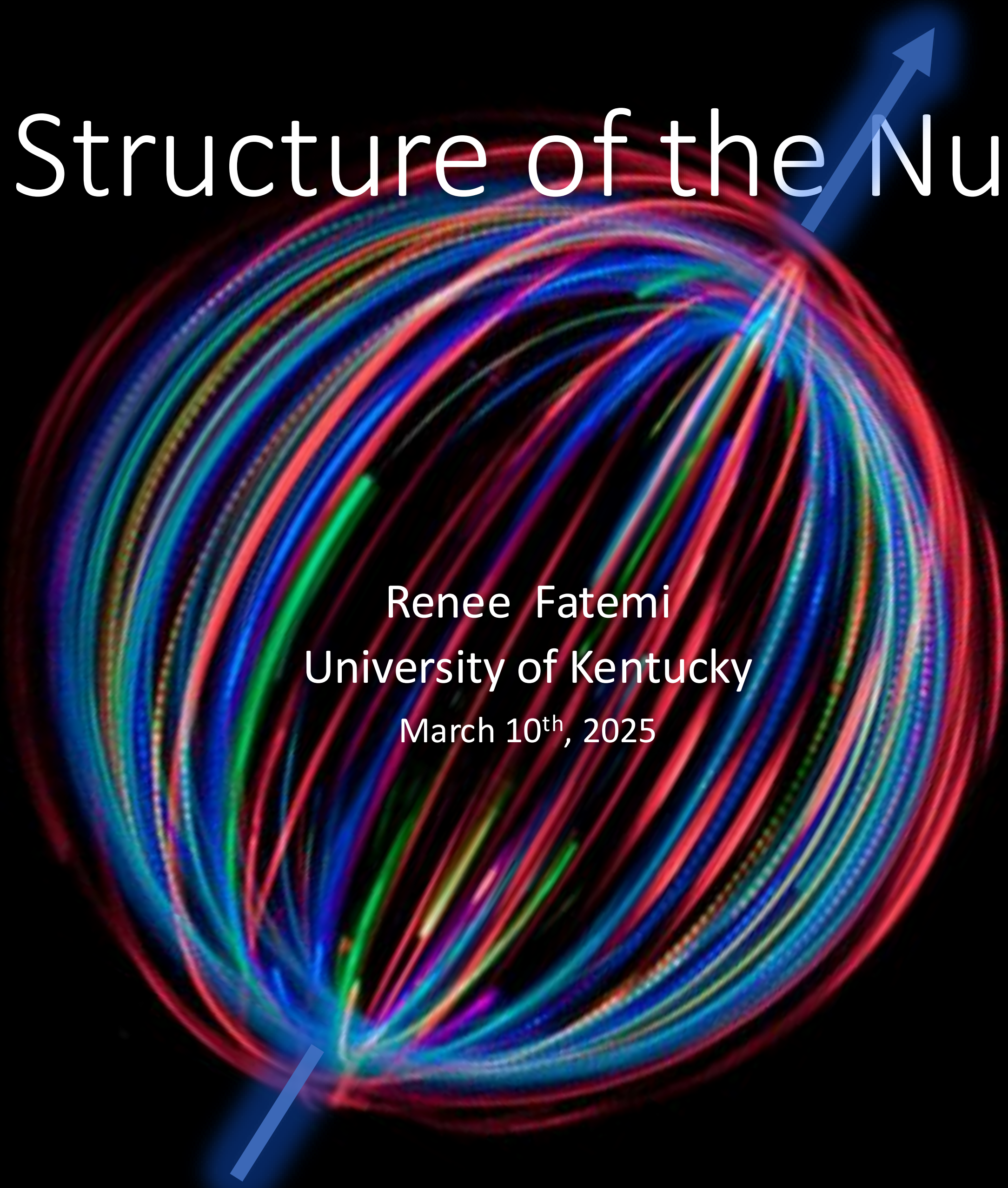
Spin Structure of the Nucleon



Renee Fatemi
University of Kentucky
March 10th, 2025

Center for Frontiers in Nuclear Science Special Conference on Polarized Sources and Beams at the EIC

How do we “see” quarks and gluons?

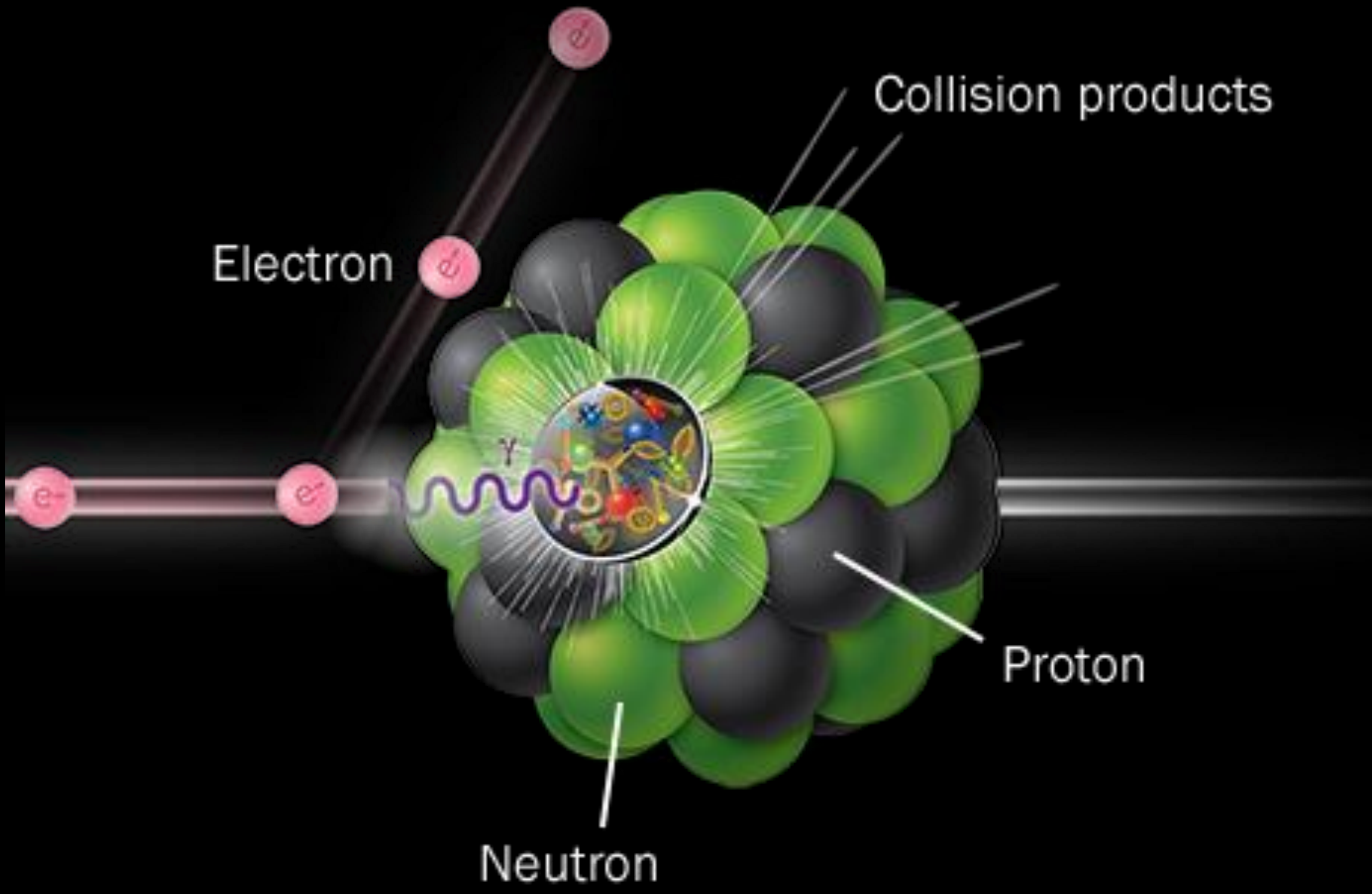
At the EIC we will use matter, electrons, to probe inside nucleons and nuclei.

Resolution of matter microscope:

$$Q^2 = -(p_e - p_e')^2$$

Momentum Fraction of struck quark:

$$x = \frac{Q^2}{2p_p \cdot p_\gamma}$$



When you close your eyes … what proton do you see?

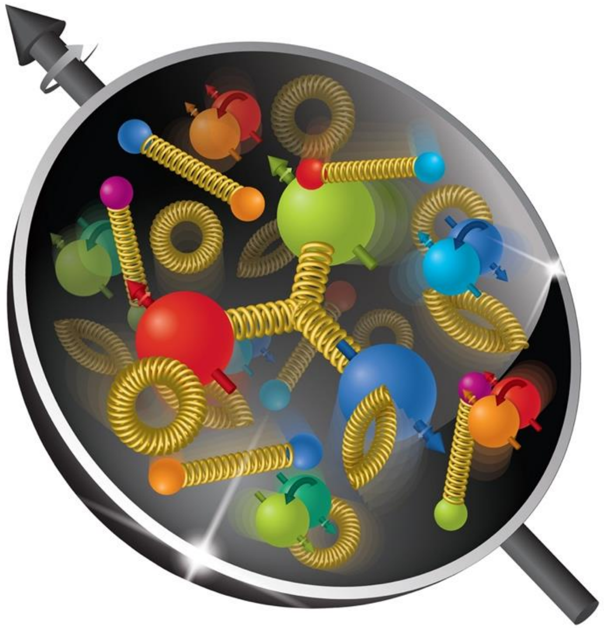
Credits

This work was a collaborative effort of Rolf Ent (Physicist, Jefferson Lab) and Richard Milner (Physicist, MIT). Proton animations by James LaPlante (Animator, Sputnik Animation). Edited by Alexander Higginbottom (MIT Video Productions). Film consultants Christopher Boebel and Joe McMaster (Film Producers, MIT).

Now add in spin degrees of freedom….

Spin Sum Rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta G(\mu) + L_{Q+G}(\mu)$$



QUARK Helicity

$$\Delta\Sigma(\mu) = \sum_f \boxed{\int_0^1} \Delta q(x,\mu)dx$$

GLUON Helicity

$$\Delta G(\mu) = \boxed{\int_0^1} \Delta g(x,\mu)dx$$

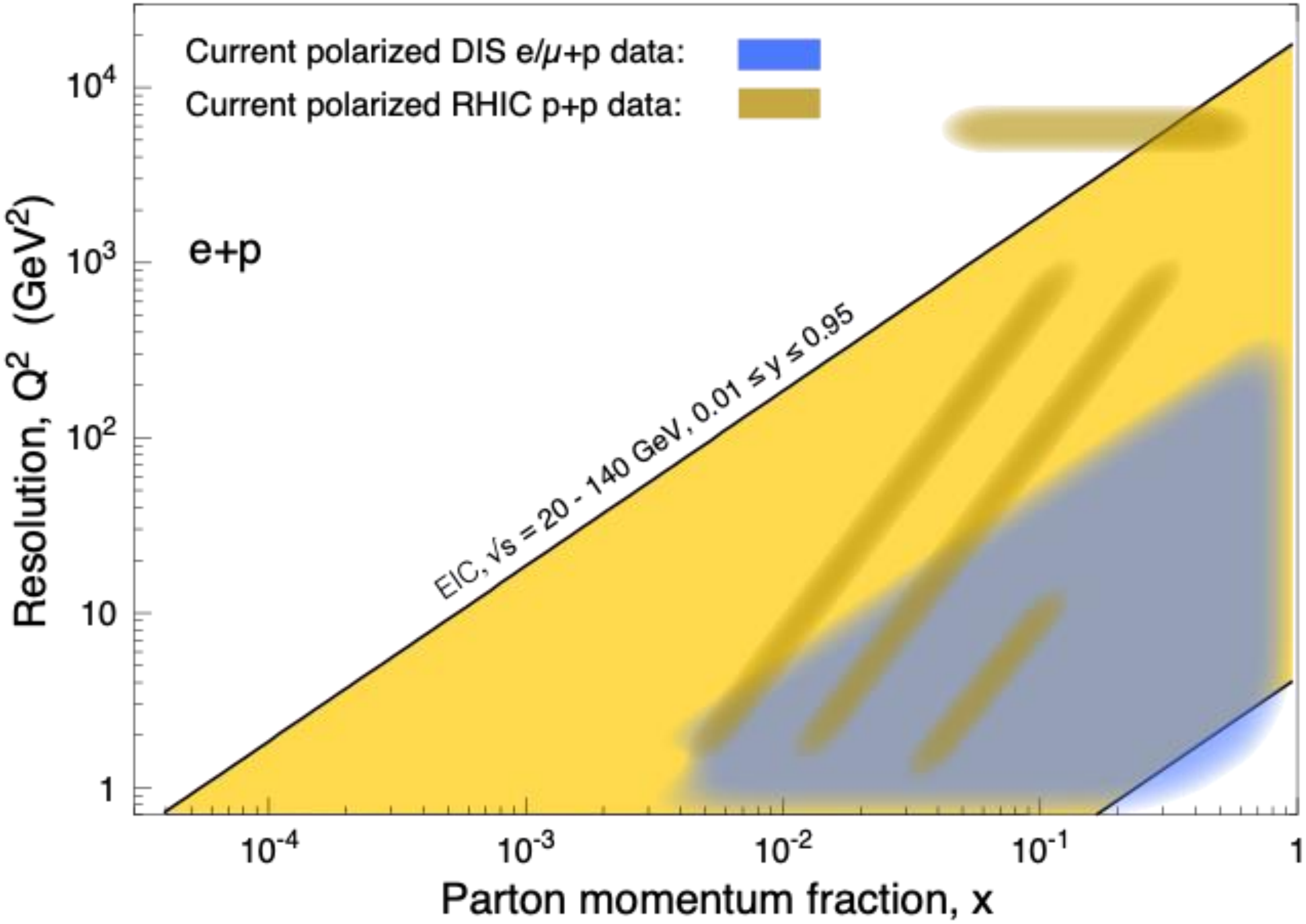
QUARK+GLUON Angular Momentum

$$L_{Q+G}(\mu) = \boxed{\int_0^1} [l_q(x,\mu) + l_g(x,\mu)]dx$$

All distributions are defined at renormalization scale **$\mu \sim Q^2$** setting the effective resolution at which the proton is probed.

Spin Sum Rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta G(\mu) + L_{Q+G}(\mu)$$



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta G(\mu) + L_{Q+G}(\mu)$$

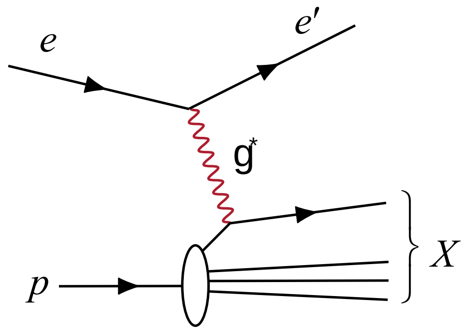
Helicity Distributions

- Quark Sum and Gluon
- Flavor separated quarks
- Sea quark distributions
- Bjorken Sum Rule

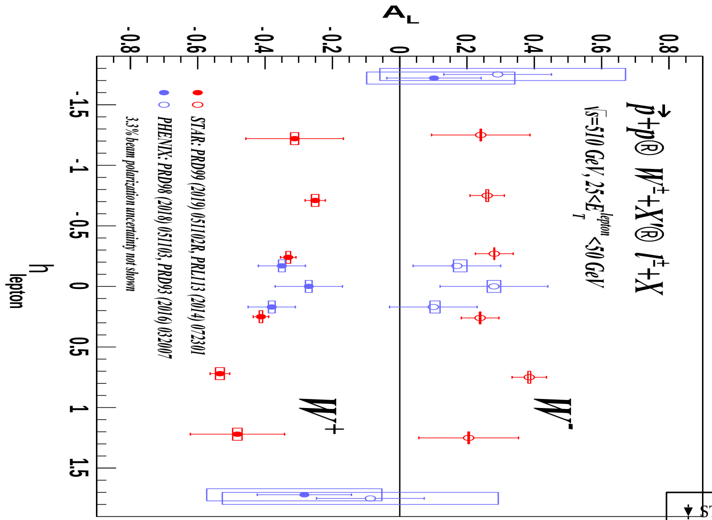
Orbital Angular Momentum

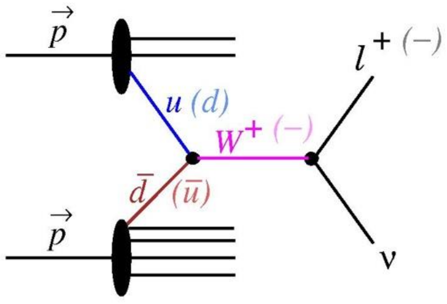
- Sum Rule constraints
- Generalized Parton Distribution Functions
- Transverse Momentum Distributions

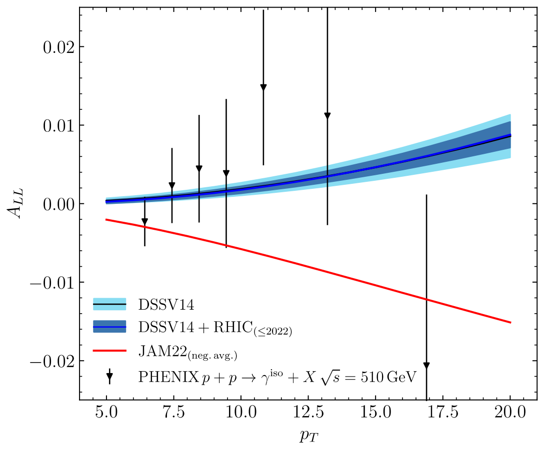
Quark and Gluon HELICITY

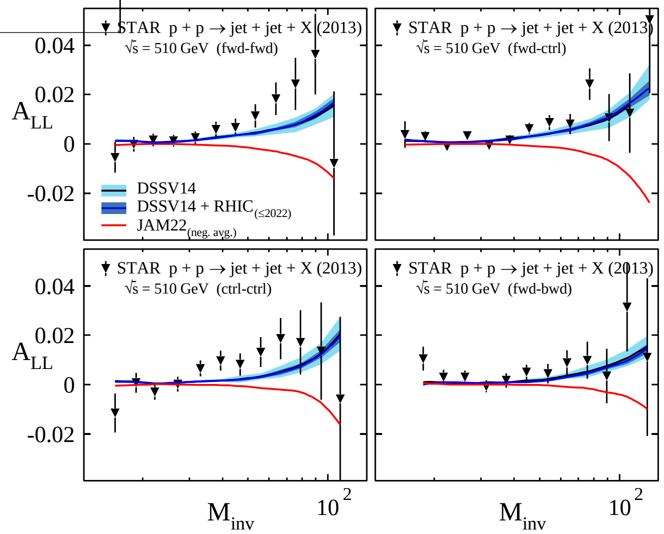


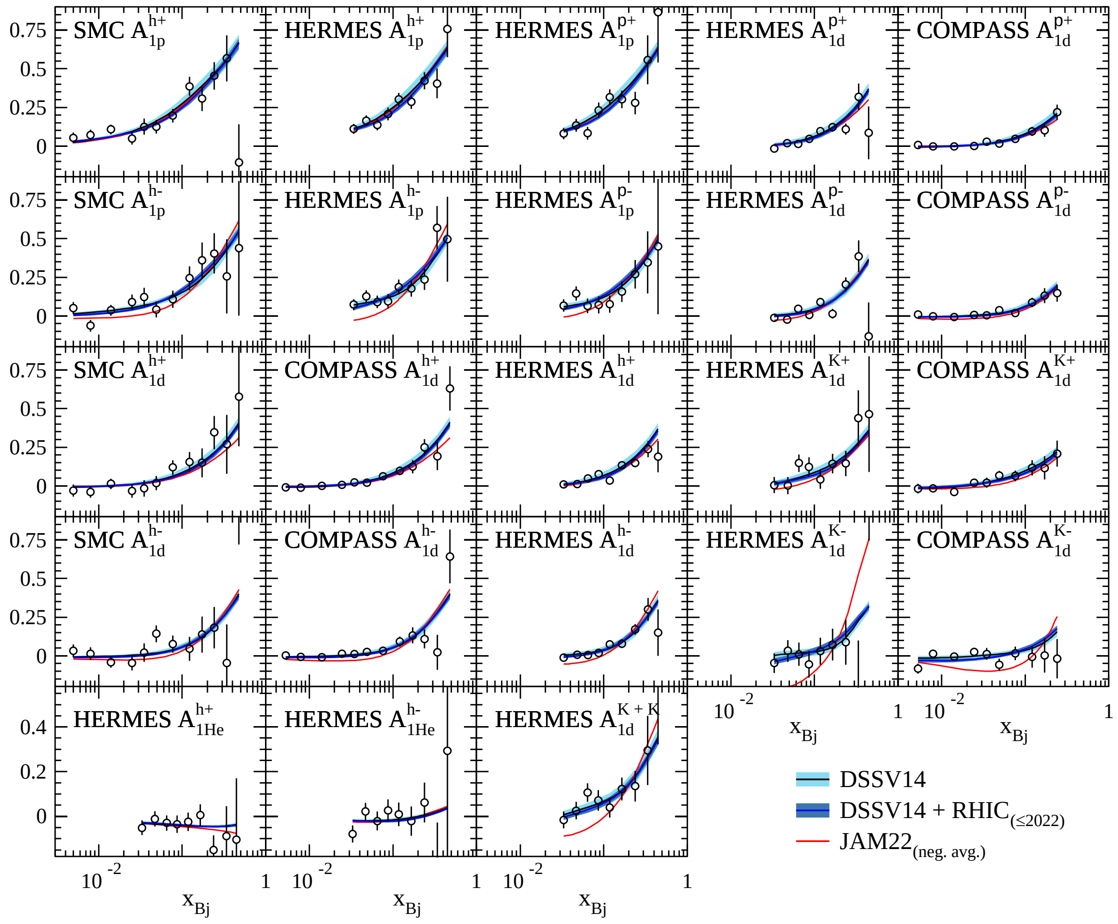
Four decades of asymmetry measurements in polarized lepton-proton and proton-proton scattering experiments has produced a wealth of data that is sensitive to quark and gluon helicity distributions.





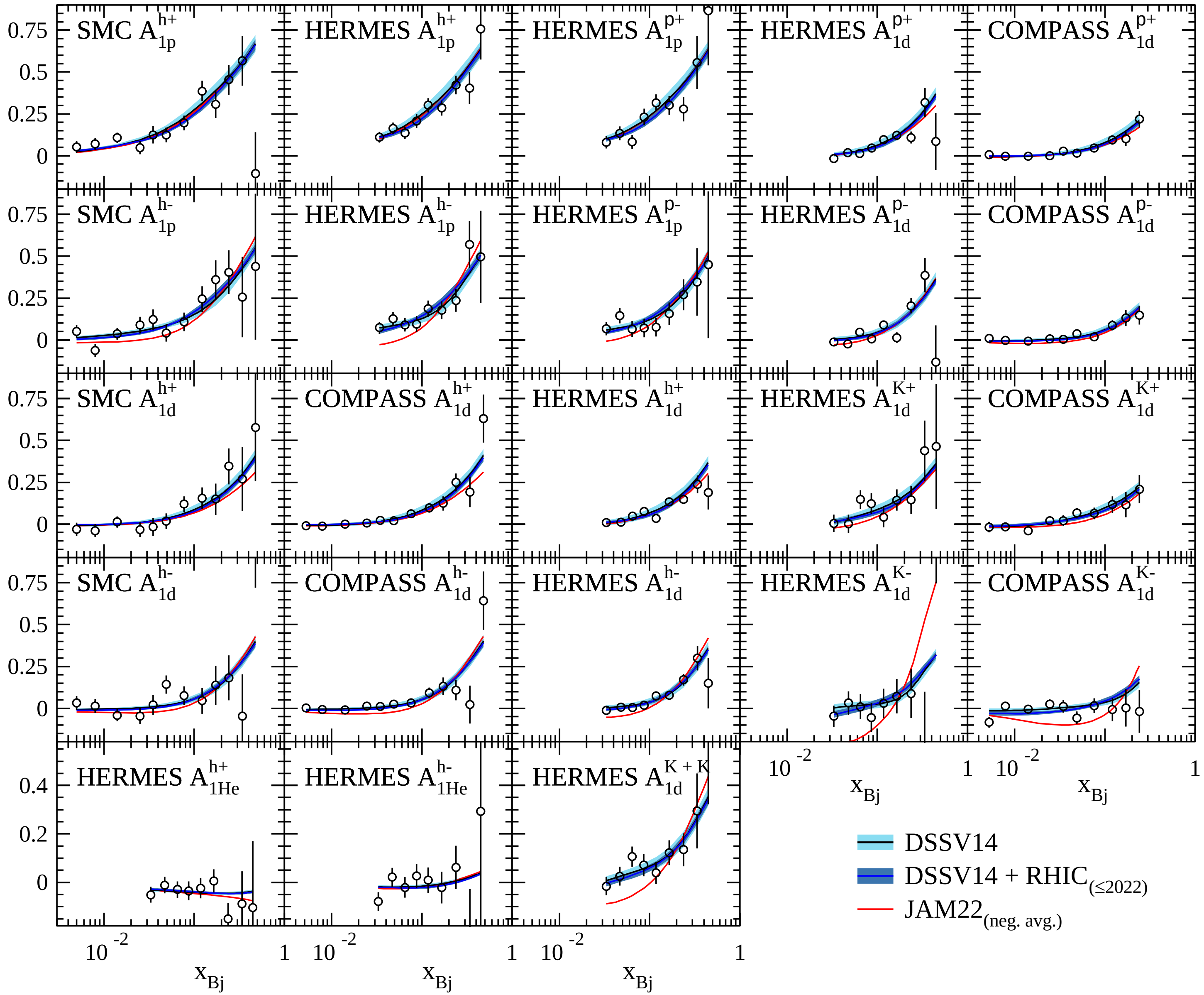






Quark and Gluon HELICITY

Global QCD Analysis of inclusive DIS + SIDIS and pp data allows for extraction of state-of-the art helicity PDFs at NLO and NNLO.



DSSV

PRL 101 (2008) 072001

PRD 80 (2009) 034030

PRL 113 (2014) 012001

PRD 100 (2019) 114027

JAM

PRD 93 (2016) 074005

PRL 119 (2017) 132001

PRD 104 (2021) L031501

NNPDF **only inclusive*

NPB 874 (2013) 36

NPB 887 (2014) 276

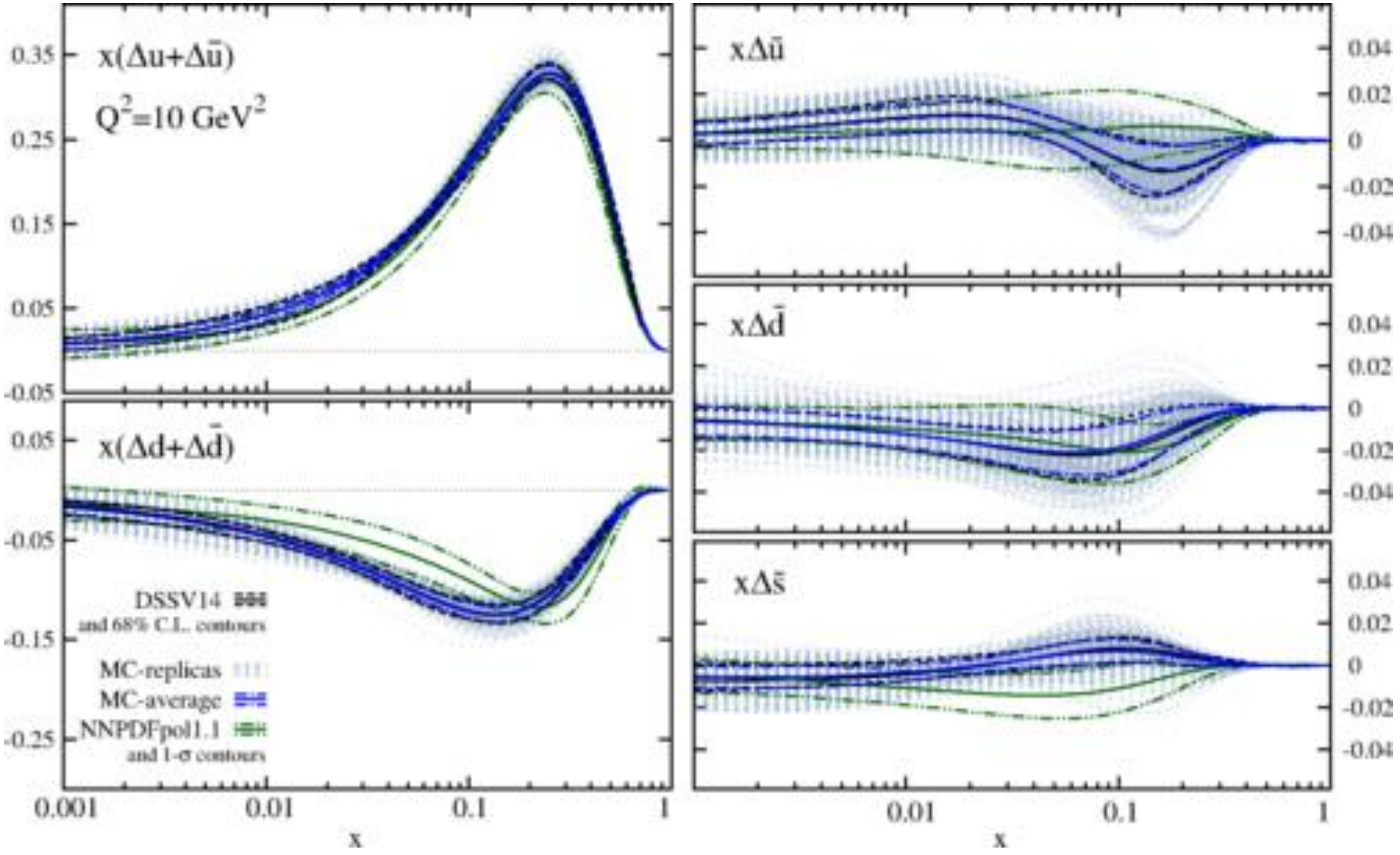
arXiv : 1510.04248

arXiv : 1702.05077

Quark and Gluon HELICITY

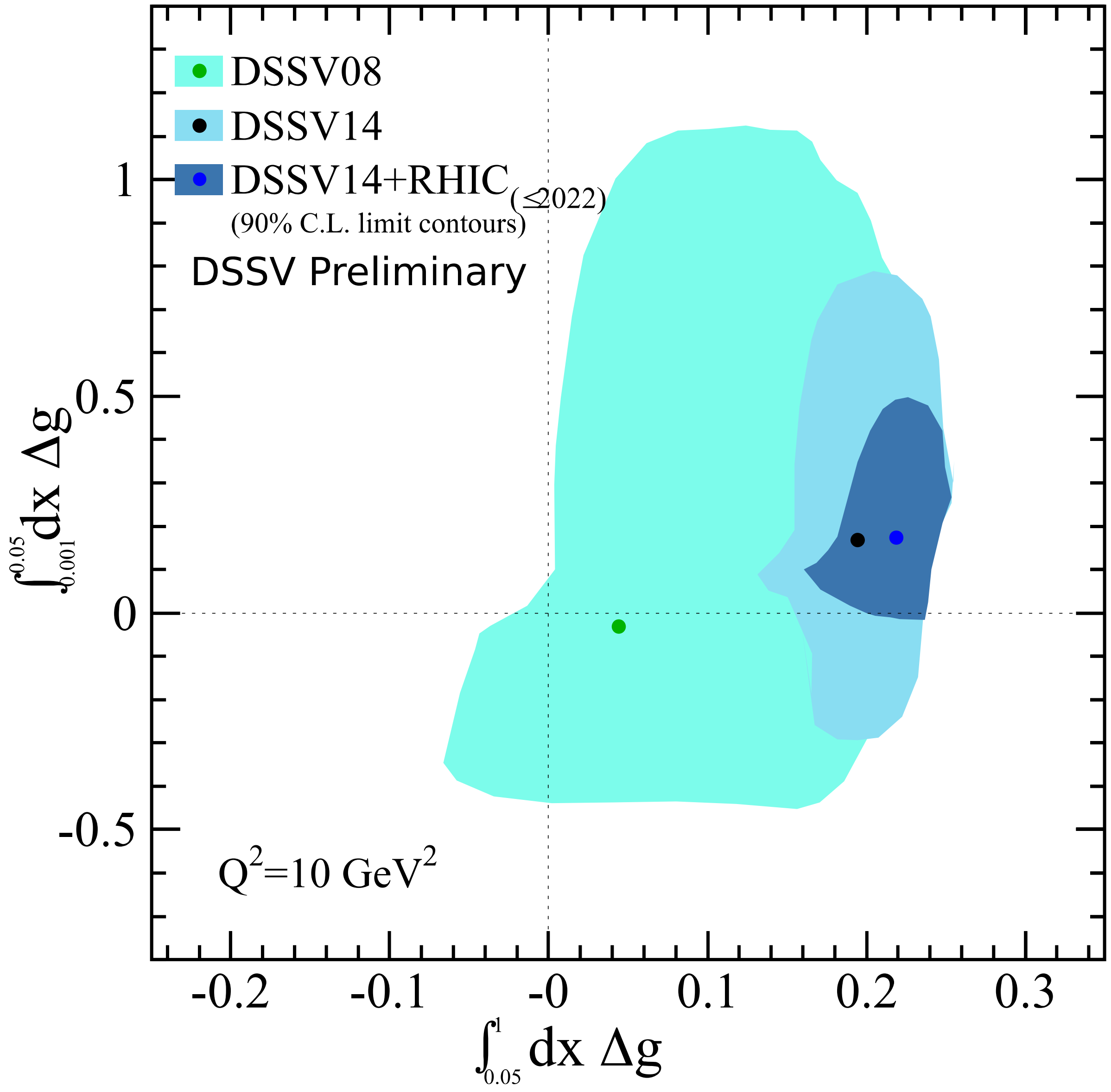
- 25% of the proton spin originates with the quarks (@ Q^2=10 GeV^2)
- Consistent with original EMC result $14 \pm 9 \pm 21\%$!
- The up (down) quarks like to (anti) align with the spin of the proton.
- Strange quark contribution is small
- Precision is driven by existing DIS + SIDS data
- Quarks evolve slowly with Q^2 -> lots of room for additional contributions from gluons, OAM….

$$\Delta\Sigma(10\ \mathrm{GeV}^2) = \int dx[\Delta q + \Delta\bar{q}] \sim 0.25$$

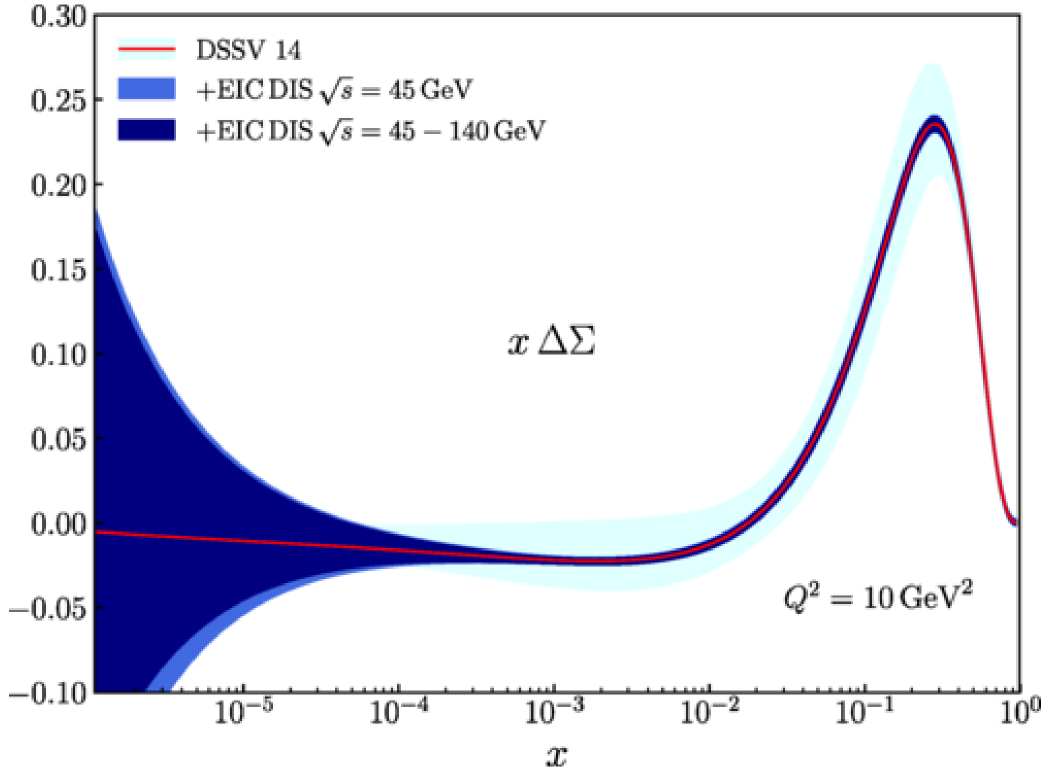


Quark and Gluon HELICITY

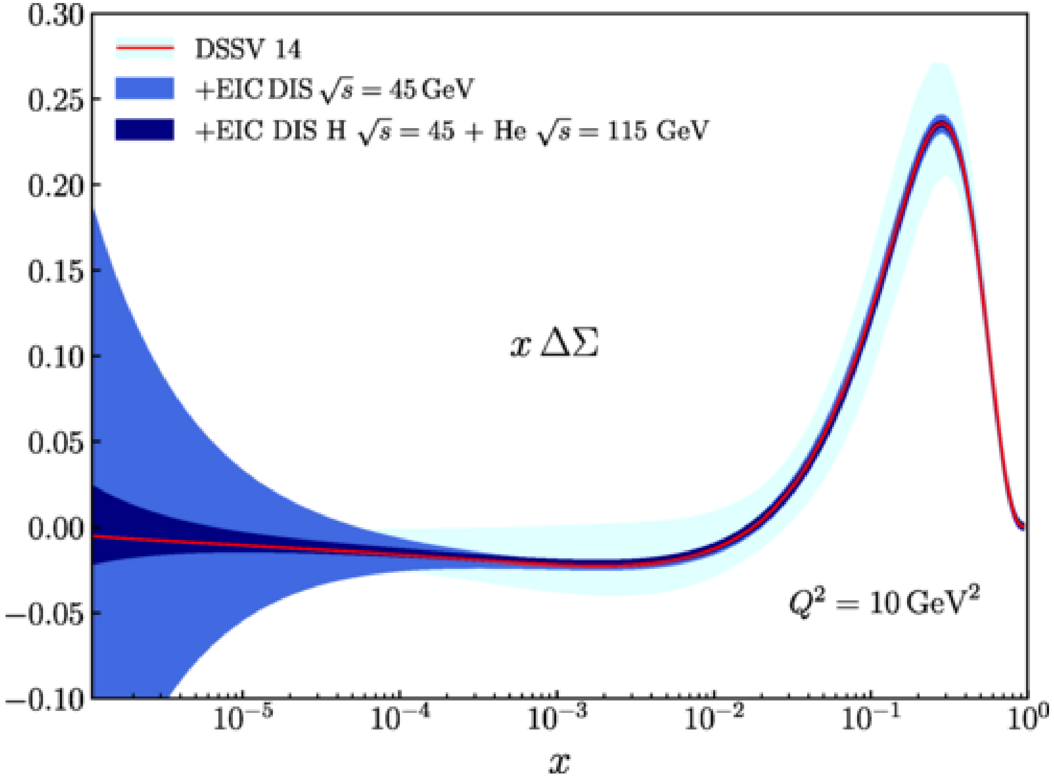
- Inclusive DIS fixed target data do not cover a wide enough kinematic range to really constrain the gluon helicity distribution.
- Inclusive jet and pion A_{LL} results from RHIC have steadily narrowed the contribution from gluon for x > 0.05.
- Dijet and prompt photon A_{LL} show clearly that ΔG is positive.
- Large uncertainties remain for the low-x gluons
- High x gluons appear to contribute 40% to a high energy proton's spin.



EIC constraints on $\Delta\Sigma$



Inclusive e+p data only!



Inclusive data e+p and e+He data

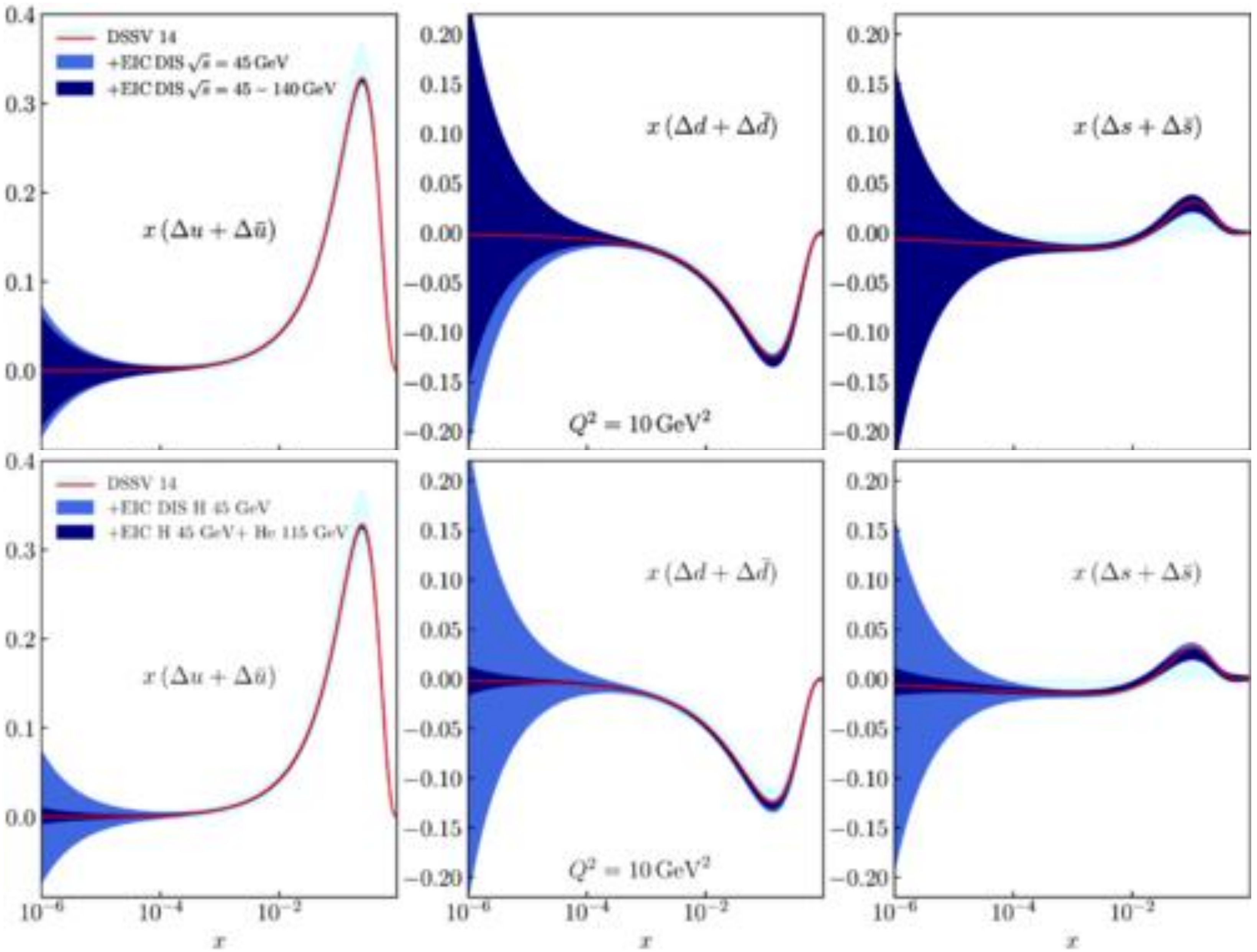
PRD 102 (2020) 094018

Quark and Gluon HELICITY

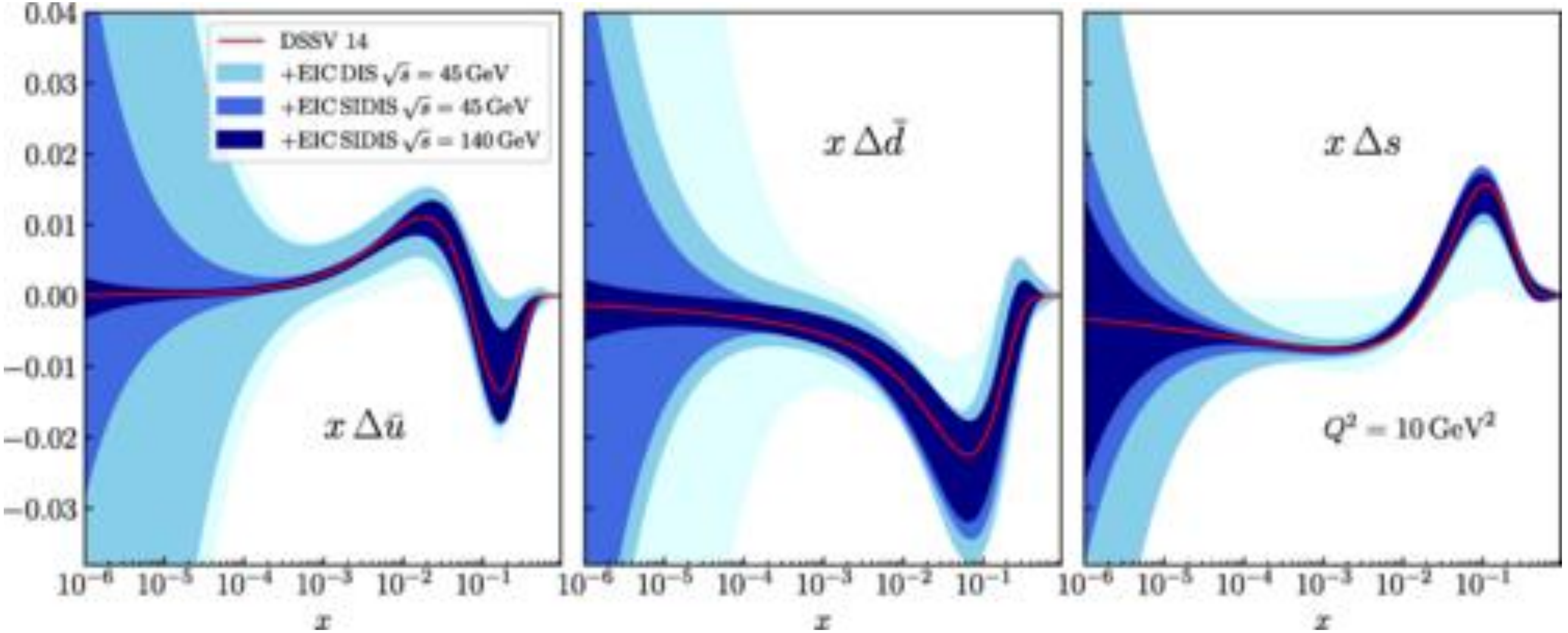
Comparison of EIC constraints on flavor separated $\Delta q(x)$ with only e+p data and with e+^{3}He data added in.

This improvement comes without any SIDIS data or any of the associated systematic uncertainties.

PRD 102 (2020) 094018



Quark and Gluon HELICITY

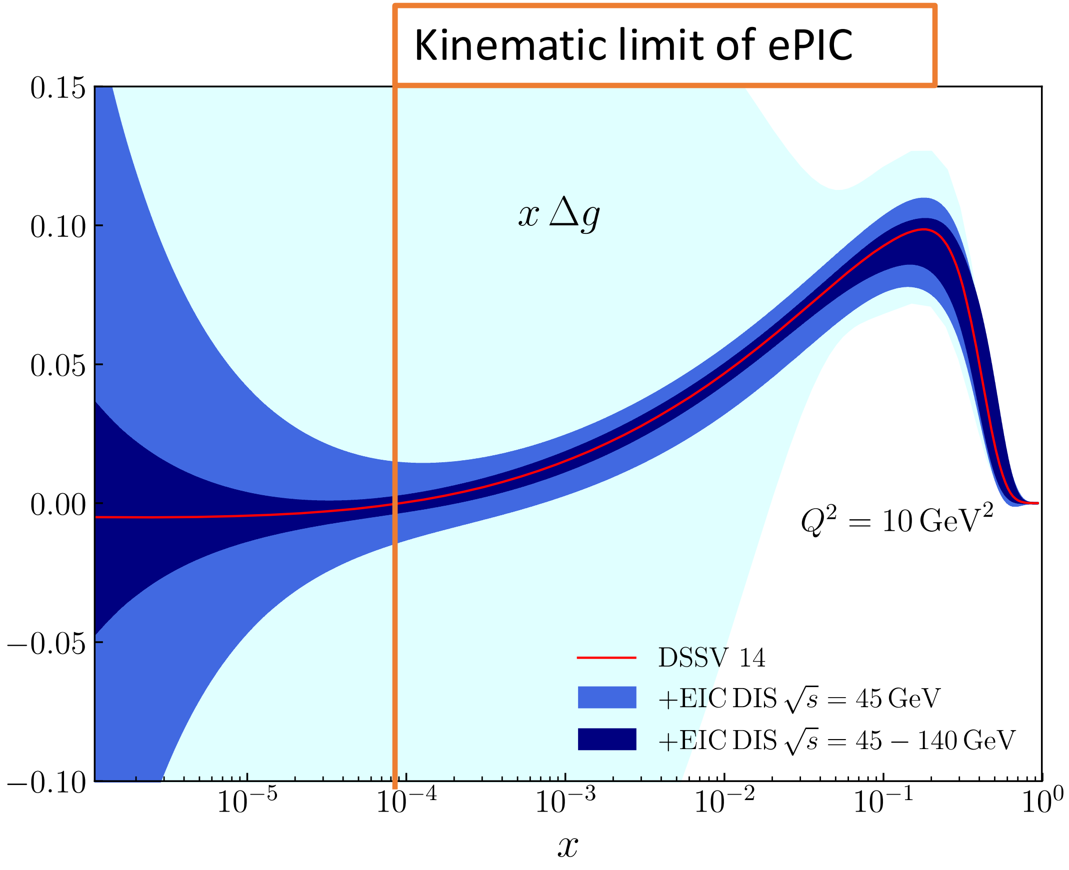


PRD 102 (2020) 094018

EIC constraints on $\Delta q(x)$ from both Inclusive and SIDIS data.

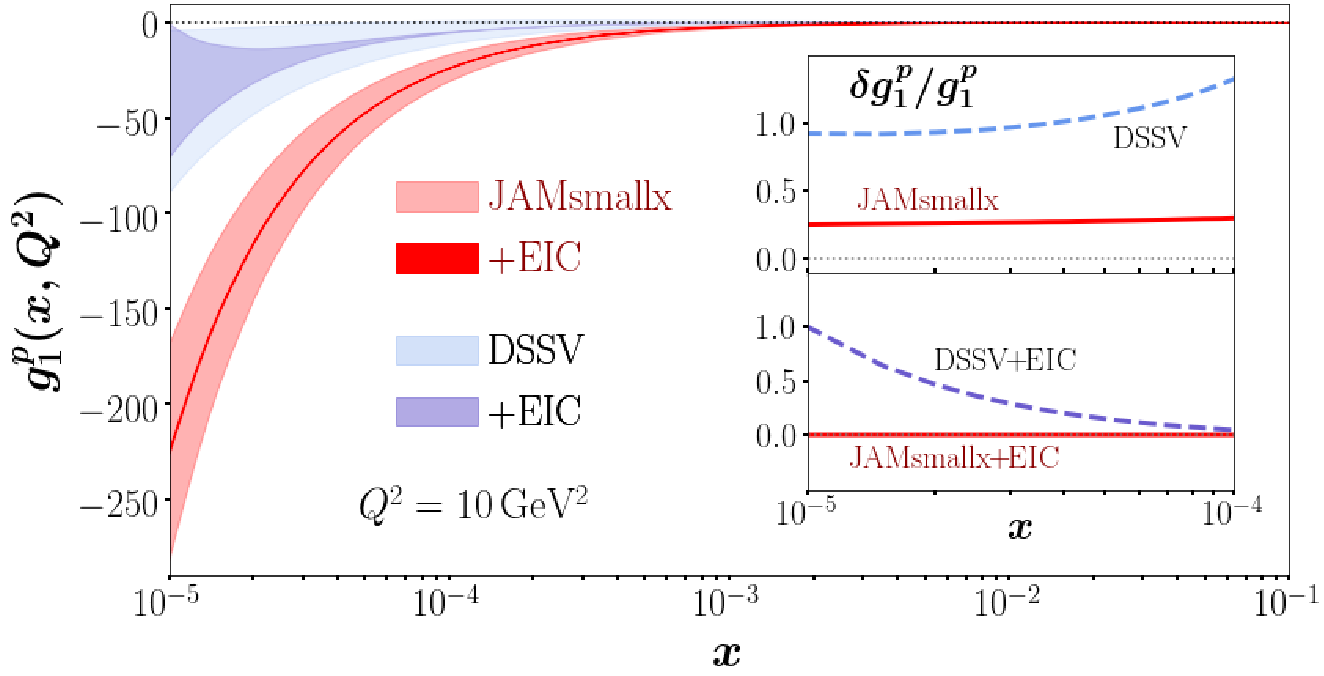
Quark and Gluon HELICITY

EIC constraints on $\Delta g(x)$



PRD 102 (2020) 094018

Curves $x < 10^{-4}$ are constrained by evolution equations. ***DSSV*** and ***JAMsmallx*** use Q^2 and x evolution respectively.

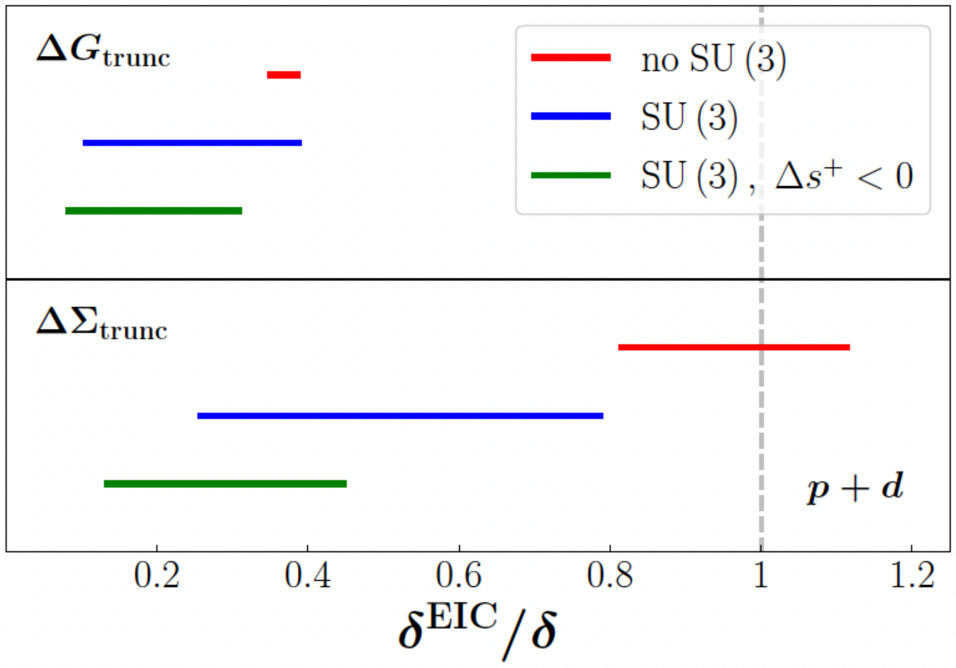


PRD 104 (2021) L031501

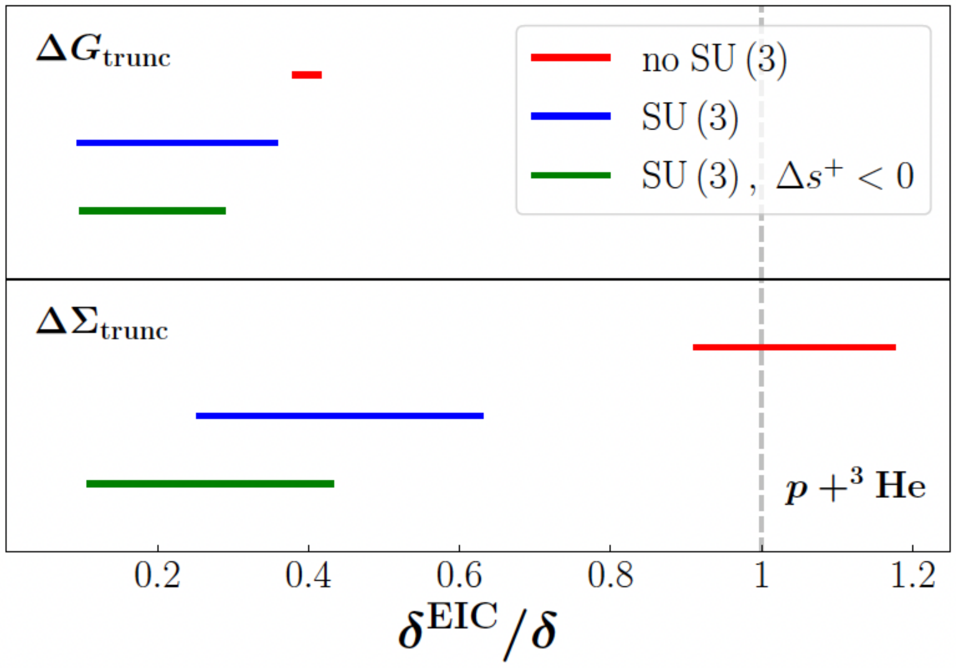
Quark and Gluon HELICITY

JAM Collaboration
Phys Rev D. 111, 05201 (2024)

Proton + deuteron



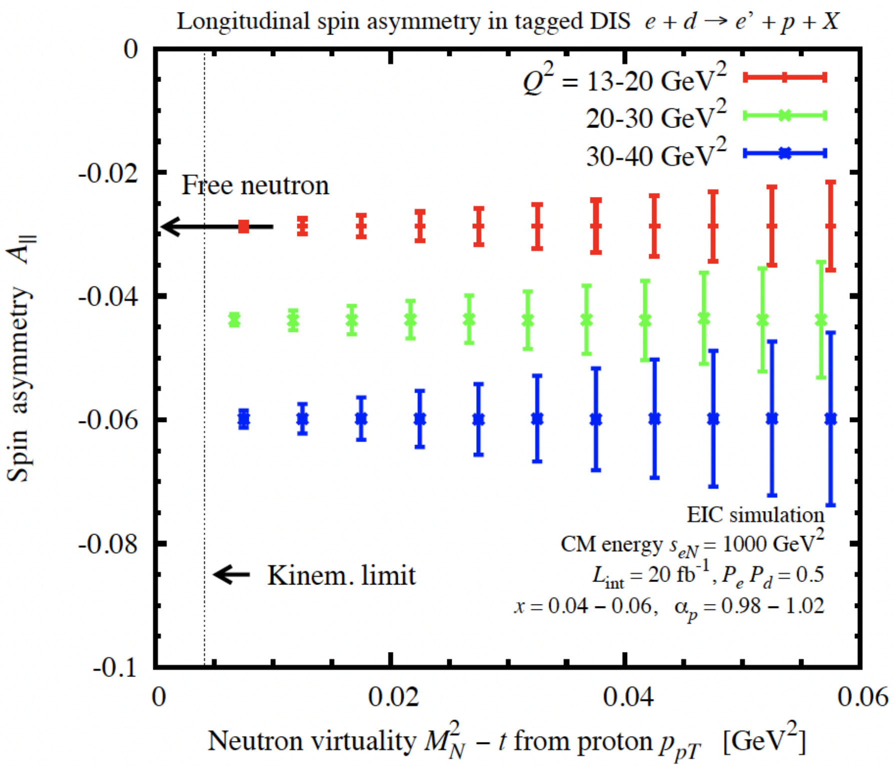
Proton + ^{3}He

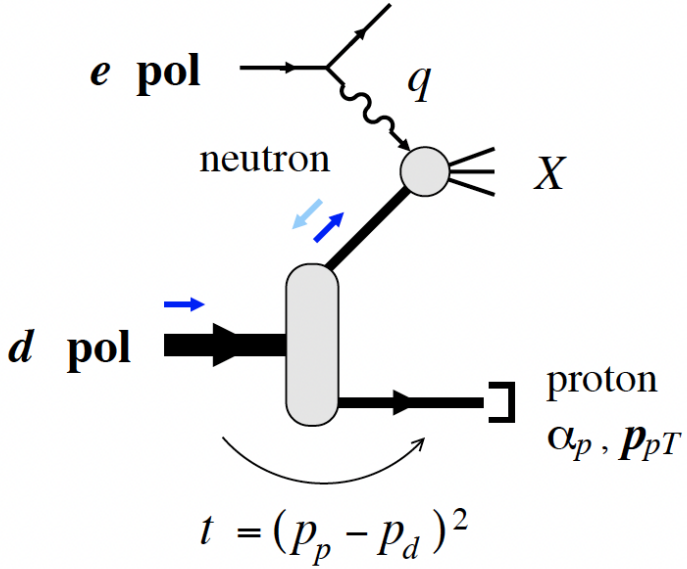


Ratio of the uncertainties on the truncated (x_{min} = 0.0001) quark singlet and gluon moments with and without EIC data as evaluated by JAM collaboration. The width of the lines correspond to uncertainty on extrapolation to lower x.

Quark and Gluon HELICITY

- Analysis of ^{3}He data relies on effective neutron polarizations inferred from non-relativistic nuclear structure.
- Nuclear modifications arise from Δ isobars in the ^{3}He nucleus for x > 0.1 and from spin-dependent nuclear anti-shadowing and shadowing at x < 0.1.
- If the proton is tagged and the asymmetry plotted as a function of the neutron virtuality, then the free neutron spin asymmetry can be extracted in the limit of virtuality ~ 0.





Phys Rev D. 111, 05201 (2024)

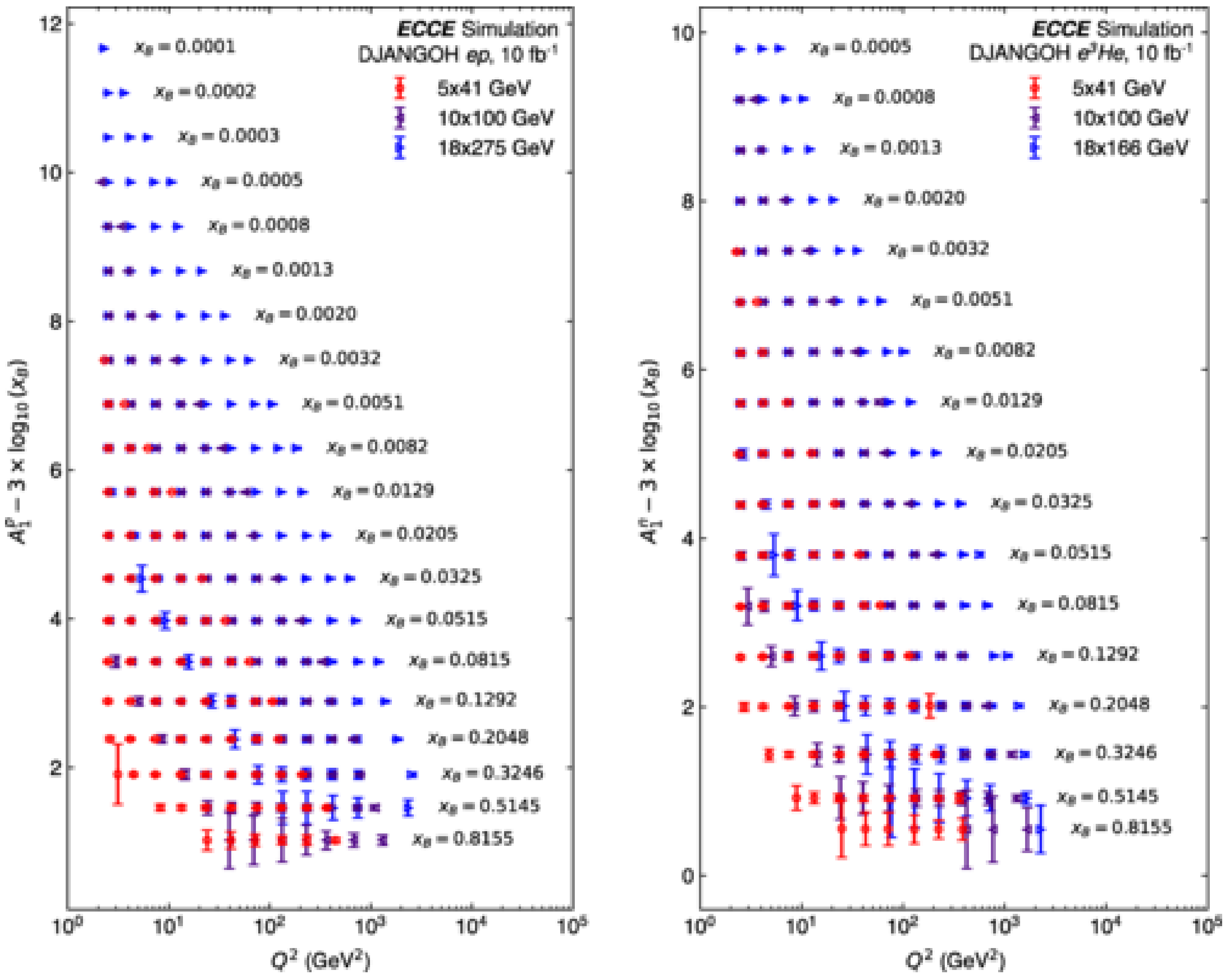
Quark and Gluon HELICITY

Phys Rev D. 110, 074004 (2024)

Highly polarized proton and ^{3}He beams (~70%), spanning a range of center-of-mass energies, allow for a precision measurement of the Bjorken Integral:

$$\Gamma_1^{p-n}(Q^2) = \int_0^1 \left[g_1^p(x,Q^2) - g_1^n(x,Q^2)\right] dx = g_A/6$$

In the limit of $Q^2 \to \infty$ the integral is equal to the axial vector coupling constant

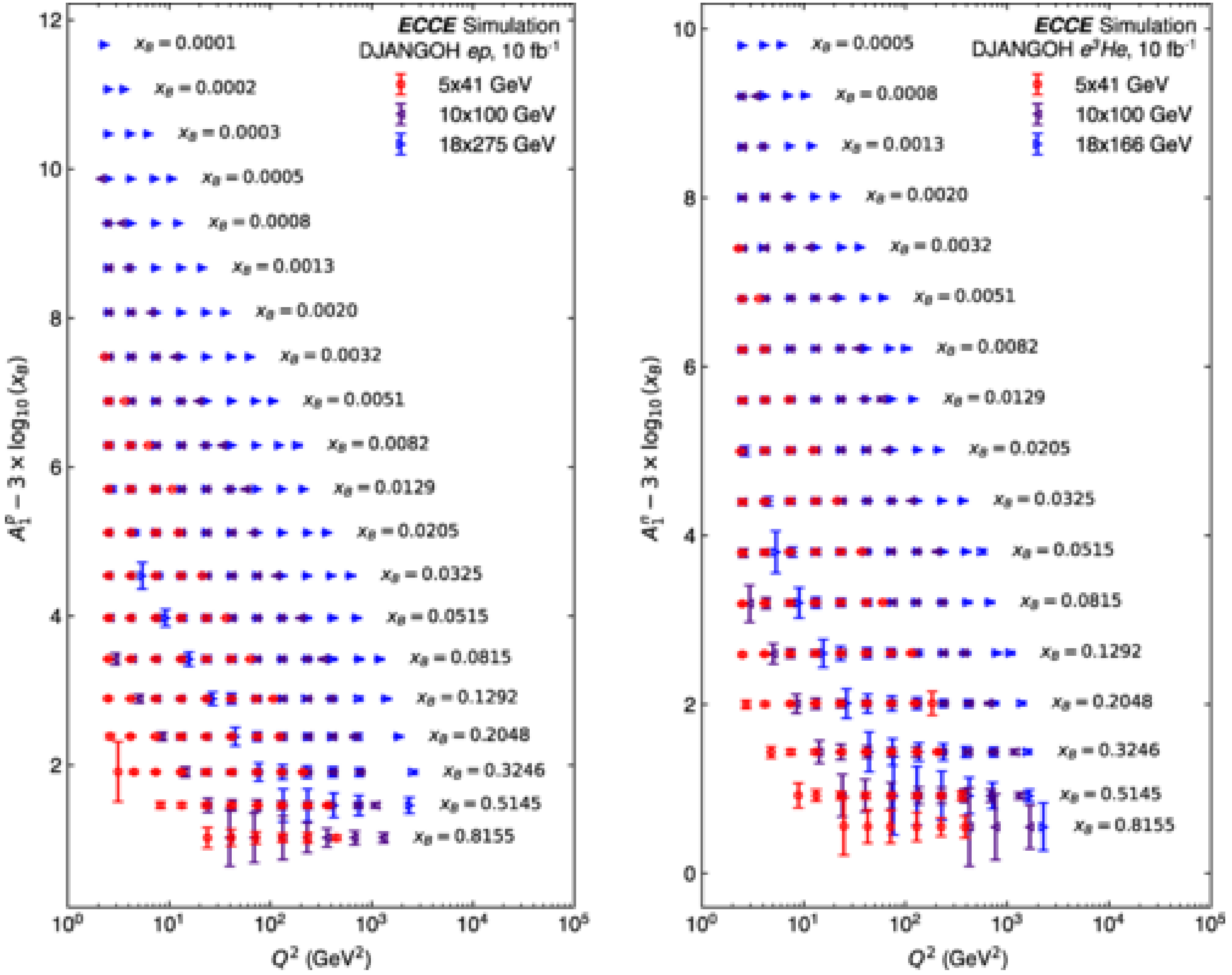


Quark and Gluon HELICITY

Phys Rev D. 110, 074004 (2024)

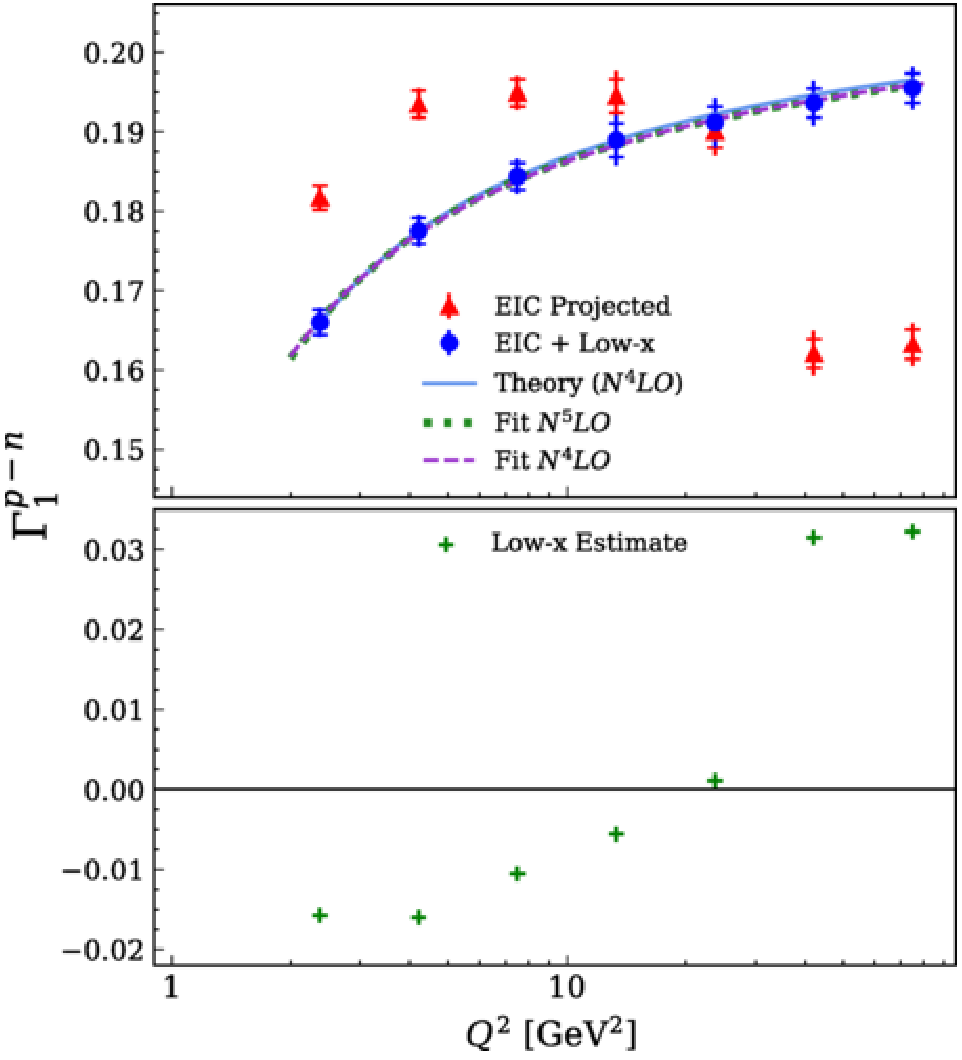
Requires:

- Measurement of double spin asymmetries where hadron spin is longitudinal and transverse to momentum. Electron spin is always longitudinal.
- Double tagging, i.e. both spectator protons from ^{3}He are detected using far forward tracking and roman pot detectors spanning $4 < \eta < 6$.
- Low x contribution to integral determined by subtracting simulated (aka measured) portion from calculation of total sum rule (next page).

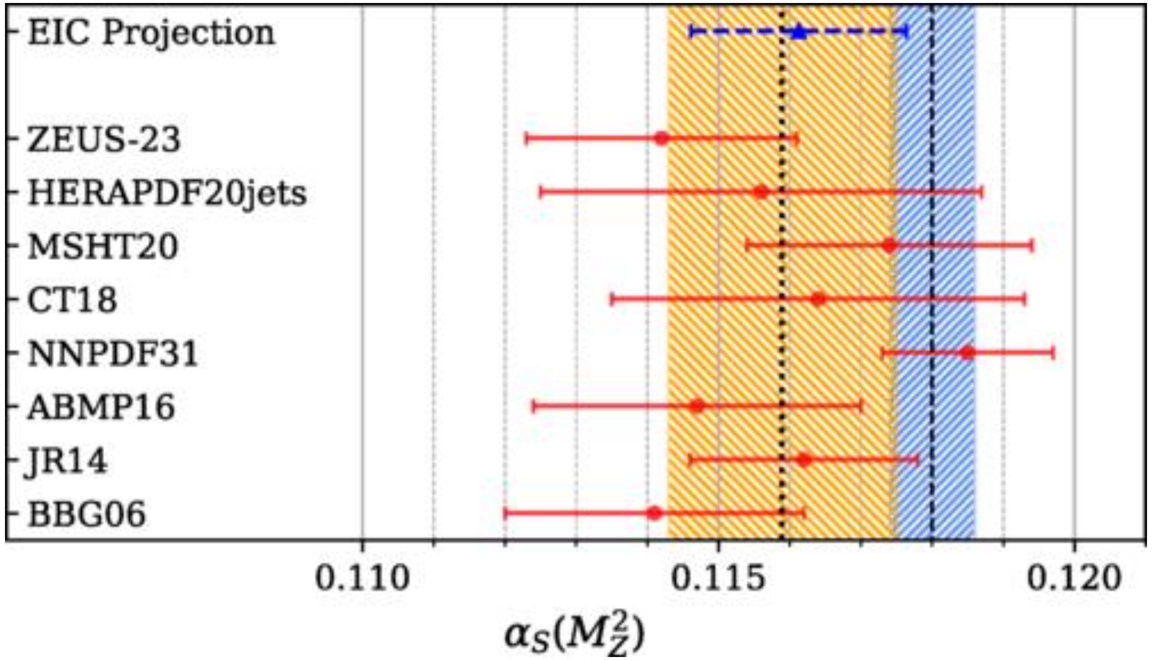


Exploit the Q^2 evolution of BSR to constrain α_s !

Phys Rev D. 110, 074004 (2024)



$$\Gamma_1^{p-n}(Q^2) = \frac{g_A}{6}\left[1 - \frac{\alpha_s(Q^2)}{\pi} - 3.58\left(\frac{\alpha_s(Q^2)}{\pi}\right)^2 - 20.21\left(\frac{\alpha_s(Q^2)}{\pi}\right)^3 - 175.7\left(\frac{\alpha_s(Q^2)}{\pi}\right)^4 - (\sim 893.38)\left(\frac{\alpha_s(Q^2)}{\pi}\right)^5 + \mathcal{O}\left((\alpha_s)^6\right)\right] + \sum_{\tau>1}\frac{\mu_{2\tau}^{p-n}(\alpha_s)}{Q^{2\tau-2}},$$



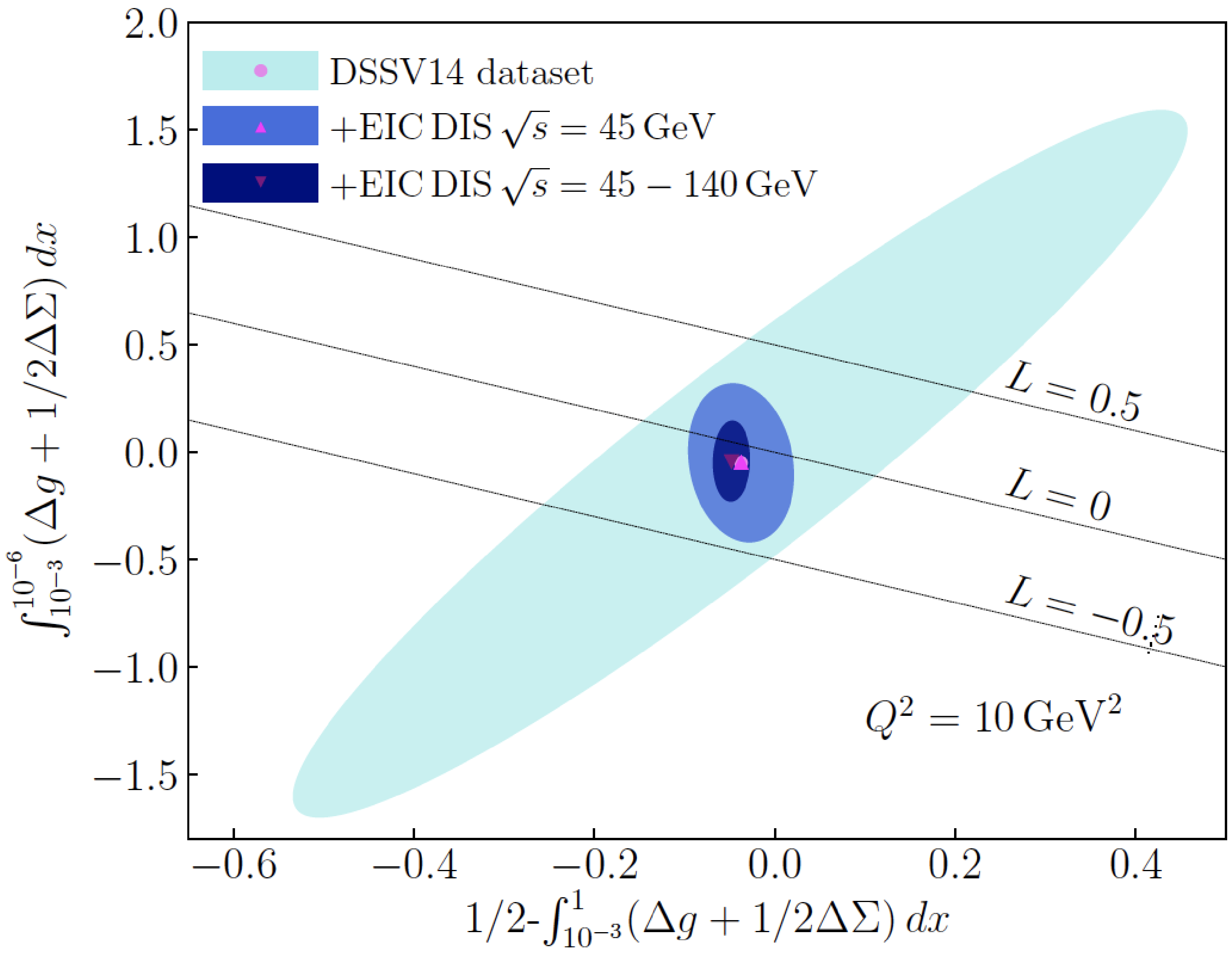
Orbital Angular Momentum

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + \Delta G(\mu) + L_{Q+G}(\mu)$$

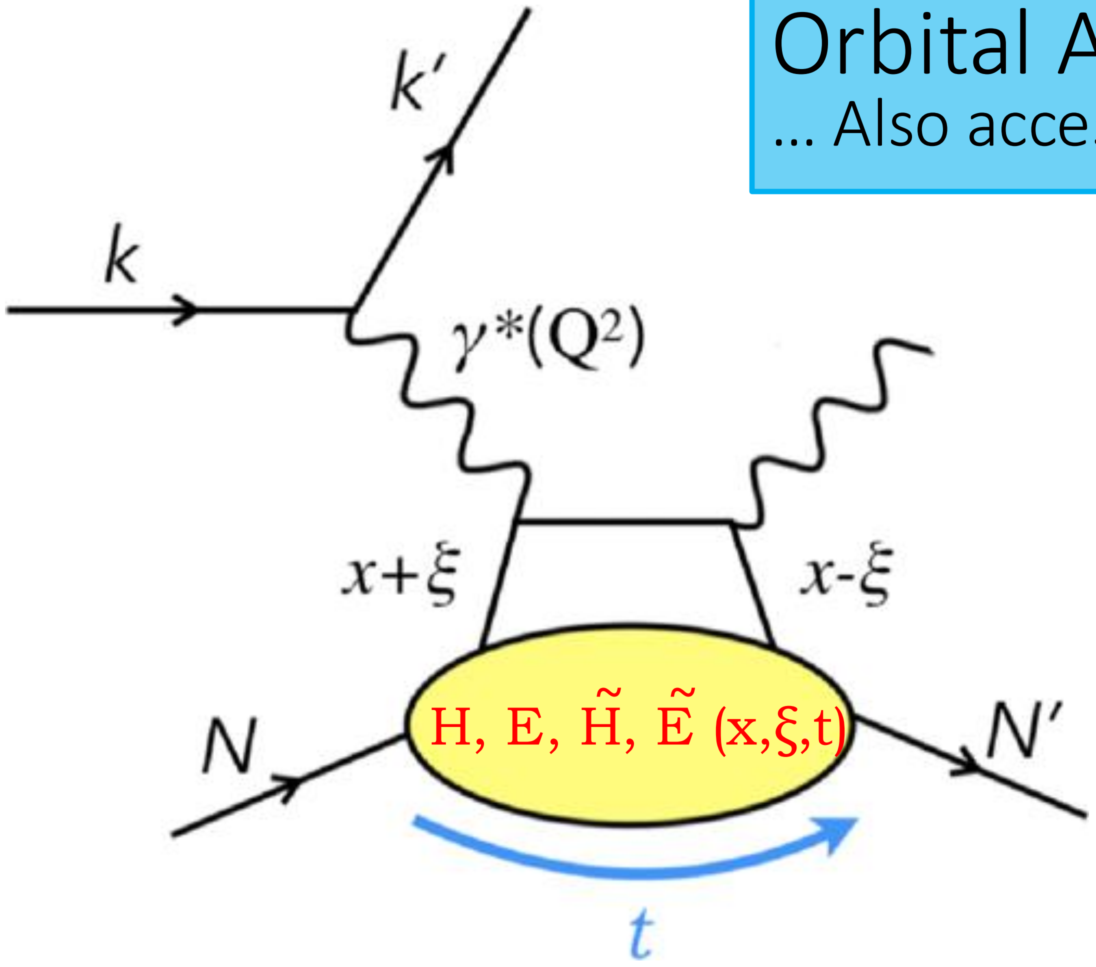
Orbital Angular Momentum

Direct constraints from the evaluation of values and errors on $\Delta\boldsymbol{\Sigma}$ and ΔG from EIC inclusive and SIDIS data.

Ellipses correspond to the 1σ correlated uncertainty.



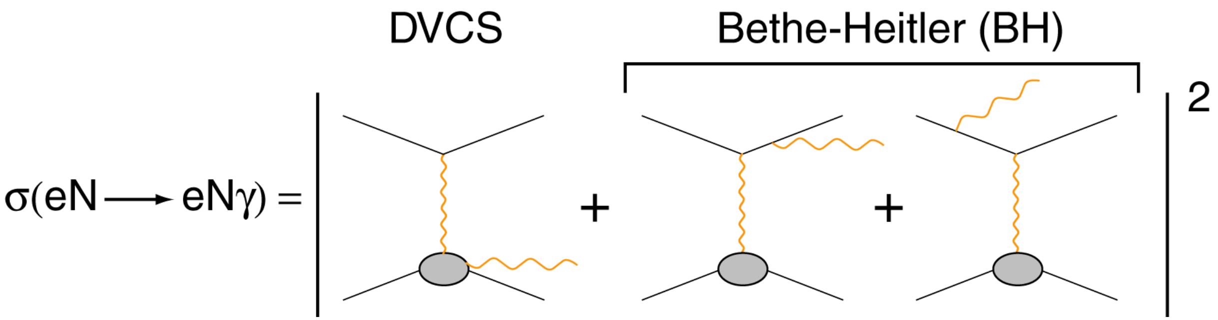
Orbital Angular Momentum
… Also accessible via Deeply Virtual Compton Scattering



x parton longitudinal momentum fraction

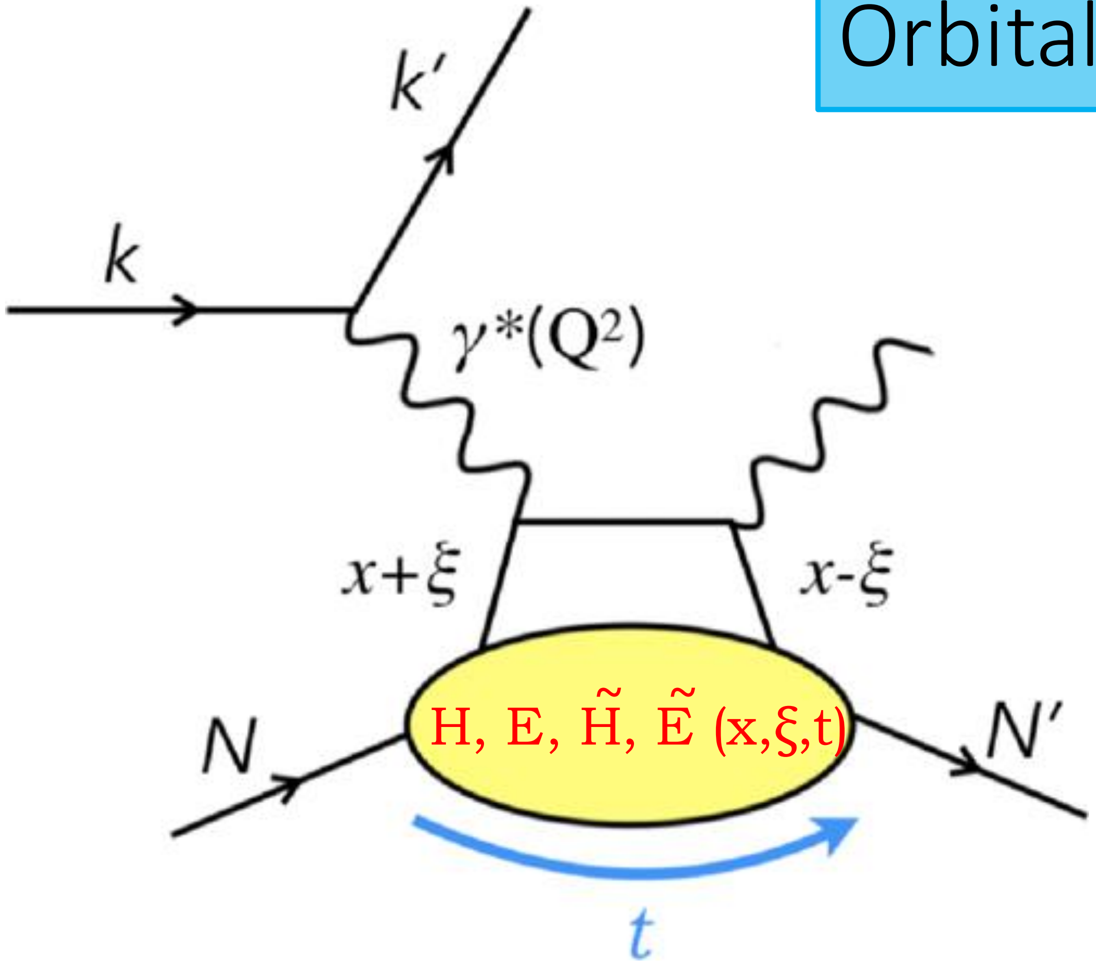
2ξ change in x of interacting parton

$t = \Delta^2 = (p-p')^2$ Fourier transform in t of GPDs at $\xi = 0$ gives impact parameter $b_\perp$ distribution



$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to} \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

Orbital Angular Momentum



3D QUARK NUMBER DENSITY & HELICITY

$$q(x, \mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} H(x,0,-\Delta_\perp^2)$$

$$\Delta q(x, \mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} \tilde{H}(x,0,-\Delta_\perp^2)$$

M. Burkardt, PRD 62, 71503 (2000)

QUARK ANGULAR MOMENTUM : Ji Sum Rule

$$\frac{1}{2}\int_{-1}^{1} x dx (H(x,\xi,t=0) + E(x,\xi,t=0)) = J = \frac{1}{2}\Delta\Sigma + \Delta L$$

X. Ji, Phy.Rev.Lett.78 (1997)

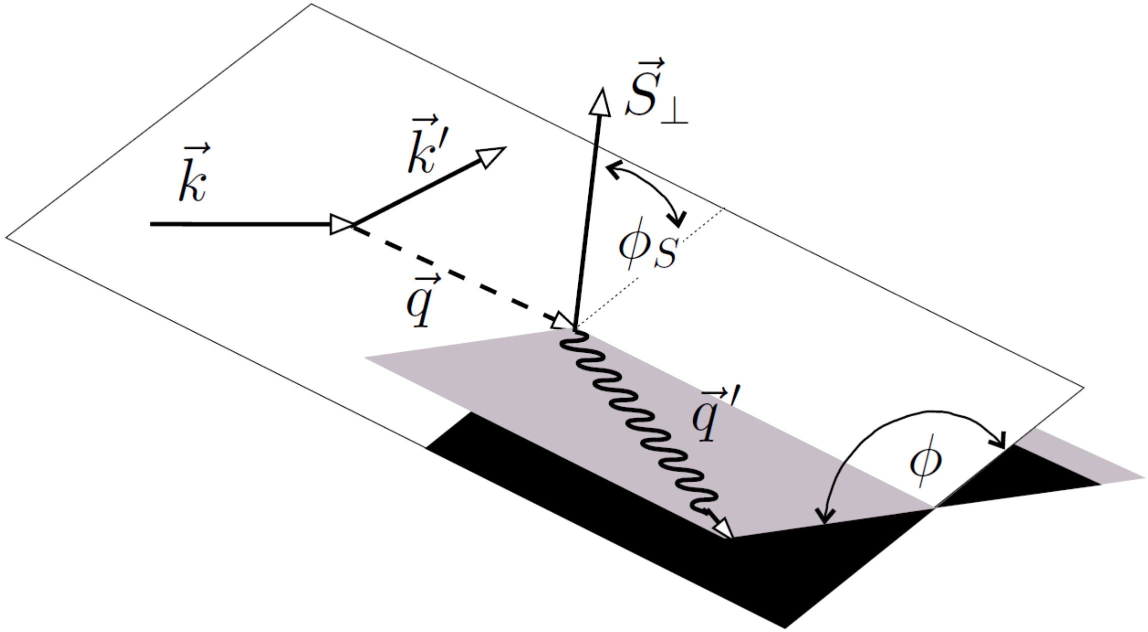
GPD Extraction

DVCS cross-section is parameterized in terms of Compton form factors (CFF). *Nucl.Phys. B629 (2002) 32*

CFF are complex functions
- imaginary component accesses GPDs along the diagonal of $x = \pm\xi$
- real component accesses convolution of GPD with initial parton momentum.

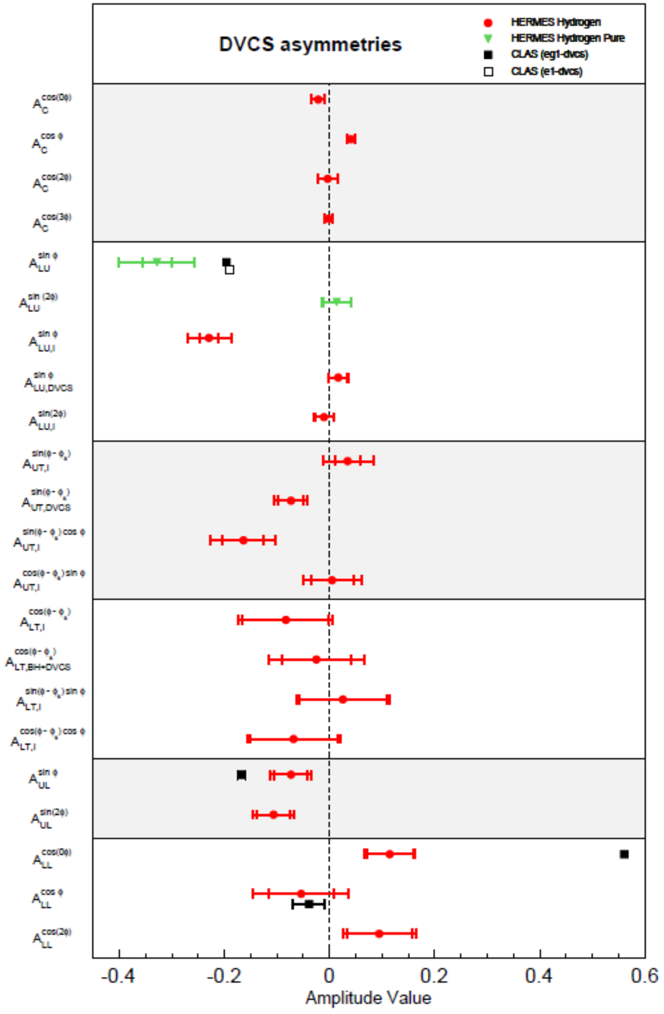
Various spin asymmetries, measured as a function of ϕ are sensitive to different CFF.

Full extraction of GPDs will requires a global analysis.

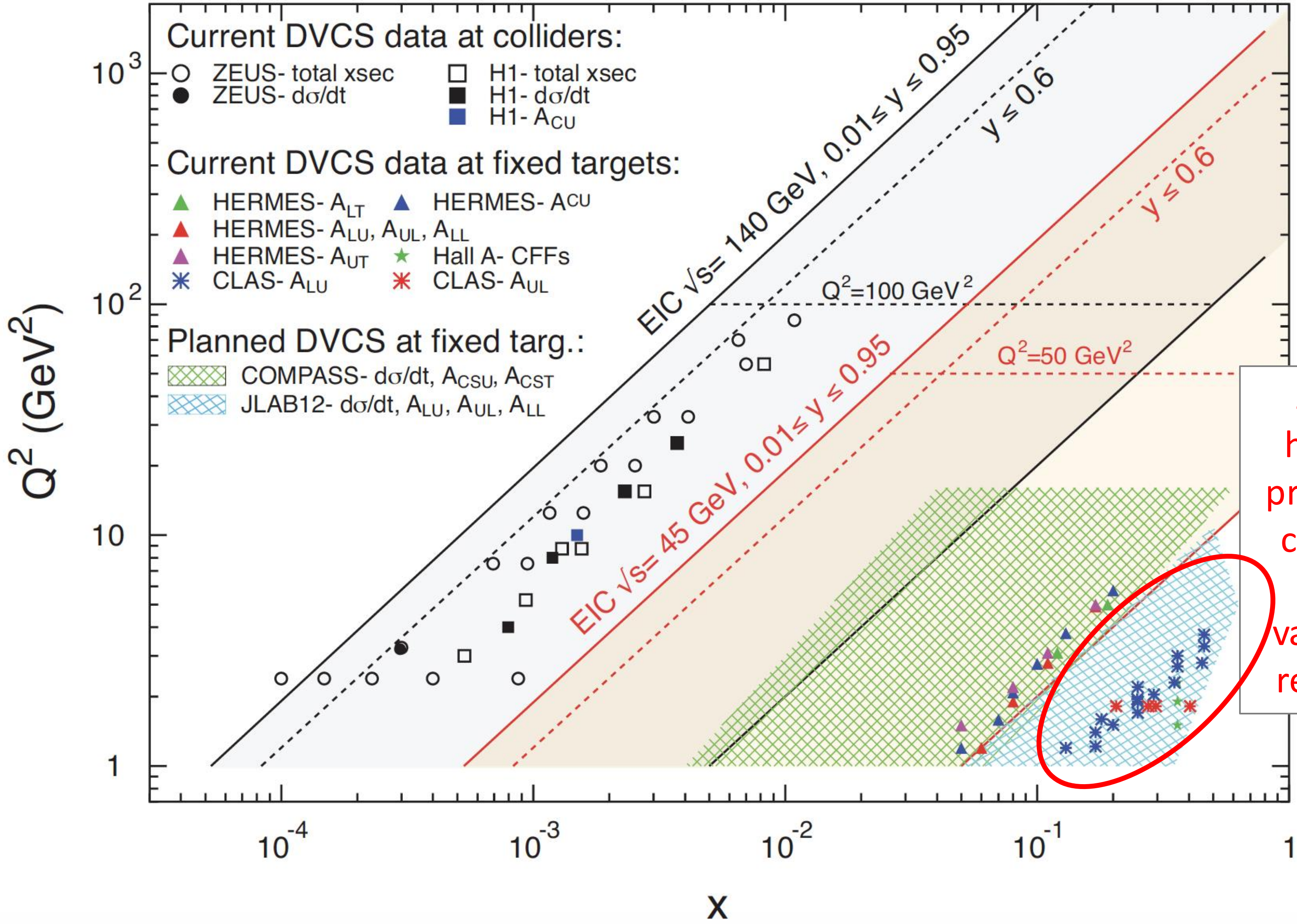


CFF	Im	Re
H	A_{LU}	A_{LL} A_{LT} σ
$\widetilde{H}$	A_{UL}	A_{LL} A_{LT} σ
E	A_{UT}	A_{LL} A_{LT} σ

Current and Future DVCS Experiments



from Silvia Niccolai, SPIN 2023

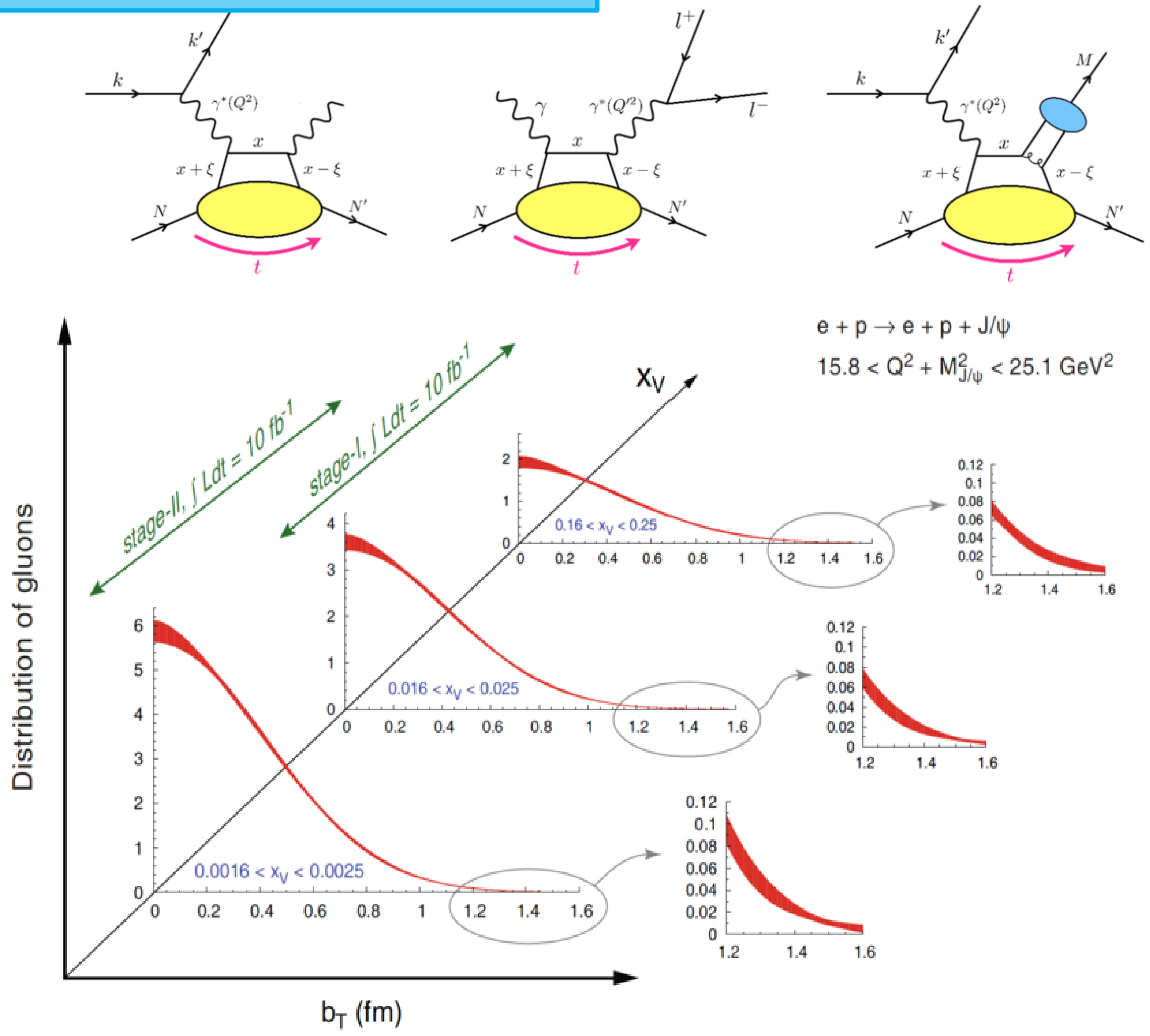


JLAB high-x program critical for valence region!

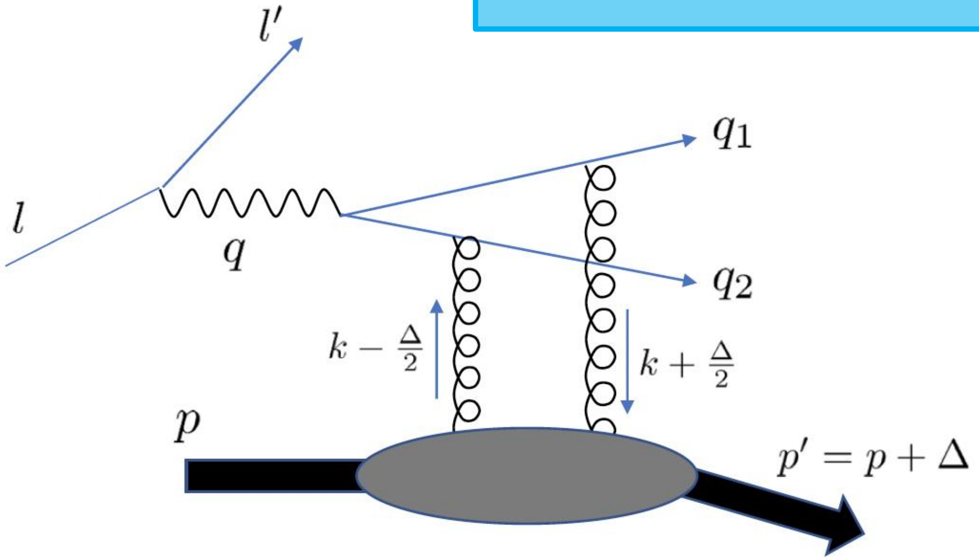
Orbital Angular Momentum

GPDs at the EIC

- Will access a unique kinematic space that is sensitive to gluons and sea quarks.
- GPD program is one of the most experimentally demanding at the EIC.
- Requires multi-dimensional binning over broad range of center-of-mass energies.
- Requires precision calorimetry to reconstruct scattered electron and photon.
- Requires careful design of the interaction region to allow for reconstruction of protons scattered at small forward angles.

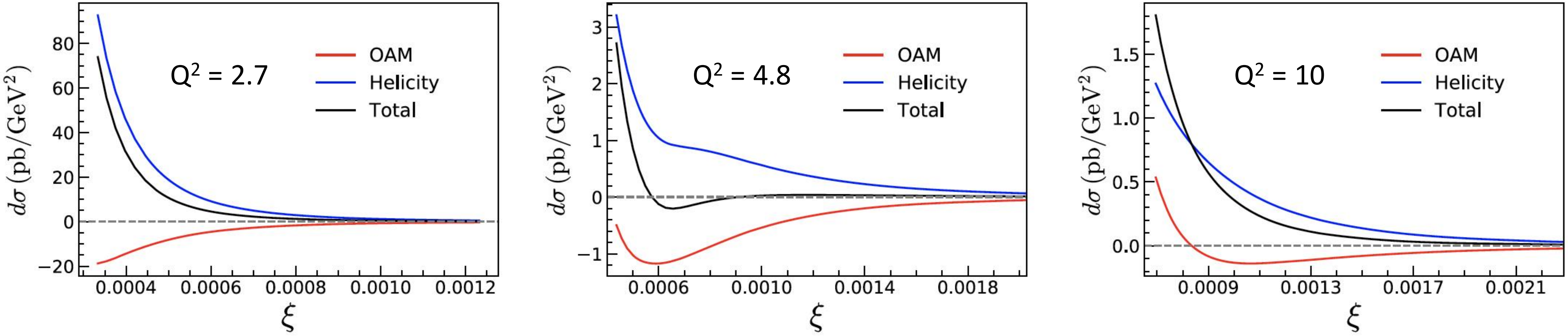


Exclusive Dijet Double Spin Asymmetry



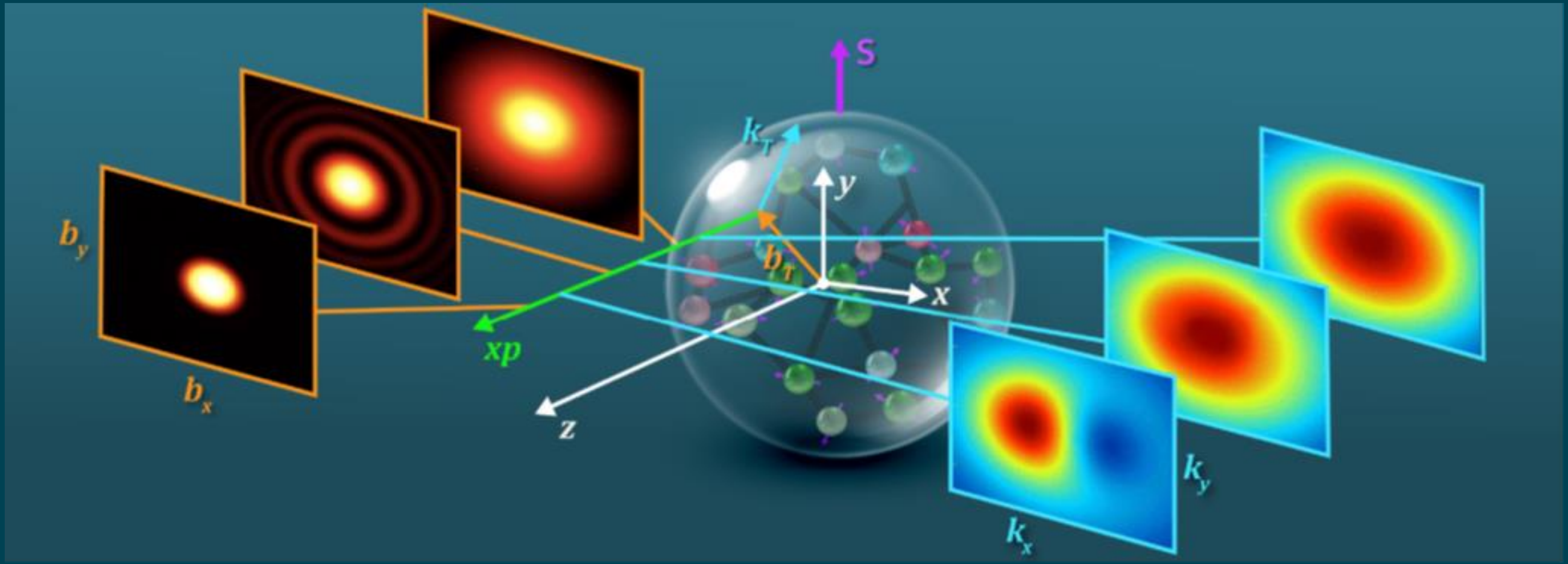
- Requires longitudinally polarized electron and proton beams
- Azimuthal angle of scattered electron must be measured
- Dijets emerge in backwards region (-2 < η < -1)
- DSA is sensitive to GPDs that encapsulate gluon OAM and helicity information.
- Precisely mapping out gluon helicity GPD will allow for extraction of gluon OAM component.

Phys. Rev. Lett. 128, 182002 (20222)



3D Imaging

GPD

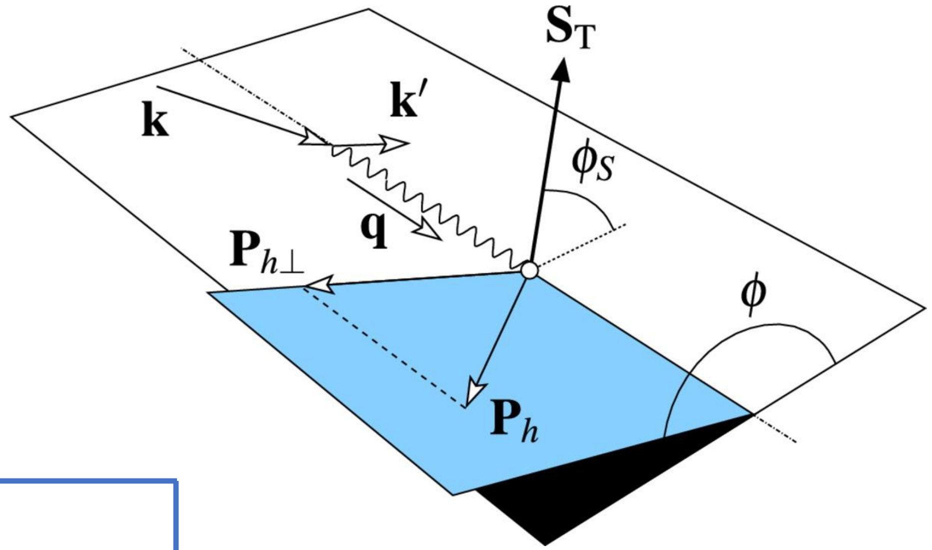


TMD

- 2D in parameter space +1 in momentum space
- Collinear factorization
- Gives access to parton helicity and OAM
- Multiple channels, including Deeply Virtual Meson Production are necessary for full reconstruction.

- 3D in momentum space
- Non-trivial factorization
- Origin of spin-orbit correlations is orbital angular momentum.

TMDs in SIDIS



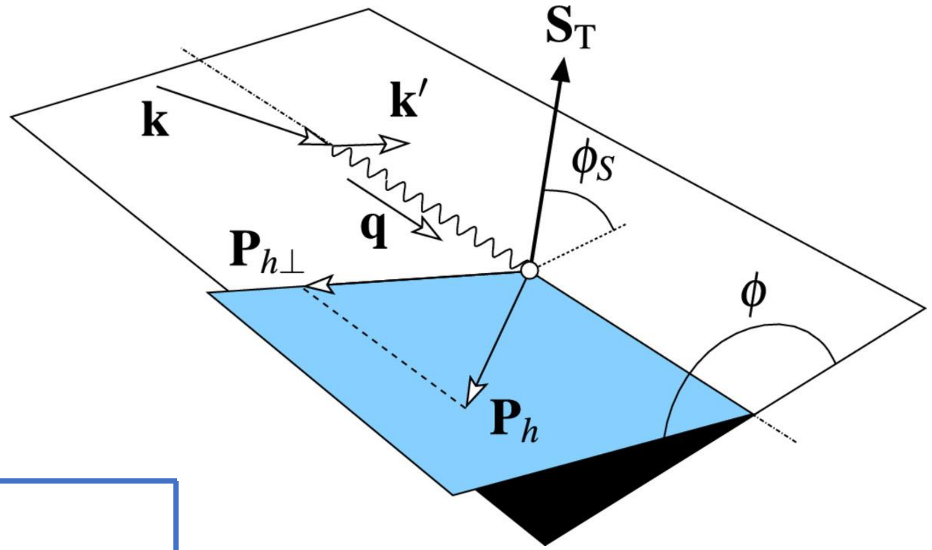
$$\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2}
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{\boxed{F_{UU,T}} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}\\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]\\
&\quad + S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]\\
&\quad + S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,\boxed{F_{UT}^{\sin(\phi_h+\phi_S)}}\\
&\quad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}\\
&\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\\
&\quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}$$

$$A_{\mathrm{COLLINS}} \propto \frac{h_1^q(x,k_T)\otimes H_1^{\perp,q}(z,j_T^2)}{f_1^q(x,k_T)\otimes D_1^q(z,j_T^2)}$$

$h_1^q(x,k_T)$ Probability for quark to be transversely polarized inside a proton with transverse spin.

$H_1^{\perp,q}(z,j_T^2)$ Correlations between quark transverse spin and azimuthal modulations in the fragmentation.

TMDs in SIDIS



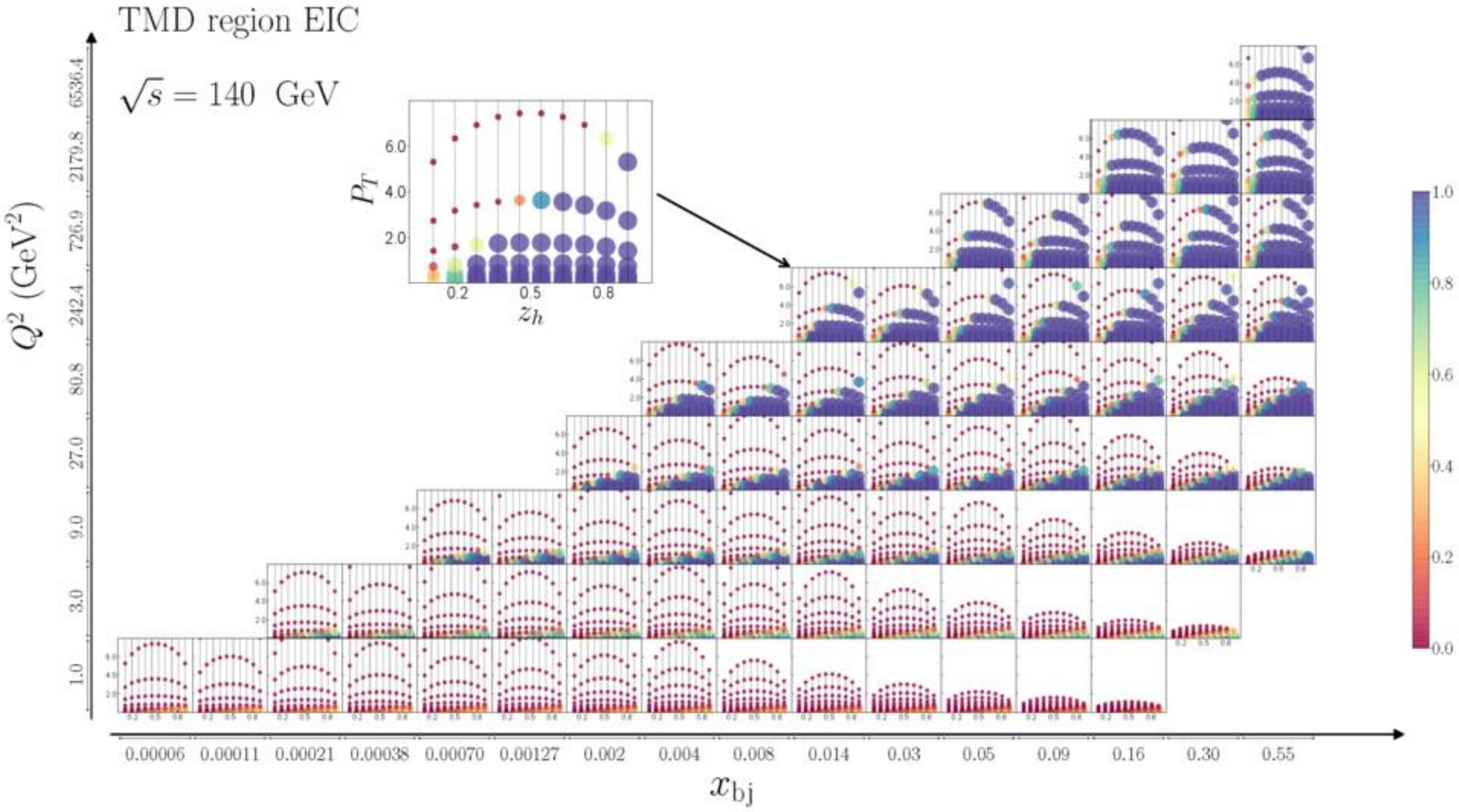
$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{\boxed{F_{UU,T}} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad + S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad + S_T\Bigg[\sin(\phi_h-\phi_S)\left(\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)}} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}
\end{aligned}
$$

$$A_{\text{SIVERS}} \propto \frac{f_{1T}^{\perp,q}(x,k_T)\otimes D_1^q(z,j_T^2)}{f_1^q(x,k_T)\otimes D_1^q(z,j_T^2)}$$

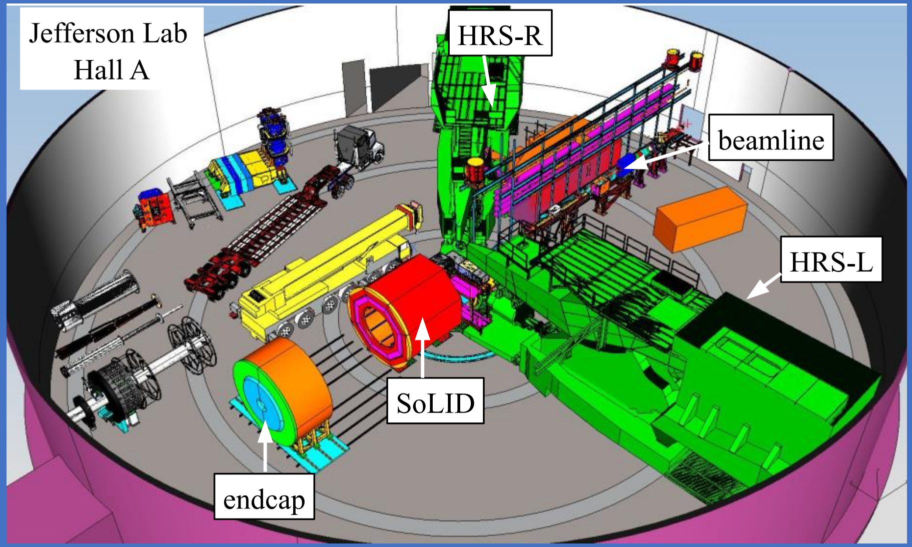
$f_{1T}^{\perp,q}(x,k_T)$ correlation between the quark k_T and proton momentum and transverse spin.

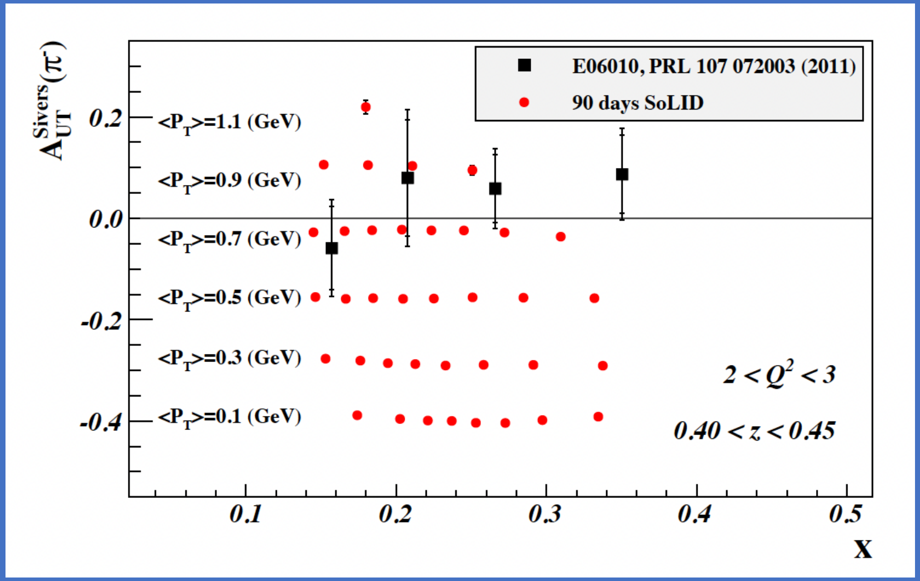
$D_1^q(z,j_T^2)$ Probability for a quark to fragment into a hadron with z and j_T

Future TMD measurements



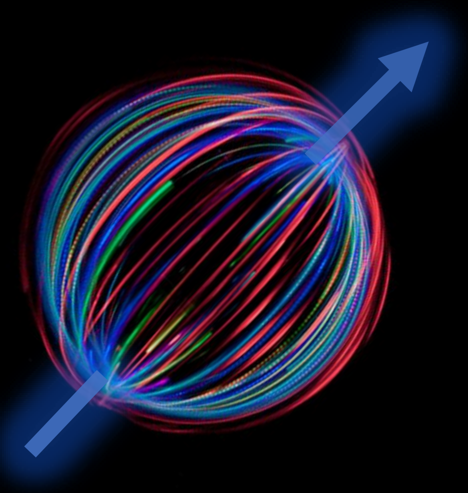
Low-x at the EIC





High-x at the JLAB 12 GeV

Take Home Messages



- The advent of highly polarized beams and targets, nearly four decades ago, opened a frontier in experimental hadronic physics and transformed our understanding of nucleon spin structure and the theory of Quantum Chromodynamics.

- As we embark on the EIC era it is ***imperative*** that we pursue highly polarized ^2H and ^3He beams in addition to polarized proton beams. ``Neutron" beams :
  - Provide significant increase in precision in the determination of the quark helicity PDFs for $x < 10^{-3}$
  - Provide leverage to reduce uncertainties on the flavor separated distributions, at a level similar to SIDIS, but without the systematic errors associated with fragmentation functions.
  - Allow for precision measurements of the Bjorken Integral, which allows in turn, for the first time, a competitive extraction of the strong coupling constant.

- It is critical to install detectors, along the beamline, that can detect spectator protons, allowing for a clean extraction of the neutron signal.

- The EIC will measure a suite of channels that will allow us to evaluate the total orbital angular momentum of the nucleon. These channels range from DVCS and DVMP to exclusive dijet production.

Postcard credit : CERN

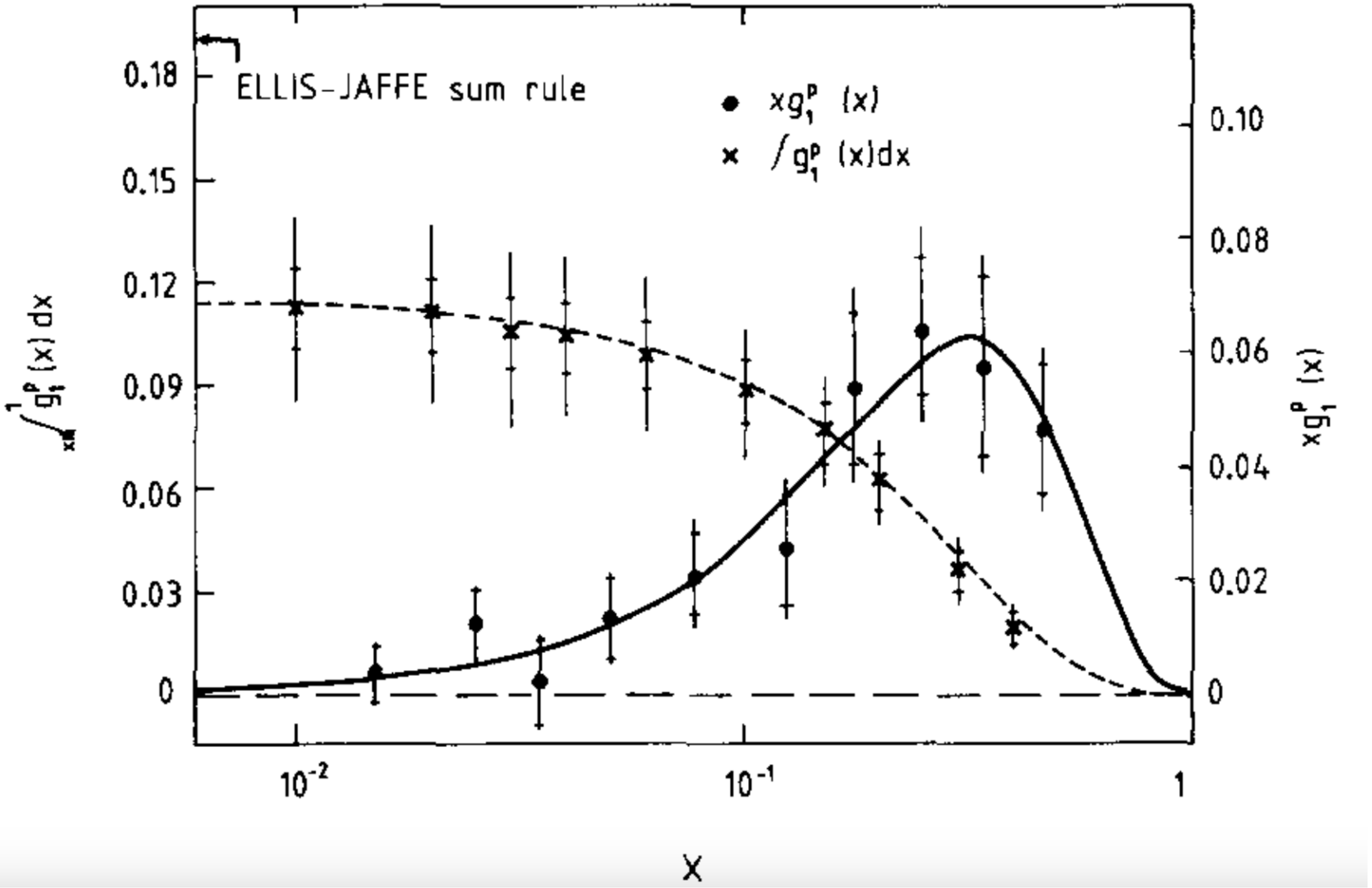
The plot that launched the “spin-crisis”

The Ellis-Jaffe Sum Rule predicts a value for the integral of $g_1(x)$ over all x assuming:

1) No gluon contribution to the spin of the proton
2) No strange sea contribution to spin of the proton.

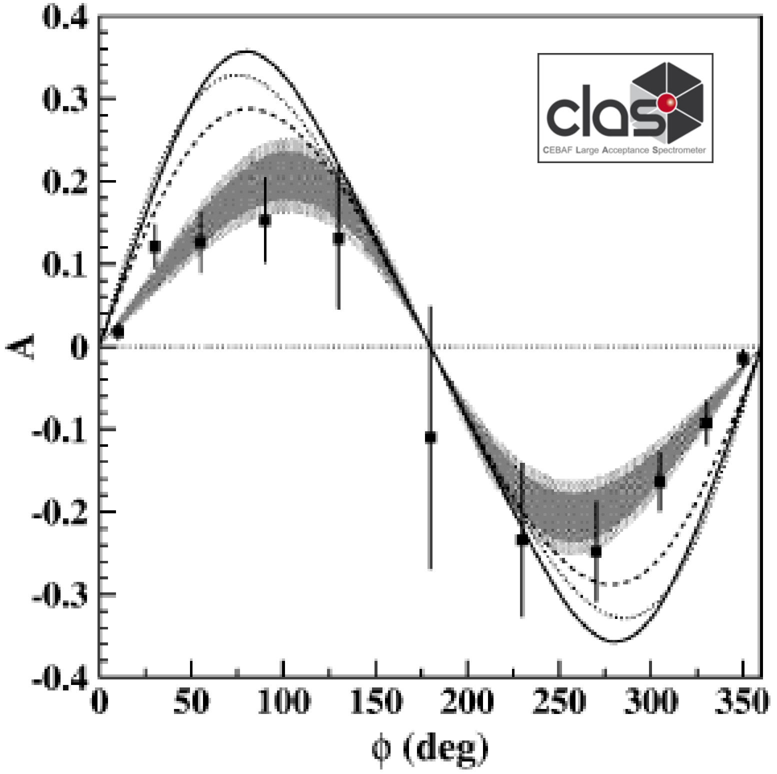
Conclusion was that quarks carry very little of the spin of the proton -> $14 \pm 9 \pm 21\%$!

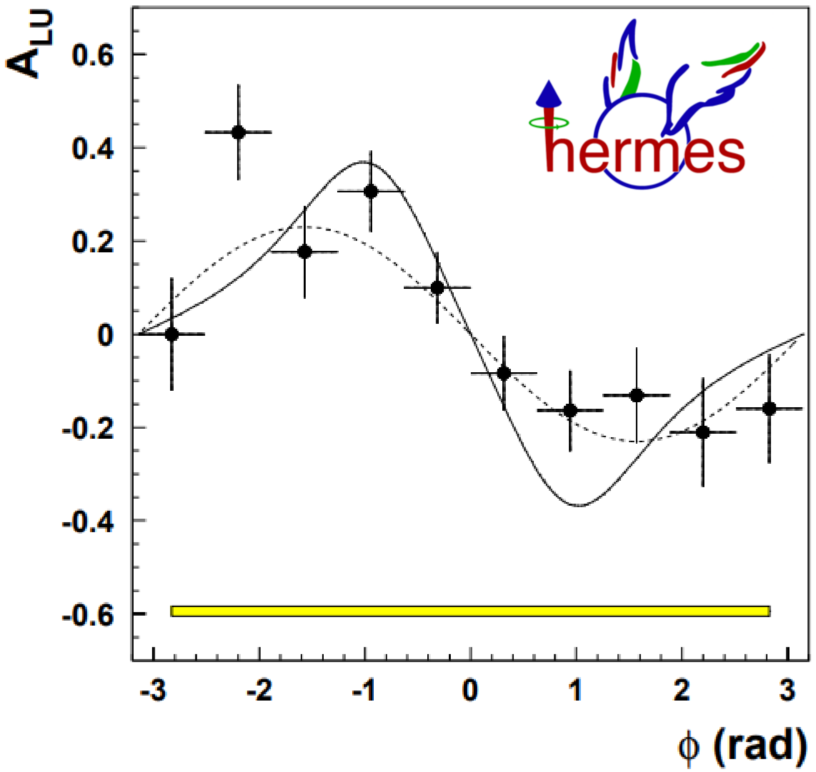
This generated a lot of discussion in the high energy physics community.



First DVCS Measurements

… published back-to-back in PRL 87 (2001)





Beam Spin Asymmetries – polarized beam + unpolarized target – sensitive to $H, E, \tilde{H}$

Global TMD Analysis

- Requires the development of methodology to handle differences in hard scale Q^2.
- Unlike collinear observables, evolution contains a non-perturbative component that cannot be calculated from first principles.

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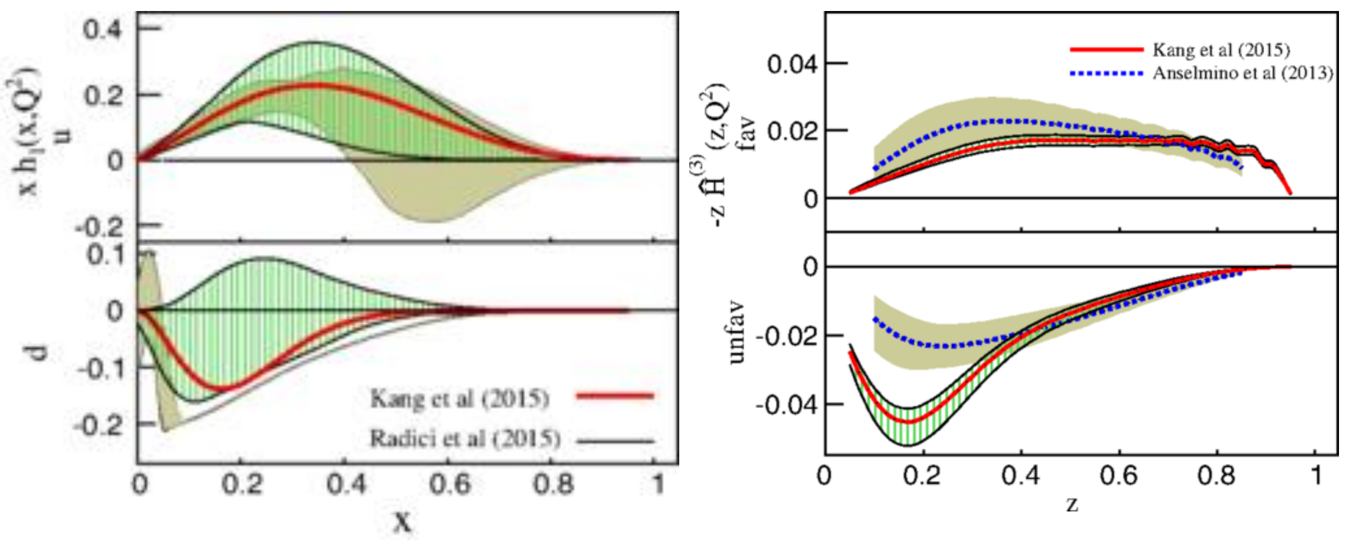

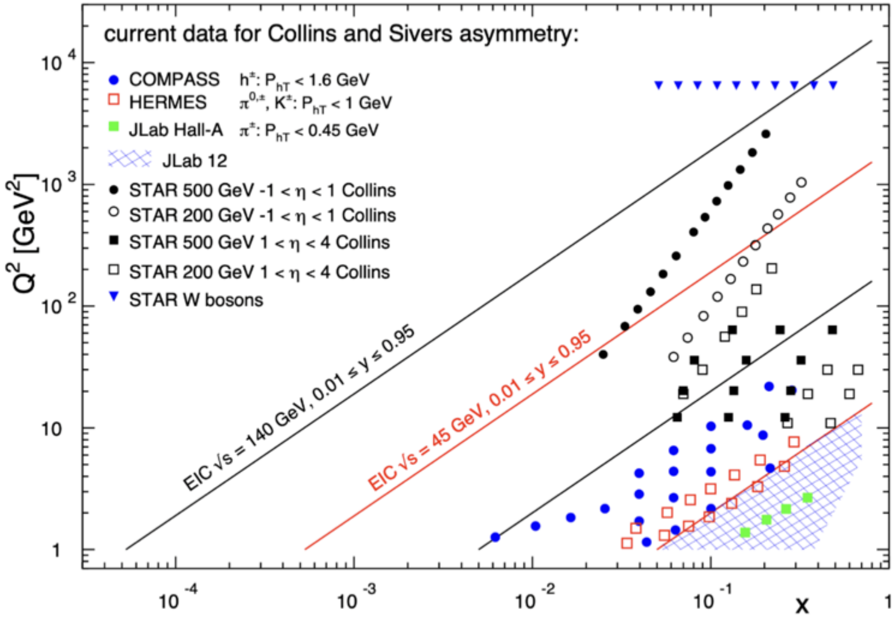

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