Nuclear matrix elements for neutrino-nucleus scattering from lattice QCD

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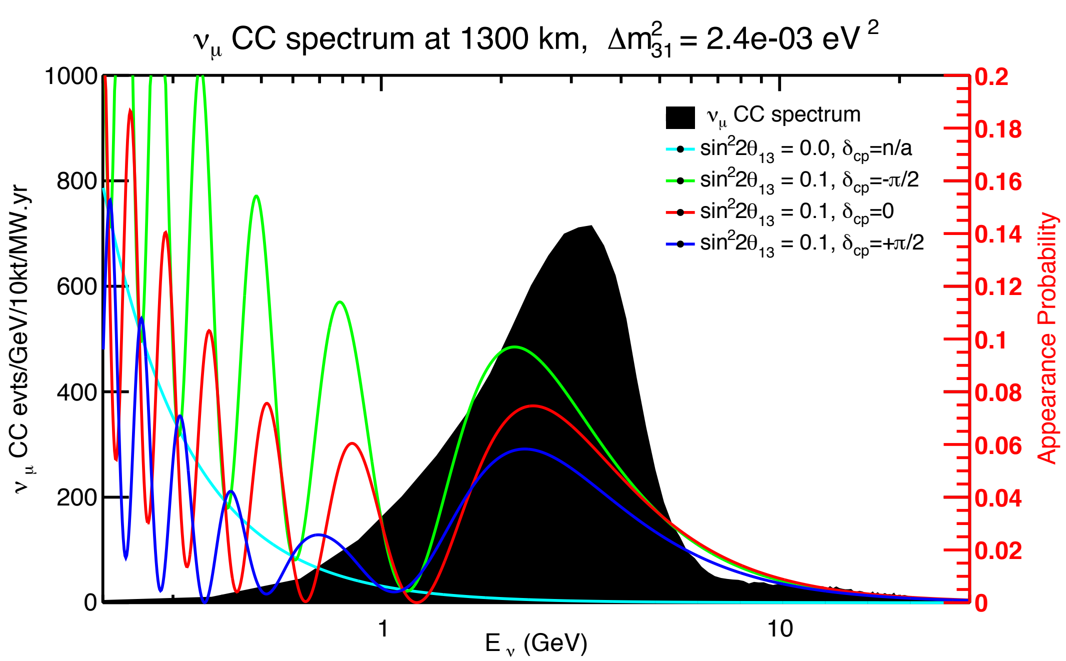
Image Credit: 2018 EIC User's Group Meeting

Massachusetts Institute of Technology

Neutrino oscillation experiments

Seek to determine neutrino mass hierarchy, mixing parameters, CP violating phase

To differentiate between mixing & CP parameter scenarios → Need neutrino energy reconstruction from final state to better than 100 MeV



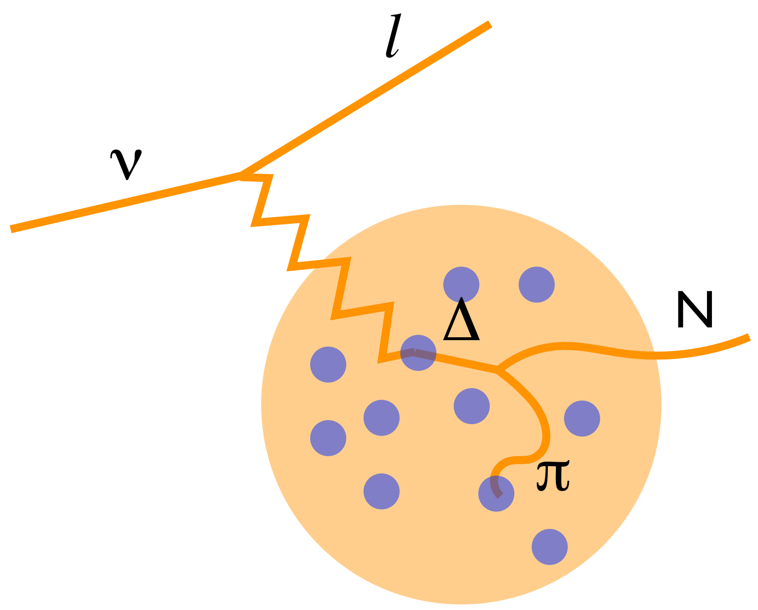
Lattice QCD: direct non-perturbative QCD predictions for nucleon and nuclear matrix elements

e.g., **axial** and **pseudo-scalar form factors** important in **quasi-elastic** region

[J.A. Formaggio, G.P. Zeller, RMP84 (2012) 1307]

Nuclear effects

- Targets are nuclei (C, Fe, Ar, Pb, H_2O) so how relevant are nucleon FFs, PDFs?
  - EMC effect
  - Suppression of g_A in Gamow-Teller transitions



- Experimental investigations: MINERνA

Calculate matrix elements in light nuclei from lattice QCD

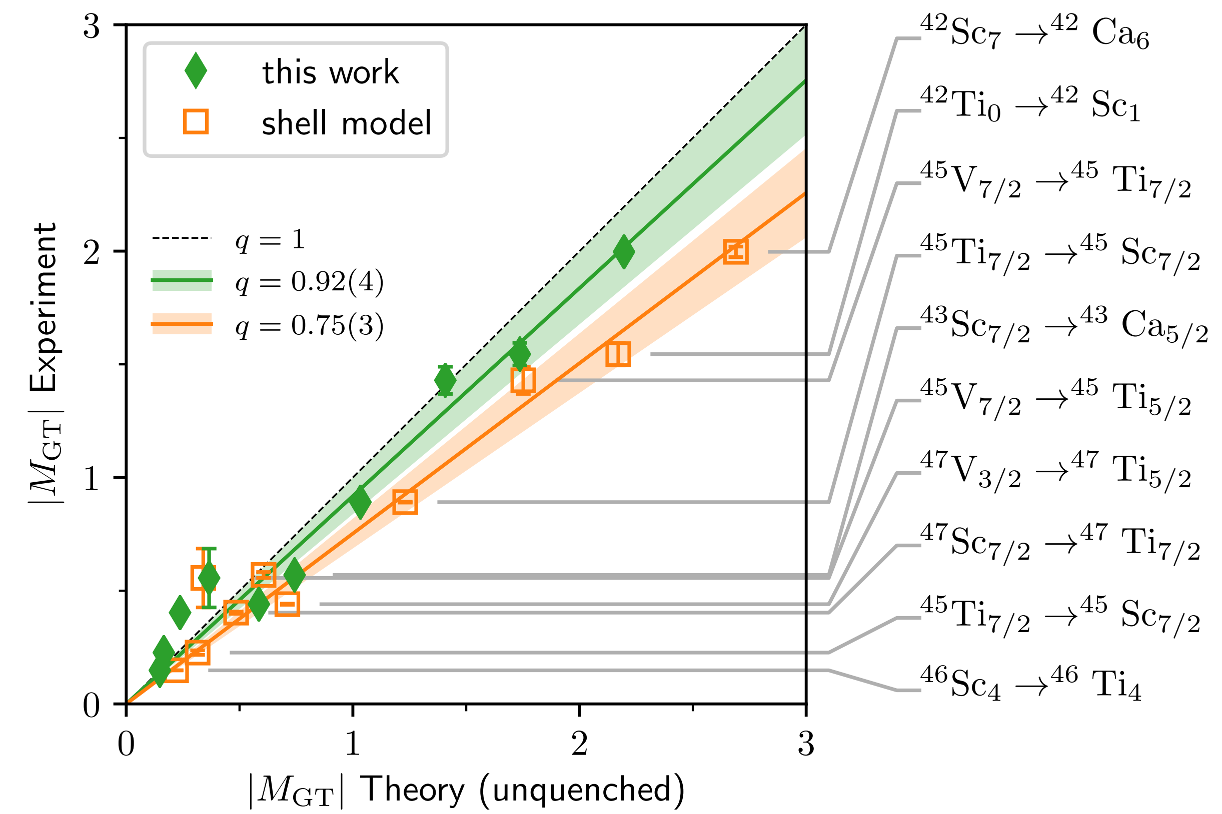
EFT to reach heavy nuclear targets relevant to experiment

e.g., First calculations of axial charge of light nuclei, EMC effect in light nuclei

Nuclear effects

How well do we know nuclear matrix elements?

- Gamow-Teller transitions in nuclei are a stark example of importance of nuclear effects
  - Well-measured for large range of nuclei where the spectrum is well described (30<A<60)
  - Historically nuclear structure calculations were systematically off by 20–30%
  - Correct using two-body currents where they are known

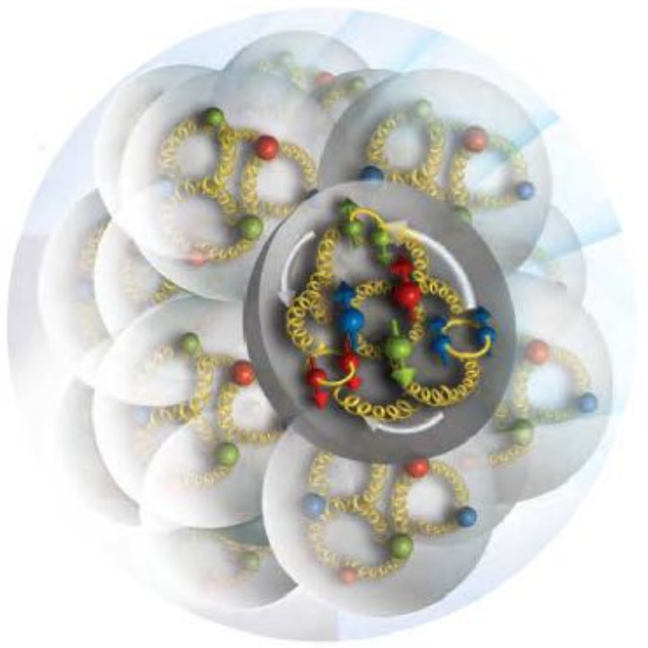


[Gysbers et al, Nature Phys. 15 (2019) no. 5 428-431]

Nuclear physics from lattice QCD

Nuclei on the lattice are HARD

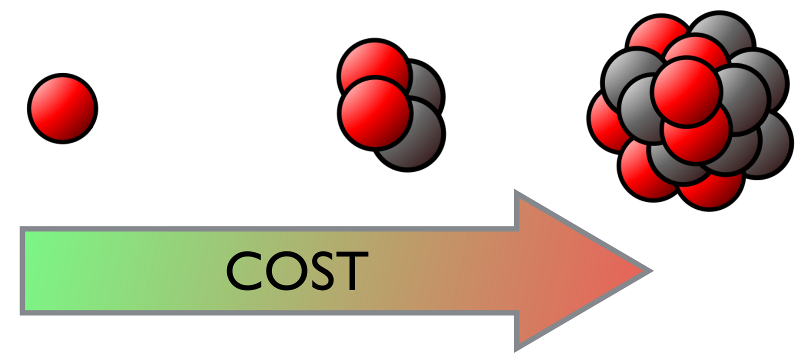
- Calculations of matrix elements of currents in light nuclei just beginning:
  - Controlled calculations of spectrum of light nuclei yet to be achieved
  - First exploratory calculations of matrix elements taking place now
- With sufficient computing resources, calculations are in principle possible:
  - Deeply bound nuclei: same techniques as for single hadron matrix elements
  - Near threshold states: need to be careful with volume effects



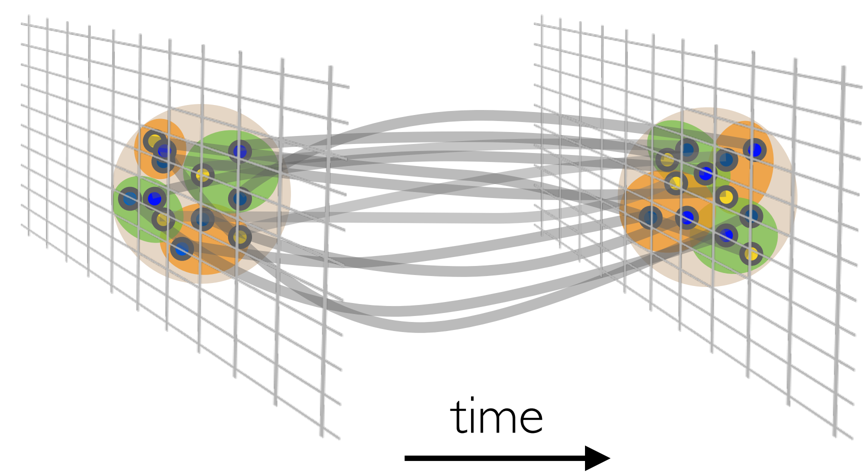
Nuclear physics from lattice QCD

Nuclei on the lattice are HARD

- **Noise:**
  Statistical uncertainty grows exponentially with number of nucleons



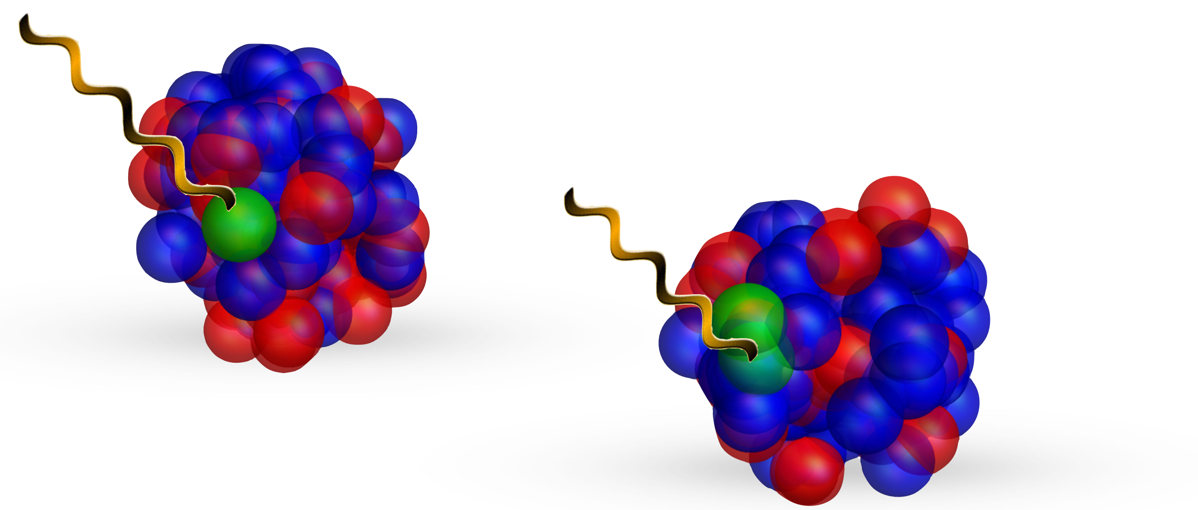
- **Complexity:**
  Number of contractions grows factorially

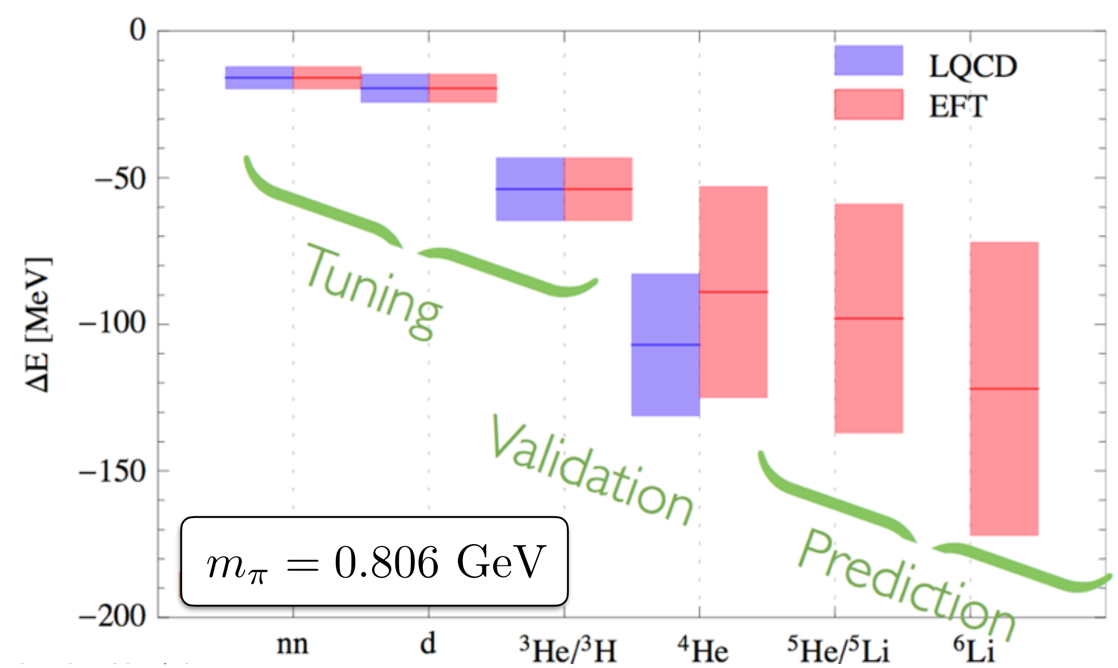


Calculations possible for A<5

Larger nuclei

- What about larger (phenomenologically-relevant) nuclei?
- Nuclear effective field theory:
  - 1-body currents are dominant
  - 2-body currents are sub-leading but non-negligible
- Determine one body contributions from single nucleon
- Determine few-body contributions from A=2,3,4...
- Match EFT and many body methods to LQCD to make predictions for larger nuclei





[Barnea et al., PRL 2015]

Nuclear physics from lattice QCD

Nuclear matrix elements from lattice QCD studied only by the NPLQCD Collaboration to date

- Proton-proton fusion and tritium β-decay [PRL 119, 062002 (2017)]
- Double β-decay [PRL 119, 062003 (2017), PRD 96, 054505 (2017)]
- Gluon structure of light nuclei [PRD 96 094512 (2017)]
- Scalar, axial, tensor MEs [PRL 120 152002 (2018), PRD 103, 074511 (2021)]
- Baryon-baryon interactions, including QED [PRD 103, 054504 (2021), PRD 103, 054508 (2021)]
- EMC-type effects in light nuclei [PRD 96 094512 (2017), PRL 126, 202001 (2021)]

Many other collaborations are studying nuclei from lattice QCD

- **PACS-CS**
  e.g. ,Yamazaki et al, PRD 92 (2015);
- **Callatt**
  e.g., E Berkowitz et al, PLB 765 (2017); Hörz et al, PRC 103 (2021)
- **Mainz**
  e.g., A. Francis et al, PRD 99 (2019); Green et al, [2103.01054]
- **HALQCD**
  e.g., Ishii et al, PRL 99 (2007) (potential approach)

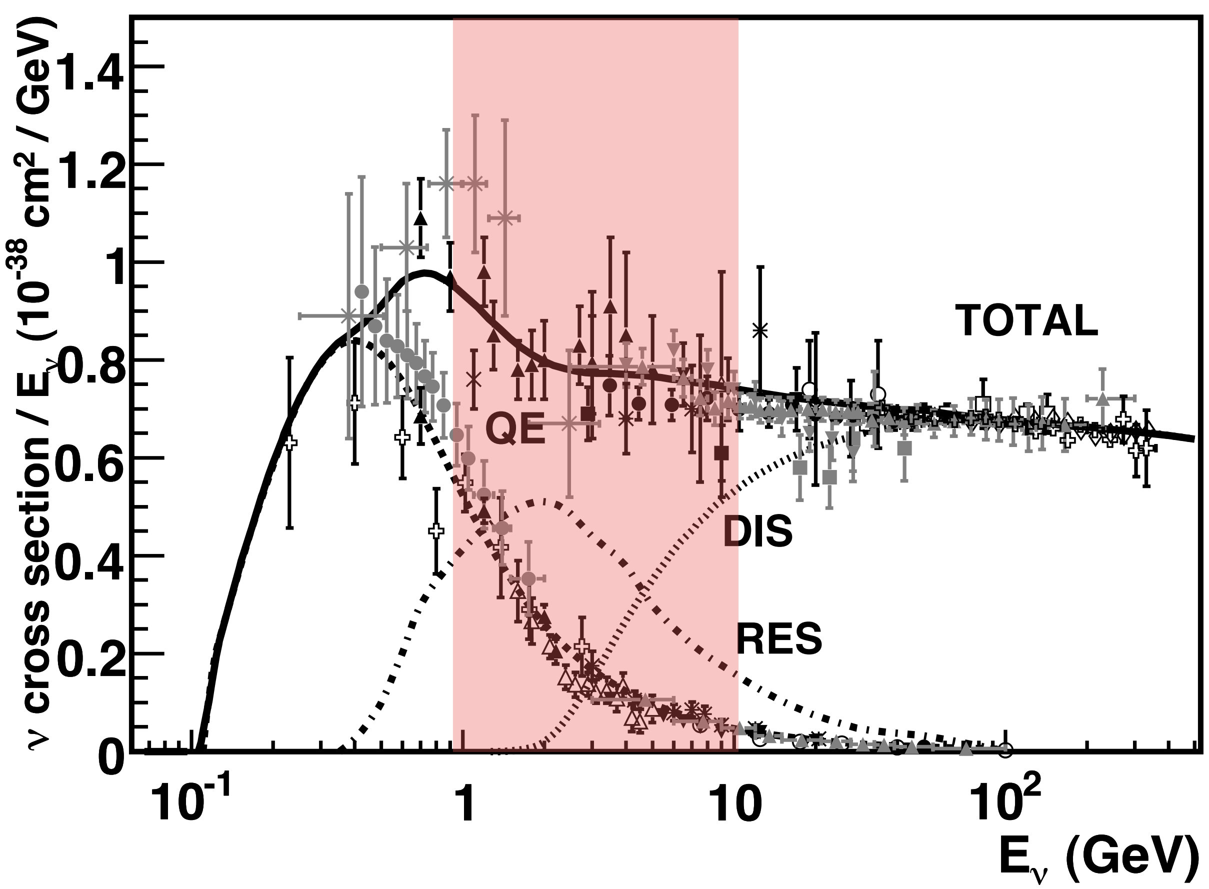
Constraining ν-nucleus interactions

- For DUNE neutrino energy distributions peak at 1-10 GeV

- Challenging region: several processes contribute
    - Quasielastic lepton scattering
    - Deep inelastic scattering
    - Resonances

- Lattice QCD can provide direct non-perturbative QCD predictions of nucleon and **nuclear** matrix elements

Neutrino charged-current cross-section



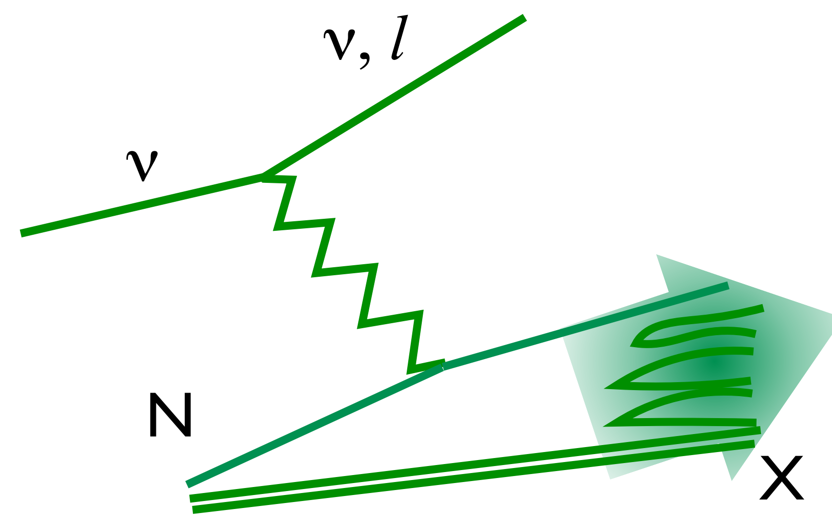
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

Inelastic region

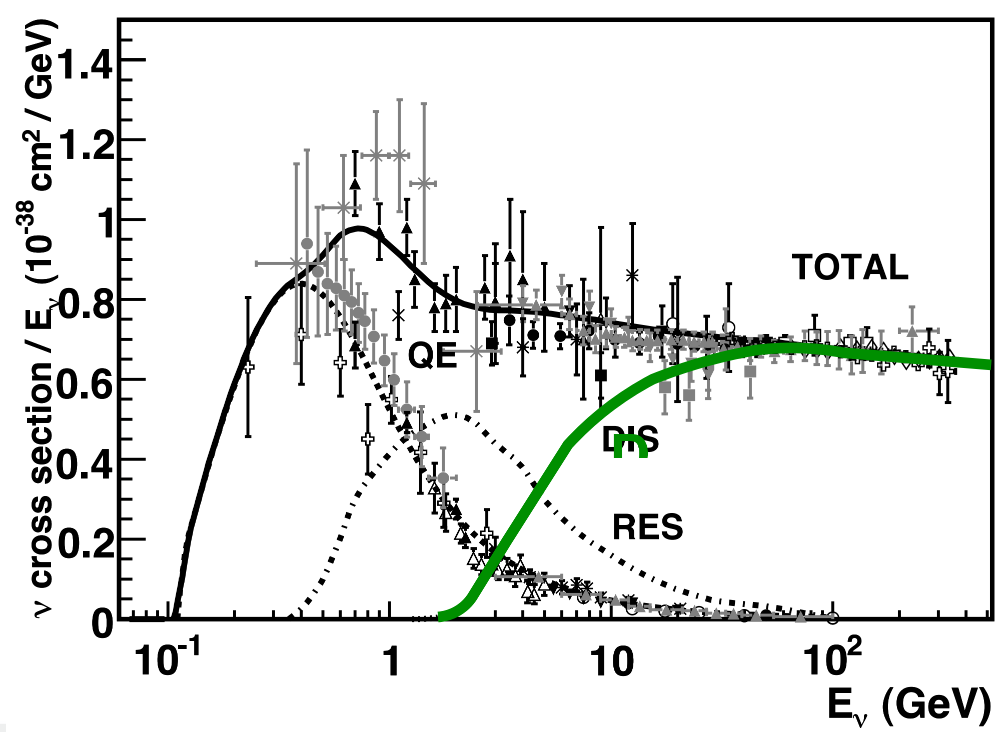
- In inelastic regime, quark PDFs of the nucleon control scattering cross-section
- Both resonances and DIS are important
- Multi-meson channels may become important
- Nuclear effects are different in νA vs. eA
- DIS structure functions accessible in LQCD
    - Low moments of structure functions controlled

$$M_n = \int_{-1}^{1} x^n f(x) dx, \quad n \lessapprox 4$$

    - x-dependence: systematics challenging, but rapid and exciting progress!



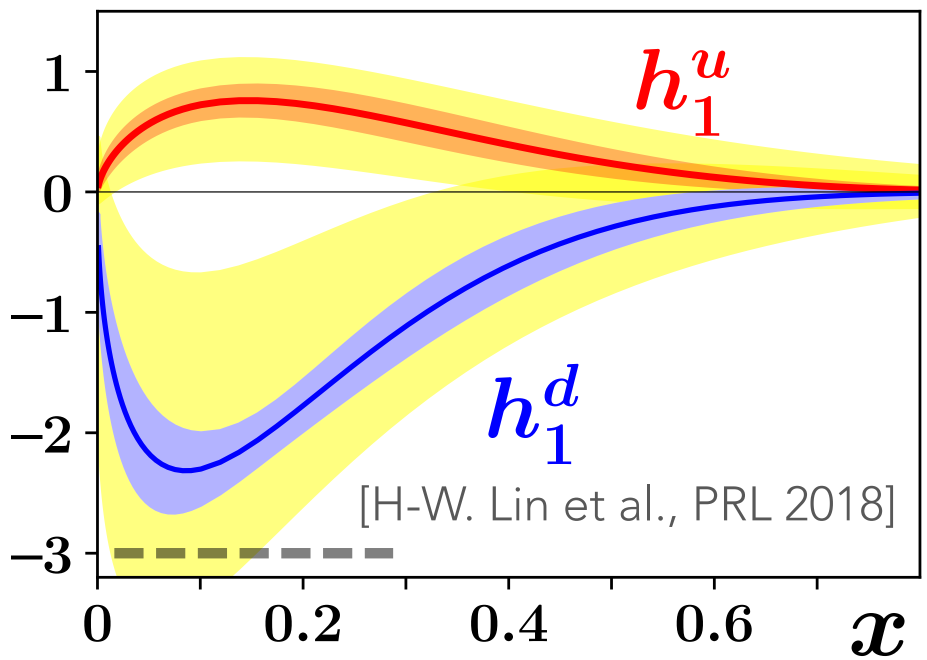
ν charged-current cross-section



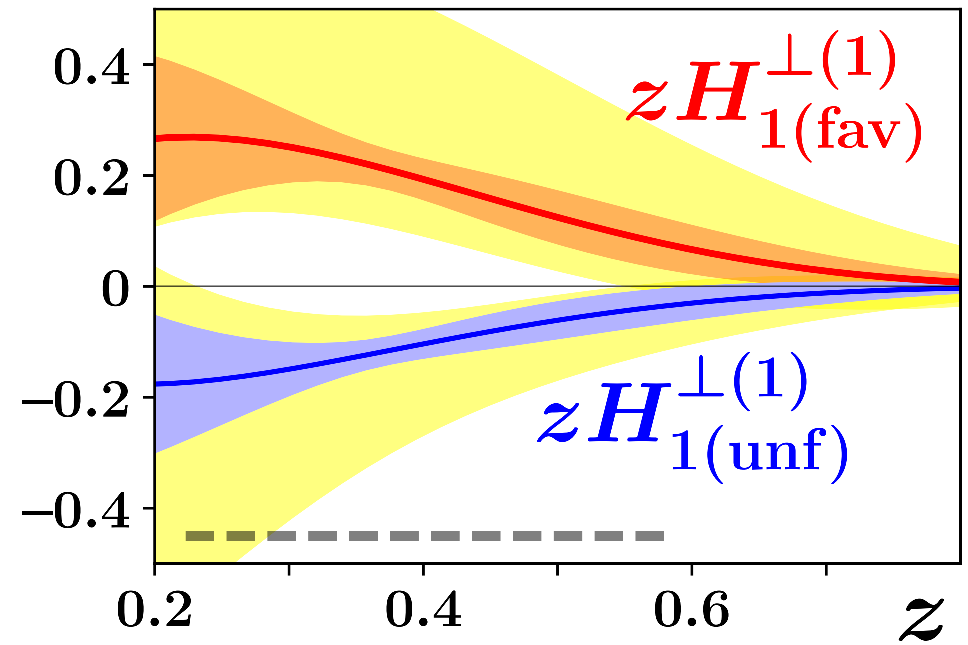
Constraints on global PDF fits

- Including lattice QCD results for moments in global PDF fits can yield significant improvements
- Community white paper (LQCD + phenomenologists) assessed potential impacts [Lin et al., Prog. Part. Nucl. Phys 100 (2018), 107]

Transversity PDFs



Collins fragmentation functions

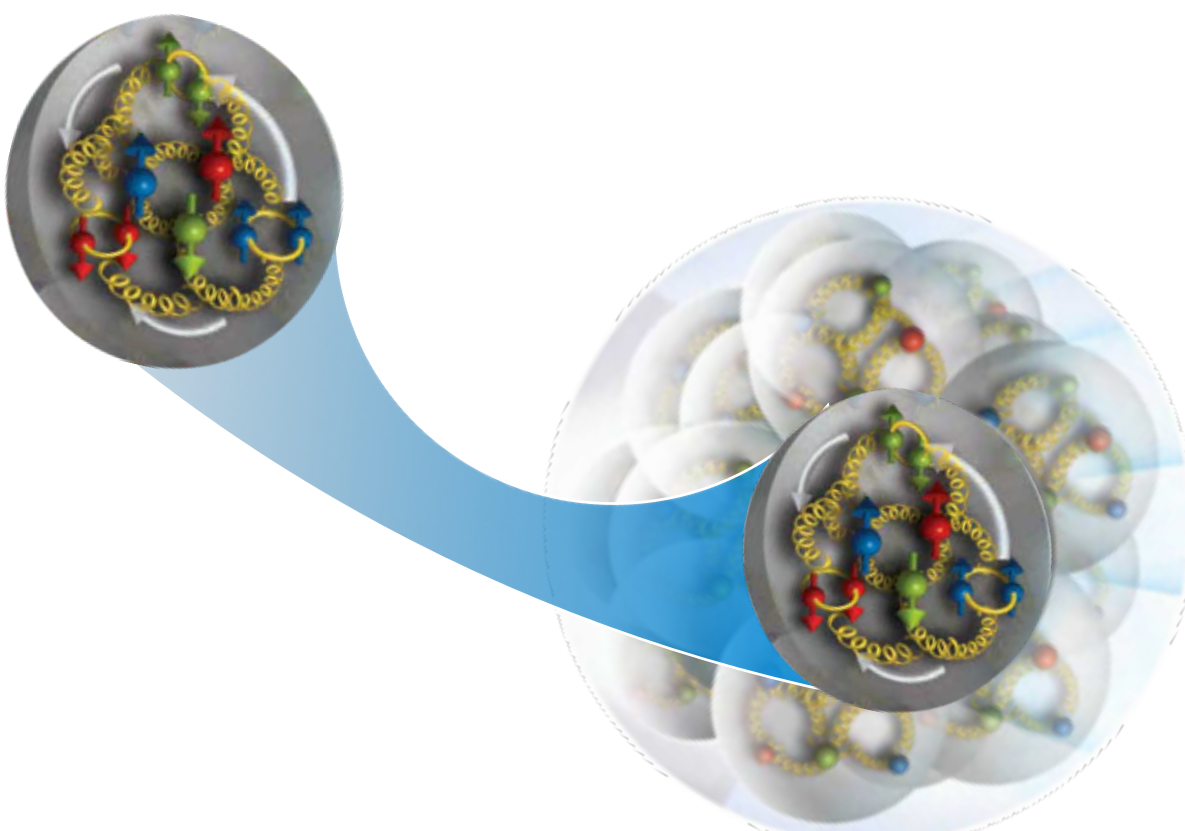


Yellow: SIDIS data only: direct constraints in region indicated by dashes
Blue/Red: SIDIS + lattice QCD for tensor charge (zeroth moment)

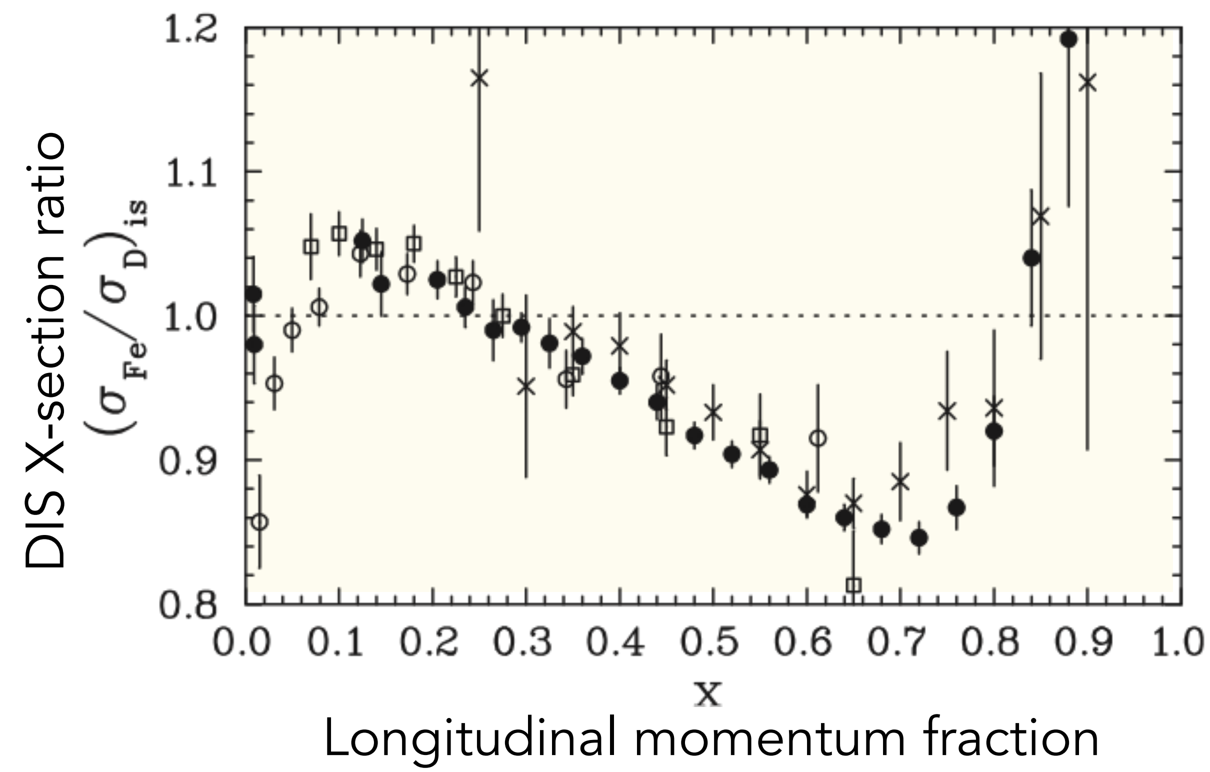
EMC-type effects from Lattice QCD

Understanding the quark and gluon structure of matter

How is the partonic structure of nuclei different from that of nucleons?



Encoded in EMC-type effects



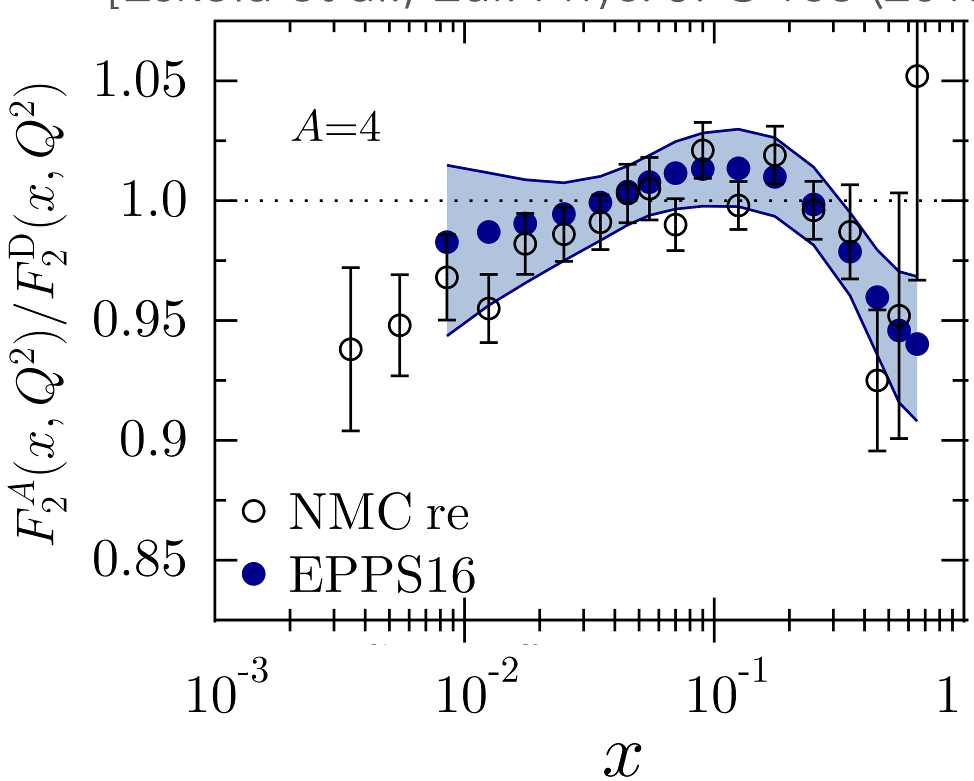
(EMC: Aubert et al., 1983)

EMC effects in Mellin moments

First investigation of EMC-type effects from LQCD:
Nuclear effects in Mellin moments of PDFs

- Calculable from local operators
- BUT EMC effects in moments are very small

[Eskola et al., Eur. Phys. J. C 163 (2017)]



Classic EMC effect is defined in F_2:

$$F_2(x,Q^2) = \sum_{q=u,d,s\ldots} x\, e_q^2 \left[q(x,Q^2) + \overline{q}(x,Q^2)\right]$$

Number density of partons of flavour q

x-integrals of numerator and denominator $\int_0^1 dx\, x^n q(x,Q^2)$

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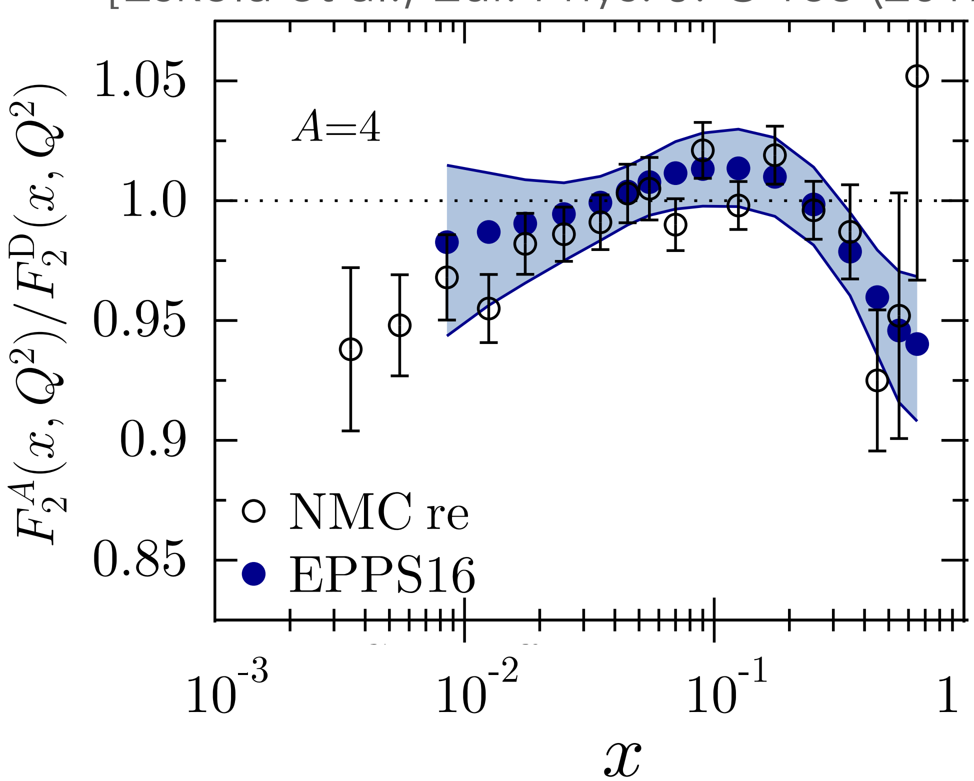
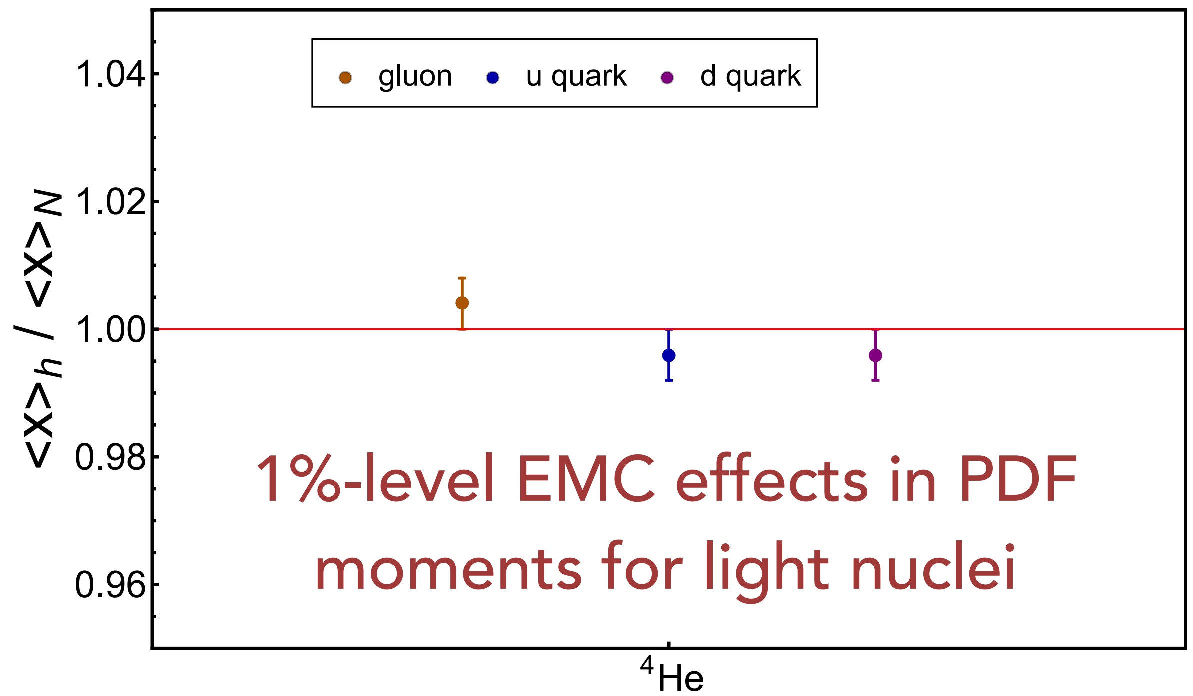




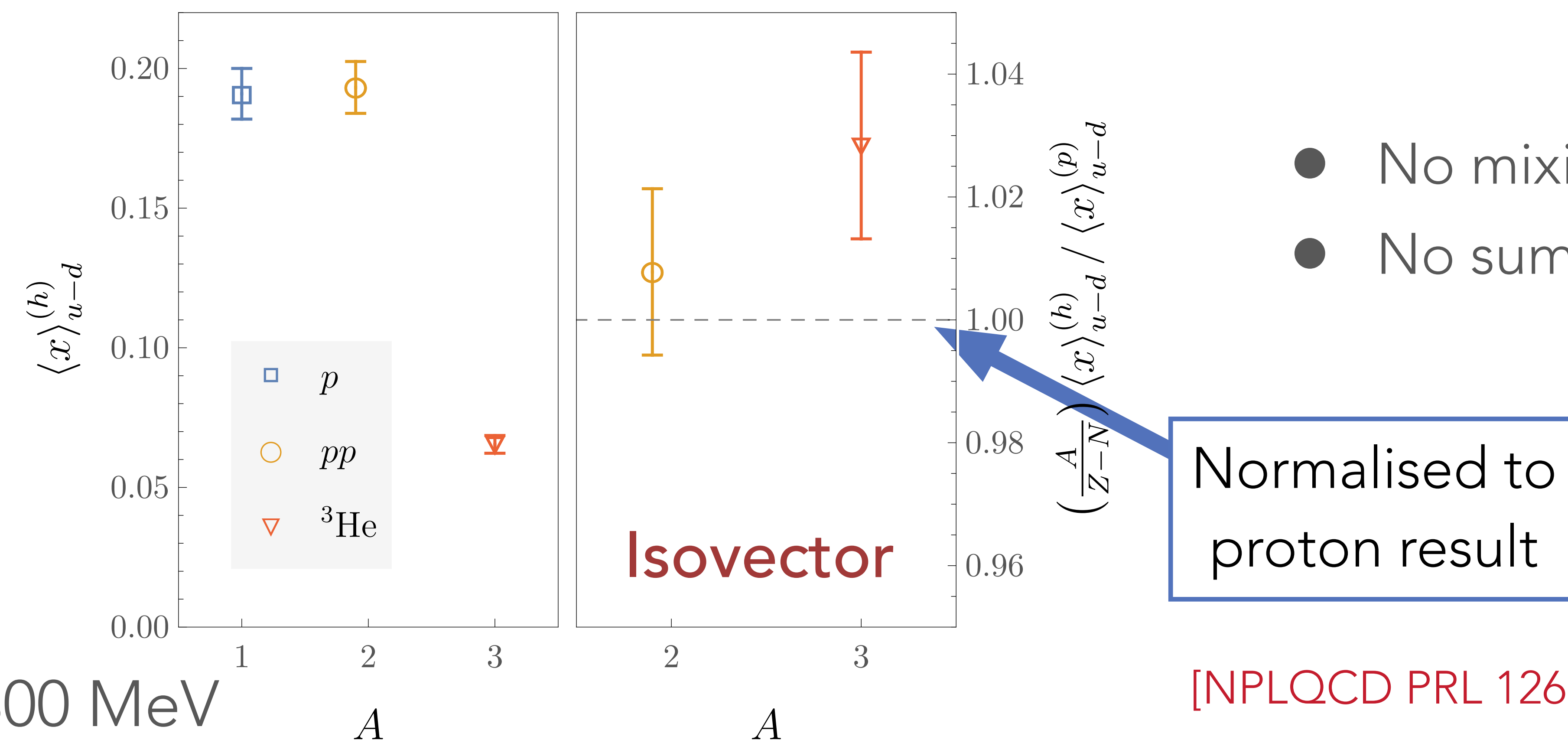
1%-level EMC effects in PDF moments for light nuclei

Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei
first QCD determination of momentum fraction of nuclei

- Bounds on EMC effect in moments at ~few percent level, consistent with phenomenology [2009.05522 [hep-lat] (2021)]

Ratio of quark momentum fraction in nucleus to nucleon



- No mixing
- No sum rule constraint

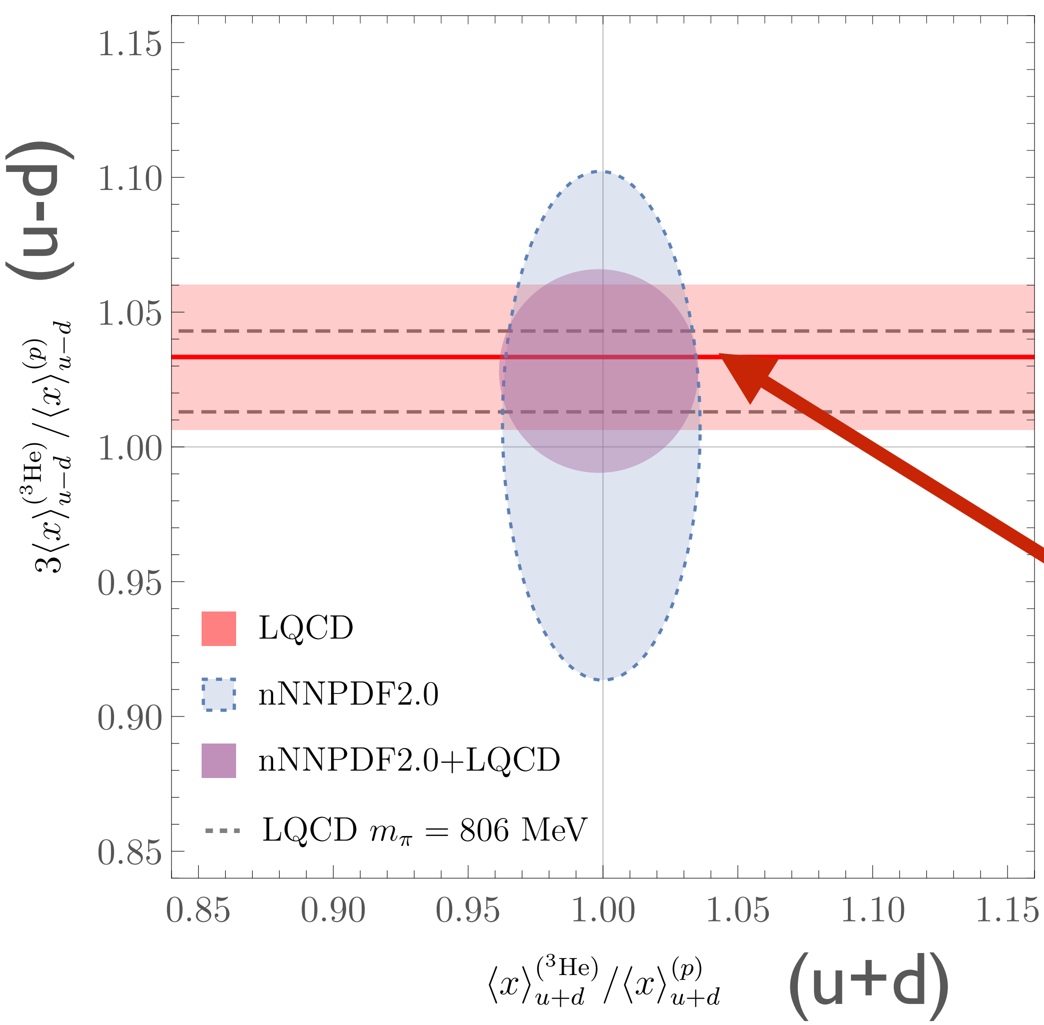
m_{π} ~800 MeV

[NPLQCD PRL 126, 202001 (2021) [2009.05522]]

Momentum fraction of ^{3}He

Matrix elements of the Energy-Momentum Tensor in light nuclei
→ **first QCD determination of momentum fraction of nuclei**

Ratio of $^3\mathrm{He}$ to proton momentum fractions



- Match isovector (u-d quark combination) momentum fraction to low-energy constants of effective field theory, extrapolate to physical quark masses
- Include into nNNPDF global fits of experimental lepton-nucleus scattering data

Blue → Purple:
Improvement using theory constraints

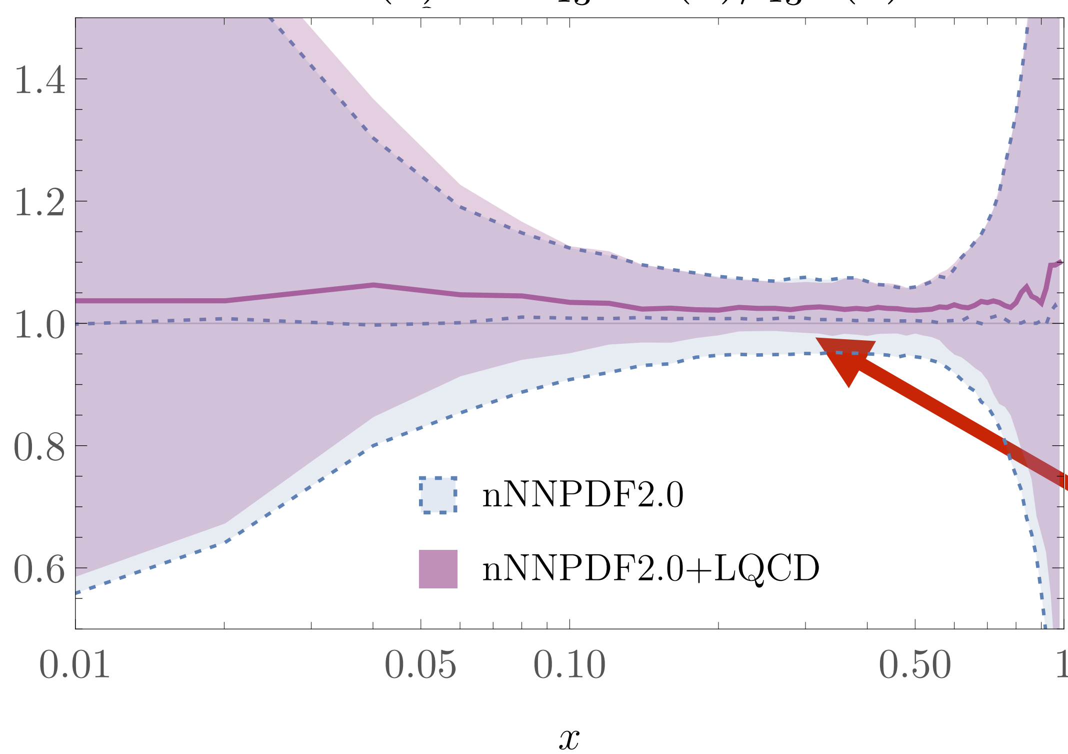
[NPLQCD PRL 126, 202001 (2021) [2009.05522]]

Momentum fraction of ^{3}He

Matrix elements of the Energy-Momentum Tensor in light nuclei
first QCD determination of momentum fraction of nuclei

Ratio of ^{3}He to proton parton distributions

$$R^{(^3\mathrm{He})}(x) = 3q_3^{(^3\mathrm{He})}(x)/q_3^{(p)}(x)$$



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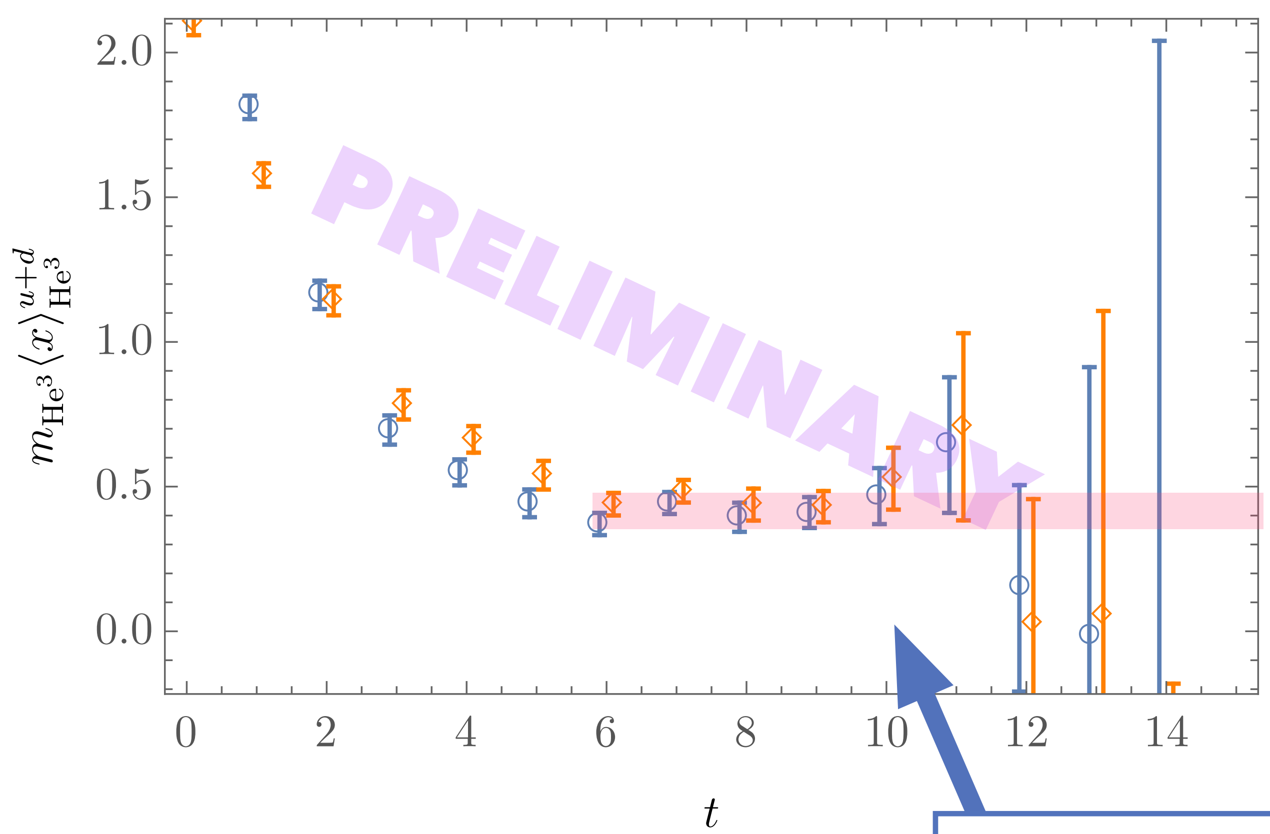
[NPLQCD PRL 126, 202001 (2021) [2009.05522]]

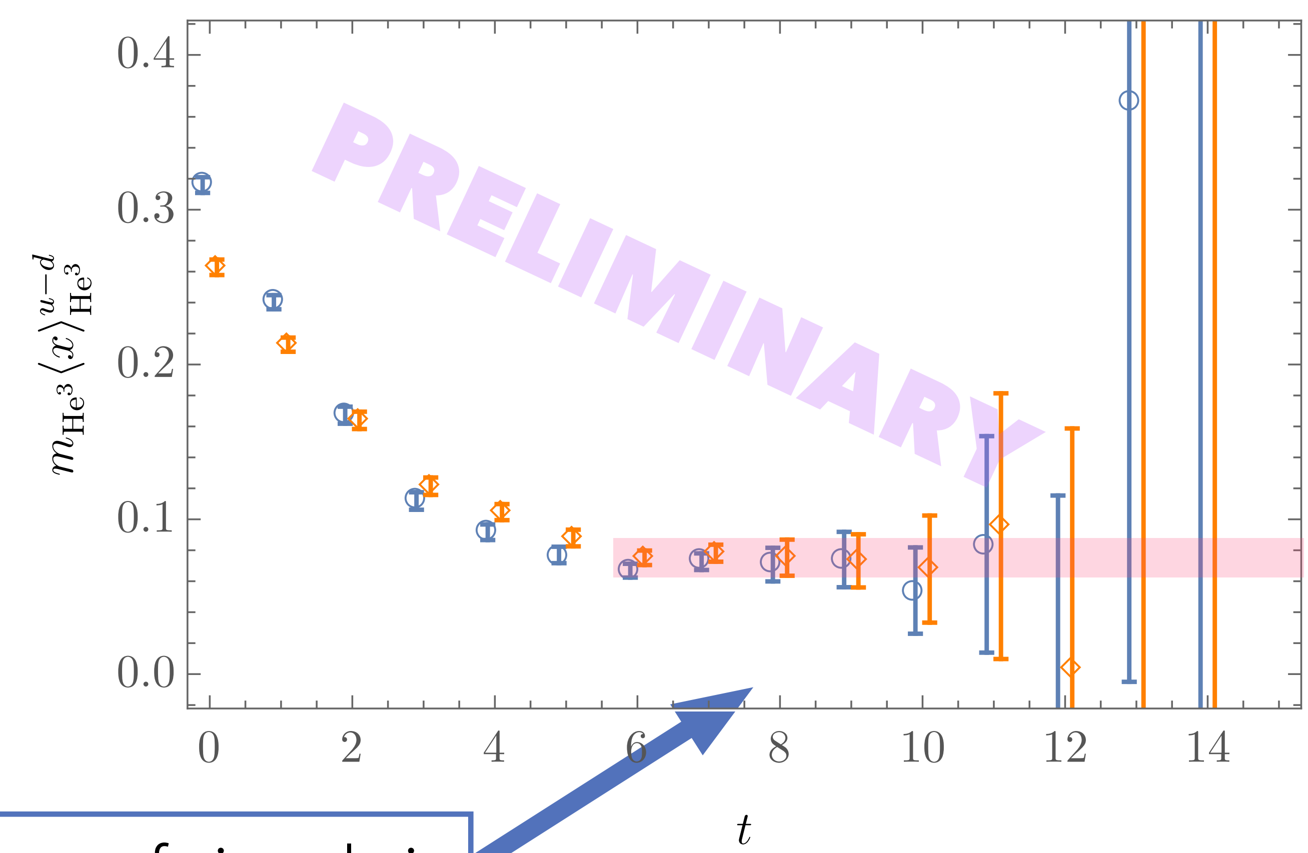
Momentum fractions of nuclei

- Work in progress at close-to-physical values of the quark masses

Isoscalar



Isovector



First evidence of signals in physical-point data

- Polarised PDFs also accessible from moments

NPLQCD

Quasi-elastic scattering

Cross-section for quasi-elastic neutrino-nucleon scattering

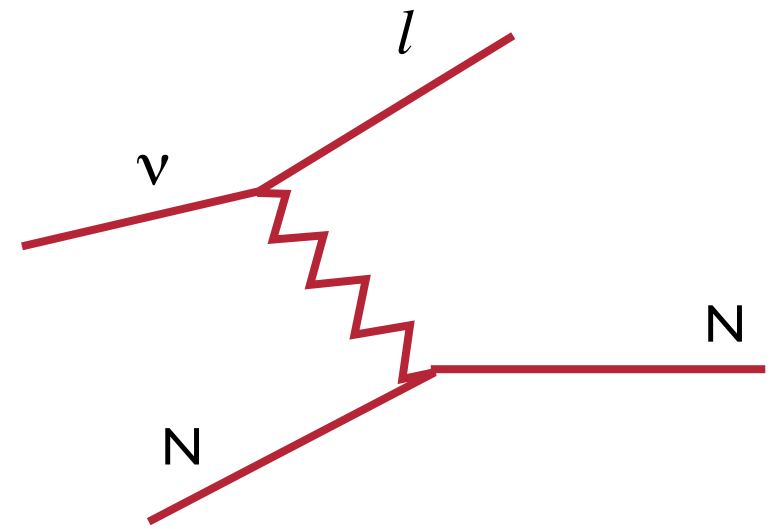
$$\frac{d\sigma}{dQ^2} = \frac{G_f^2 M^2 \cos^2\theta_C}{8\pi E_\nu^2}\left[A \mp \frac{(s-u)}{M^2}B + \frac{(s-u)^2}{M^4}C\right]$$

$$A = \frac{(m^2+Q^2)}{M^2}\Big[(1+\tau)G_A^2 - (1-\tau)F_1^2 + \tau(1-\tau)F_2^2 + 4\tau F_1 F_2$$
$$-\frac{m^2}{4M^2}\left((F_1+F_2)^2 + (G_A+2G_P)^2 - \left(\frac{Q^2}{M^2}+4\right)G_P^2\right)\Big]$$

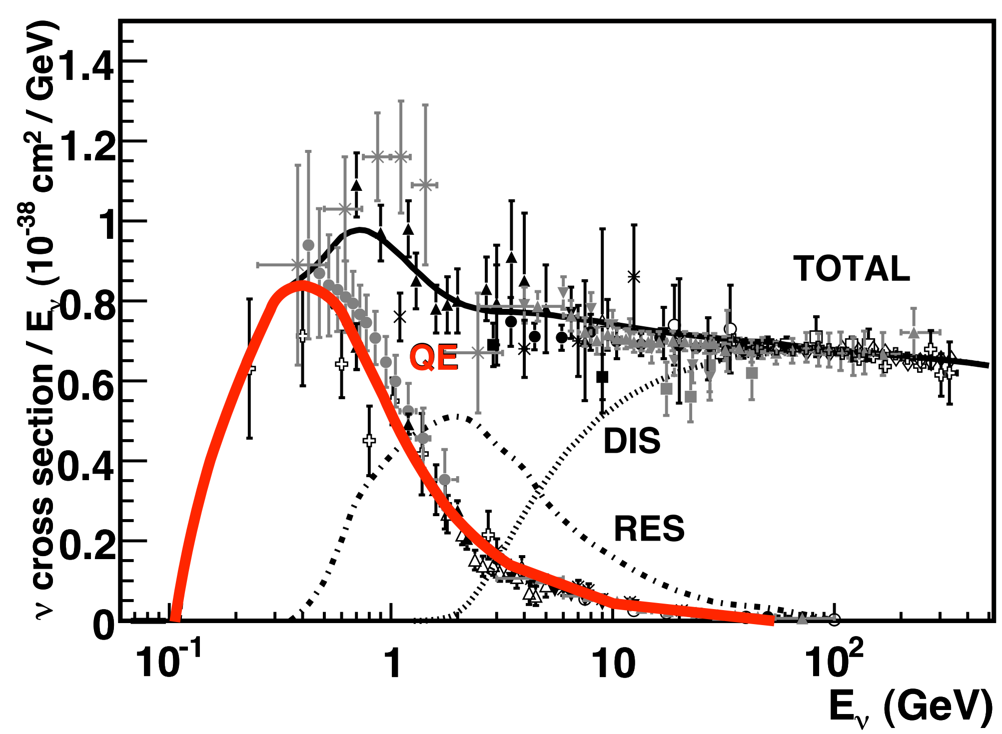
$$B = \frac{Q^2}{M^2}G_A(F_1+F_2)$$

$$C = \frac{1}{4}(G_A^2 + F_1^2 + \tau F_2^2)$$

G_A
- dominant contribution
- largest uncertainty



ν charged-current cross-section

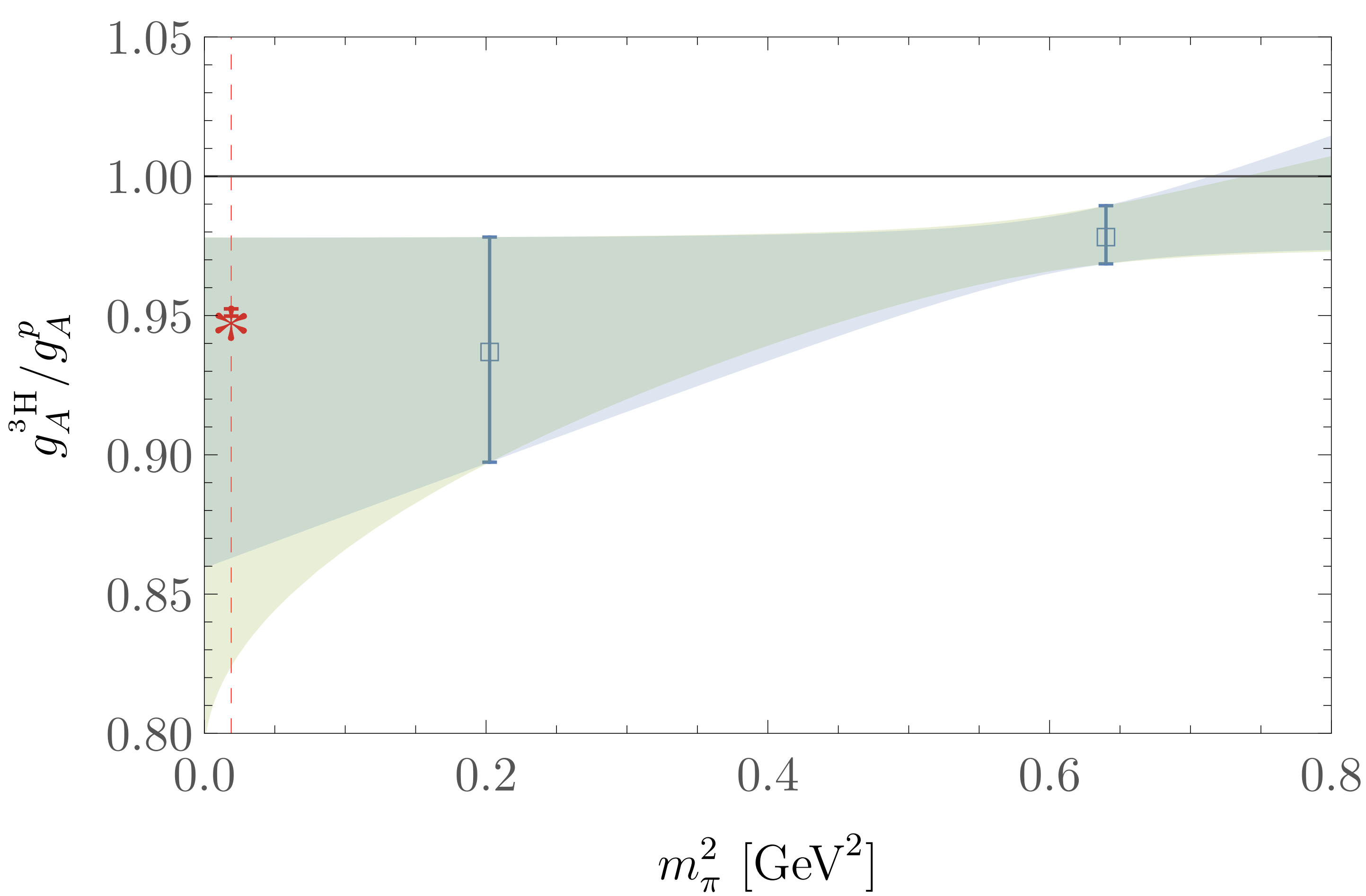


$F_{1,2}$ Well-determined from electron scattering expts

G_P can be related to G_A by pion pole dominance

Axial charge of the triton

- No axial form factors of nuclei from lattice QCD yet
- Axial charge of He: first extrapolation to the physical quark masses this year



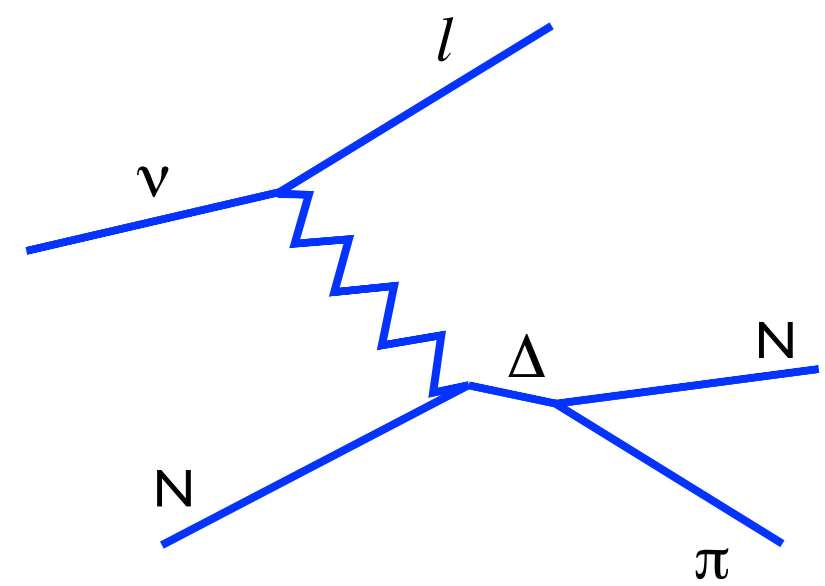
[NPLQCD Phys.Rev.D 103 (2021) 074511]

Development of finite-volume effective field theory for nuclear matrix elements allows connection to larger nuclei

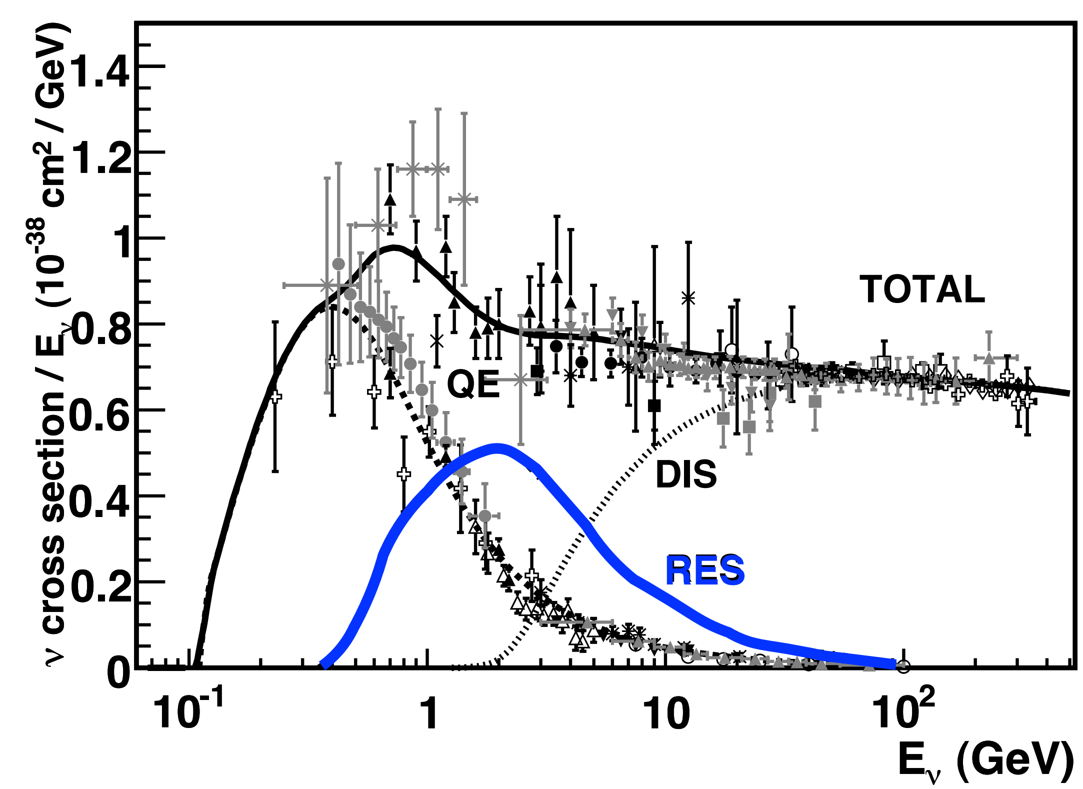
[Detmold & Shanahan, Phys.Rev.D 103, 074503 (2021)]

Resonance region

- Energies above ~200 MeV, inelastic excitations from pion production: Δ resonance dominant
- Very difficult to access experimentally
  Constrained only from PCAC
- QCD calculations possible:
  Need to account for unstable nature of resonance, extract N→Nπ transition FFs
- **Nuclear effects in transition FFs are beyond the scope of even exploratory lattice QCD calculations at this stage**



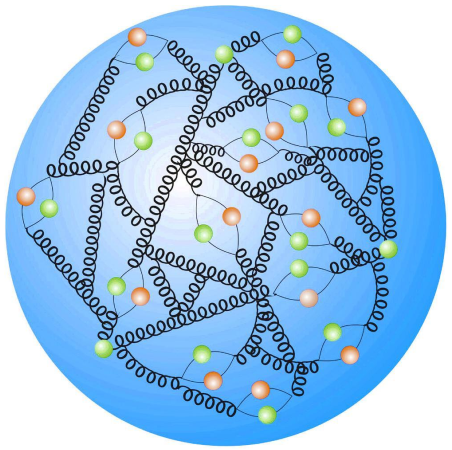
ν charged-current cross-section



LQCD input for ν-nucleus interactions

1. **Directly access QCD single-nucleon form factors without nuclear corrections**

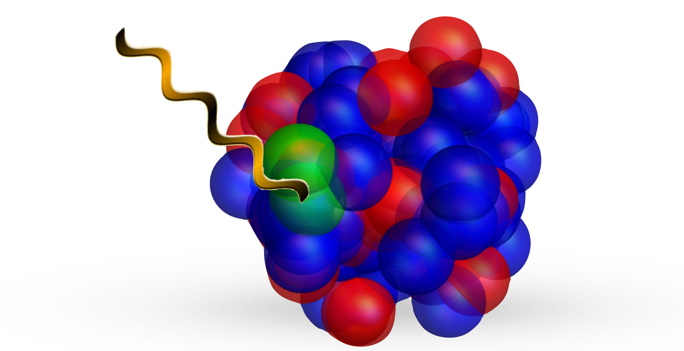
   Reliable calculations with fully-controlled uncertainties



2. **Calculate matrix elements in light nuclei from first principles**

   → EFT to reach heavy nuclear targets relevant to experiment

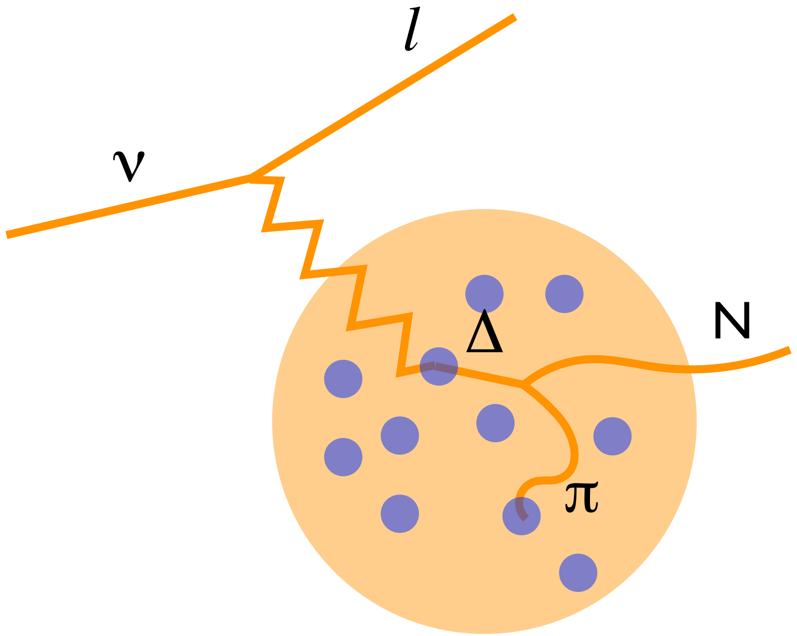
   e.g., First calculations of axial charge of light nuclei, EMC effect in light nuclei



LQCD input for ν-nucleus interactions

Constraints on nuclear matrix elements are possible:

- Pipeline well-defined and tested
- Still quite far from controlled calculations

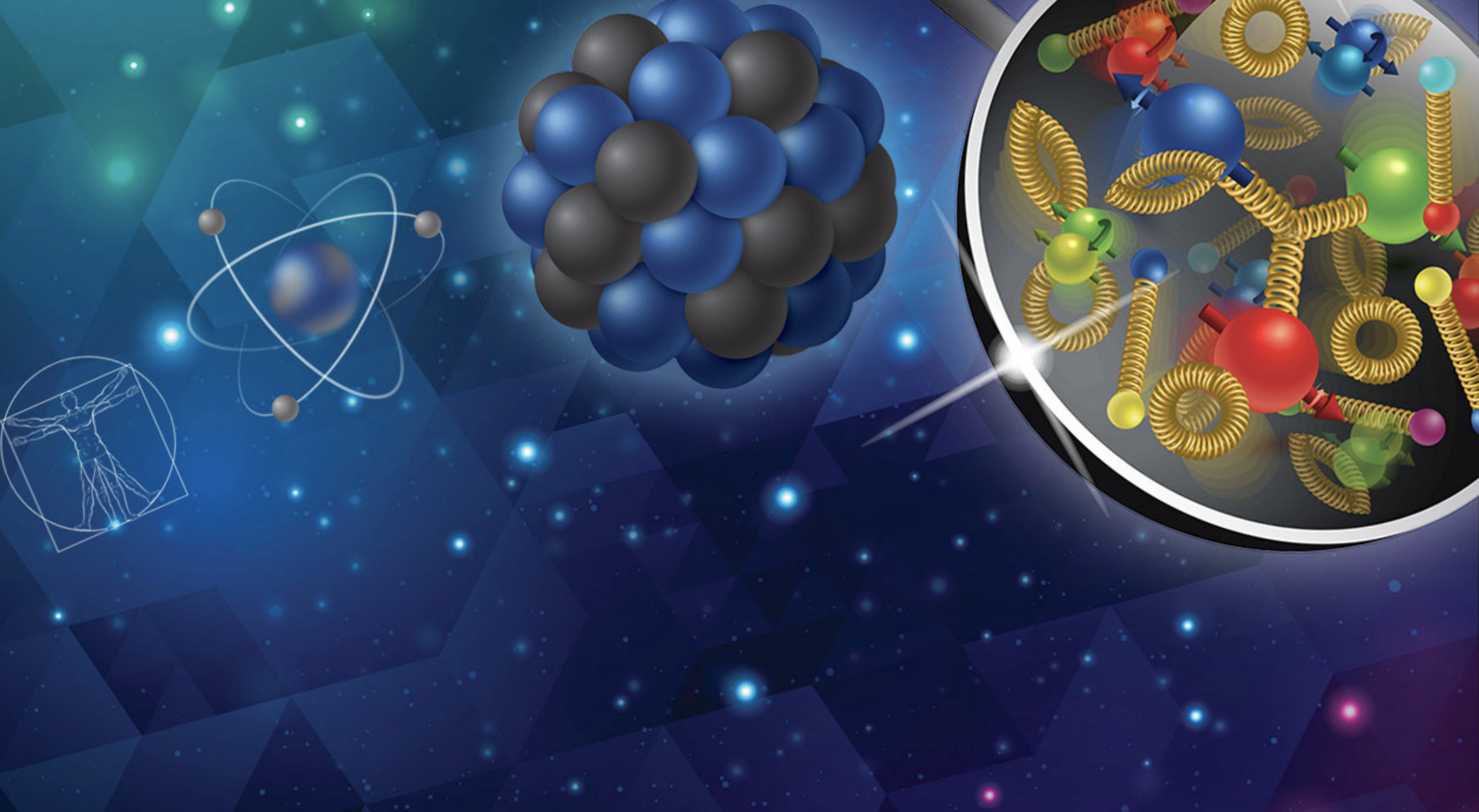


Controlled calculations achievable with ~10-20% uncertainty in 10-year timeframe:

- Axial MEs of nuclei with A<5, including form factors
- Constraints on nuclear PDFs of nuclei with A<5 via moments

Would require substantial investment of computing resources

What are community priorities?



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