EMC-type effects from Lattice QCD

Phiala Shanahan, MIT

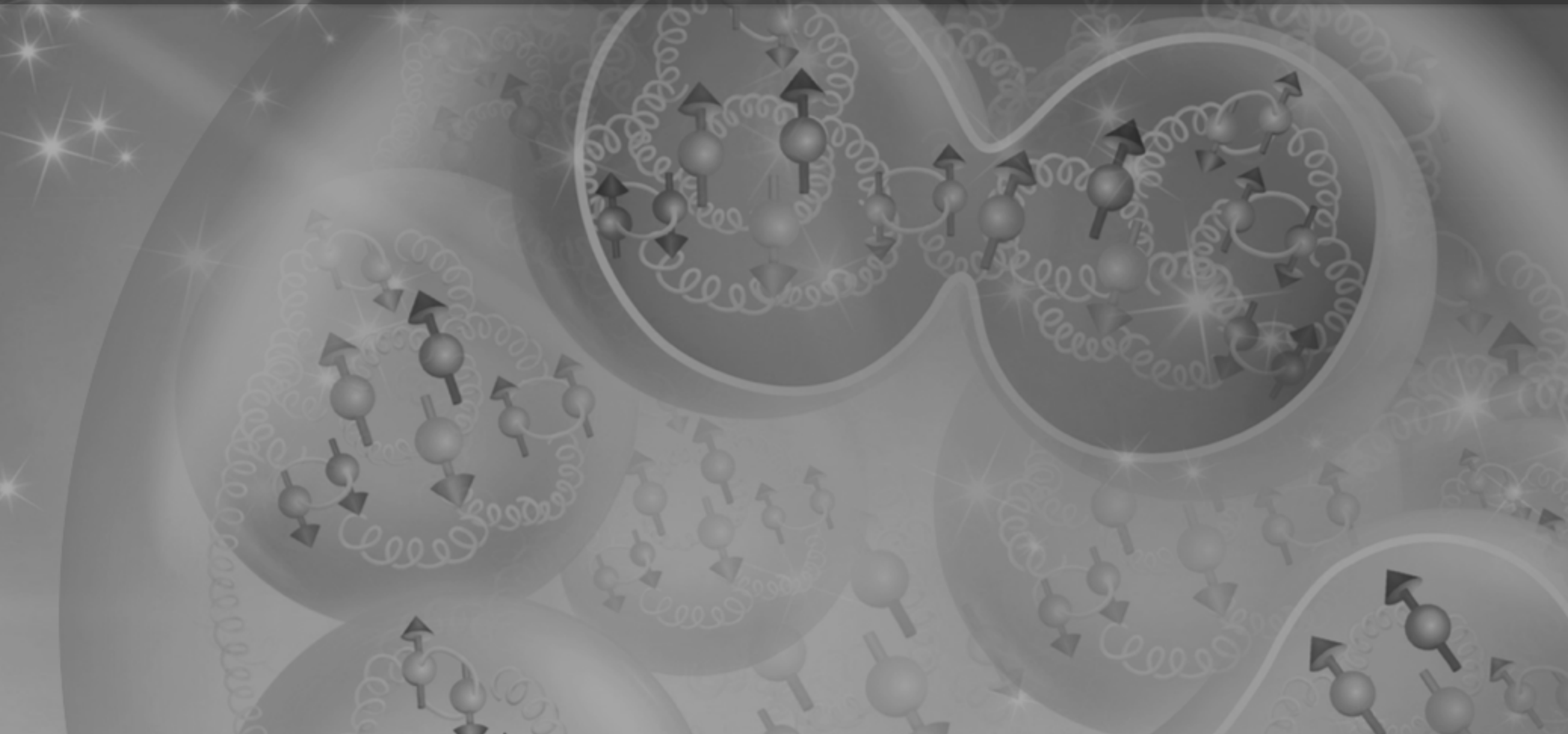


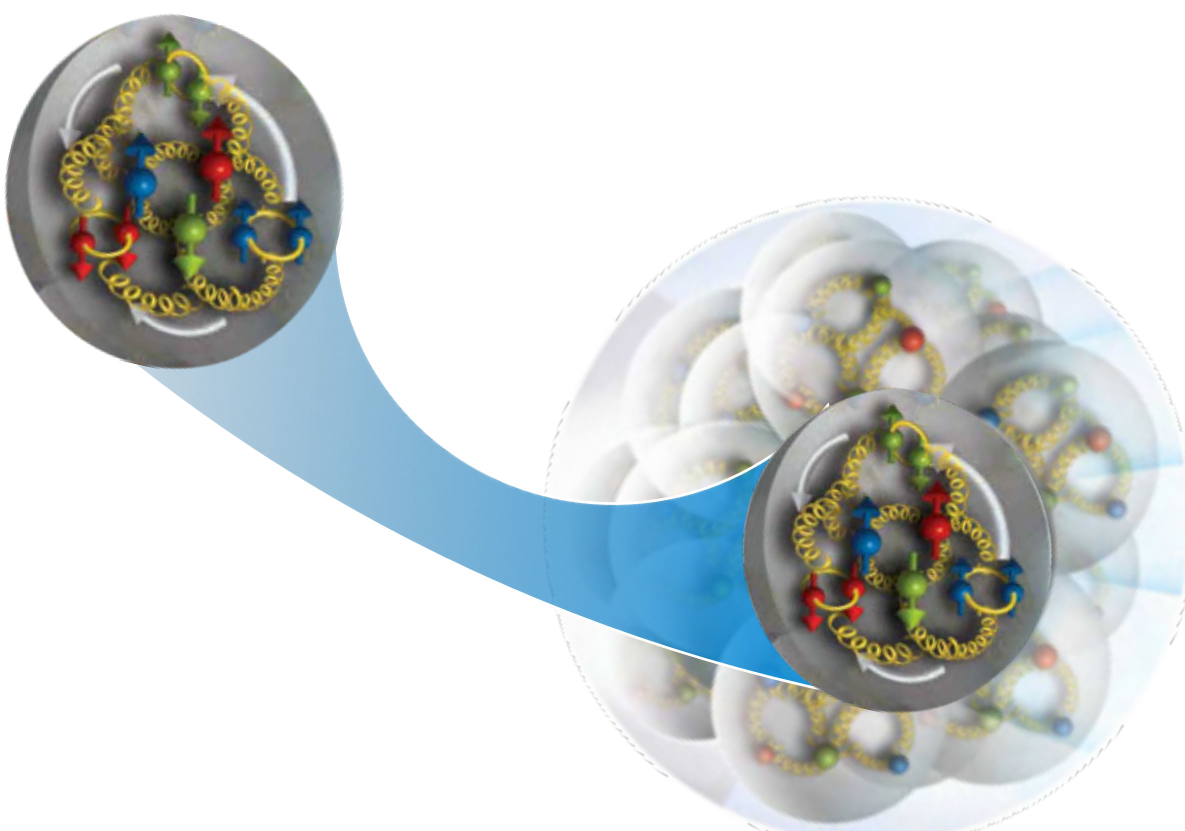
Image Credit: 2018 EIC User’s Group Meeting

Massachusetts Institute of Technology

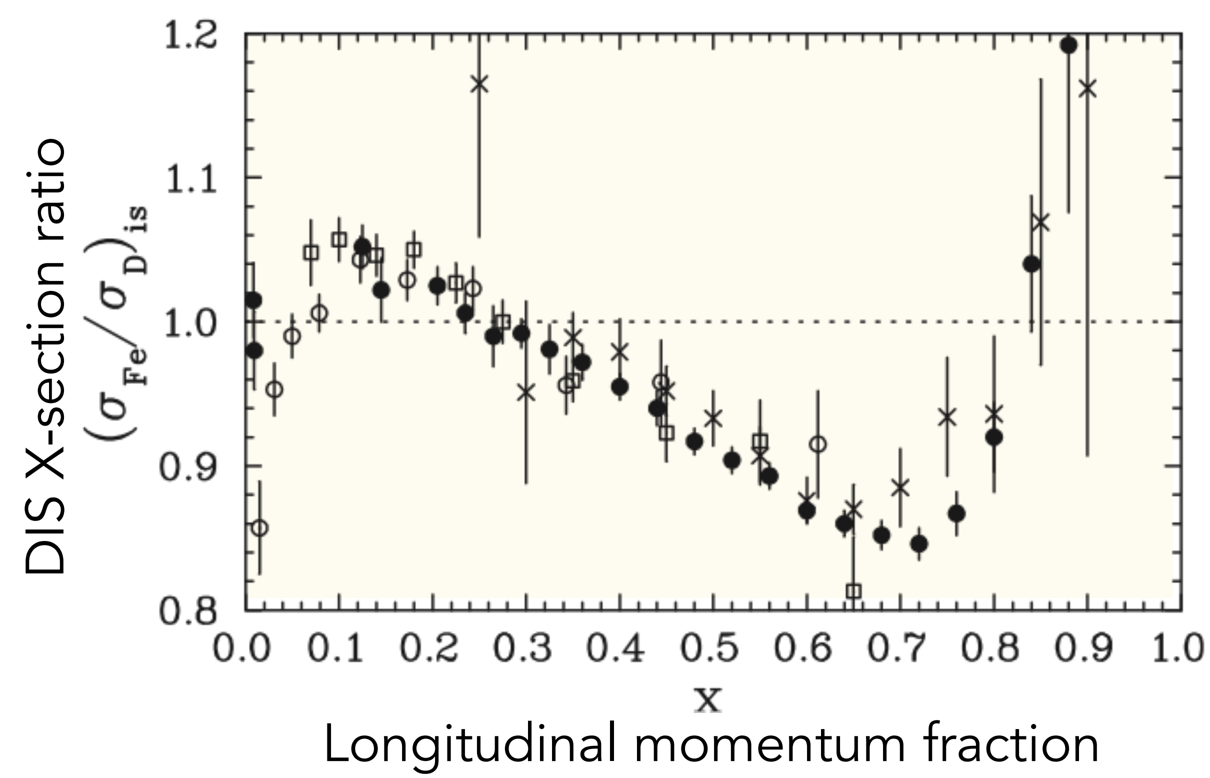
EMC-type effects from Lattice QCD

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

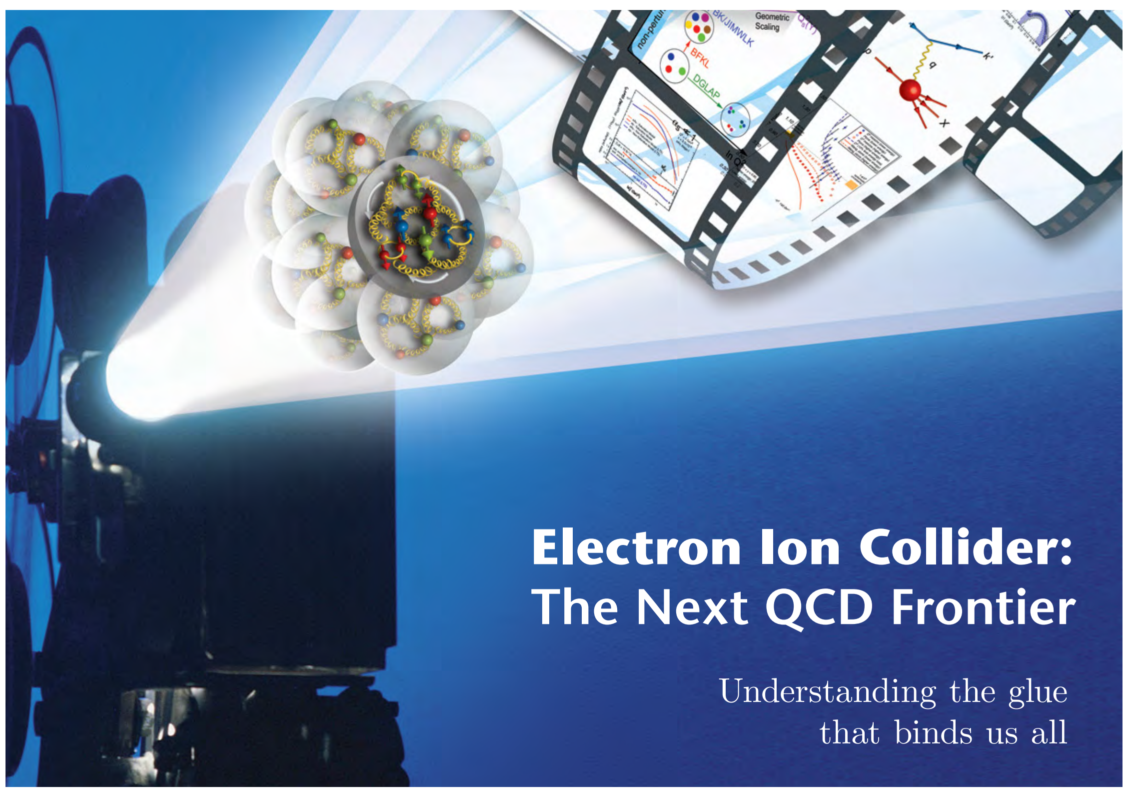


(EMC: Aubert et al., 1983)

EMC-type effects from Lattice QCD

Understanding the quark and gluon
structure of matter

Many aspects of EMC effects will be accessible at a future Electron-Ion Collider



Cover image from EIC whitepaper arXiv::1212.1701

- Polarised EMC (polarised light ions)
- Isovector EMC (SIDIS)
- Gluon EMC (quarkonium production)
- LQCD will make predictions!

Lattice QCD

Numerical first-principles approach to non-perturbative QCD

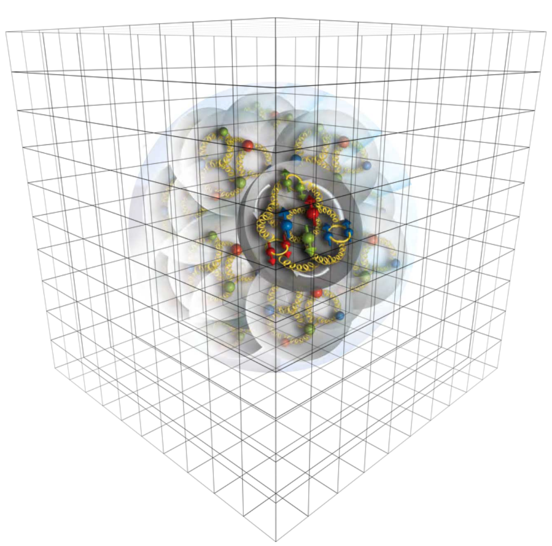
INPUT

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 Υ, or f_π or Ω mass

OUTPUT

Calculations of all other quantities are QCD predictions



Parton physics from Lattice QCD

Precision Era

Fully-controlled w/ few-percent errors within ~5y

- Static properties of nucleon incl. spin, flavour decomp.
- Mellin moments of PDFs, GPDs

Early Era

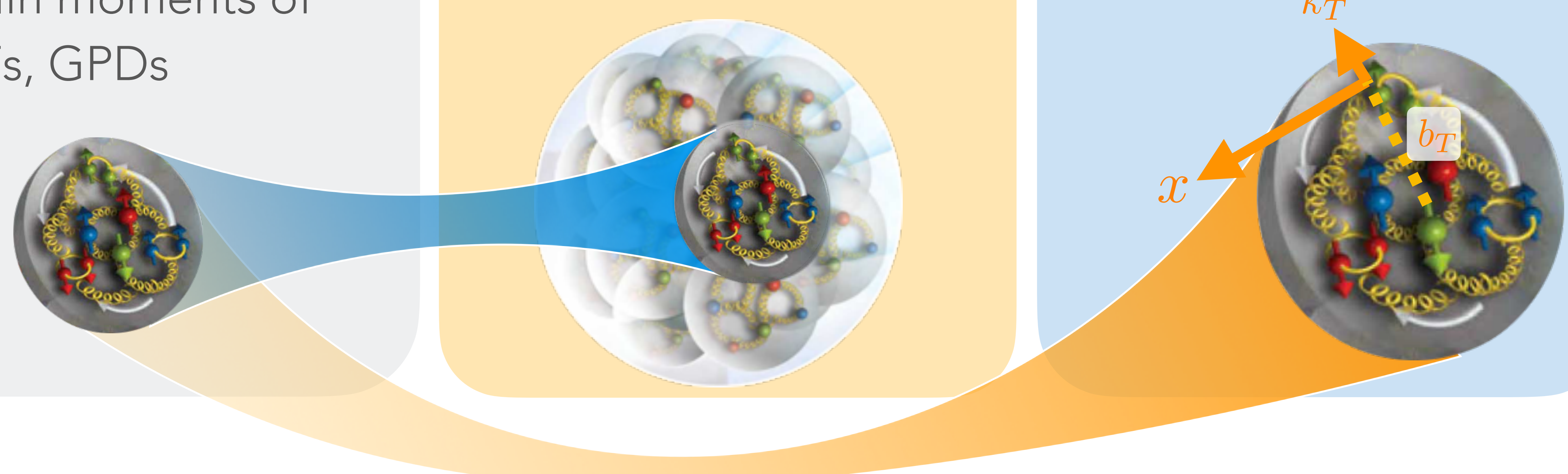
Fully-controlled w/ ~15–percent errors within ~5y

- Nuclear structure A<5
- Spin, flavour decomp. of EMC-type effects

Exploratory Era

First calculations, timeline for controlled calculations unclear

- x-dependence of PDFs
- TMDs



Nuclear physics from lattice QCD

- Nuclear physics from lattice QCD Collaboration

- Nuclei with A<5 unphysical quark masses
  First calculations with physical masses in progress 2021

Other lattice studies of nuclei:

PACS-CS e.g. ,Yamazaki et al, Phys.Rev.D 92 (2015);

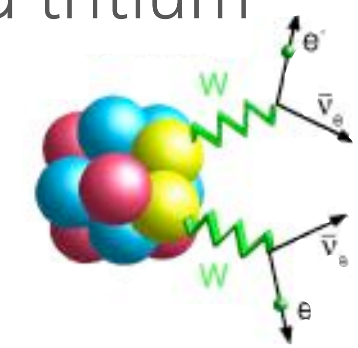
Callatt e.g., E Berkowitz et al, Phys.Lett.B 765 (2017) 285

Mainz e.g., A. Francis et al, Phys.Rev.D 99 (2019)

HALQCD e.g., Ishii et al, Phys.Rev.Lett. 99 (2007) (potential approach)

Recent highlights

- Proton-proton fusion and tritium β-decay
  [PRL 119, 062002 (2017)]



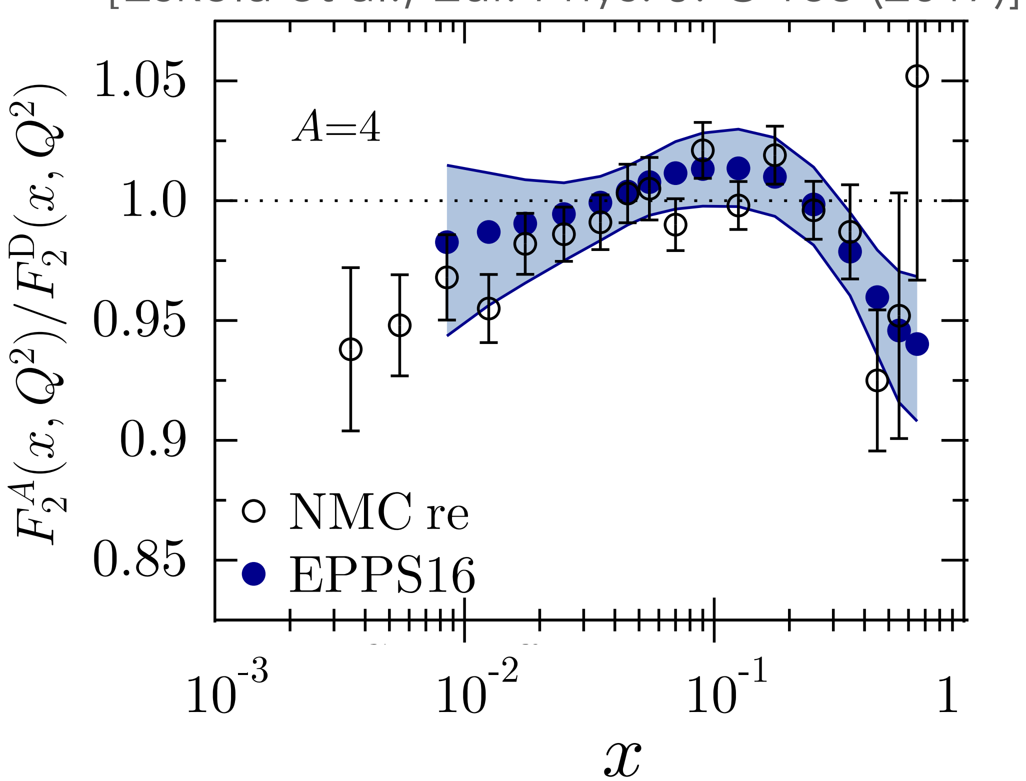
- Double β-decay
  [PRL 119, 062003 (2017), PRD 96, 054505 (2017)]
- Gluon structure of light nuclei
  [PRD 96 094512 (2017)]
- Scalar, axial, tensor MEs
  [PRL 120 152002 (2018), 2102.03805 (2021)]
- Baryon-baryon interactions, including QED
  [2003.12130 (2020), 2009.12357 (2020)]
- EMC-type effects in light nuclei
  [PRD 96 094512 (2017), 2009.05522 (2020)]

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 $\int_0^1 dx\, x^n q(x,Q^2)$

EMC effects in Mellin moments

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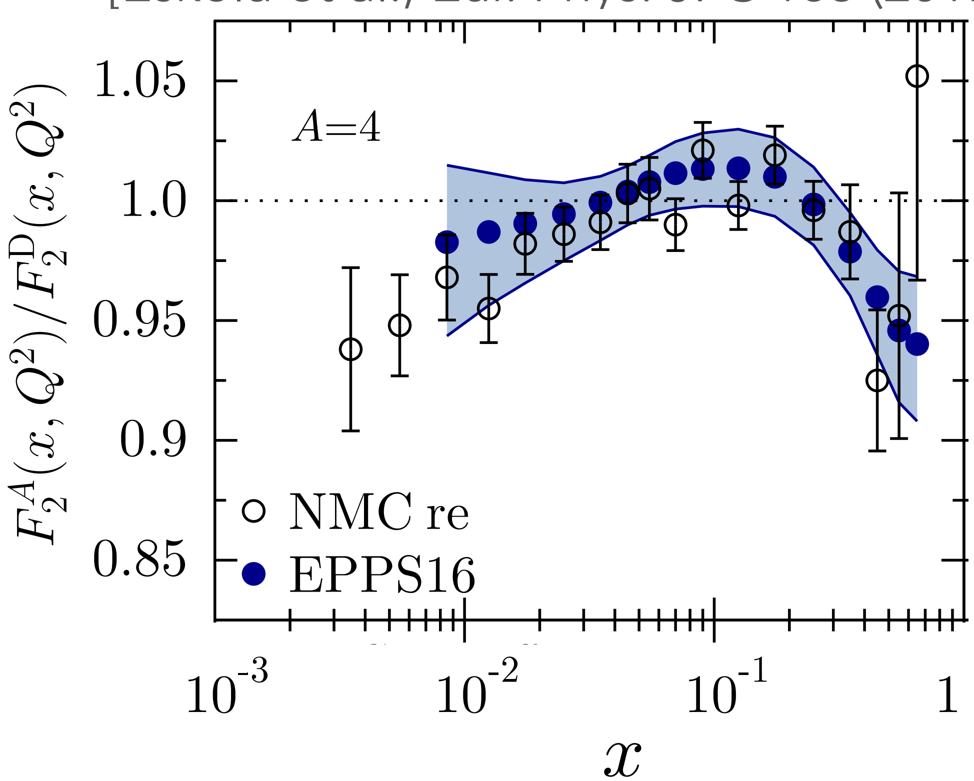
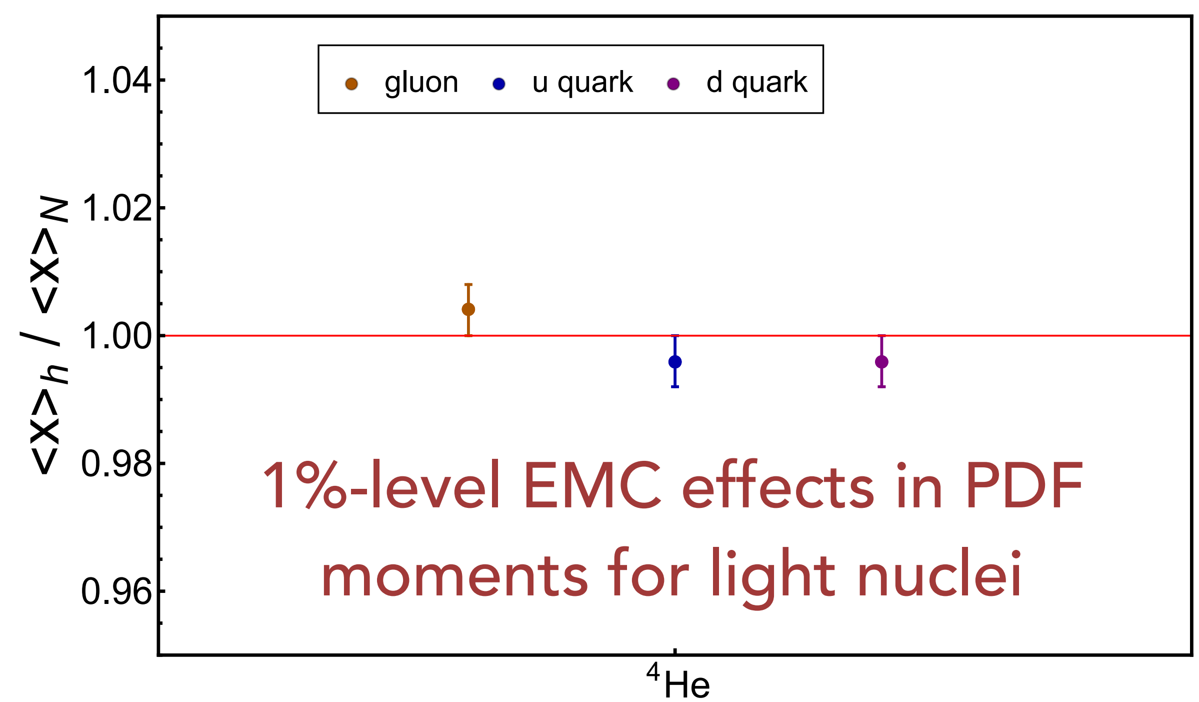




1%-level EMC effects in PDF moments for light nuclei

Momentum fraction of nuclei

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

- Lowest Mellin moment of spin-independent PDF defines fraction of momentum of nucleus A carried by parton of type f

$$\langle x \rangle_A^f = \int_0^1 dx\, x f^A(x) \qquad \sum_{f=q,g} \langle x \rangle_h^f = 1$$

- Momentum sum rule implies **nucleus-independent ratio of quark and gluon EMC effects** in the first moment

$$\left(\frac{\langle x \rangle_A^f}{\langle x \rangle_p^f} - 1 \right) = E_A^f \qquad \frac{E_A^g}{E_A^q} = -\frac{\langle x \rangle_p^q}{\langle x \rangle_p^g} \approx -1.4$$

$\overline{\mathrm{MS}}\,(\mu = 2\mathrm{GeV})$

Gluon momentum fraction of nuclei

Matrix elements of the spin-independent gluon operator in nucleon + light nuclei [NPLQCD PRD96 094512 (2017)]

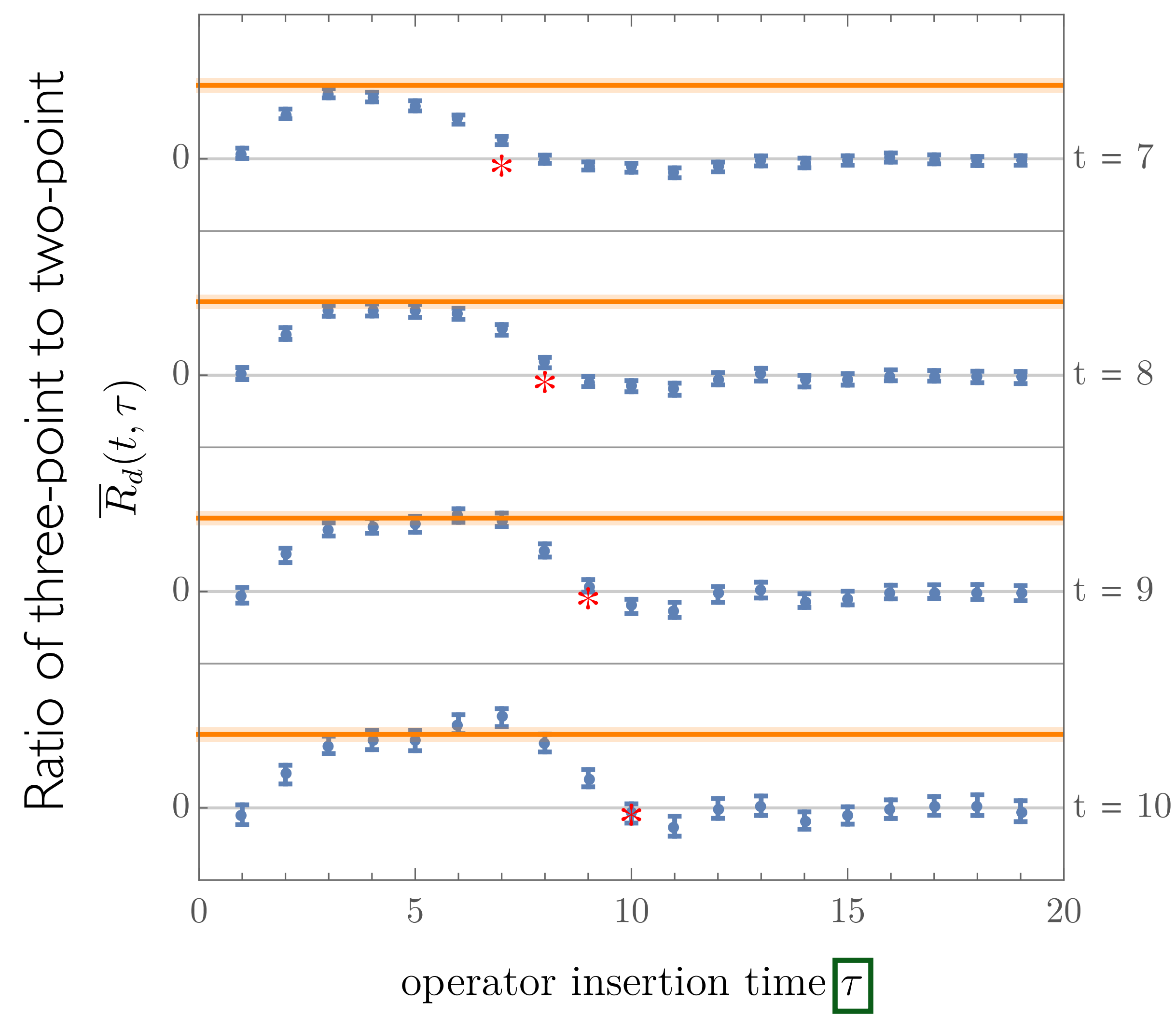
first determination of gluon momentum fraction of nuclei

Doubly challenging:

- Nuclear matrix element
- Gluon observable (suffer from poor signal-to-noise)
- BUT: clean signals at ~5% precision

[NPLQCD PRD96 094512 (2017)]

Deuteron gluon momentum fraction



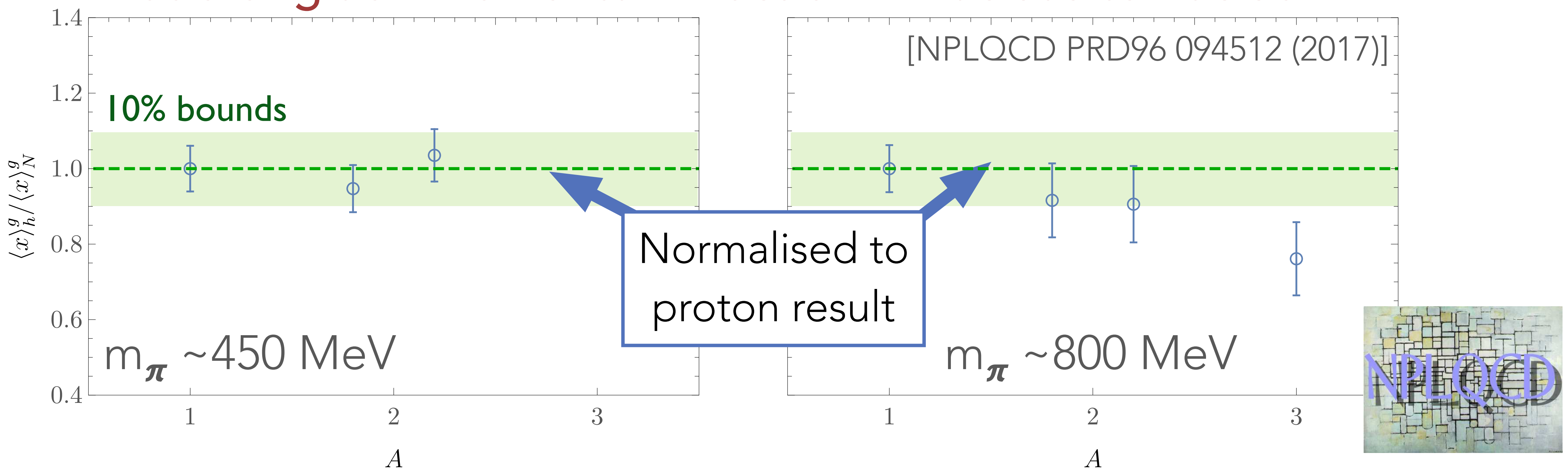
Gluon momentum fraction of nuclei

Matrix elements of the spin-independent gluon operator in nucleon + light nuclei [NPLQCD PRD96 094512 (2017)]

first determination of gluon momentum fraction of nuclei

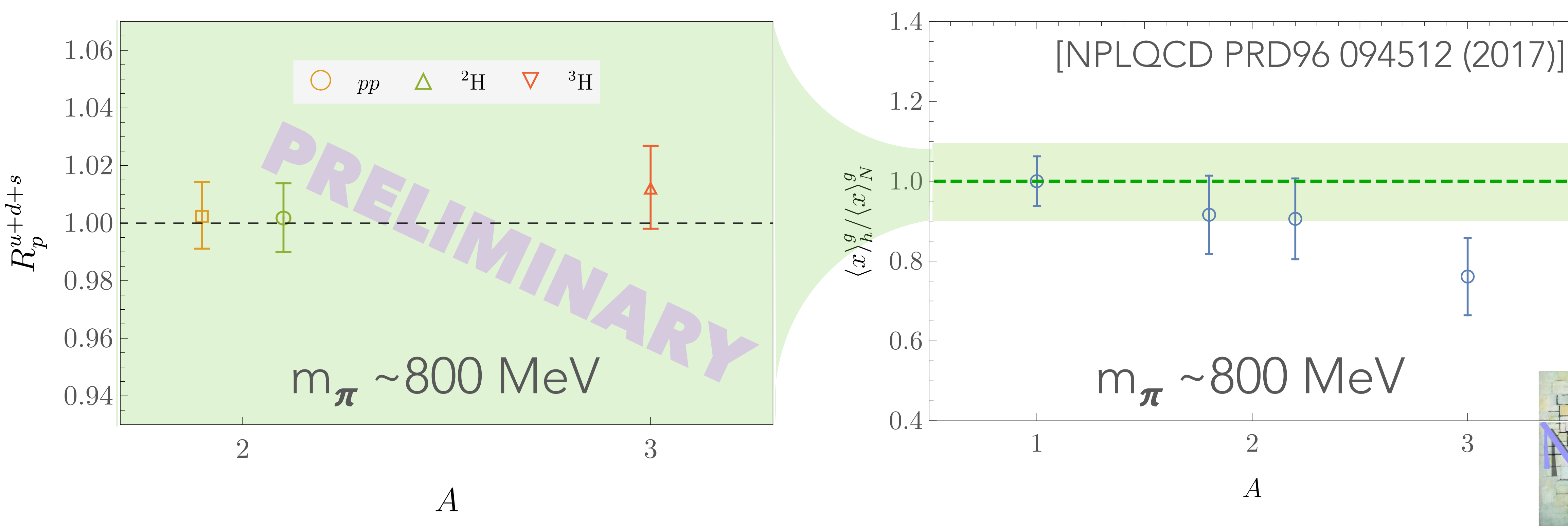
- Constraints at ~10% level on EMC-effect in gluon momentum fraction
- Small mixing with quark EMT operators (neglected)
- Sum rule constraint

Ratio of gluon momentum fraction in nucleus to nucleon



Momentum fractions of nuclei

- First determination of all components of momentum decomposition of light nuclei
- Small mixing between quark and gluon EMT operators neglected
- Constraint on either quark or gluon EMC in this quantity implies constraint on the other from sum rules:

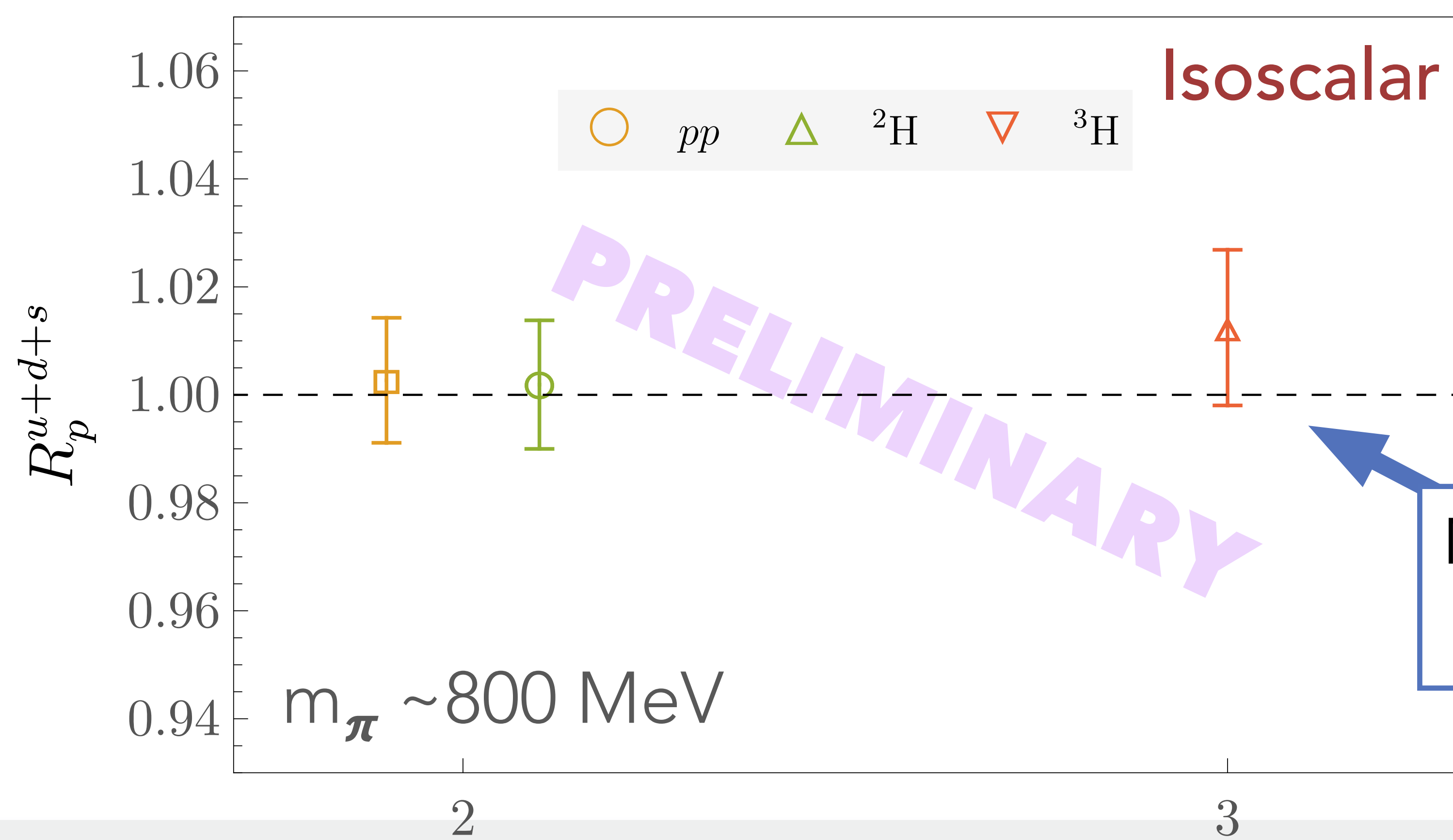


Momentum fraction of nuclei

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

Ratio of quark momentum fraction in nucleus to nucleon



- Small mixing with gluon EMT operators (neglected)
- **Sum rule constraint**

Normalised to proton result

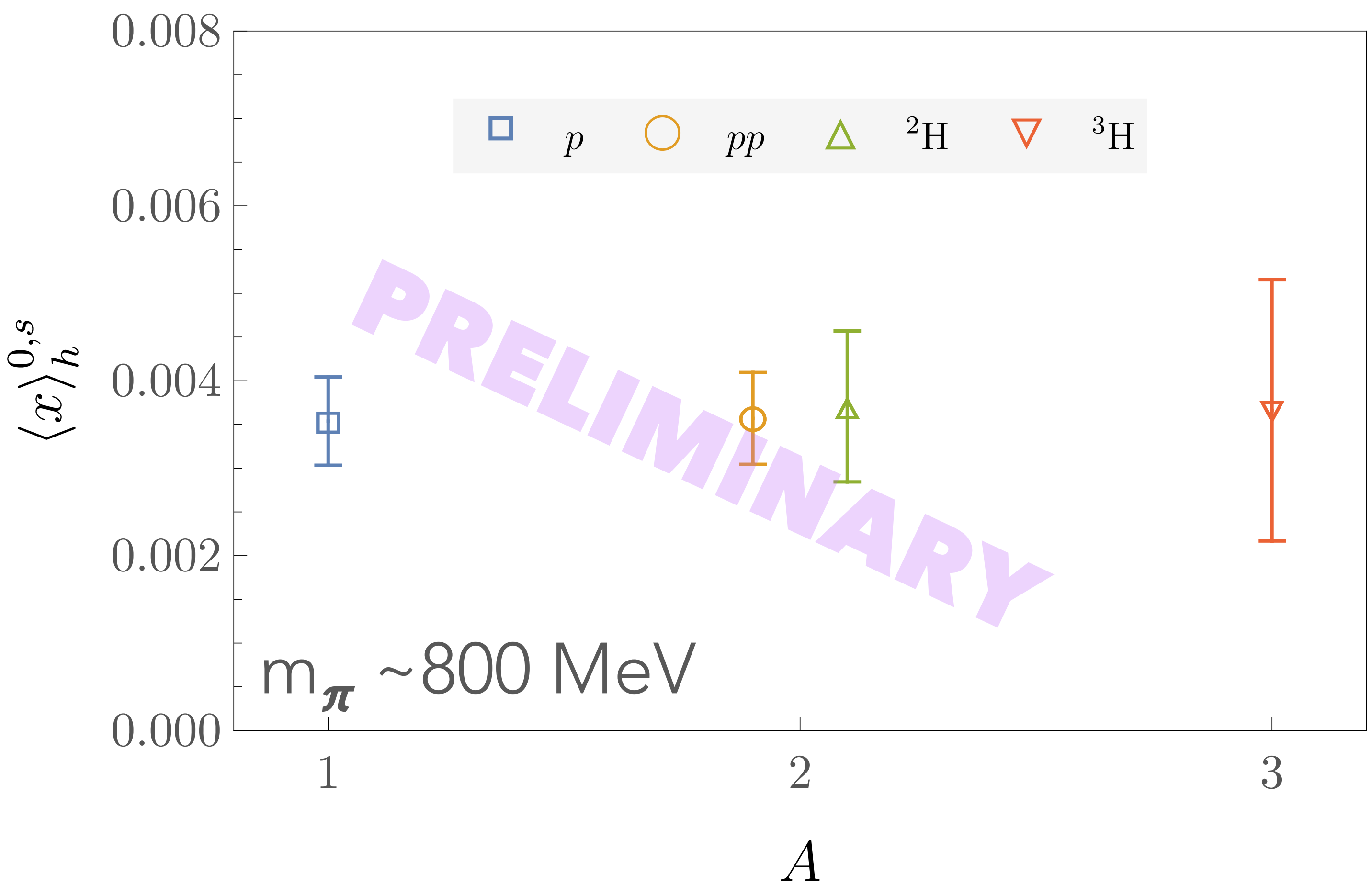
Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei

→ **first QCD determination of momentum fraction of nuclei**

- Few-percent determination of quark momentum fraction
  ~10% determination of strange quark contributions

Strange
(BARE)



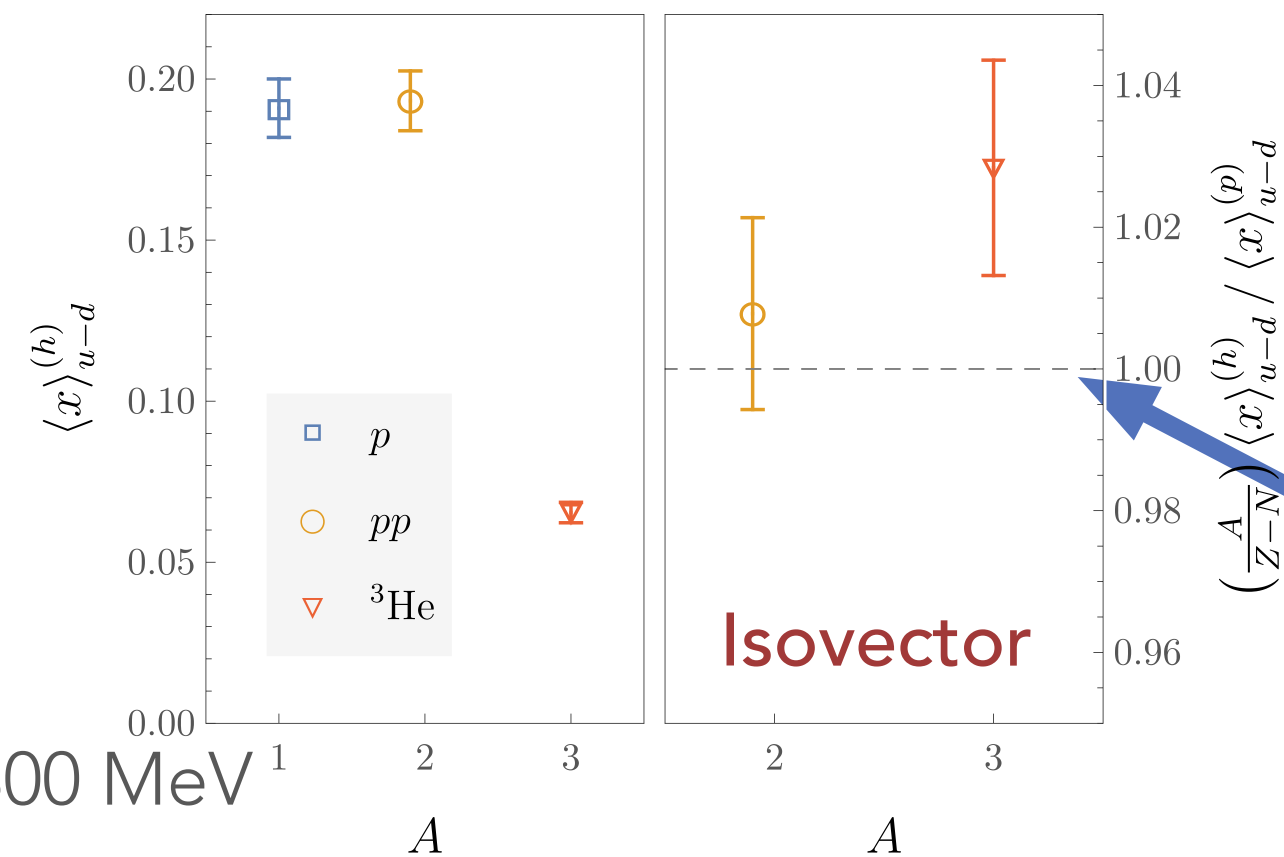
Momentum fraction of nuclei

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



Normalised to proton result

- No mixing
- No sum rule constraint

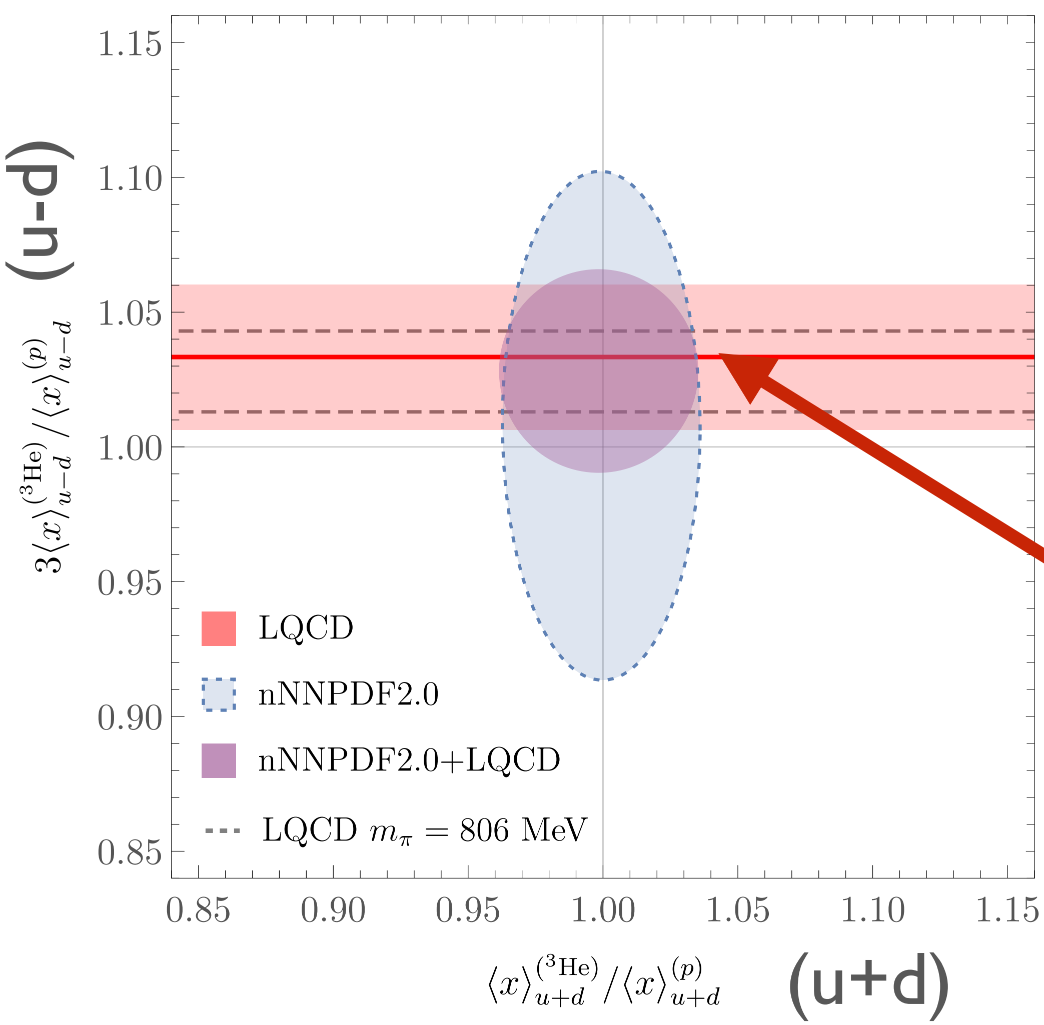
m_π ~800 MeV

NPLQCD

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 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

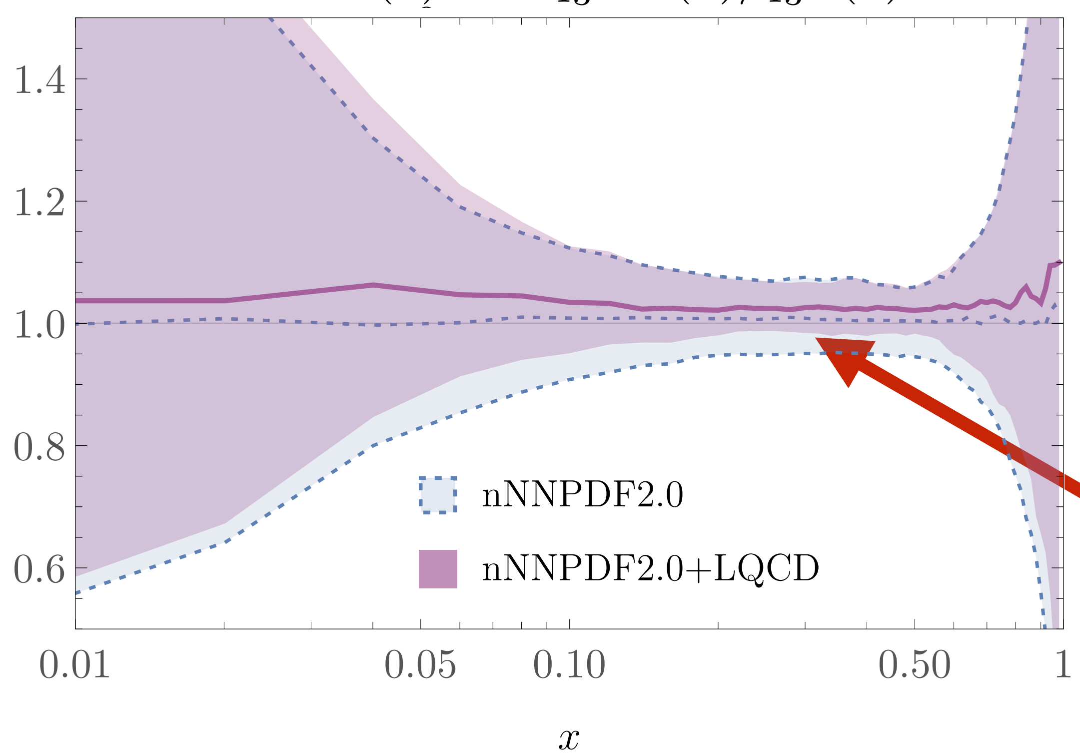
[NPLQCD 2009.05522 (2020)]

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 parton distributions

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



- Match isovector (u-d quark combination) momentum fraction to low-energy constants of effective field theory, extrapolate to physical quark masses
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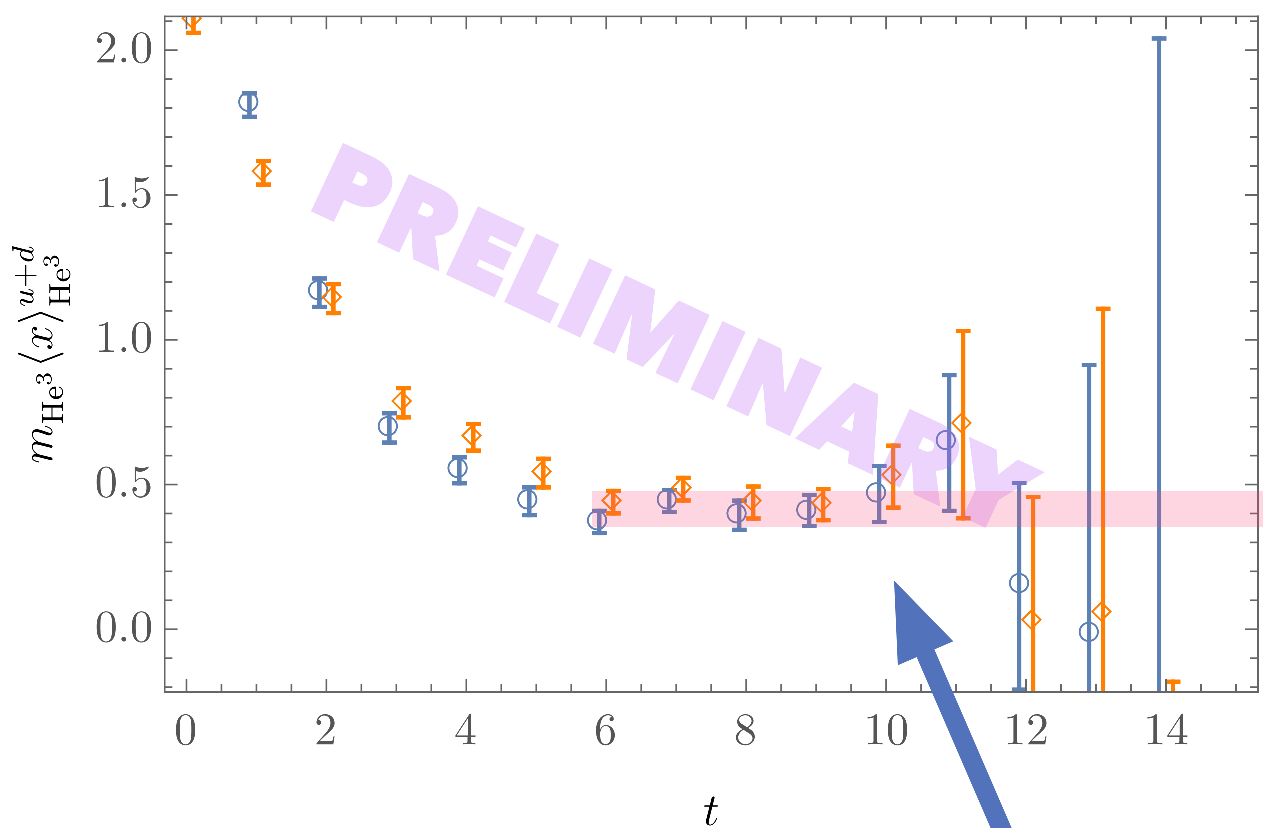
Blue → Purple:
Improvement using theory constraints

[NPLQCD 2009.05522 (2020)]

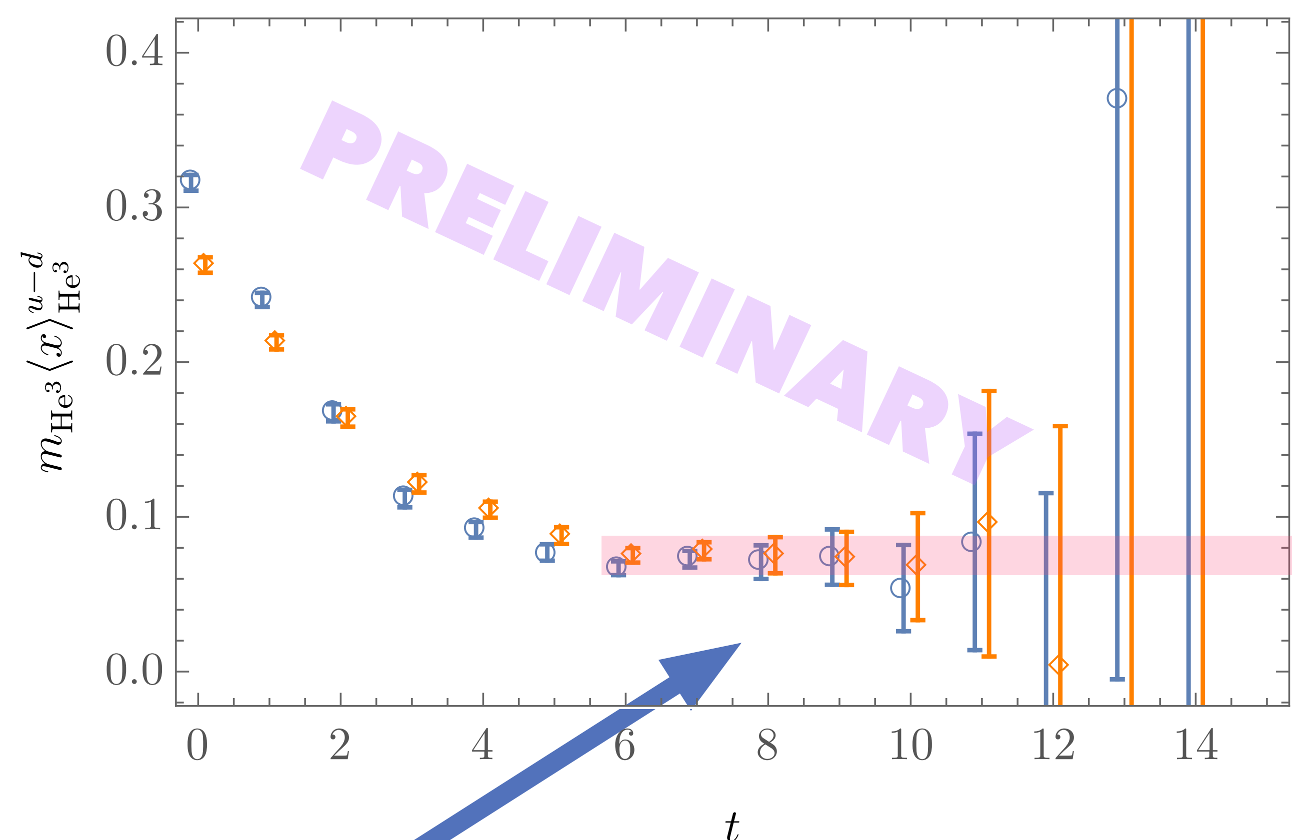
Momentum fractions of nuclei

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

Isoscalar



Isovector



First evidence of signals in physical-point data

Exotic glue in the deuteron

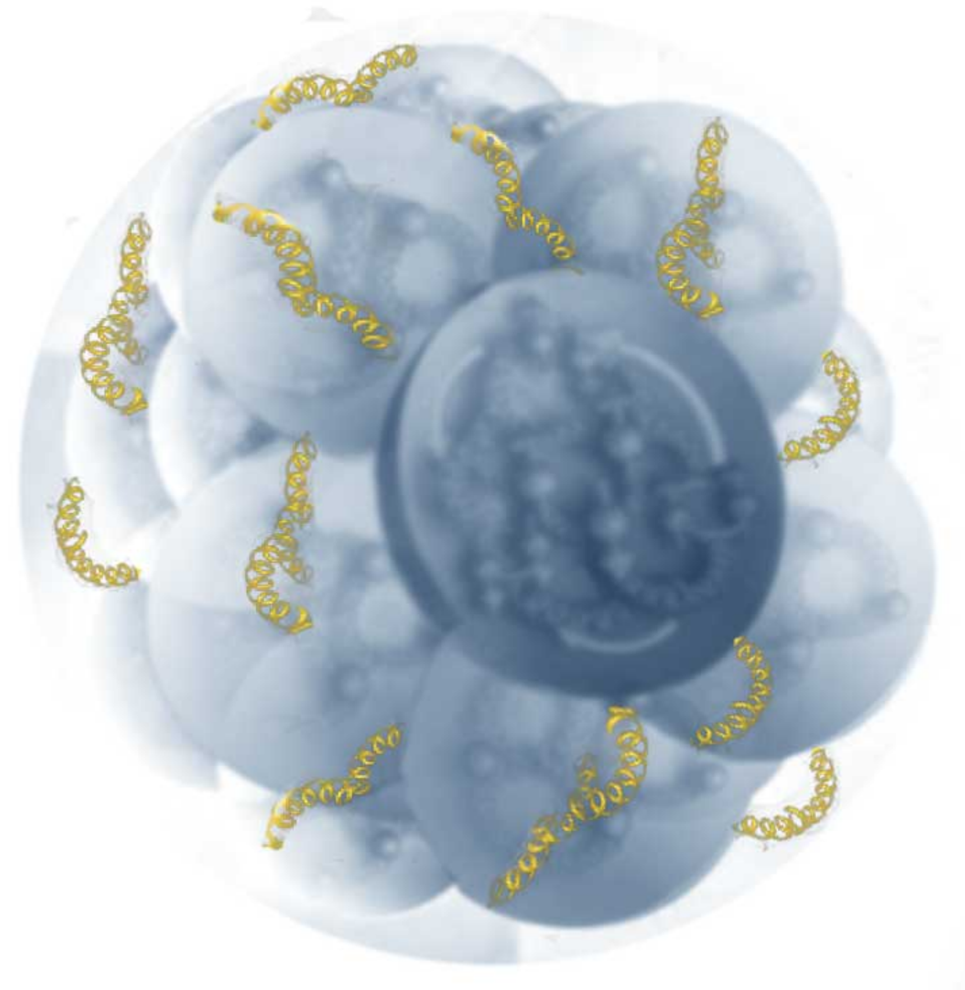
a "pure" EMC-type effect

Contributions to nuclear structure from gluons not associated with individual nucleons in nucleus

Exotic glue operator:

nucleon $\langle p|\mathcal{O}|p\rangle = 0$

nucleus $\langle N,Z|\mathcal{O}|N,Z\rangle \neq 0$

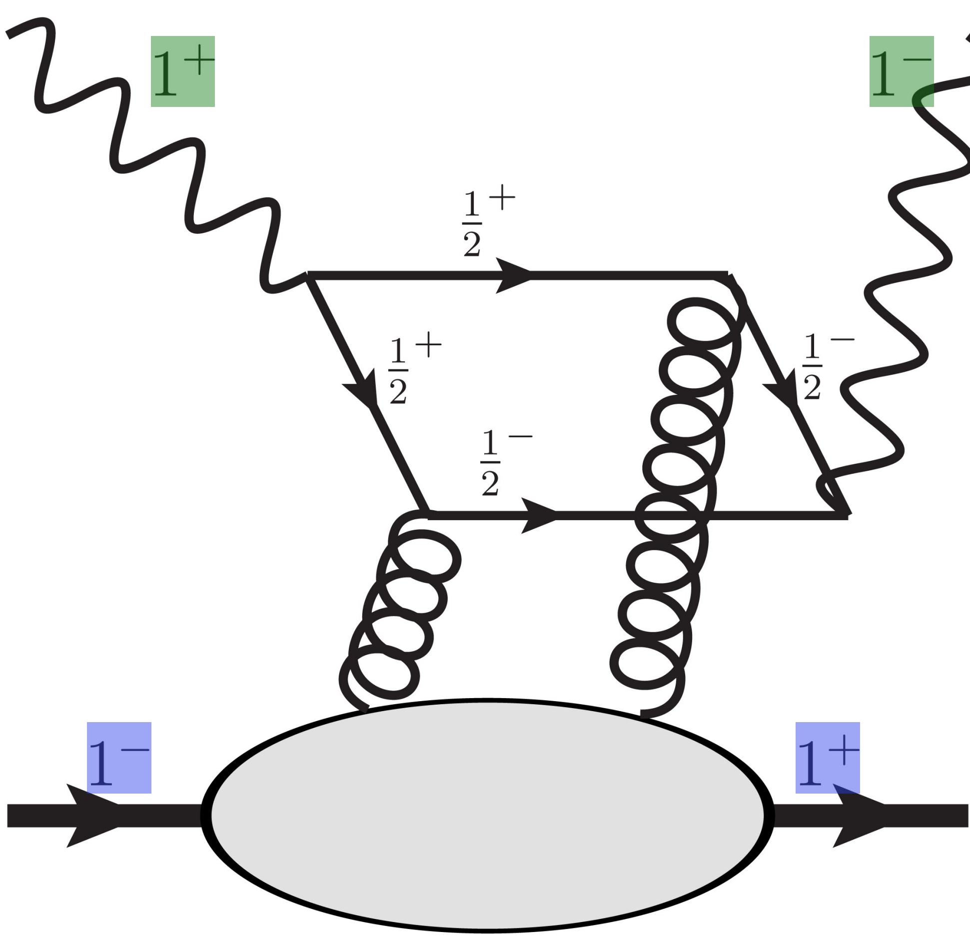


Jaffe and Manohar, "Nuclear Gluonometry" Phys. Lett. B223 (1989) 218

Exotic glue in the deuteron

a “pure” EMC-type effect

Double helicity flip structure function $\Delta(x,Q^2)$:
changes both photon and target helicity by 2 units



- **Unambiguously gluonic:** no analogous quark PDF at twist-2
- Non-vanishing in forward limit for targets with spin≥1
- **Experimentally measurable**
  - Unpolarised electron DIS on polarised target: JLab LoI 2015
  - Proton-deuteron Drell-Yan at FNAL
  - J/ψ production at NICA
- **Moments calculable in LQCD**

Exotic glue in the deuteron

a "pure" EMC-type effect

Double helicity flip structure function $\Delta(x,Q^2)$:
changes both photon and target helicity by 2 units

Parton model interpretation: gluonic transversity

$$\Delta(x,Q^2) = -\frac{\alpha_s(Q^2)}{2\pi}\mathrm{Tr}\mathcal{Q}^2\, x^2 \int_x^1 \frac{dy}{y^3}\left[g_{\hat{x}}(y,Q^2) - g_{\hat{y}}(x,Q^2)\right]$$

$g_{\hat{x},\hat{y}}(y,Q^2)$: probability of finding a gluon with momentum fraction y linearly polarised in $\hat{x}$, $\hat{y}$ direction

Exotic glue in the deuteron

Contributions to nuclear structure from gluons not associated with individual nucleons in nucleus

nucleon: $\langle p|\mathcal{O}|p\rangle = 0$

nucleus: $\langle N, Z|\mathcal{O}|N, Z\rangle \neq 0$

- First moment of gluon transversity distribution in the deuteron
  [Jaffe, Manohar PLB223 (1989) 218]
- First evidence for non-nucleonic gluon contributions to nuclear structure: LQCD with m_π ~800 MeV [NPLQCD PRD96 (2017)]
- Magnitude relative to momentum fraction as expected from large-N_c

Signal in LQCD data

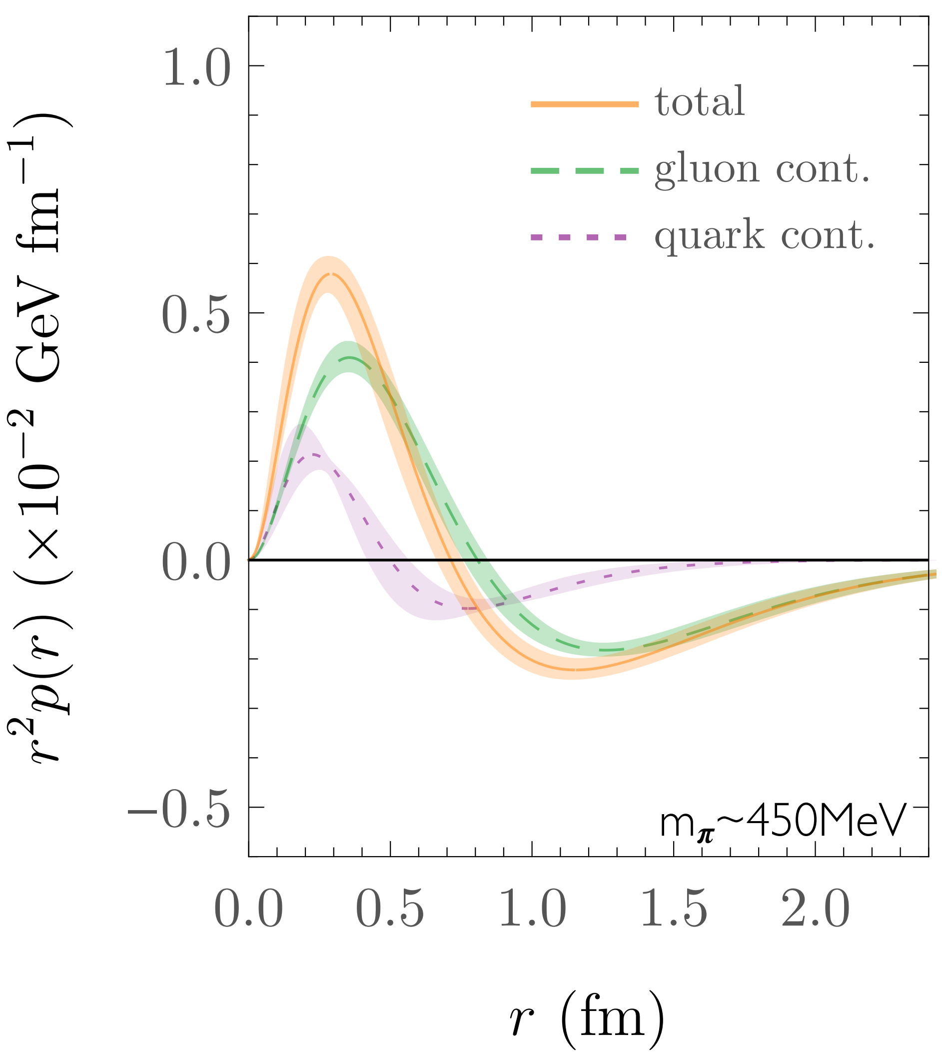
Next steps towards EMC constraints from LQCD

- Higher statistics, physical quark masses
- Continue to investigate effect of LQCD constraints on global nuclear PDF fits
- EMC-type effects in more complicated quantities perhaps statistically easier to reveal
  - → Polarised EMC effect
  - → Generalised form factors (moments of GPDs)

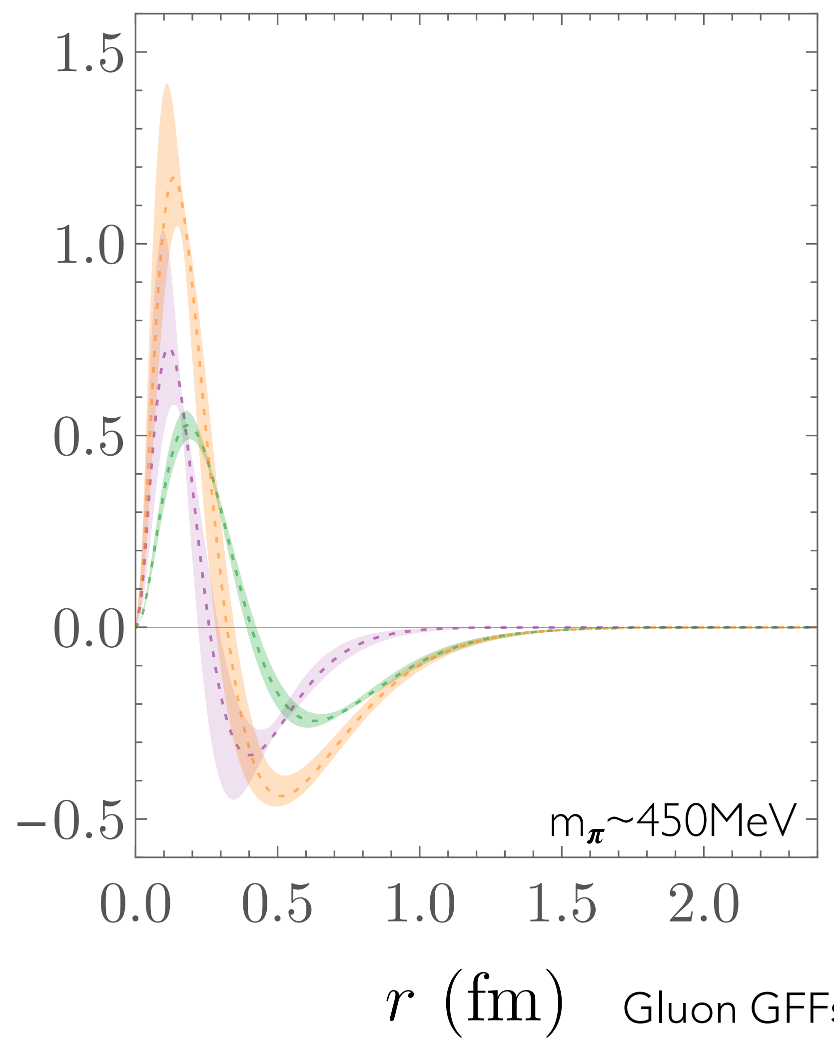
Next: pressure distribution in nuclei

Pressure in light nuclei
c.f. pressure in the nucleon?

Nucleon



Pion



Light nuclei

?

coming soon

Insights into equation of state of neutron stars?

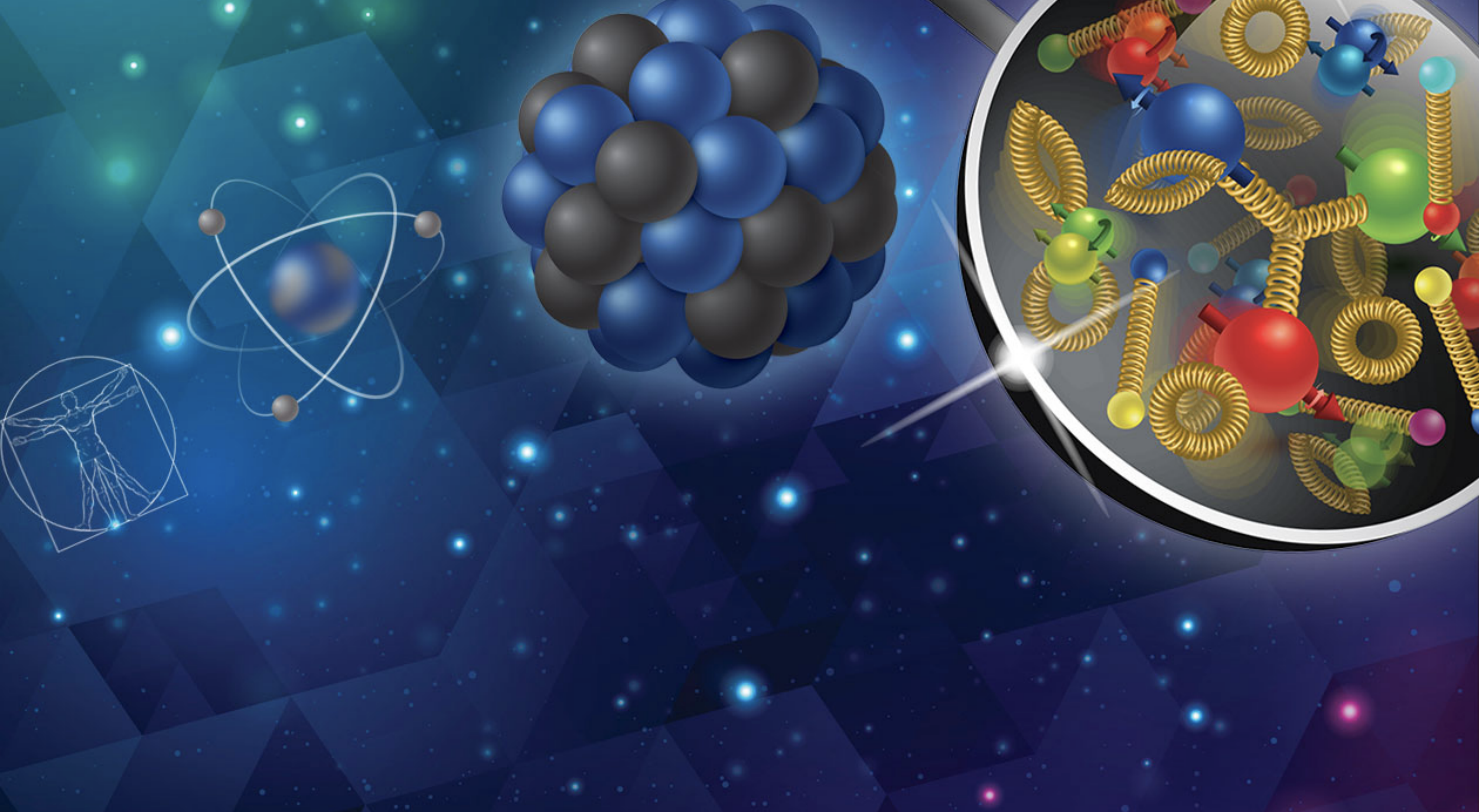
Gluon GFFs: Shanahan, Detmold, PRD 99, 014511

Quark GFFs: P. Hägler et al. (LHPC), PRD77, 094502 (2008)

Summary and outlook

EMC-type effects are accessible to LQCD

- **Current state-of-the-art:** significant systematics but approaching phenomenologically interesting precision
- **Near future:** systematics controlled for A<5, predictions for
  - Polarised EMC (polarised light ions)
  - Isovector EMC (SIDIS)
  - Gluon EMC (quarkonium production)



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