Nuclear structure from lattice QCD for BSM physics searches

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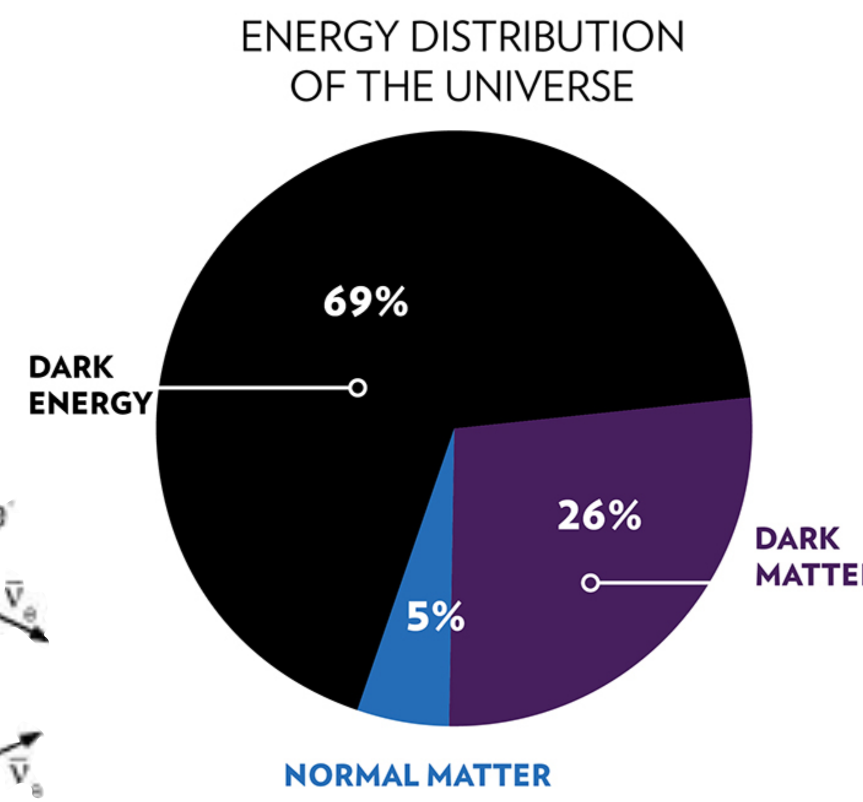
The search for new physics

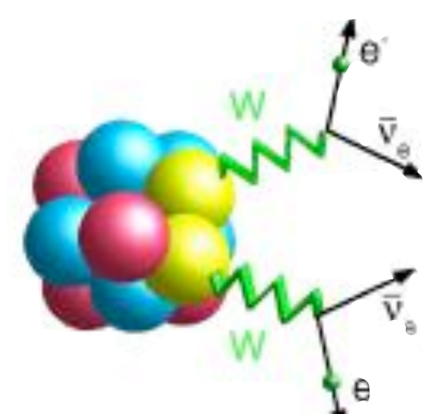
Precise experiments seek new physics at the "Intensity Frontier"

- Sensitivity to reveal small beyond—Standard-Model effects

- Magnetic moments
- Dark matter direct detection
- Neutrino physics
- Charged lepton flavour violation, ββ-decay, proton decay, neutron-antineutron oscillations…

DEEP UNDERGROUND NEUTRINO EXPERIMENT





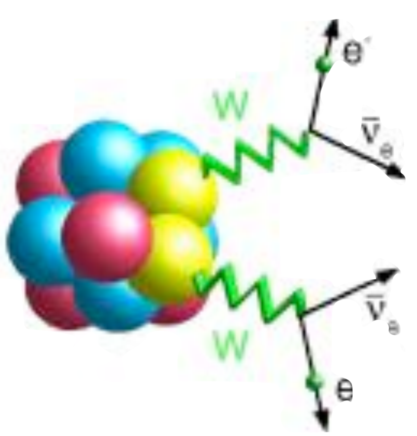
The search for new physics

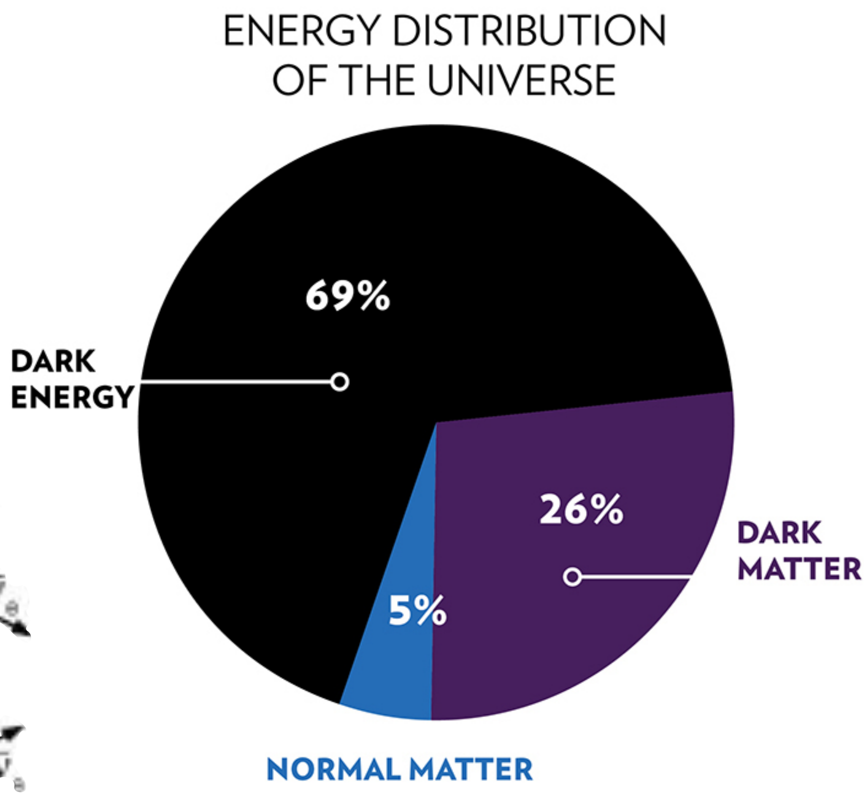
Need to understand the Standard Model physics of nucleons and nuclei

Interpretation of intensity-frontier experiments

- Axial form factors of Argon A=40 DUNE long-baseline neutrino experiment
- Double-beta decay rates of Calcium A=48
- Scalar matrix elements in A=131 XENON1T dark matter direct detection search

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

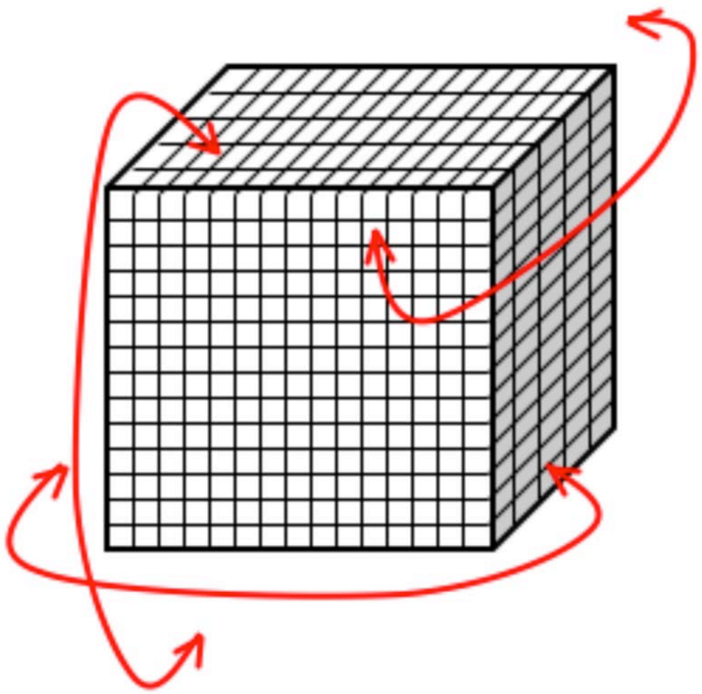




Lattice QCD

Numerical first-principles approach to non-perturbative QCD

- Euclidean space-time
  - Non-zero lattice spacing
  - Finite volume
- Some calculations use larger-than-physical quark masses (cheaper)



Calculate the QCD path integral by **Monte Carlo**

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}A \mathcal{D}\overline{\psi} \mathcal{D}\psi \mathcal{O}[A, \overline{\psi}\psi] e^{-S[A,\overline{\psi}\psi]} \rightarrow \langle \mathcal{O} \rangle \simeq \frac{1}{N_{\mathrm{conf}}} \sum_i^{N_{\mathrm{conf}}} \mathcal{O}([U^i])$$

with field configurations U^i distributed according to $e^{-S[U]}$

Lattice QCD

Numerical first-principles approach to non-perturbative QCD

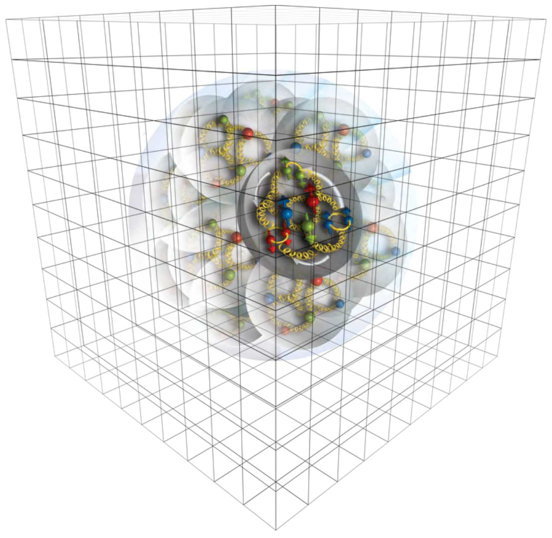
INPUT

Lattice QCD action has same free parameters as QCD: quark masses, α_S

- Fix quark masses by matching to measured hadron masses, e.g., π, K, D_s, B_s for u, d, s, c, b
- One experimental input to fix lattice spacing in GeV (and also α_S), e.g., $2S$-$1S$ splitting in Y, or f_π or Ω mass

OUTPUT

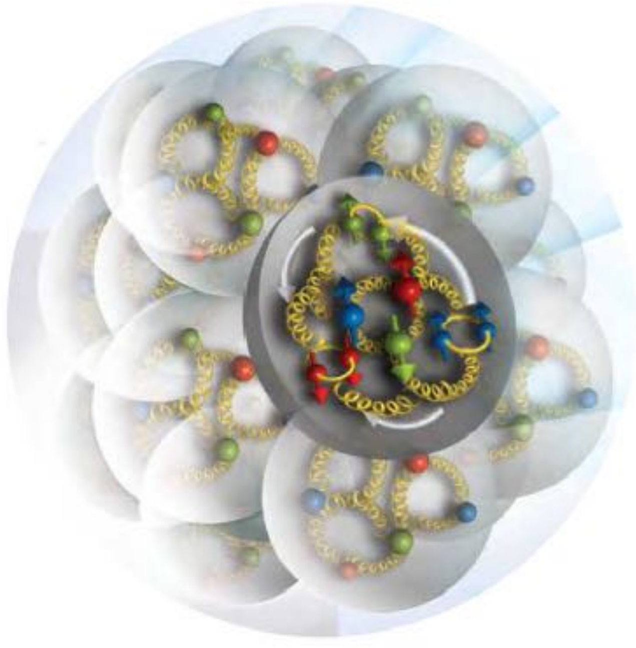
Calculations of all other quantities are QCD predictions



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

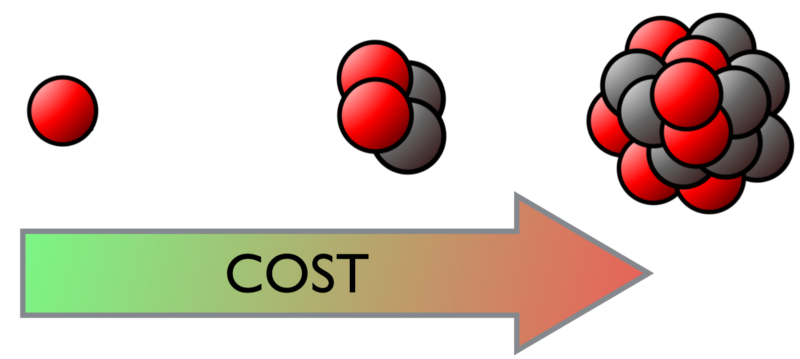


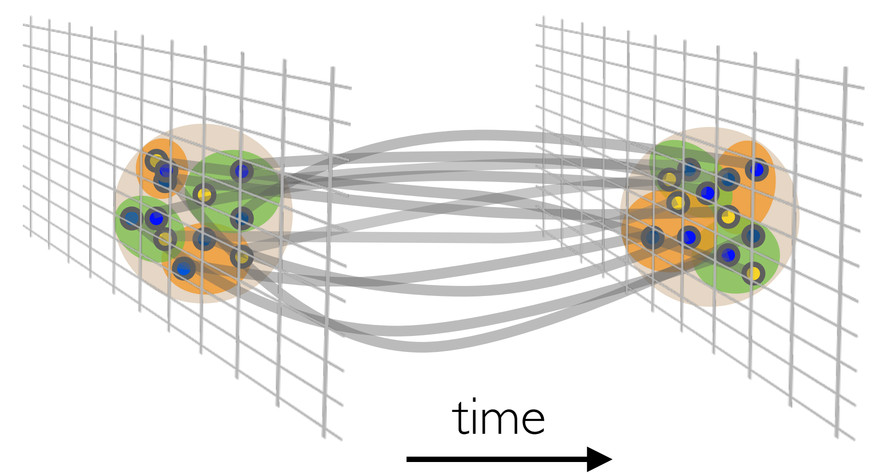
Nuclear physics from lattice QCD

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

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What about larger
(phenomenologically-relevant) nuclei?
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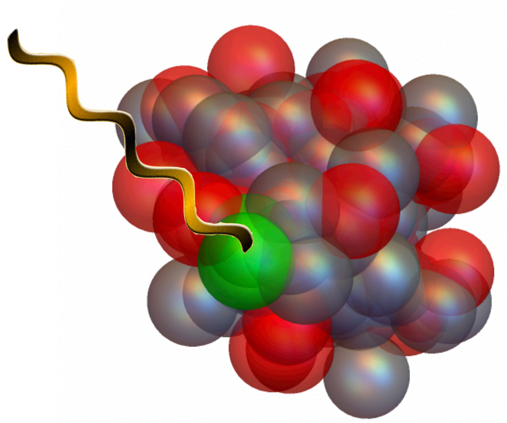
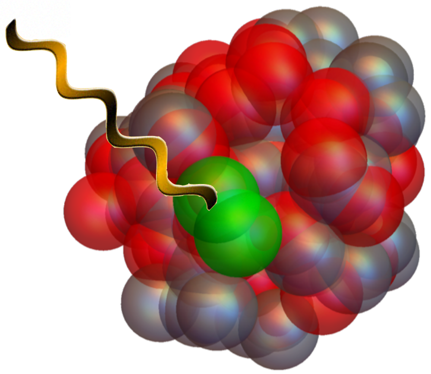


- Nuclear effective field theory:
  - 1-body currents are dominant
  - 2-body currents are sub-leading *but non-negligible*



- Determine one body contributions from single nucleon
- Determine few-body contributions from A=2,3,4...
- Match effective theory and many body methods to lattice results to make predictions for larger nuclei
- Can reproduce axial matrix elements for large nuclei

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)]

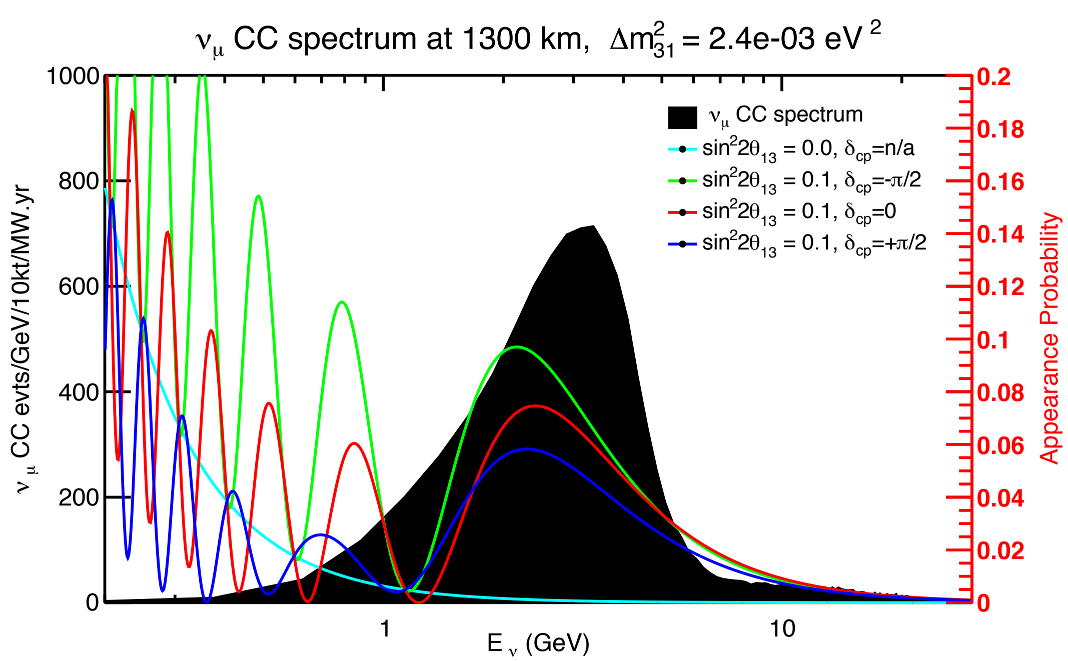
Many other collaborations are studying nuclei from lattice QCD

- **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, PRL 127 (2021)
- **HALQCD**
  e.g., Ishii et al, PRL 99 (2007) (potential approach)

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



Need robust understanding of relevant nucleon and nuclear level amplitudes

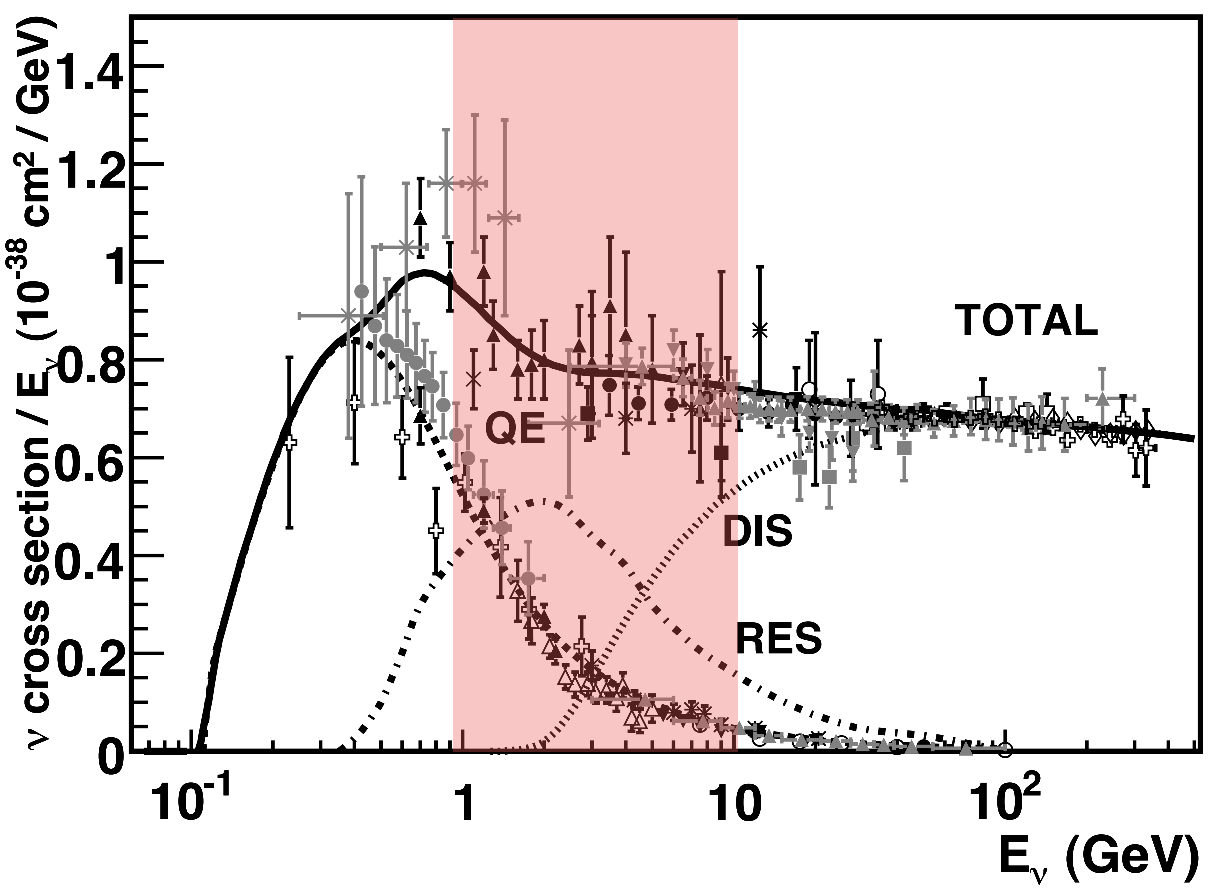
e.g., **axial** and **pseudo-scalar form factors** in quasi-elastic region

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

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

Quasi-elastic scattering

Cross-section for quasi-elastic neutrino-nucleon scattering

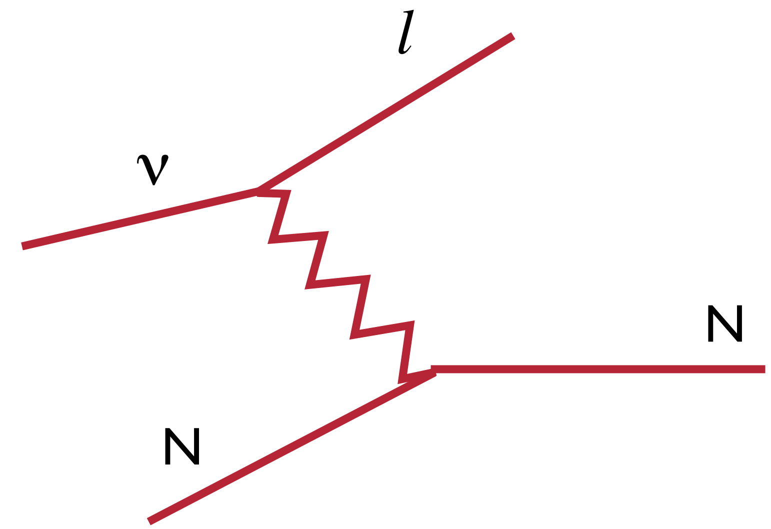
$$\frac{d\sigma}{dQ^2} = \frac{G_f^2 M^2 \cos^2\theta_C}{8\pi E_\nu^2}\left[A \mp \frac{(s-u)}{M^2}B + \frac{(s-u)^2}{M^4}C\right]$$

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

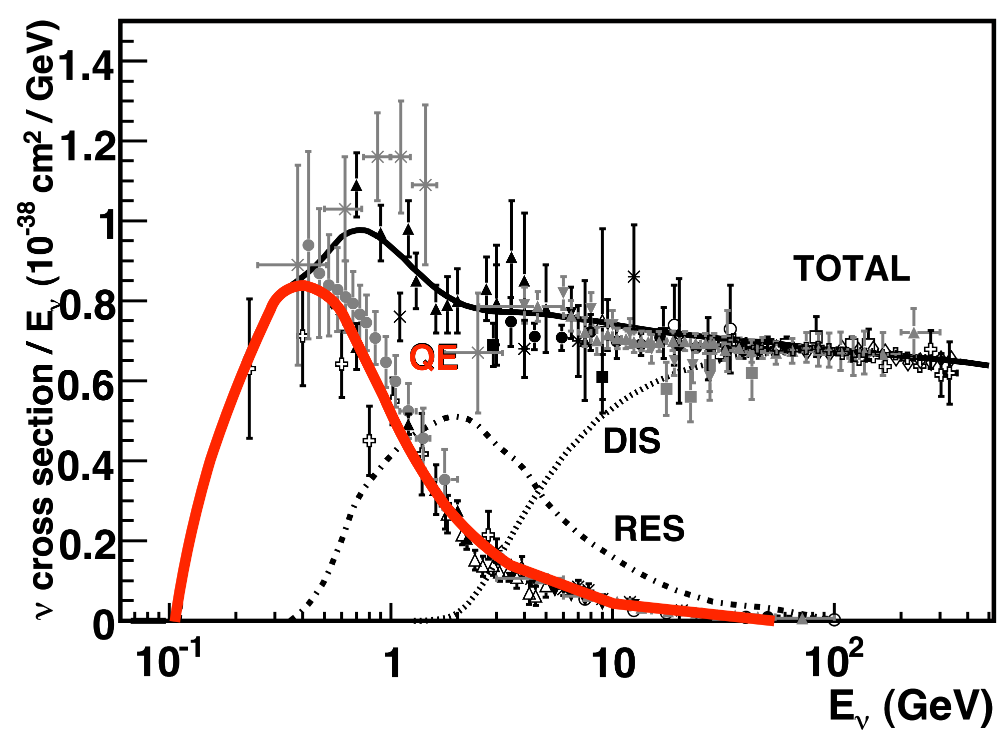
$$B = \frac{Q^2}{M^2}G_A(F_1+F_2)$$

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

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

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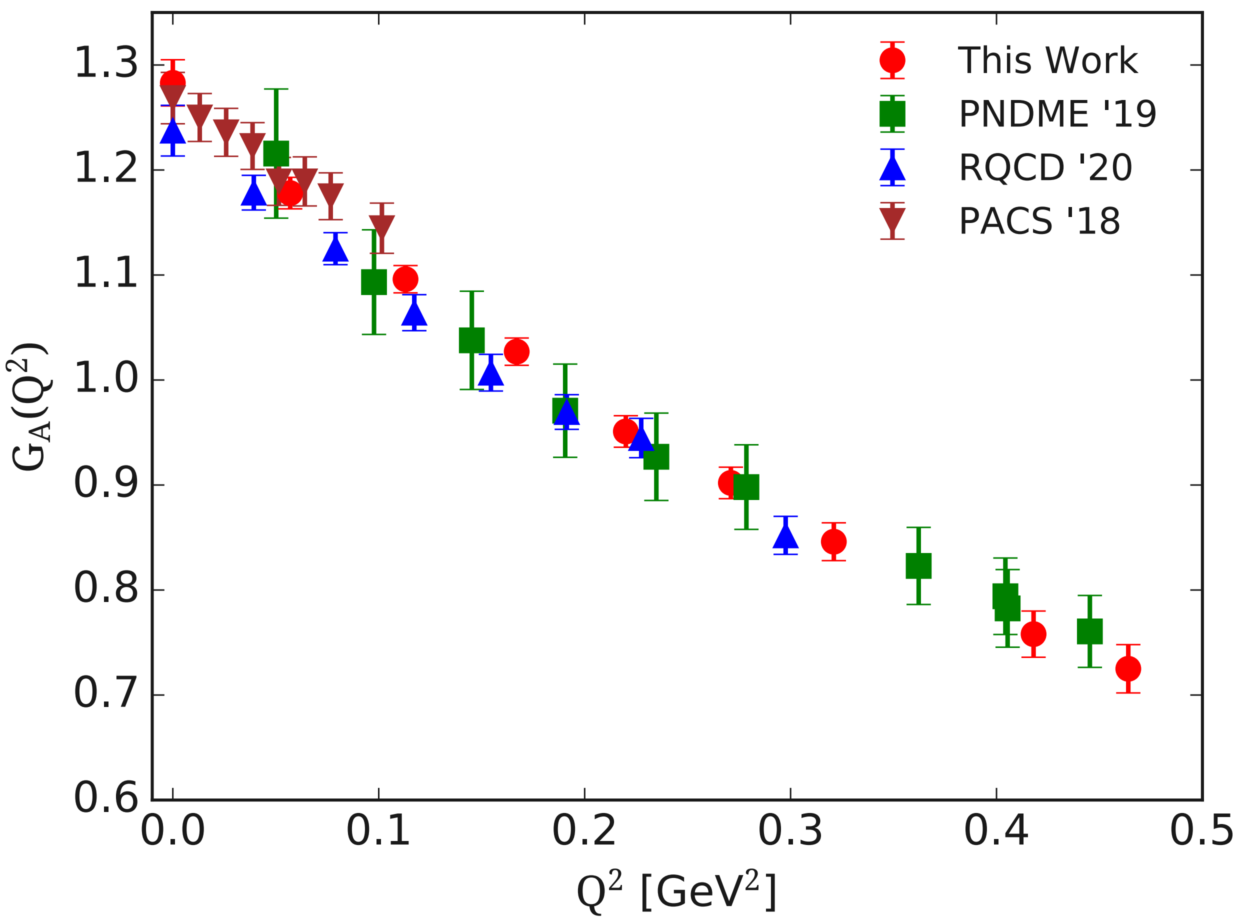
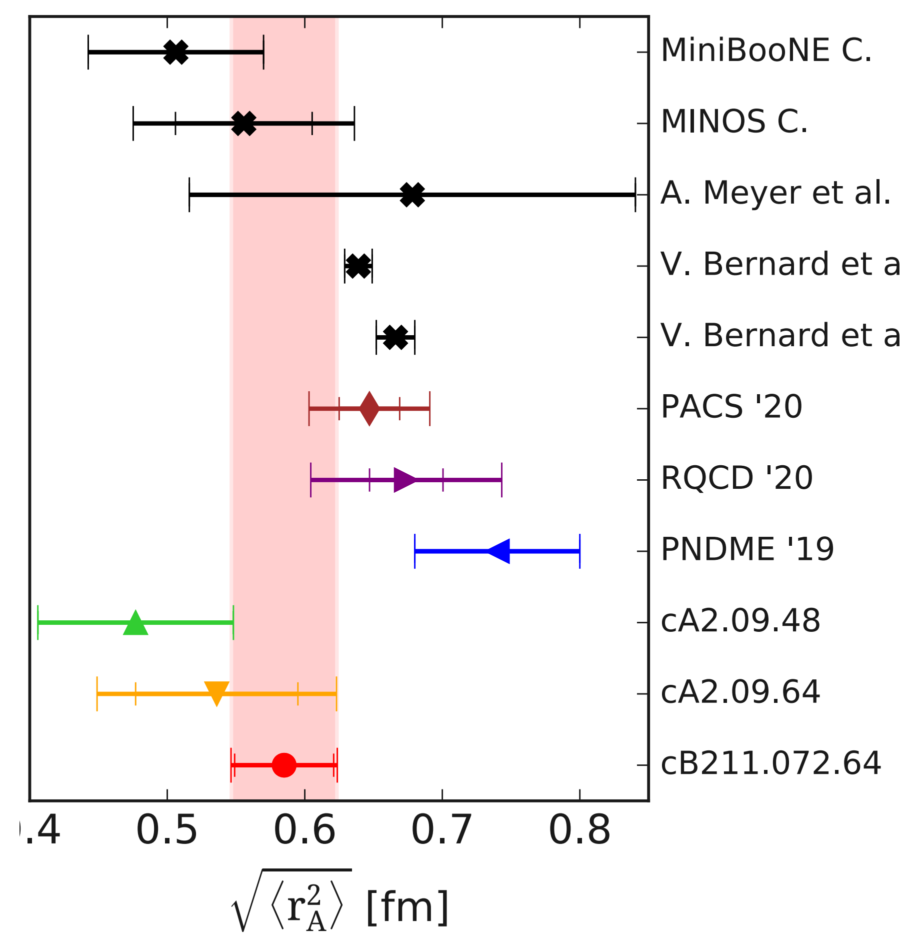
Nucleon axial form factors

- Recent calculations of nucleon form factors including axial in agreement with experiment with fully-controlled uncertainties
- Q^2-dependence well-determined in LQCD: competitive with experiment

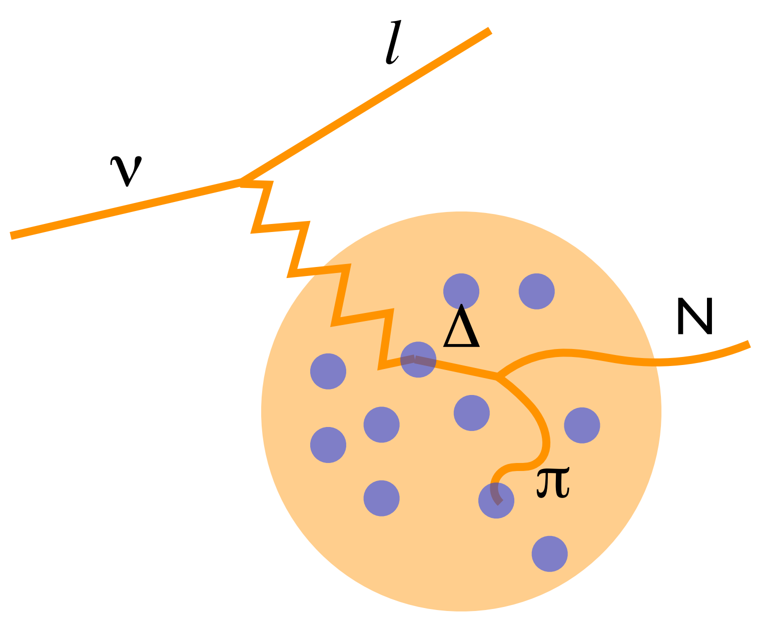




[Alexandrou et al., Phys. Rev. D 103, 034509 (2021)]

Nuclear effects in matrix elements

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



- Experimental investigations: MINERνA

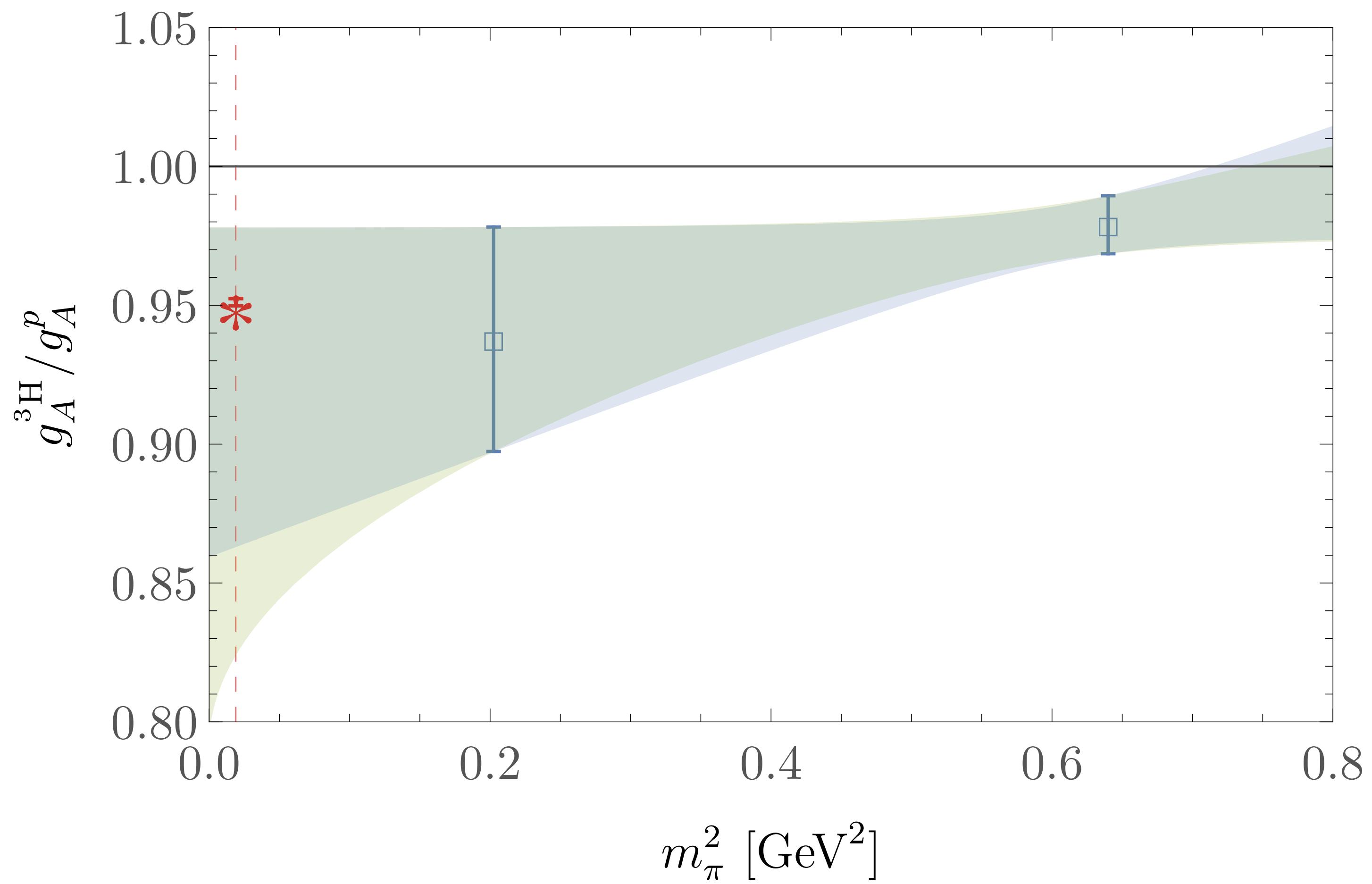
Calculate matrix elements in light nuclei from lattice QCD

→ EFT to reach heavy nuclear targets relevant to experiment

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

Axial charge of the triton

- Axial charge of He: first extrapolation to the physical quark masses last year
- No axial form factors of nuclei from lattice QCD yet (coming soon!)



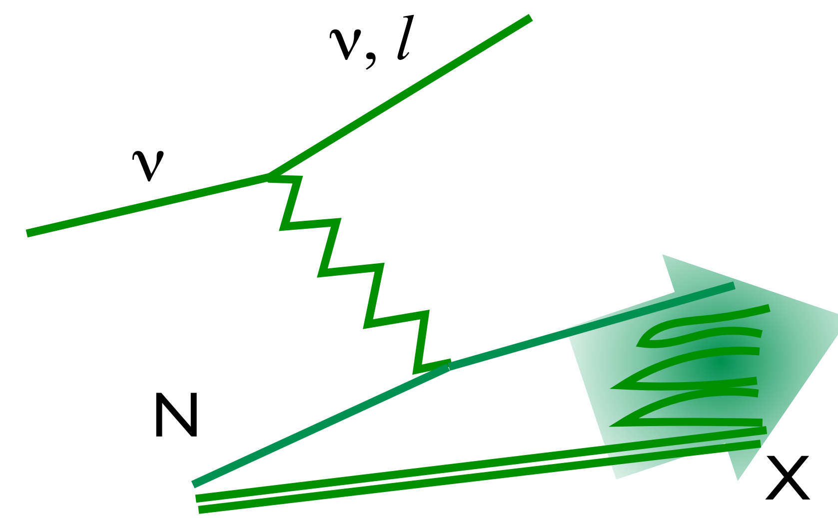
[NPLQCD Phys.Rev.D 103 (2021) 074511]

Inelastic region

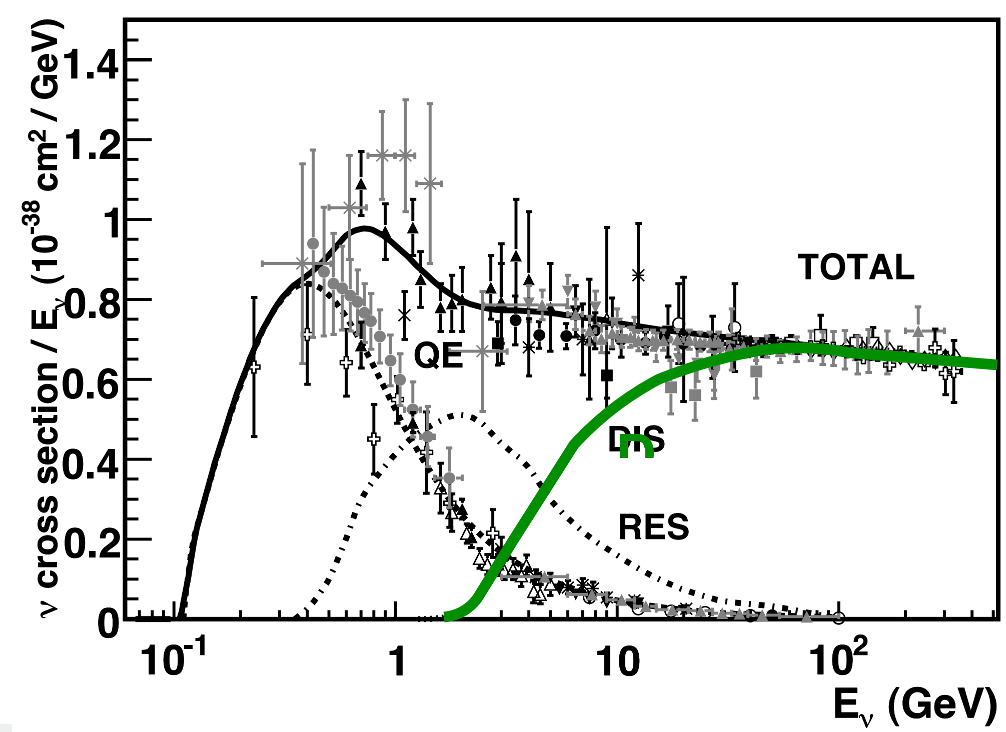
- In inelastic regime, quark PDFs of the nucleon control scattering cross-section
- Both resonances and DIS are important
- Multi-meson channels may become important
- Nuclear effects are different in νA vs. eA
- DIS structure functions accessible in LQCD
  - Low moments of structure functions controlled

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

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



ν charged-current cross-section



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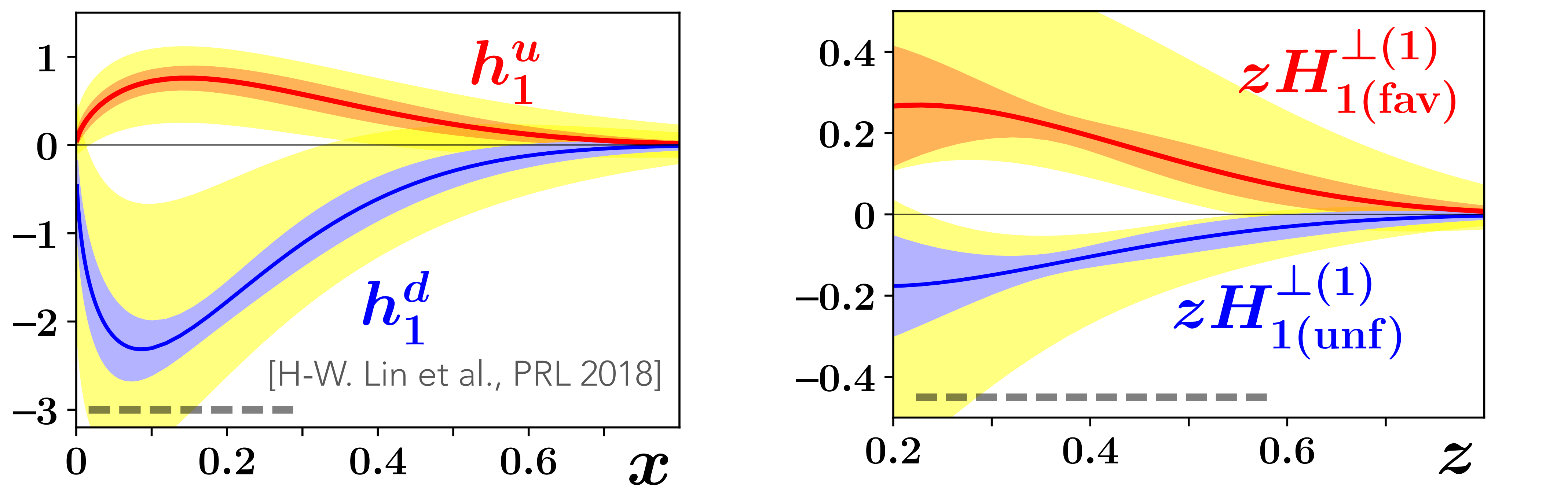
Constraints on global PDF fits

- Including lattice QCD results for moments in global parton distribution function 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



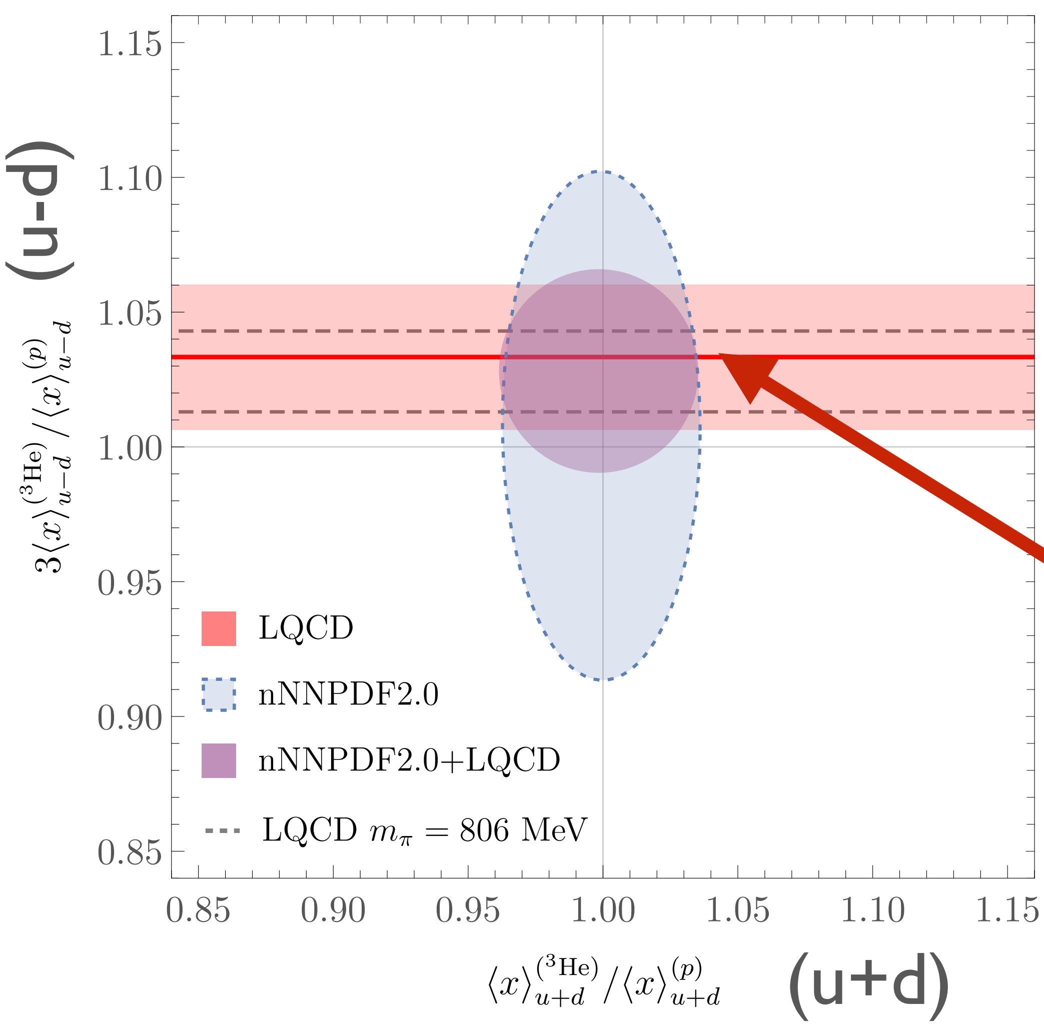
Yellow: SIDIS data only: direct constraints in region indicated by dashes

Blue/Red: SIDIS + lattice QCD for tensor charge (zeroth moment)

Momentum fraction of ^{3}He

Study nuclear effects in the breakdown of momentum carried by quarks in nuclei

Ratio of ^{3}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

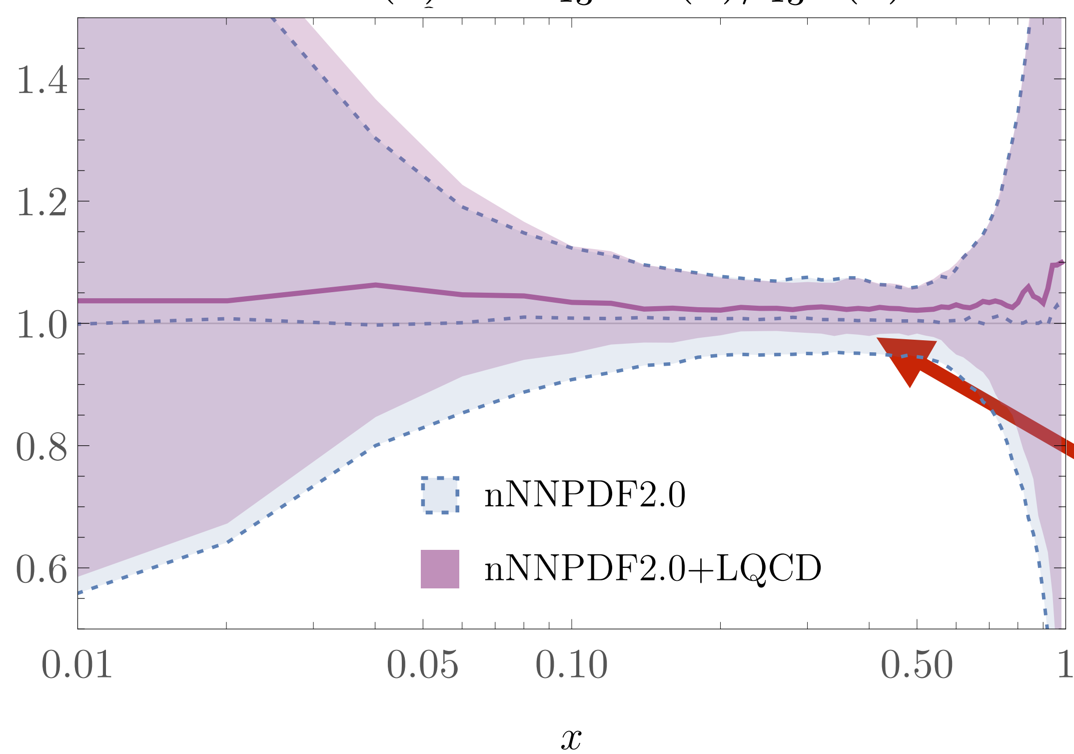
[NPLQCD PRL 126, 202001 (2021) [2009.05522]]

Momentum fraction of ^{3}He

Study nuclear effects in the breakdown of momentum carried by quarks in 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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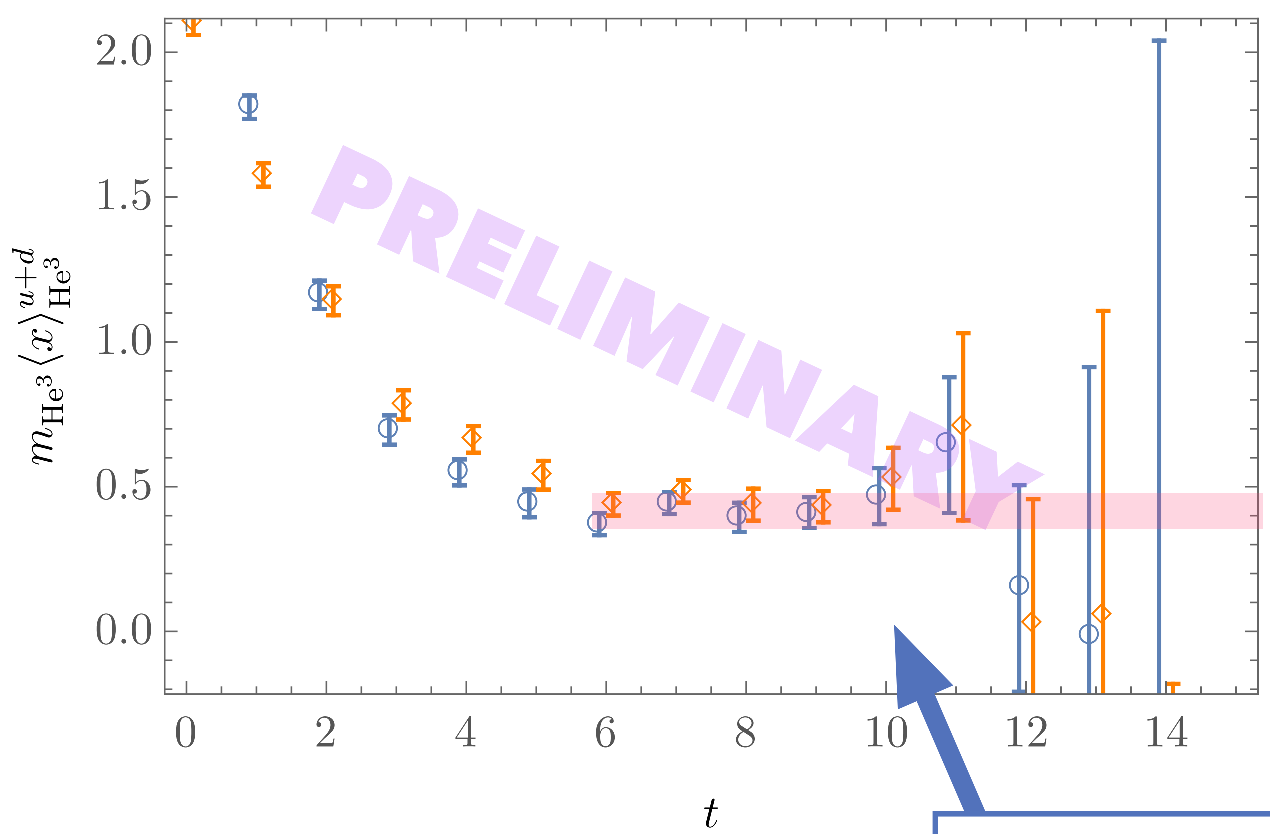
Blue → Purple:
Improvement using theory constraints

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

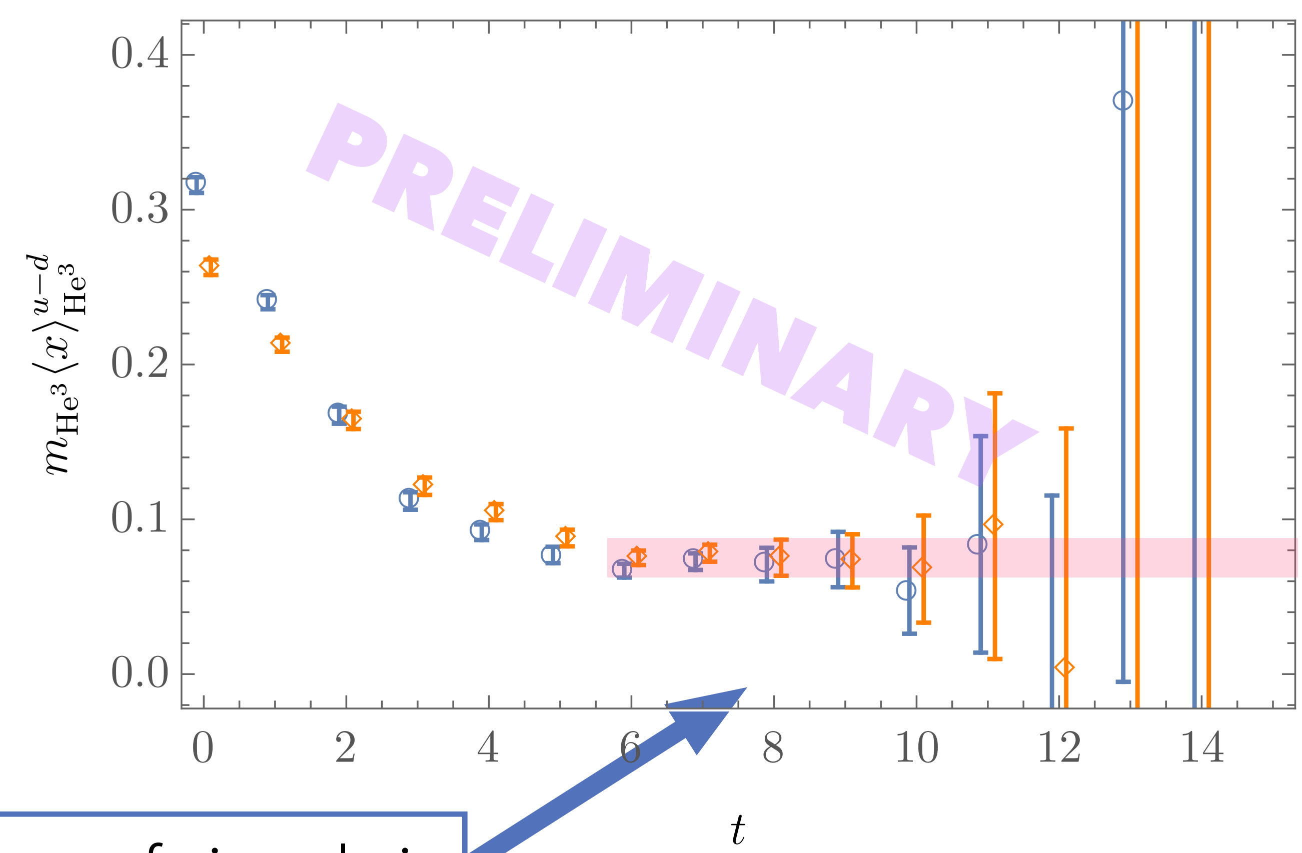
Momentum fraction of ^{3}He

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

Isoscalar



Isovector



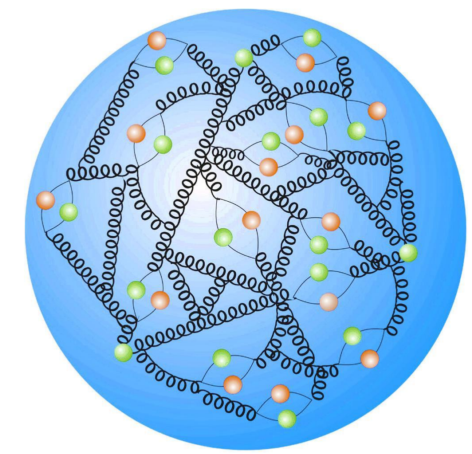
First evidence of signals in physical-point data

- Polarised PDFs, gluon PDFs, also accessible from moments

LQCD input for ν-nucleus interactions

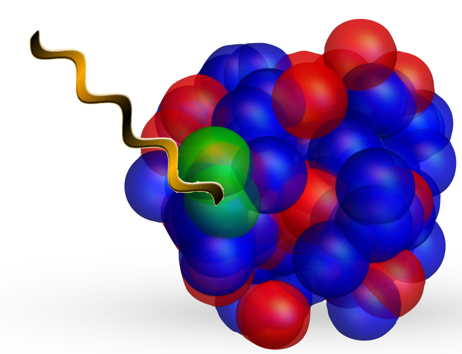
1. **Directly access QCD single-nucleon form factors without nuclear corrections**

Reliable calculations with fully-controlled uncertainties



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

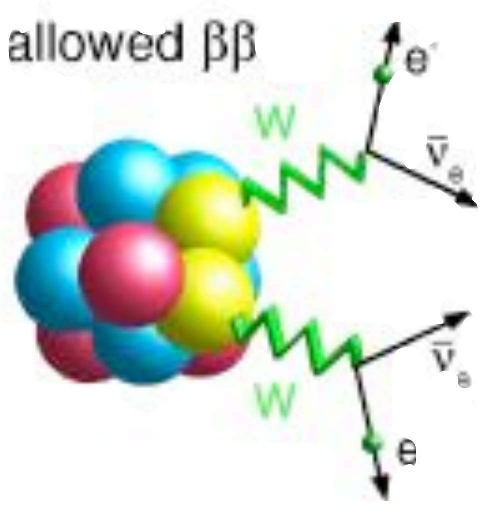
➡ EFT to reach heavy nuclear targets relevant to experiment



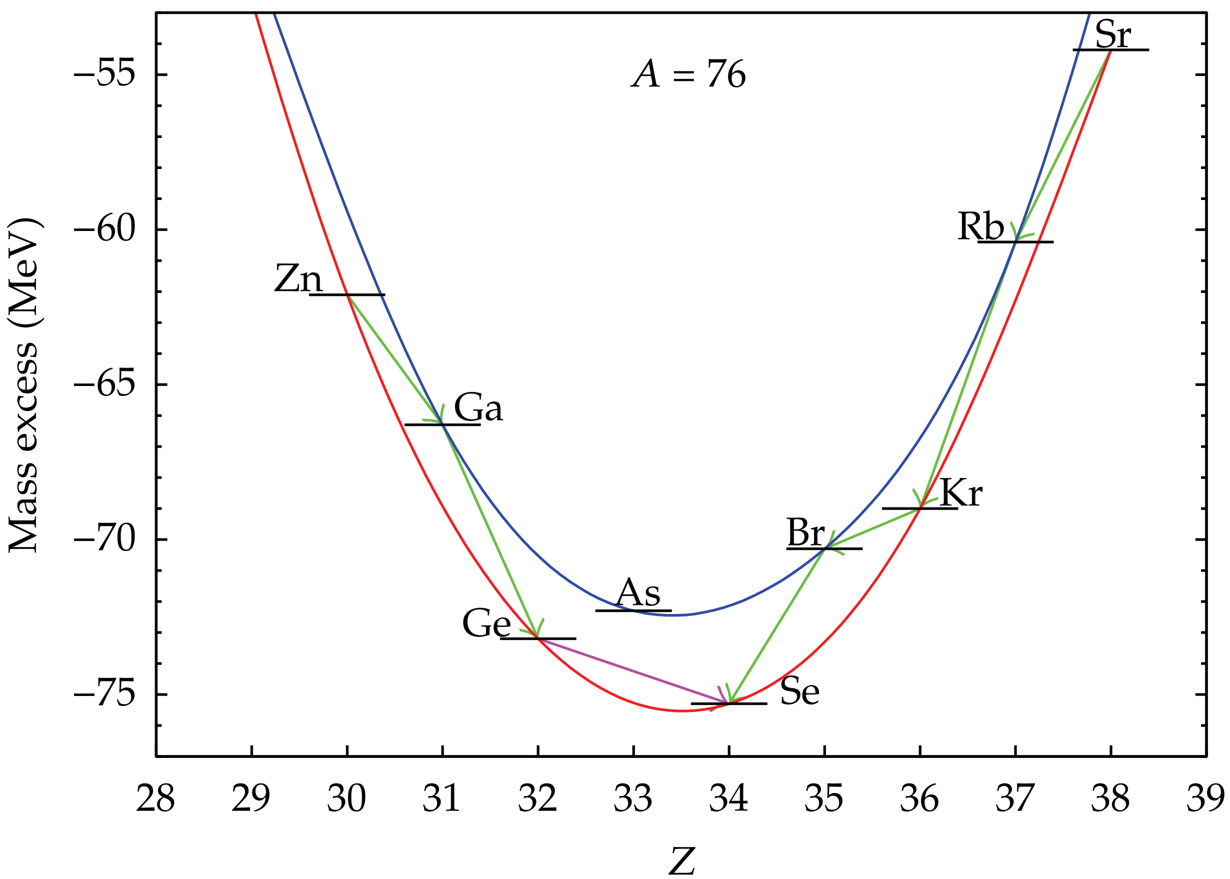
e.g., First calculations of axial charge of light nuclei, EMC effect in light nuclei

Double-beta decay

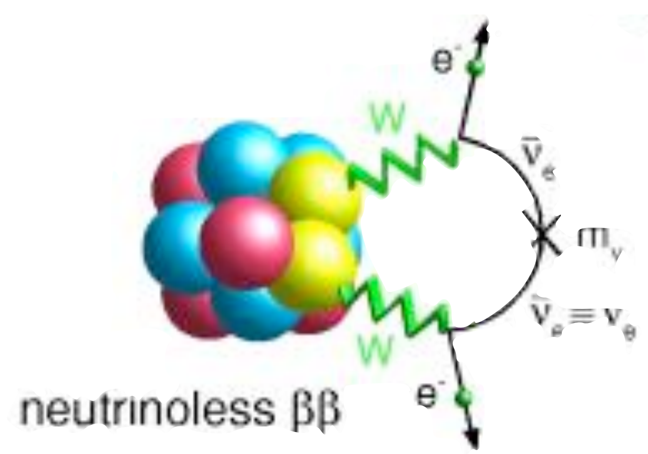
- Certain nuclei allow observable ββ decay



$T_{1/2}^{2\nu\beta\beta} \gtrsim 10^{19}$ y



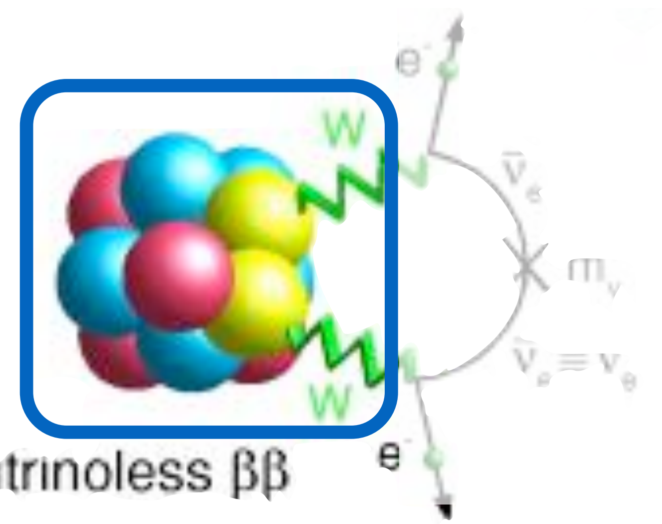
- If neutrinos are massive Majorana fermions 0νββ decay is possible
- In addition to light Majorana neutrino exchange, short-distance contributions to 0νββ can arise from BSM physics resulting in dim-9 operators in SMEFT



$T_{1/2}^{0\nu\beta\beta} > 10^{25}$ y

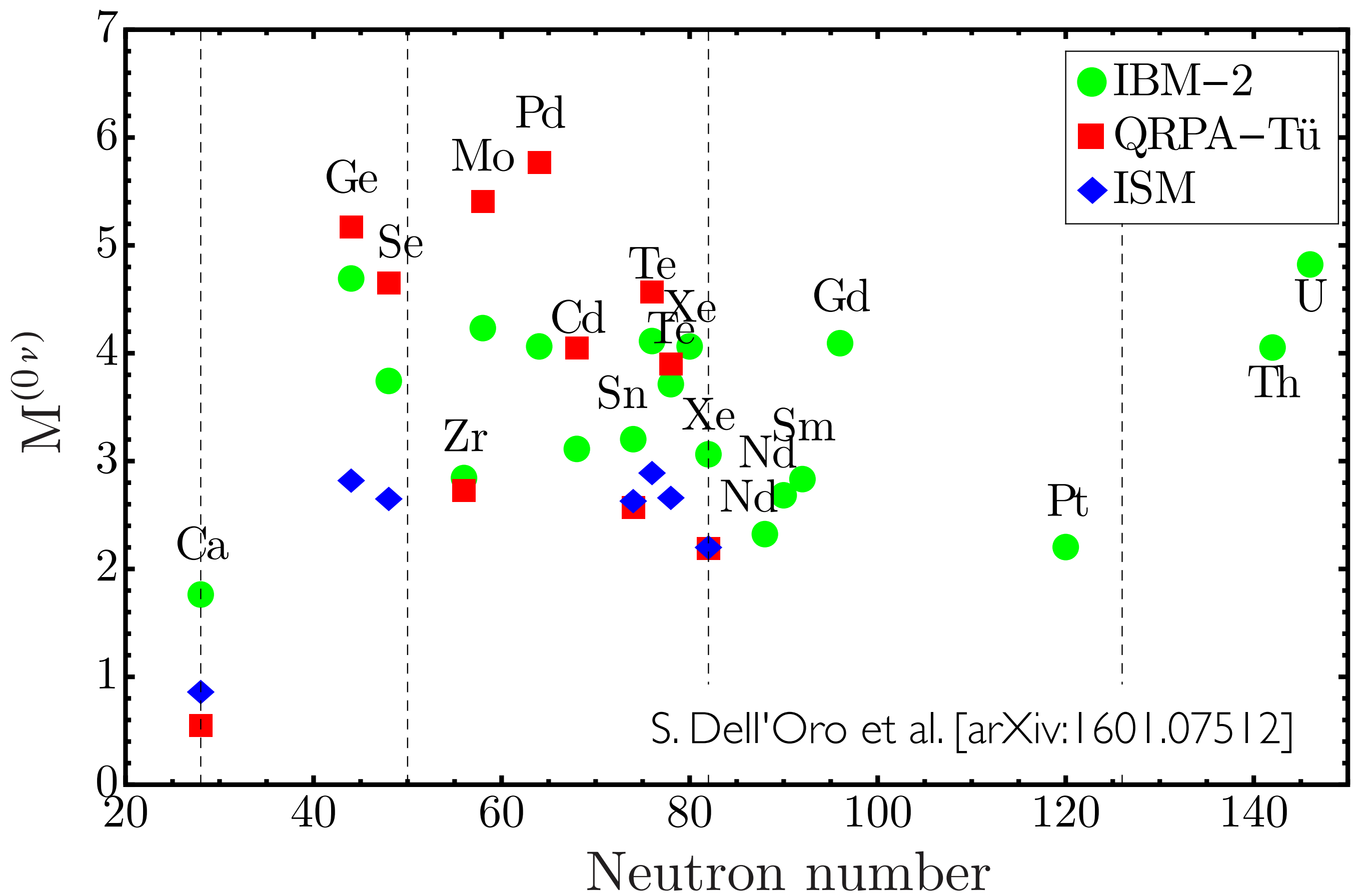
Double-beta decay

Want to understand 2νββ and 0νββ decay from theory



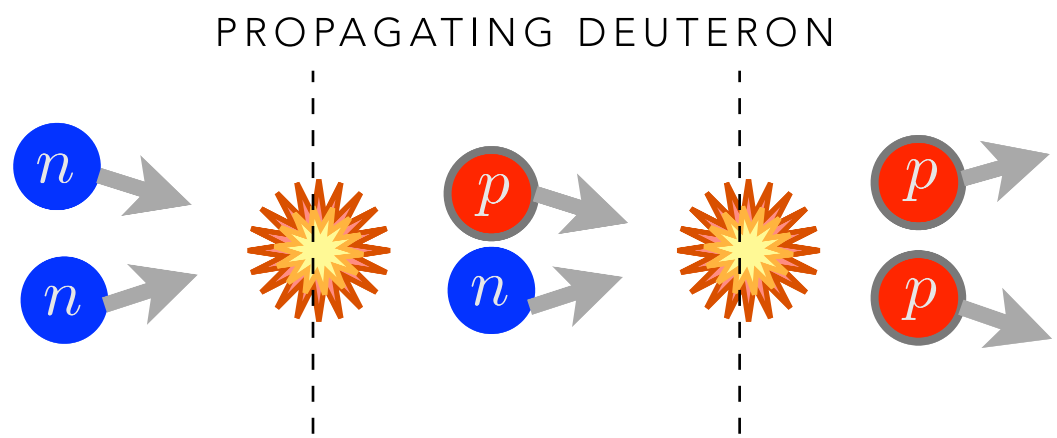
Calculate two-current nuclear matrix elements → dictate half-life

Model calculations have large uncertainties

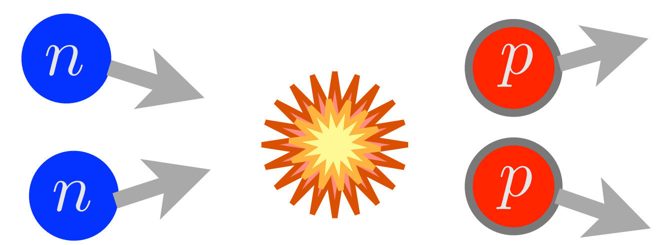


Neutrinoful double-beta decay

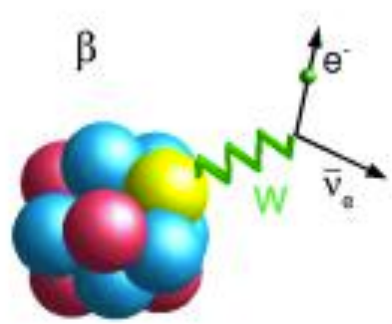
Lattice QCD: Calculate nn→pp transition matrix element

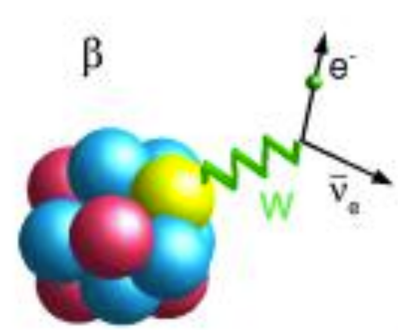


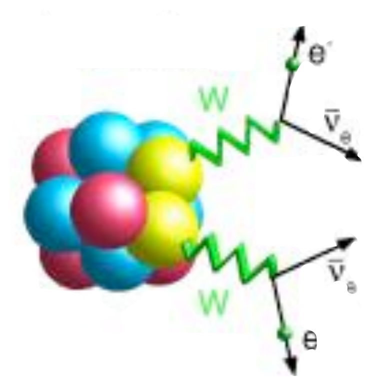
Two single-beta decays



Two-body effect







[NPLQCD PRL 119, 062003 (2017), PRD 96, 054505 (2017)]

Neutrinoful double-beta decay

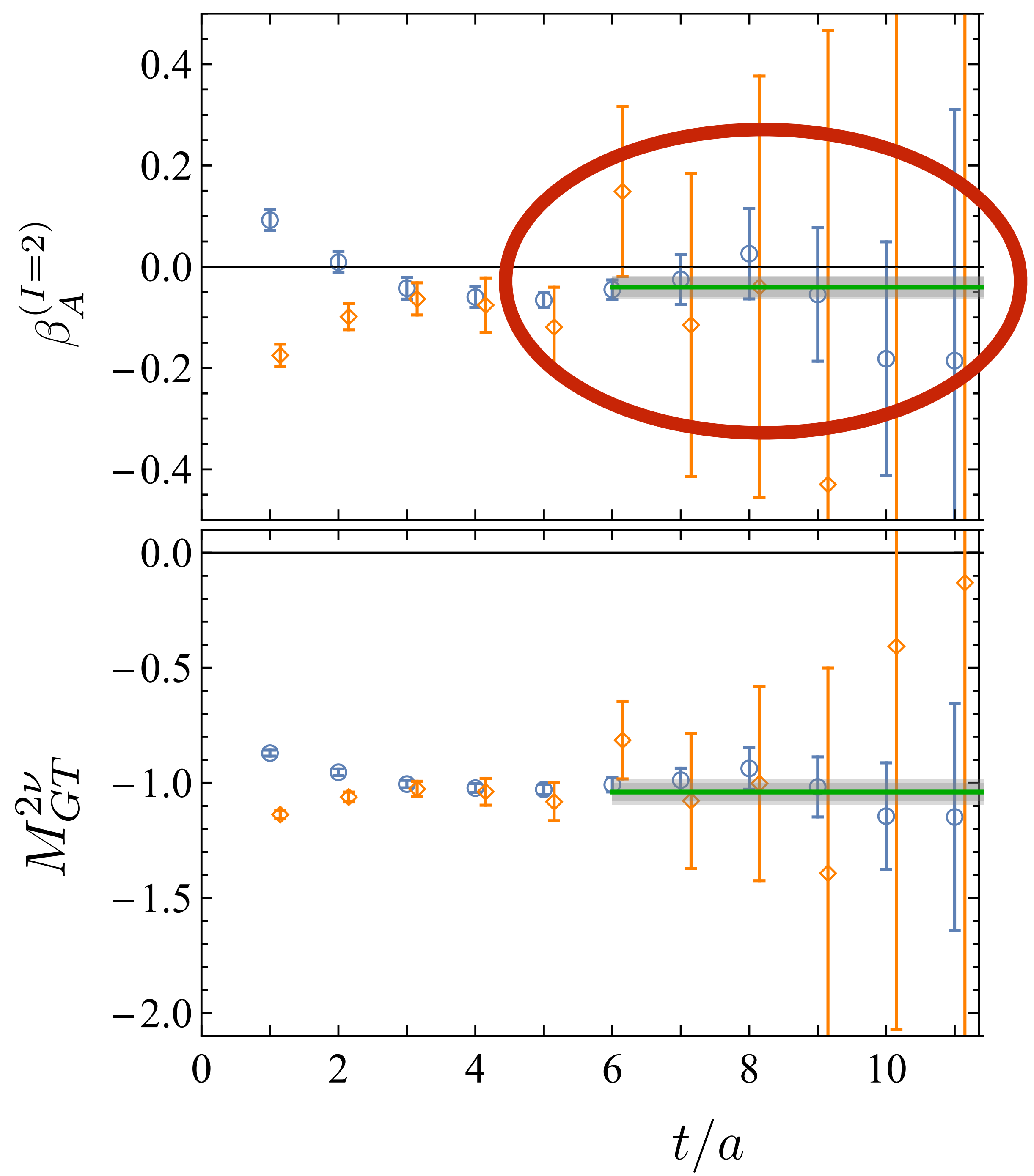
- Non-negligible deviation from deuteron intermediate state contribution

Isotensor axial polarisability

$$M_{GT}^{2\nu} = -\frac{|M_{pp\to d}|^2}{E_{pp} - E_d} + \beta_A^{(I=2)}$$

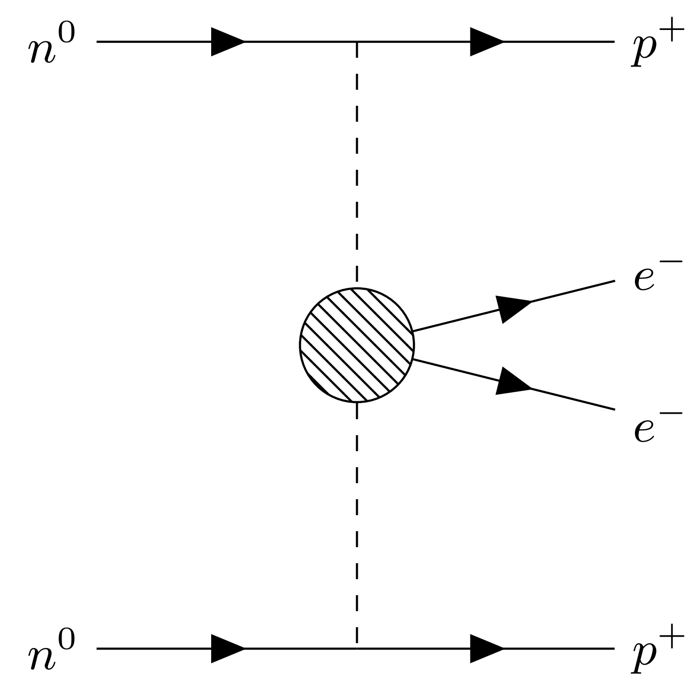
➡ Multi-body effects can't be neglected!

- TBD: connect to models / effective field theory for larger systems



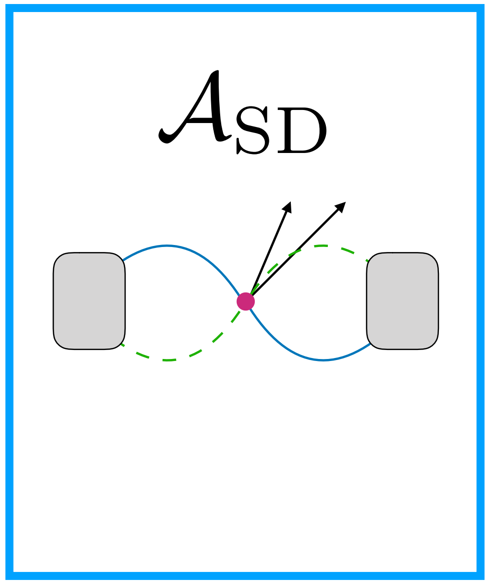
[NPLQCD PRL 119, 062003 (2017), PRD 96, 054505 (2017)]

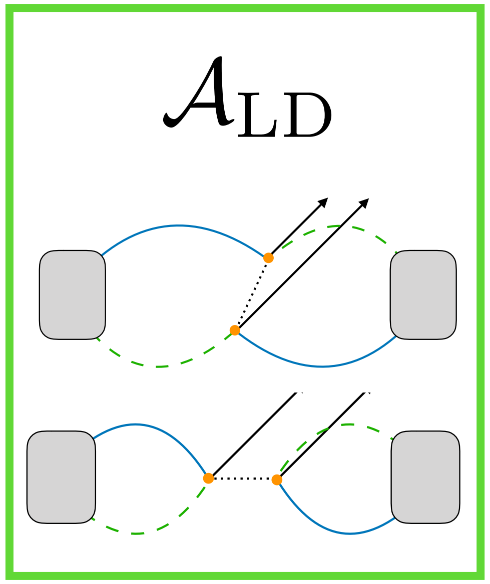
Neutrinoless double-beta decay



- Calculations of pion matrix elements (statistically clean) give access to key pion exchange contributions to neutrinoless decay process
- New calculations compare short (SD) and long-distance (LD) contributions
- With estimates of BSM Wilson coefficients for minimal left-right symmetric model with heavy right-handed neutrinos:
  [Cirigliano et al, JHEP 97 (2018)]:

$$\frac{\mathcal{A}_{\mathrm{SD}}}{\mathcal{A}_{\mathrm{LD}}} = \frac{1}{v^2}\frac{\sum_k |c_k\langle\pi|\mathcal{O}_k|\pi\rangle|}{|M^{0\nu}|} \sim 10^{-4}$$





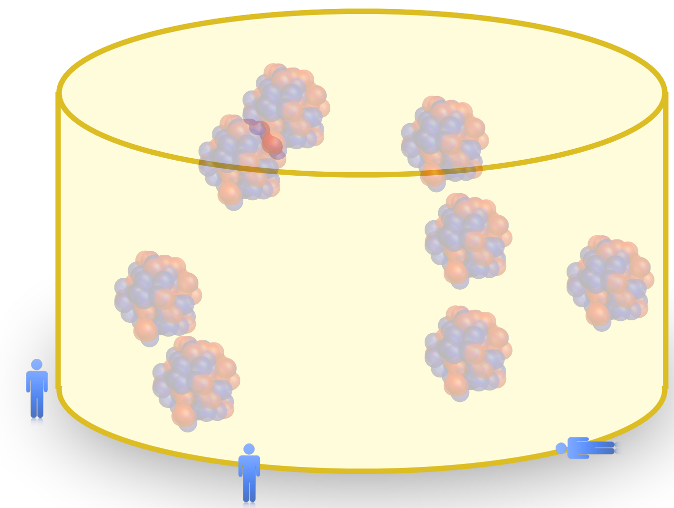
[see also Nicholson et al. PRL121 172501 (2018), Feng et at PRL 122 (2019), Tuo et al PRD 100, 094511 (2019), Detmold&Murphy 2004.07404 (2020)]

Dark matter direct detection

Look for scattering of WIMP dark matter on nuclear target

Detection rate depends on

- Dark matter properties
- Probability of interaction with nucleus
  i.e., *nuclear* effects are important



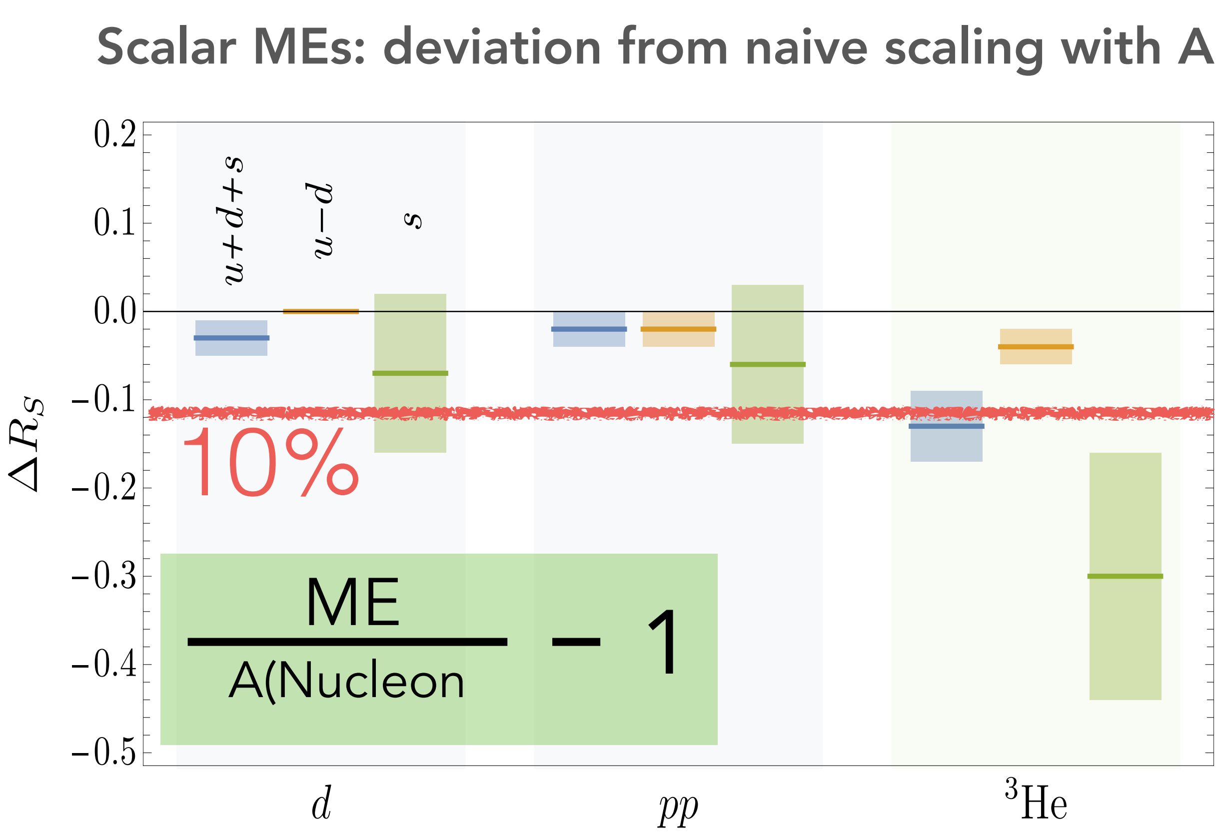
Low-energy limit of a generic spin-independent interaction is scalar → Determine **nucleon and nuclear scalar matrix elements** from lattice QCD

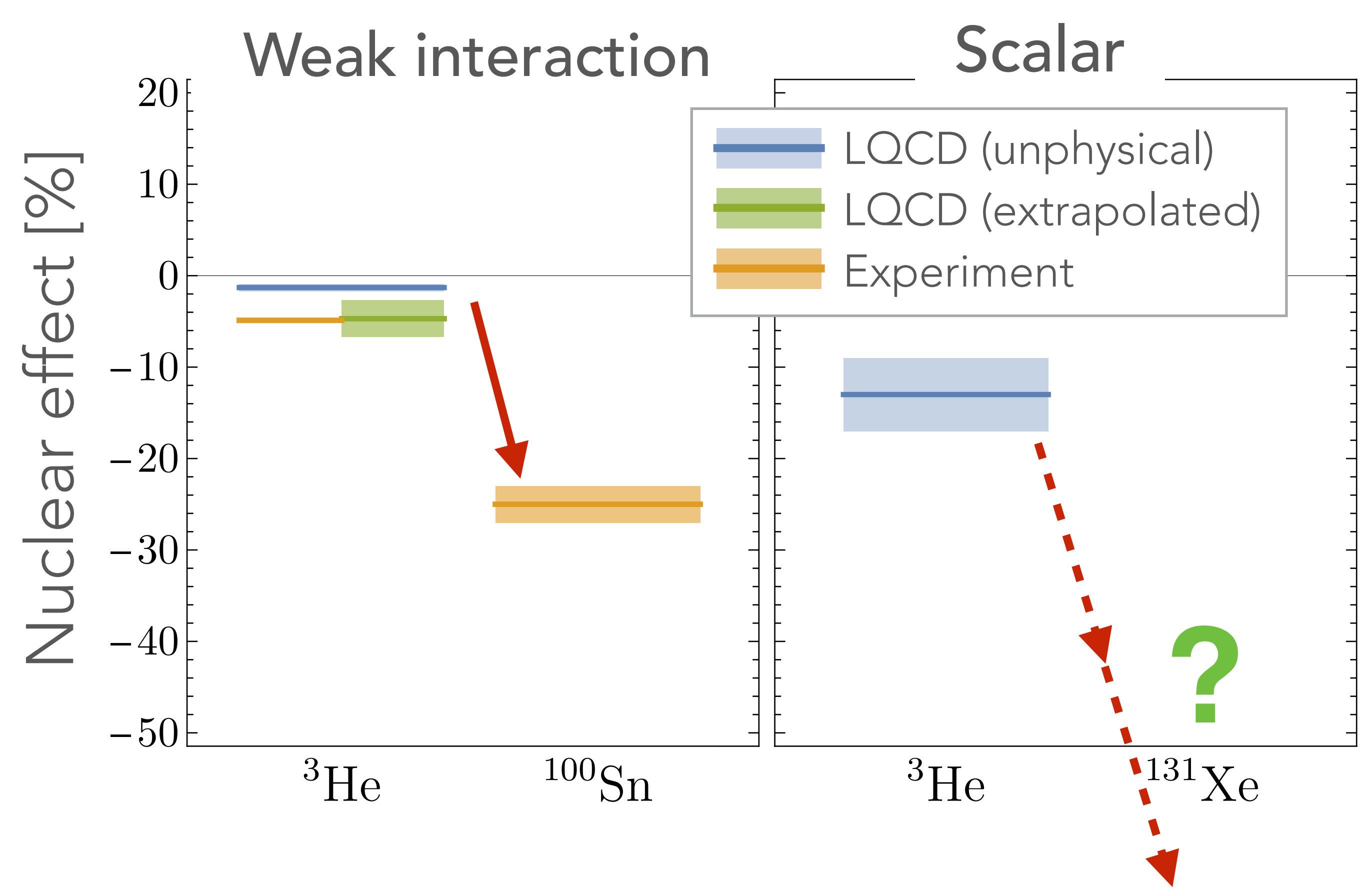
Other e.g., spin-dependent couplings can also be constrained

e.g., [Hoferichter et al., arXiv:1503.04811], [Hill et al., arXiv:1409.8290], [Fitzpatrick et al., arXiv:1203.3542]

Scalar matrix elements of nuclei

- Lattice QCD calculation with m_π~800 MeV shows 10% nuclear effects in scalar MEs of ^{3}He ➡ potentially very significant effects in larger nuclei e.g., Xenon
- Calculations in progress with ~physical quark masses



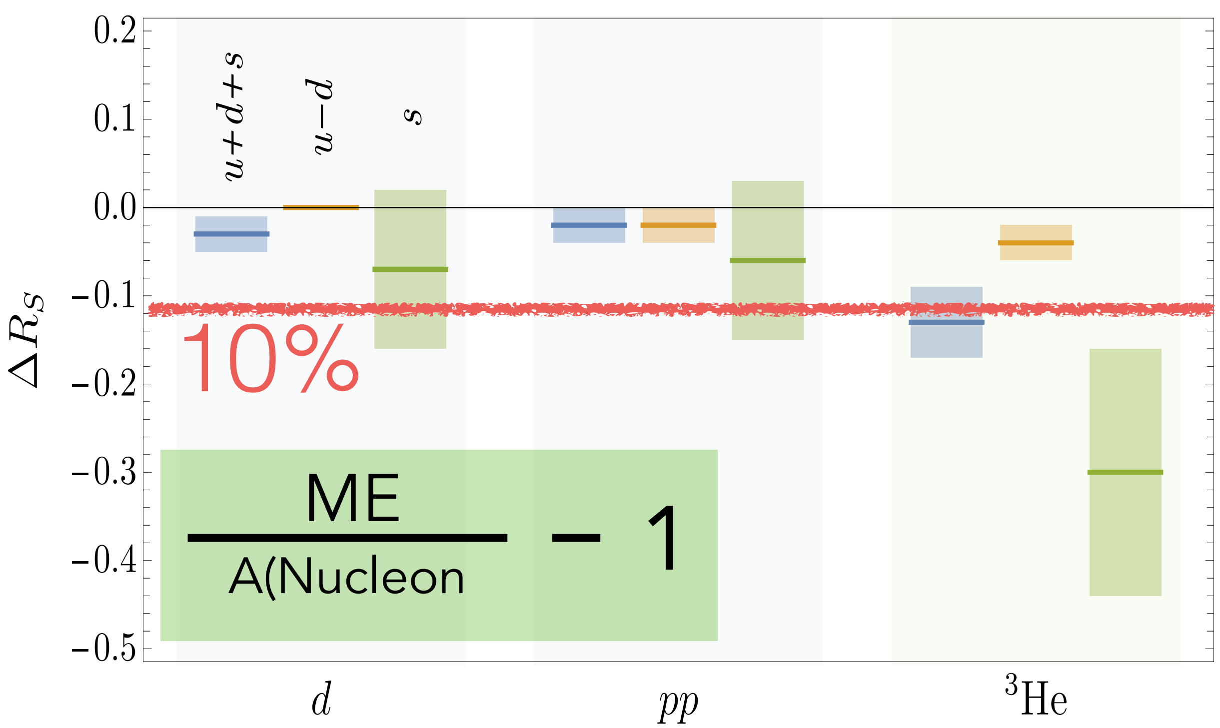


[NPLQCD PRL120 (2018), 152002]

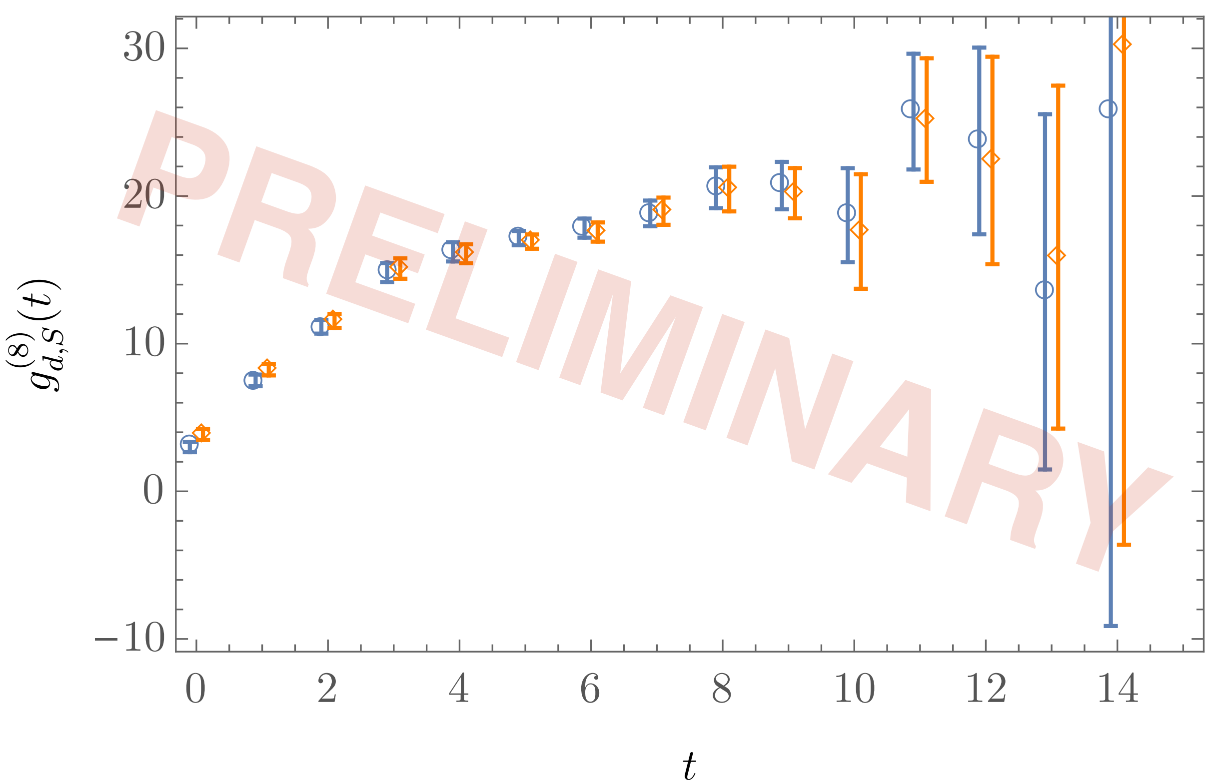
Scalar matrix elements of nuclei

- Lattice QCD calculation with m_π~800 MeV shows 10% nuclear effects in scalar MEs of ^{3}He → potentially very significant effects in larger nuclei e.g., Xenon
- Calculations in progress with ~physical quark masses

Scalar MEs: deviation from naive scaling with A



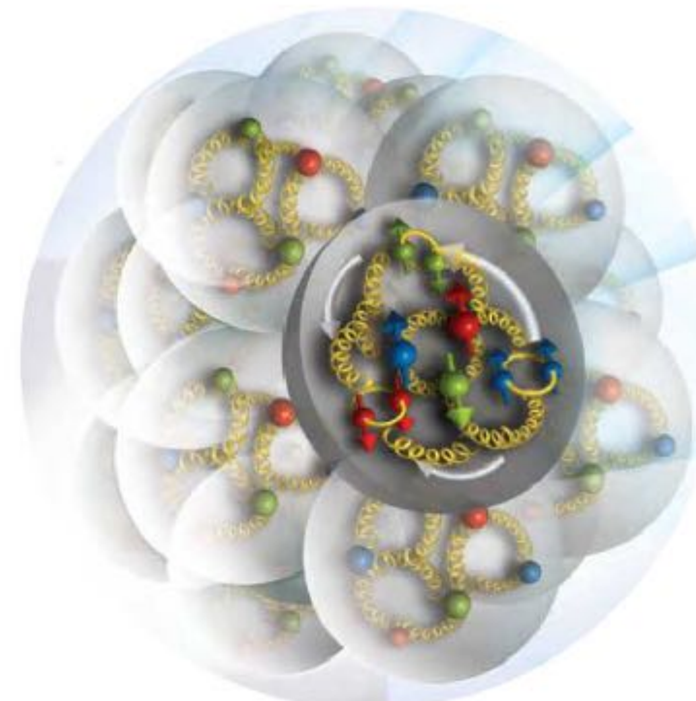
Signal for physical scalar ME of the deuteron



[NPLQCD PRL120 (2018), 152002]

Nuclear physics from lattice QCD

Calculations of nuclear MEs are HARD

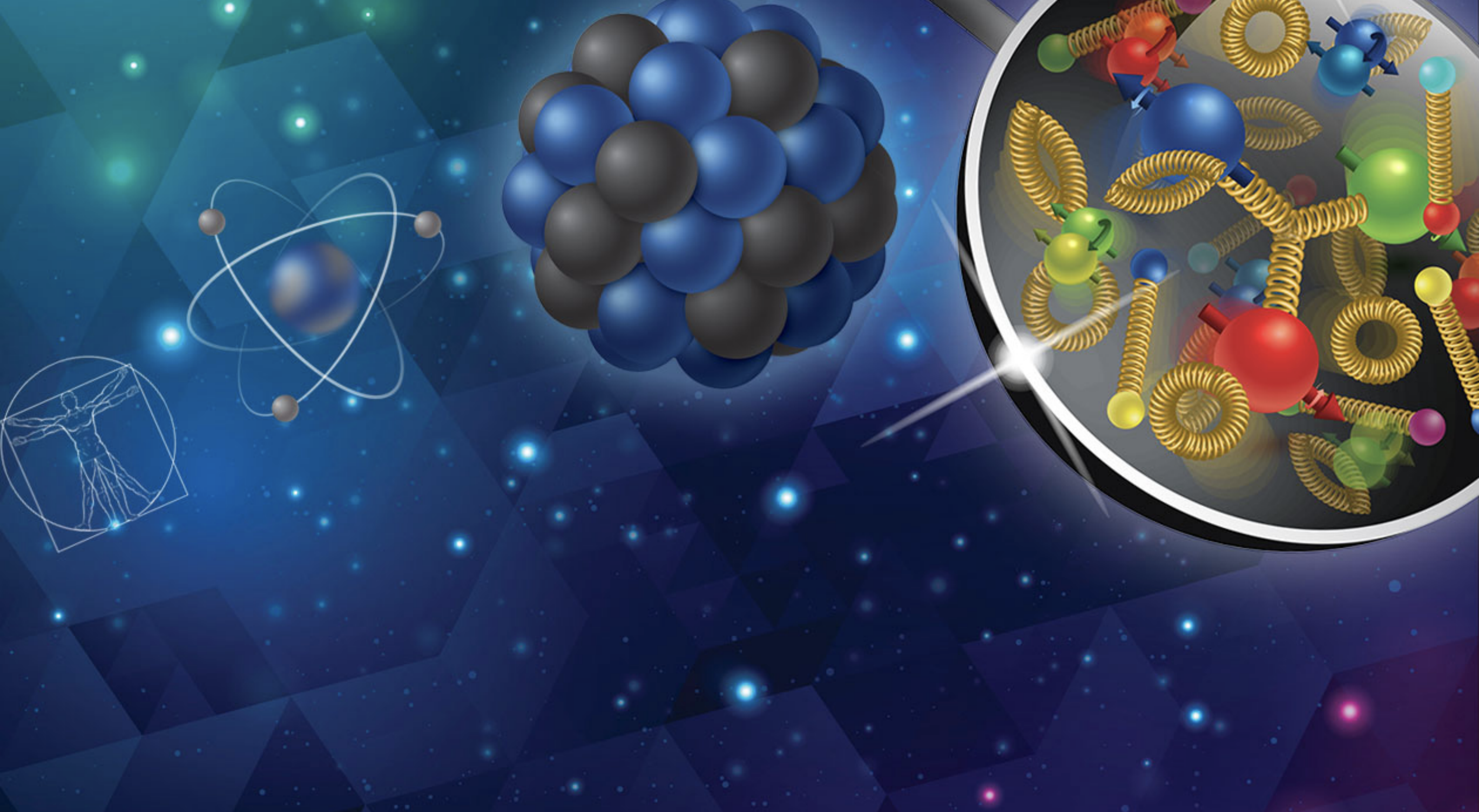


Constraints on nuclear matrix elements are possible:

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

Controlled calculations achievable for nuclei with A<5 with ~10-20% uncertainty in 10-year timeframe:

- Axial MEs, including form factors
- Scalar MEs relevant for e.g., dark matter direct detection
- Double beta-decay matrix elements
- Constraints on PDFs, GPDs of nuclei via moments
- …



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