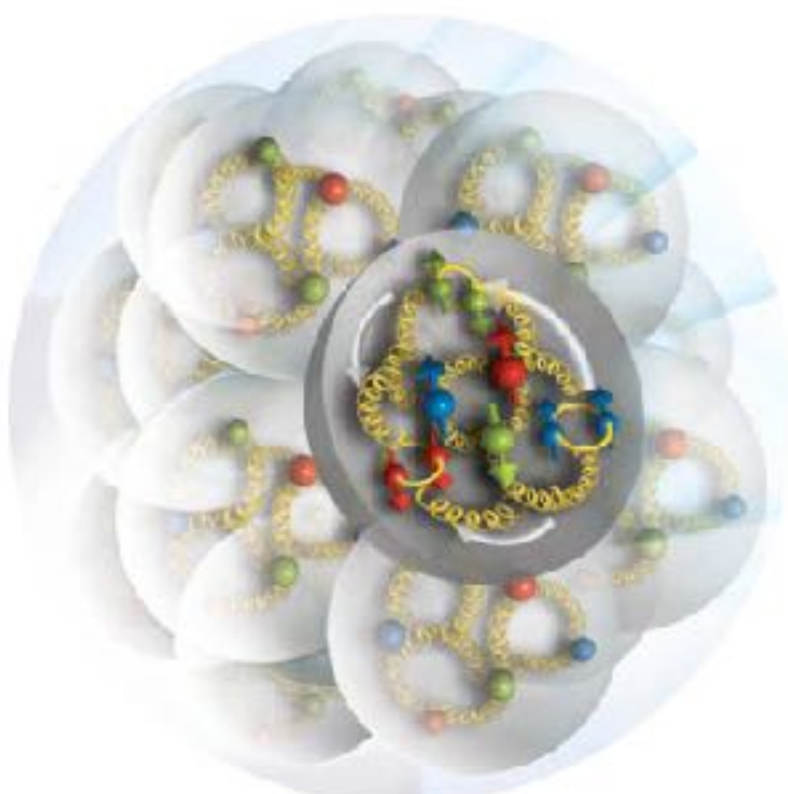
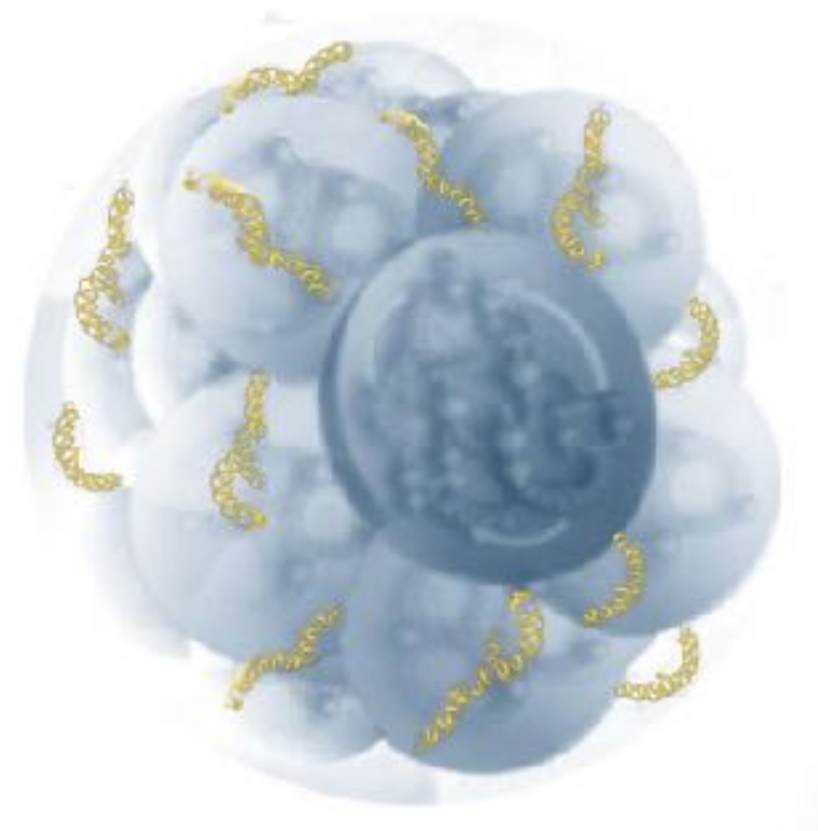
Gluon Structure of Hadrons and Nuclei





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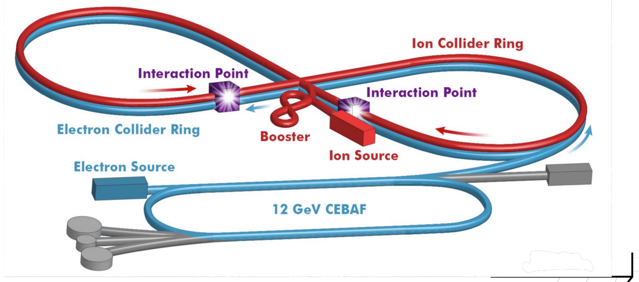
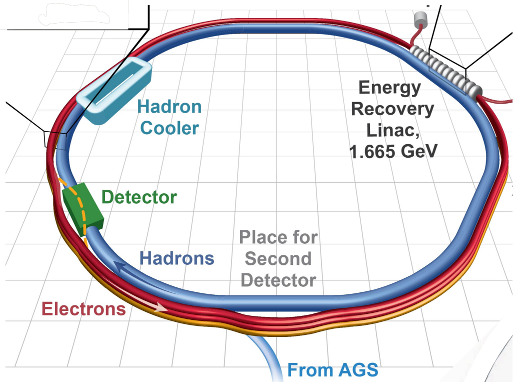
Gluon Structure

- Past 60+ years: detailed view of quark structure of nucleons
- Gluonic structure (beyond gluon density) relatively unexplored
- **Gluon Structure of N* spectrum**
  - Better understand and classify N* resonances
  - Identify gluonic excitations
- Electron-Ion Collider
  - Priority in 2015 nuclear physics long range plan
  - "Understanding the glue that binds us all"
- Insights from Lattice QCD?

Cover image from EIC whitepaper arXiv::1212.1701





Gluonic Structure

Studying gluonic structure of hadrons/nuclei is hard

- Gluon probed only indirectly in electron scattering from hadrons/nuclei (does not couple to photon)

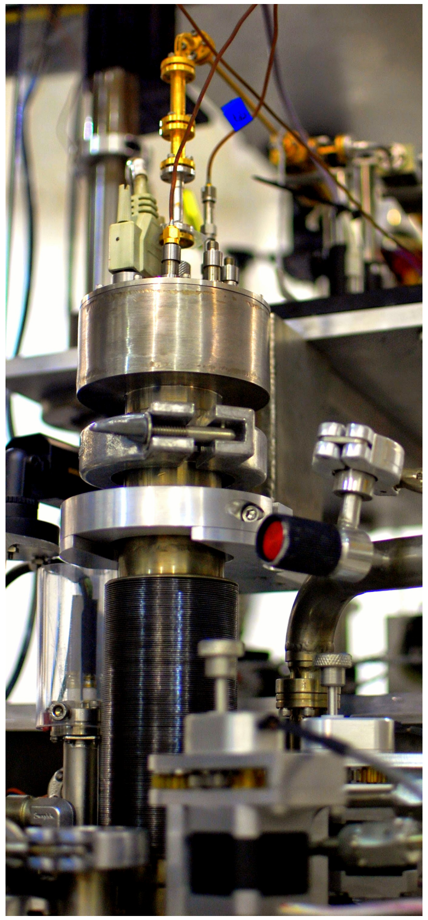
- Other processes less clean: heavy flavour production

- Quarks and gluons mix via evolution
  - **Uniquely quarky:** nonsinglet quantities
  - **Uniquely gluonic:** double helicity flip/ gluonic transversity

Gluonic Transversity

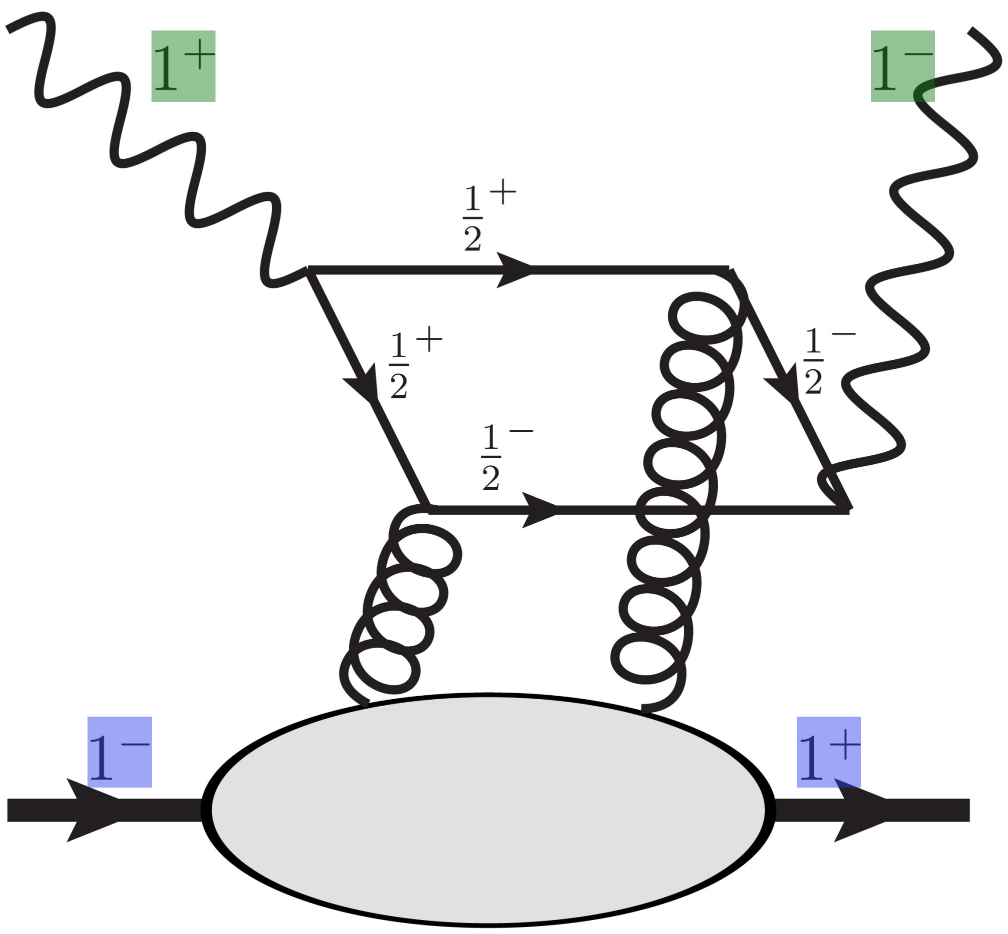
Leading twist gluon parton distribution $\Delta(x,Q^2)$:
double helicity flip [Jaffe & Manohar 1989]

- **Unambiguously gluonic:** no analogous quark PDF at twist-2
- Non-vanishing in forward limit for targets with spin ≥ 1
- **Experimentally measurable** in unpolarised electron DIS on polarised target
  - Nitrogen target: JLab LoI 2015
  - Polarised nuclei at EIC
- **Moments calculable in LQCD**



Gluonic Transversity

Double helicity flip structure function $\Delta(x,Q^2)$



Changes both photon and target helicity by 2 units

Gluonic Transversity

Double helicity flip structure function Δ(x,Q²)

- **Hadrons:** Gluonic Transversity (parton model interpretation)

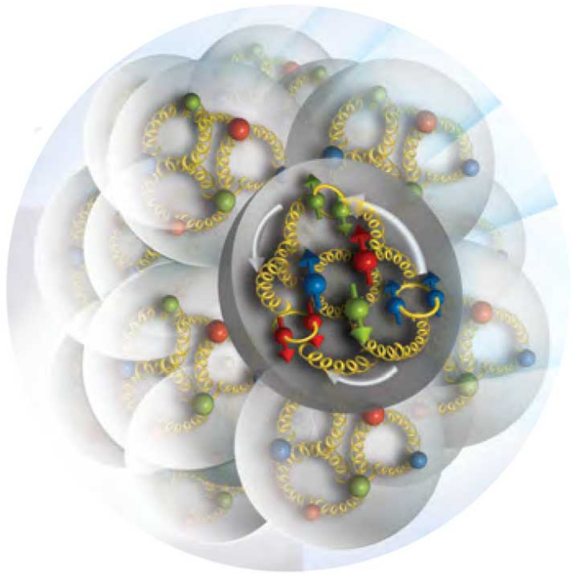
$$\Delta(x,Q^2) = -\frac{\alpha_s(Q^2)}{2\pi}\mathrm{Tr}\mathcal{Q}^2\, x^2 \int_x^1 \frac{dy}{y^3}\left[g_{\hat{x}}(y,Q^2) - g_{\hat{y}}(x,Q^2)\right]$$

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

- **Nuclei:** Exotic Glue

gluons not associated with individual nucleons in nucleus

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



Gluonic Transversity

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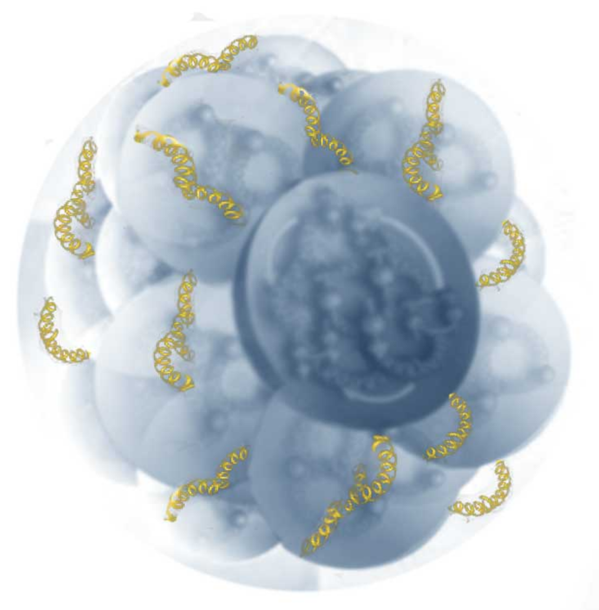


Gluonic Transversity

Moments of $\Delta(x,Q^2)$ are calculable in LQCD

Moment of Structure Function — Reduced Matrix Element

$$\int_0^1 dx x^{n-1}\Delta(x,Q^2) = \frac{\alpha_s(Q^2)}{3\pi}\frac{A_n(Q^2)}{n+2}, \qquad n = 2,4,6\ldots,$$

Determined by matrix elements of local gluonic operators

$$\langle pE'|\underline{S}\left[G_{\mu\mu_1}\overleftrightarrow{D}_{\mu_3}\ldots\overleftrightarrow{D}_{\mu_n}G_{\nu\mu_2}\right]|pE\rangle$$

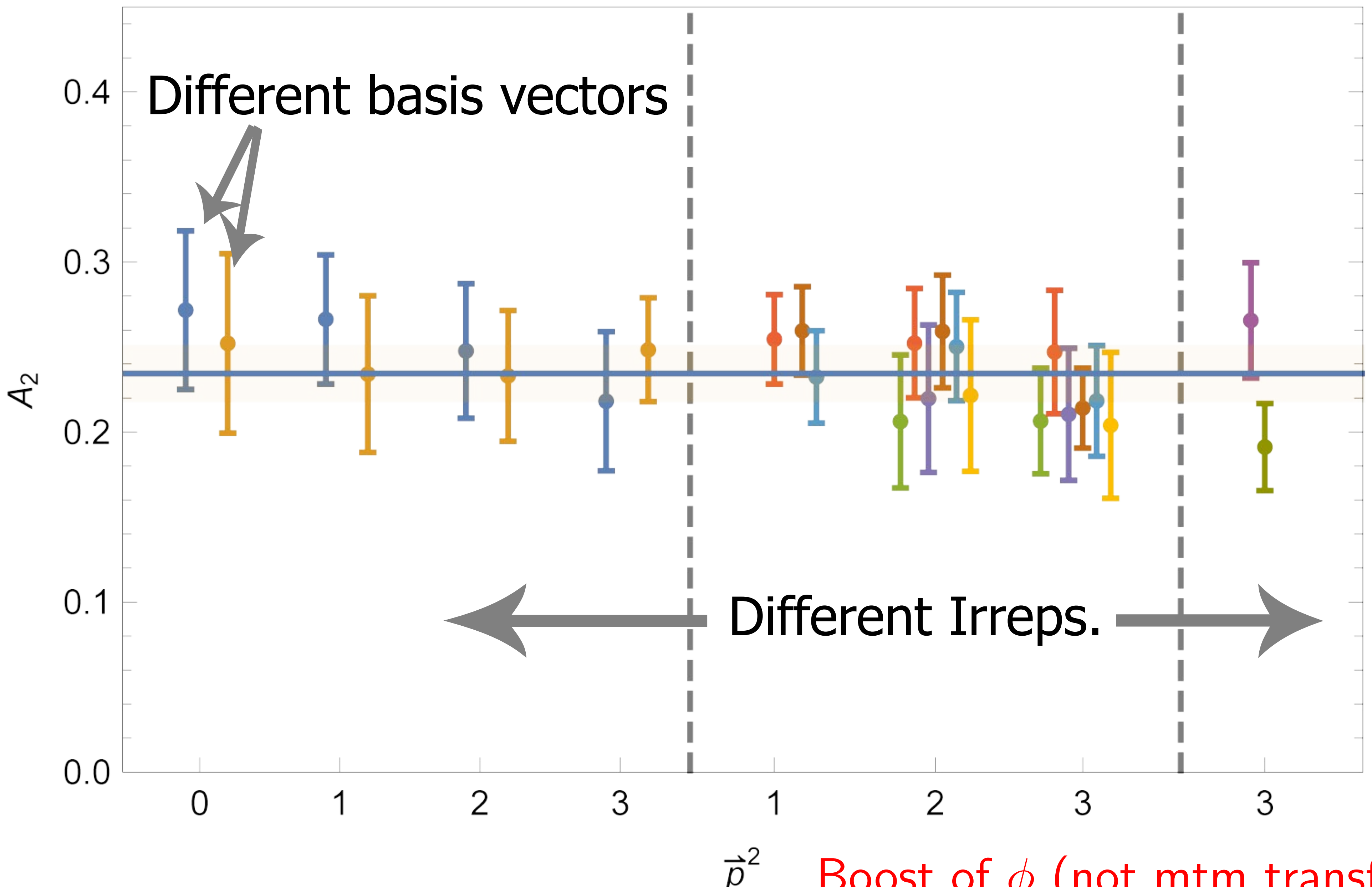
Symmetrise in $\mu_1,\ldots,\mu_n$, trace subtract in all free indices

$$= (-2i)^{n-2}\underline{S}\left[(p_\mu E'^*_{\mu_1} - p_{\mu_1}E'^*_\mu)(p_\nu E_{\mu_2} - p_{\mu_2}E_\nu) + (\mu\leftrightarrow\nu)\right]p_{\mu_3}\ldots p_{\mu_n}A_n(Q^2)\ldots,$$

Reduced Matrix Element

LQCD Calculation

Simplest spin-1 system: ϕ meson (unphysically heavy)



Boost of ϕ (not mtm transfer)

W. Detmold, PES, PRD 94 (2016), 014507

Spin-indep. gluon structure

W. Detmold, PES, PRD 94 (2016), 014507

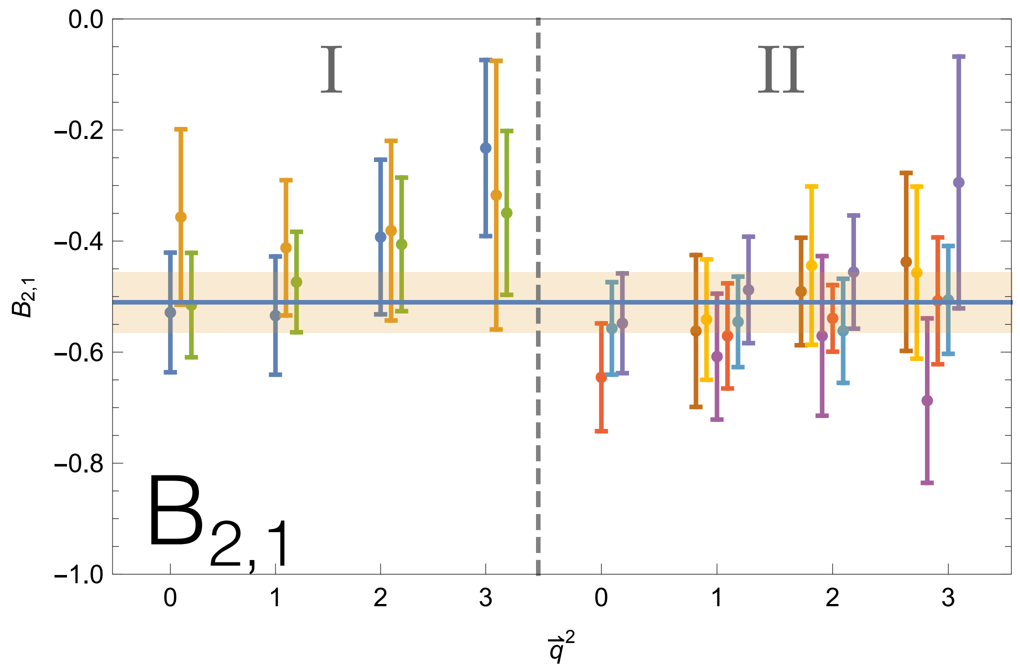
Spin-independent gluon operator:

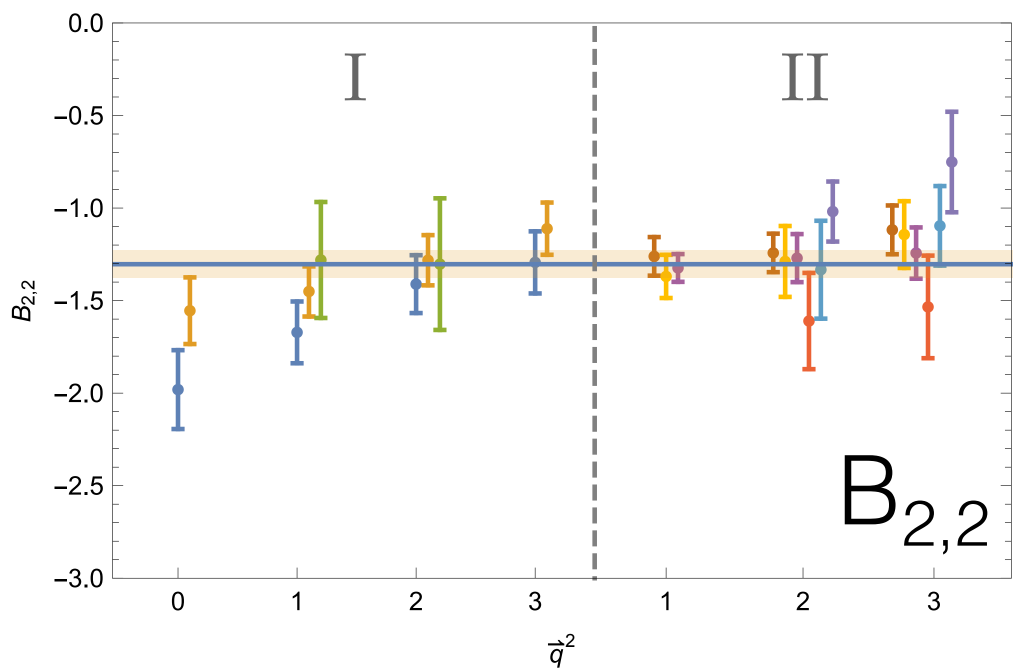
$$\overline{\mathcal{O}}_{\mu_1\ldots\mu_n} = S\left[G_{\mu_1\alpha}\overleftrightarrow{D}_{\mu_3}\ldots\overleftrightarrow{D}_{\mu_n}G_{\mu_2}{}^{\alpha}\right]$$

Matrix elements at n=2 define lowest moment of structure functions

$$\langle pE'|\overline{\mathcal{O}}_{\mu_1\mu_2}|pE\rangle = S\left[M^2 E'^{*}_{\mu_1}E_{\mu_2}\right] \boxed{B_{2,1}(\mu^2)} + S\left[(E\cdot E'^{*})p_{\mu_1}p_{\mu_2}\right]\boxed{B_{2,2}(\mu^2)}$$

Two reduced matrix elements



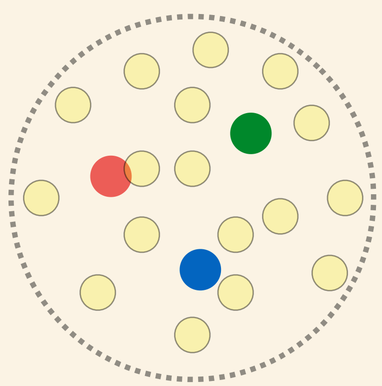


- Analysis as in transversity case
- Mixing with quark ops. neglected, pQCD calcs. shown that it is small: Alexandrou 1611.06901

Gluon Radii

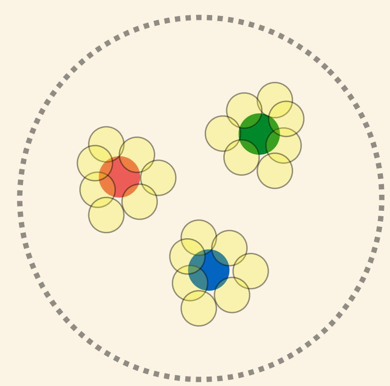
How does the gluon radius of a proton compare to the quark/charge radius?

Bag Model



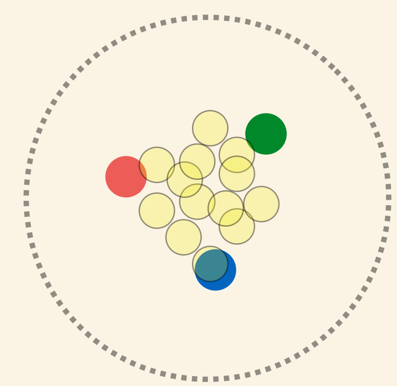
gluon radius > charge radius

Constituent Quark Model



gluon radius ~ charge radius

LQCD with heavy quarks



gluon radius < charge radius

Or is the picture more complicated?

Gluon Generalised FFs

Matrix elements of the spin-independent gluon structure function

- Off-forward matrix elements are complicated:

$$
\begin{aligned}
&\left\langle p'E' \middle| S\left[G_{\mu\alpha} i\overleftrightarrow{D}_{\mu_1}\dots i\overleftrightarrow{D}_{\mu_n} G_{\nu}{}^{\alpha}\right] \middle| pE\right\rangle \\
&\quad = \sum_{\substack{m \text{ even} \\ m=0}}^{n} \Bigg\{ B_{1,m}^{(n+2)}(\Delta^2) M^2 S\left[E_\mu E'^*_\nu \Delta_{\mu_1}\dots\Delta_{\mu_m} P_{\mu_{m+1}}\dots P_{\mu_n}\right] \\
&\qquad + B_{2,m}^{(n+2)}(\Delta^2) S\left[(E\cdot E'^*) P_\mu P_\nu \Delta_{\mu_1}\dots\Delta_{\mu_m} P_{\mu_{m+1}}\dots P_{\mu_n}\right] \\
&\qquad + B_{3,m}^{(n+2)}(\Delta^2) S\left[(E\cdot E'^*) \Delta_\mu \Delta_\nu \Delta_{\mu_1}\dots\Delta_{\mu_m} P_{\mu_{m+1}}\dots P_{\mu_n}\right] \\
&\qquad + B_{4,m}^{(n+2)}(\Delta^2) S\left[\left((E'^*\cdot P) E_\mu P_\nu + (E\cdot P) E'^*_\mu P_\nu\right) \Delta_{\mu_1}\dots\Delta_{\mu_m} P_{\mu_{m+1}}\dots P_{\mu_n}\right] \\
&\qquad + B_{5,m}^{(n+2)}(\Delta^2) S\left[\left((E'^*\cdot P) E_\mu \Delta_\nu - (E\cdot P) E'^*_\mu \Delta_\nu\right) \Delta_{\mu_1}\dots\Delta_{\mu_m} P_{\mu_{m+1}}\dots P_{\mu_n}\right] \\
&\qquad + \frac{B_{6,m}^{(n+2)}(\Delta^2)}{M^2} S\left[(E\cdot P)(E'^*\cdot P) P_\mu P_\nu \Delta_{\mu_1}\dots\Delta_{\mu_m} P_{\mu_{m+1}}\dots P_{\mu_n}\right] \\
&\qquad + \frac{B_{7,m}^{(n+2)}(\Delta^2)}{M^2} S\left[(E\cdot P)(E'^*\cdot P) \Delta_\mu \Delta_\nu \Delta_{\mu_1}\dots\Delta_{\mu_m} P_{\mu_{m+1}}\dots P_{\mu_n}\right] \Bigg\}.
\end{aligned}
$$

Gluon Generalised FFs

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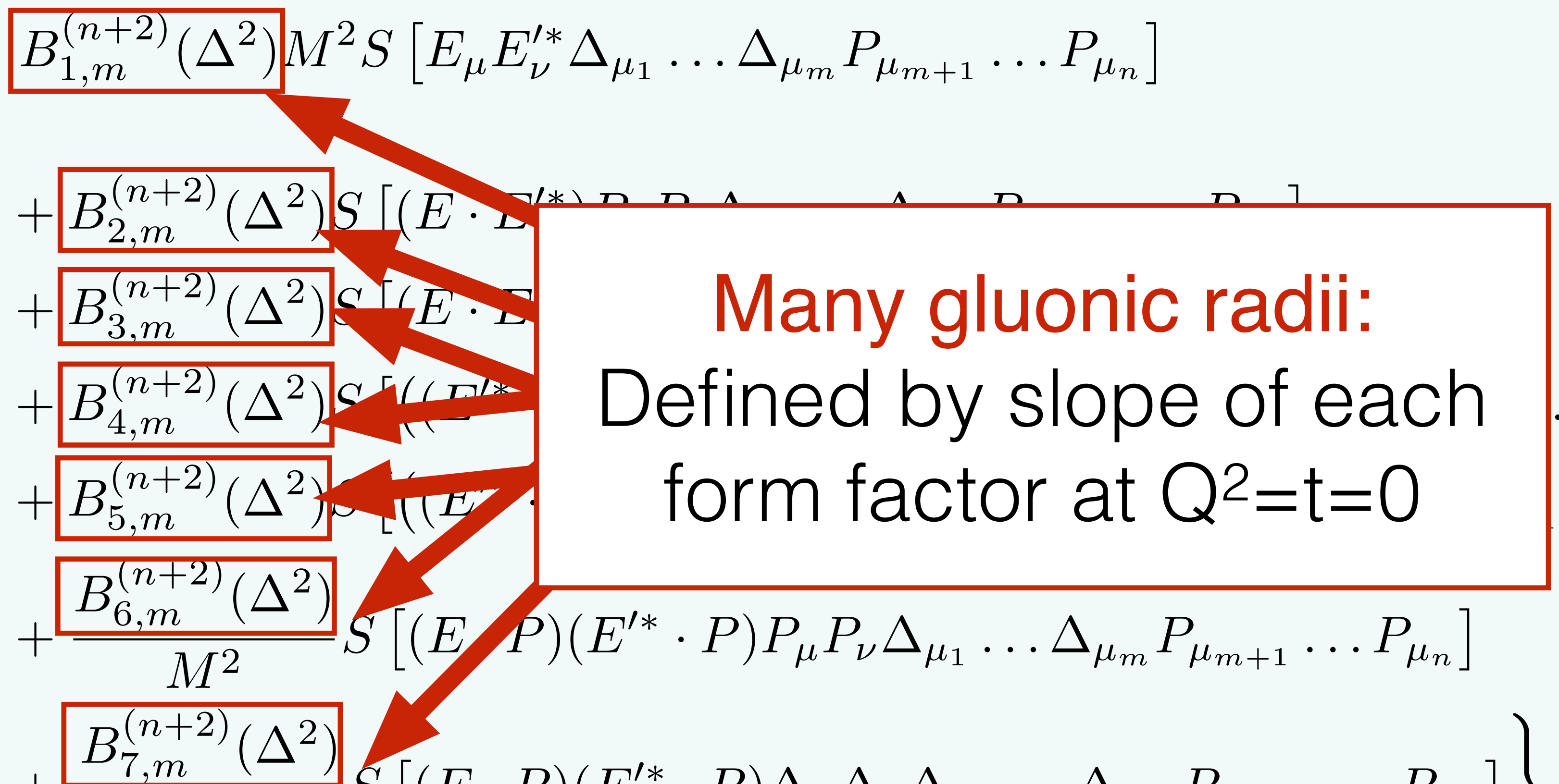
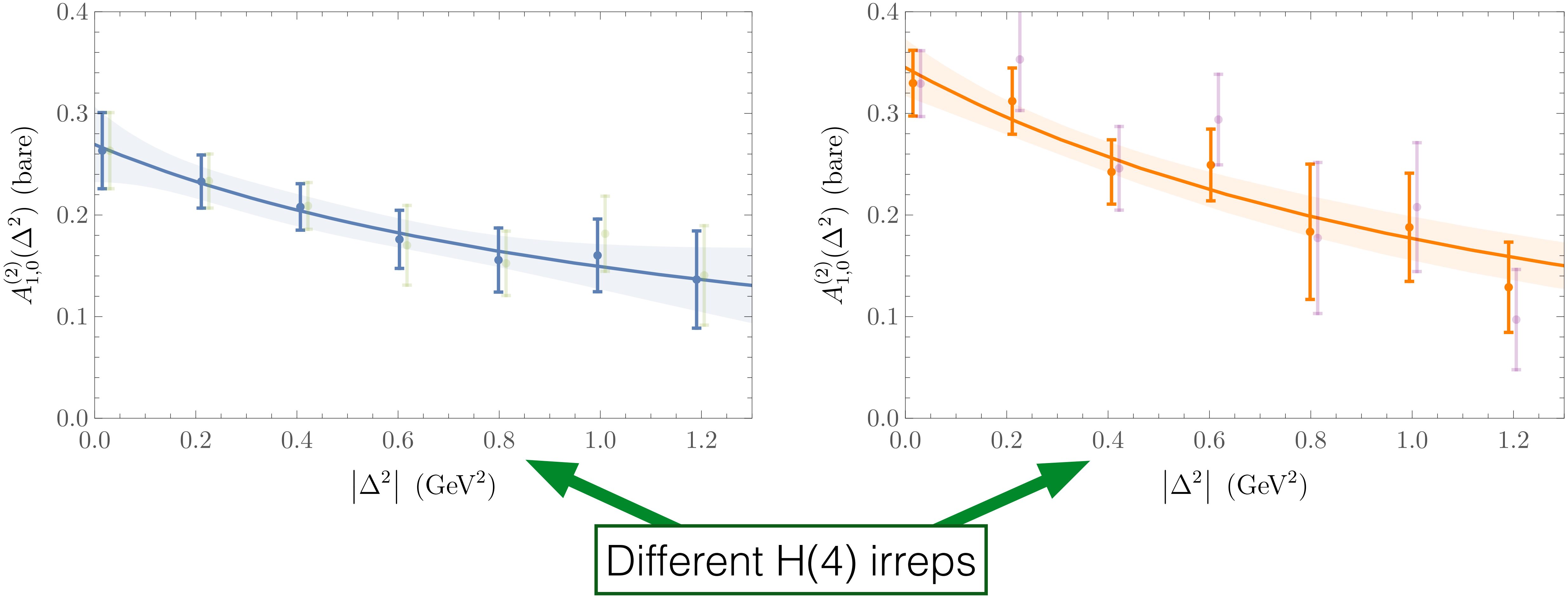
$$
\begin{aligned}
&\left\langle p'E' \left| S\left[G_{\mu\alpha} i\overleftrightarrow{D}_{\mu_1}\ldots i\overleftrightarrow{D}_{\mu_n} G_{\nu}{}^{\alpha}\right]\right| pE\right\rangle \\
&= \sum_{\substack{m\ \mathrm{even}\\ m=0}}^{n} \Big\{ B_{1,m}^{(n+2)}(\Delta^2) M^2 S\left[E_\mu E'^*_\nu \Delta_{\mu_1}\ldots\Delta_{\mu_m} P_{\mu_{m+1}}\ldots P_{\mu_n}\right] \\
&\quad + B_{2,m}^{(n+2)}(\Delta^2) S\left[(E\cdot \cdots\right] \\
&\quad + B_{3,m}^{(n+2)}(\Delta^2) S\left[(E\cdot \cdots\right] \\
&\quad + B_{4,m}^{(n+2)}(\Delta^2) S\left[((E'^* \cdots \ldots P_{\mu_n}\right] \\
&\quad + B_{5,m}^{(n+2)}(\Delta^2) S\left[((E \cdots \ldots P_{\mu_n}\right] \\
&\quad + \frac{B_{6,m}^{(n+2)}(\Delta^2)}{M^2} S\left[(E\cdot P)(E'^*\cdot P) P_\mu P_\nu \Delta_{\mu_1}\ldots\Delta_{\mu_m} P_{\mu_{m+1}}\ldots P_{\mu_n}\right] \\
&\quad + \frac{B_{7,m}^{(n+2)}(\Delta^2)}{M^2} S\left[(E\cdot P)(E'^*\cdot P) \Delta_\mu \Delta_\nu \Delta_{\mu_1}\ldots\Delta_{\mu_m} P_{\mu_{m+1}}\ldots P_{\mu_n}\right] \Big\}.
\end{aligned}
$$



Gluon Transversity GFFs

W. Detmold, PES, PRD 94 (2016), 014507 + W. Detmold, D. Pefkou, PES PRD 95 (2017), 114515

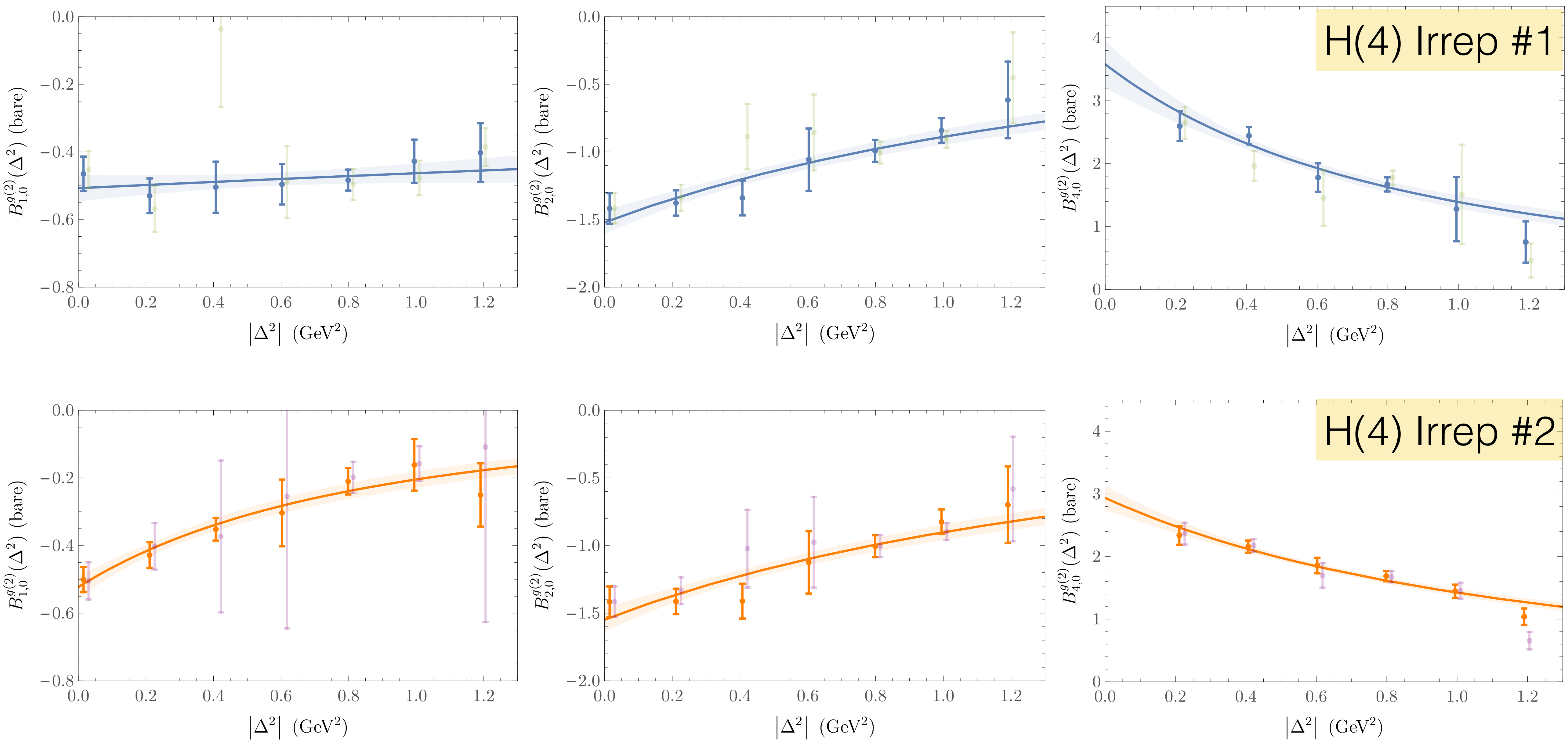
One GFF can be resolved for all momenta



Spin-Indep. Gluon GFFs

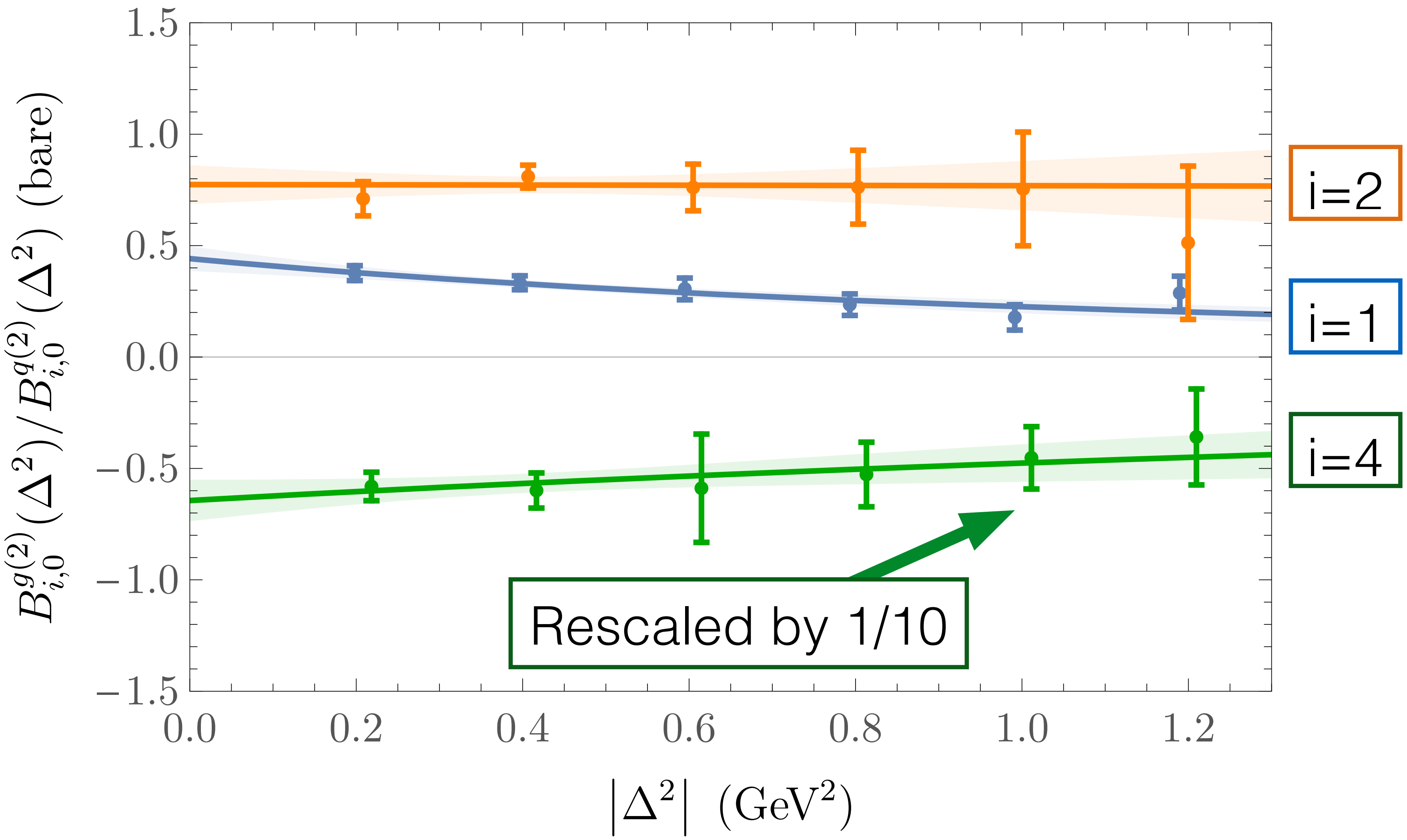
W. Detmold, PES, PRD 94 (2016), 014507 + W. Detmold, D. Pefkou, PES PRD 95 (2017), 114515

Three GFFs can be resolved for all momenta



Quark and Gluon GFFs

Ratio of gluon to quark unpolarised GFFs

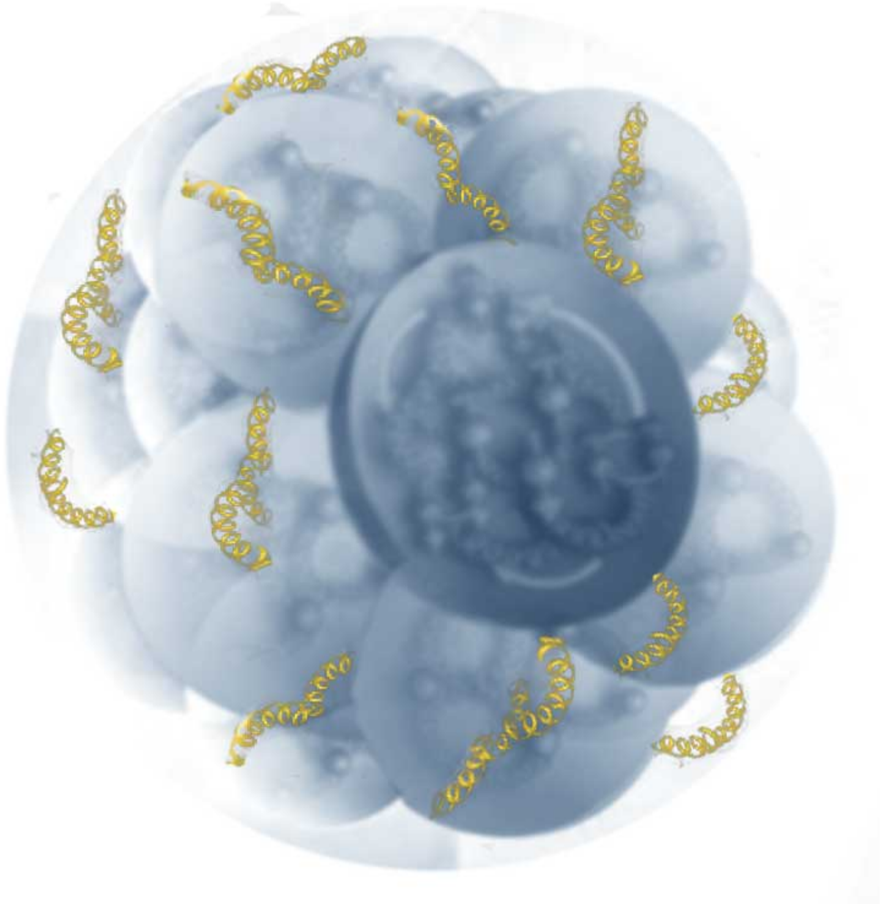


Gluon vs quark radius is a non-trivial question
Much more complicated than intuitive pictures

Gluon structure of nucleons and nuclei

- **First investigations:**
  ϕ meson
  simplest spin-1 system (has fwd limit gluon transversity)

- **Phenomenologically relevant:**
  nucleon, N*, excited mesons, nuclei



Gluon structure - nuclei

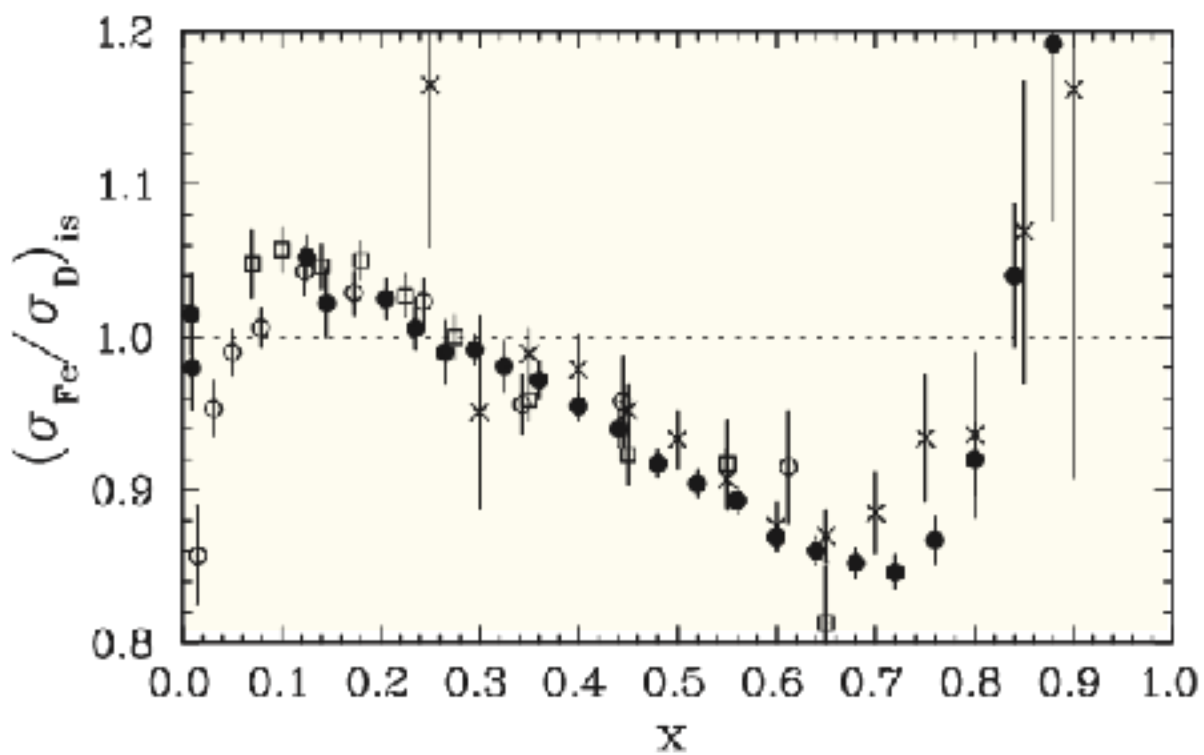
European Muon Collaboration (1983):

Modification of per-nucleon cross section of nucleons bound in nuclei

Precise understanding of nuclear targets essential for DUNE expt: extraction of neutrino mass hierarchy, mixing parameters

Ratio of structure function F_2 per nucleon for iron and deuterium

$$F_2(x, Q^2) = \sum_{q=u,d,s..} x z_q^2 \left[q(x, Q^2) + \bar{q}(x, Q^2) \right]$$

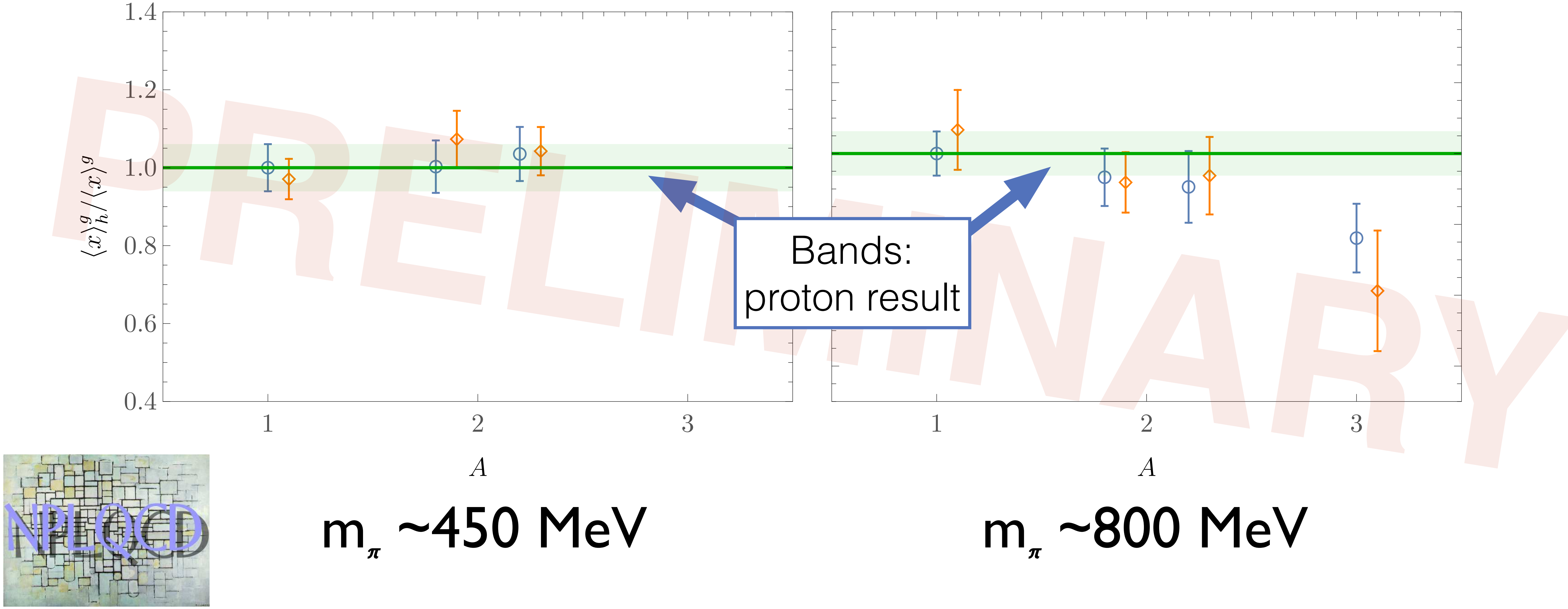


What is the gluonic analogue of the EMC effect?

Gluon momentum fraction

NPLQCD Collaboration, in preparation

- **Spin-independent structure function** in nucleon and light nuclei
- Present statistics: can't distinguish from no-EMC effect scenario
- Small additional uncertainty from mixing with quark operators



m_π ~450 MeV

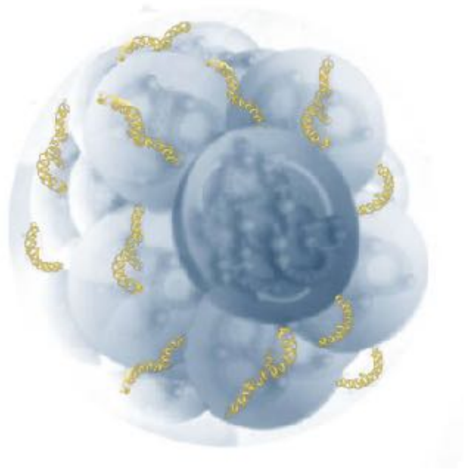
m_π ~800 MeV

Gluon structure circa 2025

- Electron-Ion collider will dramatically alter our knowledge of the gluonic structure of hadrons and nuclei
  - Work towards a complete 3D picture of parton structure (moments, x-dependence of PDFs, GPDs, TMDs)
  - $\Delta(x,Q^2)$ has an interesting role

    Purely gluonic

    Non-nucleonic: directly probe nuclear effects



  - Compare quark and gluon distributions in hadrons and nuclei
  - Potentially revel new information about the nature of gluon excitations and the N* spectrum
- Lattice QCD calculations in hadrons and light nuclei will complement and extend understanding of fundamental structure of nature