Nucleon Three-Dimensional Spin Structures

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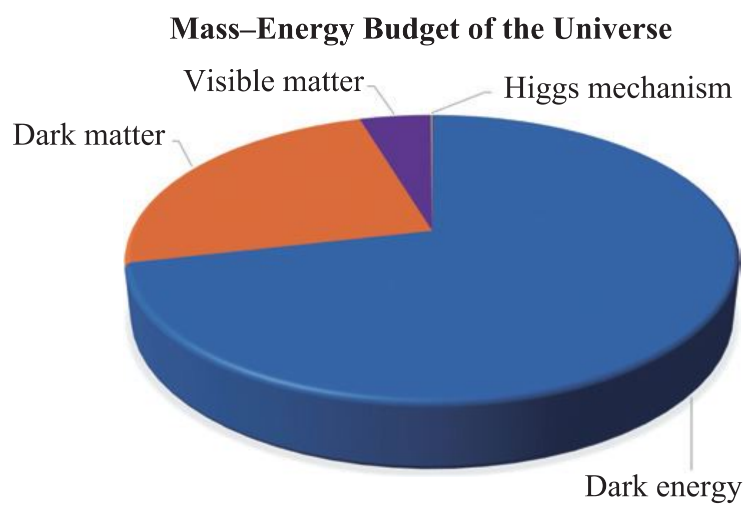
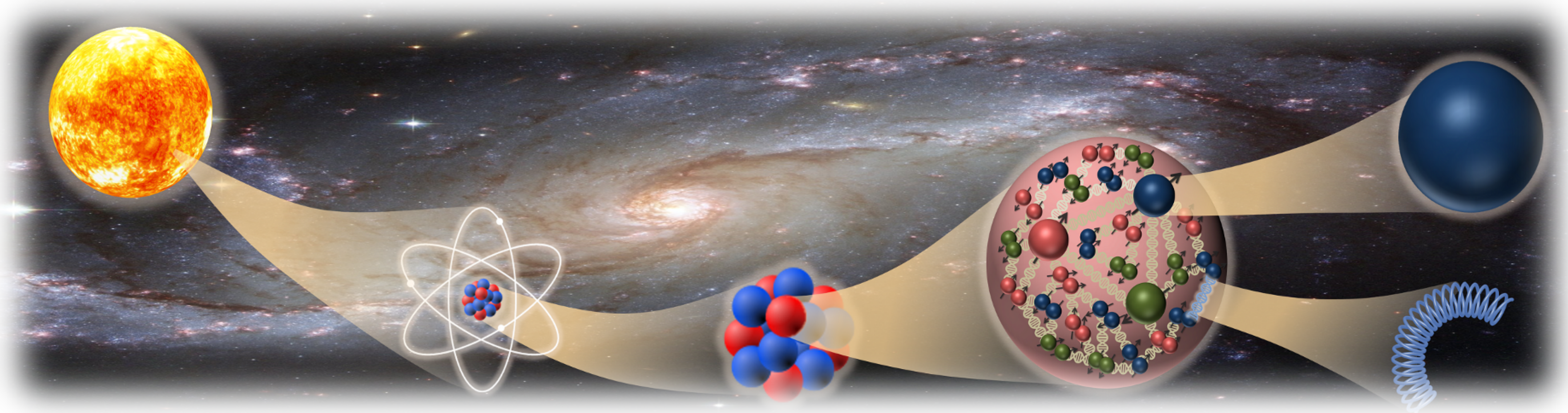
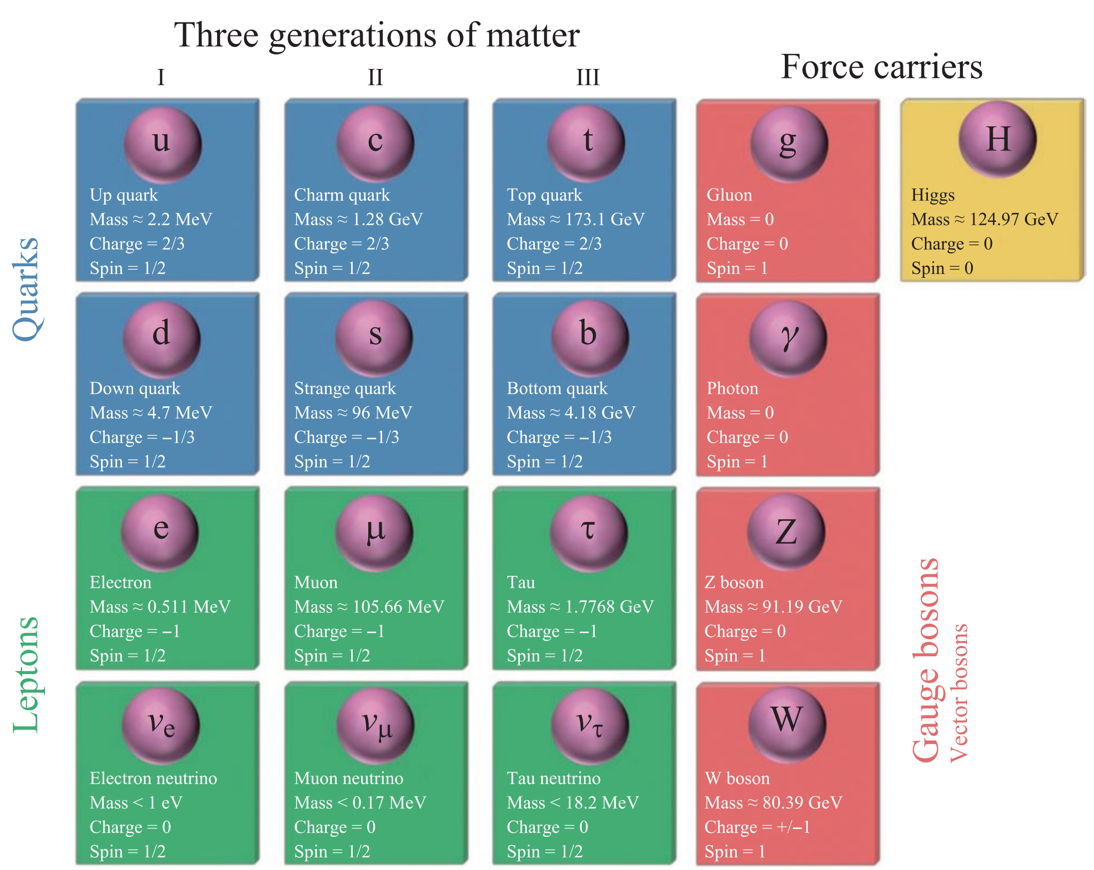
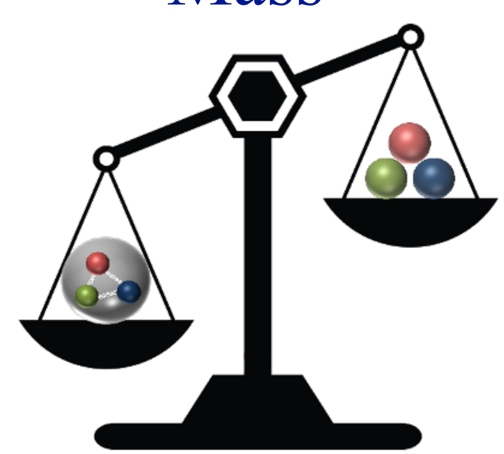
How much do we understand our world?



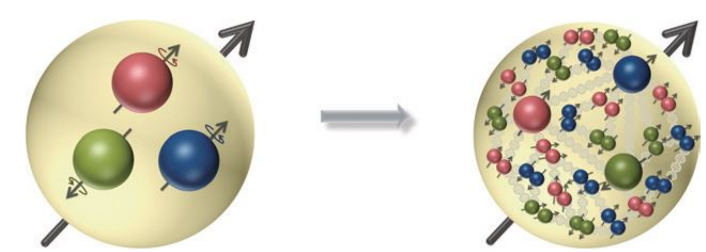




Mass



Spin



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

Lepton-Hadron Deep Inelastic Scattering

Inclusive DIS at a large momentum transfer: $Q \gg \Lambda_{\mathrm{QCD}}$

- dominated by the scattering of the lepton off an active quark/parton
- not sensitive to the dynamics at a hadronic scale ~ 1/fm
- collinear factorization:

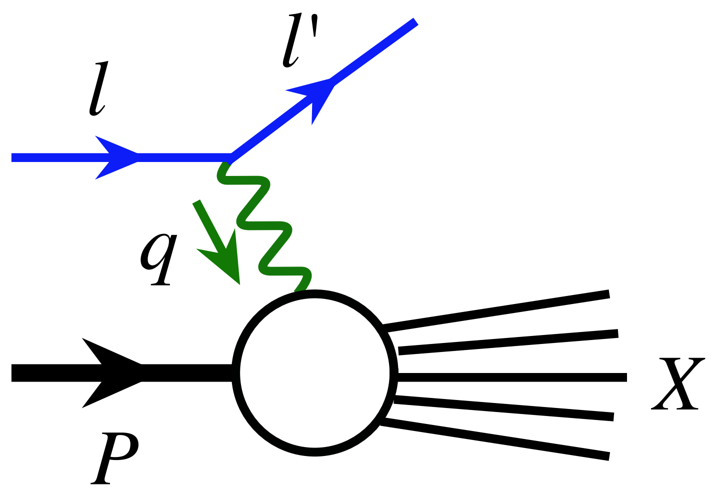
$$\sigma \propto H(Q) \otimes f_{i/P}(x, \mu^2)$$

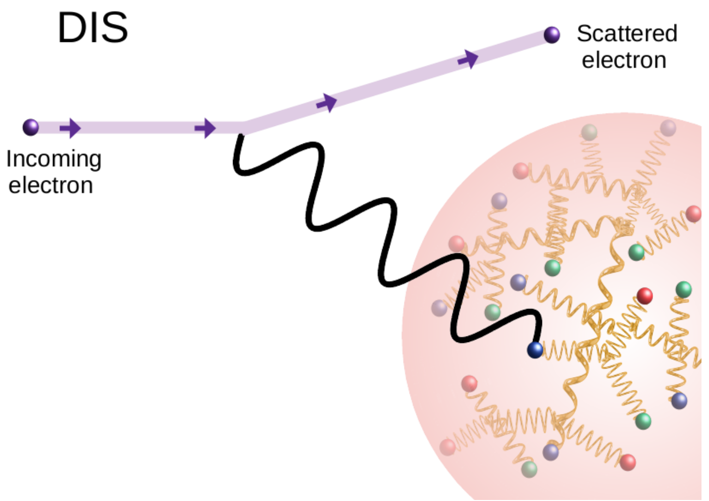
- overall corrections suppressed by $1/Q^n$
- indirectly "see" quarks, gluons and their dynamics
- predictive power relies on

— precision of the probe

— universality of $f_{i/P}(x, \mu^2)$

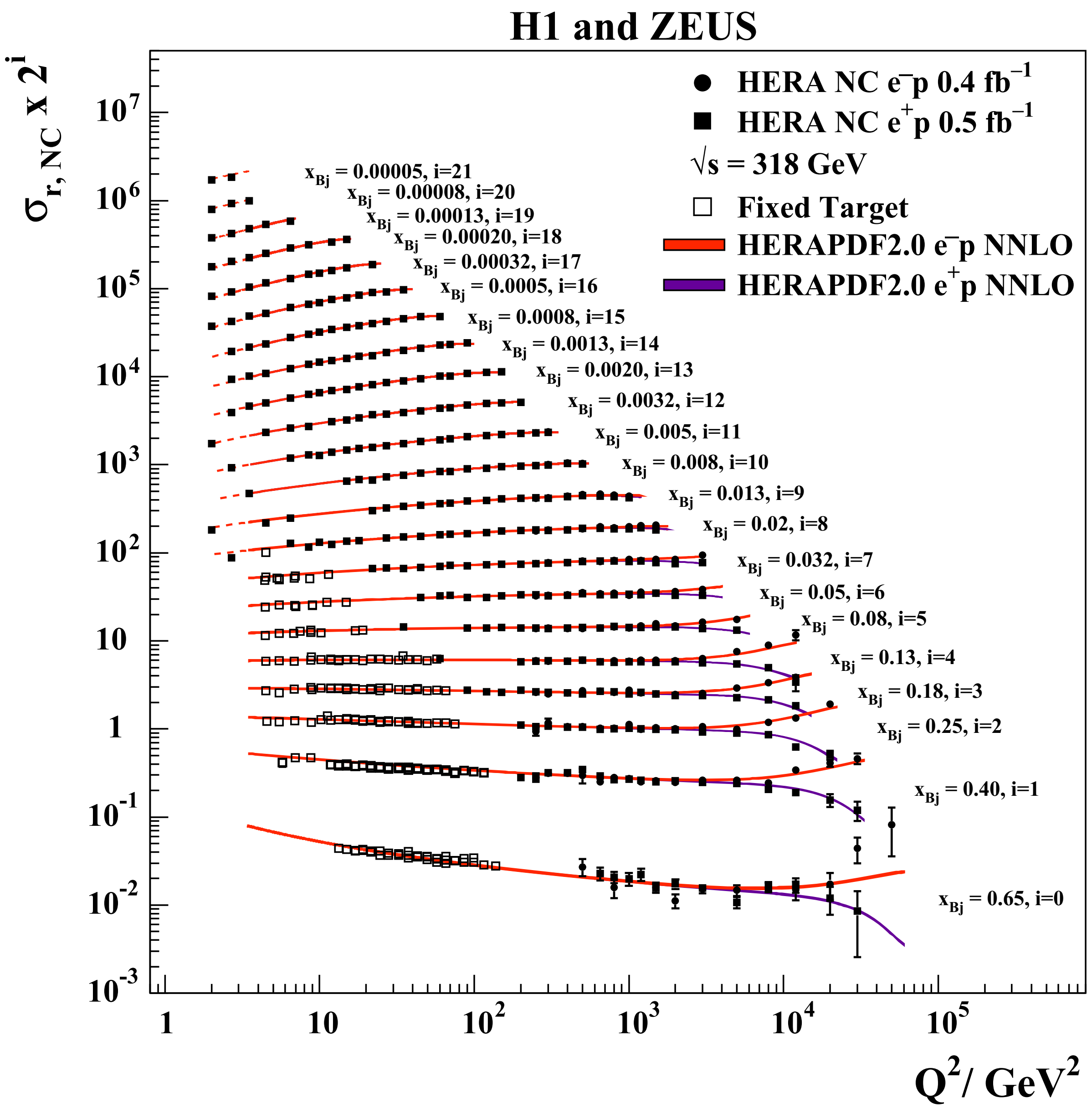
Modern "Rutherford" experiment.



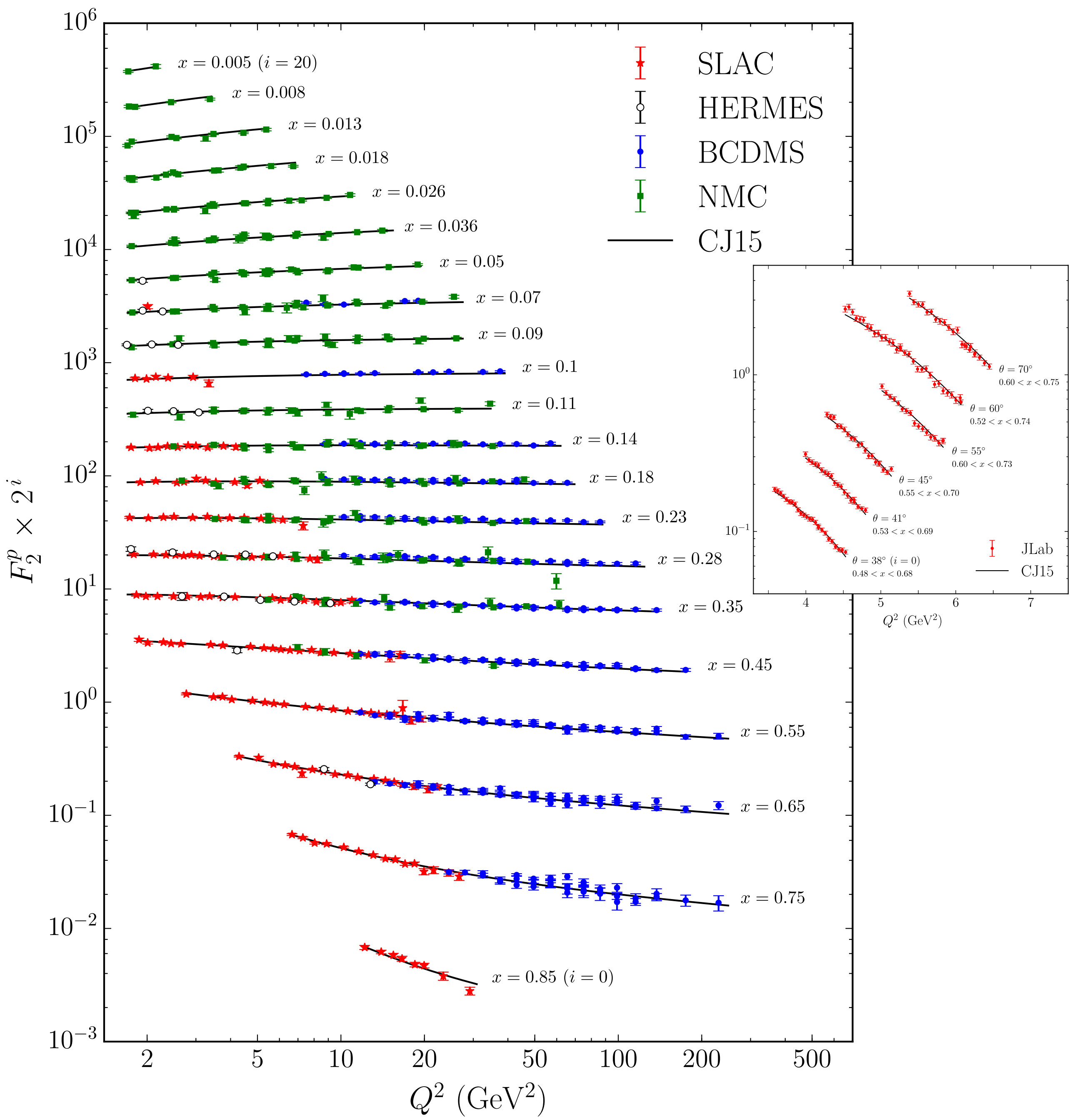


[Figure from DESY-21-099]

Lepton-Hadron Deep Inelastic Scattering

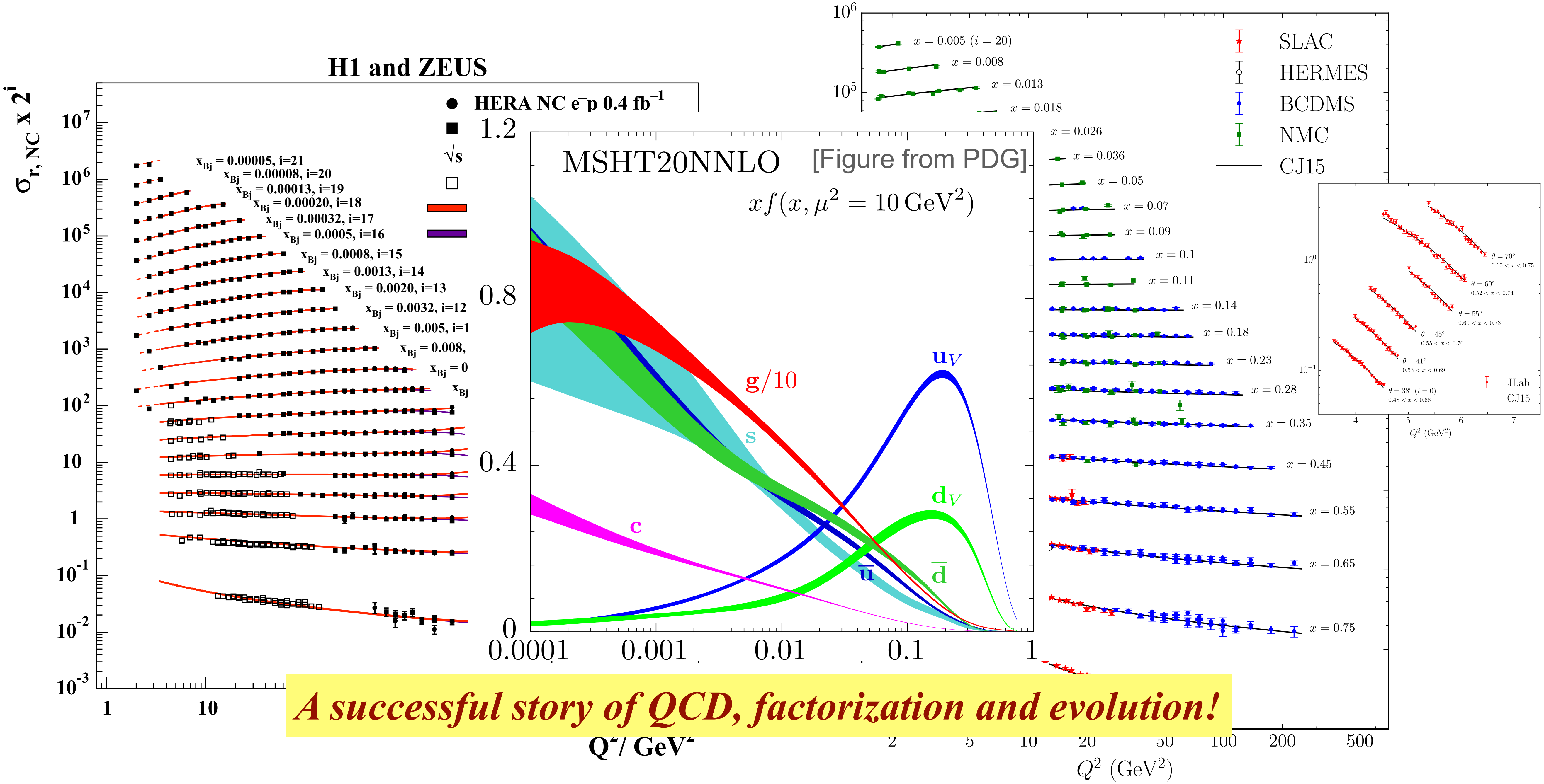


H. Abramowicz *et al.*, EPJC 78, 580 (2015).



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

Lepton-Hadron Deep Inelastic Scattering



A successful story of QCD, factorization and evolution!

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

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

See next talk: 杨思奇 PDF global fitting

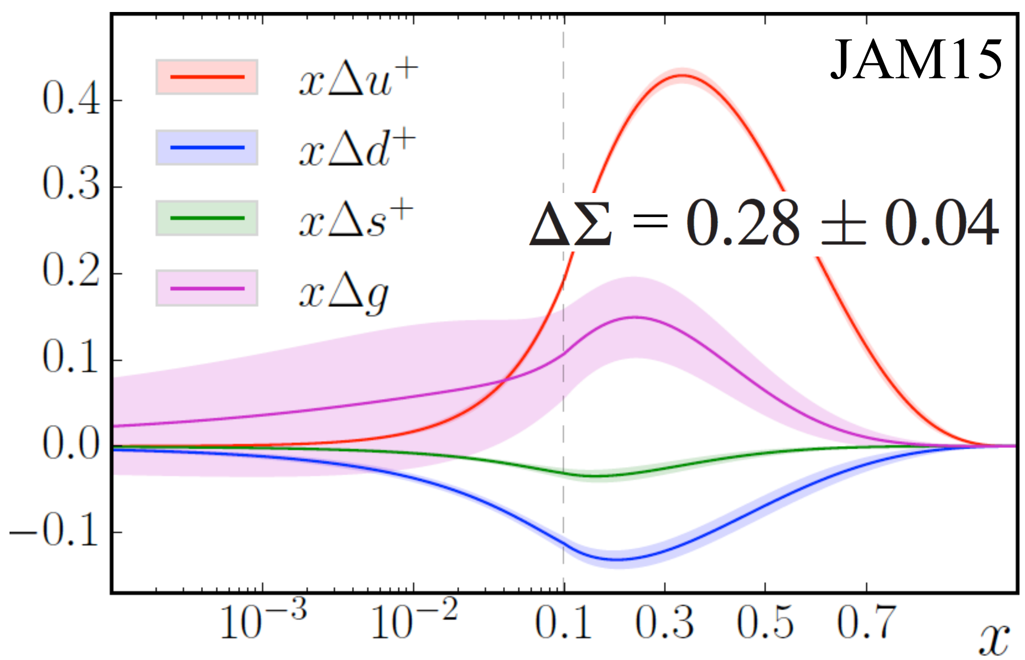
Nucleon Spin Structure

Proton spin puzzle

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

Spin decomposition

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



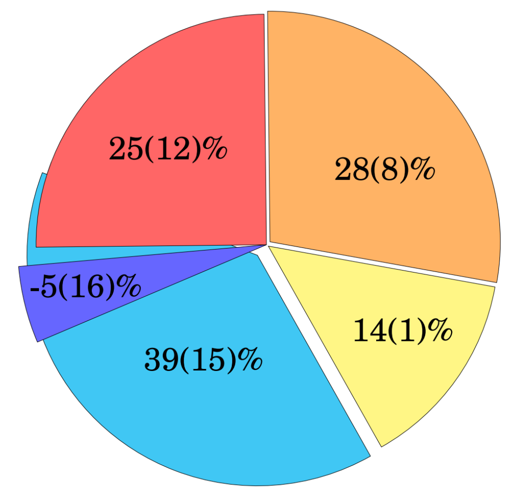
JAM Collaboration, PR D 93, 074005 (2016).

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

JAM Collaboration, PRL 119, 132001 (2017).

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

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



Lattice QCD (kinetic decomposition)

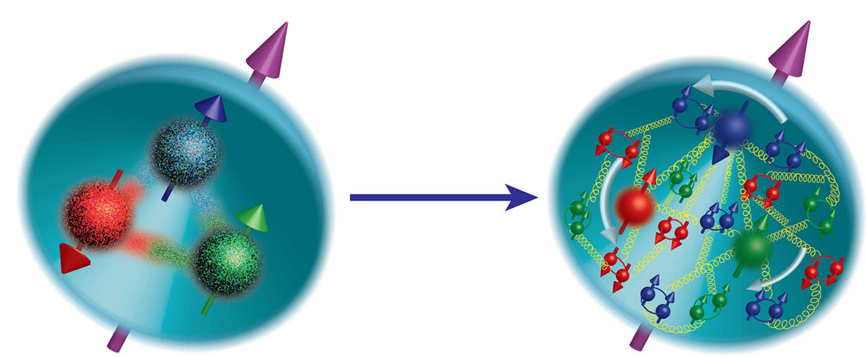
- L^u (CI + DI)
- L^d (CI + DI)
- L^s (DI)
- J^g
- $\frac{\Delta\Sigma}{2}\Big|^{u+d+s}$

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).



Wigner Rotation Effect

Melosh-Wigner rotation

quark spin in a rest proton $\neq$ quark spin in a moving proton

If applying a kinetic boost, one may relate the spin states in *proton rest frame* to the spin states in *infinite momentum frame*

$$\chi_T^{\uparrow} = w\left[\left(k^+ + m\right)\chi_F^{\uparrow} - \left(k^1 + ik^2\right)\chi_F^{\downarrow}\right]$$

$$\chi_T^{\downarrow} = w\left[\left(k^+ + m\right)\chi_F^{\downarrow} + \left(k^1 - ik^2\right)\chi_F^{\uparrow}\right]$$

$$k^+ = k^0 + k^3$$

$$w = \left[2k^+\left(k^0 + m\right)\right]^{-1/2}$$

E.P. Wigner, Ann. Math 40 (1939) 149; H.J. Melosh, Phys. Rev. D 9 (1974) 1095.

The effect on quark polarization

$$\Delta q = \int \mathrm{d}^3\mathbf{k}\mathscr{M}\left[q^{\uparrow}(k) - q^{\downarrow}(k)\right]$$

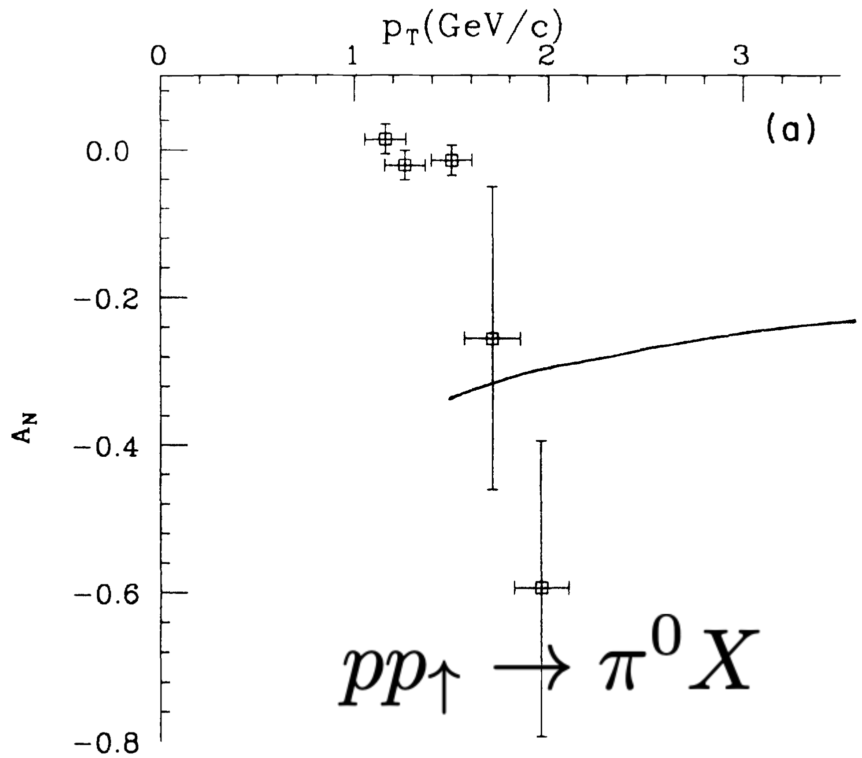
$$\mathscr{M} = \frac{(k^+ + m)^2 - k_T^2}{2k^+(k^0 + m)}$$

B.-Q. Ma, J. Phys. G 17 (1991) L53-L58; B.-Q. Ma, Q.-R. Zhang, Z. Phys. C 58 (1993) 479.

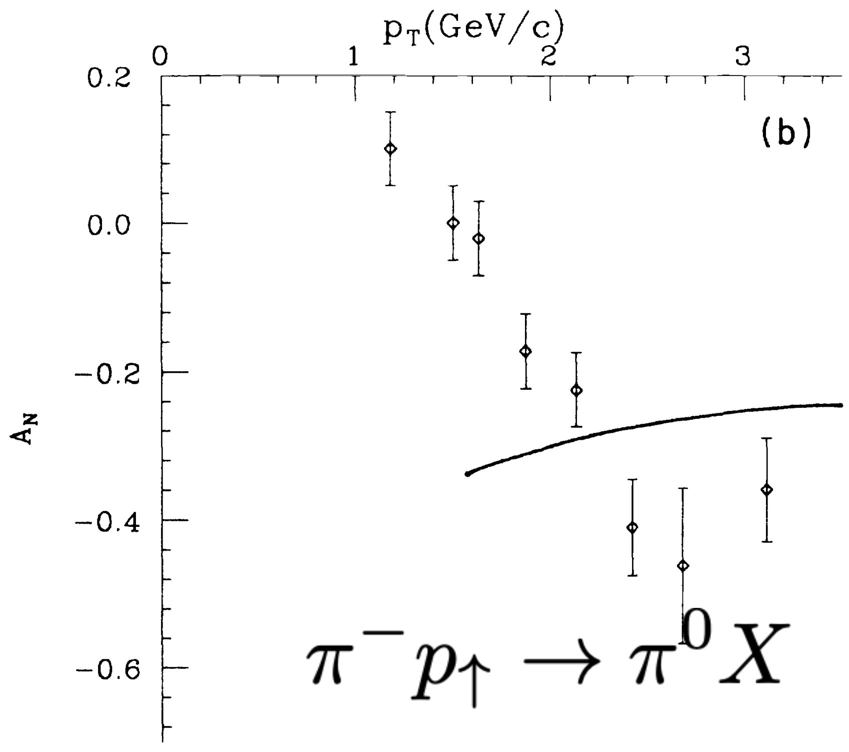
It predicts decreasing polarization with k_T, which should be tested by data.
This interpretation is based on a kinetic boost, but a complete boost including QCD dynamics is challenging.

The Sivers Function: Early Story

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.

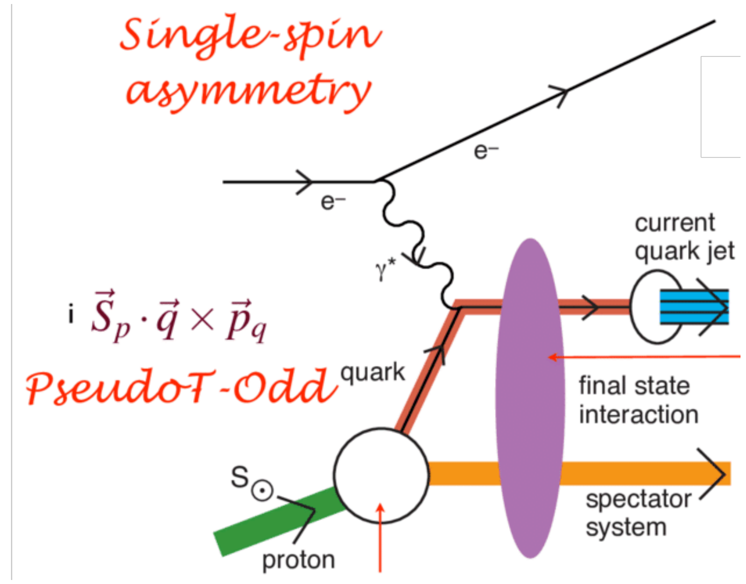
For the next decade, the "Sivers effect" was thought to vanish.

The Sivers Function: Early Story

Until an explicit model calculation showing …

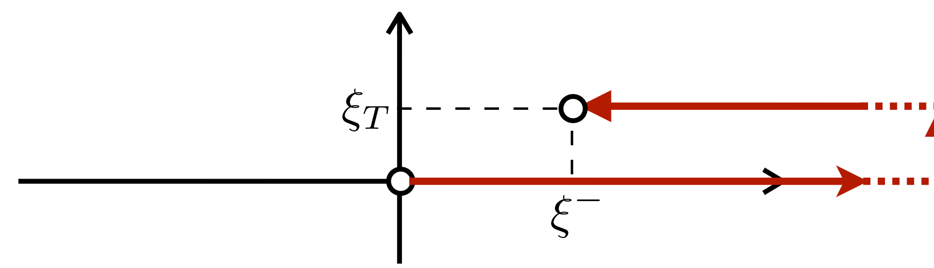
nonzero Sivers effects exist at leading twist
due to final-state interactions

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.

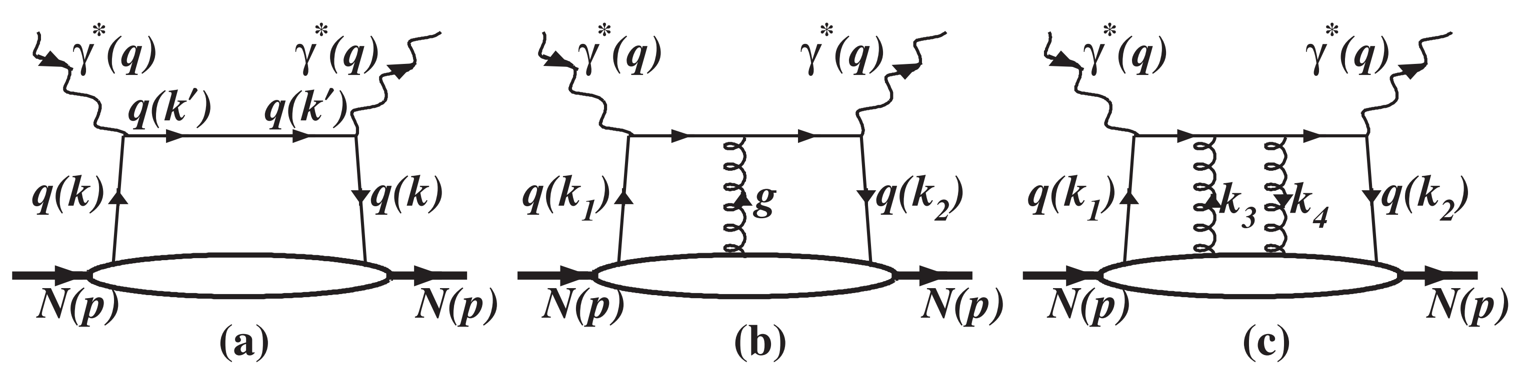
[Figure from A. Bacchetta]

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

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

Collinear expansion

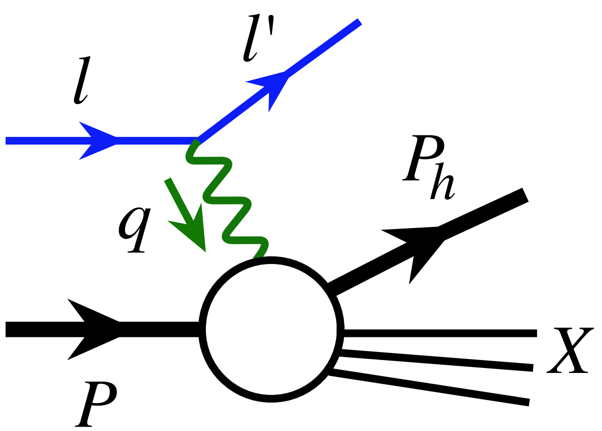
Z.T. Liang and X.N. Wang,
Phys. Rev. D 75 (2007) 094002.

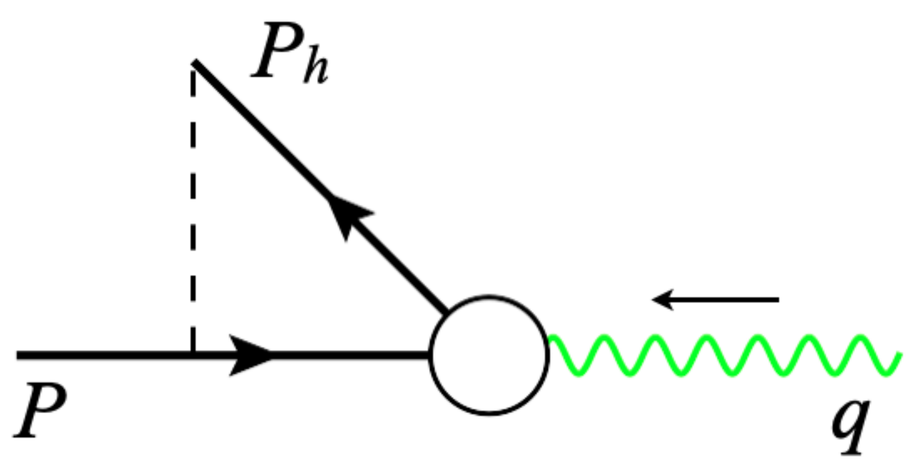


Semi-inclusive Deep Inelastic Scattering

Semi-inclusive DIS: a final state hadron (P_h) is identified

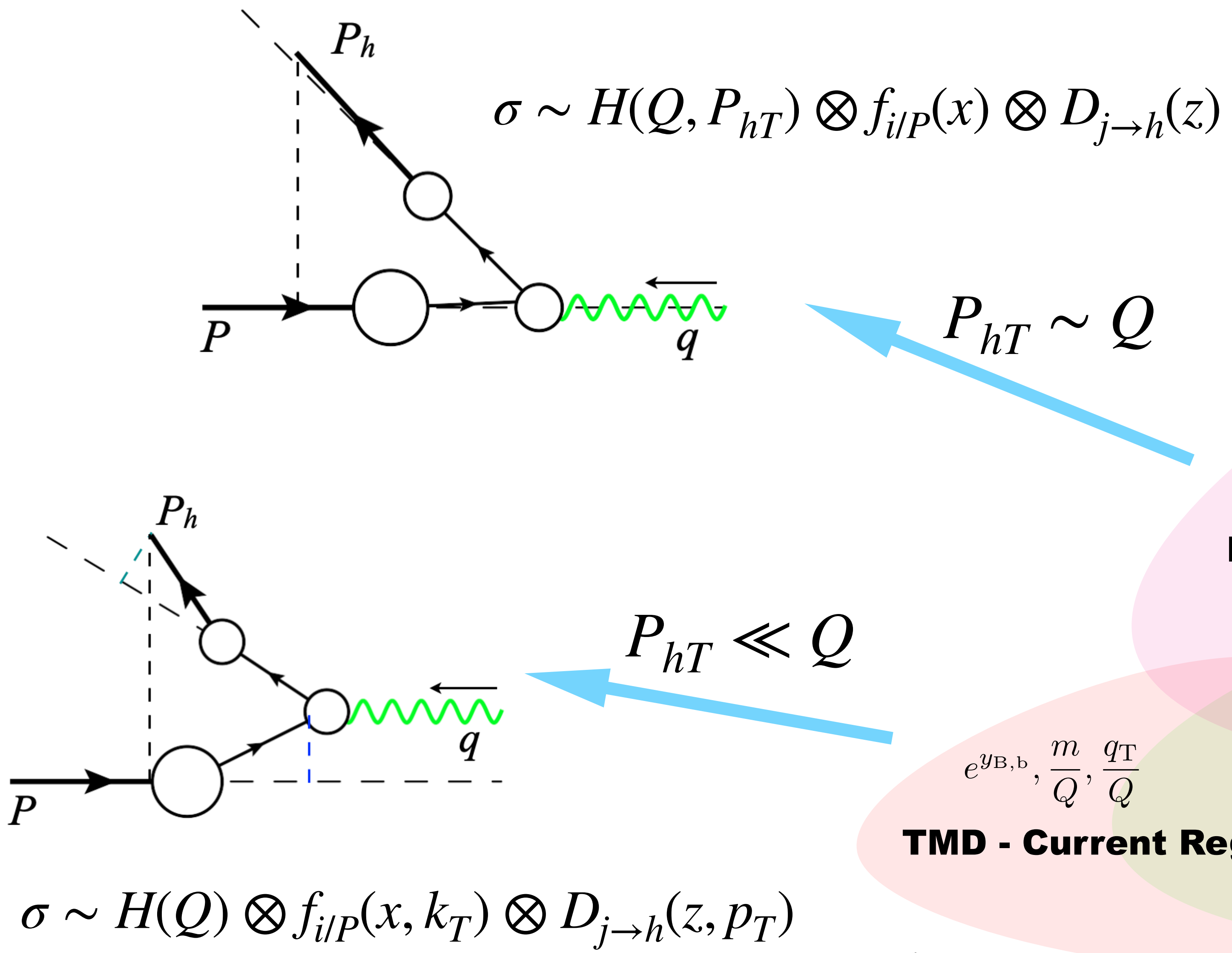
- enable us to explore the emergence of color neutral hadrons from colored quarks/gluons
- flavor dependence by selecting different types of observed hadrons: pions, kaons, …
- a large momentum transfer Q provides a short-distance probe
- an additional and adjustable momentum scale P_{hT}
- multidimensional imaging of the nucleon

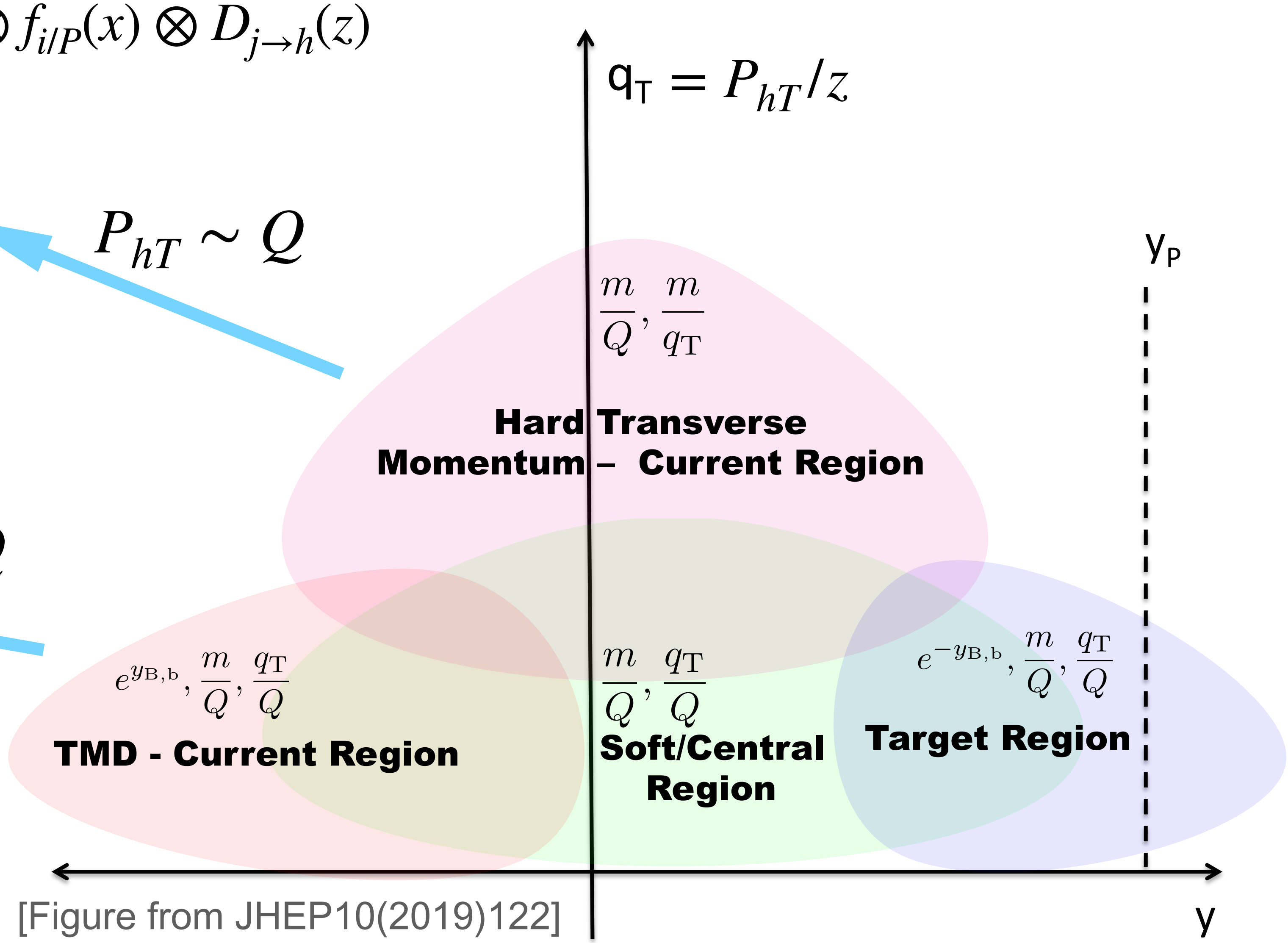




SIDIS Kinematic Regions

Sketch of kinematic regions of the produced hadron





[Figure from JHEP10(2019)122]

P_{hT} is defined in the photon-hadron frame

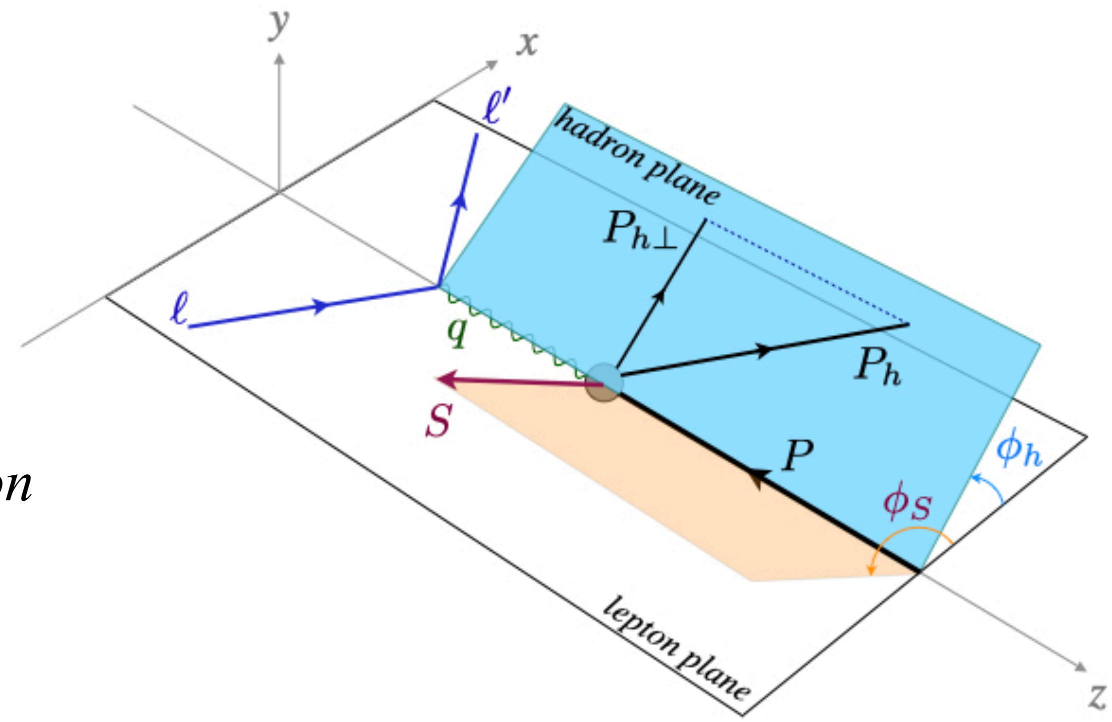
See also: 4月26日10:55 陈开宝 SIDIS in TF region

Poster 116 赵晓燕 Spin transfer suppression by TF

Structure Functions of SIDIS

SIDIS differential cross section

in terms of 18 structure functions



$$F_{AB,C}(x_B, z, P_{hT}^2, Q^2)$$

A: lepton polarization
B: nucleon polarization
C: virtual photon polarization

$$\frac{d\sigma}{dx_B\, dy\, dz\, dP_{hT}^2\, d\phi_h\, d\phi_S} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)$$

$$\times\Big\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h$$

$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h+\epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right]+\lambda_e S_L\left[\sqrt{1-\epsilon^2}F_{LL}+\sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

$$+S_T\Big[\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\sin(\phi_h-\phi_S)+\epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)$$

$$+\epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big]$$

$$+\lambda_e S_T\Big[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)$$

$$+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}$$

$$x_B = \frac{Q^2}{2P\cdot q}\qquad y = \frac{P\cdot q}{P\cdot l}\qquad z = \frac{P\cdot P_h}{P\cdot q}\qquad \gamma = \frac{2x_B M}{Q}$$

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

See also Poster 214 马凌泉 Lattice calculation of BM function

Longitudinal Double Spin Asymmetry

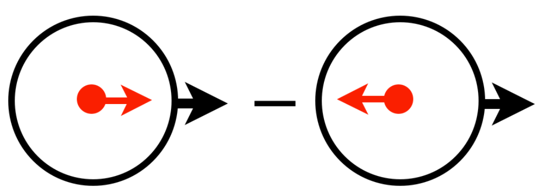
Longitudinal DSA in SIDIS

$$A_{LL} \equiv \frac{\sigma_{++} - \sigma_{+-} + \sigma_{--} - \sigma_{-+}}{\sigma_{++} + \sigma_{+-} + \sigma_{--} + \sigma_{-+}} = \frac{\sqrt{1-\varepsilon^2}\,F_{LL}\left(x, z, P_{hT}^2, Q^2\right)}{F_{UU}\left(x, z, P_{hT}^2, Q^2\right)}$$

In TMD region:

$$F_{LL}\left(x, z, P_{hT}^2, Q^2\right) \sim g_{1L}(x, k_T^2) \otimes D_1(z, p_T^2)$$

$$F_{UU}\left(x, z, P_{hT}^2, Q^2\right) \sim f_1(x, k_T^2) \otimes D_1(z, p_T^2)$$

g_{1L} 

(both collinear and TMD)

Several global analyses of collinear helicity but no extraction of TMD helicity before!

P_{hT} dependent DSA measurements

HERMES: proton (H_2) and deuteron (D_2) targets

HERMES Collaboration, Phys. Rev. D 99 (2019) 112001.

JLab CLAS: proton (NH_3) target

CLAS Collaboration, Phys. Lett. B 782 (2018) 662.

TMD Evolution

Evolution equations

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

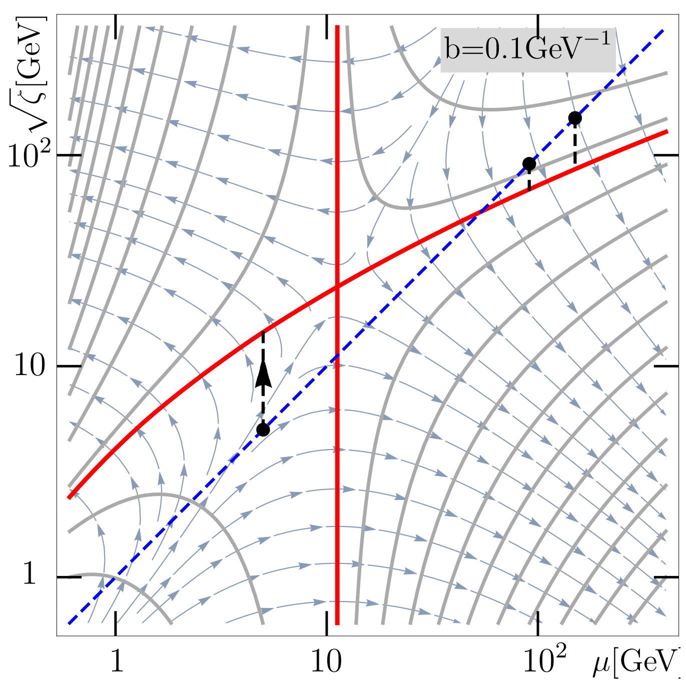
$$\zeta \frac{dF(x,b;\mu^2,\zeta)}{d\zeta} = -\mathscr{D}(\mu,b) F(x,b;\mu^2,\zeta)$$

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

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

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

ζ-prescription



equipotential lines:

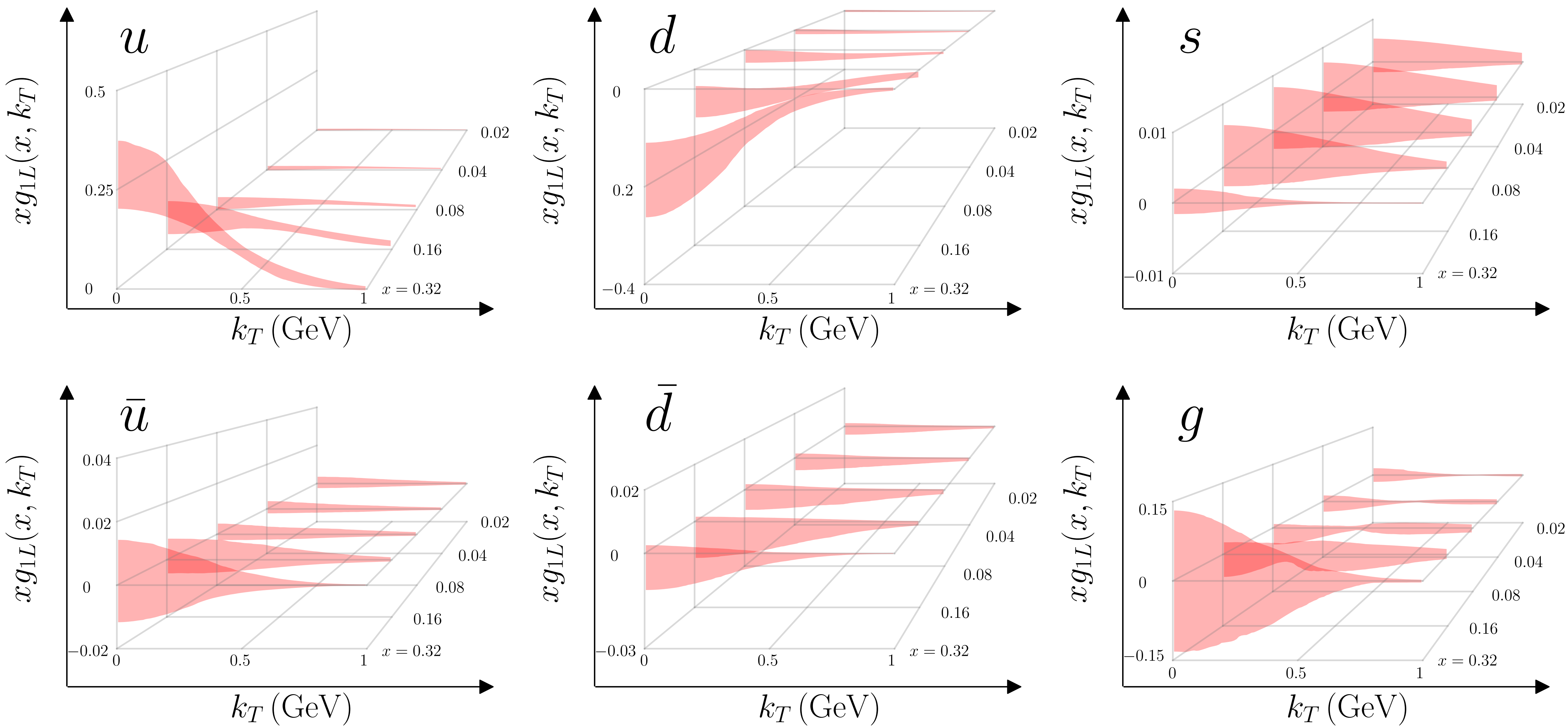
$$\frac{d\ln\zeta_\mu(\mu,b)}{d\ln\mu^2} = \frac{\gamma_F\left(\mu,\zeta_\mu(\mu,b)\right)}{2\mathscr{D}(\mu,b)}$$

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

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

First Extraction of TMD Helicity

NLO+NNLL analysis results

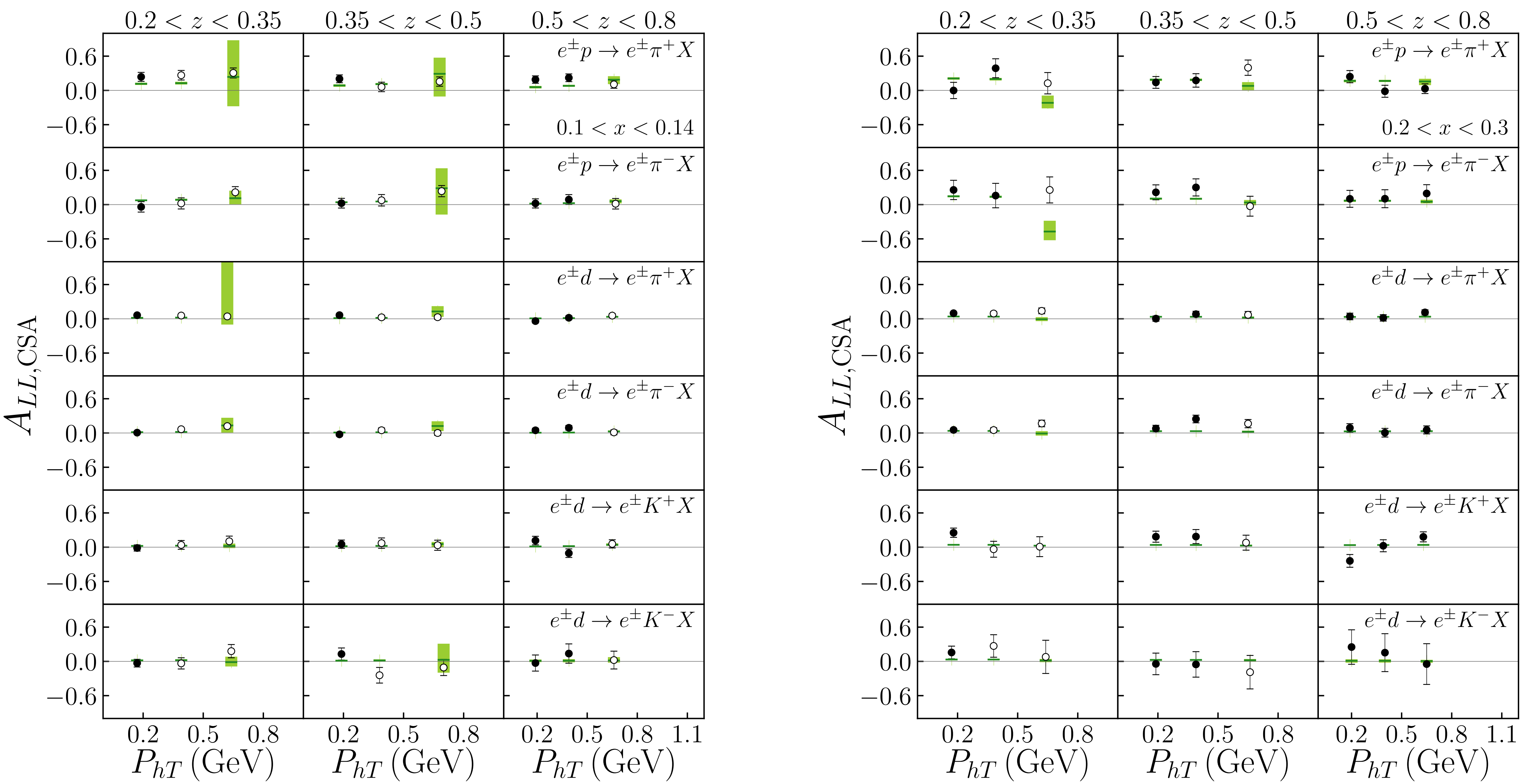


Nonzero signals for u and d quarks, while sea quarks and gluons are loosely constrained.

K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902.

Comparison with Data

Compare with HERMES data



K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902.

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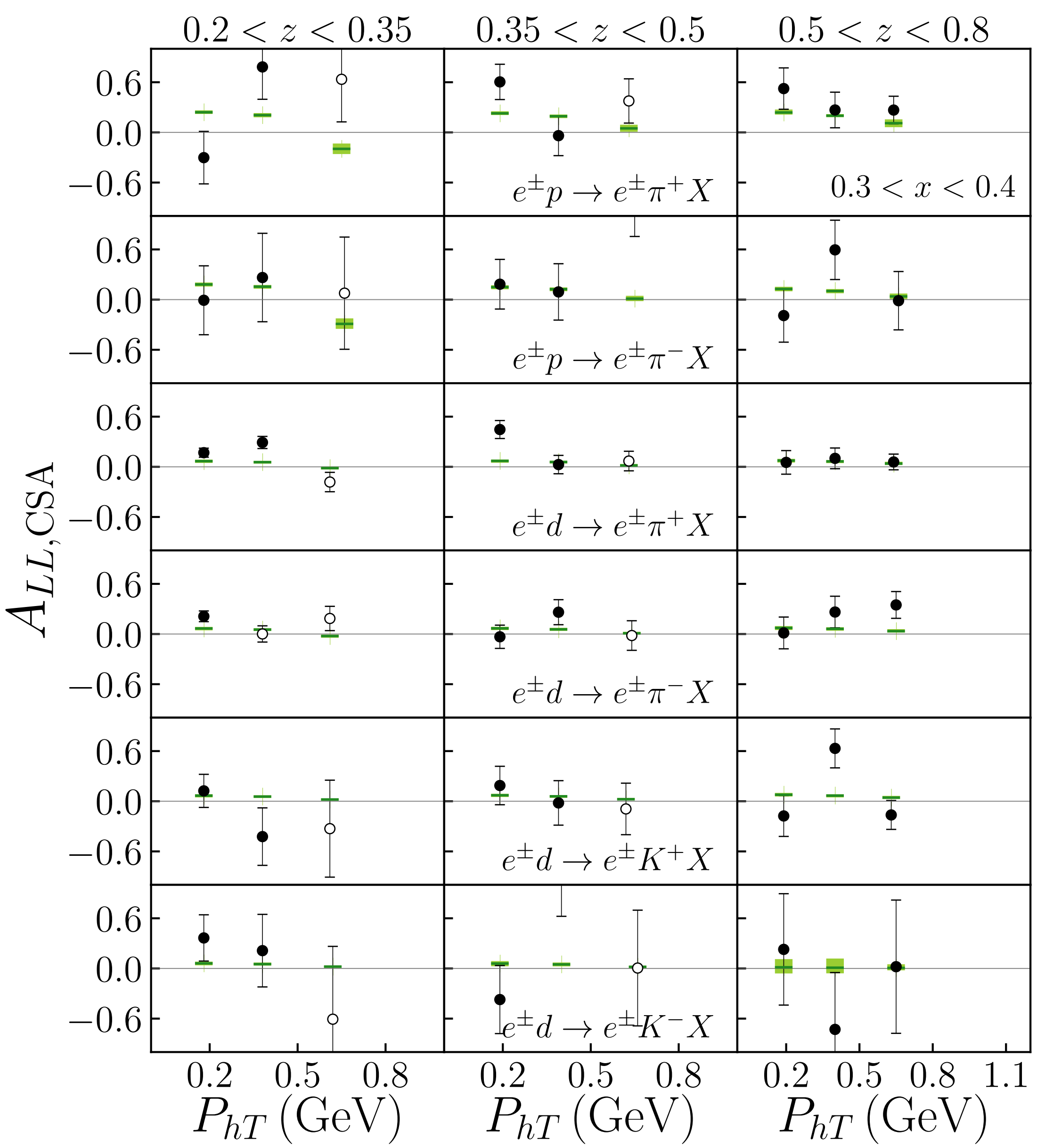

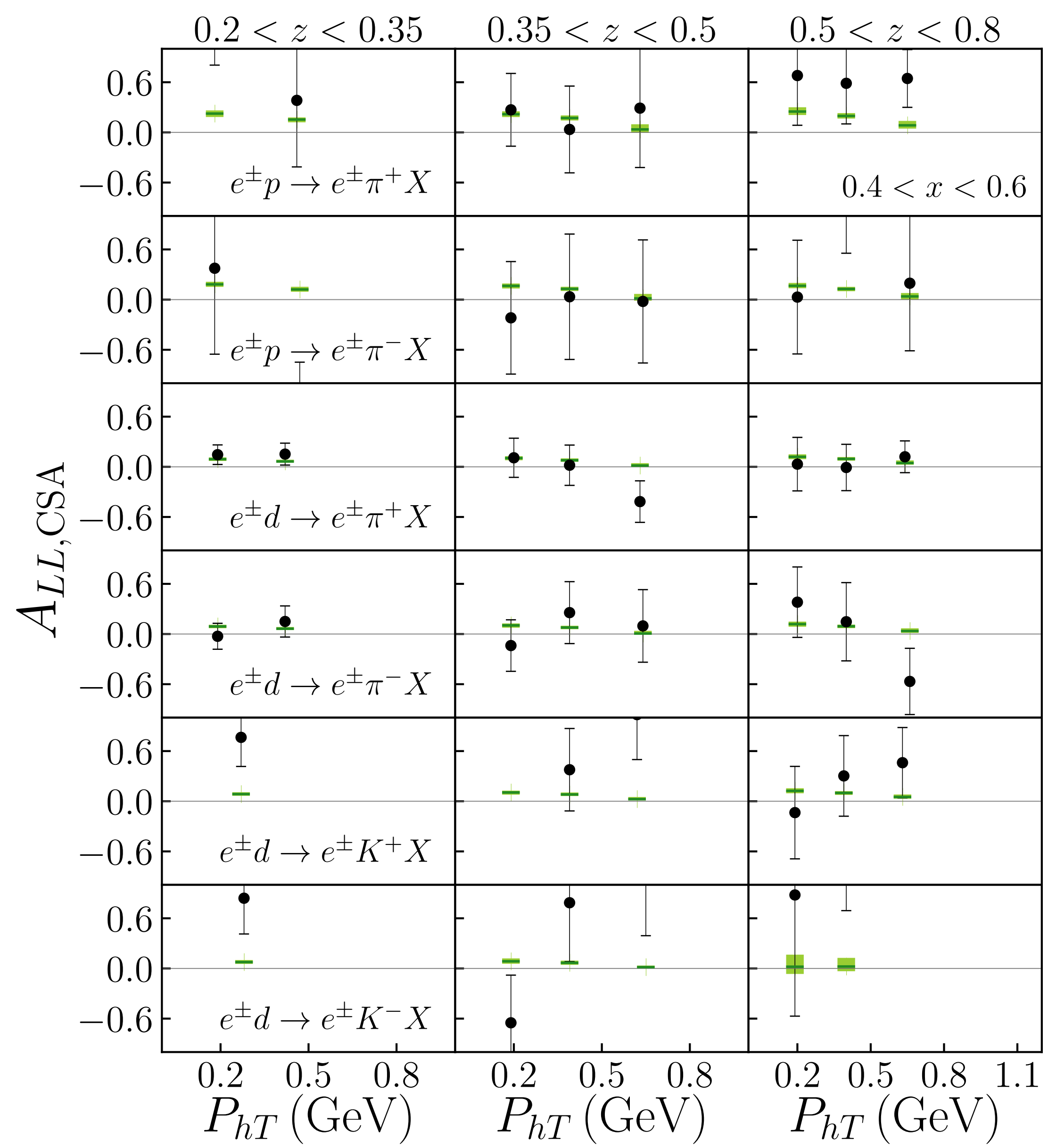

K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902.

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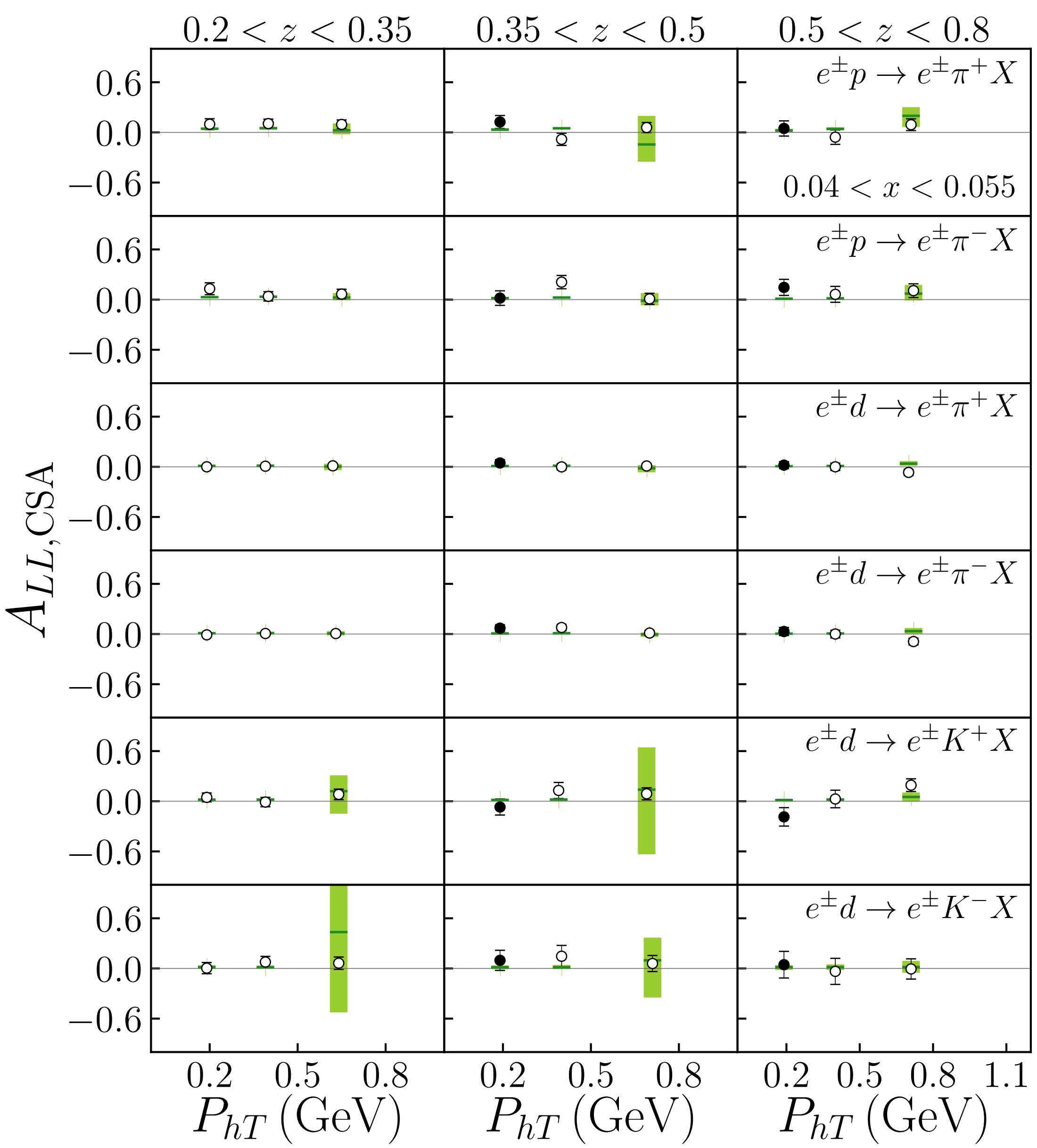

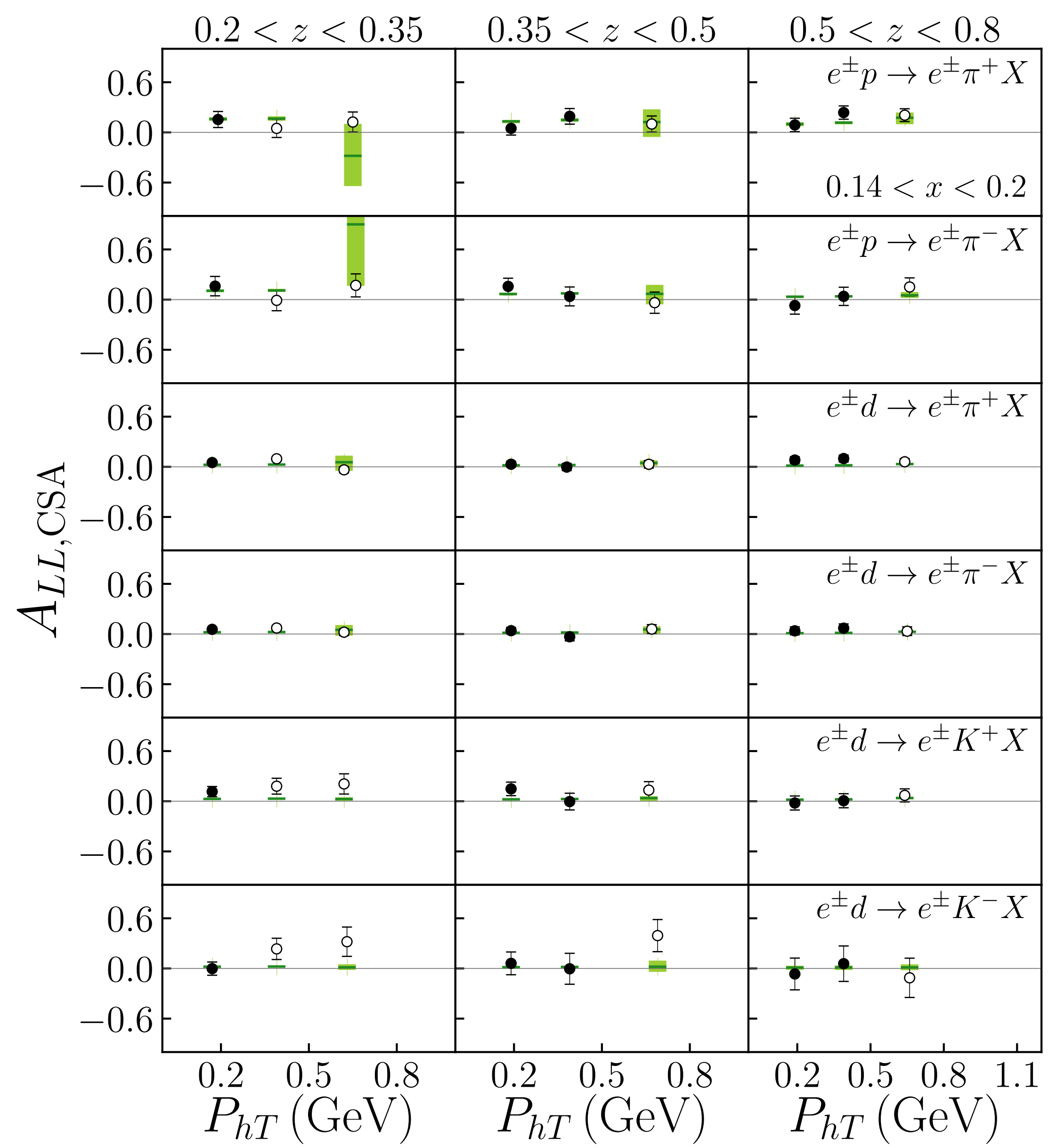

K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902.

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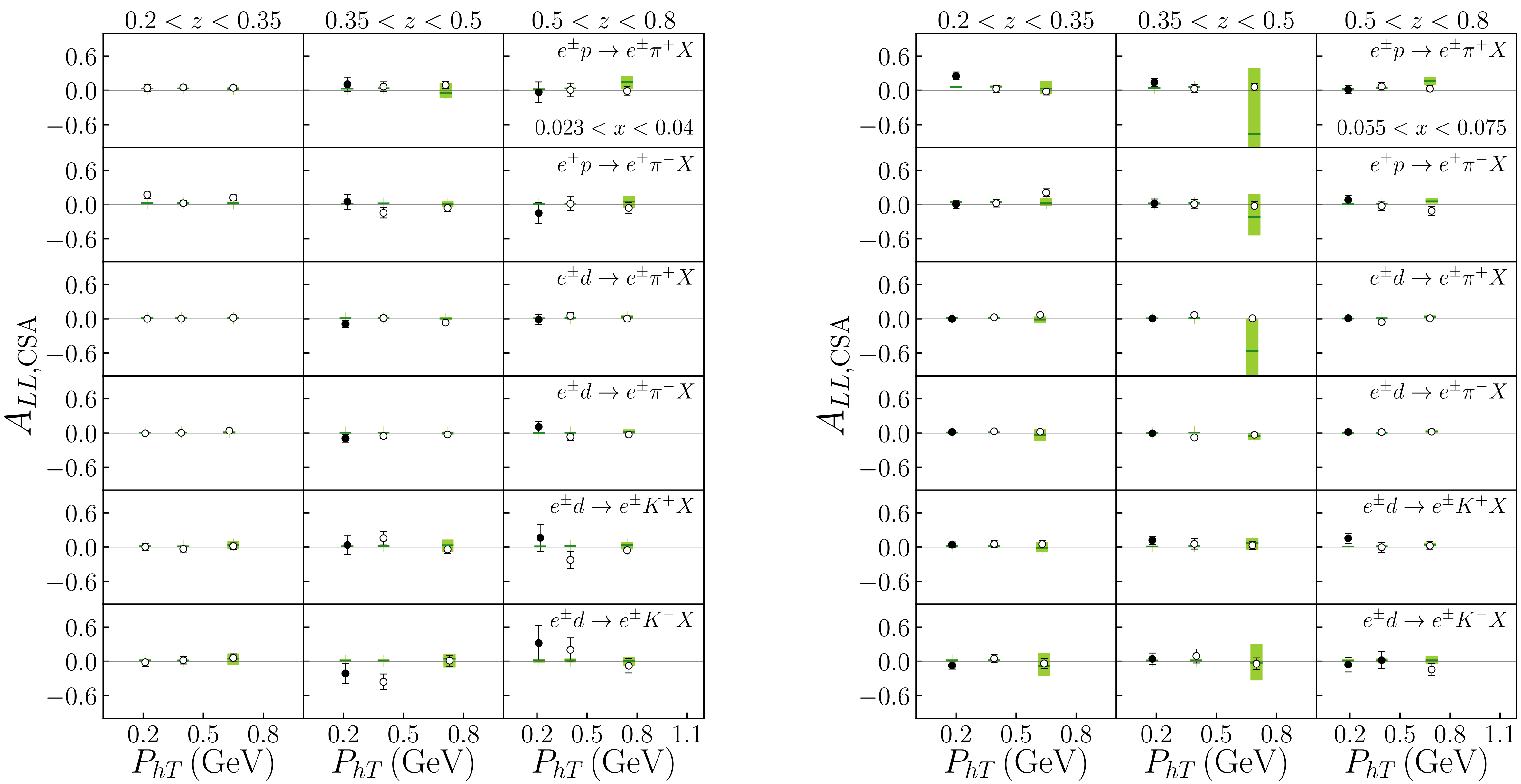

K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902.

Comparison with Data

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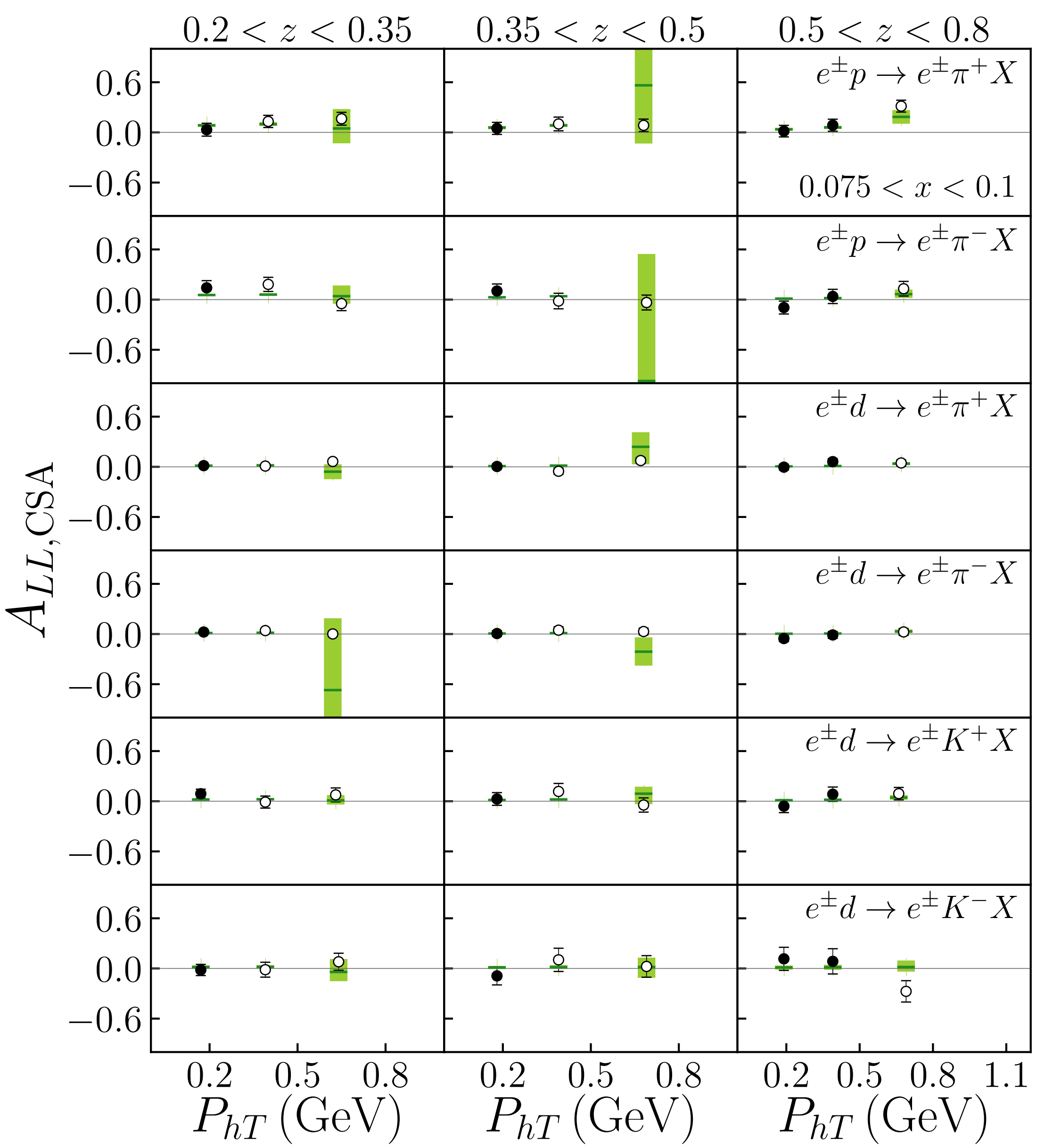
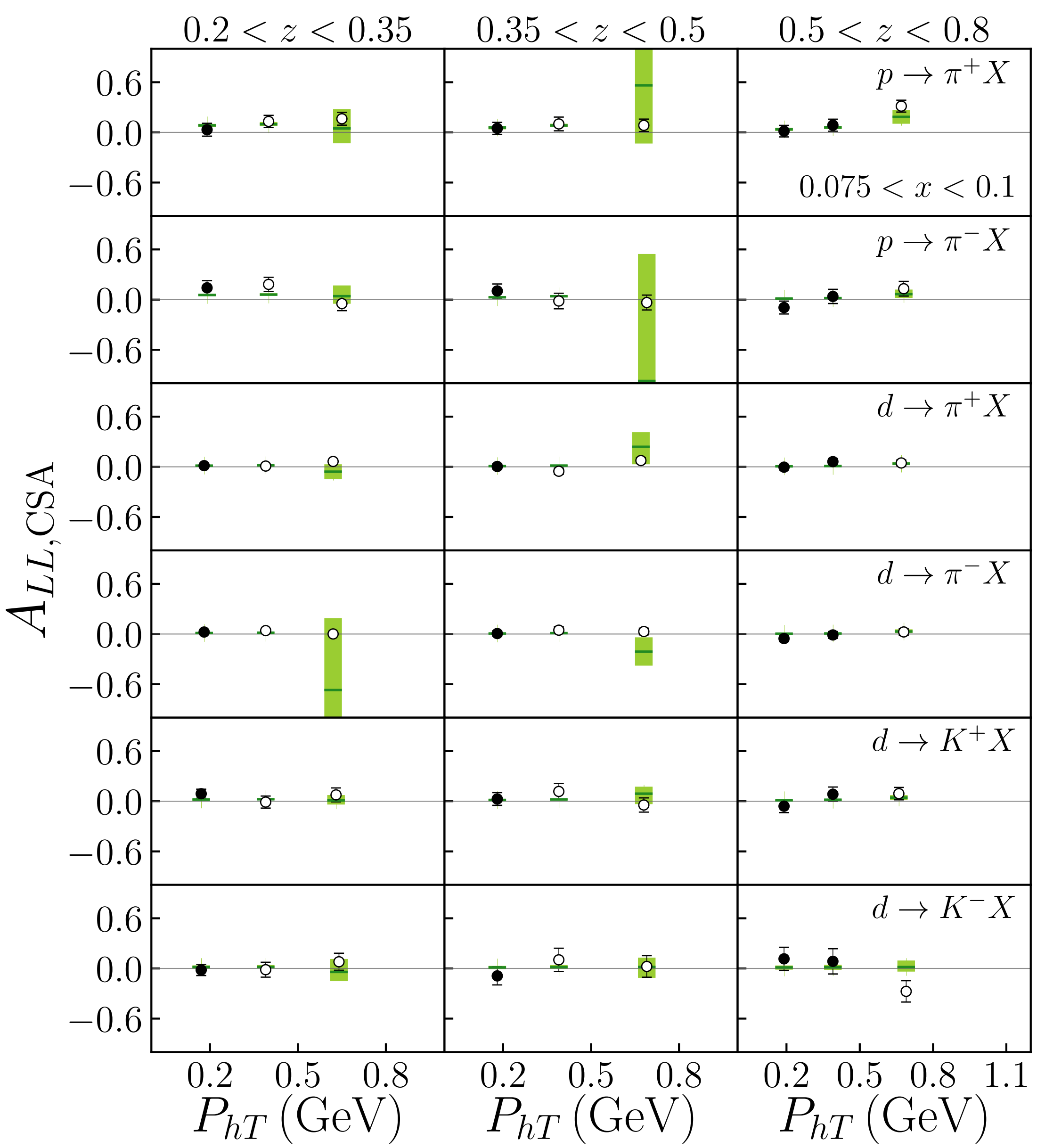
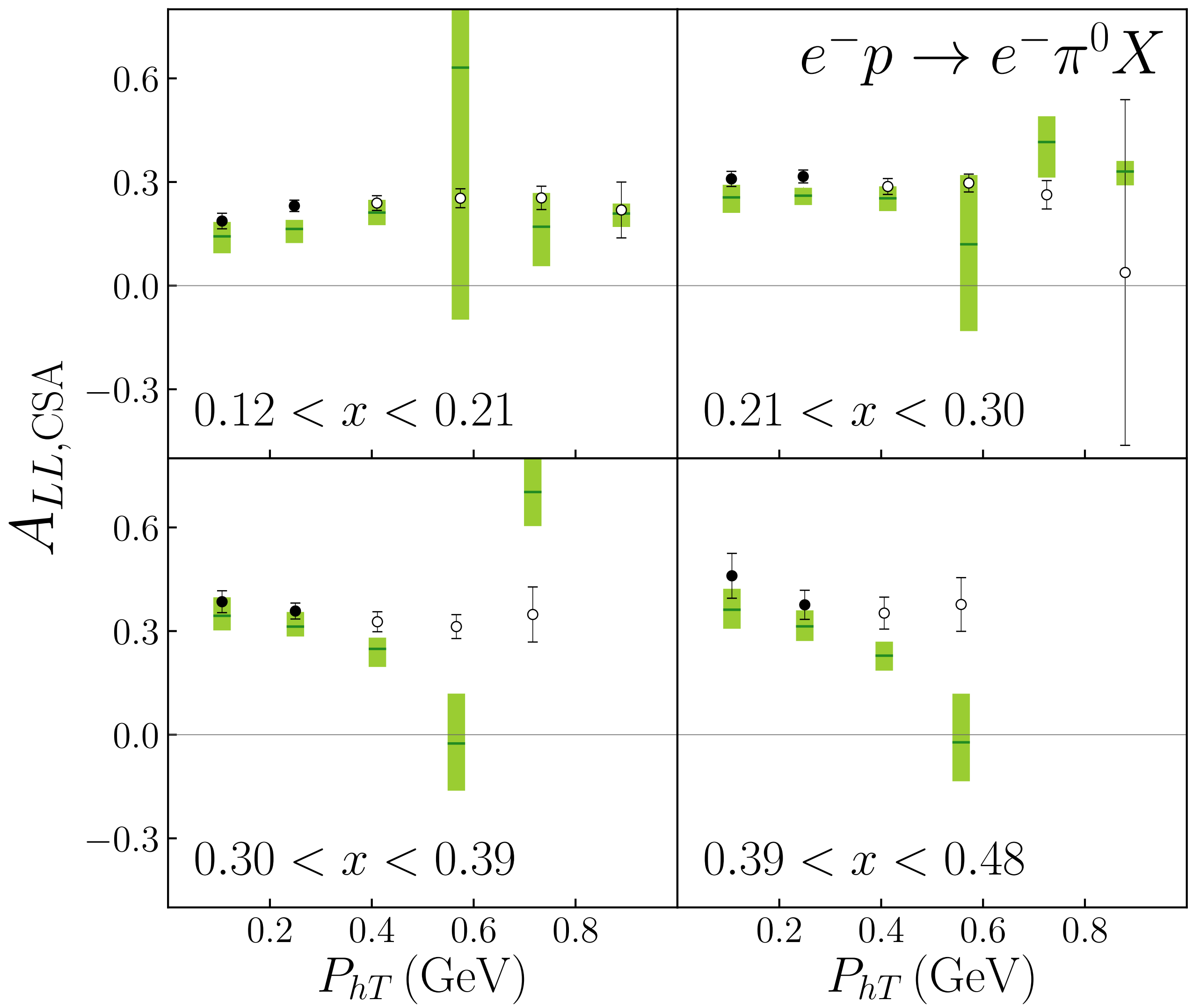




K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902.

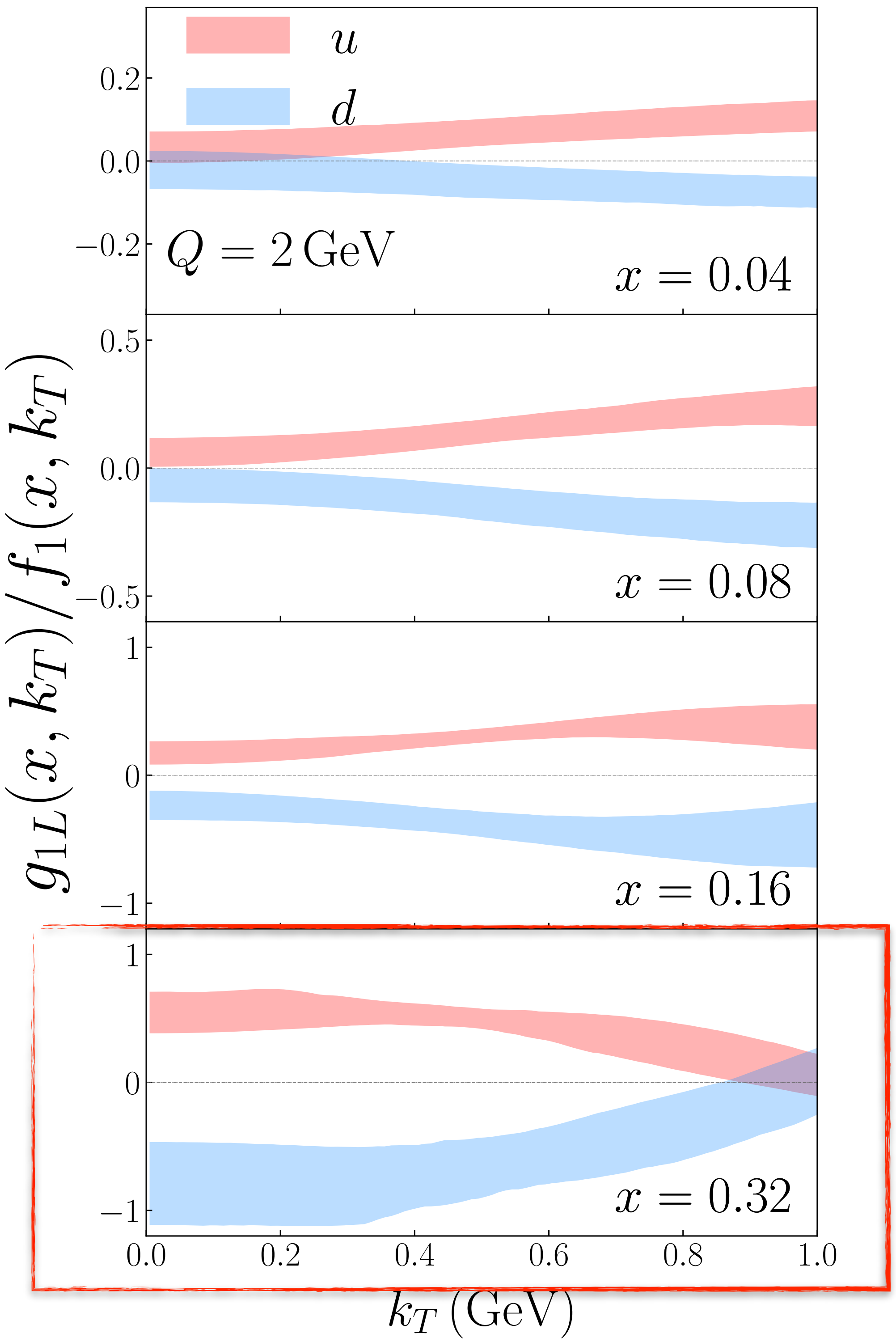
Comparison with Data

Compare with CLAS data



K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902.

Transverse Momentum Dependent Polarization



$g_{1L}(x, k_T^2)$ gives the absolute number density difference between spin-parallel and spin-antiparallel quarks.

The ratio $g_{1L}(x, k_T^2)/f_1(x, k_T^2)$ measures the polarization rate of quarks.

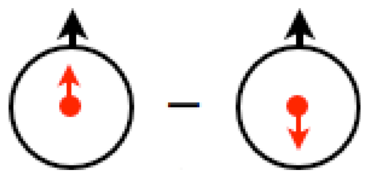
- At large x, where valence components dominate, the polarization decreases with increasing k_T
  Qualitatively consistent with kinetic Wigner rotation effects
- At low x, where the valence component is no longer adequate, distributions are highly driven by complex QCD dynamics
  The polarization is found increasing with k_T

K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902.

See also:Poster 179 杨科 TMD helicity; 70 陈毅 axial radius

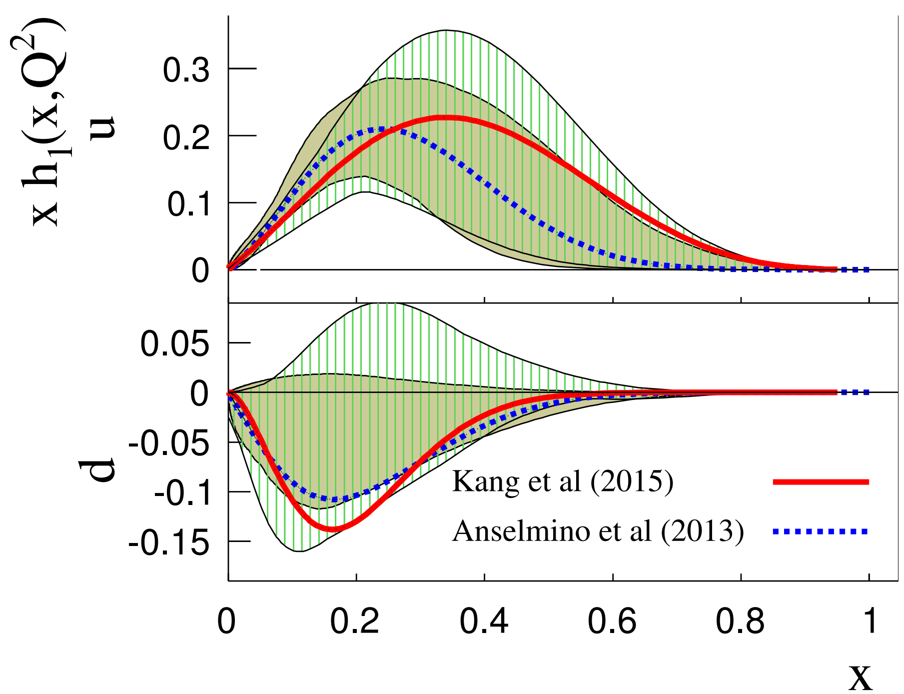
Transversity Distribution

Transversity distribution

h_1  (Collinear & TMD)

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

Phenomenological extractions



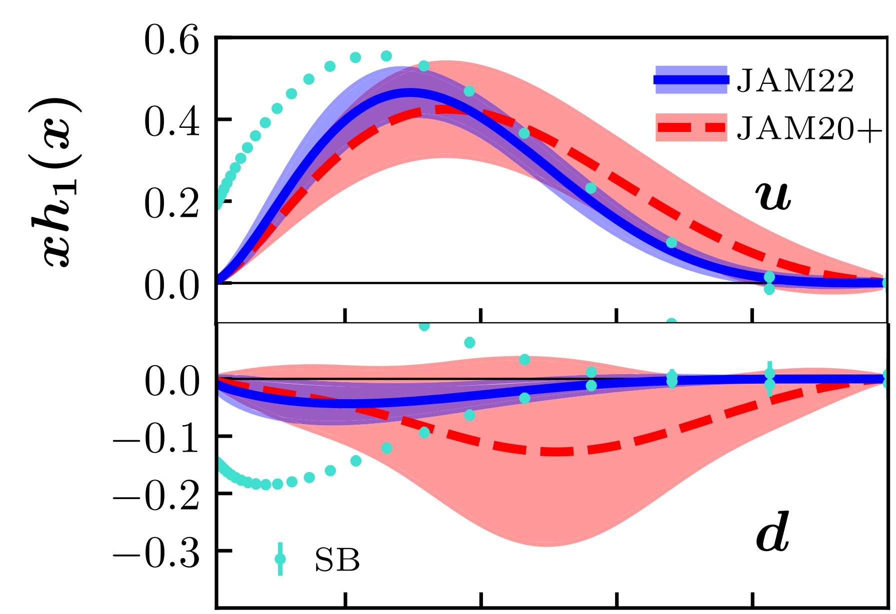
Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, PRD 93, 014009 (2016).

Chiral-odd:

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

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

$$A_{UT}^{\sin(\phi_h+\phi_S)} \sim h_1(x,k_T^2) \otimes H_1^\perp(z,p_T^2)$$

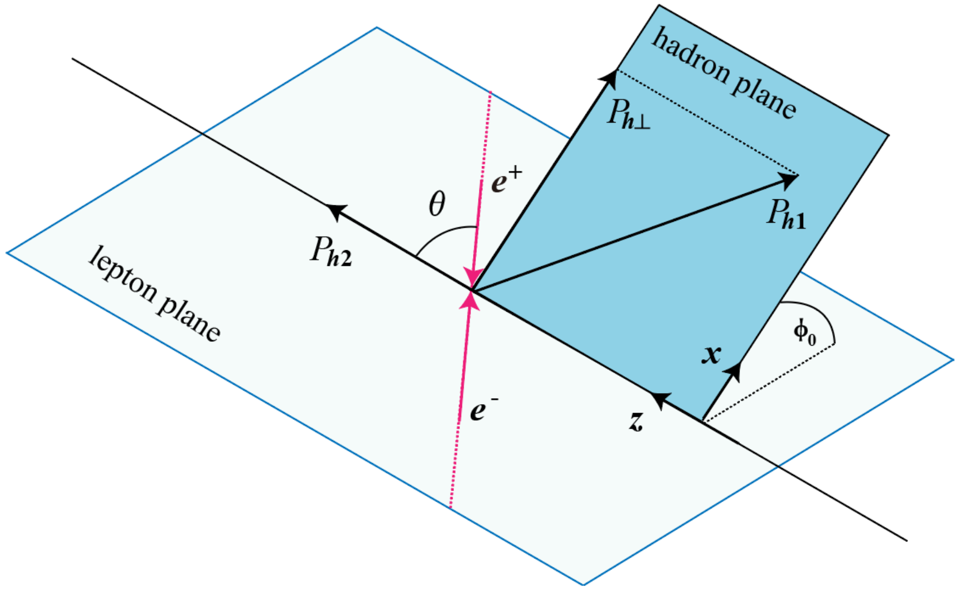


JAM Collaboration, PRD 104, 034014 (2022).

Assuming vanishing transverse polarization of sea quarks!

Complementary Process

Semi-inclusive e^+e^- annihilation: $e^+e^- \to h_1 h_2 X$



$$\frac{d^5\sigma}{dz_1 dz_2 d^2\boldsymbol{P}_{h\perp} d\cos\theta} = \frac{3\pi\alpha^2}{2Q^2} z_1^2 z_2^2 \left[\left(1+\cos^2\theta\right) F_{UU}^{h_1h_2} + \sin^2\theta \cos\left(2\phi_0\right) F_{\rm Collins}^{h_1h_2} \right]$$

In TMD region: h_1 and h_2 are near back-to-back, $P_{hT} \ll Q$ $\qquad F_{\rm Collins}^{h_1h_2} \sim H_1^{\perp h_1} \otimes H_1^{\perp h_2}$

Experimental measurements:

Belle: $\sqrt{s} = 10.58\,\mathrm{GeV}$ — Phys. Rev. D 78 (2008) 032011; 86 (2012) 039905(E).

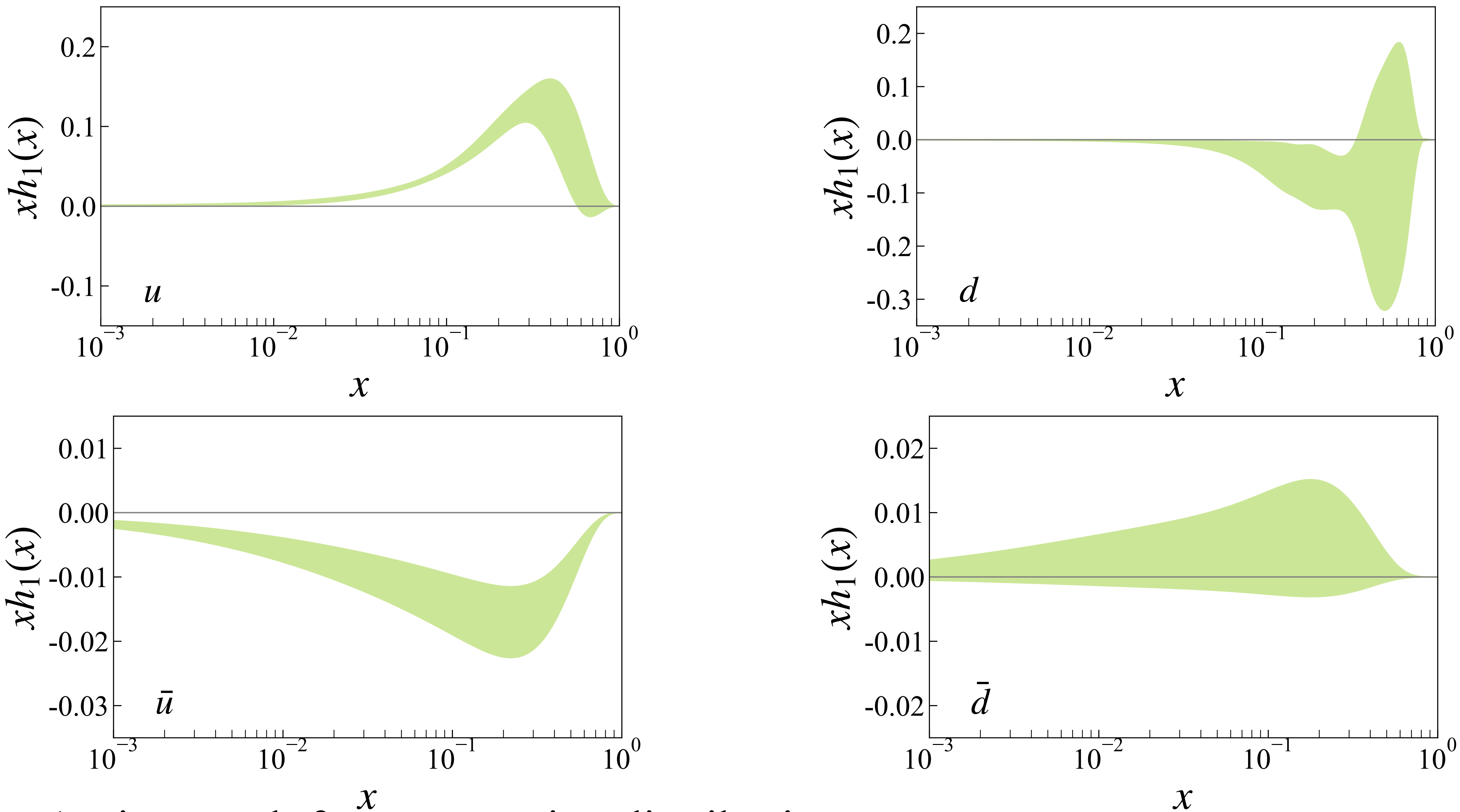
BaBar: $\sqrt{s} = 10.6\ \mathrm{GeV}$ — Phys. Rev. D 90 (2014) 052003; Phys. Rev. D 92 (2015) 111101.

BESIII: $\sqrt{s} = 3.68\ \mathrm{GeV}$ — Phys. Rev. Lett. 116 (2016) 042001.

See also: 4月26日10:30 邵鼎煜 and Poster 195 张宜新
transverse SSA and hadron in jets

Sea Quark Transversity

First determination of sea quark transversity, including TMD evolution



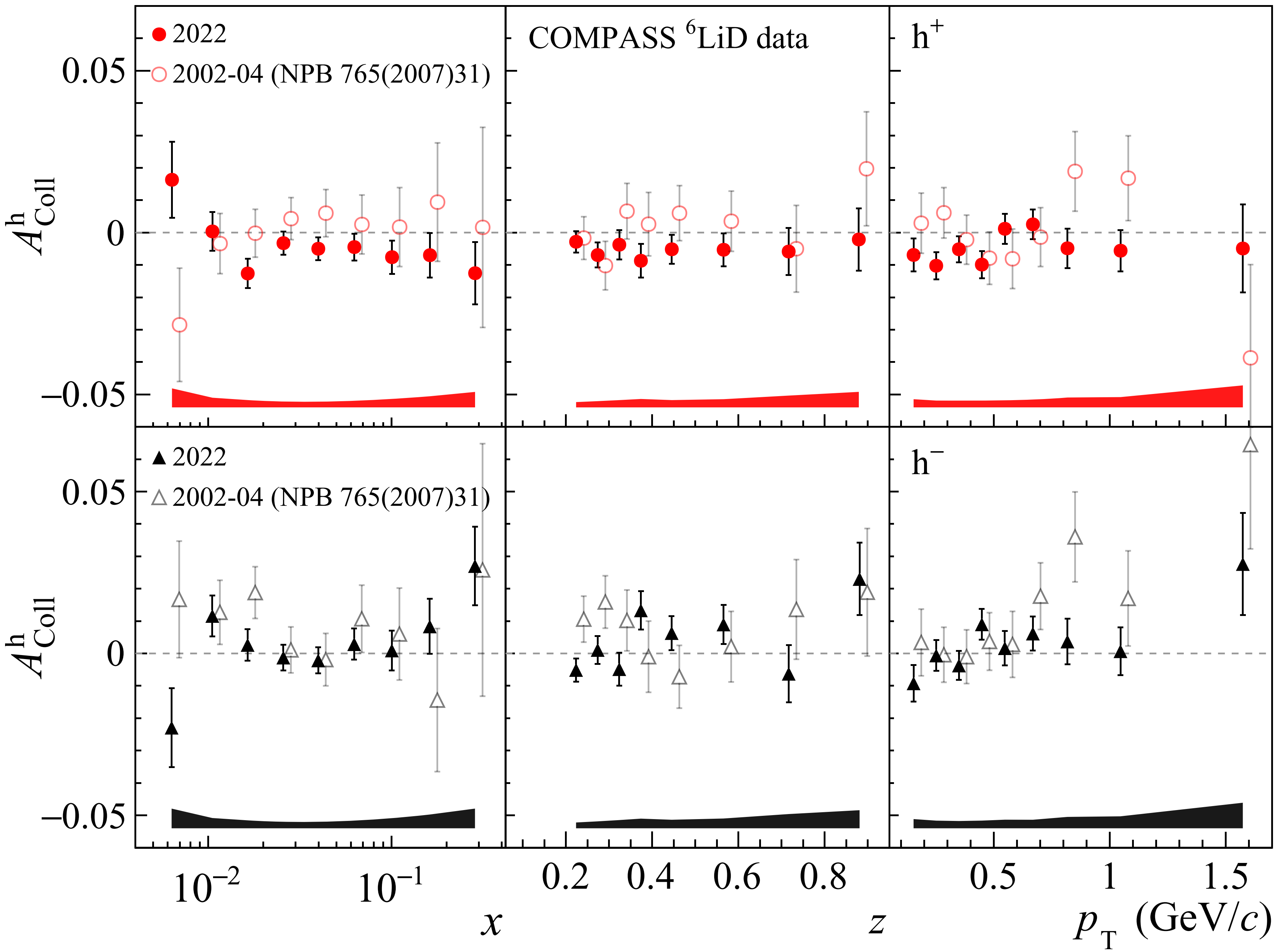
Anti-u quark favors negative distribution

Anti-d quark consistent with zero with current precision

C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, PRD 109 (2024) 056002.

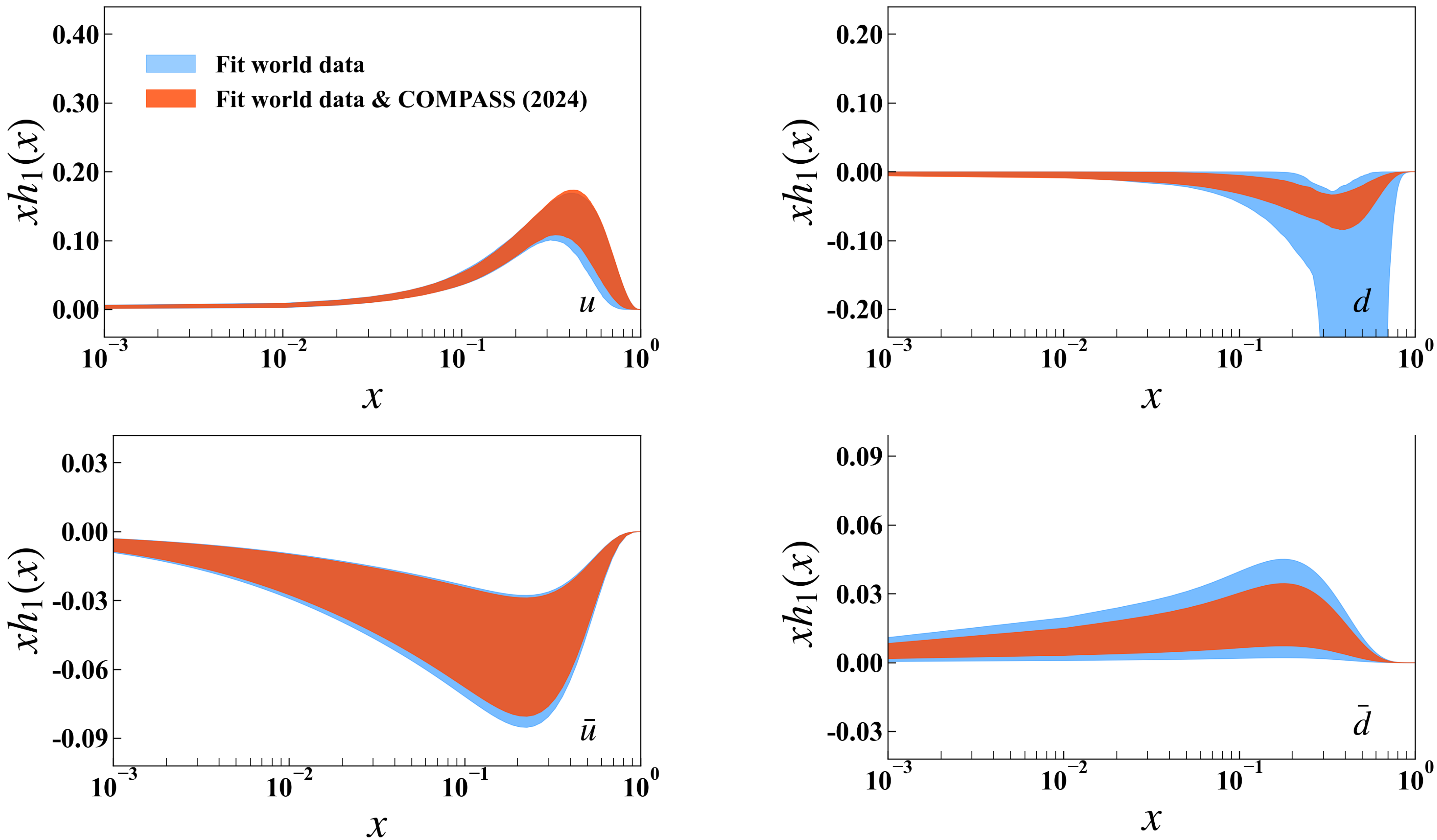
New COMPASS Data

SIDIS on transversely polarized deuteron target



COMPASS Collaboration, Phys. Rev. Lett. 133 (2024) 101903.

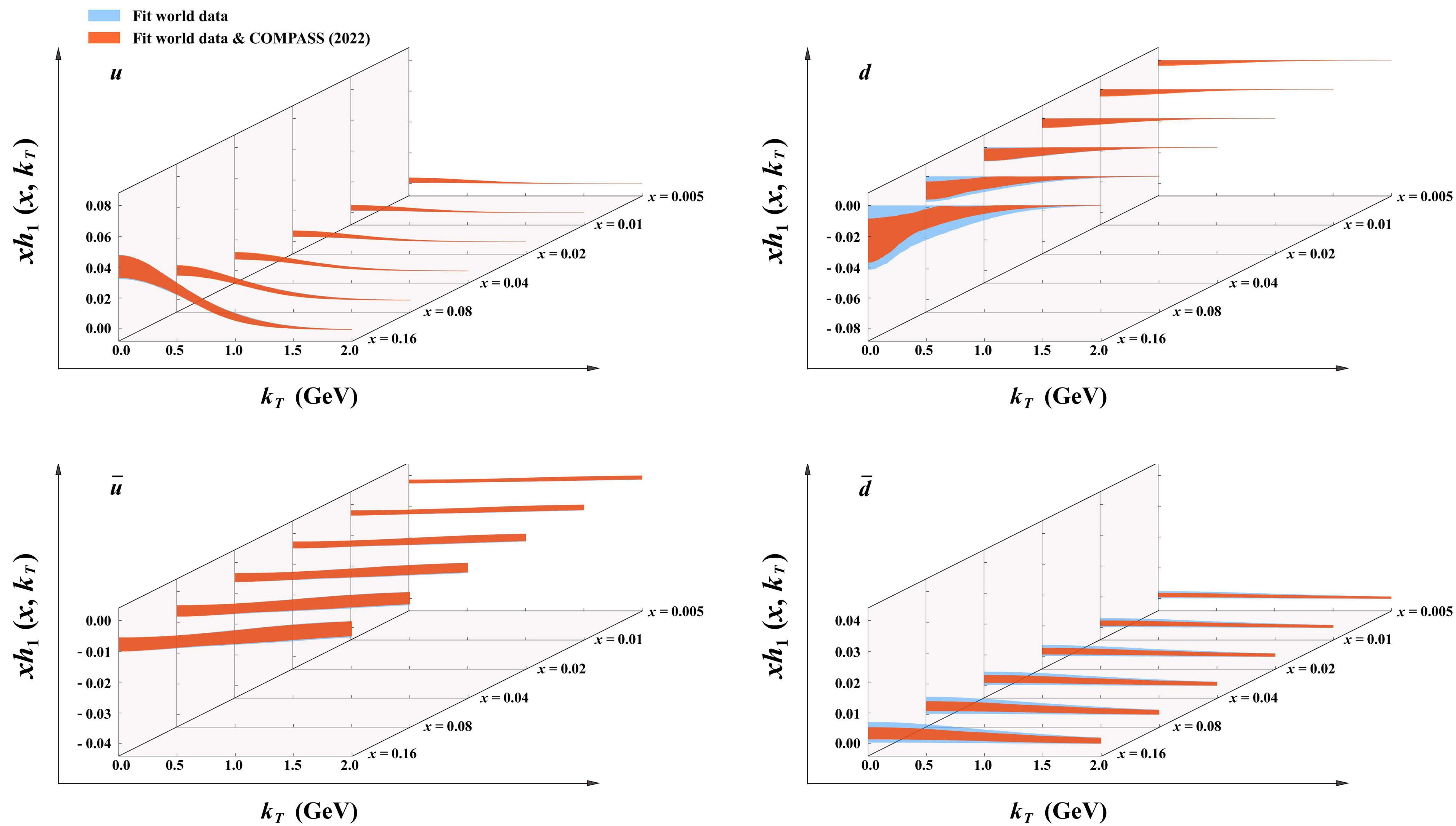
Transversity Distributions



Reconfirmed by new COMPASS data.
Significant improvement on d and $\bar{d}$ distributions.

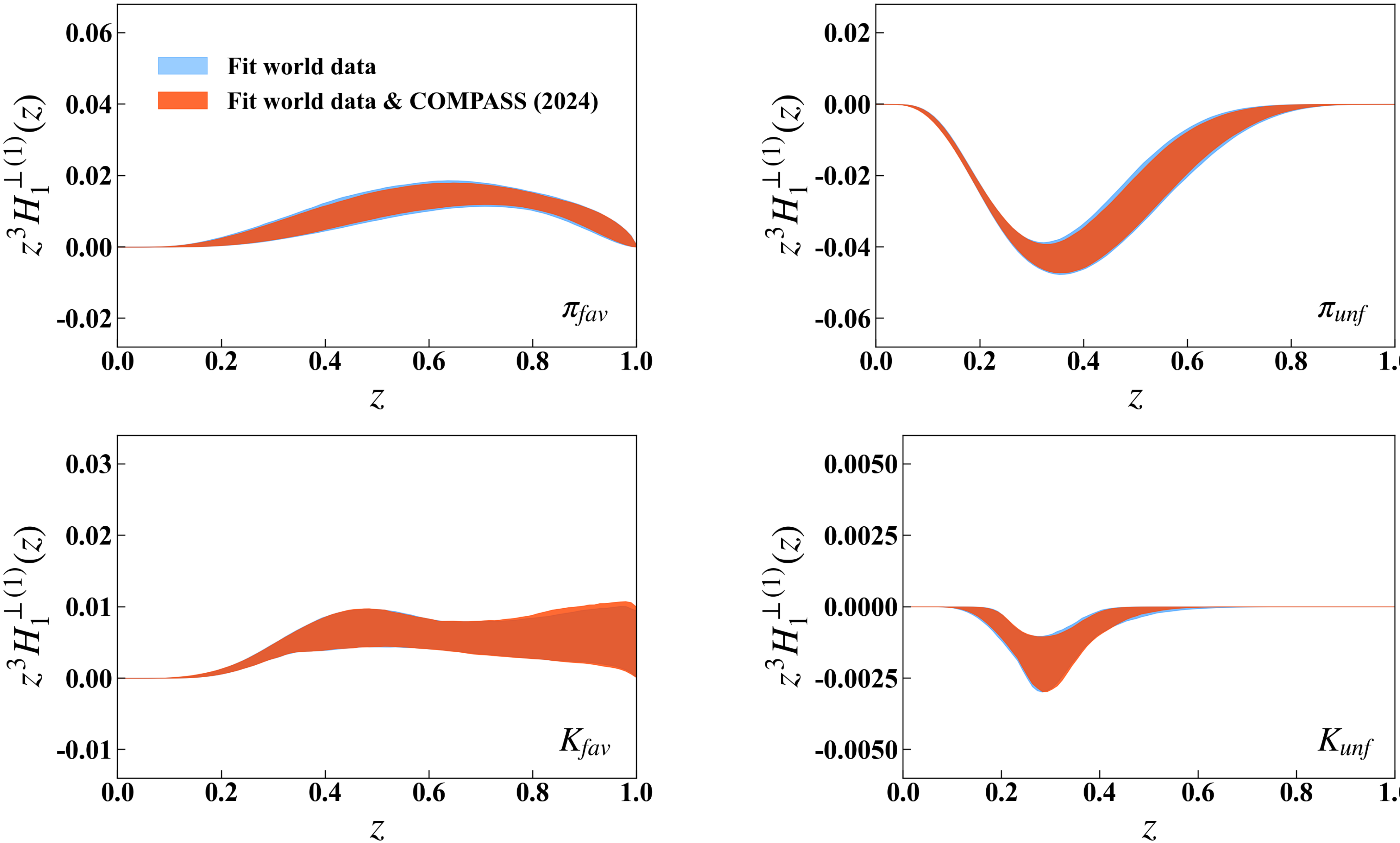
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2412.18324

Transversity Distributions



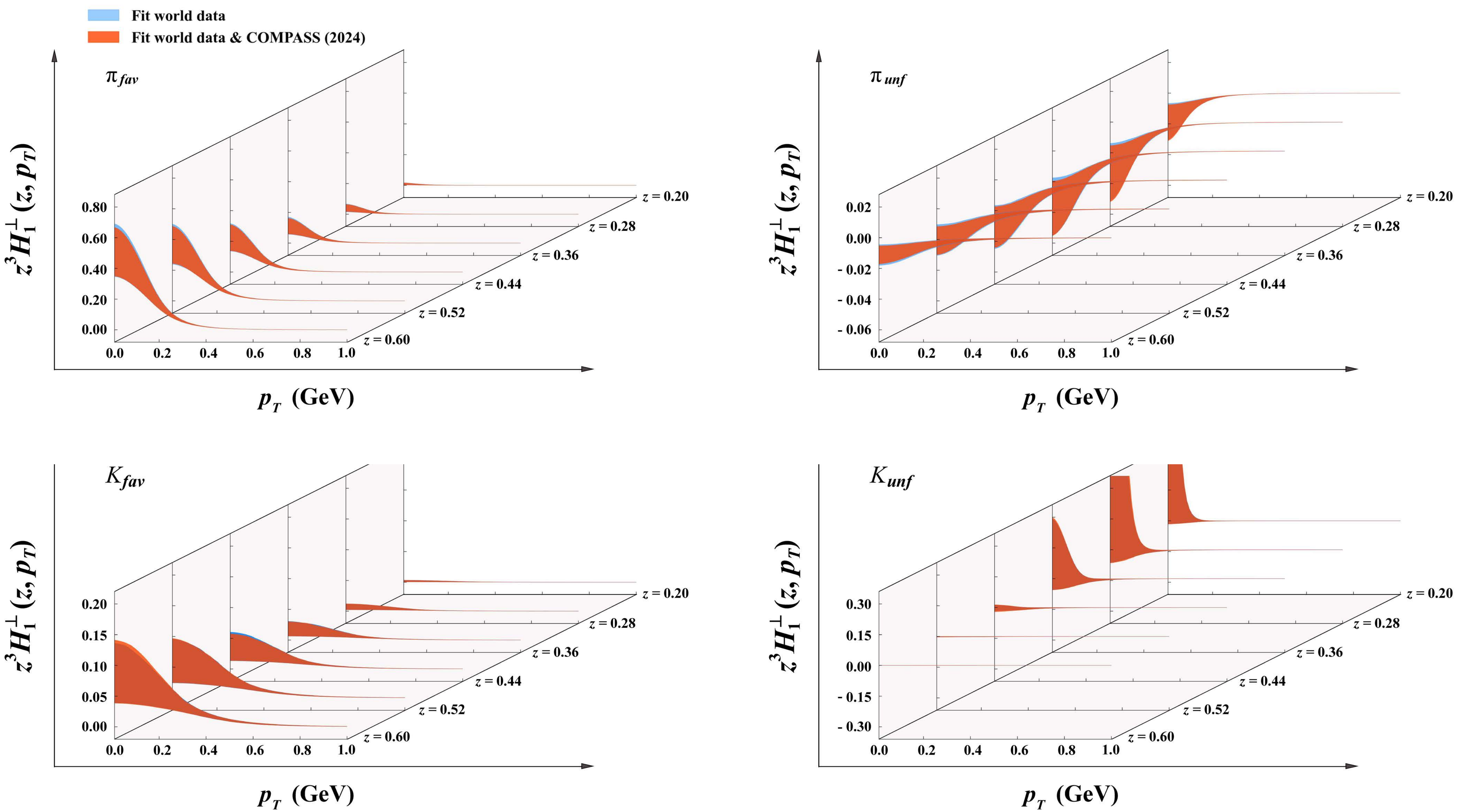
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2412.18324

Collins Fragmentation Functions



C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2412.18324

Collins Fragmentation Functions



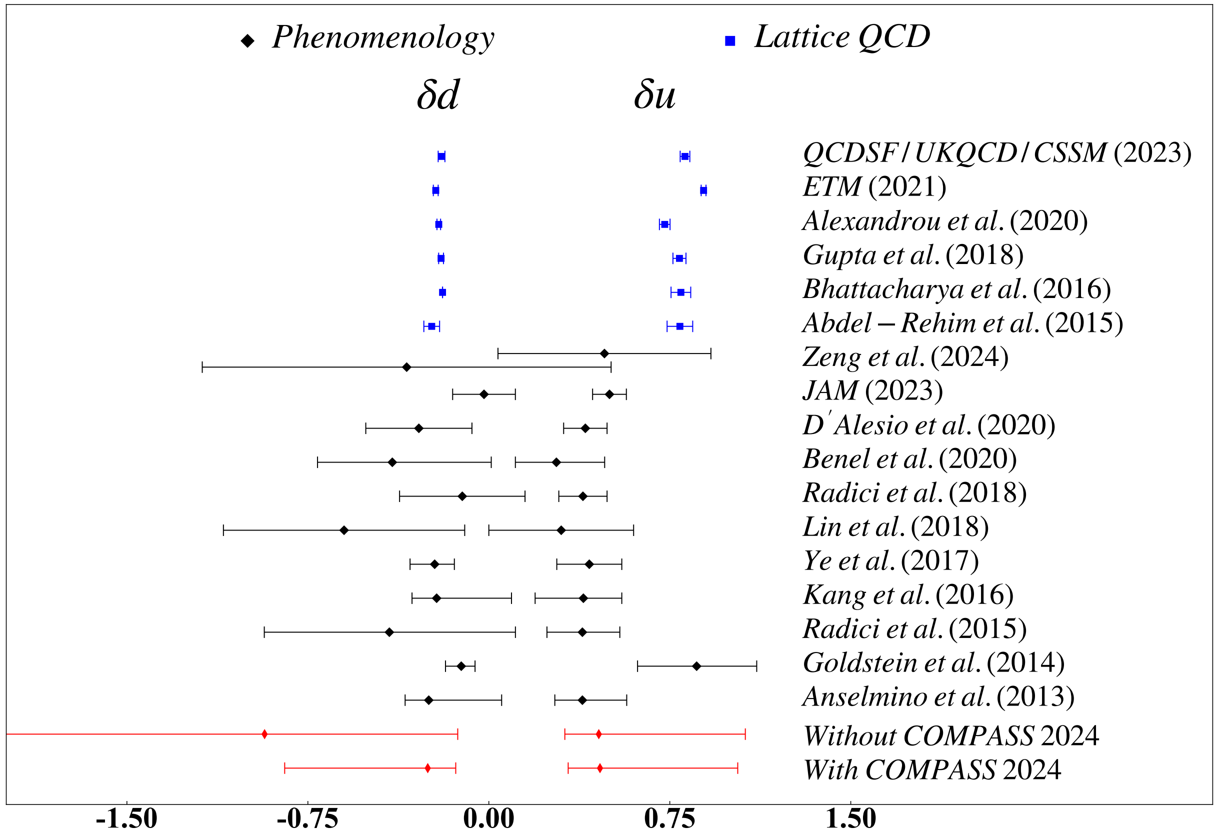
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2412.18324

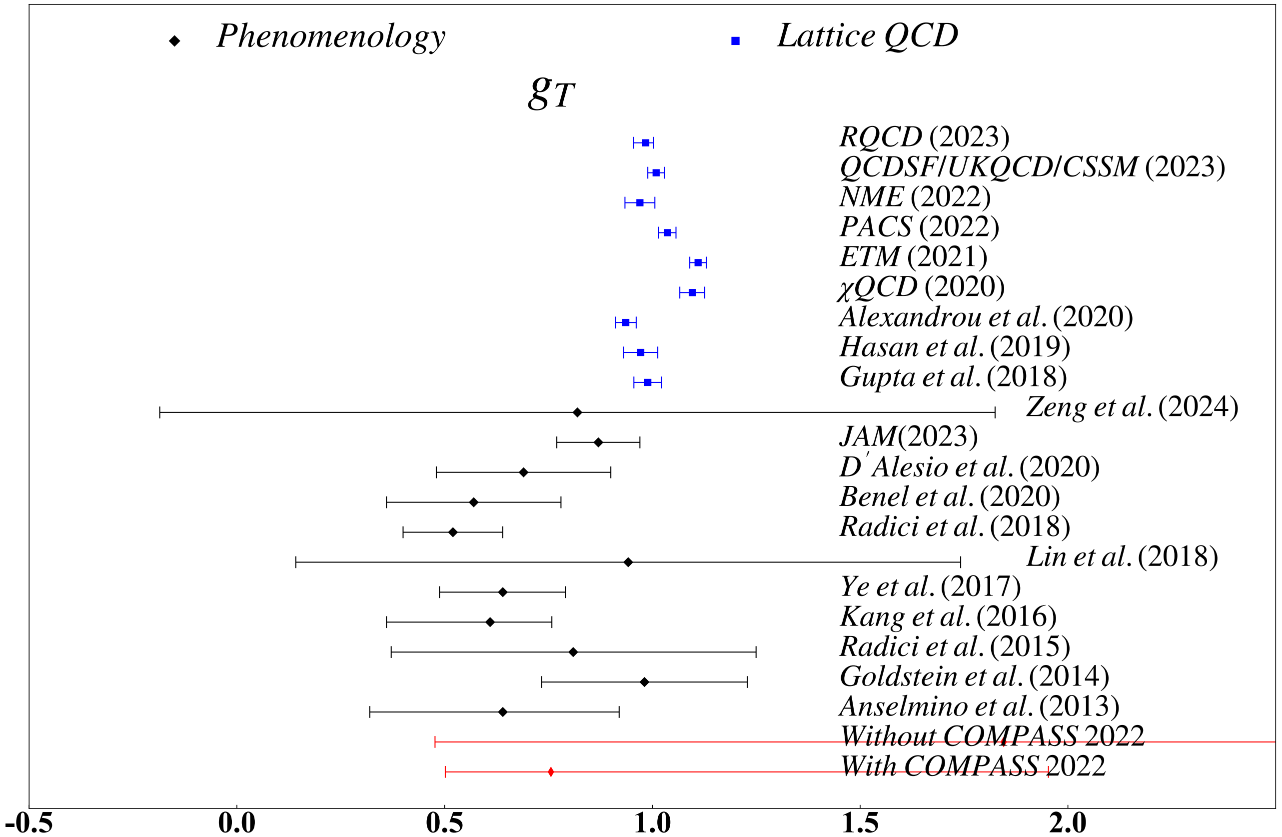
Tensor Charge

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.





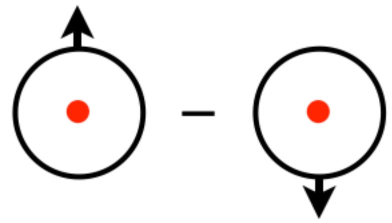
Larger uncertainties when including anti-quarks (less biased)
Compatible with lattice QCD calculations

C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2412.18324

The Sivers Function

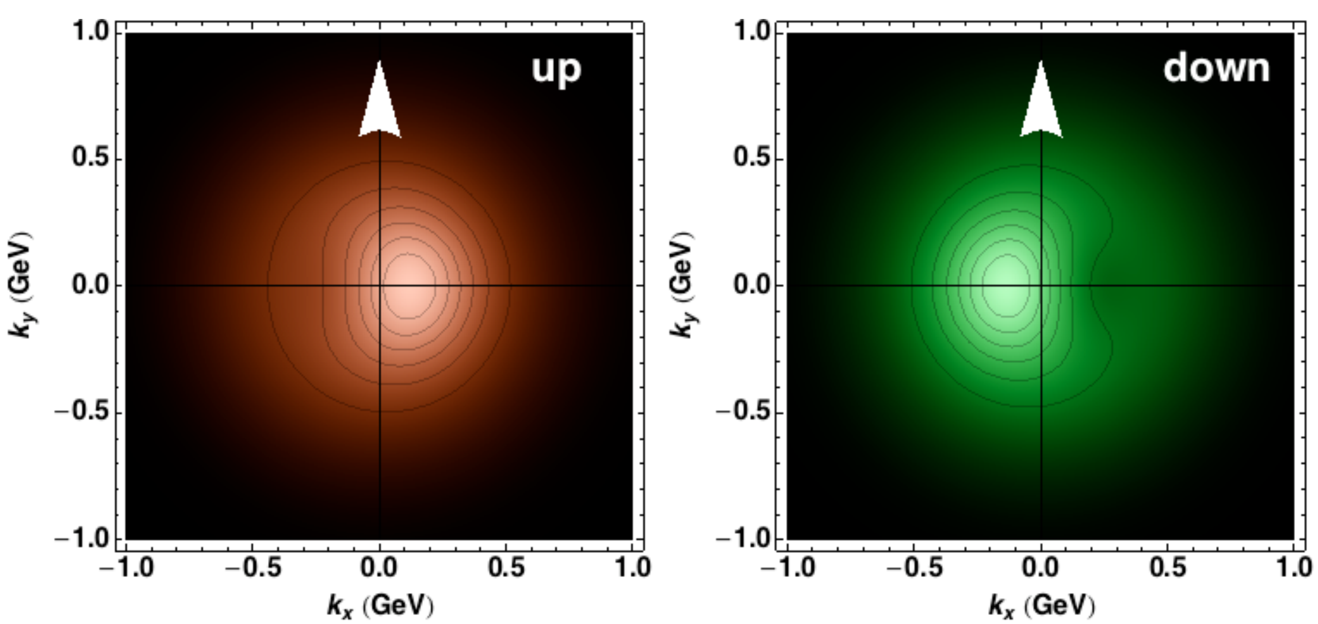
Sivers TMD distribution function

$$\frac{\epsilon_{ij} k_T^i S_T^j}{M} f_{1T}^{\perp}(x, k_T^2)$$



A naive T-odd distribution function

Transverse momentum distribution distorted by nucleon transverse spin



[Figure from A. Bacchetta]

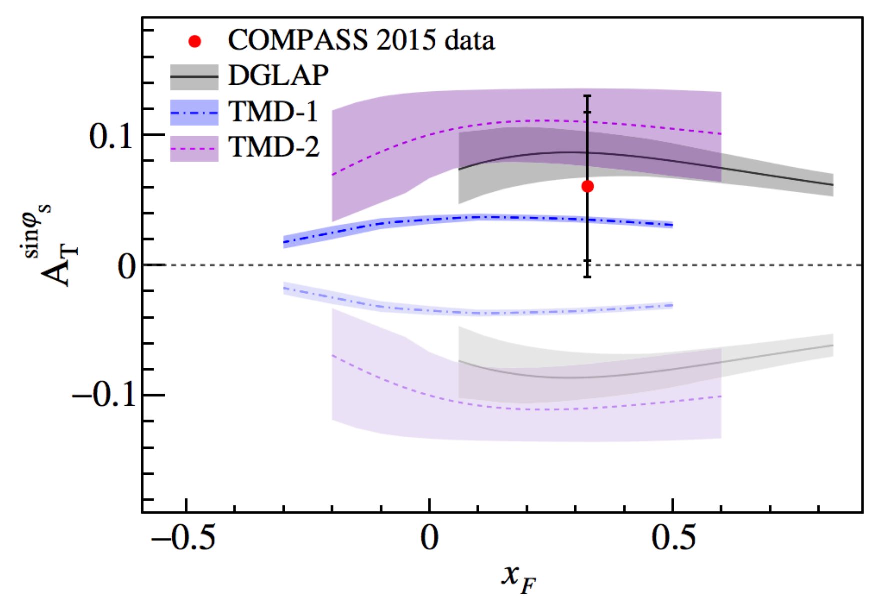
Effect in SIDIS:
transverse single spin asymmetry (Sivers asymmetry)

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

sizable Sivers asymmetry observed by HERMES, COMPASS, JLab

Sign change prediction:

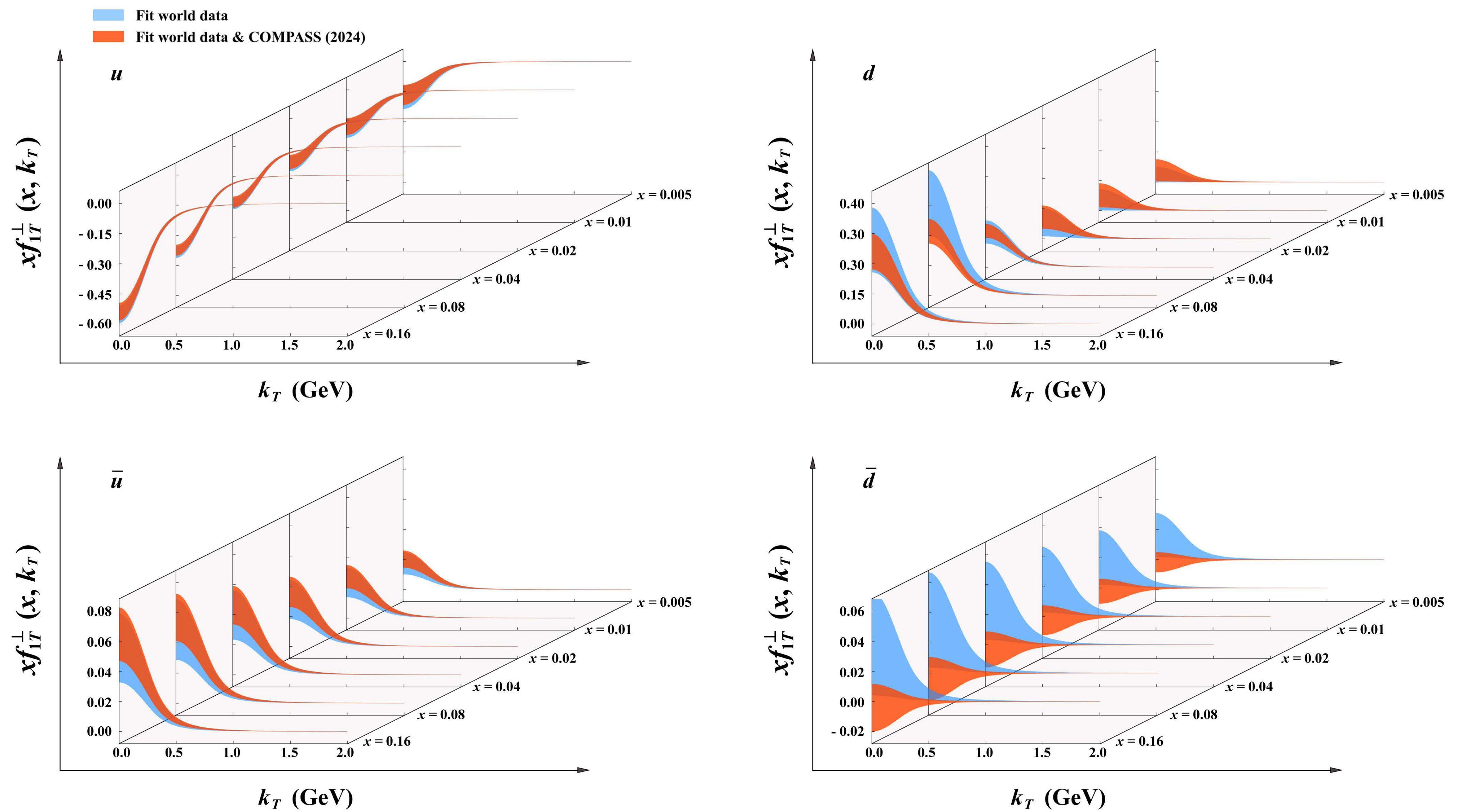
$$f_{1T}^{\perp}(x, k_T^2)\,|_{\text{SIDIS}} = -f_{1T}^{\perp}(x, k_T^2)\,|_{\text{DY}}$$



COMPASS Collaboration, PRL 119, 112002 (2017).

Sivers Functions

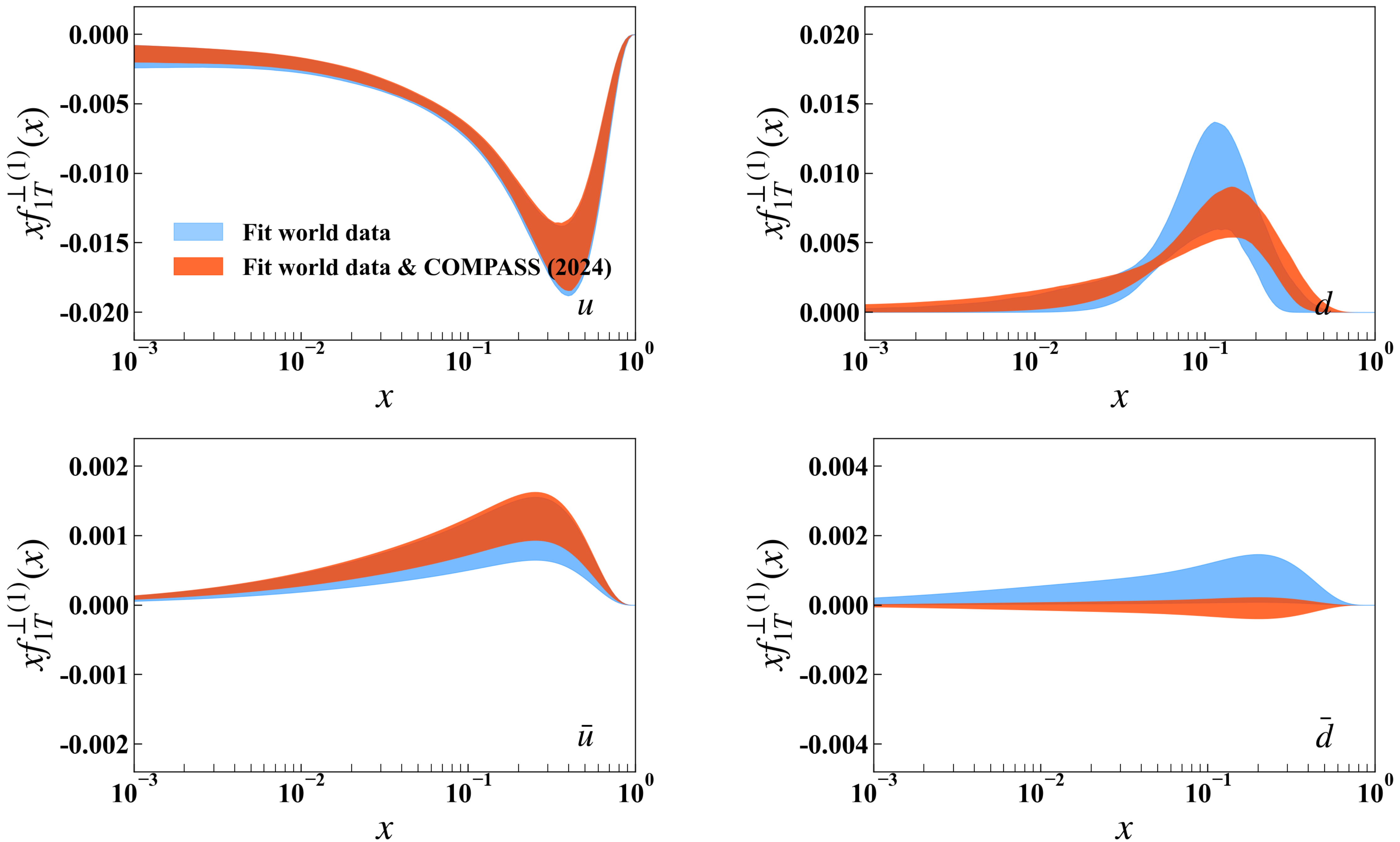
Global analysis of SIDIS, Drell-Yan, $W^{\pm}/Z^0$ production data



C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2412.18324

Sivers Functions

Global analysis of SIDIS, Drell-Yan, $W^{\pm}/Z^0$ production data

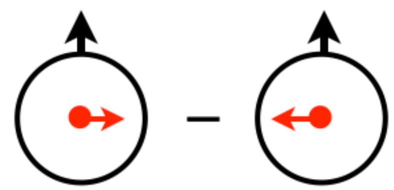


C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2412.18324

Double Spin Asymmetry and Worm-gear

Trans-helicity worm-gear distribution

$$\frac{k_T \cdot S_T}{M} g_{1T}^{\perp}(x, k_T^2)$$

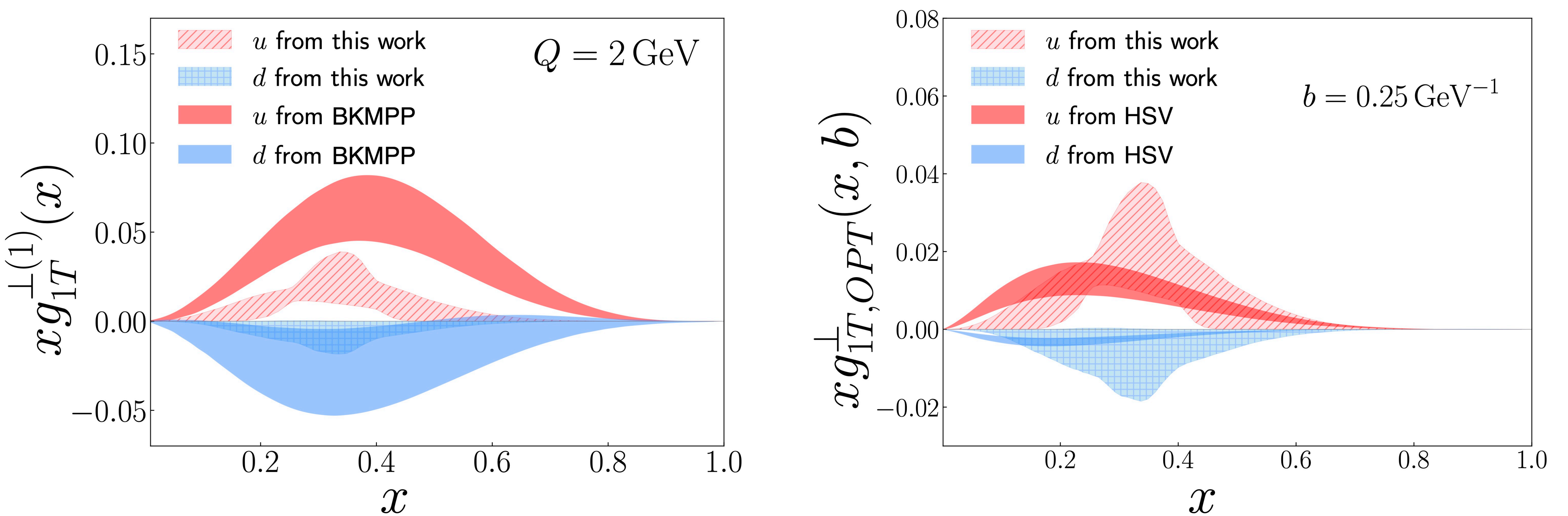


Effect in SIDIS:
A longitudinal-transverse double spin asymmetry

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

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

Phenomenological extraction



K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. D 110 (2024) 034036.

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
  - helicity: quark polarization has nontrivial dependence on transverse momentum;
  - transversity: sea quarks may have nonzero transverse polarization, suggest intrinsic sea;
  - Sivers: quark transverse momentum is distorted by the nucleon transverse spin;
  - …
- SIDIS with polarized beam and target is a main process to study polarized TMDs
- Electron-positron annihilation is an important complementary reaction to constrain TMDs and to understand the role of spin in hadronization process
- There are still challenges on the theoretical side
  - power correction, radiative correction, target fragmentation, …
- Opportunities from existing experiments at JLab12, BESIII, BelleII, and future facilities, EIC, EicC, STCF, to understand nucleon spin structures and fragmentation functions.

Thank you!