TMD Physics at Electron-ion Collider in China

The 12th Workshop on Hadron Physics and Opportunities Worldwide
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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

In collaboration with: Y. Deng, H. Dong, Z.-t. Liang, B.-Q. Ma, P. Sun, K. Yang, C. Zeng, X. Zhao, Y. Zhao, Y.-j. Zhou and the EicC working group

SHANDONG UNIVERSITY

SCNT
Southern Center for Nuclear-Science Theory

Lepton-Hadron Deep Inelastic Scattering

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

- 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:

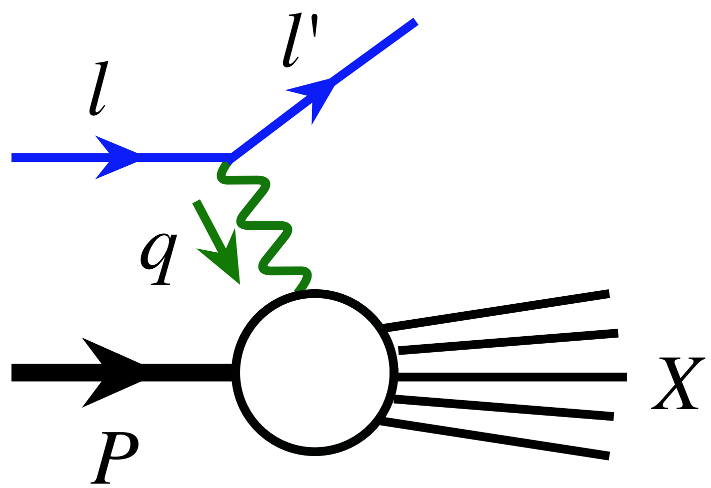
$$\sigma \propto H(Q) \otimes f_{i/P}(x, \mu^2)$$

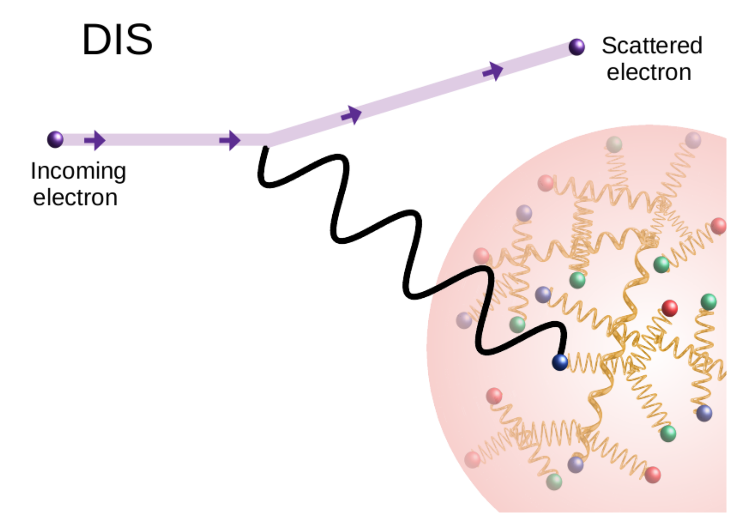
- overall corrections suppressed by $1/Q^n$
- indirectly “see” quarks, gluons and their dynamics
- predictive power relies on

— precision of the probe

— universality of $f_{i/P}(x, \mu^2)$

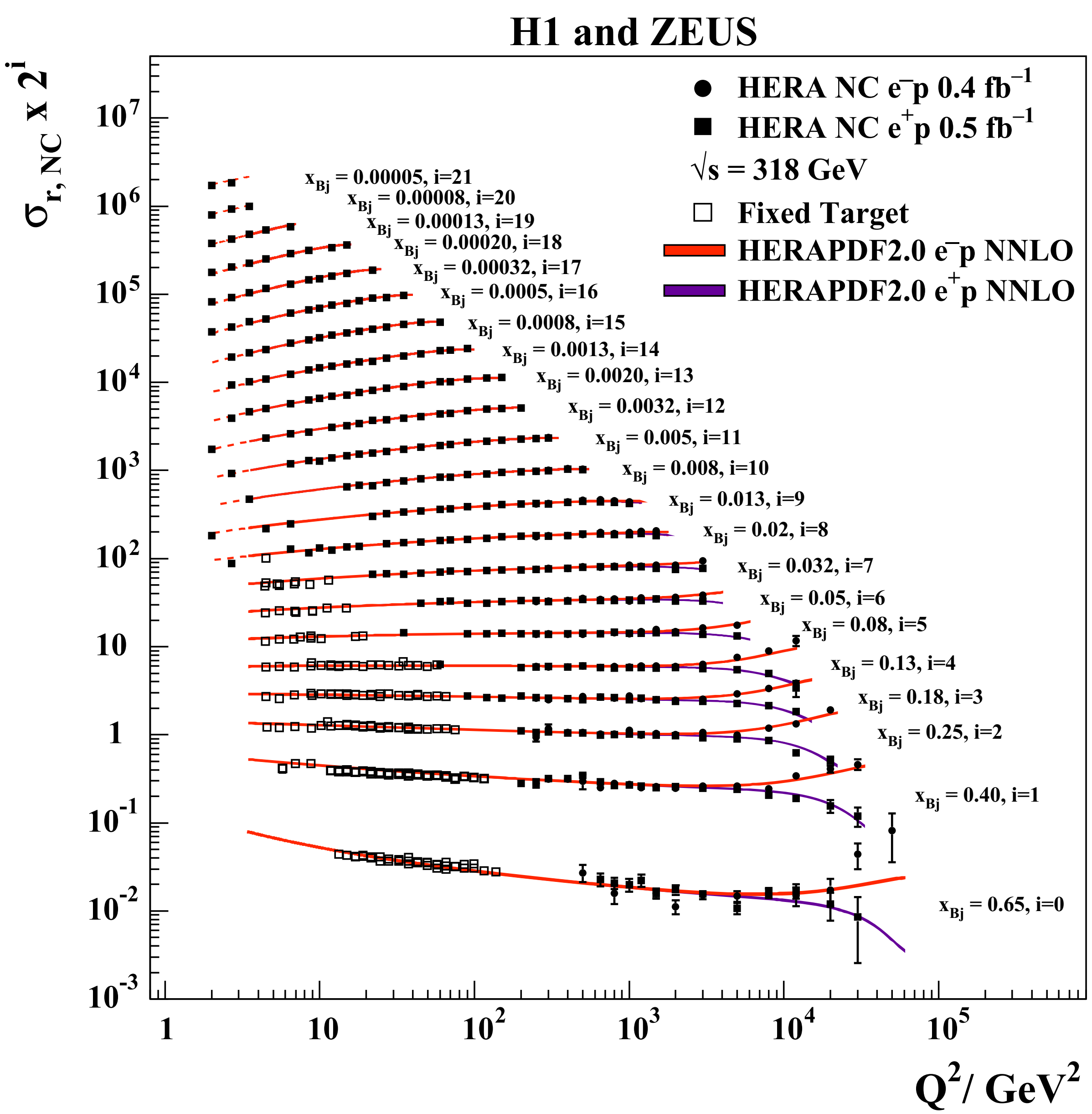
Modern “Rutherford” experiment.



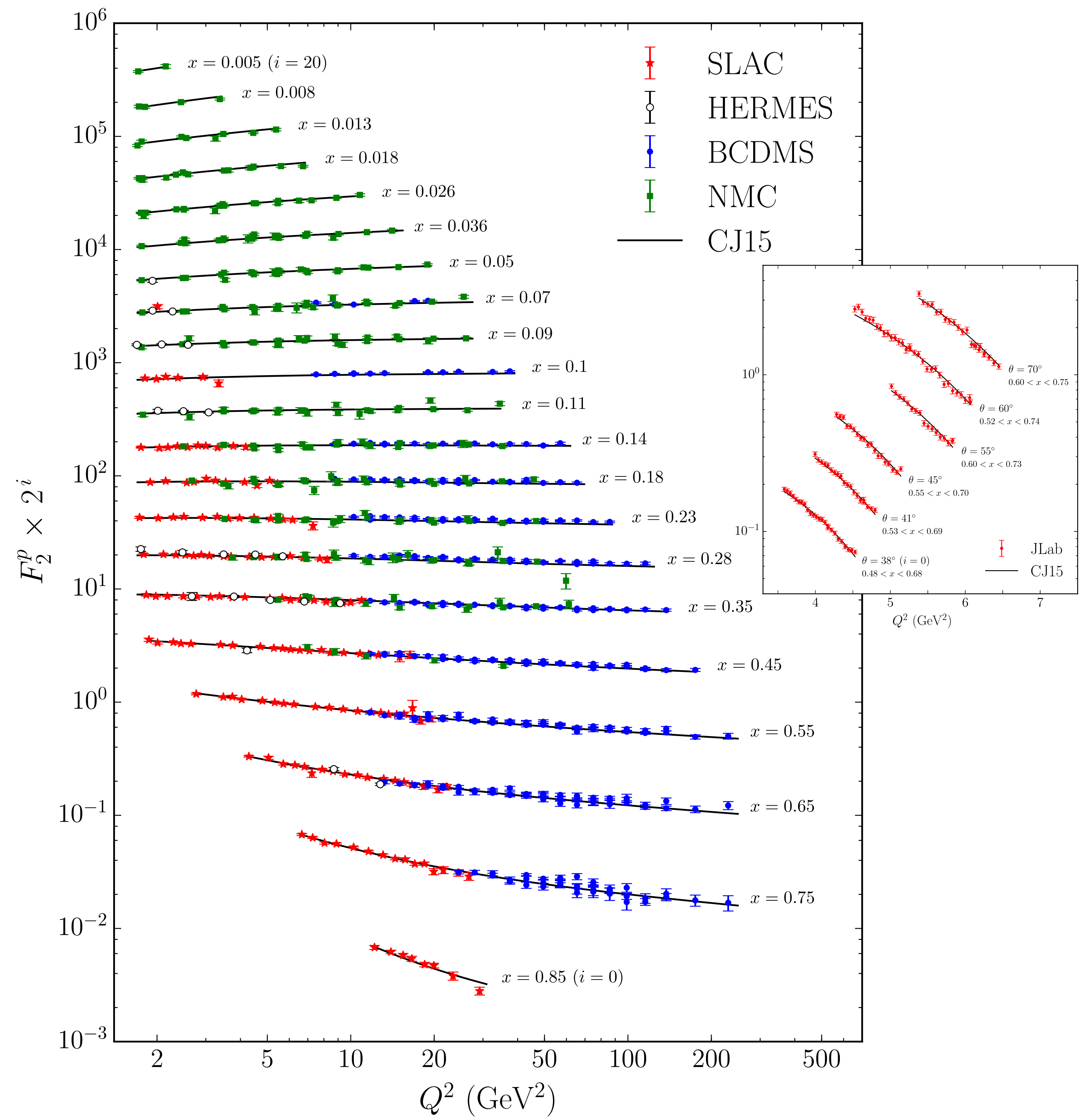


[Figure from DESY-21-099]

Lepton-Hadron Deep Inelastic Scattering

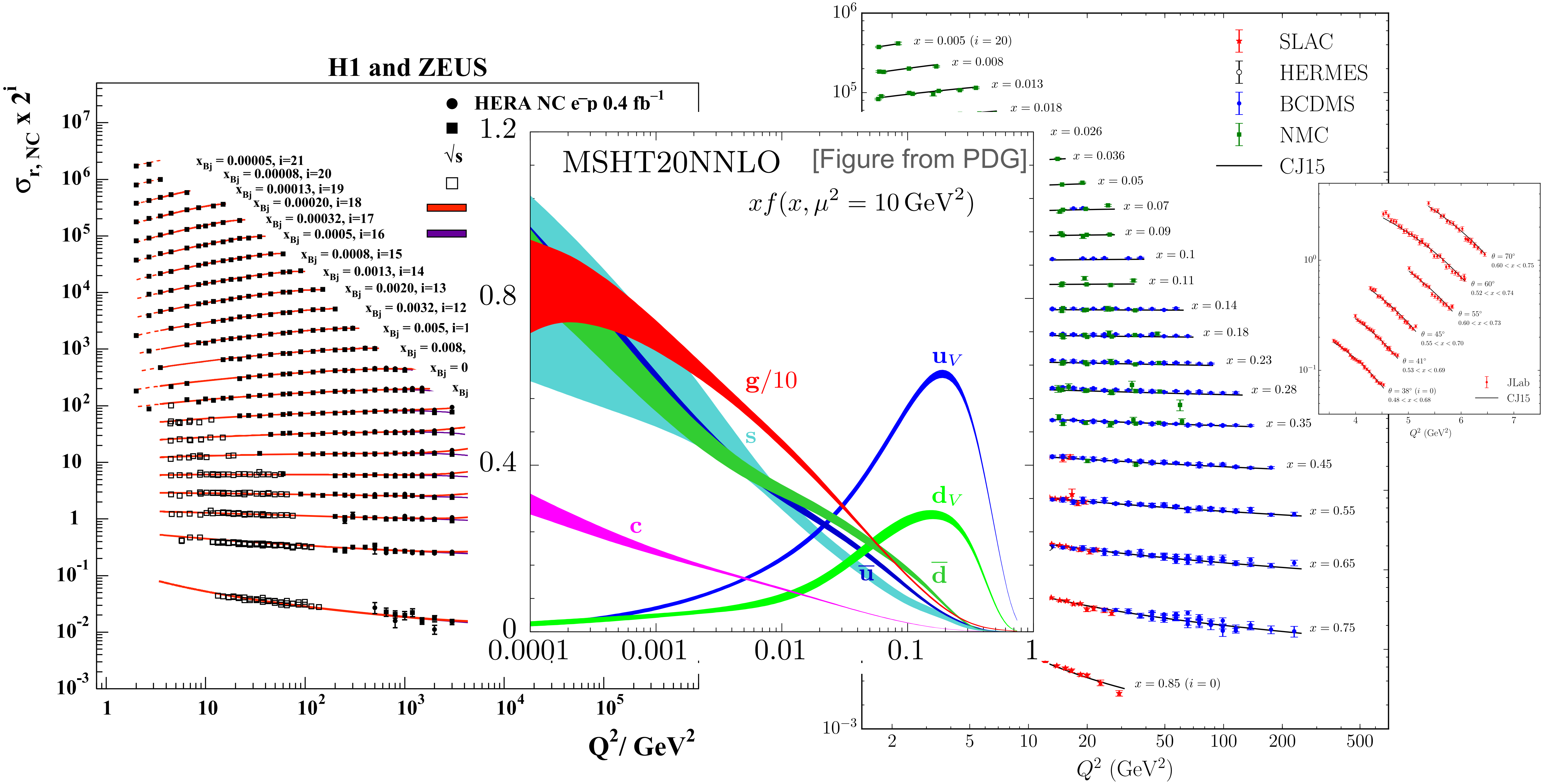


H. Abramowicz *et al.*, EPJC 78, 580 (2015).



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

Lepton-Hadron Deep Inelastic Scattering



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

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

A successful story of QCD, factorization and evolution!

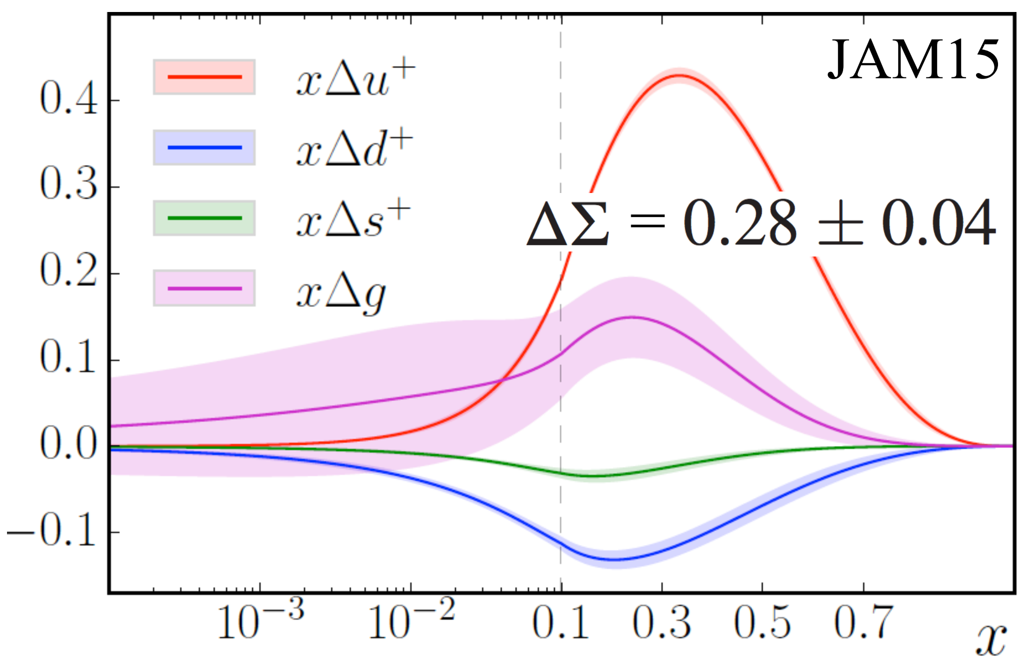
Nucleon Spin Structure

Proton spin puzzle

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

Spin decomposition

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



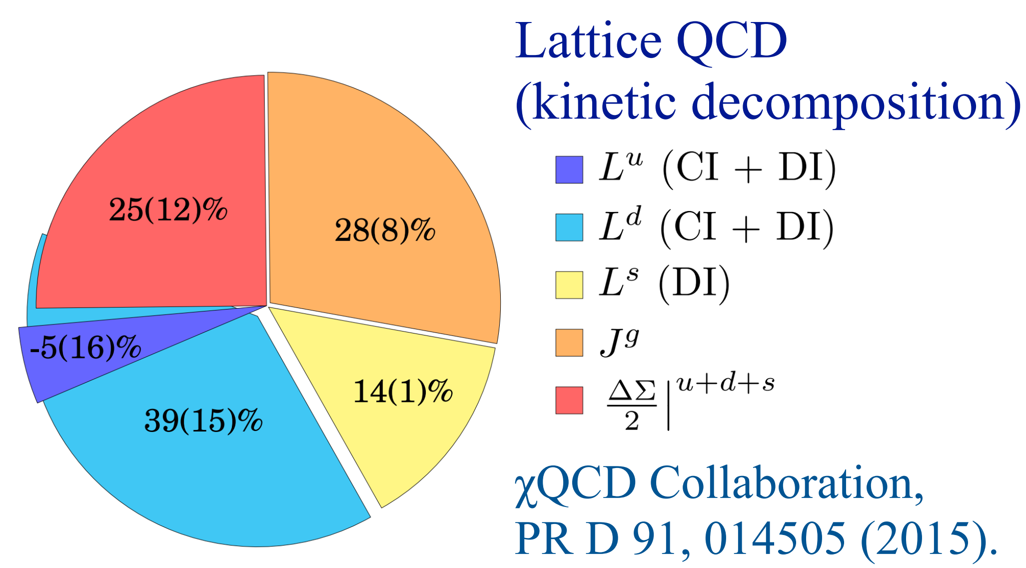
JAM Collaboration, PR D 93, 074005 (2016).

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).

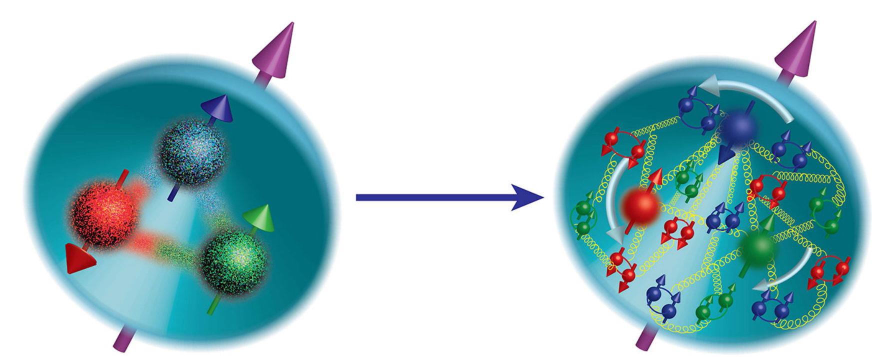


χQCD Collaboration, PR D 91, 014505 (2015).

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

50% of total proton spin

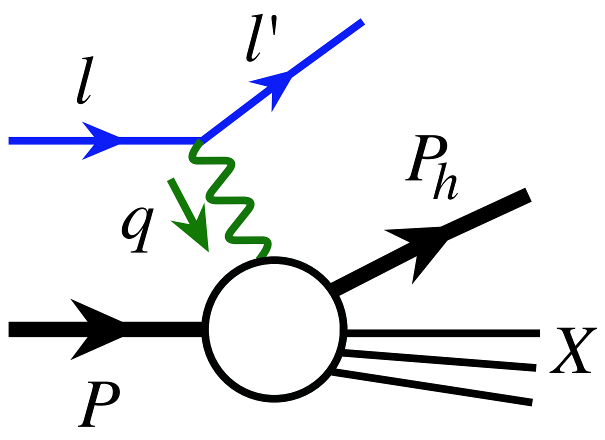
Y.-B. Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017).

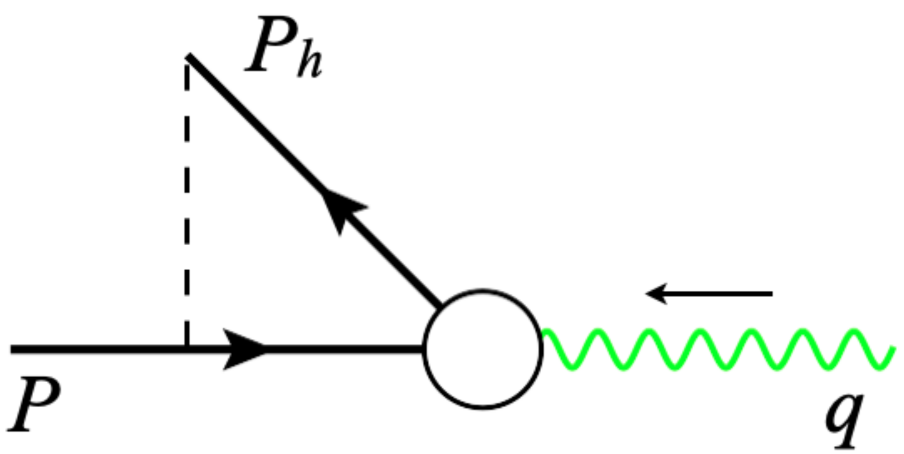


Semi-inclusive Deep Inelastic Scattering

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

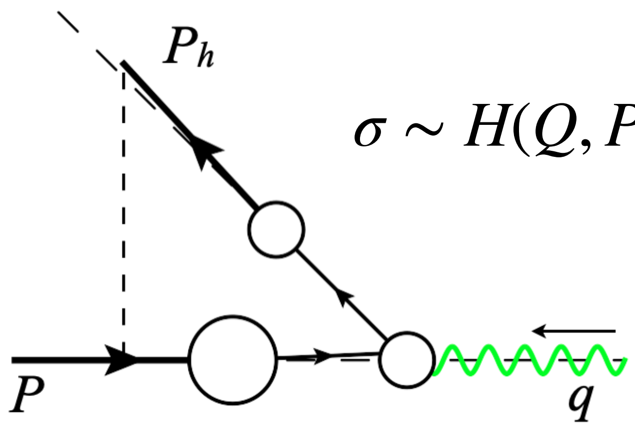
- enable us to explore the emergence of color neutral hadrons from colored quarks/gluons
- flavor dependence by selecting different types of observed hadrons: pions, kaons, …
- a large momentum transfer Q provides a short-distance probe
- an additional and adjustable momentum scale P_{h_T}
- multidimensional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





SIDIS Kinematic Regions

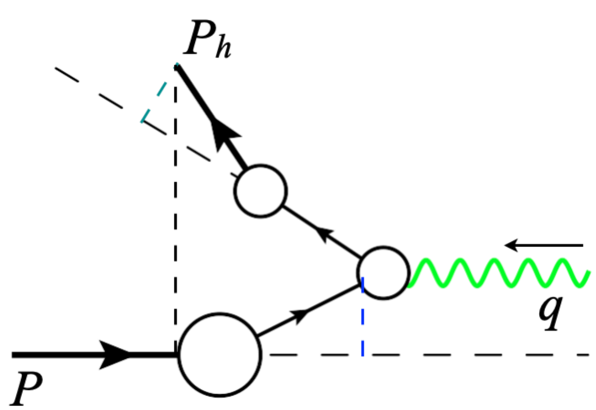
Sketch of kinematic regions of the produced hadron



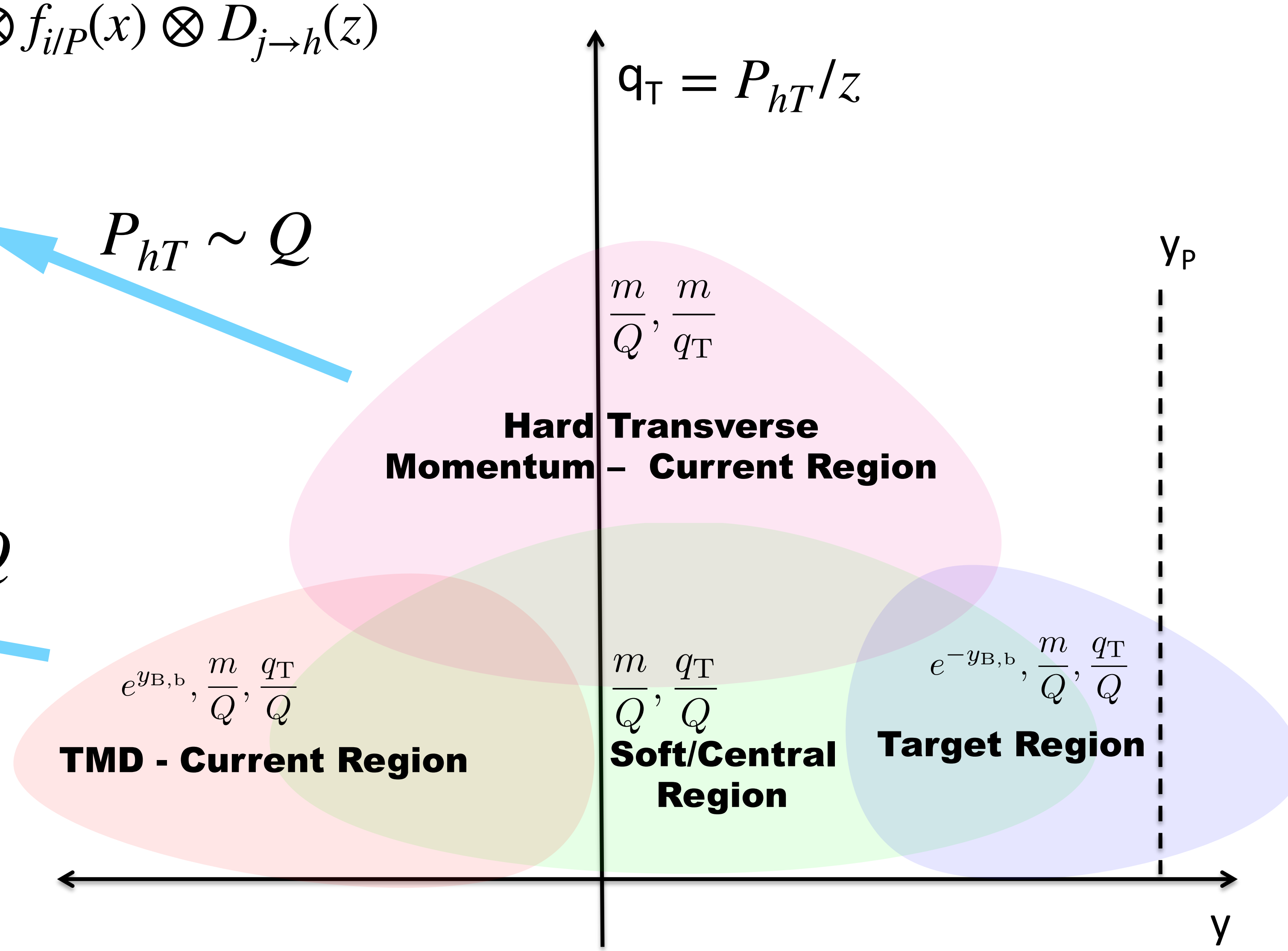
$$\sigma \sim H(Q, P_{hT}) \otimes f_{i/P}(x) \otimes D_{j\to h}(z)$$

$P_{hT} \sim Q$

$P_{hT} \ll Q$



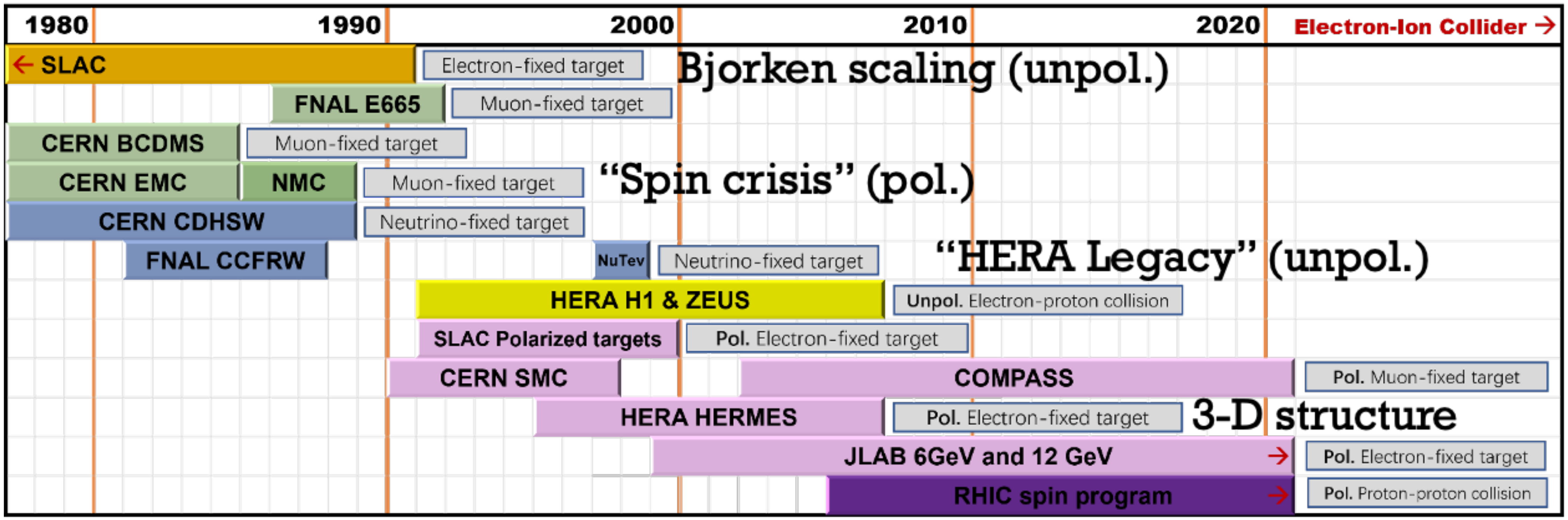
$$\sigma \sim H(Q) \otimes f_{i/P}(x, k_T) \otimes D_{j\to h}(z, p_T)$$



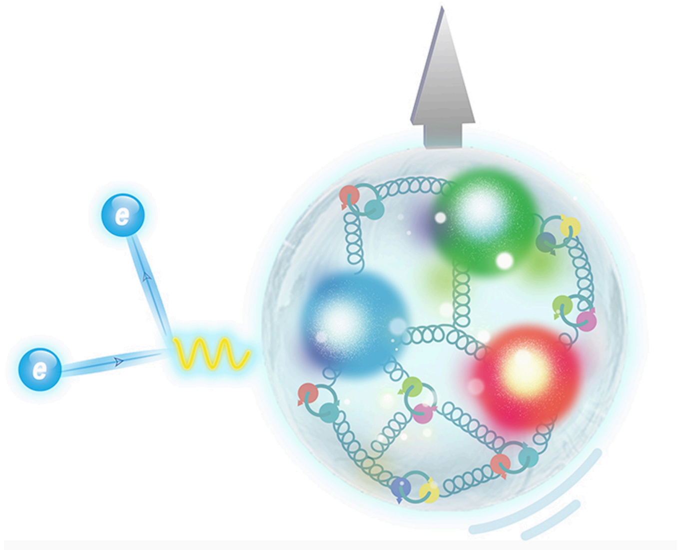
P_{hT} is defined in the photon-hadron frame

[Figure from JHEP10(2019)122]

Lepton Scattering: An Ideal Tool



[Figure from X.Y. Zhao]



[Figure credit: Weizhi Xiong]

Modern "Rutherford Scattering" Experiment

- Start from unpolarized fixed targets
- Extended unpolarized collider experiments
- and polarized fixed-target experiments

Need polarized electron-ion collider

- High luminosity: $10^2 \sim 10^3 \times$ HERA lumi.
- High polarization: both electron and ion beams
- Large acceptance: nearly full detector coverage

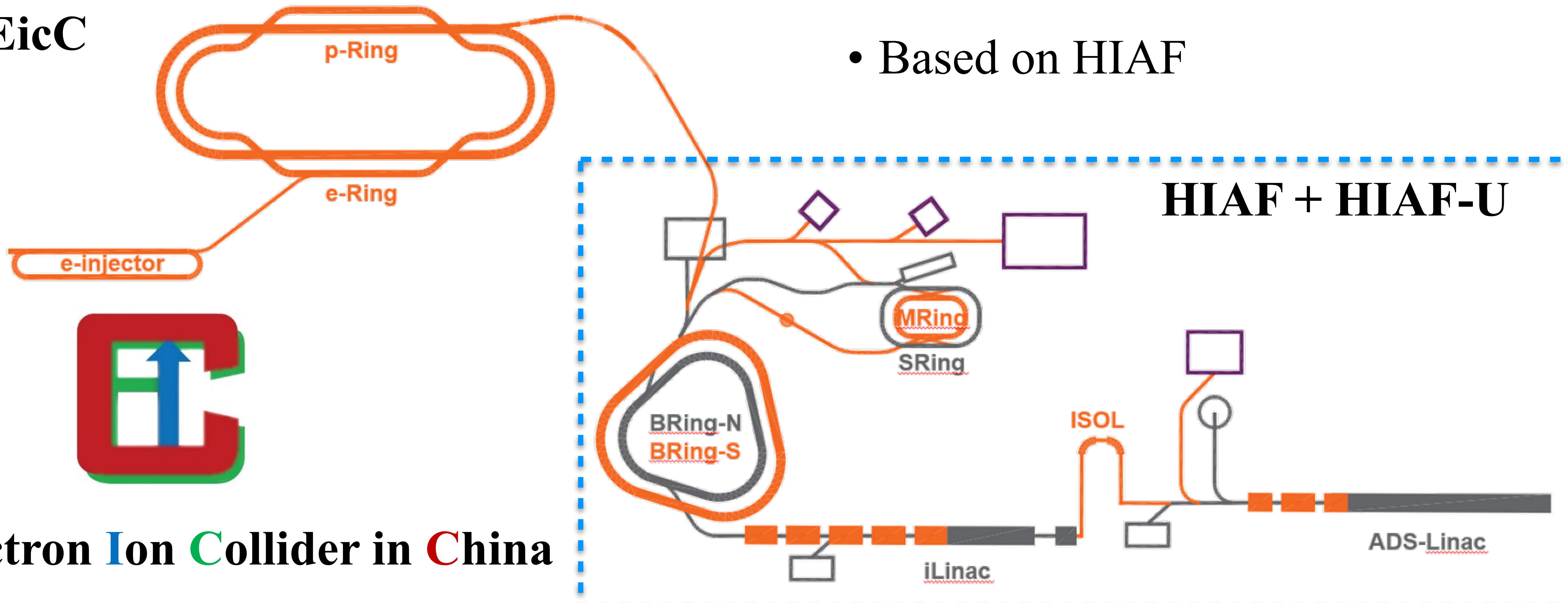
HIAF in Huizhou (惠州)

High Intensity heavy-ion Accelerator Facility

- a national facility on nuclear physics, atomic physics, heavy-ion applications …
- open to scientists all over the world
- provide intense beams of primary and radioactive ions
- beam commissioning is planned in 2025

Electron-ion Collider in China

EicC



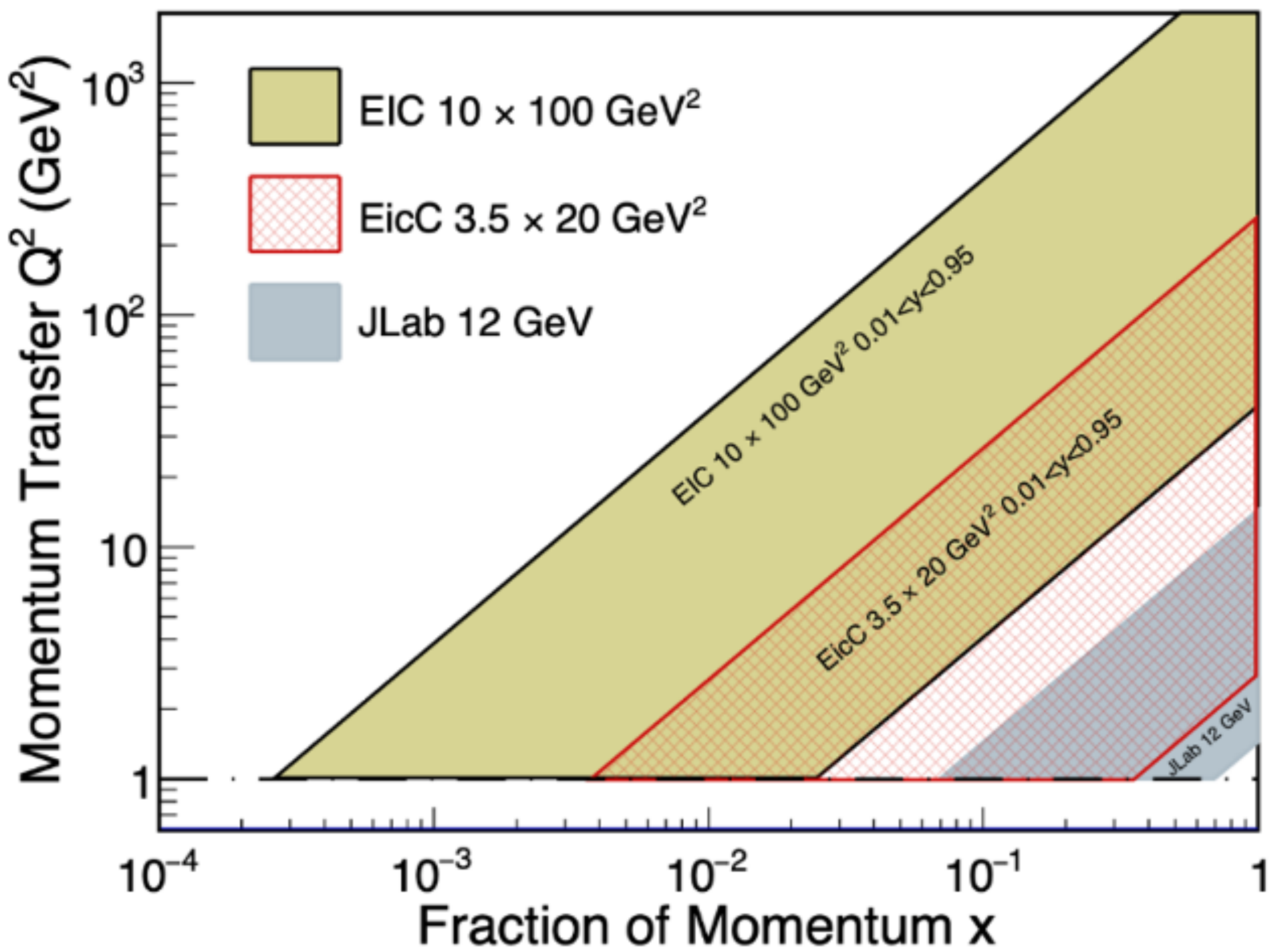
- Based on HIAF

Electron Ion Collider in China

[Figure by EicC Accelerator WG]

- energy in c.m.: 15 ~ 20 GeV
- luminosity: $\gtrsim 2 \times 10^{33}$ cm$^{-2} \cdot$ s^{-1}
- electron beam: 3.5 GeV, polarization ~ 80%
- proton beam: 20 GeV, polarization ~ 70%
- other available polarized ion beams: d, $^3He^{++}$
- available unpolarized ion beams: $^7Li^{3+}$, $^{12}C^{6+}$, $^{40}Ca^{20+}$, $^{197}Au^{79+}$, $^{208}Pb^{82+}$, $^{238}U^{92+}$

Complementary Kinematic Coverage

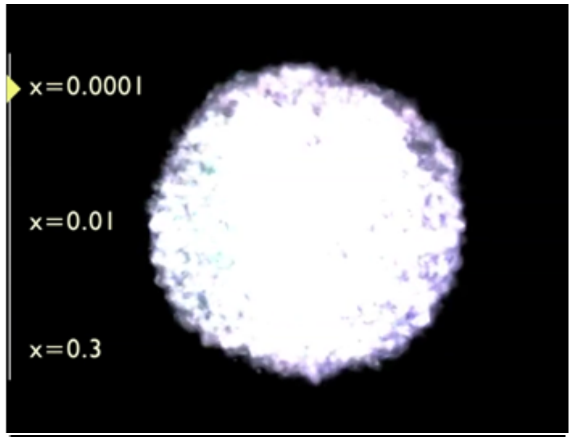


[Figure from EicC White paper]

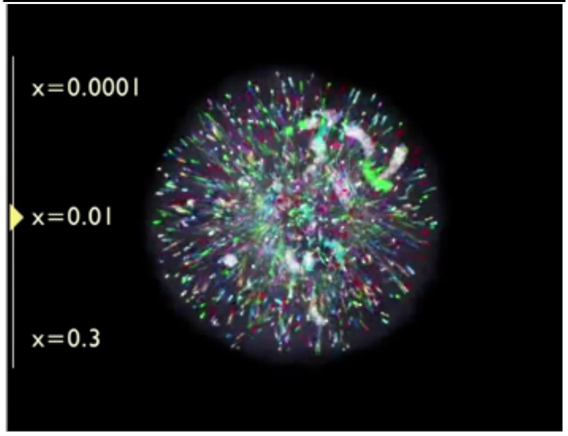
EicC is optimized to systematically explore the gluon and sea quarks in moderate *x* regime

At a crucial place between JLab and EIC-US

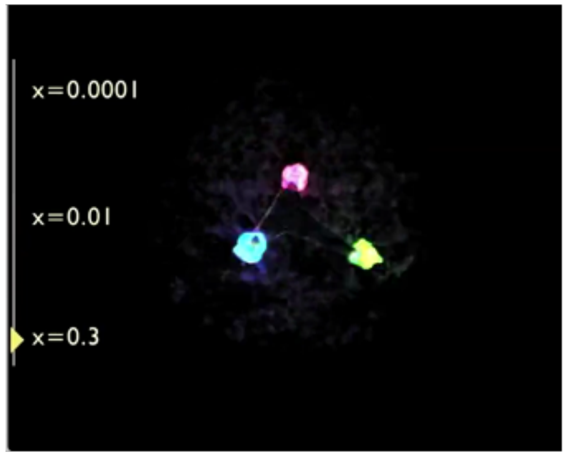
gluon dominates



sea quarks + gluons



valence dominates

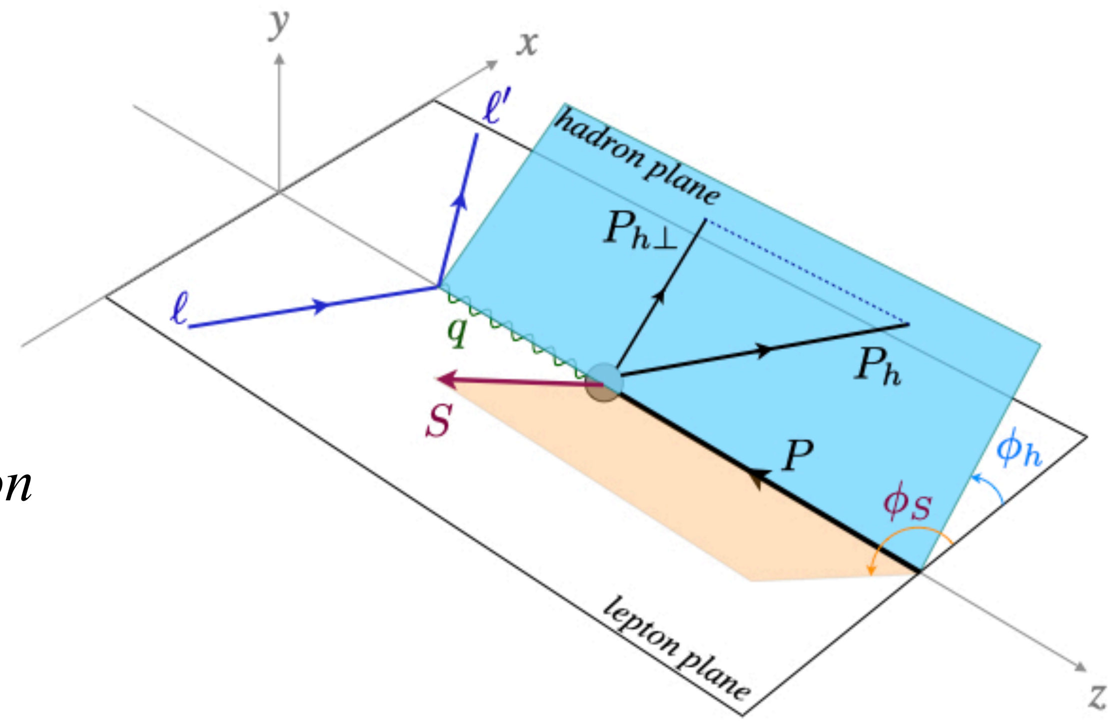


R.G. Milner and R. Ent, *Visualizing the proton* 2022

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

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

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

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

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

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

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

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

Leading Twist TMDs

		Quark Polarization		
		U	L	T
Nucleon Polarization	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

EicC Impact Studies

Baseline:

An independent global analysis of world SIDIS and e^+e^- data within the TMD factorization and evolution

Uncertainty estimation using MC replicas

EicC pseudo data:

50 fb^{-1}: 3.5 GeV e × 20 GeV p

50 fb^{-1}: 3.5 GeV e × 40 GeV ^{3}He

p and ^{3}He pol.: 70%

electron pol: 80%

Observables (examples):

Transverse single spin asymmetry $A_{UT}^{\sin(\phi_h-\phi_S)} \Rightarrow f_{1T}^{\perp}$

Transverse single spin asymmetry $A_{UT}^{\sin(\phi_h+\phi_S)} \Rightarrow h_1$

Longitudinal-transverse double spin asymmetry $A_{LT}^{\cos(\phi_h-\phi_S)} \Rightarrow g_{1T}^{\perp}$

TMD Evolution

Evolution equations

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

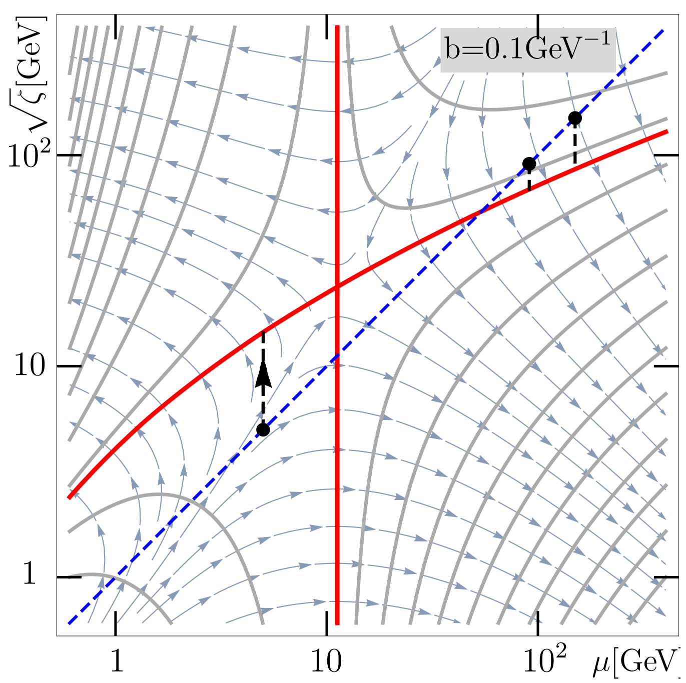
$$\zeta \frac{dF(x,b;\mu^2,\zeta)}{d\zeta} = -\mathscr{D}(\mu,b) F(x,b;\mu^2,\zeta)$$

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

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

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

ζ-prescription



equipotential lines:

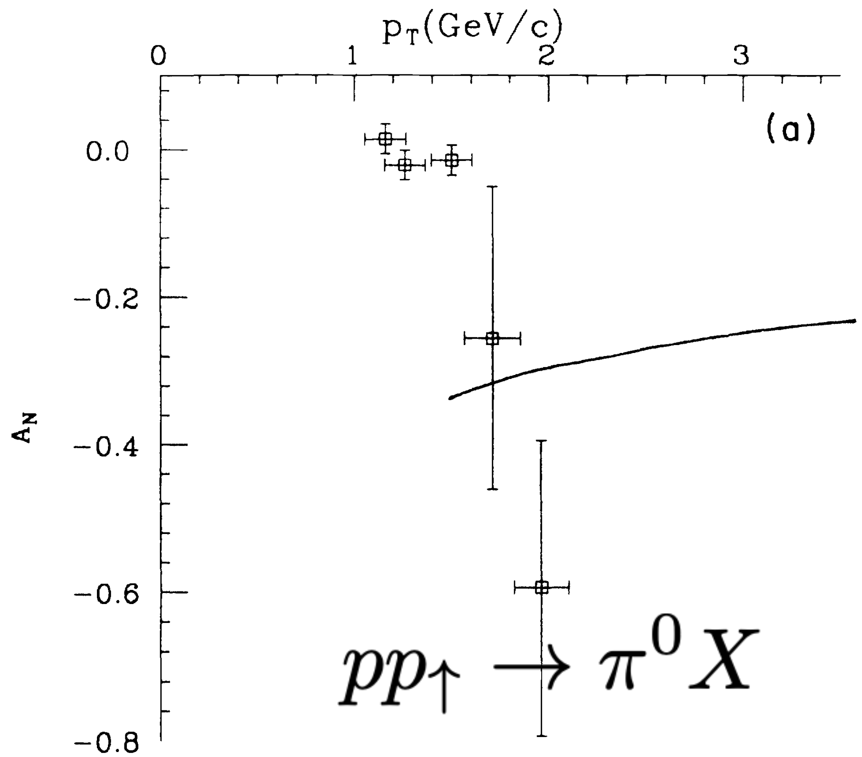
$$\frac{d \ln \zeta_\mu(\mu,b)}{d \ln \mu^2} = \frac{\gamma_F\left(\mu,\zeta_\mu(\mu,b)\right)}{2\mathscr{D}(\mu,b)}$$

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

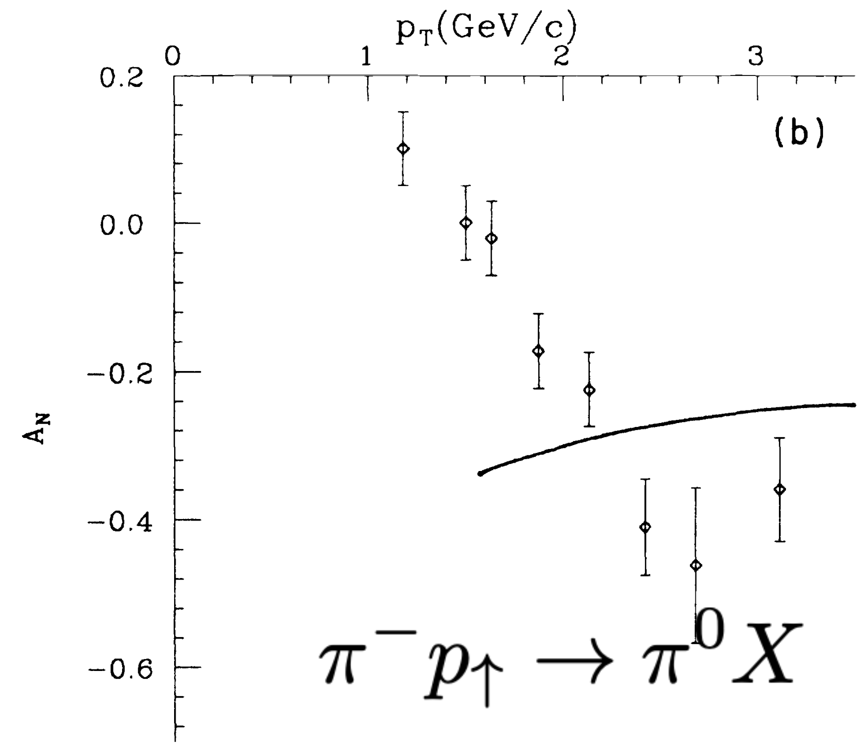
$$F\left(x,b;Q,Q^2\right) = \left(\frac{Q^2}{\zeta_Q(b)}\right)^{-\mathscr{D}(Q,b)} F(x,b), \quad \mu_f^2 = \zeta_f = Q^2$$

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.

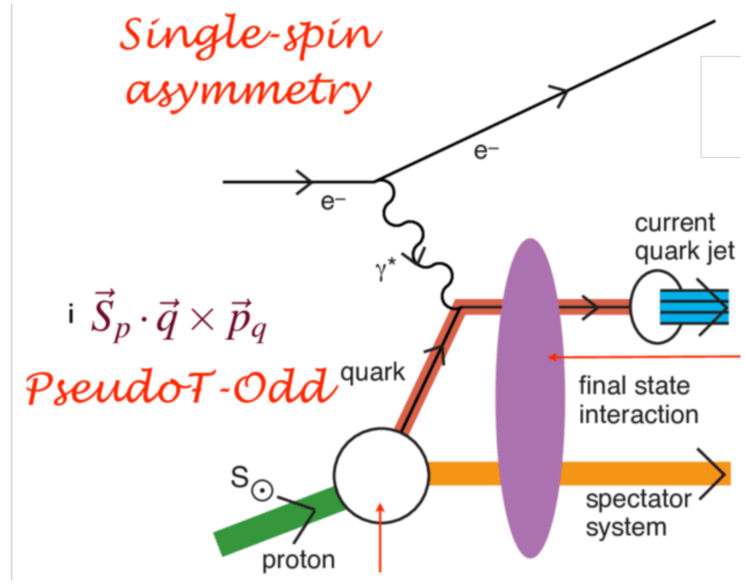
For the next decade, the "Sivers effect" was thought to vanish.

The Sivers Function: Early Story

Until an explicit model calculation showing …

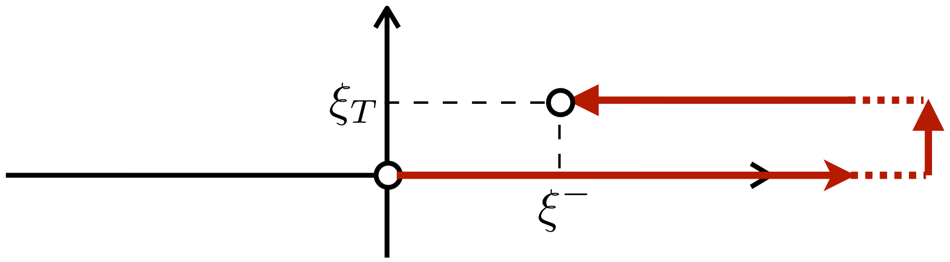
nonzero Sivers effects exist at leading twist
due to final-state interactions

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.

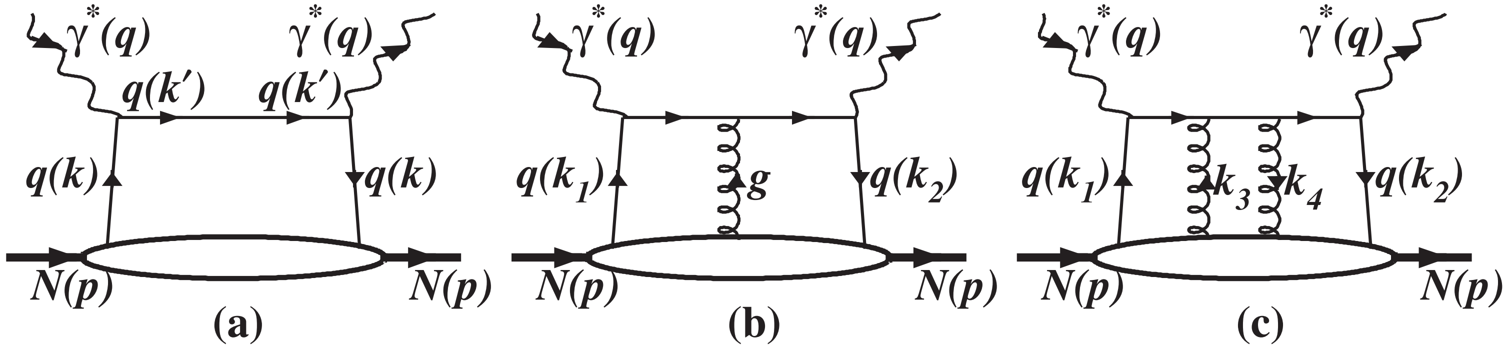
[Figure from A. Bacchetta]

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

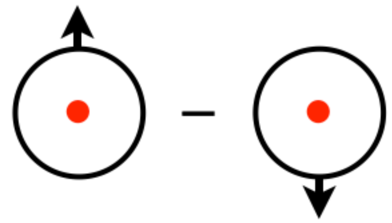
Z.-t. Liang and X.N. Wang,
Phys. Rev. D 75 (2007) 094002.



The Sivers Function

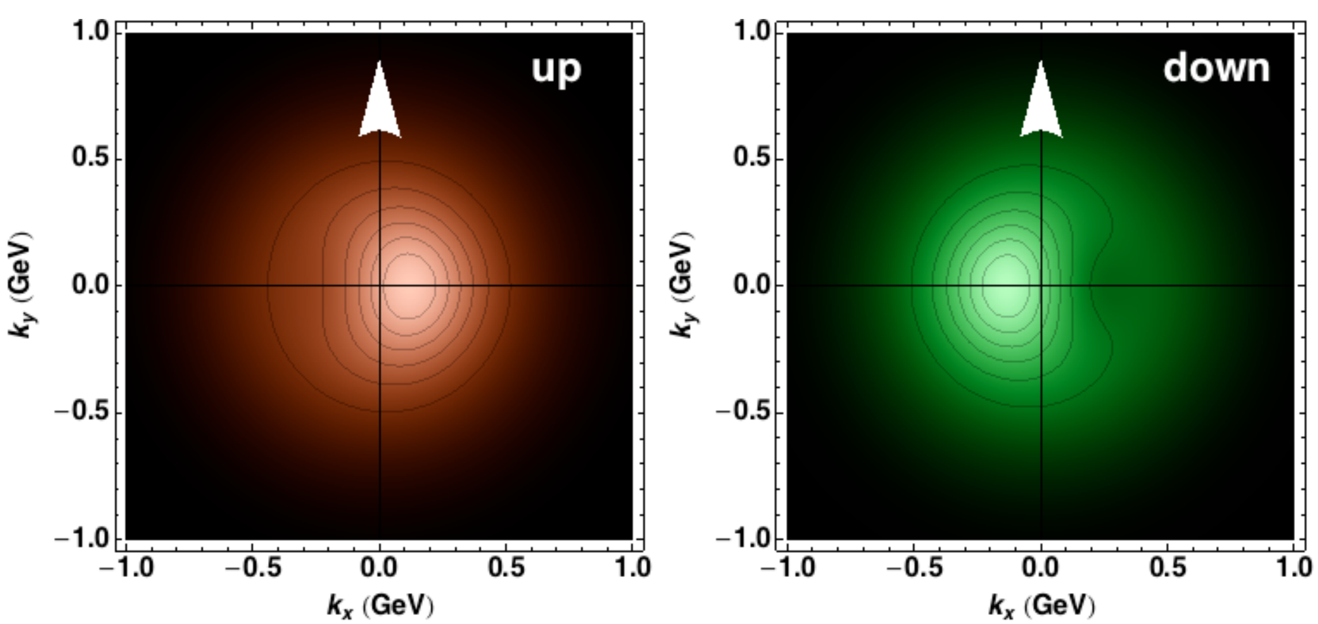
Sivers TMD distribution function

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



A naive T-odd distribution function

Transverse momentum distribution distorted by nucleon transverse spin



[Figure from A. Bacchetta]

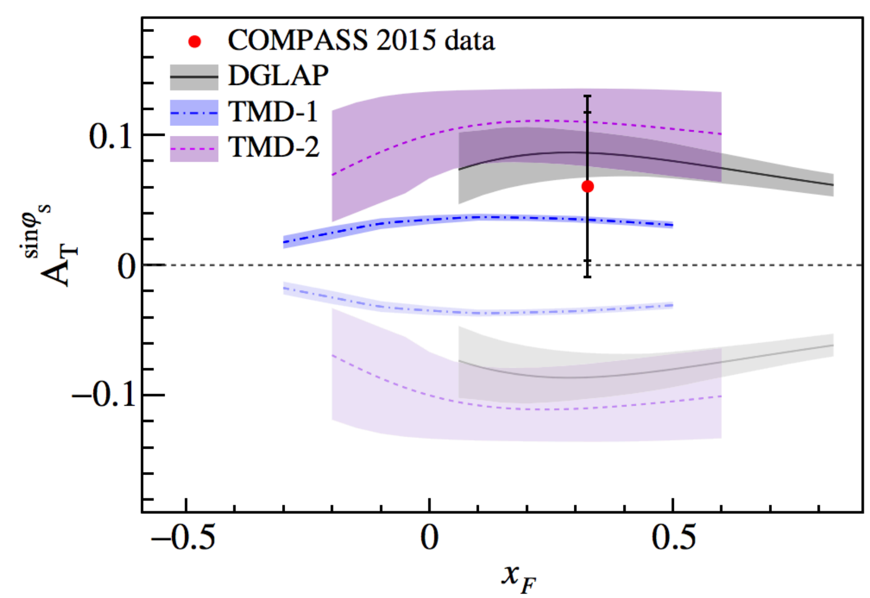
Effect in SIDIS:
transverse single spin asymmetry (Sivers asymmetry)

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

sizable Sivers asymmetry observed by HERMES, COMPASS, JLab

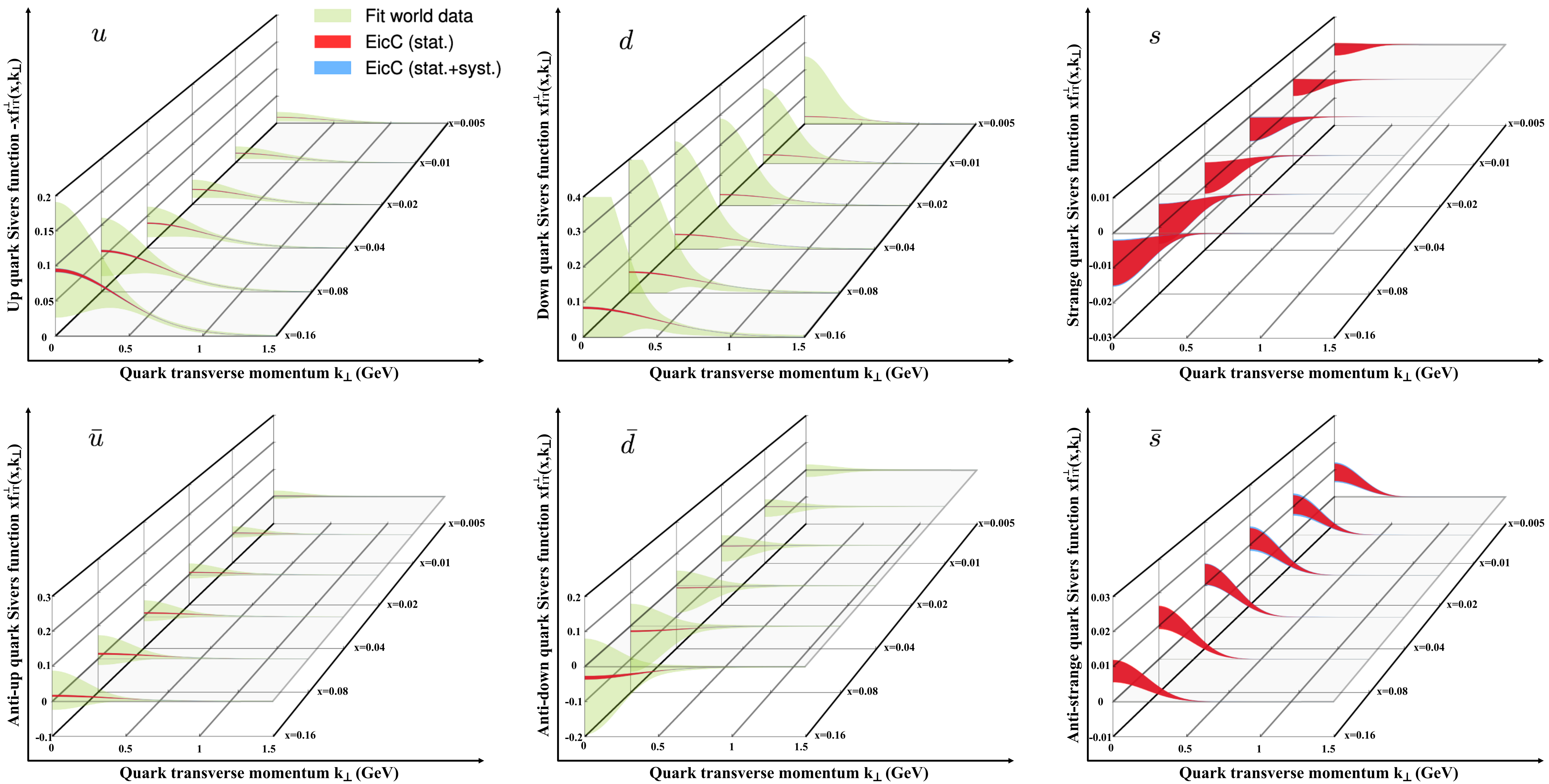
Sign change prediction:

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



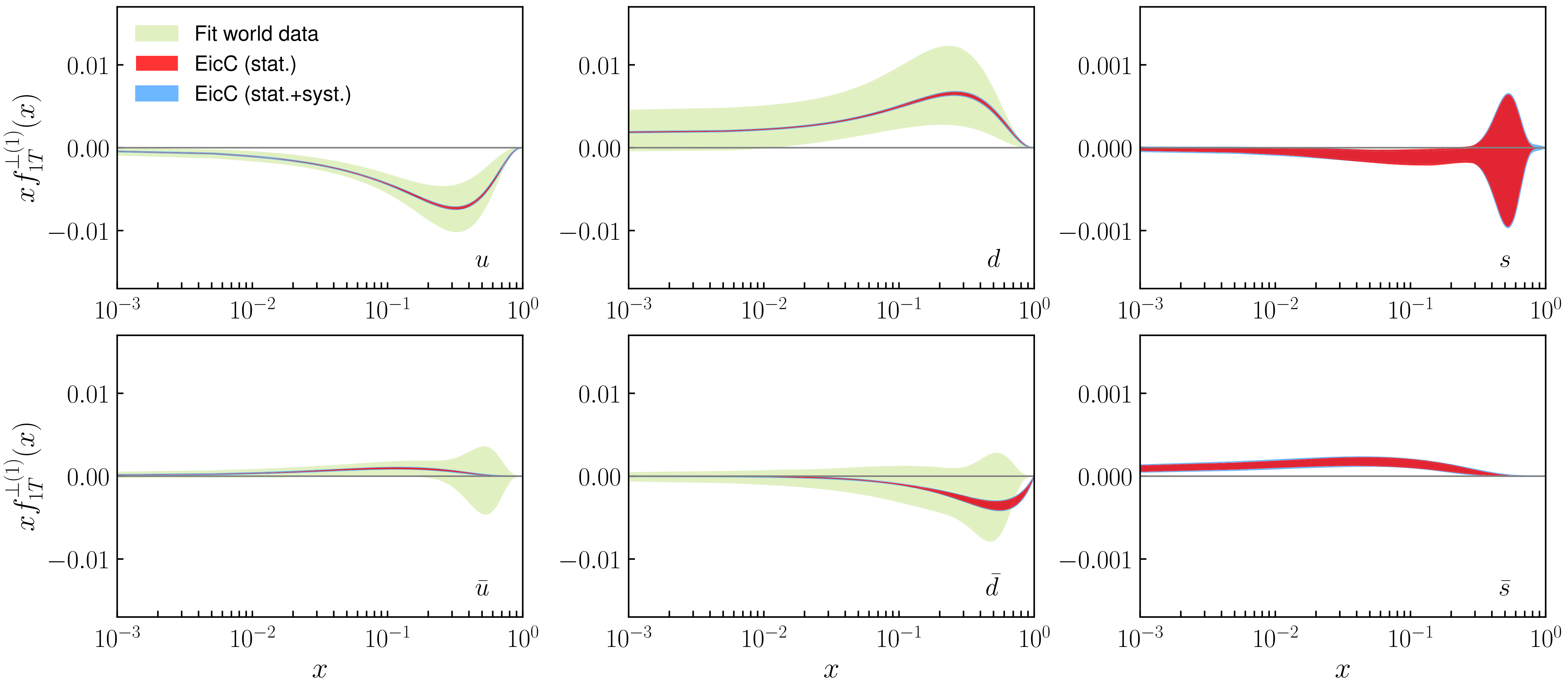
COMPASS Collaboration, PRL 119, 112002 (2017).

EicC Impact: Sivers Function



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

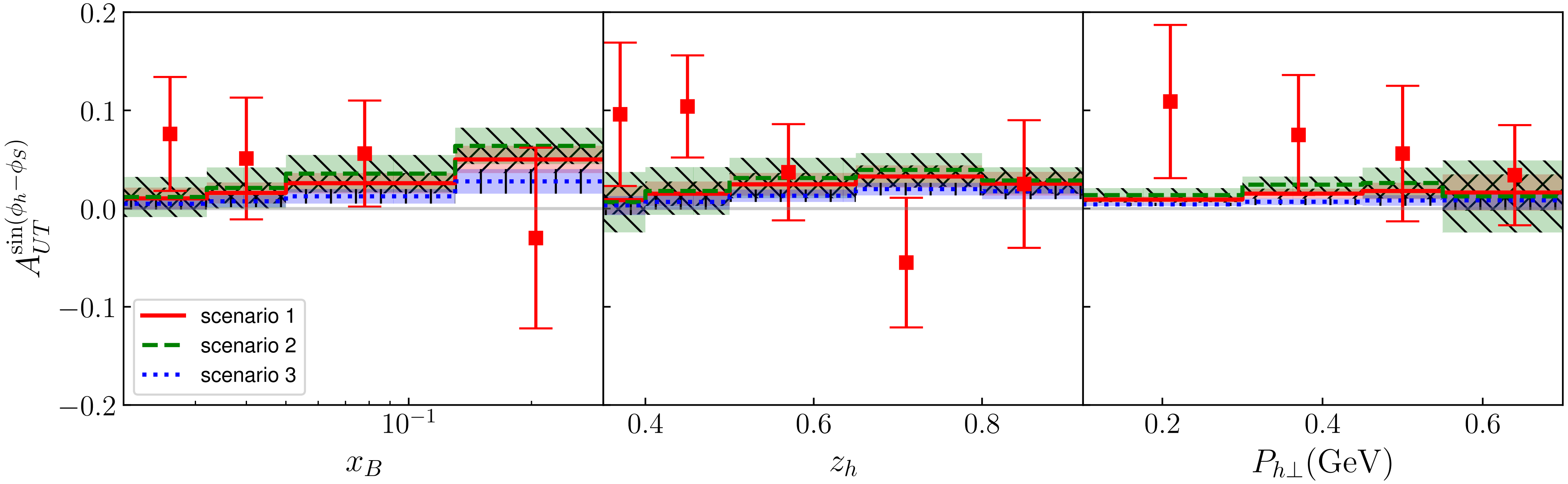
EicC Impact: Sivers Function



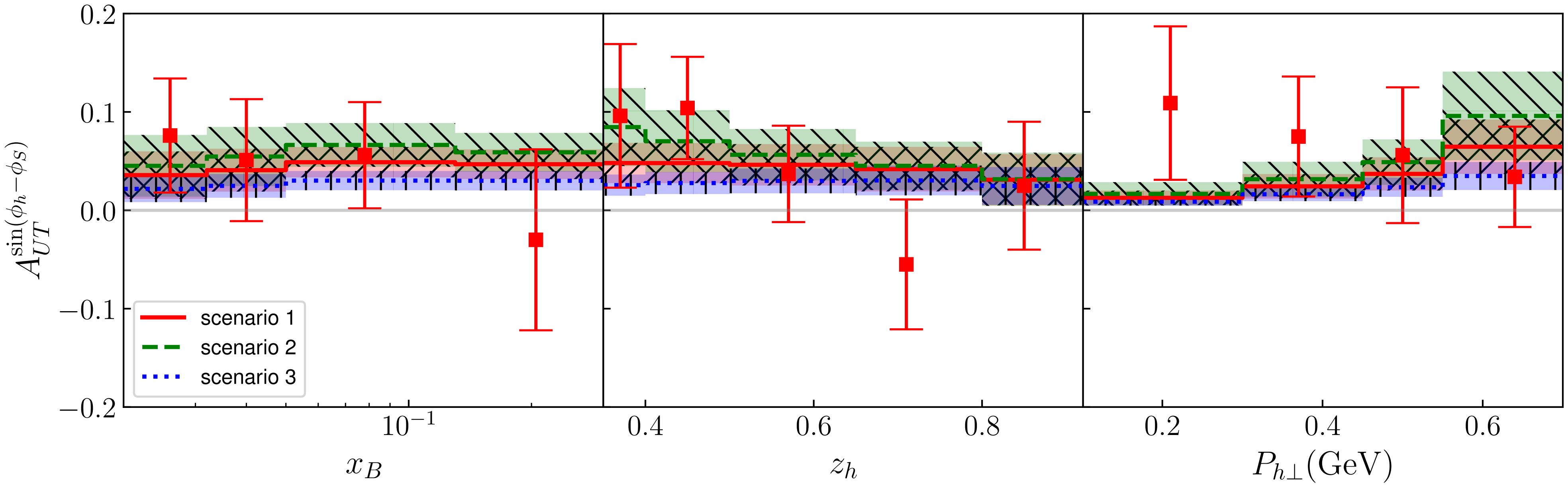
$$f_{1T}^{\perp(1)}(x) = \int d^2k_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x, k_T^2)$$

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

Sivers Asymmetry of ρ^0 Production



Sivers functions from C. Zeng, TL, P. Sun, Y. Zhao, PRD 106 (2022) 094039.



Sivers functions from M. Bury, A. Prokudin, A. Vladmirov, JHEP 05 (2021) 151.

Data from COMPASS Collaboration, PLB 843 (2023) 137950.

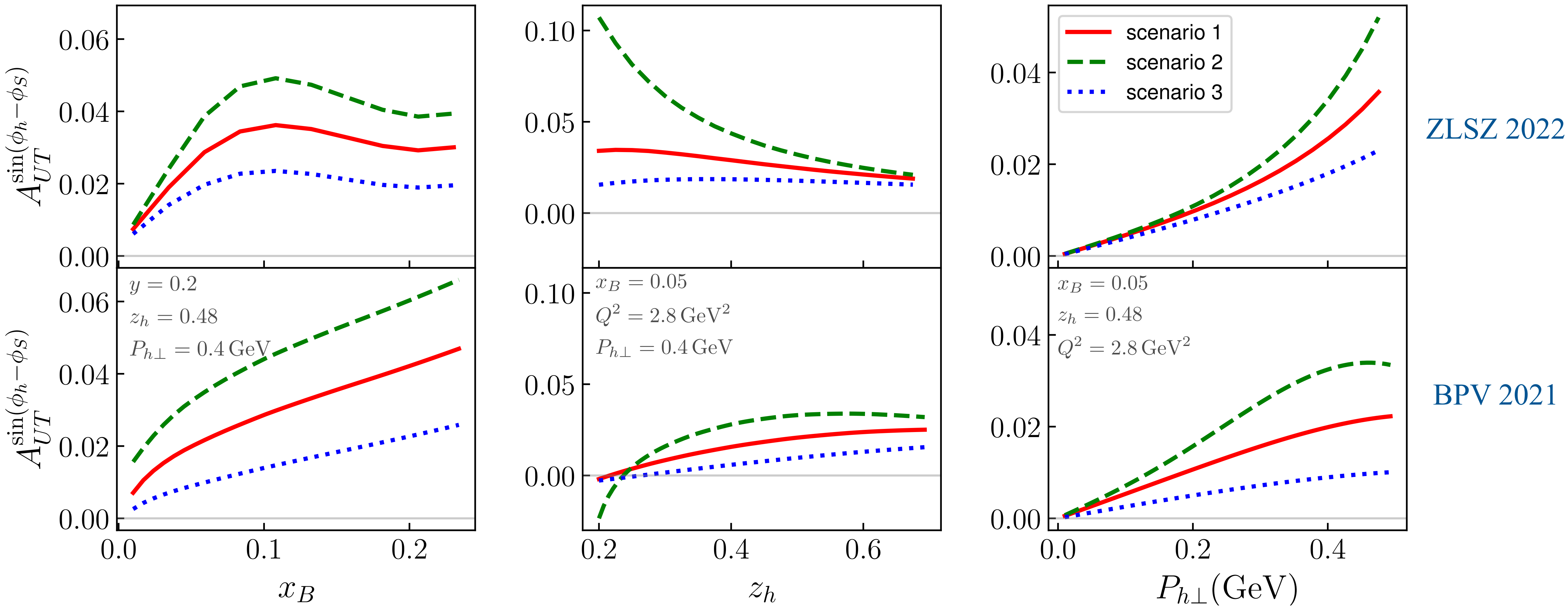
Scenarios: different transverse momentum dependences of ρ^0 fragmentation functions

Y. Deng, TL, Y.-j. Zhou, 2024

Sivers Asymmetry of ρ^0 Production

Predictions at EicC kinematics:

$\sqrt{s} = 16.7\,\mathrm{GeV}$

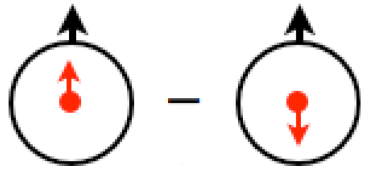


Different predictions to be tested at EicC kinematics

Y. Deng, TL, Y.-j. Zhou, 2024

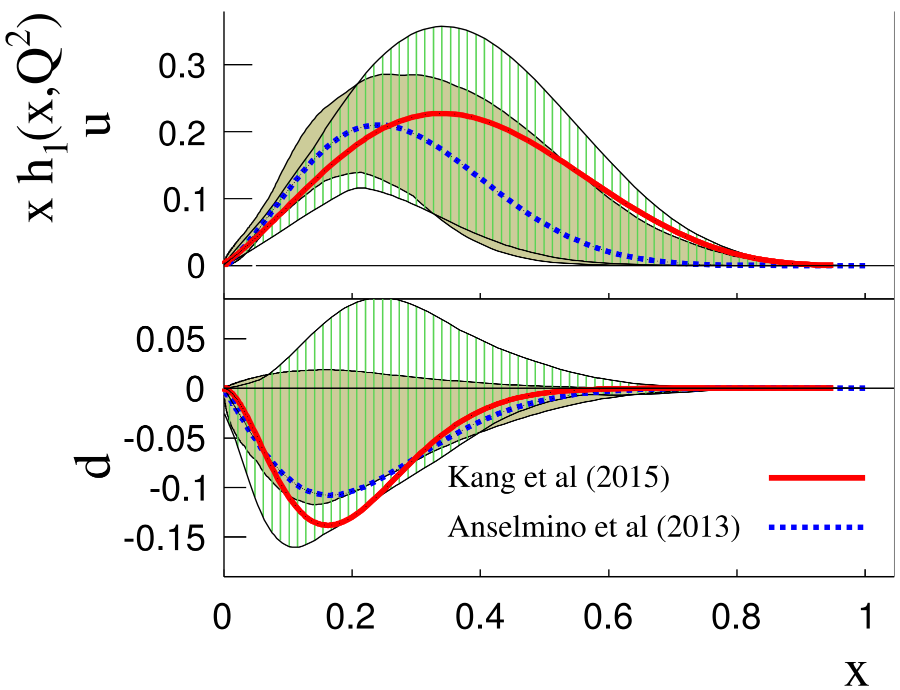
Transversity Distribution

Transversity distribution

h_1  (Collinear & TMD)

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

Phenomenological extractions



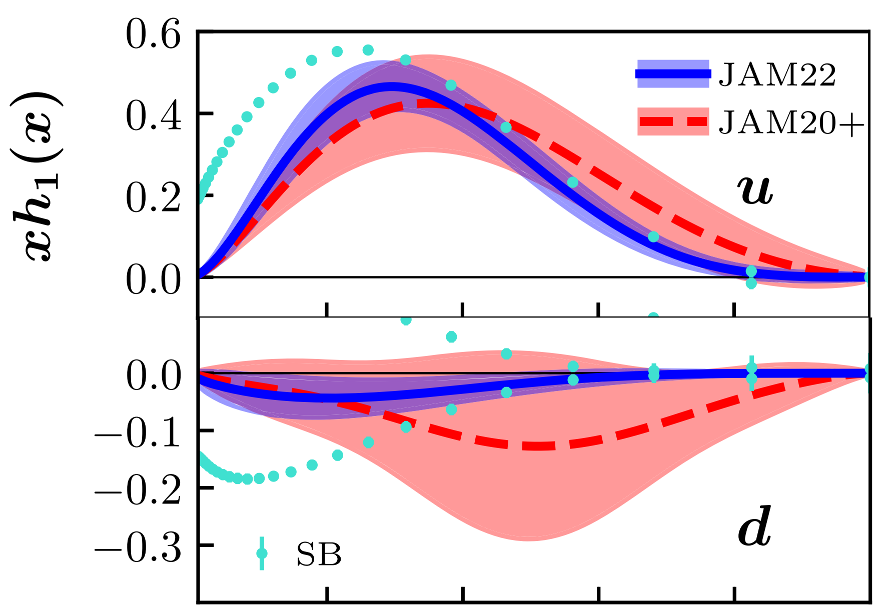
Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, PRD 93, 014009 (2016).

Chiral-odd:

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

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

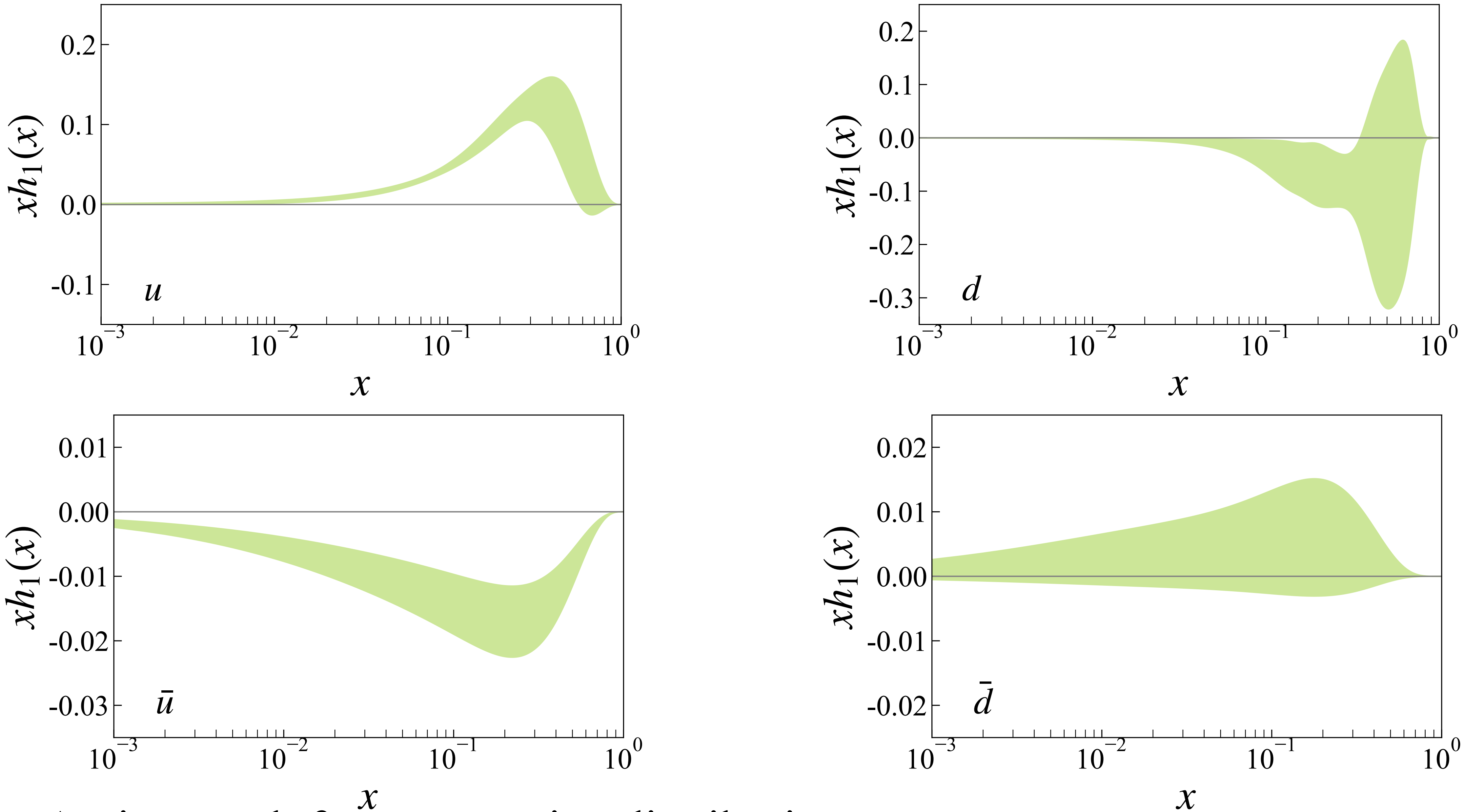
$$h_1(x, \mathbf{k}_\perp^2) \otimes H_1^\perp(z, \mathbf{p}_\perp^2)$$



JAM Collaboration, PRD 104, 034014 (2022).

Sea Quark Transversity

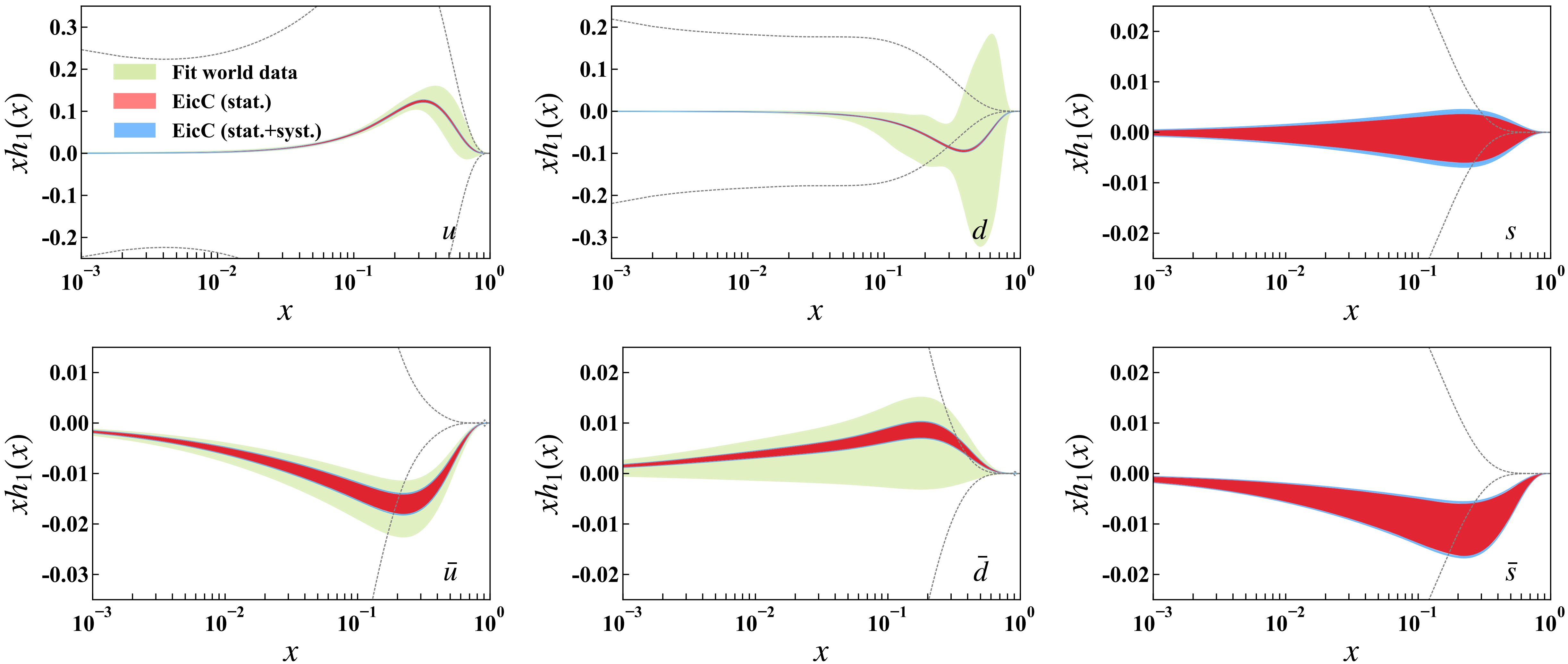
First determination of sea quark transversity, including TMD evolution



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.

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, PRD 109 (2024) 056002.

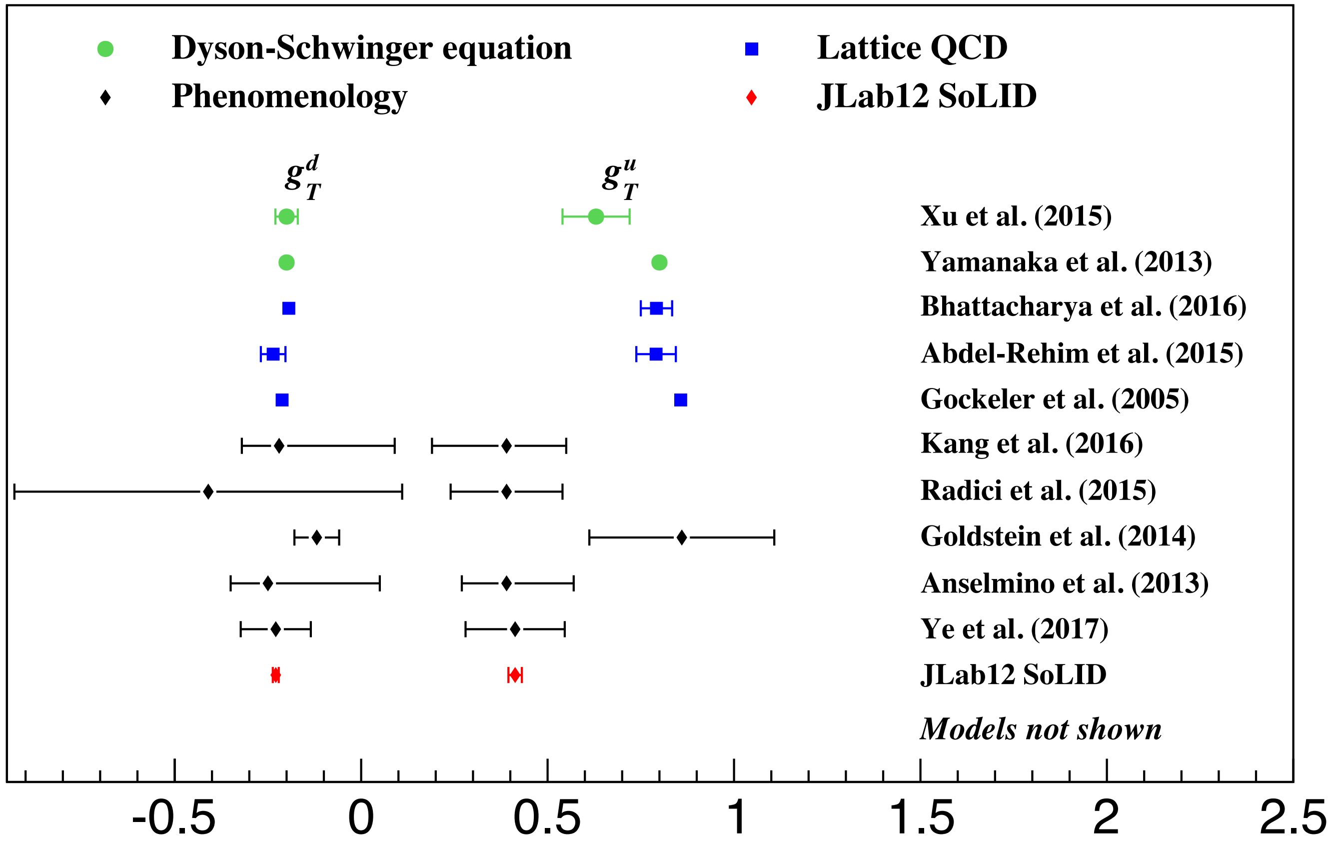
Tensor Charge

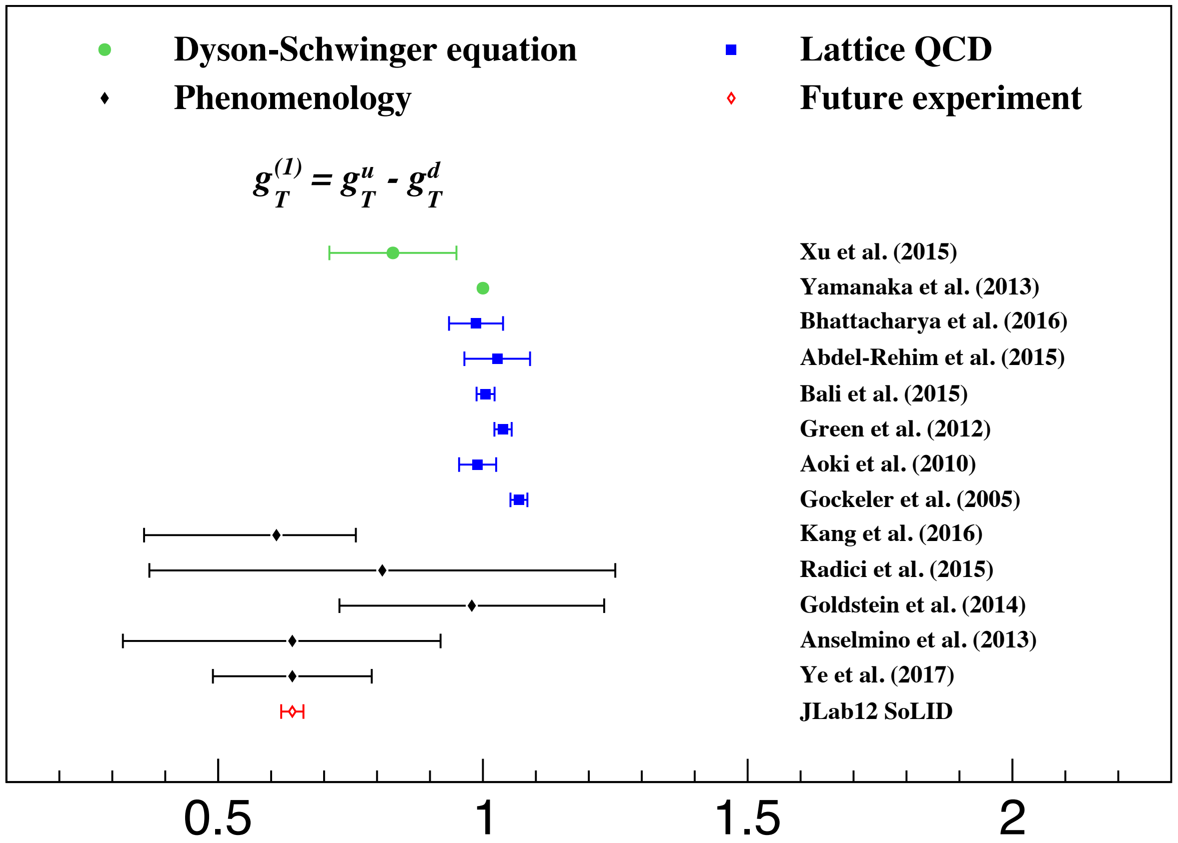
Tensor charge

$$\langle P,S|\bar{\psi}^q i\sigma^{\mu\nu}\gamma_5\psi^q|P,S\rangle = g_T^q \bar{u}(P,S)i\sigma^{\mu\nu}\gamma_5 u(P,S)$$

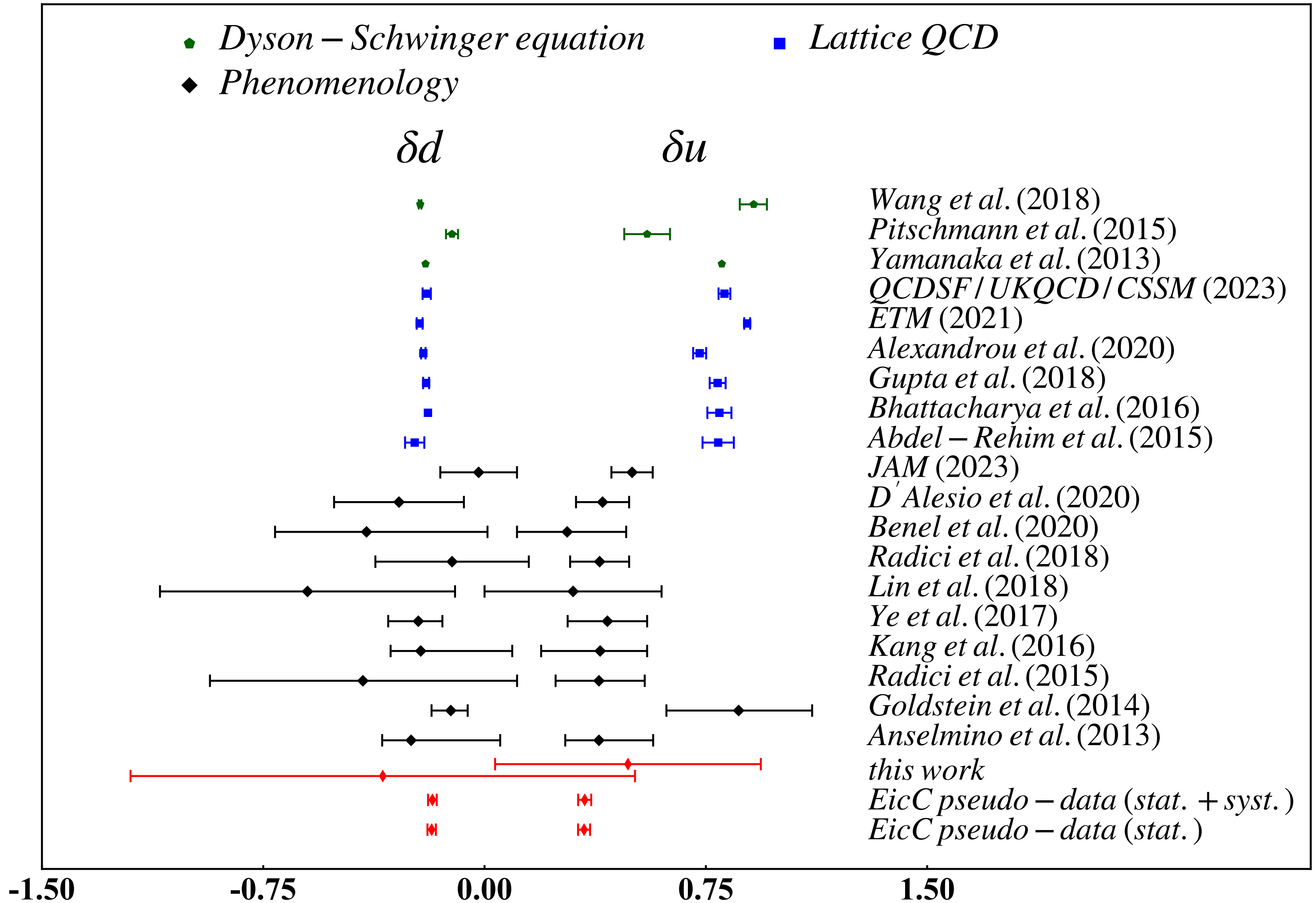
$$g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]\,dx$$

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





Tensor Charge



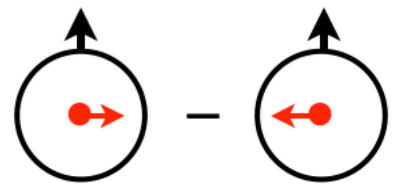
Larger uncertainties when including anti-quarks (less biased)
Compatible with lattice QCD calculations

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

Double Spin Asymmetry and Worm-gear

Trans-helicity worm-gear distribution

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

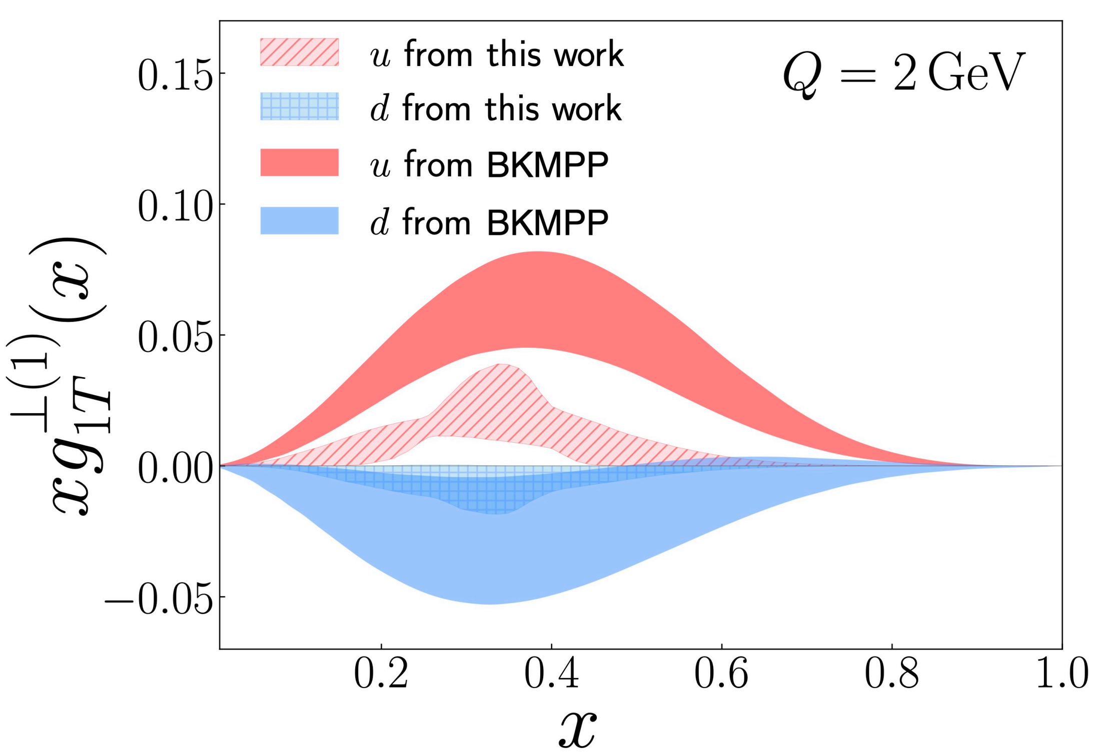


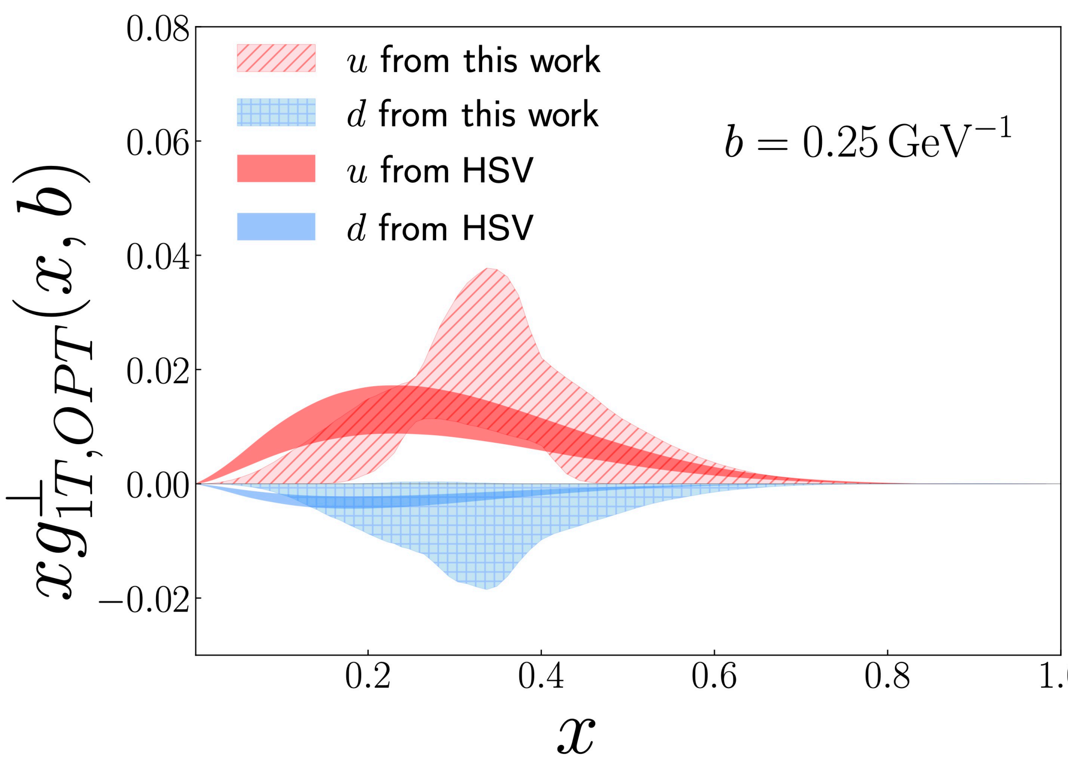
- Longitudinally polarized quark density in a transversely polarized nucleon
- Overlap between wave functions differing by one unit of orbital angular momentum

Effect in SIDIS:
A longitudinal-transverse double spin asymmetry

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

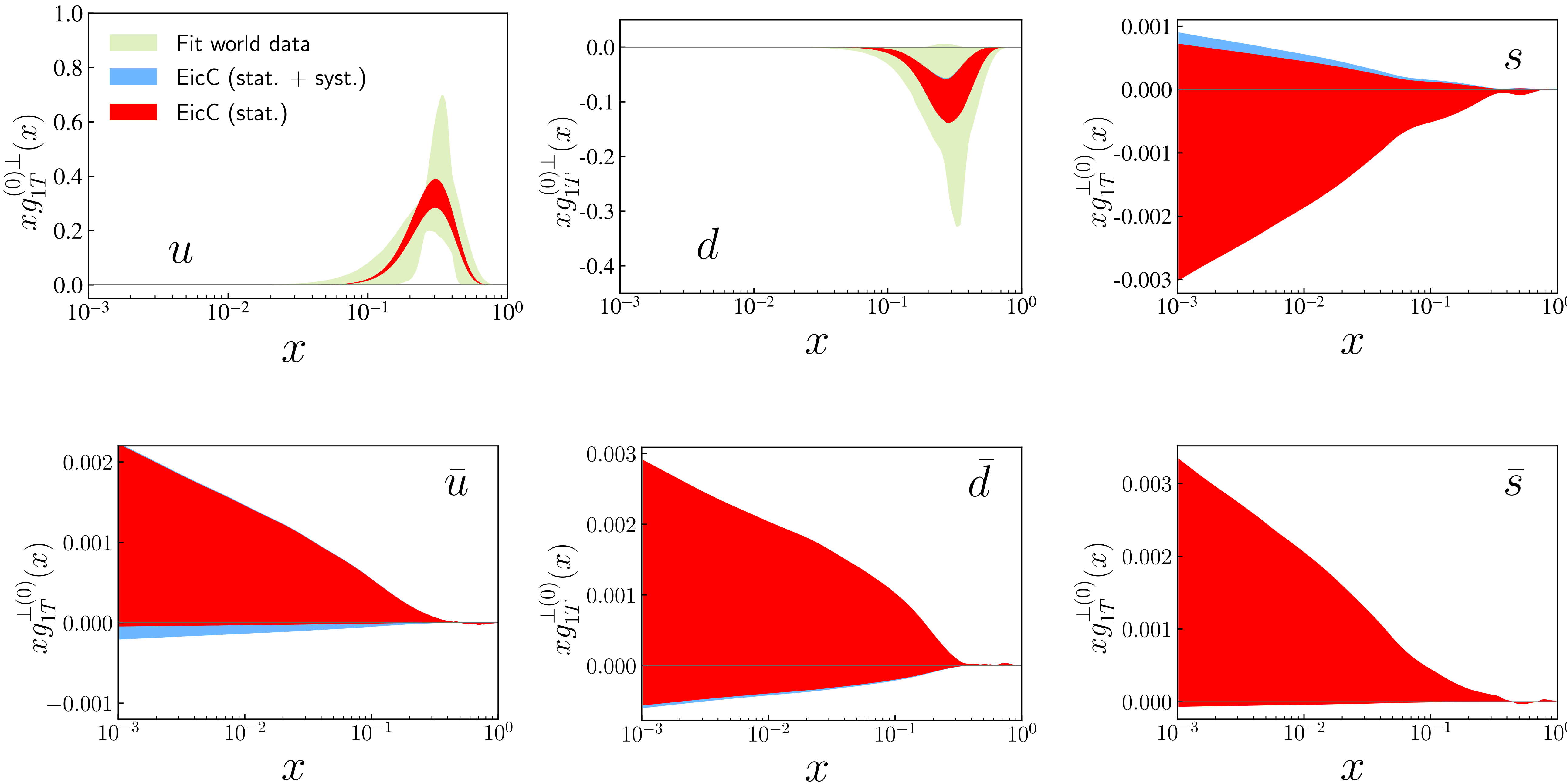
Phenomenological extraction





K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, arXiv:2403.12795, PRD (2024).

EicC Impact on Trans-helicity Distributions



K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, arXiv:2403.12795, PRD (2024).

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.
- There are still challenges on the theoretical side (not covered in this talk)
  - power corrections, higher twist effects
  - radiative corrections
  - target fragmentation
  - …

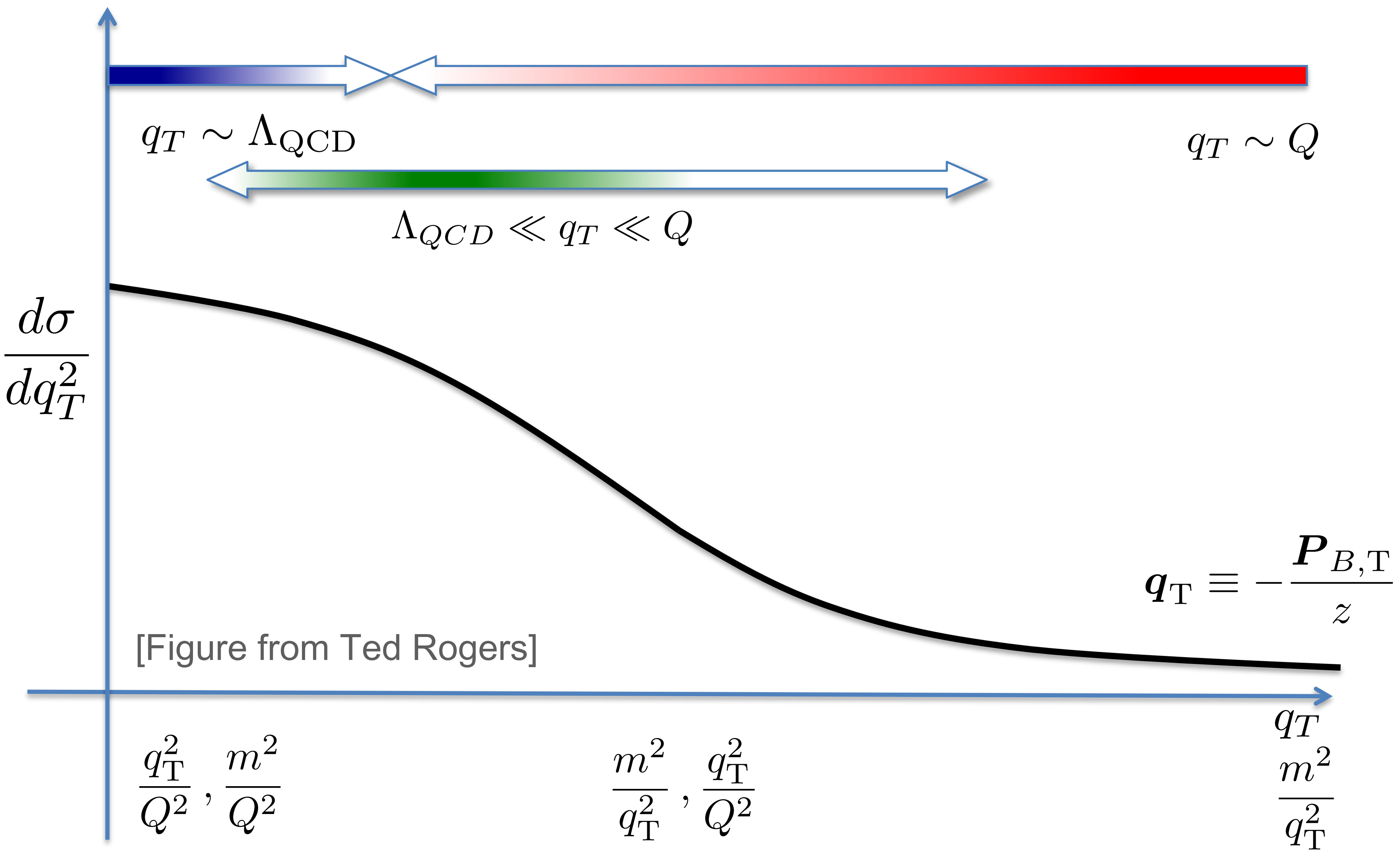
Thank you!

Backup

Small and Large Transverse Momentum

W + Y formalism

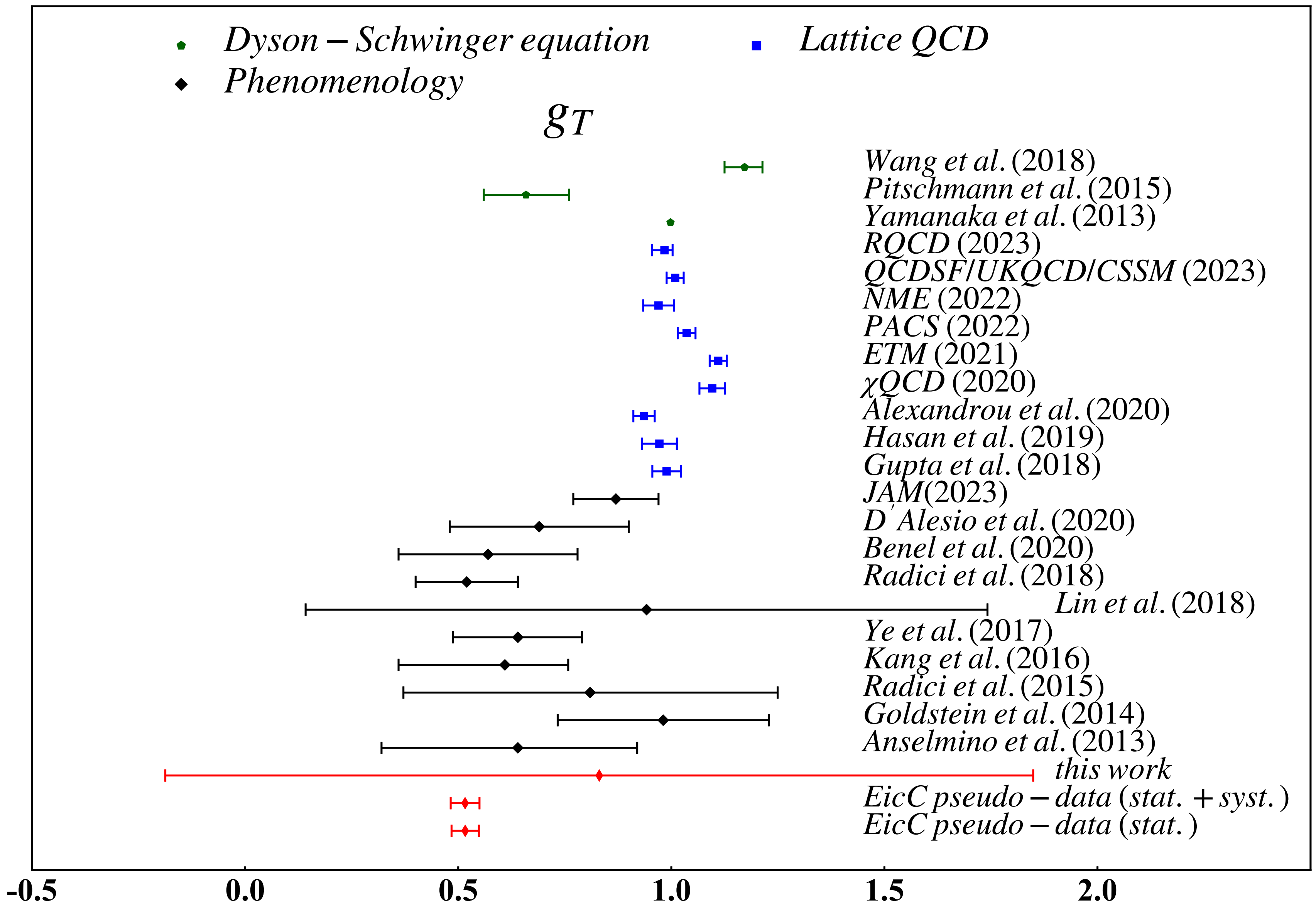
$$\frac{d\sigma}{d^2 q_{\rm T} dQ \cdots} = W(q_{\rm T}, Q) + Y(q_{\rm T}, Q) + \mathcal{O}\left(\frac{m}{Q}\right)^n$$



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

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

Tensor Charge



Larger uncertainties when including anti-quarks (less biased)
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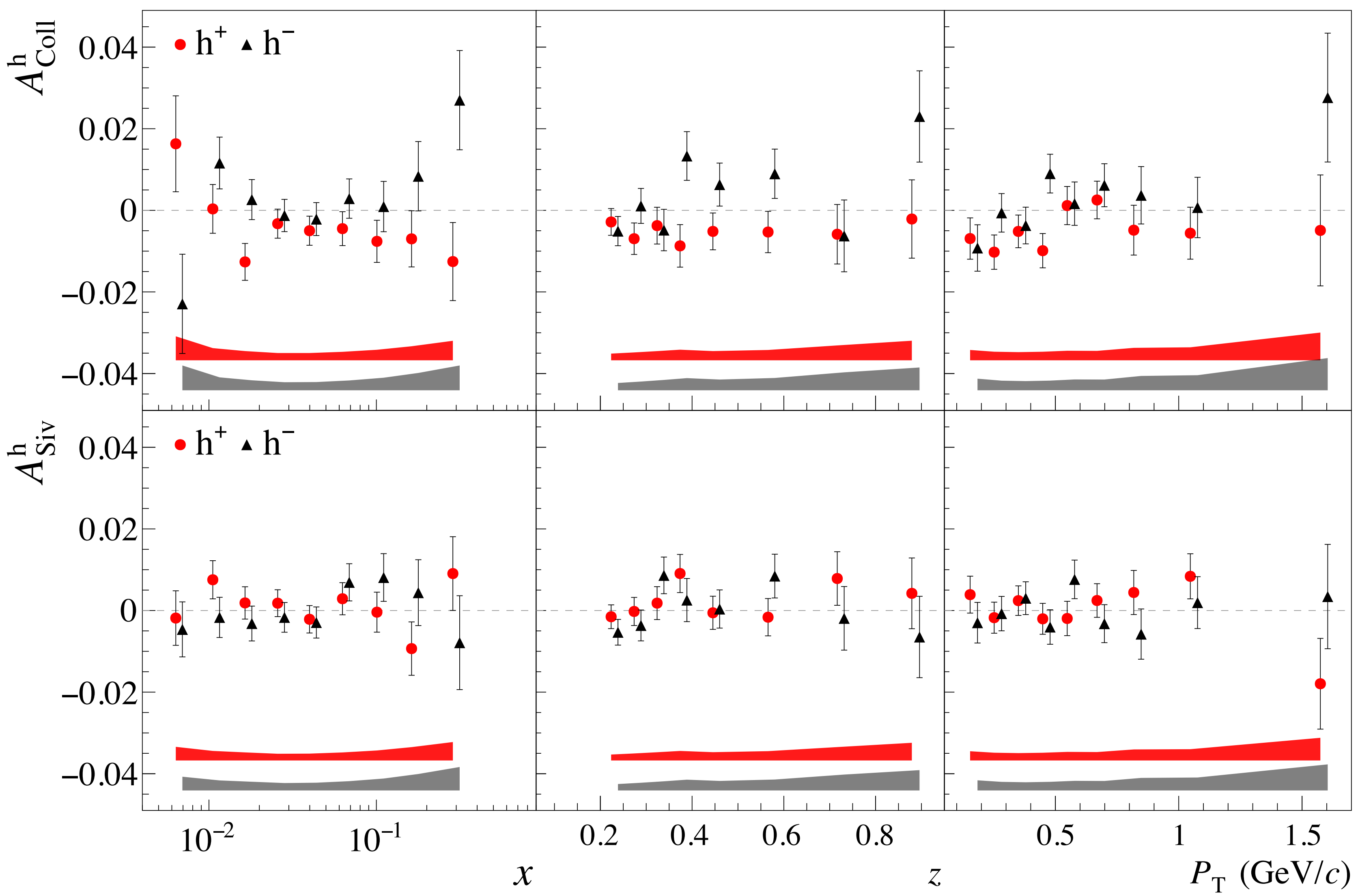
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, PRD 109 (2024) 056002.

Some More on Transversity

New data released by COMPASS

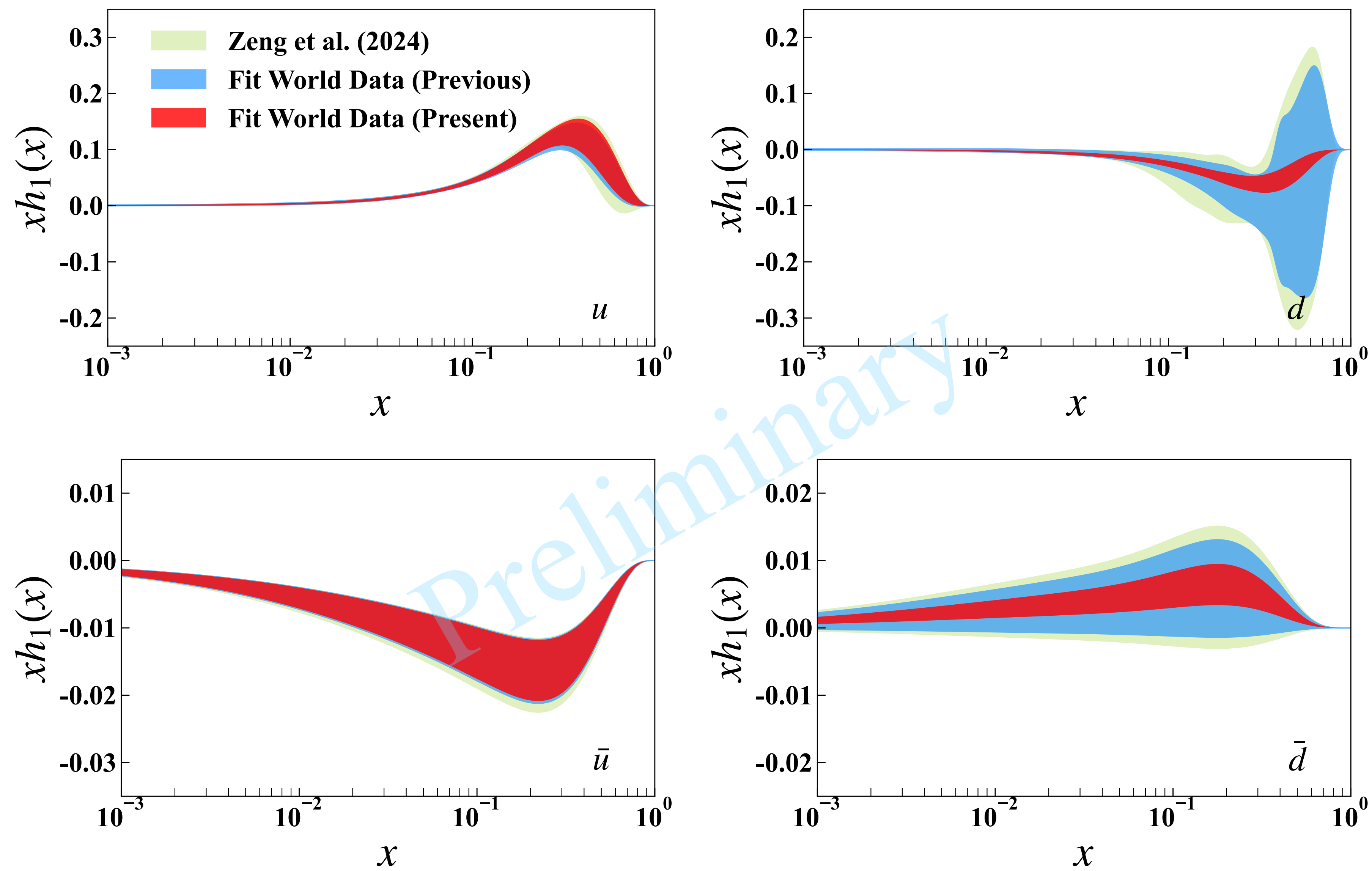
SIDIS on transversely polarized deuteron target



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

Some More on Transversity

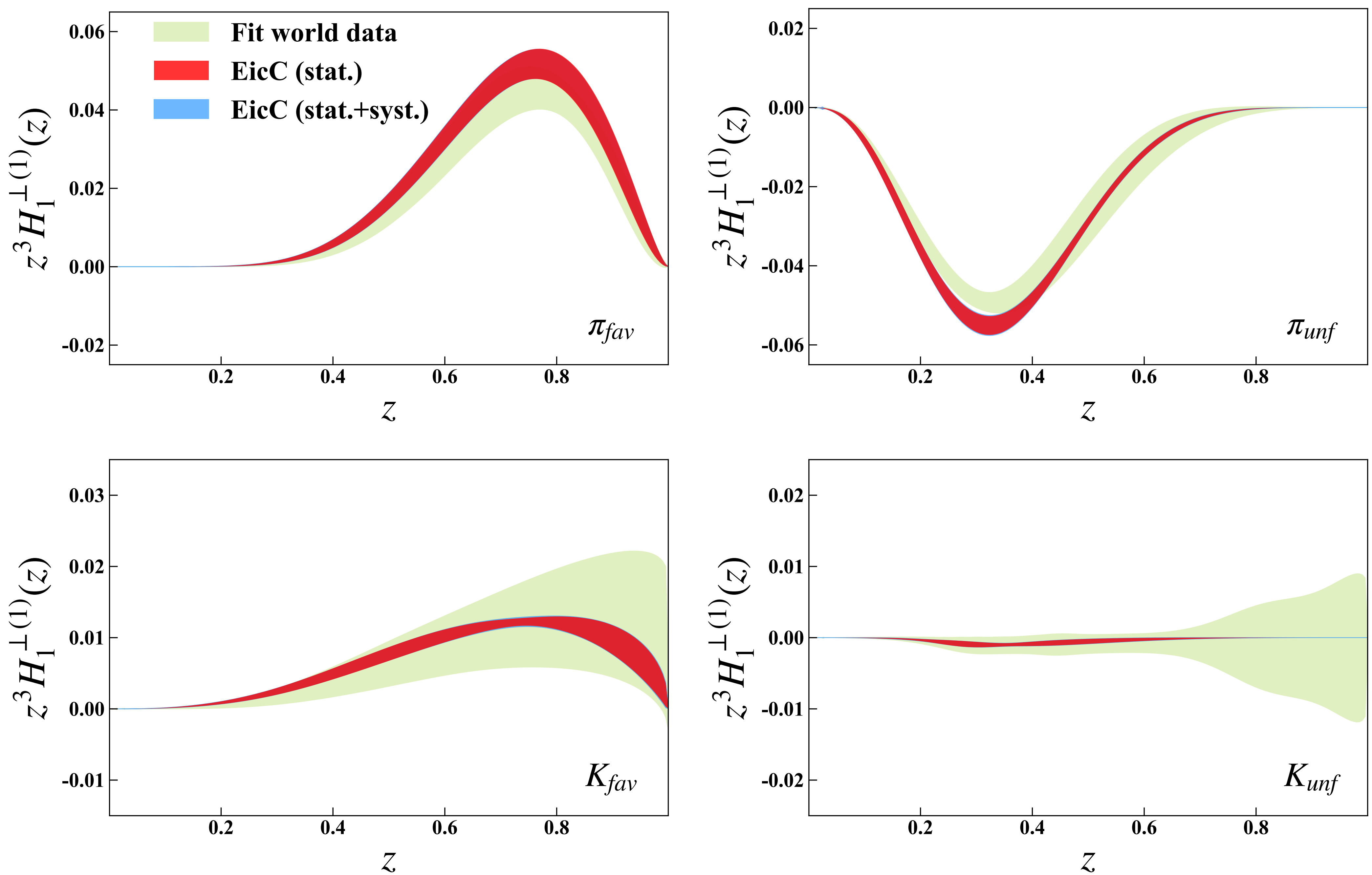
An updated world data fit



The new COMPASS data have significant impact on *d* (anti-*d*) quark distributions

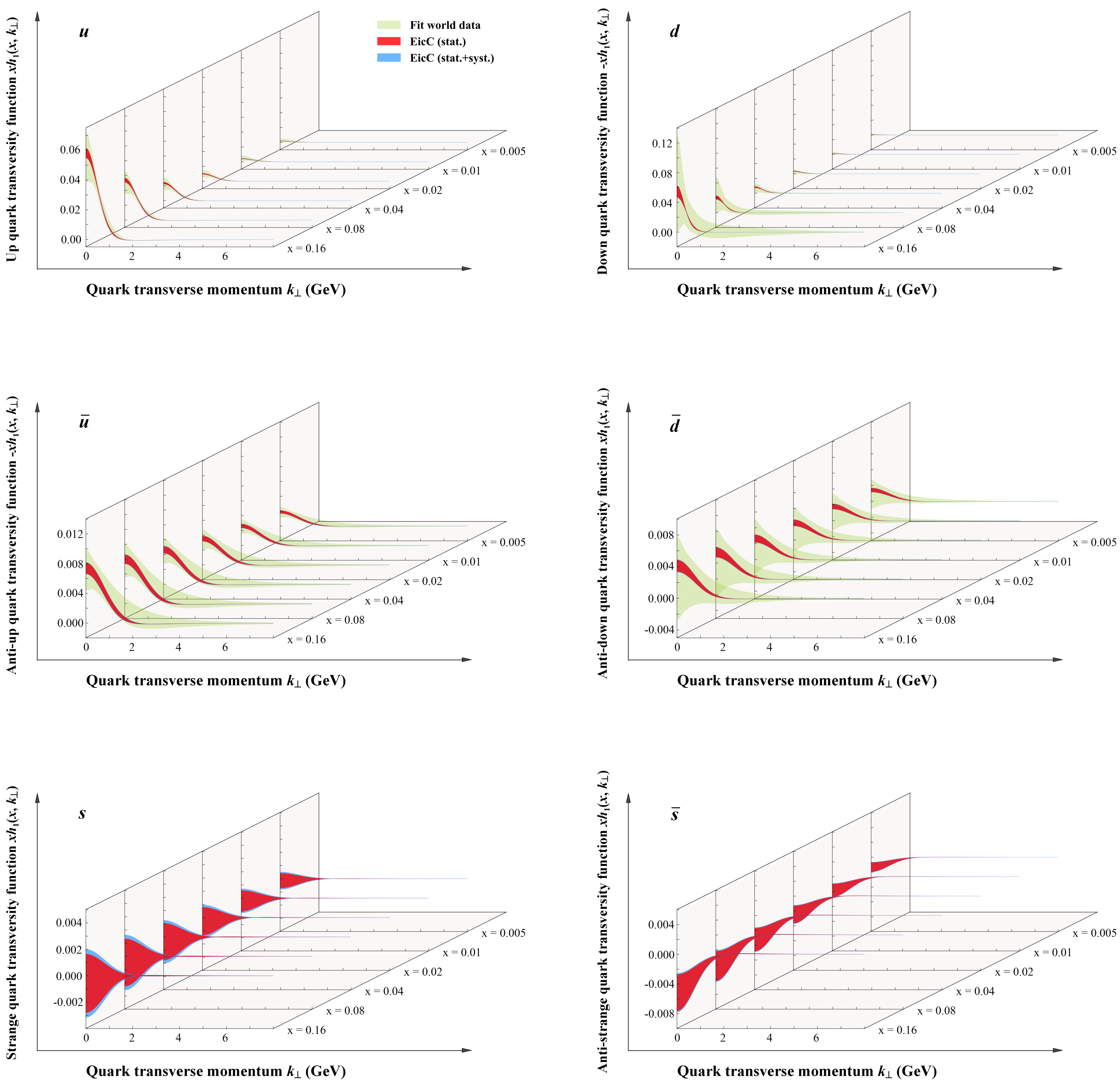
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao

Result: Collins Fragmentation Function

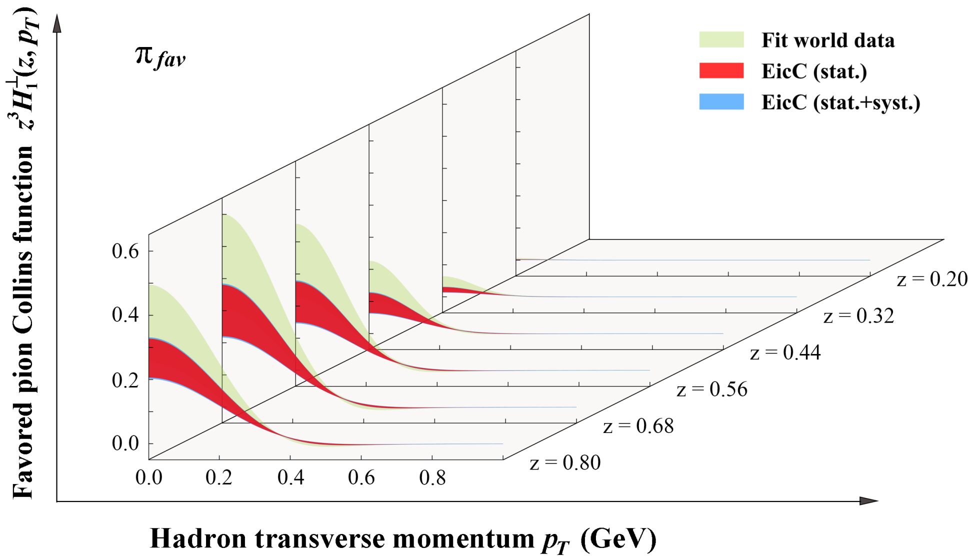


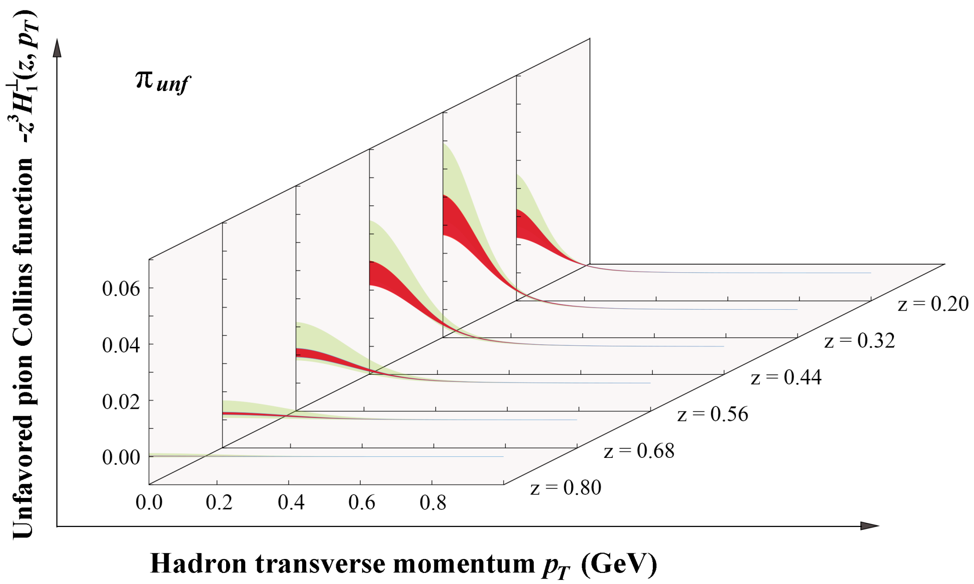
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2310.15532

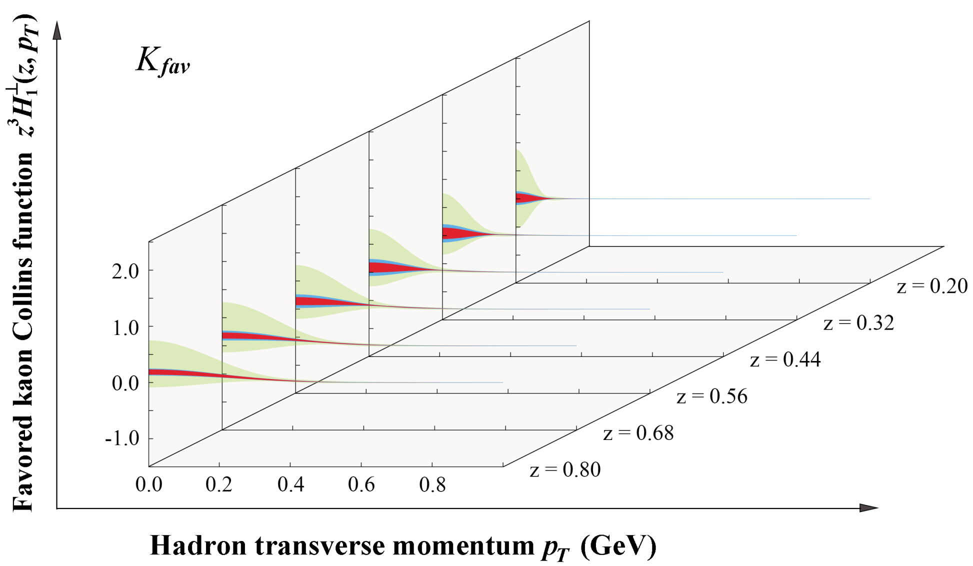
Transversity TMDs

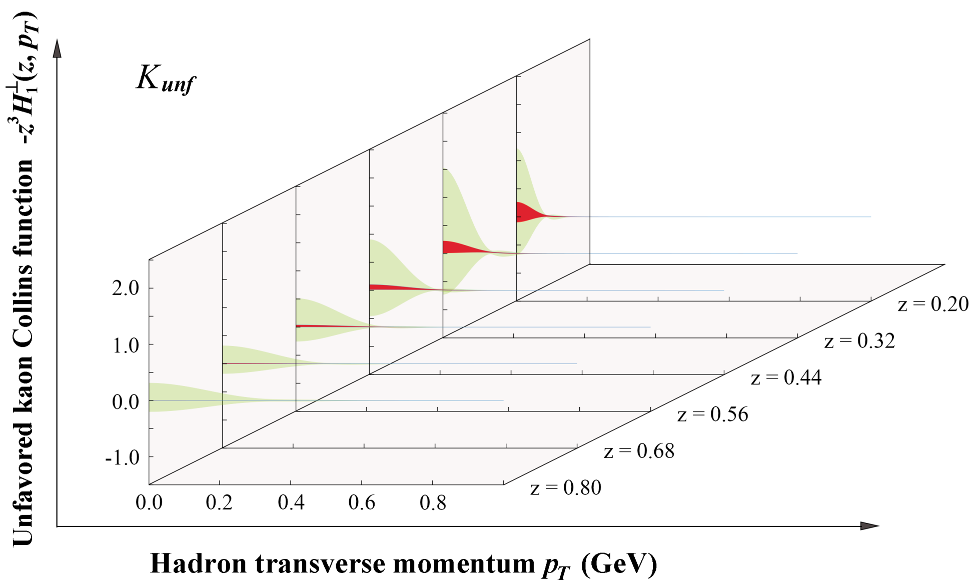


Collins TMD FFs

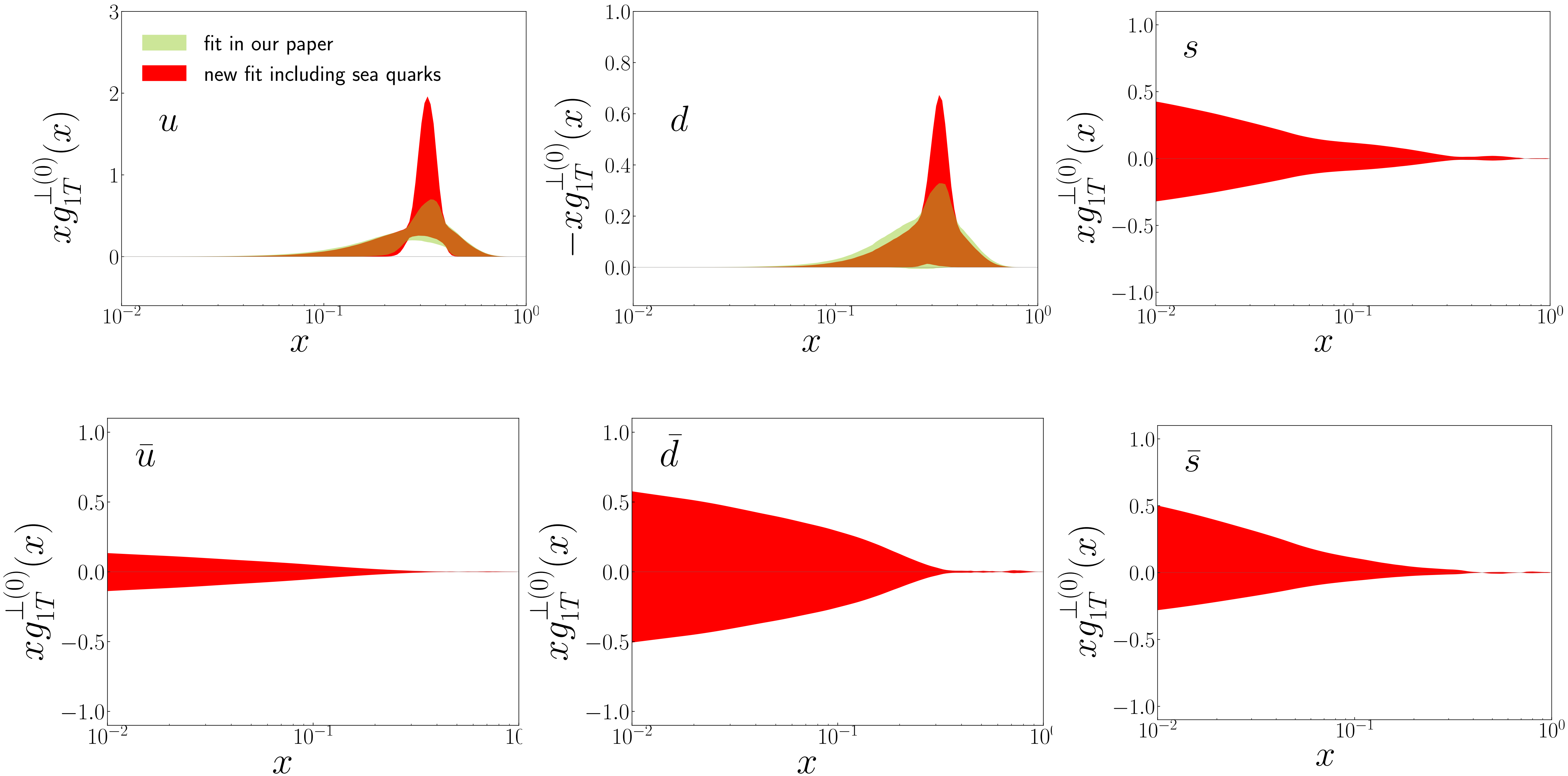






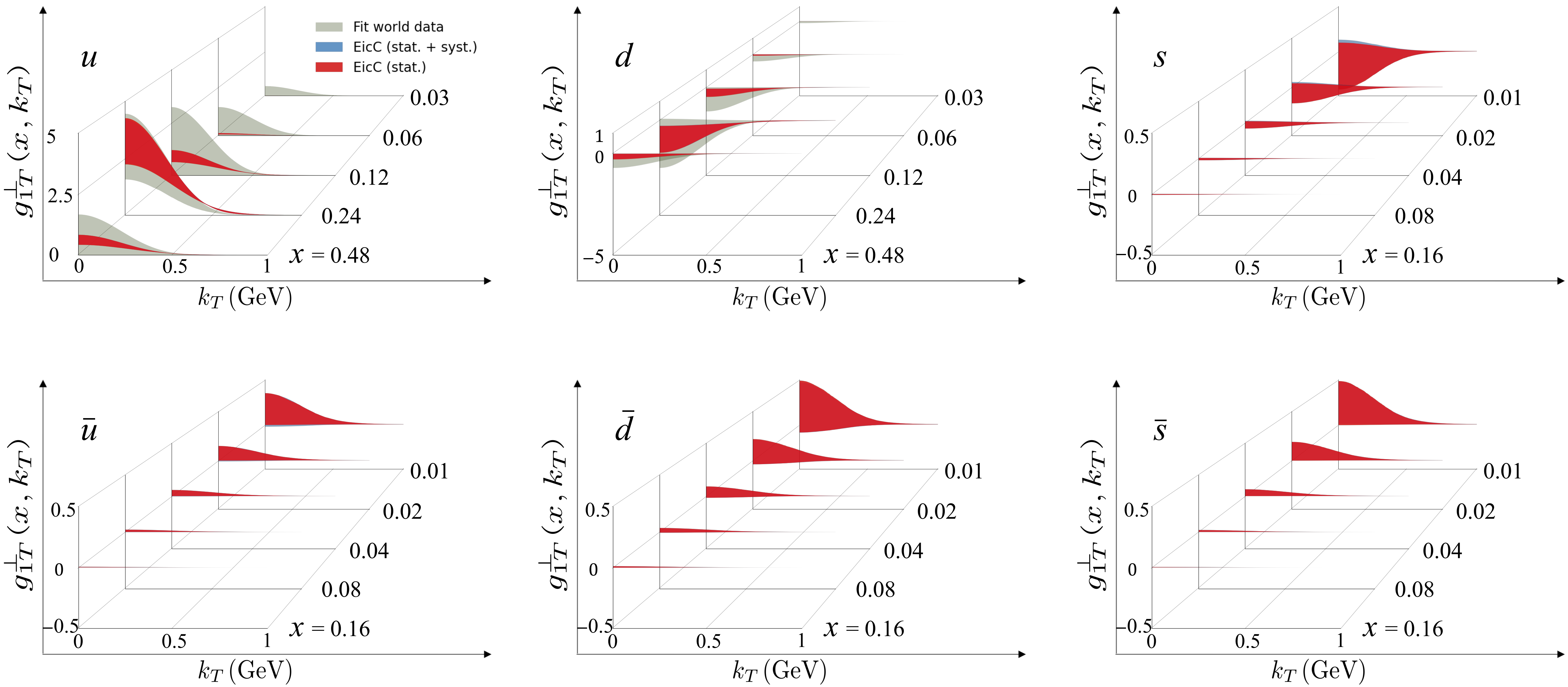


Trans-helicity Worm-gear Distributions



K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, arXiv:2403.12795, PRD (2024).

Trans-helicity Worm-gear Distributions



K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, arXiv:2403.12795, PRD (2024).