Form Factors from Lattice QCD

Phiala Shanahan, MIT

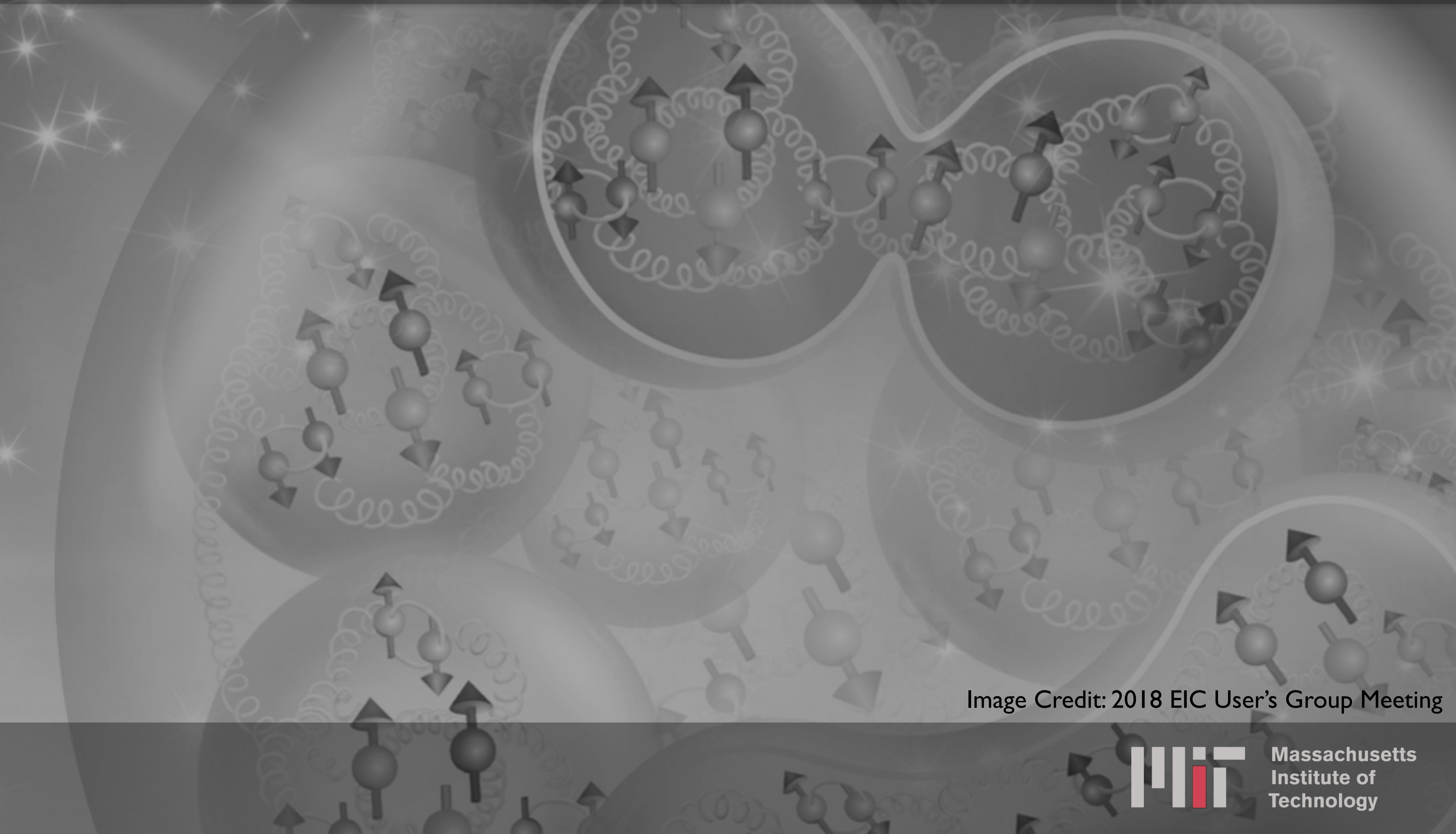


Image Credit: 2018 EIC User's Group Meeting

Massachusetts Institute of Technology

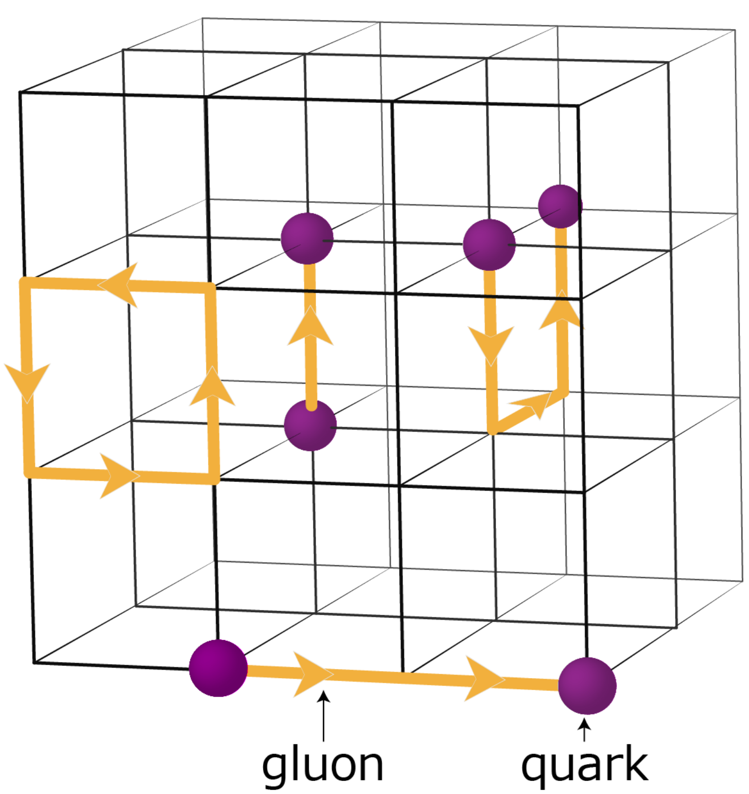
Nucleon and Nuclear Form Factors from Lattice QCD

- Electromagnetic form factors
- Axial and pseudo-scalar form factors
- Generalised form factors incl. gravitational
- Nuclear form factors

Lattice QCD

Numerical first-principles approach to non-perturbative QCD

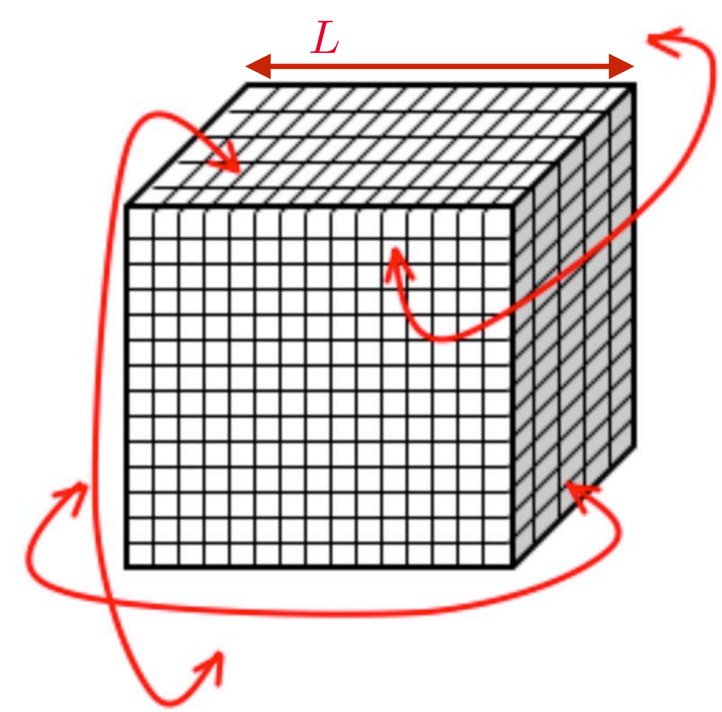
- Discretise QCD onto 4D space-time lattice
- Approximate QCD path integral using Monte-Carlo methods and importance sampling
- Run on supercomputers and dedicated clusters
- Take limit of vanishing discretisation, infinite volume, physical quark masses



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)



Approximate 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

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Numerical first-principles approach to
non-perturbative QCD
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Calculations use world's largest computers

- Many millions of CPU/GPU/KNL hours
- Specifically designed processors for QCD (QCDOC precursor of BlueGene computers)

Lattice QCD

Numerical first-principles approach to non-perturbative QCD

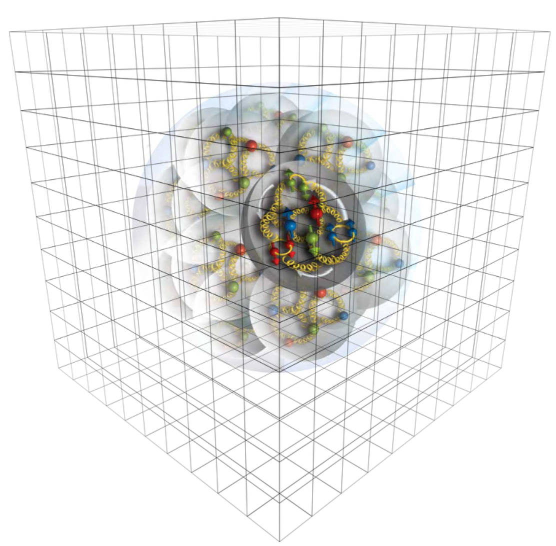
INPUT

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

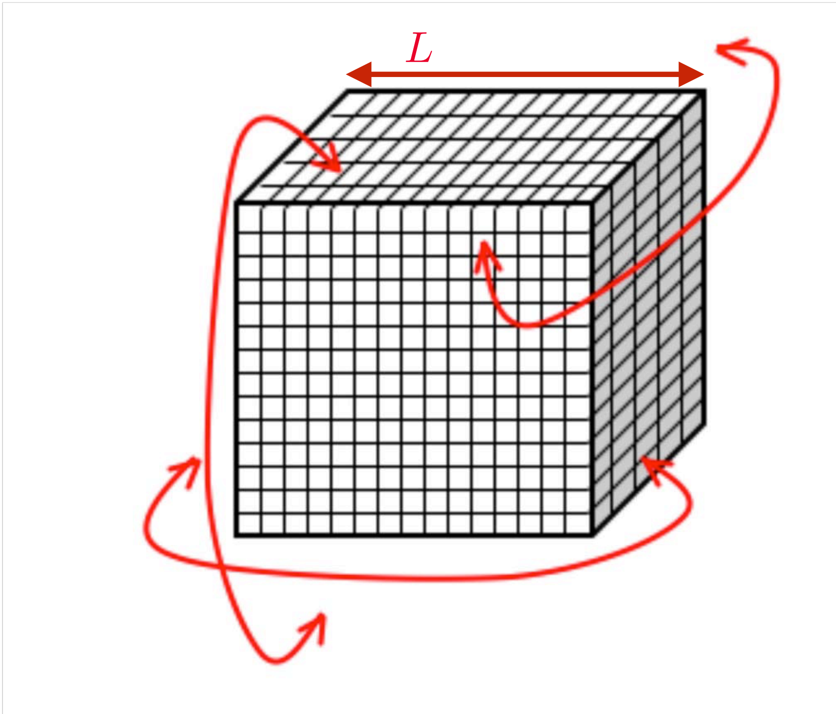
OUTPUT

Calculations of all other quantities are QCD predictions

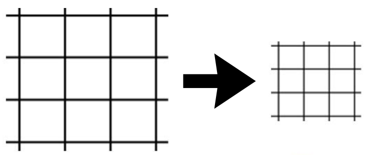


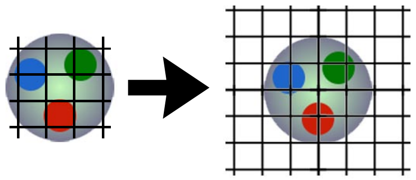
Uncertainties in lattice QCD

Differences between calculations



- **Uncertainties on a single "ensemble"**
  - Data volume (statistical sampling)
  - Fitting methodology (e.g., treatment of "excited-state contamination")
  - Renormalisation procedure (i.e., matching from lattice quantities to $\overline{\mathrm{MS}}$)
- **Uncertainties of result "extrapolated to physical point"**
  - Continuum extrapolation: range of lattice spacings
  - Infinite-volume extrapolation: range of volumes
  - Tuning of the bare quark masses: values of pion, kaon masses, extrapolation/interpolation thereof, isospin-breaking, …





$m_\pi \to 140\mathrm{MeV}$

FLAG 2021 Flavour Lattice Averaging Group

Many lattice calculations of what are now "simple" flavour physics and hadron structure quantities

FLAG: Flavour Lattice Averaging Group
Similar effort to the PDG, for Lattice QCD

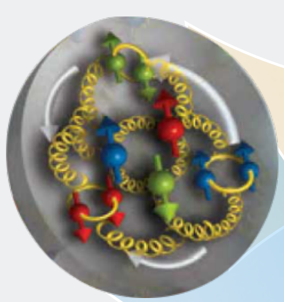
- Members from most major lattice QCD collaborations
- Evaluates and grades different aspects of each calculation ★ ○ ■
- Provides averages as the "Lattice QCD community consensus" value for a given quantity
- Includes lattice dictionary and summaries for non-experts
- Summary report every ~2 years: Feb 2024 update at http://flag.unibe.ch
- **New version planned for October 2024:** coverage expanded in 2019 version to include nucleon charges, continues to expand over time (FFs likely soon)

Form factors from Lattice QCD

Precision Era

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

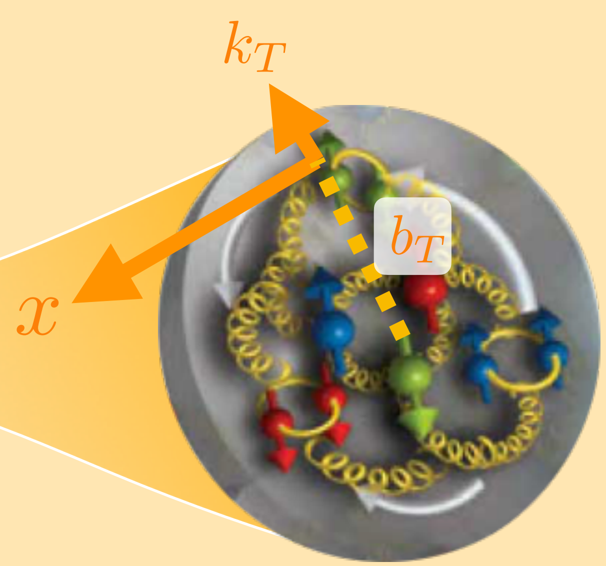
- Forward limits of FF incl. charges, moments of GPDs
- *t*-dependence of EM, axial, pseudo scalar FFs



Early Era

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

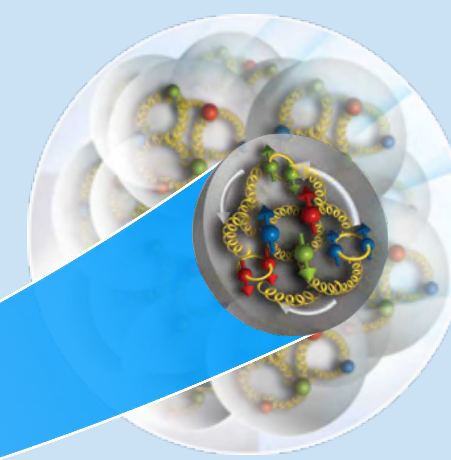
- *t*-dependence of GFFs
- Forward limits of nuclear FFs



Exploratory Era

First calculations, timeline for controlled calculations unclear

- Many transition and resonance FFs
- *t*-dependence of nuclear FFs



Nucleon and Nuclear Form Factors from Lattice QCD

- Electromagnetic form factors
- Axial and pseudo-scalar form factors
- Generalised form factors incl. gravitational
- Nuclear form factors

Nucleon electromagnetic form factors

Electromagnetic form factors encode coupling of the nucleon to an electromagnetic current

$$\langle N(p',s')|\bar{q}\gamma^\mu q|N(p,s)\rangle = \bar{u}_N(p',s')\left[\underbrace{F_1(Q^2)}_{\text{Dirac FF}}\gamma^\mu + \underbrace{F_2(Q^2)}_{\text{Pauli FF}}\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}\right]u_N(p,s) \qquad \begin{aligned} q &= p' - p \\ q^2 &= -Q^2 \end{aligned}$$

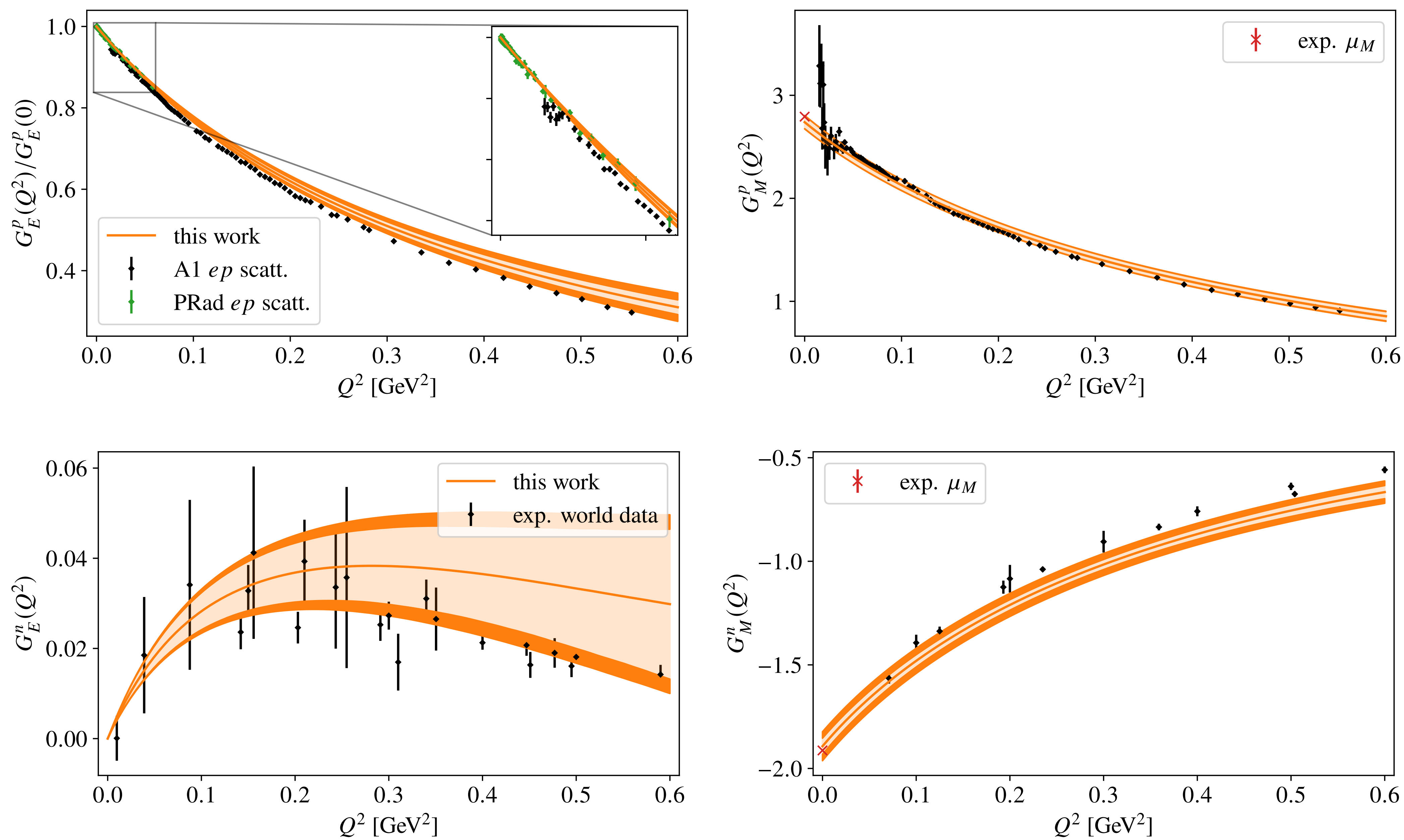
- Linear combinations define the **Sachs electric and magnetic** form factors

$$G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M_N^2}F_2(Q^2) \qquad G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

- LQCD results for EMFFs and associated radii are now **fully-controlled** for $0 \leq Q^2 \lesssim 1\text{GeV}^2$; physical quark masses, several lattice volumes, spacings
- Few calculations of strange contributions from LQCD, but reasonably precise
- Efforts **driving to large** $Q^2 \lesssim 10\text{GeV}^2$, but still work-in-progress
- Work ongoing to study more complicated FFs, **e.g., transition, resonance FFs**

Nucleon electromagnetic form factors

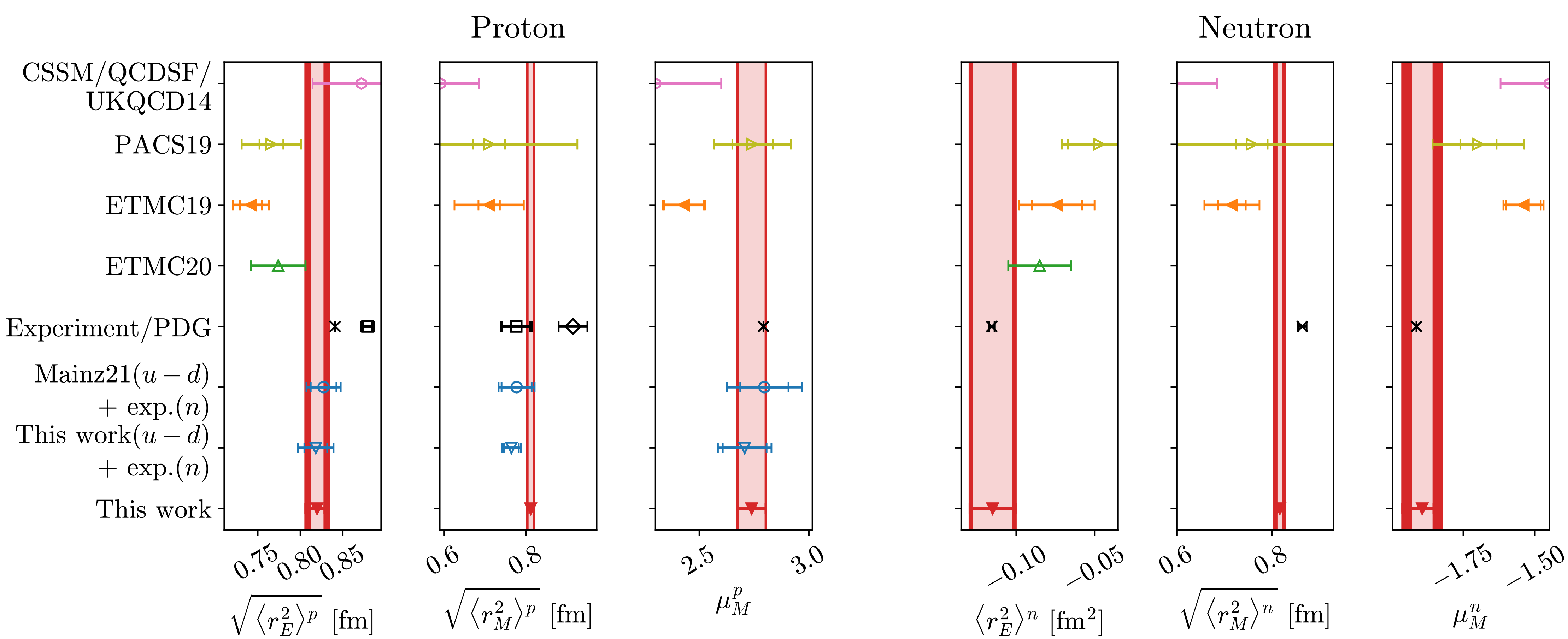
New work in 2023 that separates proton and neutron FFs with complete uncertainty quantification [Djukanovic et al., arXiv:2309.06590 (2023)]



Nucleon electromagnetic form factors

New work in 2023 that separates proton and neutron FFs with complete uncertainty quantification [Djukanovic et al., arXiv:2309.06590 (2023)]

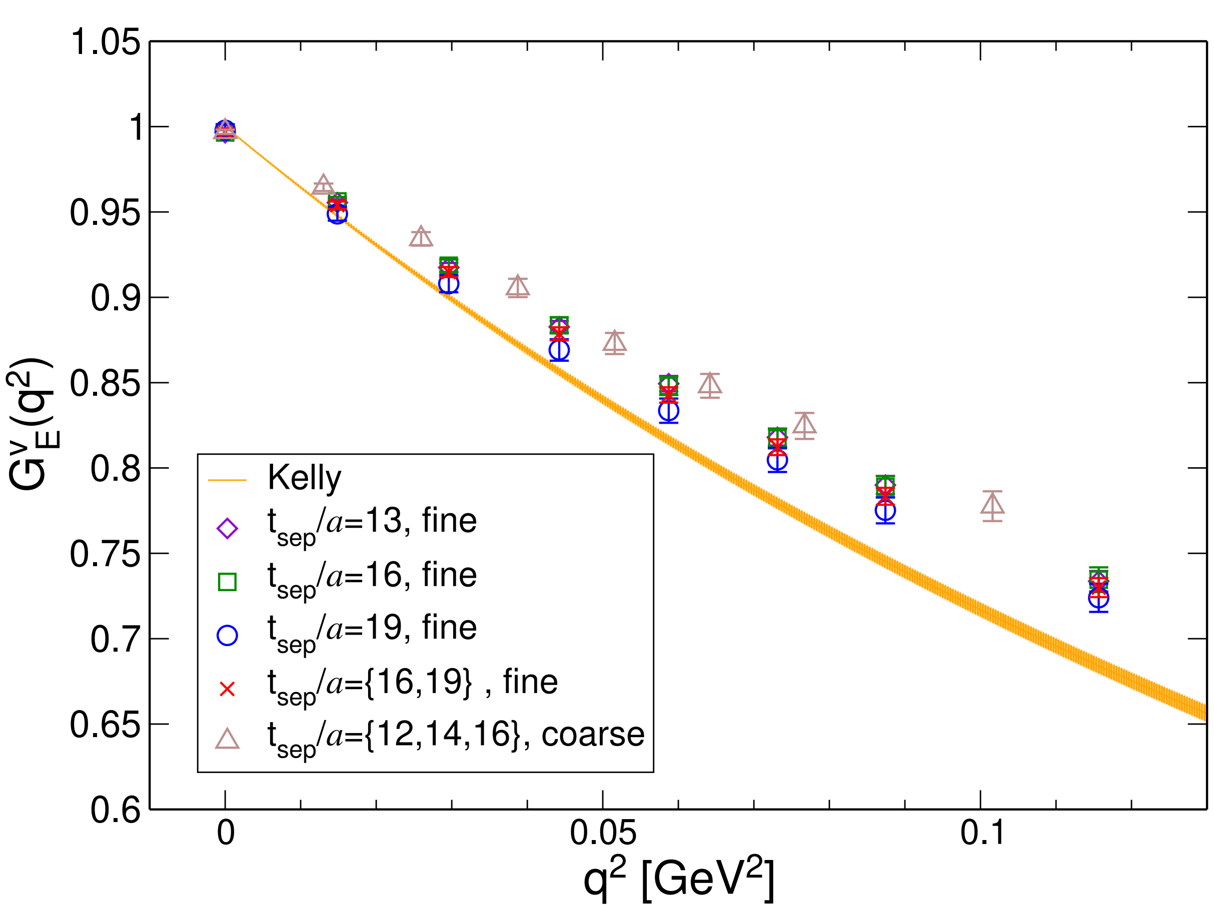
- Electric (charge) radius of the proton closer to muonic hydrogen spectroscopy & recent *ep*-scattering experiments than to the A1 *ep*-scattering result
- Magnetic radius compatible with the analyses of A1 data, in tension with the other collected world data
- Interesting tension with magnetic neutron radius

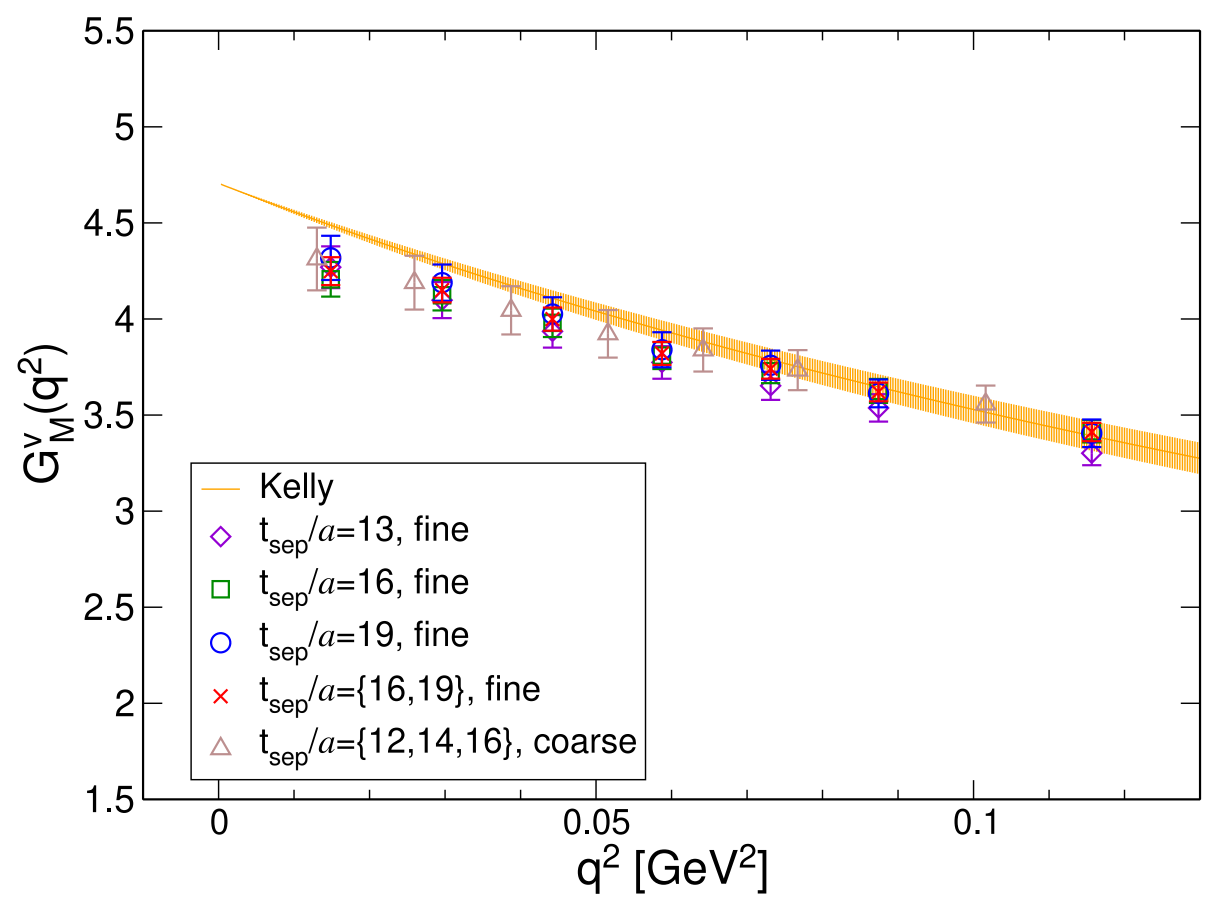


Nucleon electromagnetic form factors

New work in 2023 with large lattice volumes (up to 160^4) and yields many points in the low-Q^2 region [Tsuji et al. [PACS Collaboration], arXiv:2311.10345 (2023)]

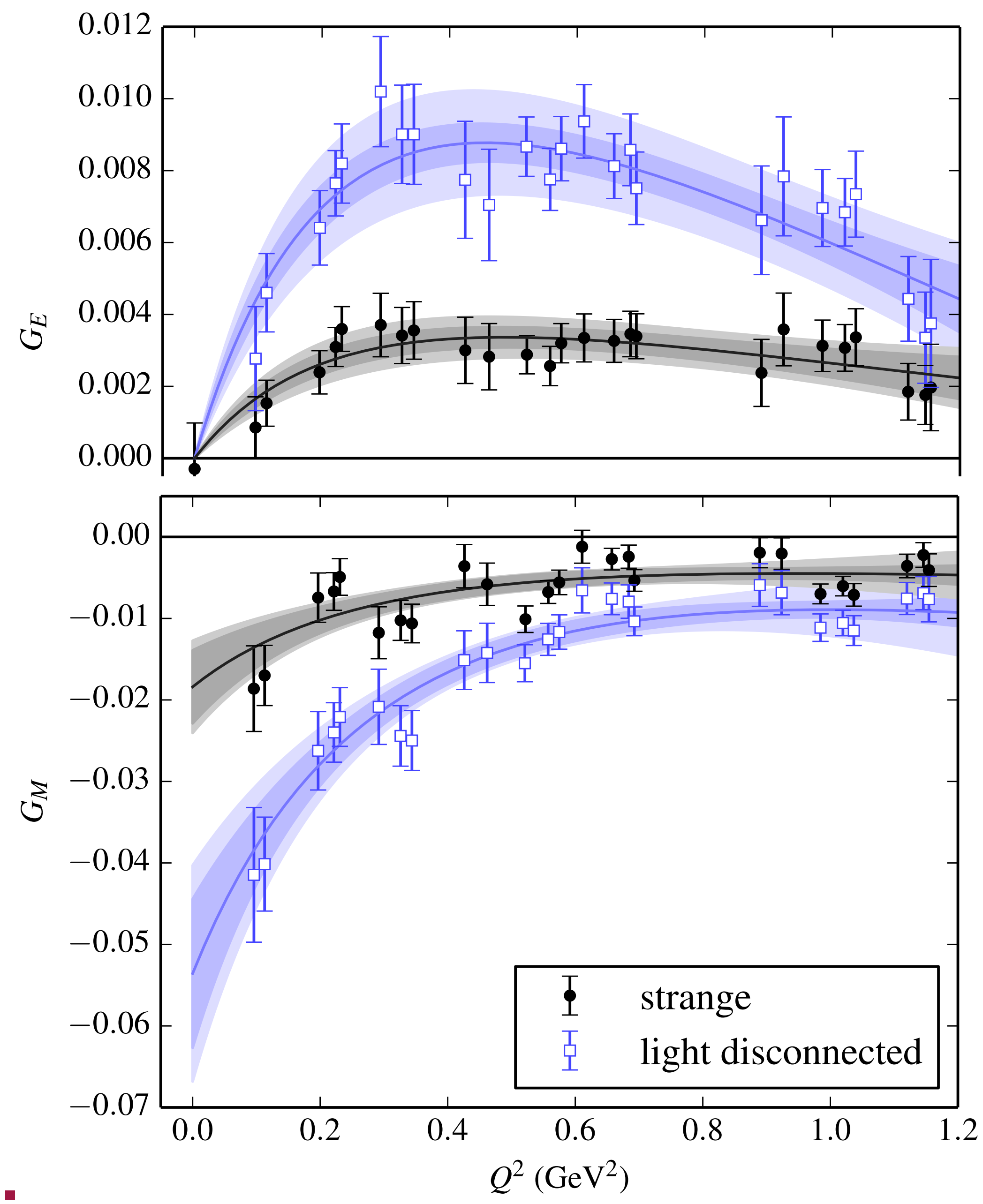
- Improves control over finite-volume and discretisation uncertainties; consistent with recent *ep*-scattering data
- Isovector combinations only so far (with systematic control)



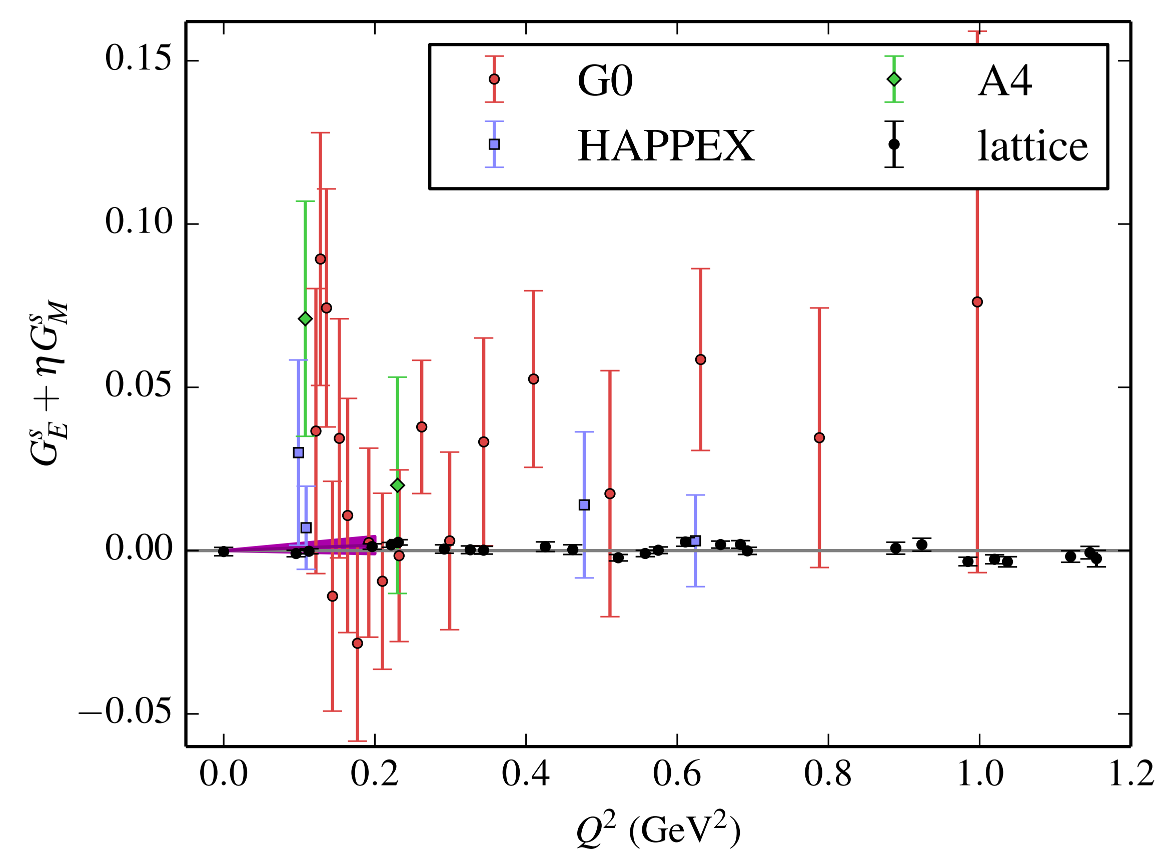


Strange quark EM form factors

2015 results on strange EM form factors remain state-of-the-art
[Green et al., arXiv:1505.01803 (2015)]



- Not fully-controlled; larger-than-physical $m_\pi \sim 300$MeV, strange-quark mass close-to-physical

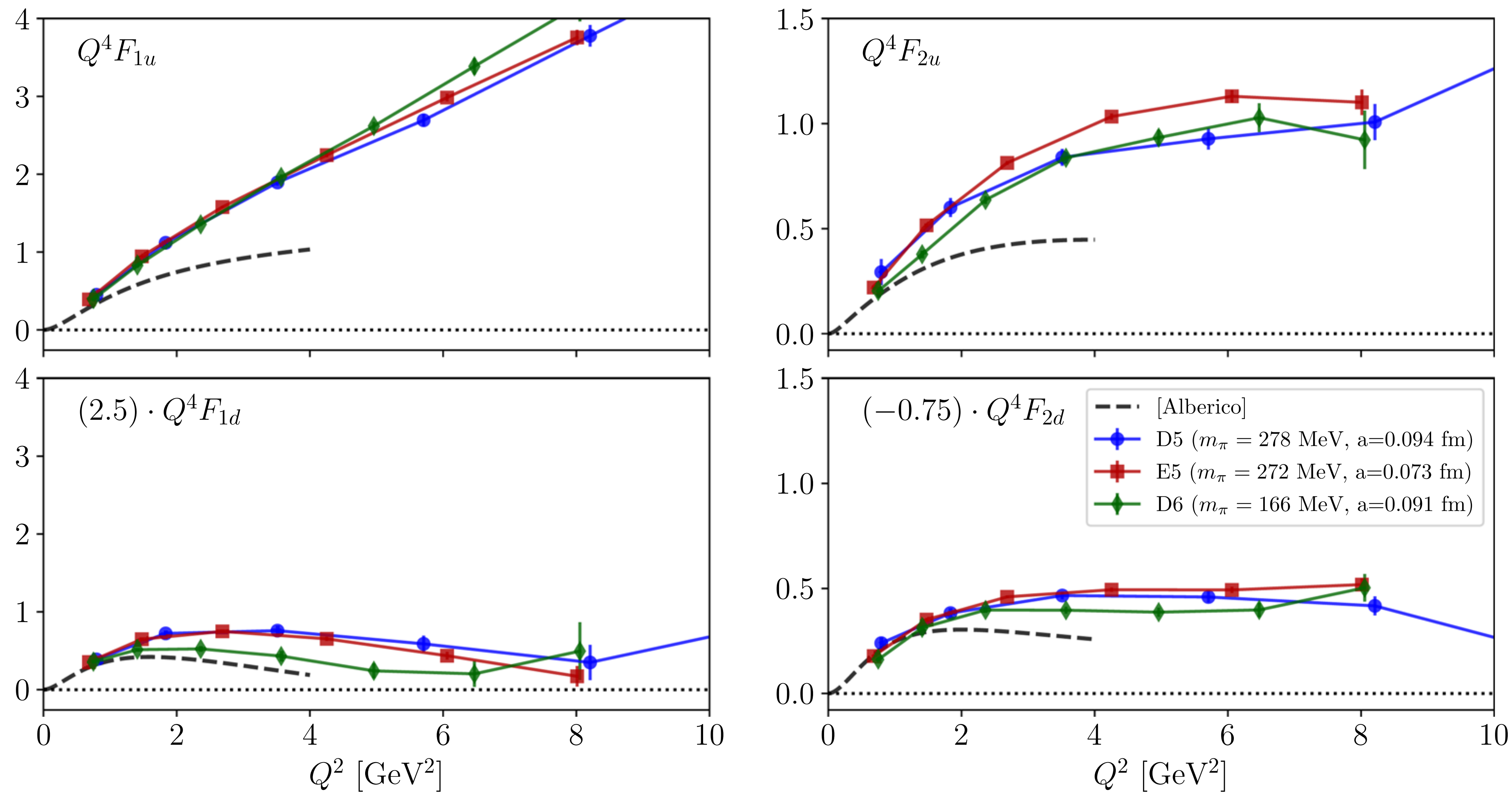


High-momentum form factors

New efforts pushing towards high-Q^2 form factors

[Syritsyn et al. Few-Body Syst 64:72 (2023), see also QCDSF-UKQCD-CSSM], 2202.01366 (2022)]

- Not completely controlled (discretisation, neglected disconnected contributions, …)
- Significant discrepancies with phenomenology [Alberico et al, PRC79:065204 (2008)]



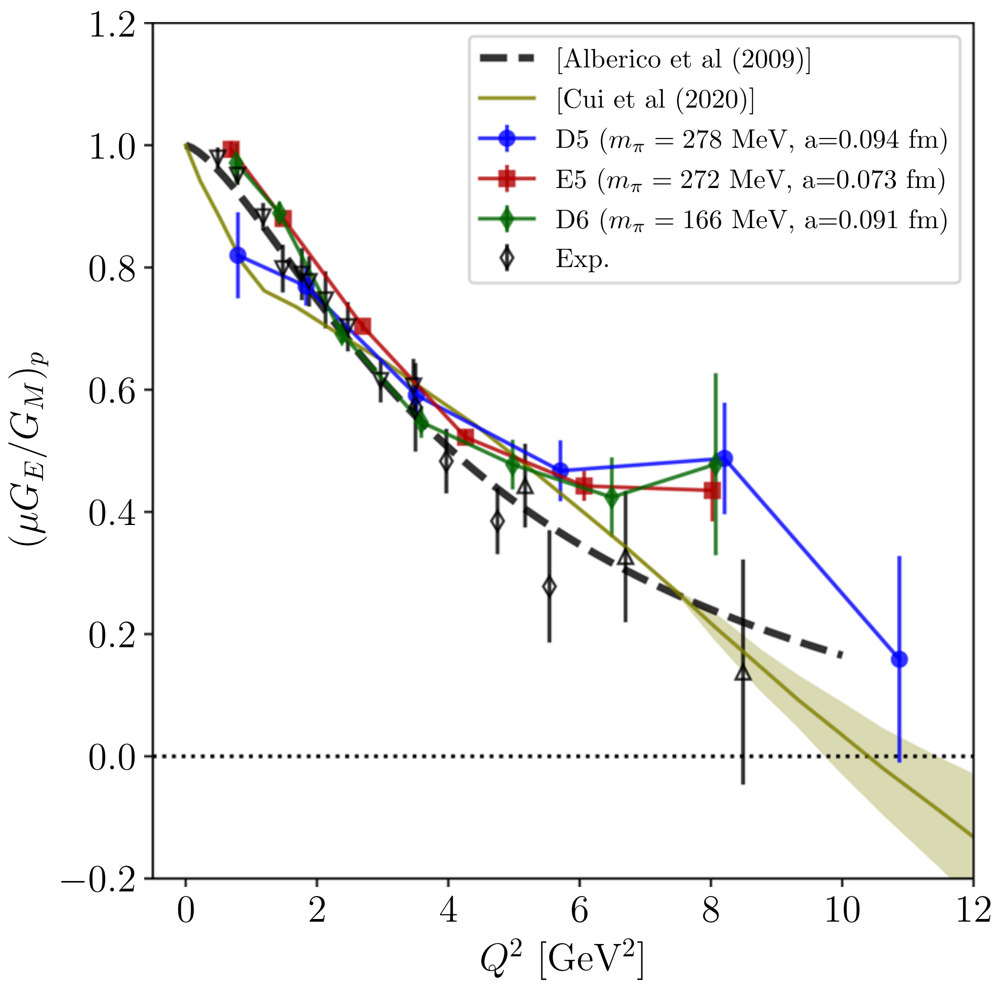
[Syritsyn et al. Few-Body Syst 64:72 (2023)]

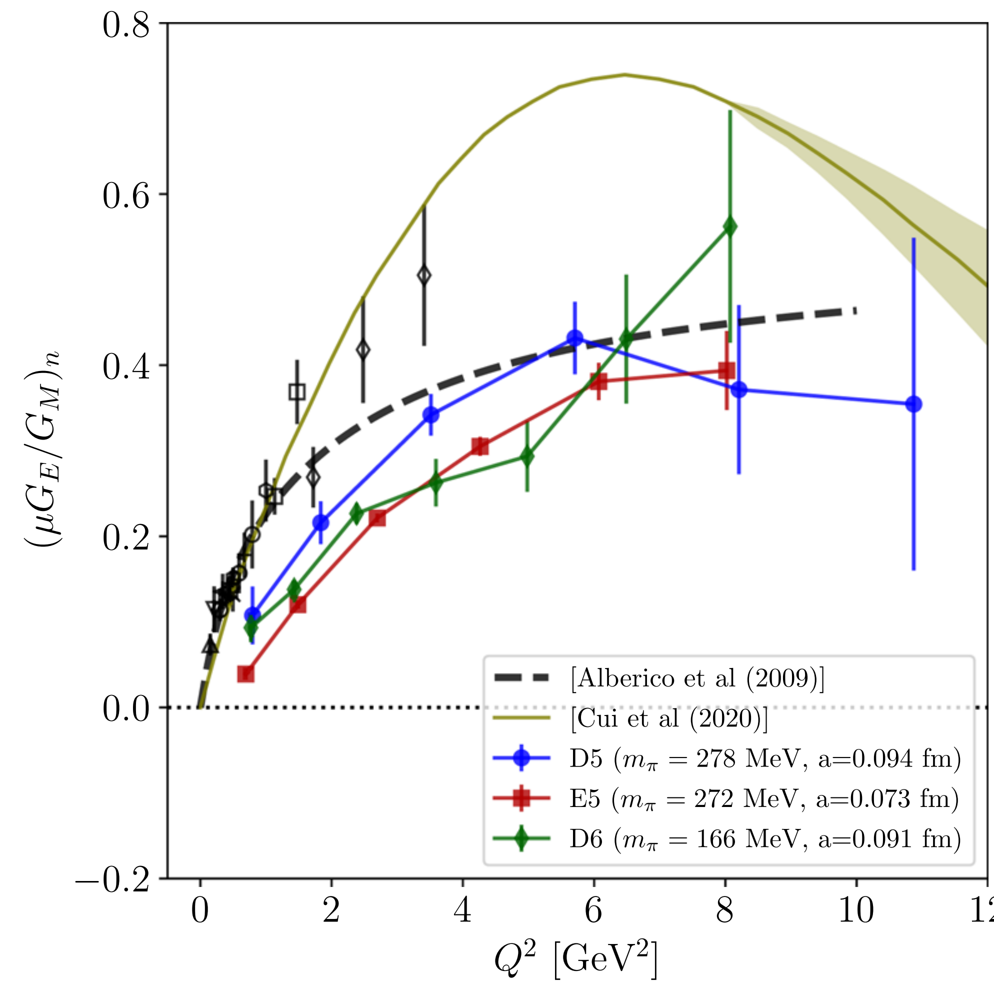
High-momentum form factors

New efforts pushing towards high-Q^2 form factors

[Syritsyn et al. Few-Body Syst 64:72 (2023), see also QCDSF-UKQCD-CSSM], 2202.01366 (2022)]

- Not completely controlled (discretisation, neglected disconnected contributions, …)
- Ratios qualitatively consistent with phenomenological fits of expt. data [Alberico] & quark+diquark Faddeev equation calculations [Cui]





[Syritsyn et al. Few-Body Syst 64:72 (2023)]

Odd-parity EM transition FFs

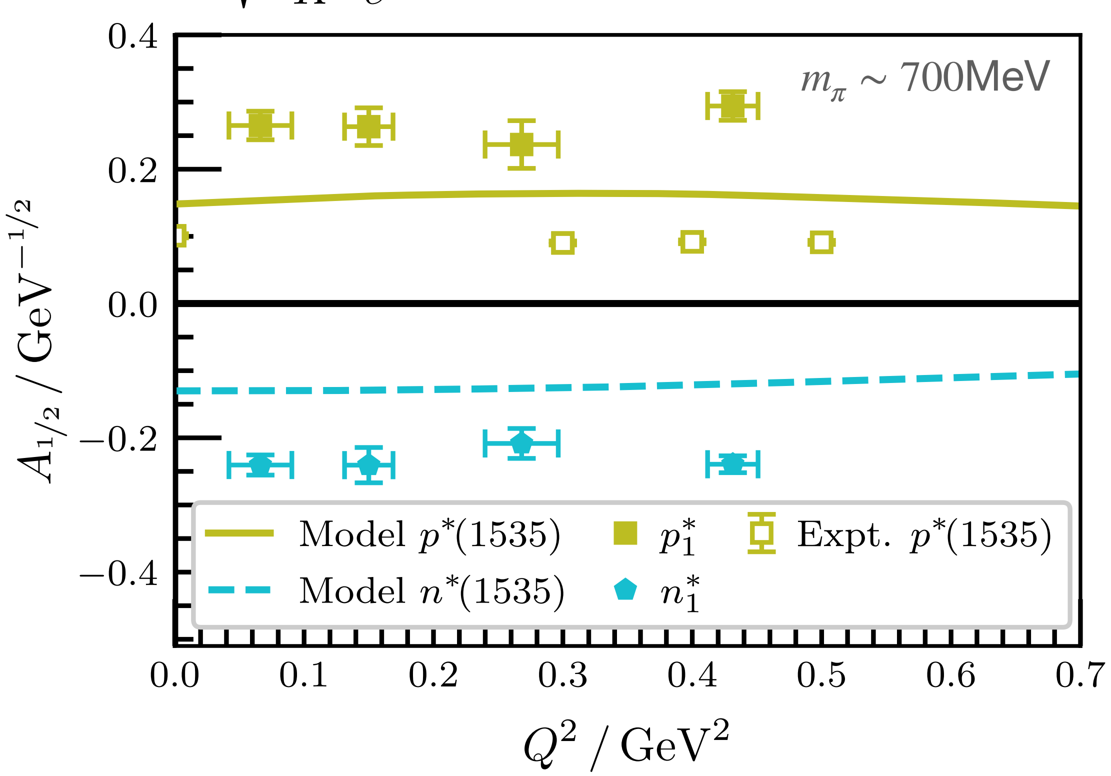
New work to study **helicity amplitudes for electromagnetic transitions** from the ground state nucleon to the first two odd-parity excitations

[Stokes et al., 2404.07625 (2024)]

- First attempt to establish formalism, numerical study with $m_\pi \sim 700\text{MeV}$
- Qualitatively consistent with relativised constituent quark model

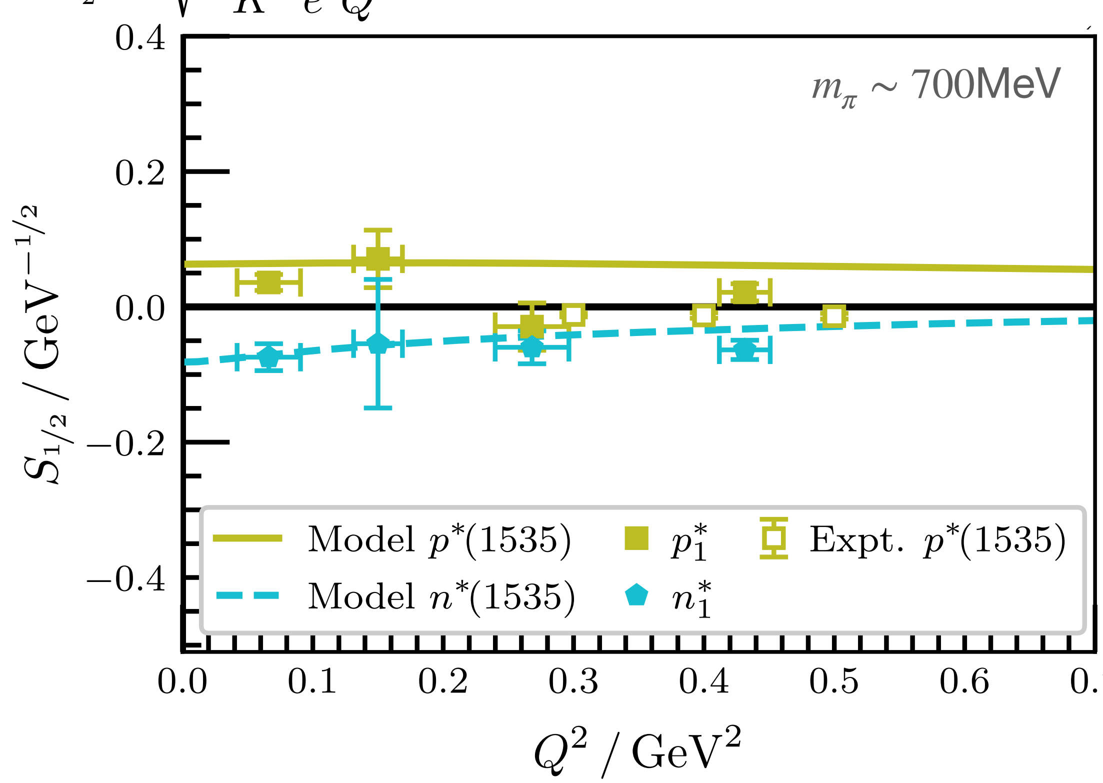
Transverse helicity amplitude

$$\mathcal{A}_{\frac{1}{2}} = \sqrt{\frac{2\pi\alpha}{K}}\,\frac{1}{e}\,\langle\, N^*, s'_z = {}^{1}\!/\!_{2}{}^{+} \,|\, \epsilon^{(+)}_{\mu} J^{\mu} \,|\, N, s_z = {}^{1}\!/\!_{2}{}^{-} \,\rangle$$



Longitudinal helicity amplitude

$$\mathcal{S}_{\frac{1}{2}} = \sqrt{\frac{2\pi\alpha}{K}}\,\frac{1}{e}\,\frac{|\vec{q}|}{Q}\,\langle\, N^*, s'_z = {}^{1}\!/\!_{2}{}^{+} \,|\, \epsilon^{(0)}_{\mu} J^{\mu} \,|\, N, s_z = {}^{1}\!/\!_{2}{}^{+} \,\rangle$$



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- Nuclear form factors

Axial charges and form factors

Axial and **induced pseudoscalar form factors** encode coupling of the proton to an axial current $A_\mu^q = \bar{q}\gamma_\mu\gamma_5 q$

Axial FF

Induced pseudoscalar FF

$$\langle N(p',s')|A_\mu|N(p,s)\rangle = \bar{u}_N(p',s')\left[\gamma_\mu G_A(Q^2) - \frac{Q_\mu}{2m_N} G_P(Q^2)\right]\gamma_5 u_N(p,s)$$

$$q = p' - p$$
$$q^2 = -Q^2$$

- W-boson interaction incl. $A_\mu^{(u-d)}$: relevant in quasi-elastic ν scattering, μ capture
- Z-boson interaction incl. $A_\mu^{(u-d-s)}$: relevant in elastic νp, parity-violating ep scattering
- **Axial charges** defined in forward limits $g_A^q \equiv G_A^q(0)$
- Combination of axial, induced pseudoscalar, pseudoscalar FFs constrained by Axial Ward-Takahashi / **Partially Conserved Axial Current identity (PCAC)**

$$G_A(Q^2) - \frac{Q^2}{4m_N^2} G_P(Q^2) = \frac{m_q}{m_N} G_5(Q^2)$$

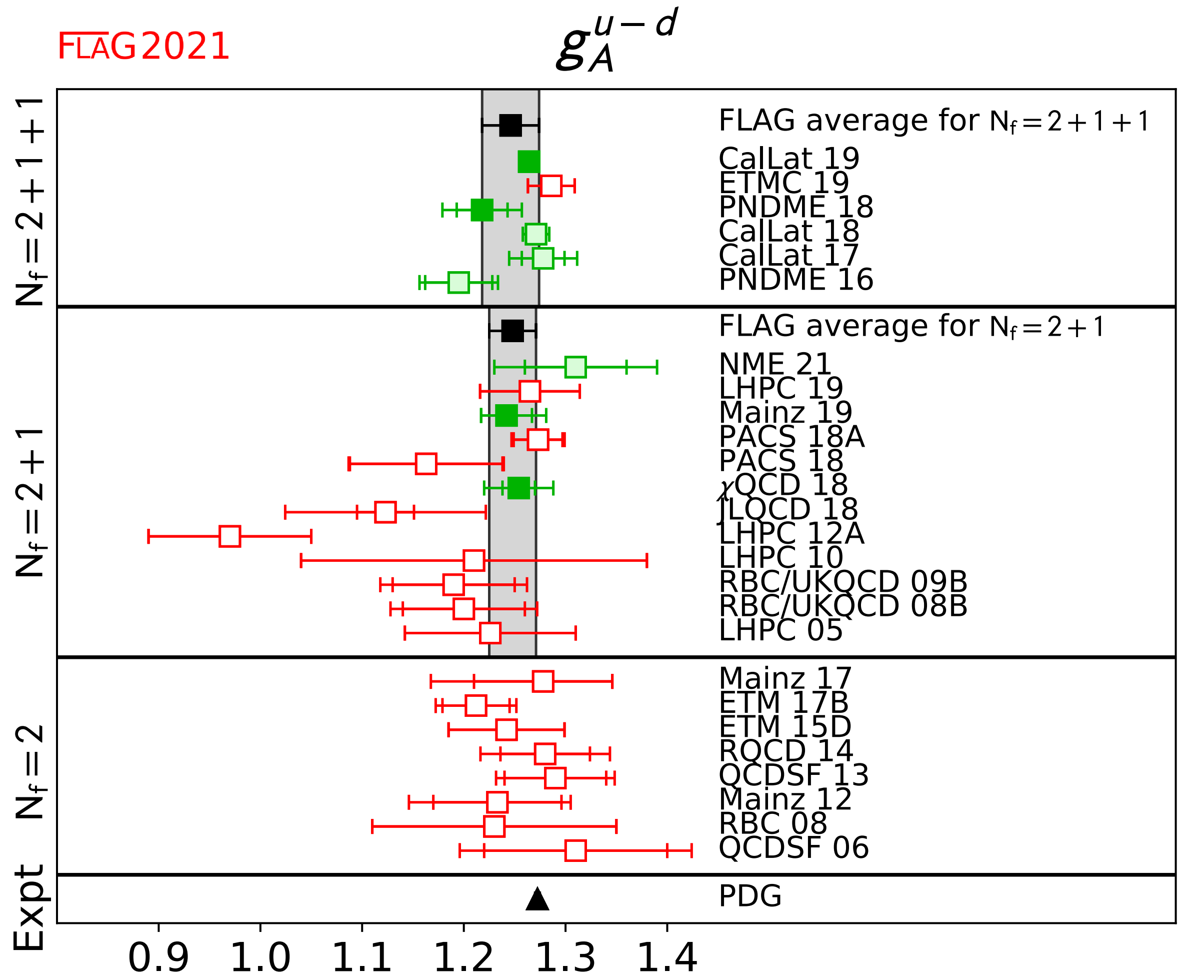
Pseudoscalar FF

$$\langle N(p',s')|P|N(p,s)\rangle = G_5(Q^2)\bar{u}_N(p',s')\gamma_5 u_N(p,s)$$

Nucleon isovector axial charge

FLAG includes summaries and averaged values of axial charges from lattice QCD

- Community consensus for isovector charge, with few-percent uncertainties

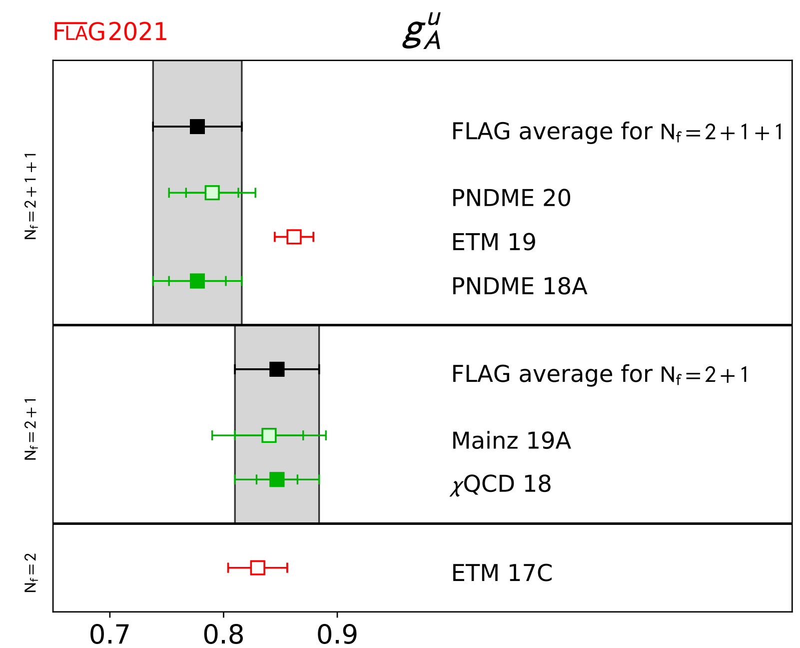


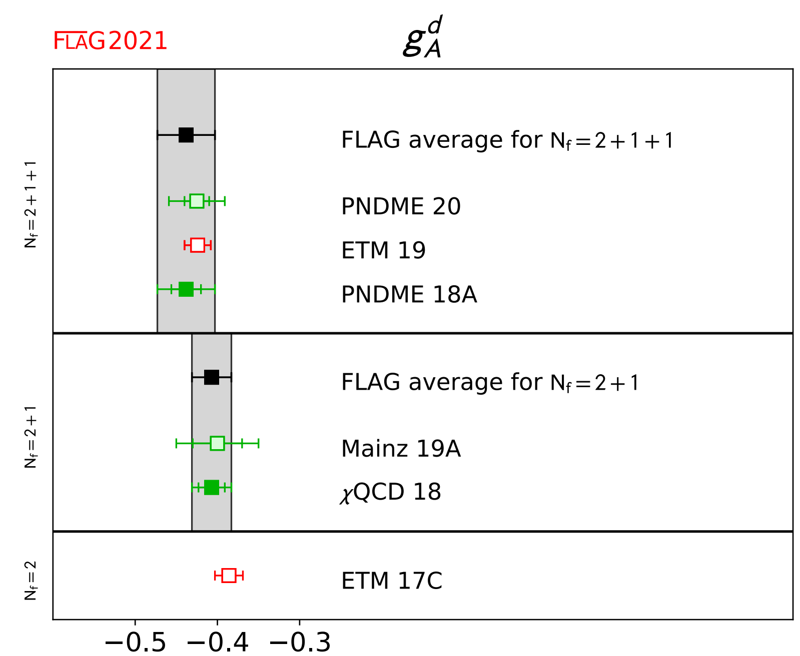
[FLAG, arXiv:2111.09849]

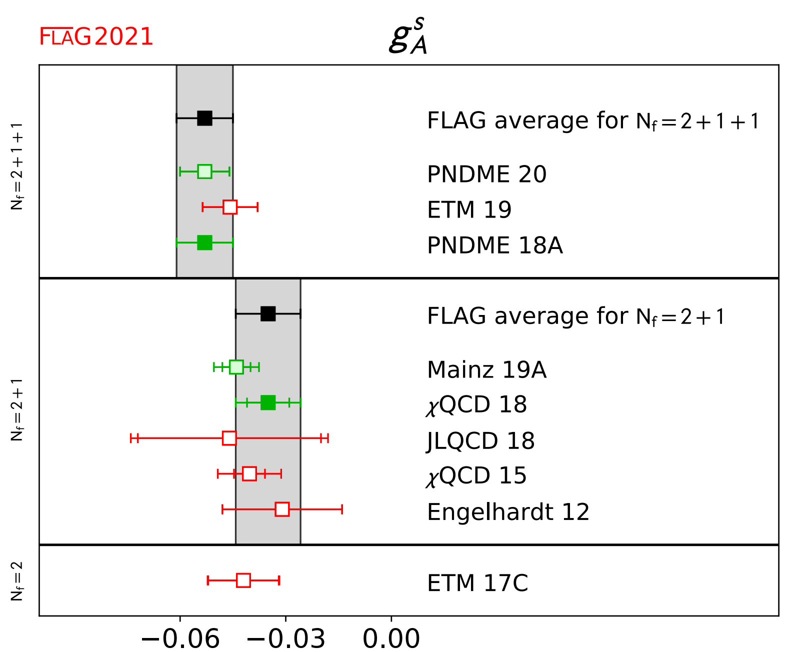
Nucleon flavour-diagonal axial charges

FLAG includes summaries and averaged values of axial charges from lattice QCD

- Flavour-diagonal charges have been less well-studied, but community consensus is developing







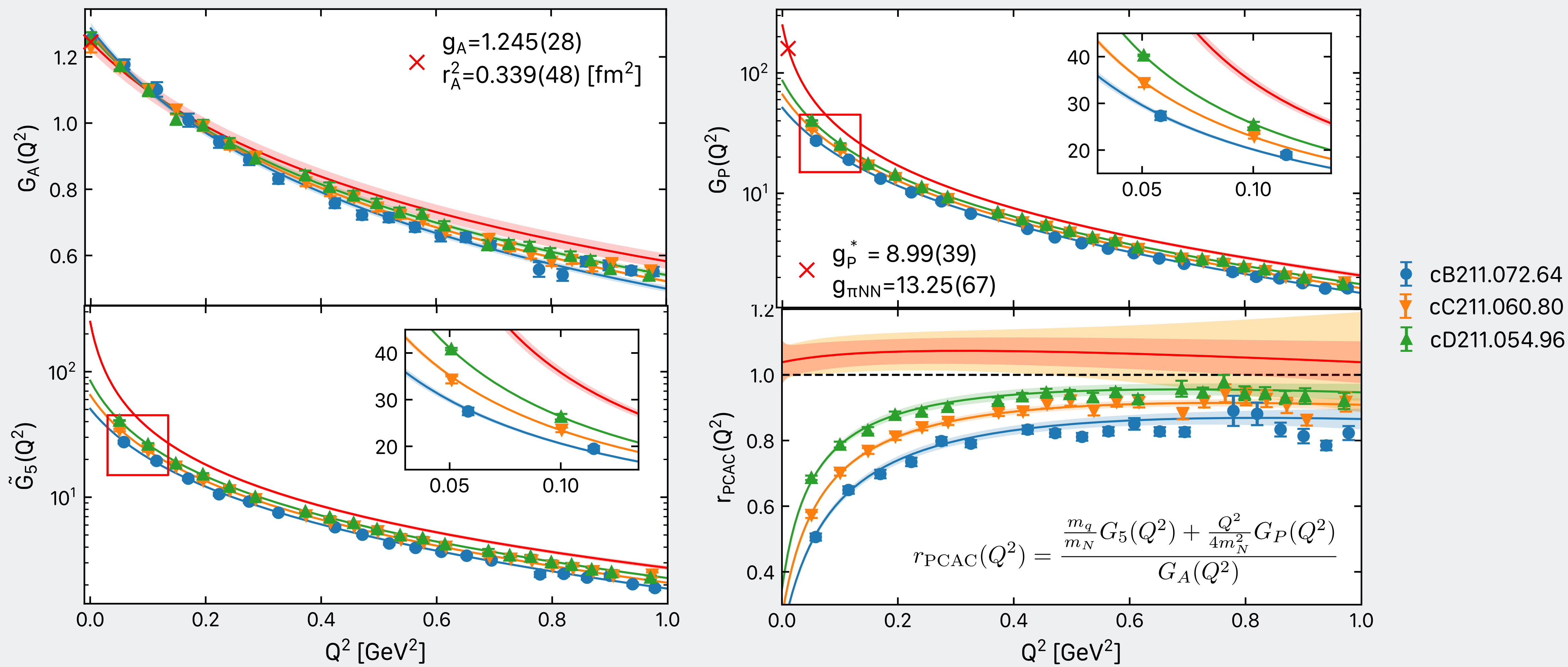
[FLAG, arXiv:2111.09849]

Isovector axial & pseudoscalar FFs

Isovector axial & pseudoscalar FFs studied by many LQCD collabs

- Systematic control: physical pion mass, control of discretisation systematics etc
- PCAC relation satisfied within uncertainties

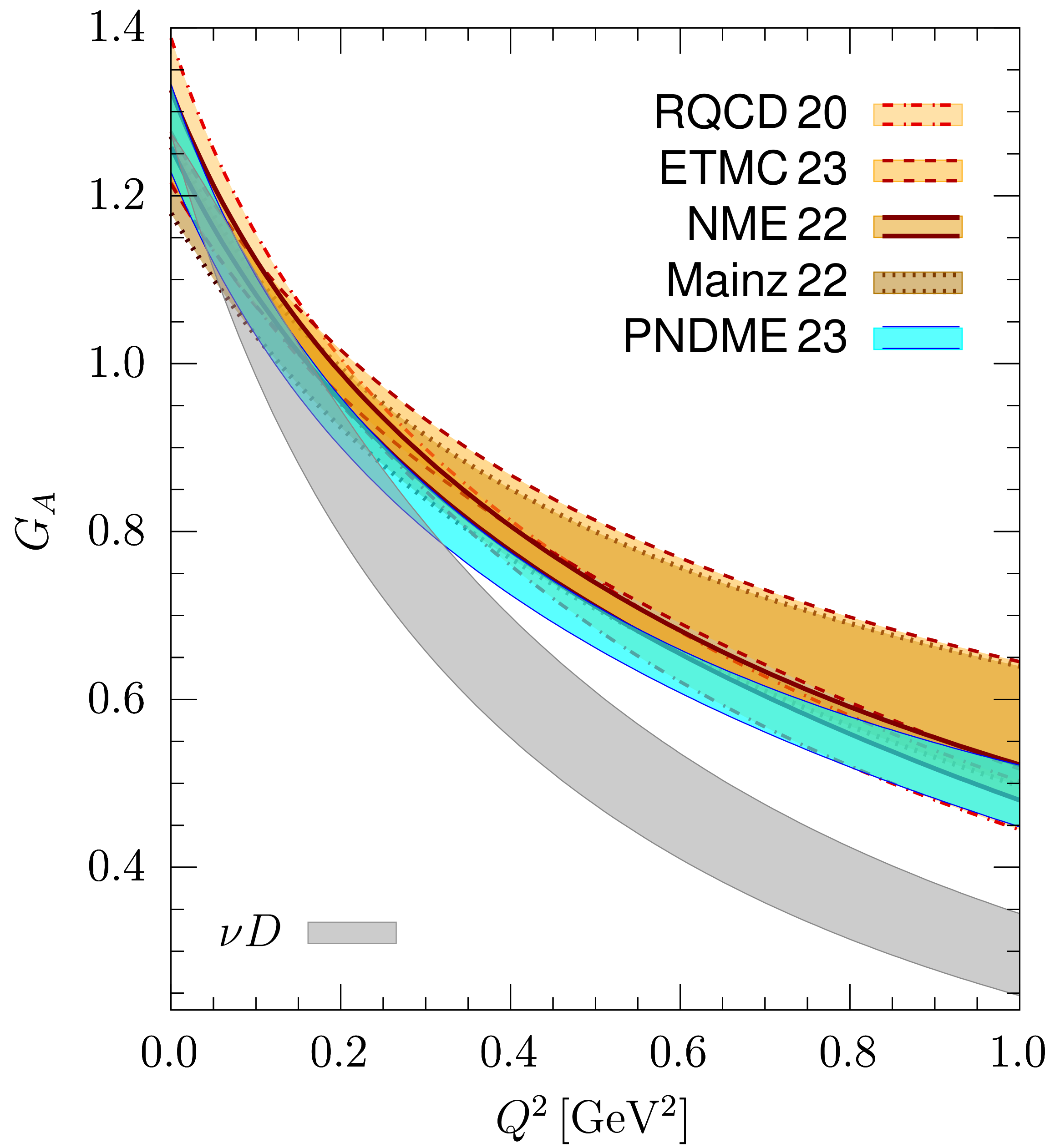
Recent example from one collaboration in 2023 [ETMC 2309.05774 (2023)]:



Isovector axial & pseudoscalar FFs

Isovector axial & pseudoscalar FFs studied by many LQCD collabs

- Consensus between different LQCD calculations/collaborations



- Combined~10% uncertainties for $0 \le Q^2 \le 1\mathrm{GeV}^2$
- Consistent with experimental results from MINERνA
- Tension with older ν-deuterium bubble chamber scattering data
- Dipole fit ansatz insufficient

[Compilation from Gupta 2401.16614]

Lattice QCD: PNDME 2305.11330 (2023), RQCD 1911.13150 (2019), ETMC 2309.05774 (2023), NME 2103.05599 (2021), Mainz 2207.03440 (2022)

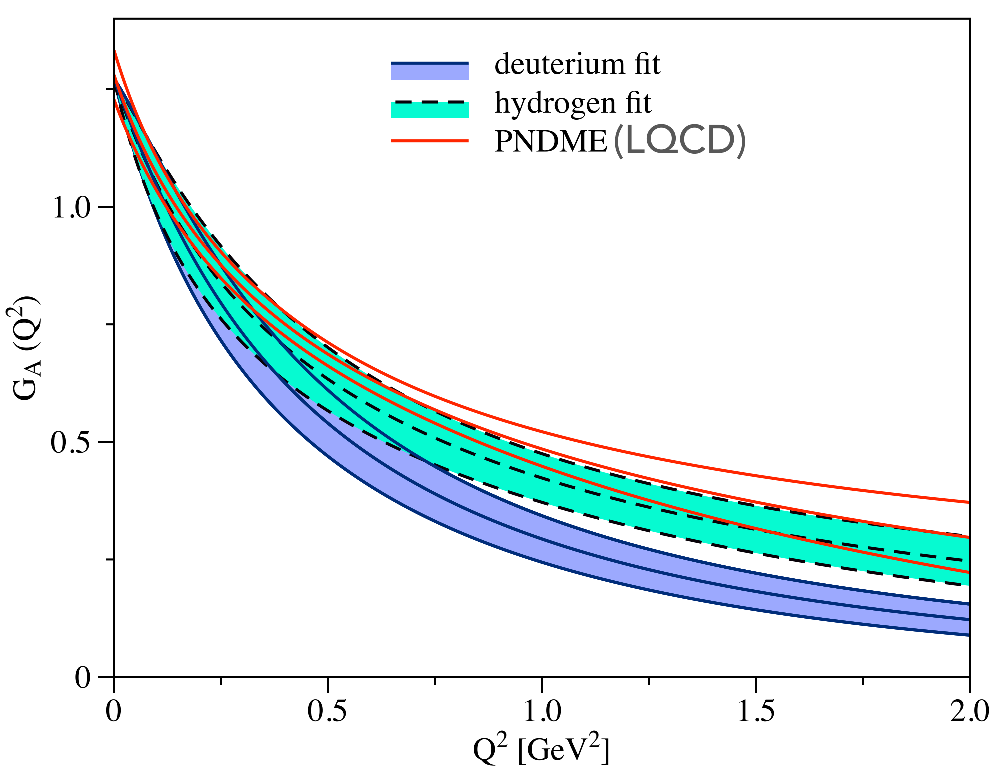
νD fit: Taken from 1603.03048 (2016)

Lattice QCD compared with MINERνA

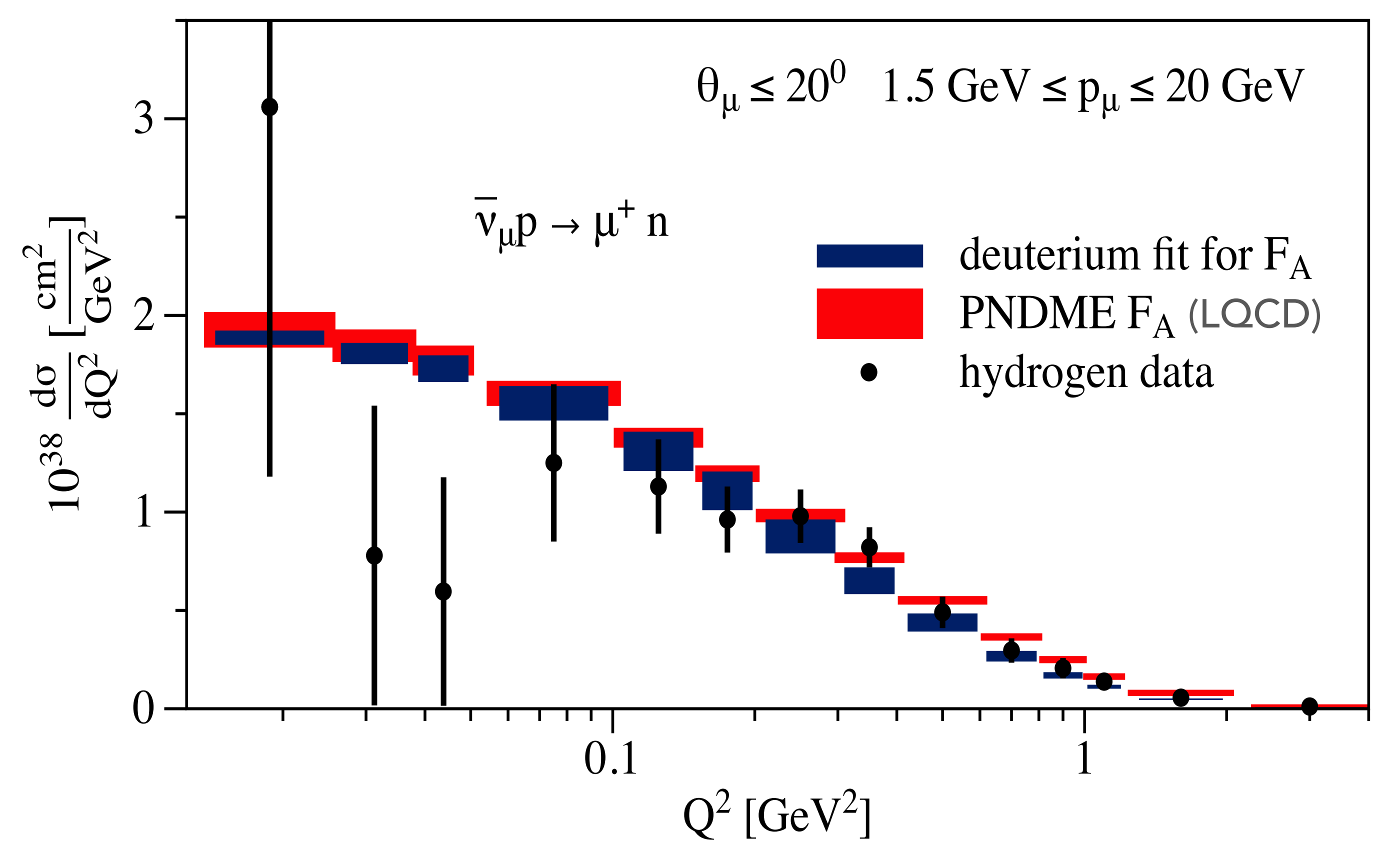
Isovector axial & pseudoscalar FFs studied by many LQCD collabs

- Consensus between different LQCD calculations/collaborations
- Consistent with experimental results from MINERνA antineutrino-hydrogen data

Axial FF



Antineutrino-nucleon charged current elastic differential cross-section



[Tomalak, Gupta, Bhattacharya, 2307.14920 (2023)]

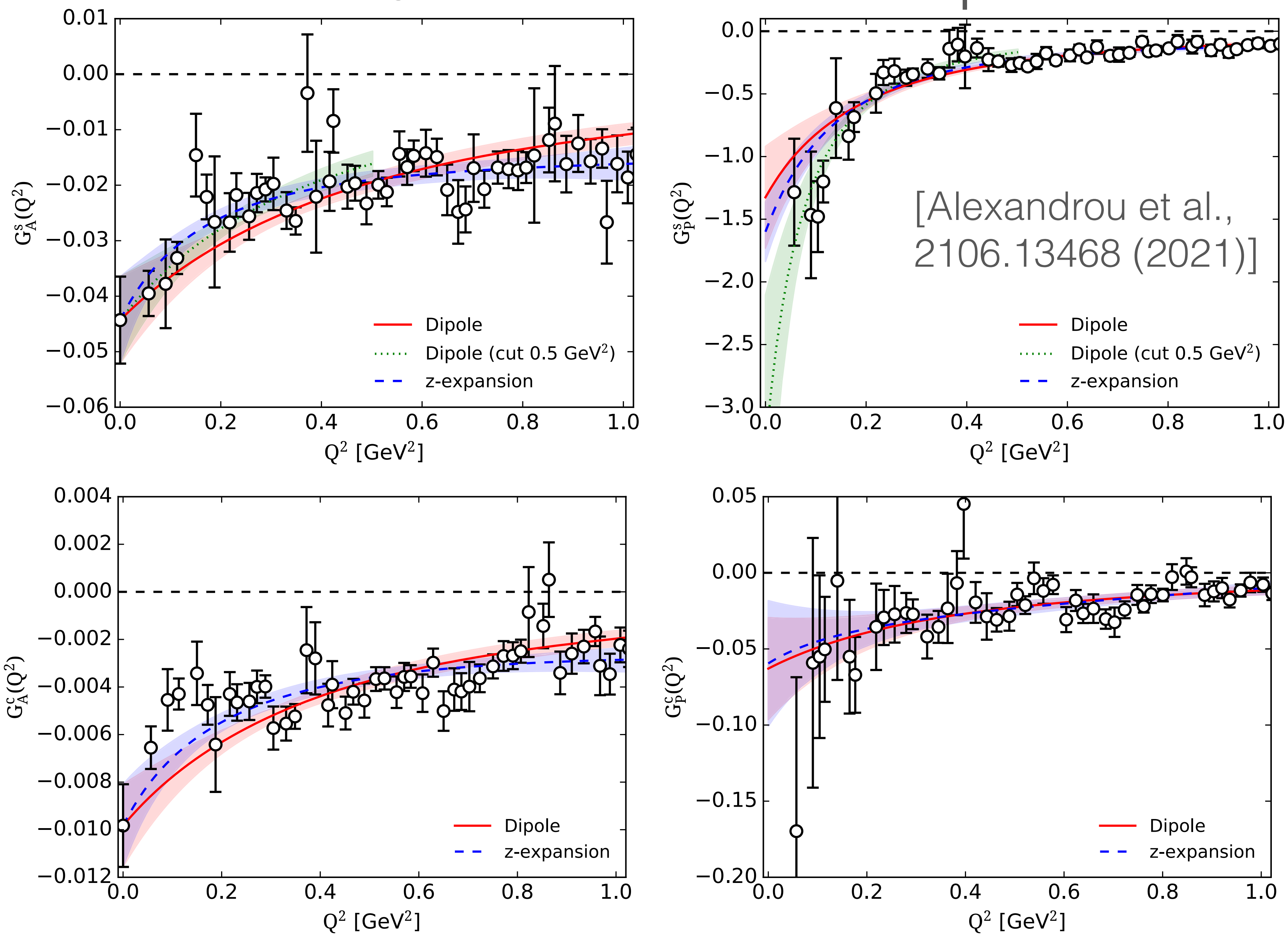
Strange and charm form factors

Flavour-decomposition of FFs also calculated, but less well-studied

Axial | Induced pseudoscalar

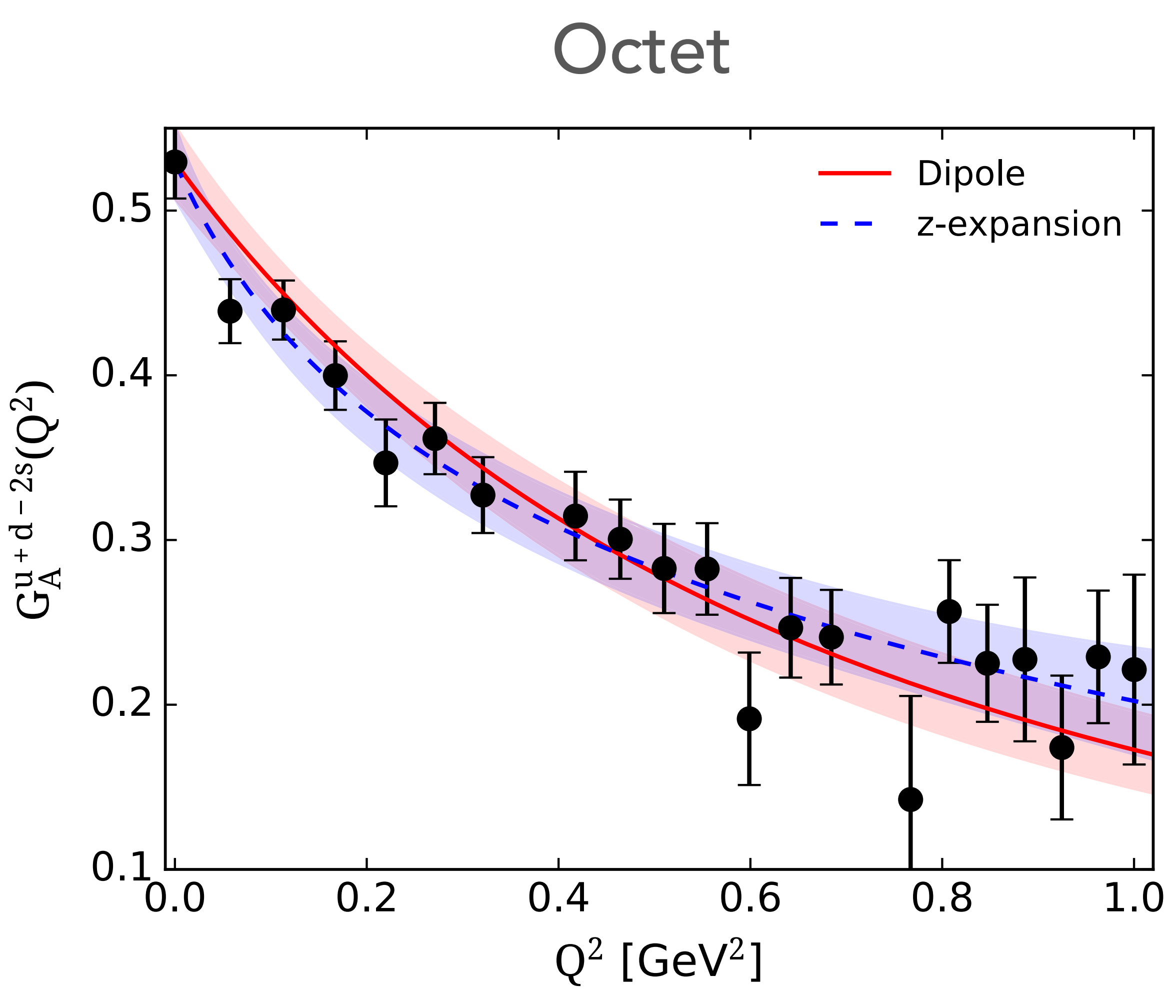
Strange

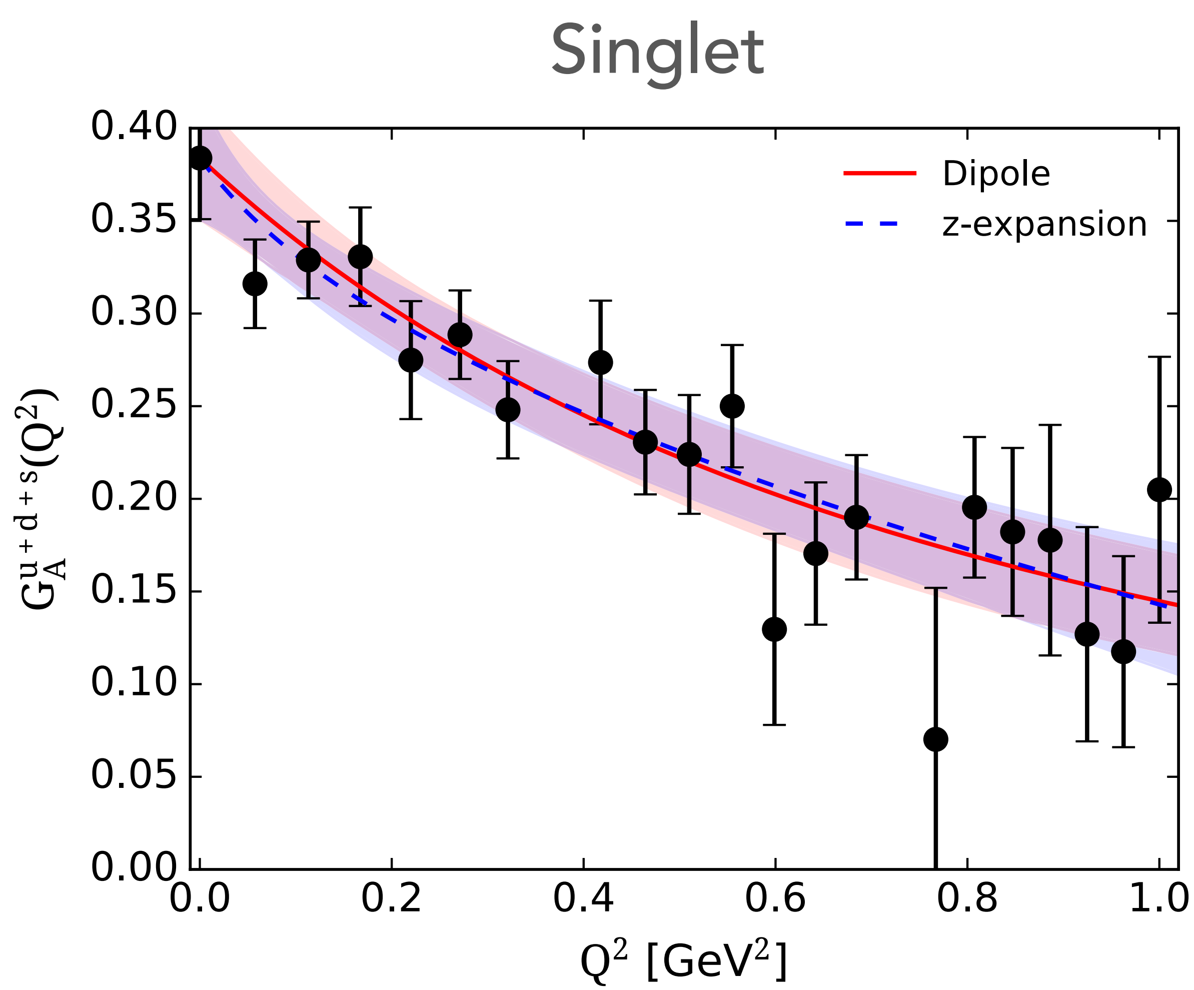
Charm



Flavour octet and singlet FFs

Flavour-decomposition of FFs also calculated, but less well-studied





[Alexandrou et al., 2106.13468 (2021)]

Axial charges and form factors

- LQCD results for isovector charges & FFs **fully-controlled**
  - Axial, induced pseudoscalar, pseudoscalar satisfy PCAC relation
  - Results from different collaborations **consistent within ~10% uncertainties** for $0 \leq Q^2 \leq 1\text{GeV}^2$
- **Consistent with experimental results from MINERνA**, tension with older ν-deuterium bubble chamber scattering data
- Dipole fit ansatz insufficient
- **Complete flavour decomposition** (including s, c quark contributions) also computed, but less well-studied, less precise, c.f. isovector

Community-consensus isovector **axial** and **pseudoscalar form factors** from LQCD likely to reach ~1% precision for $Q^2 \lesssim 2\text{GeV}^2$ by ~2030

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Generalised Form Factors

Generalised form factors encode moments of Generalised Parton Distribution functions (GPDs)

e.g., Gravitational form factors

- Encode "graviton scattering" from the nucleon
- Related to leading-twist chiral-even GPDs

Gluon field-strength tensor

$$\int_{-\infty}^{\infty} \frac{d\lambda}{2\pi} e^{i\lambda x} \langle p', s' | G_a^{\{\mu\alpha}(-\frac{\lambda}{2}n) \left[\mathcal{U}^{(A)}_{[-\frac{\lambda}{2}n, \frac{\lambda}{2}n]}\right]_{ab} G_{b\alpha}^{\ \ \nu\}}(\frac{\lambda}{2}n) | p, s\rangle$$

$$= \frac{1}{2}\left(H_g(x,\xi,t) \bar{U}(p',s') P^{\{\mu}\gamma^{\nu\}} U(p,s) + E_g(x,\xi,t) \bar{U}(p',s') \frac{P^{\{\mu} i\sigma^{\nu\}\alpha}\Delta_\alpha}{2M} U(p,s) \right) + \dots ,$$

GPDs(Bjorken x, skewness, mom transfer)

$$\int_0^1 \mathrm{d}x\ H_g(x,\xi,t) = A_g(t) + \xi^2 D_g(t) , \qquad \int_0^1 \mathrm{d}x\ E_g(x,\xi,t) = B_g(t) - \xi^2 D_g(t)$$

Gluon gravitational form factors

$$\Delta_\mu = p'_\mu - p_\mu$$
$$P_\mu = (p_\mu + p'_\mu)/2$$
$$t = \Delta^2$$
$$n^2 = 0$$

Gravitational FFs encode EMT

- **Gravitational form factors** describe matrix elements of Energy-Momentum Tensor
  e.g., traceless gluon EMT for nucleon:

$$\langle p', s' | G^{a}_{\{\mu\alpha} G^{a\alpha}{}_{\nu\}} | p, s \rangle = \bar{U}(p', s') \left(A_g(t)\, \gamma_{\{\mu} P_{\nu\}} + B_g(t)\, \frac{i\, P_{\{\mu} \sigma_{\nu\}\rho} \Delta^{\rho}}{2M_N} + D_g(t)\, \frac{\Delta_{\{\mu} \Delta_{\nu\}}}{4M_N} \right) U(p, s)$$

Gluon field-strength tensor

Gluon gravitational form factors

$\Delta_\mu = p'_\mu - p_\mu \quad P_\mu = (p_\mu + p'_\mu)/2 \quad t = \Delta^2$

- Sum rules of gluon and quark GFFs in forward limit
  - Momentum fraction $A_a(0) = \langle x \rangle_a$ $\Rightarrow$ $\sum_{a=q,g} A_a(0) = 1$
  - Spin $J_a(t) = \frac{1}{2}(A_a(t) + B_a(t))$ $\Rightarrow$ $\sum_{a=q,g} J_a(0) = \frac{1}{2}$
  - D-terms $D_a(0)$ less known but equally fundamental!
    - $D_a(t)$ GFFs encodes pressure and shear distributions

D-term from JLab DVCS

Experimental determination of DVCS D-term and extraction of proton pressure distribution
[Burkert, Elouadrhiri, Girod, Nature 557, 396 (2018)]

$$s(r) = -\frac{r}{2}\frac{d}{dr}\frac{1}{r}\frac{d}{dr}\widetilde{D}(r), \quad p(r) = \frac{1}{3}\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}\widetilde{D}(r)$$

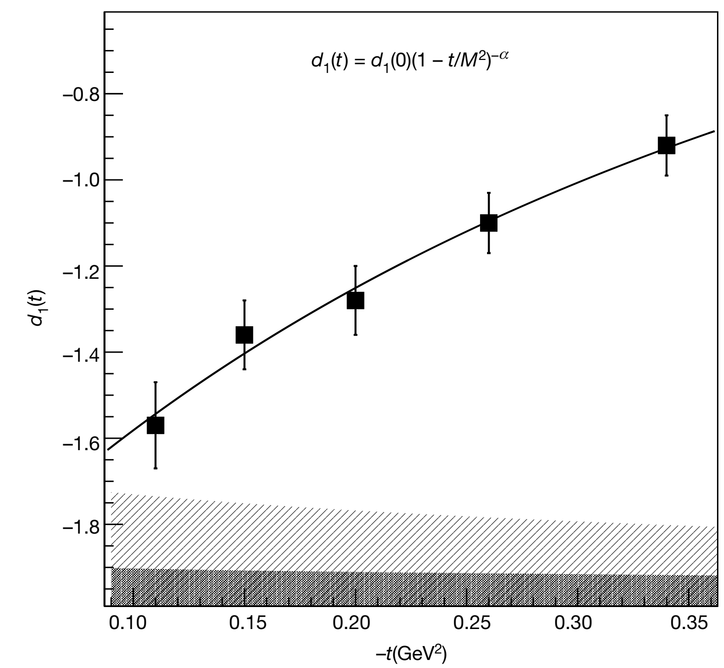
- Peak pressure near centre ~10^{35} Pascal, greater than pressure estimated for neutron stars
- Key assumptions: gluon D-term same as quark term, tripole form factor model, $D_u(t,\mu) = D_d(t,\mu)$

EXP + LQCD

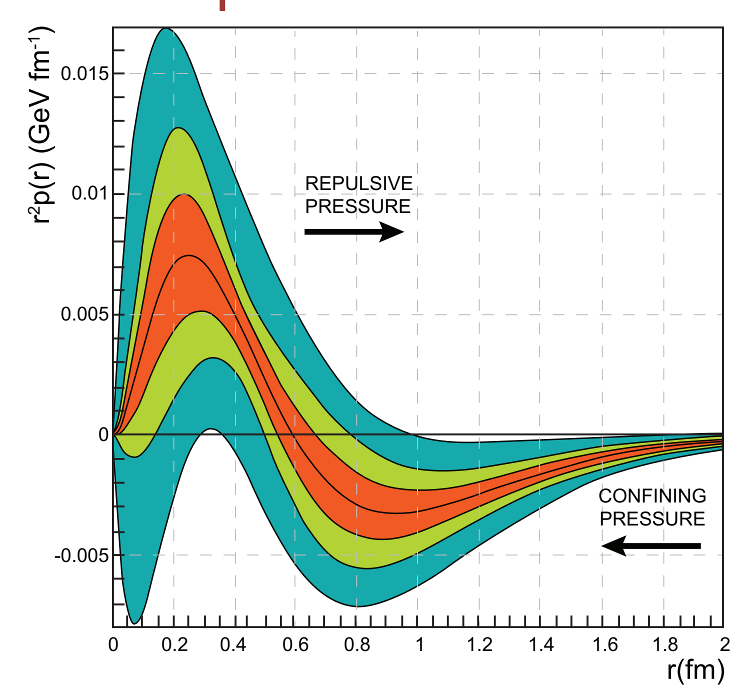
complete pressure determination

[Shanahan, Detmold PRL 122 072003 (2019)]

DVCS (quark) D-term



Radial pressure distribution

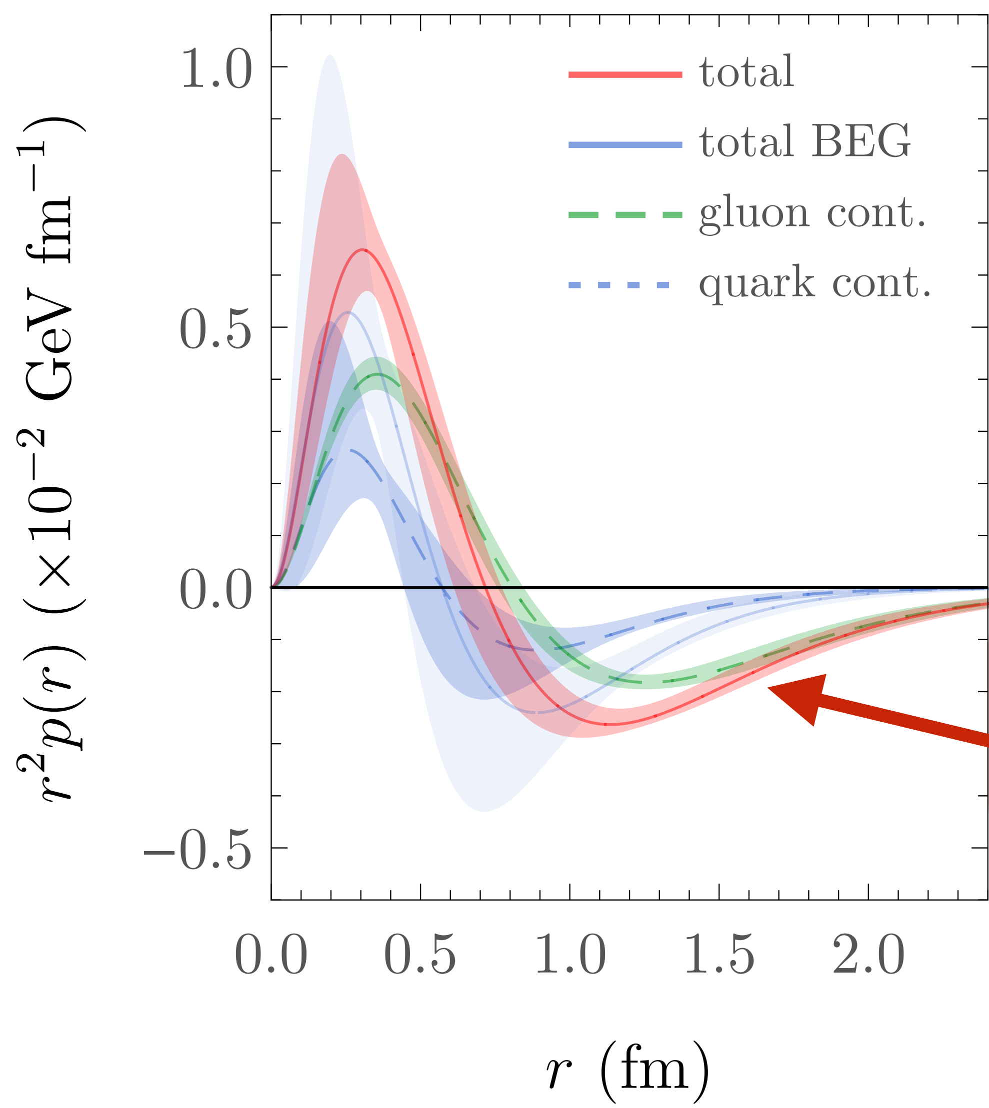


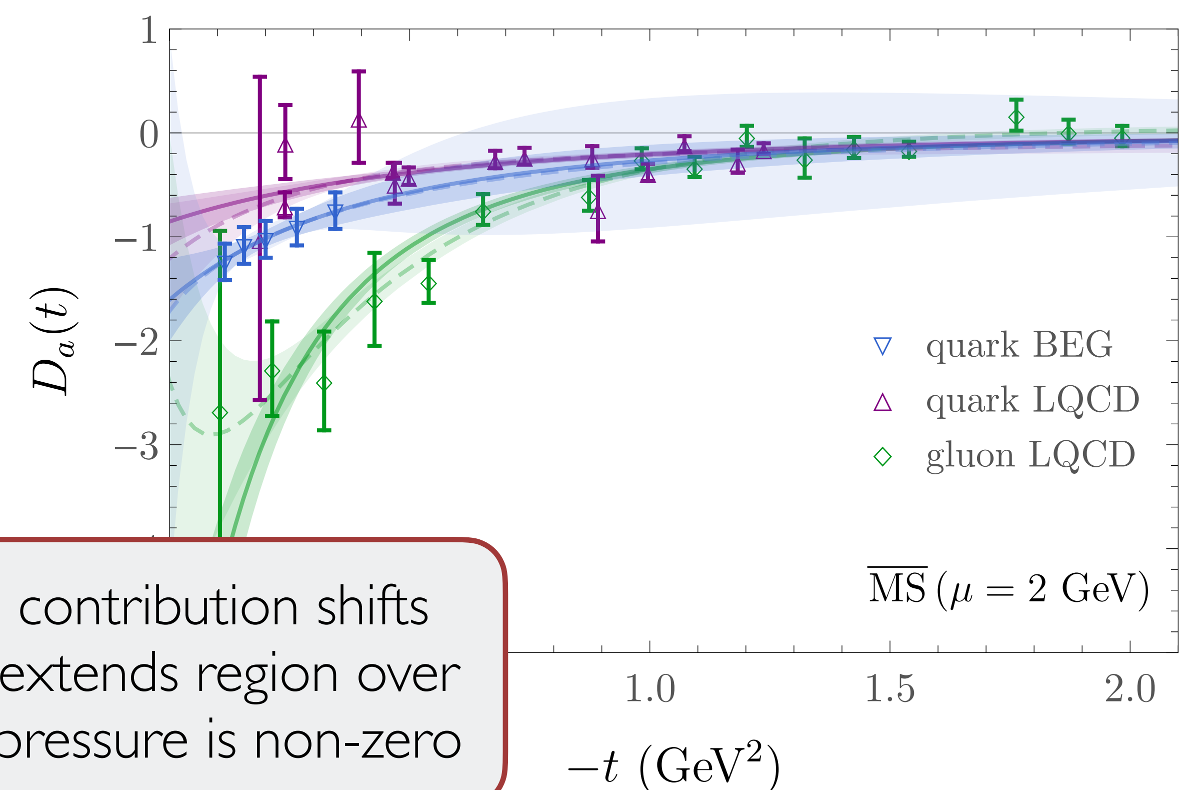
Nucleon D-term GFFs from LQCD

EXP + LQCD

complete pressure determination

[Shanahan, Detmold PRL 122 072003 (2019)]





gluon contribution shifts peaks, extends region over which pressure is non-zero

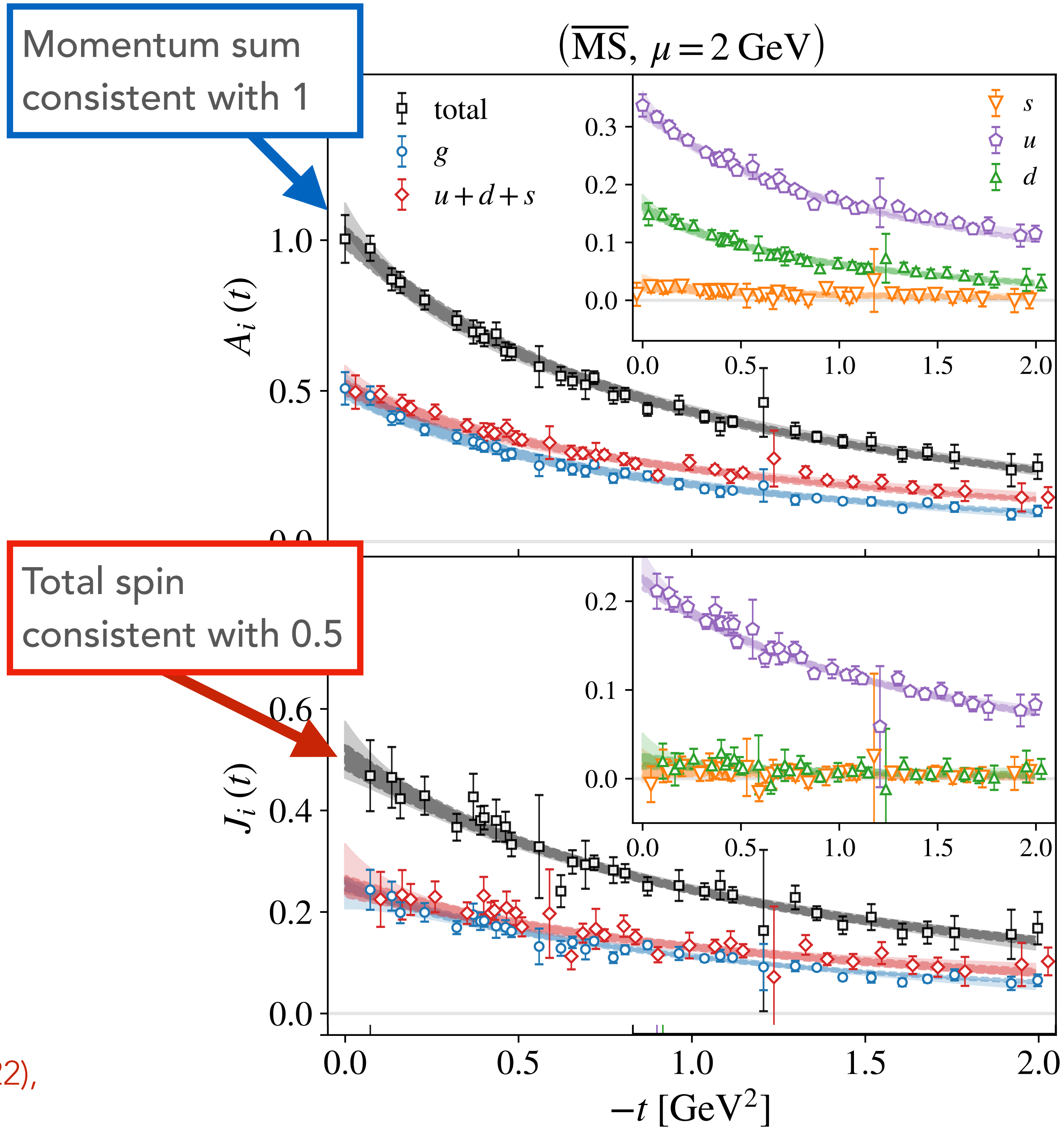
Gluon GFFs: Shanahan, Detmold, PRD 99, 014511 (2019)

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

Expt quark GFFs (BEG): Burkert et al, Nature 557, 396 (2018)

Proton GFFs from lattice QCD

- **First complete decomposition** of proton gravitational form factors into u, d, s, g contributions from lattice QCD in 2023
- Physical pion mass
- Non-pert. renormalisation incl. mixing
- [Still a single ensemble, no control of discretisation effects]



Lattice QCD: Pefkou, Hackett, Shanahan, PRD 105, 054509 (2022), PRD 108, 114504 (2023), 2310.08484 (2023)

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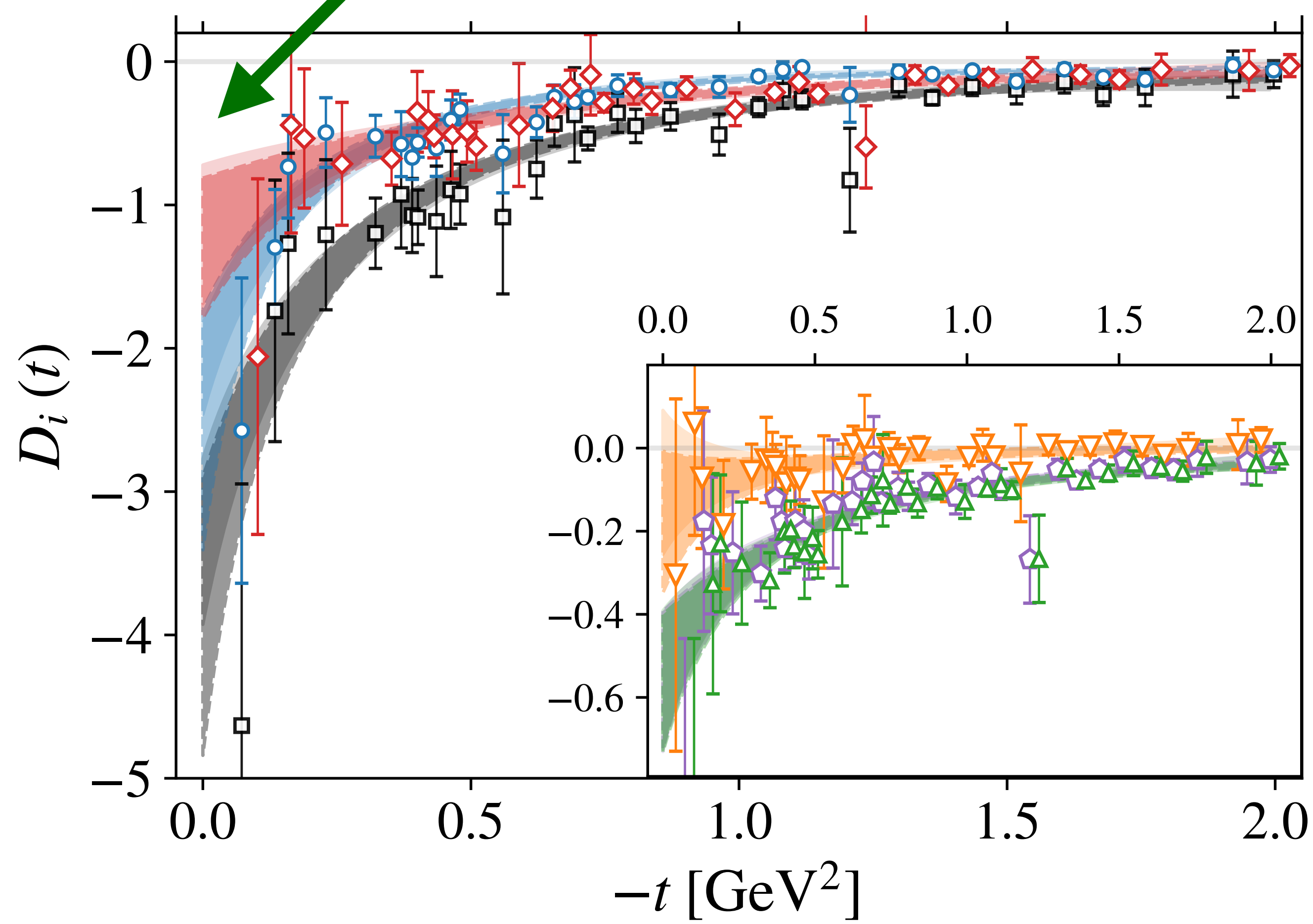
D-term decomposition previously unknown

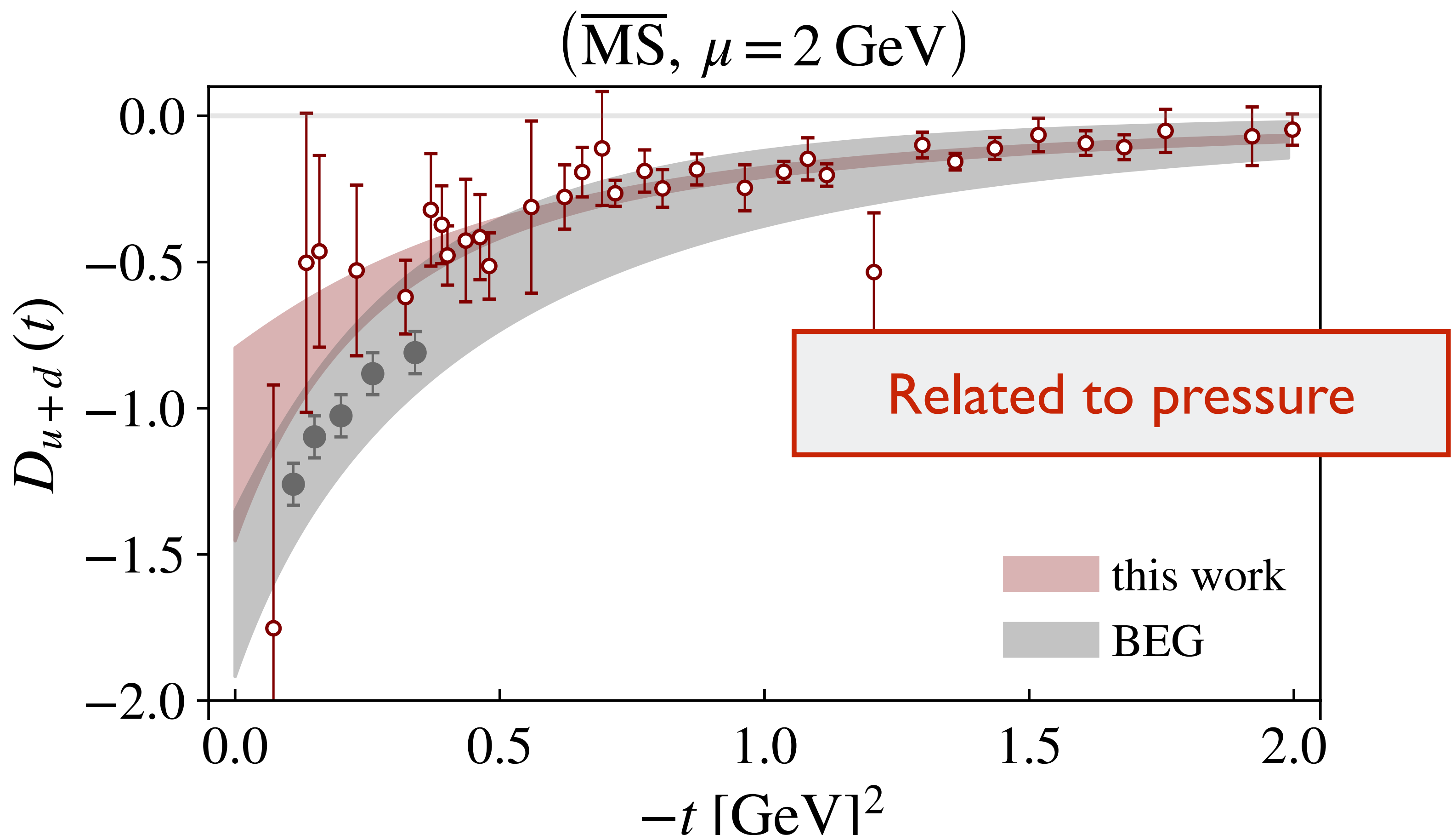


Lattice QCD: Pefkou, Hackett, Shanahan, PRD 105, 054509 (2022), PRD 108, 114504 (2023), 2310.08484 (2023)

Gravitational FFs c.f. experiment

Compare quark D GFF with 2018 results from DVCS
[Burkert, Elouadrhiri, Girod, Nature 557, 396 (2018)]

- Consistency and complementarity: lattice result more precise at large t, experimental constraints are at small t

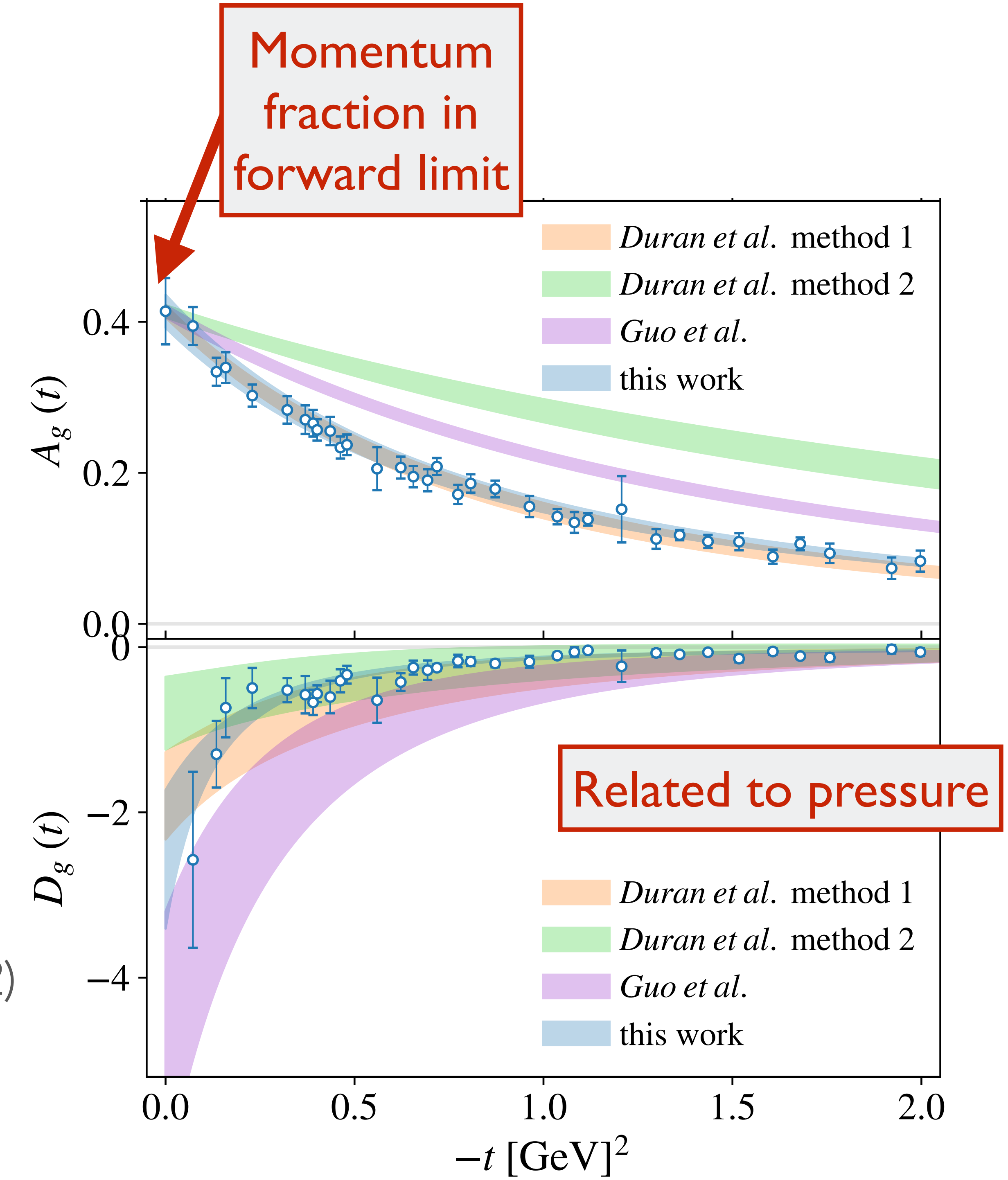


Lattice QCD: Pefkou, Hackett, Shanahan, PRD 105, 054509 (2022), PRD 108, 114504 (2023), 2310.08484 (2023)

Gravitational FFs c.f. experiment

Synergy between lattice QCD and experiment continues!

- First experimental constraint on gluon "generalised form factors" in 2023 from J/ψ photoproduction
  [Duran et al., Nature 615, 813-816 (2023)]
- Lattice calculation important in distinguishing between models based on
  - Holographic QCD (method 1)
  - Generalised Parton Distributions (method 2)



Lattice QCD: Pefkou, Hackett, Shanahan, PRD 105, 054509 (2022), PRD 108, 114504 (2023), 2310.08484 (2023)
Experiment: Duran et al., Nature 615, 813-816 (2023)
Guo et al., 2308.13006 (2023); BEG 2310.11568 (2023)

Proton quark and gluon radii

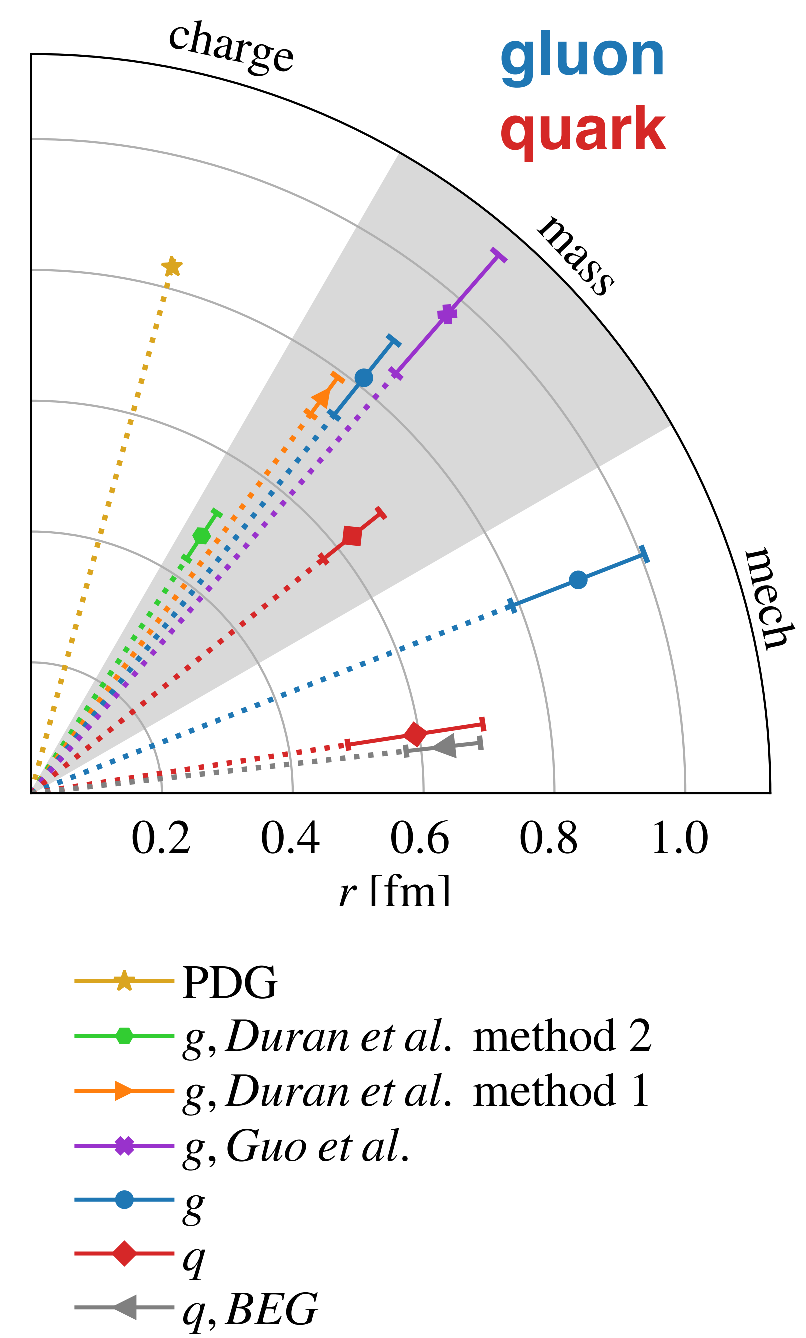
Define quark and gluon radii from energy and longitudinal force densities

$$\langle r_i^2\rangle^{\text{mass}} = \frac{\int d^3\mathbf{r}\, r^2 \varepsilon_i(r)}{\int d^3\mathbf{r}\, \varepsilon_i(r)}\,, \quad \langle r_i^2\rangle^{\text{mech}} = \frac{\int d^3\mathbf{r}\, r^2 F_i^{||}(r)}{\int d^3\mathbf{r}\, F_i^{||}(r)}\,.$$

- Mass and mechanical radii of proton comparable to charge radius
- Gluons act to extend radius defined by quark contributions

$$\varepsilon_i(r) = m\left[A_i(t) - \frac{t(D_i(t)+A_i(t)-2J_i(t))}{4m^2}\right]_{\text{FT}}\,,$$

$$F_i^{||}(r) = p_i(r) + 2s_i(r)/3$$



Lattice QCD: Pefkou, Hackett, Shanahan, PRD 105, 054509 (2022), PRD 108, 114504 (2023), 2310.08484 (2023)
Experiment: Duran et al., Nature 615, 813-816 (2023)
Guo et al., 2308.13006 (2023); BEG 2310.11568 (2023)

Glue trace anomaly form factor

- Matrix elements of the **trace** of the energy-momentum tensor are related to hadron mass

$$m_{\mathrm{H}} = \langle \frac{\beta}{2g} F^2 + \sum_f \gamma_m m_f \overline{\psi}_f \psi_f \rangle_{\mathrm{H}} + \sum_f m_f \langle \overline{\psi}_f \psi_f \rangle_{\mathrm{H}}$$

Trace anomaly term

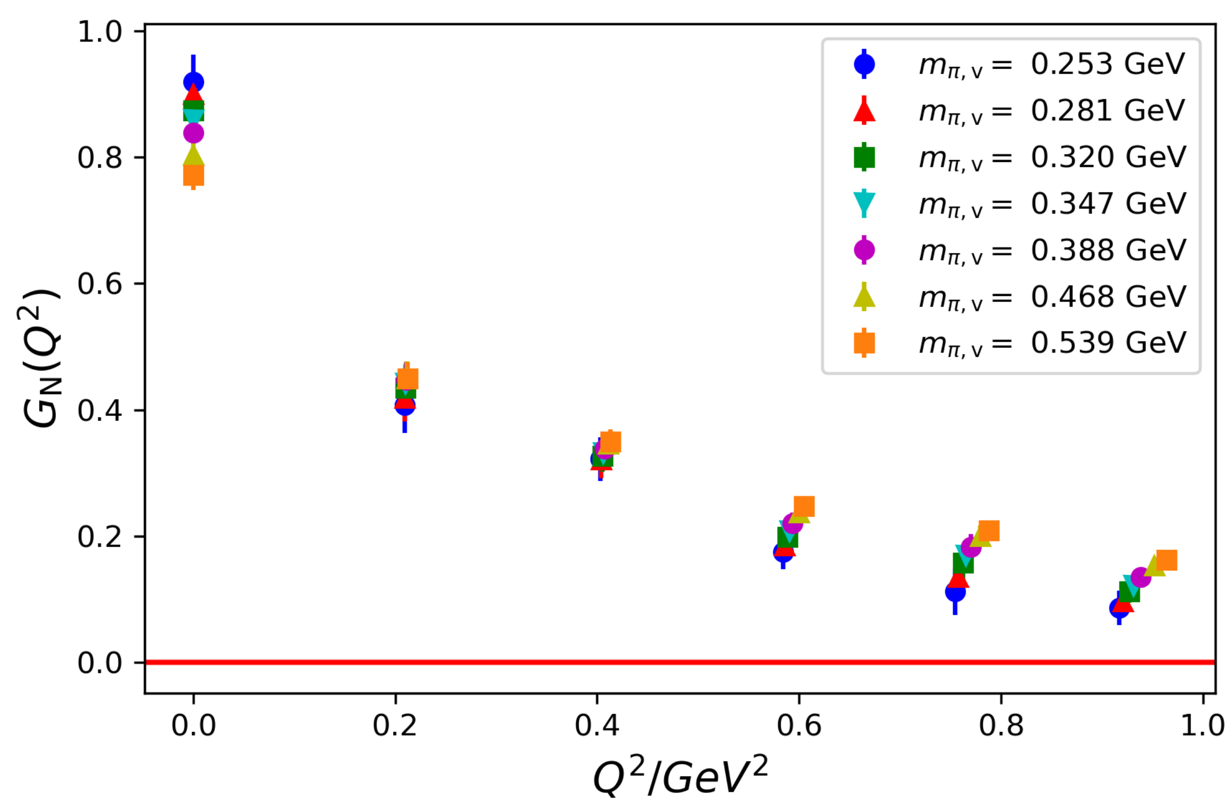
Sigma term

- **First calculation of glue part of trace anomaly FF in 2024**

[Wang et al., 2401.05496 (2024)]

$$G_{\mathrm{H}} \equiv \frac{\beta(g)}{2g} \langle F^2 \rangle_{\mathrm{H}} / m_{\mathrm{H}}$$

- One lattice ensemble (fixed sea quark masses $m_\pi \sim 340$MeV)
- Complications with renormalisation and mixing to be further explored



[Wang et al., 2401.05496 (2024)]

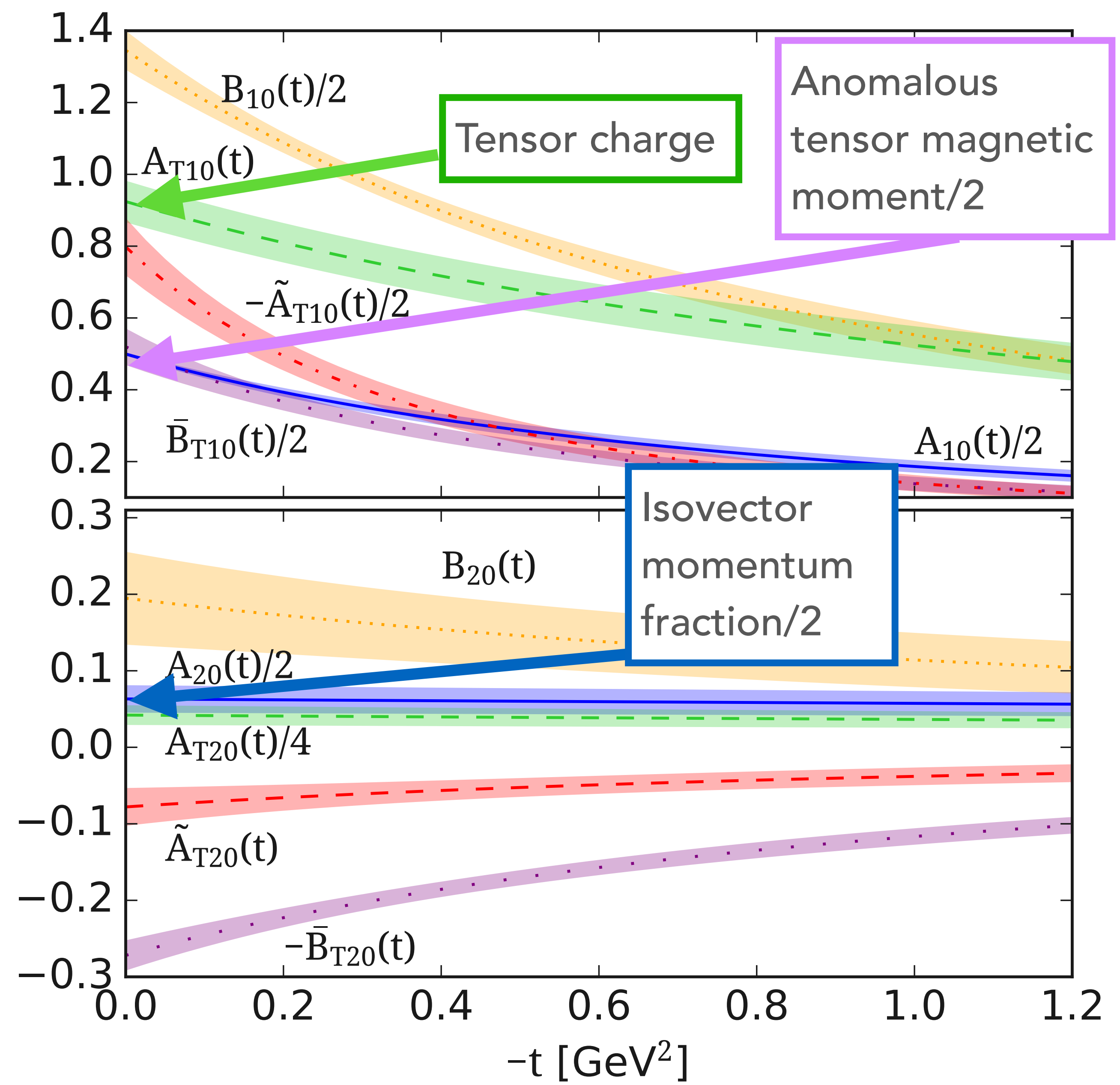
Other generalised form factors

Other GFFs can also be computed from LQCD

- New calculation in 2022 of moments of isovector transverse quark spin densities
  [Alexandrou et al., arXiv:2202.09871 (2022)]
- Physical pion mass, 3 lattice spacings
- Multipole fits in t

$$F(t) = \frac{F(0)}{(1 - t/m_p^2)^p}$$

Isovector GFFs from LQCD



$$A_{n0} = \int dx\ x^{n-1} H\ ,\ B_{n0} = \int dx\ x^{n-1} E$$

[Alexandrou et al., arXiv:2202.09871 (2022)]

Nucleon and Nuclear Form Factors from Lattice QCD

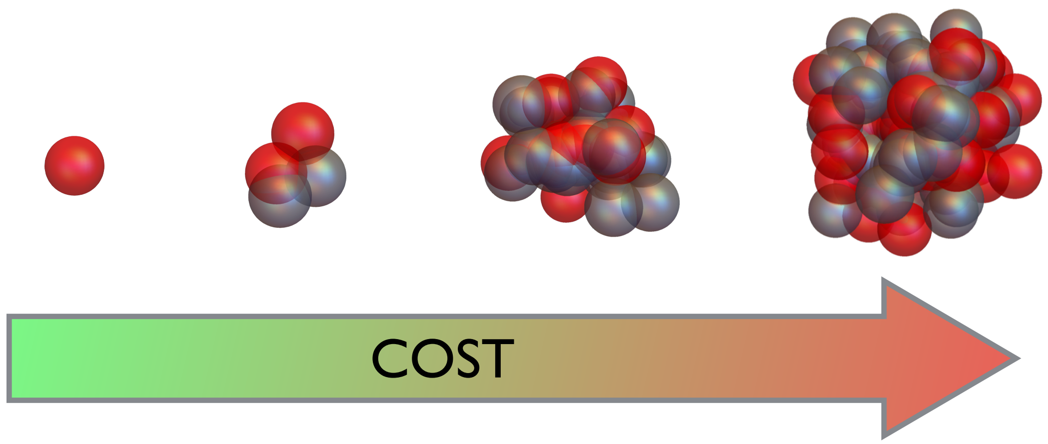
- Electromagnetic form factors
- Axial and pseudo-scalar form factors
- Generalised form factors incl. gravitational
- Nuclear form factors

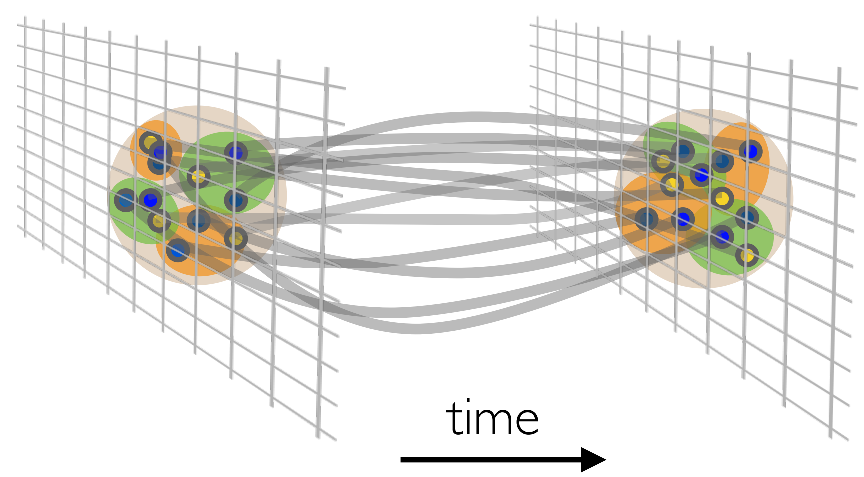
Nuclear physics from lattice QCD

Nuclei on the lattice are HARD

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

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

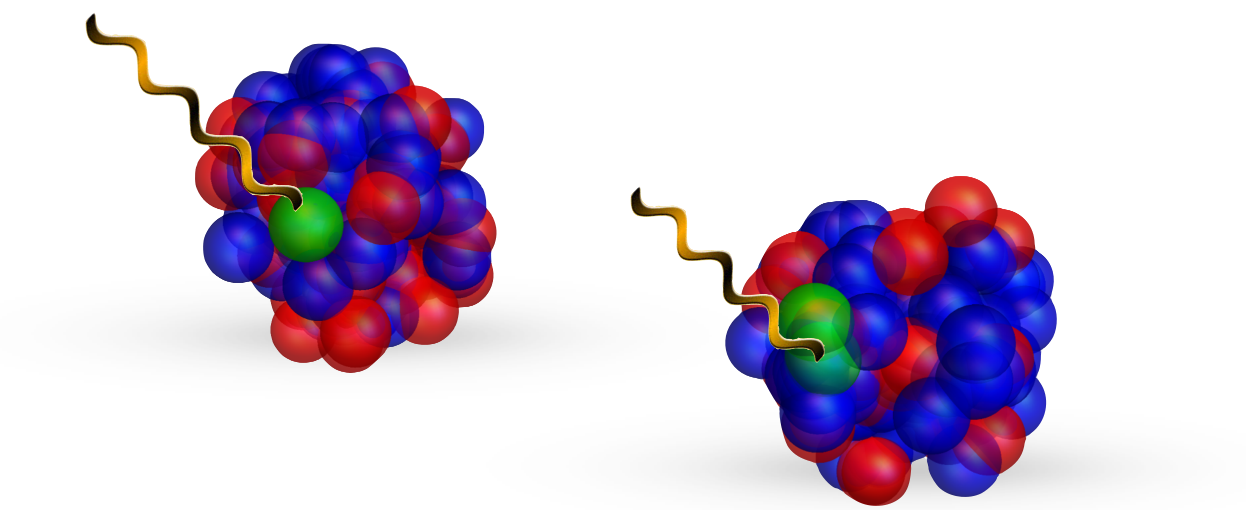


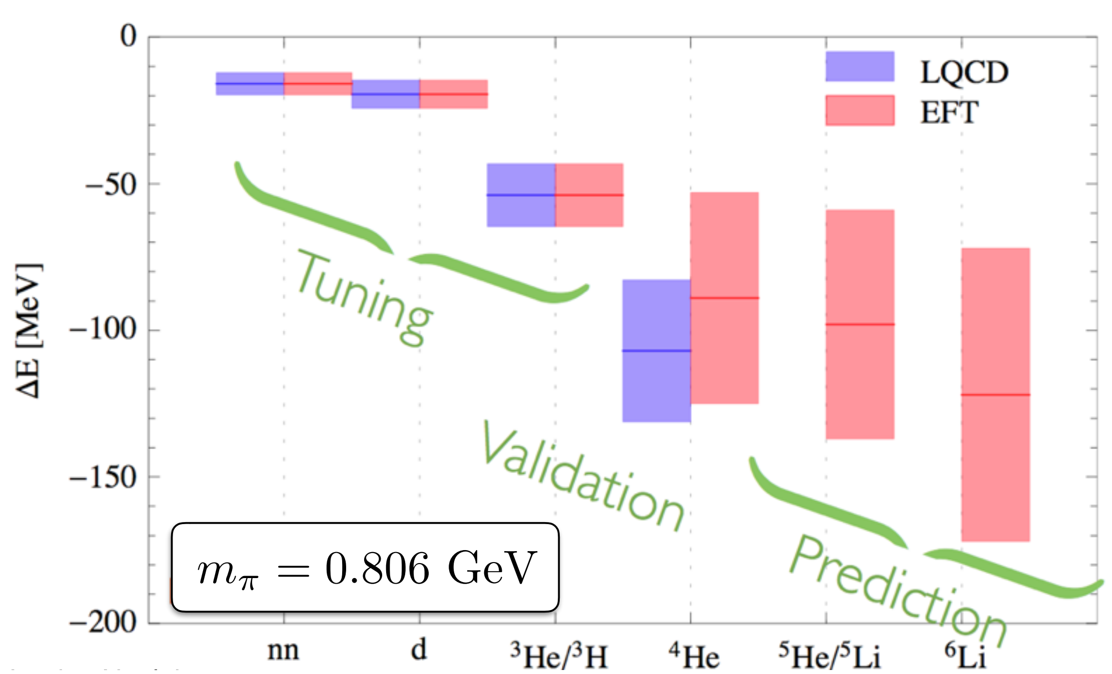


Calculations possible for A<5

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



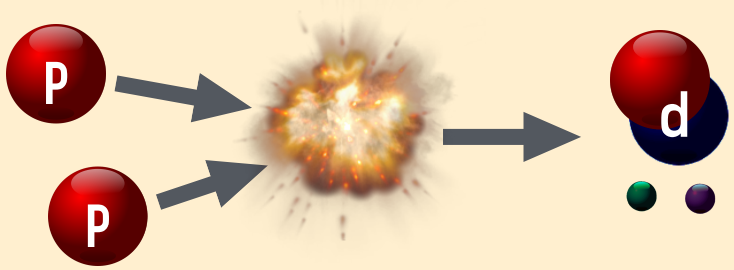


[Barnea et al., PRL 2015]

Nuclear matrix elements

"Nuclear physics from LQCD Collaboration"
NPLQCD

- Nuclei with A<5 unphysical quark masses
- Physical-mass calculations begun 2021

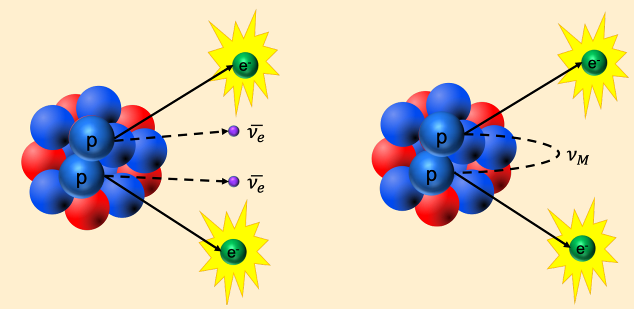


Proton-proton fusion and tritium β-decay
[Phys.Rev.Lett. 119, 062002 (2017)]

Scalar, axial, tensor matrix elements
[Phys.Rev.Lett. 120 (2018), Phys.Rept. 900 (2021), Phys.Rev.D 103, 074511(2021)]

Baryon-baryon interactions, incl. QED
[Phys.Rev.D 96 (2017), Phys.Rev.D 103 (2021), Phys.Rev.D 103 (2021), Phys.Rev.D 107 (2023), 2403.00672 (2024)]

Double β-decay
[Phys.Rev.Lett. 119 (2017), Phys.Rev.D 96 (2017), Phys.Rev.D 107 (2023), 2402.09362 (2024)]



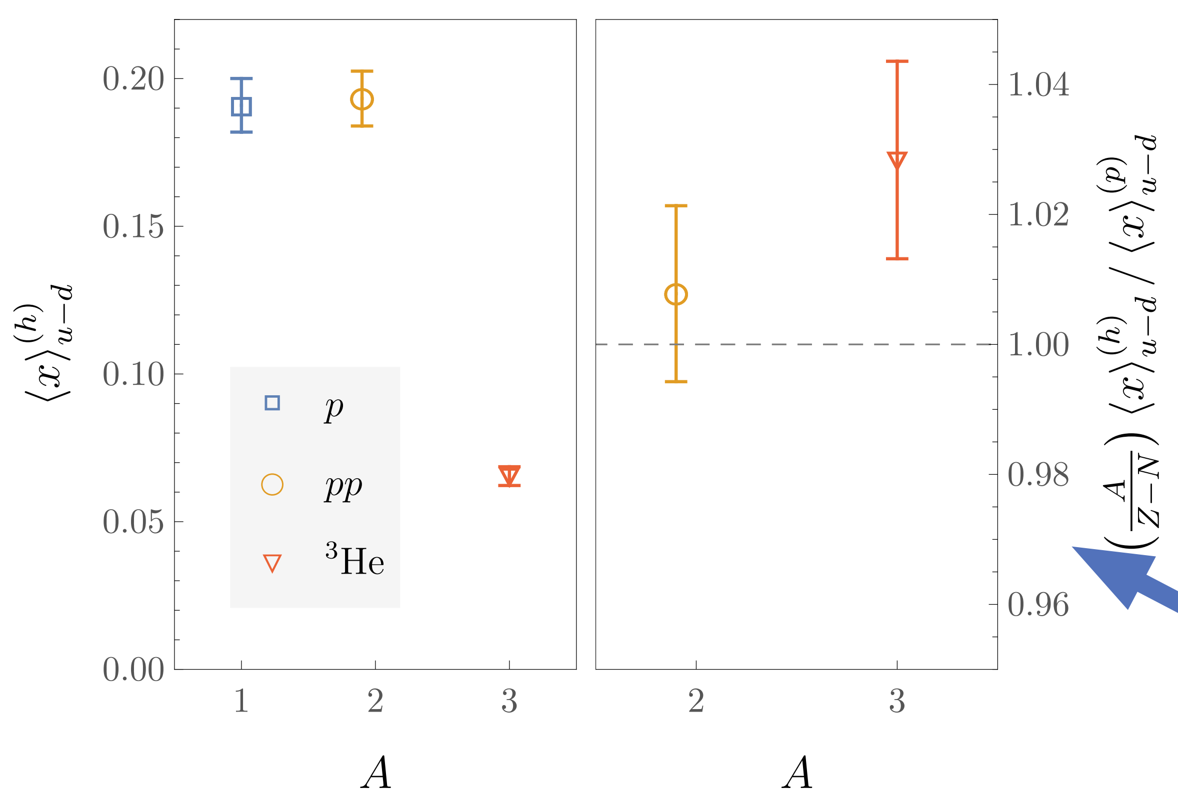
Nuclear parton distribution functions
[Phys.Rev.D 96 (2017), Phys.Rev.Lett. 126 (2021)]

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



Isovector
m_π ~800 MeV

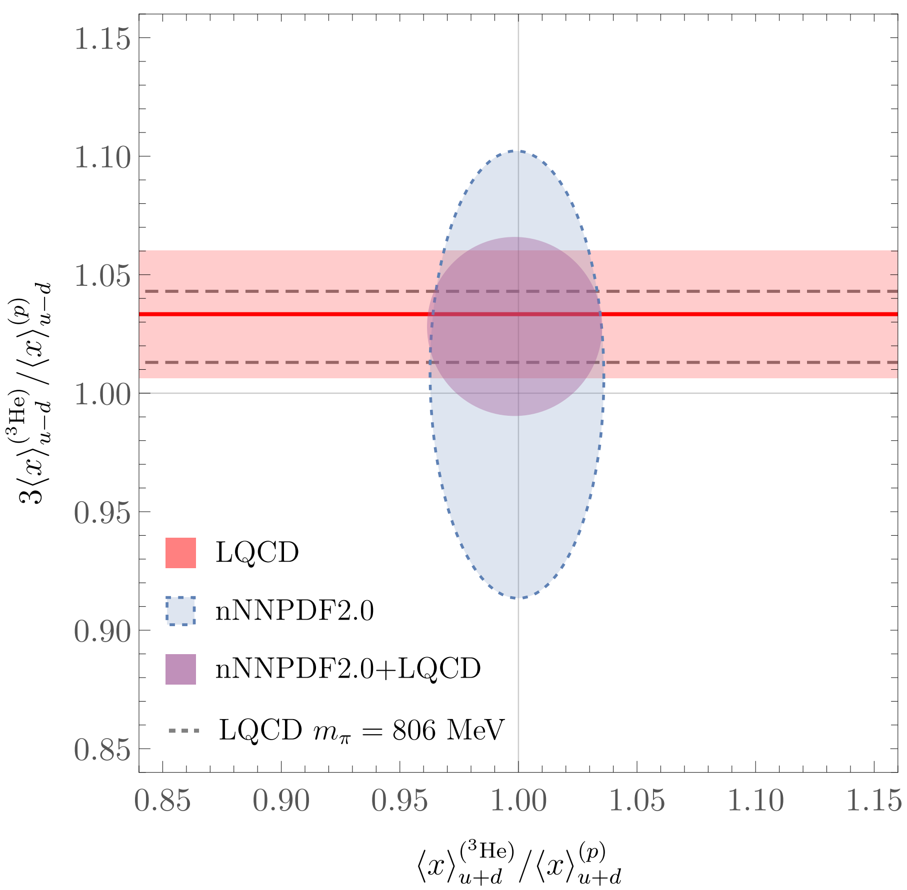
Normalised to proton result

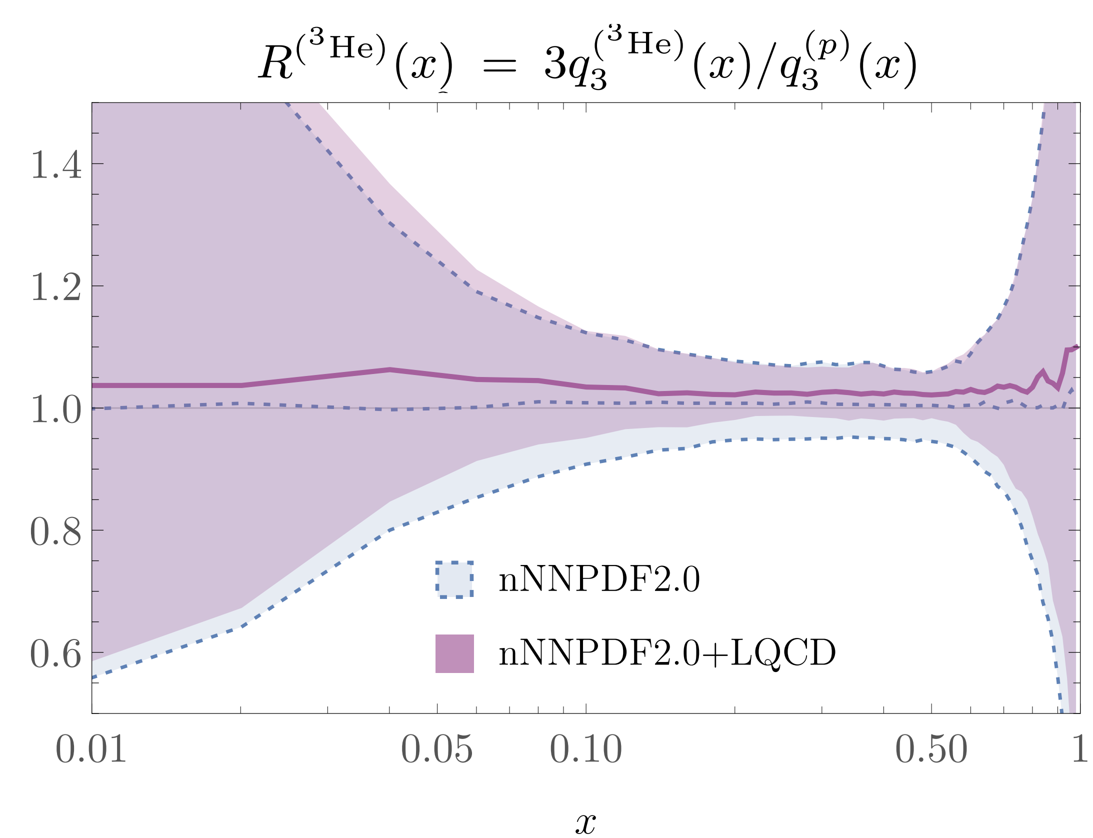
[NPLQCD 2009.05522 (2020)]

Momentum fraction of nuclei

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

- Match isovector moments to low-energy constants of EFT, extrapolate to physical quark masses
- Include into nNNPDF framework → improved nuclear PDFs of $^3\mathrm{He}$

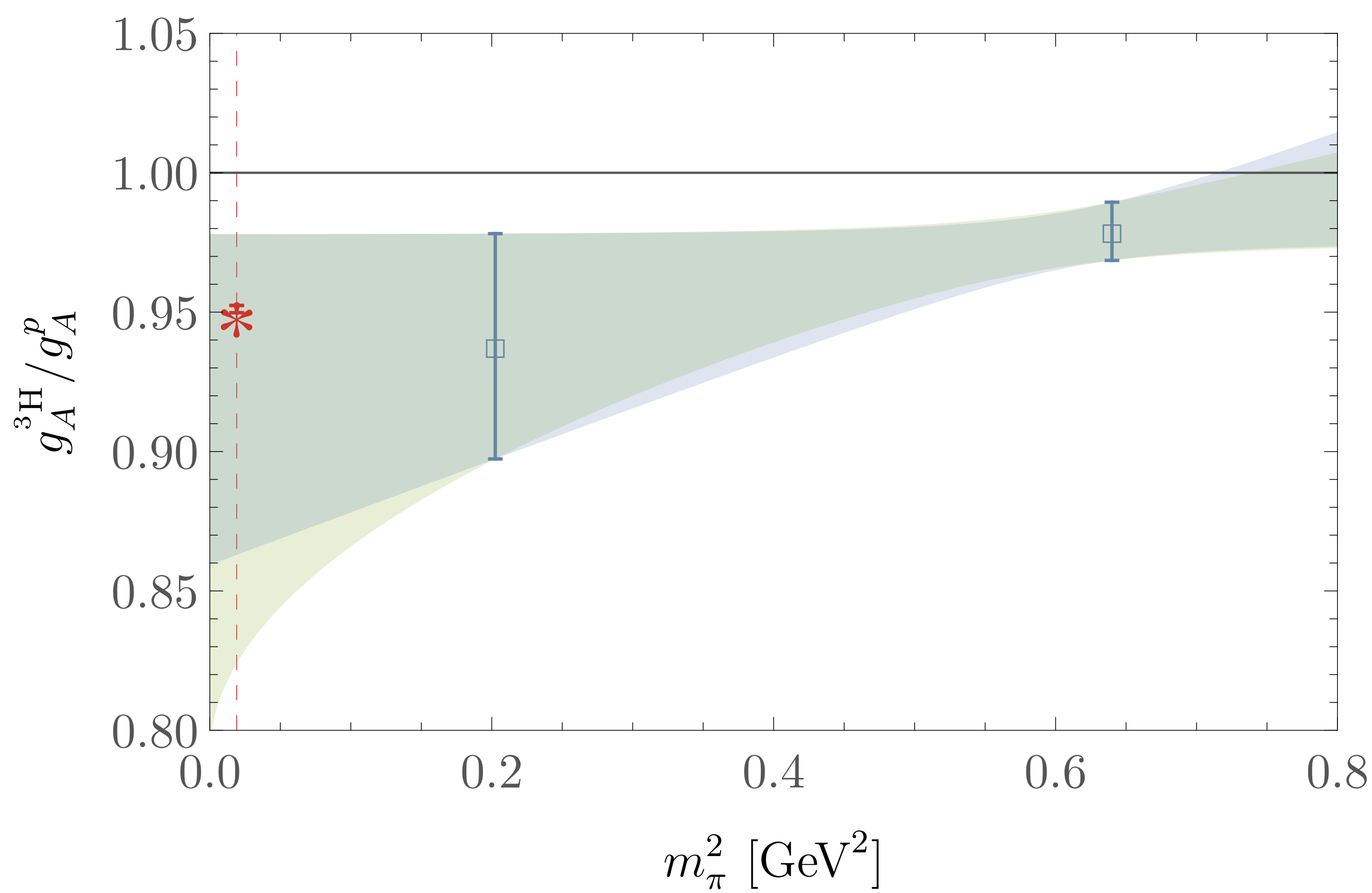




[NPLQCD 2009.05522 (2020)]

Axial charge of the triton

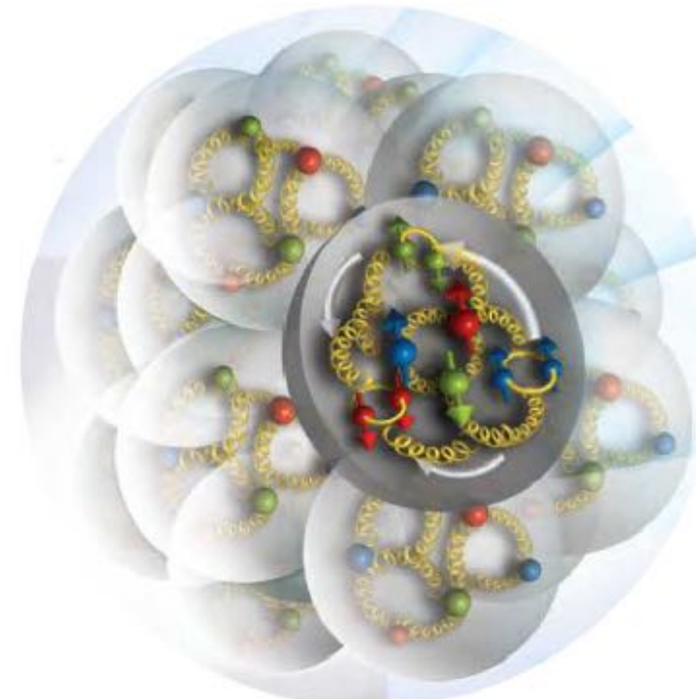
- No axial form factors of nuclei from lattice QCD yet
- Axial charge of He: first extrapolation to the physical quark masses in 2021



[NPLQCD 2102.03805 (2021)]

Nuclear physics from lattice QCD

Nuclei on the lattice 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
- …

Form factors from Lattice QCD

Precision Era

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

- Forward limits of FF incl. charges, moments of GPDs
- *t*-dependence of EM, axial, pseudo scalar FFs

Early Era

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

- *t*-dependence of GFFs
- Forward limits of nuclear FFs

Exploratory Era

First calculations, timeline for controlled calculations unclear

- Many transition and resonance FFs
- *t*-dependence of nuclear FFs