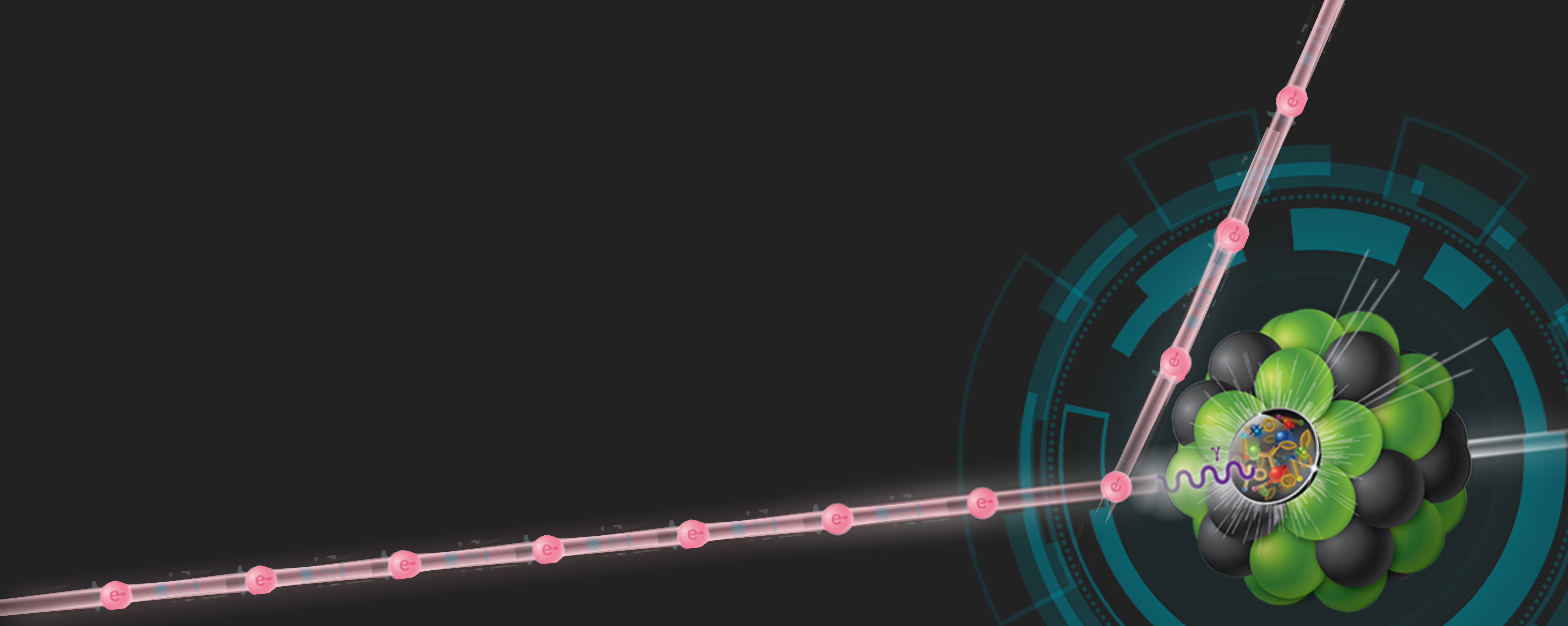


WILL DETMOLD

MIT

LATTICE QCD FOR EIC

image credit: Brookhaven National Lab

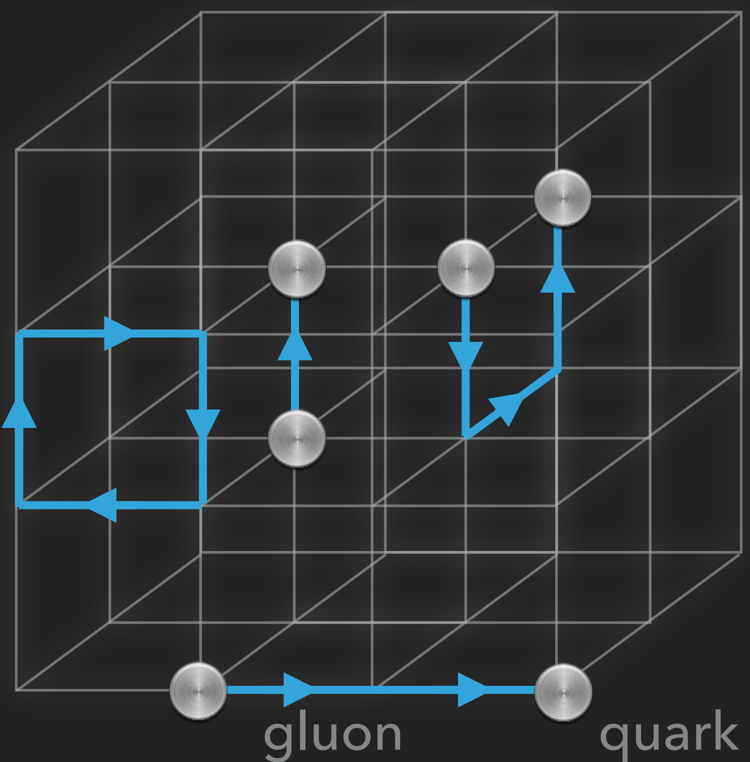
Center for Frontiers in Nuclear Science Inaugural Symposium, Nov 28th 2018

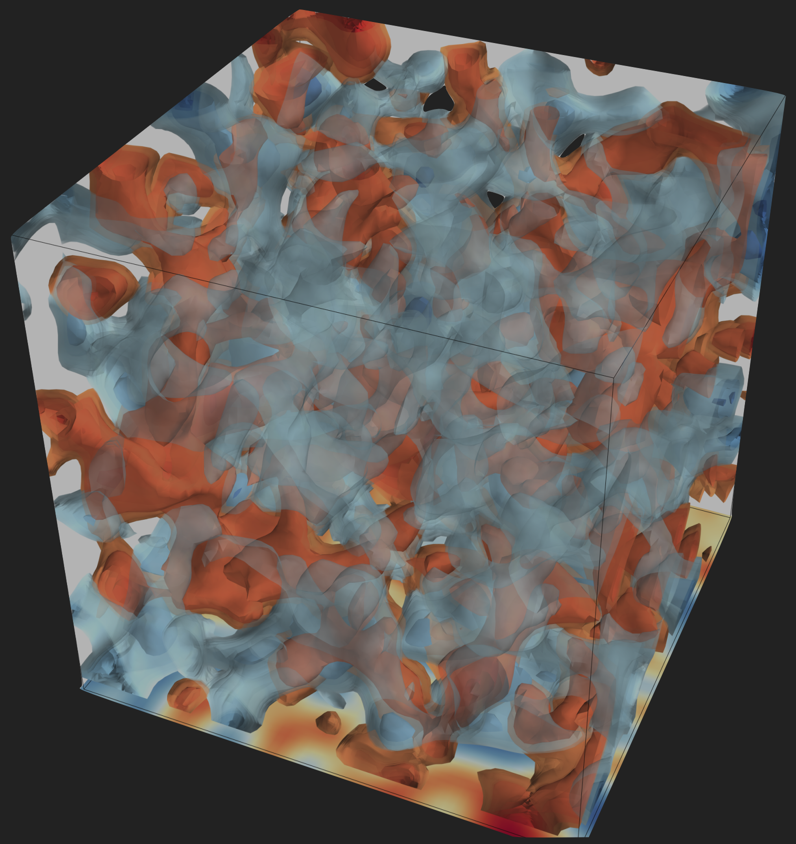
OUTLINE

1. The glue that binds us all
   - LQCD: mass, momentum, spin, pressure
2. (3D) proton tomography
   - LQCD: x-dependence of PDFs; TMDs
3. Structure of light nuclei
   - LQCD: EMC effects, exotic gluons

HIGH FIDELITY LATTICE QCD

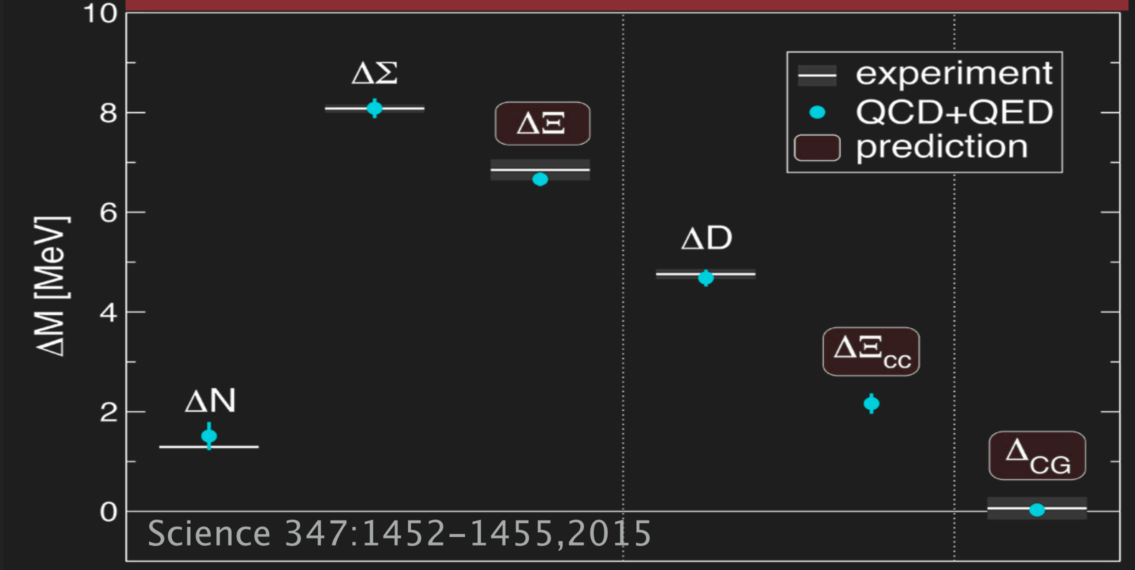
- LQCD: strong coupling definition of QCD and method to handle quarks & gluons
- Numerical LQCD entering precision era
- Modern calculations control all systematics
  - Physical quark masses, infinite volume and continuum limits
  - Blind analyses, multiple independent groups
  - Include QED in numerical calculations



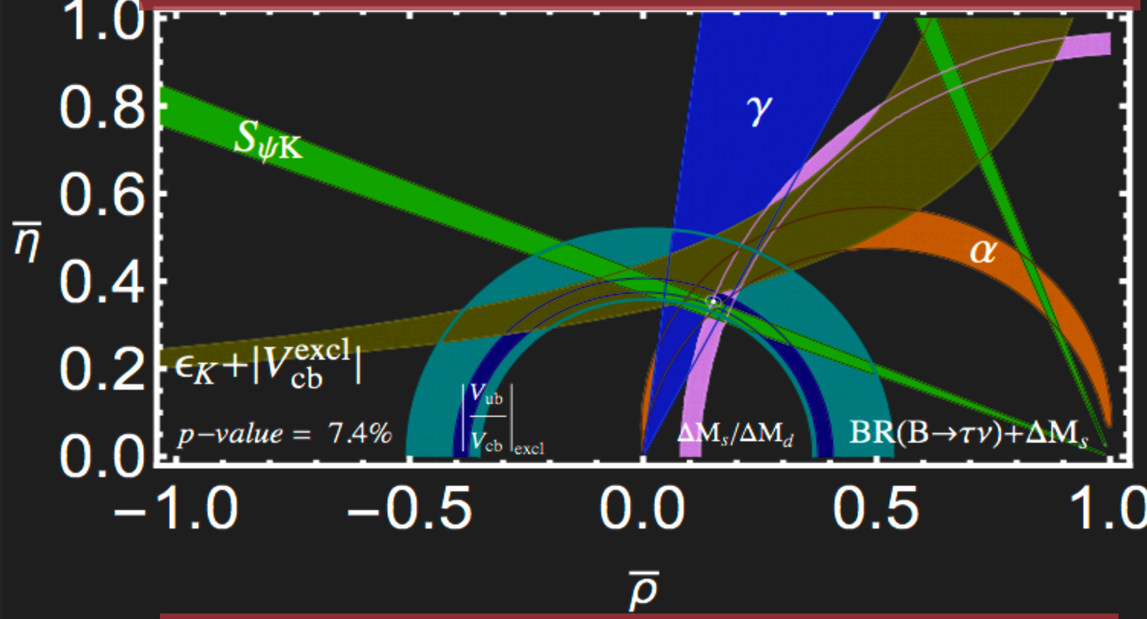


GOLDEN AGE FOR LQCD

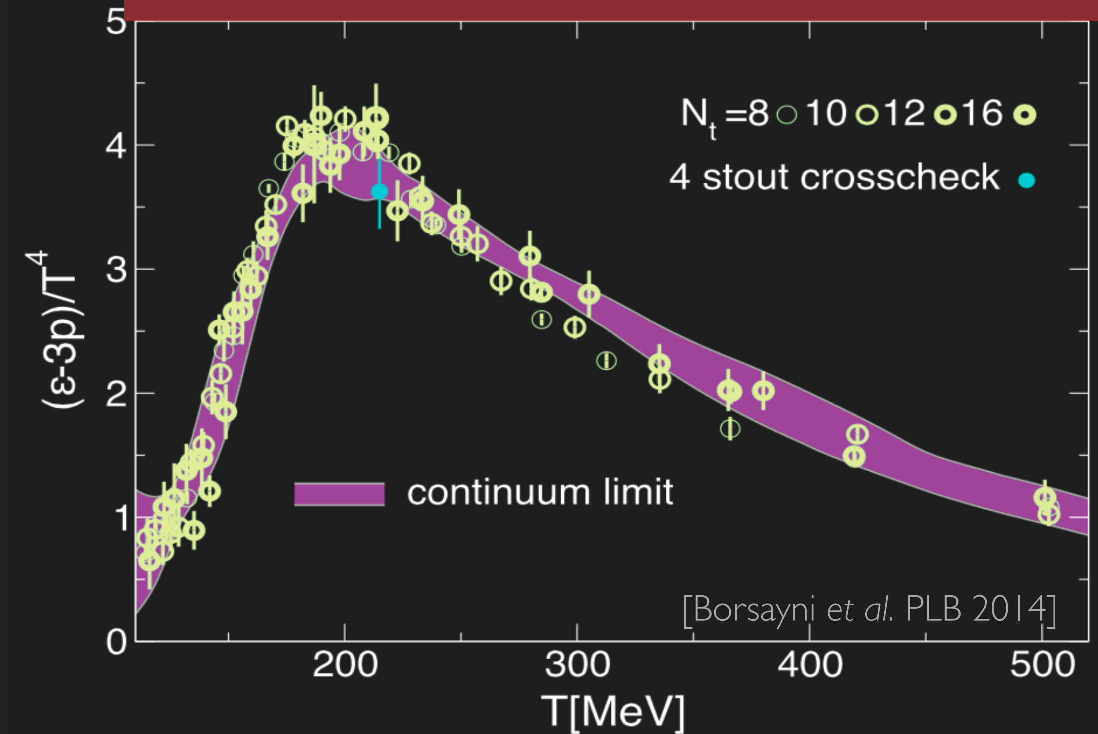
p-n mass splitting reproduced



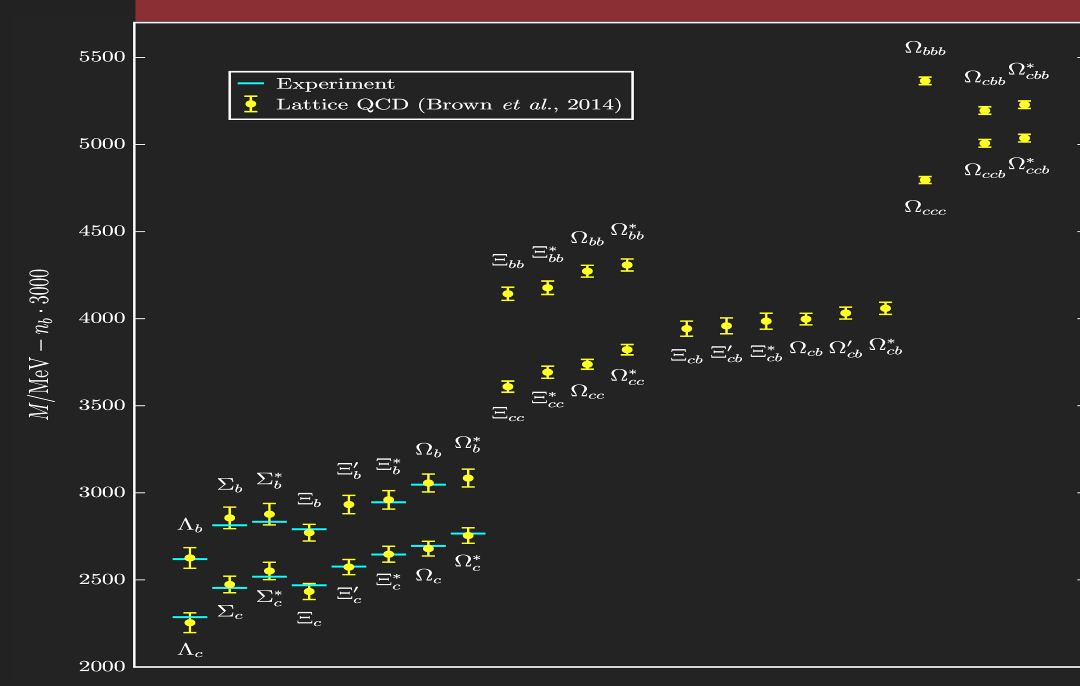
CKM matrix elements, BSM tests



QCD Equation of state vs T



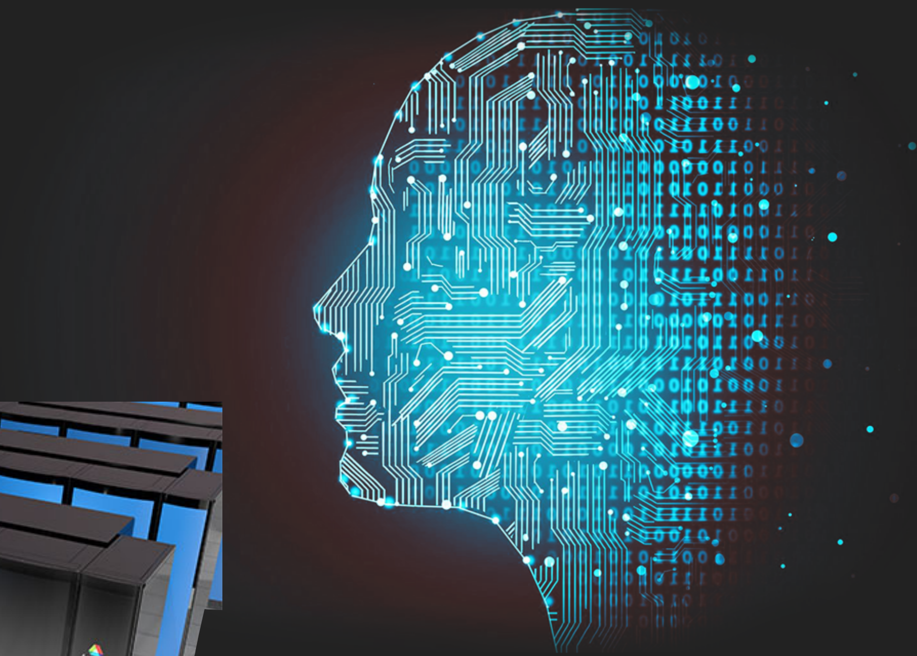
Predictions for new states



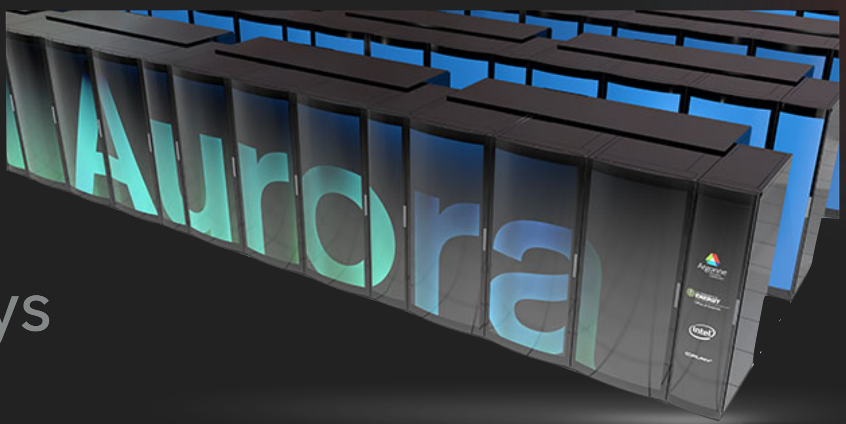
LQCD IN 2025: PHYSICS

- Improved calculations
  - Even finer control of systematic and statistical uncertainties
  - Inclusion of QED and isospin breaking
- Scope of physics addressed even more extensive
  - Full flavour decompositions
  - More complex process:
    - Larger nuclei
    - Non-local matrix elements

LQCD IN 2025: ALGORTIHMS AND MACHINES

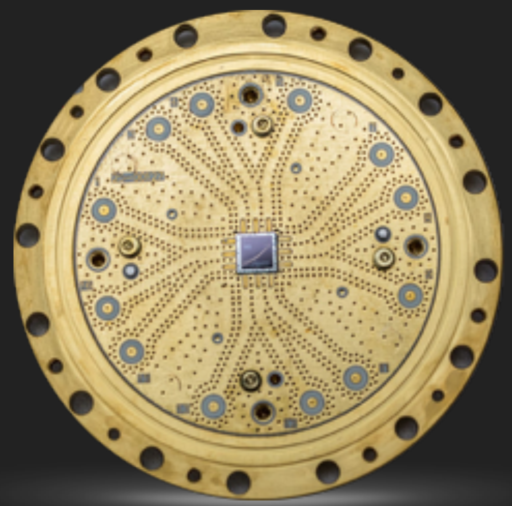


- Machine Learning [Shanahan et al PRD 2018]
- Exascale Computing
  - Aurora, CORAL-2, …



- Field Programmable Gate Arrays
  - Custom computers for specific calculations

- Quantum computers
  - Address quantities that are exponentially hard
  - See Martin Savage's talk

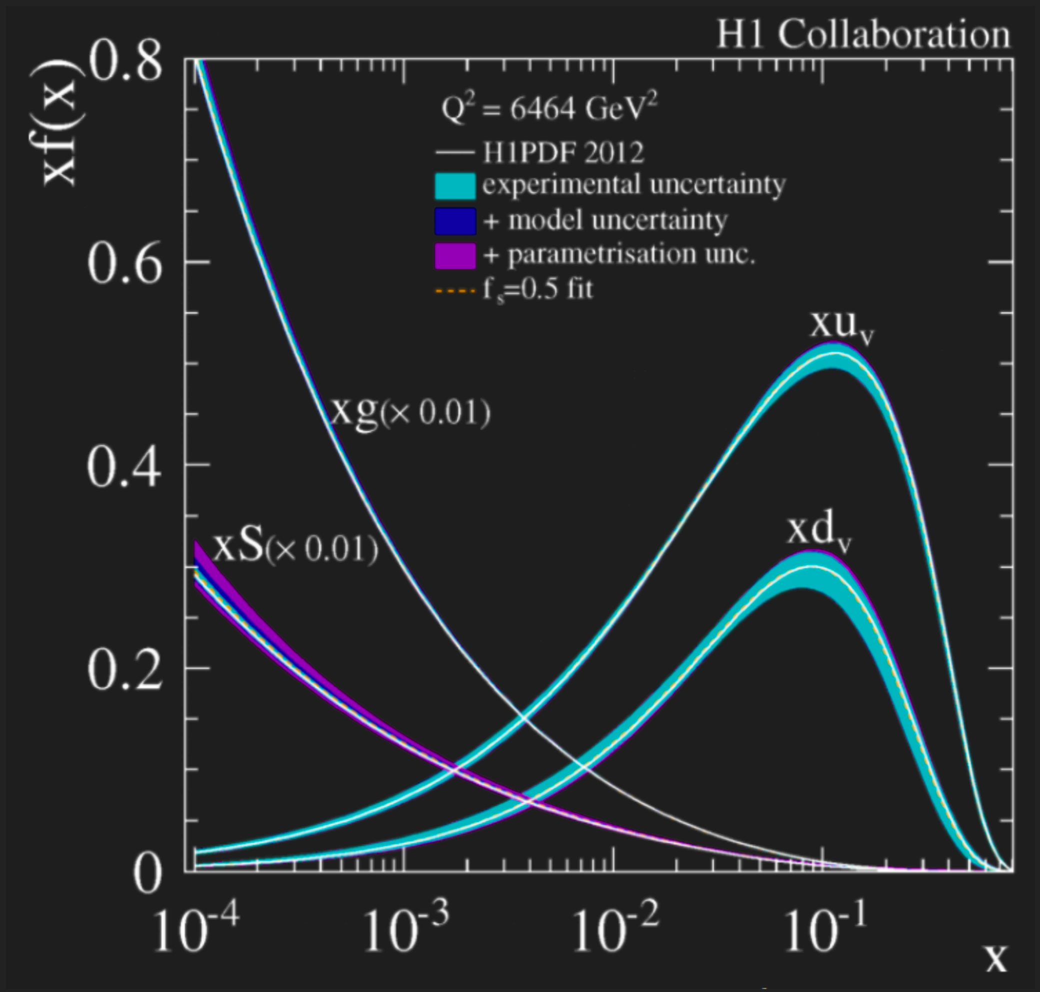


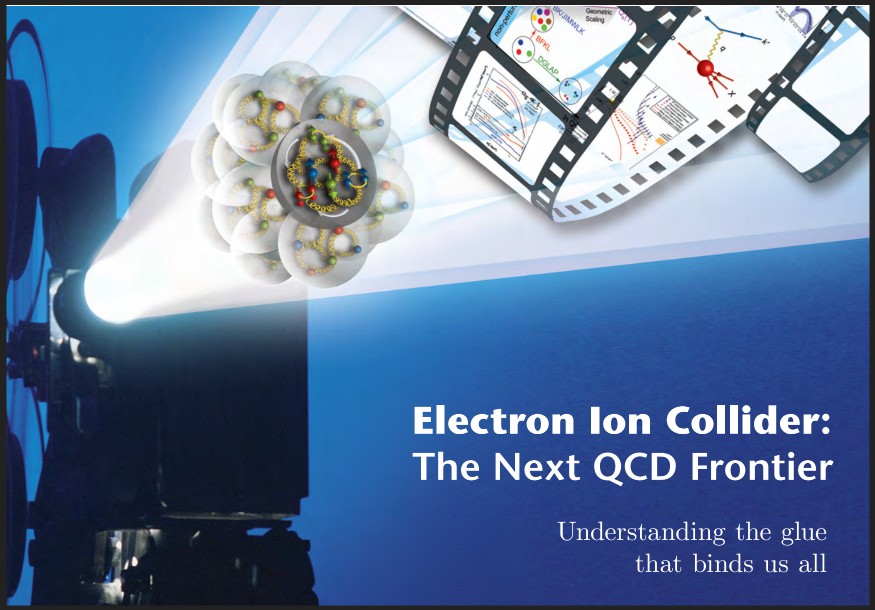
THE GLUE THAT BINDS US ALL

[image: © JLab]

PROTON STRUCTURE

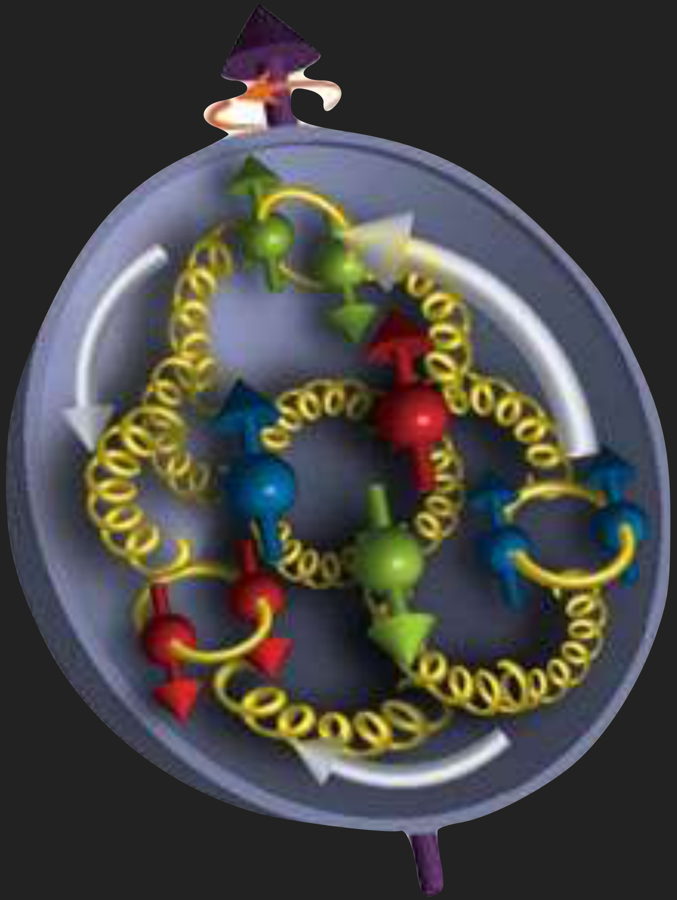
- Past 60+ years: detailed view of quark structure of nucleons
- Gluon structure also important
  - Unpolarised gluon PDF dominates at small x
  - Other aspects of gluon structure relatively unexplored
- Key target of EIC
  - LQCD opportunity to provide benchmarks and make predictions

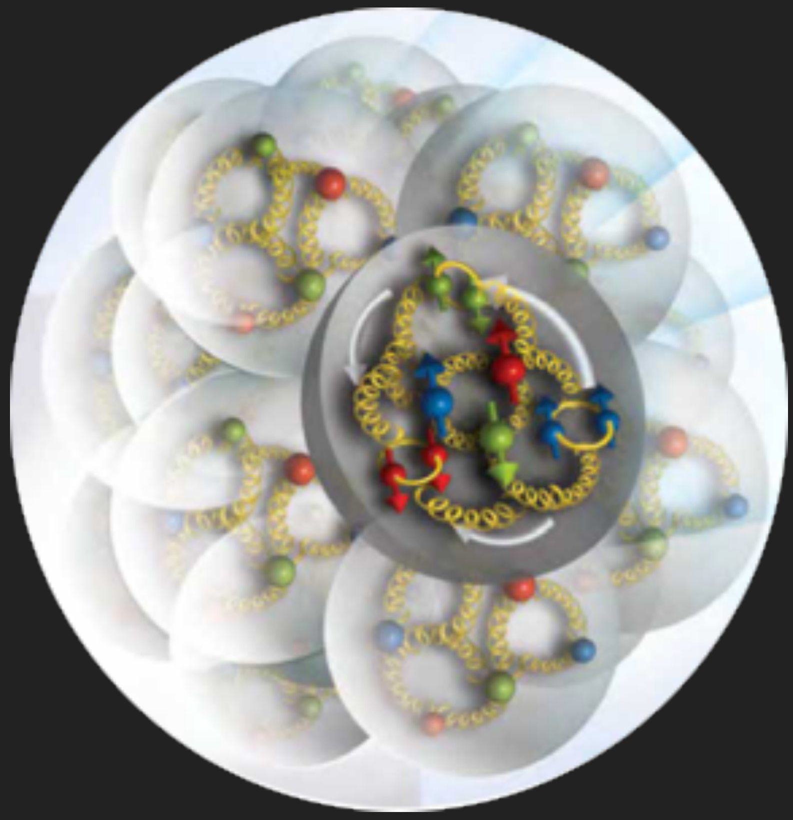




THE GLUE THAT BINDS US ALL

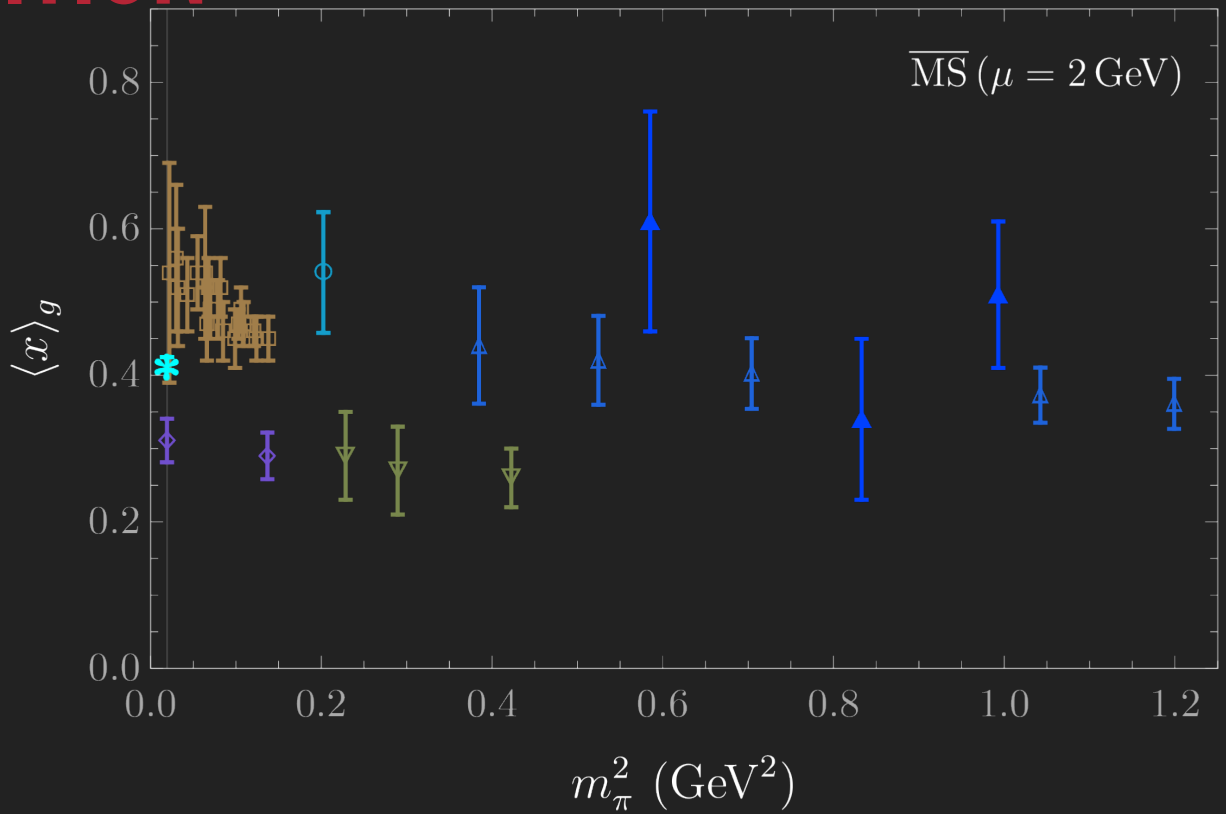
- Questions to answer
- What are gluon contributions to the proton's mass, spin, momentum, D-term
- What is the gluon distribution in a proton
  - PDFs, GPDs, TMDs
  - Pressure, Shear
  - Gluon radius
- How is the gluon structure of a proton modified in a nucleus



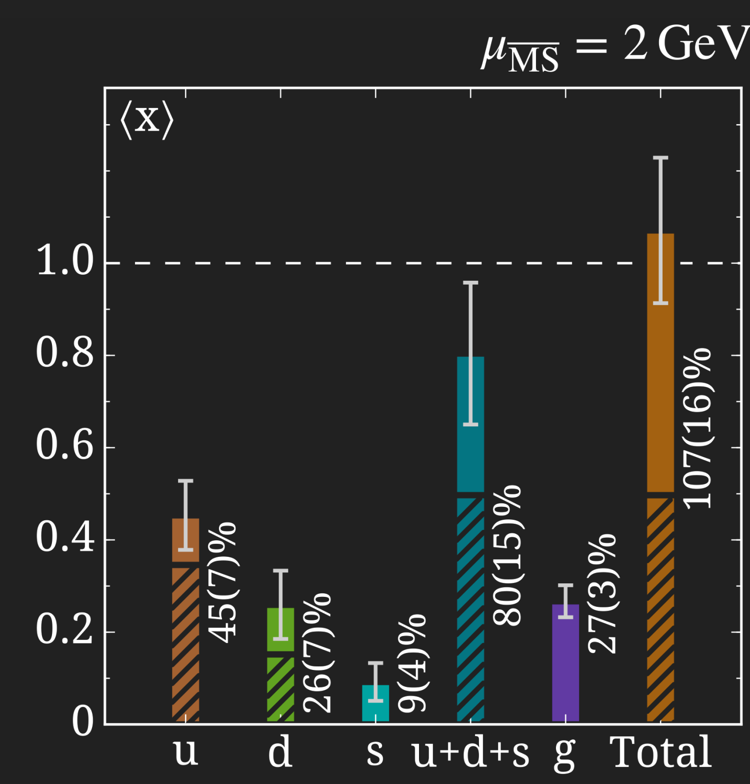


MOMENTUM FRACTION DECOMPOSITION

[Shanahan, WD,1810.04626]



- Gluon momentum fraction difficult to calculate
  - All groups see flat mass dependence
- First calculation of full proton momentum decomposition [Alexandrou et al. PRL 2017]
  - Physical quark masses, including disconnected quark (striped)



[Alexandrou et al. PRL 2017]

PROTON SPIN DECOMPOSITION

- Spin sum rules
- Ji decomposition

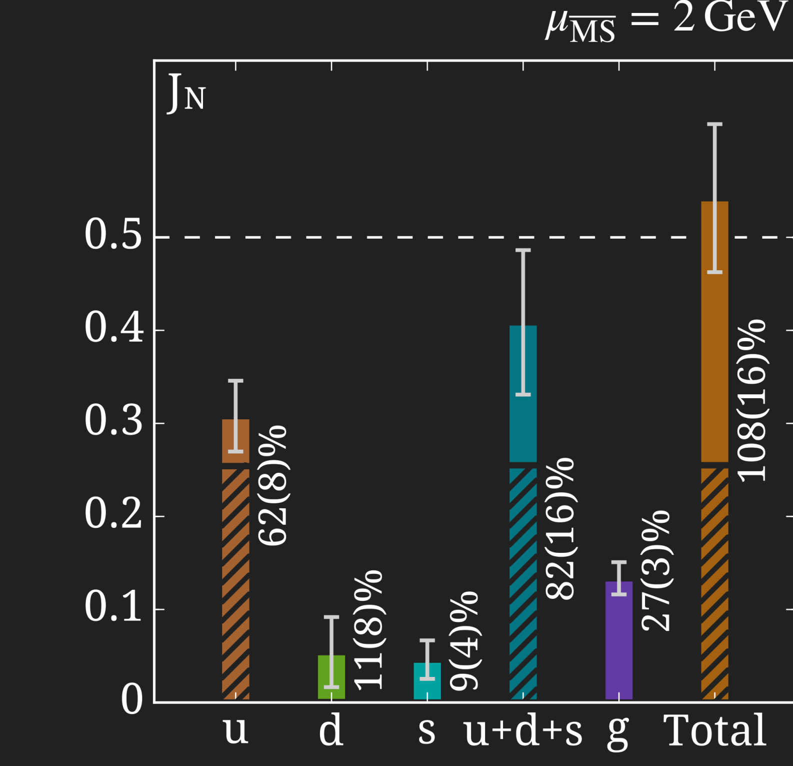
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma_{u+d+s} + L_{u+d+s} + J_g$$

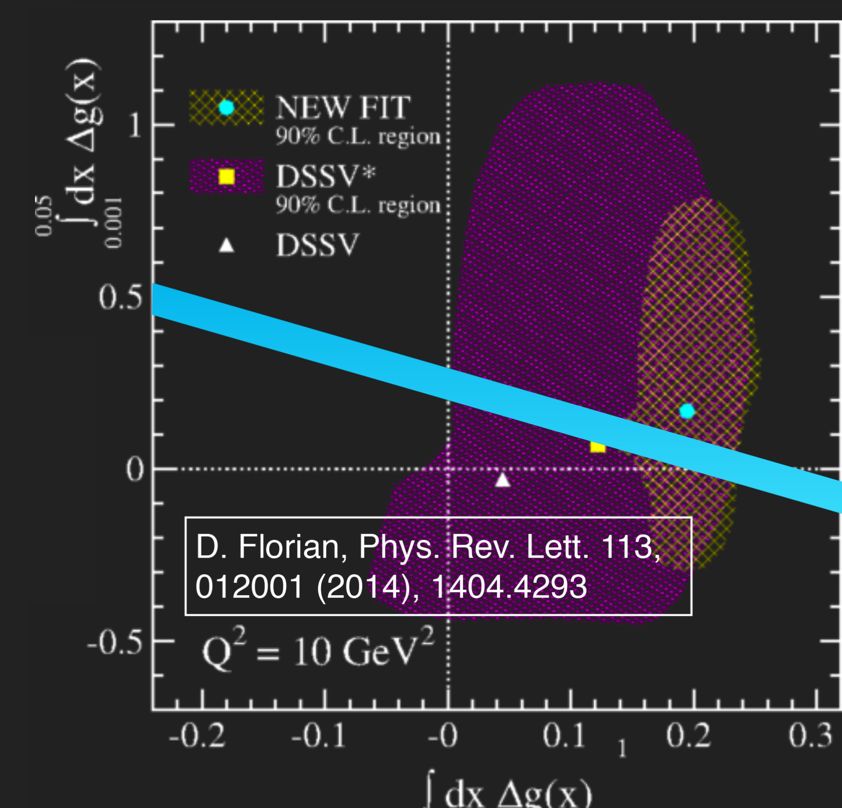
- Jaffe-Manohar decomposition

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma_{u+d+s} + \mathcal{L}_{u+d+s} + \mathcal{L}_g + \Delta G$$

  - Gluon helicity ΔG accessible using LaMET approach [Ji, Zhang,Zhao PRL 2013]
- Gluon pieces in both recently calculated
- Interpolation between two definitions [Engelhardt 2017]

[Alexandrou et al. PRL 2017]





[Yang, Lattice 2018; Yang et al. PRL 2017]

ENERGY-MOMENTUM TENSOR

- Many of these properties derived from Energy-Momentum Tensor (conserved Noether current associated with Lorentz translations)
- Matrix elements of traceless gluon EMT for spin-half nucleon:

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

Generalised gluon form factors

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

- Three generalised gluon form factors $A_g(t), B_g(t), D_g(t)$
- Sum rules with quark pieces in forward limit
  - Momentum fraction $A_a(0) = \langle x \rangle_a$ ➡ $\sum_{a=g,q} A_a(0) = 1$
  - Spin $J_a(t) = \frac{1}{2}(A_a(t) + B_a(t))$ ➡ $\sum_{a=g,q} J_a(0) = \frac{1}{2}$
  - D-terms $D_a(0)$ unknown but equally fundamental!

D-TERM

- D-term GFF encodes the pressure and shear distributions in the nucleon (Breit frame)

$$\widetilde{D}(r) = \int \frac{d^3\vec{p}}{2E(2\pi)^3}\; e^{-i\vec{p}\cdot\vec{r}}\; D(-\vec{p}^{\,2})$$

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

- Quark and gluon shear forces individually well-defined [i.e., scale-dependent partial contributions $s_{q,g}(r)$]
- Pressure defined only for the total system (pieces depend also on GFFs related to the trace terms of the EMT that cancel in the sum)

GLUON GPDS

- GFFs correspond to lowest moments of GPDs:

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

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

- Quark GPDs: constraints from JLab, HERA, COMPASS, by DVCS, DVMP, future improvements from JLab 12GeV
- Gluon GPDs: almost unknown from experiment, future constraints are a goal of EIC

Leading twist nucleon gluon GPDs:

Gluon field-strength tensor

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

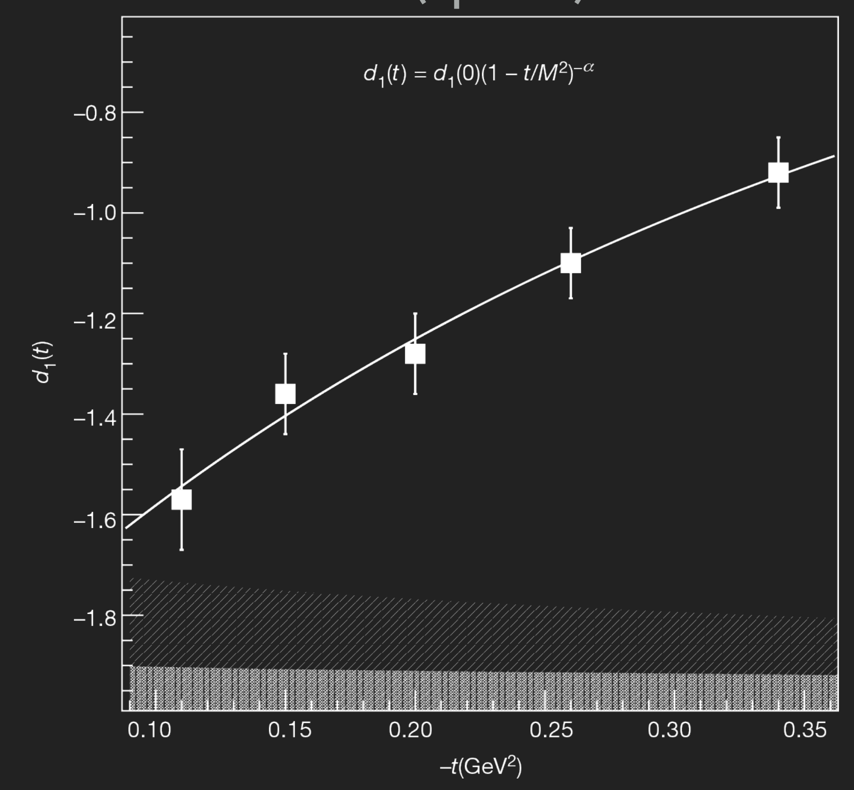
$$\int_{-\infty}^{\infty} \frac{d\lambda}{2\pi} e^{i\lambda x} \langle p', s' | G_a^{\{\mu\alpha}(-\frac{\lambda}{2}n) \left[\mathcal{U}^{(A)}_{[-\frac{\lambda}{2}n, \frac{\lambda}{2}n]}\right]_{ab} G_{b\alpha}{}^{\nu\}}(\frac{\lambda}{2}n) | p, s\rangle$$
$$= \frac{1}{2}\left(H_g(x,\xi,t) \bar{U}(p',s') P^{\{\mu}\gamma^{\nu\}} U(p,s) + E_g(x,\xi,t) \bar{U}(p',s') \frac{P^{\{\mu} i\sigma^{\nu\}\alpha}\Delta_\alpha}{2M} U(p,s) \right) + \ldots\,,$$

GPDs(Bjorken x, skewness, mom transfer)

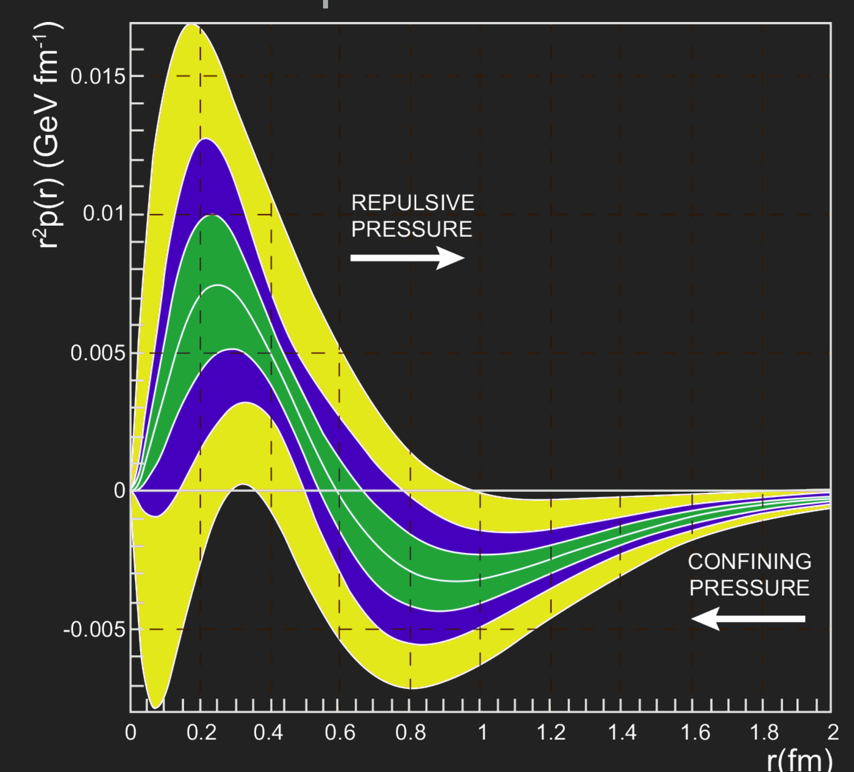
D-TERM FROM JLAB DVCS

- Recent experimental determination of DVCS D-term and extraction of proton pressure distribution
  [Burkert, Elouadrhiri, Girod, Nature 557, 396 (2018)]
- Strong repulsive pressure near the centre of the proton
- Binding pressure at greater distances.
- Peak pressure near the centre ~10^{35} Pascal, greater than pressure estimated for neutron stars
- Key assumptions: gluon D-term same as quark term,
  tripole form factor model
  - LQCD can test these assumptions

DVCS (quark) D-term

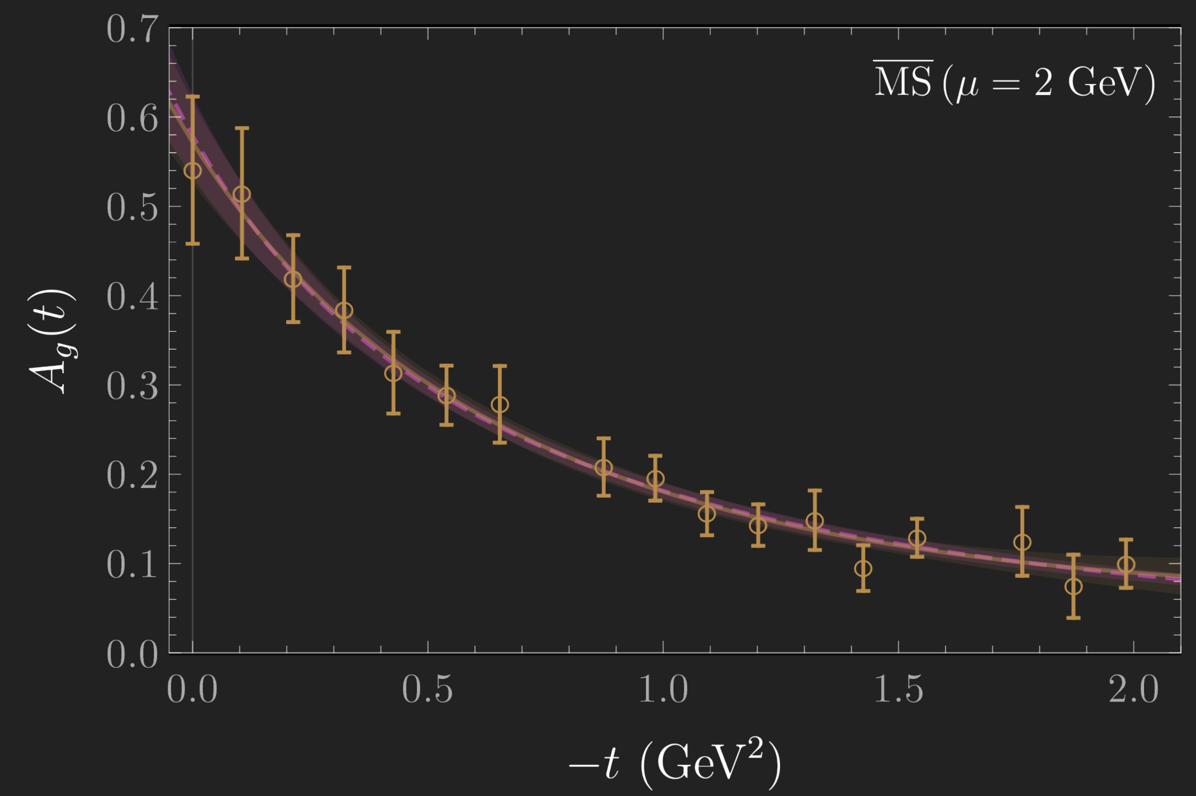


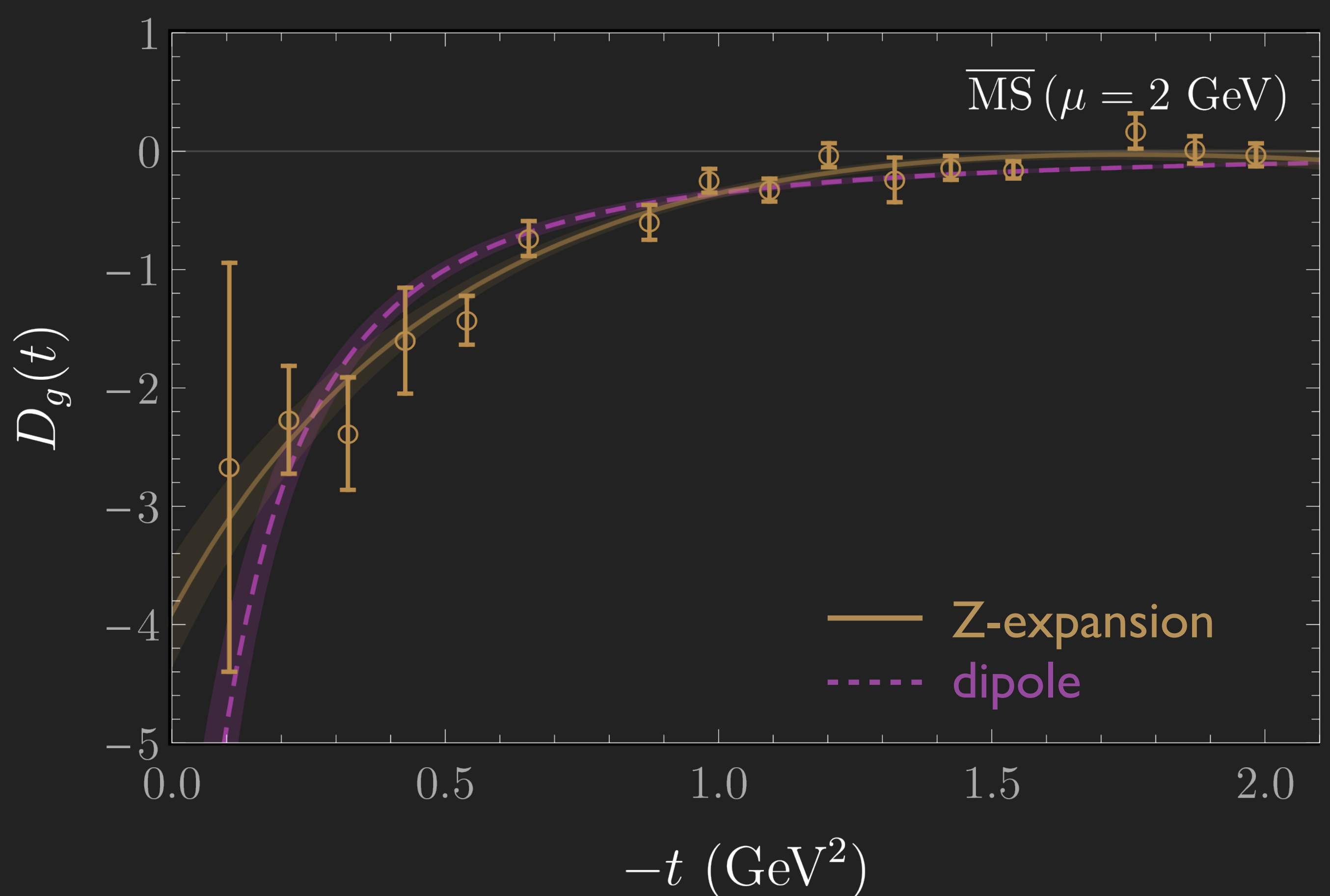
Radial pressure distribution

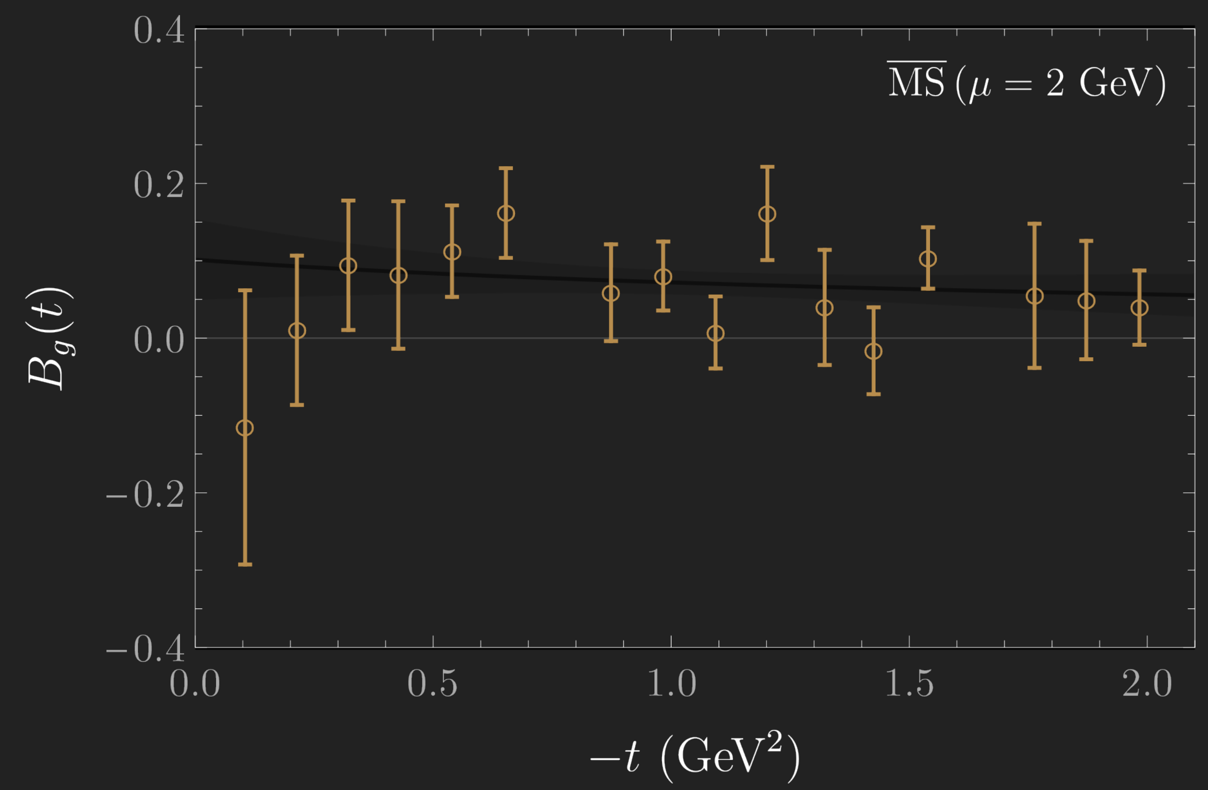


GLUON GFFS

- First calculation of all 3 nucleon gluon GFFs [Shanahan, WD,1810.04626, 1810.07589]
- LQCD results at m_π ~450 MeV

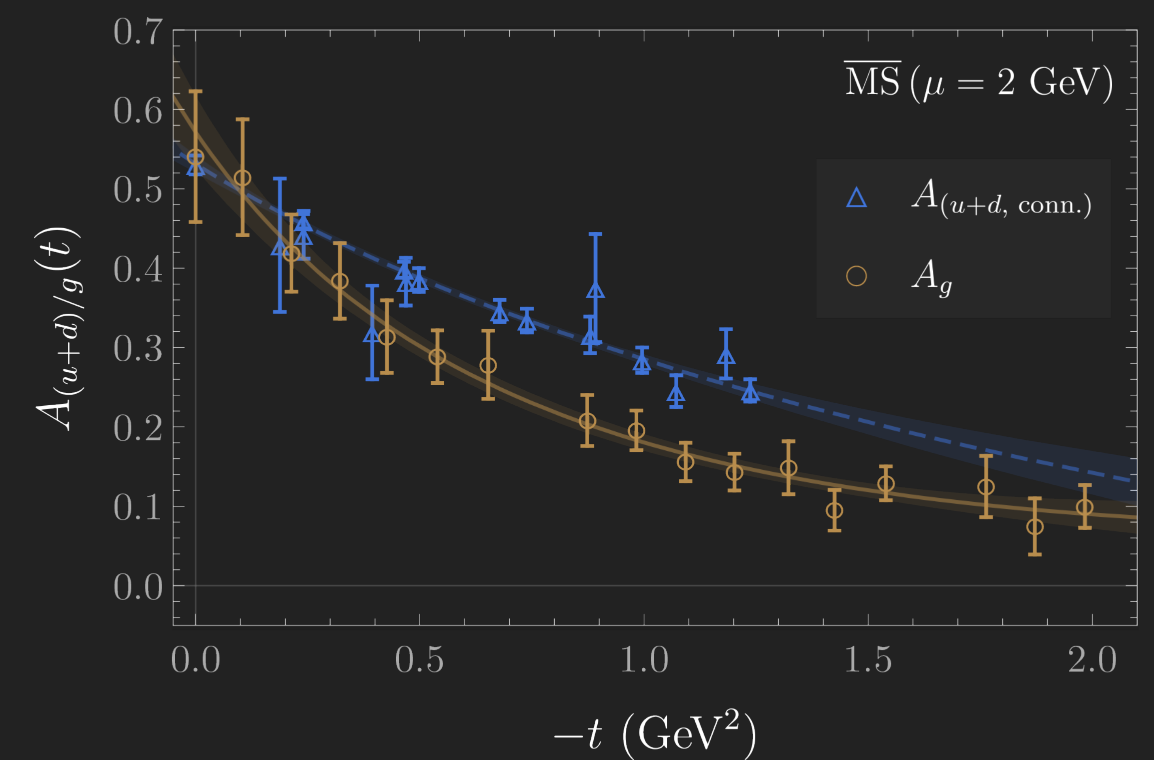


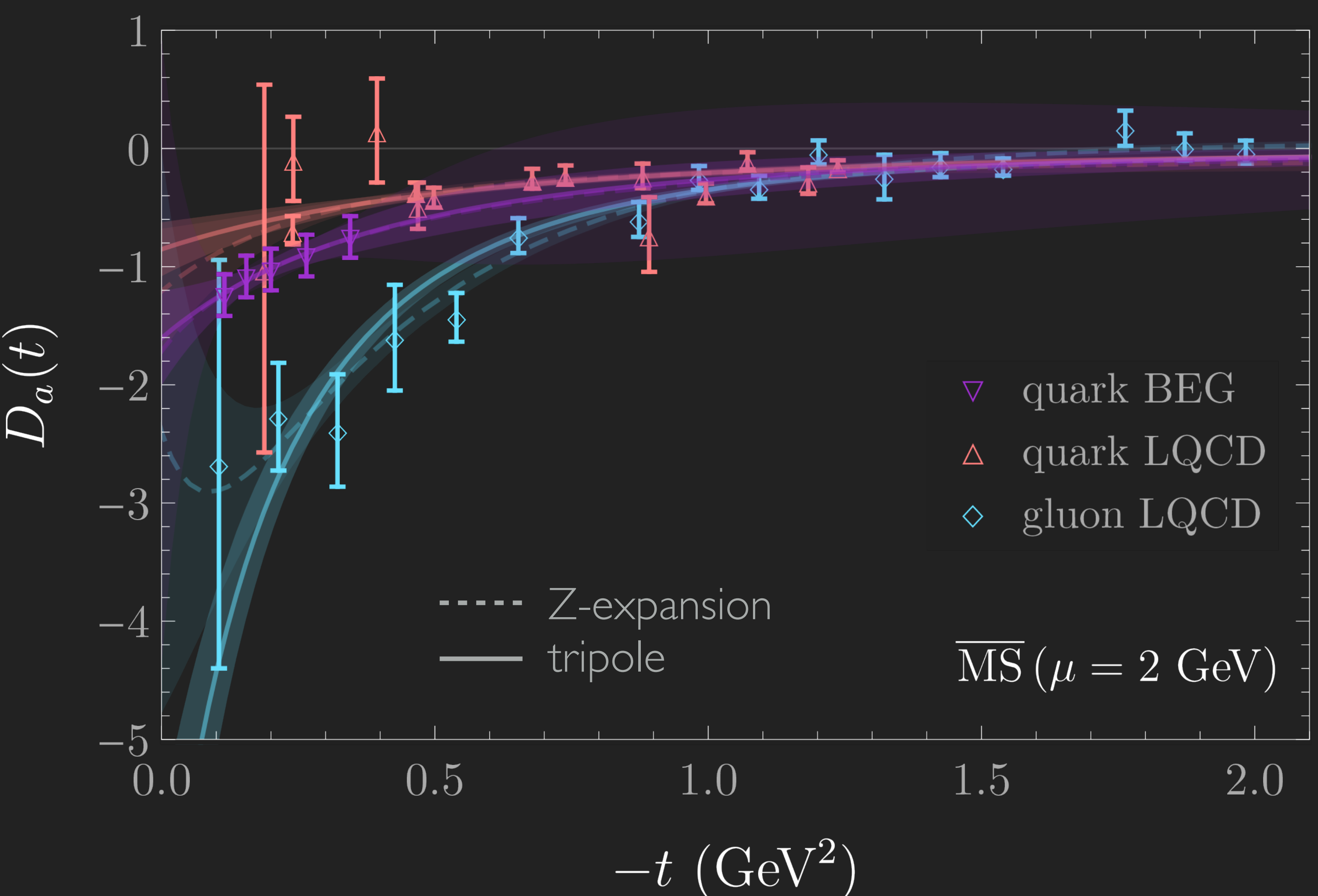


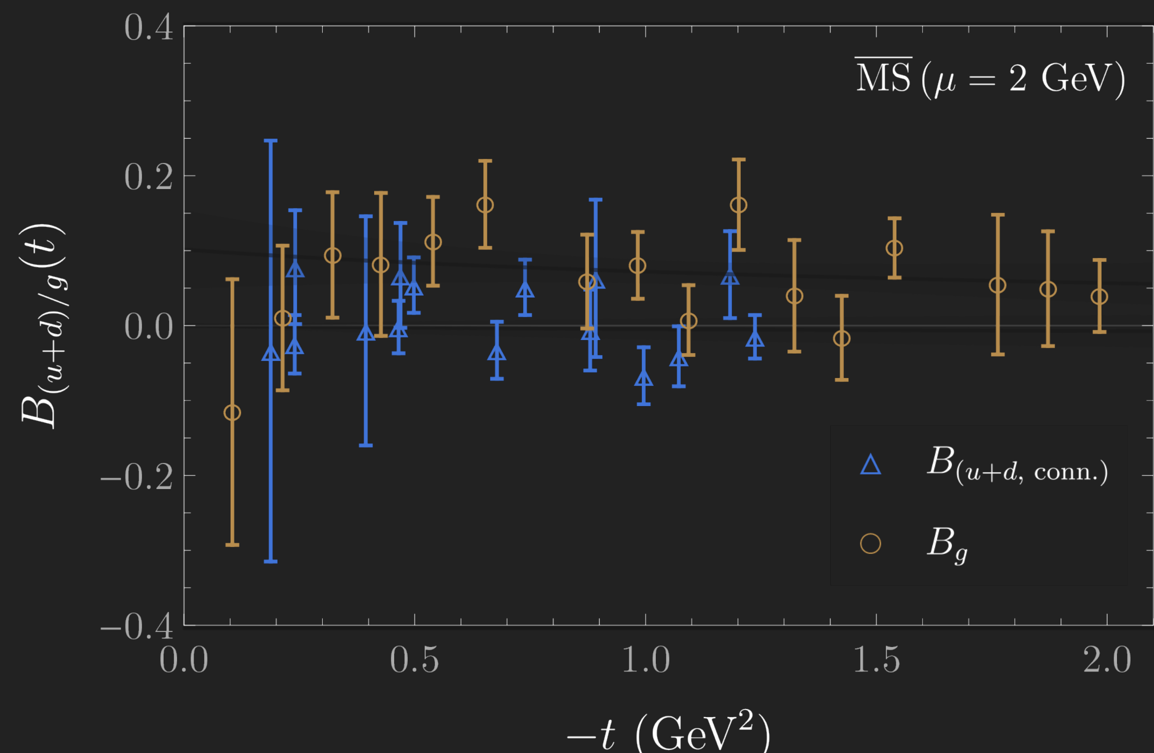


QUARK AND GLUON GFFS

- Gluon GFFs: Shanahan, Detmold, 1810.04626,1810.07589
- Quark GFFs: P. Hägler et al. (LHPC), PRD77, 094502 (2008)
- Expt quark GFFs (BEG): Burkert et al, Nature 557, 396 (2018)







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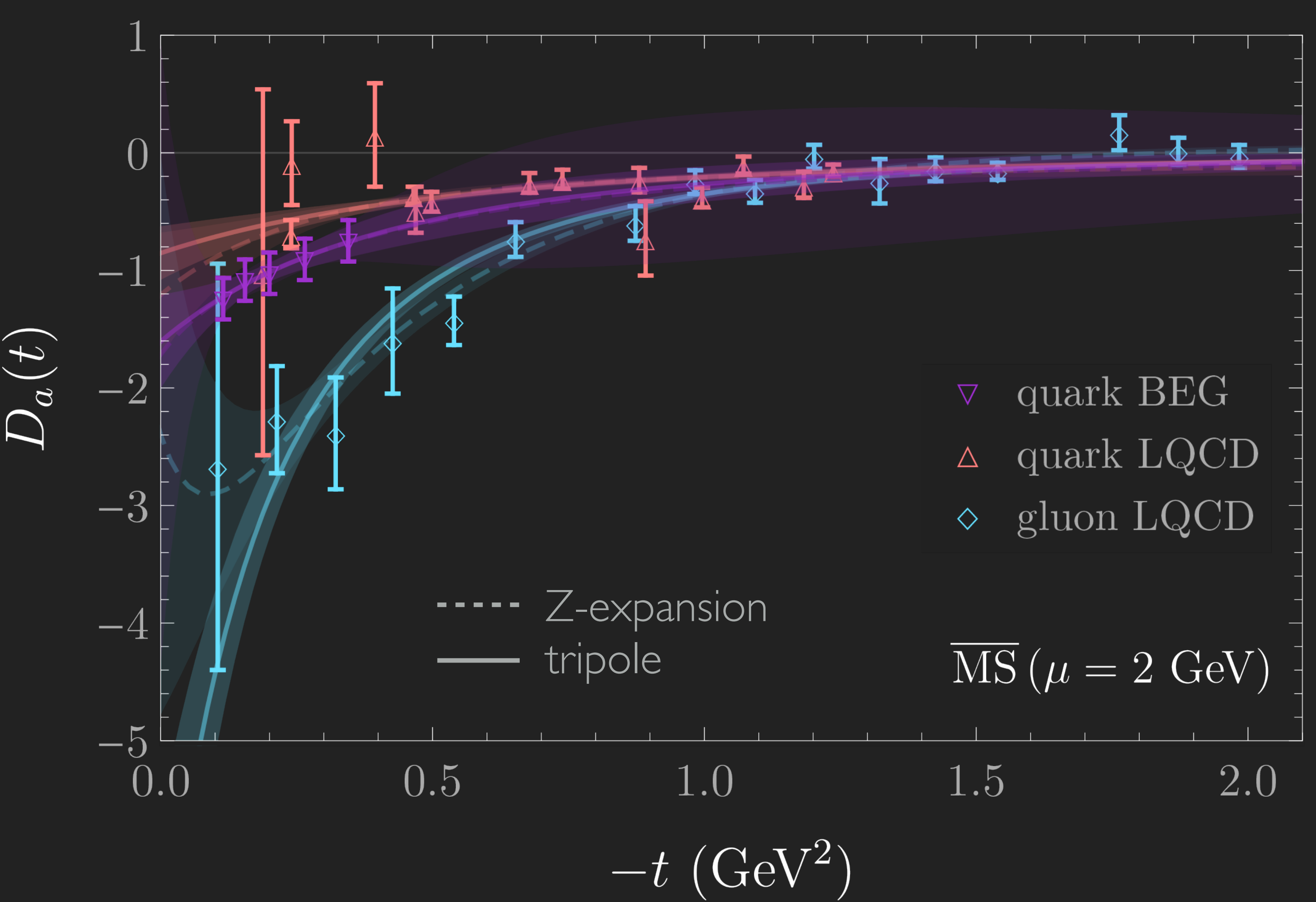
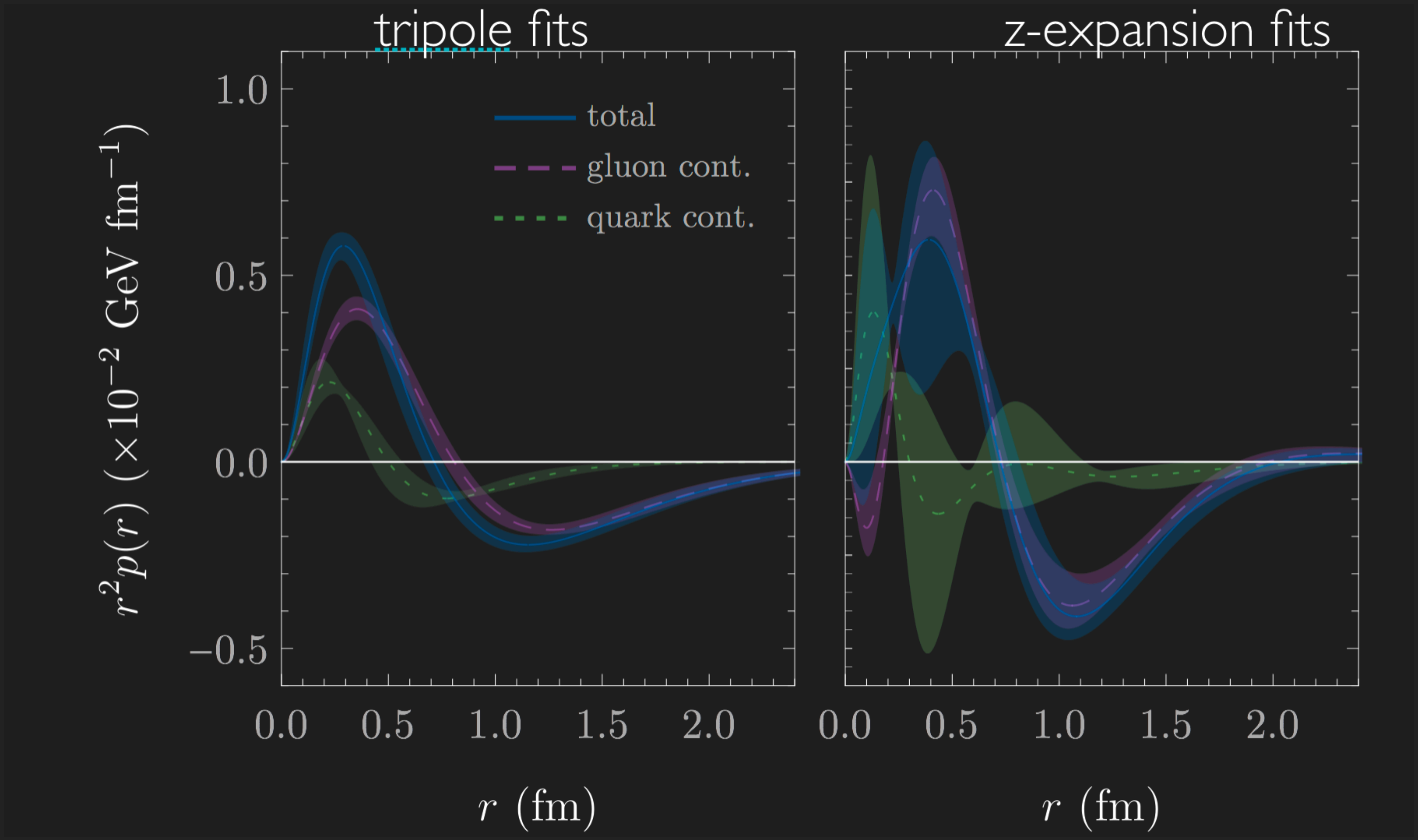


Key assumptions in pressure extraction from DVCS

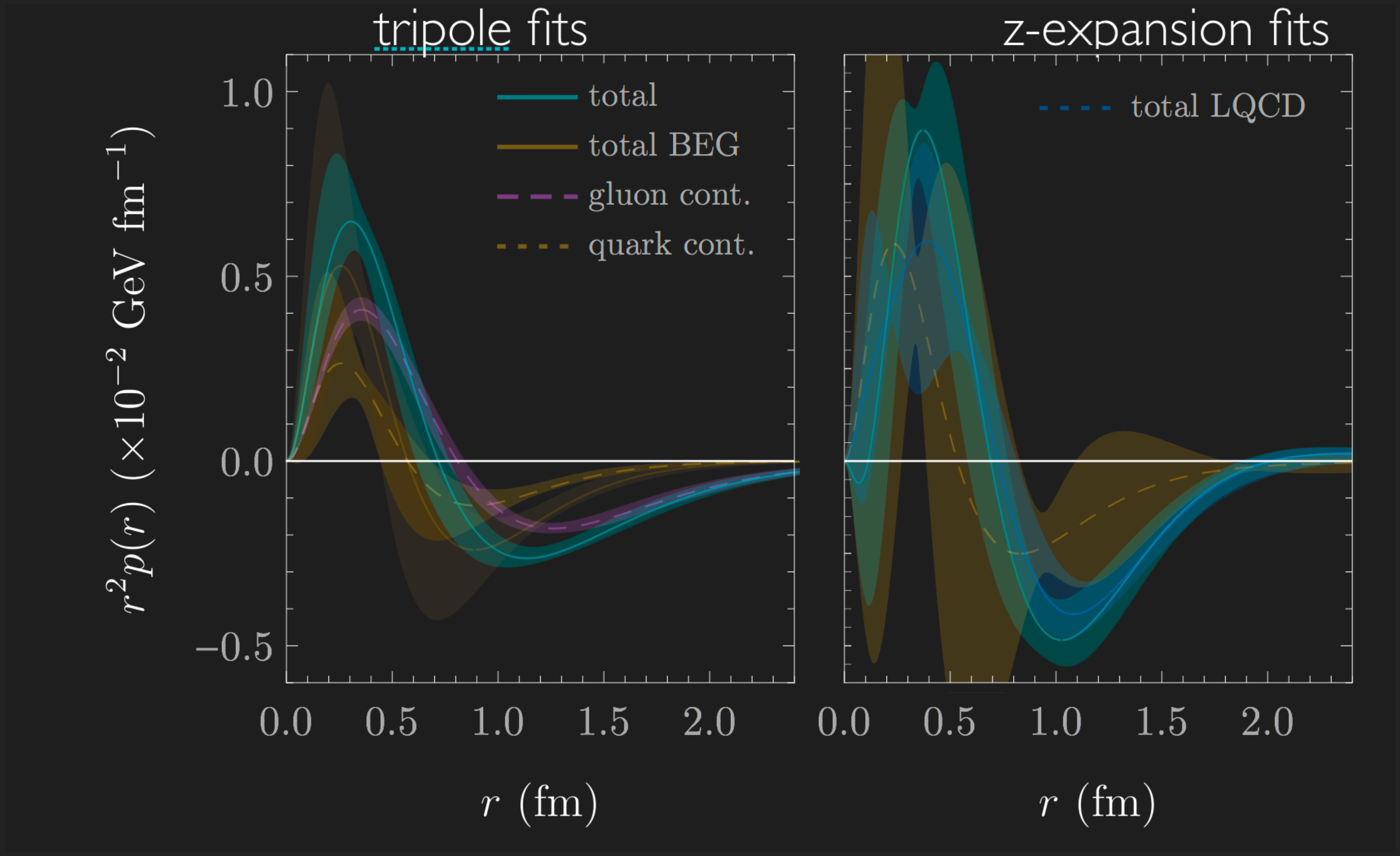
- Gluon D-term same as quark term in magnitude and shape
  - Factor of ~2 difference in magnitude, somewhat different t-dependence
- Tripole form factor model
  - LQCD results consistent with ansatz, but more general form is less well constrained
- Isovector quark D-term vanishes: $D_{u\text{-}d} \sim 0$ from other LQCD studies

LQCD PROTON PRESSURE



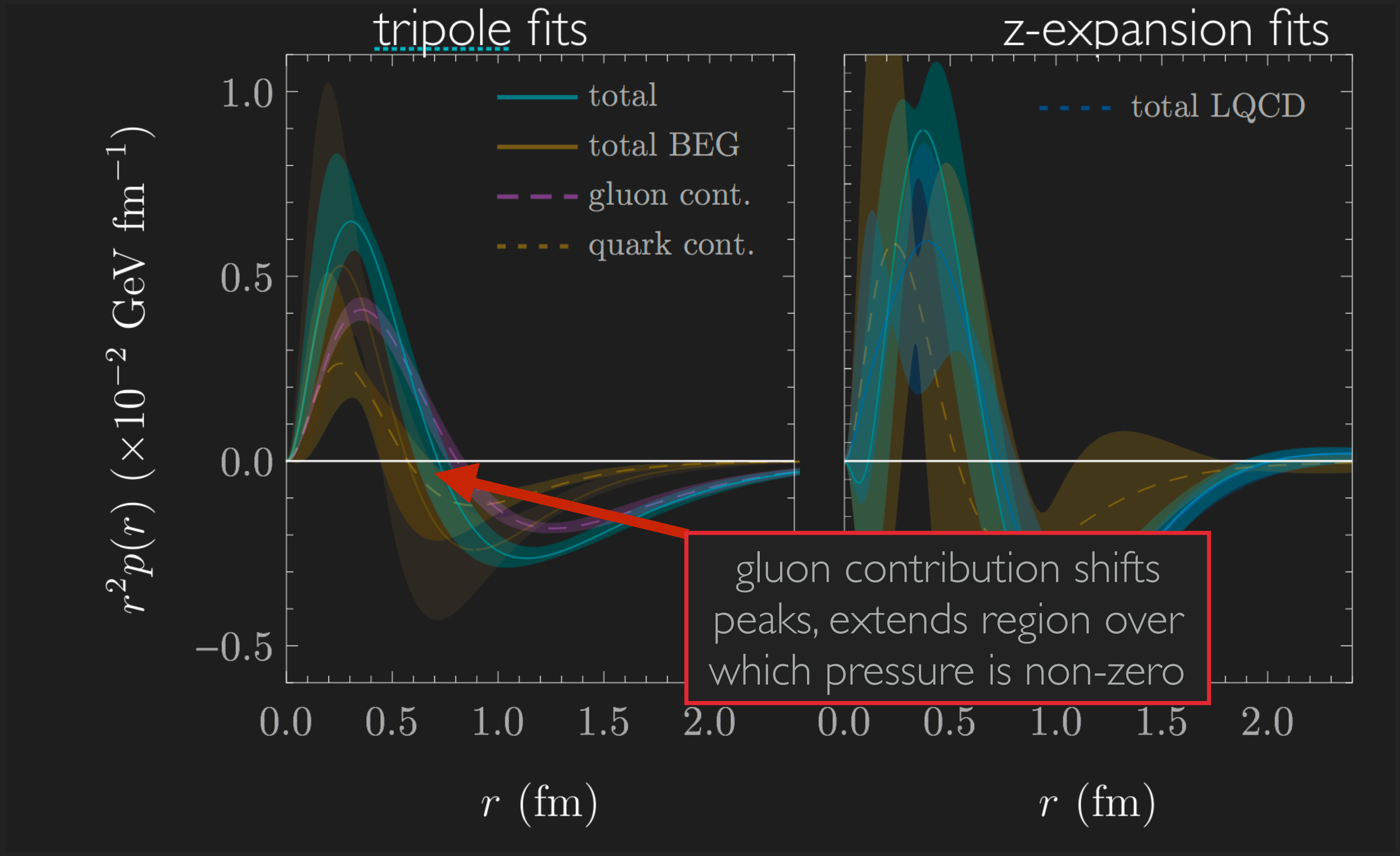
- Nucleon pressure using LQCD results for quark and gluon GFFs
  - Gluon GFFs: Shanahan, Detmold, 1810.04626,1810.07589
  - Quark GFFs: P. Hägler et al. (LHPC), PRD77, 094502 (2008)

LQCD+EXPT PROTON PRESSURE



- Nucleon pressure using LQCD results for gluon and JLab for quarkGFFs
  - Gluon GFFs: Shanahan, Detmold, 1810.04626,1810.07589
  - Quark GFFs: Burkert et al, Nature 557, 396 (2018)

LQCD+EXPT PROTON PRESSURE



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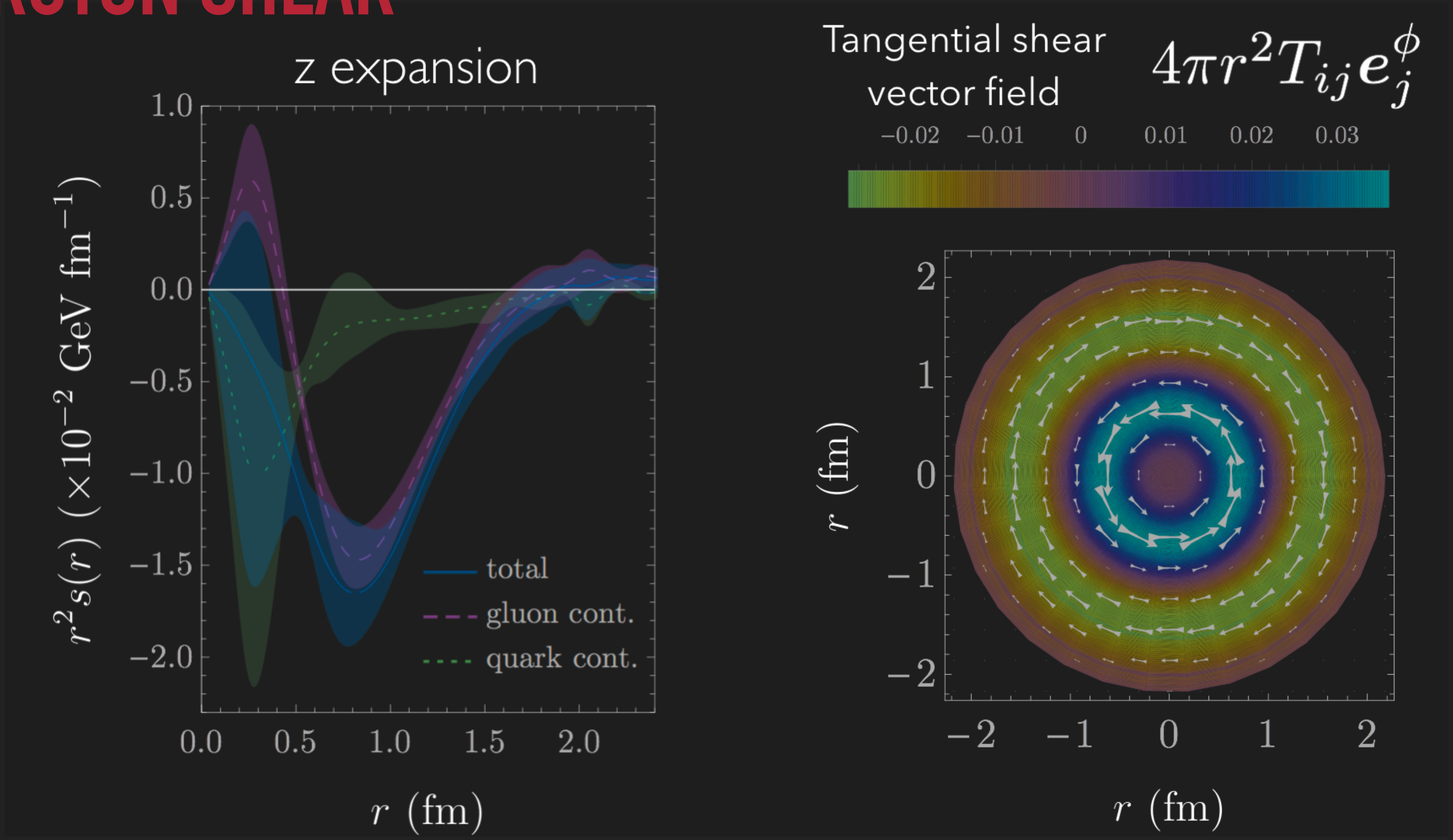
  - Quark GFFs: Burkert et al, Nature 557, 396 (2018)

LQCD PROTON SHEAR



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

LQCD EMT

- Complements recent experimental studies
  - Supports analysis assumptions
  - Suggest target kinematics for future model independent extractions at JLab12 and EIC
- First model independent determinations of Shear and Pressure distributions

PARTONIC PHYSICS

[See also : Monahan review talk at Lattice 2018]

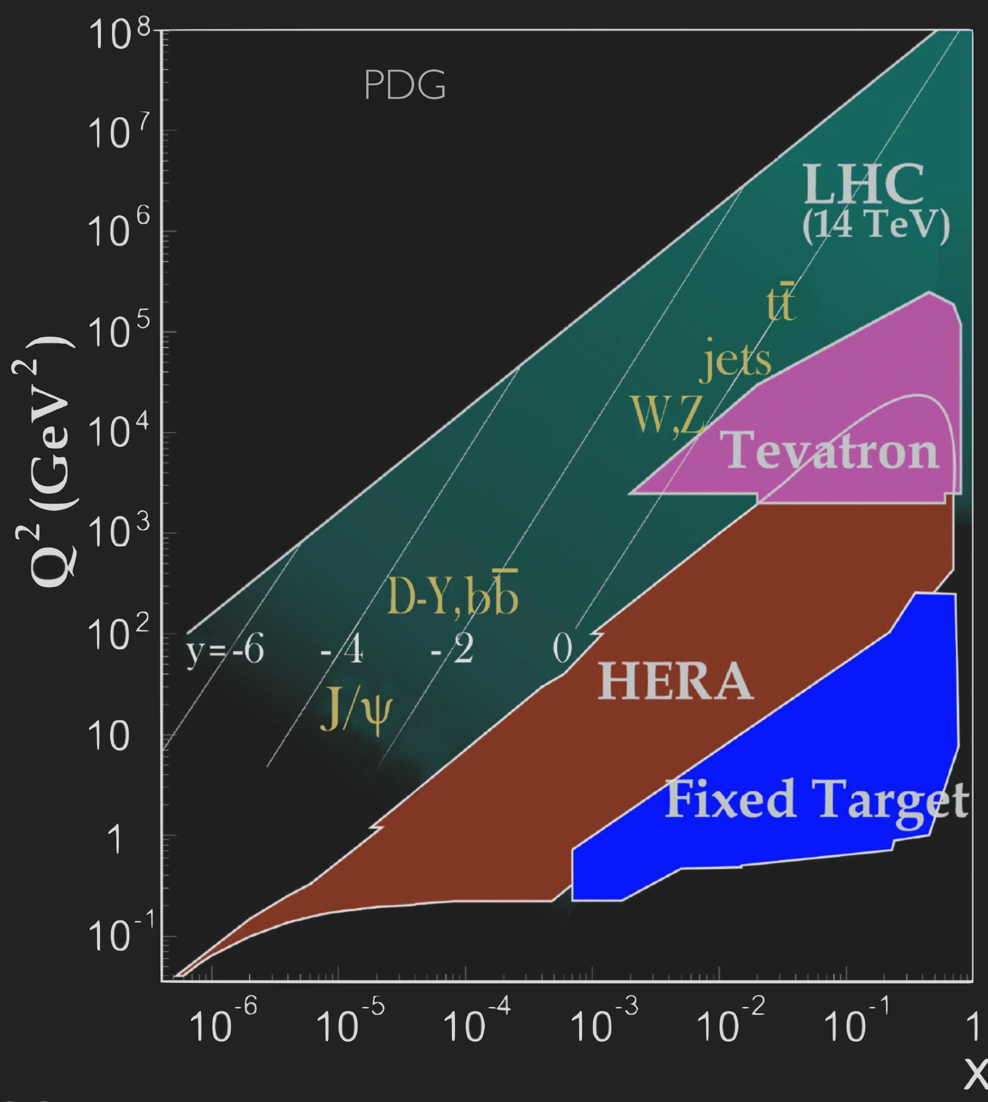
[image: © JLab]

PARTONIC PHYSICS

- Parton distributions: non-local light cone correlations:

$$q(x,\mu^2) = \int \frac{d\xi^-}{4\pi} \langle P|\overline{\psi}(\xi^-)\gamma^+ W(\xi^-,0)\psi(0)|P\rangle$$

- Nonperturbative objects
    - Parameterised from experiment
- Calculate in LQCD
    - Euclidean signature of LQCD calculations makes challenging
    - Light cone reduces to a point
    - Moments accessible using operator product expansion

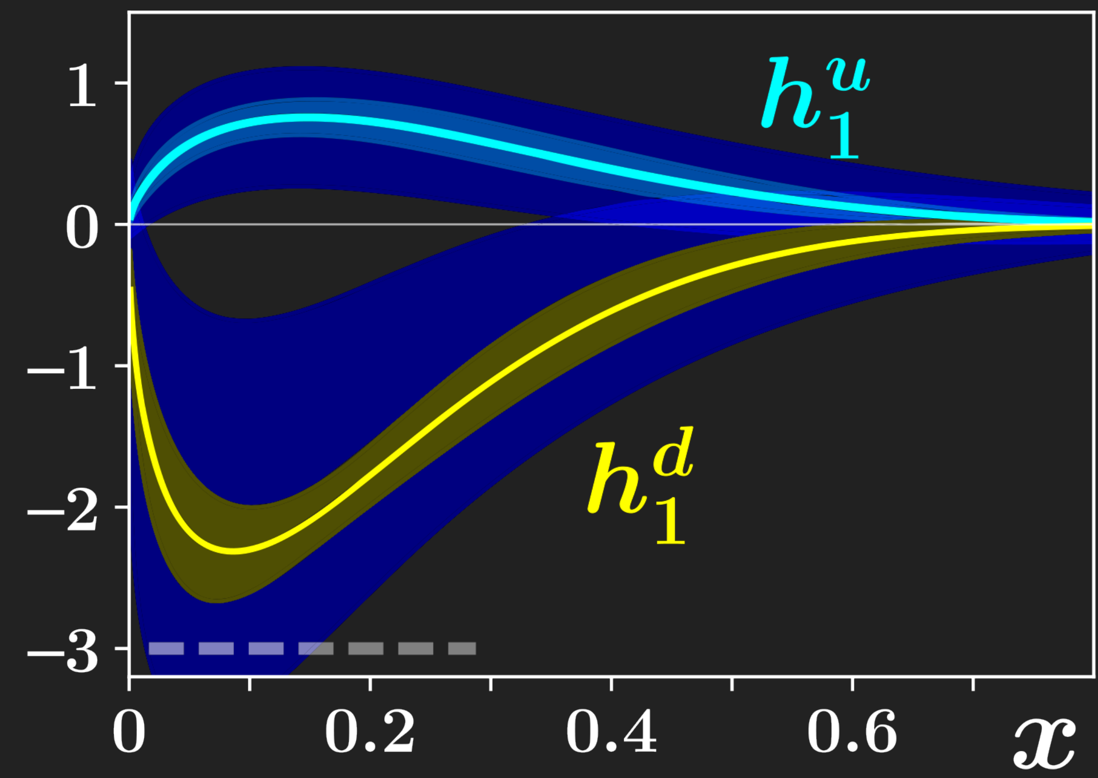


POTENTIAL IMPACT

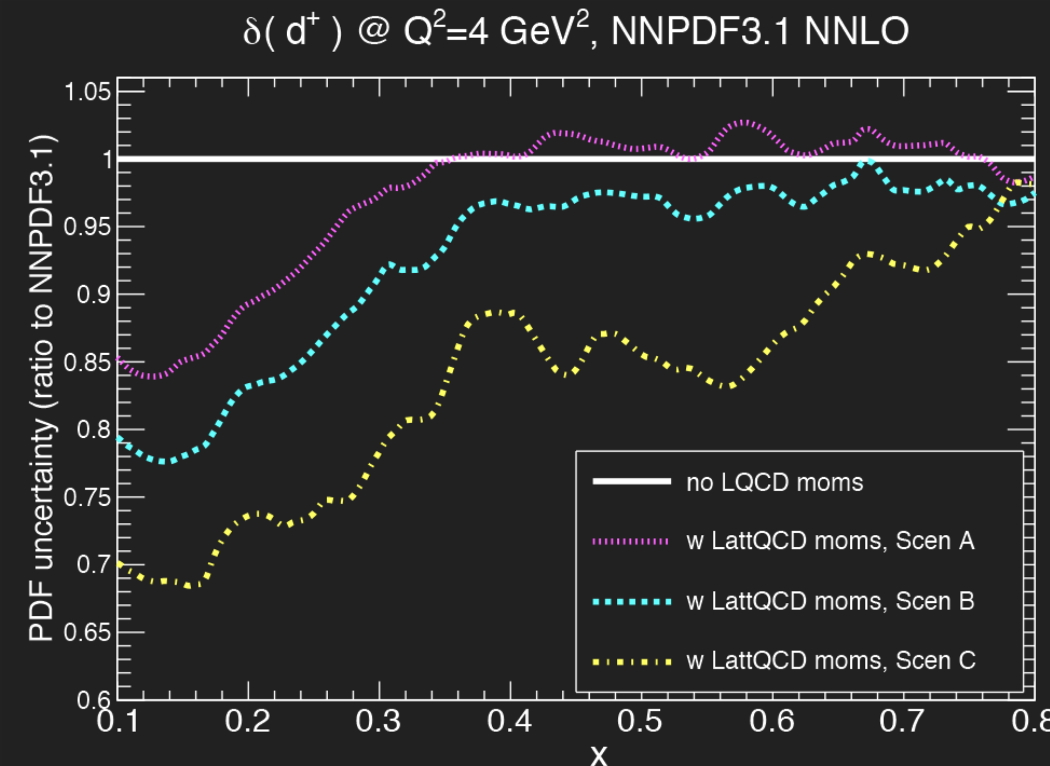
- Experiment is not uniformly constraining
  - Polarised/transversity distributions also less constrained
  - Large x less constrained
  - Flavour separation incomplete
- LQCD can contribute
- Community white paper (LQCD + PDF fitters) assessed potential impacts

  [Lin et al., Prog. Part. Nucl. Phys 100 (2018), 107]

  - Significant opportunities in EIC timeframe



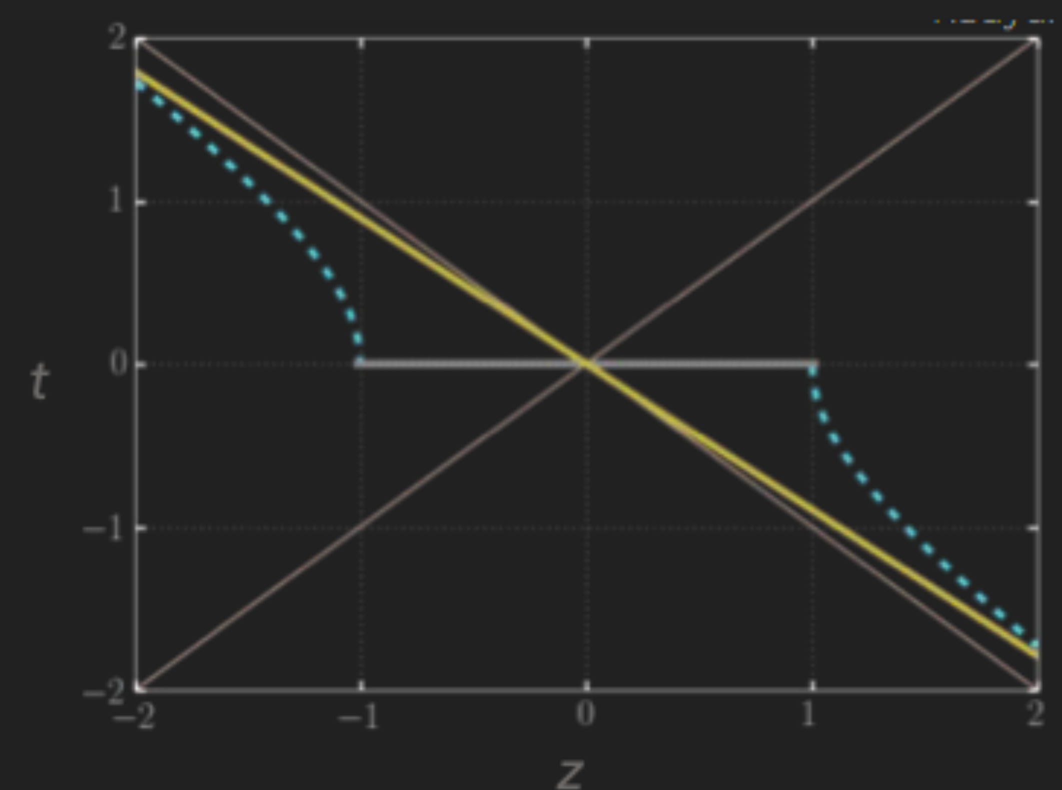
[Lin et al., PRL 120, 152502 (2018)]



[Lin et al., Prog. Part. Nucl. Phys 100 (2018), 107]

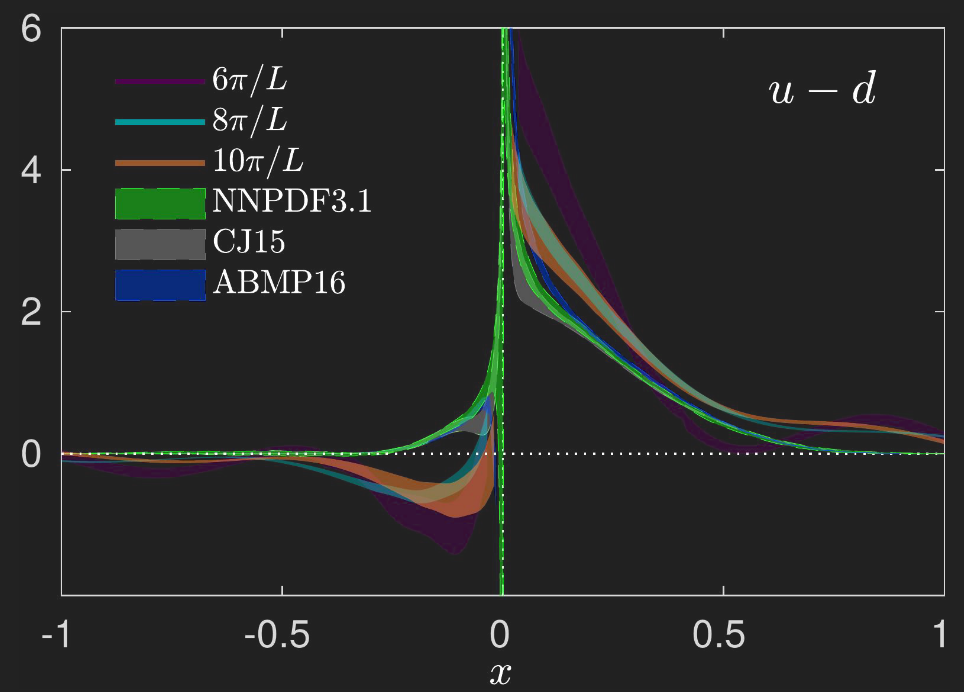
X-DEPENDENCE OF PDFS

- Even calculations of PDF moments limited by reduced lattice symmetry (n>3 hard)
- Extracting x-dependence/higher moments is an important goal
- Solutions relate spacelike non-local operator matrix elements to lightlike
  - Quasi-PDFs [Ji, PRL 110 (2013) 262002]
  - Pseudo-PDFs [Radyushkin, PRD 96 (2017) 034025]
  - Factorisable matrix elements [Ma & Qiu, PRL 120 (2018) 022003]
  - (Heavy quark) Compton tensor [Braun & Müller, EPJ C55 (2008) 349; Chambers et al., PRL 118 (2017) 242001 Detmold & Lin, PRD 73 (2006) 014501 Liu & Dong, PRL 72 (1994) 1790]

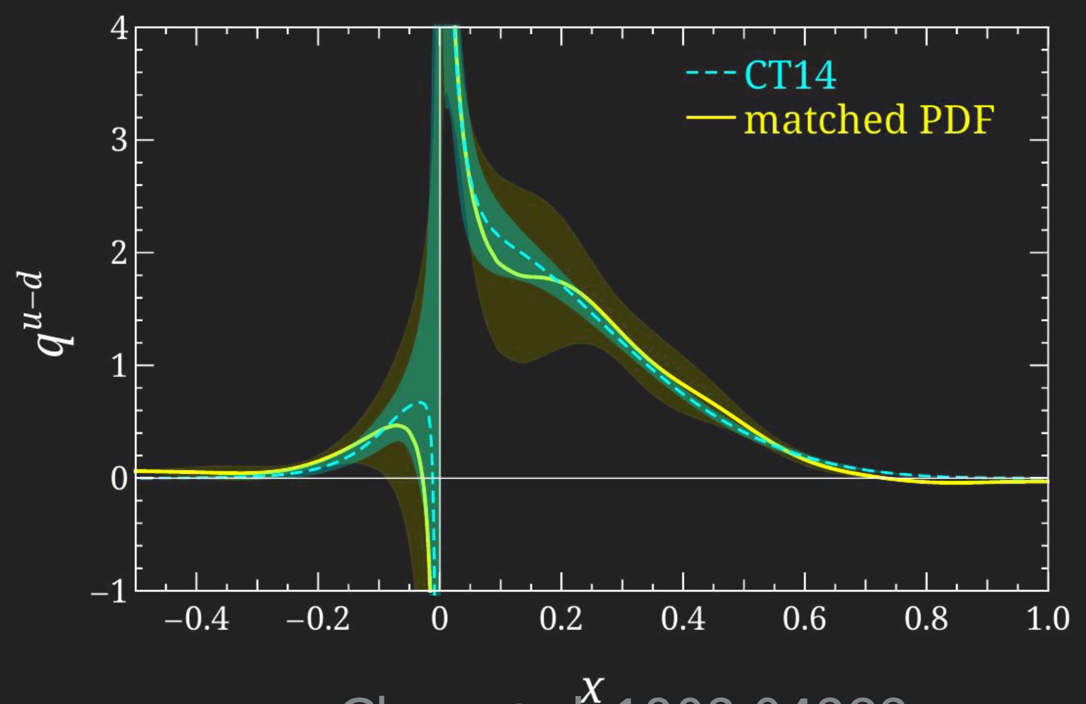


QUASI PDFS

- Much progress since initial calculations [Lin et al 2014]
- Renormalisation understood (mild controversies)
- Many systematics studied
- Physical quark masses



Alexandrou et al, 1803.02685



Chen et al, 1803.04393

- Other approaches similarly advancing

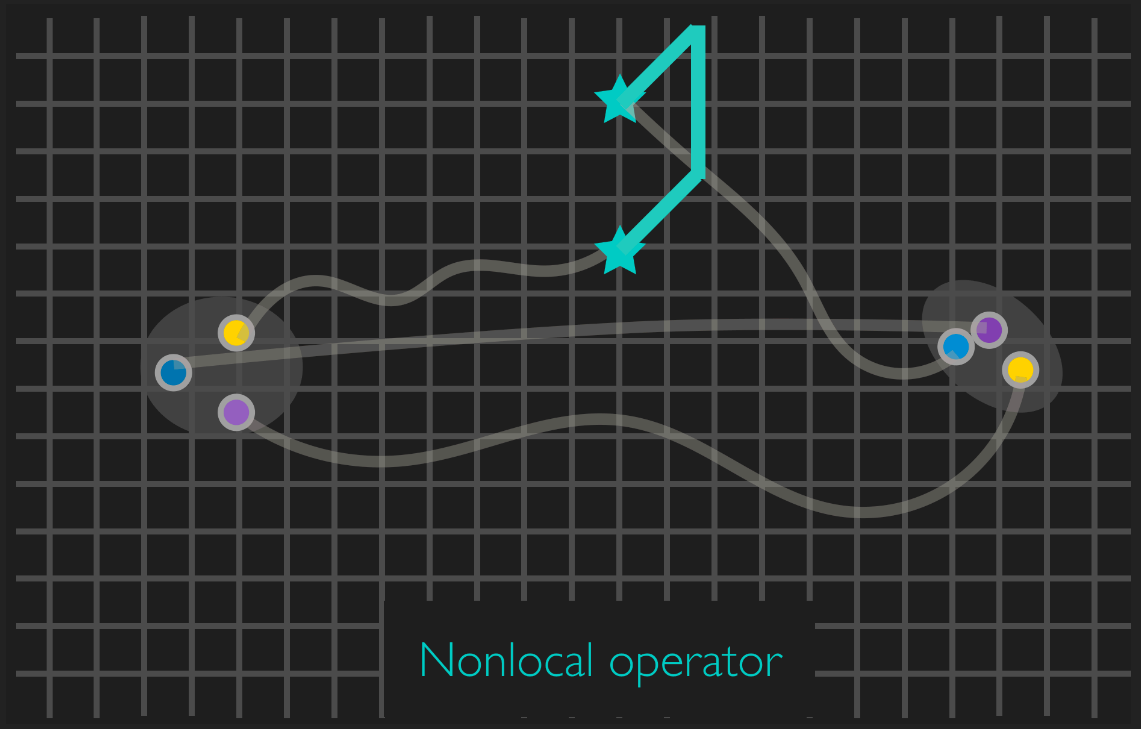
TMDS

- TMDs provide a more detailed picture of the nucleon
- Defined by matrix element of non-local quark bilinear operator

$$\widetilde{\Phi}^{[\Gamma]}_{\text{unsubtr.}}(b, P, S, \hat{\zeta}, \mu) \equiv \frac{1}{2}\langle P, S|\ \bar{q}(0)\ \Gamma\ \mathcal{U}[0, \eta v, \eta v + b, b]\ q(b)\ |P, S\rangle$$

- Lattice calculations: gauge links are taken in spatial direction
  - Use matrix elements to extract Lorentz invariant amplitudes
  - Extrapolate in kinematics to connect to phenomenology

$$\eta \to \infty \qquad \hat{\zeta} = \frac{P \cdot v}{|P||v|} \to \infty$$



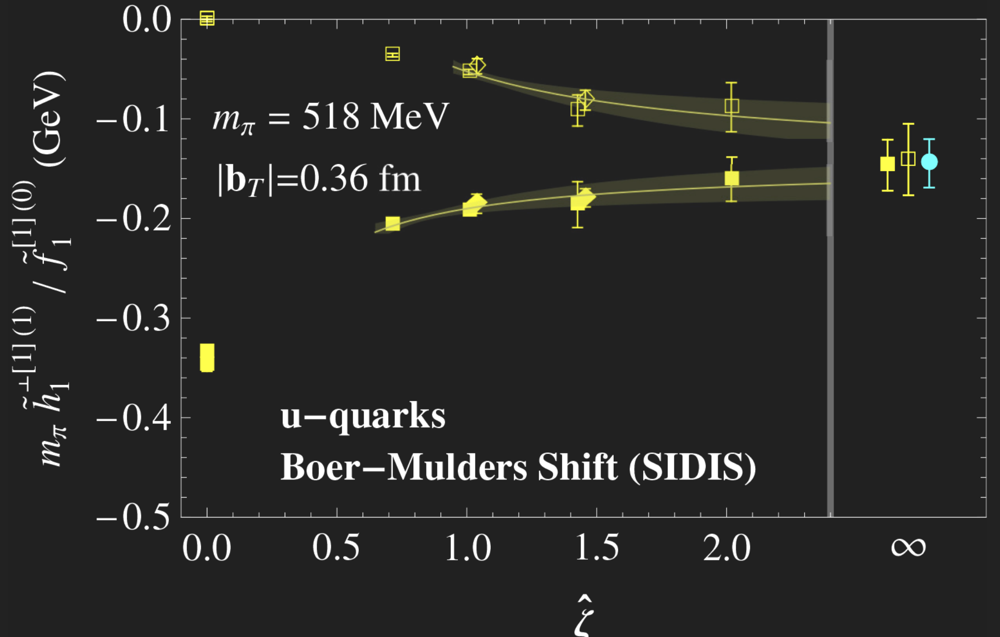
[Musch, Engelhardt, Hägler, Negele, Schäfer 2010—present]

TMDS

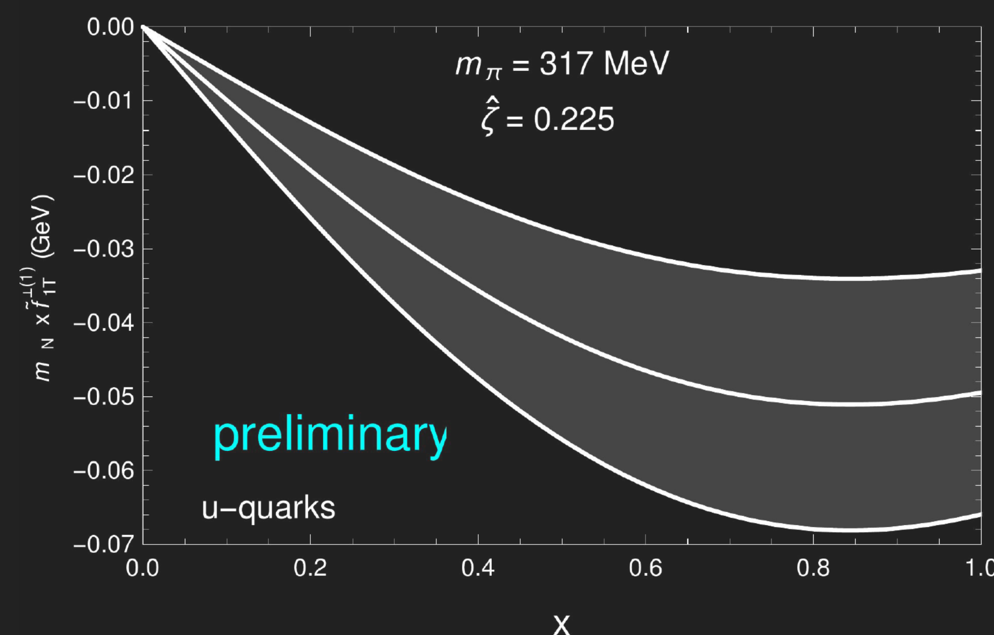
- Most robust results for ratios because of renormalisation ambiguities and soft factors
- Ex: Boer-Mulders shift

$$\left.\frac{\int dx \int d^2k_T\, k_y \Phi^{[\gamma^+ + s^j i\sigma^{j+}\gamma^5]}(x, k_T, P, \ldots)}{\int dx \int d^2k_T\, \Phi^{[\gamma^+ + s^j i\sigma^{j+}\gamma^5]}(x, k_T, P, \ldots)}\right|_{s_T=(1,0)}$$

  - Preliminary results available
- Used to access orbital angular momentum
- Now tackling x- dependence of TMDs



Phys.Rev. D93 (2016) no.5, 054501



Engelhardt Lattice 2018

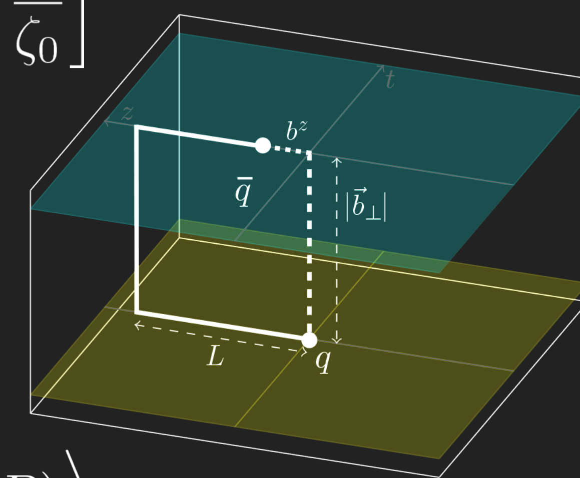
CS EVOLUTION KERNEL

- Collins-Soper evolution kernel governs b_T-dependent evolution

$$f_q^{\mathrm{TMD}}(x,\vec{b}_T,\mu,\zeta_a) = \lim_{\eta\to 0} Z_{\mathrm{uv}}(\mu,\zeta_a,\epsilon)\frac{B_{q/n}(x,\vec{b}_T,\epsilon,\eta,\zeta_a)}{S^{q,0}_{n\bar{n}}(\vec{b}_T,\epsilon,\eta)}\sqrt{S^q_{n\bar{n}}(\vec{b}_T,\epsilon,\eta)}$$

$$f_i^{\mathrm{TMD}}(x,\vec{b}_T,\mu,\zeta) = f_i^{\mathrm{TMD}}(x,\vec{b}_T,\mu_0,\zeta_0)\times\exp\left[\int_{\mu_0}^{\mu}\frac{\mathrm{d}\mu'}{\mu'}\gamma^i_\mu(\mu',\zeta_0)\right]\exp\left[\frac{1}{2}\gamma^i_\zeta(\mu,b_T)\ln\frac{\zeta}{\zeta_0}\right]$$

  - Non-perturbative anomalous dimension



- Construct Quasi-beam functions

$$\tilde{B}_{q/\hat{z}}(b^z,\vec{b}_T;a,L,P^z) = \left\langle p(P)\middle|\bar{q}(b^\mu)W_{\hat{z}}(b^\mu;L)\frac{\Gamma}{2}W_T(-L\hat{z};\vec{b}_T,\vec{0}_T)W^\dagger_{\hat{z}}(0;L)q(0)\middle|p(P)\right\rangle$$

- Ratio at different large hadron momenta accesses CS kernel and calculable in LQCD

$$\gamma^q_\zeta(\mu,b_T) = \frac{1}{\ln(P_1^z/P_2^z)}\ln\frac{C^{\mathrm{TMD}}_{\mathrm{ns}}(\mu,xP_2^z)\int\mathrm{d}b^z\,e^{ib^z xP_1^z}\tilde{Z}'(b^z,\mu,\tilde{\mu})\tilde{Z}_{\mathrm{uv}}(b^z,\tilde{\mu},a)\tilde{B}_{\mathrm{ns}/\hat{z}}(b^z,\vec{b}_T,a,L,P_1^z)}{C^{\mathrm{TMD}}_{\mathrm{ns}}(\mu,xP_1^z)\int\mathrm{d}b^z\,e^{ib^z xP_2^z}\tilde{Z}'(b^z,\mu,\tilde{\mu})\tilde{Z}_{\mathrm{uv}}(b^z,\tilde{\mu},a)\tilde{B}_{\mathrm{ns}/\hat{z}}(b^z,\vec{b}_T,a,L,P_2^z)}$$

Wilson coeffs — Renorm factors — Quasi-beam functions

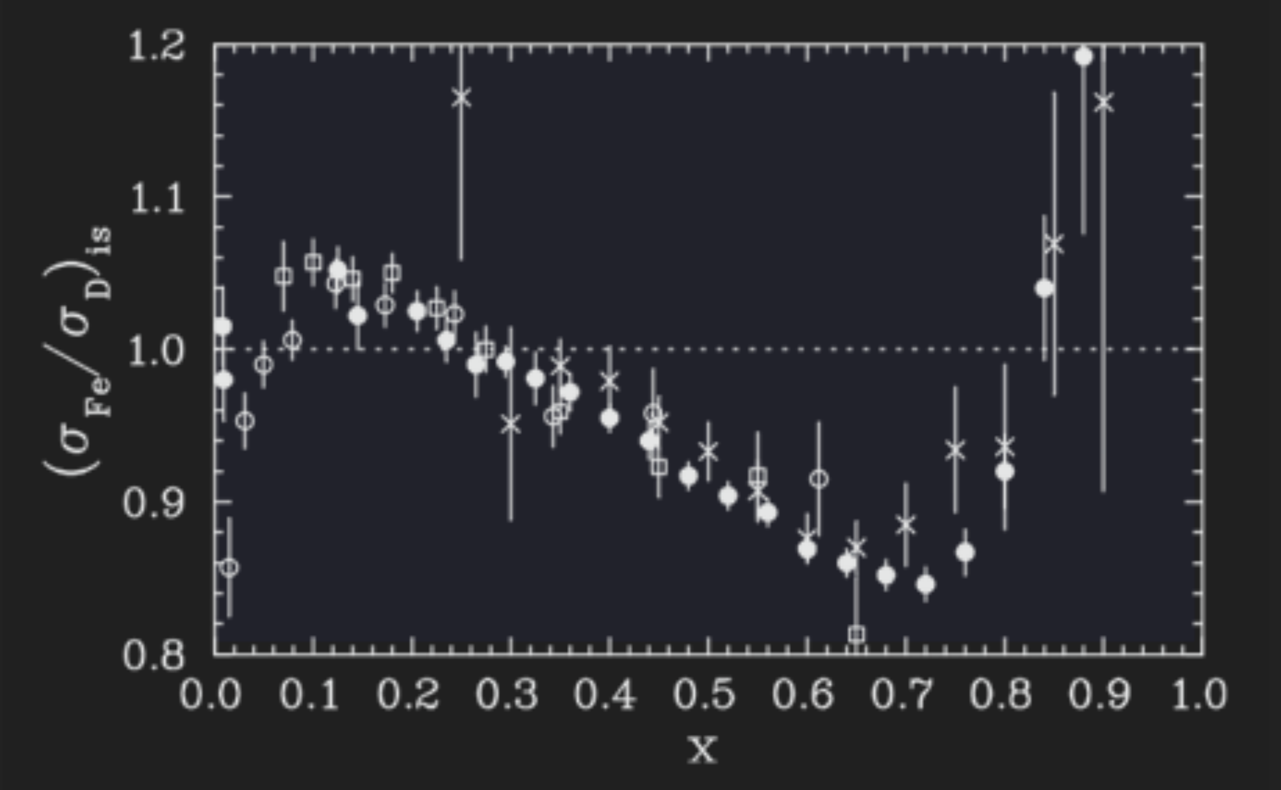
Ebert, Stewart, Zhao 1811.00026

NUCLEI

[image: © JLab]

NUCLEAR STRUCTURE @ EIC

- How does nucleon structure change in a nucleus?
  - EMC effect: Modification of per-nucleon DIS cross section of nucleons bound in nuclei [EMC 1983]
- Many EMC effects accessible at EIC
  - Polarised EMC (polarised light ions)
  - Isovector EMC (SIDIS)
  - Gluon EMC (quarkonium production)
- LQCD will make predictions!



NUCLEI IN LQCD

- Case study LQCD with unphysical quark masses (m_π~800 MeV, 450 MeV)

1. Spectrum and scattering of light nuclei (A<5) [PRD 87 (2013), 034506]
2. Nuclear structure: magnetic moments, polarisabilities (A<5) [PRL **113**, 252001 (2014), PRL **116**, 112301 (2016)]
3. Nuclear reactions: np→dγ [PRL **115**, 132001 (2015)]
4. Gamow-Teller transitions: pp→deν, $g_A(^3H)$ [PRL **119** 062002 (2017)]
5. Double β decay: pp→nn [PRL **119**, 062003 (2017)]
6. Gluon structure (A<4) [PRD **96** 094512 (2017)]
7. Scalar/tensor currents (A<4) [PRL **120** 152002 (2018)]

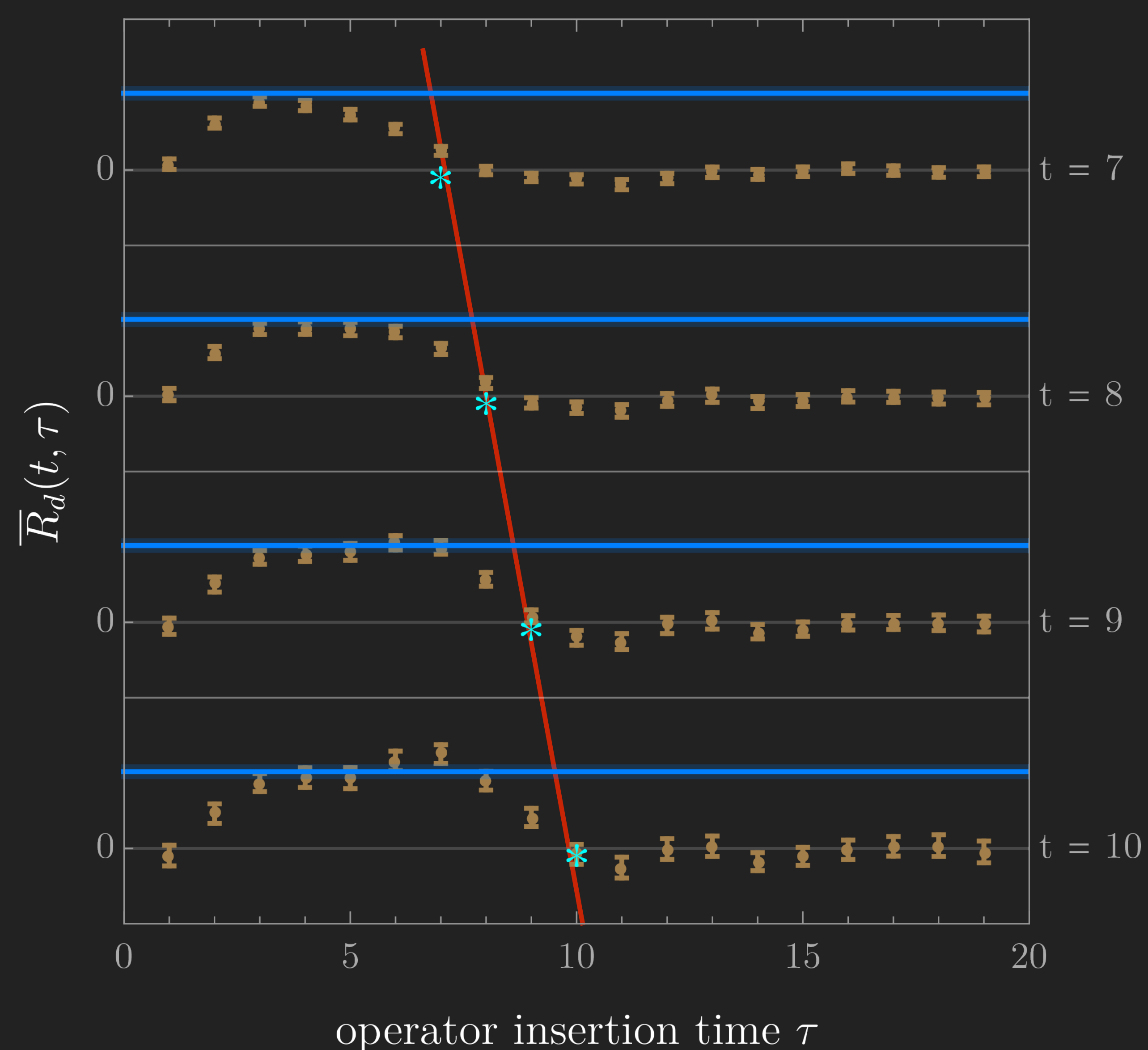
+ Arjun Gambhir + David Murphy

GLUON MOMENTUM FRACTION

NPLQCD

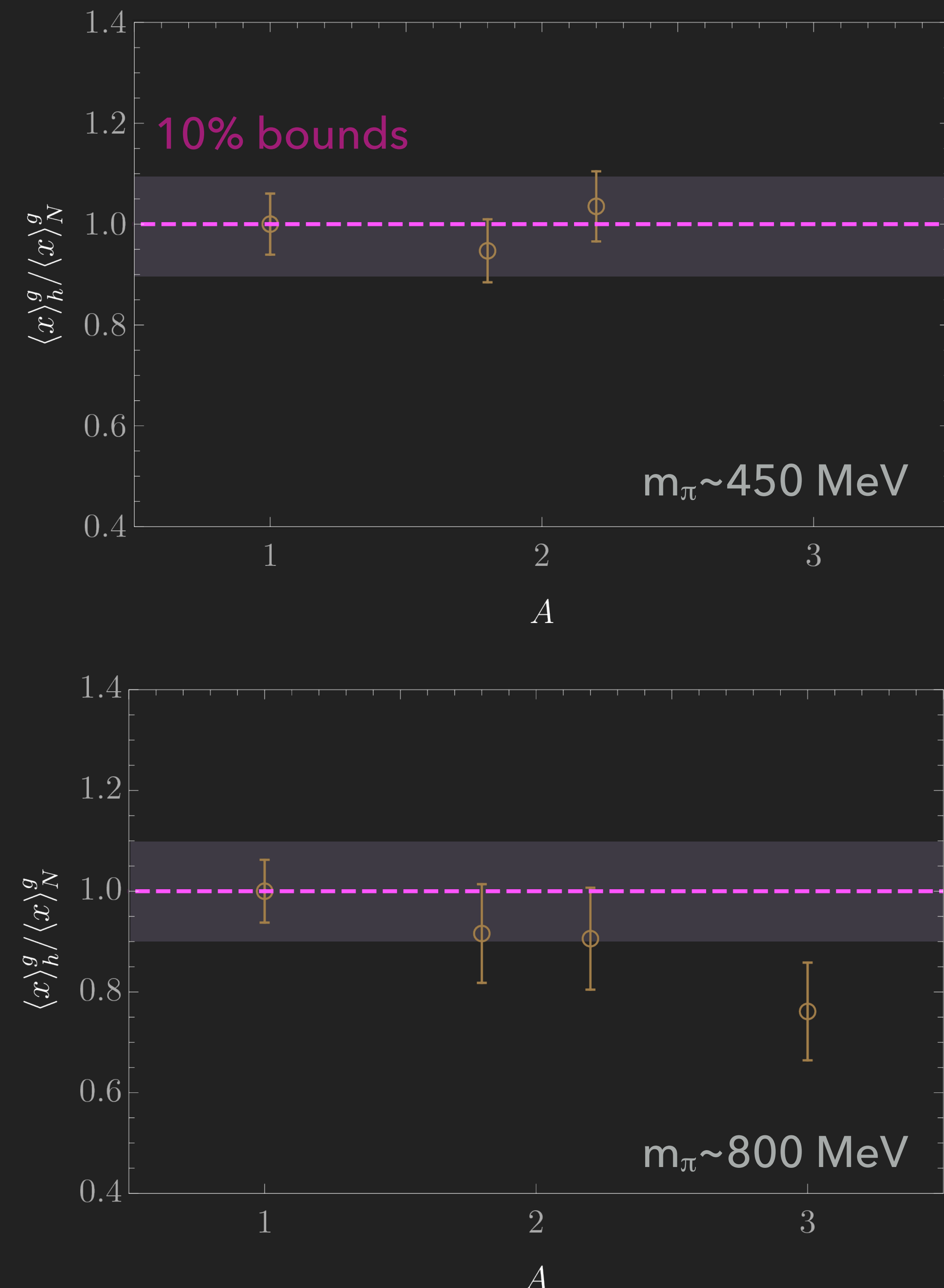
- First attempt: Look for nuclear effects in the first moments of the spin-independent gluon structure function
  [NPLQCD Collaboration PRD96 094512 (2017)]
- Doubly challenging
  - Nuclear matrix element
  - Gluon observable (suffer from poor signal-to-noise)
- Study for A=2,3 systems at heavy quark masses

Deuteron: ratio matrix element for 0<<τ<<t



GLUON MOMENTUM FRACTION

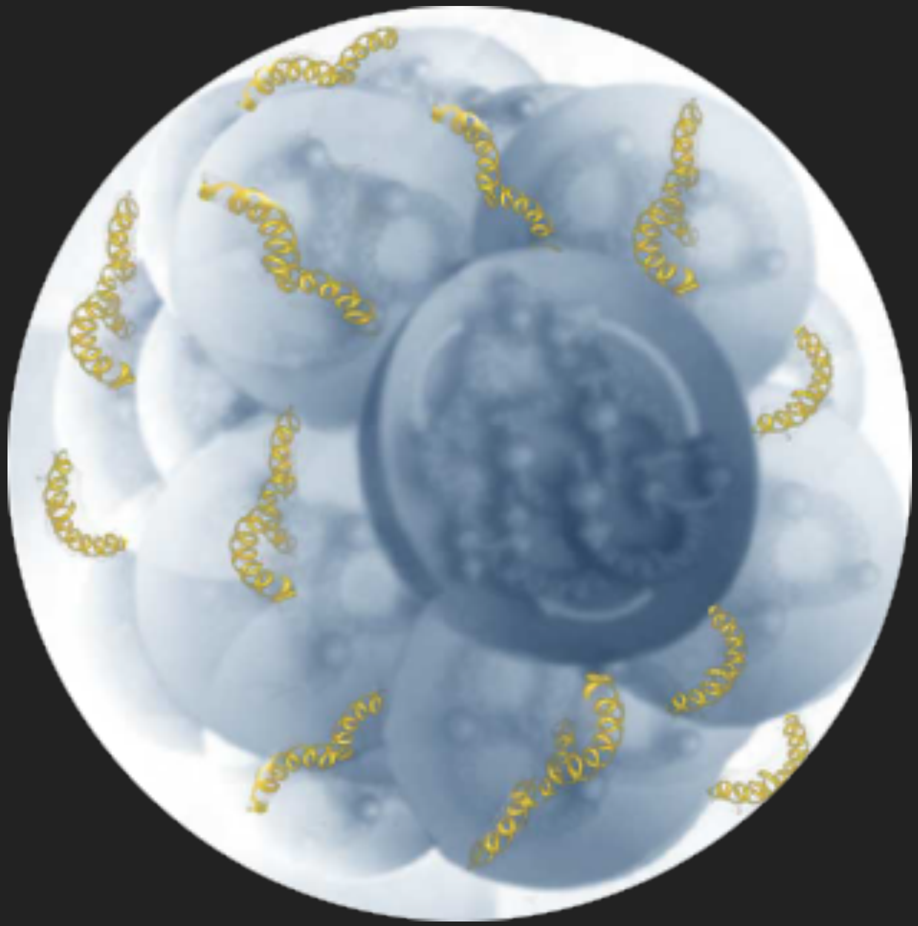
- Spin-independent gluon operator in nucleon and light nuclei
  - Ratios of matrix elements
- Present statistics: can't distinguish from no-EMC effect scenario
- Small additional uncertainty from mixing with quark operators



[NPLQCD Collaboration PRD96 094512 (2017)]

EXOTIC GLUE

- Contributions to nuclear structure from gluons not associated with individual nucleons in nucleus
- Exotic glue operator:
  - Nucleon: $\langle p|\mathcal{O}|p\rangle = 0$
  - Nuclear: $\langle A, Z|\mathcal{O}|A, Z\rangle \neq 0$
- Example is gluon transversity



GLUON TRANSVERSITY

- Double helicity flip distribution Δ(x,Q²)
  [Jaffe & Manohar, "Nuclear Gluonometry" PLB223 (1989) 218]

- Hadrons: gluonic transversity (parton model interpretation)

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

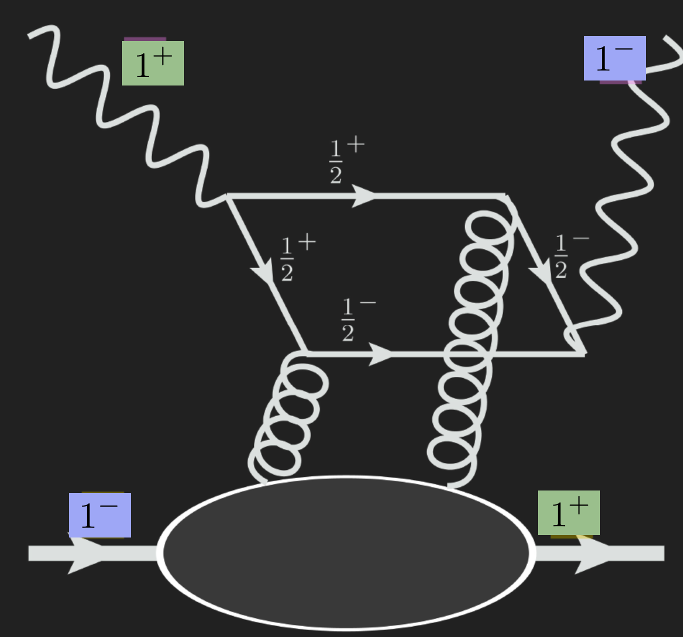
$g_{\hat{x},\hat{y}}(x,Q^2)$: probability of finding a gluon with momentum fraction *x* linearly polarised in *x,y* directions in a target polarised in *x* direction

- Unambiguously gluonic: no analogous quark PDF at twist-2

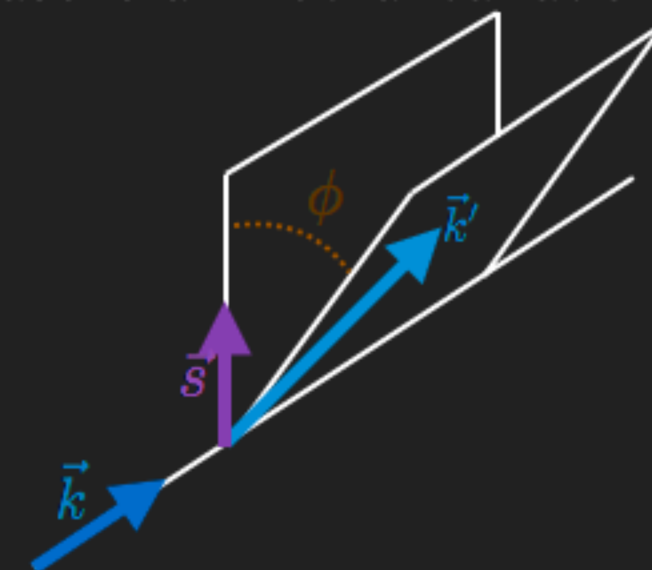
GLUON TRANSVERSITY

- Double helicity flip: non-vanishing in forward limit for targets with spin≥1 (nuclei)
  - The ultimate EMC effect
- Experimentally measurable in unpolarised electron DIS on polarised target
  - Nitrogen target: JLab LoI 2015 (James Maxwell)
  - Polarised nuclei at EIC

$$\Delta(x, Q^2) = A_{+-,-+}$$



Measure azimuthal variation

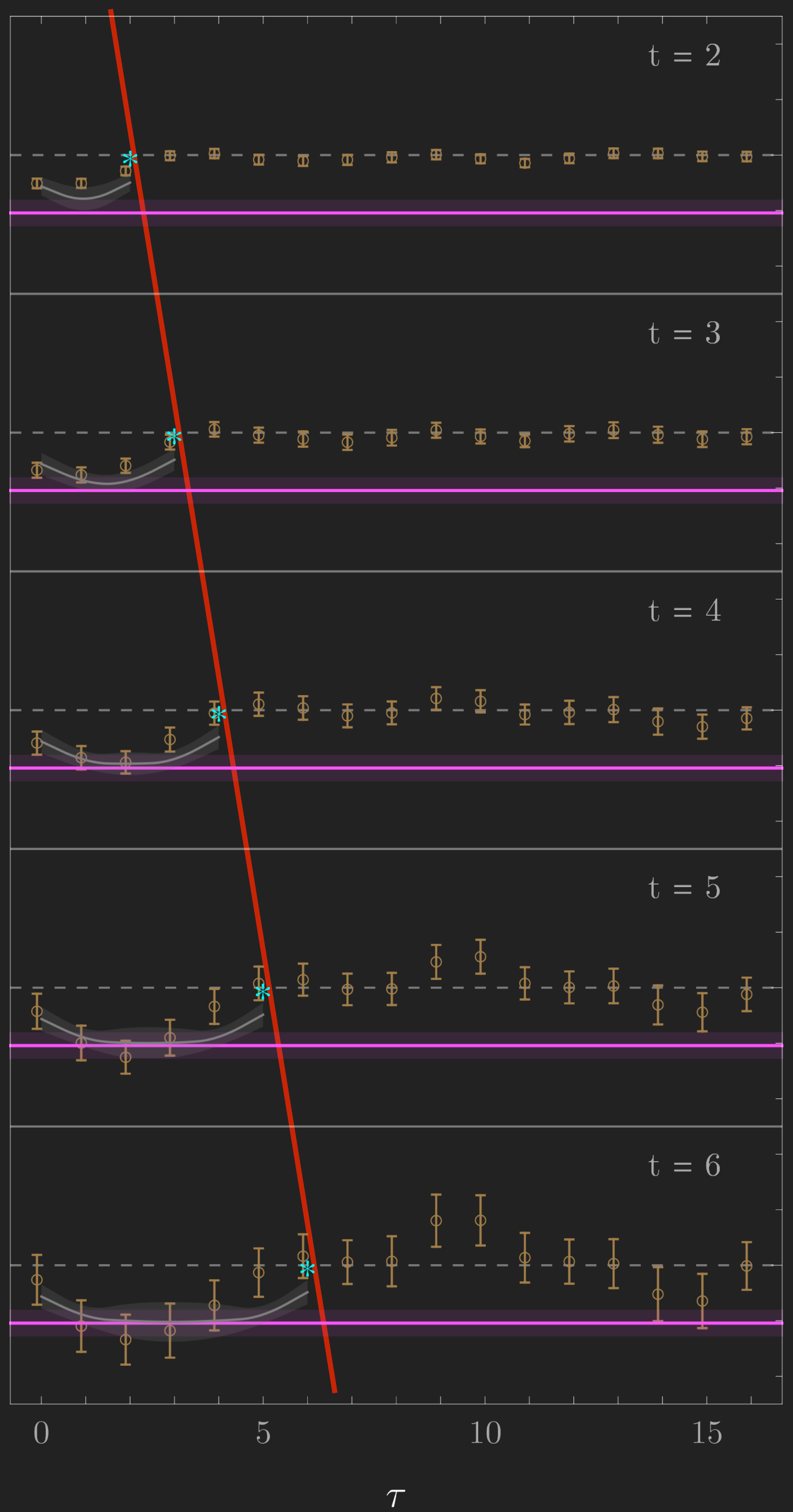


$$\lim_{Q^2\to\infty} \frac{d\sigma}{dx\,dy\,d\phi} = \frac{e^4 M E}{4\pi^2 Q^4}\left[x y^2 F_1(x,Q^2) + (1-y) F_2(x,Q^2) - \frac{x(1-y)}{2}\Delta(x,Q^2)\cos 2\phi \right]$$

GLUON TRANSVERSITY

- First moment of gluon transversity distribution in the deuteron, m_π~800 MeV
- First evidence for non-nucleonic gluon contributions to nuclear structure
- Clear signal but not sufficient systematic control to determine moment
- Magnitude relative to momentum fraction as expected from large-N_c

Ratio of 3pt and 2pt functions



[NPLQCD Collaboration PRD96 094512 (2017)]

LQCD WILL PROVIDE VITAL INPUT TO EIC PLANNING AND PROGRAM

1. The glue that binds us all
   - LQCD: mass, momentum, spin, pressure
2. (3D) proton tomography
   - LQCD: x-dependence of PDFs; TMDs
3. Structure of light nuclei
   - LQCD: EMC effects, exotic gluons

THEORY COMPLEMENTS EXPERIMENT