Studying the Longitudinal Spin Structure of the Proton at the EIC

Christine A. Aidala
University of Michigan

International Workshop on Probing Hadron Structure at the Electron-Ion Collider
ICTS, Bangalore, India
February 5, 2024

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**EIC Physics with Longitudinally Polarized Hadron Beams*

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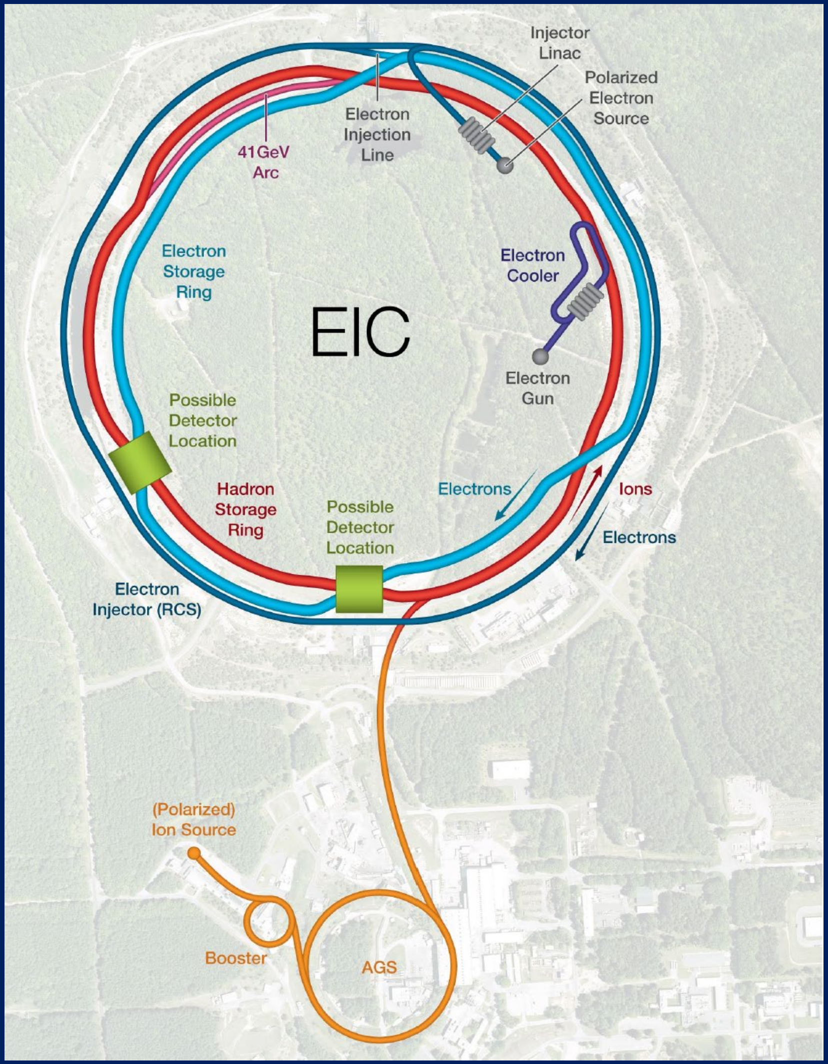
The future Electron-Ion Collider

Key science questions:

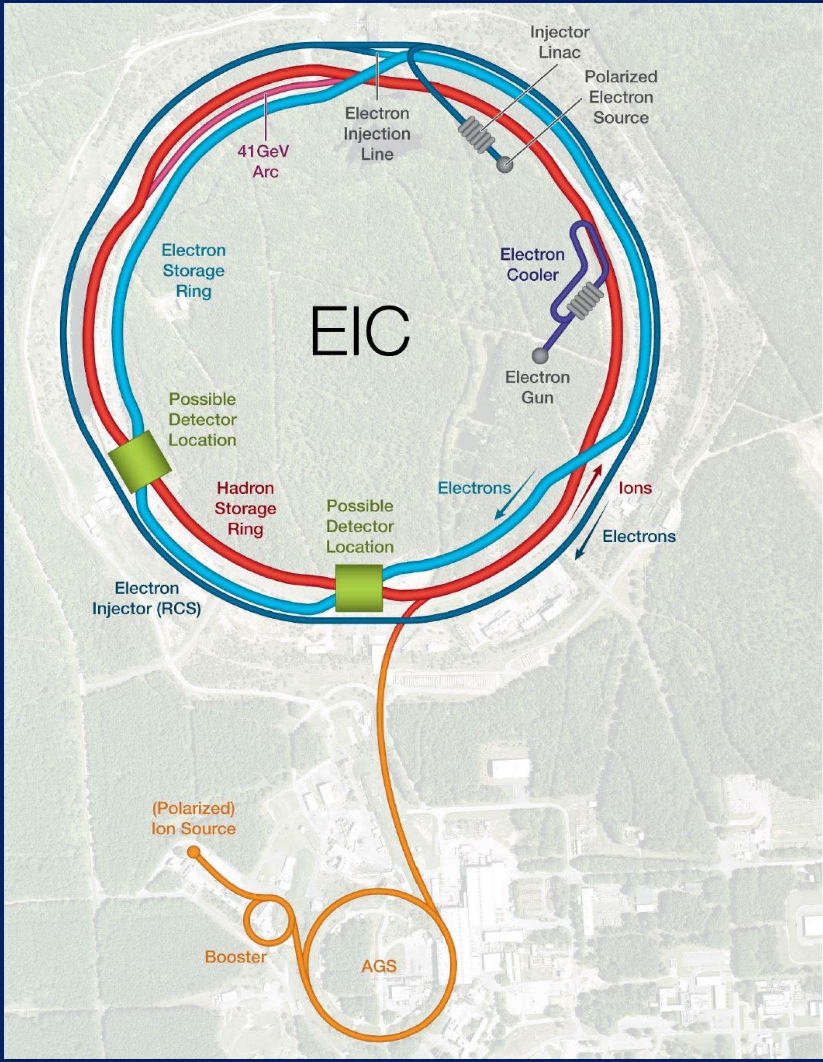
- *How does a nucleon acquire mass?*
- *How does the spin of the nucleon arise from its elementary quark and gluon constituents?*
- *What are the emergent properties of dense systems of gluons?*



The future Electron-Ion Collider

- Highly polarized electron (~70%) and proton (~70%) beams
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium

- Variable $e + p$ center-of-mass energies from 29-140 GeV
- $e + p$ luminosity $10^{33} - 10^{34}$ cm^{-2} s^{-1}



The future Electron-Ion Collider

- Highly polarized electron (~70%) and proton (~70%) beams
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium
  - Including polarized ^3He and possibilities for polarized deuterons!
- Variable $e + p$ center-of-mass energies from 29-140 GeV
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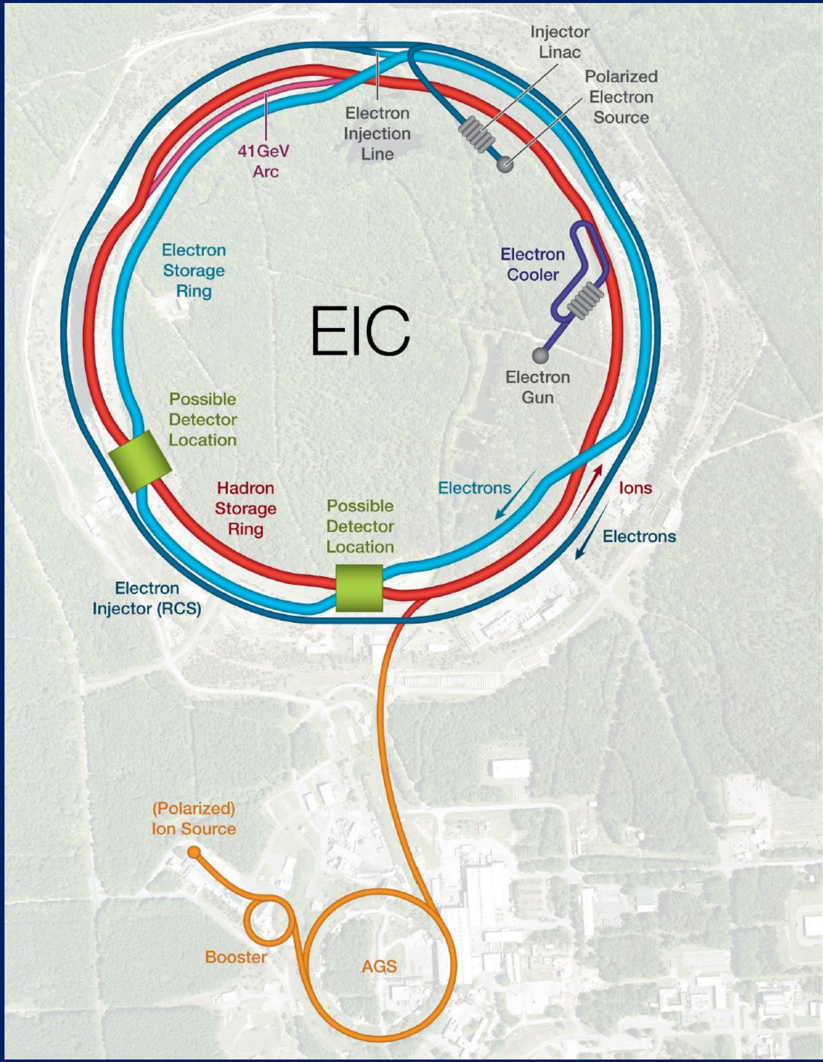
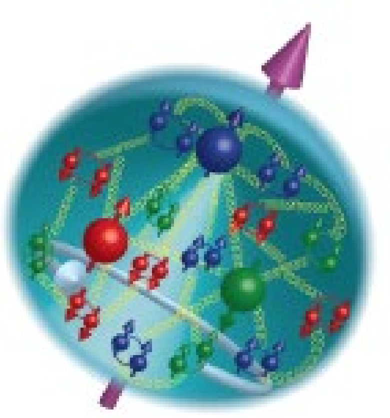


Proton helicity structure

Can decompose total proton spin of ½ into contributions from quark spin, gluon spin, and quark and gluon orbital angular momentum (OAM)



Jaffe-Manohar spin decomposition

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu^2) + \Delta G(\mu^2) + L_Q(\mu^2) + L_G(\mu^2)$$

$$\Delta\Sigma(\mu^2) = \int_0^1 dx\, \Delta\Sigma(x,\mu^2)$$

$$\Delta G(\mu^2) = \int_0^1 dx\, \Delta g(x,\mu^2)$$

NPB337, 509 (1990)

What have we already learned about proton helicity structure?

- $\Delta\Sigma\left(\mu^2 = 10\ GeV^2\right) \approx 0.35$
  - I.e. total quark spin contributes ~35% of proton spin
- $\Delta G\left(\mu^2 = 10\ GeV^2\right) \approx 0.2$, still with large uncertainties

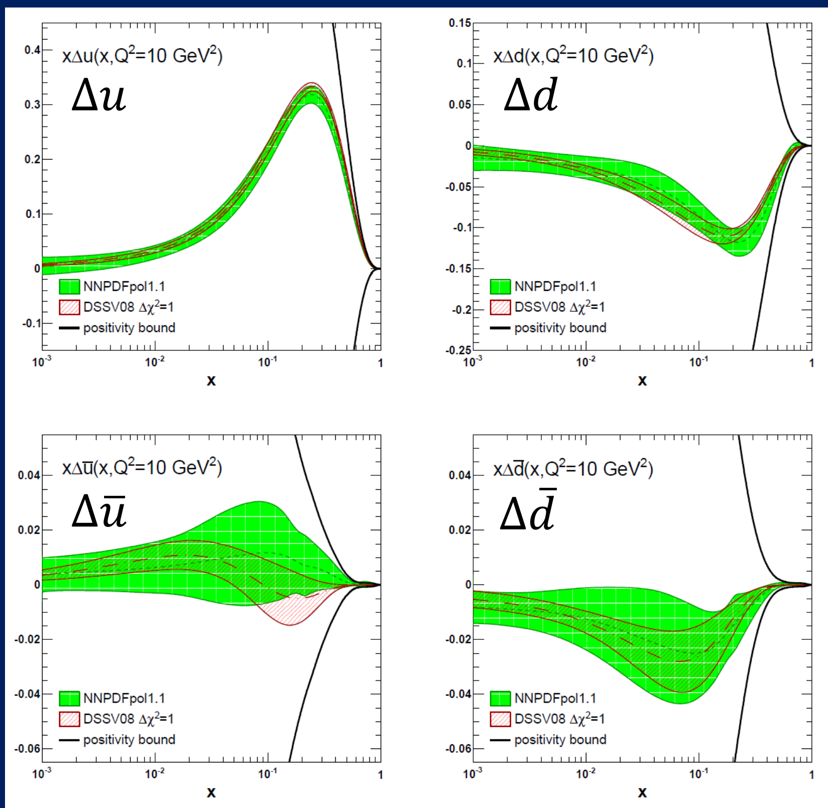
So there must be a significant contribution from orbital angular momentum, which is challenging to measure . . .

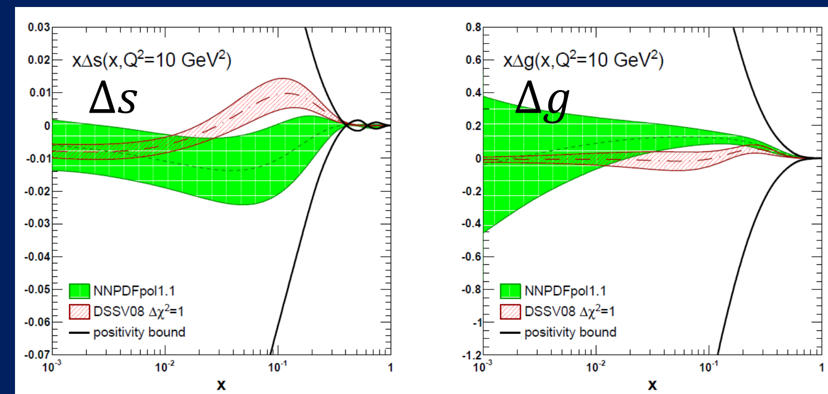
What have we already learned about proton helicity structure?

Breaking down $\Delta\Sigma$:

- $\Delta u > 0$
- $\Delta d < 0$
- Light quark sea shows evidence of flavor asymmetry
  - $\Delta\bar{u}(\mathrm{x}) \neq \Delta\bar{d}(x)$
- Possible contribution from $\Delta s(x)$ remains highly uncertain

Helicity PDF extractions: NNPDFpol1.1.



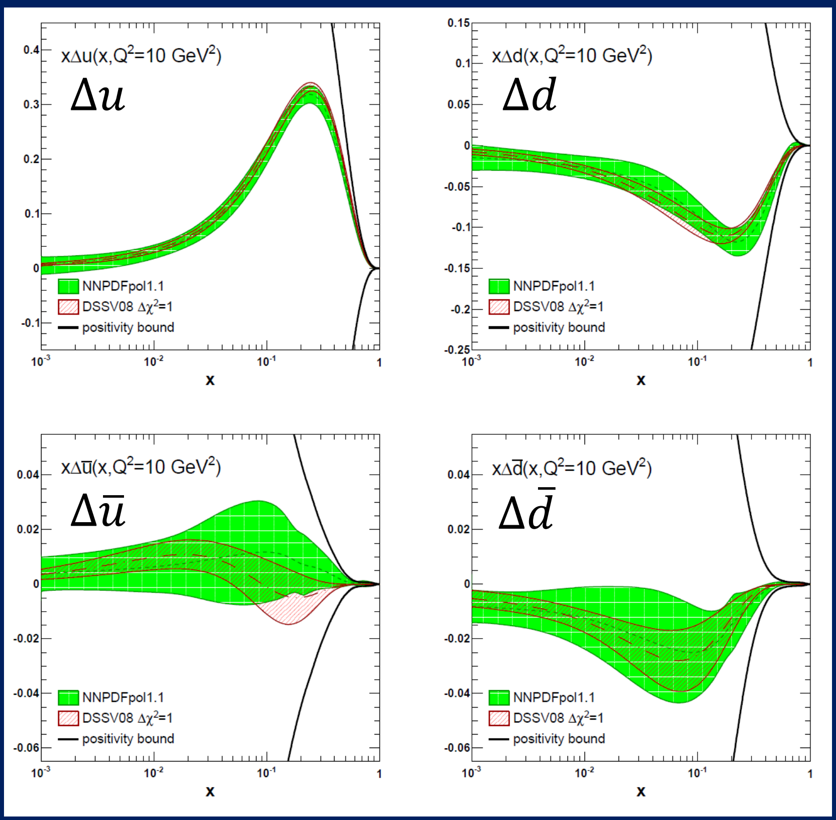


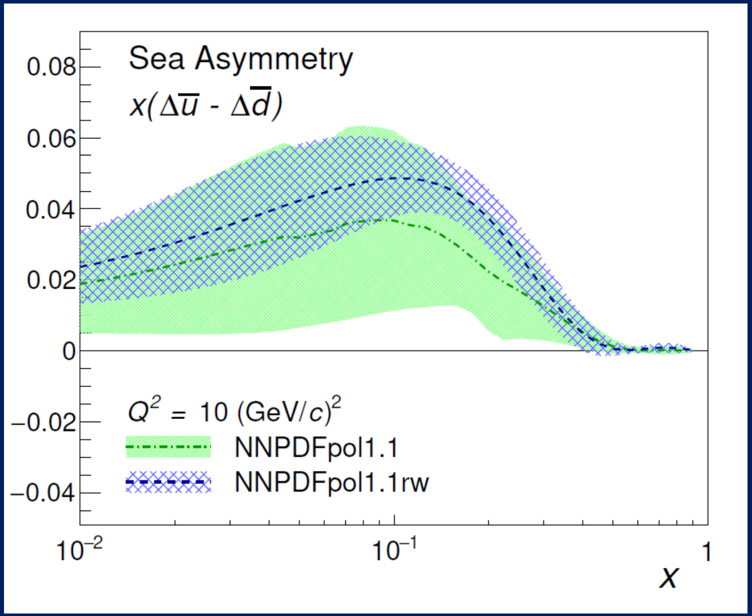
Note different y-axis scales!

NPB887, 276 (2014)

Helicity PDF extractions: NNPDFpol1.1.

PRD102, 094018 (2020)





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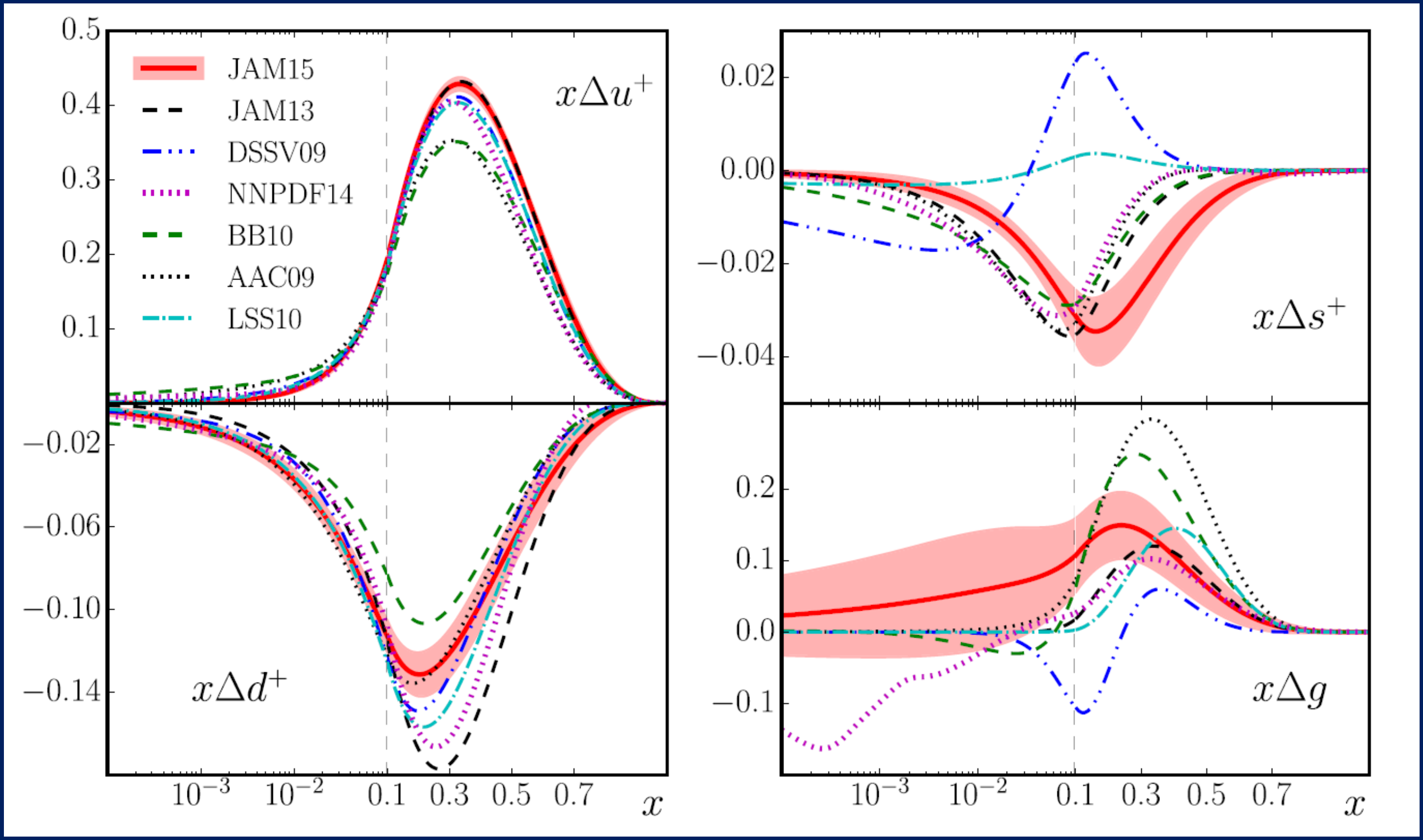
NNPDFpo11.1 $\Delta\bar{u} - \Delta\bar{d}$ extraction and reweighted with 2013 W boson A_L measurement from STAR

NPB887, 276 (2014)

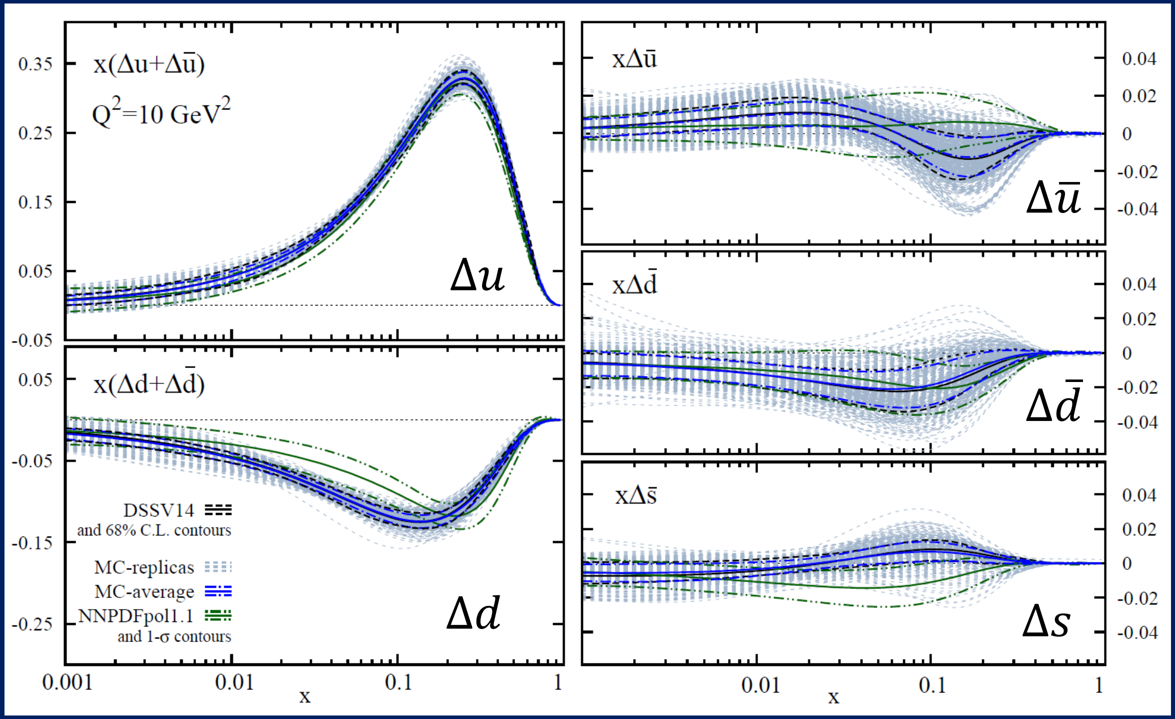
Helicity PDF extractions: JAM15

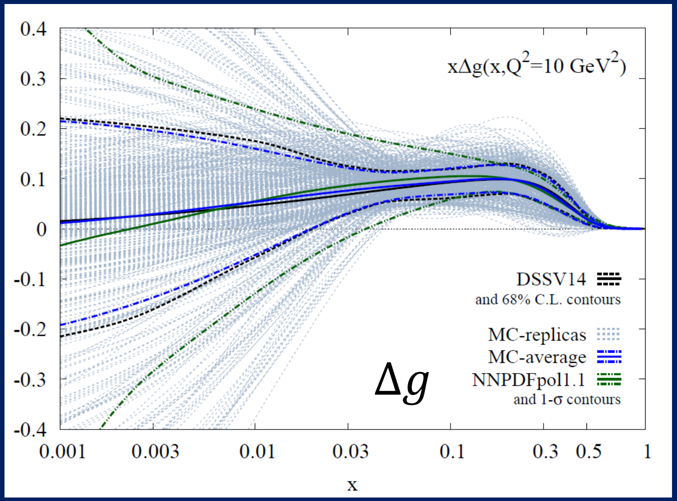


Note different y-axis scales!

PRD93, 074005 (2016)

Helicity PDF extractions: DSSV14 with Monte Carlo sampling





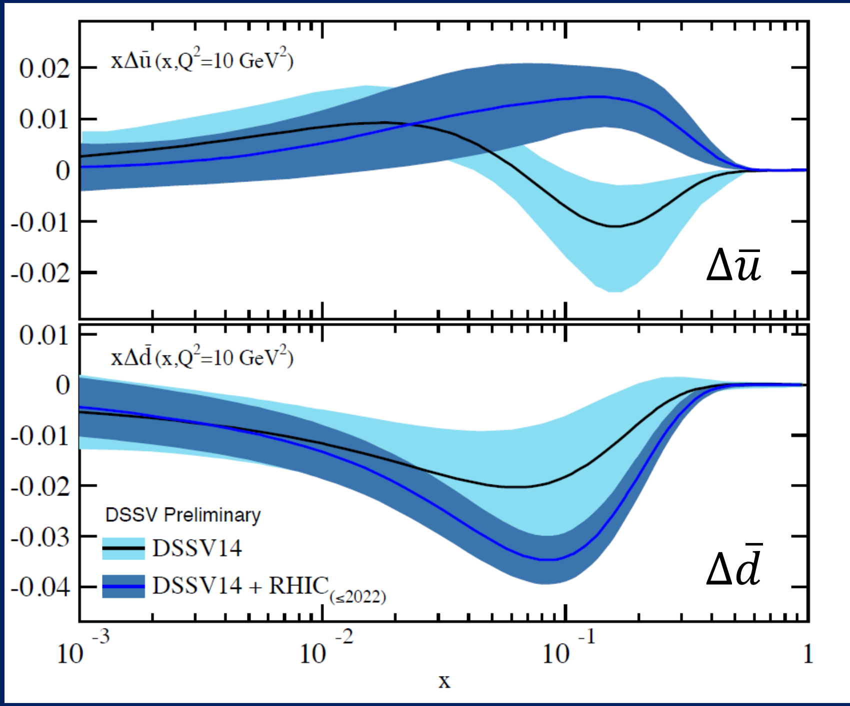
Note different y-axis scales!

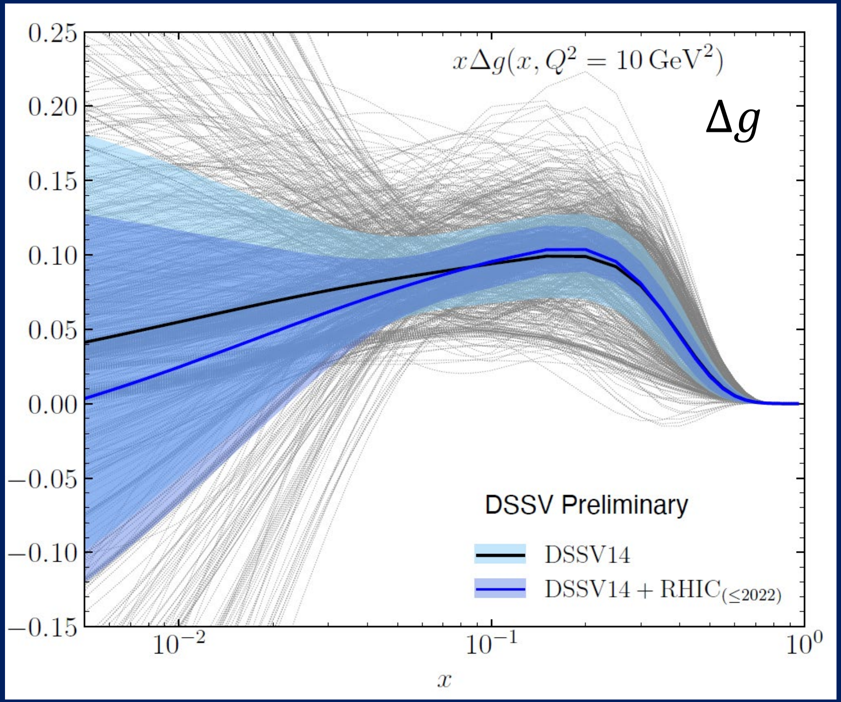
PRD100, 114027 (2019)
DSSV14: PRL113, 012001 (2014)

Latest DSSV extraction of light sea and gluon

RHIC Cold QCD White Paper - arXiv:2302.00605
DSSV14: PRL113, 012001 (2014)

Note different y-axis scales!

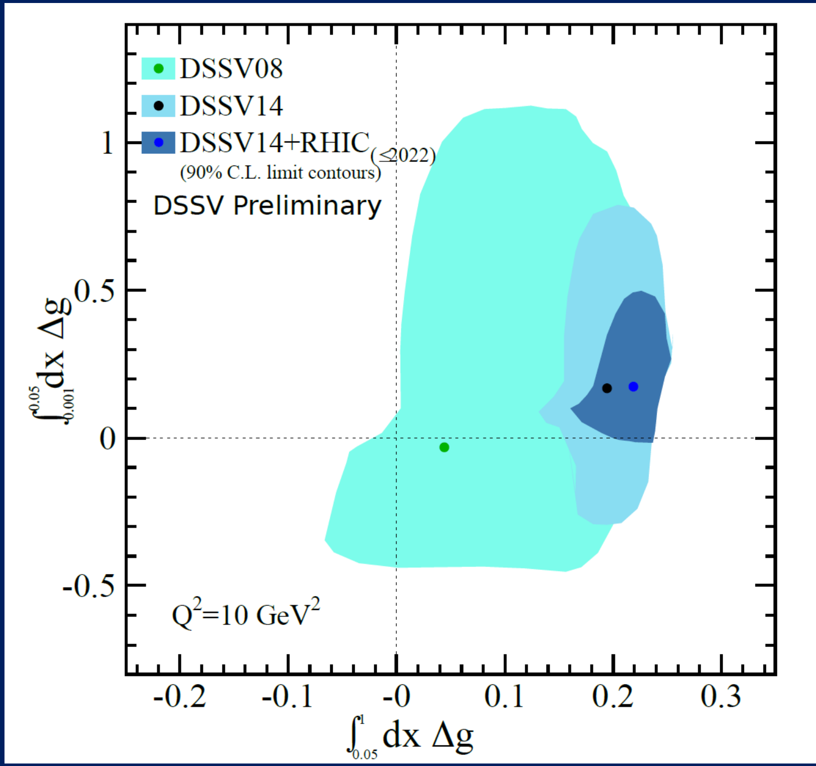




- Fit includes RHIC data released as of 2022: W boson A_L impacting light sea and jet, dijet, and pion A_{LL} impacting gluon distribution
- Asymmetry between $\Delta\bar{u}(x)$and $\Delta\bar{d}(x)$ became more significant

Could contributions from low-momentum gluons be large?

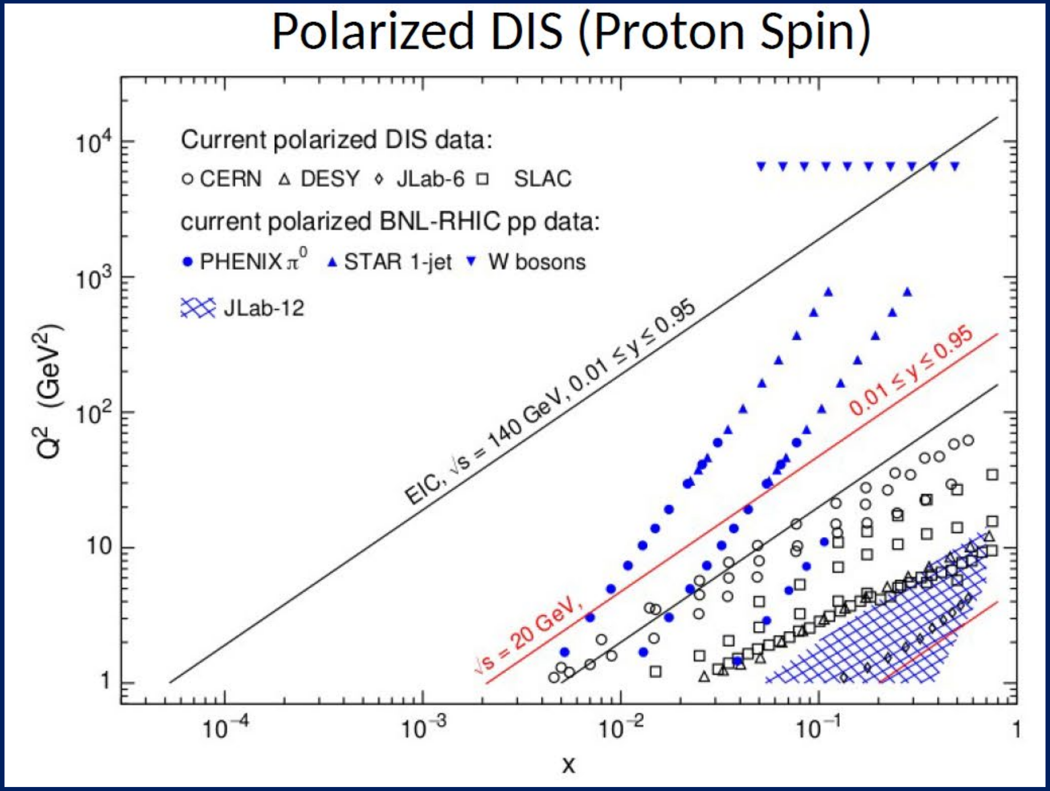
RHIC Cold QCD White Paper - arXiv:2302.00605



Note different horizontal and vertical axis scales!

- Inclusion of RHIC data released as of 2022 (jets, dijets, and pions) has constrained truncated first moment of $\Delta g(x)$ from $0.05 < x < 1$ relatively well
- Constraints for $0.001 < x < 0.05$ improved, but still large uncertainties
- $\Delta g(x)$ remains ~unconstrained for $x < 0.001$

Complementarity of EIC with ongoing and previous polarized experiments

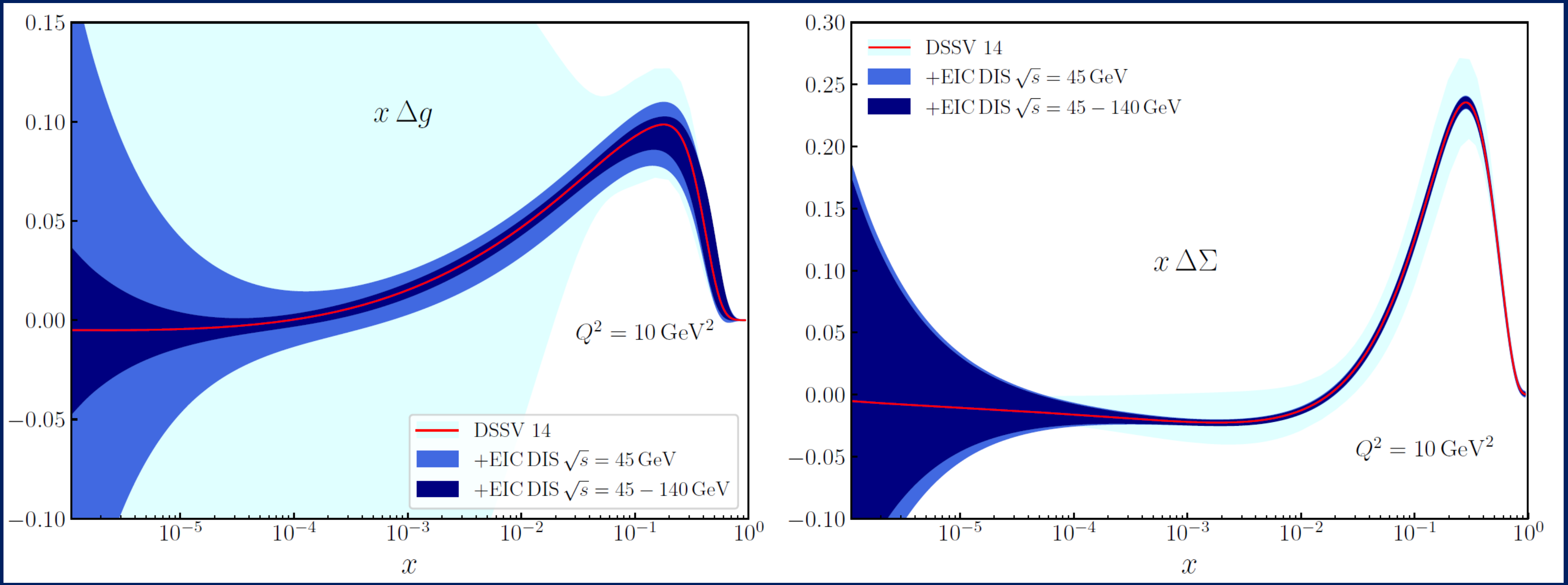


- EIC will greatly expand kinematic coverage for polarized measurements
- EIC at high energy will be critical to reach down to $x \sim 10^{-4}$

EIC: Improving the gluon and quark singlet helicity distributions

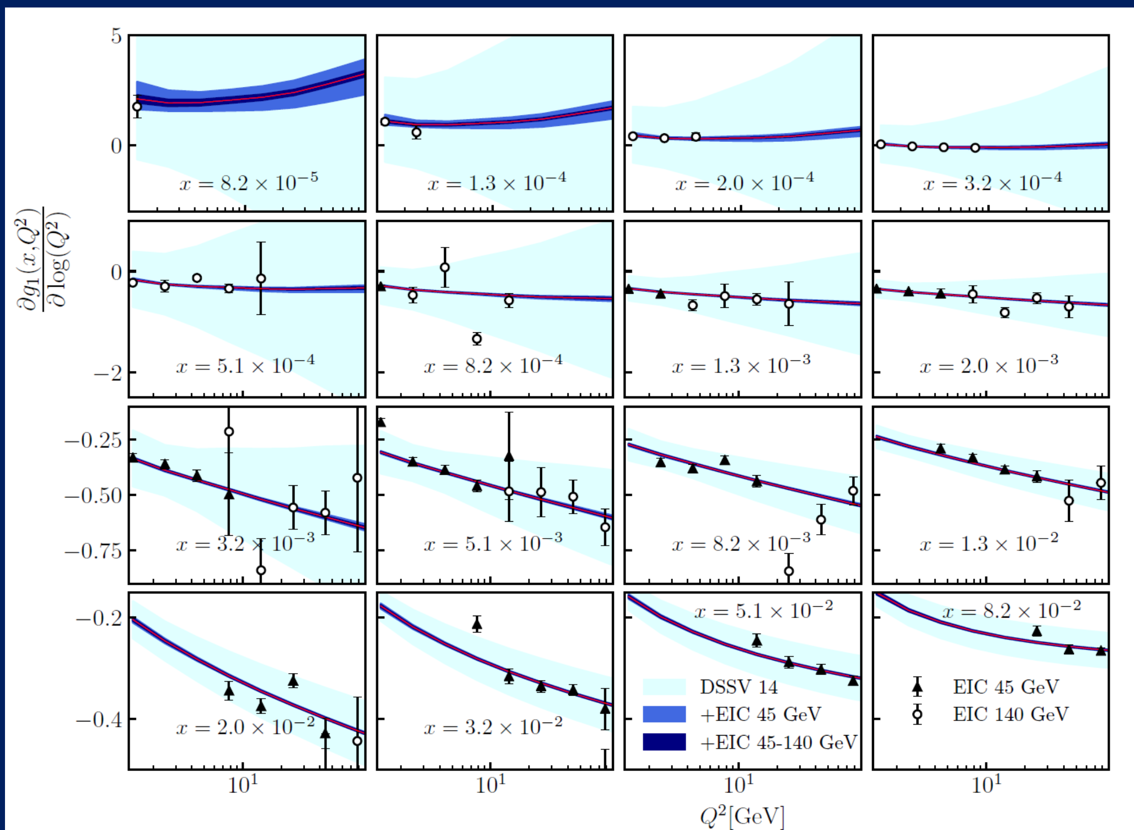
PRD102, 094018 (2020)
DSSV14: PRL113, 012001 (2014)

Note different y-axis scales!



Impact of projected EIC A_{LL} data on the gluon helicity and quark singlet helicity distributions, relative to DSSV14 global analysis

EIC: Accessing gluon helicity through scaling violations of g_1



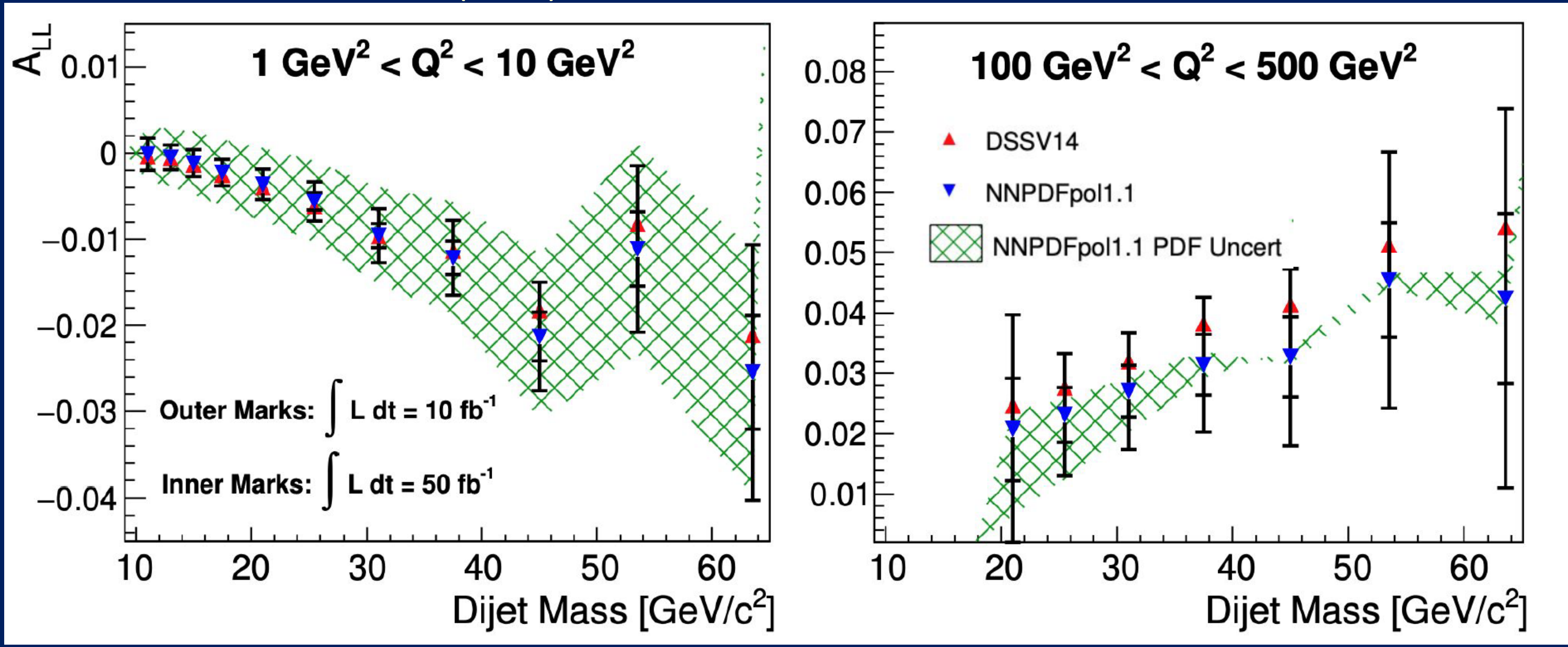
EIC pseudodata for scaling of g_1 with Q^2

PRD102, 094018 (2020)
DSSV14: PRL113, 012001 (2014)

- Large kinematic coverage across x and Q^2 at EIC
  - Scaling violations of polarized structure function g_1 will be most powerful way to access Δg
  - Inclusive DIS measurements

EIC: Accessing gluon helicity through double-longitudinal asymmetry for dijets

PRD101, 072003 (2020)

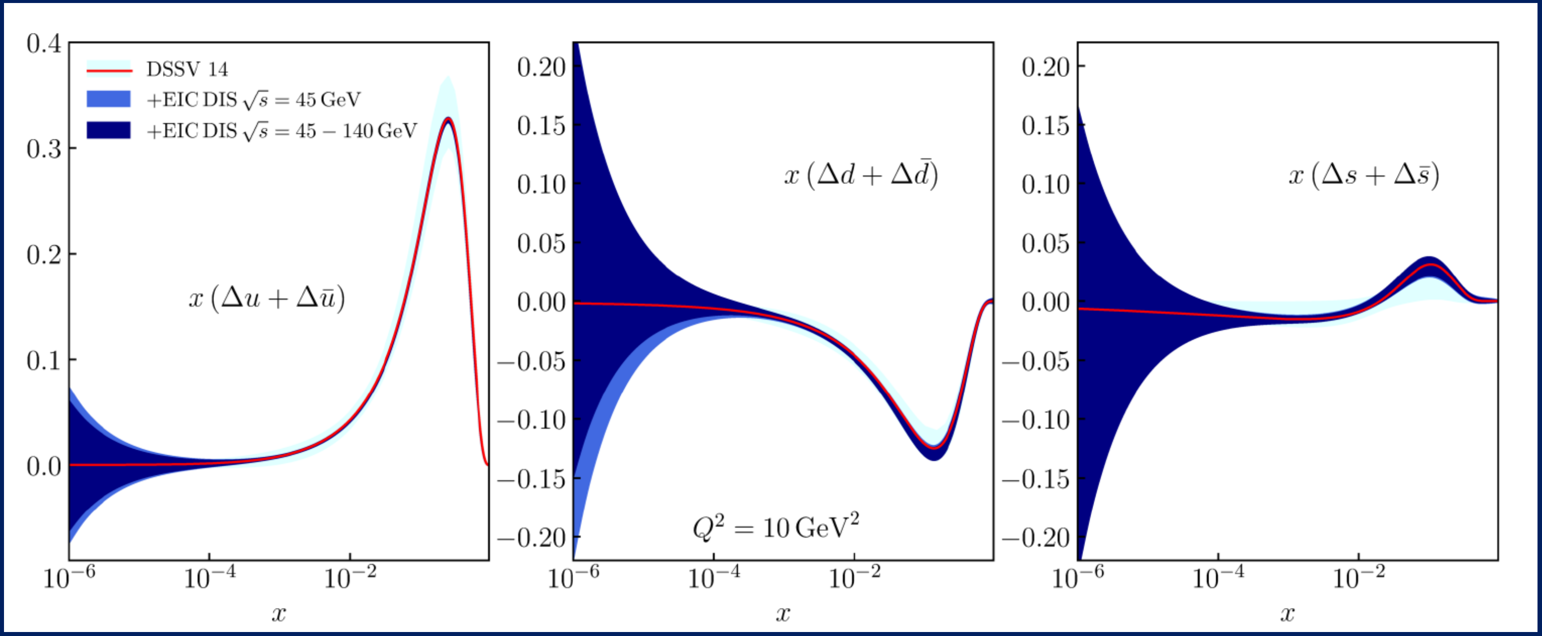


EIC pseudodata for dijets from QCD Compton scattering and photon-gluon fusion. Complementary measurement to inclusive polarized DIS structure function g_1

EIC: Improving the total quark helicity distributions

PRD102, 094018 (2020)
DSSV14: PRL113, 012001 (2014)

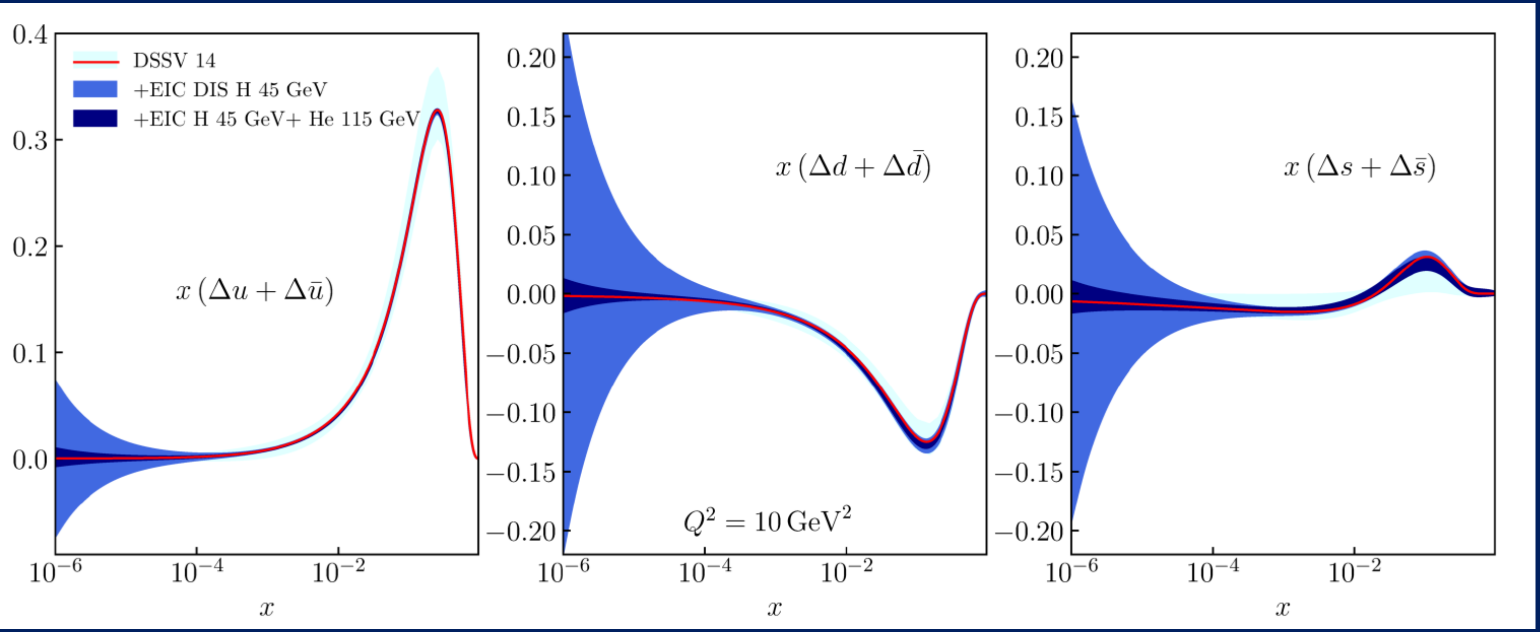
Note different y-axis scales!



Impact of projected EIC A_{LL} data on the total quark helicity distributions, relative to DSSV14 global analysis

EIC: Improving the total quark helicity distributions, including ^{3}He data

PRD102, 094018 (2020)
DSSV14: PRL113, 012001 (2014)

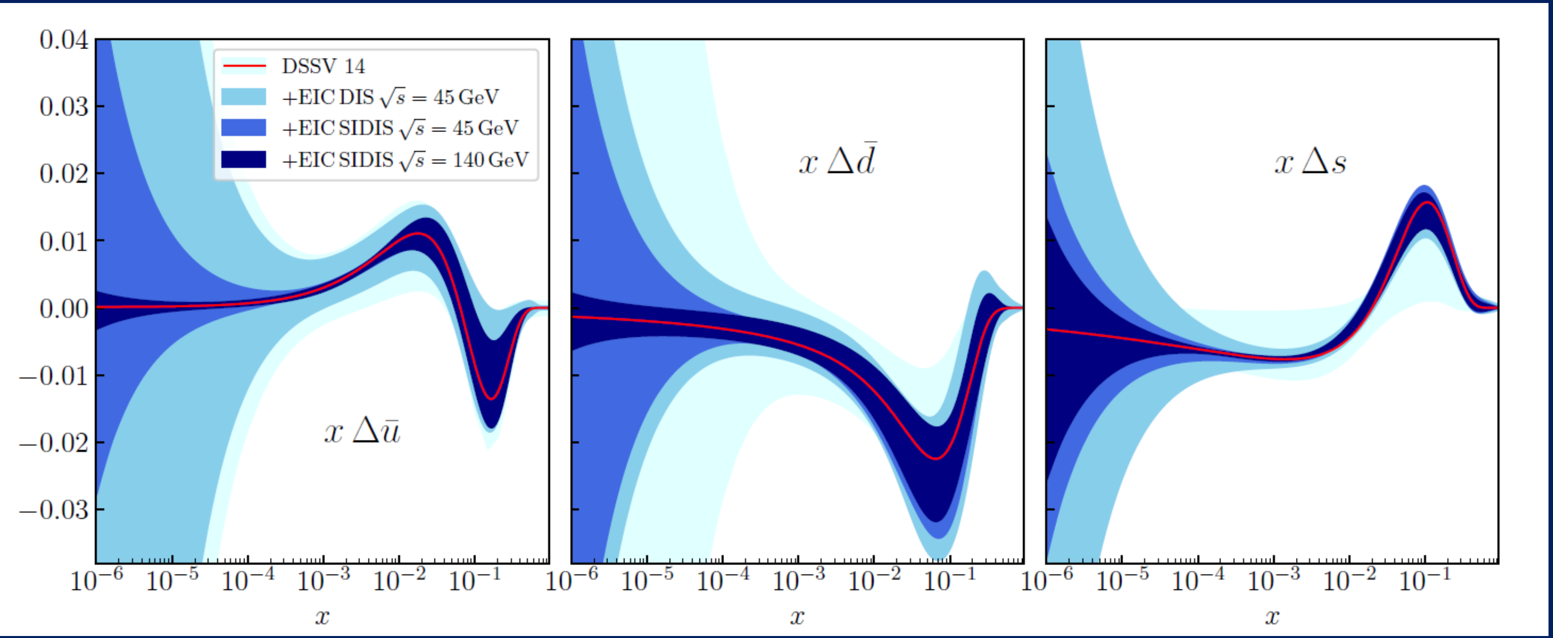


Impact on total quark helicity distributions using inclusive DIS measurements on polarized ^{3}He

EIC: Improving the flavor-separated helicity distributions of the proton sea through SIDIS

PRD102, 094018 (2020)
DSSV14: PRL113, 012001 (2014)

Note different y-axis scale w.r.t. plots on previous slide!

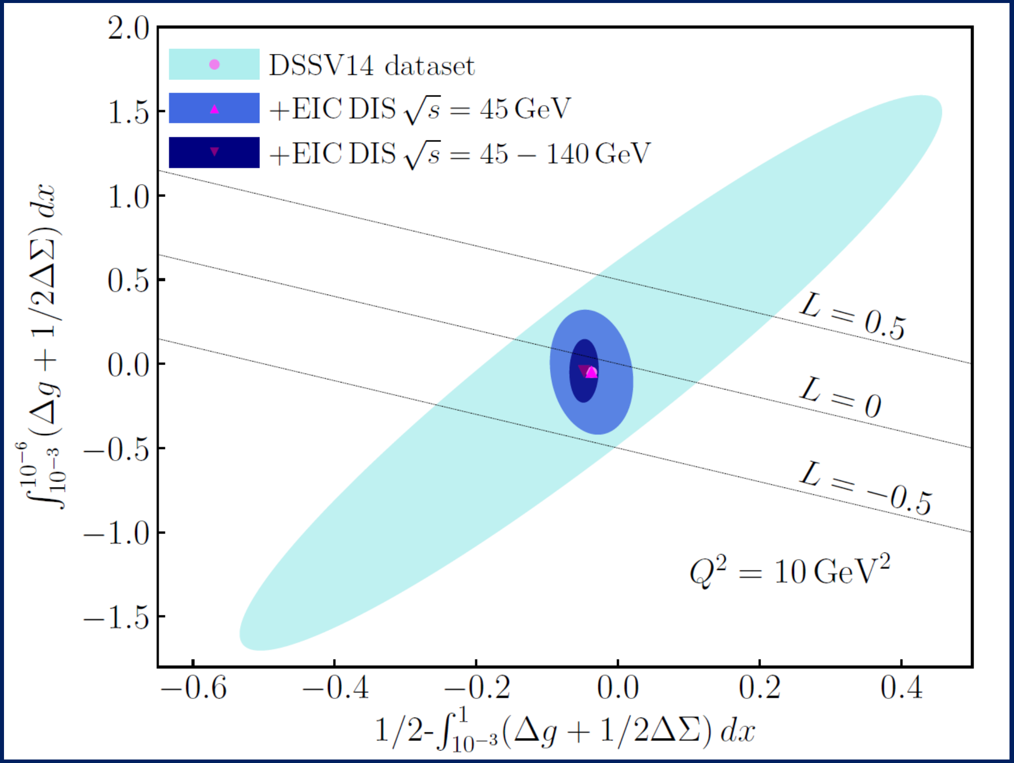


Access flavor through SIDIS measurements of identified charged pions and kaons.

Current treatment of strangeness assumes $\Delta s = \Delta\bar{s}$ and incorporates constraints from hyperon β decay. In the future could use positive and negative kaons to separate Δs and $\Delta\bar{s}$.

EIC: Spin sum rule, low-x conributions, and OAM

PRD102, 094018 (2020)
DSSV14: PRL113, 012001 (2014)

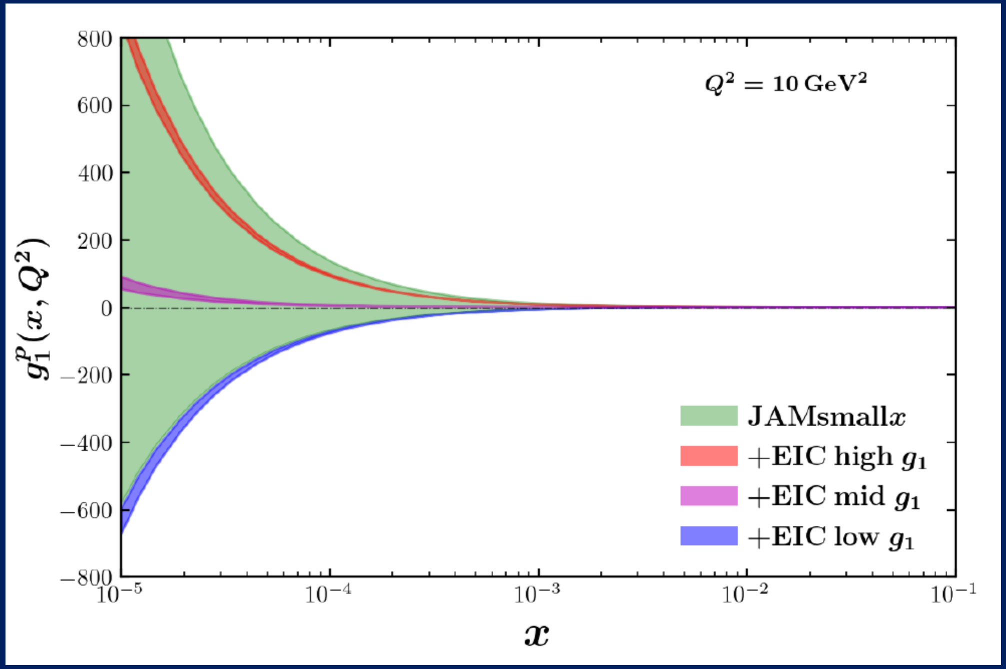


Note different horizontal and vertical axis scales!

- Current polarized data cover $x > \sim 10^{-3}$
- Could there be significant spin contributions for $10^{-6} < x < 10^{-3}$?
- EIC data for Δg at low x will significantly improve uncertainty on the total quark and gluon contributions to proton spin
- Remainder must be orbital angular momentum!

EIC: Pinning down g_1^p at low x

PRD108, 114007 (2023)

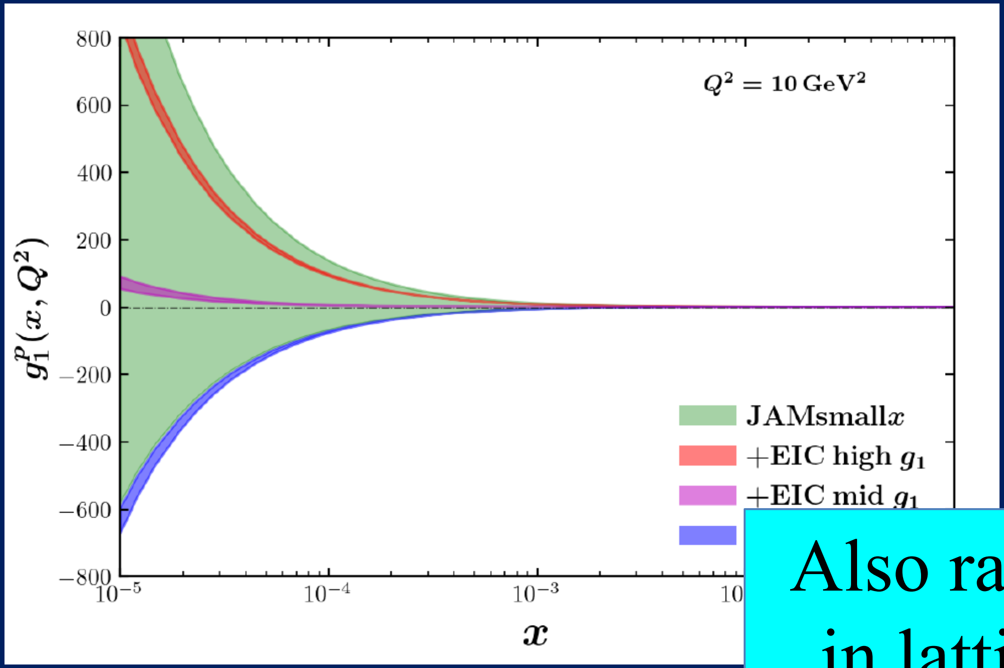


Impact of EIC pseudodata on g_1^p at low x, assuming three different replicas

- Recent series of papers from Kovchegov and collaborators on small-x helicity evolution has led to new phenomenology considering possible large spin contributions from $x < \sim 10^{-4}$

EIC: Pinning down g_1^p at low x

PRD108, 114007 (2023)



Impact of EIC pseudodata on g_1^p at
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Also rapid theoretical progress in lattice QCD in calculating moments as well as x dependence of polarized PDFs!

Thinking more about polarized ^{3}He at the EIC

- Polarized ^{3}He can serve as a proxy for polarized neutrons
  - Already showed improvements in flavor separation from inclusive DIS measurements on ^{3}He
- We typically use isospin to map flavor-dependent distributions in the proton to those in the neutron
- As we reach the era of high-precision polarized data, might we be sensitive to differences in proton and neutron structure that break this isospin correspondence??

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- Mass difference between the proton and neutron only ~0.1%
- But what about the quark *dynamics* in protons versus neutrons?? Interplay between the helicity distributions and OAM??
  - Might naively expect different charges of the valence quarks in protons vs. neutrons to lead to different (and flavor-dependent) OAM

Proton: $+\frac{2}{3}, +\frac{2}{3}, -\frac{1}{3}$ Neutron: $-\frac{1}{3}, -\frac{1}{3}, +\frac{2}{3}$

Nuclear binding effects on helicity distributions

- How does nuclear binding affect helicity distributions in nucleons?
- If want to understand potential isospin symmetry breaking in the polarized structure of protons vs. neutrons, will need to study and disentangle nuclear binding effects on the polarized structure of the neutron in ^{3}He

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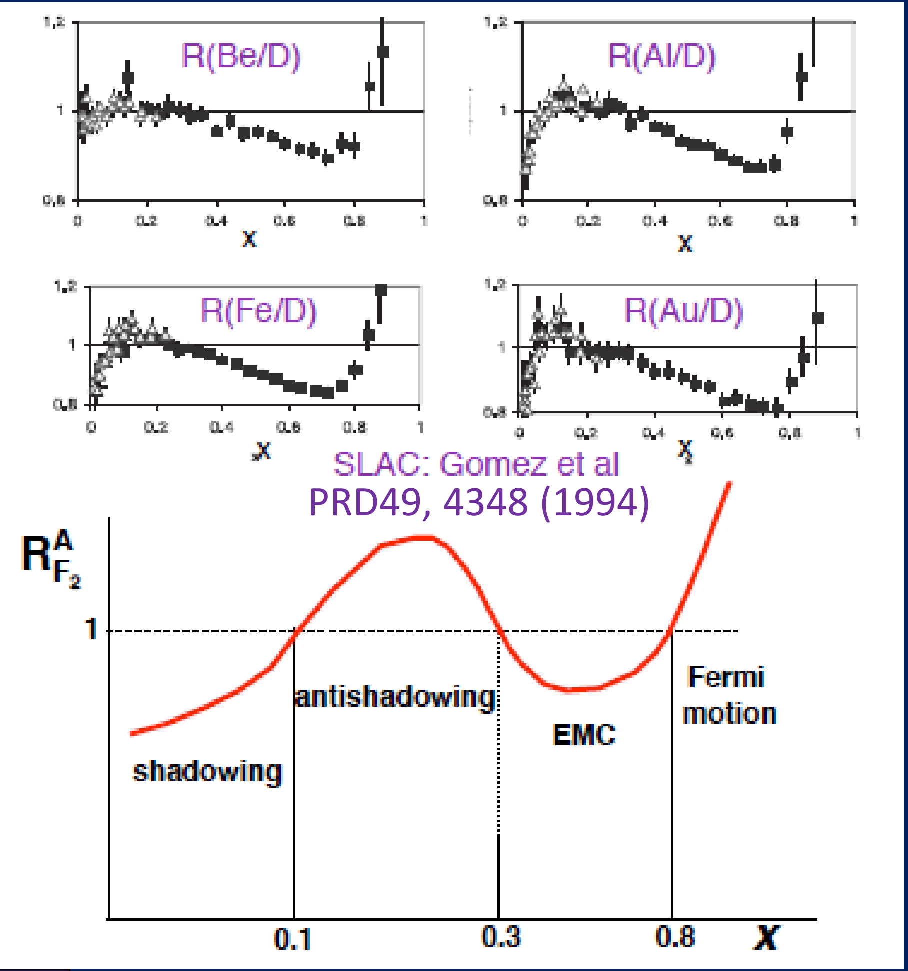
- How does polarization affect the modification of nuclear PDFs w.r.t. the nucleon in different x ranges?
- Is there a polarized EMC effect in nuclei?
  - Some theoretical work has been done, see e.g. EIC Yellow Report (2021) and J.Phys.G 49, 03 (2022)
  - Polarized beams with nuclei heavier than ^{3}He extremely challenging. Prospects for eventual fixed-target measurements with polarized heavier nuclei??

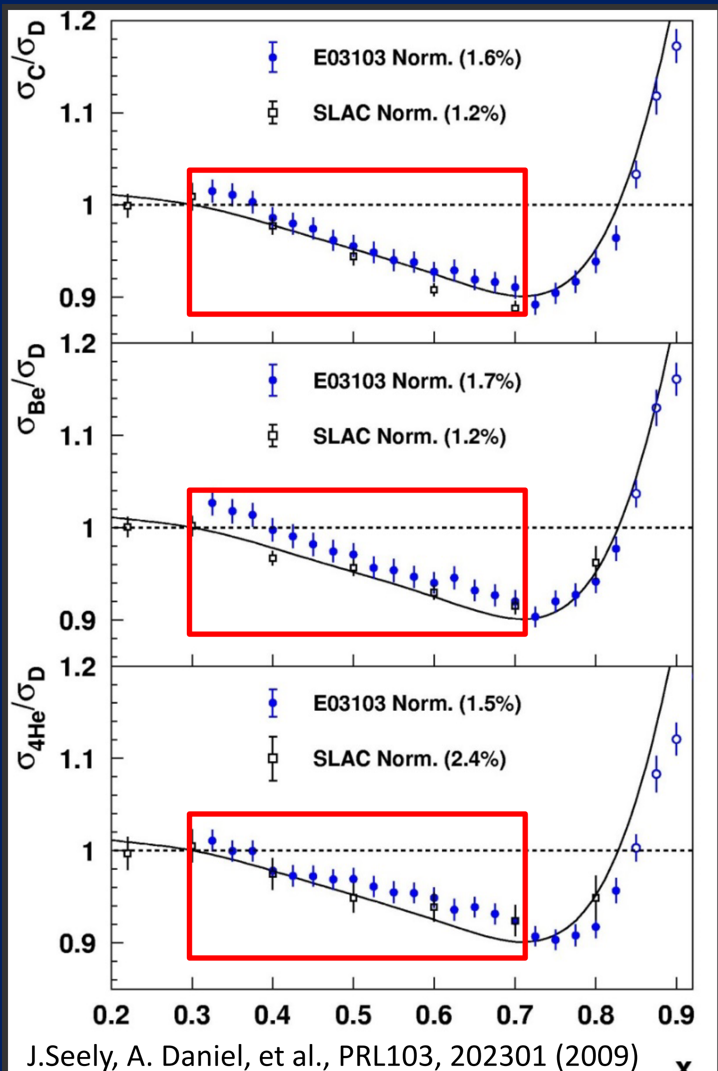
Nuclear modification of PDFs and the EMC effect



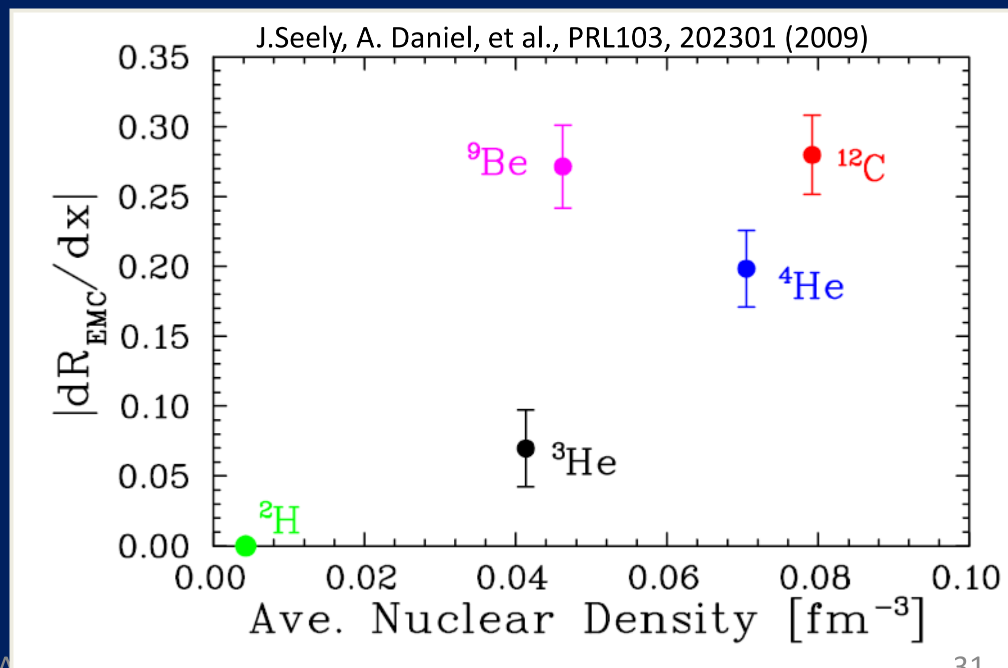
$$R_A \equiv \frac{1}{A}\frac{F_{2A}}{F_{2N}} \neq 1$$

- Ratio of cross section for e+A compared to scaled e+p collisions, shown vs. parton momentum fraction x
- Regions of both enhancement and depletion—still lots to understand in detail!

Partonic momentum structure of nuclei: EMC effect and local density



- Fit slope of ratios for 0.3<x<0.7; compare across nuclei
- EMC slope doesn't scale with A or with avg nuclear density…



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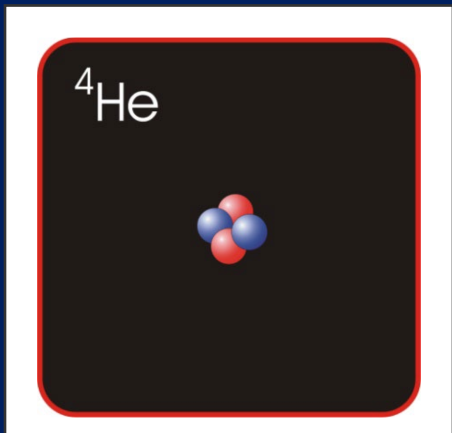
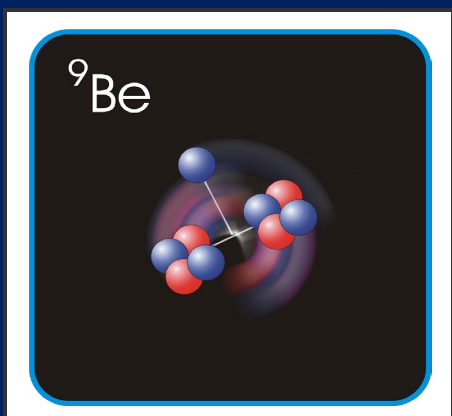
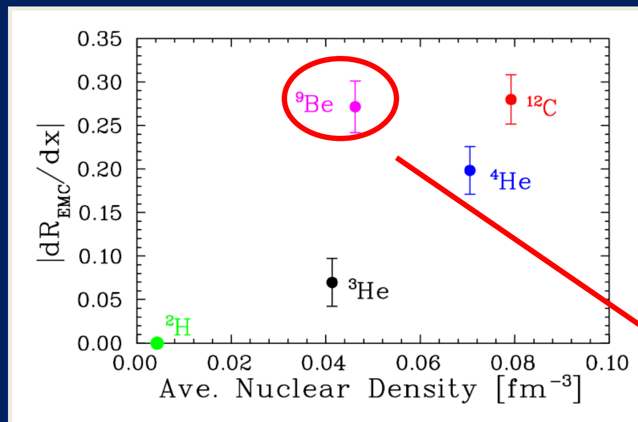
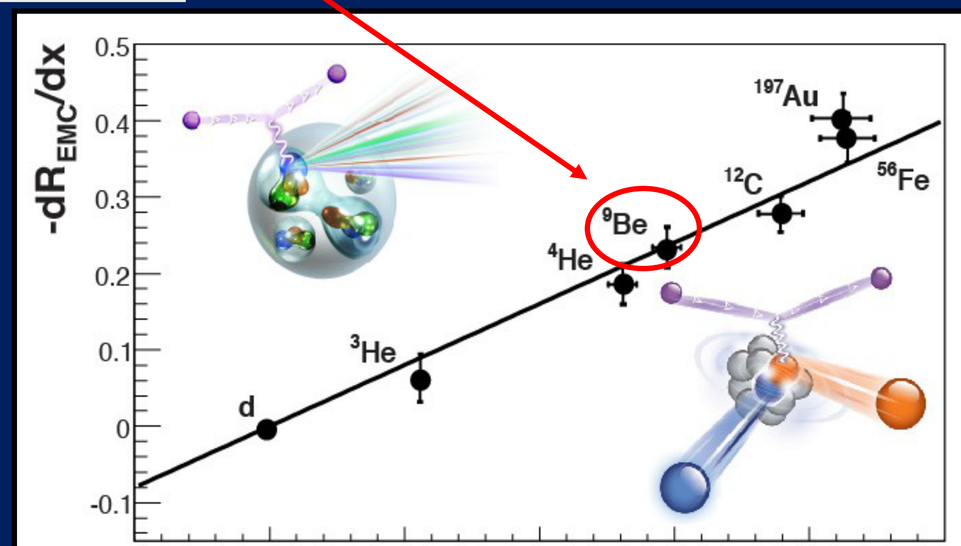






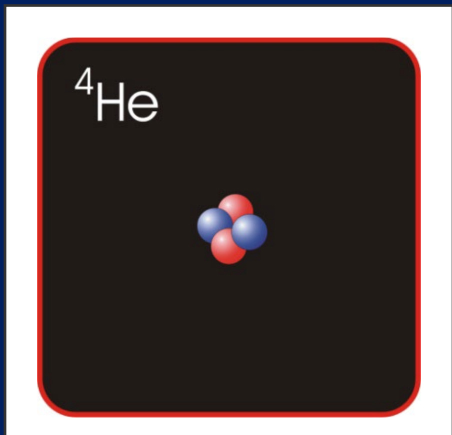
But appears to scale with local density!

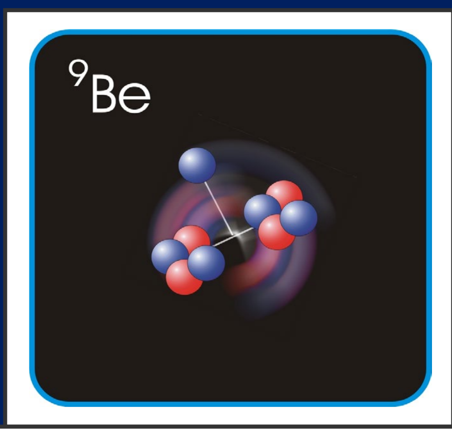


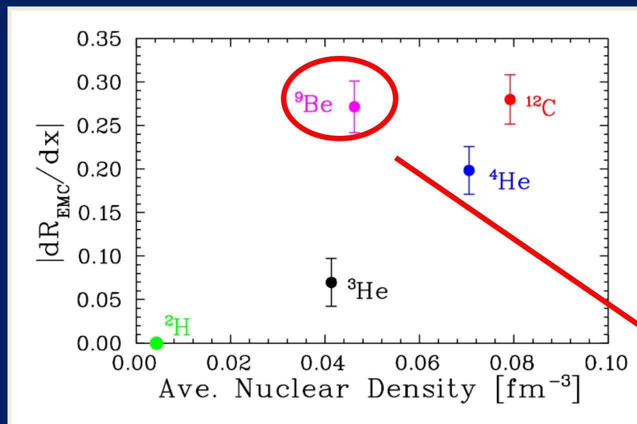
Hen, Piasetzky, Weinstein,
Phys. Rev. C85, 047301 (2012)

Density determined from *ab initio* few-body calculation
S.C. Pieper and R.B. Wiringa, Ann. Rev. Nucl. Part. Sci 51, 53 (2001)

Partonic momentum structure of nuclei: EMC effect and local density

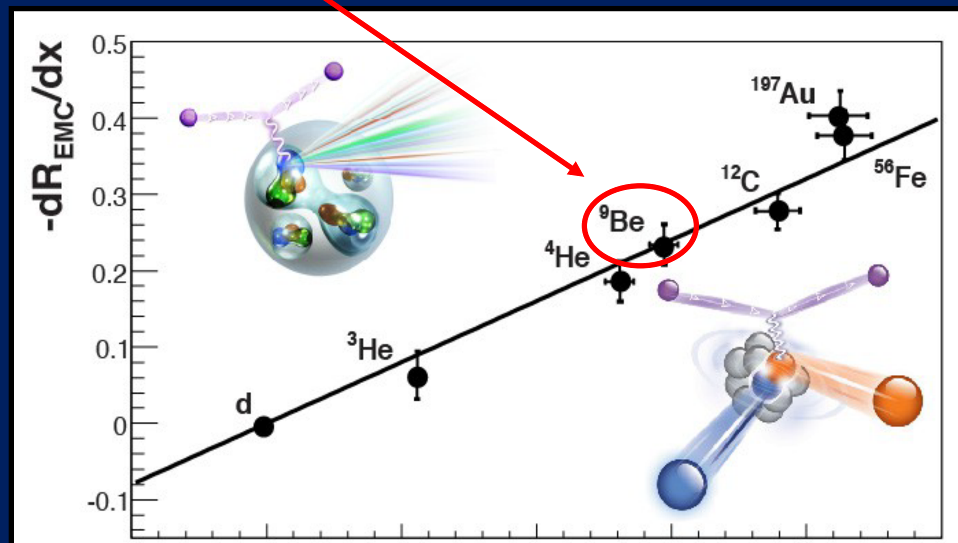






But appears to scale with local density!

Small but nonzero effect for ^{3}He



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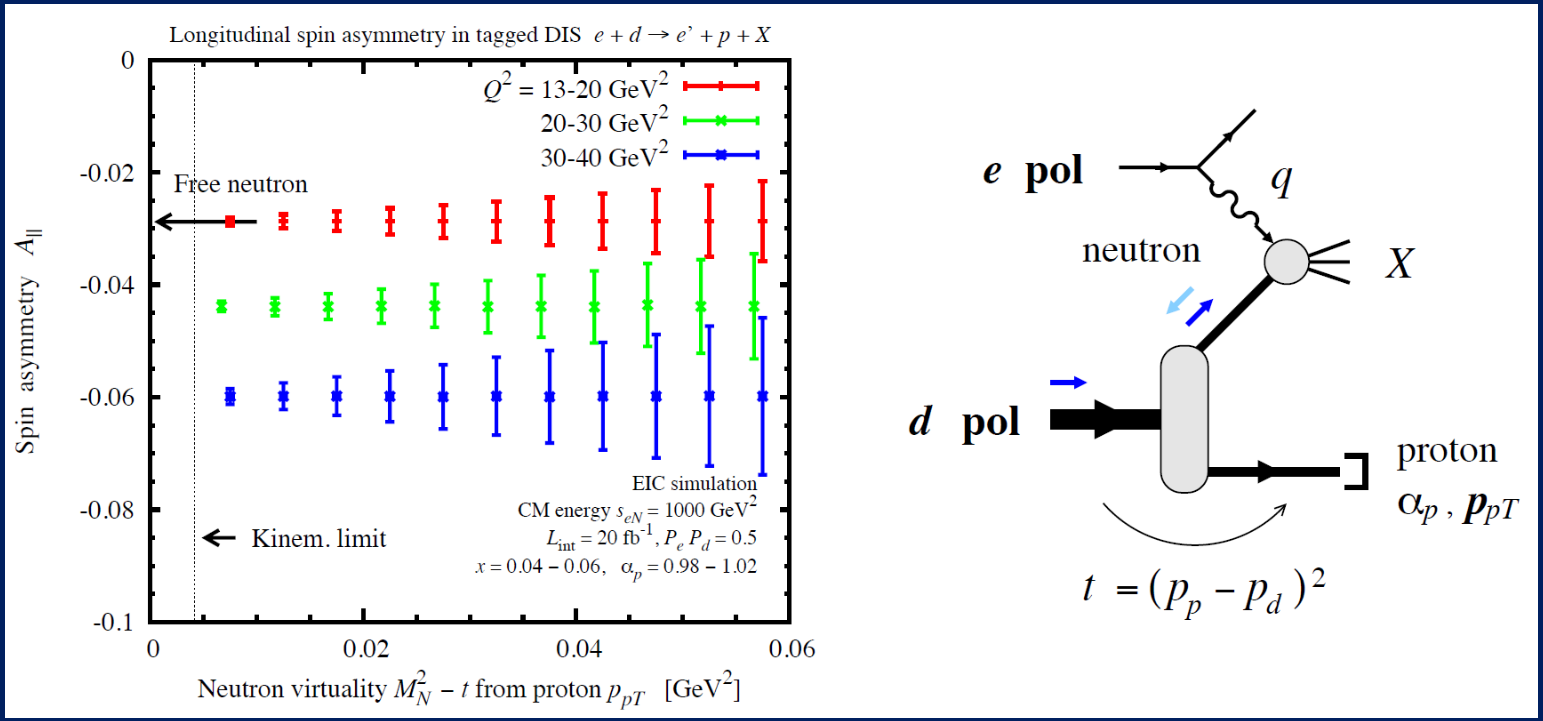
Possibility of polarized deuteron beams at the EIC

- Polarized deuteron beams at the EIC much more challenging than polarized ^{3}He but would offer a number of interesting opportunities
- Reduced nuclear effects compared to ^{3}He
- Spectator tagging would allow measurement on a nearly free neutron
- Deuterons also allow us to study *tensor polarization*
  - See discussion in EIC Yellow Report (2021)
- Much less work has been done on spin-1 systems, but there is increasing interest . . .

EIC: Spectator tagging with deuteron beam

EIC Yellow Report, 2021

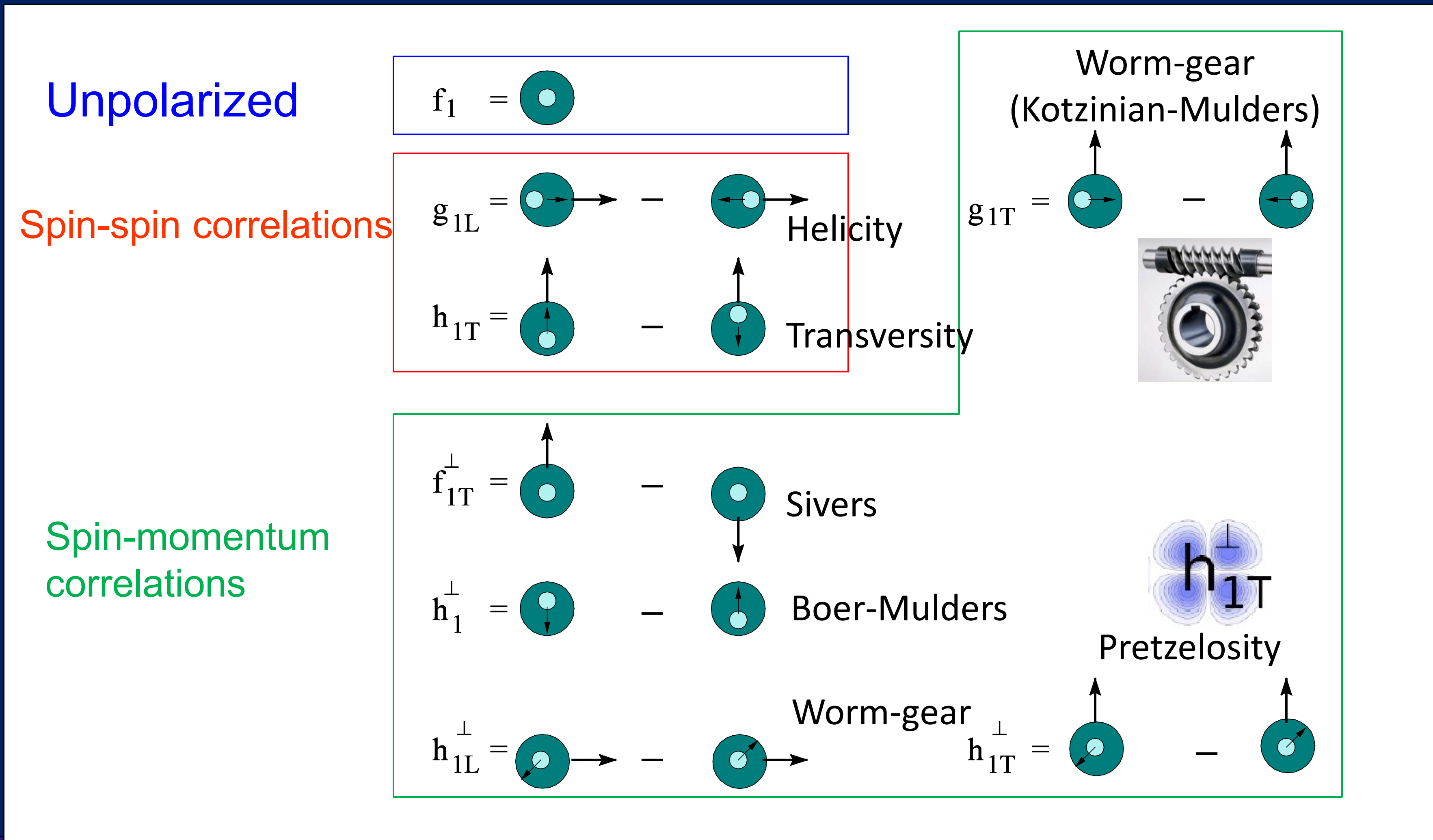


- Measure spectator proton in the far forward region, including its p_T, for sensitivity to neutron virtuality

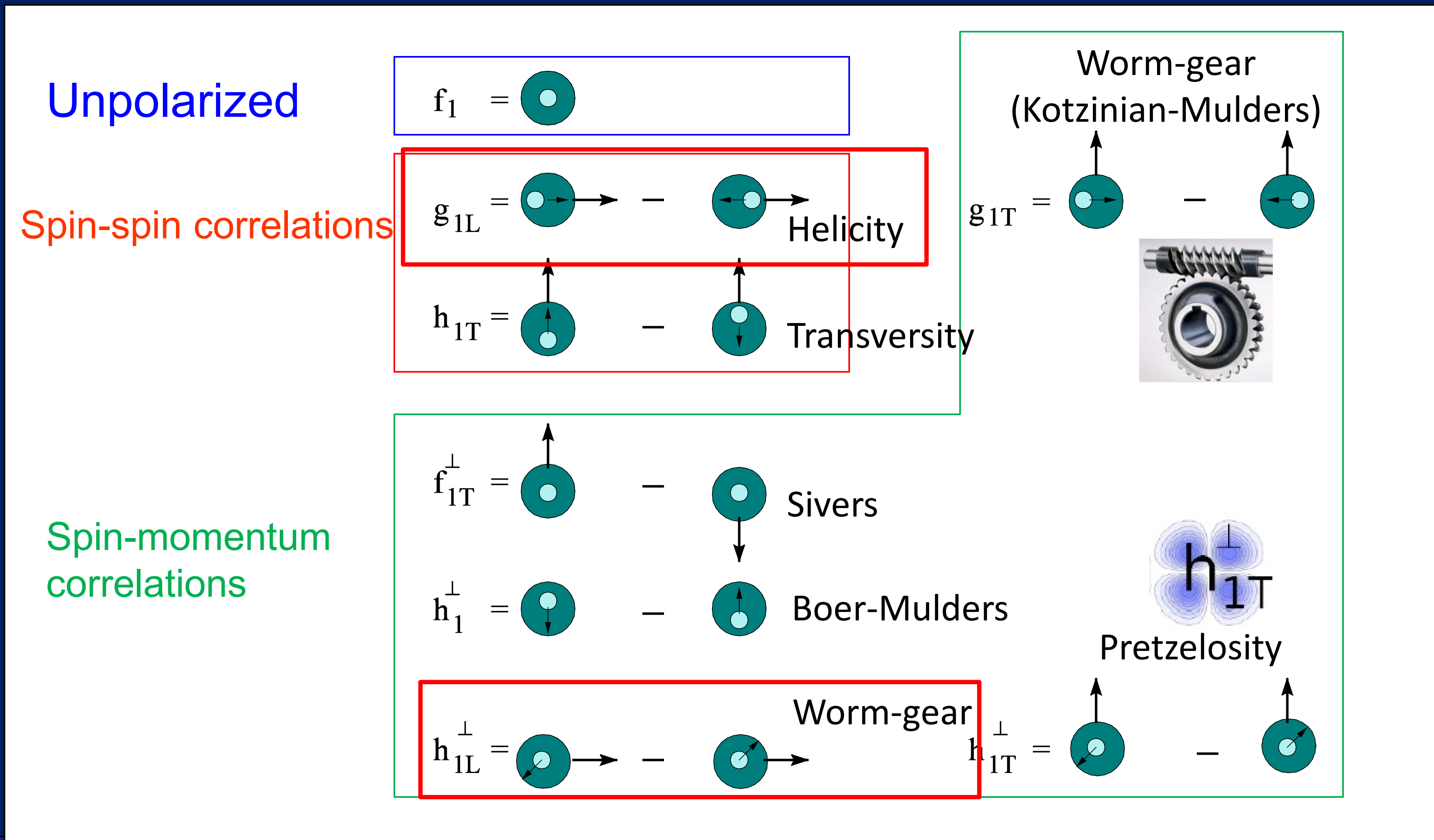
Exploring polarized deuterons

- Speculation – knowing unpolarized or polarized partonic structure of light nuclei someday helpful to improve efficiency of fusion reactions???
  - E.g. arXiv:2312.16777 – *Multiphoton fusion of light nuclei in intense laser fields*
    - "Future investigations should contemplate the utilization of a more realistic optical potential featuring a rigid core and nuclear spin"

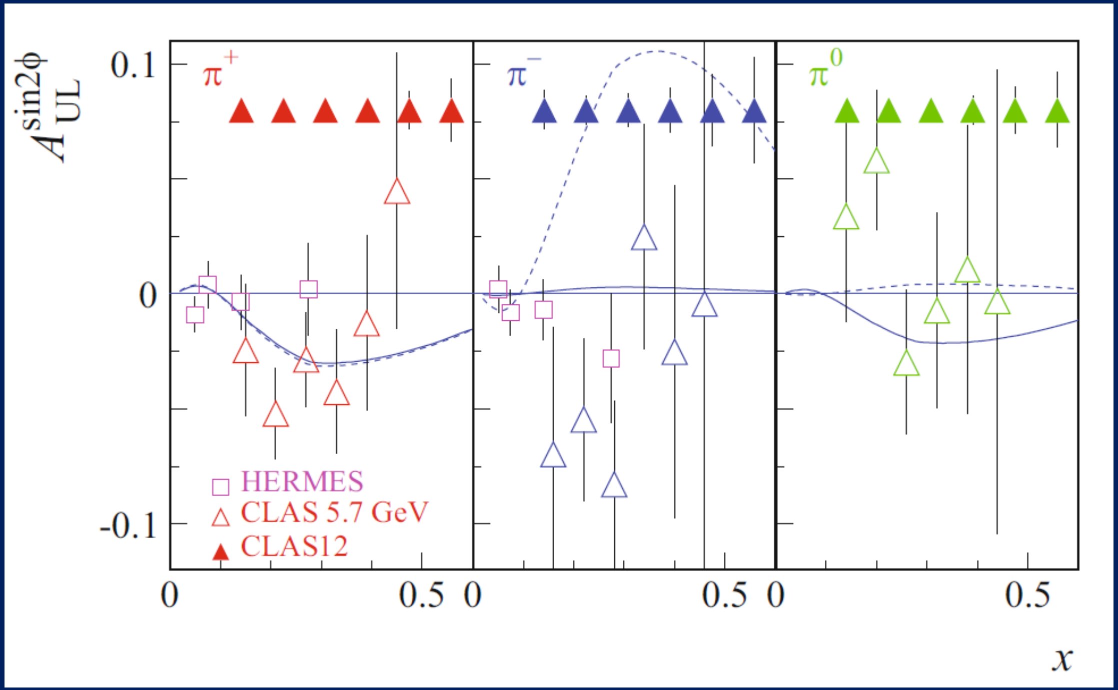
Longitudinally polarized protons and transverse-momentum-dependent PDFs



Longitudinally polarized protons and transverse-momentum-dependent PDFs



Worm-gear TMD PDF $h_{1L}^{\perp}$



EPJA 52, 150 (2016)

- $h_{1L}^{\perp}$ sensitive to transversely polarized quarks in a longitudinally polarized proton
  - A spin-spin-momentum correlation
- So far no evidence for a nonzero asymmetry, but higher-precision data expected from CLAS12

Ji spin sum rule, Generalized Parton Distributions, and OAM

- Ji spin decomposition: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$ PRL78, 610 (1997)
  - Only in terms of gluon *total* angular momentum
  - Different definition of L_q than in Jaffe-Manohar sum rule – matter and gauge degrees of freedom can't be unambiguously separated in a gauge theory

- Moments of some generalized parton distributions (GPDs) for longitudinally polarized protons can be related to quark orbital angular momentum
  - GPDs measurable via exclusive processes, e.g. deeply virtual Compton scattering to access quarks

Orbital angular momentum and generalized transverse-momentum-dependent distributions

- The formulation of *generalized transverse-momentum-dependent* distributions (GTMDs) encompasses both Jaffe-Manohar and Ji decompositions
  - See e.g. JHEP08, 056 (2009), PRD84, 014015 (2011), Phys. Rep. 541, 163 (2014)
  - Relating Ji and Jaffe-Manohar OAM using GTMD approach on the lattice –PRD102, 074505 (2020)

- Also recent proposals to access gluon orbital angular momentum at EIC via single and double spin asymmetry in diffractive dijet production, using the framework of Generalized TMDs: PRL118, 192004 (2017), PRL128, 182002 (2022)

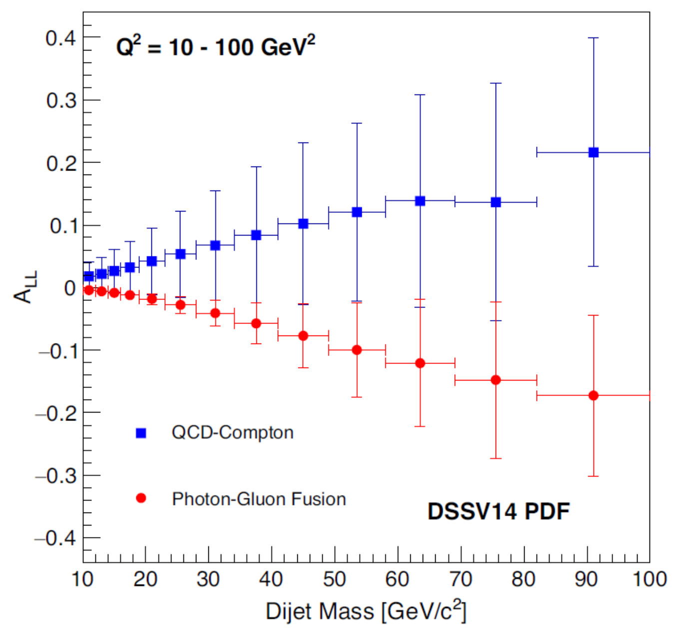
Summary

- The EIC will open up a great wealth of new opportunities to study the longitudinal spin structure of the proton and neutron as well as many other spin-dependent (and unpolarized) observables
- The more we learn in the upcoming years from theoretical developments as well as existing and near-term data, the more fully we will be able to exploit the EIC's powerful and unique capabilities once it turns on!

Extra

EIC: Accessing gluon helicity through double-longitudinal asymmetry for dijets

PRD101, 072003 (2020)



EIC: Parity-violating DIS for flavor-dependent helicity PDFs

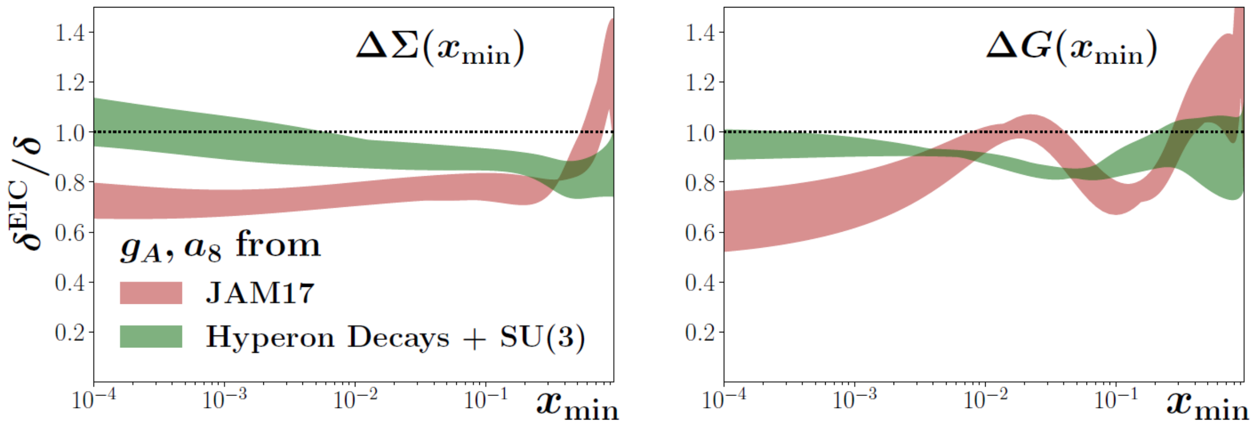
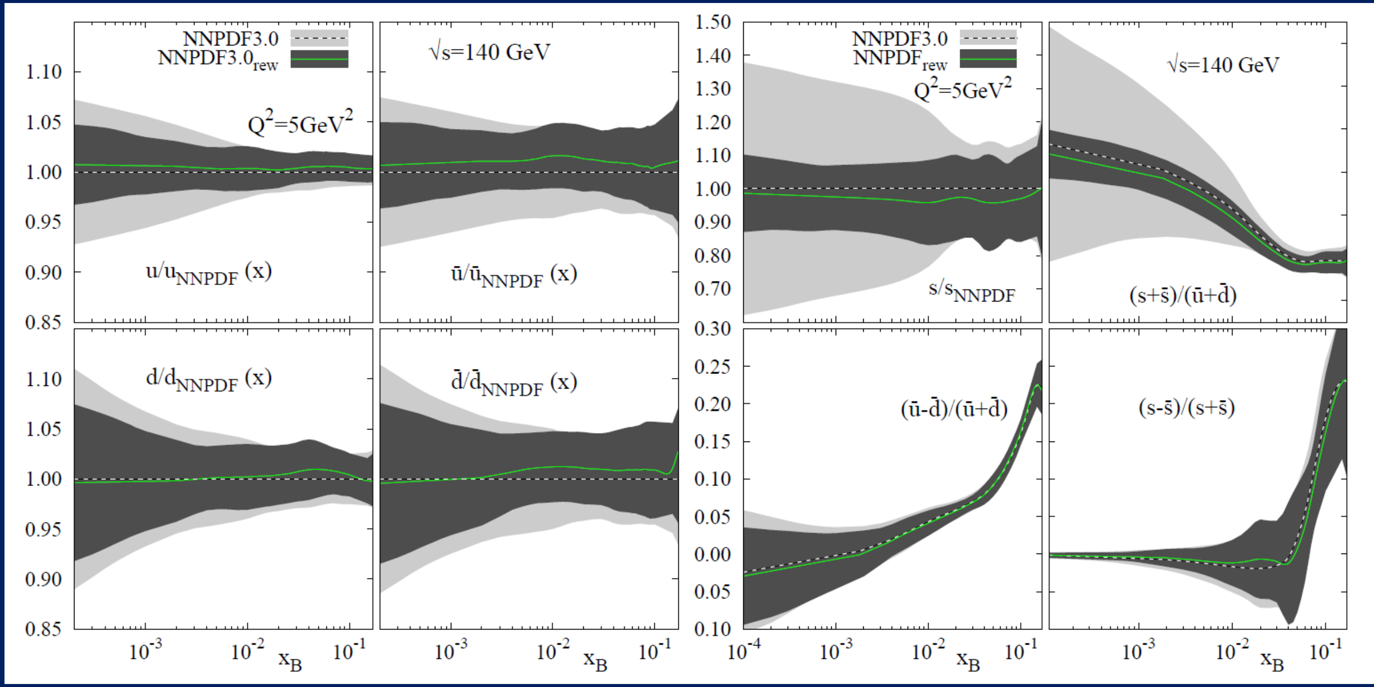


Figure 7.18: Ratio of uncertainties on the truncated moments of the quark singlet (left) and gluon (right) PDFs as functions of $x_{\rm min}$, including EIC data on the parity-violating DIS asymmetry $A_{\rm PV}^{\rm had}$ to those without EIC data, at $Q^2 = 10$ GeV^2. Results with values of g_A and a_8 taken from JAM17 [90] (red) are compared with those using values taken from hyperon decays and SU(3) (green).

EIC Yellow Report, 2021

SIDIS to probe flavor-separated unpolarized PDFs

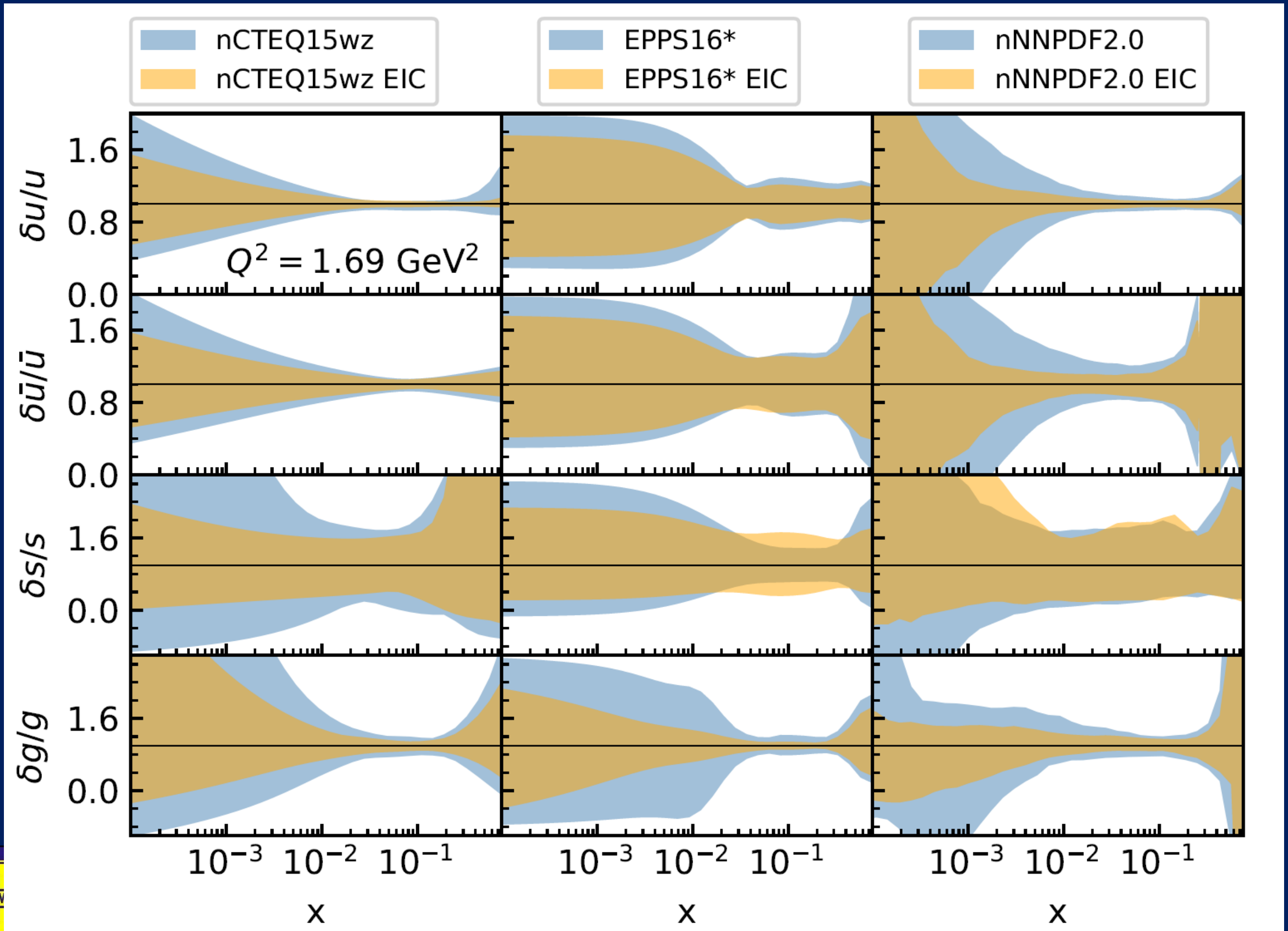


Projected impact on the **unpolarized** (sea) quark PDFs from identified charged pion and kaon SIDIS data at the EIC

EIC Yellow Report
Baseline PDFs from JHEP 04, 040 (2015)

Partonic momentum structure of nuclei: Nuclear parton distribution functions

(Traditional collinear, unpolarized) Nuclear PDFs



Expected improvement on uncertainty in nuclear PDFs - from Yellow Report

Processes sensitive to GPDs

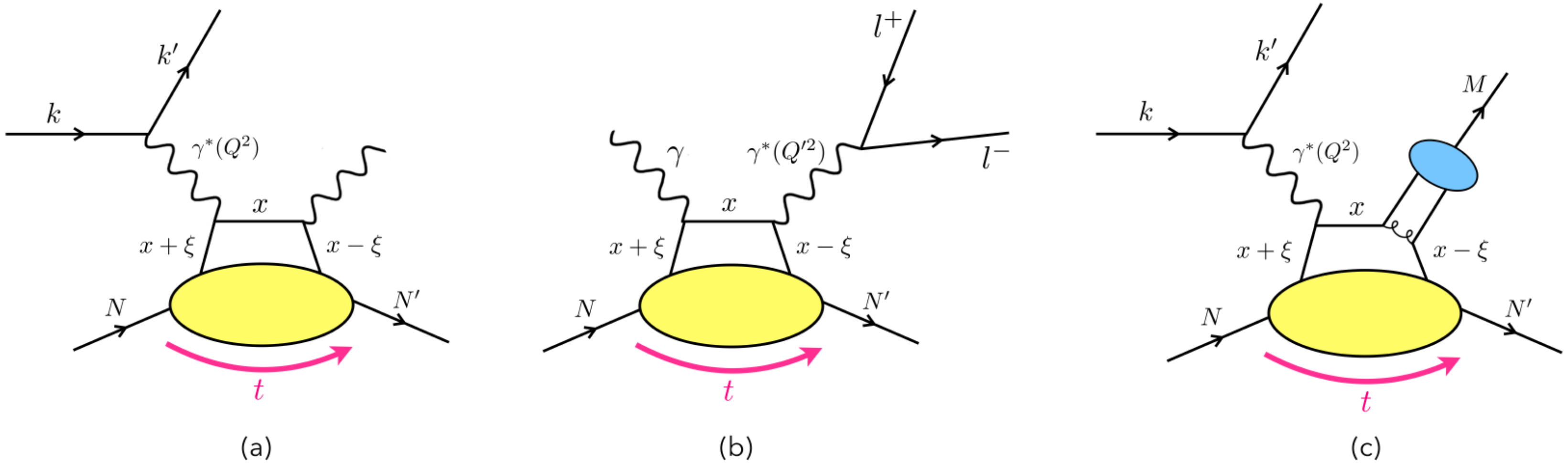


Figure 7.43: Illustrations of three main processes which are sensitive to GPDs: (a) exclusive electroproduction of a real photon, (b) TCS and (c) exclusive electroproduction of a meson.

From EIC Yellow Report (2021)

Twist-3 multiparton correlation functions

- Interference between higher Fock components in the hadron wave functions
- No probabilistic partonic interpretation, but provide information on partons involved in hard scattering interacting with color fields in the initial-state hadron

Nucleon-to-meson transition distribution amplitudes

- 3-parton exchange between the TDA and the hard part
- Potential access to helicity of correlated quarks in the nucleon
- See discussion in EIC Yellow Report

Long-term: Synthesizing what we learn

- Eventually want a unified picture linking these nonperturbative functions coming from a “hard” factorized regime to a “soft” regime where this kind of partonic language isn’t necessarily suitable.
  - Could thinking about multiparton correlation functions potentially be a step towards useful “nonperturbative color blob” descriptions of some sort???

- What might nonperturbative theoretical tools such as lattice QCD, low-energy models, or possibly future quantum computers tell us about how to fruitfully link perturbative/partonic and nonperturbative/nonpartonic descriptions of hadron structure?