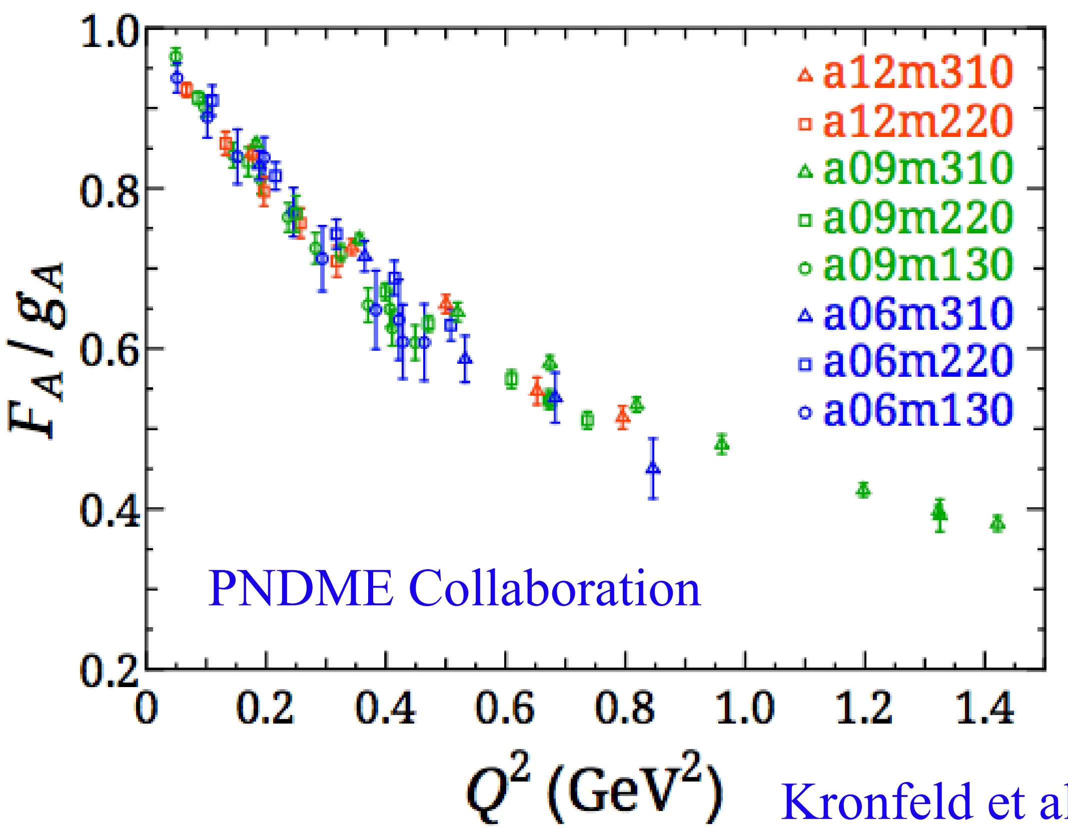
Axial charge precisely determined from LQCD with controlled uncertainties by multiple groups

Aoki et al [FLAG], arXiv:1902.08191

$$J^3_A(\mathbf{q}) = \sum_{\mathbf{x}} e^{i\mathbf{q}\cdot\mathbf{x}} \overline{q}(\mathbf{x})\gamma_z\gamma_5\tau^3 q(\mathbf{x})$$

$$g_A = \langle p | J^3_A(0) | p \rangle$$



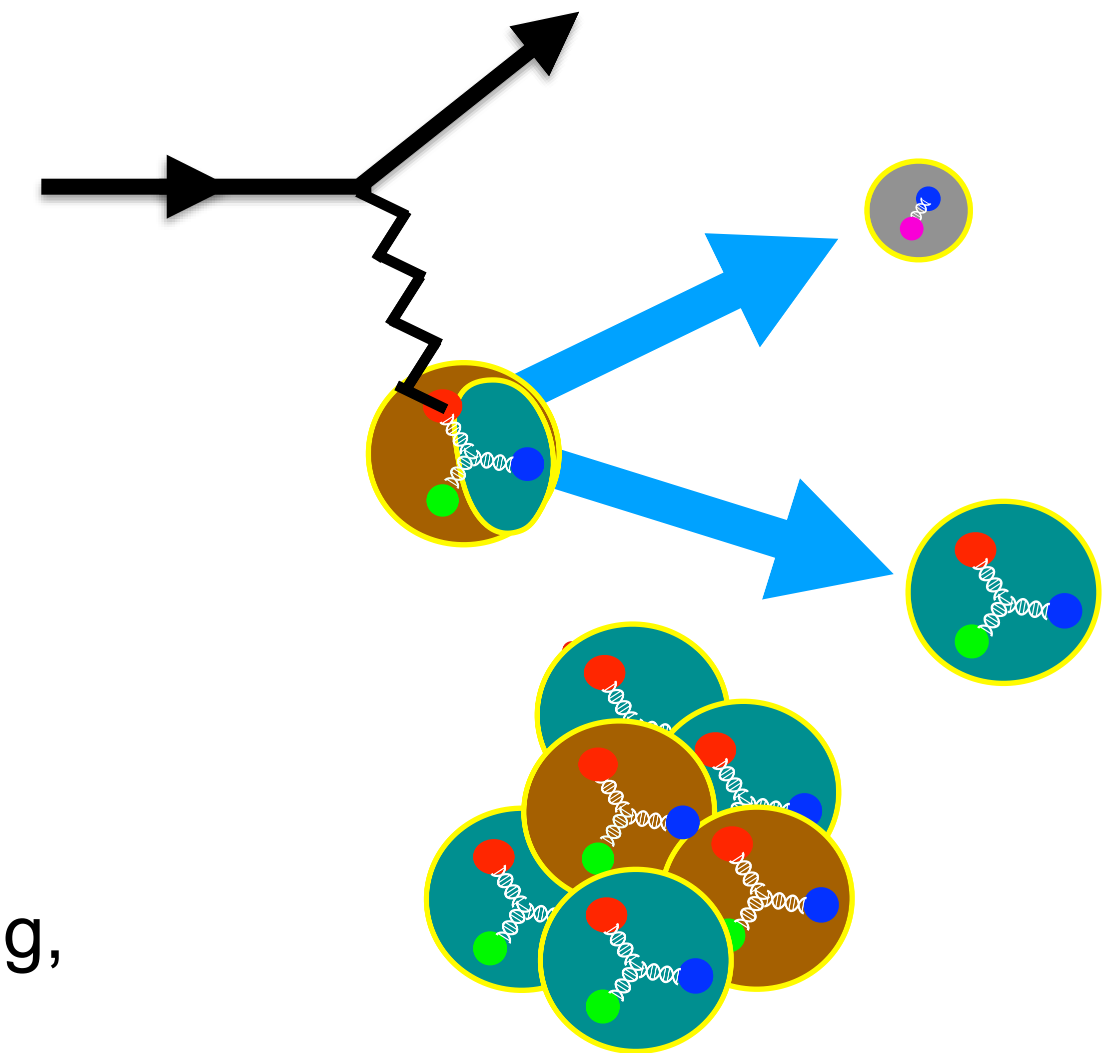


Axial form factors at non-zero momentum transfer involve additional challenges, but results with controlled systematics becoming available

See talk by Rajan Gupta

Kronfeld et al Eur. Phys. J. A 55 (2019)

Resonance region



At higher energies, pions and other resonances can be produced

Exclusive pion production and scattering processes must be modeled in event generators

Including explicit pions in EFT in a consistent power counting is challenging, still unresolved for $A \gtrsim 3$

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

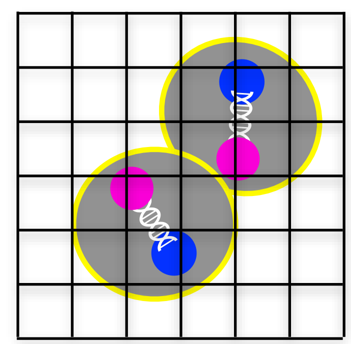
See talks by A. Nicholson and E. Mereghetti

Accurate benchmarks from experiment + LQC D are essential for validating nuclear models without controlled power counting

Finite-volume physics

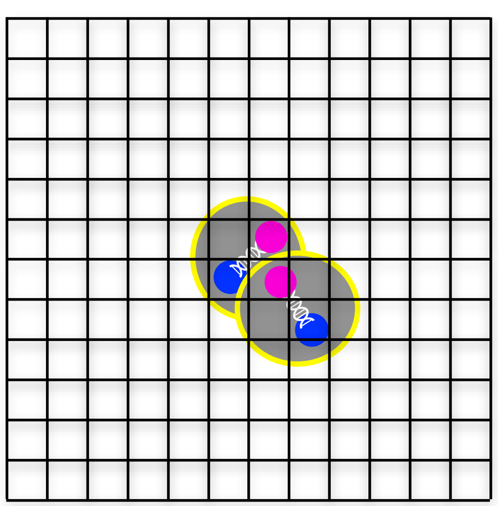
Pion production and scattering are dynamical processes that can not be determined from infinite-volume Euclidean observables

Solution — exploit the finite volume used in simulations



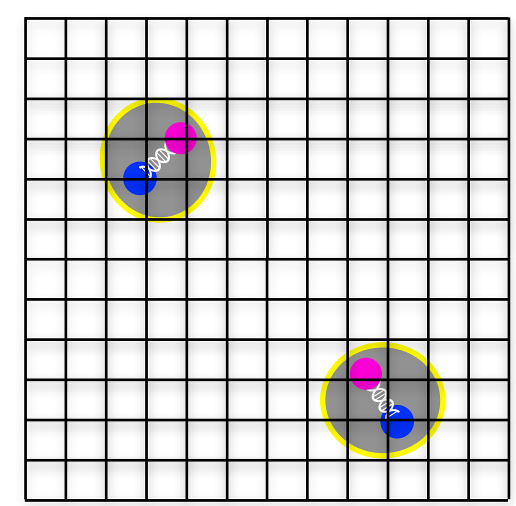
Infinite-volume bound state

$$[E(L) - E(\infty)] \propto \frac{e^{-\gamma L}}{\gamma L}$$



Infinite-volume scattering state

$$[E(L) - E(\infty)] \propto \frac{a}{ML^3}$$



Huang, Yang, Phys. Rev. 105 (1957)

Lüscher, Commun. Math. Phys. 105 (1986)

…

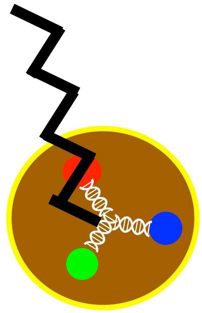
Review: Briceño, Dudek, Young, Rev. Mod. Phys. 90 (2018)

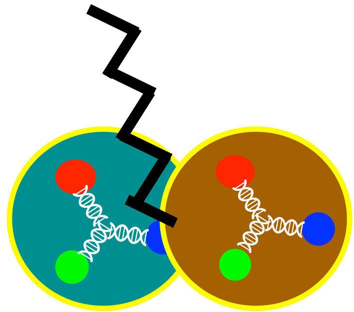
Extensions to finite-volume resonant form factors: Baroni, Briceño, Hansen, Ortega-Gama, PRD 100 (2018)

Shallow inelastic region

Correlated interactions of nucleon pairs are important at higher energies

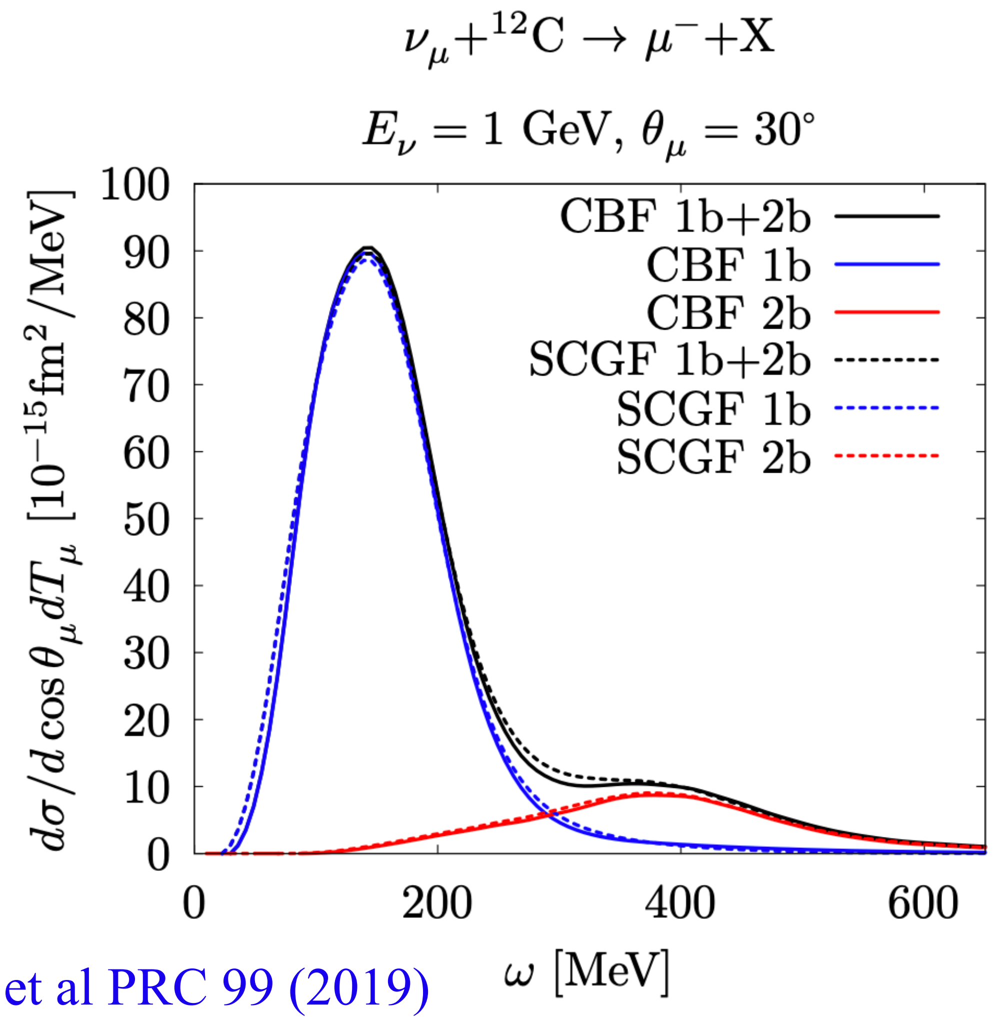
Pionless EFT:





Similar two-body current operators arise in chiral EFT and other nuclear many-body formalisms

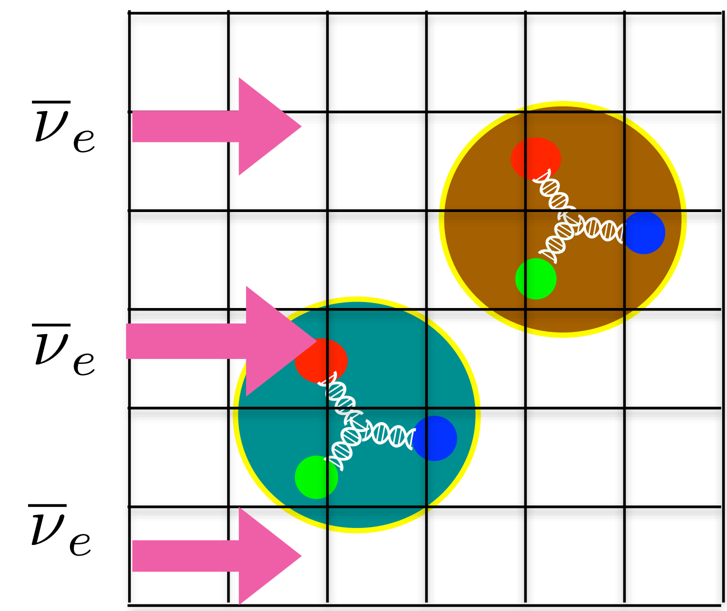
Benchmarks of two-body current effects will be essential for constraining and validating phenomenological nuclear models using spectral functions etc.

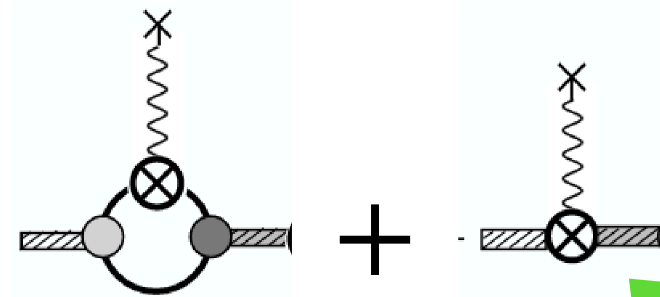


Rocco et al PRC 99 (2019)

Constraining two-body currents

First constraints on two-body axial currents obtained by matching LQCD and EFT calculations in a box with a background axial field

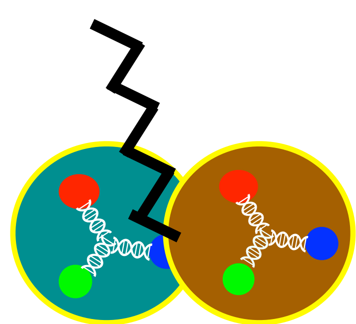


$iC_{pp\to np(^3S_1)} =$ 

$$\mathscr{M}_{pp\to np(^3S_1)} = gA(1+S) - L_{1A}$$

Short-distance QCD physics

Used for LQCD determination of L_{1A} and constraints on proton-proton fusion



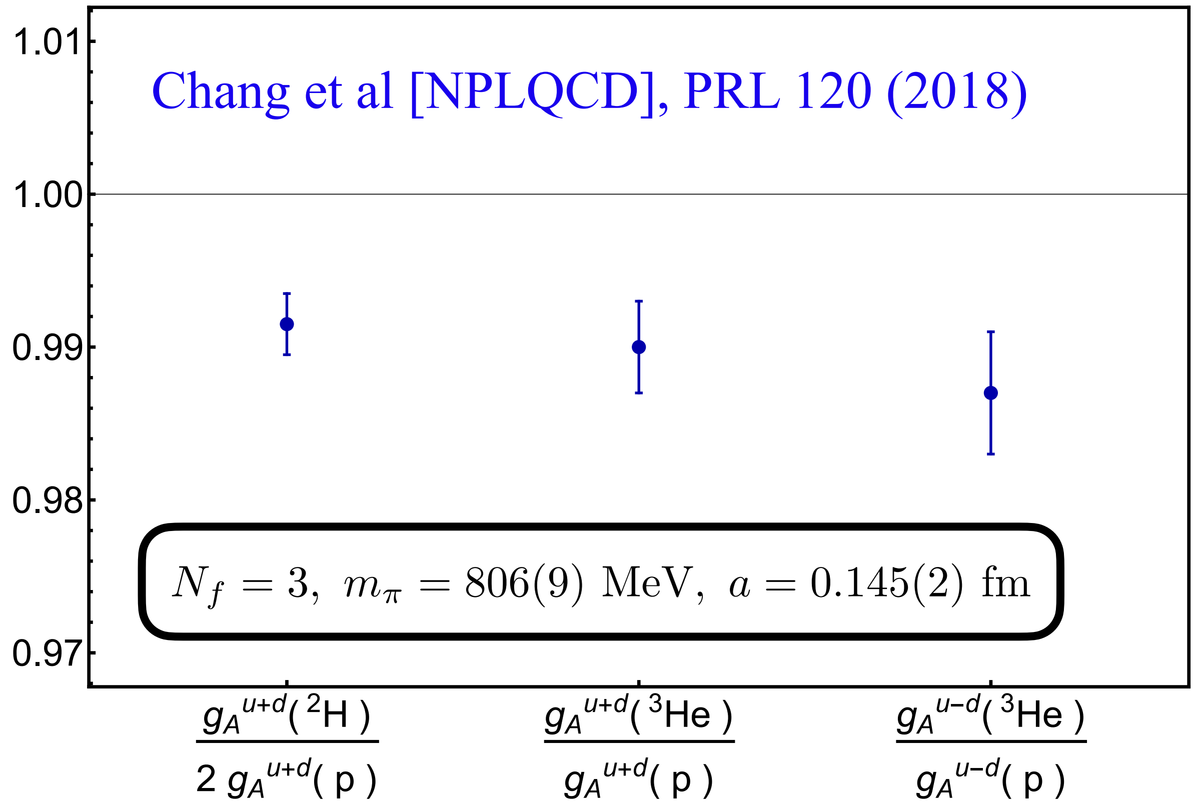
$$L_{1A} = 3.9(0.2)(1.0)(0.4)(0.9)\ \ \text{fm}^3$$

Savage et al [NPLQCD], PRL 119 (2017)

	method	L_{1A} (fm^3)
two-body		
	reactor $\bar{\nu}+d$	3.6 ± 5.5 [11]
	ES, CC, NC in SNO	4.0 ± 6.3 [41]
	MuSun proposal	$\pm$**1.25**
three-body		
	tritium beta decay	4.2 ± 3.7 [11], 4.2 ± 0.1 [41]
other		
	helioseismology	4.8 ± 6.7 [42]

Andreev et al (MuSun) arXiv 1004.1754

Two-body current effects

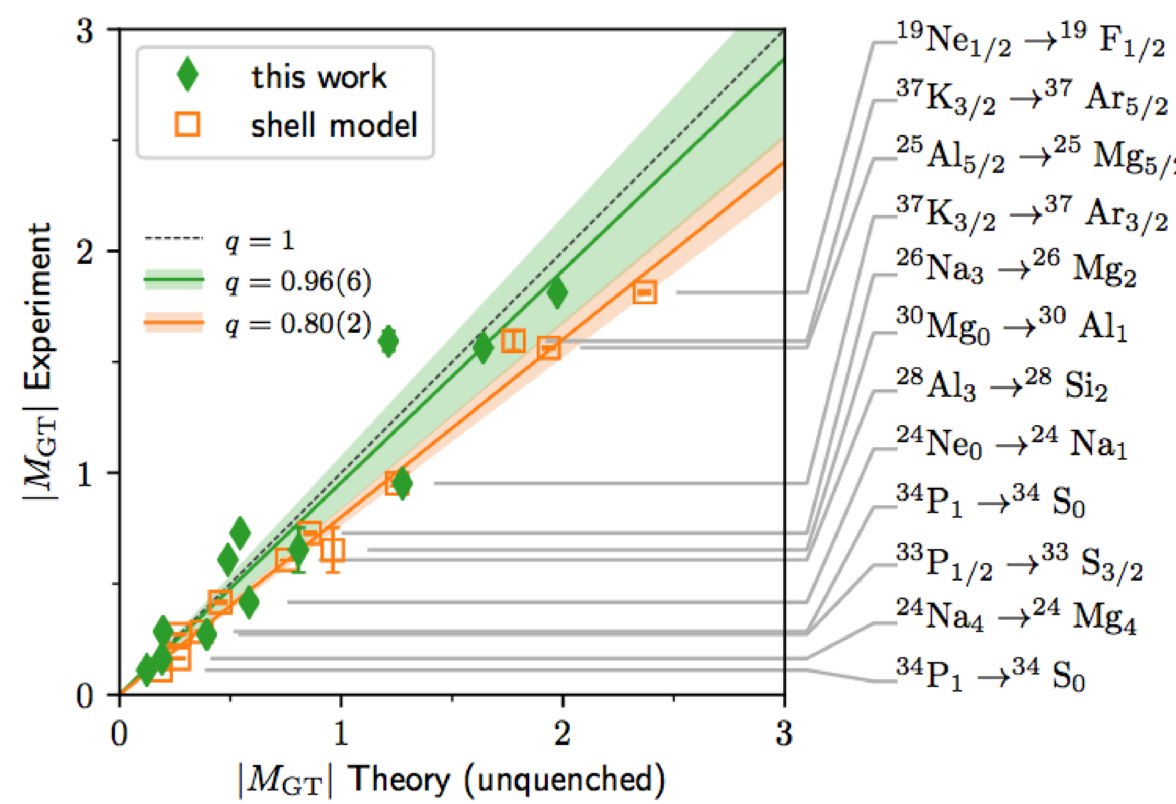


Nuclear modifications of *u* and *d* quark axial couplings O(1%) for A=2-3 nuclei, $m_\pi \sim 806$ MeV

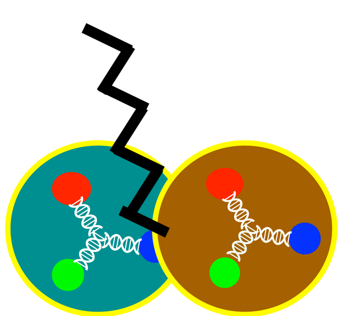
QCD effects reduce axial charge of ^{3}H by 4.89(13)% in nature

Baroni et al, PRC 94 (2016)

A=30-50 nuclei have O(30%) smaller axial couplings than predicted by shell model with single-particle couplings

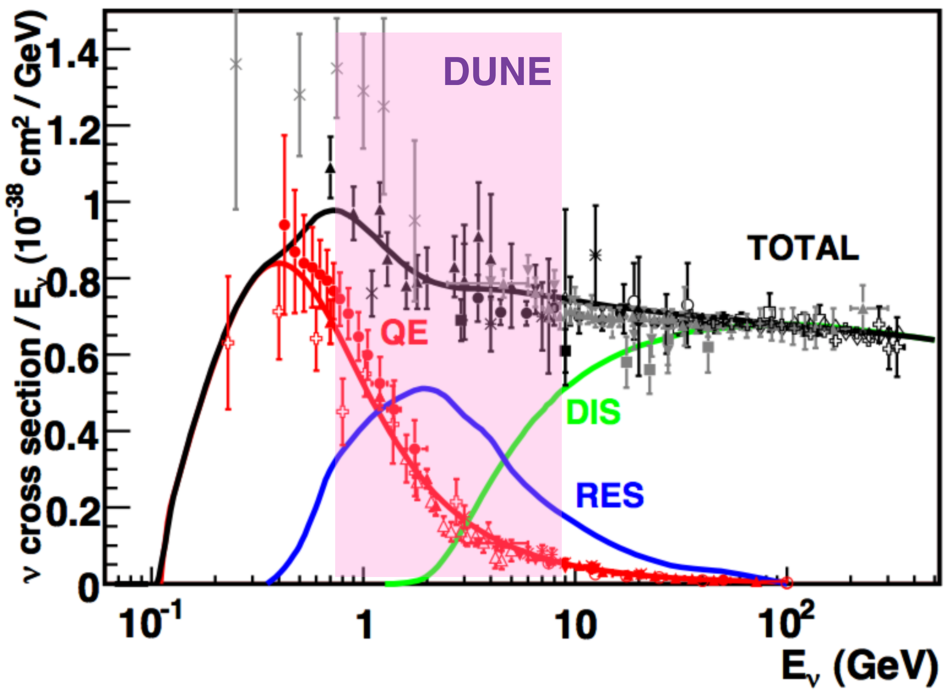


Gysbers et al, Nature Phys. 15 (2019)



Multi-nucleon correlations and currents needed to reproduce β-decay results from experiment

Deep inelastic regime



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

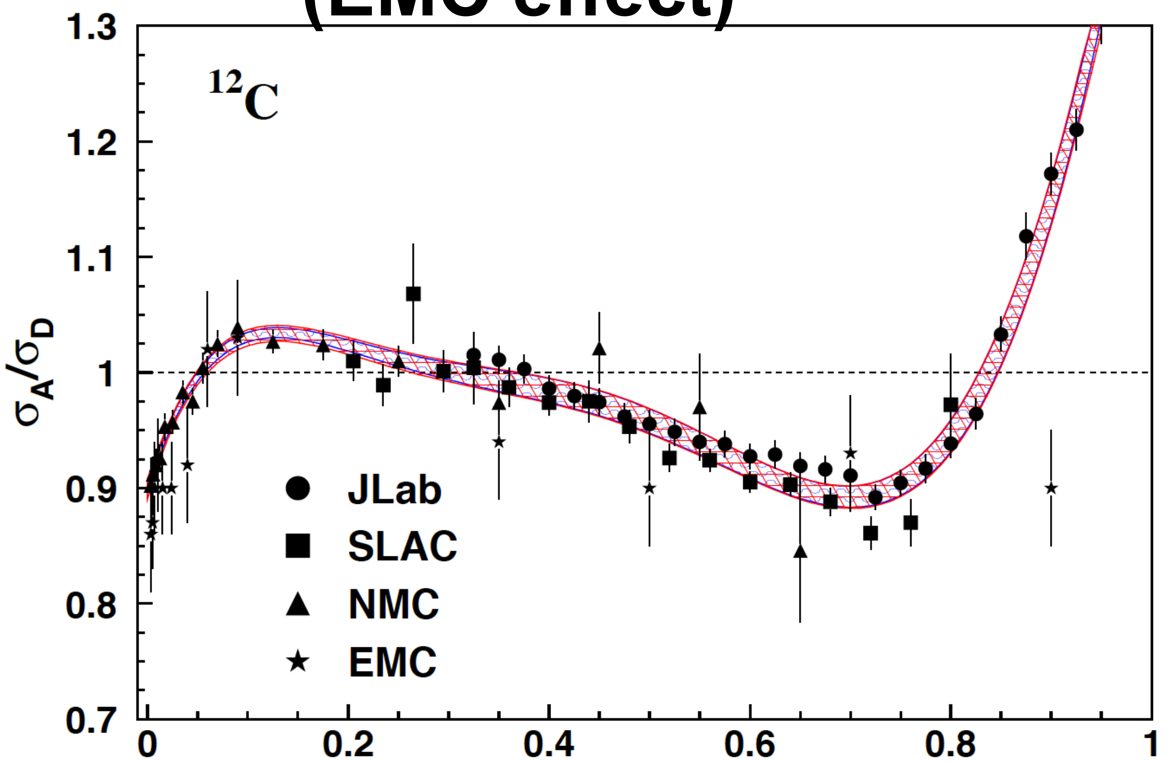
At very high energies, cross-sections factorize into convolutions of perturbative quark-and-gluon-level amplitudes and nonperturbative PDFs

Including perturbative QCD effects in event generators essential

Nonperturbative QCD effects determine the PDFs themselves

Some aspects of PDFs are experimentally well-known, but others (e.g. flavor dependence, nuclear effects) are not

Nuclear effects on PDFs (EMC effect)

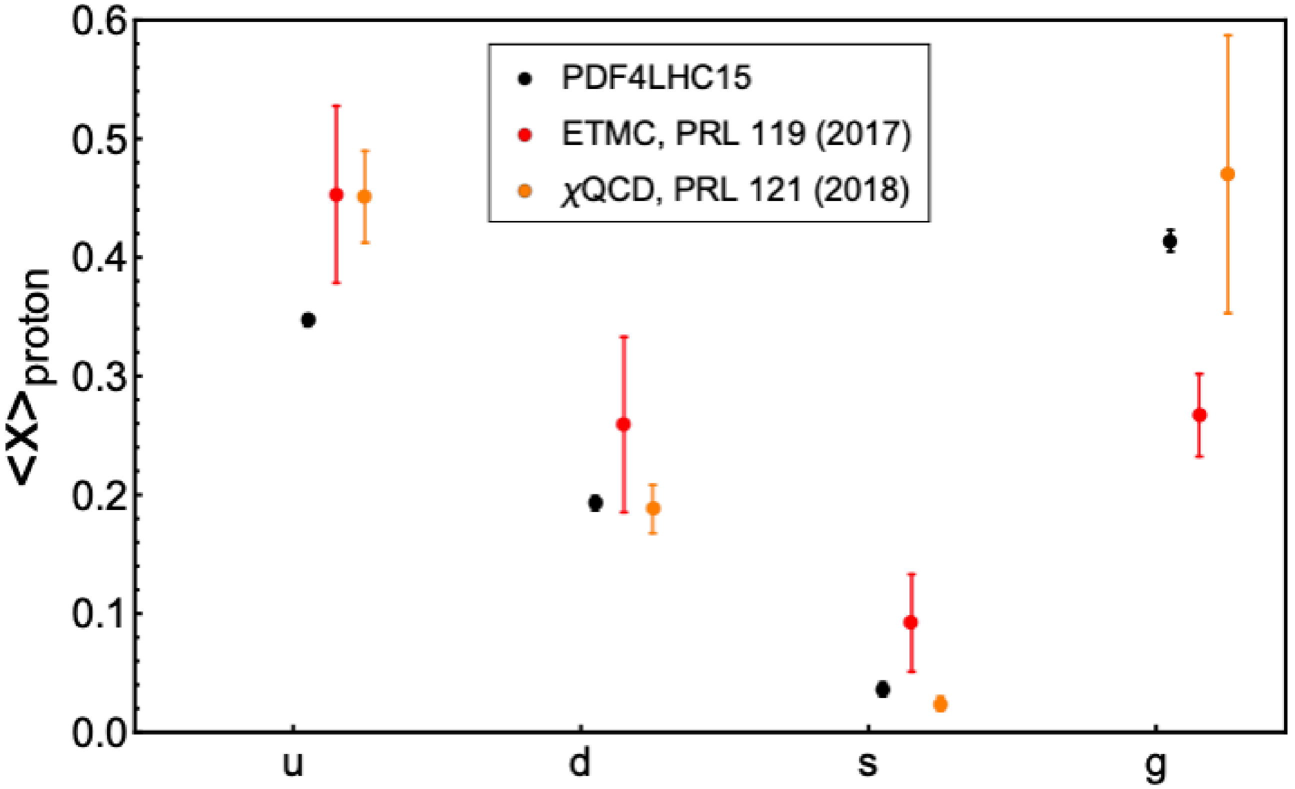


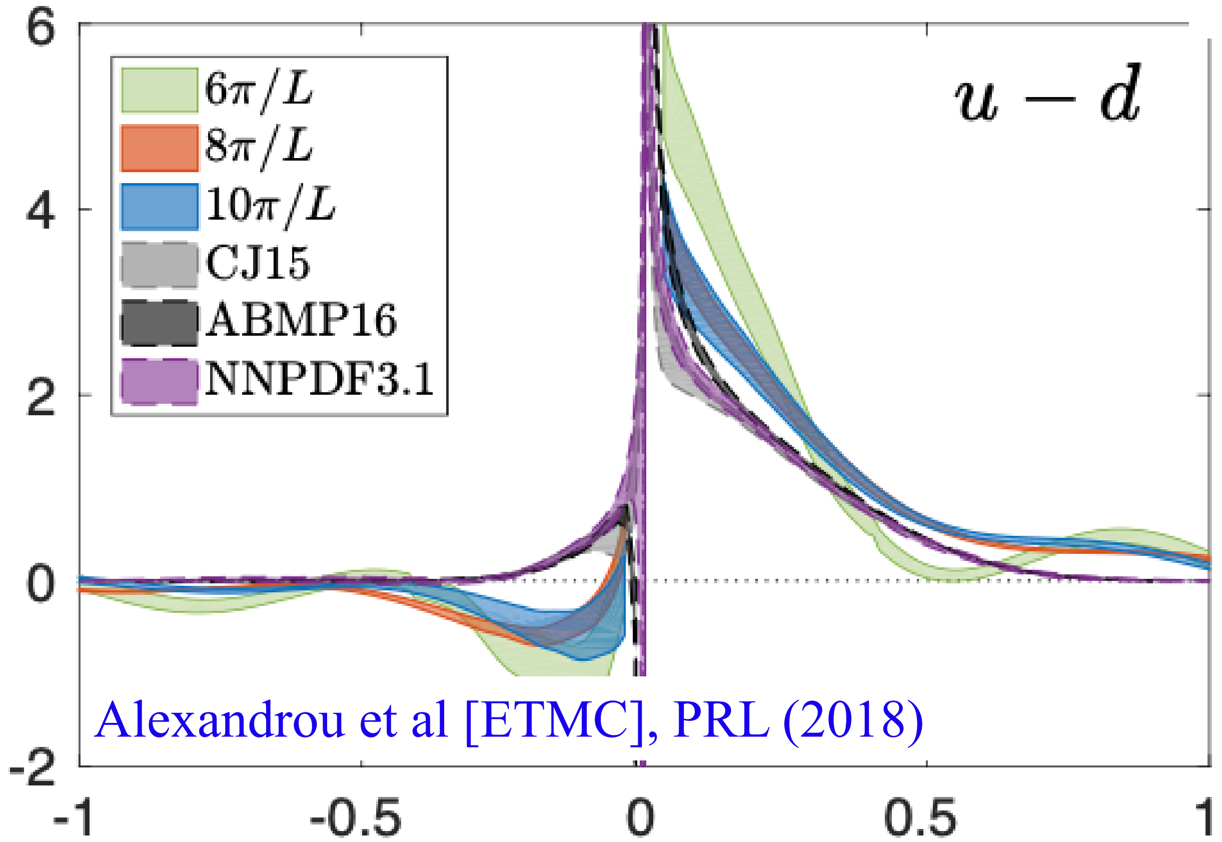
Malace et al, Int. J. Mod. Phys. E 23 (2014)

QCD constraints on PDFs

Matrix elements of local operators determine momentum fractions carried by each quark flavor and gluons

$$\langle x \rangle_q^{(h)} p_\mu p_\nu = \langle h | \bar{q} \gamma_{\{\mu} \overleftrightarrow{D}_{\nu\}} q | h \rangle$$



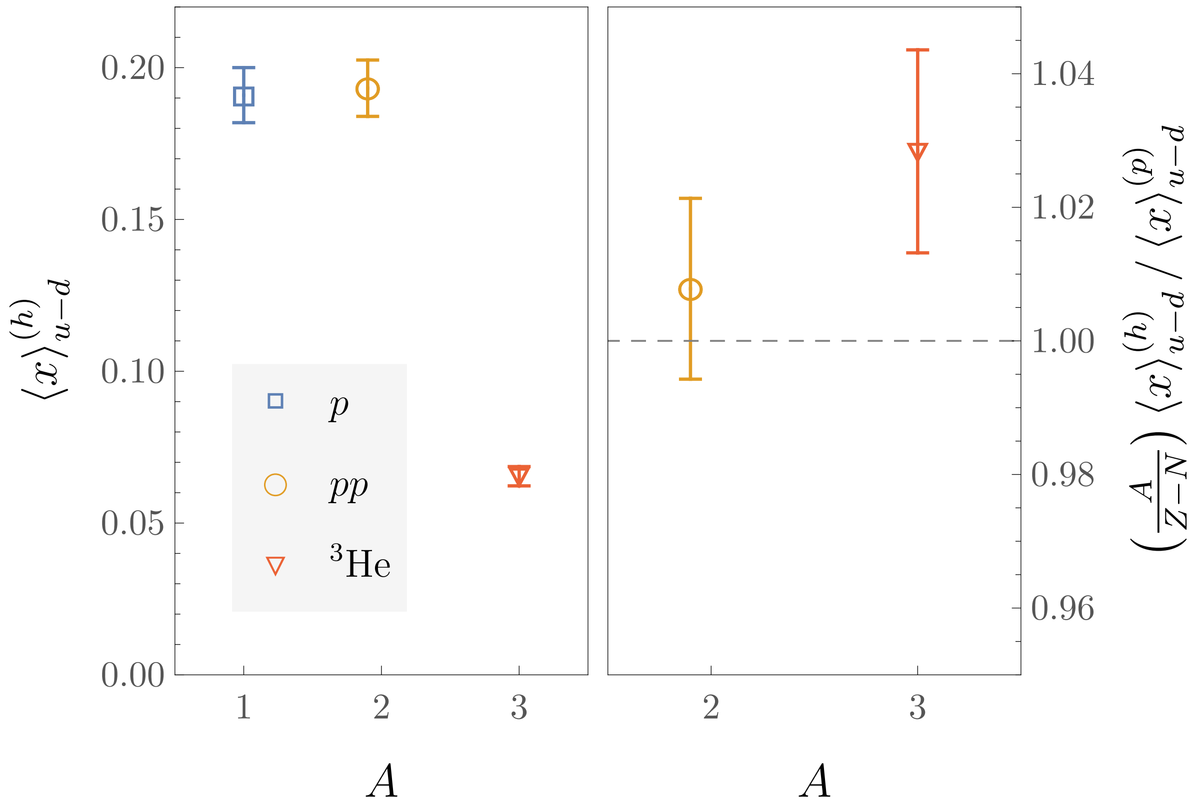


Full *x* dependence of PDFs accessible by factorizing non-local Euclidean matrix elements into perturbative hard parts and PDFs

Review of large momentum effective theory:

Ji, Liu, Liu, Zhang, Zhao, arXiv:2004.03543

Quarks in nuclei from QCD



Matrix elements of same operators in nuclear states determine momentum fractions of quarks and gluons in nuclei

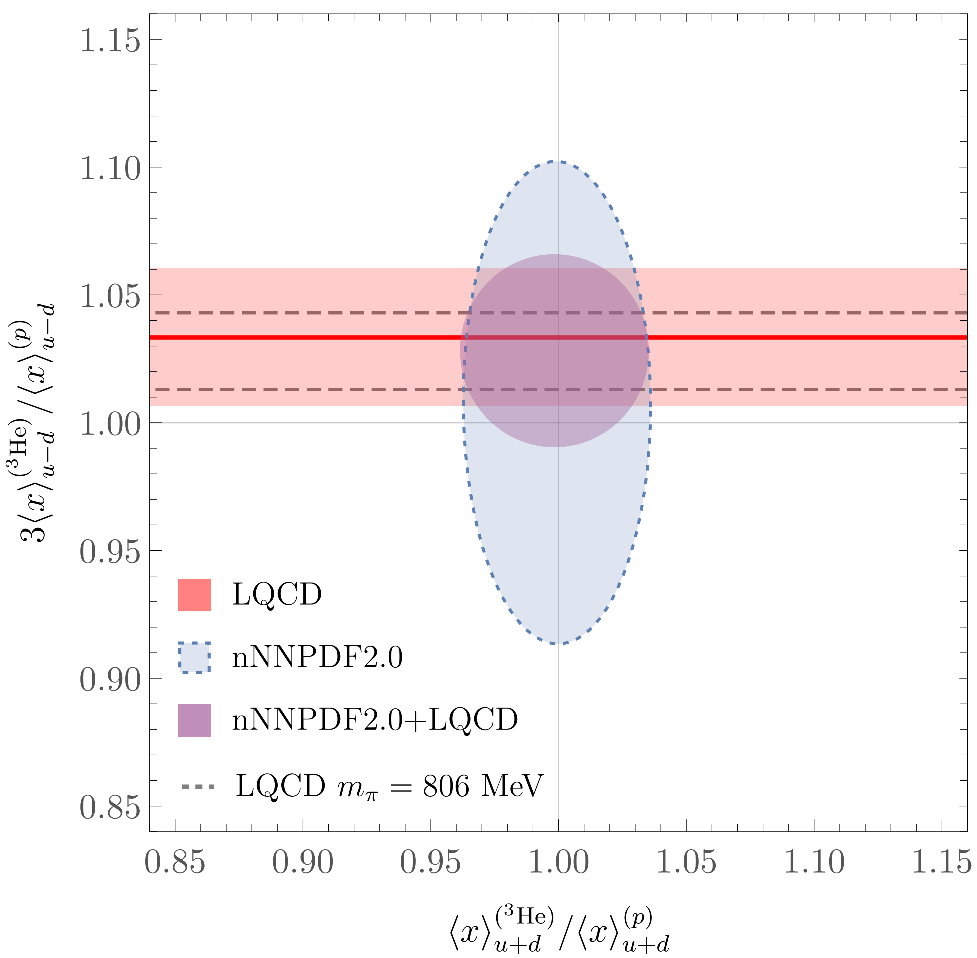
Winter et al [NPLQCD], PRD 96 (2017)

Detmold et al [NPLQCD], arXiv:2009.05522

Results used to constrain EFT, extrapolate to physical results

$$N^\dagger \tau^3 N + \alpha_{3,n} N^\dagger \tau^3 N N^\dagger N + \ldots$$

Flavor dependence of nuclear PDFs is poorly known experimentally, first LQCD + EFT results already provide non-trivial constraints on nuclear PDFs



Detmold et al [NPLQCD], arXiv:2009.05522

Conclusions

Describing νA scattering from the Standard Model requires control of QCD over a wide range of scales and physics processes

Challenging but possible through lattice QCD + nuclear many body methods

- Nucleon form factors
- Pion production
- Two-body currents
- PDF constraints

→

- Nuclear EFTs
- Spectral functions
- Nuclear PDFs

→

- Event generators