TMD with Polarized Beam and Target

The 1st Workshop on Polarized Beam and Target (PBT2024)
— Physics and Applications
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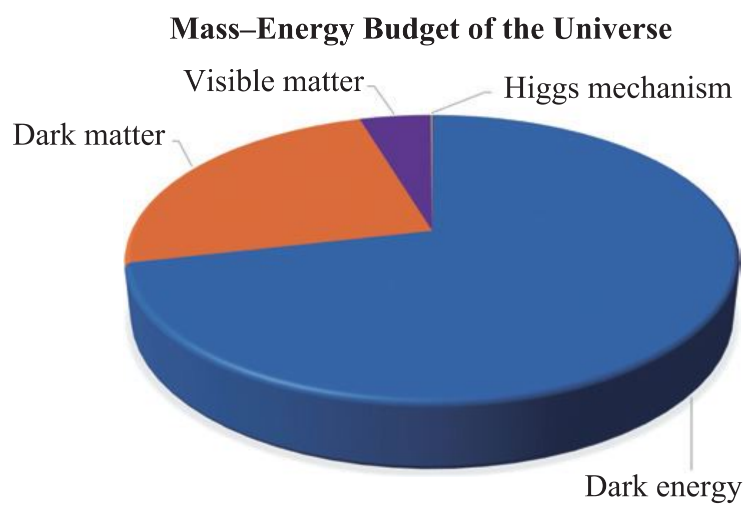
Tianbo Liu (刘天博)

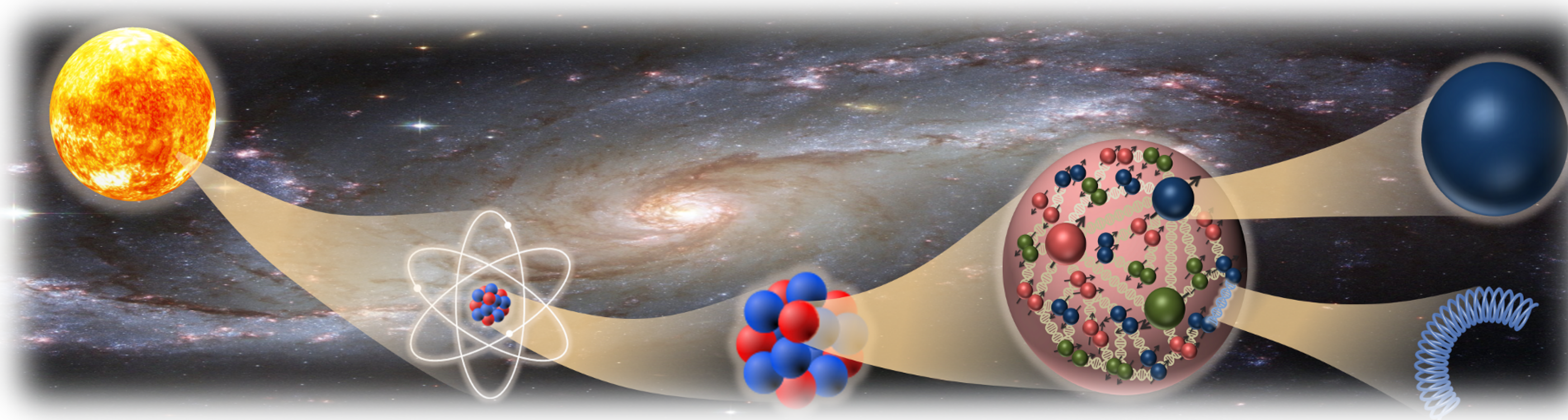
Key Laboratory of Particle Physics and Particle Irradiation (MOE)
Institute of Frontier and Interdisciplinary Science, Shandong University
Southern Center for Nuclear-Science Theory, IMP, CAS

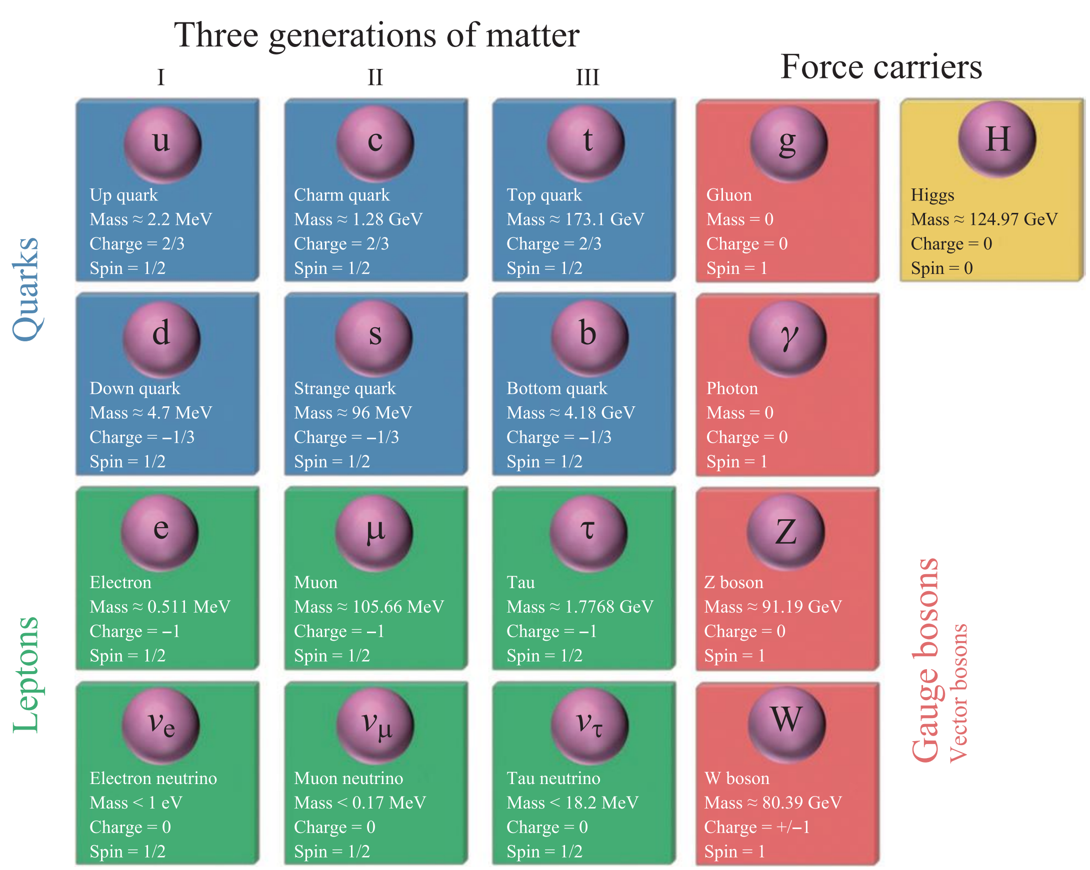
山东大学
SHANDONG UNIVERSITY

SCNT
Southern Center for Nuclear-Science Theory

How much do we understand our world?

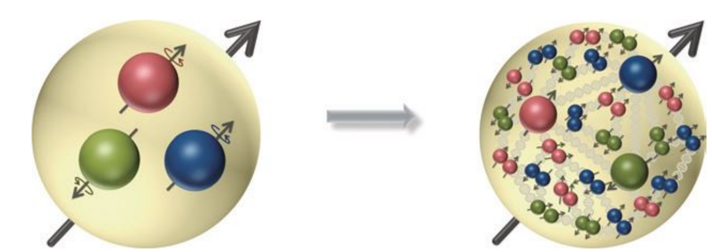






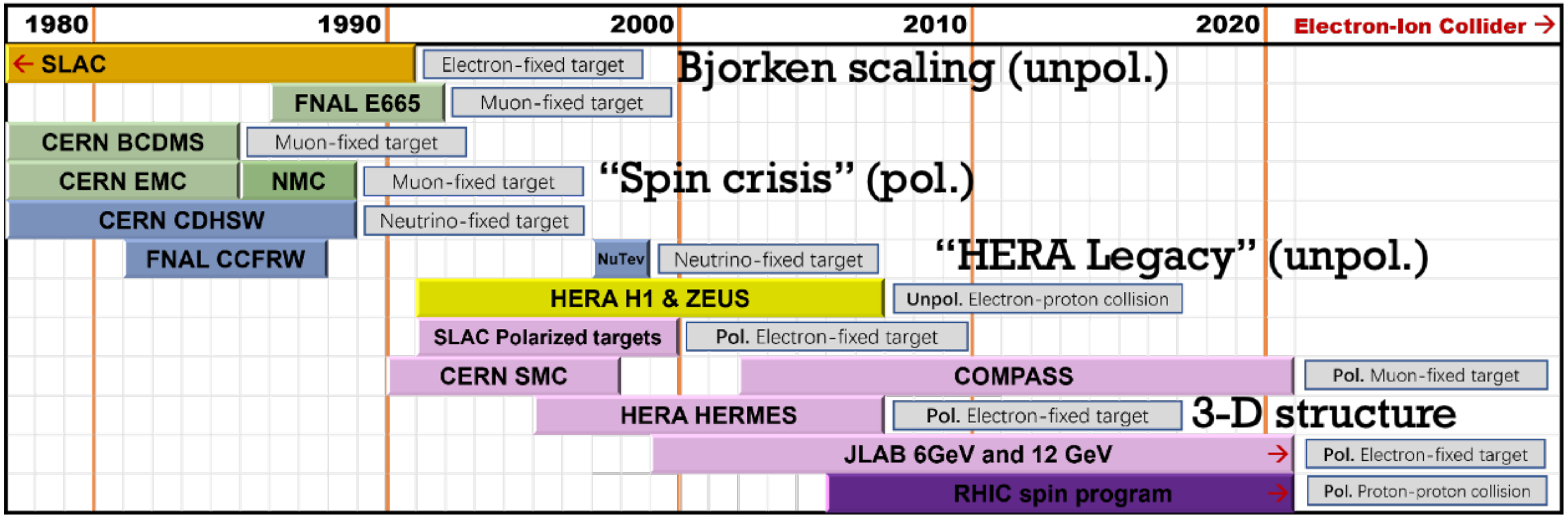
Mass

Spin

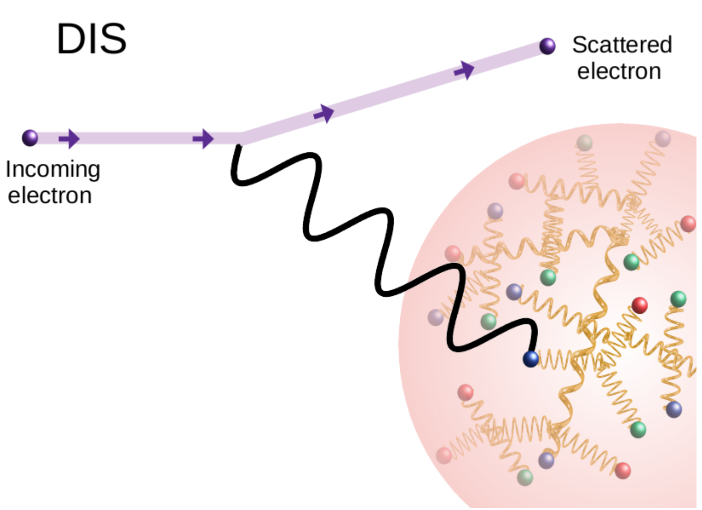


How do quarks and gluons make up a nucleon?
How can nucleon properties be explained at quarks and gluons degrees of freedom?

Lepton Scattering: An Ideal Tool



[Figure from X.Y. Zhao]



[Figure from DESY-21-099]

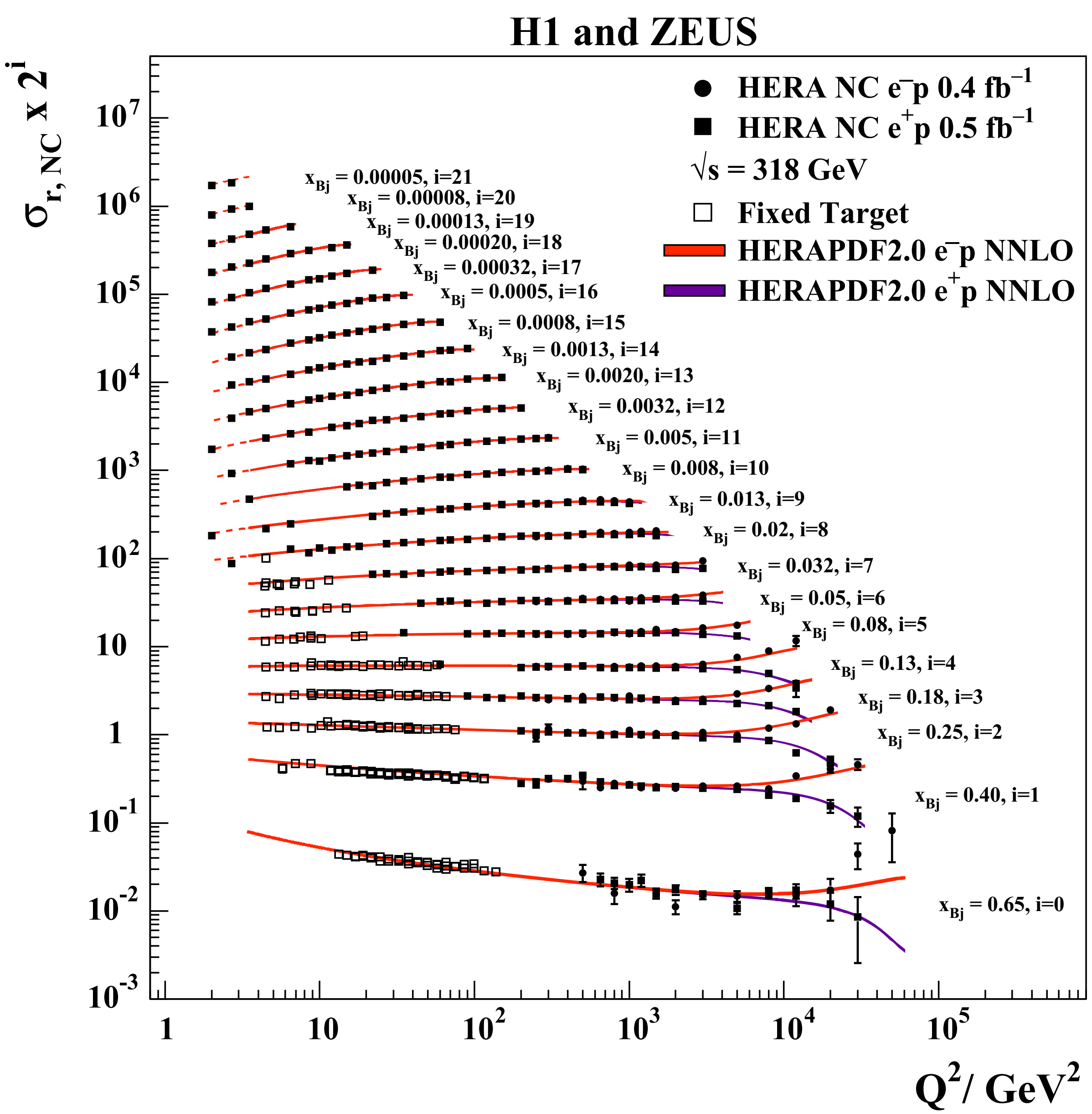
Modern "Rutherford Scattering" Experiment

- dominated by the scattering off an active quark/parton
- collinear factorization: $\sigma \propto H(Q) \otimes \phi_{a/P}(x, \mu^2)$
- overall corrections suppressed by $1/Q^n$
- indirectly "see" quarks/gluons and their dynamics
- predictive power relies on

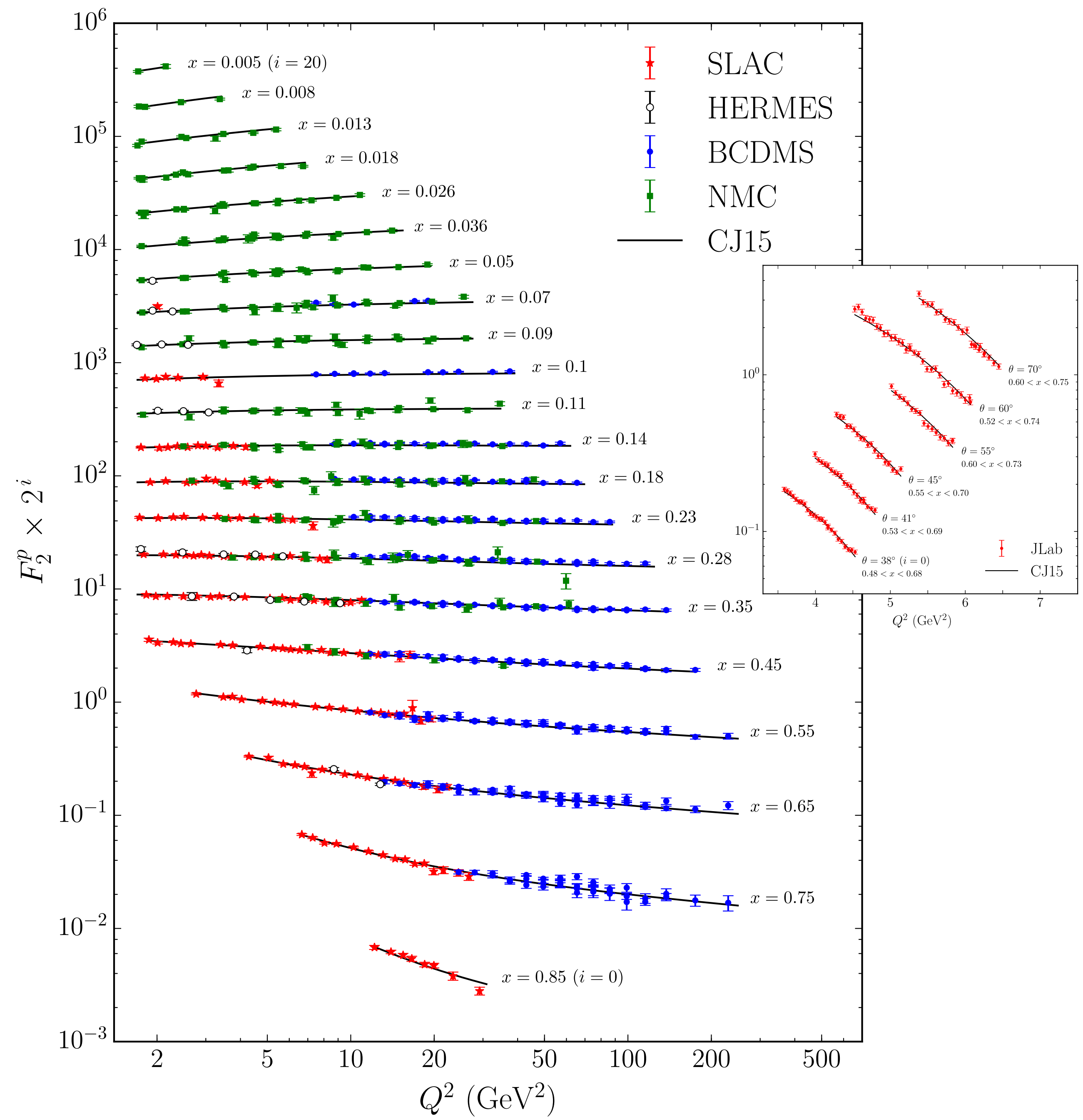
— precision of the probe

— universality of $\phi_{a/P}(x, \mu^2)$

Lepton-Hadron Deep Inelastic Scattering

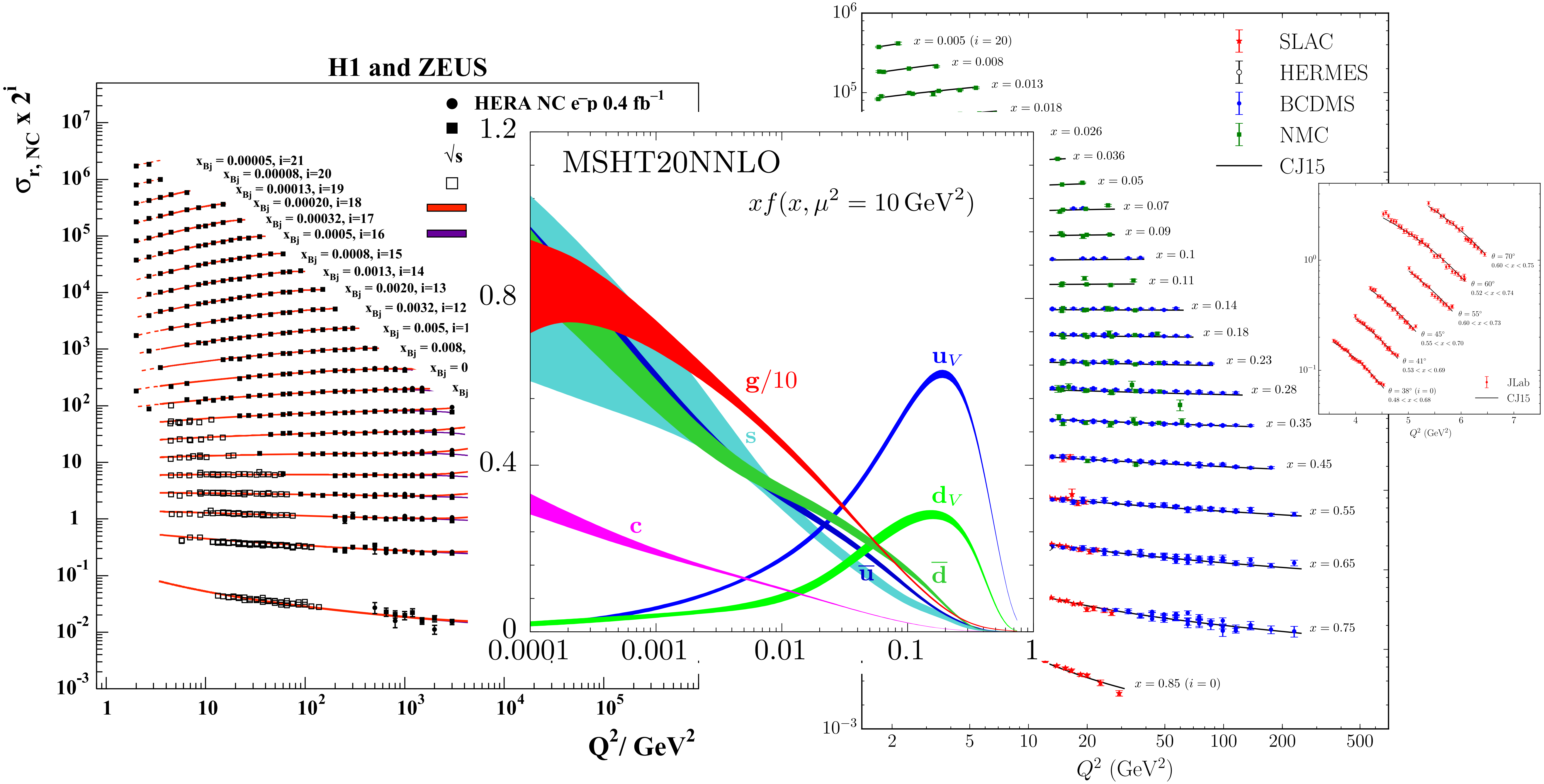


H. Abramowicz *et al.*, EPJC 78, 580 (2015).



A. Accardi *et al.*, PRD 93, 114017 (2016).

Lepton-Hadron Deep Inelastic Scattering



H. Abramowicz *et al.*, EPJC 78, 580 (2015).

A. Accardi *et al.*, PRD 93, 114017 (2016).

A successful story of QCD, factorization and evolution!

Nucleon Spin Structure

Proton spin puzzle

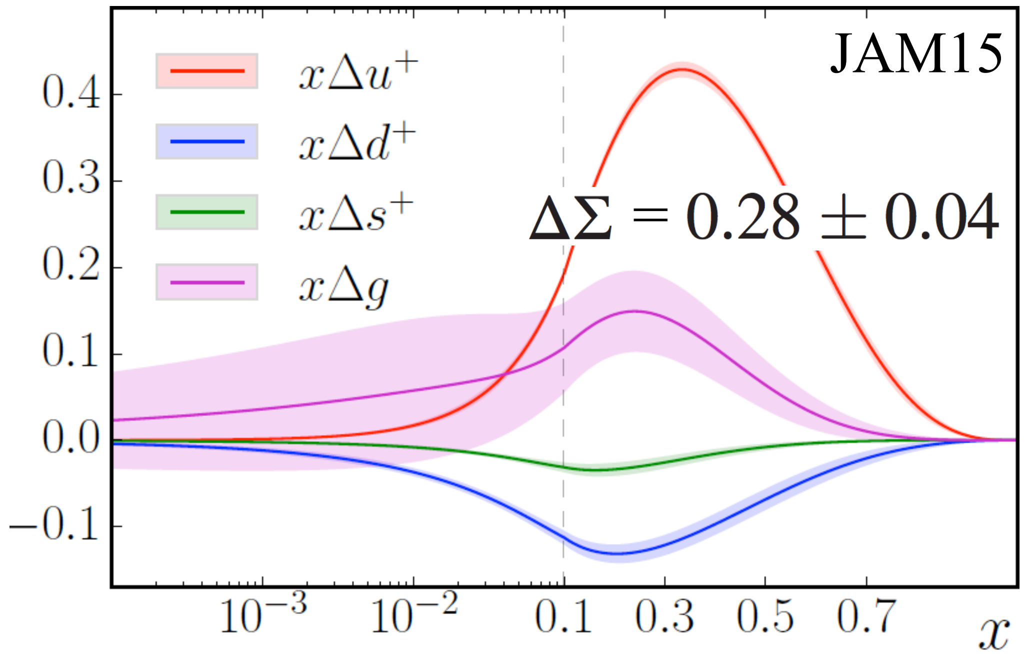
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to the nucleon spin.

J. Ashman *et al.*, PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

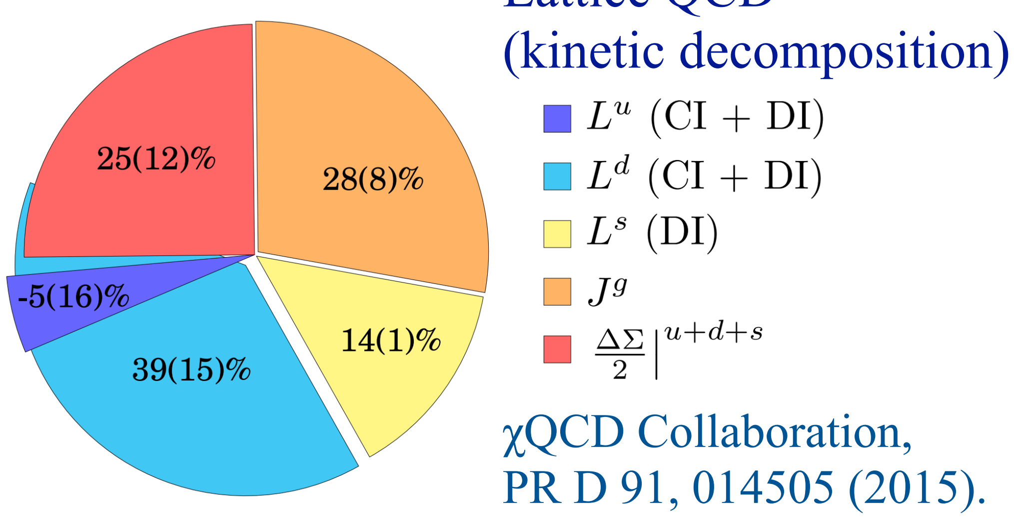
$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



JAM Collaboration, PR D 93, 074005 (2016).

JAM17: $\Delta\Sigma = 0.36 \pm 0.09$

JAM Collaboration, PRL 119, 132001 (2017).

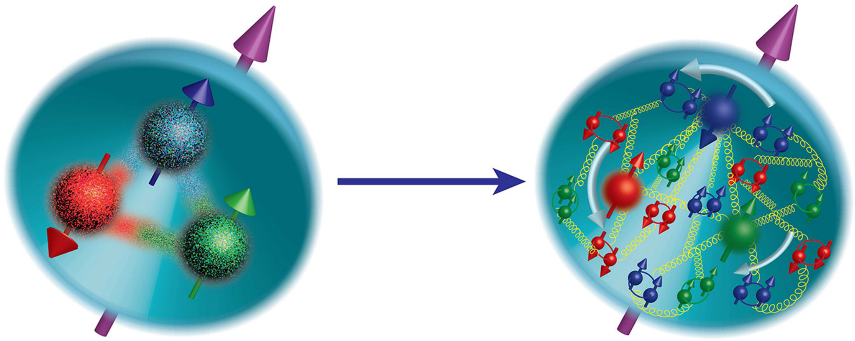


χQCD Collaboration, PR D 91, 014505 (2015).

Gluon spin from LQCD: $S_g = 0.251(47)(16)$

50% of total proton spin

Y.-B. Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017).



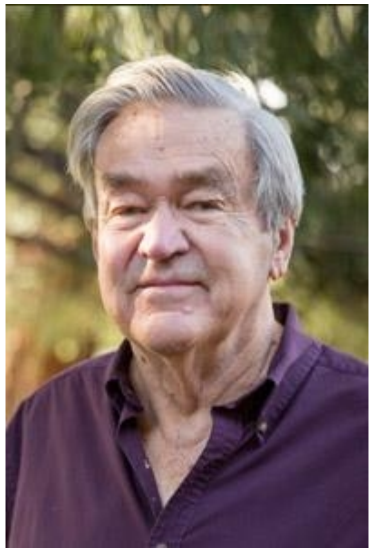
How well do we understand spin?

"Spin" has killed more theories in physics than any other single observable.

— E. Leader

If theorists had their way, they would ban all experiments with spin.

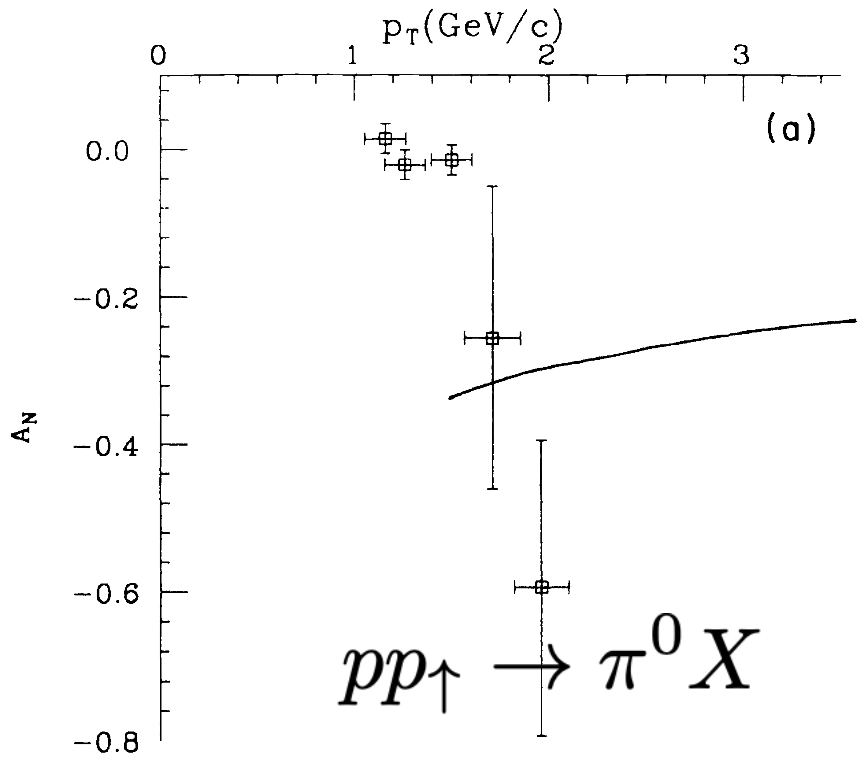
— J.D. Bjorken



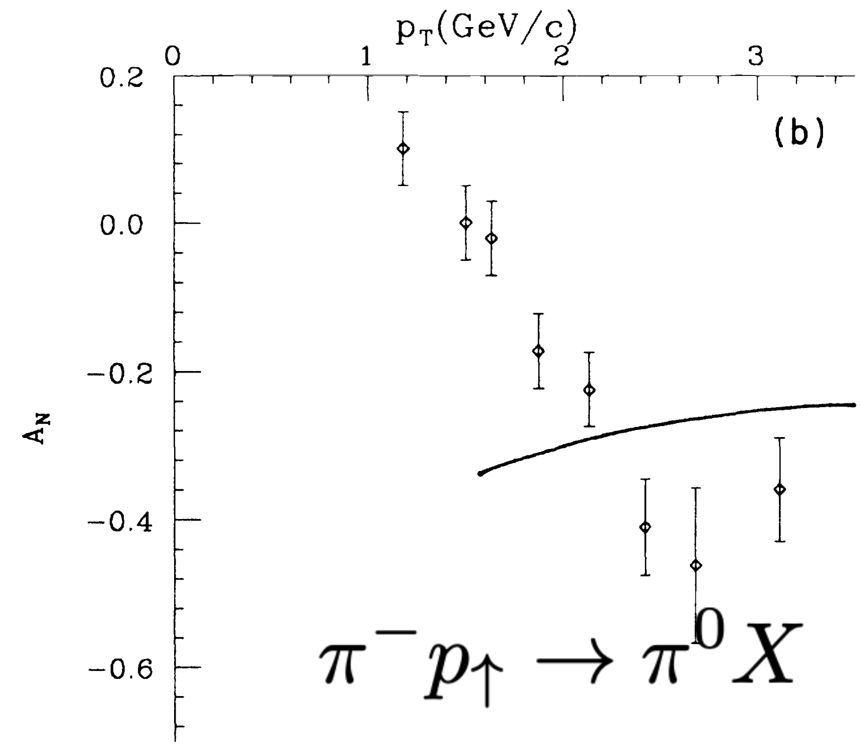
Spin: Always surprises!

Early Story: the Sivers function

Transverse single spin asymmetry observed in experiments



Data: J. Antille *et al*., Phys. Lett B94 (1980) 523.



Data: 7th Symposium on High Energy Spin Physics (1986).

D. Sivers proposed to explain such SSA a new distribution function

Sivers function $\Delta^N G_{a/p(\uparrow)}(x, \mathbf{k}_T; \mu^2)$ D. Sivers, Phys. Rev. D 41 (1990) 83.

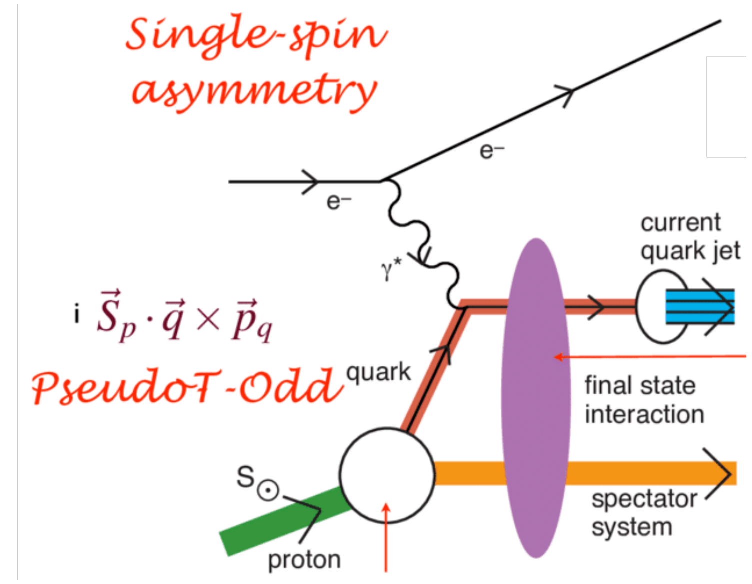
However it was soon shown this function was T-odd and prohibited by QCD

J. Collins, Nucl. Phys. B 396 (1993) 161.

For the next decade, the "Sivers effect" was thought to vanish.

Early Story: the Sivers function

Until an explicit model calculation showing …

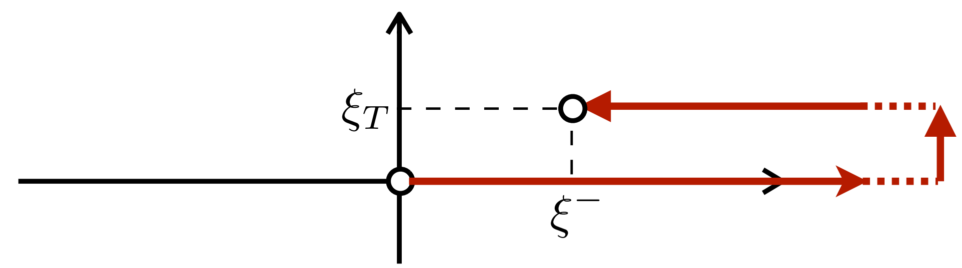


nonzero Sivers effects exist at leading twist
due to final-state interactions

S.J. Brodsky, D.S. Hwang, I. Schmidt, Phys. Lett. B 530 (2002) 99.

Sivers function can exist due to nontrivial gauge link

$$\Phi_{ij}(x, p_T) = \int \frac{d\xi^- \, d^2\xi_T}{(2\pi)^3} \, e^{ip\cdot\xi} \langle P|\bar{\psi}_j(0)\,\mathcal{U}^{n_-}_{(0,+\infty)}\,\mathcal{U}^{n_-}_{(+\infty,\xi)}\,\psi_i(\xi)|P\rangle\Big|_{\xi^+=0}$$



J.C. Collins, Phys. Lett. B 536 (2002) 43.

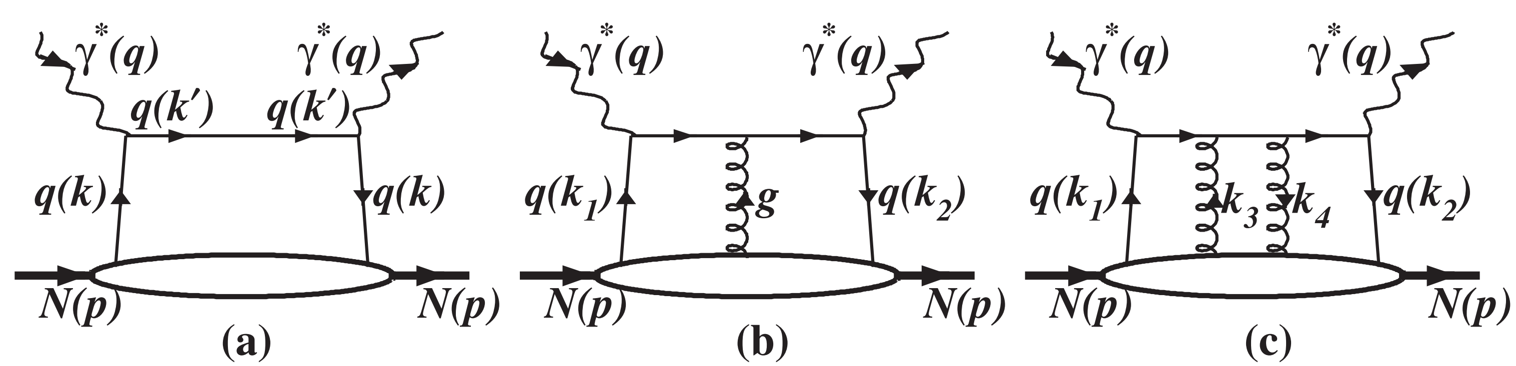
[Figure from A. Bacchetta]

This gauge link effect cannot be remove by choosing light-cone gauge $A^+ = 0$

X. Ji and F. Yuan, Phys. Lett. B 543 (2002) 66.

Collinear expansion

Z.-t. Liang and X.N. Wang,
Phys. Rev. D 75 (2007) 094002.



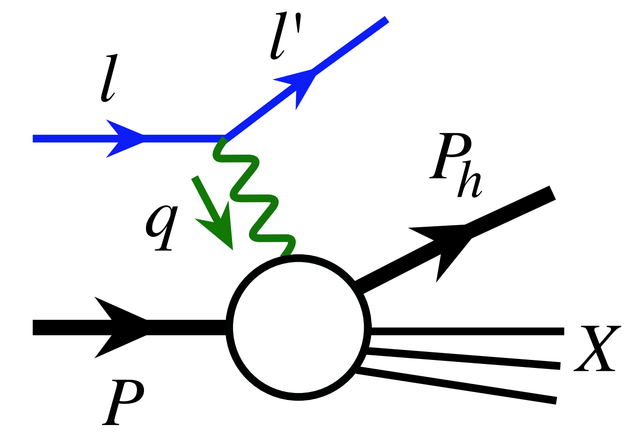
Leading Twist TMDs

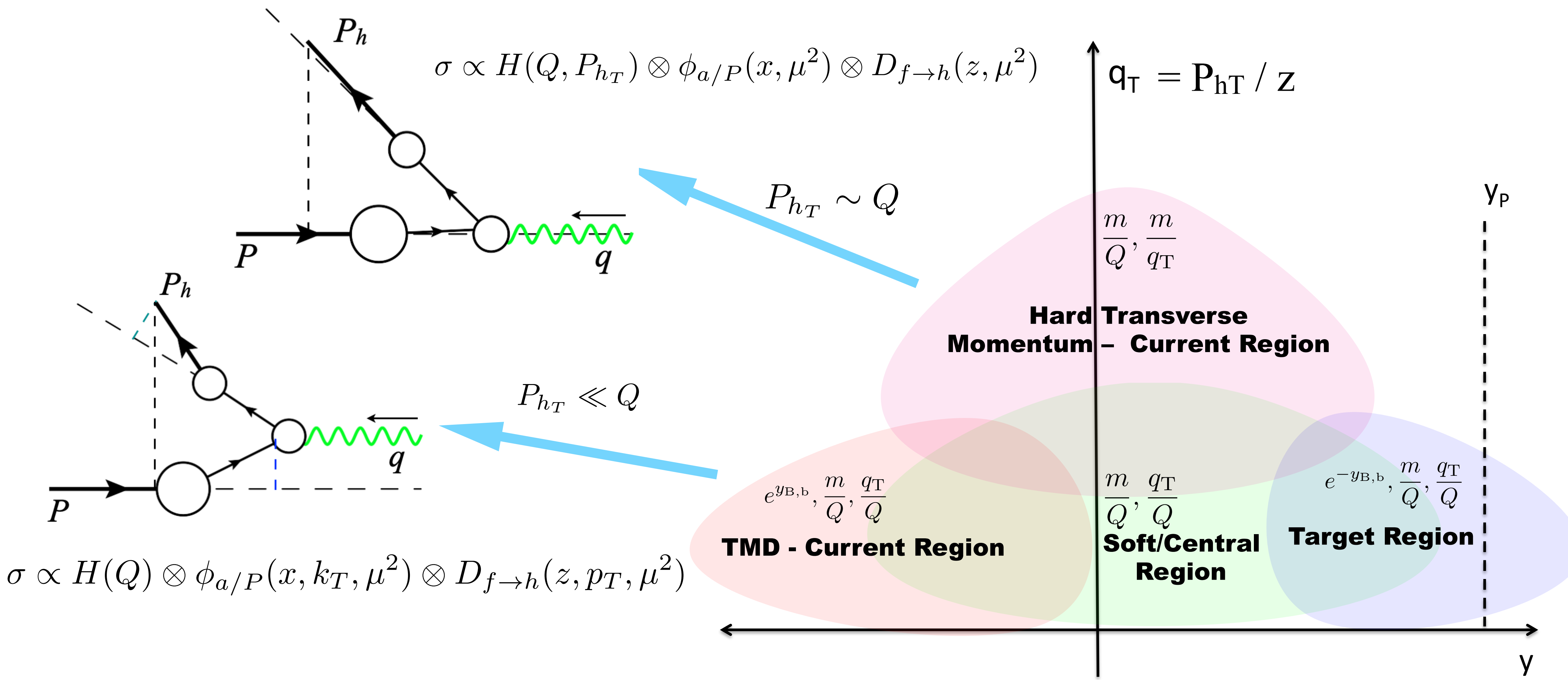
Nucleon Polarization	Quark Polarization: U	Quark Polarization: L	Quark Polarization: T
U	f_1 unpolarized		$h_1^{\perp}$ Boer-Mulders
L		g_{1L} helicity	$h_{1L}^{\perp}$ longi-transversity (worm-gear)
T	$f_{1T}^{\perp}$ Sivers	g_{1T} trans-helicity (worm-gear)	h_1 transversity $h_{1T}^{\perp}$ pretzelosity

Semi-inclusive DIS

Identify a final state hadron

- explore the emergence of hadrons from colored quarks/gluons
- flavor dependence by selecting different observed hadrons
- an additional and adjustable momentum scale



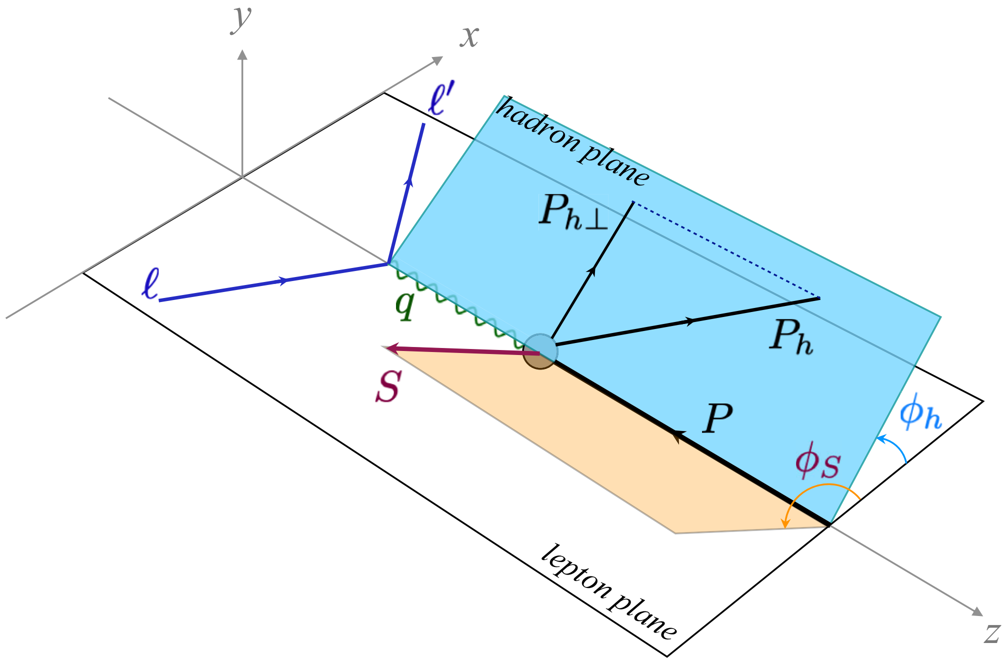


[Figure from JHEP10(2019)122]

SIDIS in Trento Convention

SIDIS differential cross section

18 structure functions $F(x_B, z, Q^2, P_{hT})$,
(one photon exchange approximation)



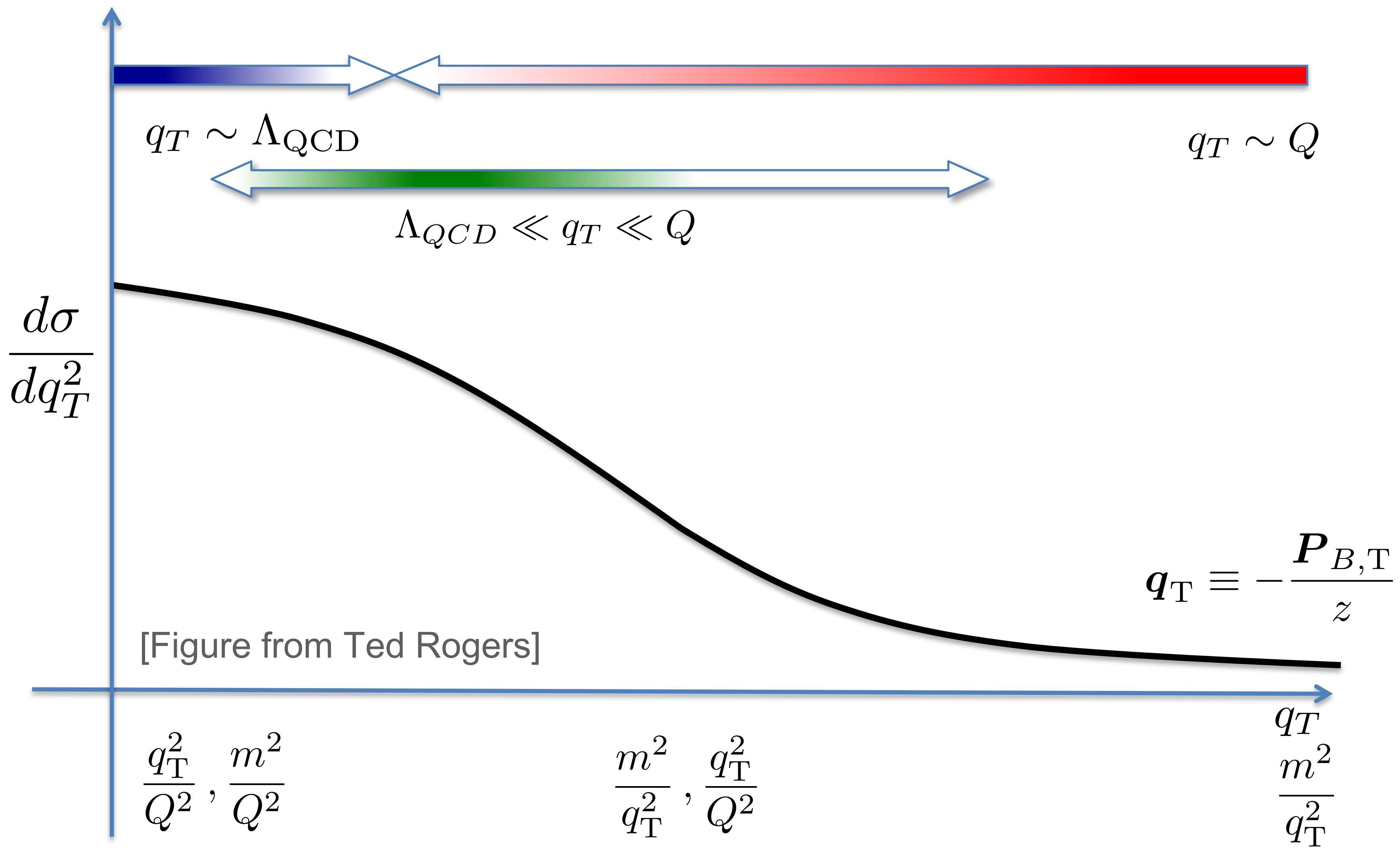
$$\frac{d^6\sigma}{dx_B\,dy\,dz\,dP_{hT}^2\,d\phi_h\,d\phi_S}$$

$$\begin{aligned}
&= \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x_B}\right) \\
&\times \Big\{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h \\
&+ S_L\left[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h + \epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] + \lambda_e S_L\left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\right] \\
&+ S_T\Big[\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\sin(\phi_h-\phi_S) + \epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\
&+ \epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \quad + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big] \\
&+ \lambda_e S_T\Big[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\
&+ \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S + \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}
\end{aligned}$$

Small and Large Transverse Momentum

W + Y formalism

$$\frac{d\sigma}{d^2 q_{\mathrm{T}} dQ \cdots} = W(q_{\mathrm{T}}, Q) + Y(q_{\mathrm{T}}, Q) + \mathcal{O}\left(\frac{m}{Q}\right)^n$$



$$W(q_{\mathrm{T}}, Q) = \mathrm{T}_{\mathrm{TMD}}\, d\sigma$$

$$\begin{aligned} Y(q_{\mathrm{T}}, Q) &= X(q_{\mathrm{T}}/\lambda)\mathrm{T}_{\mathrm{coll}}\,(d\sigma - \mathrm{T}_{\mathrm{TMD}} d\sigma) \\ &= X(q_{\mathrm{T}}/\lambda)[\mathrm{FO}(q_{\mathrm{T}}, Q) - \mathrm{ASY}(q_{\mathrm{T}}, Q)] \end{aligned}$$

TMD Evolution

Evolution equations

$$\mu^2 \frac{dF(x,b;\mu,\zeta)}{d\mu^2} = \frac{\gamma_F(\mu,\zeta)}{2} F(x,b;\mu,\zeta)$$

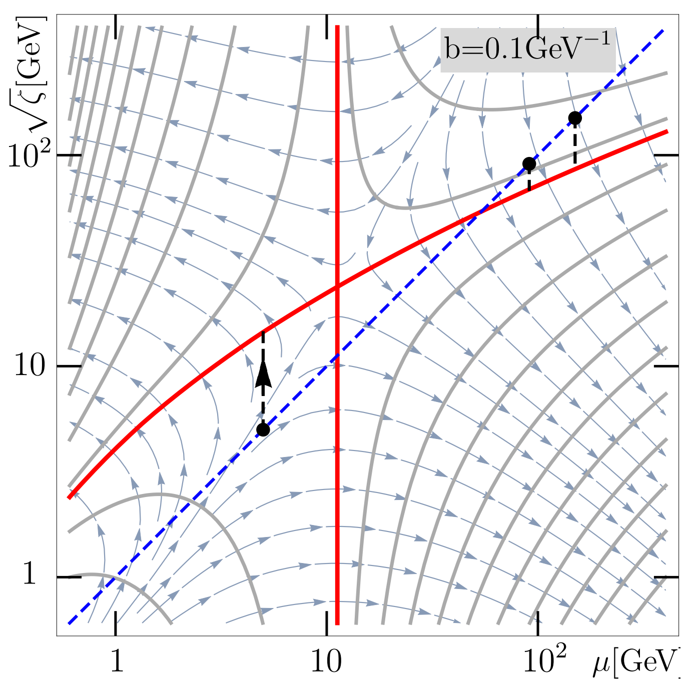
$$\zeta \frac{dF(x,b;\mu,\zeta)}{d\zeta} = -\mathcal{D}(b,\mu) F(x,b;\mu,\zeta)$$

$$-\zeta \frac{d\gamma_F(\mu,\zeta)}{d\zeta} = \mu \frac{d\mathcal{D}(\mu,b)}{d\mu} = \Gamma_{\text{cusp}}(\mu)$$

$$\gamma_F(\mu,\zeta) = \Gamma_{\text{cusp}}(\mu) \ln\left(\frac{\mu^2}{\zeta}\right) - \gamma_V(\mu)$$

$$F(x,b;\mu_f,\zeta_f) = \exp\left[\int_P \left(\gamma_F(\mu,\zeta)\frac{d\mu}{\mu} - \mathcal{D}(\mu,b)\frac{d\zeta}{\zeta}\right)\right] F(x,b;\mu_i,\zeta_i)$$

ζ-prescription



$$\mu^2 = \zeta = Q^2 \qquad R[b;(\mu_i,\zeta_i) \to (Q,Q^2)] = \left(\frac{Q^2}{\zeta_\mu(Q,b)}\right)^{-\mathcal{D}(Q,b)}$$

$$\frac{d\ln\zeta_\mu(\mu,b)}{d\ln\mu^2} = \frac{\gamma_F(\mu,\zeta_\mu(\mu,b))}{2\mathcal{D}(\mu,b)}$$

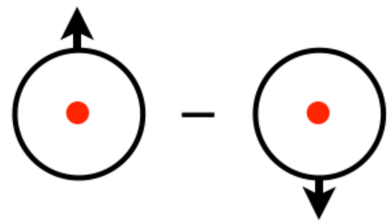
$$\mathcal{D}(\mu_0,b) = 0, \quad \gamma_F(\mu_0,\zeta_\mu(\mu_0,b)) = 0$$

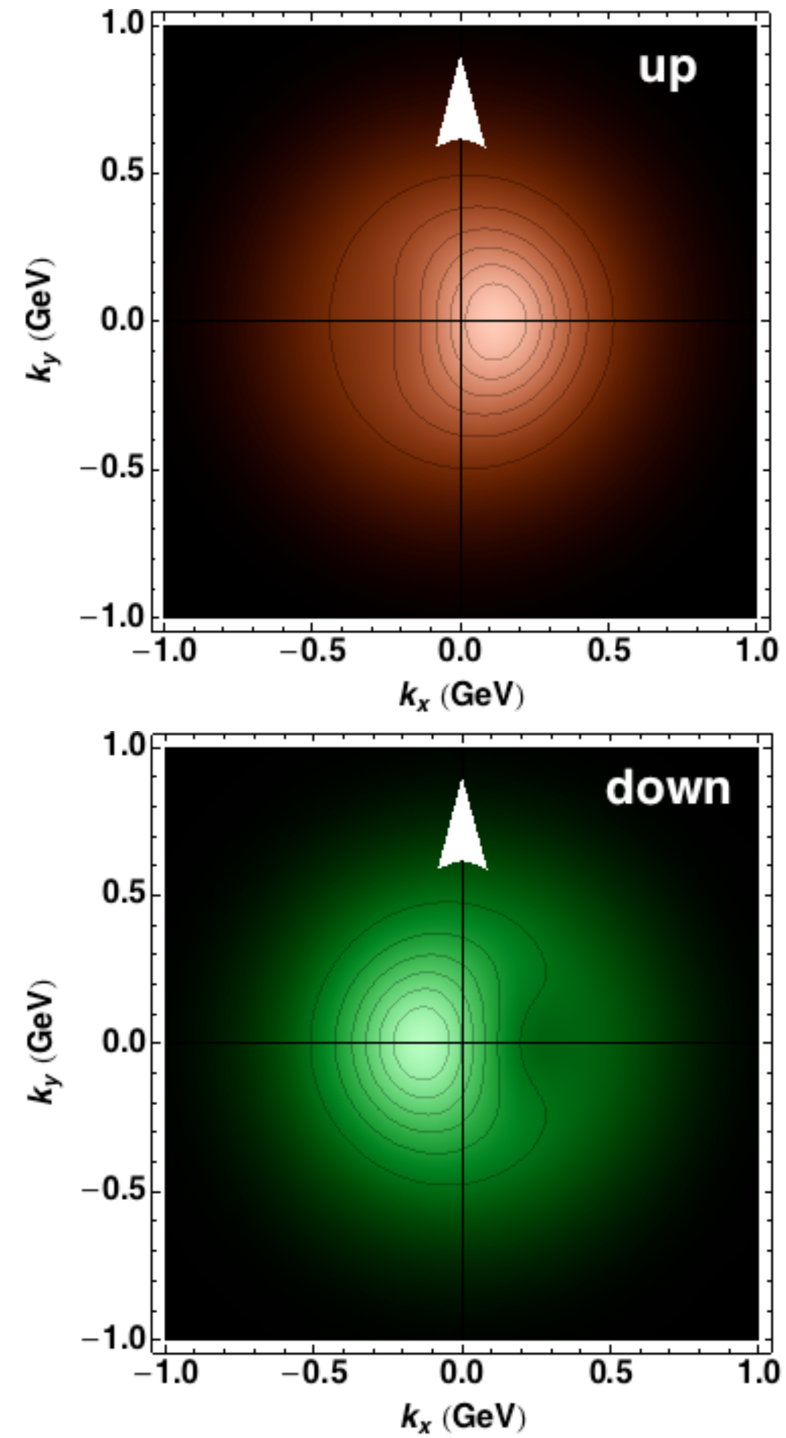
$$F(x,b;Q,Q^2) = \left(\frac{Q^2}{\zeta_Q(b)}\right)^{-\mathcal{D}(b,Q)} F(x,b)$$

The Sivers Function

Sivers TMD distribution function

$$f_{1T}^{\perp}(x, k_T)$$





[Figure from A. Bacchetta]

Quark density distortion in transverse momentum space by nucleon transverse spin

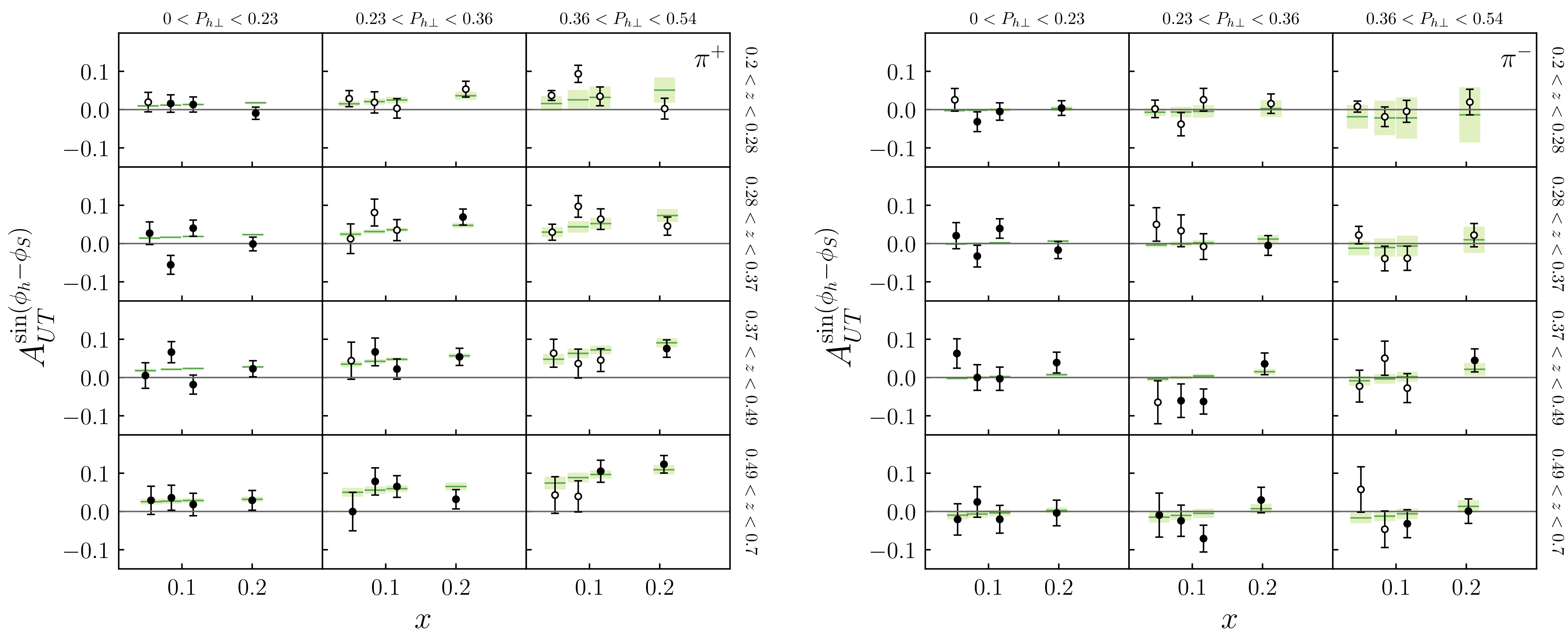
Sign change prediction:

$$f_{1T}^{\perp q}(x, k_\perp)\Big|_{\text{SIDIS}} = -f_{1T}^{\perp q}(x, k_\perp)\Big|_{\text{DY}}$$

Effect in SIDIS:
transverse single spin asymmetry
(Sivers asymmetry)

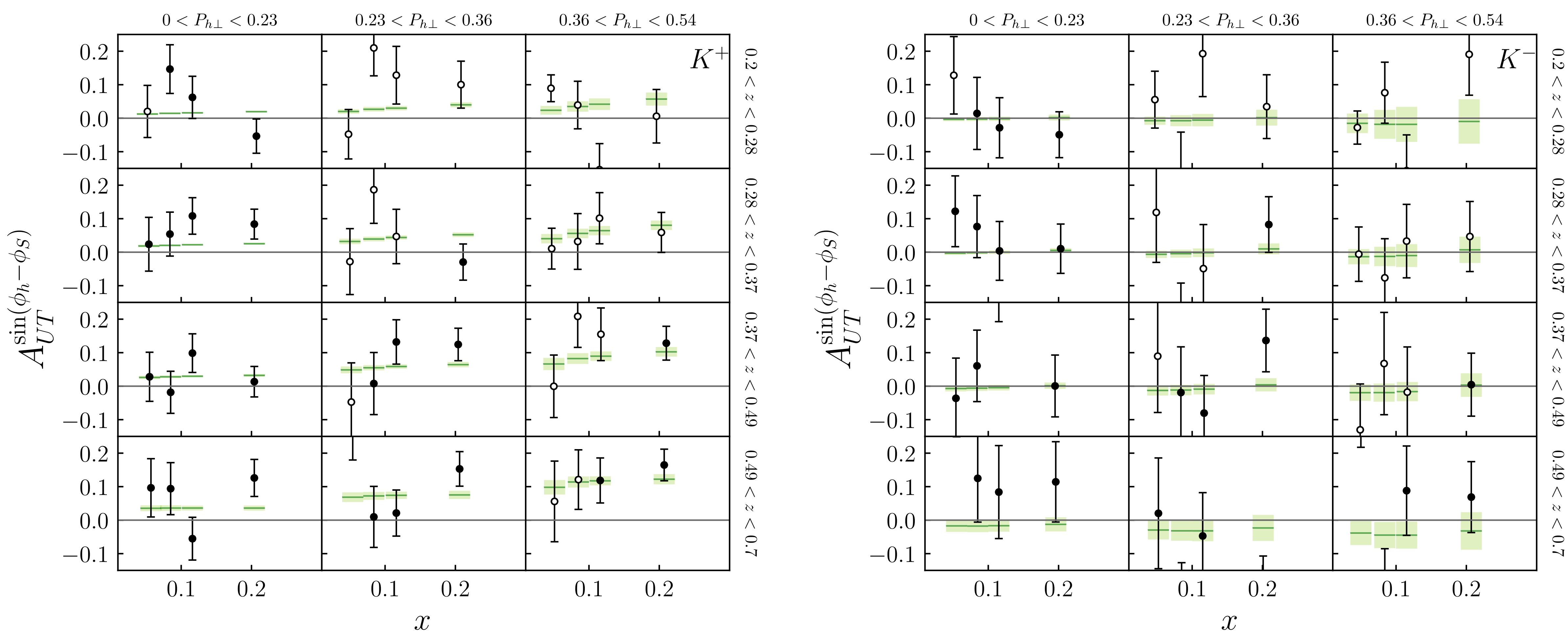
$$A_{UT}^{\sin(\phi_h - \phi_s)} \sim f_{1T}^{\perp} \otimes D_1$$

Measurements of the Sivers Asymmetry



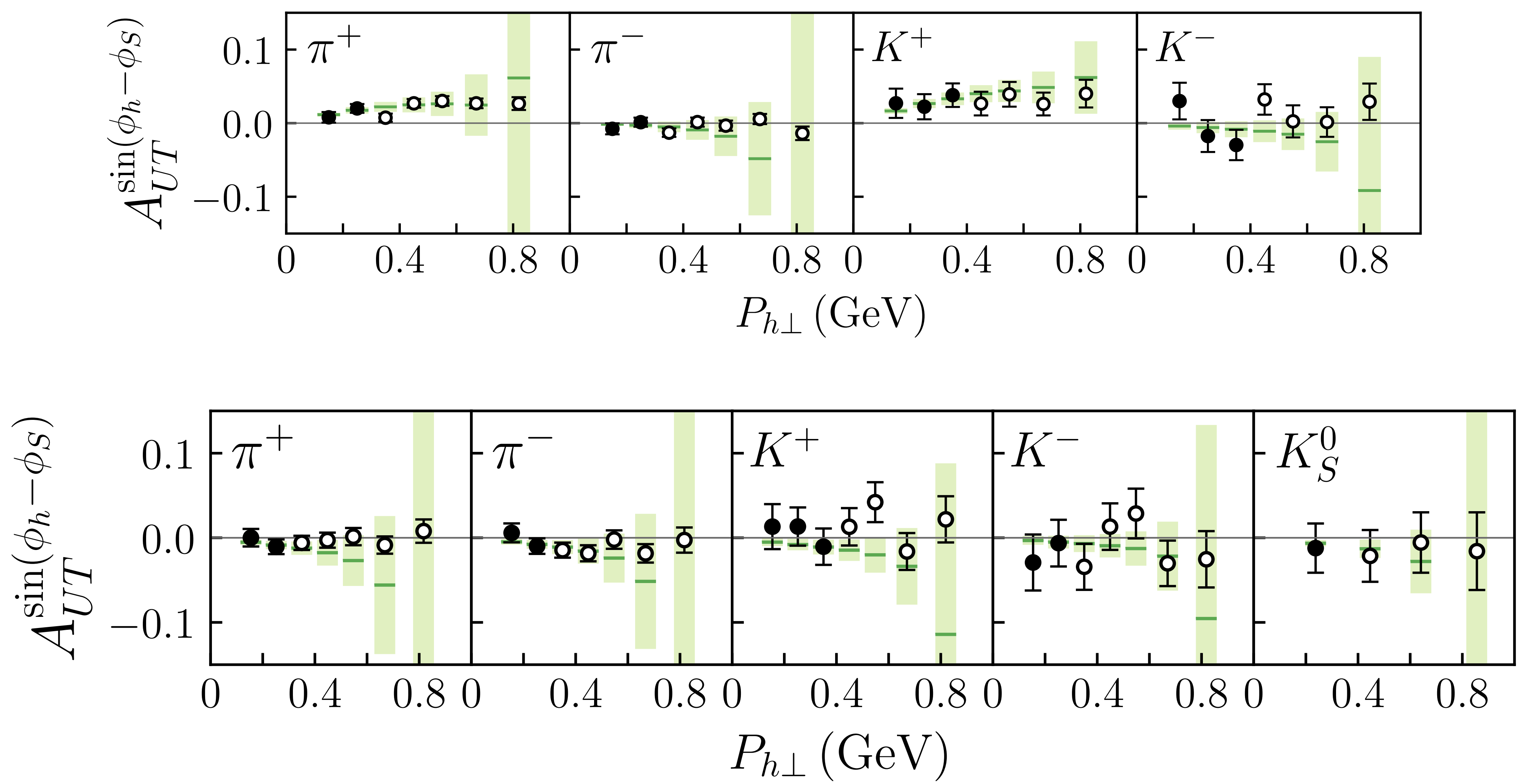
HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

Measurements of the Sivers Asymmetry



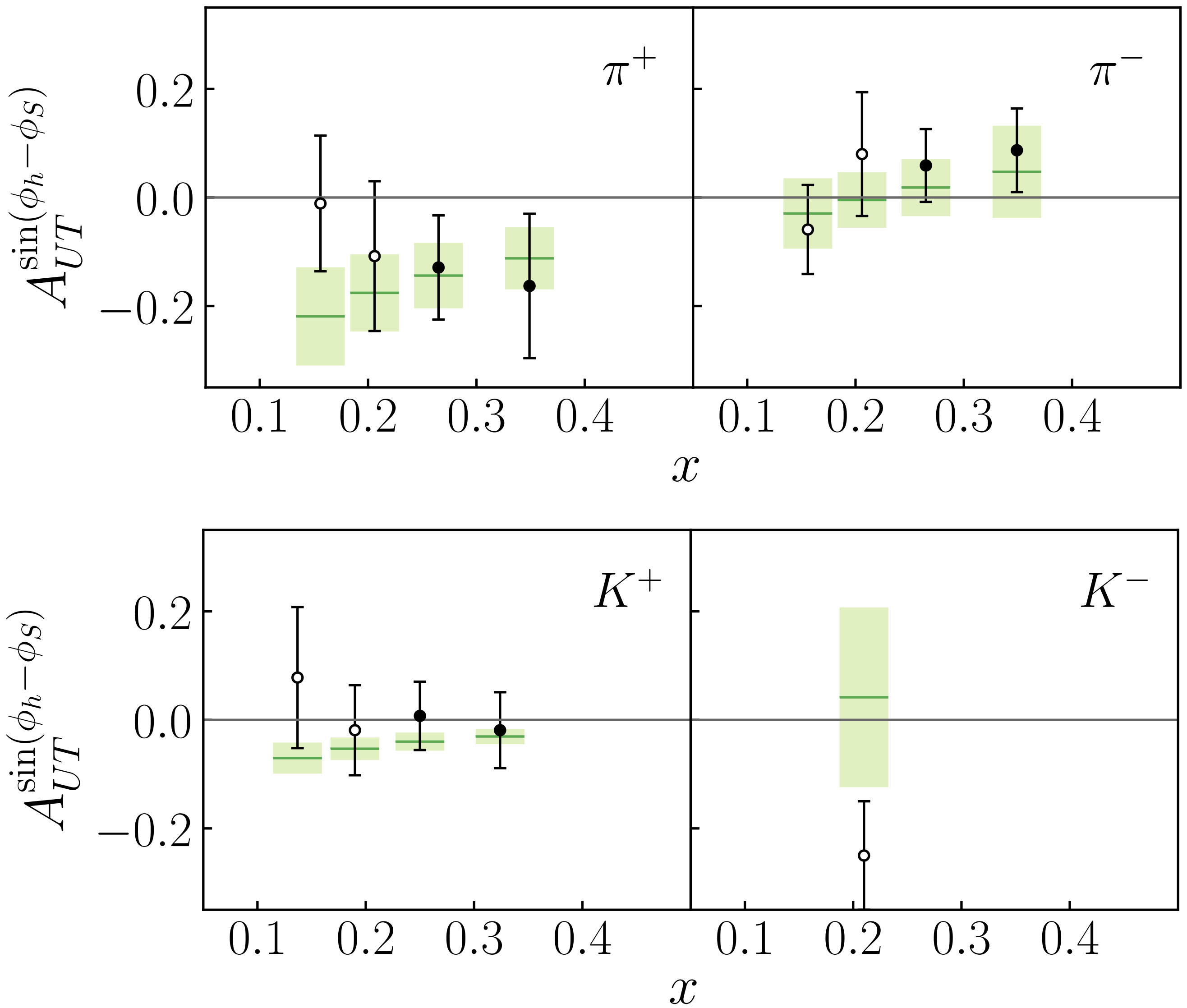
HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

Measurements of the Sivers Asymmetry



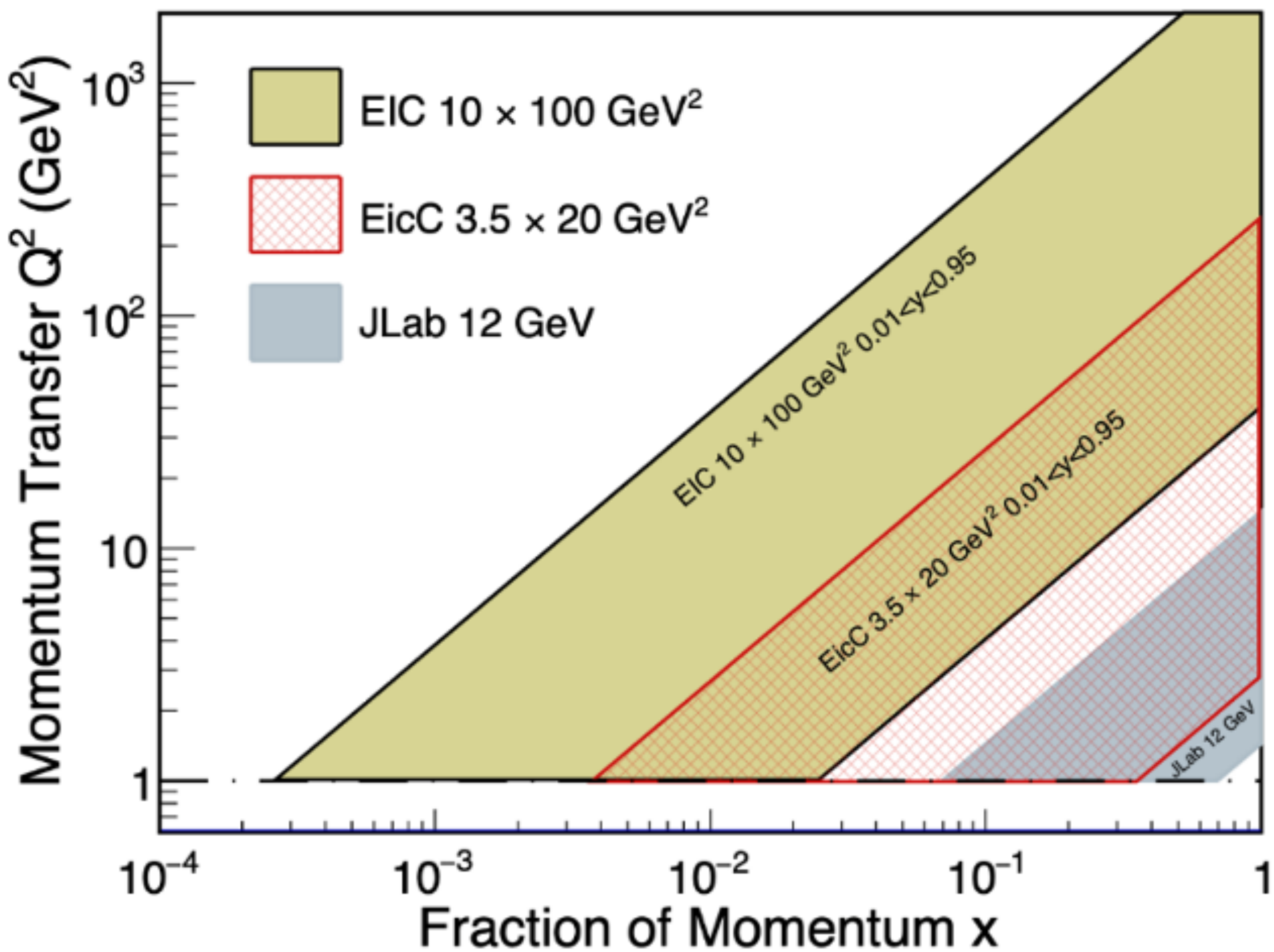
COMPASS Collaboration, Phys. Lett. B 673 (2009) 127; Phys. Lett. B 744 (2015) 250.

Measurements of the Sivers Asymmetry



JLab HallA Collaboration, Phys. Rev. Lett. (2011) 072003; Phys. Rev. C 90 (2014) 055201.

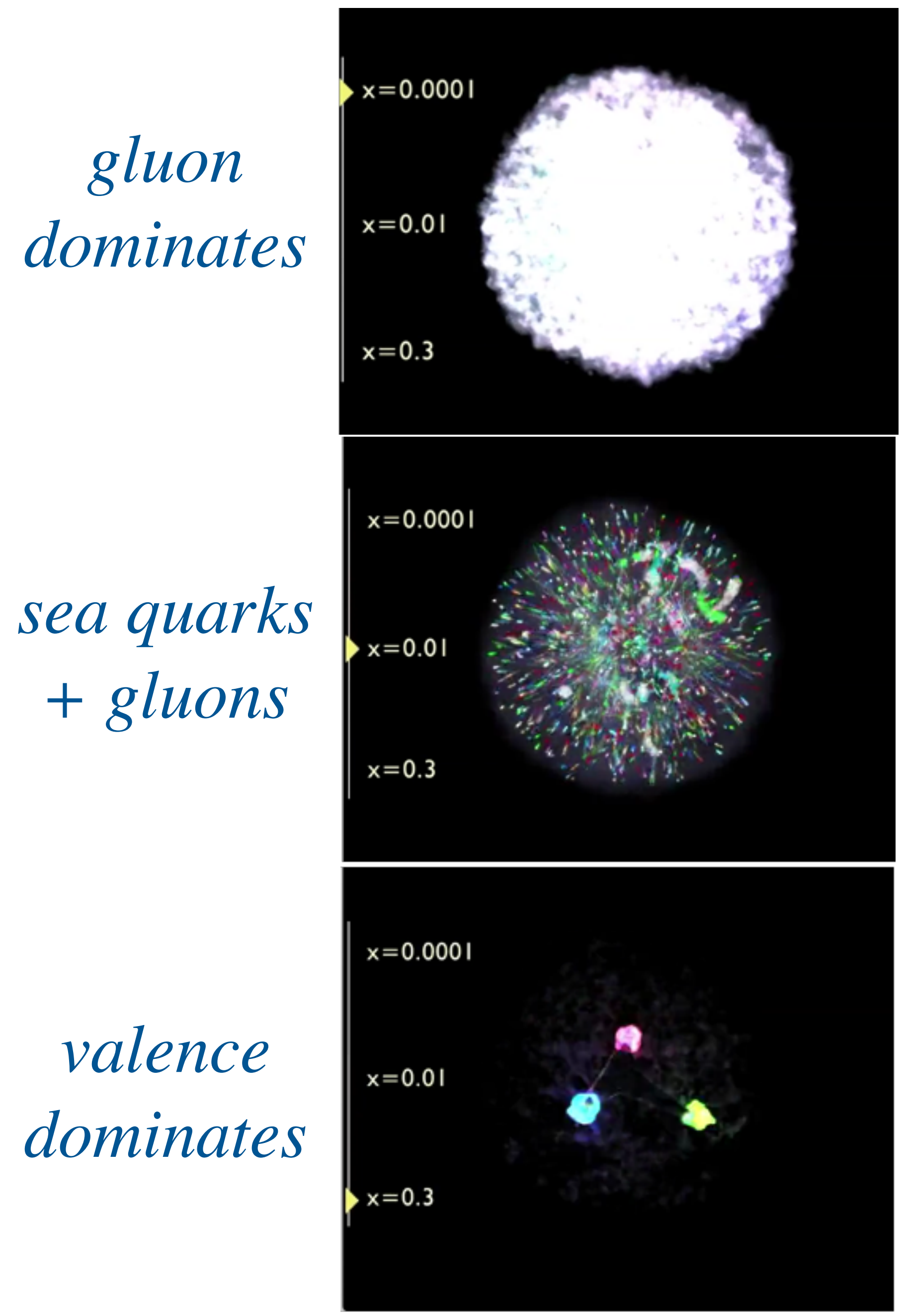
Complementary Experiments in Future



[Figure from EicC White paper]

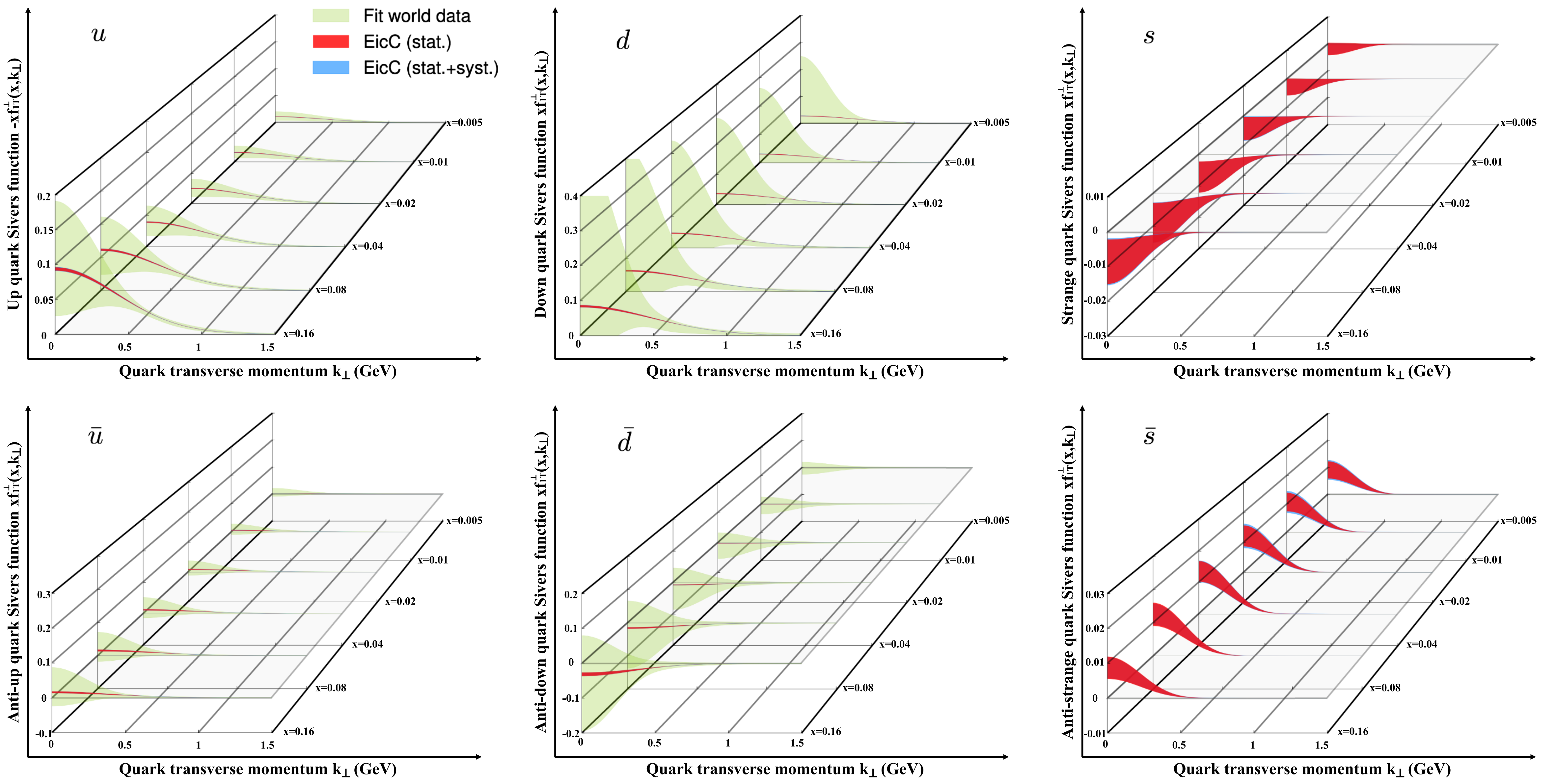
EicC is optimized to systematically explore the gluon and sea quarks in moderate *x* regime

At a crucial place between JLab and EIC-US



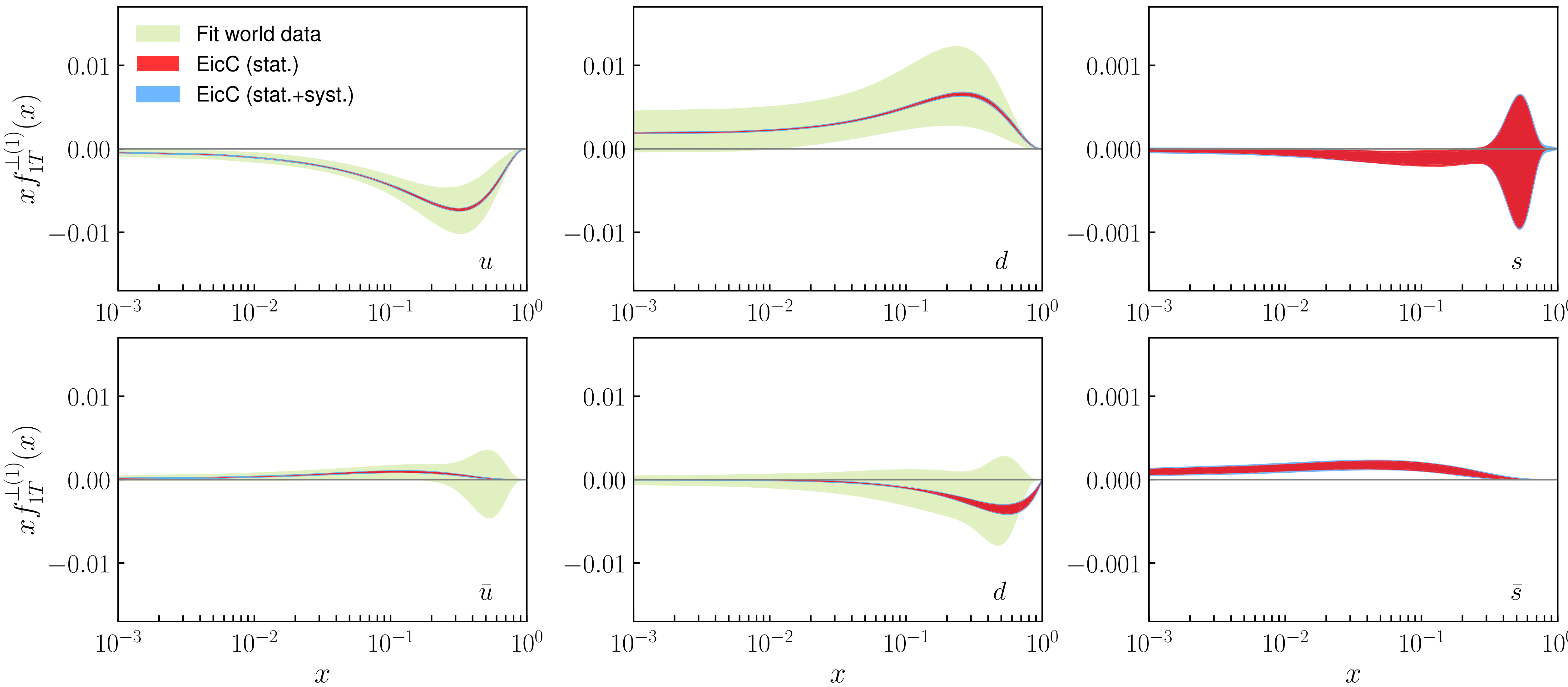
R.G. Milner and R. Ent, *Visualizing the proton* 2022

Extraction of the Sivers function



C. Zeng, T. Liu, P. Sun, Y. Zhao, Phys. Rev. D 106 (2022) 094039.

EicC Impact: Sivers function

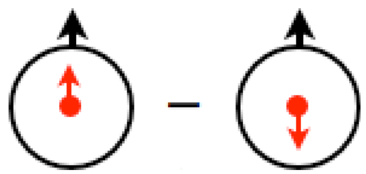


$$f_{1T}^{\perp(1)}(x) = \pi \int d\mathbf{k}_\perp^2 \frac{\mathbf{k}_\perp^2}{2M^2} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$

C. Zeng, T. Liu, P. Sun, Y. Zhao, Phys. Rev. D 106 (2022) 094039.

Transversity Distribution

Transversity distribution

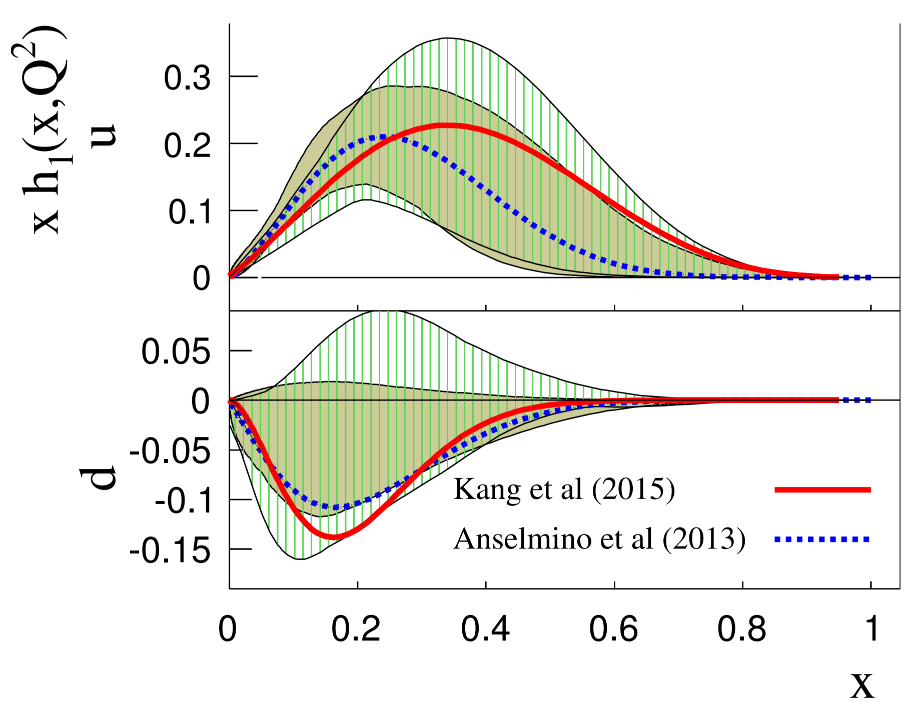
h_1  (Collinear & TMD)

A transverse counter part to the longitudinal spin structure: helicity g_{1L}, but NOT the same.

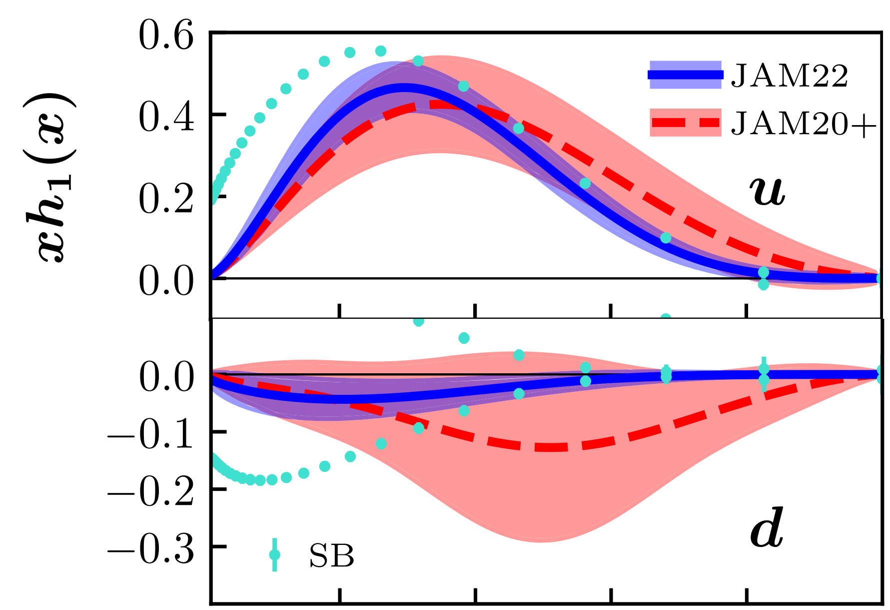
- Chiral-odd:
  No mixing with gluons
  Valence dominant
  Couple to another chiral-odd function.

e.g. $h_1(x, \mathbf{k}_\perp^2) \bigotimes H_1^\perp(z, \mathbf{p}_\perp^2)$

Phenomenological extractions

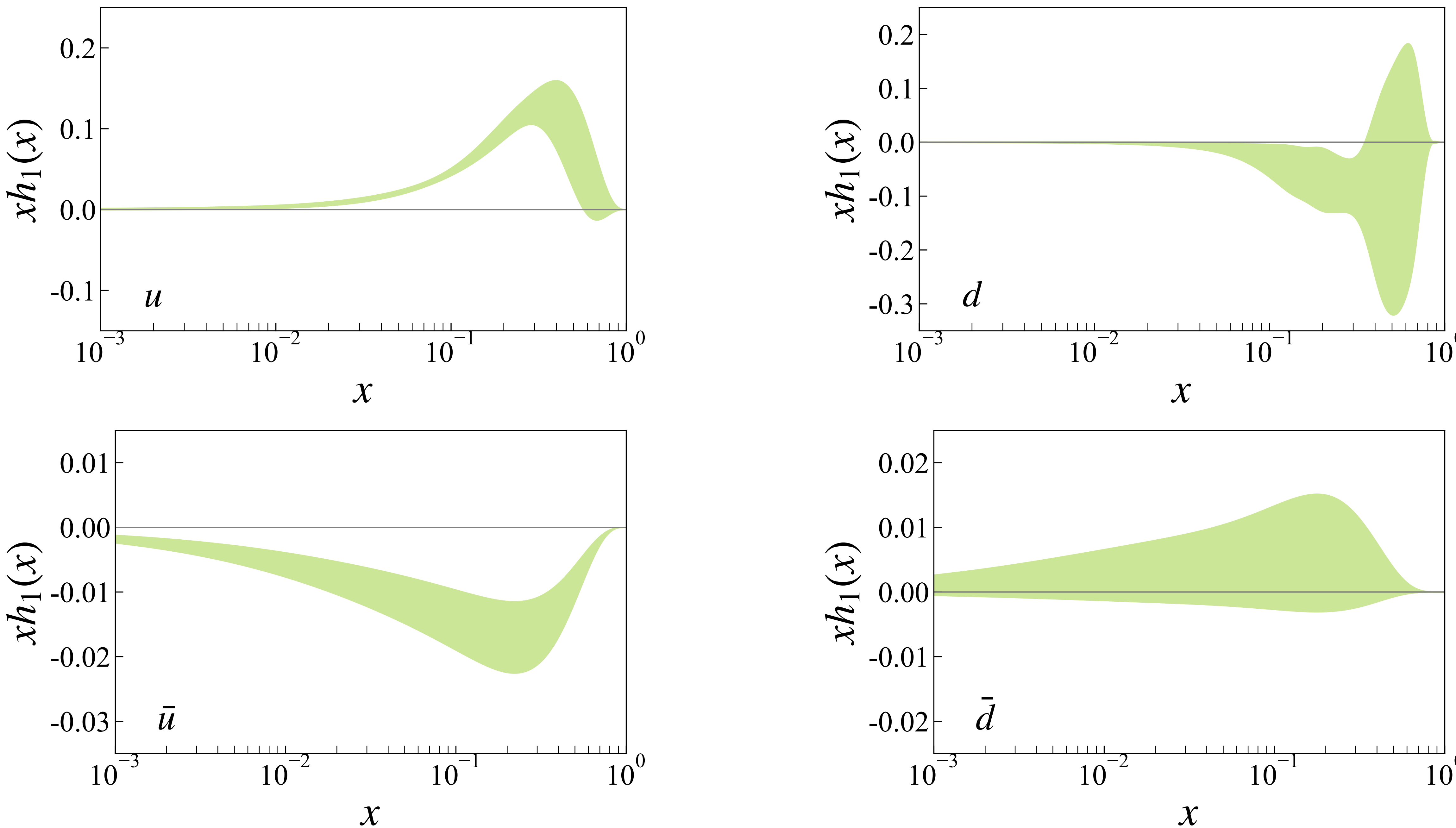


Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, PRD 93, 014009 (2016).



JAM Collaboration, PRD 104, 034014 (2022).

Sea Quark Transversity

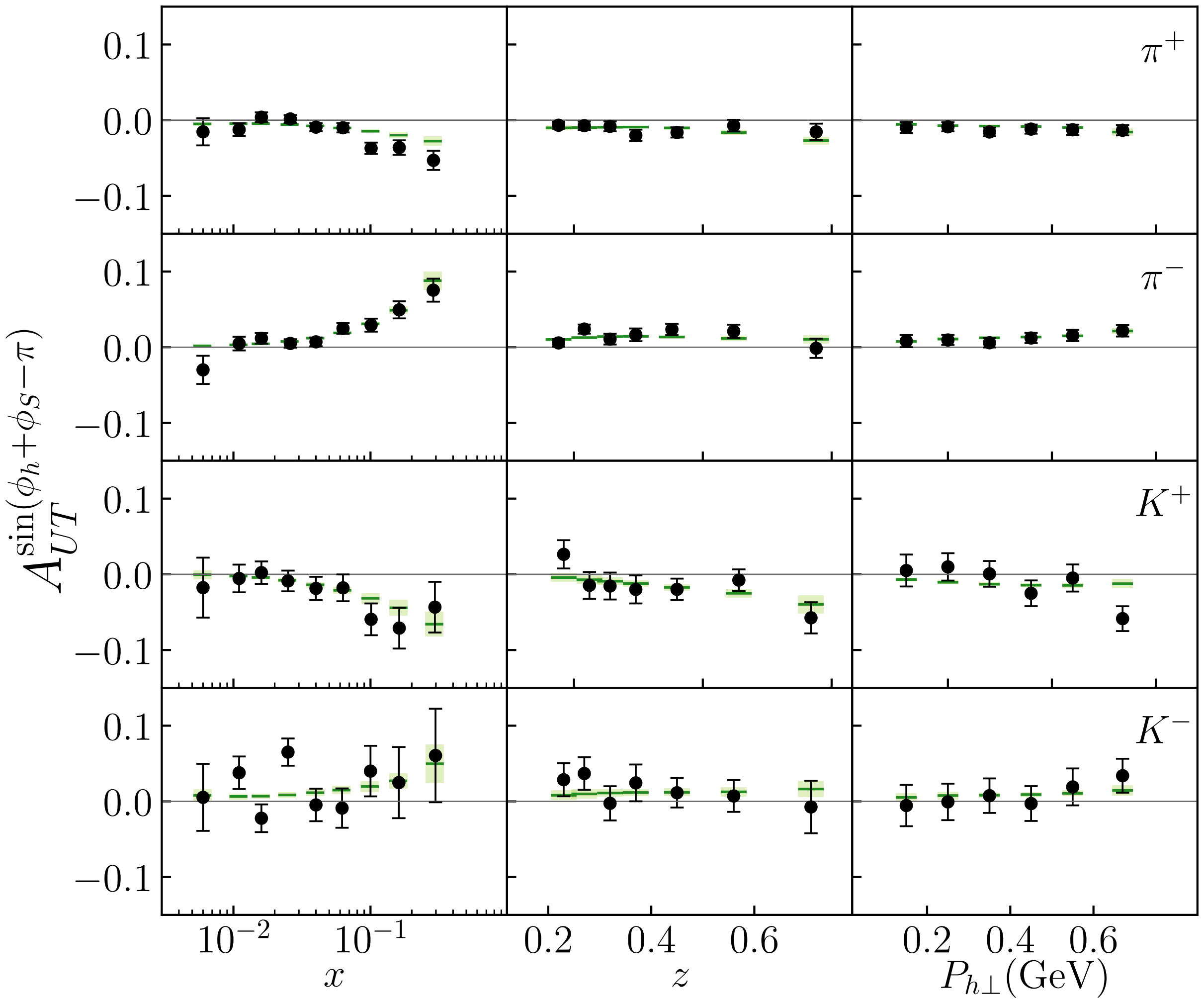


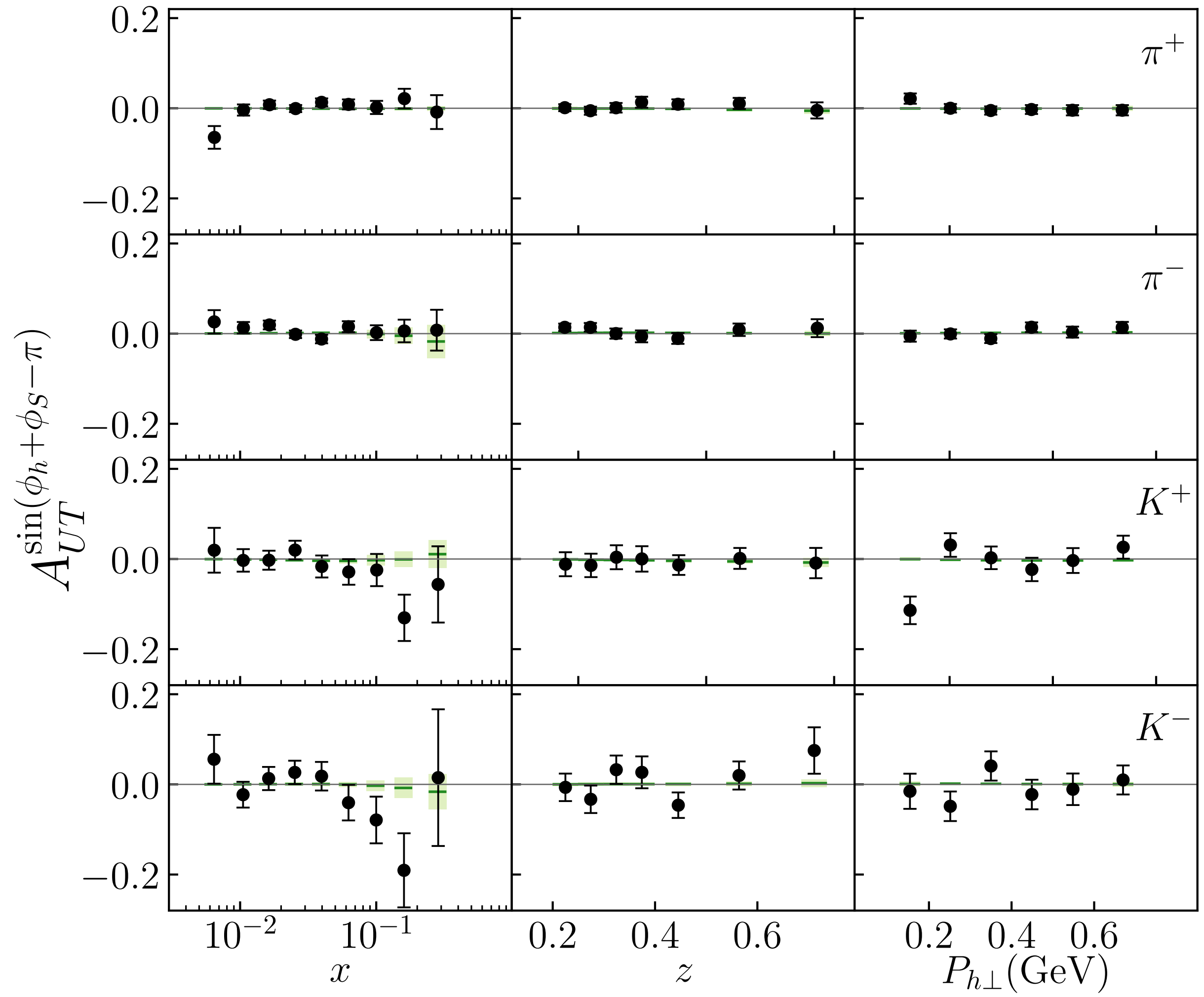
Anti-u quark favors negative distribution

Anti-d quark consistent with zero with current precision

C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2310.15532, PRD (2024).

Comparison with Data





COMPASS Collaboration, Phys. Lett. B 673 (2009) 127; Phys. Lett. B 744 (2015) 250.

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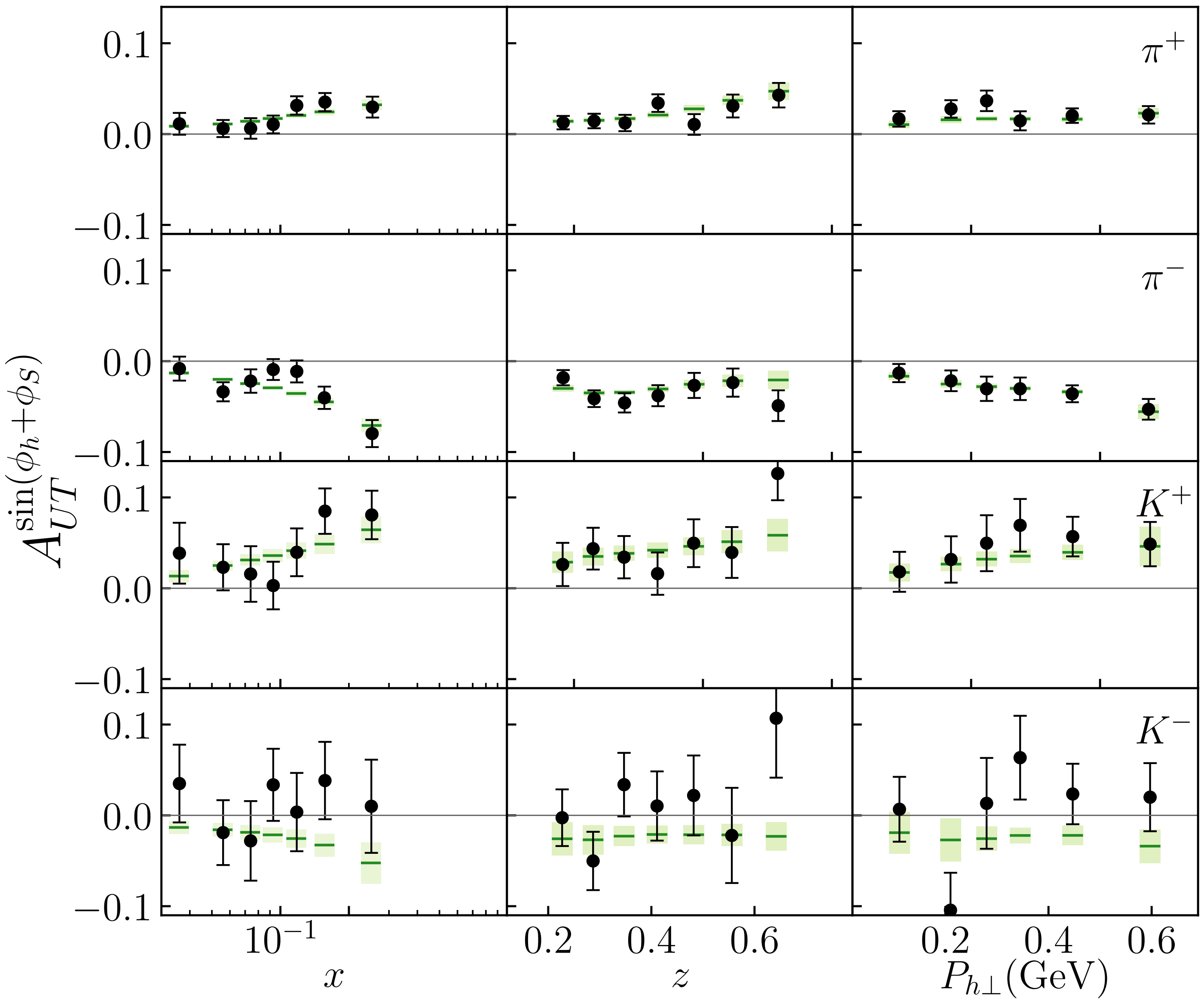
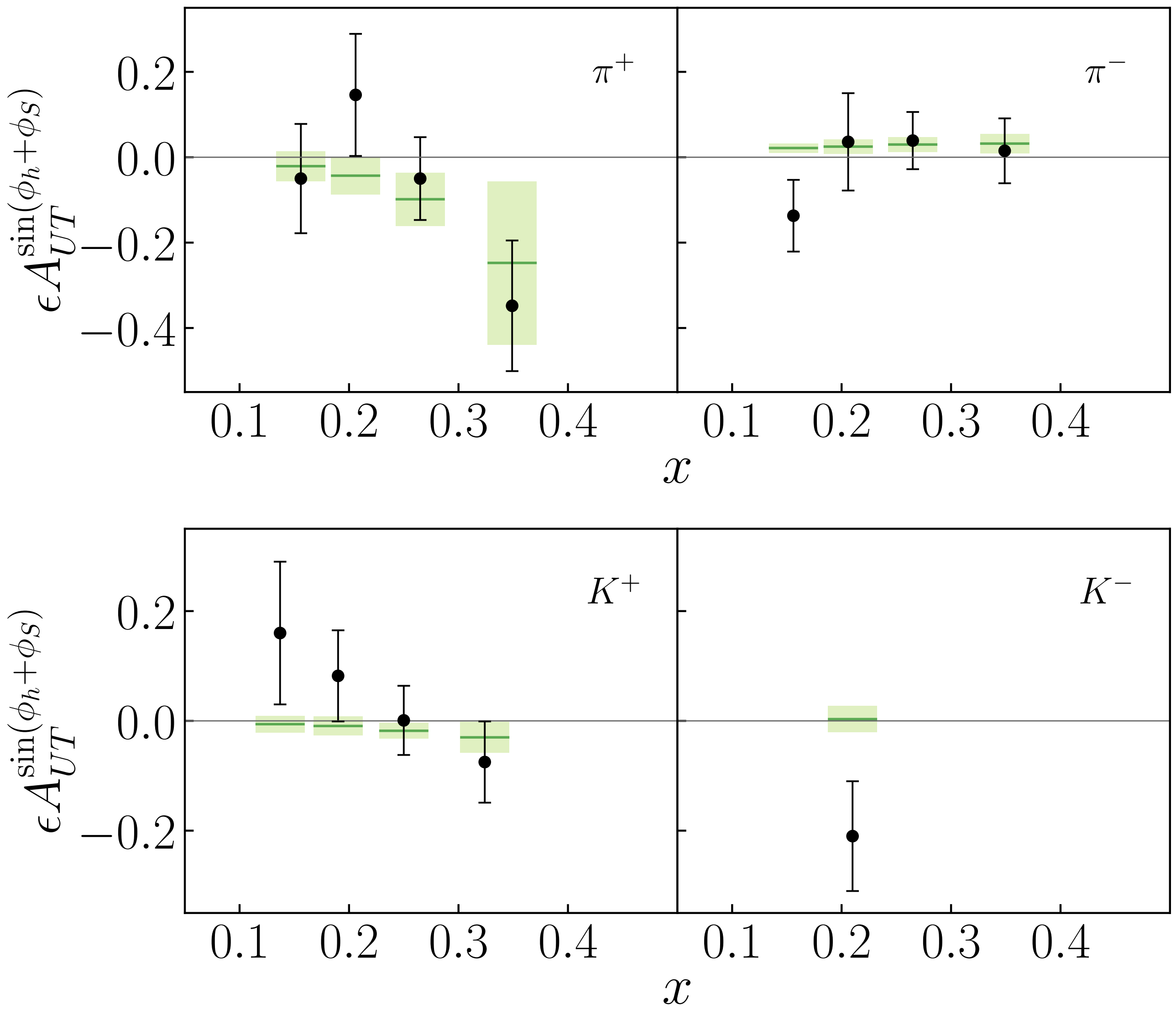


HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

Comparison with Data

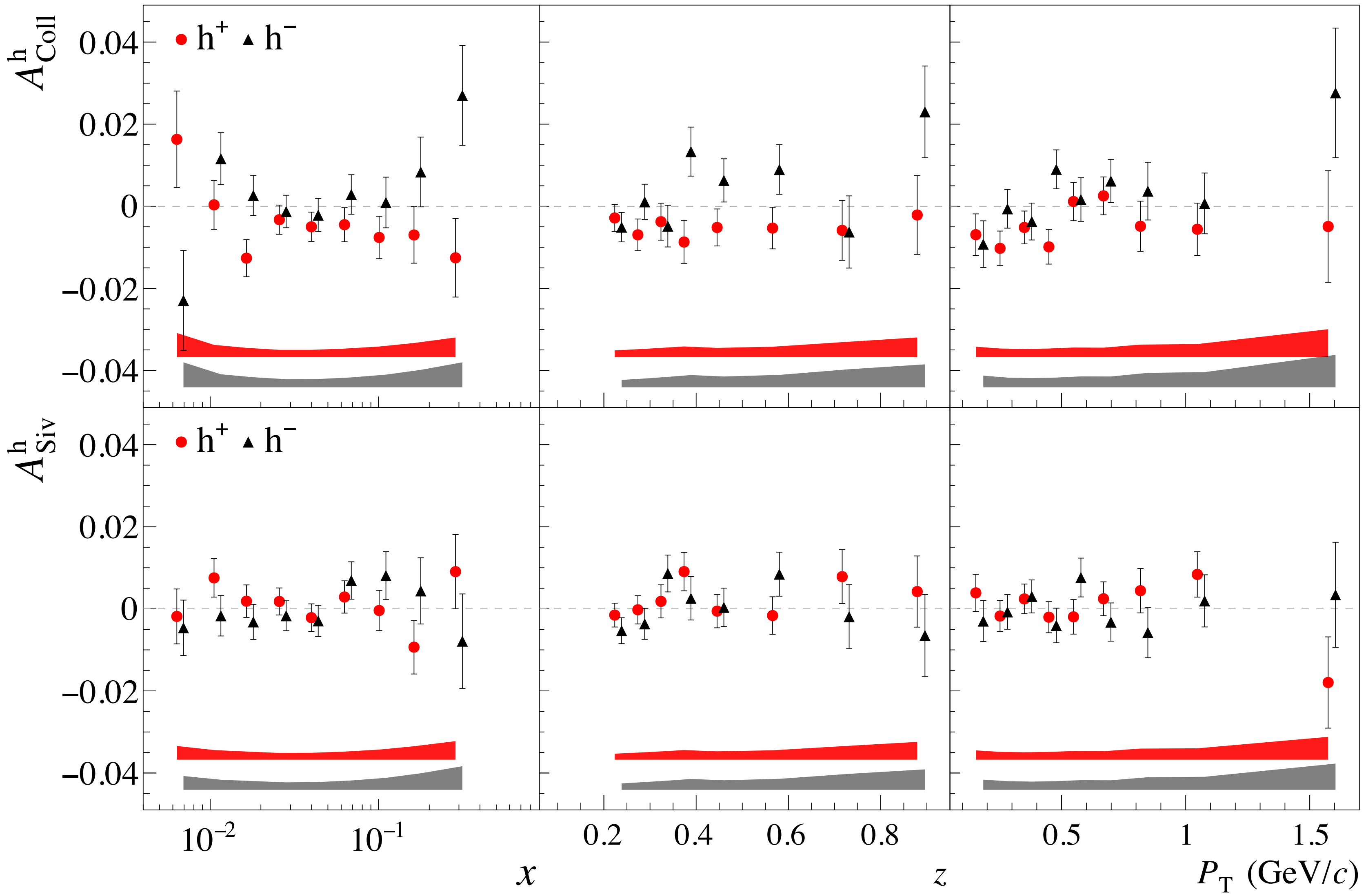


JLab HallA Collaboration, Phys. Rev. Lett. (2011) 072003; Phys. Rev. C 90 (2014) 055201.

Some More on Transversity

New data released by COMPASS

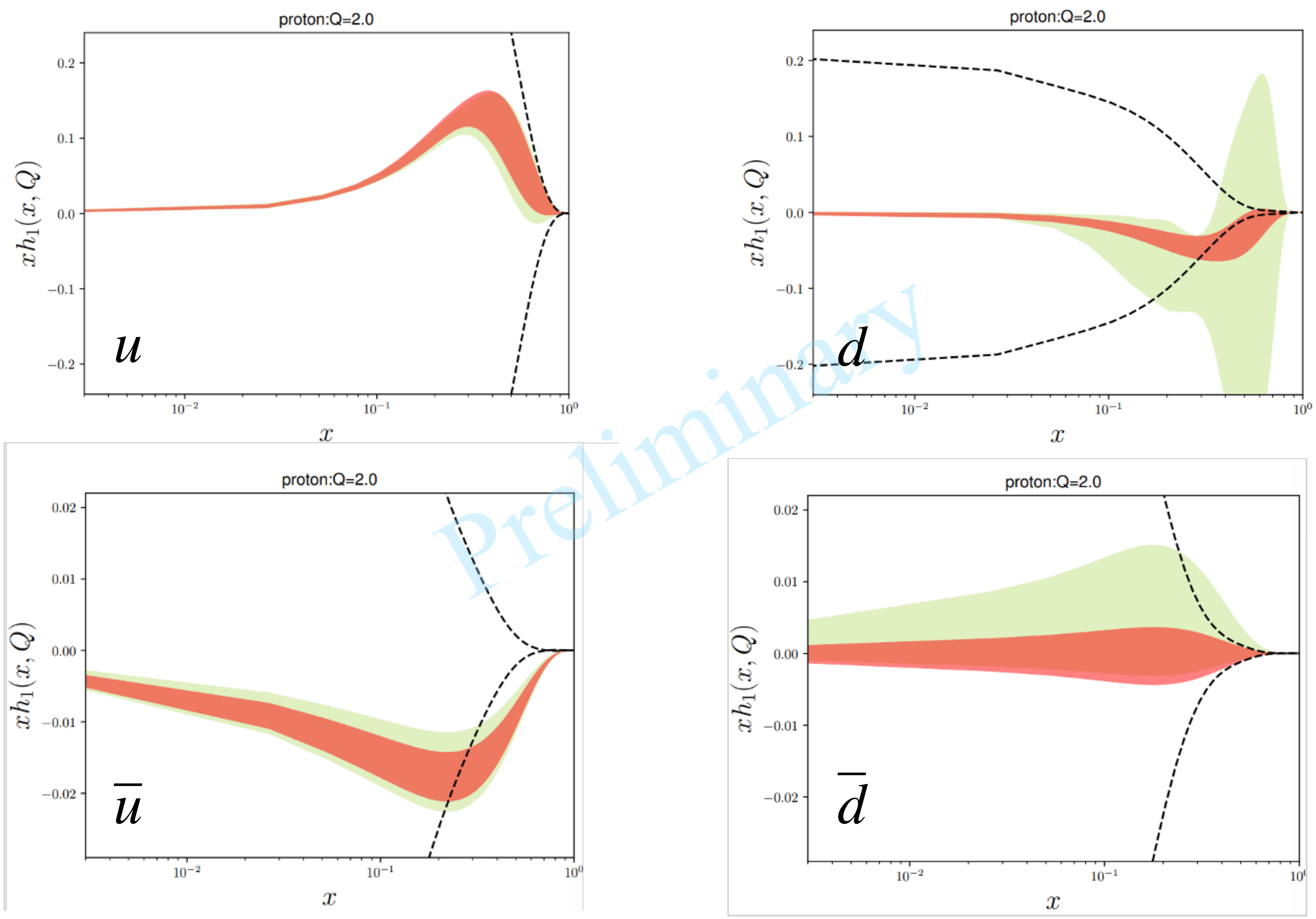
SIDIS on transversely polarized deuteron target



G.D. Alexeev *et al.*, COMPASS Collaboration, arXiv:2401.00309

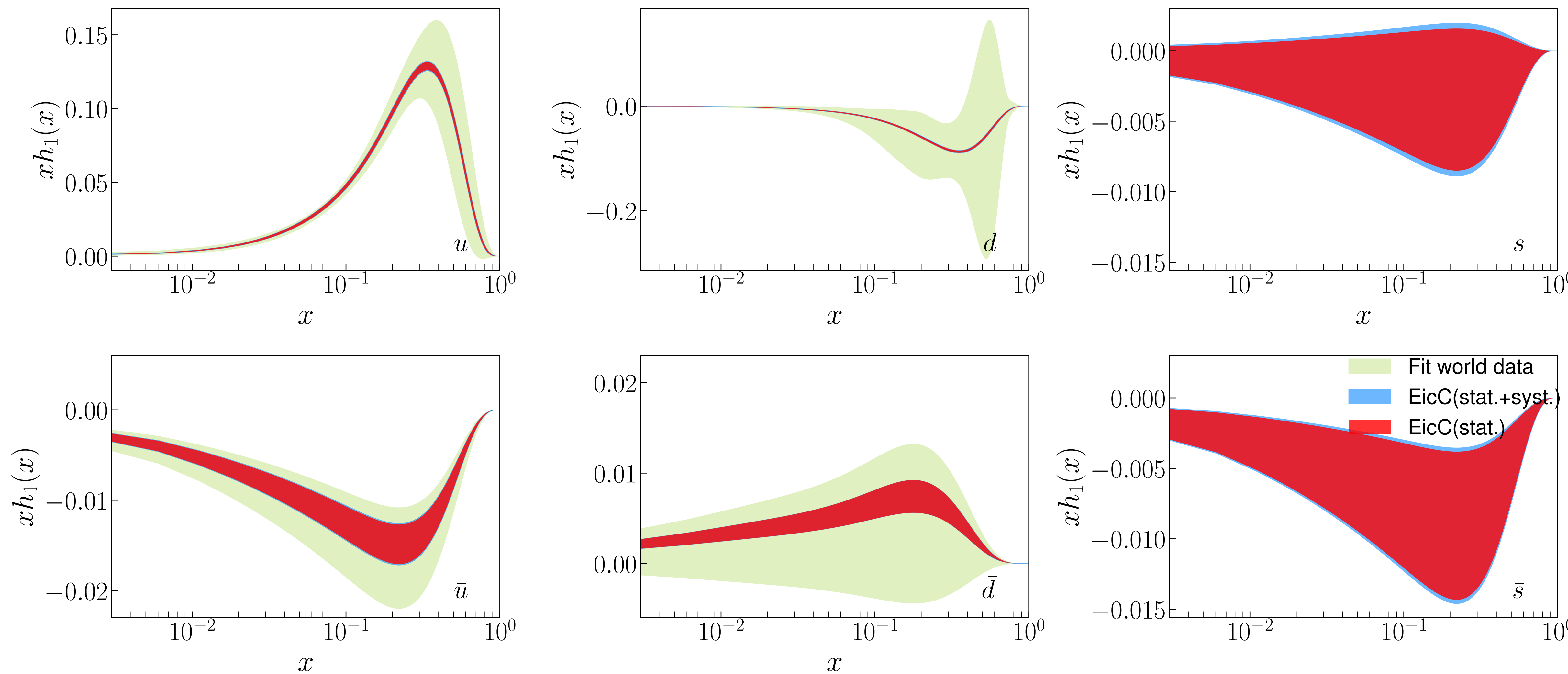
Some More on Transversity

Preliminary results (without systematic uncertainties)



C. Zeng, H. Dong, TL, P. Sun, Y. Zhao

EicC Impact on Transversity



EicC can significantly improve the precision of transversity distributions, especially for sea quarks.

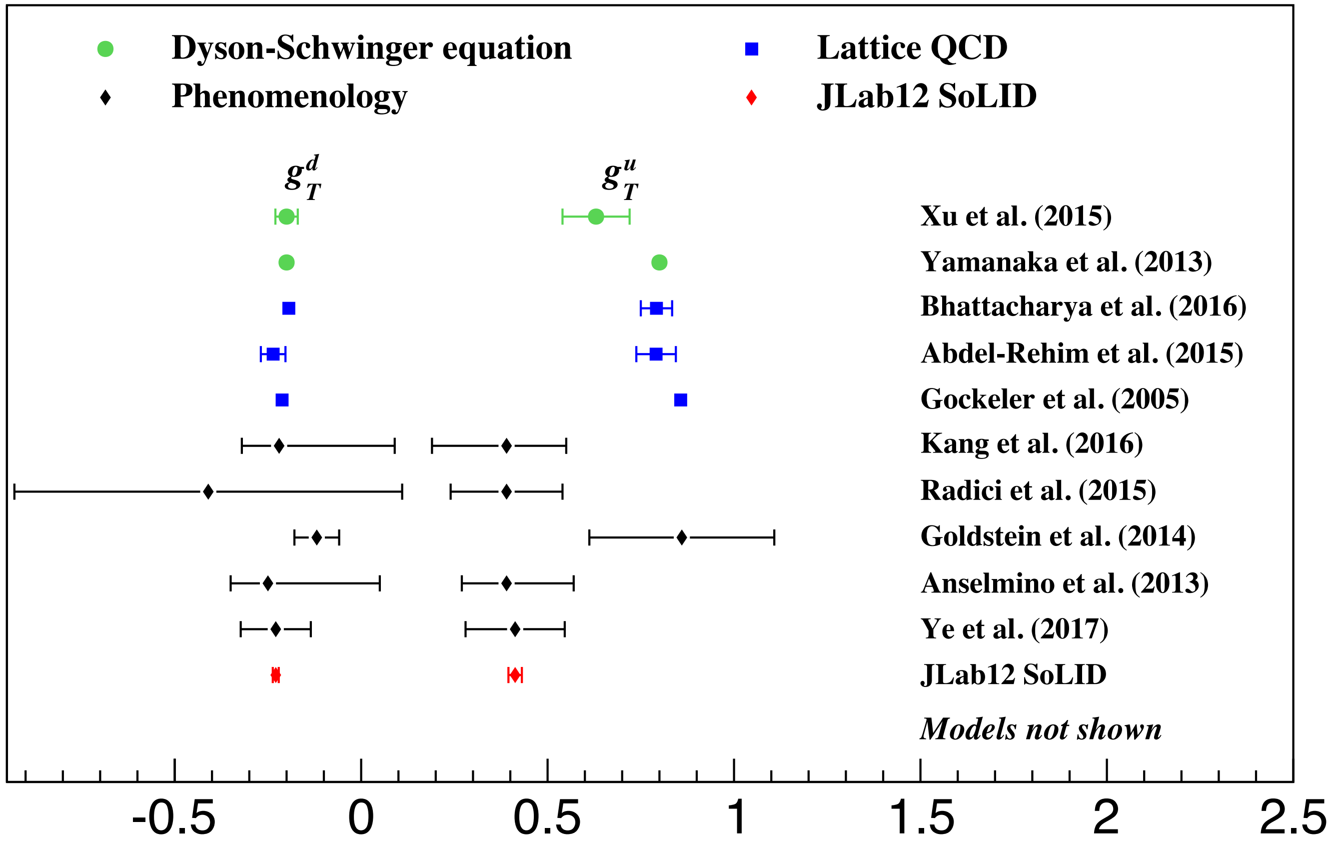
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2310.15532, PRD (2024).

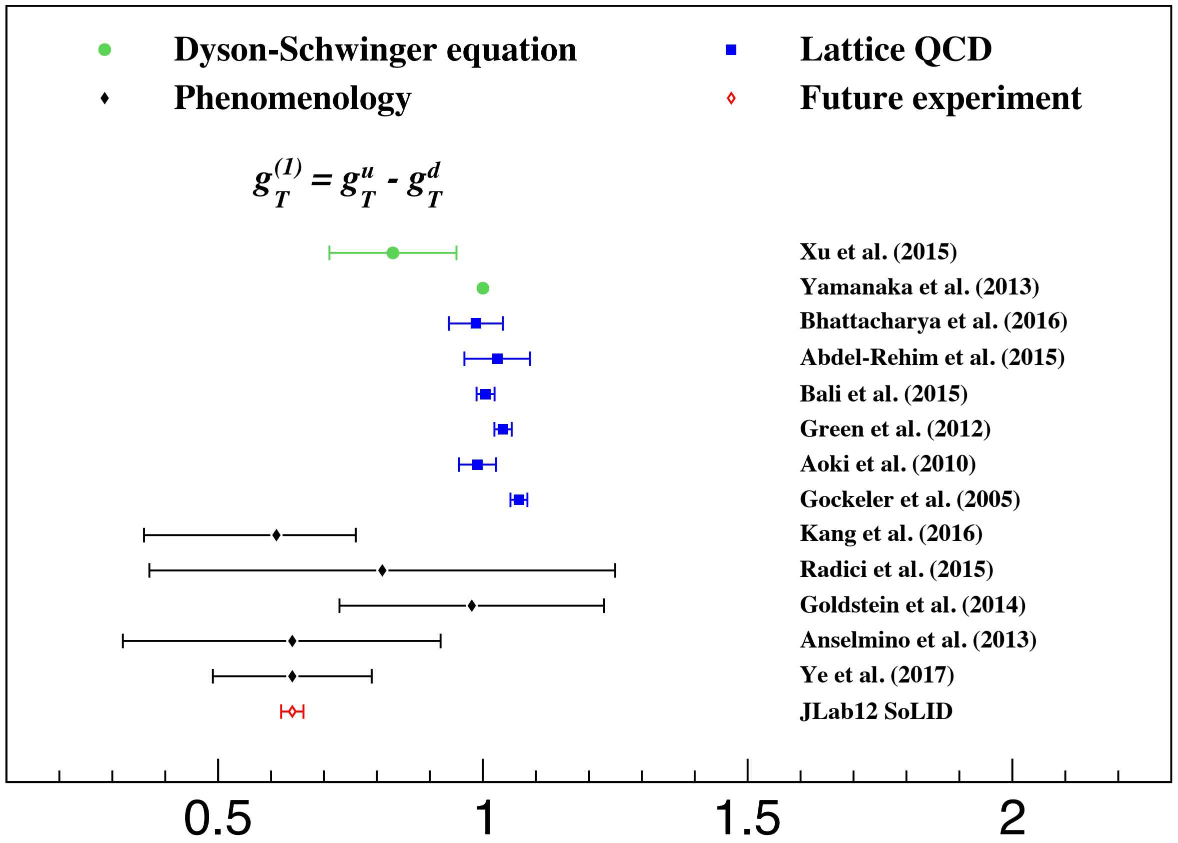
Tensor Charge

Tensor charge

$$\langle P,S|\bar{\psi}^q i\sigma^{\mu\nu}\gamma_5\psi^q|P,S\rangle = g_T^q \bar{u}(P,S)i\sigma^{\mu\nu}\gamma_5 u(P,S) \qquad g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]\,dx$$

- A fundamental QCD quantity: matrix element of local operators.
- Moment of the transversity distribution: valence quark dominant.
- Calculable in lattice QCD.





Connection to New Physics

Current upper limit on the neutron EDM (electric dipole moment)

$d_n < 1.8 \times 10^{-26}\, e$ cm (90% CL) C. Abel *et al.*, Phys. Rev. Lett. 124, 081803 (2020)

Current upper limit on the proton EDM

$d(^{199}\mathrm{Hg}) < 7.4 \times 10^{-30}\, e$ cm (95% CL) B. Graner *et al.*, Phys. Rev. Lett. 116, 161601 (2016).

$d_p < 2.1 \times 10^{-25}\, e$ cm B.K. Sahoo *et al.*, Phys. Rev. D 95, 012002 (2017).

Constraint on quark EDMs

$$d_p = g_T^u\, d_u + g_T^d\, d_d + g_T^s\, d_s \qquad d_n = g_T^d\, d_u + g_T^u\, d_d + g_T^s\, d_s$$

$$d_u < 1.27 \times 10^{-24}\, e \text{ cm} \qquad d_d < 1.17 \times 10^{-24}\, e \text{ cm}$$

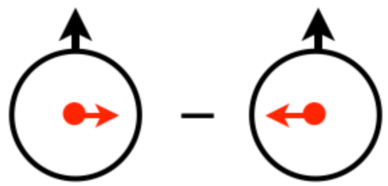
sensitivity to new physics: $d_q \sim e\, m_q / (4\pi\Lambda^2)$ → $\Lambda \sim 1$ TeV

TL, Z. Zhao, H. Gao, Phys. Rev. D 97, 074018 (2018).

Double Spin Asymmetry and Worm-gear

Trans-helicity worm-gear distribution

$$g_{1T}^{\perp}(x, k_T^2)$$



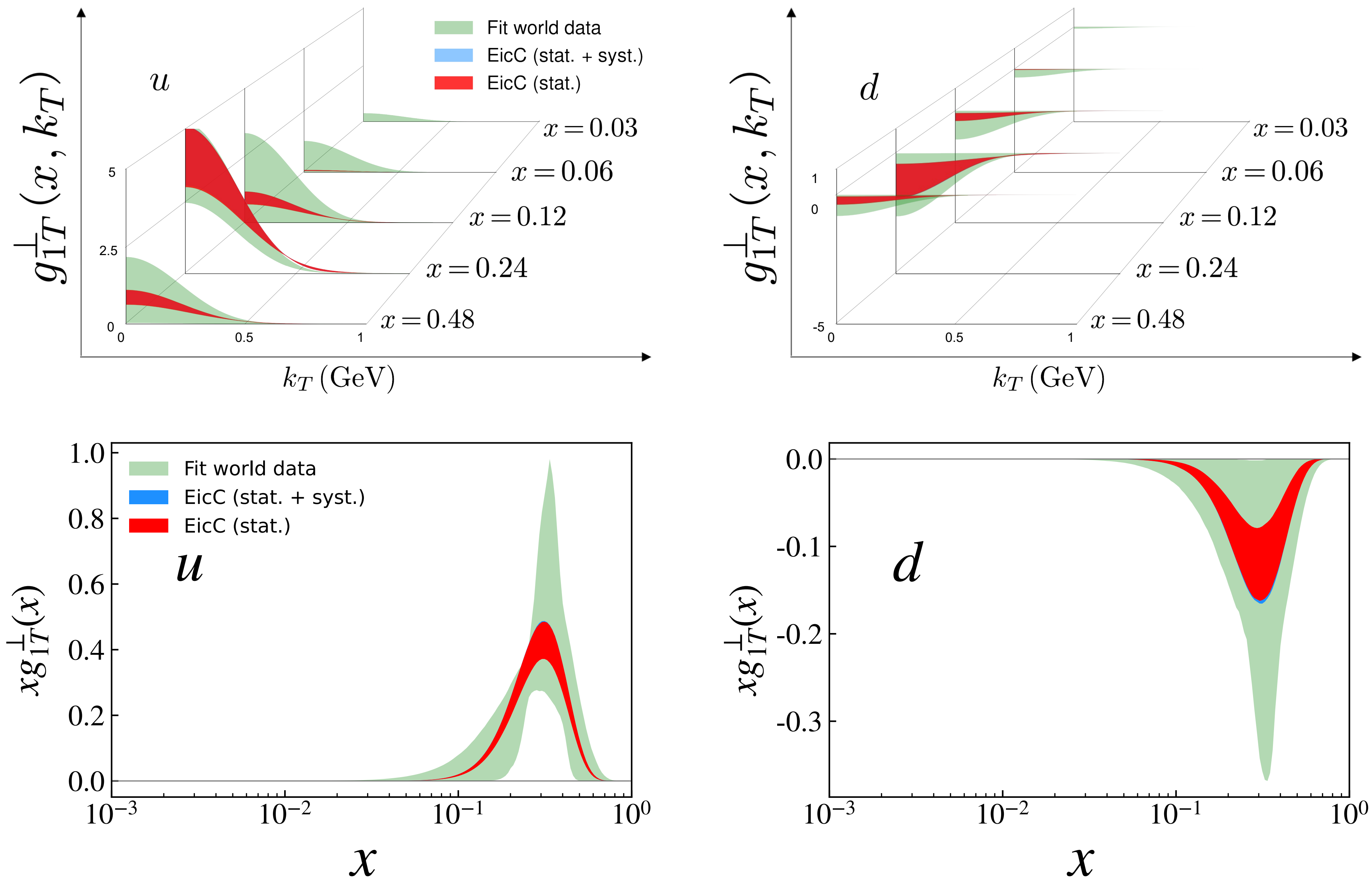
Longitudinally polarized quark density in a transversely polarized nucleon
Overlap between wave functions differing by one unit of orbital angular momentum

Effect in SIDIS:
A longitudinal-transverse double spin asymmetry

$$A_{LT}^{\cos(\phi_h - \phi_s)} \sim g_{1T}^{\perp} \otimes D_1$$

Double Spin Asymmetry and Worm-gear

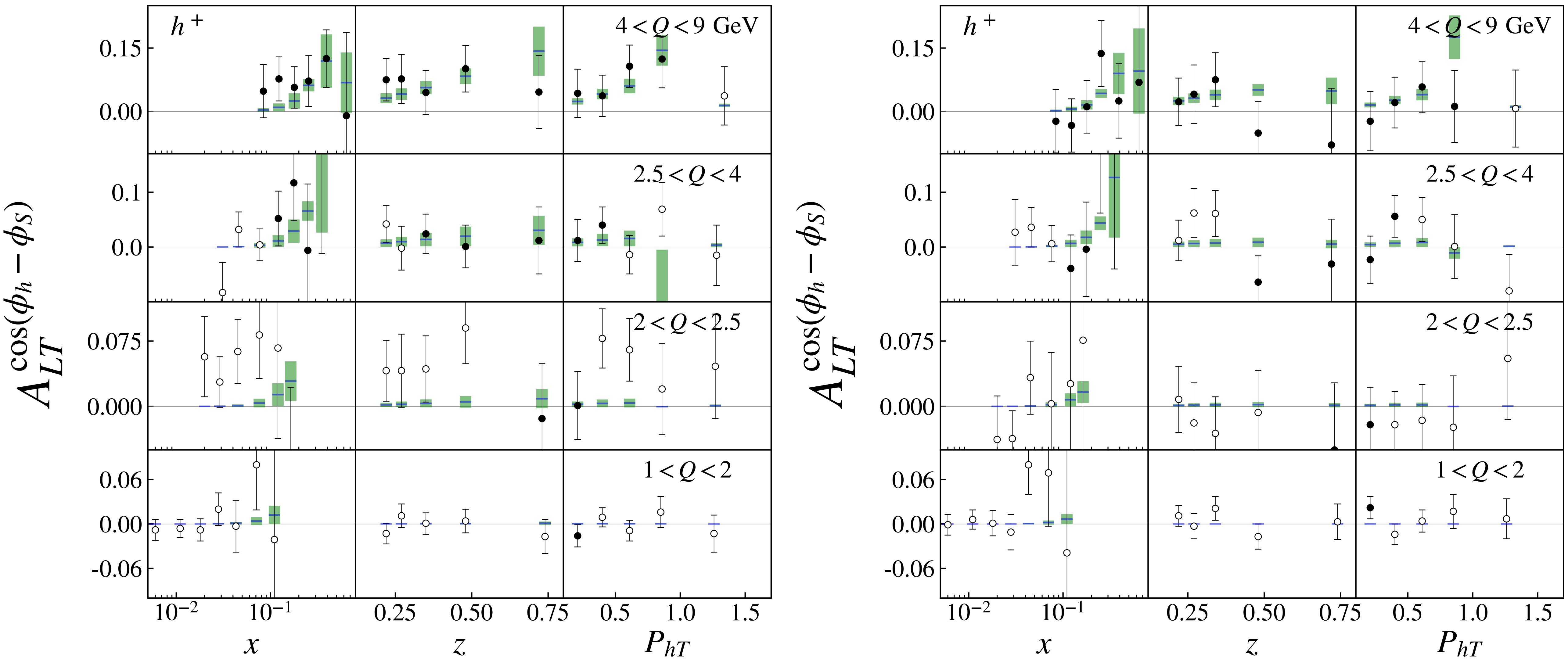
Phenomenological extraction



$$g_{1T}^{\perp(1)}(x) = \int d^2\mathbf{k}_T \left(\frac{k_T^2}{2M}\right) g_{1T}^{\perp}\left(x, \mathbf{k}_T^2\right)$$

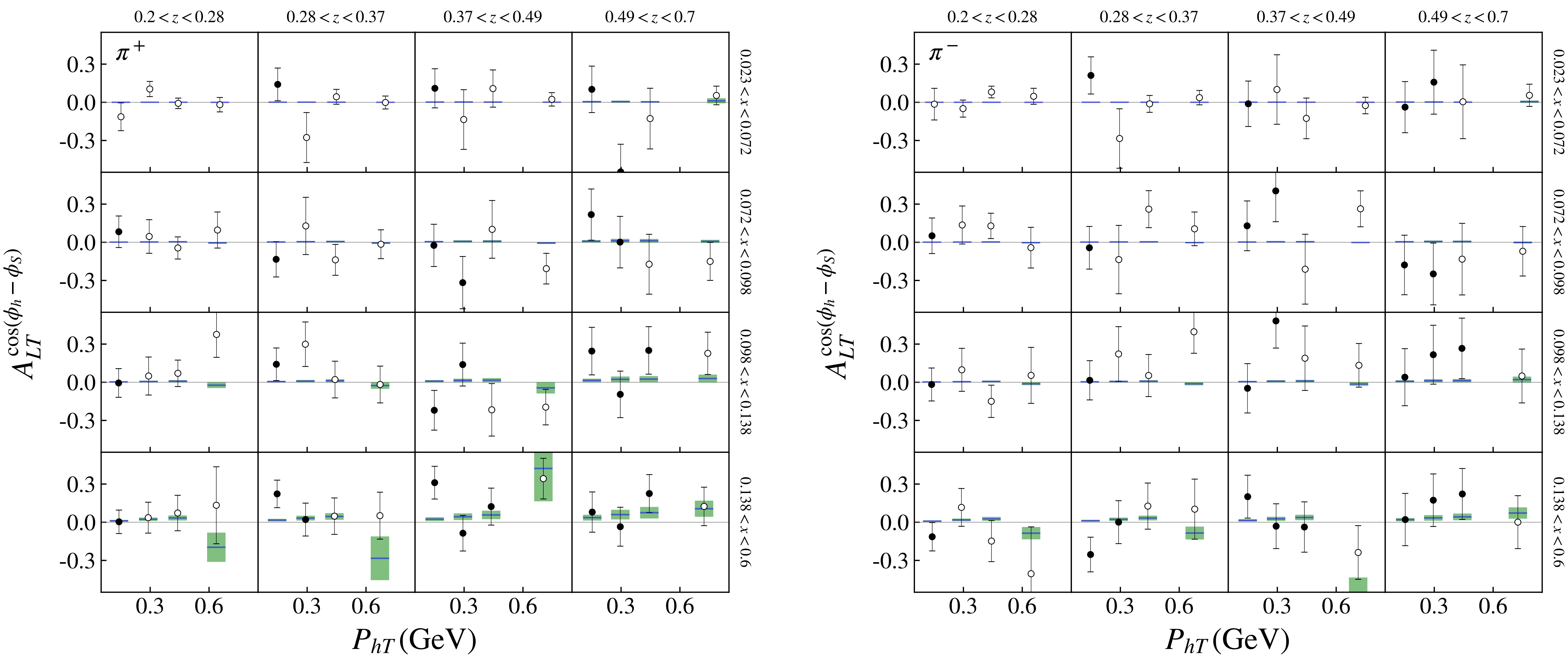
K. Yang, T. Liu, P. Sun, Y. Zhao, B.-Q. Ma, 2024

Comparison with Data



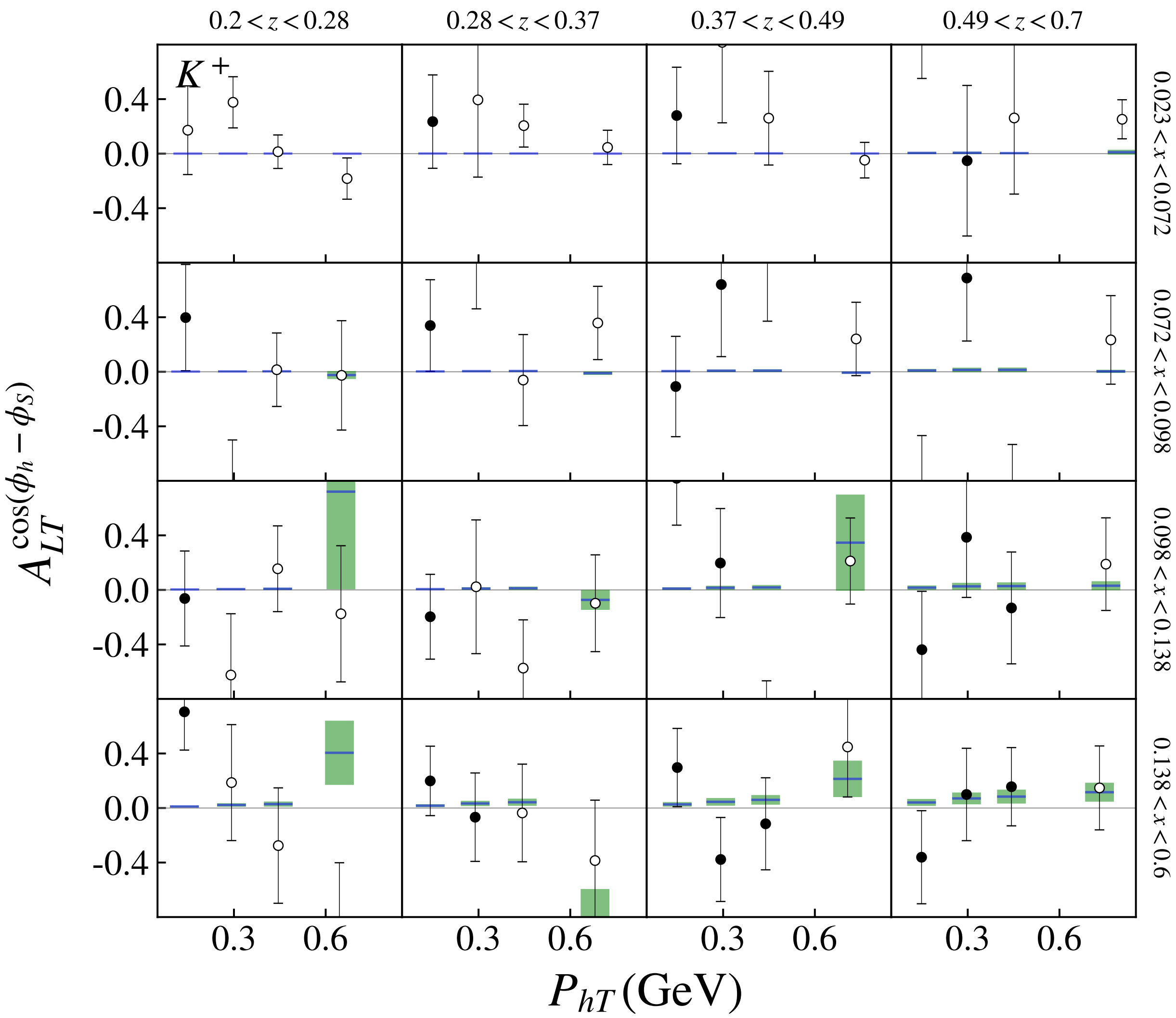
COMPASS Collaboration, Phys. Lett. B 770 (2017) 138.

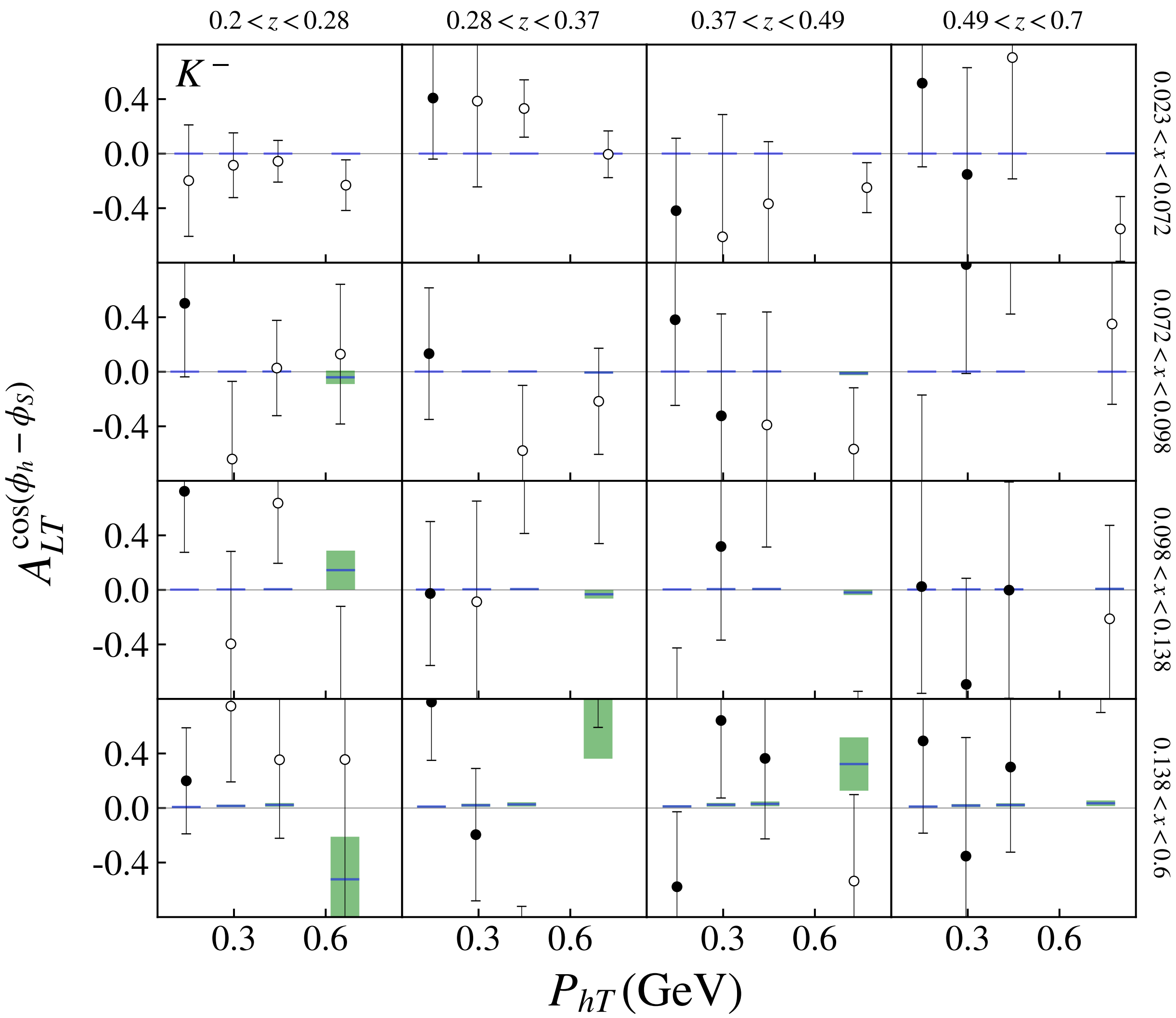
Comparison with Data



HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

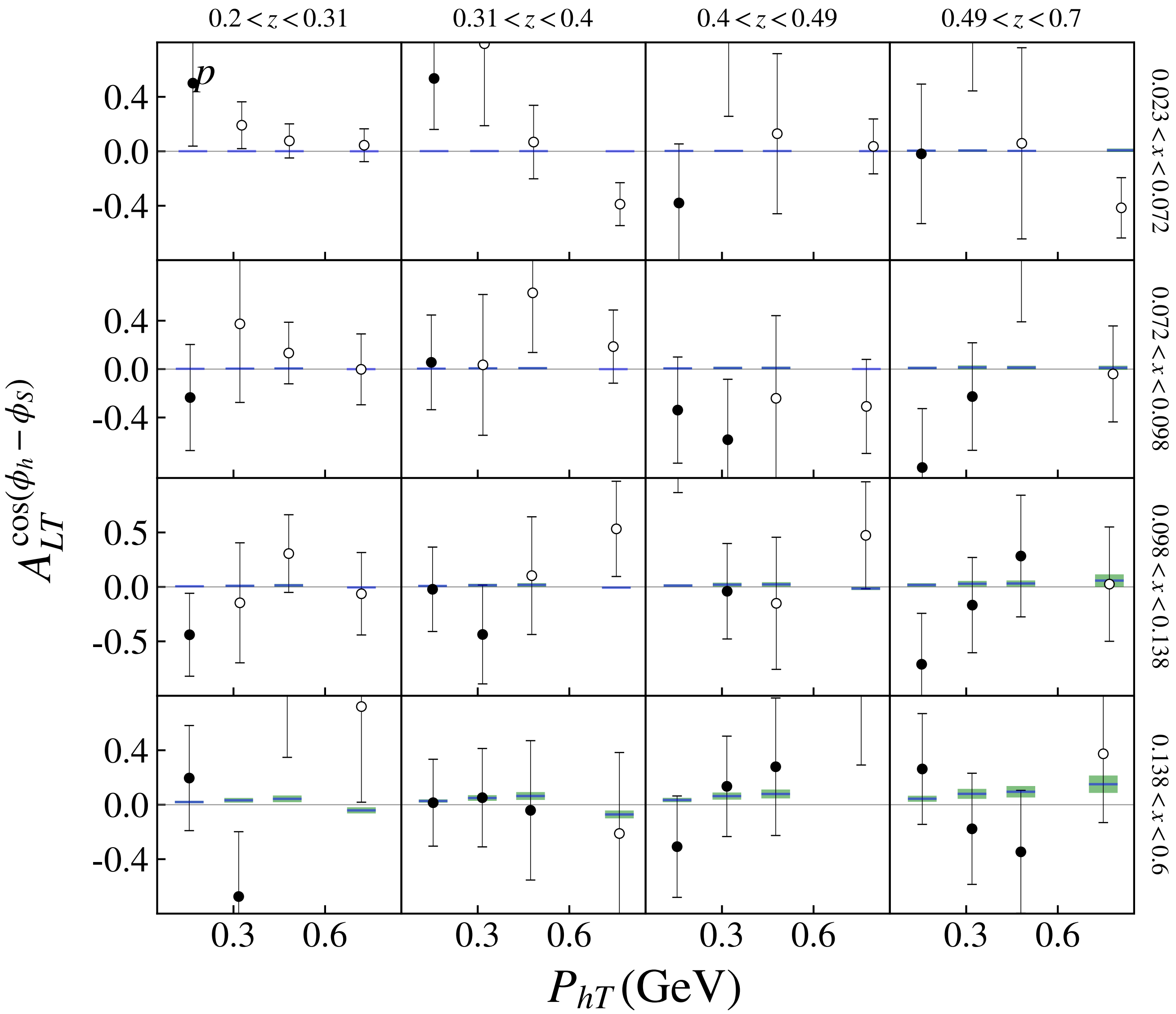
Comparison with Data





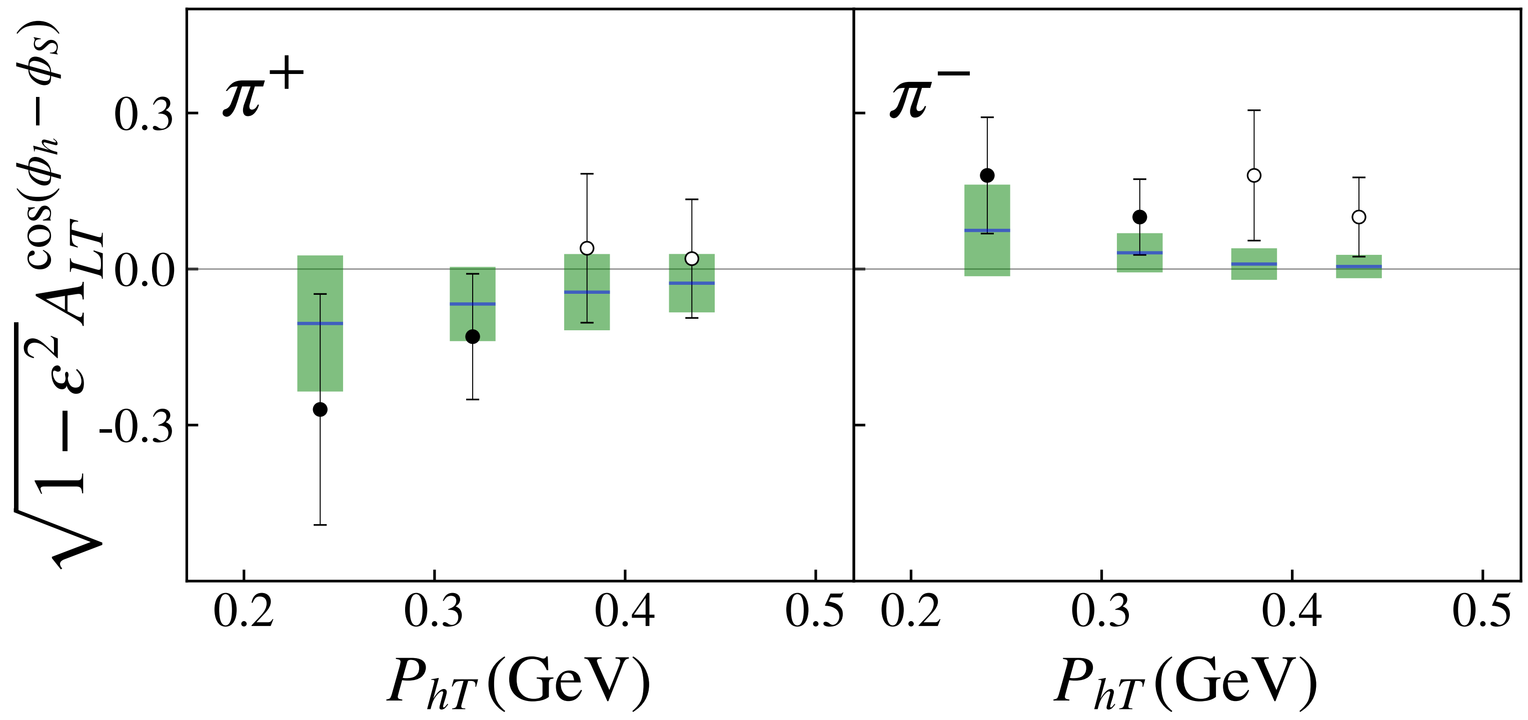
HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

Comparison with Data



HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

Comparison with Data



JLab HallA Collaboration, Phys. Rev. Lett. 108 (2012) 052001.

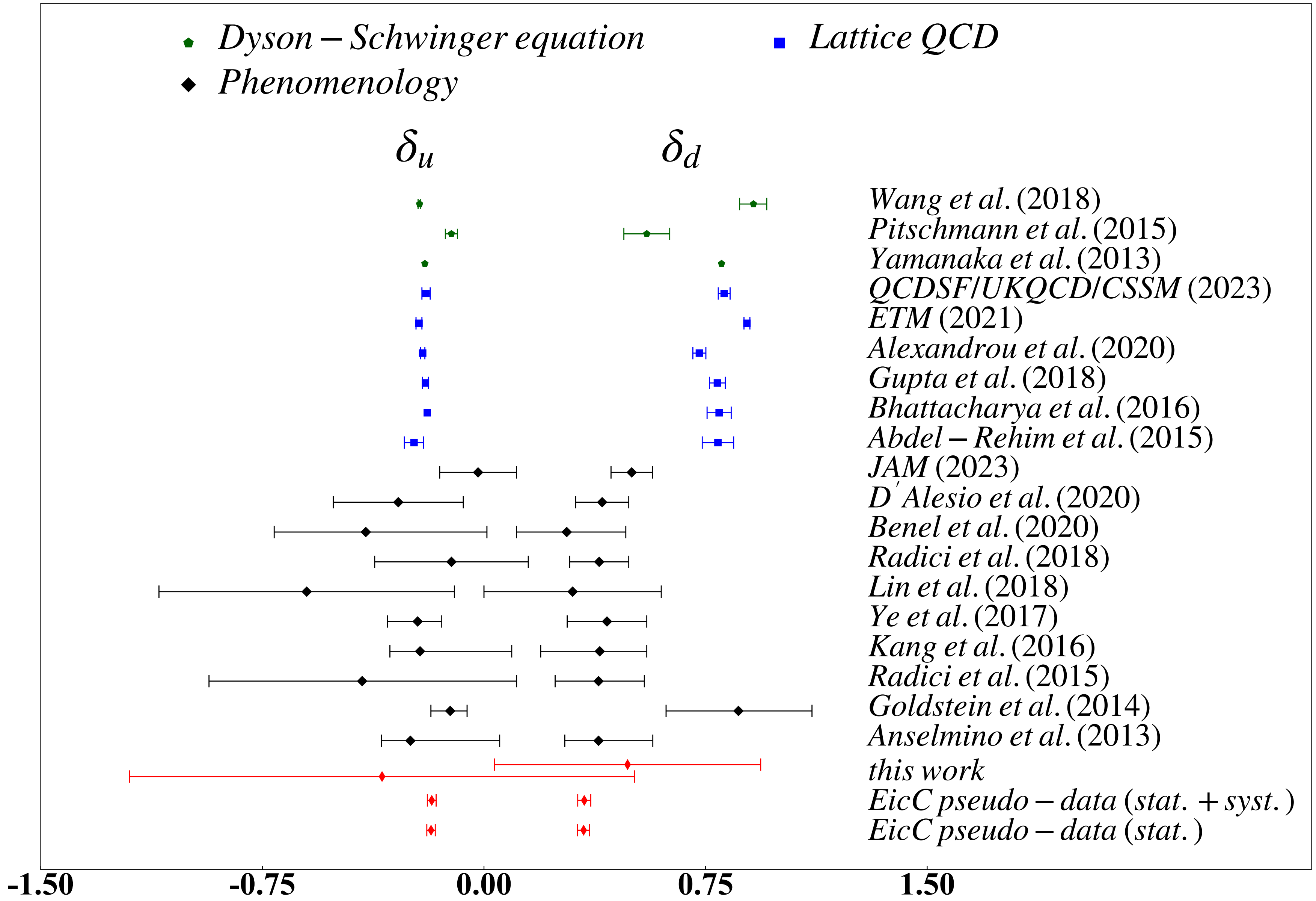
Summary

- Spin always surprises since its discovery nearly 100 years ago
- Nucleon spin structure is still not well understood
- Rich information is contained in TMDs
  - quark transverse momentum distorted by nucleon spin;
  - correlation between quark longitudinal/transverse spin and nucleon spin;
  - …
- SIDIS with polarized beam and target is a main process to study polarized TMDs
- Also an important approach to test/develop the theories/models
- EicC can significantly improve the precision of the determination of TMDs, especially for sea quarks, complementary to JLab12 and EIC-US.

Thank you!

Backup

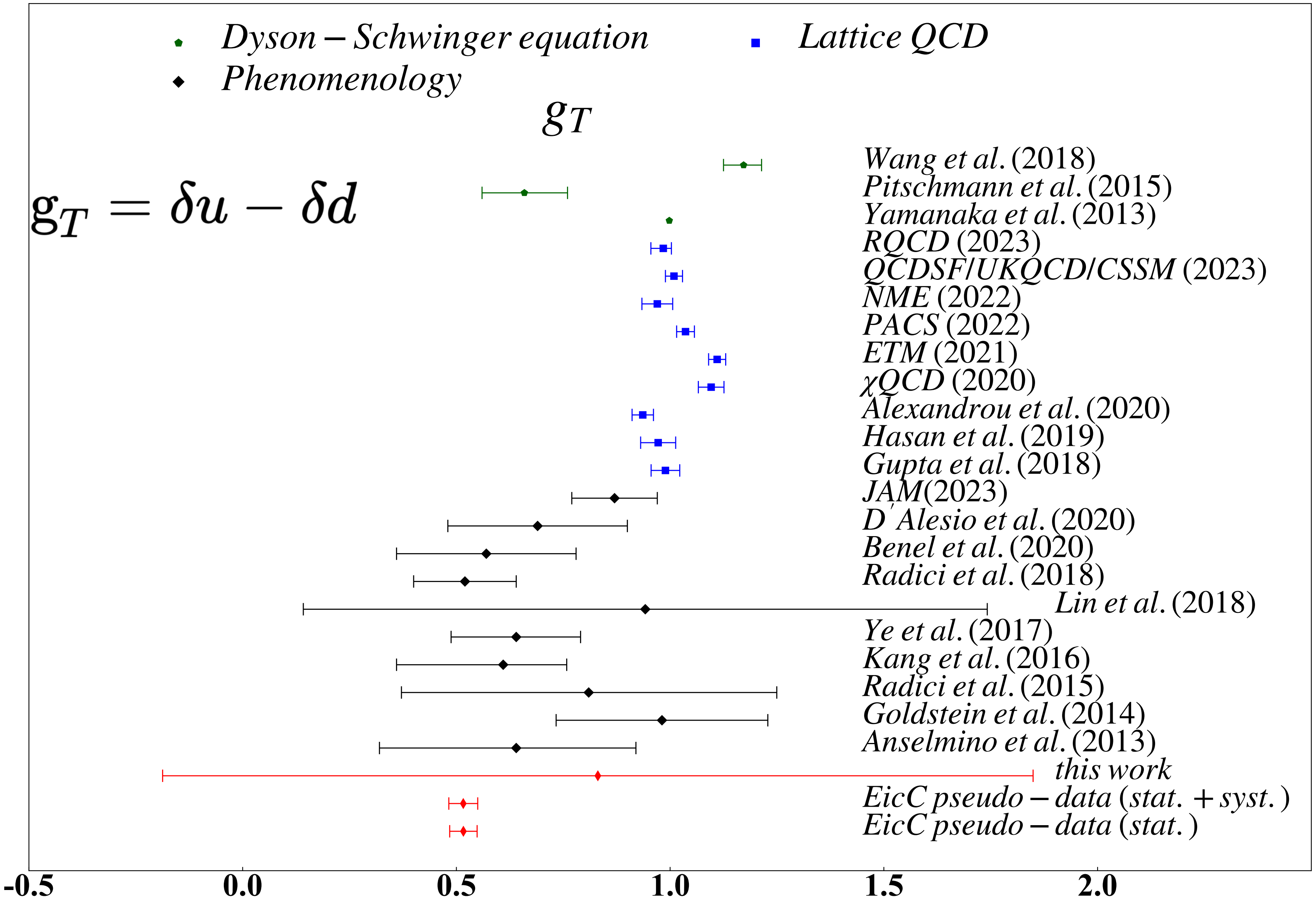
Result: Tensor Charge



Larger uncertainties when including anti-quarks (less biased)
Compatible with lattice QCD calculations

C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2310.15532, PRD (2024).

Result: Tensor Charge



Larger uncertainties when including anti-quarks (less biased)
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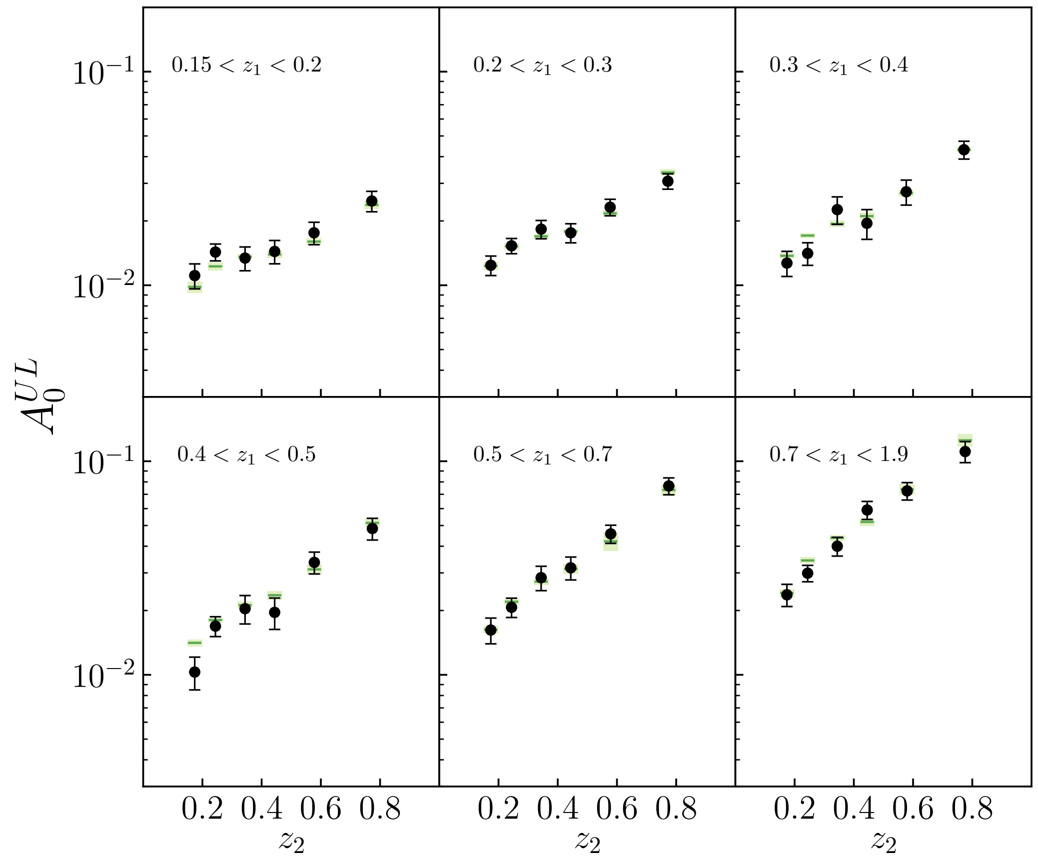
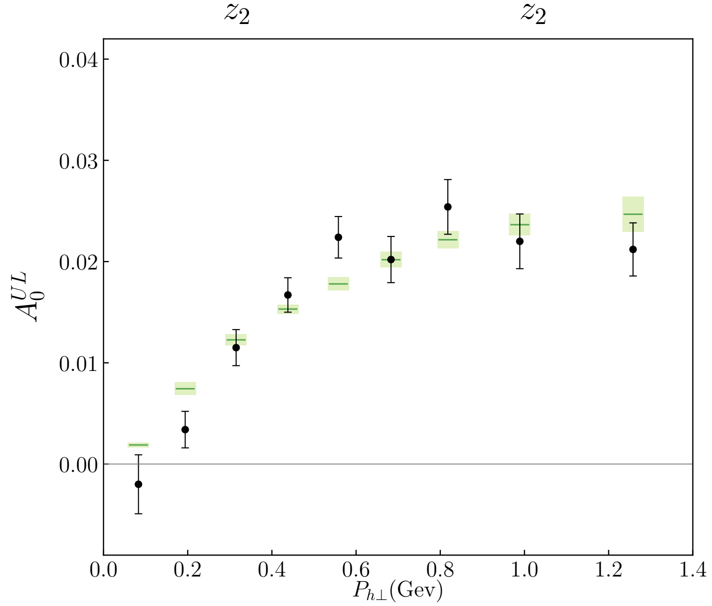
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2310.15532, PRD (2024).

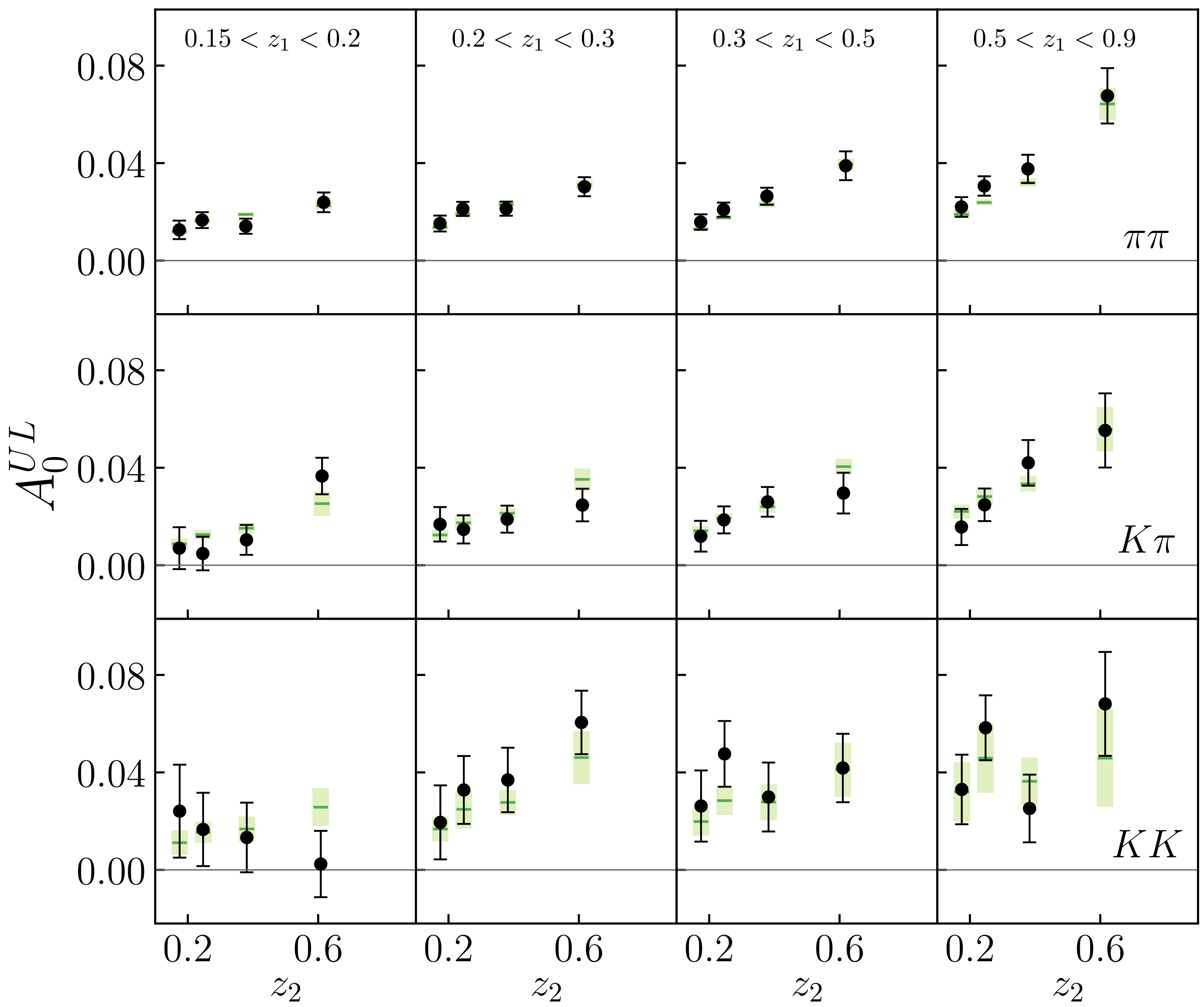
Comparison with Data

BaBar (2014)



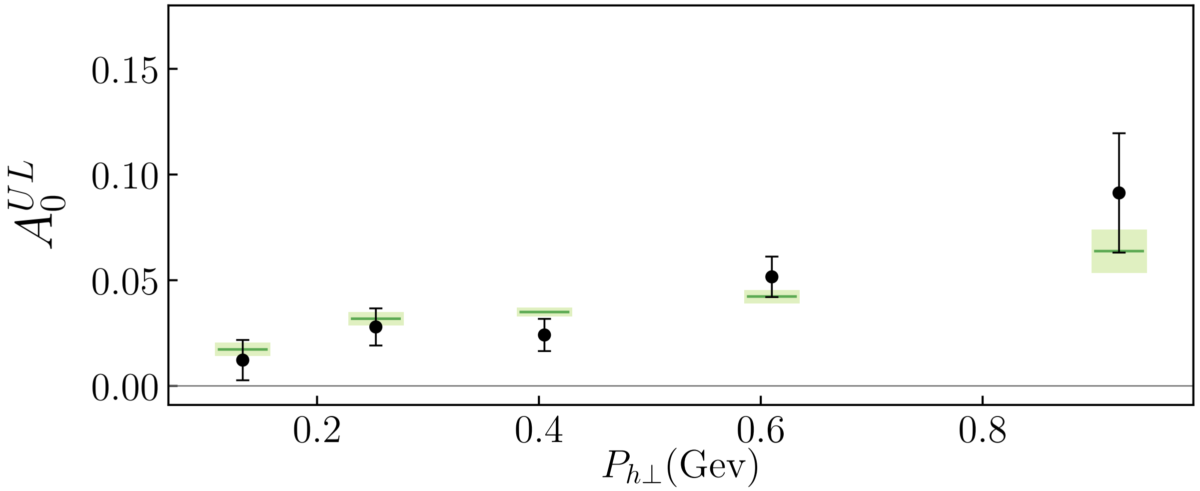


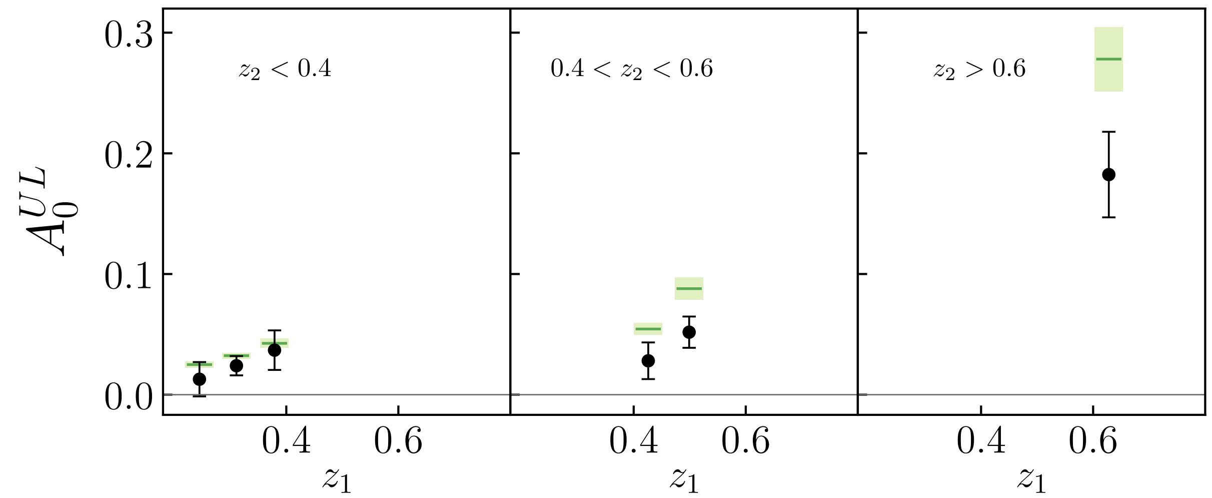
BaBar (2016)



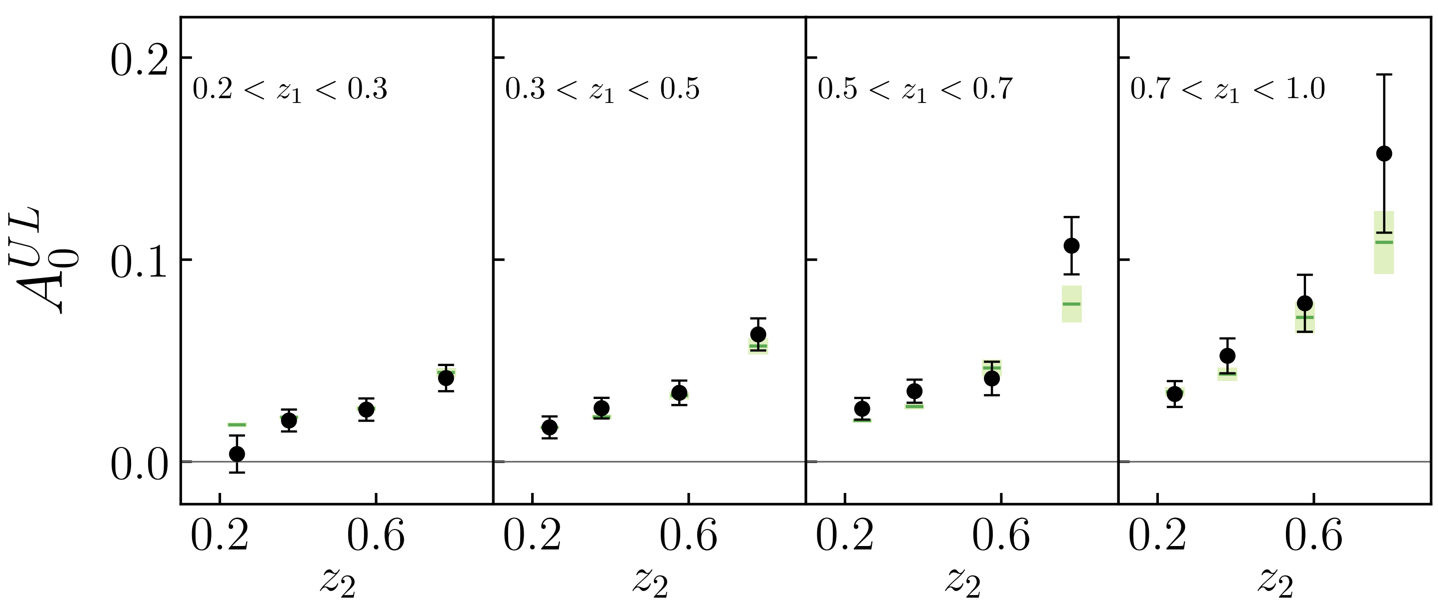
Comparison with Data

BESIII

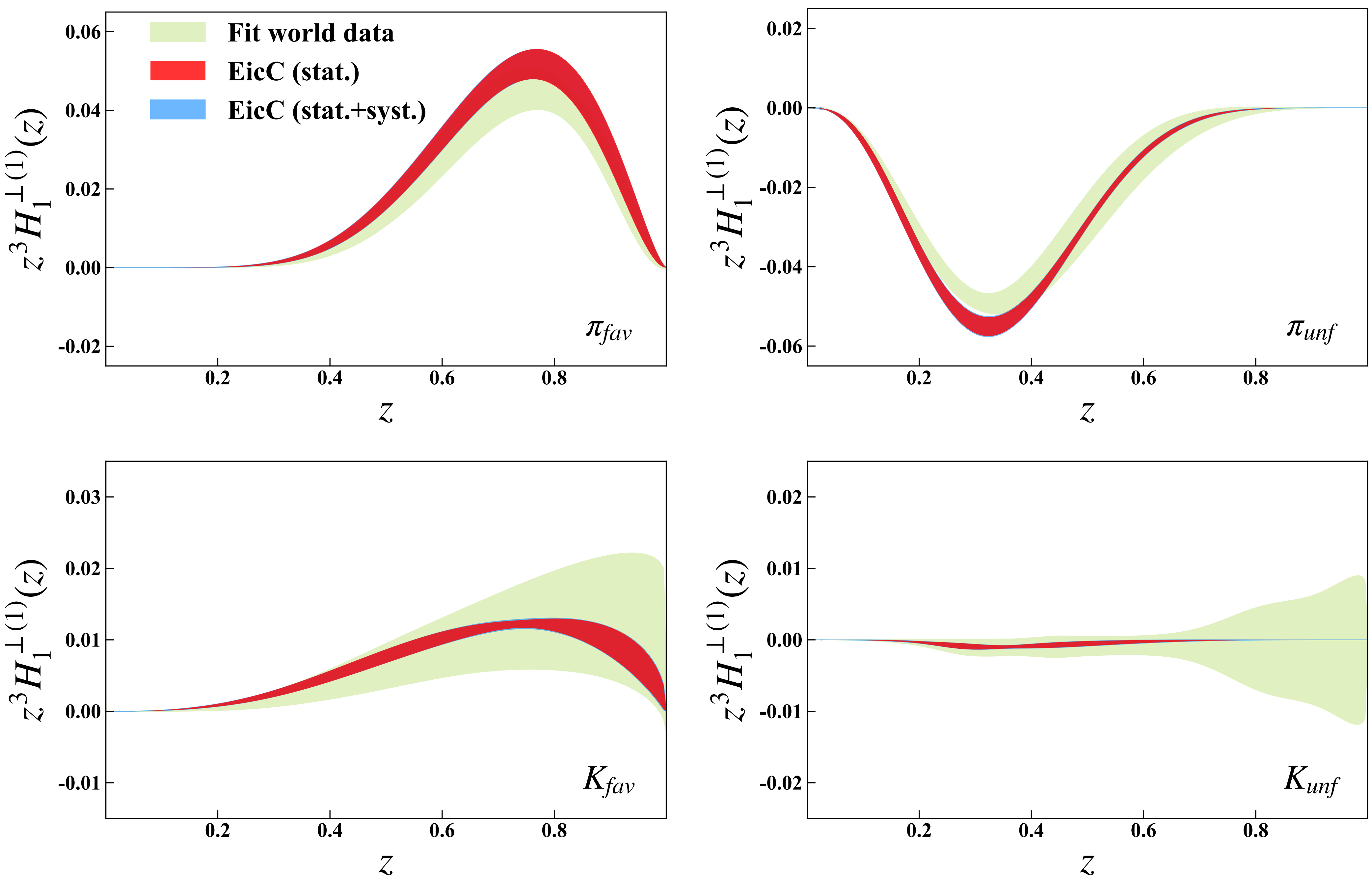




Belle

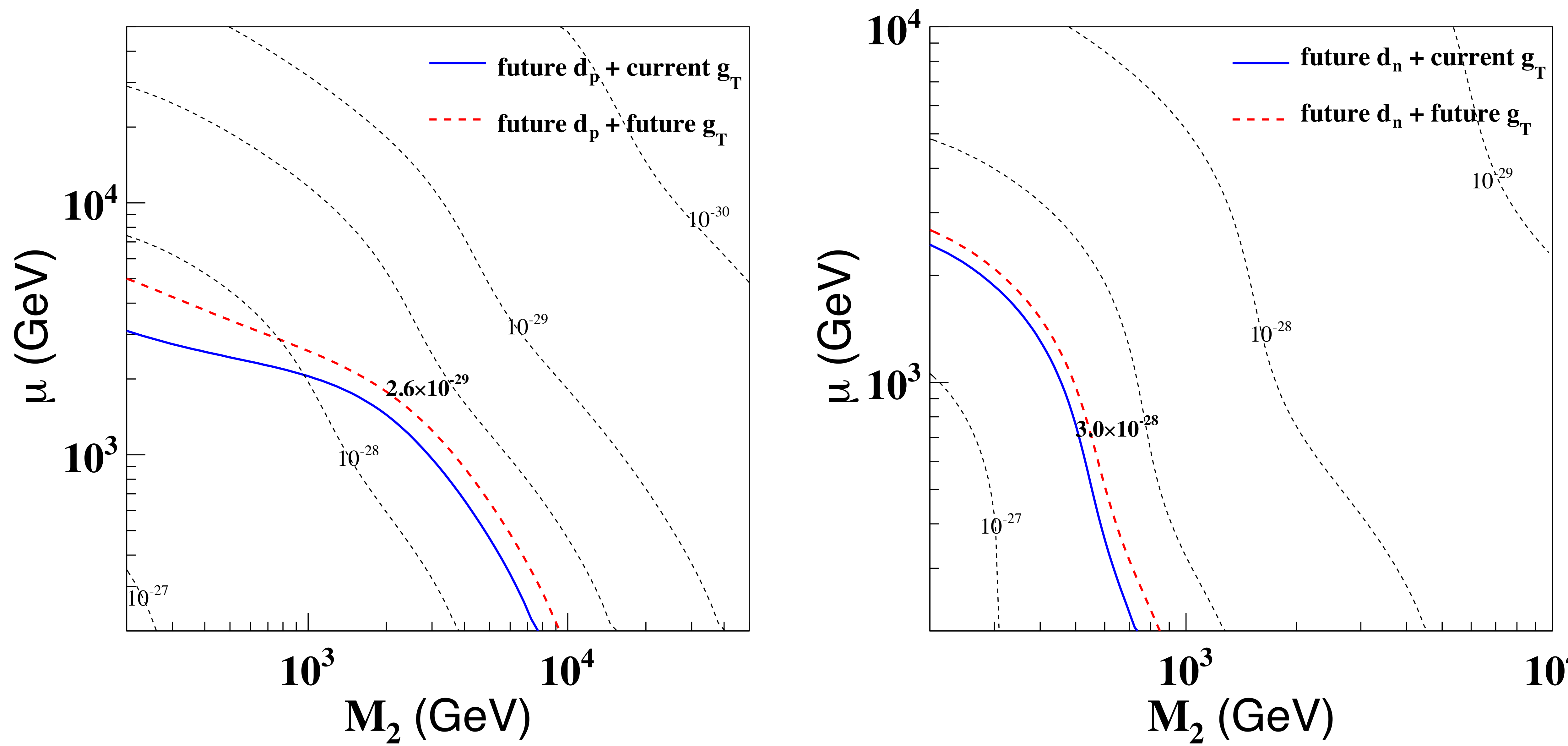


Result: Collins Fragmentation Function



C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2310.15532

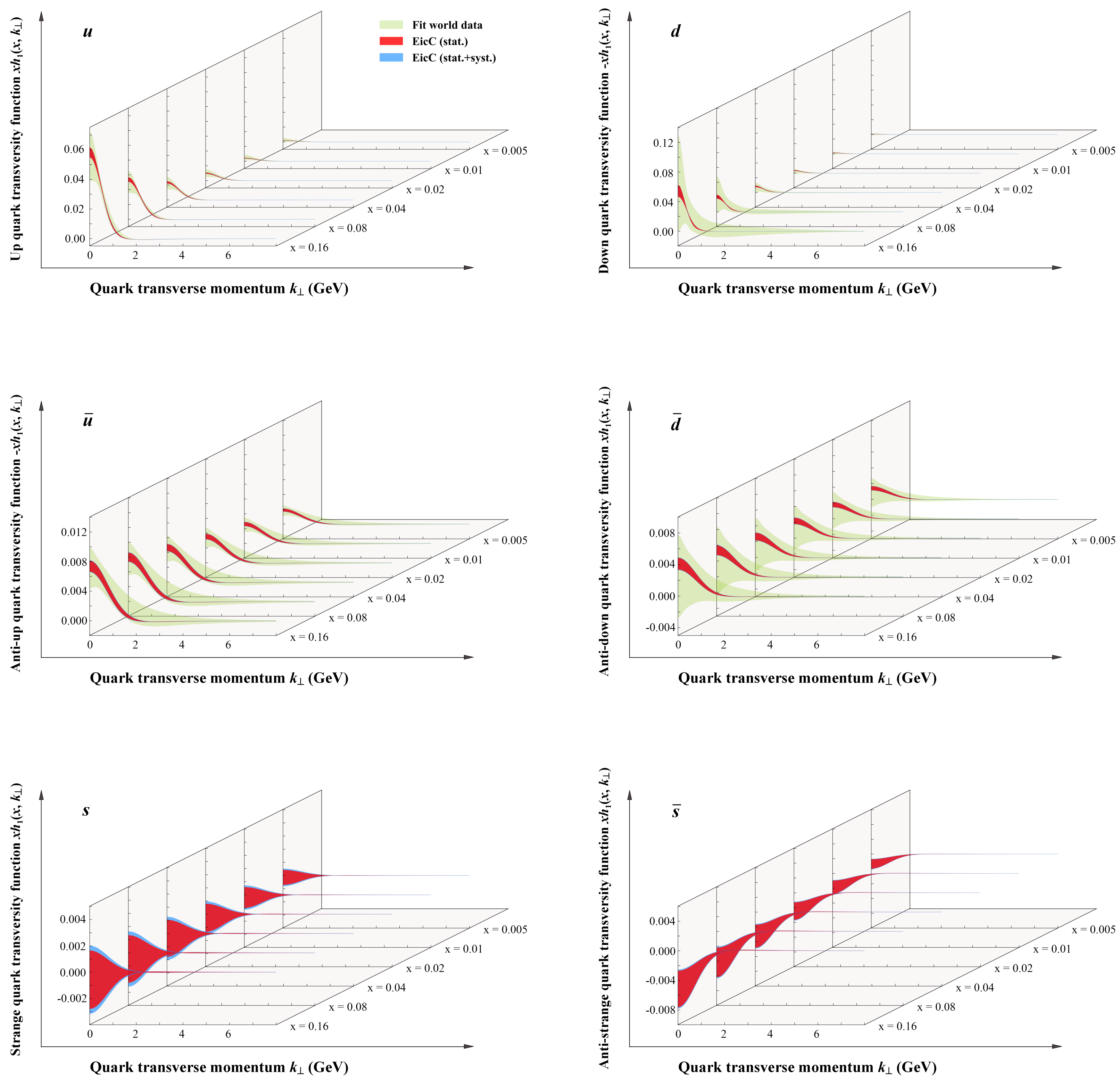
Test New Physics Model: Split-supersymmetry



- In the unified framework of gaugino masses, sfermion mass at 10^9 GeV, tanβ=1, sinφ=1

TL, Z. Zhao, H. Gao, Phys. Rev. D 97, 074018 (2018).

Transversity TMDs



Collins TMD FFs