# TMD Phenomenology and Opportunities at EicC

The 1$^{st}$ Spicy Gluons Workshop for Young Scientists
May 15$^{th}$-19$^{th}$, 2024 @ Hefei, Anhui


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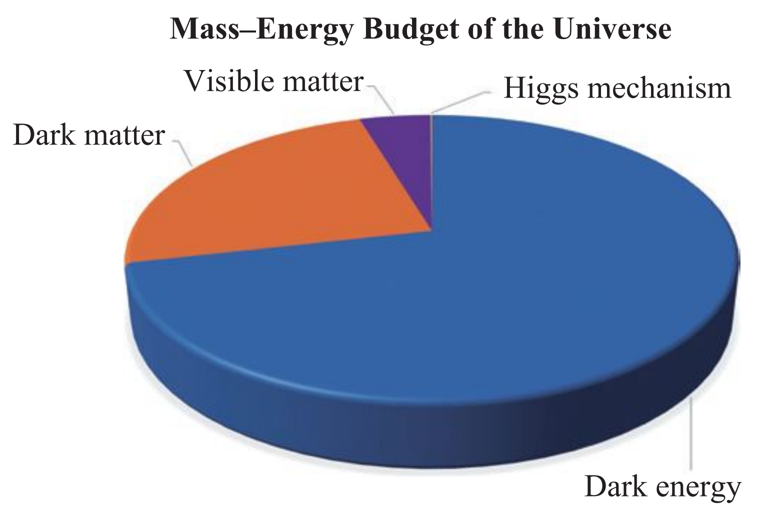
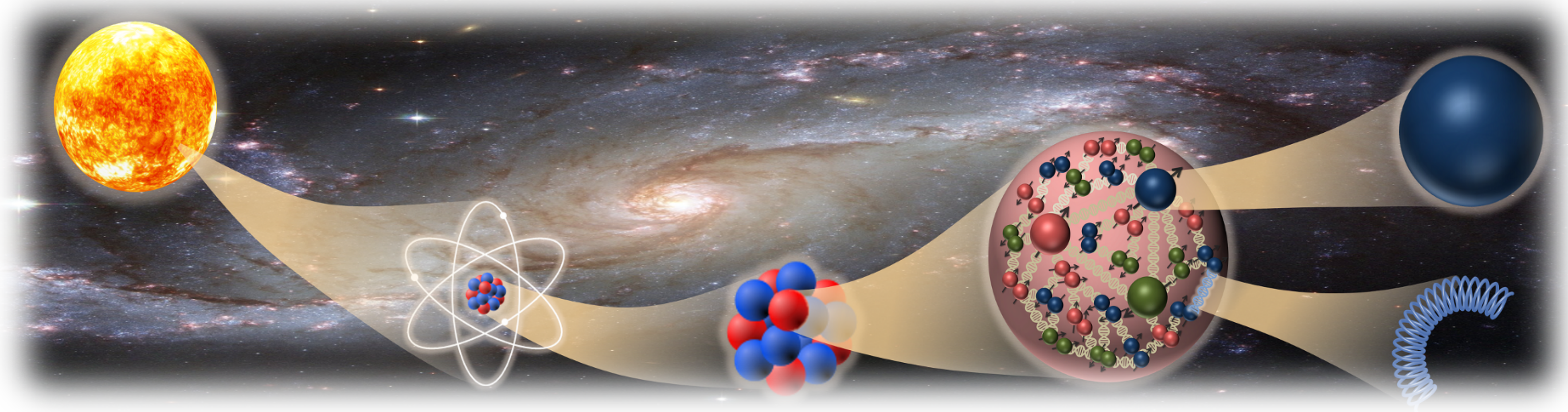
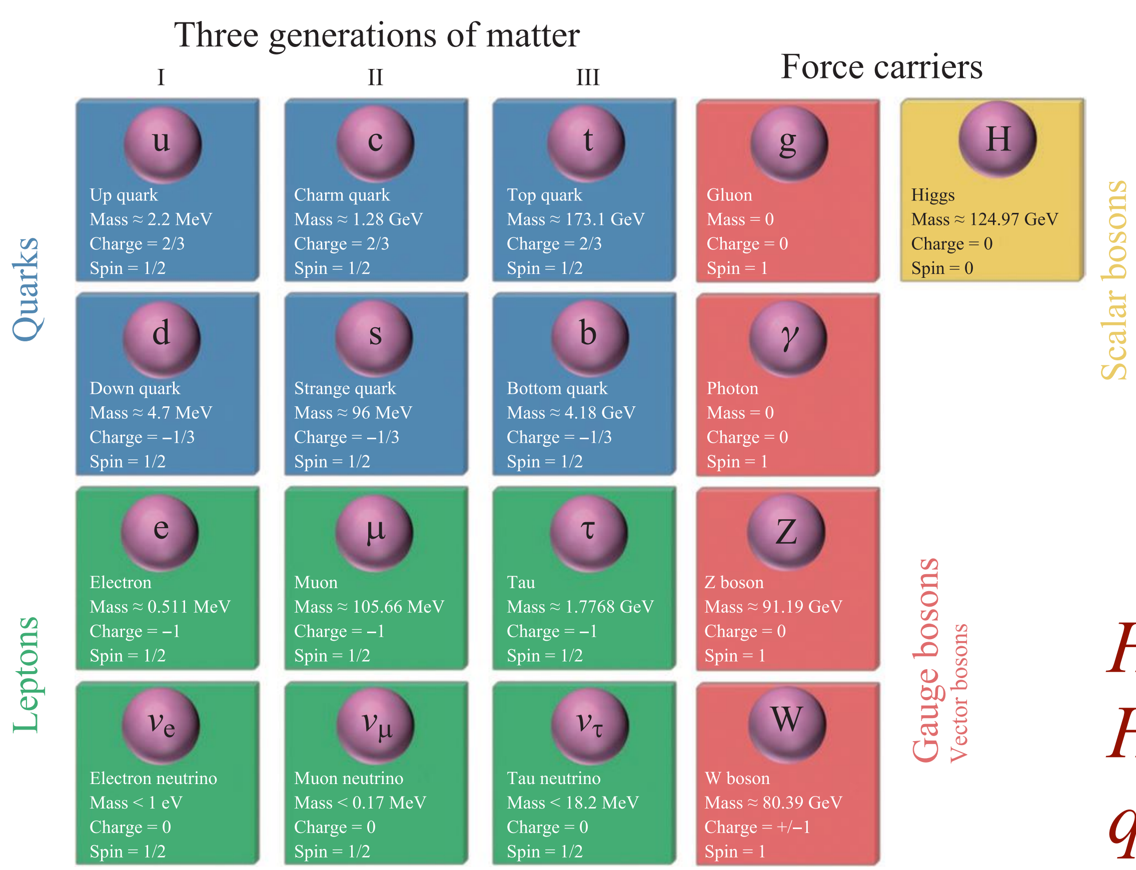
*Institute of Frontier and Interdisciplinary Science, Shandong University*
*Southern Center for Nuclear-Science Theory, IMP, CAS*

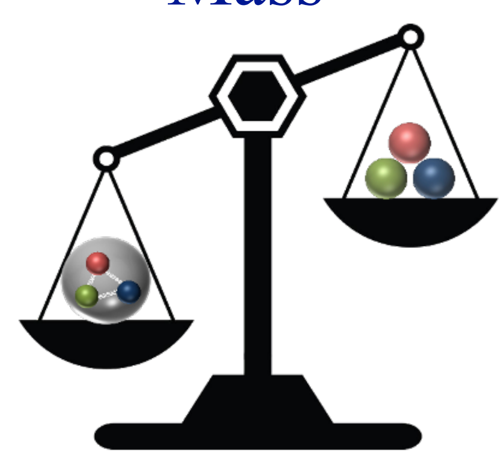
# How much do we understand our world?



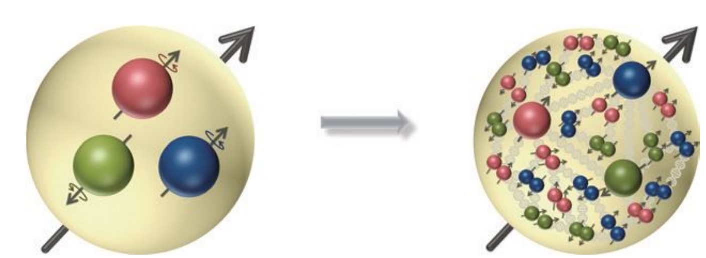






Mass



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 $Q \gg \Lambda_{\text{QCD}}$

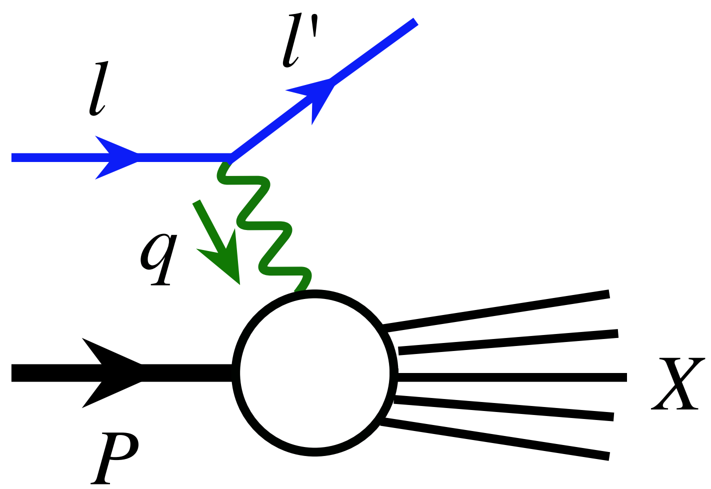
- dominated by the scattering of the lepton off an active quark/parton
- not sensitive to the dynamics at a hadronic scale ~ 1/fm
- collinear factorization: $\sigma \propto H(Q) \otimes \phi_{a/P}(x, \mu^2)$
- overall corrections suppressed by $1/Q^n$

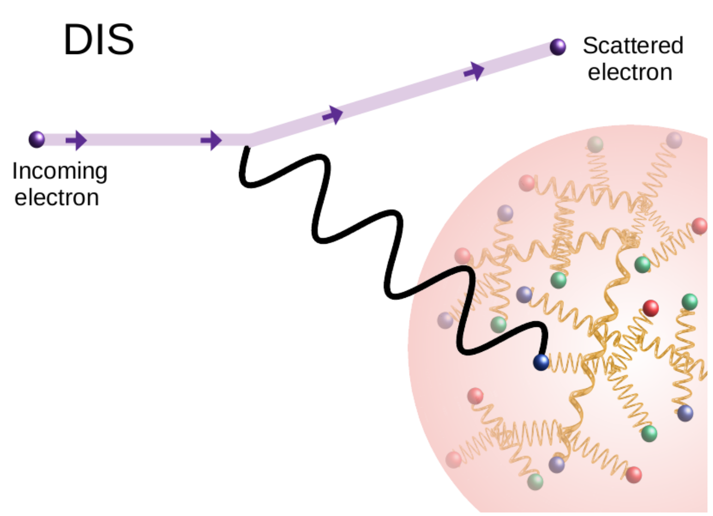
- indirectly "see" quarks, gluons and their dynamics
- predictive power relies on

— precision of the probe

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

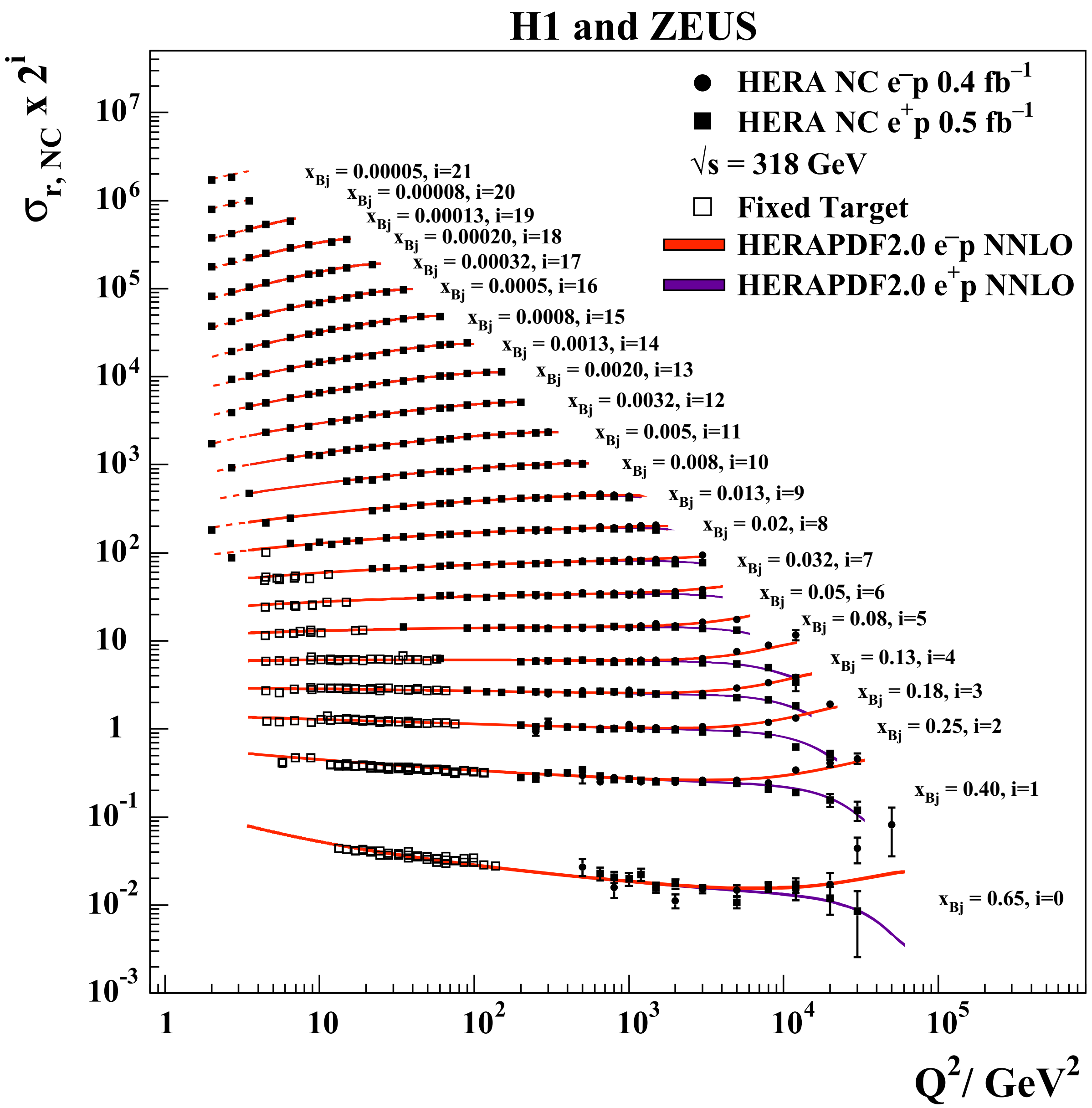
Modern "Rutherford" experiment.



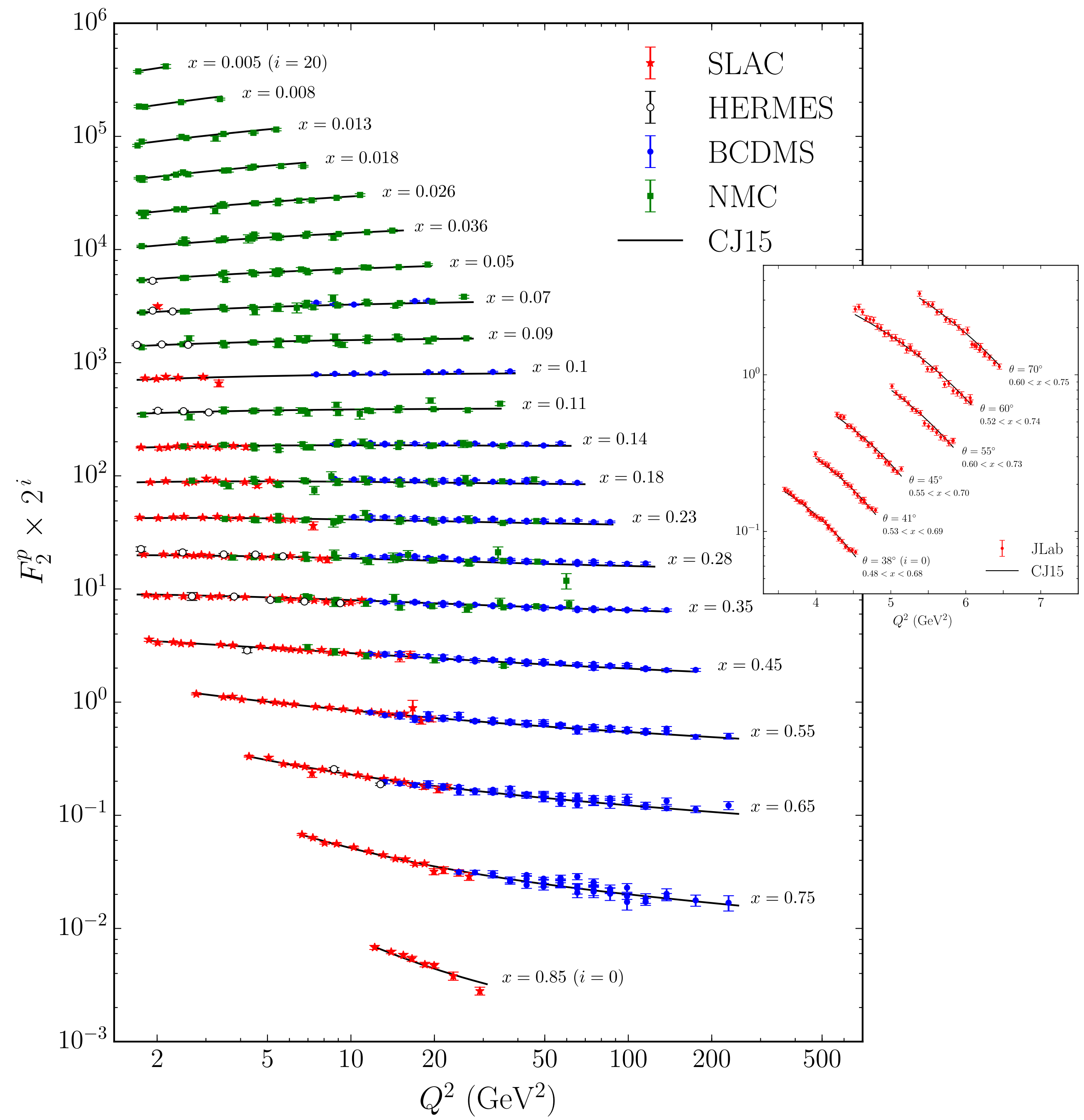




[Figure from DESY-21-099]

# Lepton-Hadron Deep Inelastic Scattering

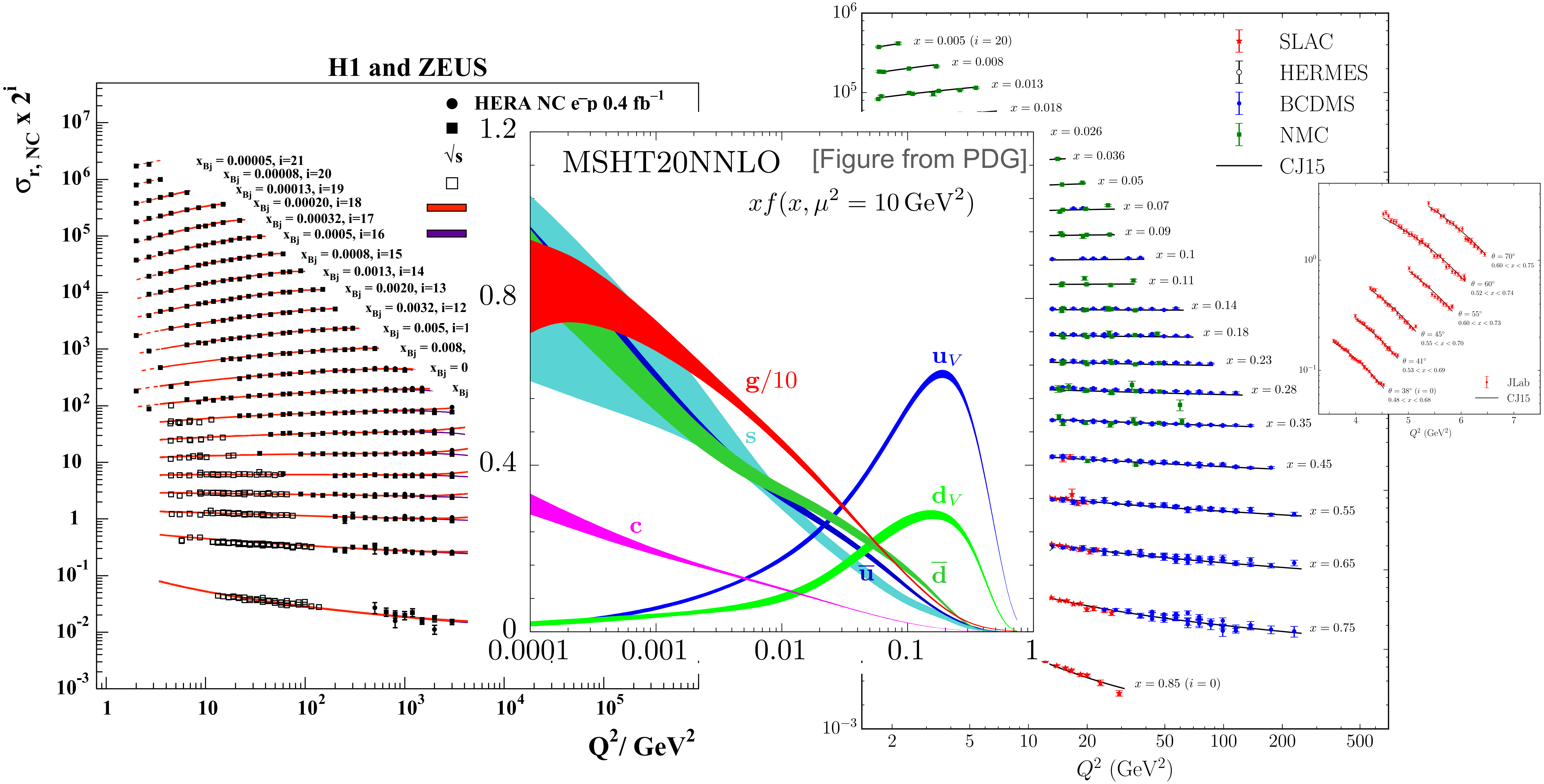



H. Abramowicz *et al.*, EPJC 78, 580 (2015).




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!*

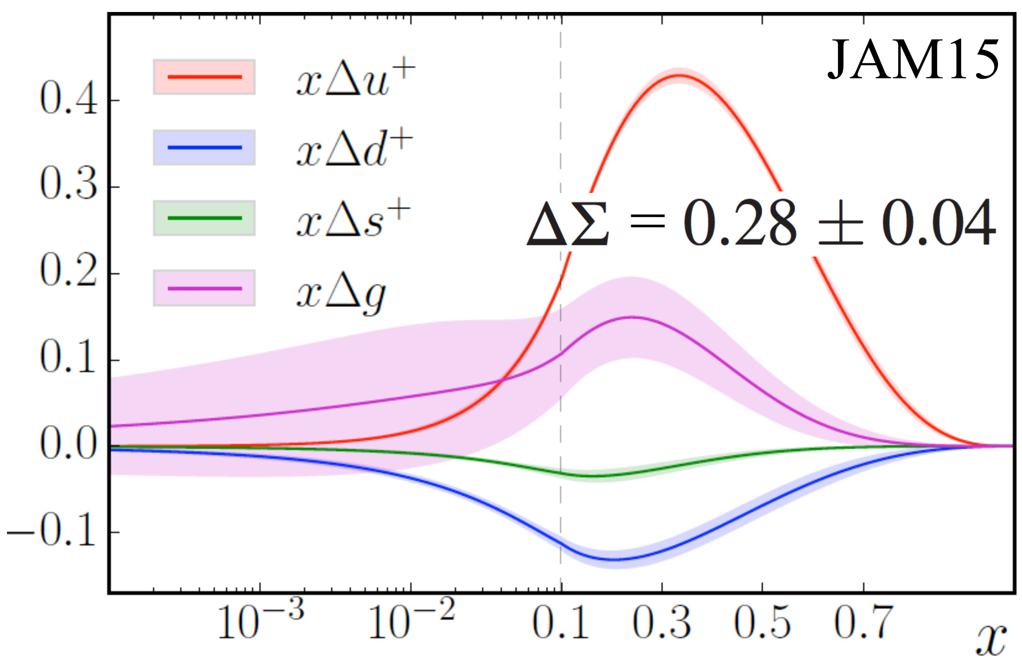
# Nucleon Spin Structure

## 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).

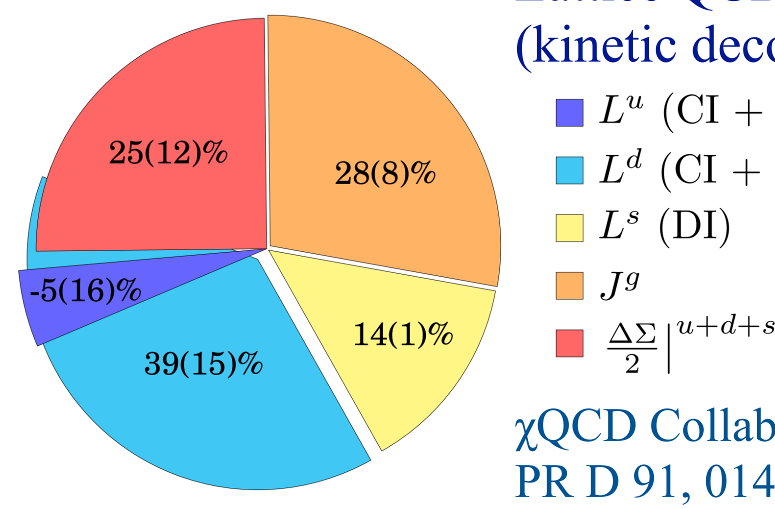
JAM17: $\Delta\Sigma = 0.36 \pm 0.09$

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).

Lattice QCD (kinetic decomposition)

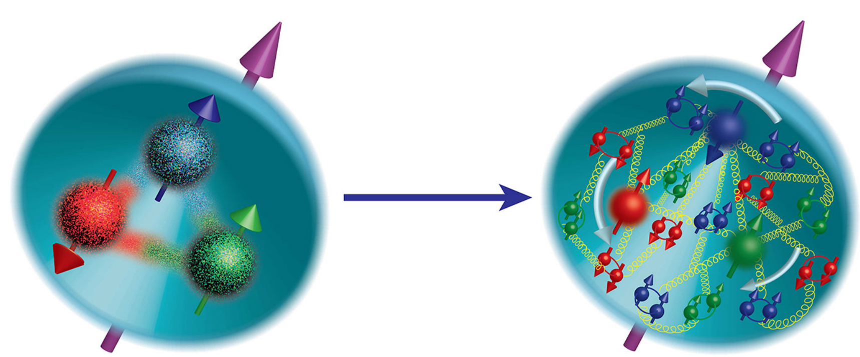



χQCD Collaboration, PR D 91, 014505 (2015).

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

50% of total proton spin

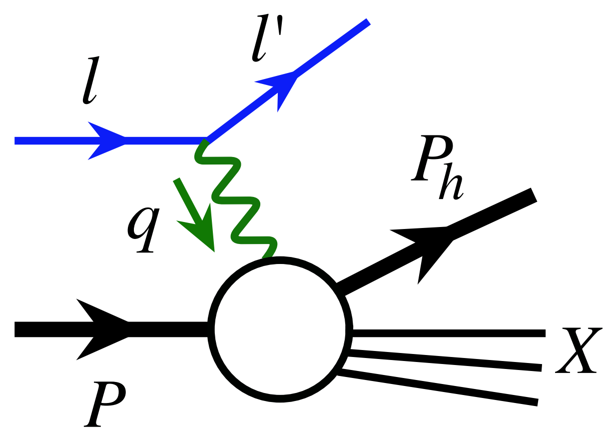
Y.-B. Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017).

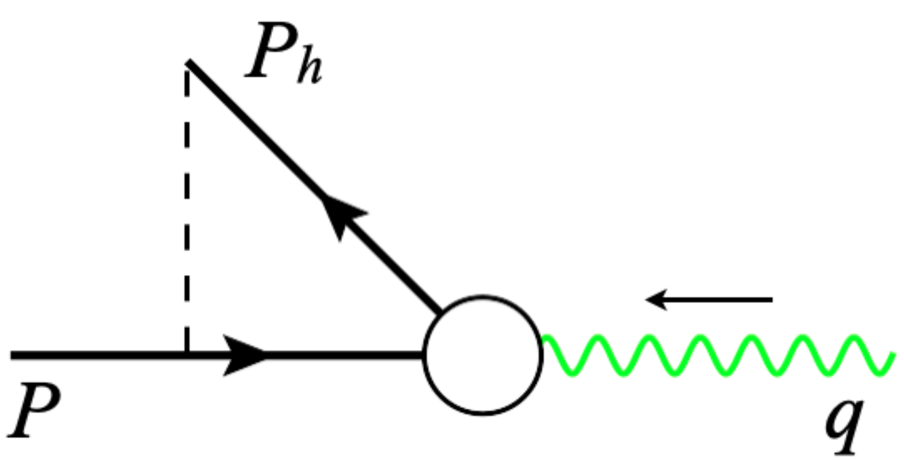


# Semi-inclusive Deep Inelastic Scattering

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

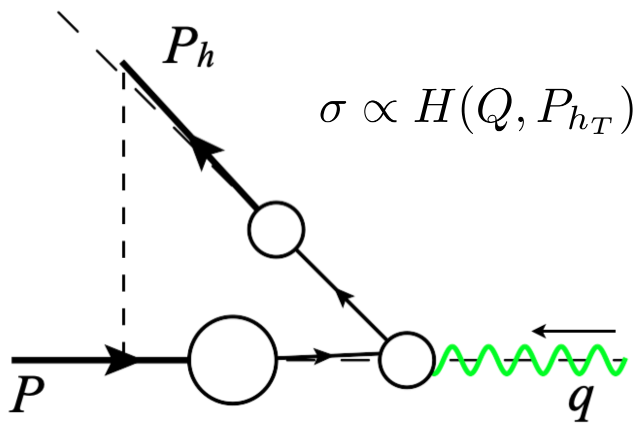
- enable us to explore the emergence of color neutral hadrons from colored quarks/gluons
- flavor dependence by selecting different types of observed hadrons: pions, kaons, …
- a large momentum transfer $Q$ provides a short-distance probe
- an additional and adjustable momentum scale $P_{h_T}$
- multidimensional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



# SIDIS Kinematic Regions

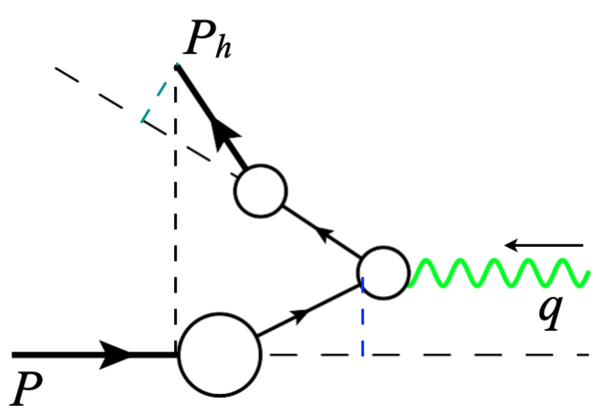
## Sketch of kinematic regions of the produced hadron



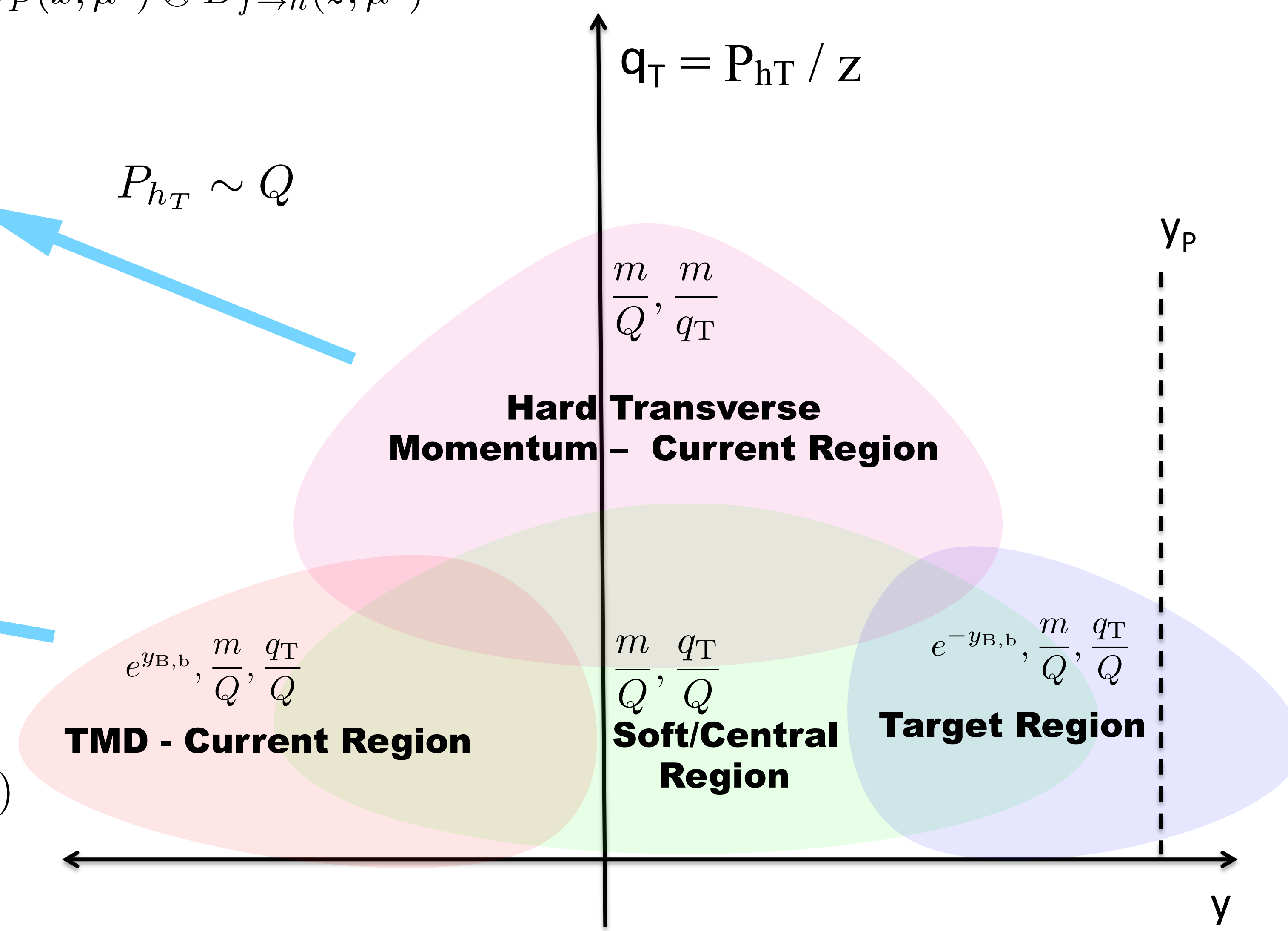

$\sigma \propto H(Q, P_{h_T}) \otimes \phi_{a/P}(x, \mu^2) \otimes D_{f\to h}(z, \mu^2)$

$P_{h_T} \sim Q$

$P_{h_T} \ll Q$




$\sigma \propto H(Q) \otimes \phi_{a/P}(x, k_T, \mu^2) \otimes D_{f\to h}(z, p_T, \mu^2)$



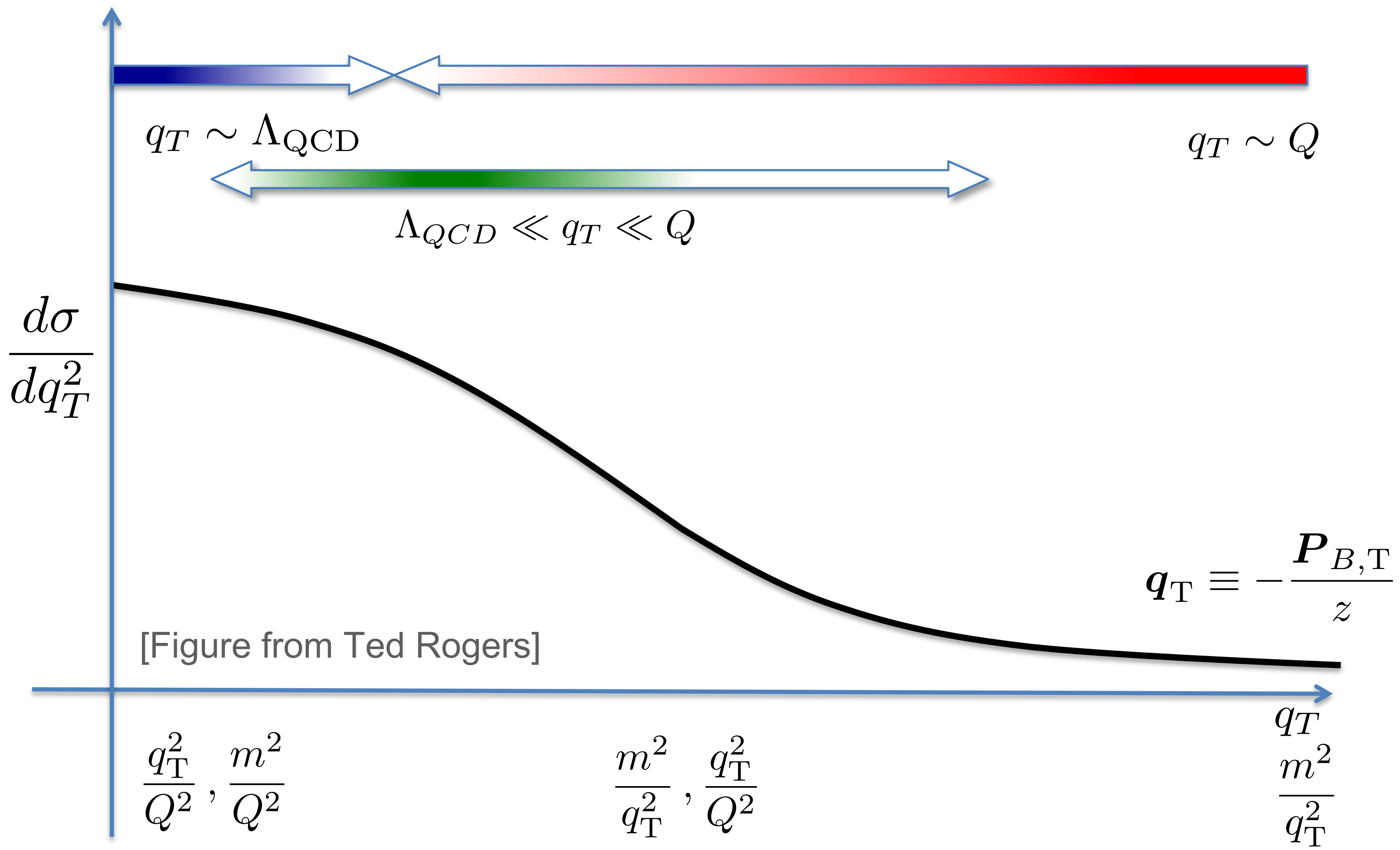

*$P_{hT}$ is defined in the photon-hadron frame*

[Figure from JHEP10(2019)122]

# Small and Large Transverse Momentum

W + Y formalism

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

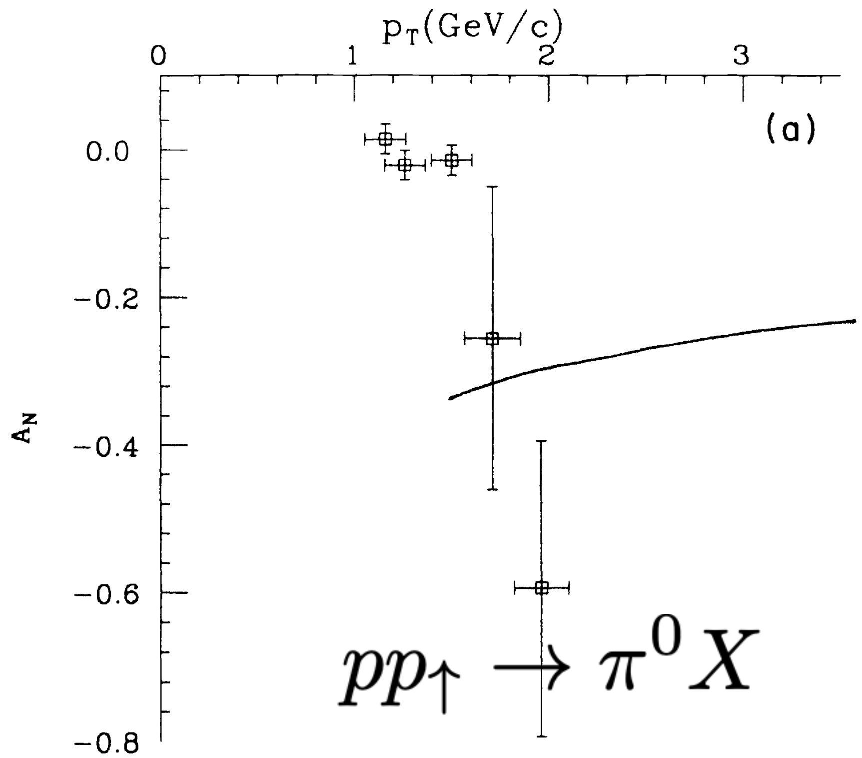



$$W(q_\mathrm{T}, Q) = \mathrm{T}_\mathrm{TMD}\, d\sigma$$

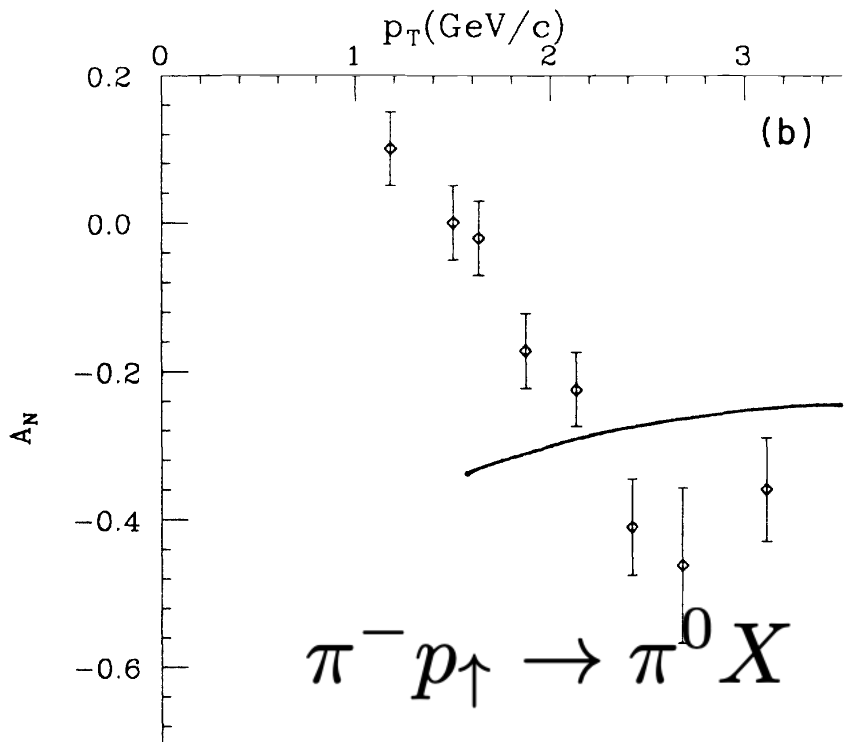
$$\begin{aligned} Y(q_\mathrm{T}, Q) &= X(q_\mathrm{T}/\lambda)\mathrm{T}_\mathrm{coll}\,(d\sigma - \mathrm{T}_\mathrm{TMD} d\sigma) \\ &= X(q_\mathrm{T}/\lambda)[\mathrm{FO}(q_\mathrm{T}, Q) - \mathrm{ASY}(q_\mathrm{T}, Q)] \end{aligned}$$

# 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.

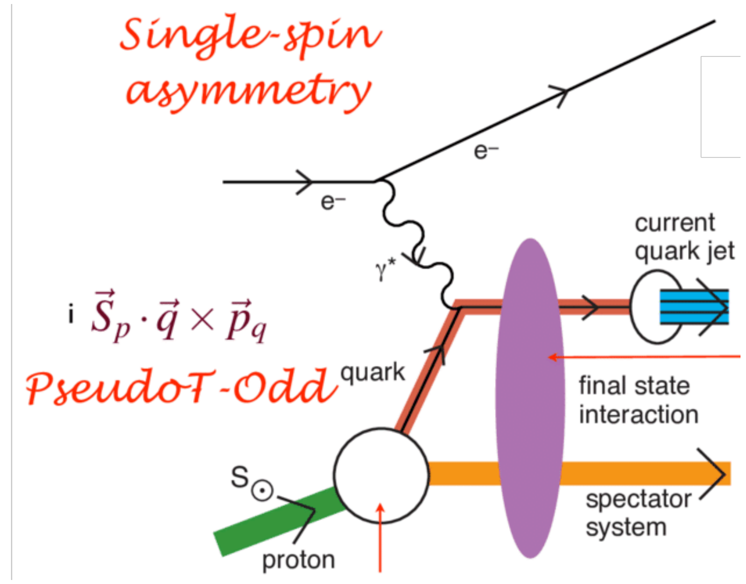
*For the next decade, the "Sivers effect" was thought to vanish.*

# Early Story: the Sivers function

**Until an explicit model calculation showing …**

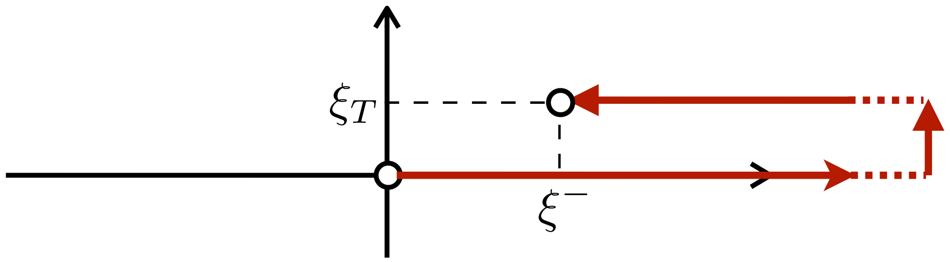
*nonzero Sivers effects exist at leading twist*
*due to final-state interactions*

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.

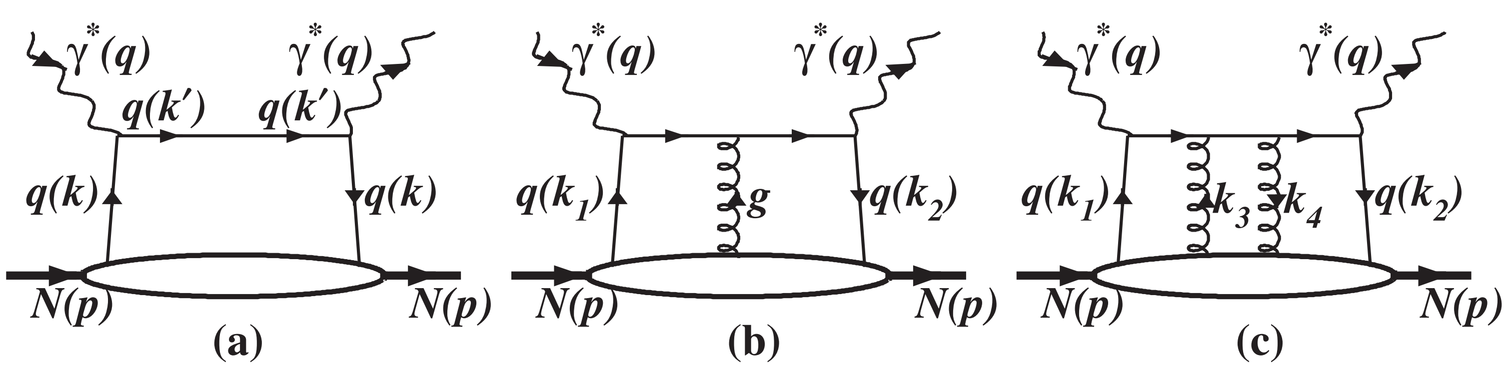
[Figure from A. Bacchetta]

This gauge link effect cannot be 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.






山东大学(青岛) SHANDONG UNIVERSITY, QINGDAO

# 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**<br>$h_{1T}^\perp$ **pretzelosity** |

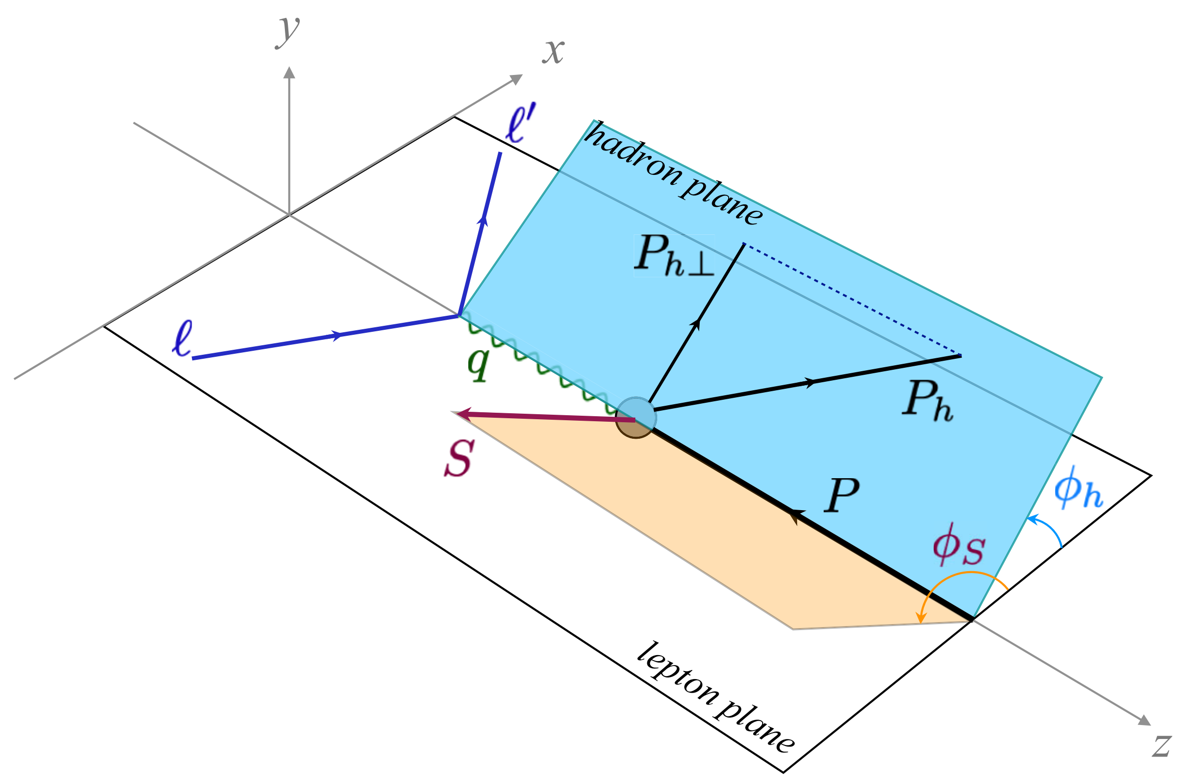
# SIDIS in Trento Convention

## SIDIS differential cross section

in terms of 18 structure functions

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

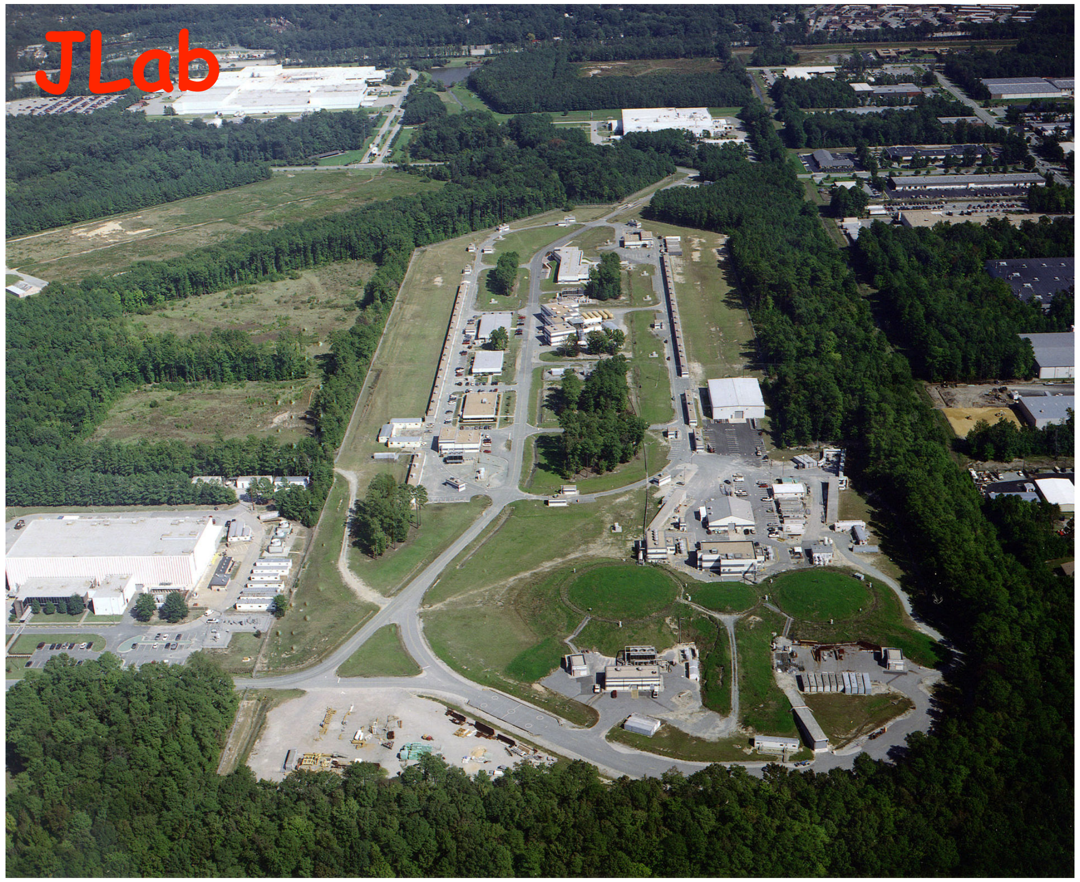
*A: lepton polarization*
*B: nucleon polarization*
*C: virtual photon polarization*

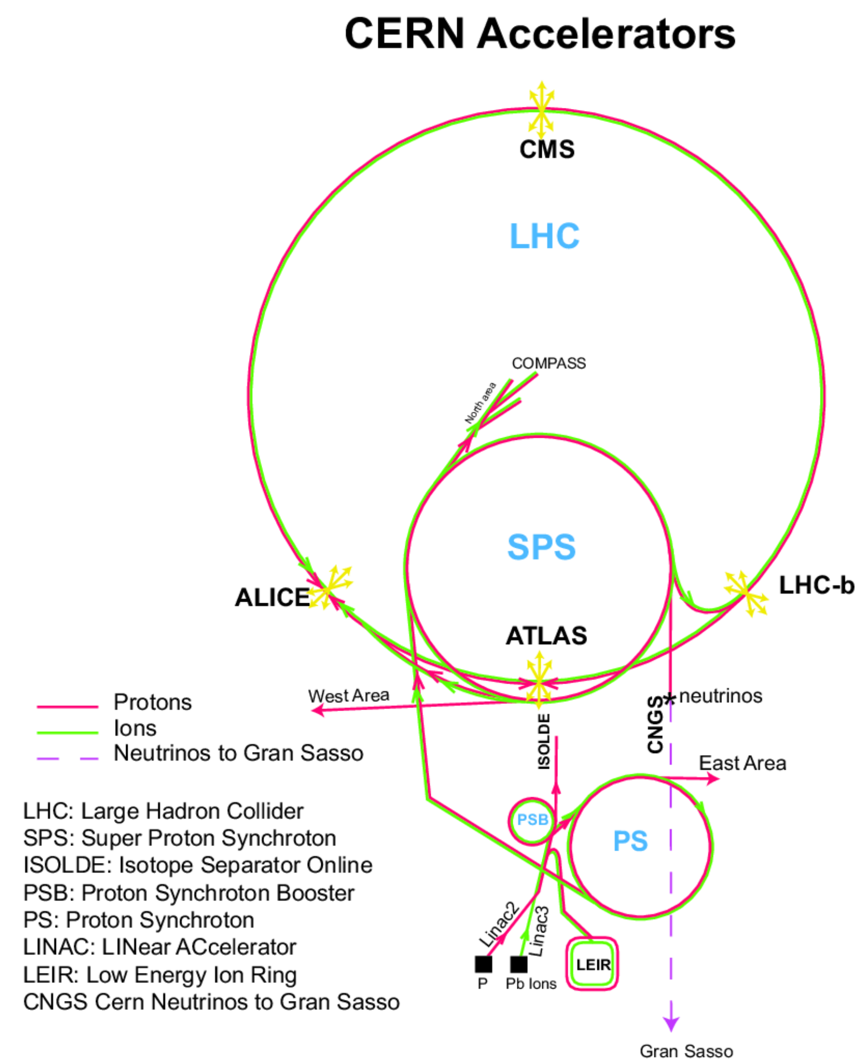


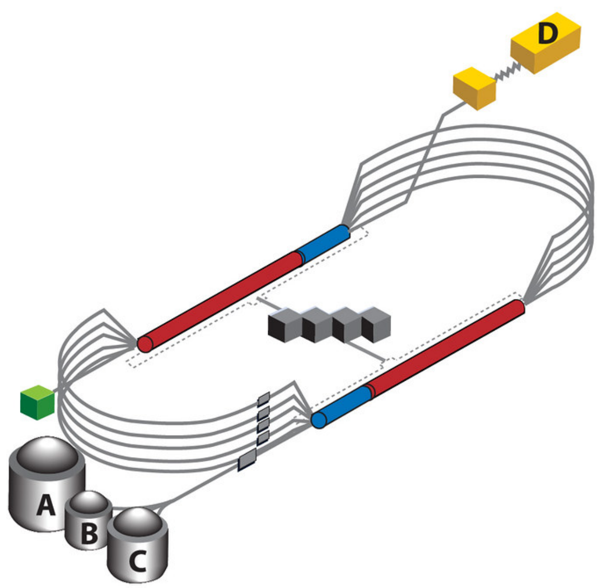

$$\frac{d\sigma}{dx_B\, dy\, dz\, dP_{hT}^2\, d\phi_h\, d\phi_S}$$

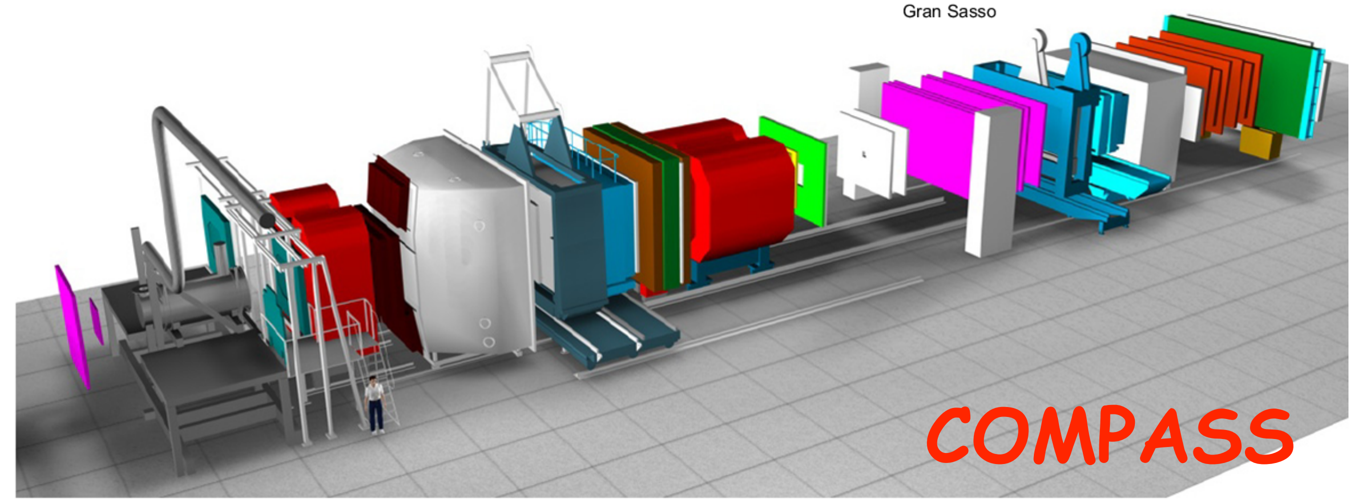
$$= \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)$$
$$\times\left\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h\right.$$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

# Fixed Target Experiments (Existing)

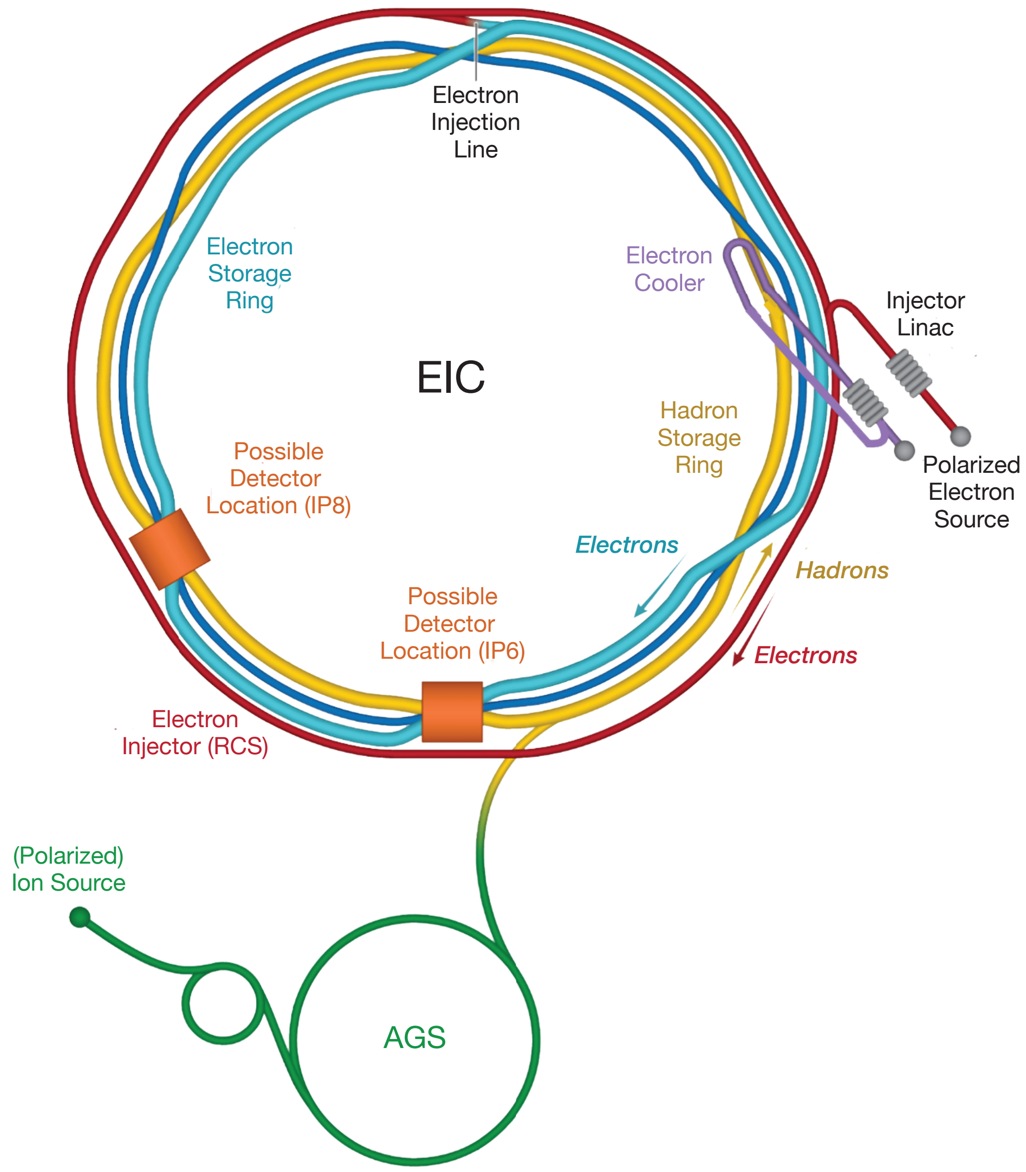


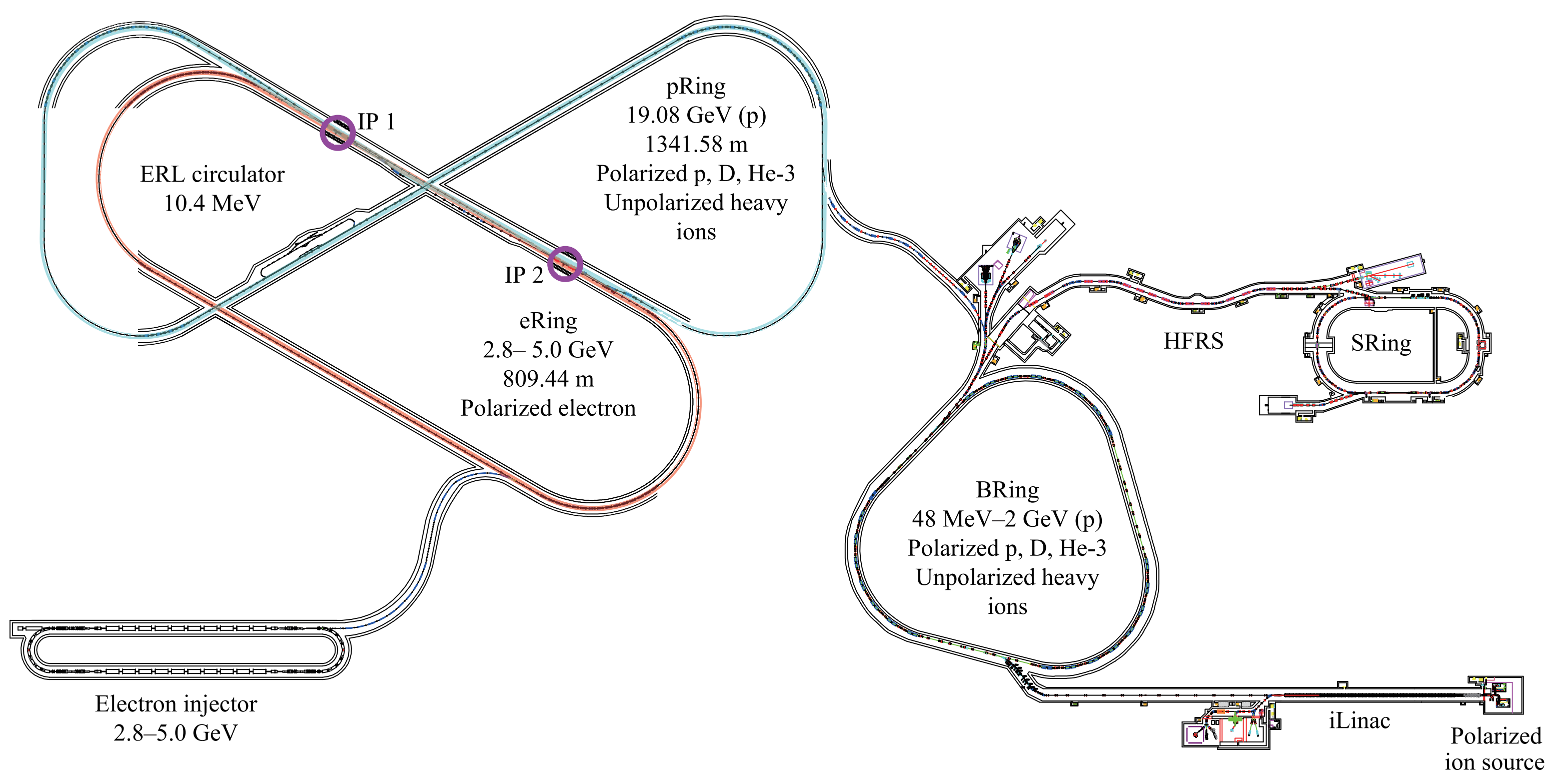



# Electron-Ion Colliders (Future)

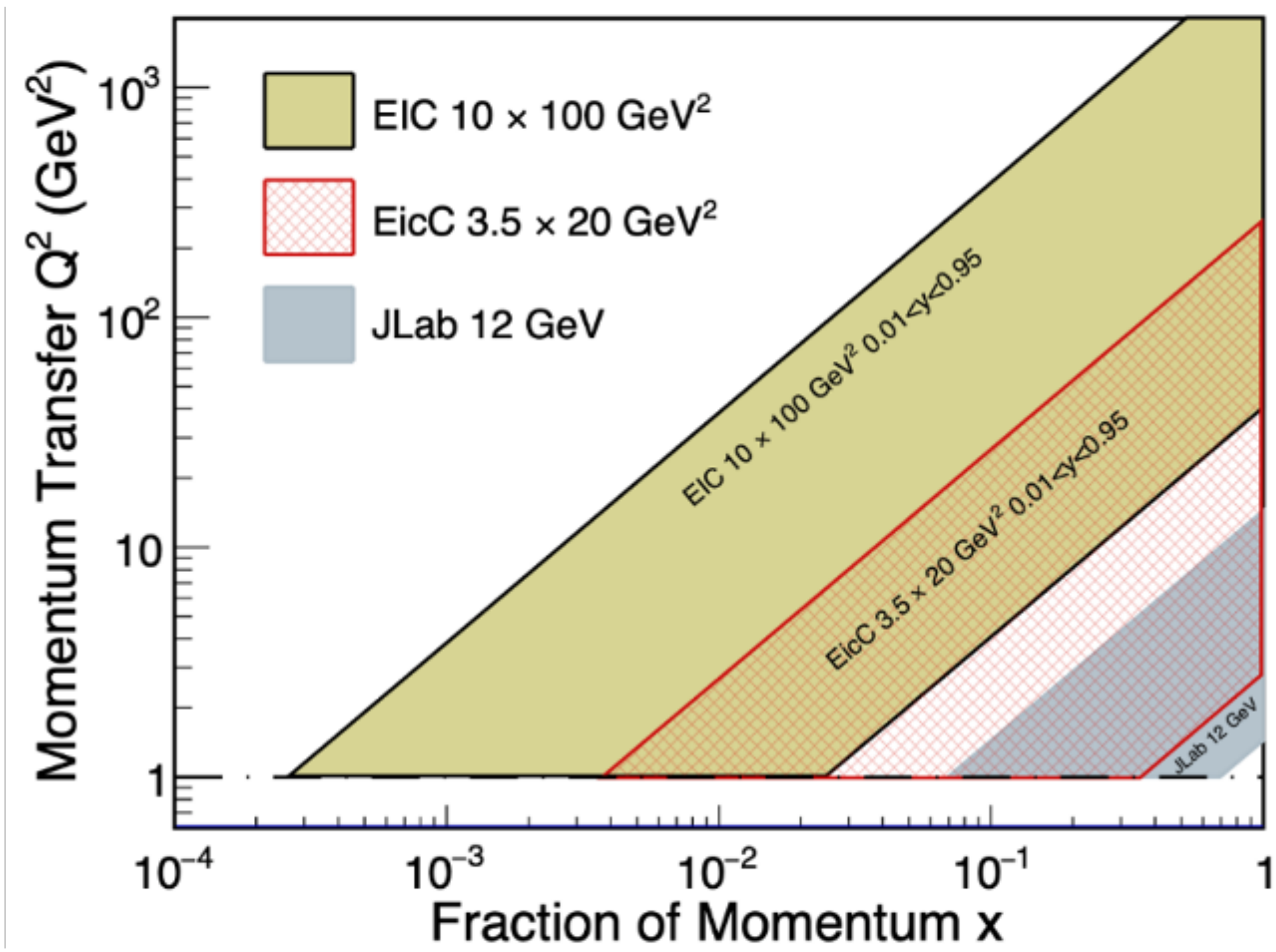



[Figure from EIC Yellow Report]




[Figure from EicC Whitepaper]

# Complementary Kinematic Coverage

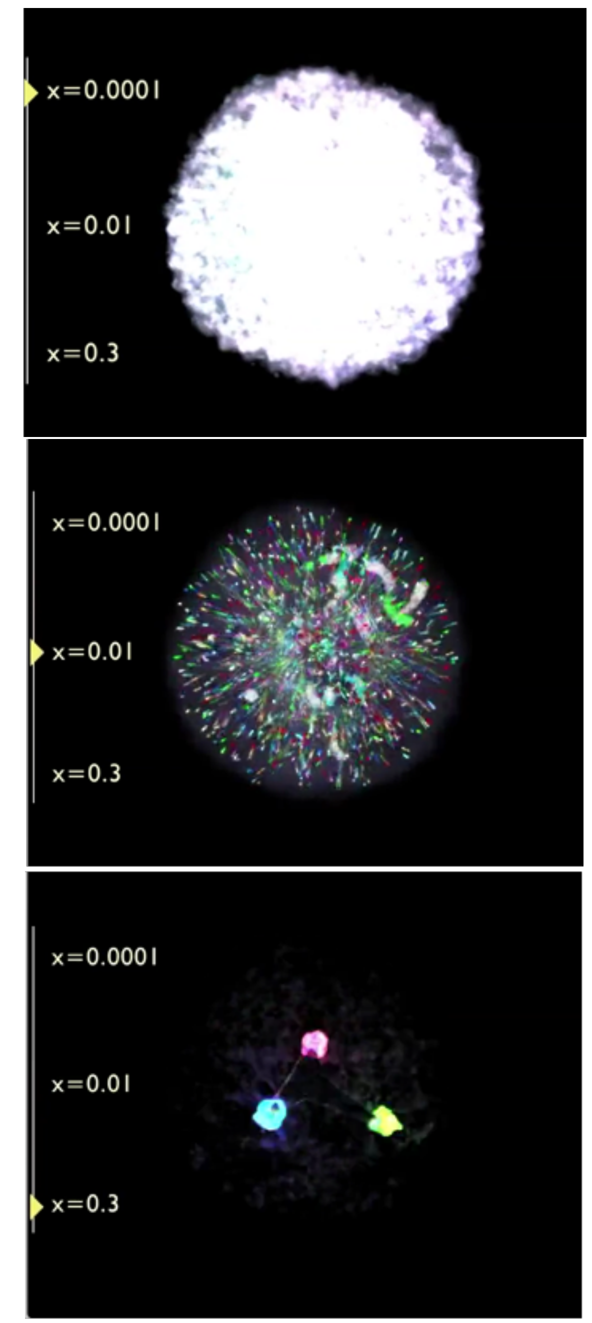



[Figure from EicC White paper]

*gluon dominates*

*sea quarks + gluons*

*valence dominates*




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

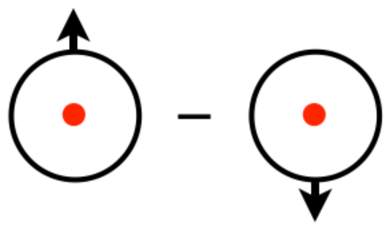
At a crucial place between JLab and EIC-US

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

# The Sivers Function

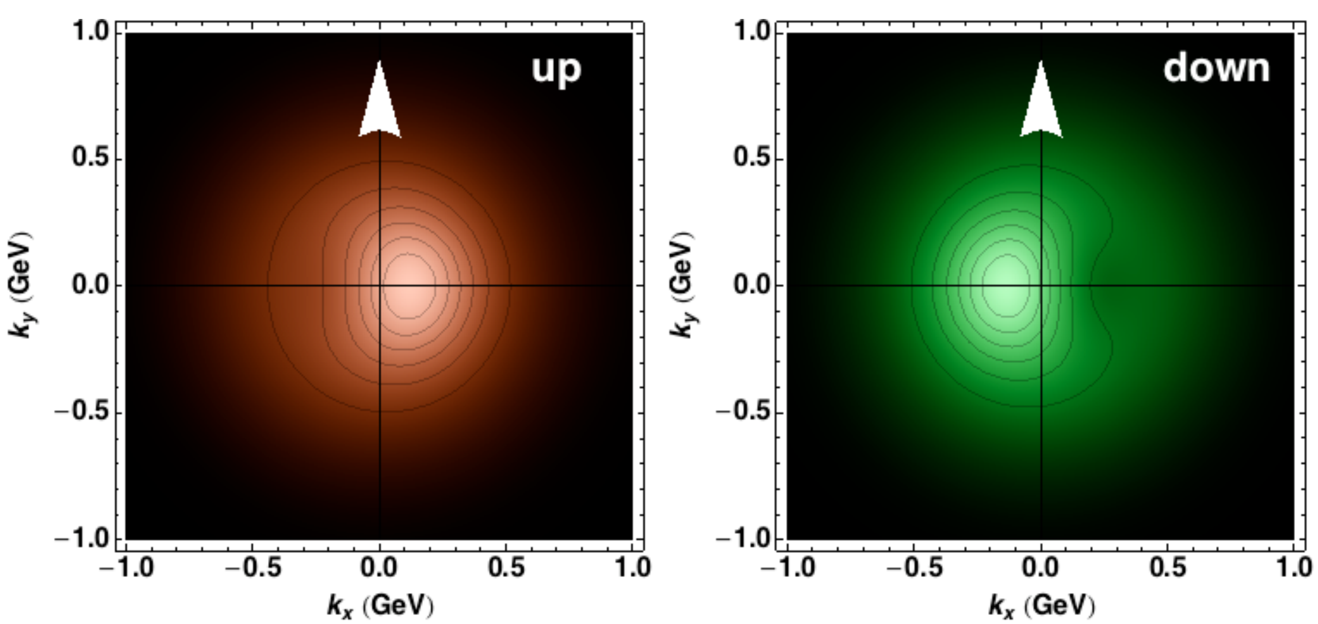
## Sivers TMD distribution function

$$f_{1T}^{\perp}(x, \mathbf{k}_{\perp})$$



*A naive T-odd distribution function*

Transverse momentum distribution distorted by nucleon transverse spin




[Figure from A. Bacchetta]

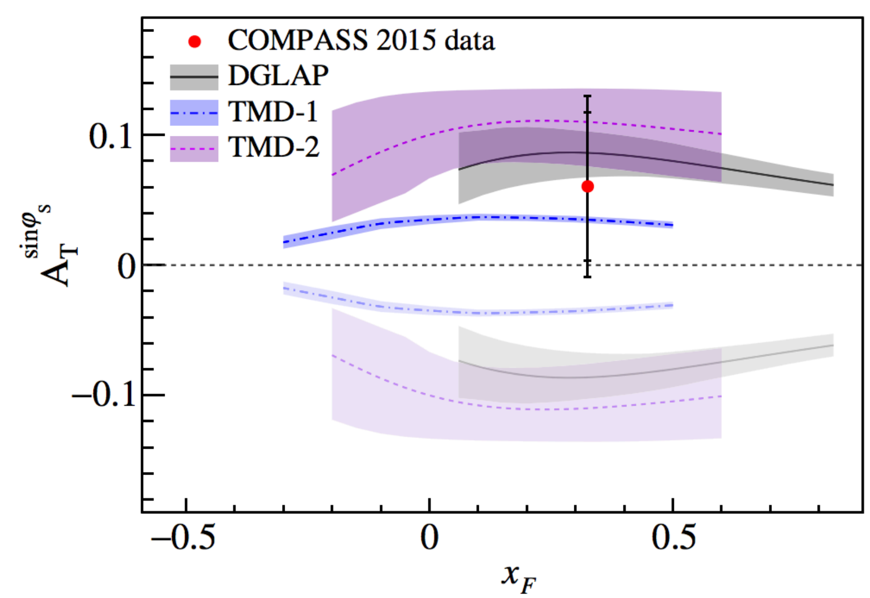
**Effect in SIDIS:**
transverse single spin asymmetry (Sivers asymmetry)

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

sizable Sivers asymmetry observed by HERMES, COMPASS, JLab

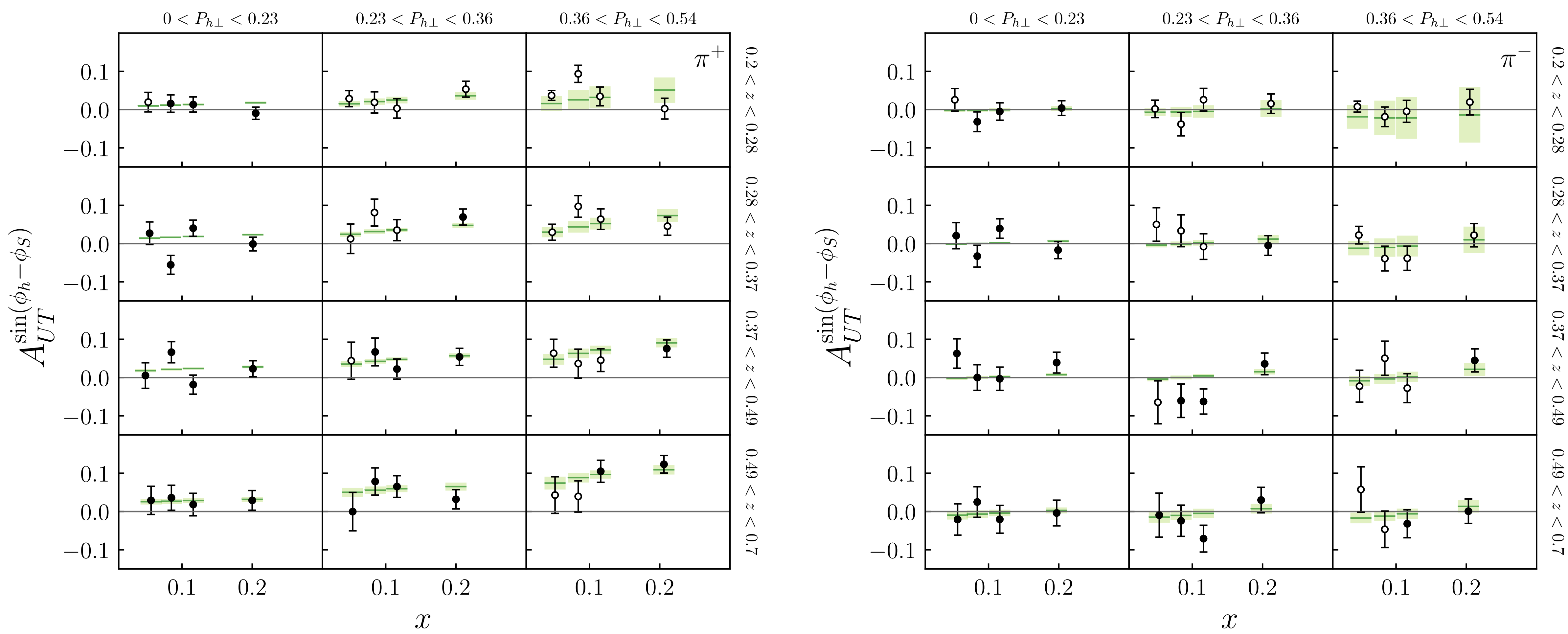
**Sign change prediction:**

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



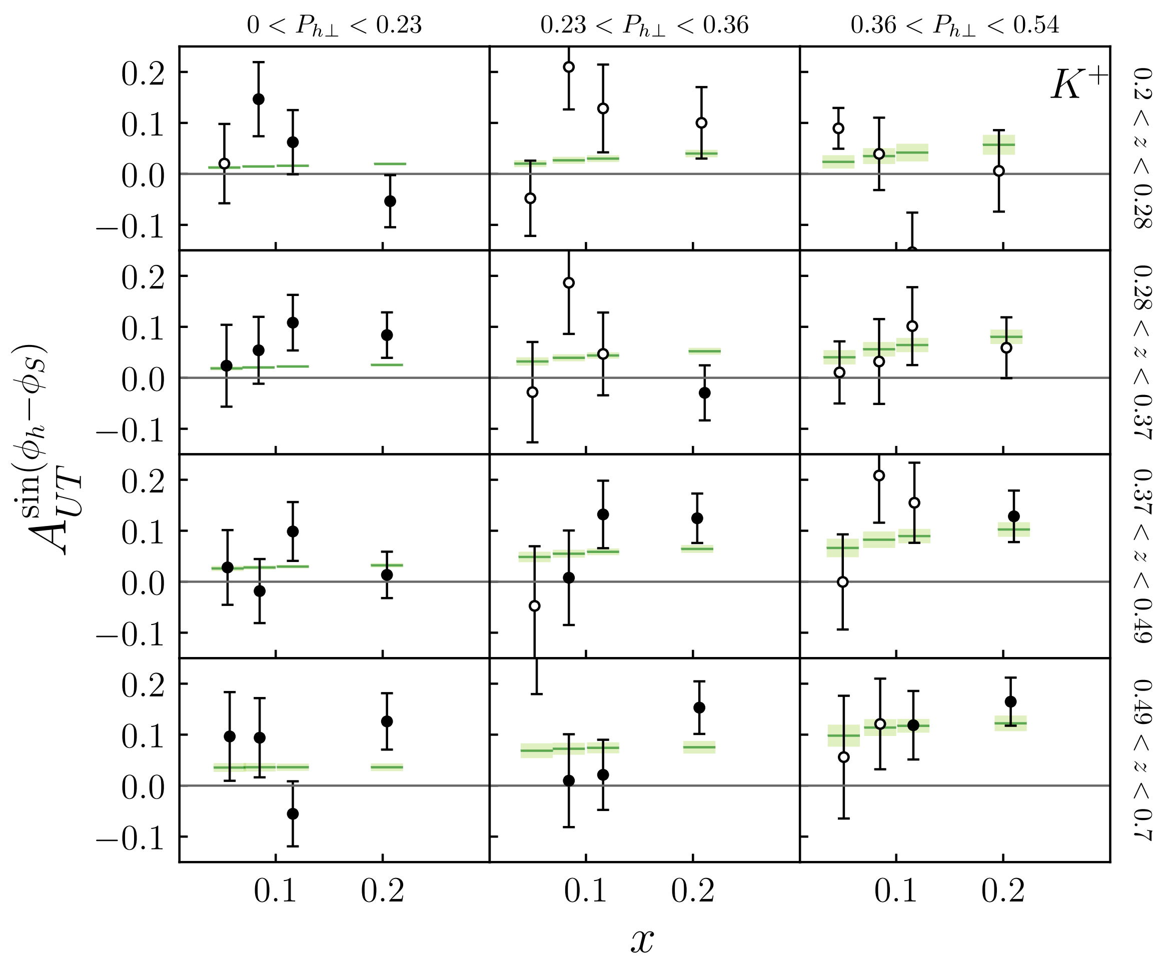

COMPASS Collaboration, PRL 119, 112002 (2017).

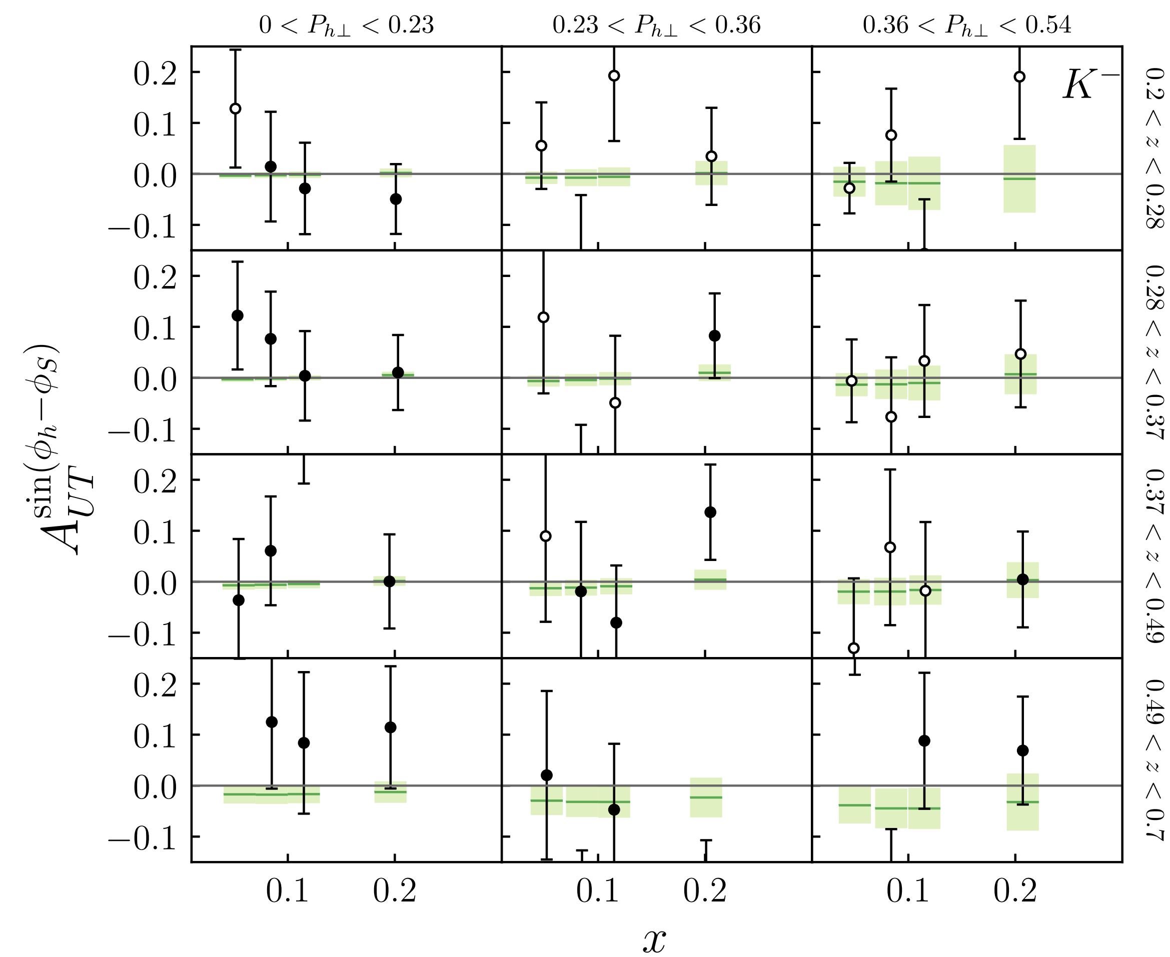
# Measurements of the Sivers Asymmetry




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

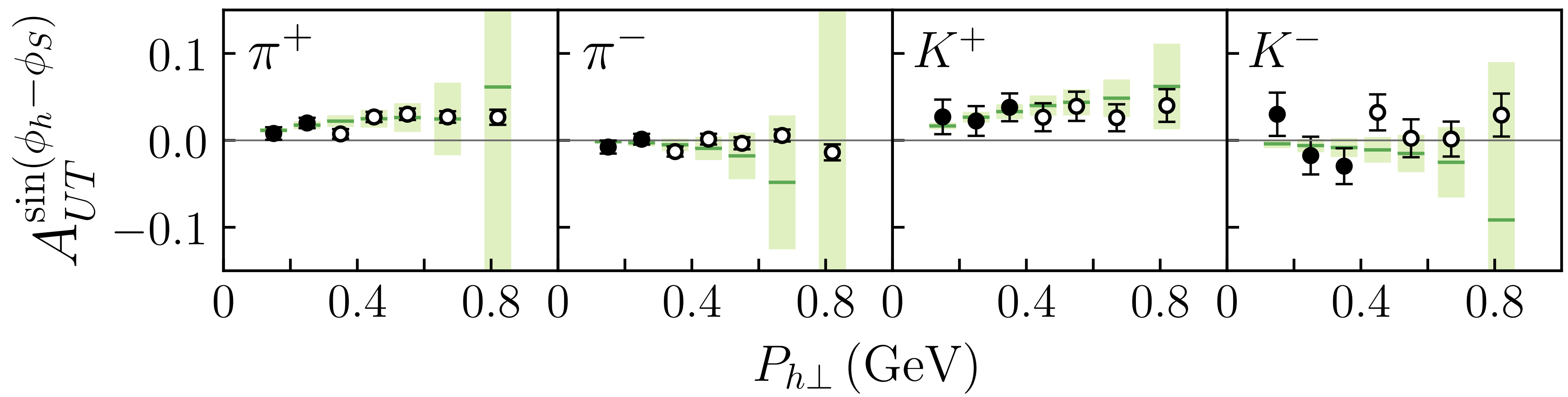
# Measurements of the Sivers Asymmetry

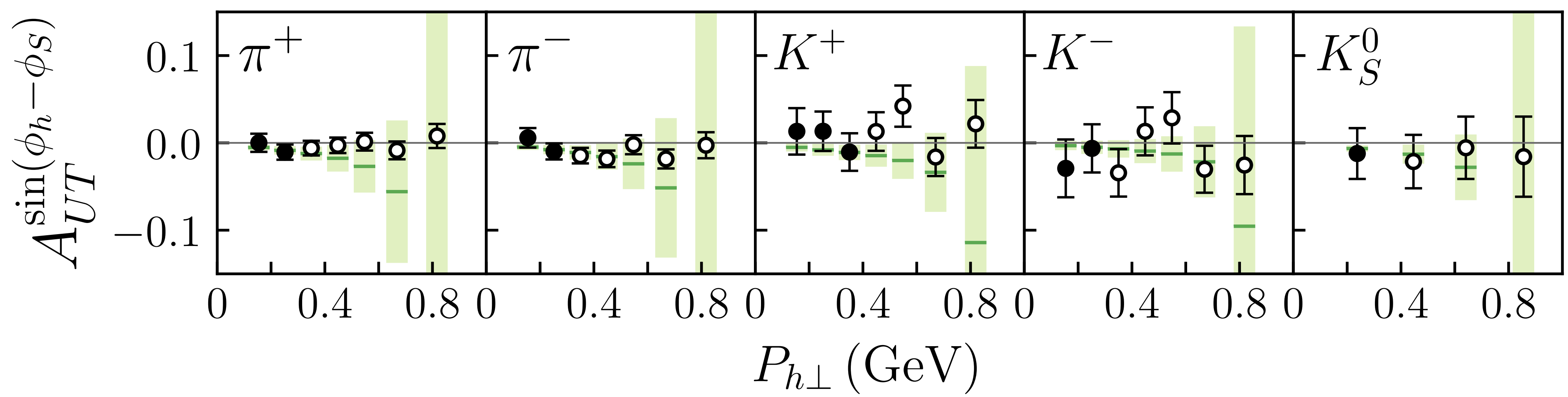



HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

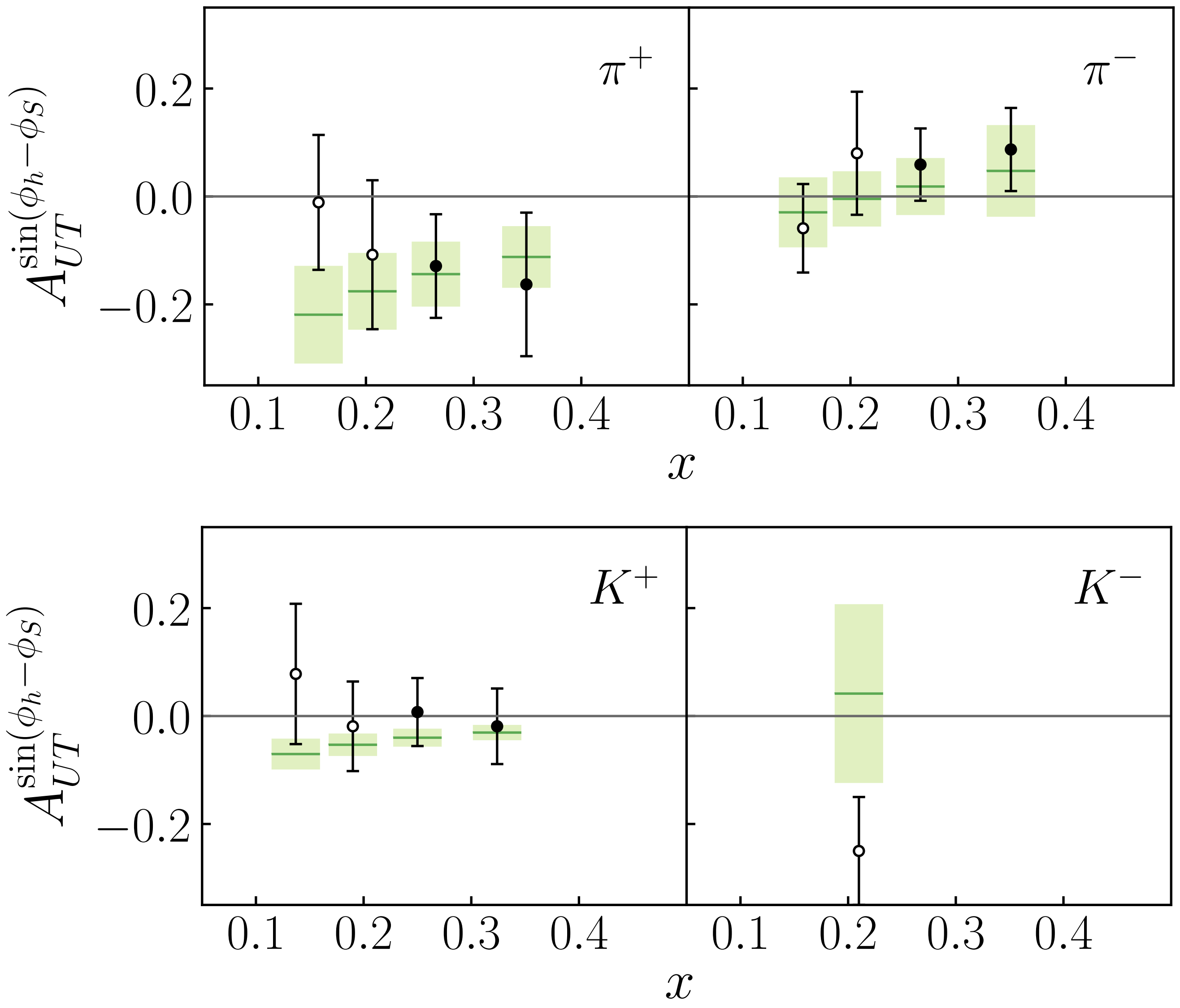
# Measurements of the Sivers Asymmetry



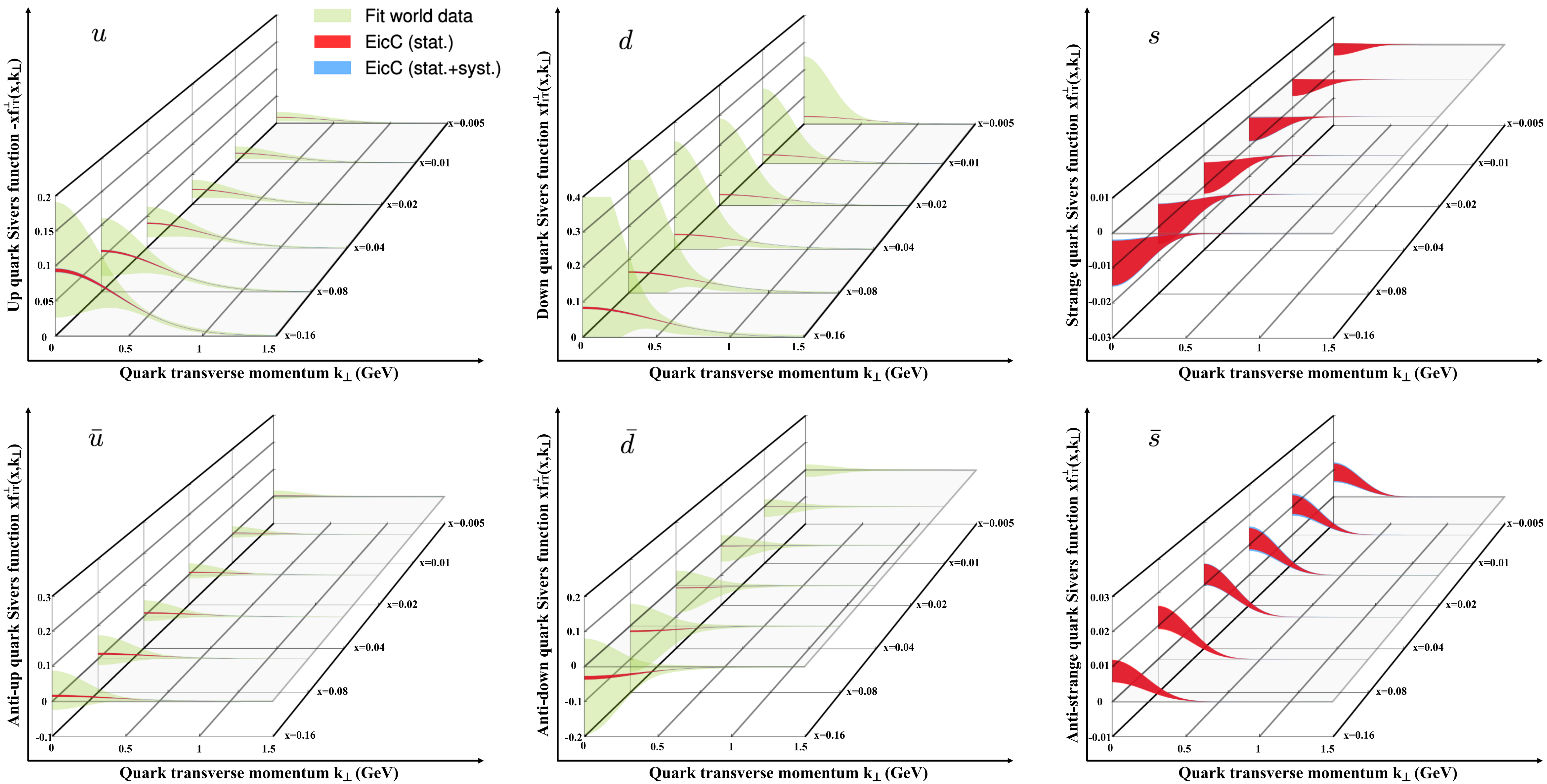

COMPASS Collaboration, Phys. Lett. B 673 (2009) 127; Phys. Lett. B 744 (2015) 250.

# Measurements of the Sivers Asymmetry



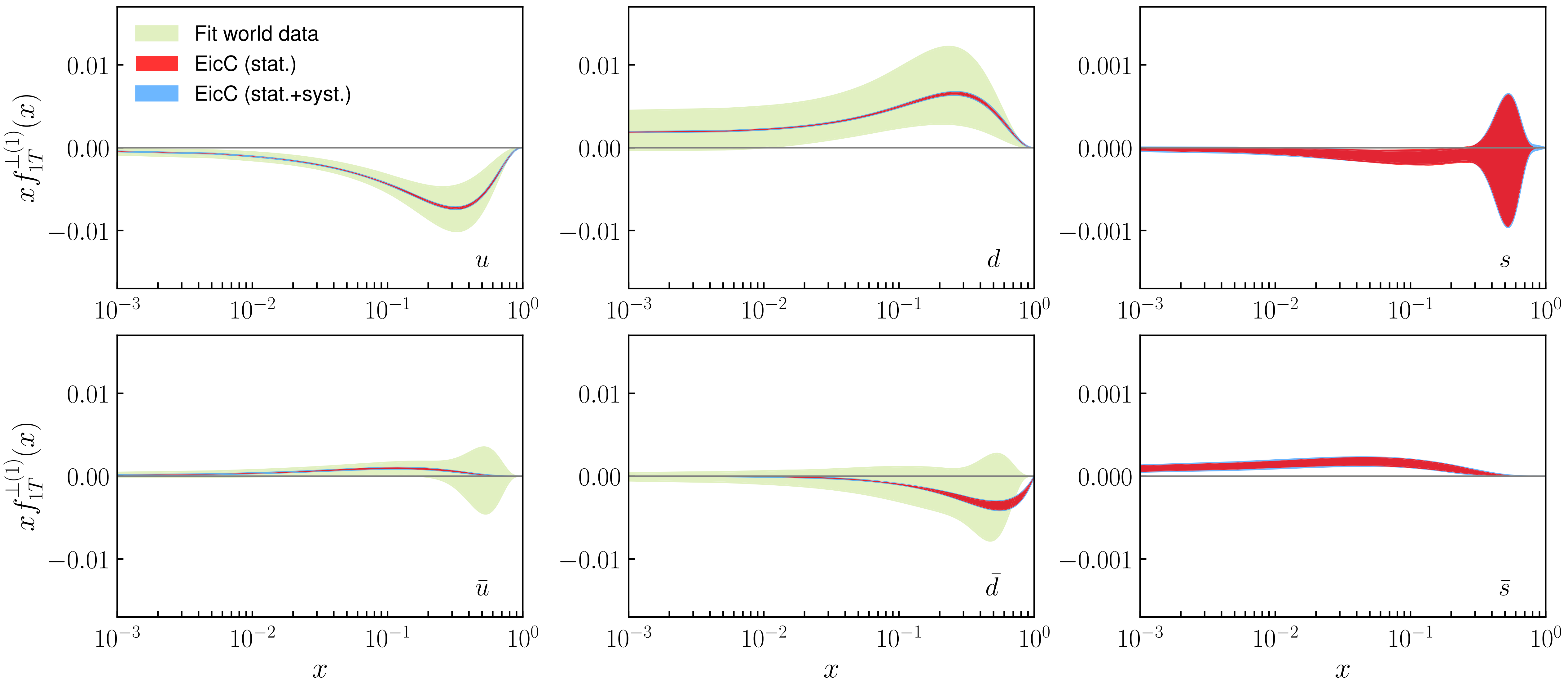

JLab HallA Collaboration, Phys. Rev. Lett. (2011) 072003; Phys. Rev. C 90 (2014) 055201.

# Extraction of the Sivers function




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

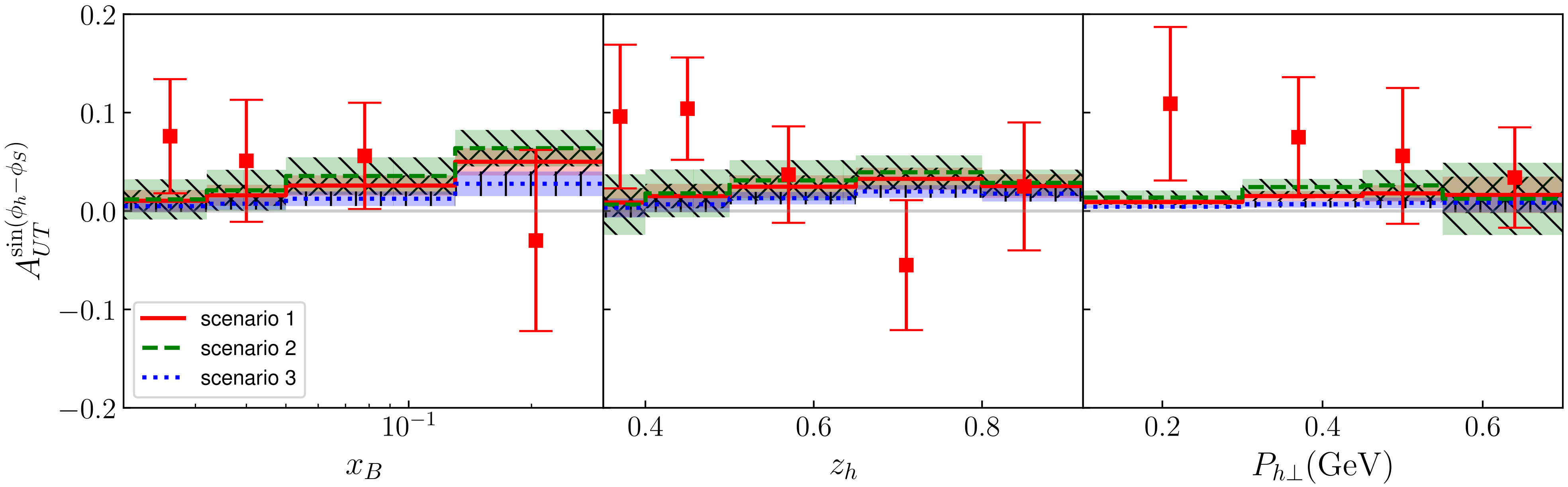
# EicC Impact: Sivers function



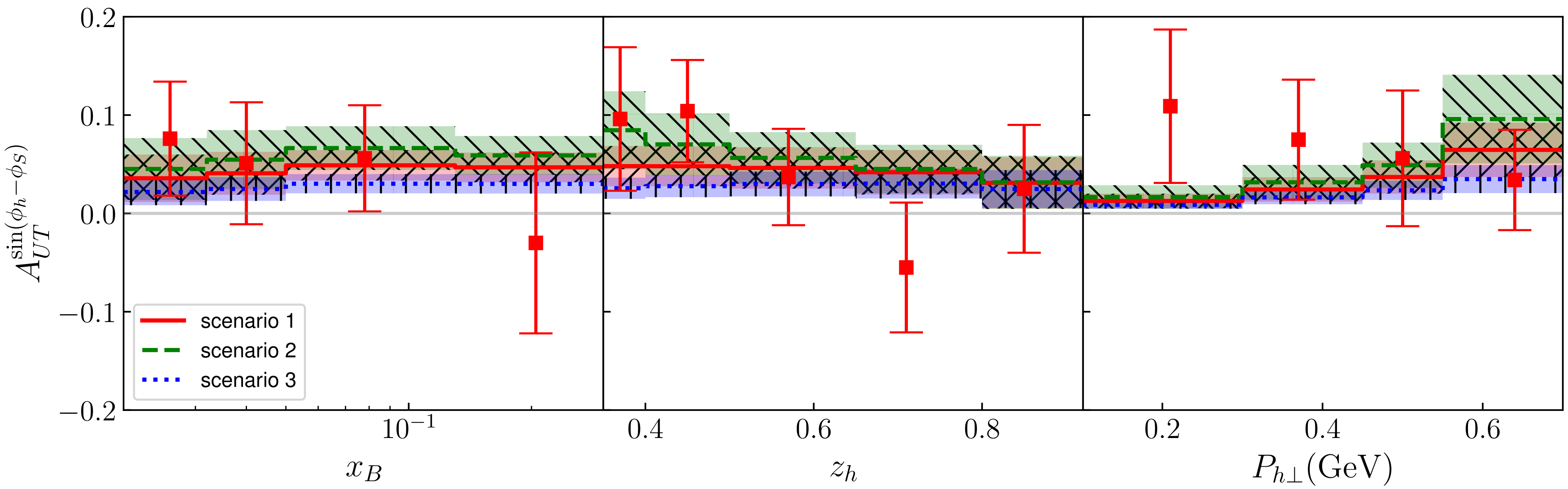

$$f_{1T}^{\perp(1)}(x) = \pi \int d\mathbf{k}_\perp^2 \frac{\mathbf{k}_\perp^2}{2M^2} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$

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

# Sivers Asymmetry of $\rho^0$ 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.

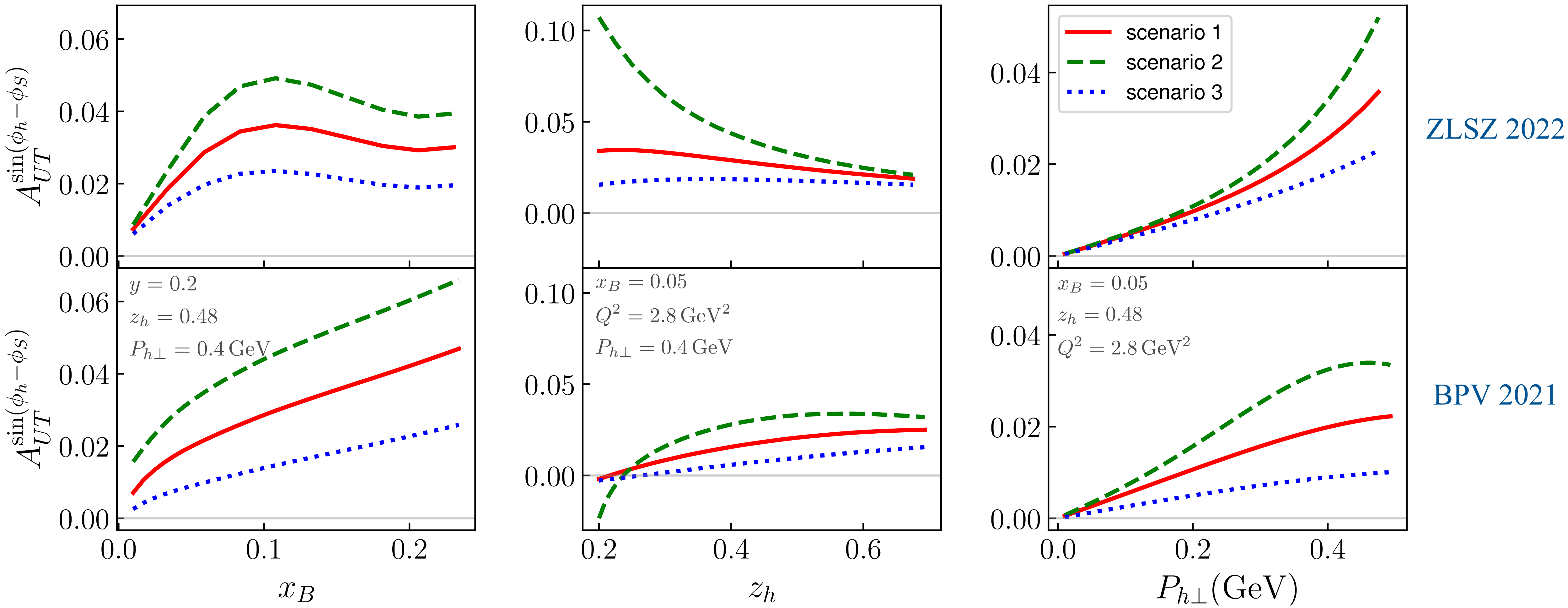
Scenarios: different transverse momentum dependences of $\rho^0$ fragmentation functions

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

# Sivers Asymmetry of $\rho^0$ Production

**Predictions at EicC kinematics:**

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

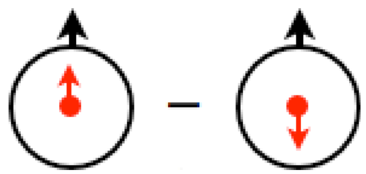



Different predictions to be tested at EicC kinematics

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

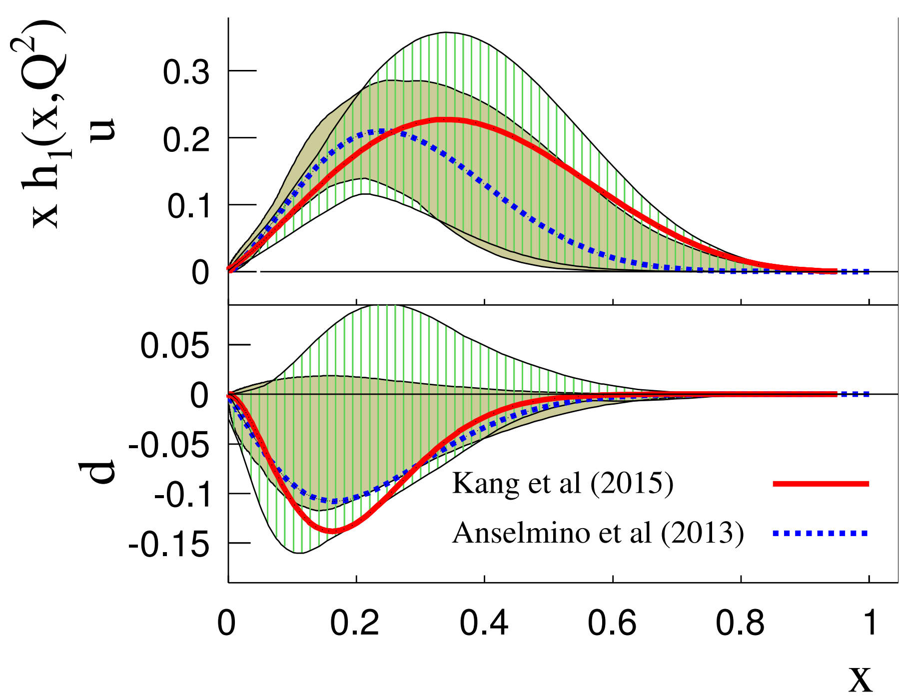
# Transversity Distribution

## Transversity distribution

$h_1$  (Collinear & TMD)

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

## Phenomenological extractions



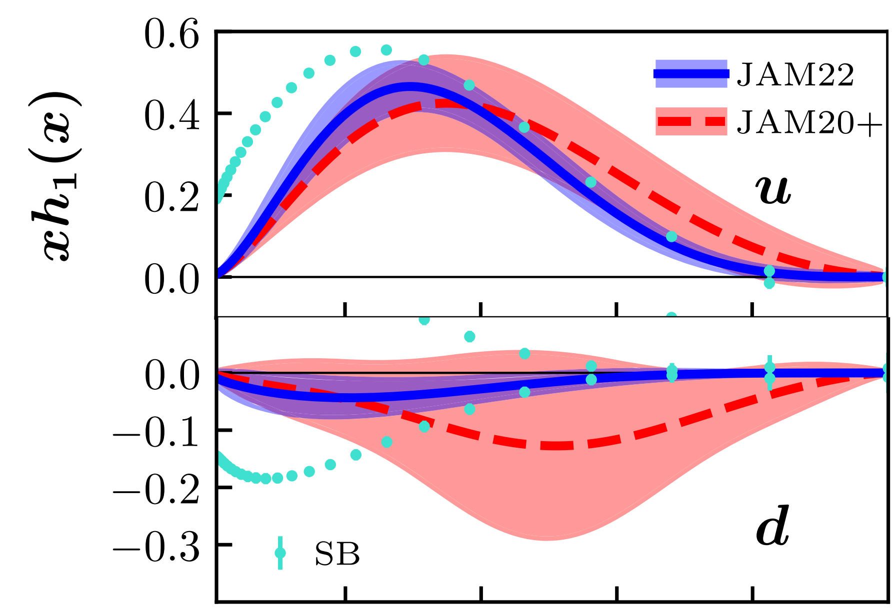

Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, PRD 93, 014009 (2016).

**Chiral-odd:**

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

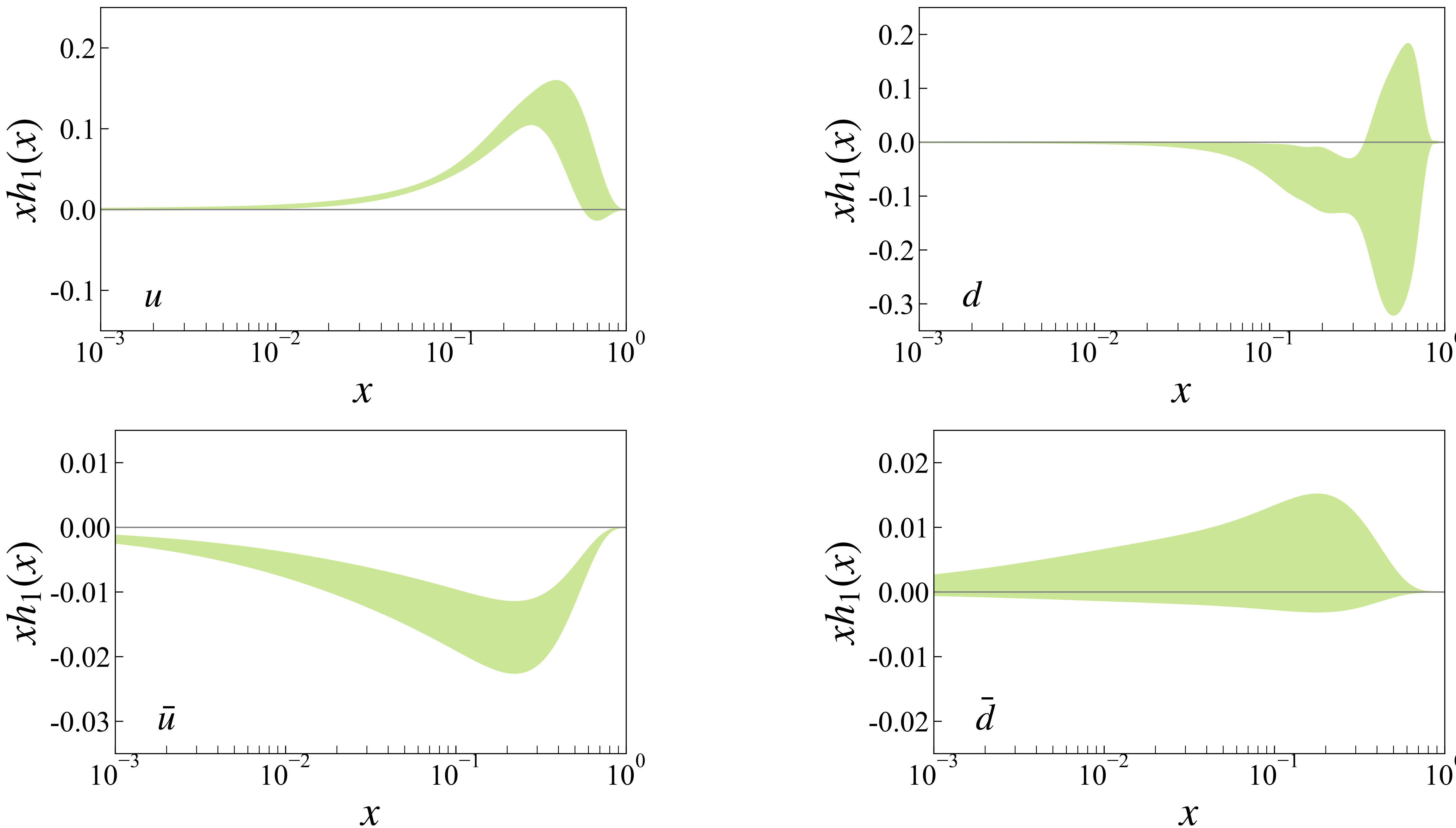
**Effect in SIDIS:**
transverse single spin asymmetry (Collins asymmetry)

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




JAM Collaboration, PRD 104, 034014 (2022).

# Sea Quark Transversity

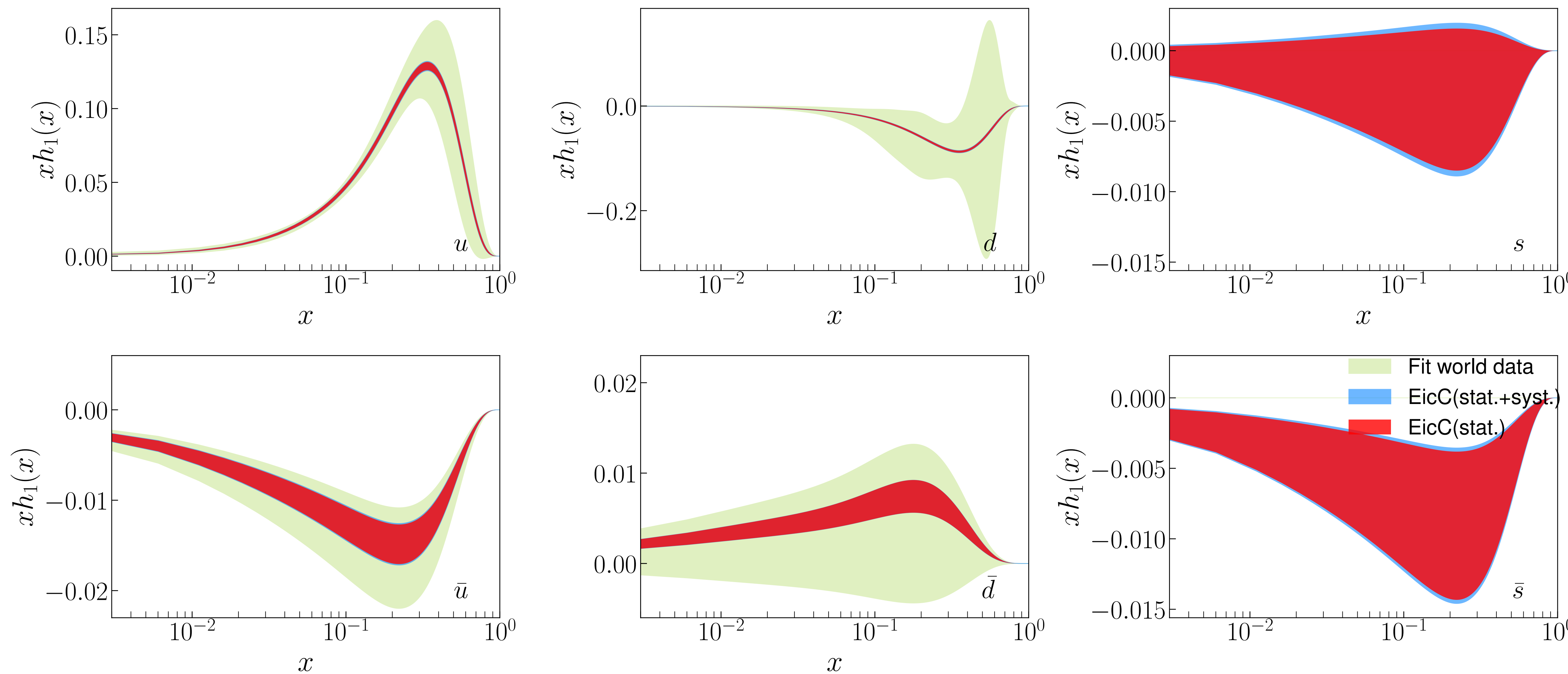



Anti-u quark favors negative distribution

Anti-d quark consistent with zero with current precision

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

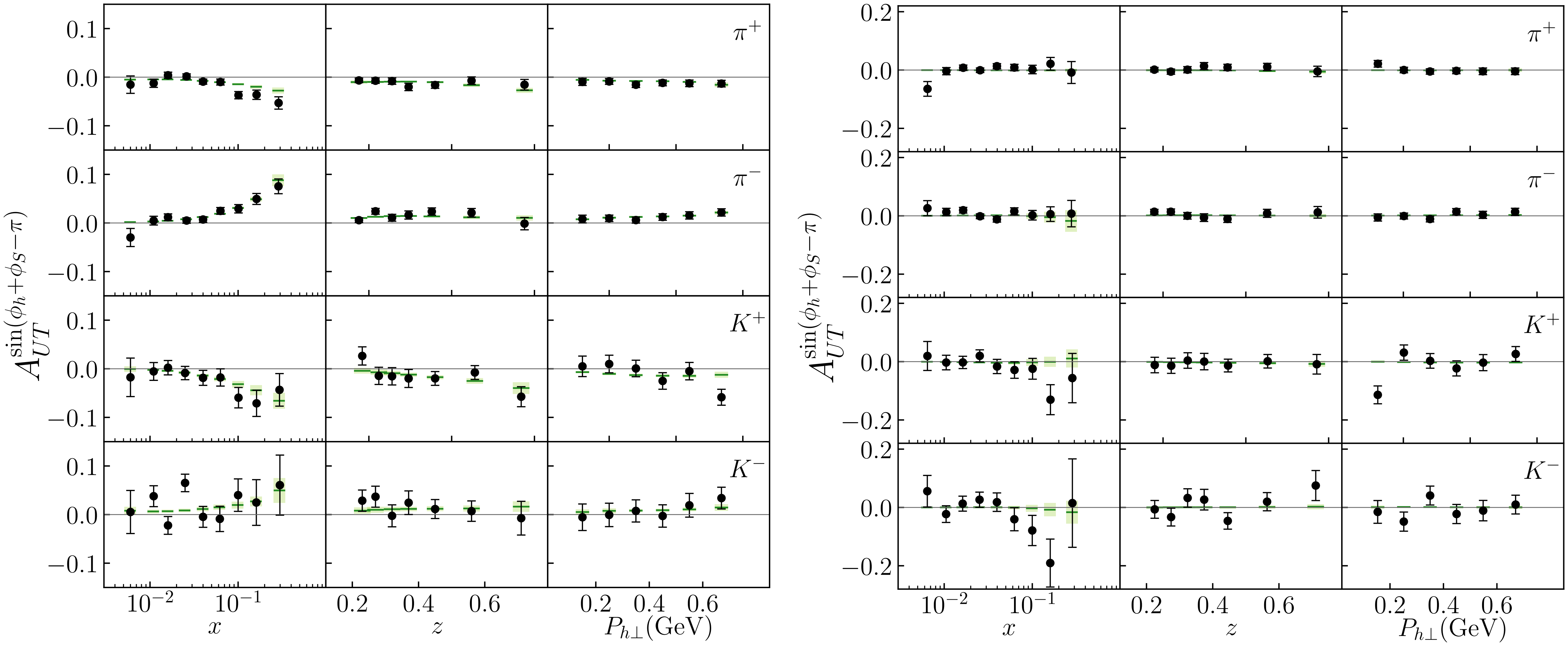
# EicC Impact on Transversity




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

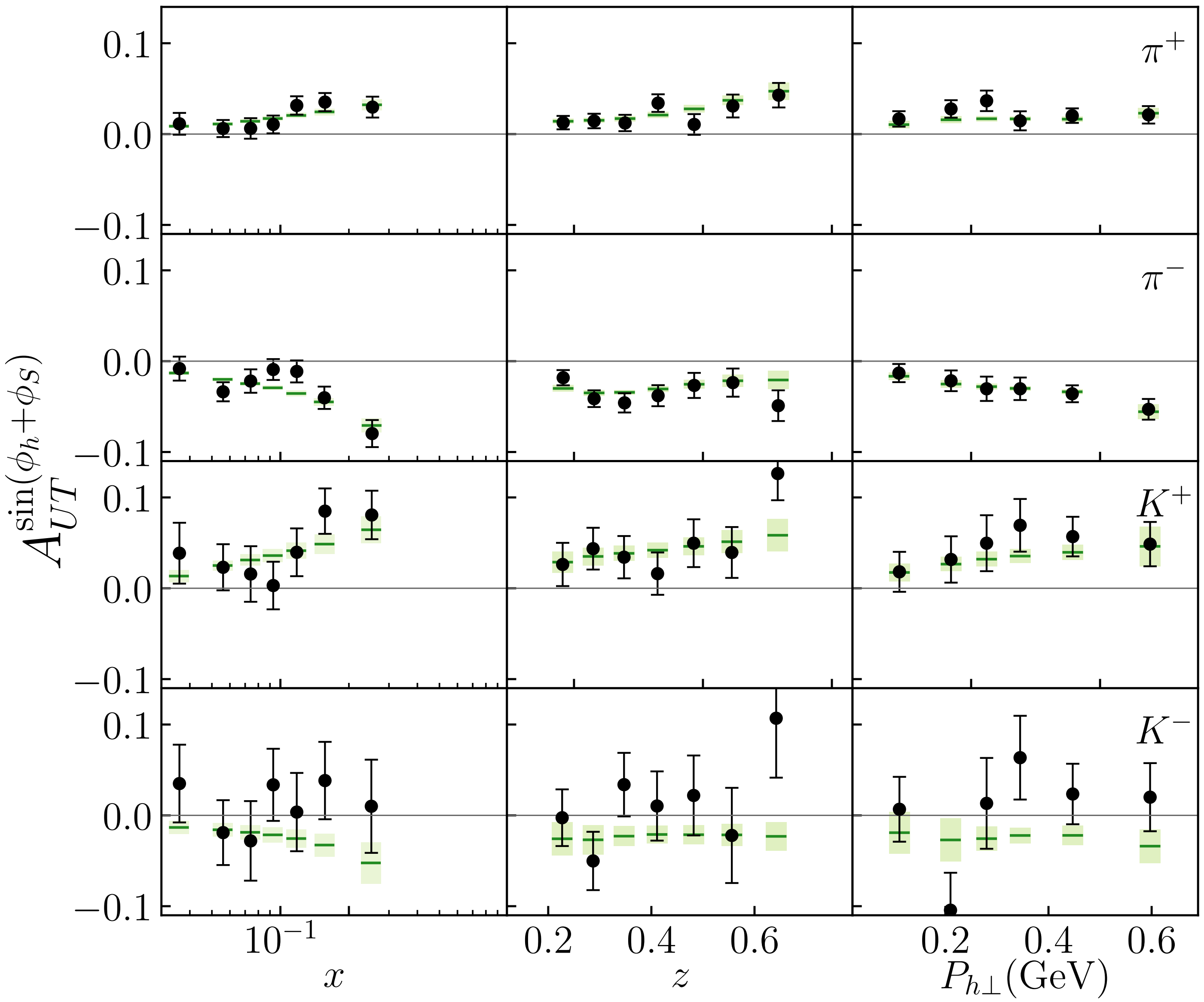
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, PRD 109 (2024) 056002.

# Comparison with Data



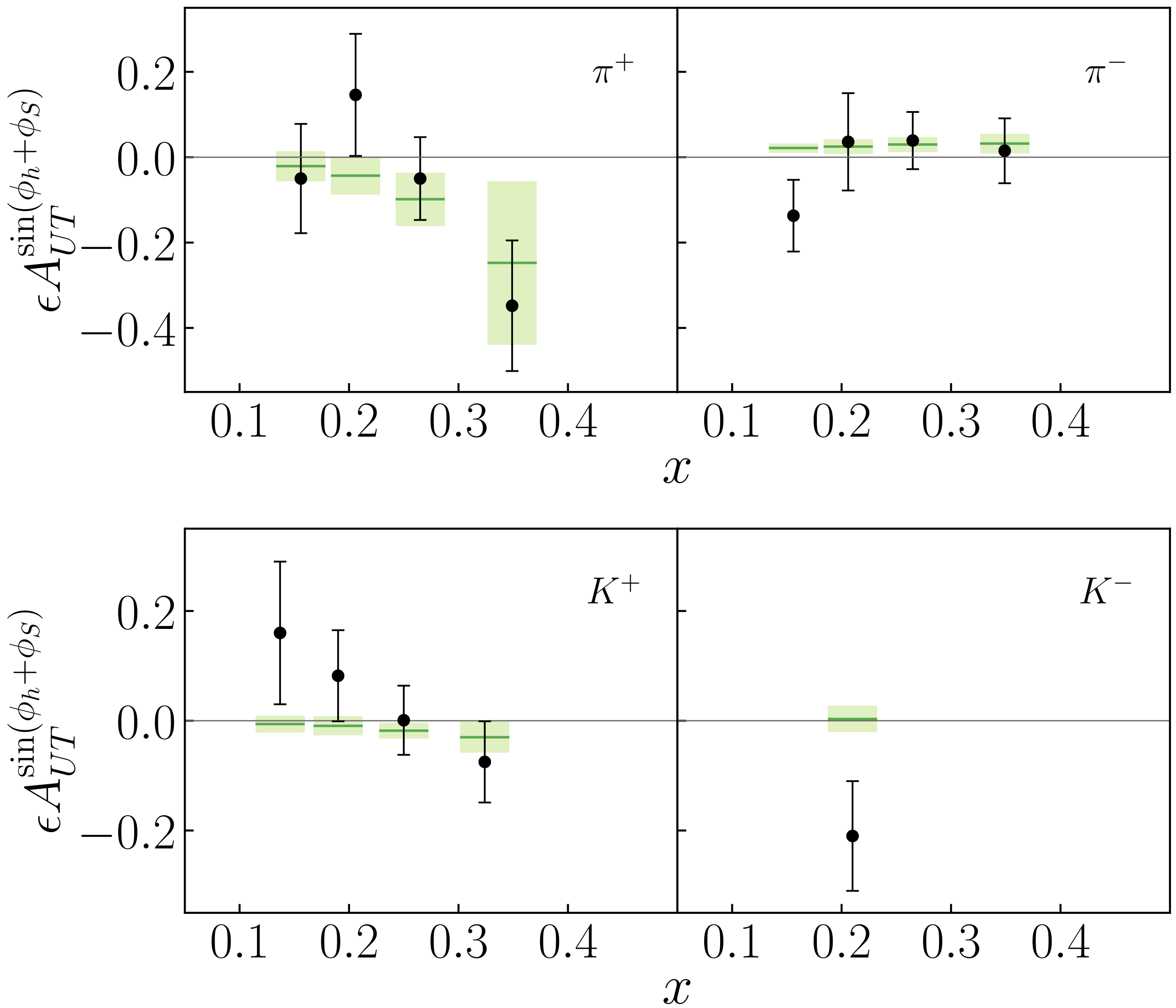

COMPASS Collaboration, Phys. Lett. B 673 (2009) 127; Phys. Lett. B 744 (2015) 250.

# Comparison with Data




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

# Comparison with Data



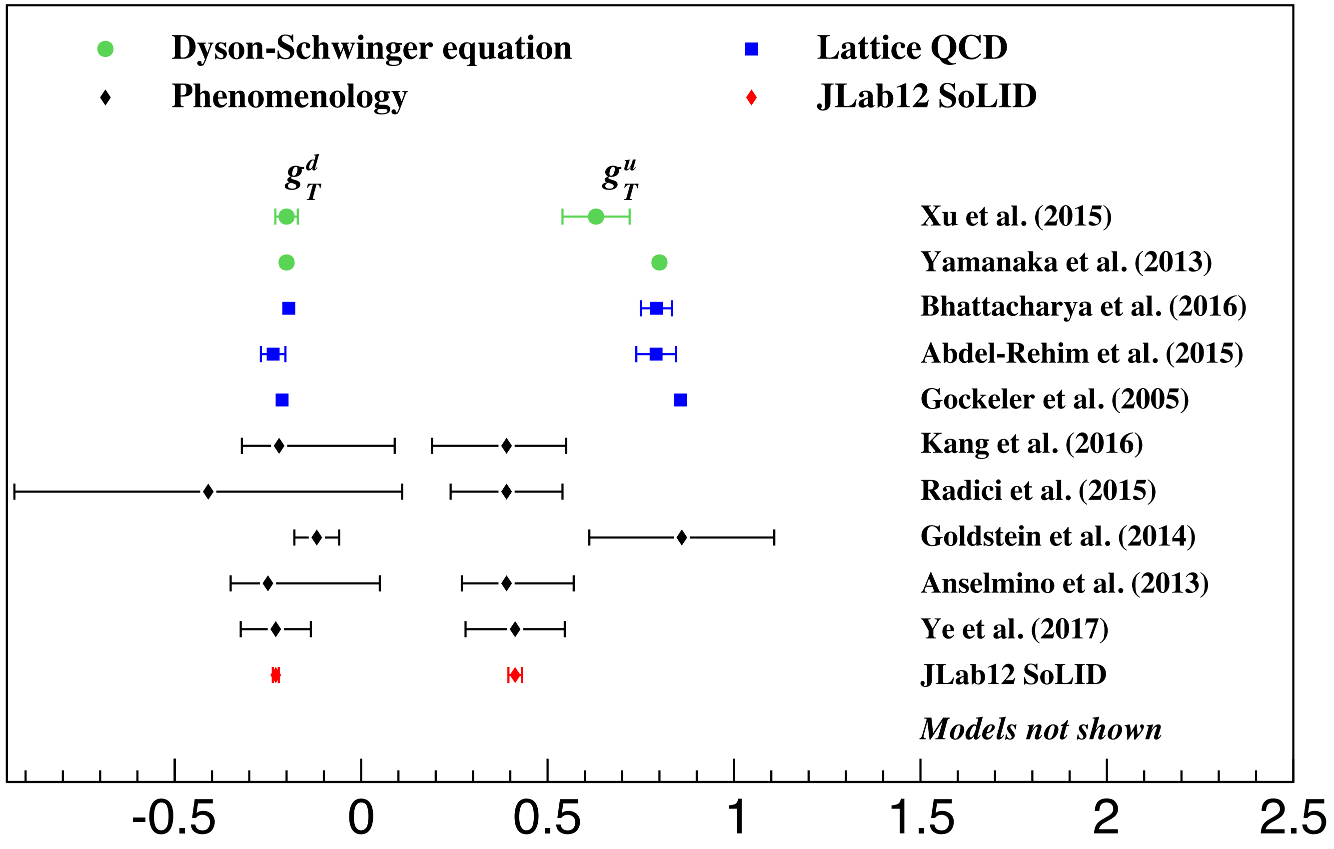

JLab HallA Collaboration, Phys. Rev. Lett. (2011) 072003; Phys. Rev. C 90 (2014) 055201.

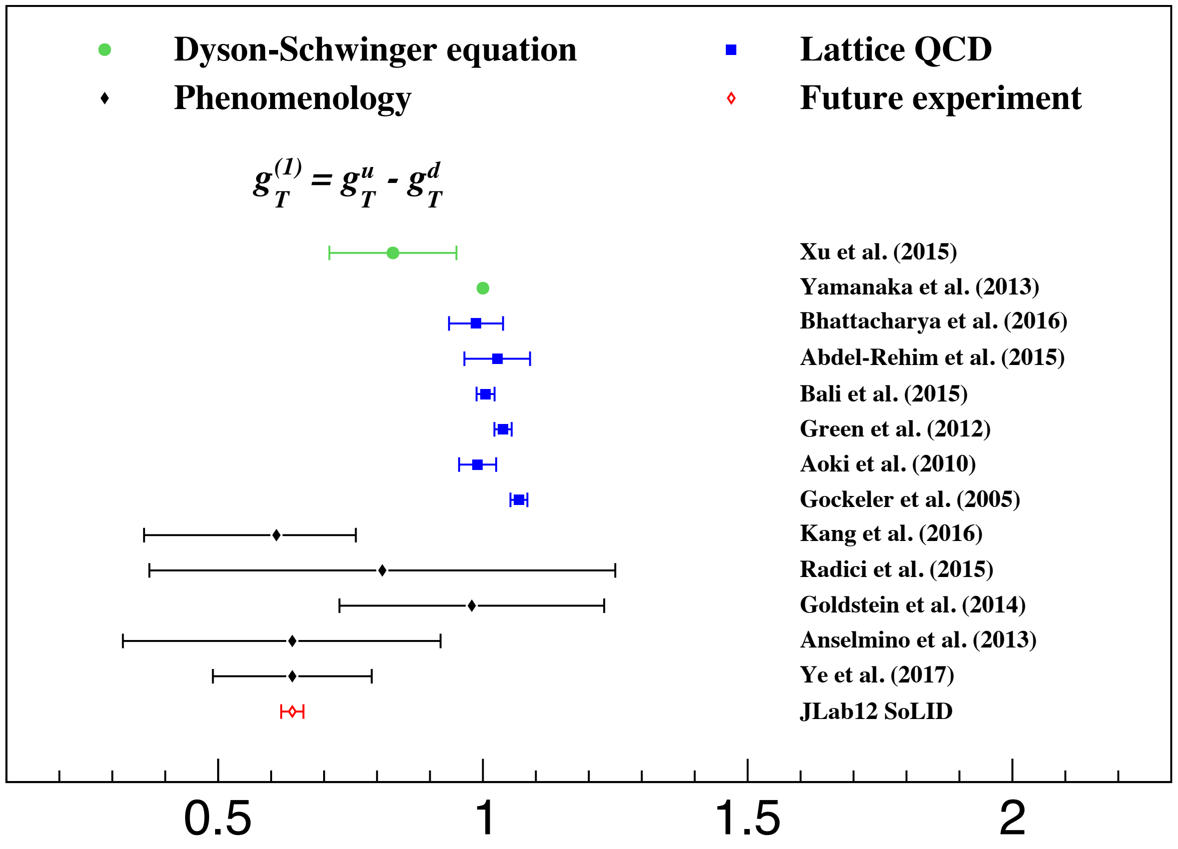
# Tensor Charge

## Tensor charge

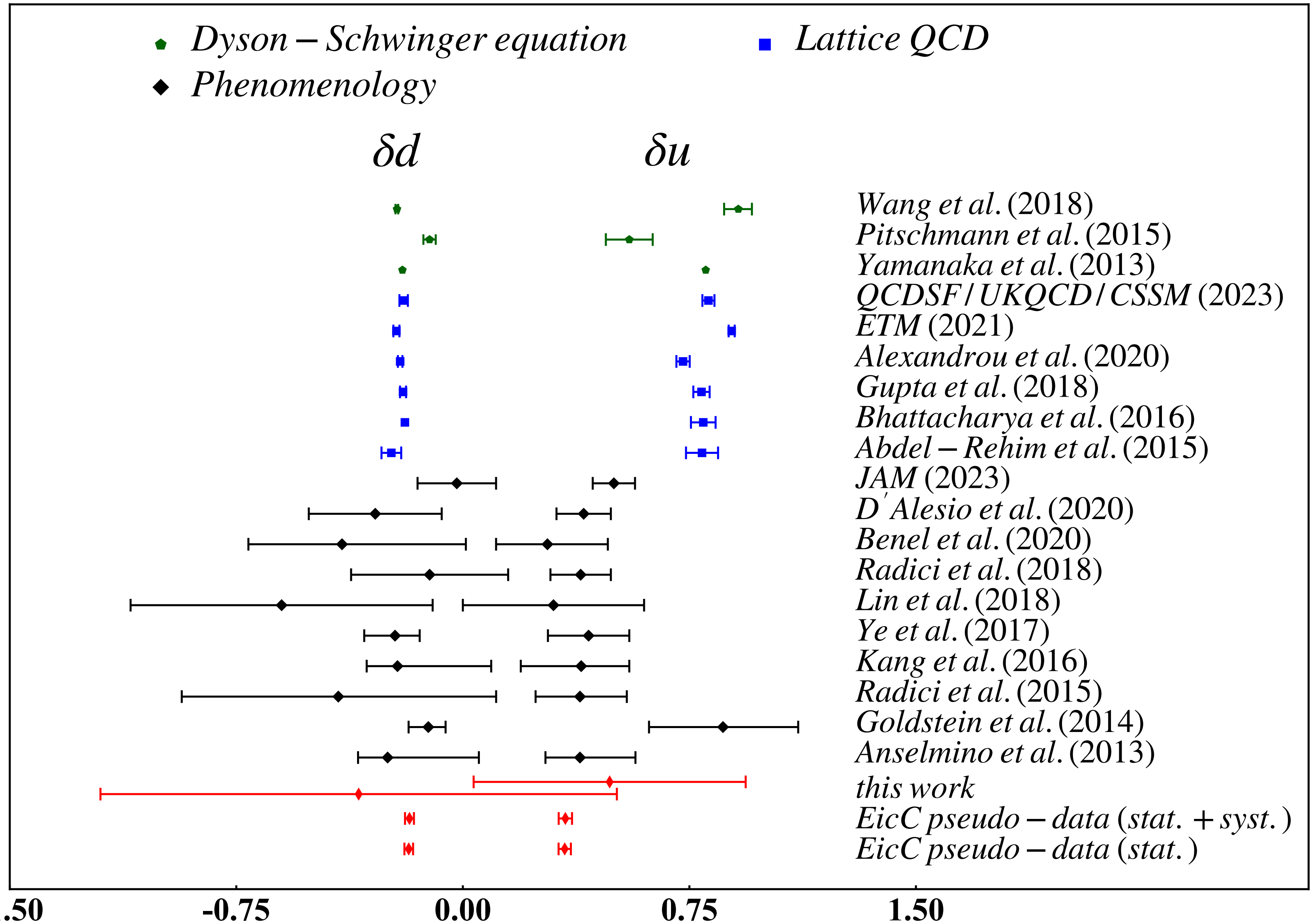
$$\langle P,S|\bar{\psi}^q i\sigma^{\mu\nu}\gamma_5\psi^q|P,S\rangle = g_T^q \bar{u}(P,S) i\sigma^{\mu\nu}\gamma_5 u(P,S) \qquad g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]\,dx$$

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



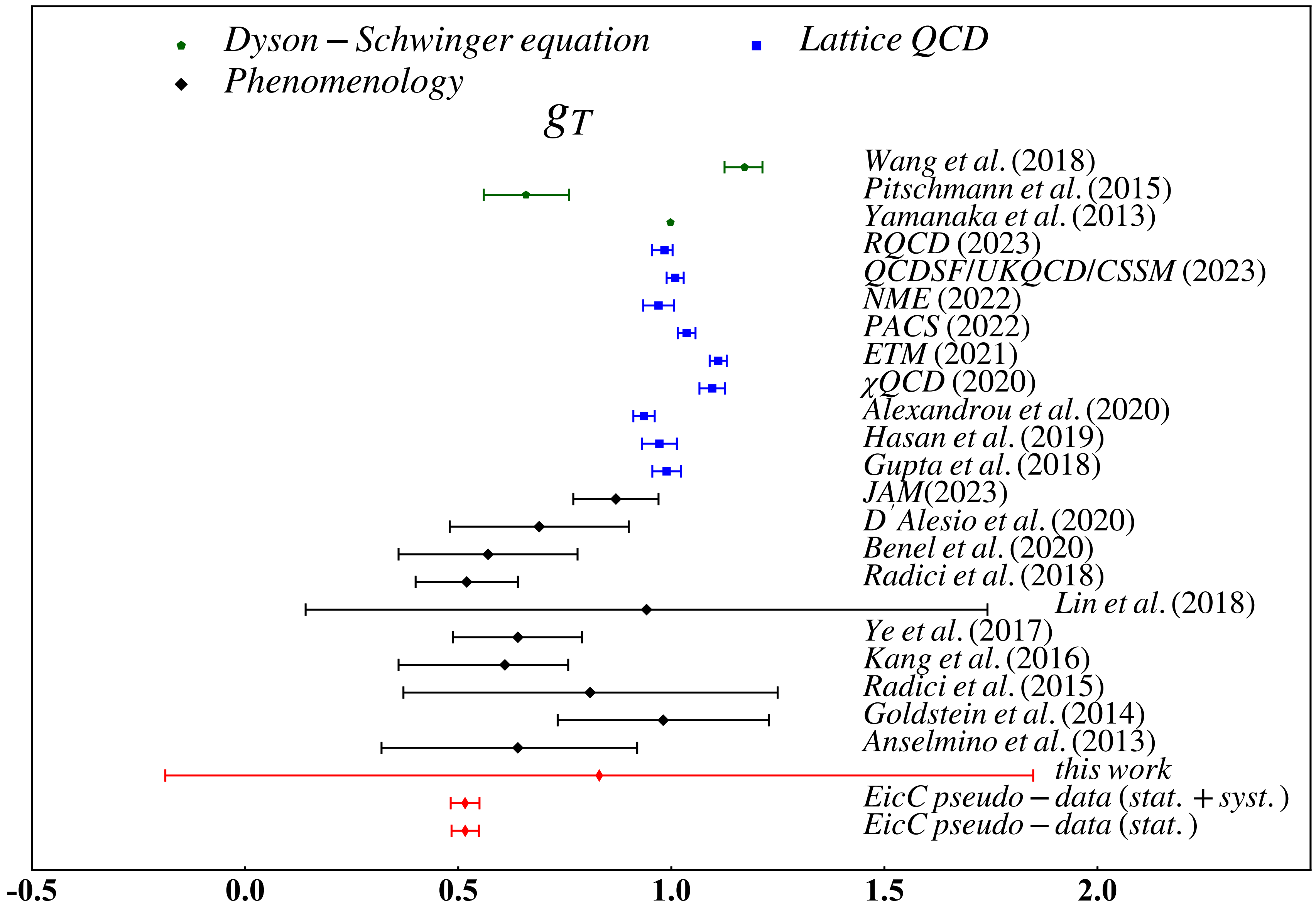
# Tensor Charge




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.**

# Tensor Charge



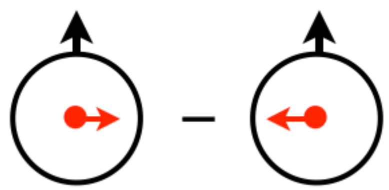

Larger uncertainties when including anti-quarks (less biased)
Compatible with lattice QCD calculations

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

# Double Spin Asymmetry and Worm-gear

## Trans-helicity worm-gear distribution

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

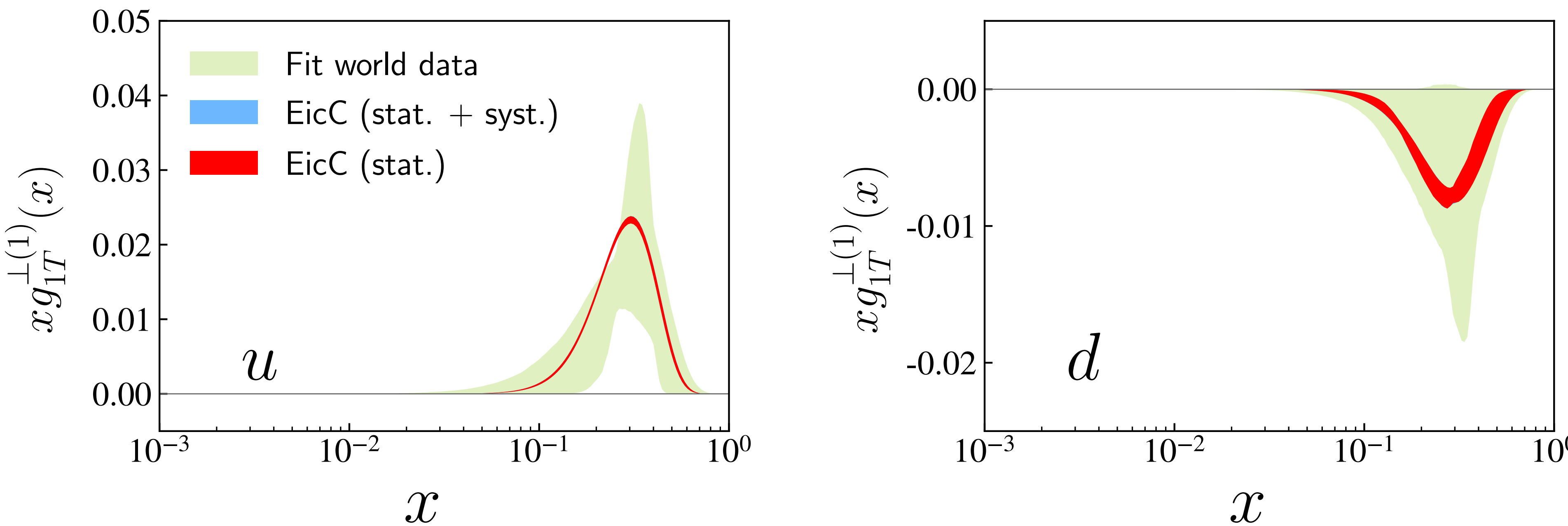



**Effect in SIDIS:**
A longitudinal-transverse double spin asymmetry

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

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

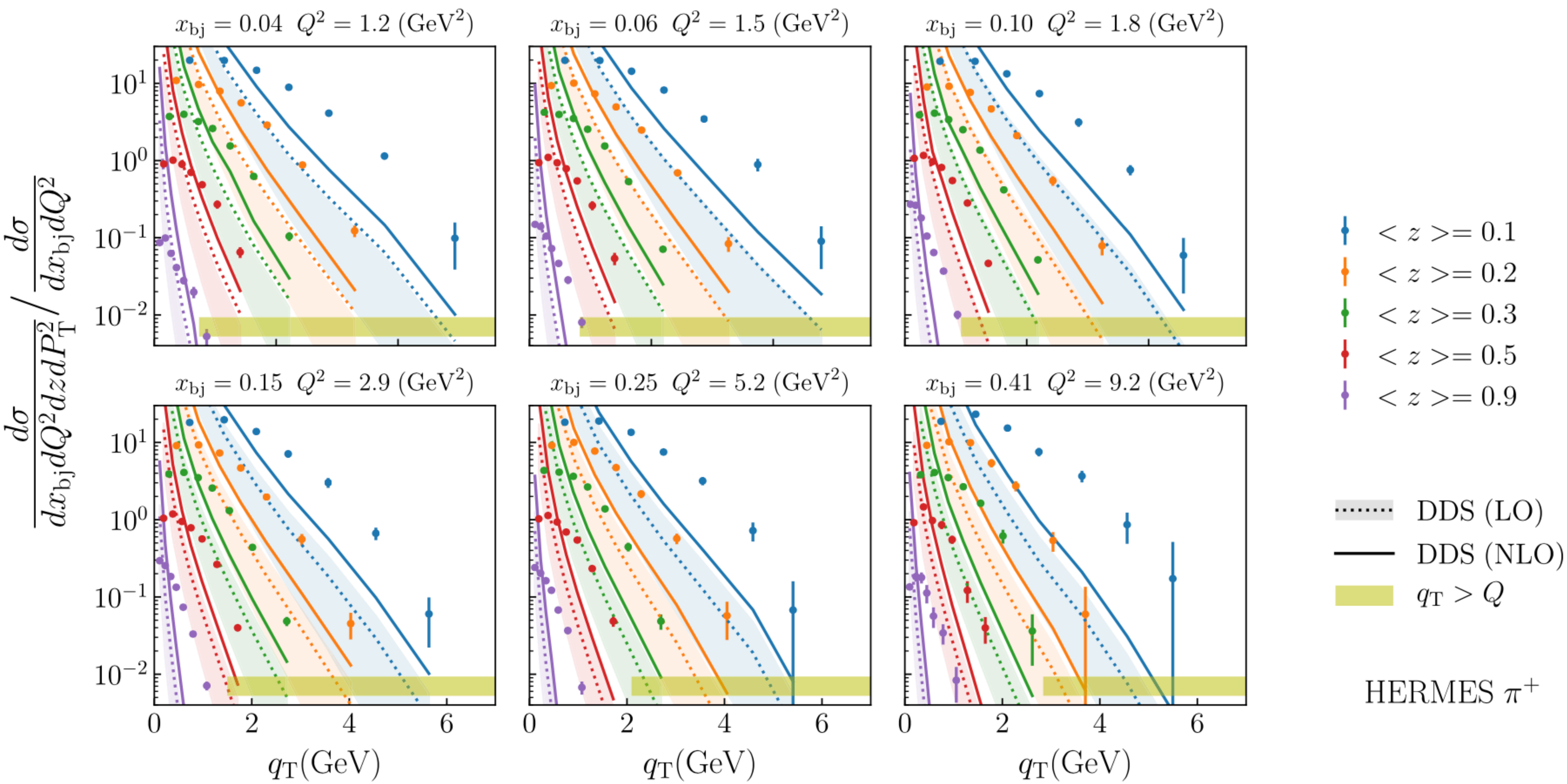
## Phenomenological extraction




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

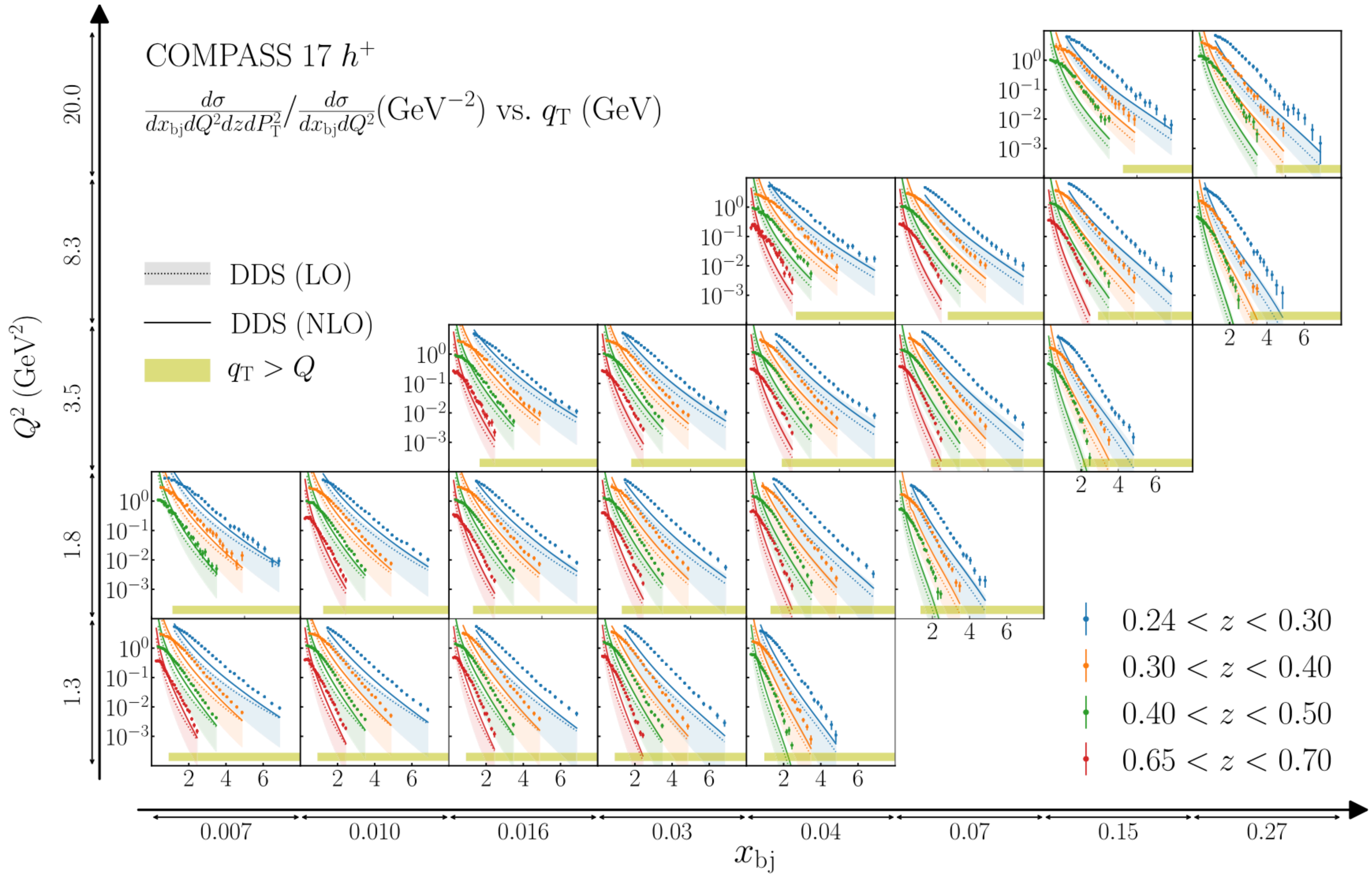
*The story is not ending …*

# Challenge at Large Transverse Momentum




J.O. Gonzalez-Hernandez, T.C. Rogers, N. Sato, B. Wang, Phys. Rev. D 98 114005 (2018).

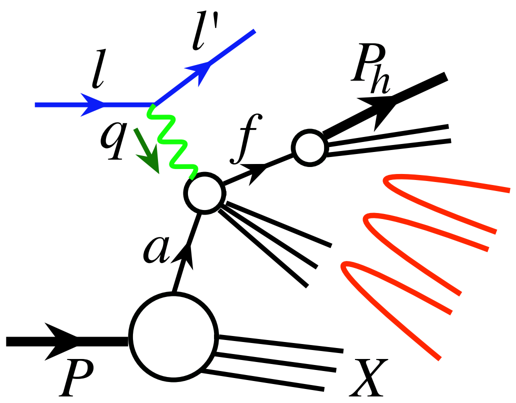
# Challenge at Large Transverse Momentum




J.O. Gonzalez-Hernandez, T.C. Rogers, N. Sato, B. Wang, Phys. Rev. D 98 114005 (2018).

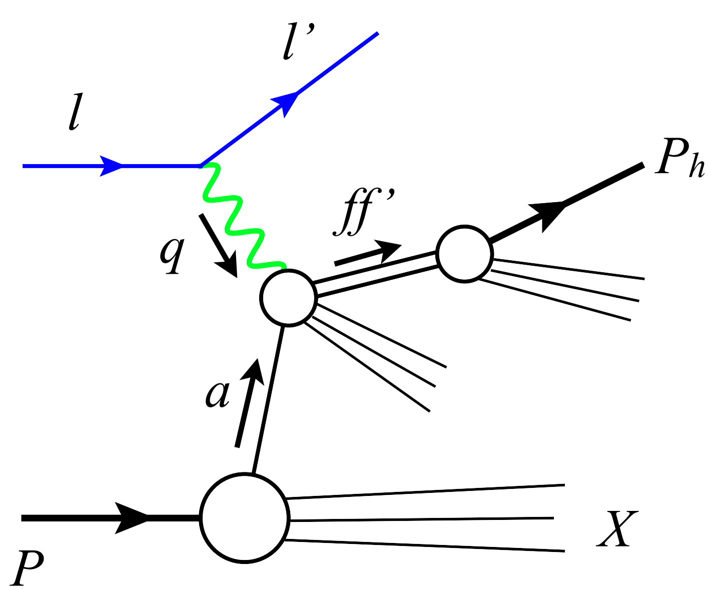
# Challenge at Large Transverse Momentum

Our proposal: power correction

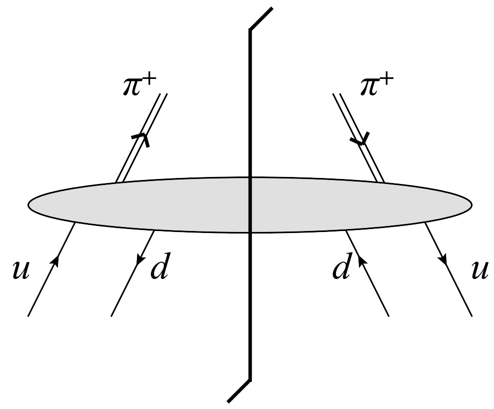



Need large enough phase space to shower
⇒ sufficiently high multiplicity

Near the edge of phase space: large $P_{hT}$ or $z_h$
⇒ low multiplicity




**NLP contribution:**
Hard part is formally suppressed by $1/Q^2$ or $1/P_{hT}^2$
Its contribution is not necessarily small,
if it gets enhancement from hadronization



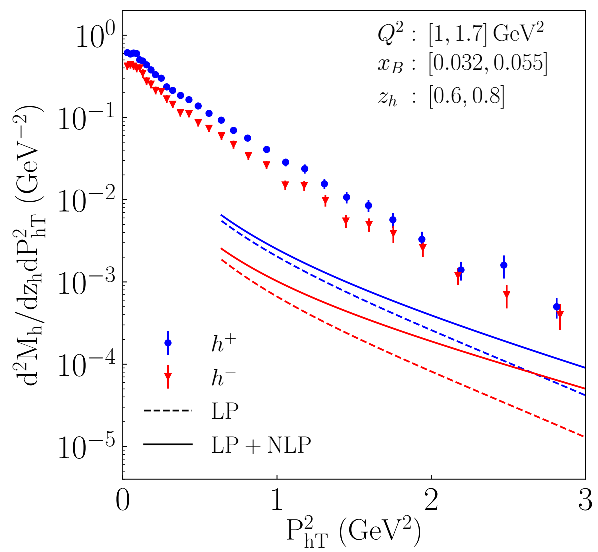

*Parton pair with the right quantum number has better chance to form the hadron.*

TL and J.W. Qiu, 2020

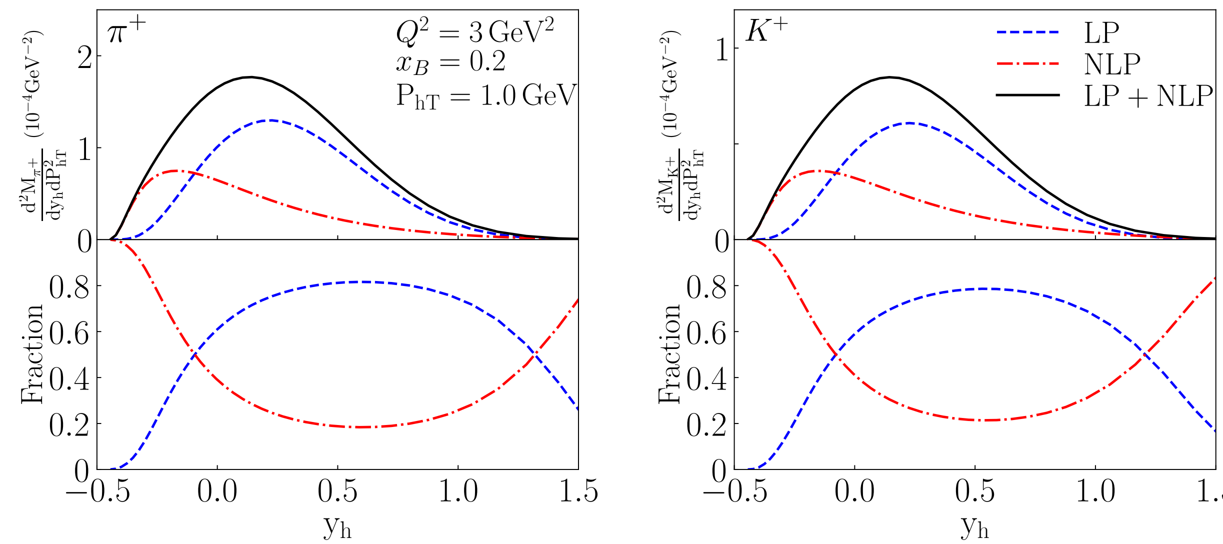
# Challenge at Large Transverse Momentum

## Numerical estimation

$E_{\text{beam}} = 160$ GeV (COMPASS)




$E_{\text{beam}} = 11$ GeV (JLab)




Only consider the leading term — *lower limit of NLP contribution.*
NLP contribution is more significant at lower collision energy.

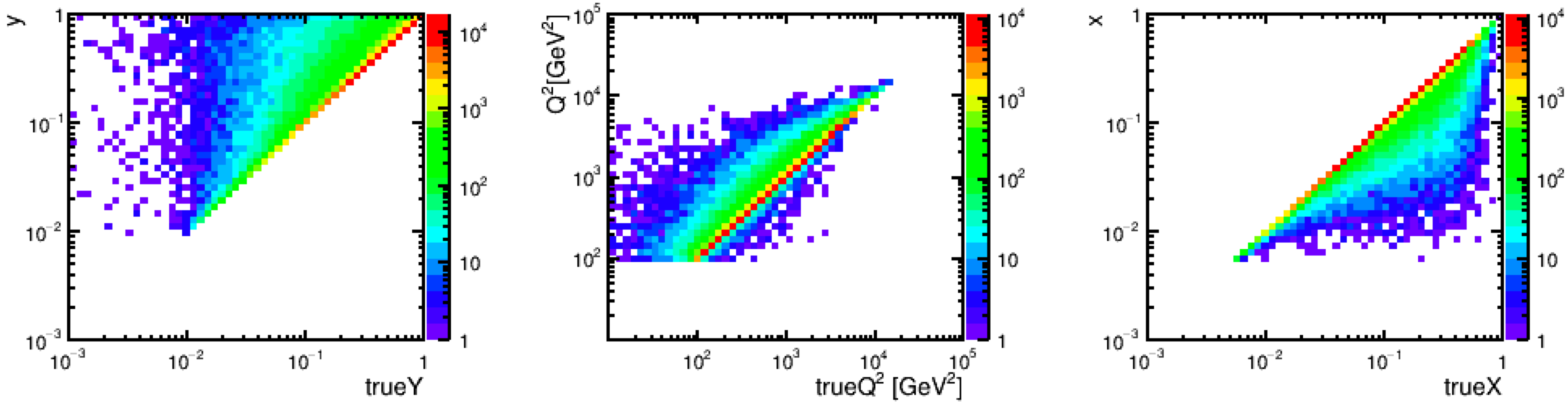
## Evolution should be modified accordingly

$$\frac{\partial}{\partial \ln \mu^2} D_{[ff'(\kappa)]\to h} = \sum_{[\tilde{f}\tilde{f}'(\kappa)']} D_{[\tilde{f}\tilde{f}'(\kappa')]\to h]} \otimes \Gamma_{[ff'(\kappa)]\to[\tilde{f}\tilde{f}'(\kappa')]}$$

$$\frac{\partial}{\partial \ln \mu^2} D_{f\to h} = \sum_{f'} D_{f'\to h} \otimes \gamma_{f\to f'} + \frac{1}{\mu^2} \sum_{[ff'(\kappa)]} D_{[ff'(\kappa)]\to h} \otimes \tilde{\gamma}_{f\to[ff'(\kappa)]}$$

**TL and J.W. Qiu, 2020**

# Radiative Corrections




[Figures from X. Chu at 2nd EIC YR workshop]

*kinematic experienced by the parton* $\neq$ *kinematic reconstructed from observed momenta*

**Challenges in traditional approach**:

- The determination of the RC factor usually relies on MC simulation, requiring the physics we want to extract or beyond the experimental acceptance.
- The extraction of the Born cross section is an inverse problem.
- Increasingly difficult for reactions beyond inclusive DIS, *e.g.* SIDIS.

*"In many nuclear physics experiments, radiative corrections quickly become a dominant source of systematics. In fact, the uncertainty on the corrections might be the dominant source for high-statistics experiment"*

—— *EIC Yellow Report*

# Radiative Corrections

## Our proposal:

- Do not try to invent any scheme to treat QED radiation to match Born kinematics.
  — No radiative correction!
- Generalize the QCD factorization to include electroweak theory, treat QED radiation in the same way as QCD radiation is treated.
- Same systematically improvable treatment of QED contributions for both inclusive DIS and SIDIS.

## From radiative correction to radiation contribution:

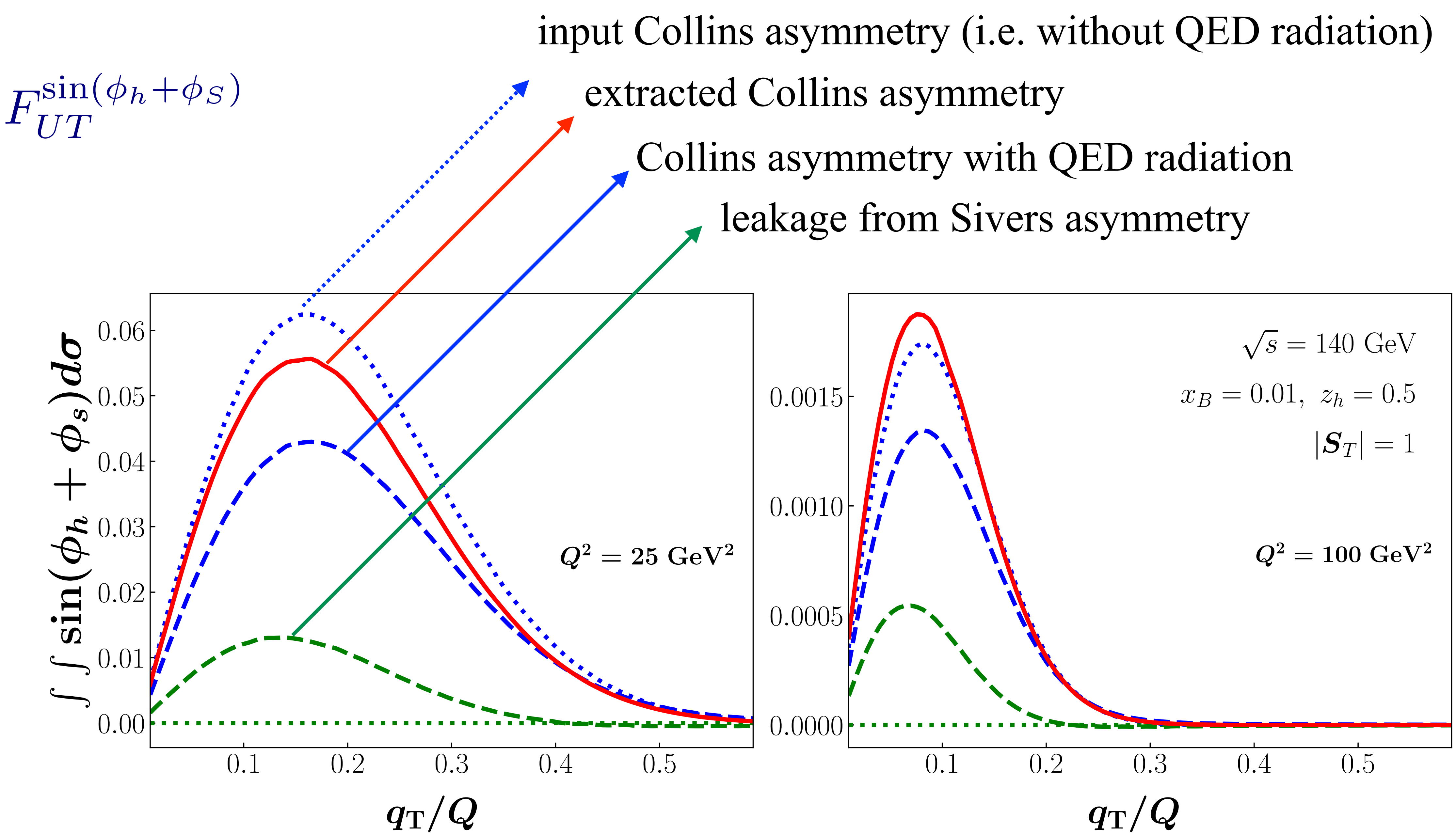
$$\sigma_{\text{Measured}}\left(x_B, Q^2\right) = \sigma_{\text{lep}}^{\text{univ}}\left(\mu^2; m_e^2\right) \otimes \sigma_{\text{had}}^{\text{univ}}\left(\mu^2; \Lambda_{\text{QCD}}^2\right) \otimes \widehat{\sigma}_{\text{IR-safe}}\left(\hat{x}_B, \widehat{Q}^2, \mu^2\right) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{Q^2}, \frac{m_e^2}{Q^2}\right)$$

- IR sensitive QED contributions are absorbed into LDF and LFF.
- IR safe QED contributions are calculated order-by-order in power of α.
- Neglect power suppressed contributions.

TL, W. Melnitchouk, J.W. Qiu, N. Sato, 2021

# Radiative Correction

Numerical estimation: Collins asymmetry




**TL, W. Melnitchouk, J.W. Qiu, N. Sato, 2021**

# 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
  - power corrections, higher twist effects
  - radiative corrections
  - target fragmentation
  - …

*Thank you!*

# Backup

# TMD Evolution

## Evolution equations

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

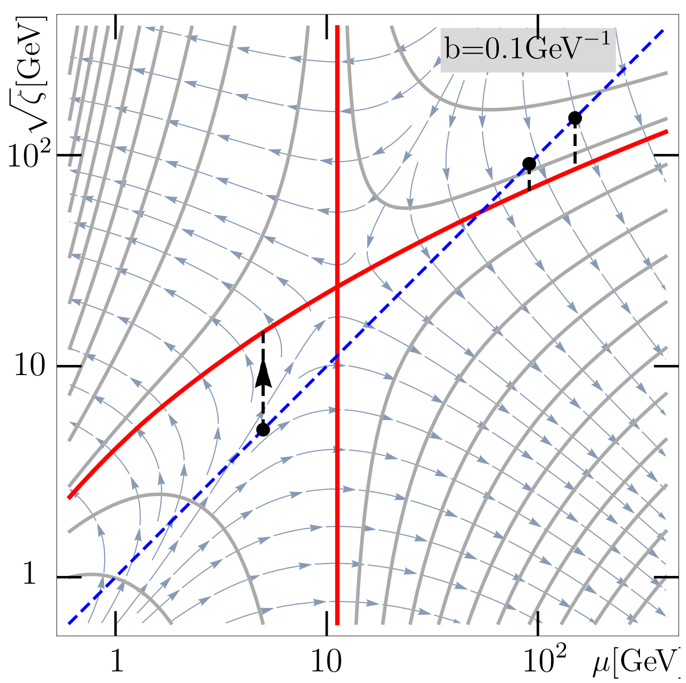
$$\zeta \frac{dF(x,b;\mu,\zeta)}{d\zeta} = -\mathcal{D}(b,\mu) F(x,b;\mu,\zeta)$$

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

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

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

## ζ-prescription




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

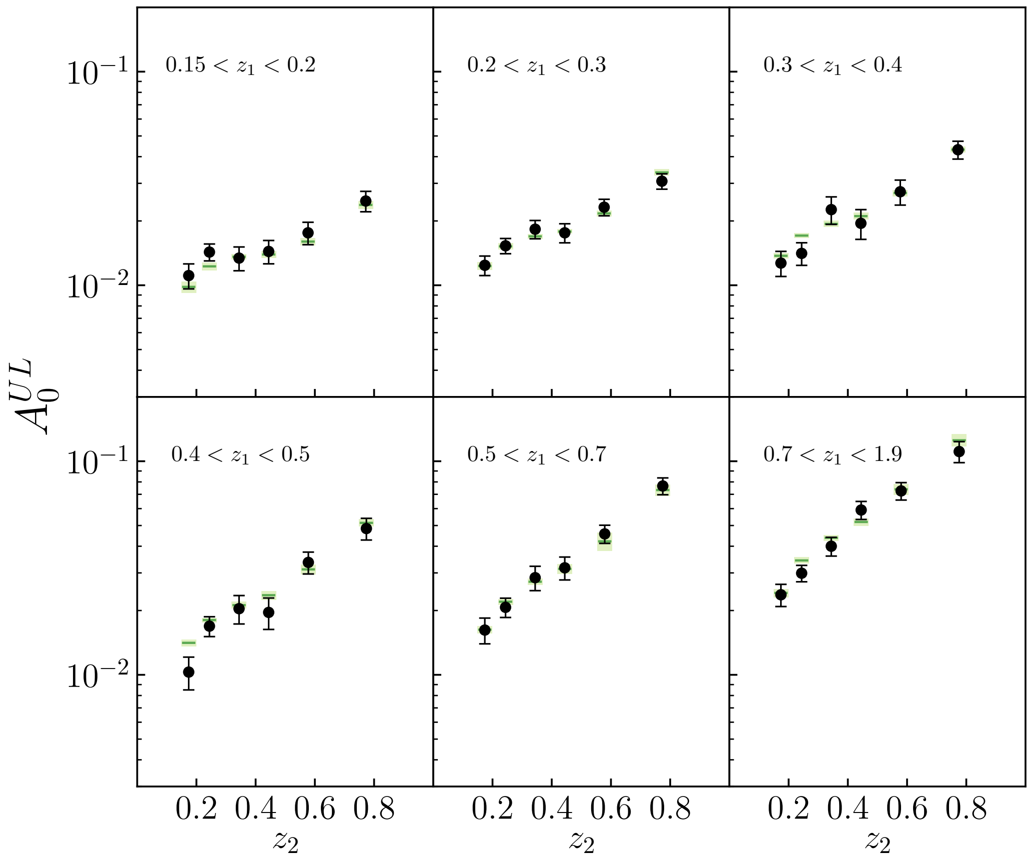
$$\frac{d\ln \zeta_\mu(\mu,b)}{d\ln \mu^2} = \frac{\gamma_F(\mu,\zeta_\mu(\mu,b))}{2\mathcal{D}(\mu,b)}$$

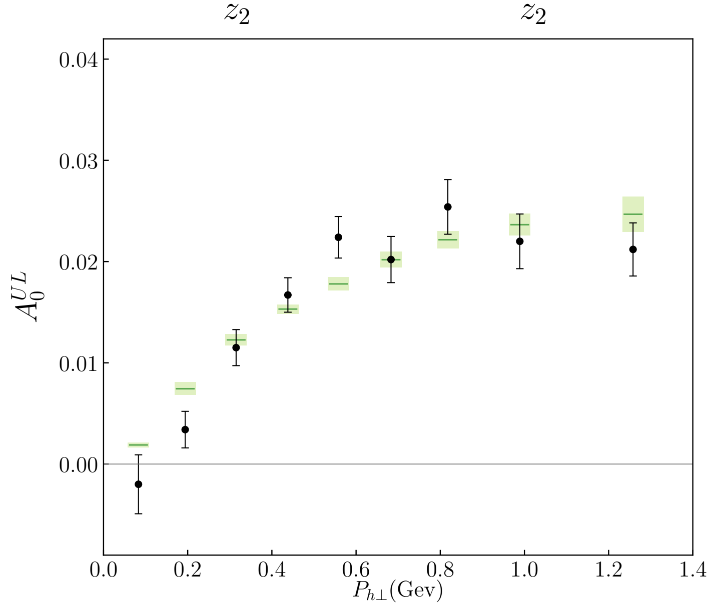
$$\mathcal{D}(\mu_0,b) = 0, \quad \gamma_F(\mu_0,\zeta_\mu(\mu_0,b)) = 0$$

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

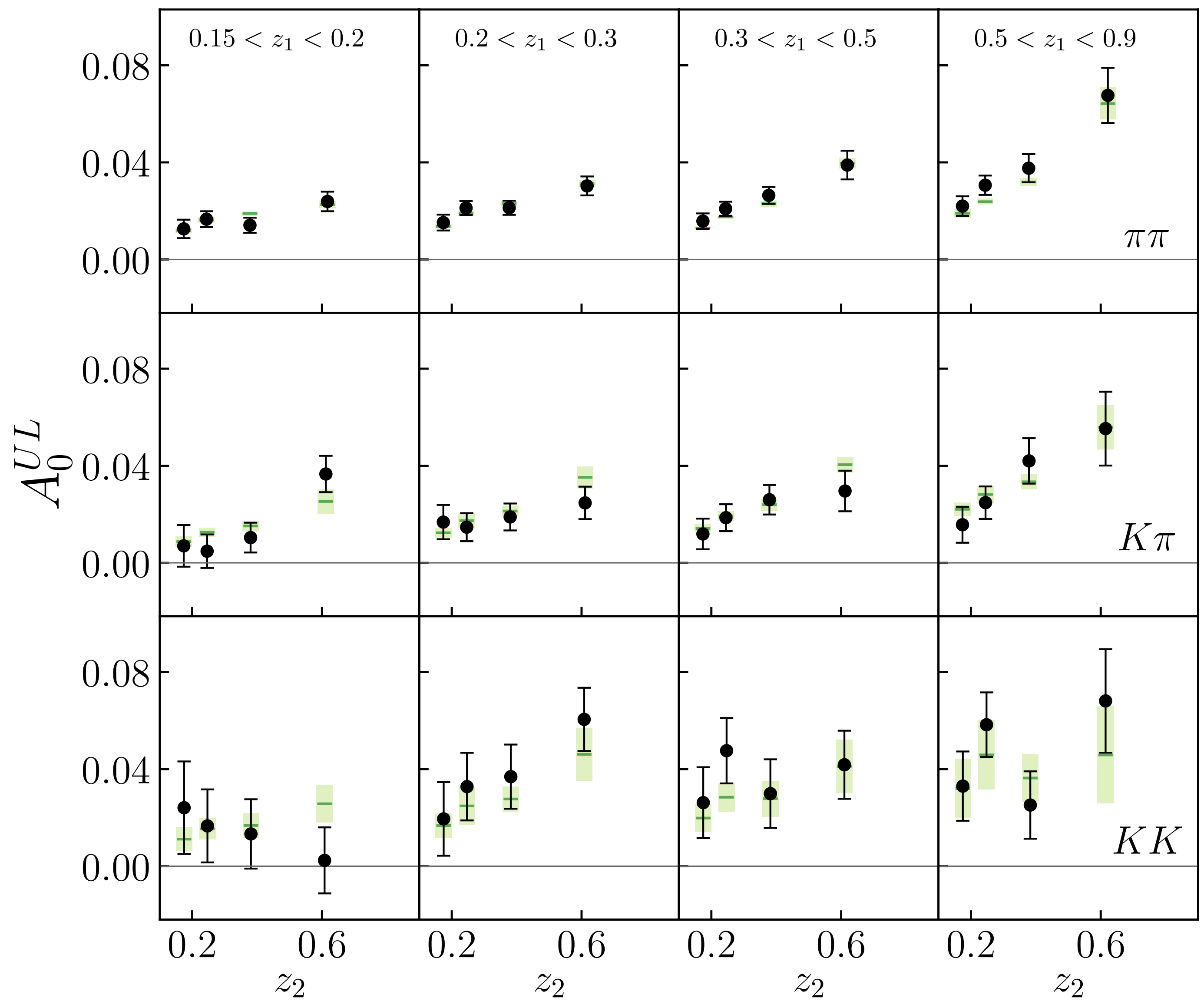
# Comparison with Data

## BaBar (2014)



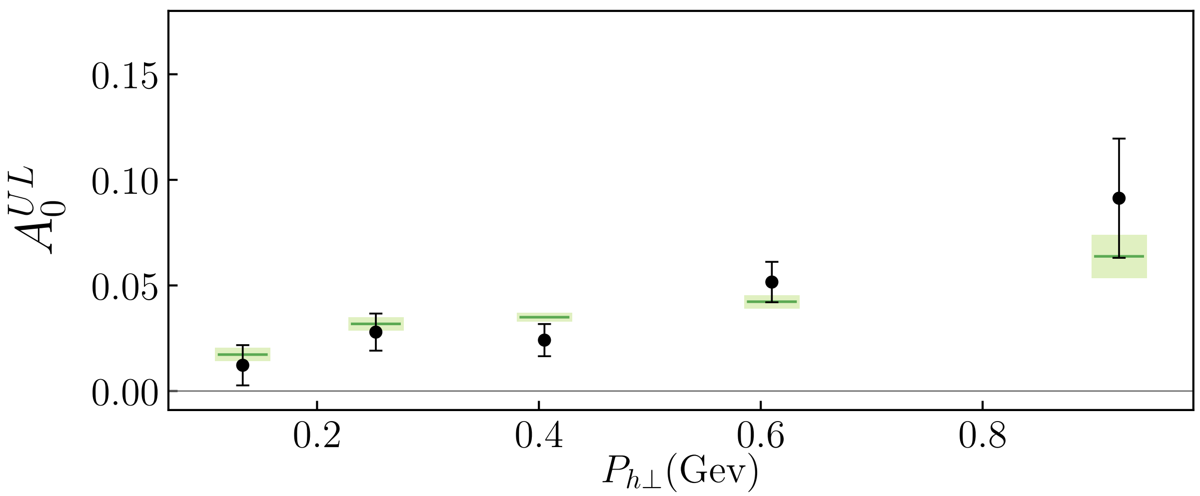



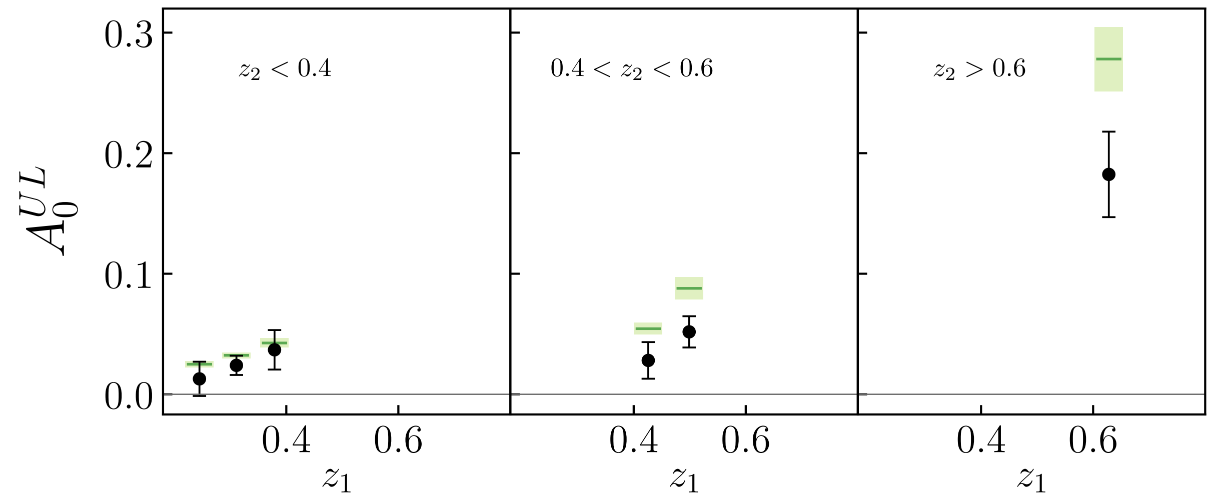

## BaBar (2016)



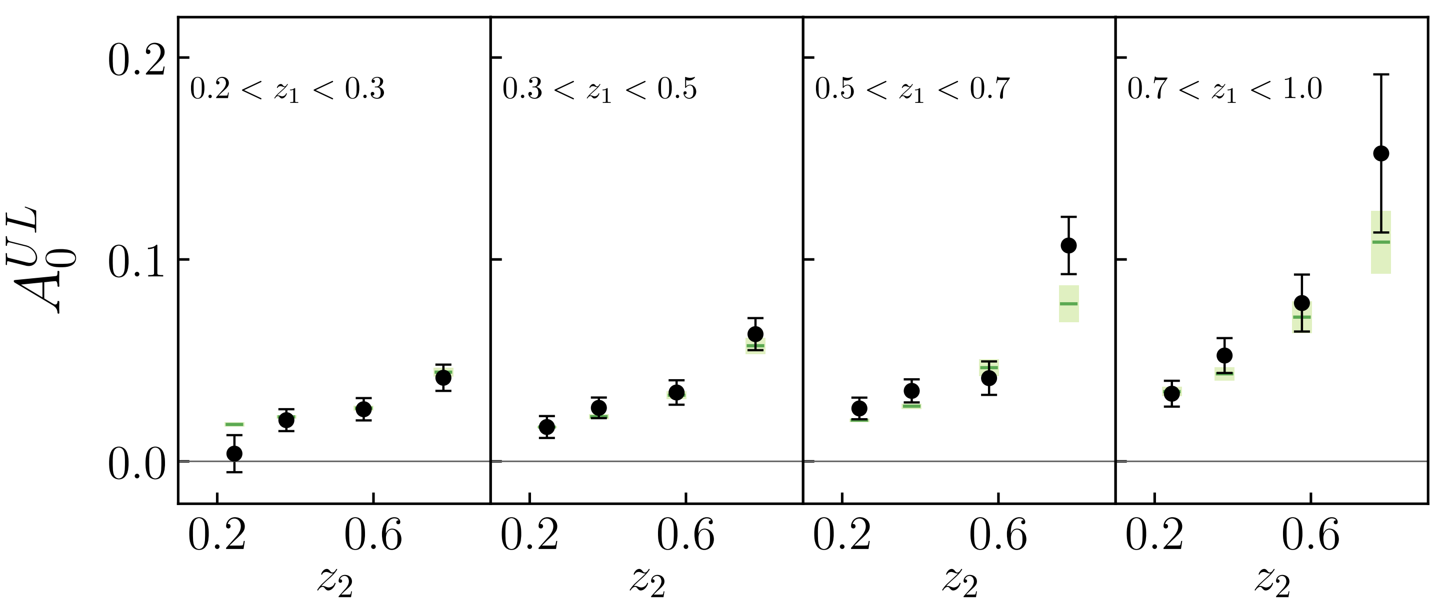
# Comparison with Data

## BESIII

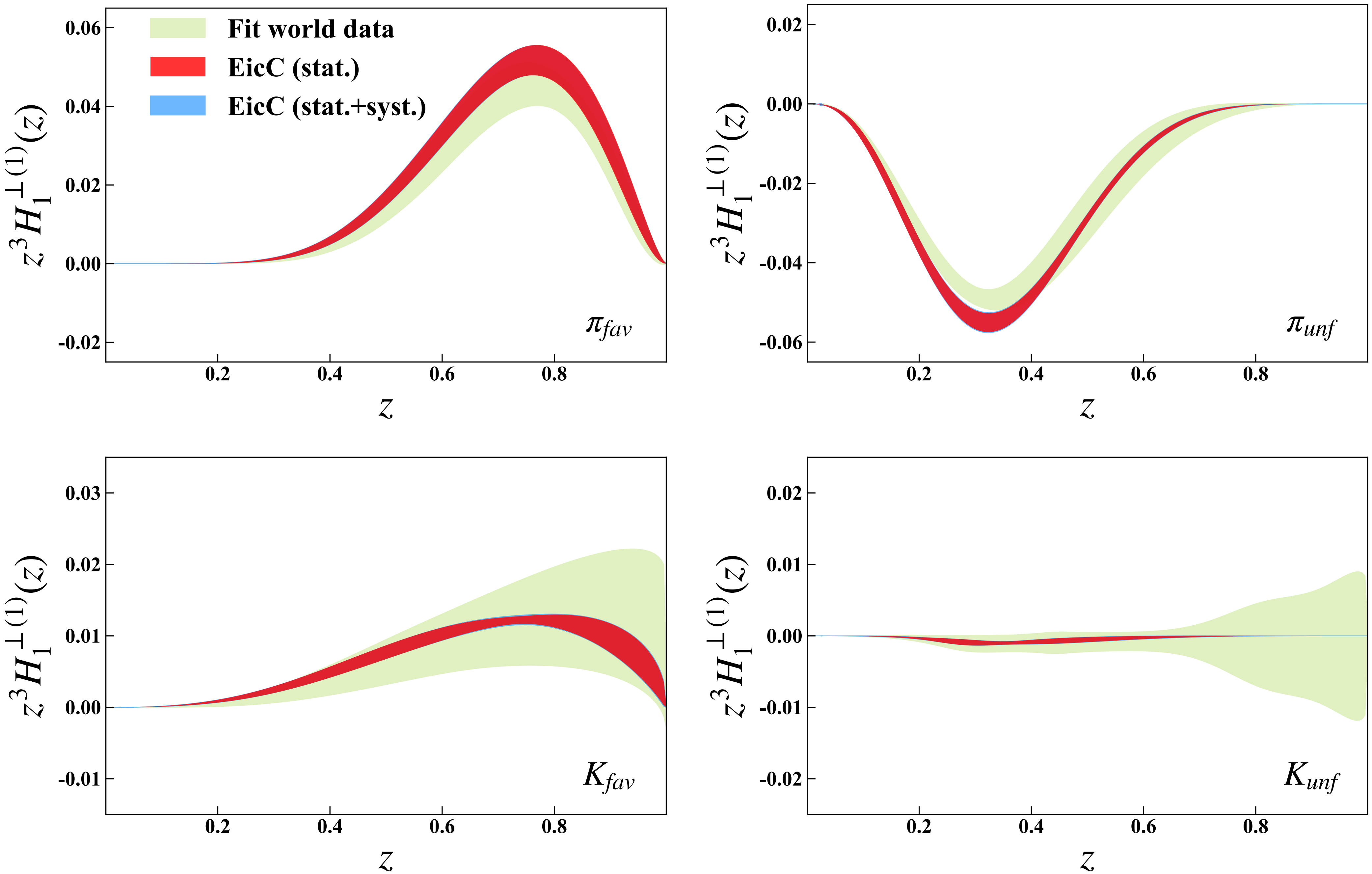



## Belle

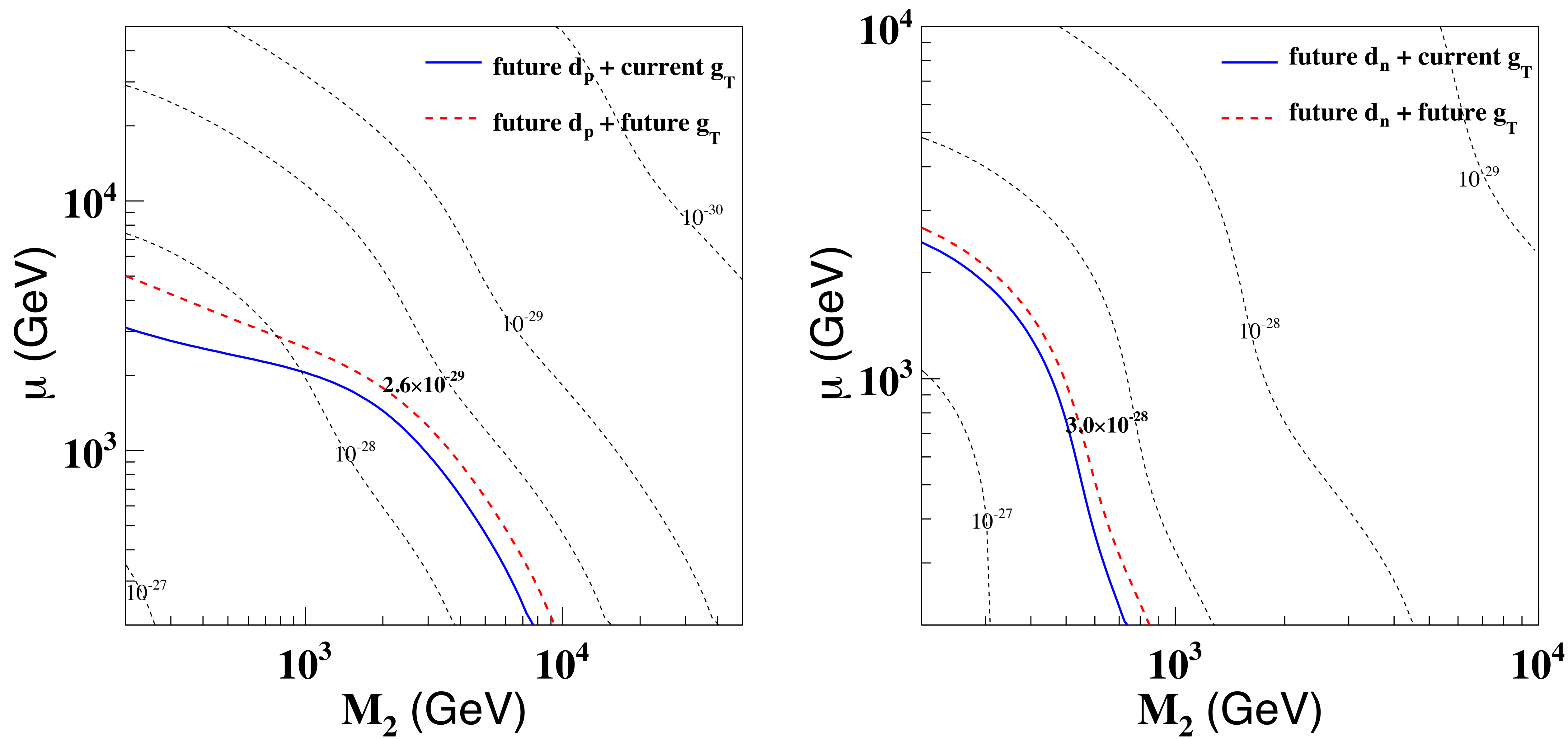


# Result: Collins Fragmentation Function




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

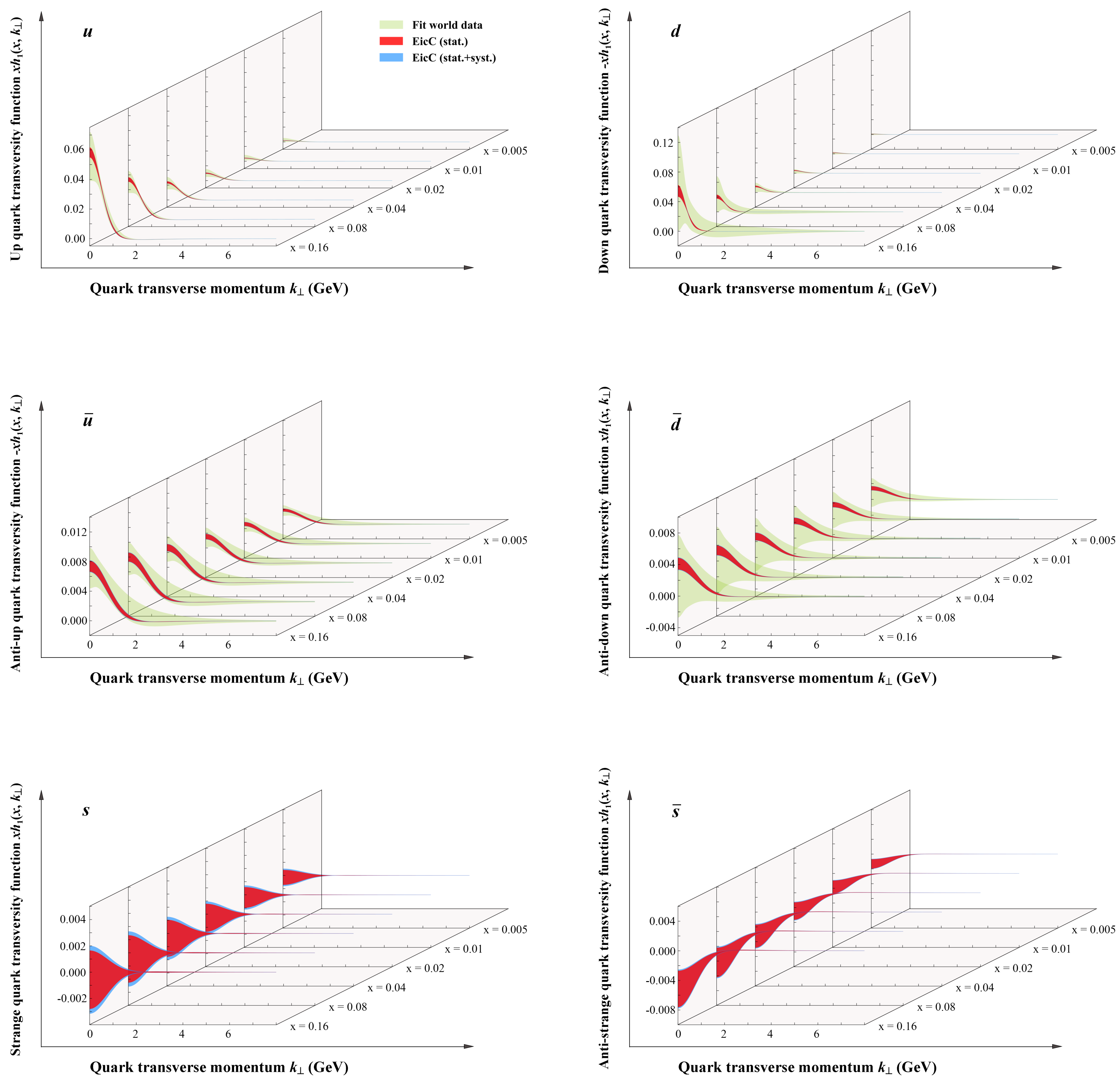
# Test New Physics Model: Split-supersymmetry



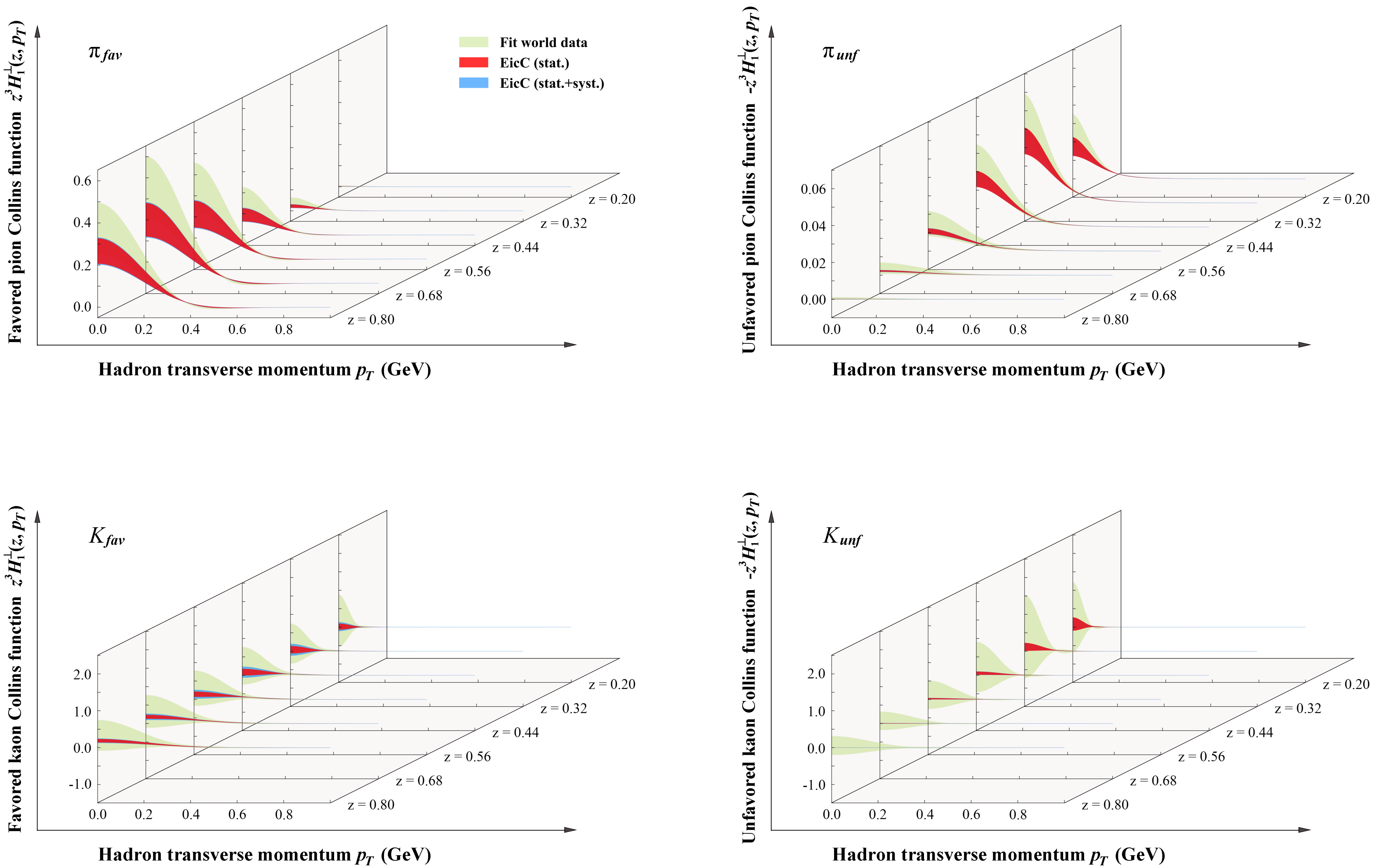

- In the unified framework of gaugino masses, sfermion mass at $10^9$ GeV, tanβ=1, sinφ=1

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

# Transversity TMDs



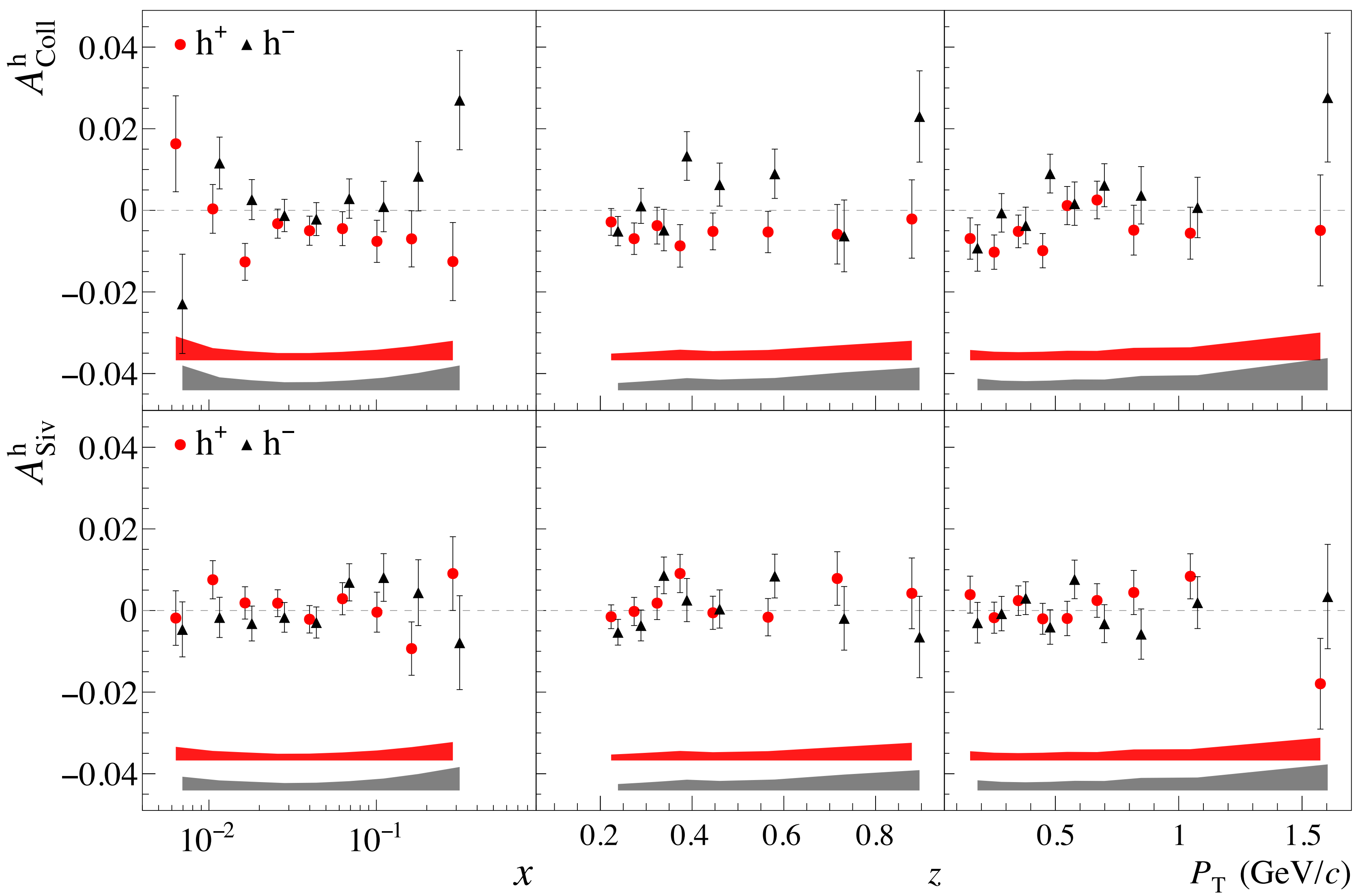
# Collins TMD FFs



# Some More on Transversity

## New data released by COMPASS

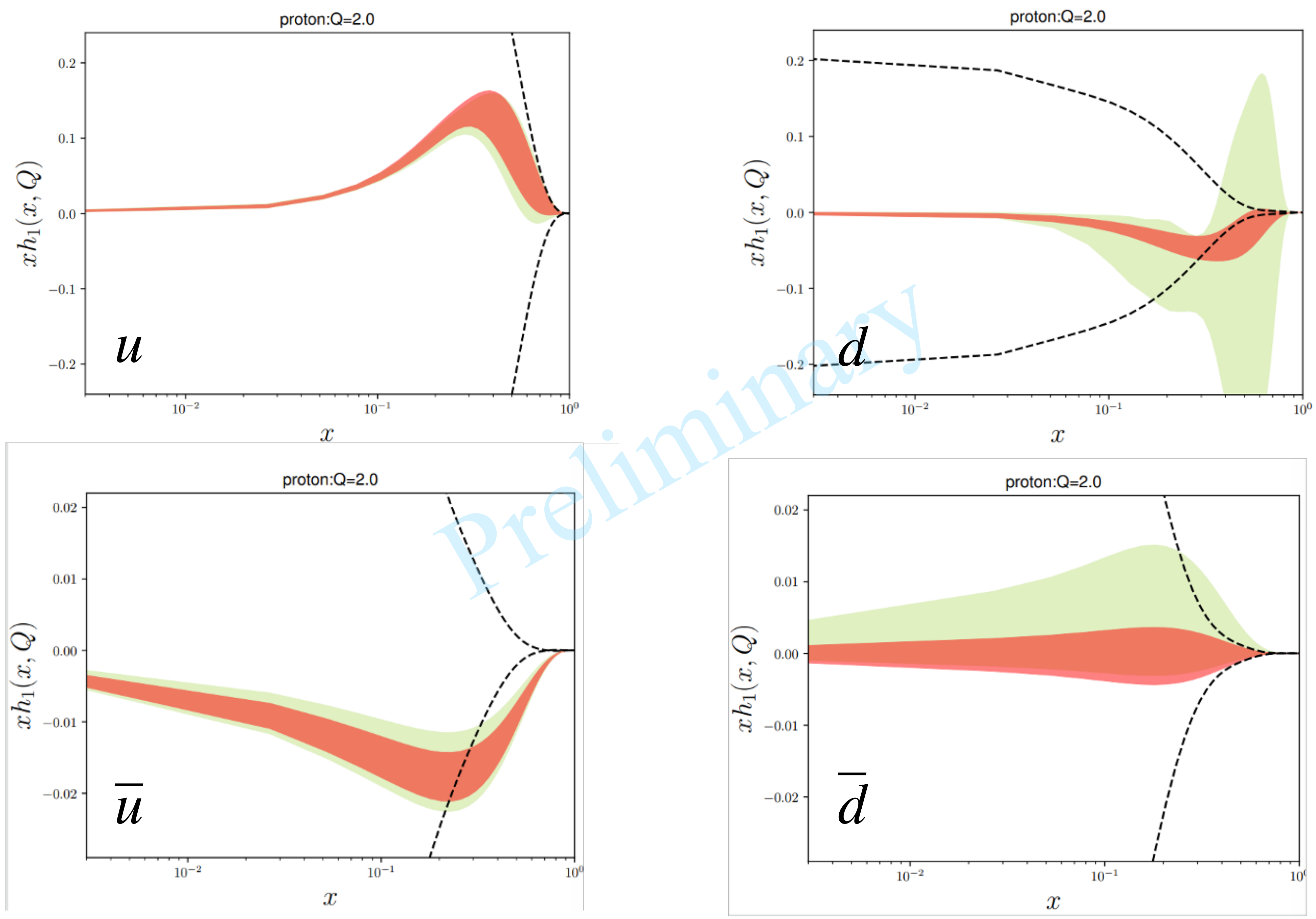
SIDIS on transversely polarized deuteron target




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

# Some More on Transversity

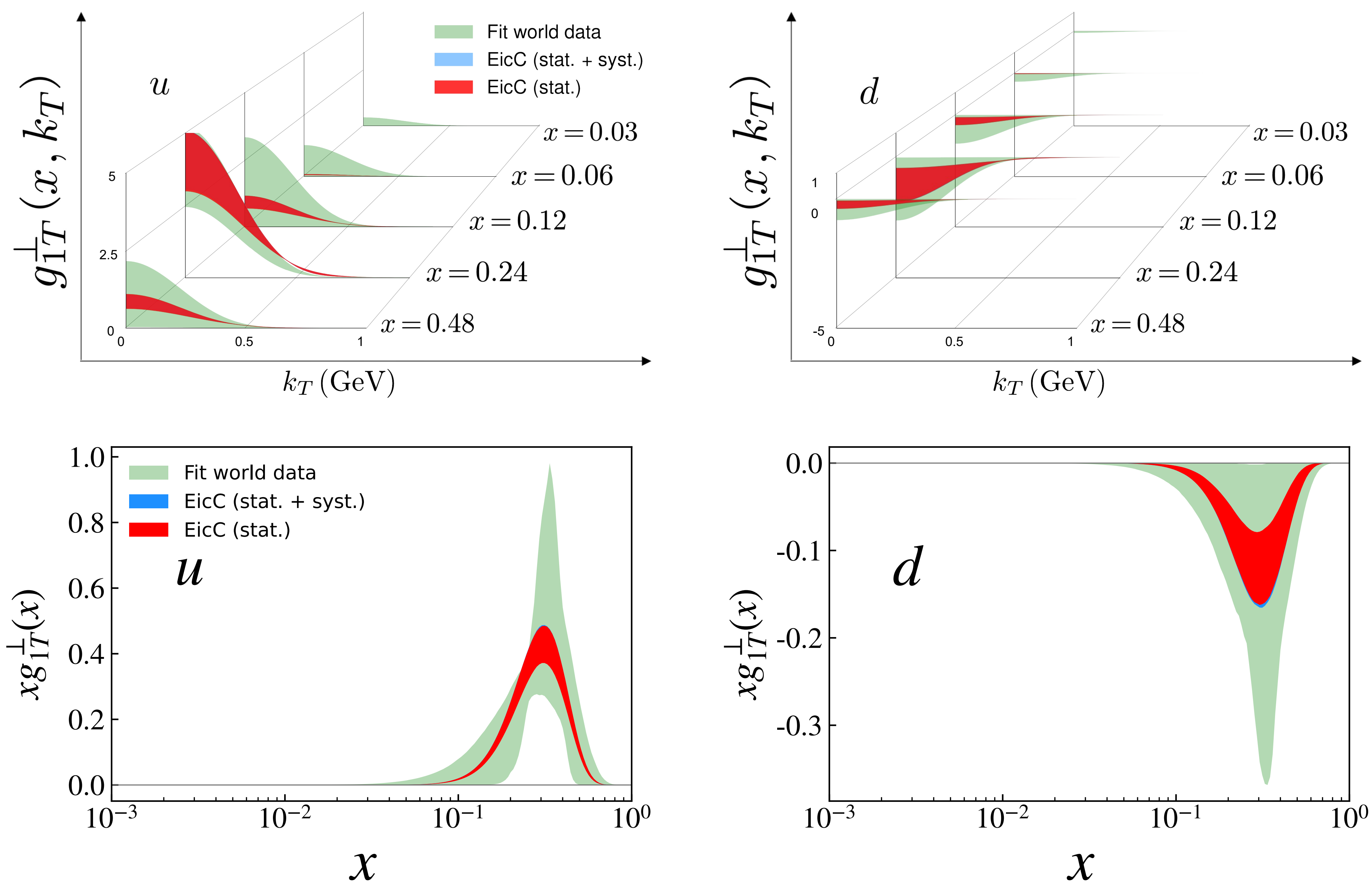
Preliminary results (without systematic uncertainties)




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

# Double Spin Asymmetry and Worm-gear

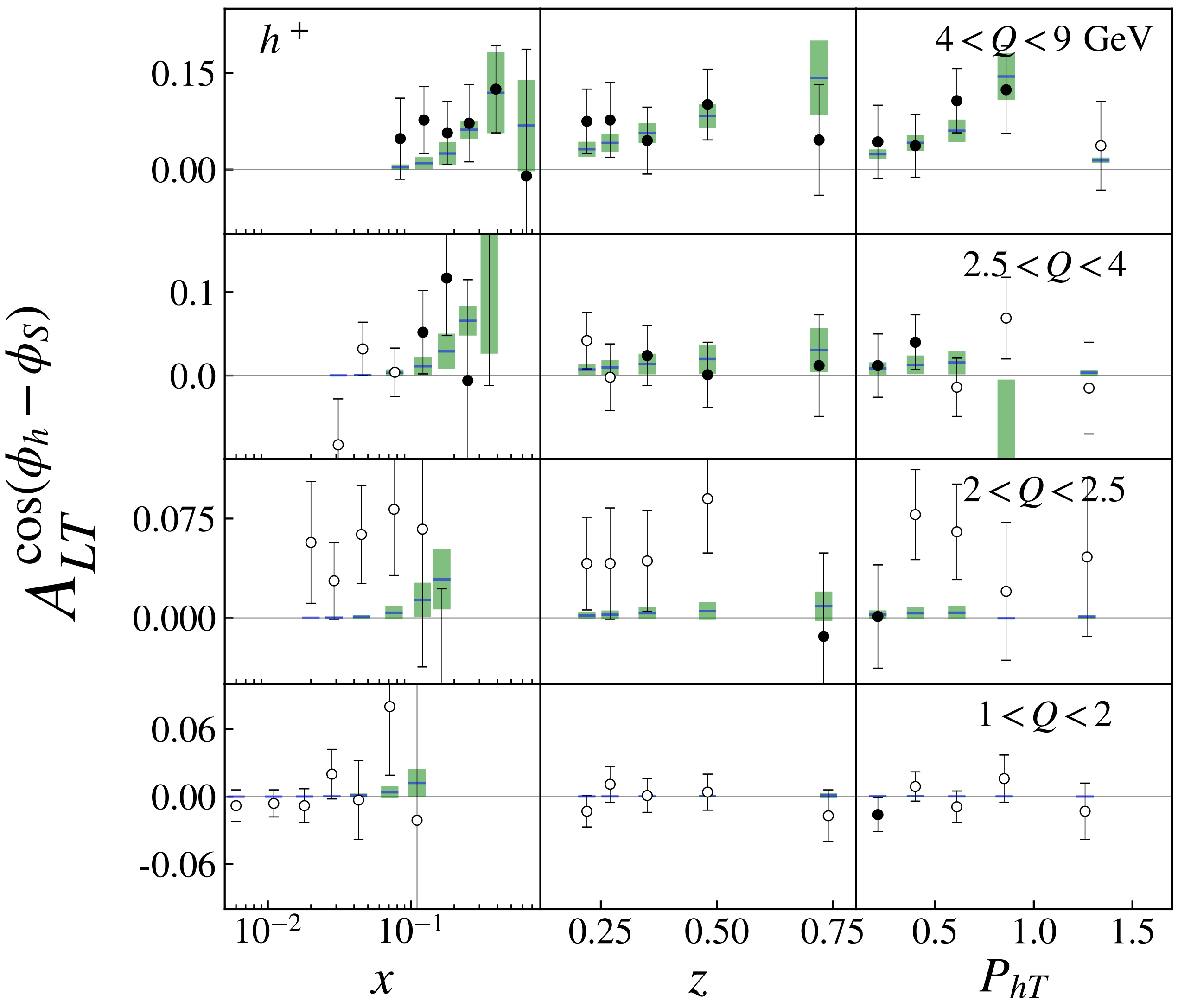
## Phenomenological extraction

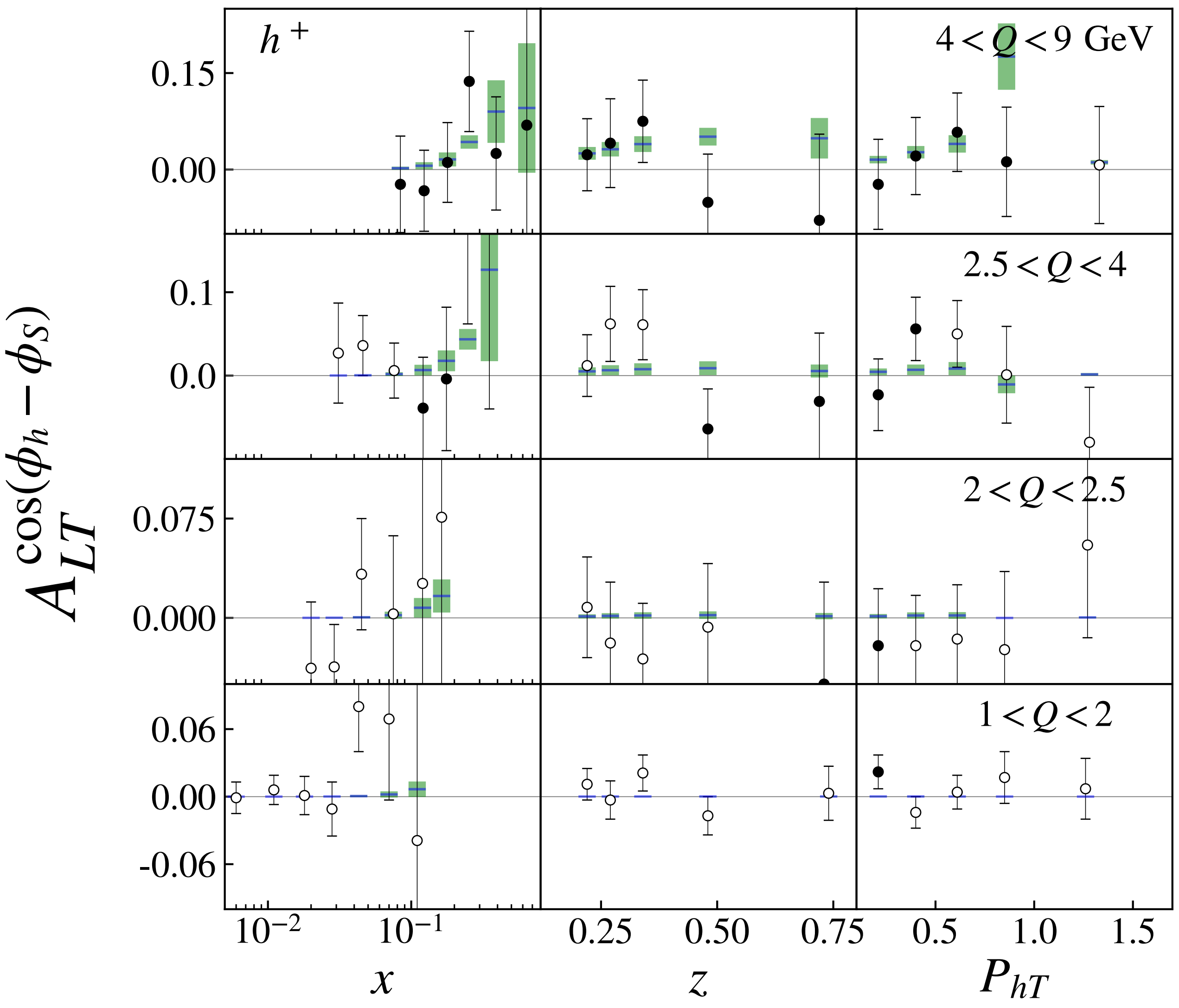



$$g_{1T}^{\perp(1)}(x) = \int d^2\mathbf{k}_T \left(\frac{k_T^2}{2M}\right) g_{1T}^{\perp}\left(x, \mathbf{k}_T^2\right)$$

**K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, arXiv:2403.12795**

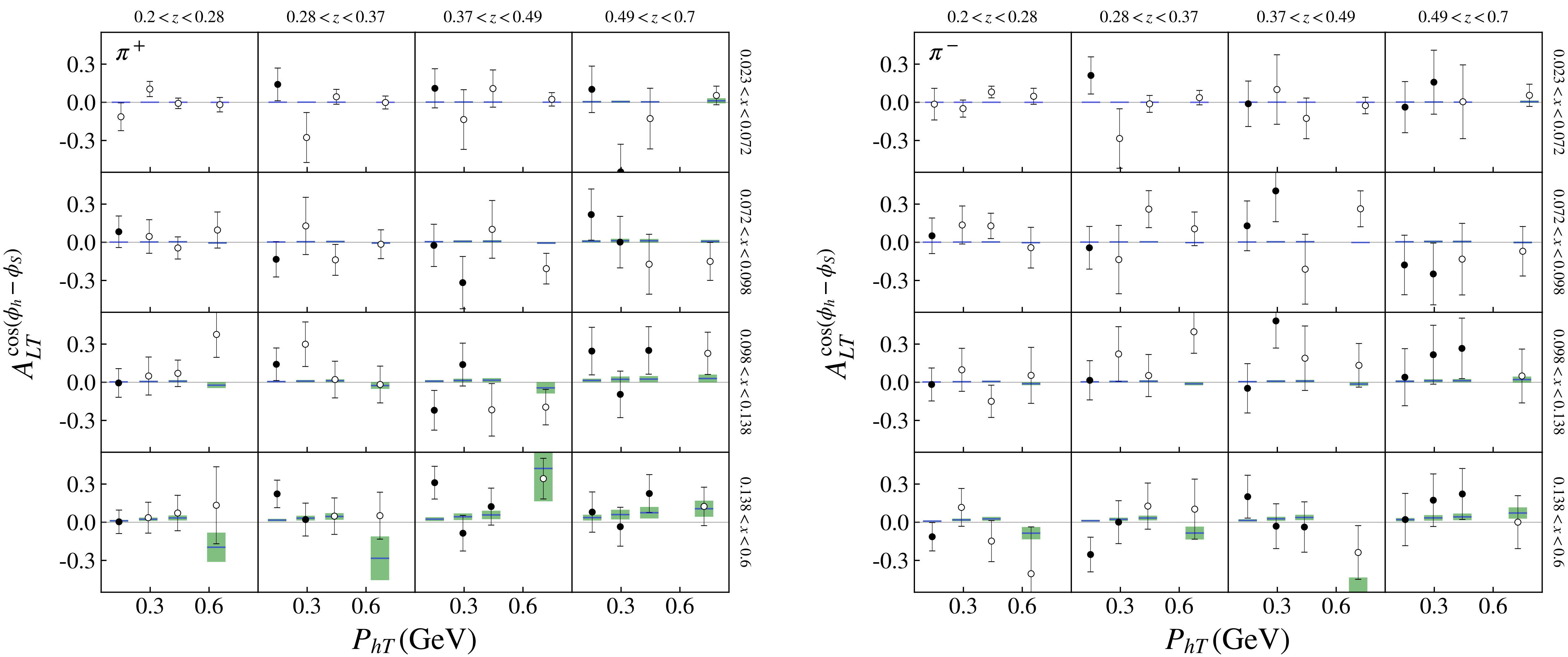
# Comparison with Data



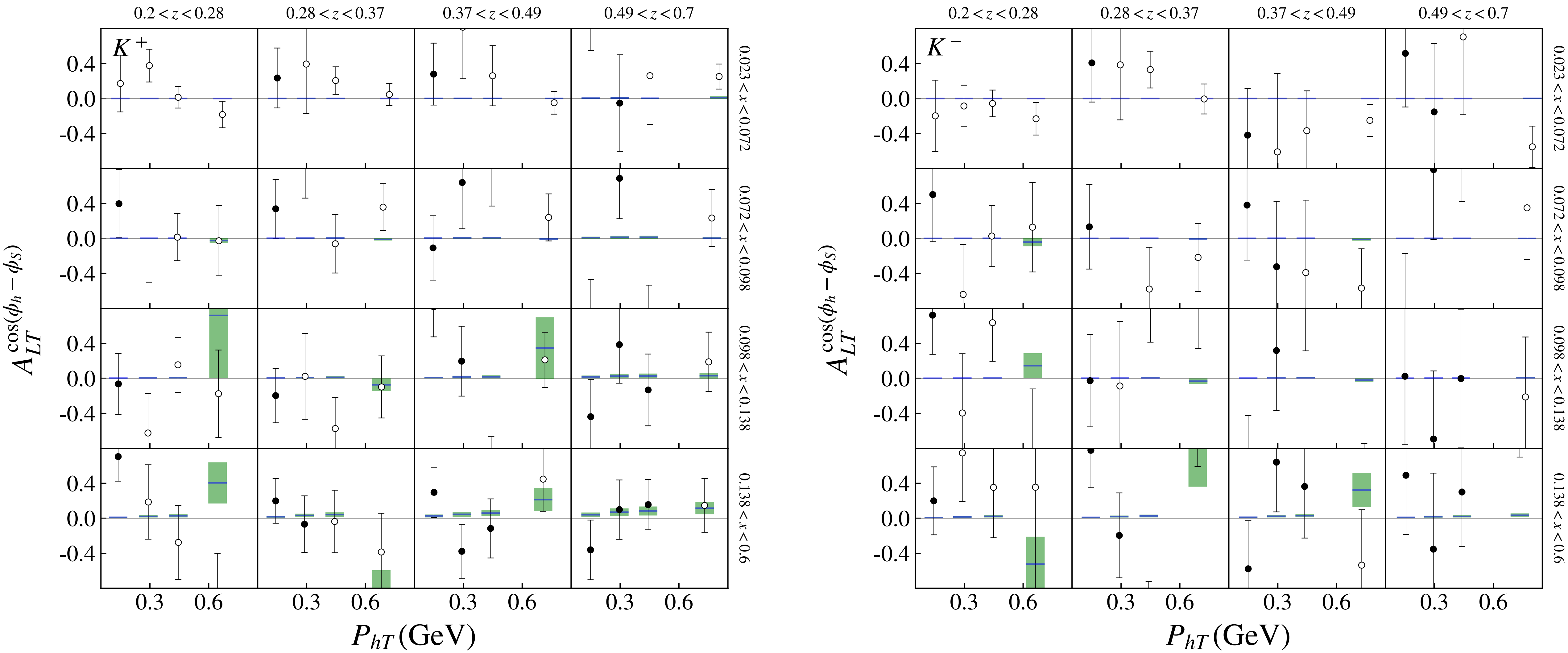

COMPASS Collaboration, Phys. Lett. B 770 (2017) 138.

# Comparison with Data



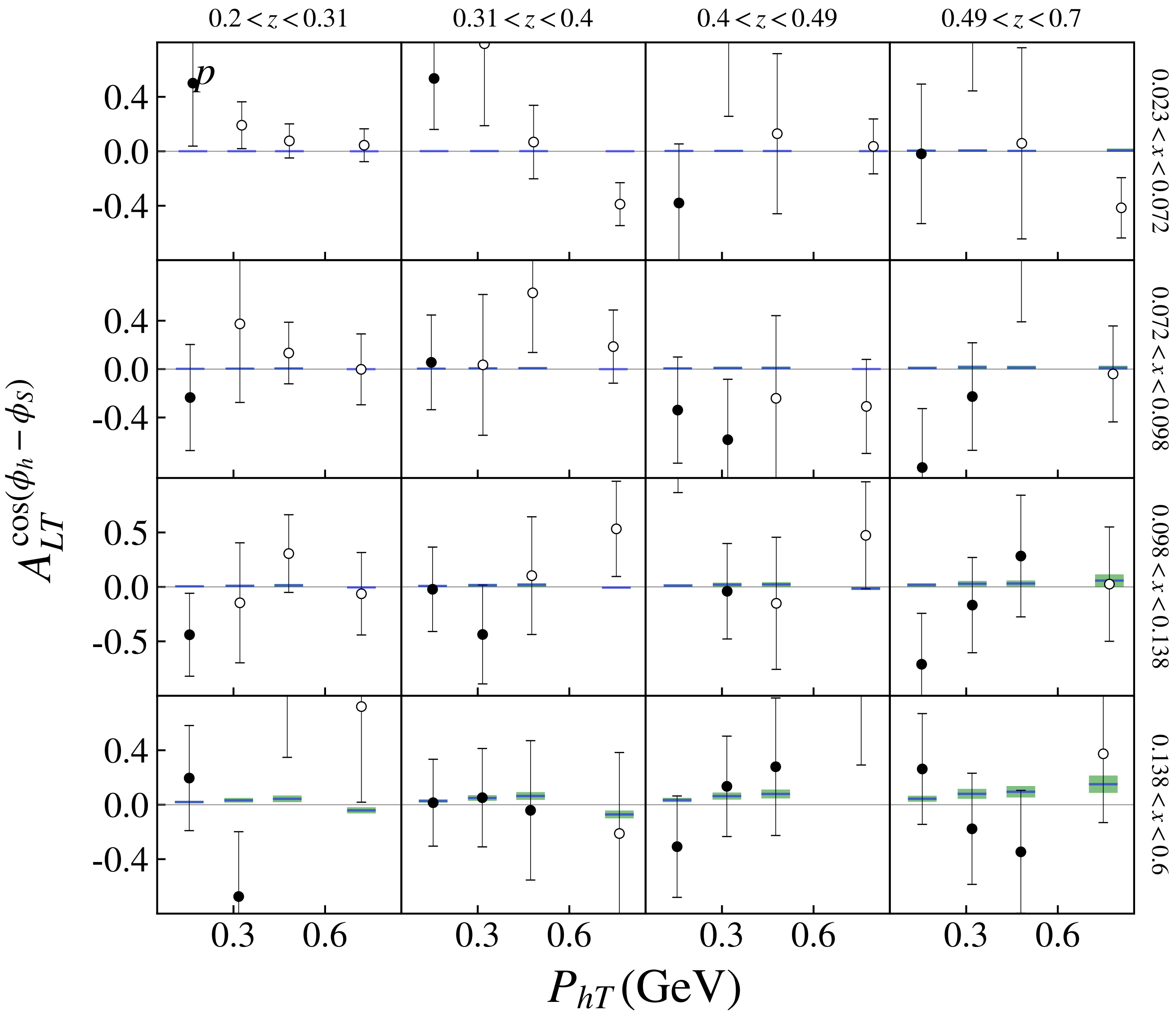

HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

# Comparison with Data



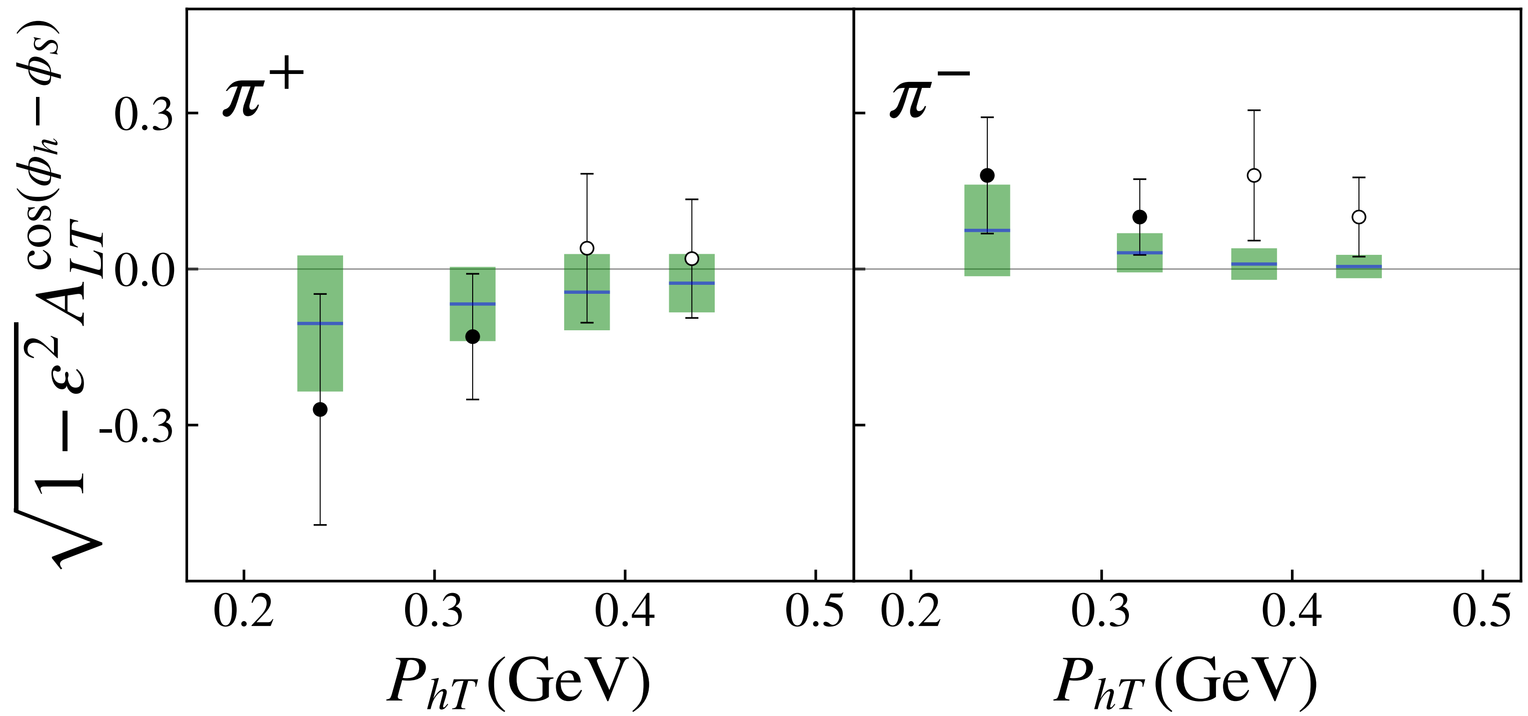

HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

# 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.

# 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).**