TMD Physics at EicC

The 2nd Workshop on Ultra-Peripheral Collision Physics:
Strong Electromagnetic Fields, UPC and EIC/EicC

Apr. 12th-15th, 2024 @ Hefei, NC

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On behalf of the EicC working groups

山东大学 SHANDONG UNIVERSITY

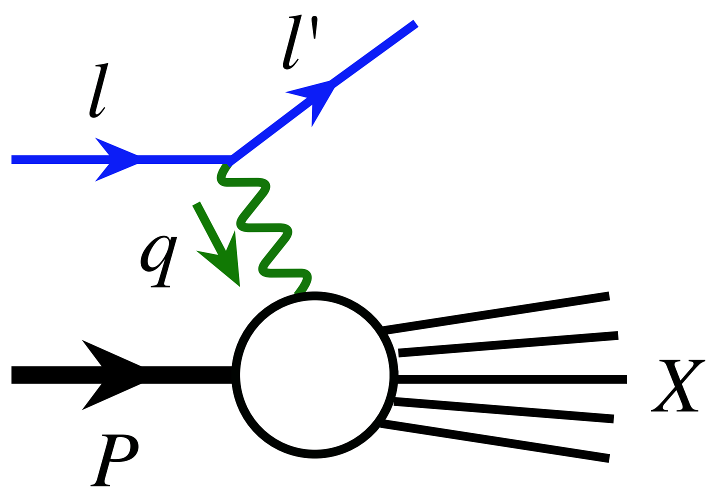
SCNT Southern Center for Nuclear-Science Theory

Lepton-Hadron Deep Inelastic Scattering

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

Modern "Rutherford" experiment.

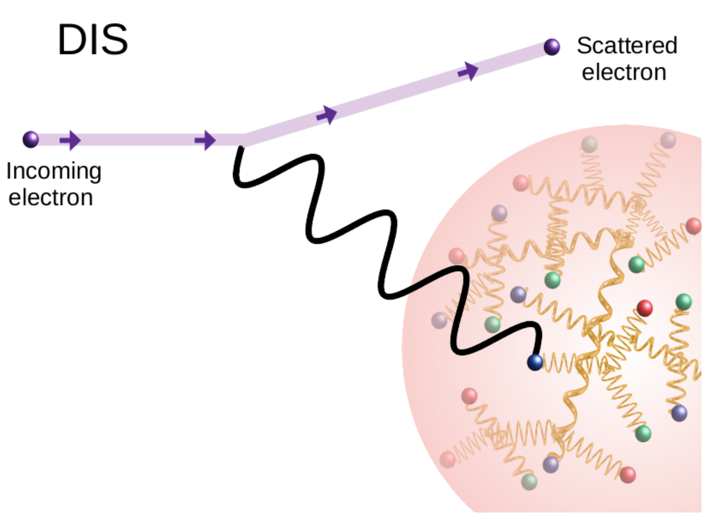
- dominated by the scattering of the lepton off an active quark/parton
- not sensitive to the dynamics at a hadronic scale ~ 1/fm
- collinear factorization: $\sigma \propto H(Q) \otimes \phi_{a/P}(x, \mu^2)$
- overall corrections suppressed by $1/Q^n$



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

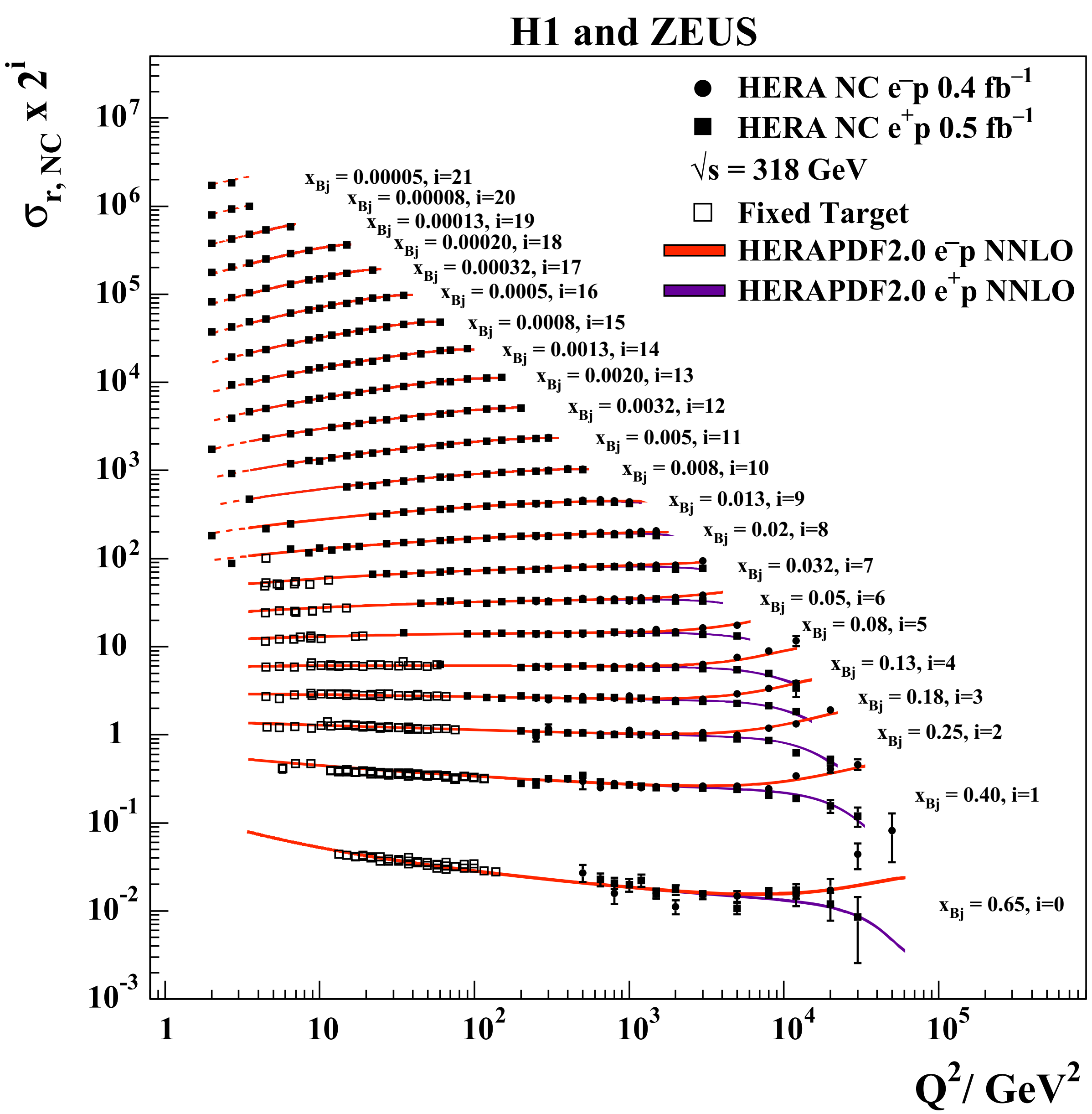
— precision of the probe

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

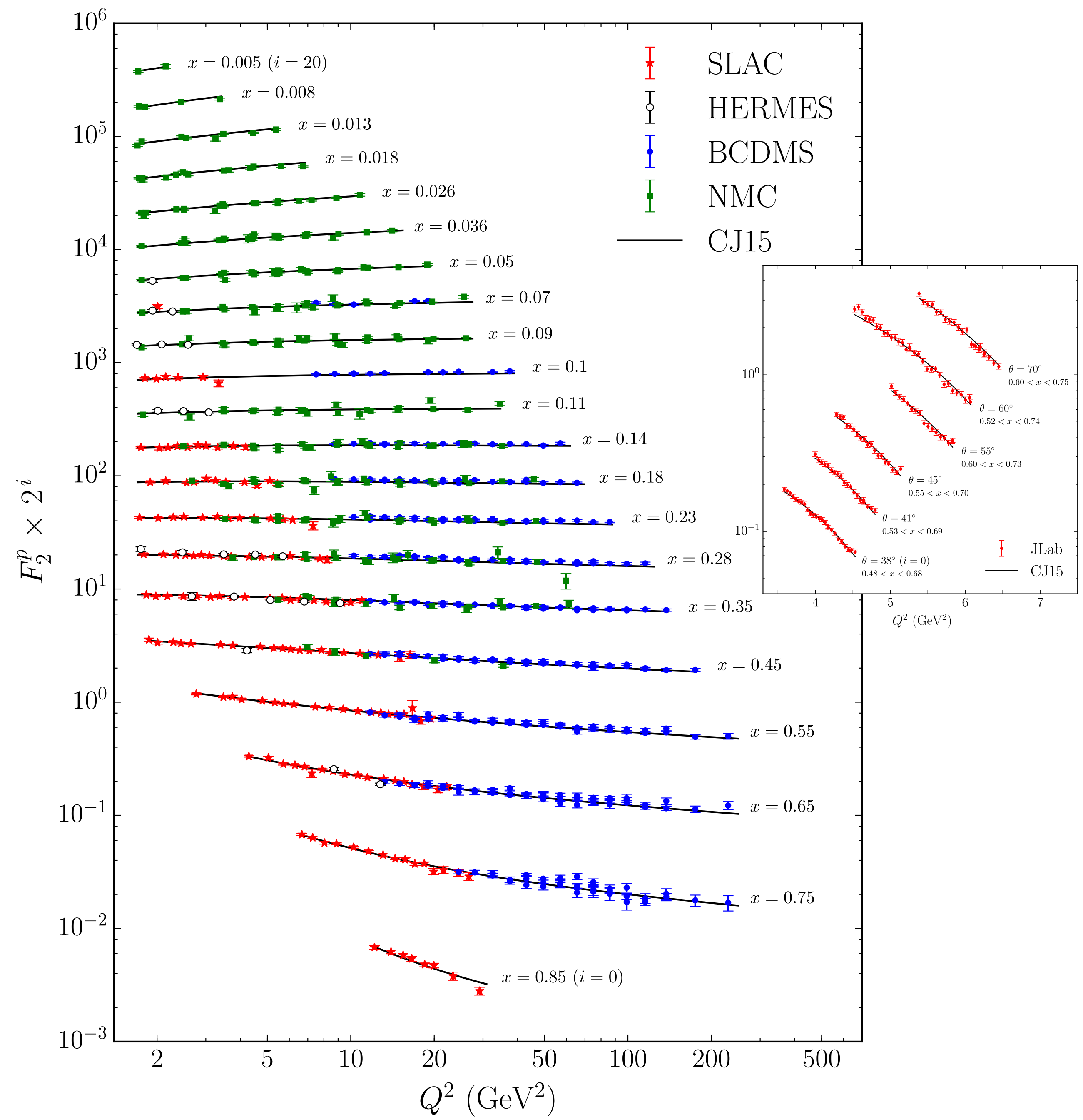


[Figure from DESY-21-099]

Lepton-Hadron Deep Inelastic Scattering



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



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

A successful story of QCD, factorization and evolution!

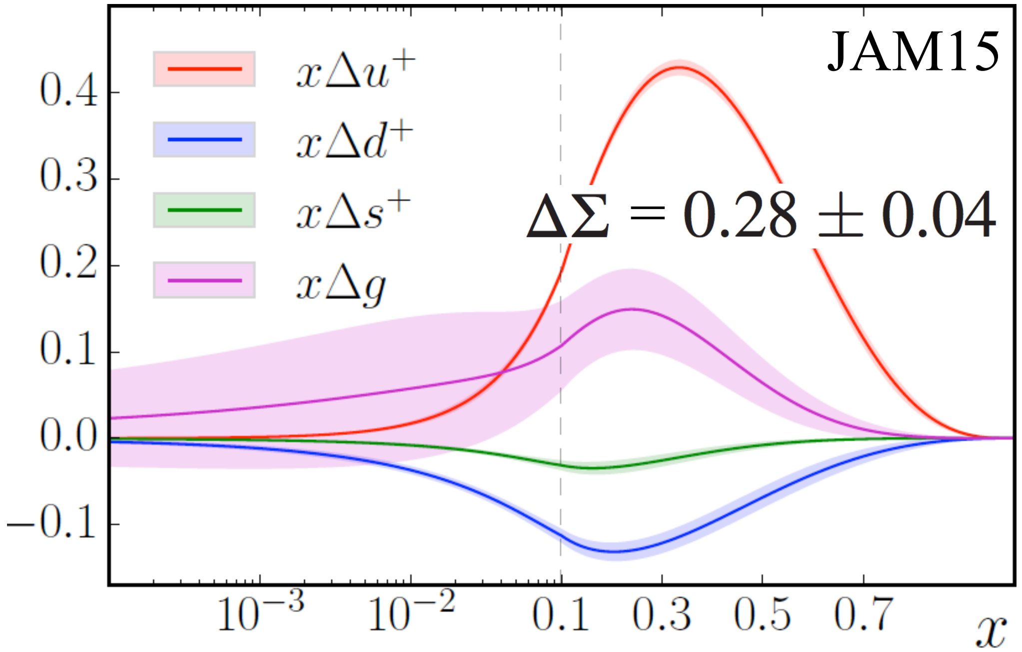
Nucleon Spin Structure

Proton spin puzzle

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

Spin decomposition

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



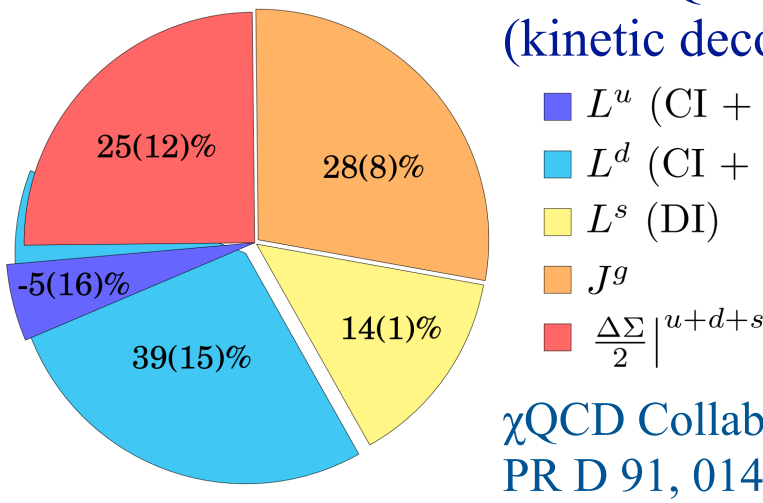
JAM Collaboration, PR D 93, 074005 (2016).

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).

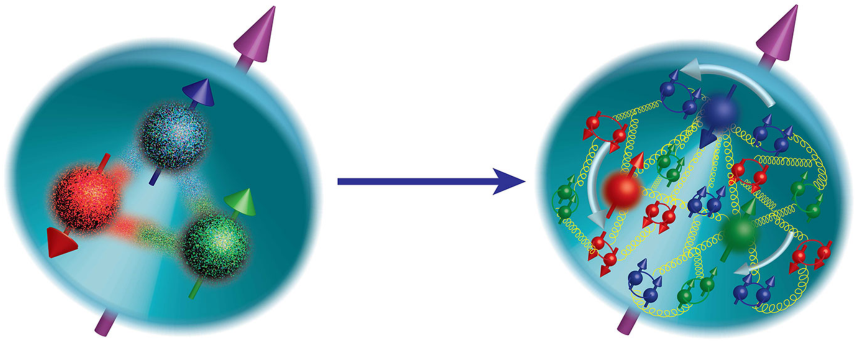


χQCD Collaboration, PR D 91, 014505 (2015).

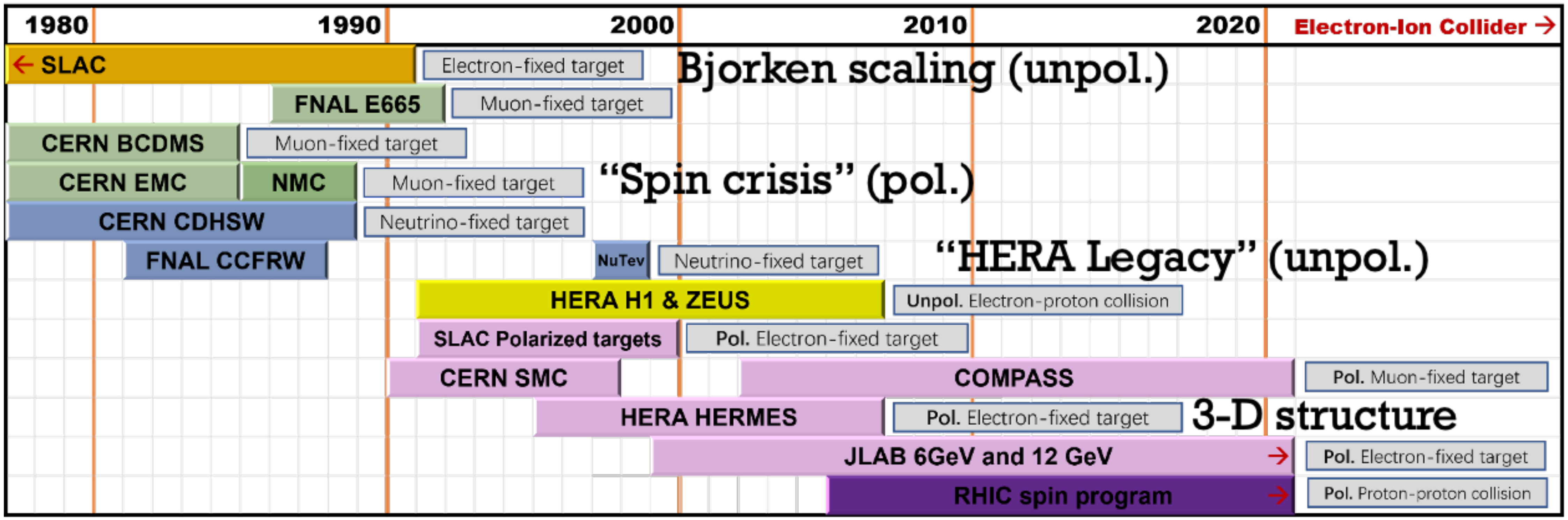
Gluon spin from LQCD: $S_g = 0.251(47)(16)$

50% of total proton spin

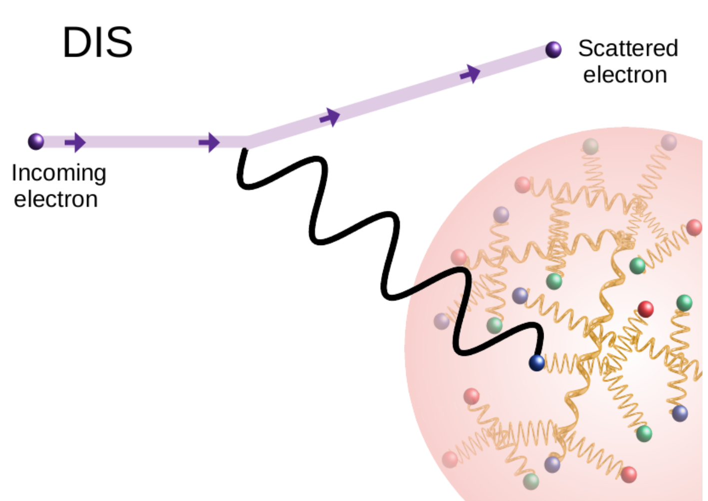
Y.-B. Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017).



Lepton Scattering: An Ideal Tool



[Figure from X.Y. Zhao]



[Figure from DESY-21-099]

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

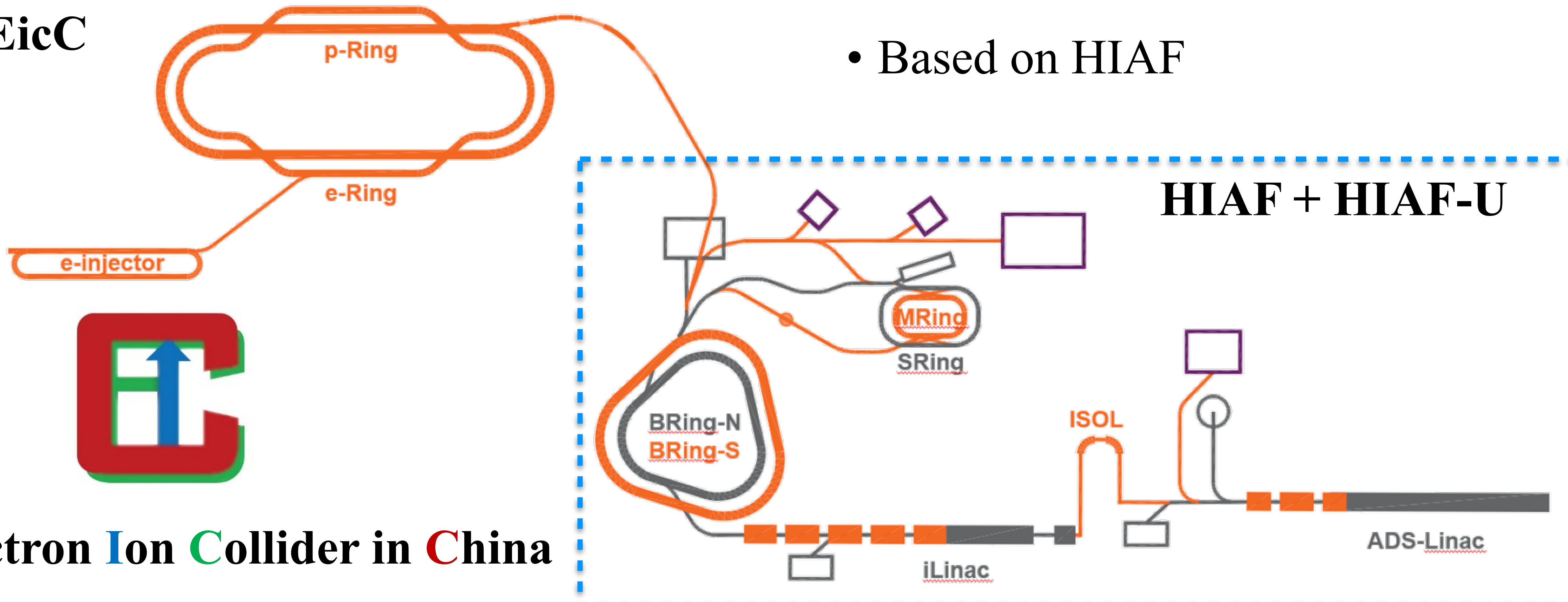
HIAF in Huizhou (惠州)

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

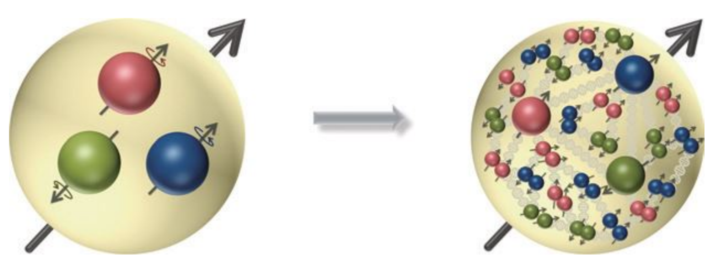
Electron Ion Collider in China

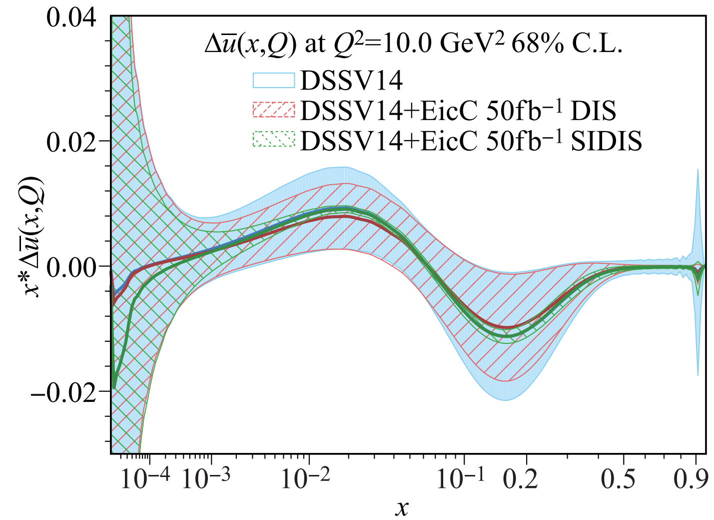
[Figure by EicC Accelerator WG]

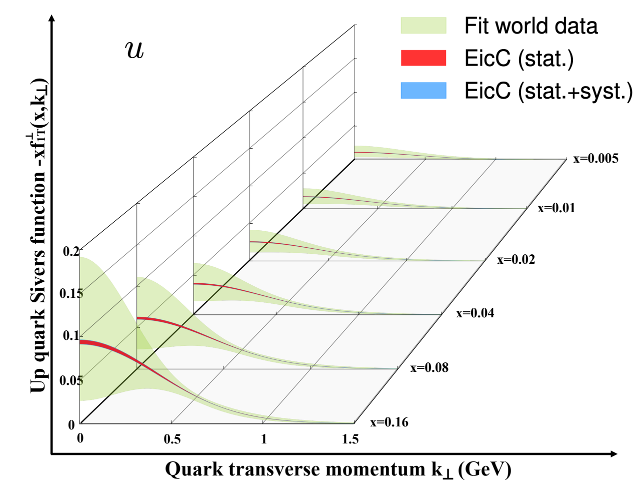
- energy in c.m.: 15 ~ 20 GeV
- luminosity: ≳ 2×10^{33} $cm^{-2} \cdot s^{-1}$
- electron beam: 3.5 GeV, polarization ~ 80%
- proton beam: 20 GeV, polarization ~ 70%
- other available polarized ion beams: d, $^3He^{++}$
- available unpolarized ion beams: $^7Li^{3+}$, $^{12}C^{6+}$, $^{40}Ca^{20+}$, $^{197}Au^{79+}$,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

Physics Highlights

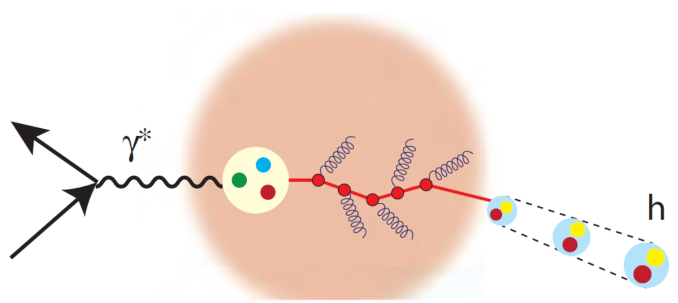
Partonic structure and three-dimensional landscape of the nucleon

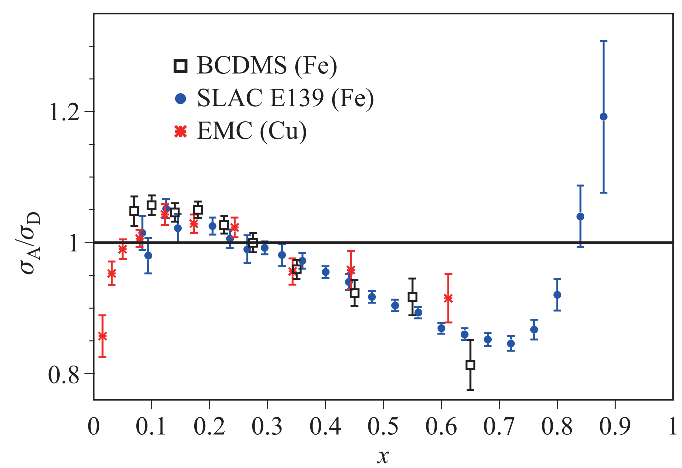


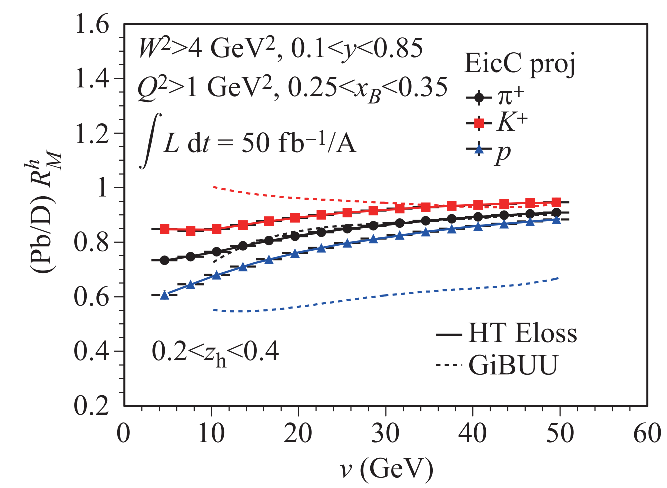




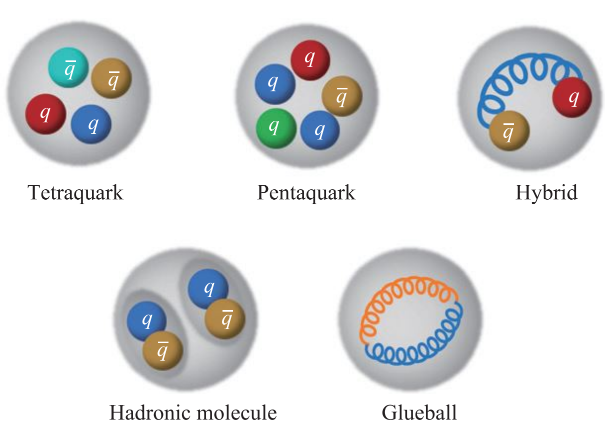
Partonic structure of nuclei

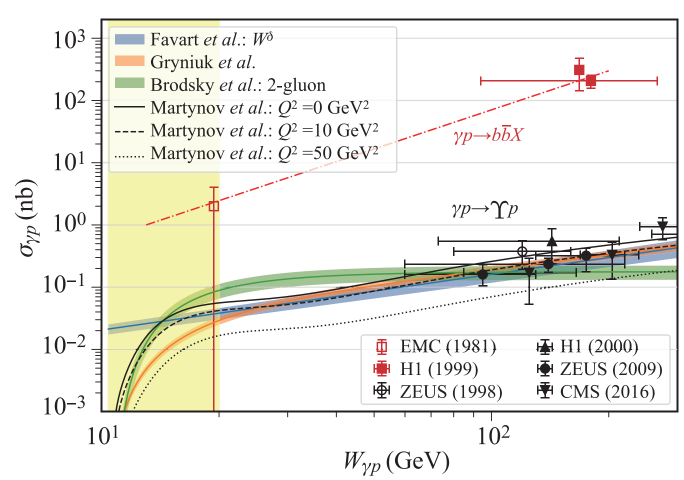


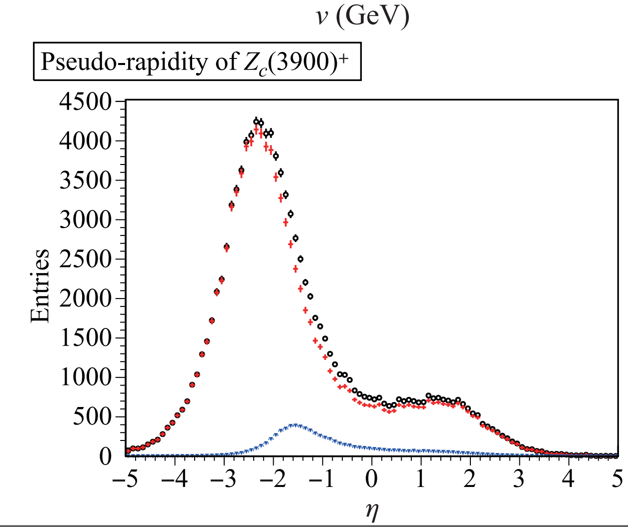




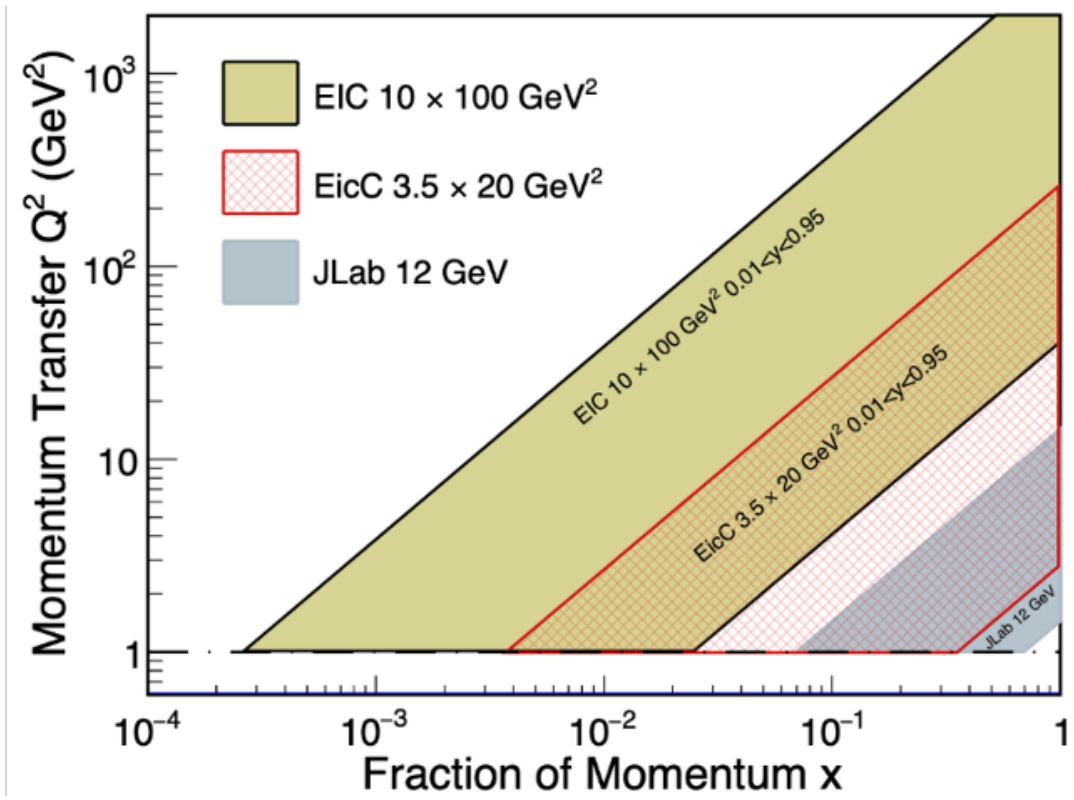
Exotic hadronic states







Complementarity of EicC and EIC-US



[Figure from EicC White paper]

Nucleon spin:

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

At a crucial place between JLab and EIC-US

Proton mass / quarkonium production:

Systematic investigation of Υ near threshold production

Complementary kinematic coverage to EIC-US

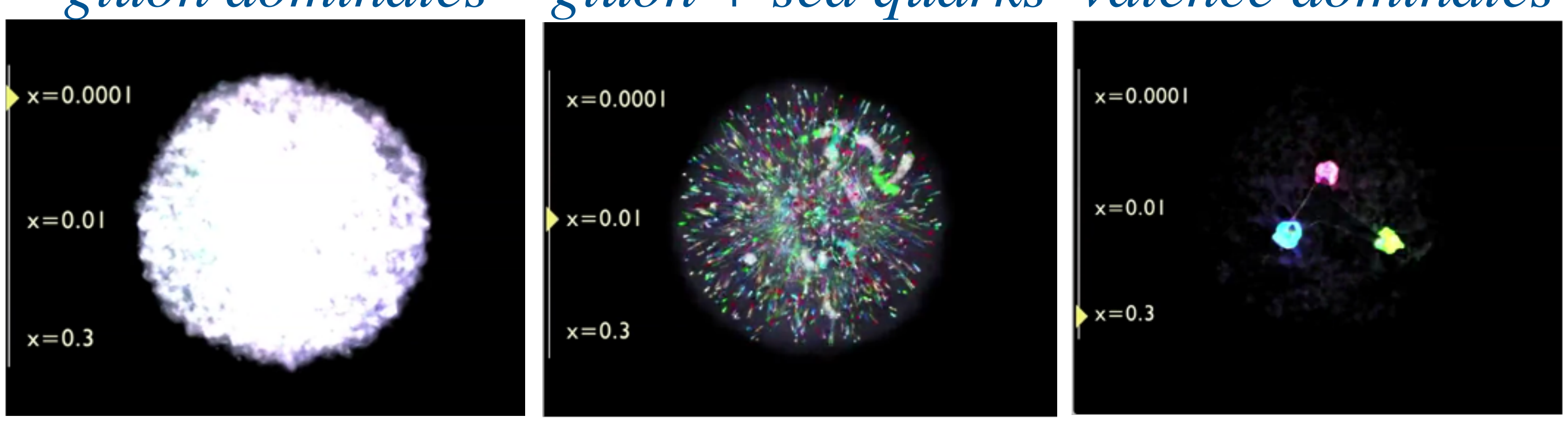
Combine with J/ψ production at JLab

Exotic hadron states:

Independent confirmation of hidden-charm pentaquarks and search for hidden-bottom analogues

Exotic hadron production: final particles in mid-rapidity

gluon dominates *gluon + sea quarks* *valence dominates*



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

Partonic structure in nuclear environment:

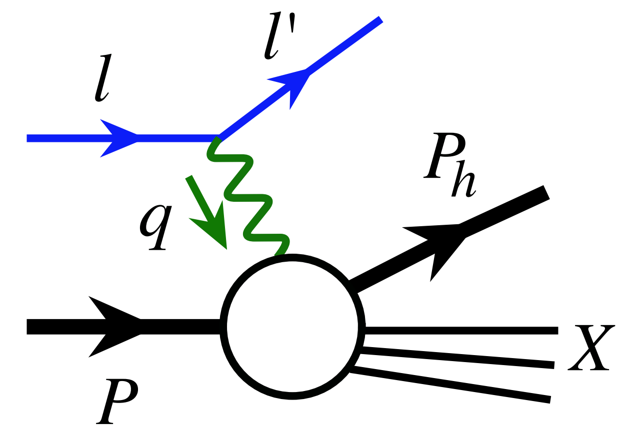
Parton distribution in nuclei at moderate x

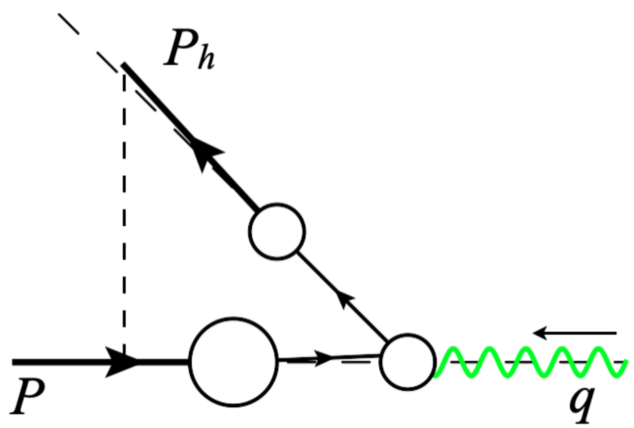
Fast parton/hadron interaction with cold nuclear matter

Semi-inclusive DIS

Identify a final state hadron

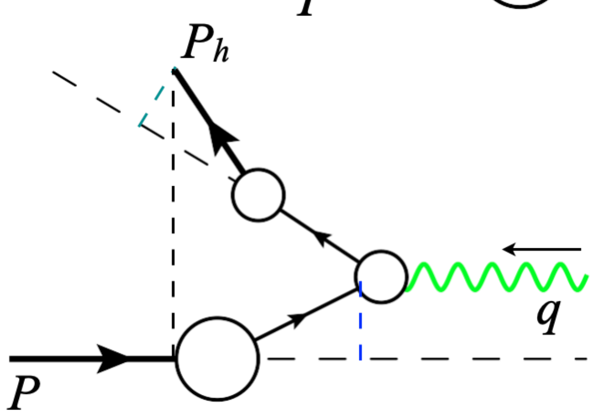
- explore the emergence of hadrons from colored quarks/gluons
- flavor dependence by selecting different observed hadrons
- an additional and adjustable momentum scale





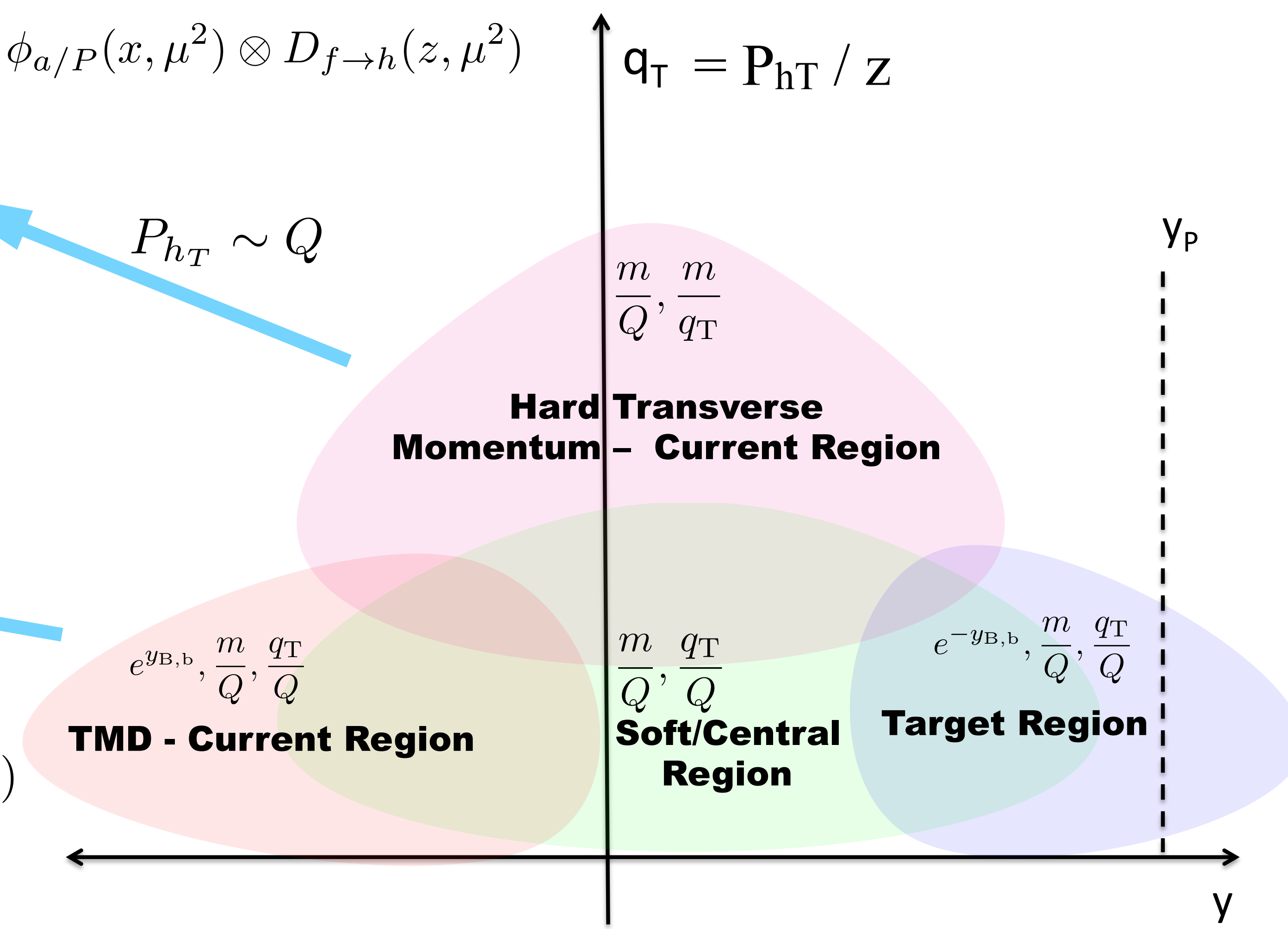
$$\otimes \phi_{a/P}(x,\mu^2) \otimes D_{f\to h}(z,\mu^2)$$

$P_{h_T} \sim Q$



$P_{h_T} \ll Q$

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

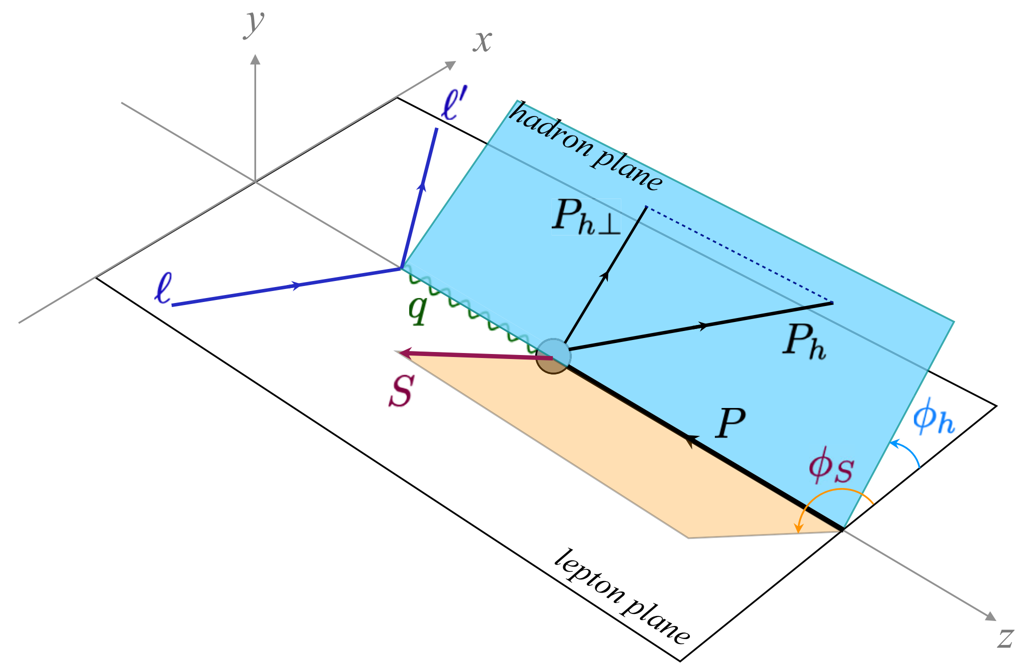


[Figure from JHEP10(2019)122]

SIDIS in Trento Convention

SIDIS differential cross section

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



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

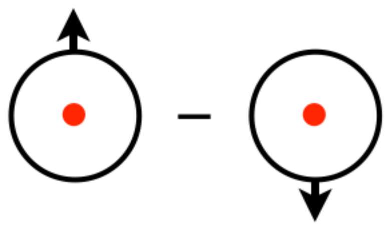
$$= \frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x_B}\right)$$
$$\times \Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} F_{UU}^{\cos\phi_h} \cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda_e \sqrt{2\epsilon(1-\epsilon)} F_{LU}^{\sin\phi_h}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

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

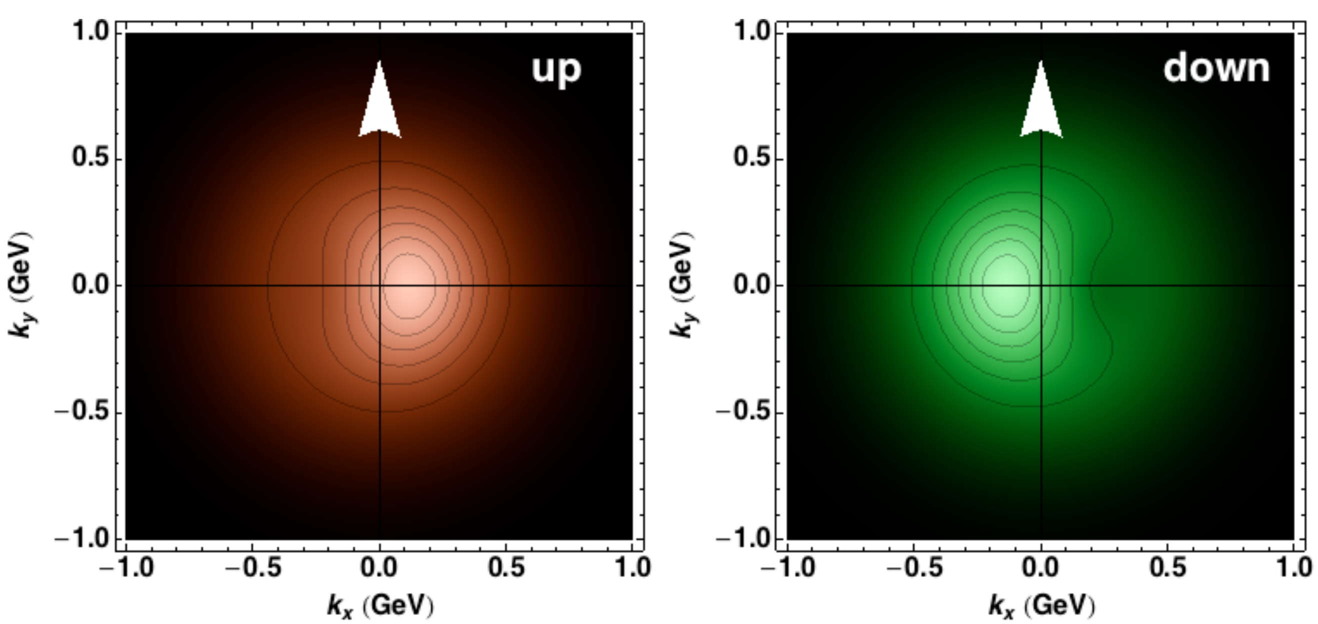
The Sivers Function

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]

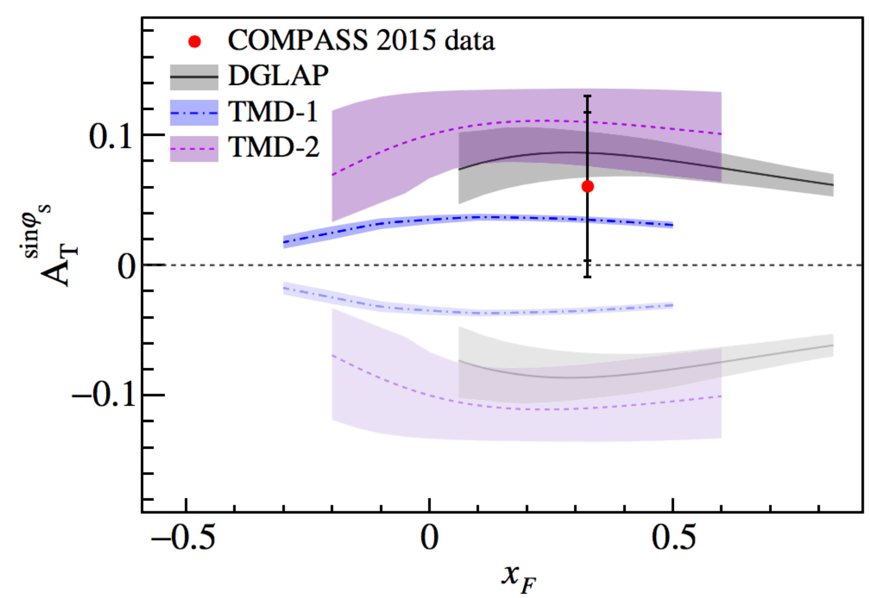
Effect in SIDIS:
transverse single spin asymmetry (Sivers asymmetry)

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

sizable Sivers asymmetry observed by HERMES, COMPASS, JLab

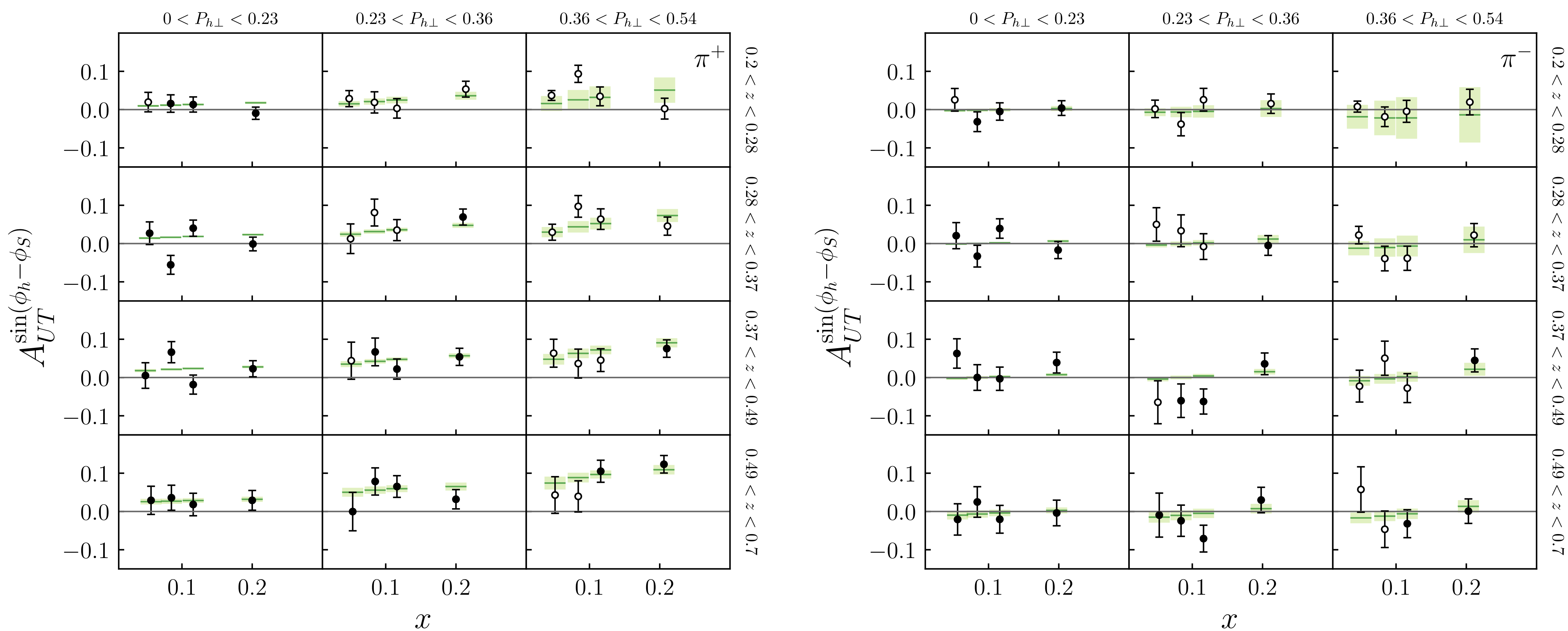
Sign change prediction:

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



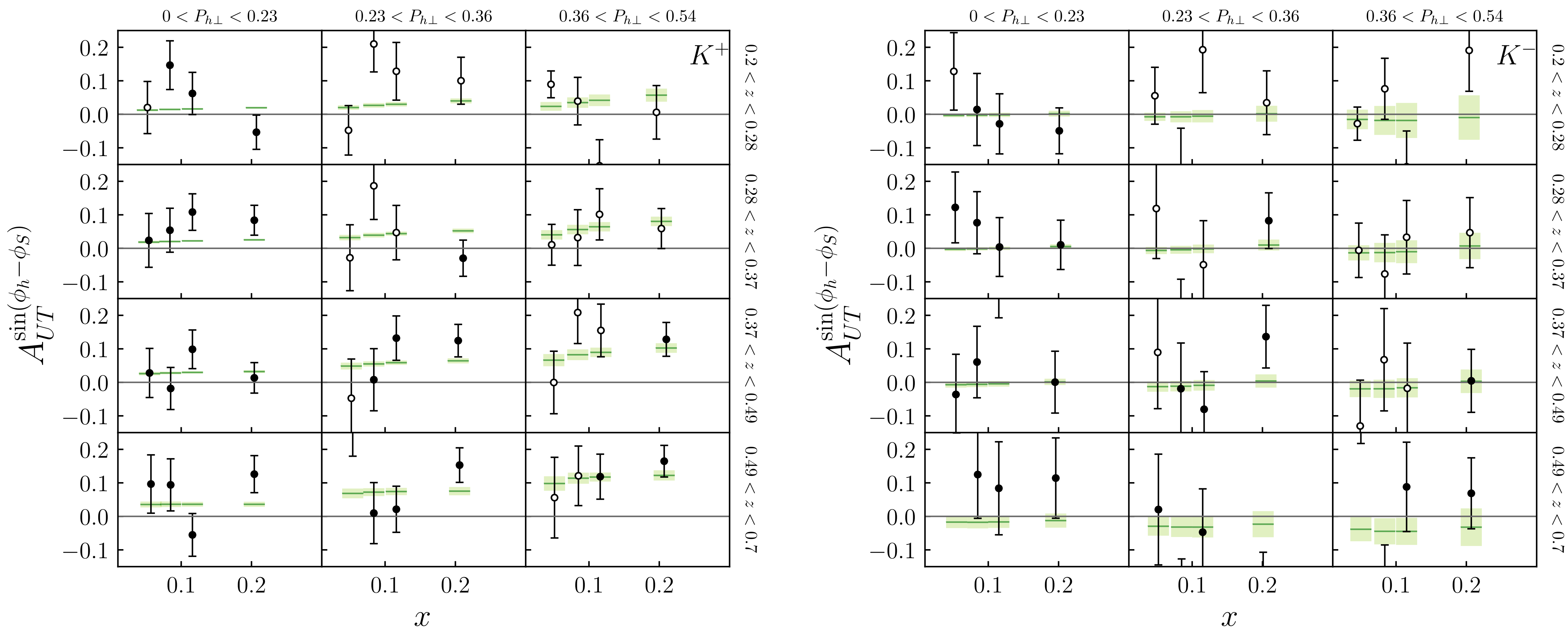
COMPASS Collaboration, PRL 119, 112002 (2017).

Measurements of the Sivers Asymmetry



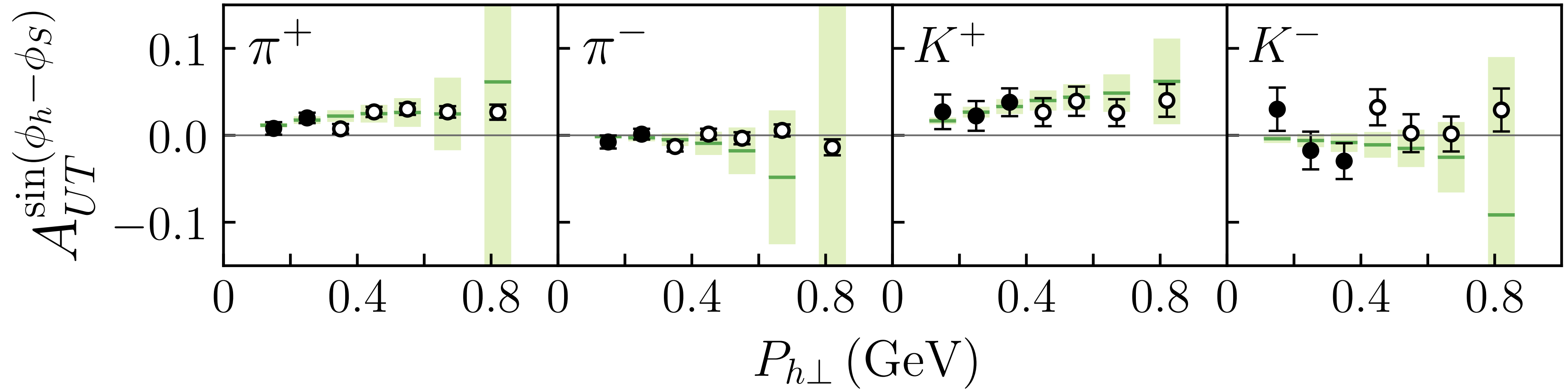
HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

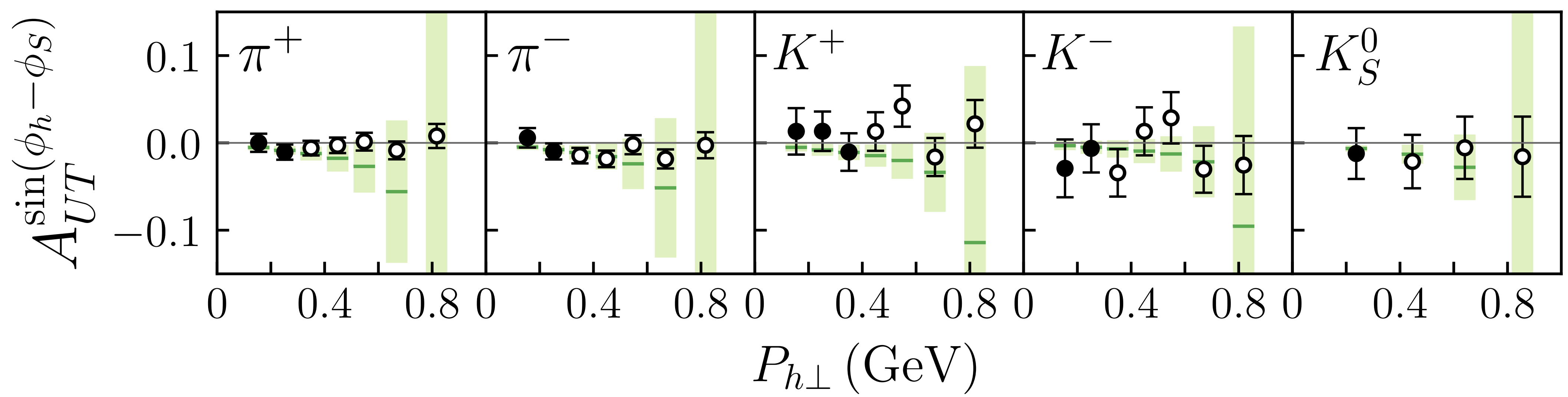
Measurements of the Sivers Asymmetry



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

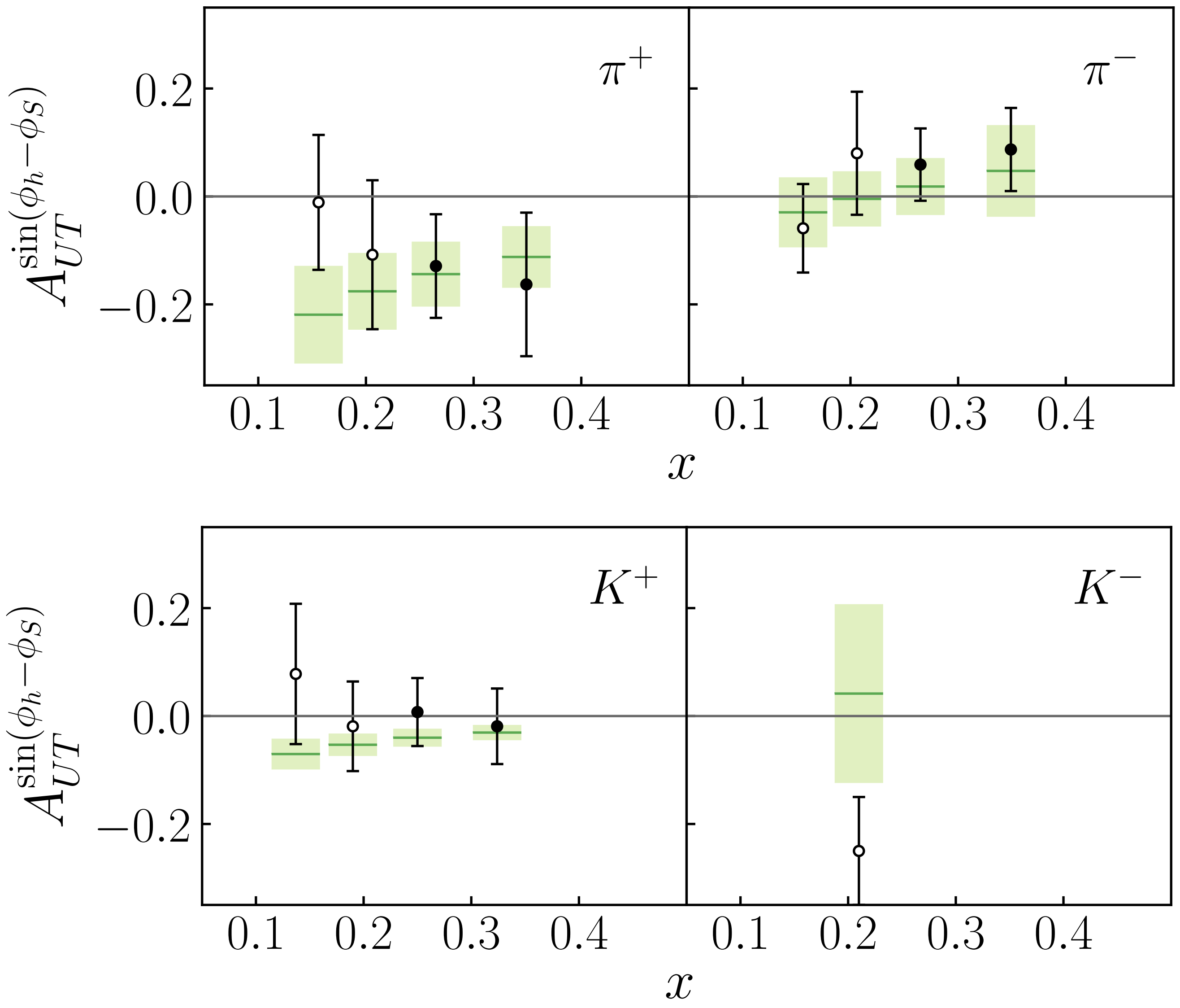
Measurements of the Sivers Asymmetry





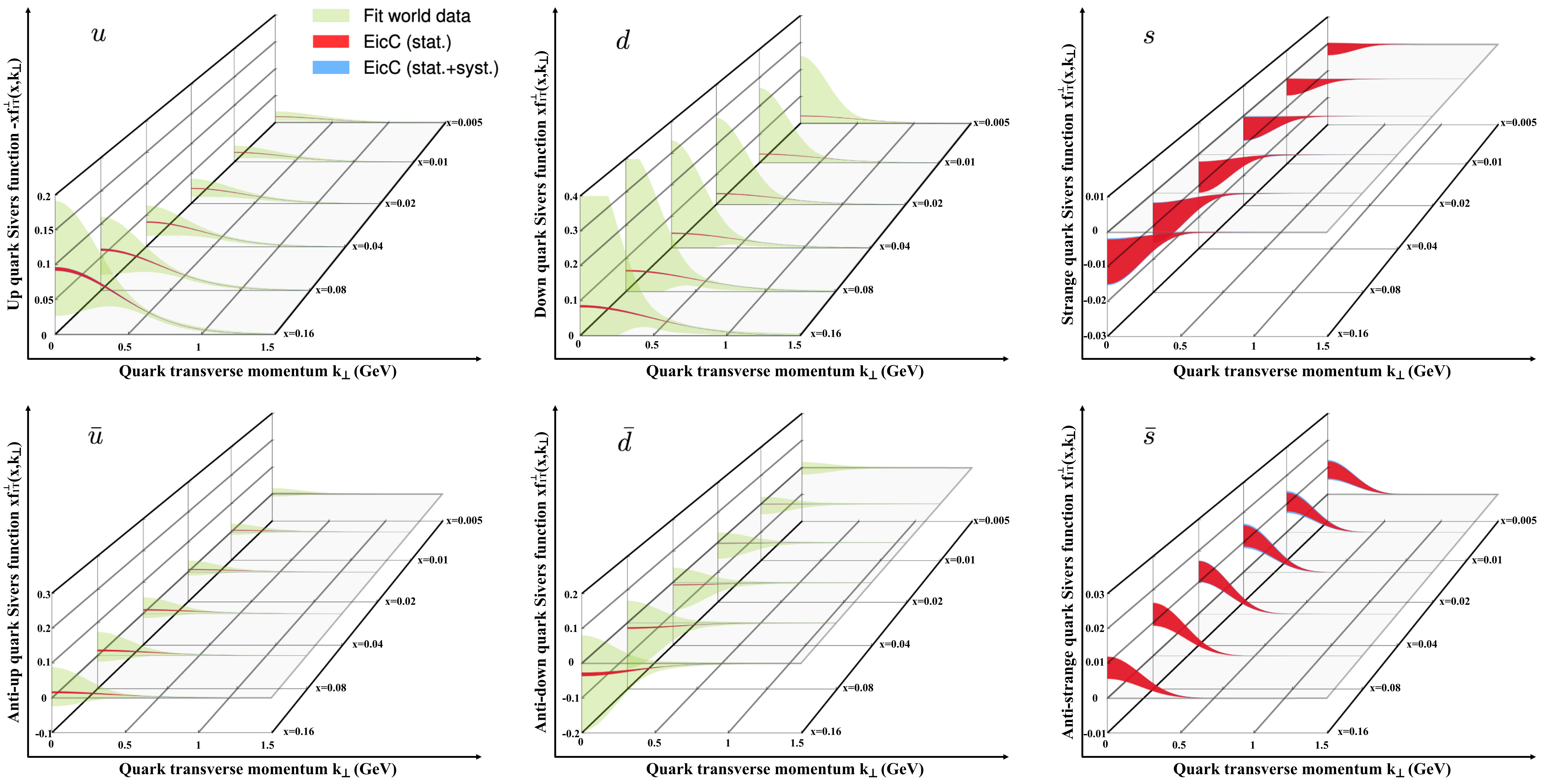
COMPASS Collaboration, Phys. Lett. B 673 (2009) 127; Phys. Lett. B 744 (2015) 250.

Measurements of the Sivers Asymmetry



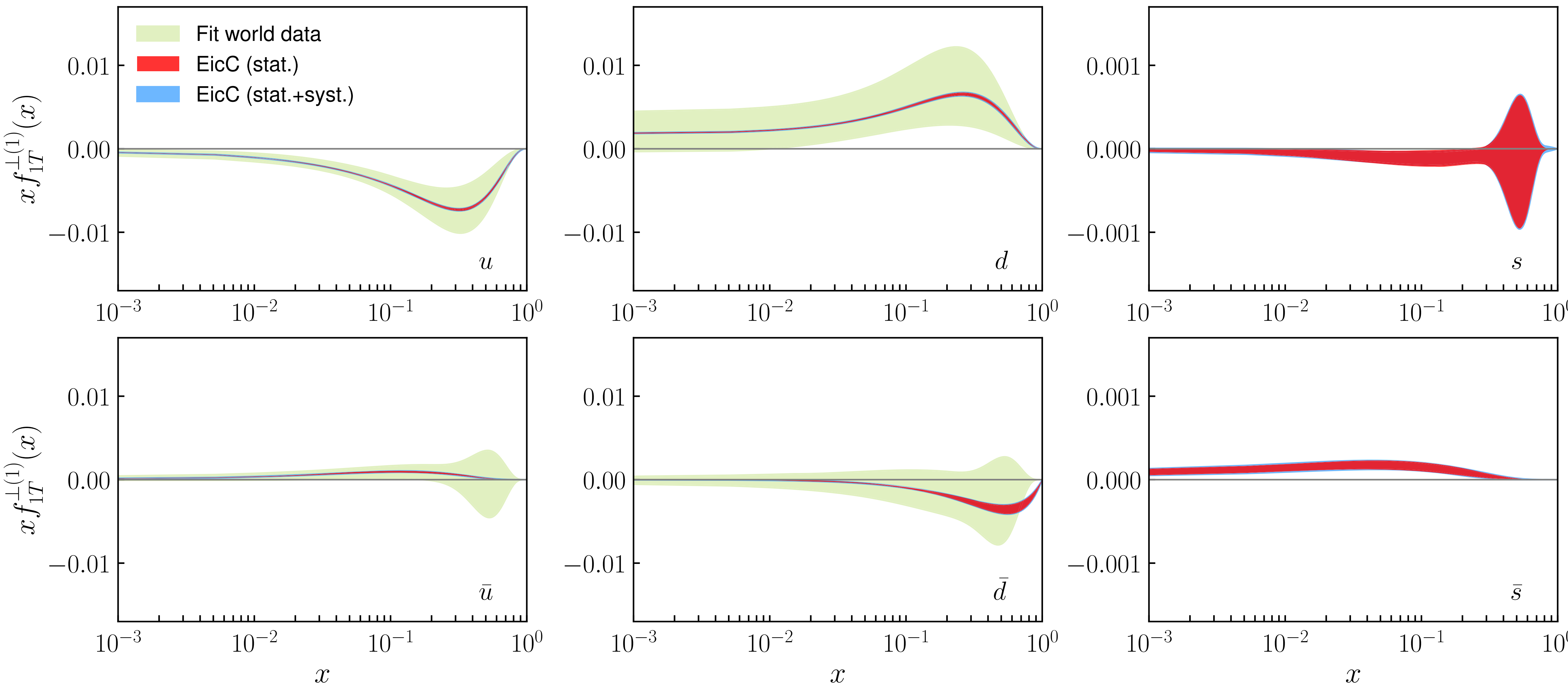
JLab HallA Collaboration, Phys. Rev. Lett. (2011) 072003; Phys. Rev. C 90 (2014) 055201.

Extraction of the Sivers function



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

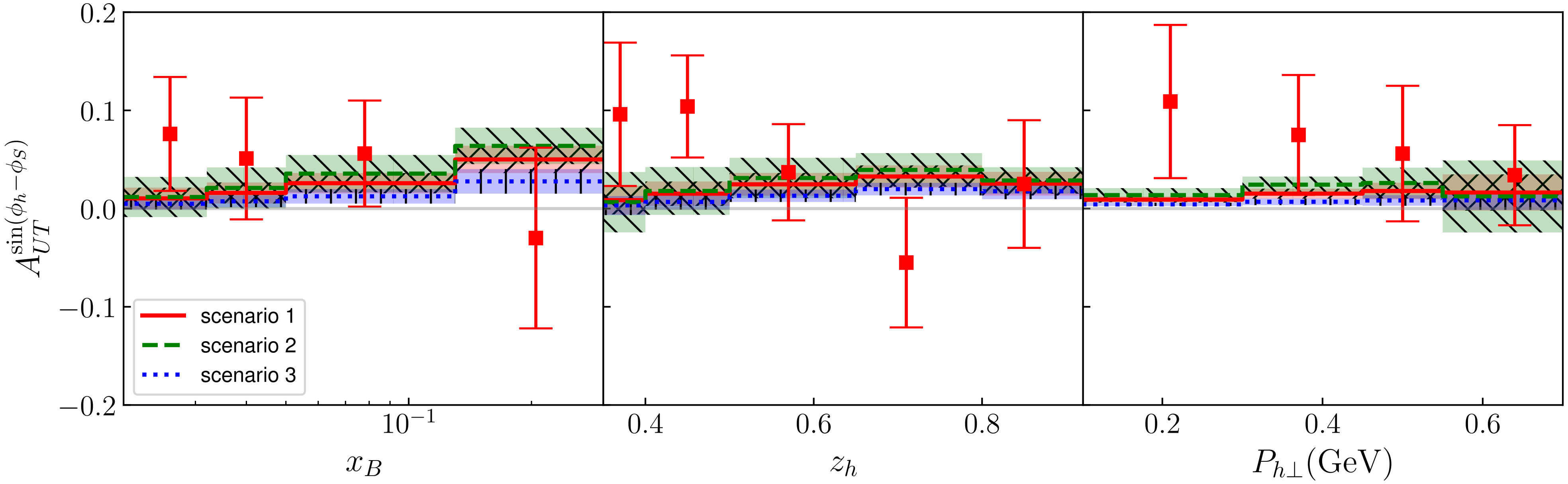
EicC Impact: Sivers function



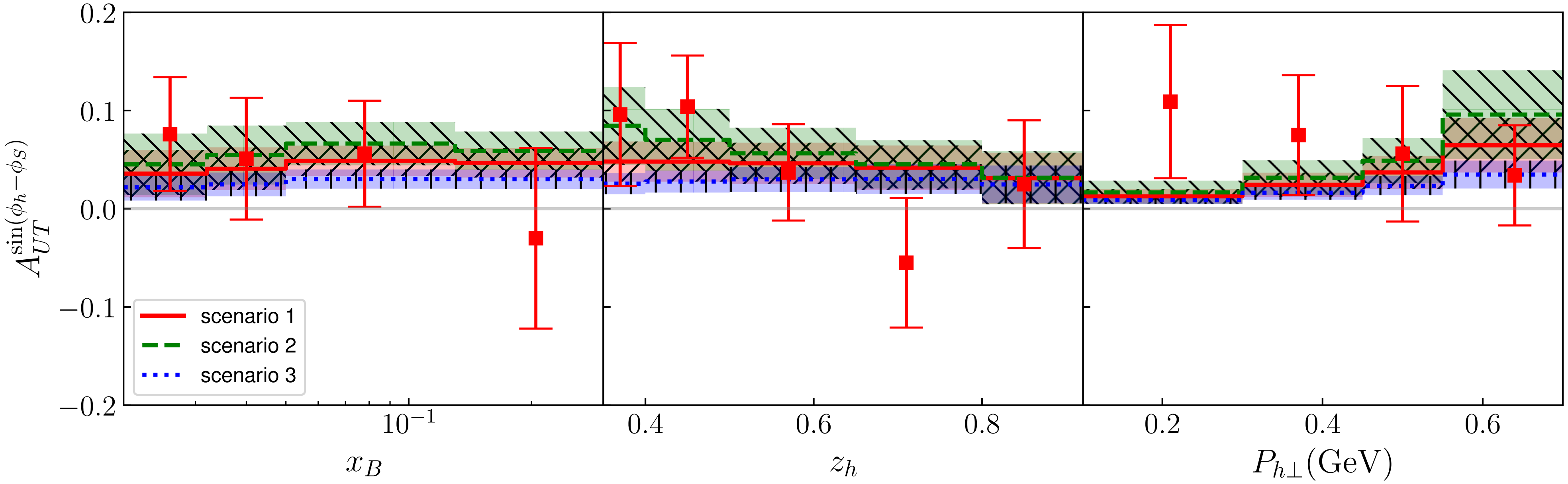
$$f_{1T}^{\perp(1)}(x) = \pi \int d\mathbf{k}_\perp^2 \frac{\mathbf{k}_\perp^2}{2M^2} f_{1T}^{\perp}(x, \mathbf{k}_\perp^2)$$

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

Sivers Asymmetry of 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.

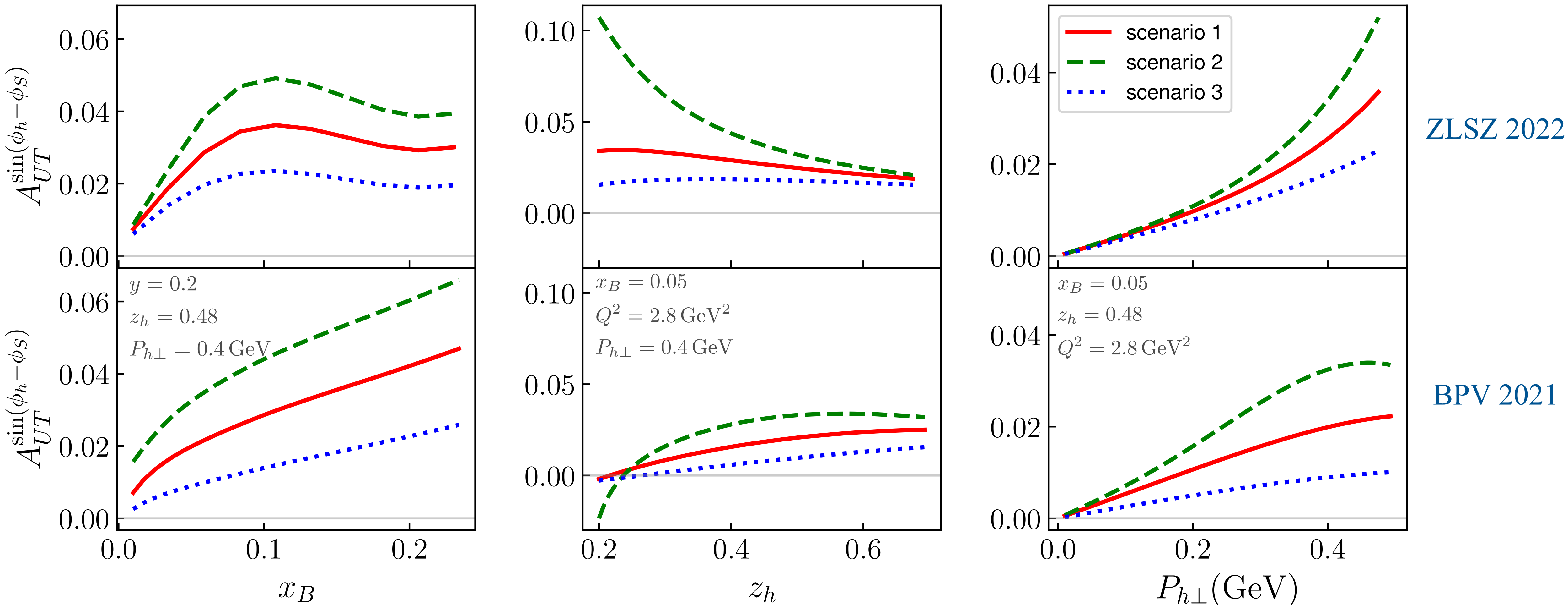
Scenarios: different transverse momentum dependences of ρ^0 fragmentation functions

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

Sivers Asymmetry of ρ^0 Production

Predictions at EicC kinematics:

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

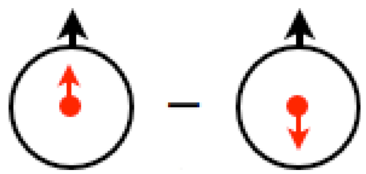


Different predictions to be tested at EicC kinematics

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

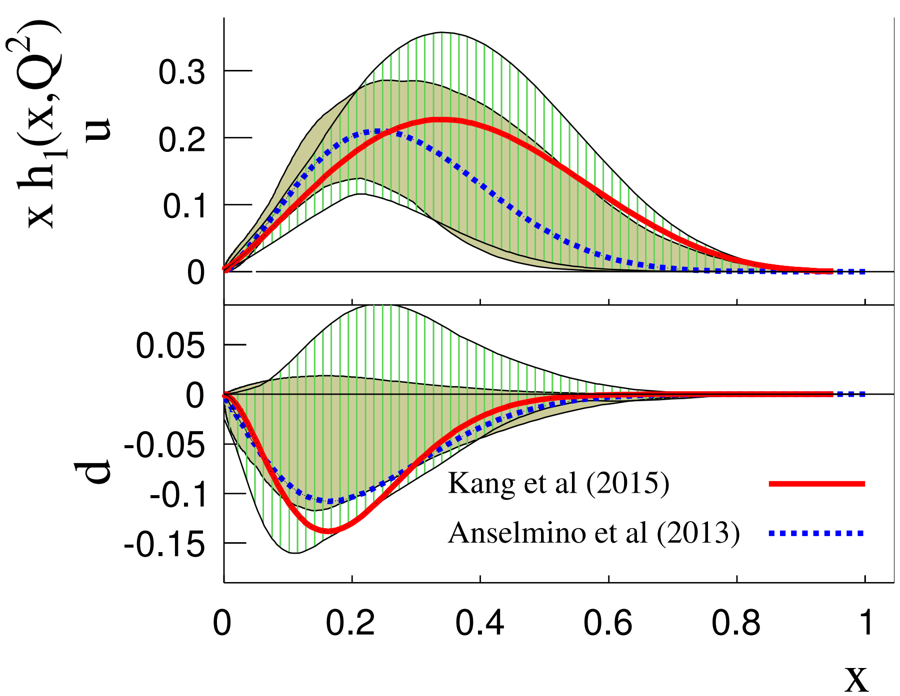
Transversity Distribution

Transversity distribution

h_1  (Collinear & TMD)

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

Phenomenological extractions



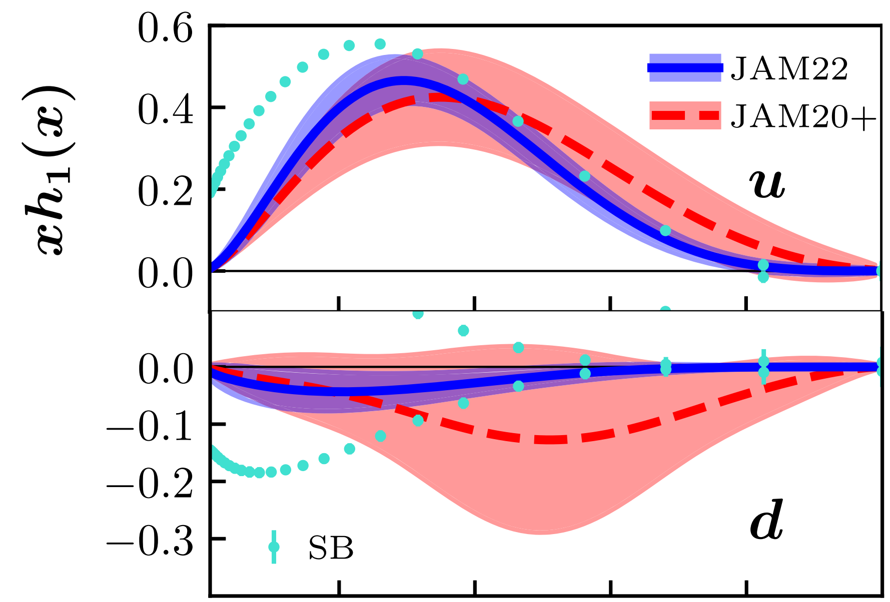
Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, PRD 93, 014009 (2016).

Chiral-odd:

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

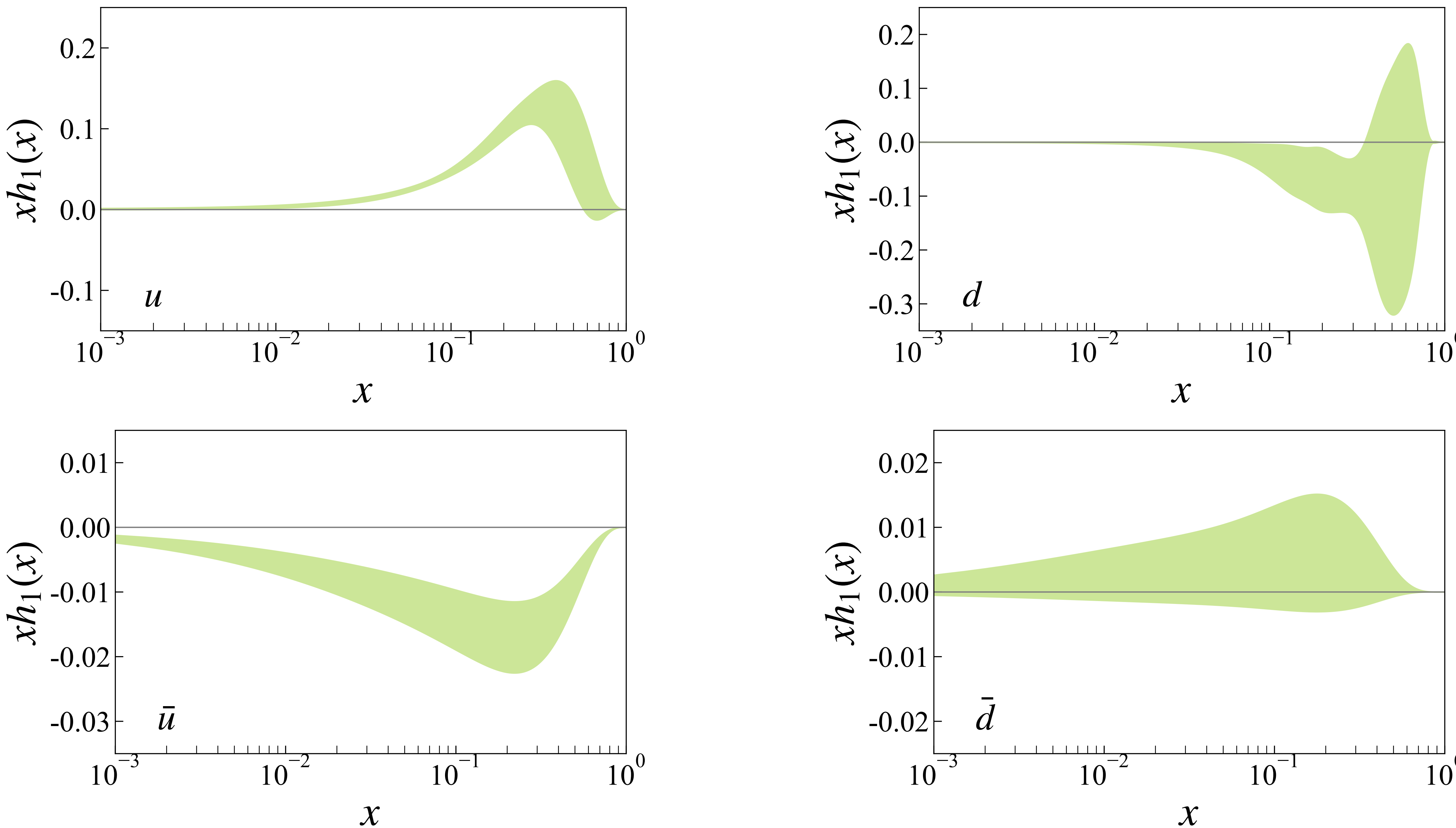
Effect in SIDIS:
transverse single spin asymmetry
(Collins asymmetry)

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



JAM Collaboration, PRD 104, 034014 (2022).

Sea Quark Transversity

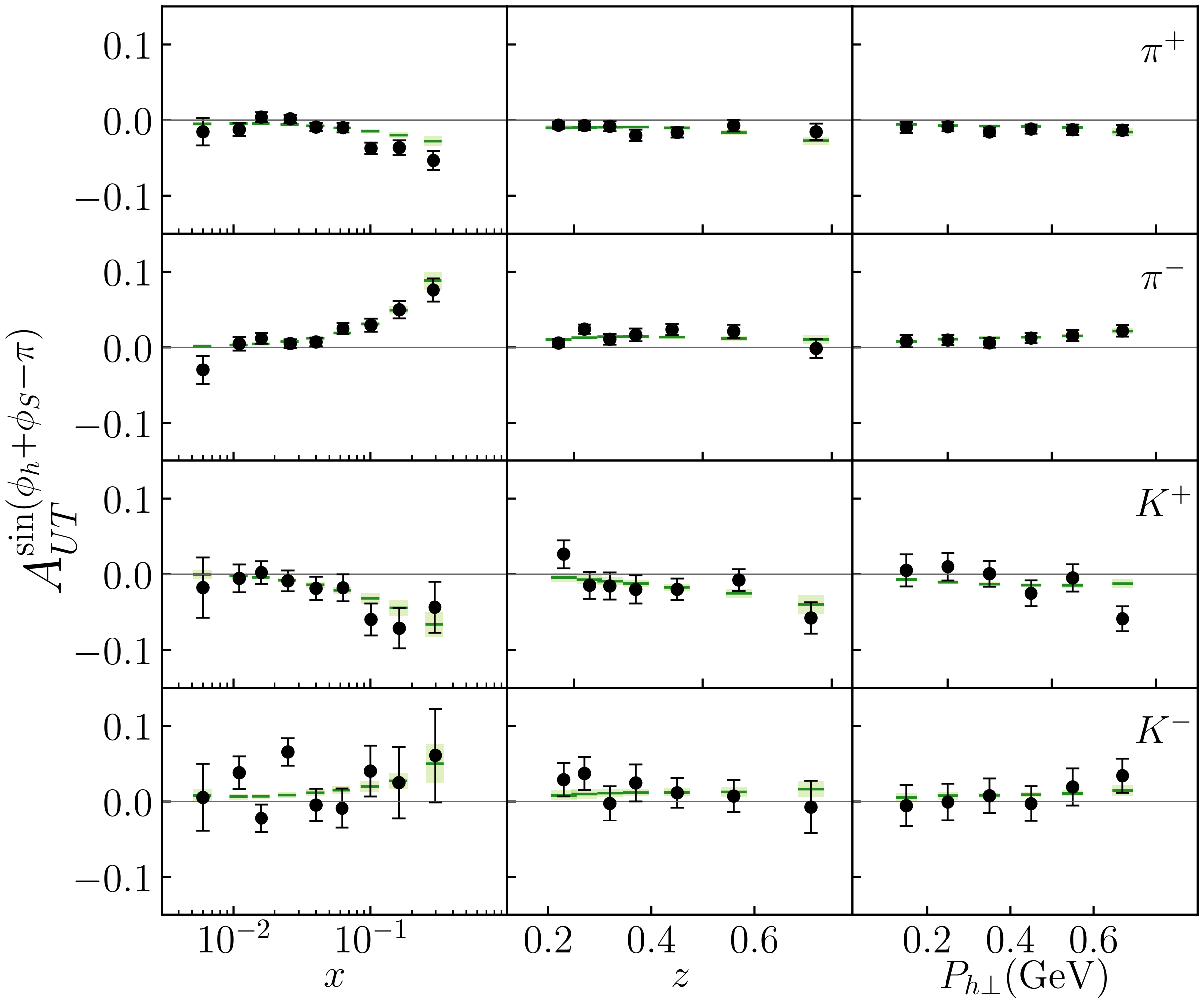


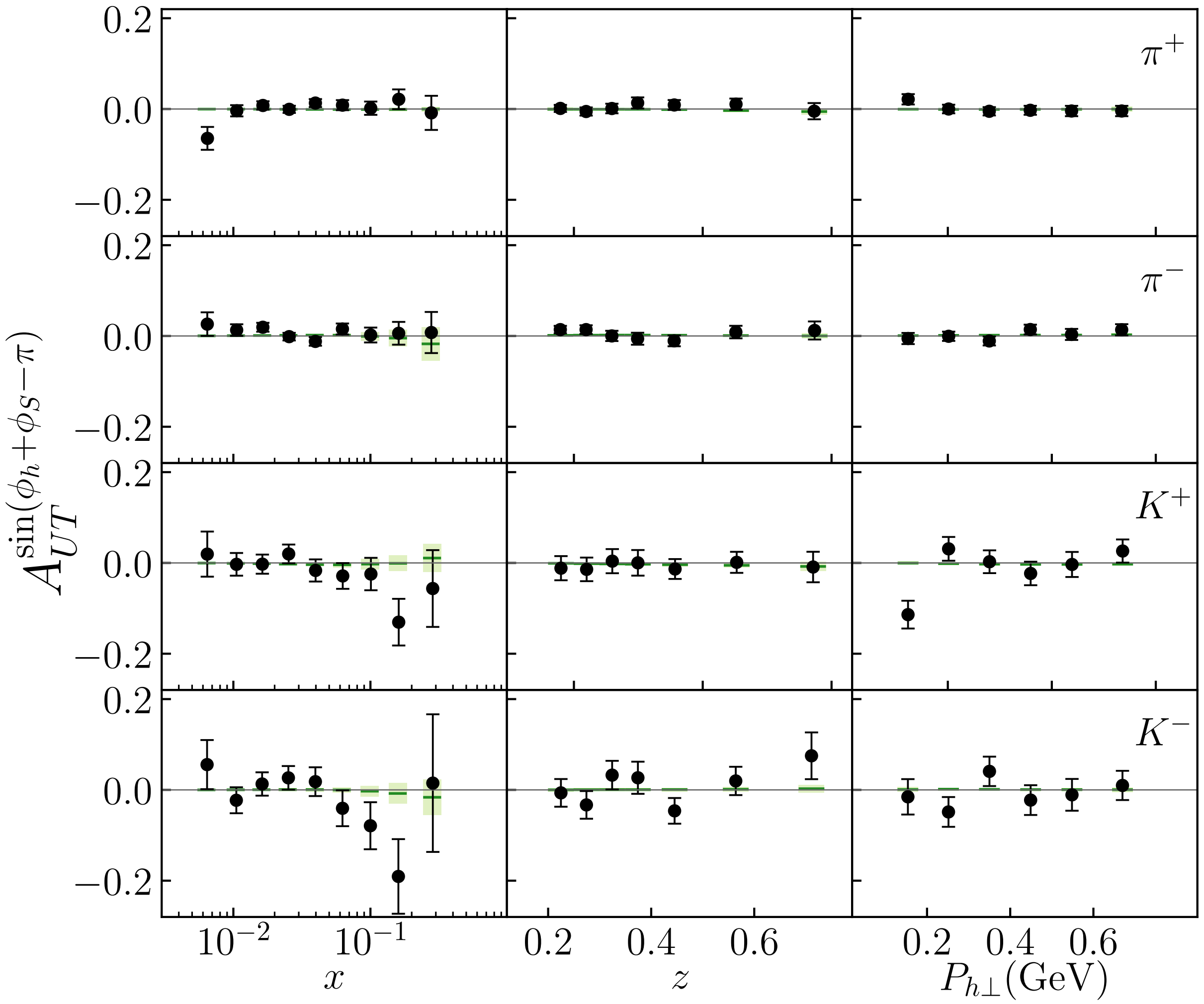
Anti-u quark favors negative distribution

Anti-d quark consistent with zero with current precision

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

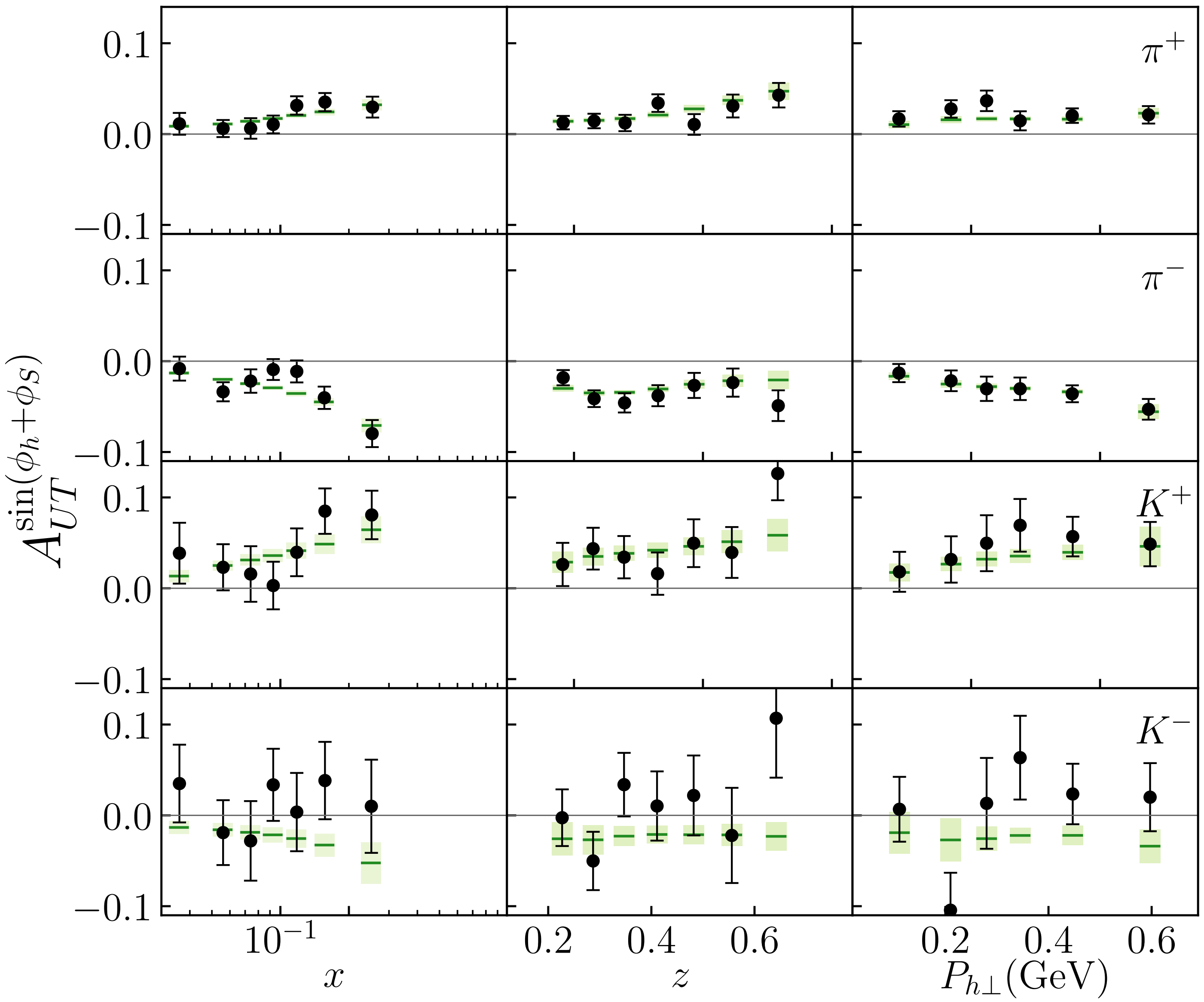
Comparison with Data





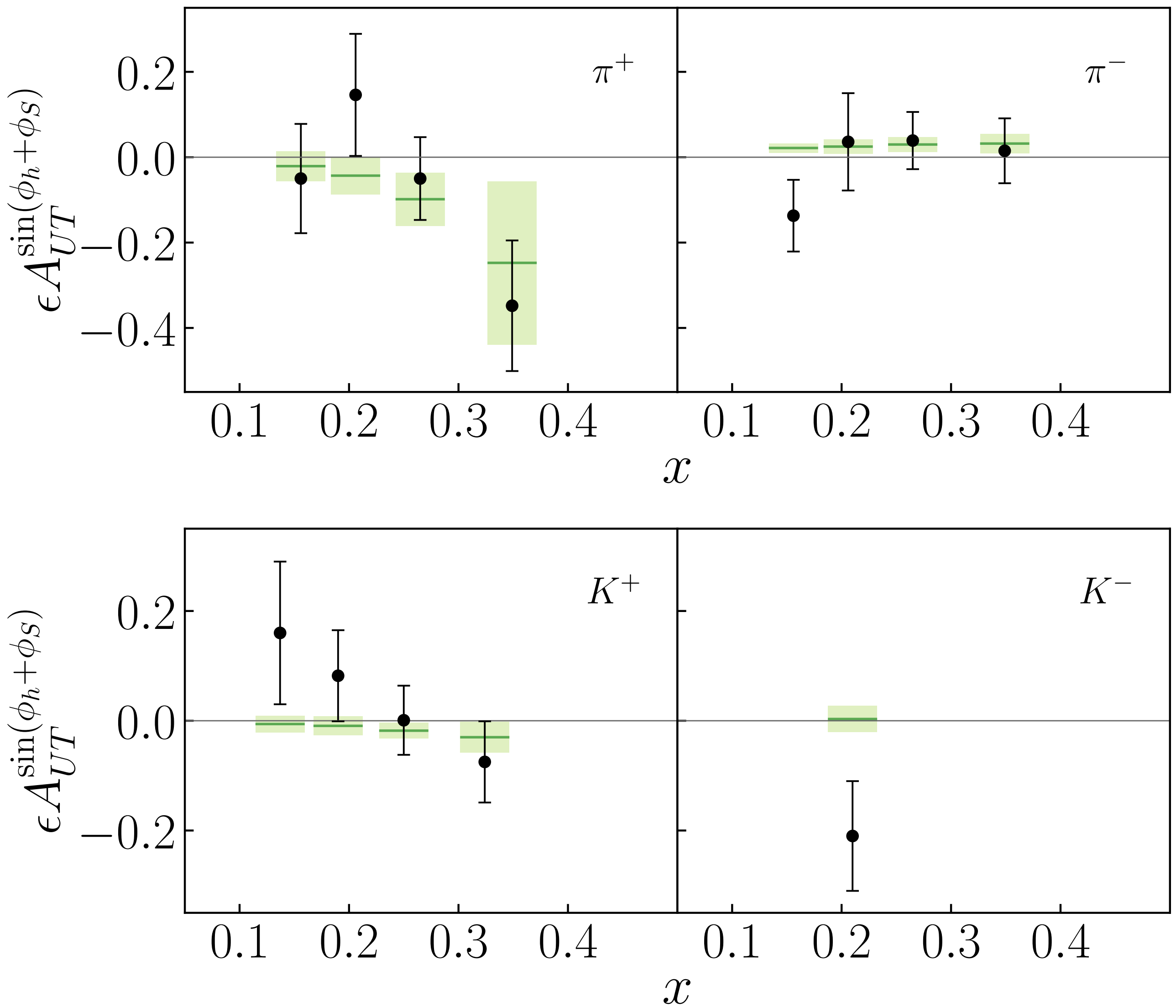
COMPASS Collaboration, Phys. Lett. B 673 (2009) 127; Phys. Lett. B 744 (2015) 250.

Comparison with Data



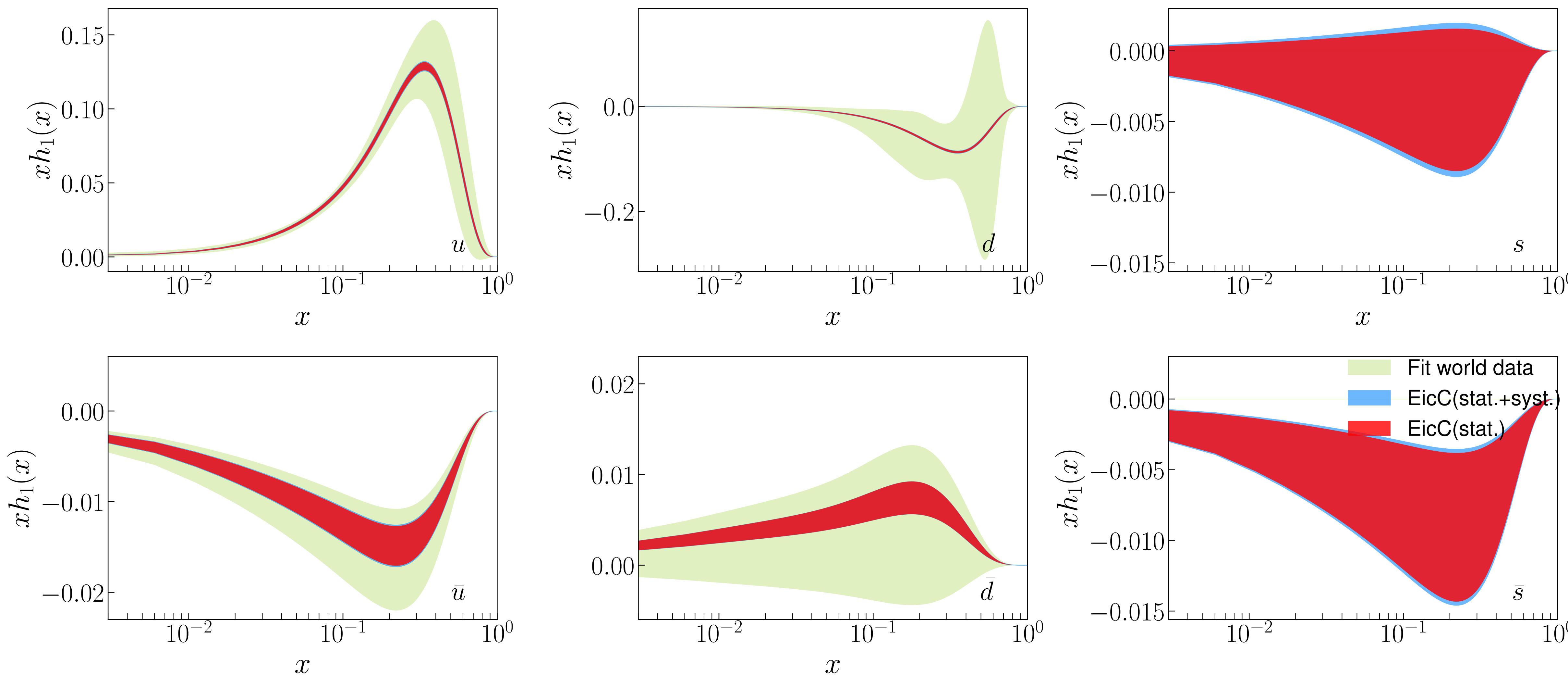
HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

Comparison with Data



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

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.

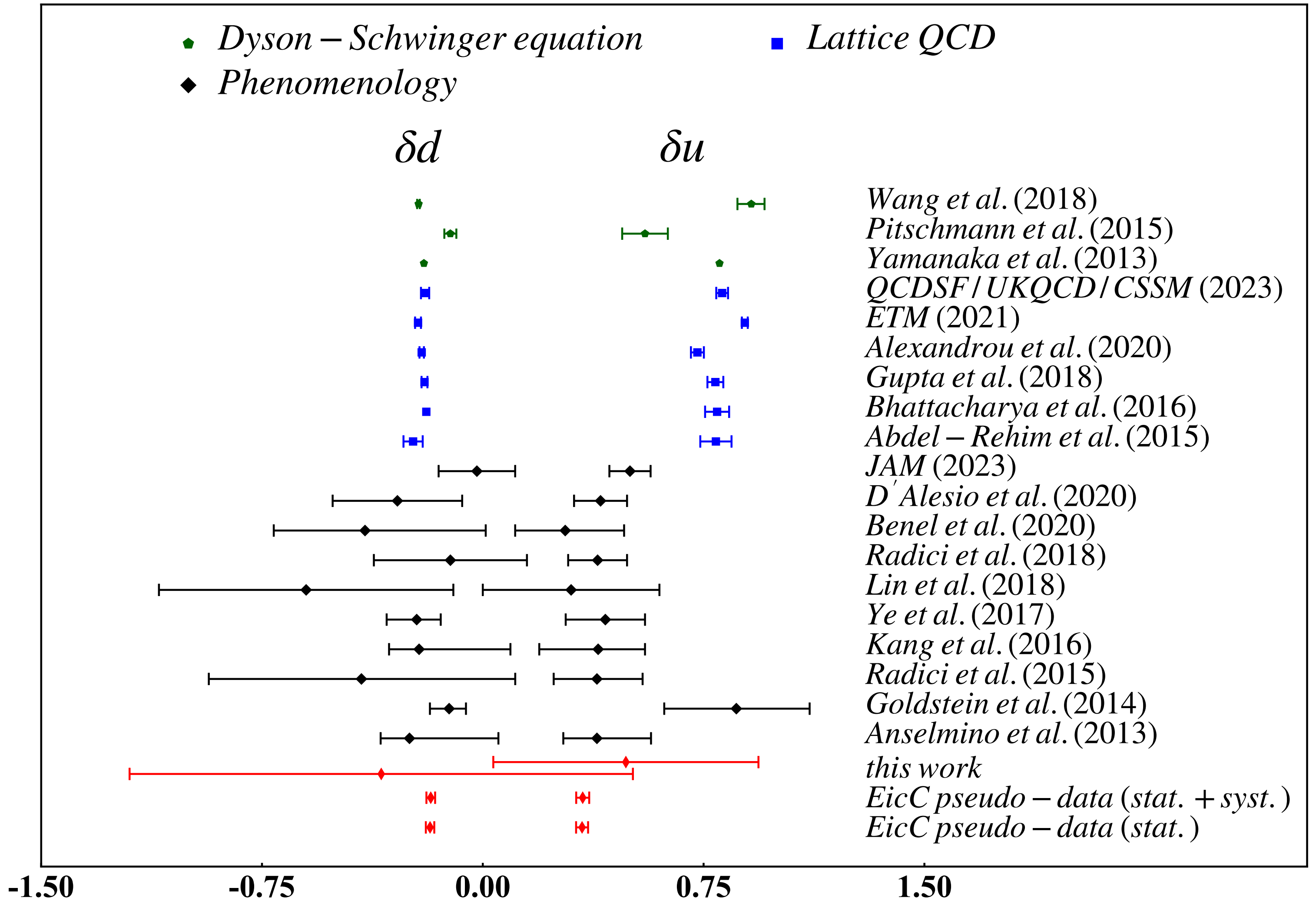
Tensor Charge

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.

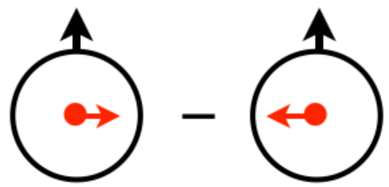


C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, PRD 109 (2024) 056002.

Double Spin Asymmetry and Worm-gear

Trans-helicity worm-gear distribution

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

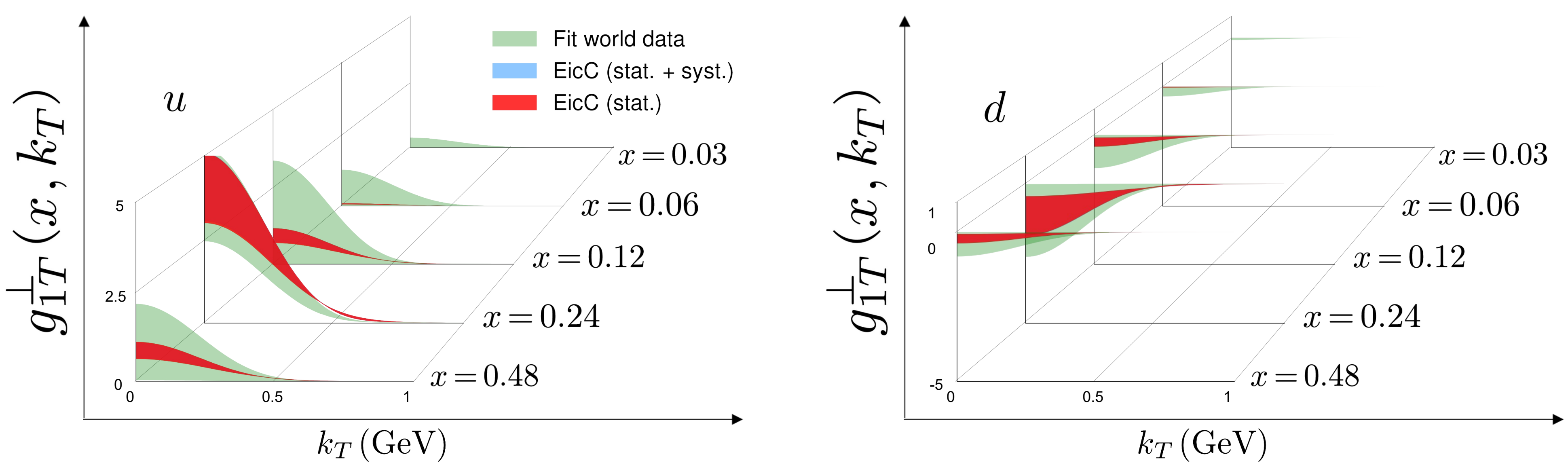


Effect in SIDIS:
A longitudinal-transverse double spin asymmetry

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

- 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

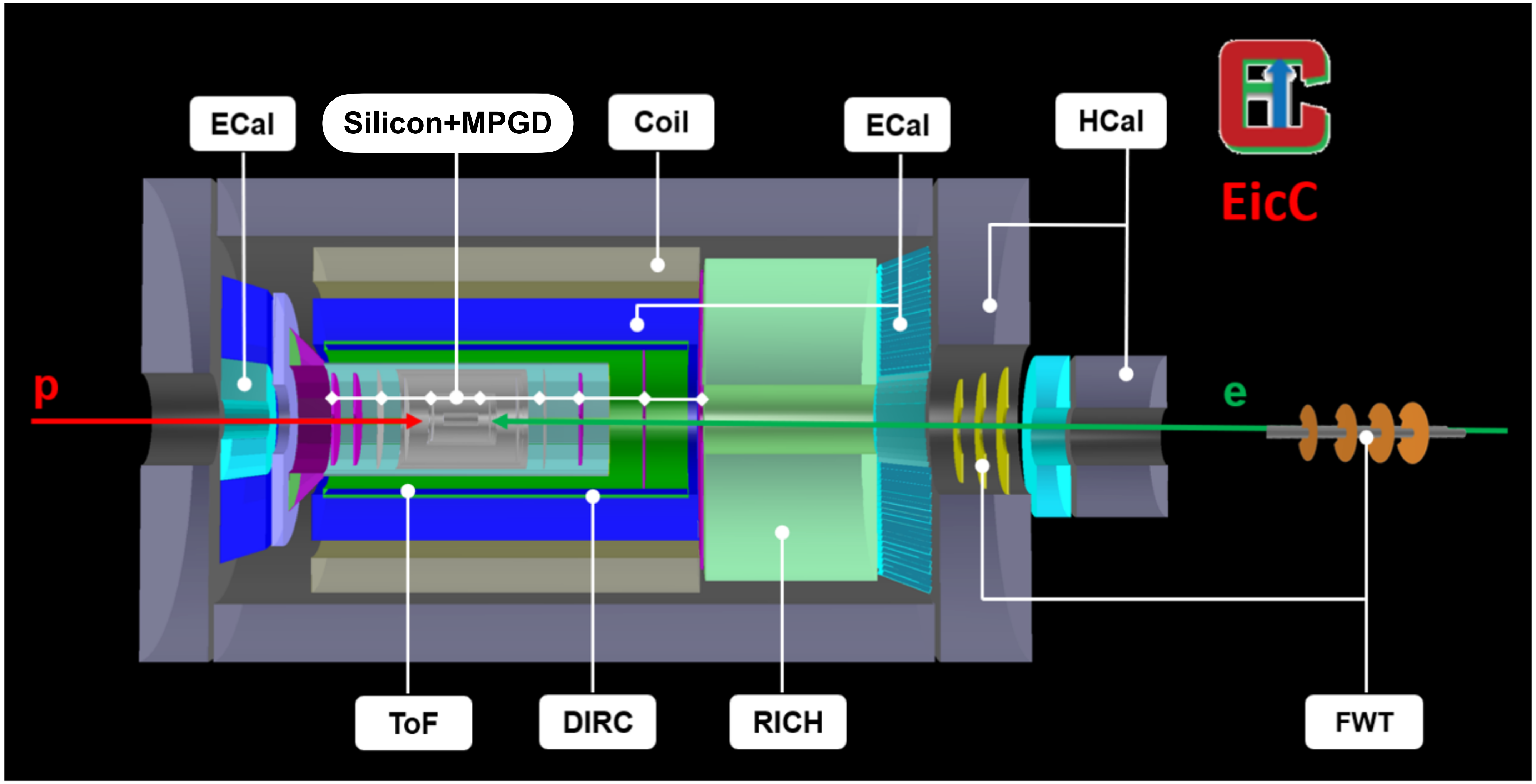
Summary

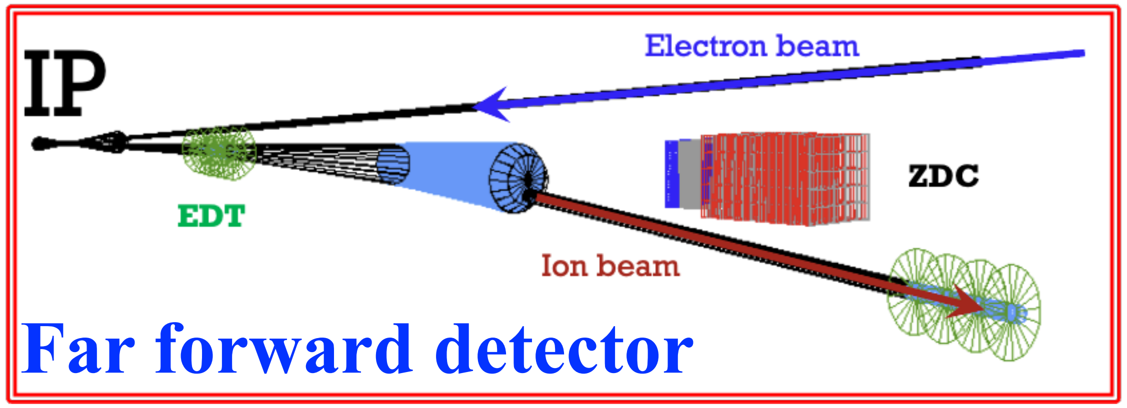
- Nucleon spin structure is still not well understood since the proton spin crisis;
- Rich information is contained in TMDs
  - quark transverse momentum distorted by nucleon spin;
  - correlation between quark longitudinal/transverse spin and nucleon spin;
  - …
- SIDIS with polarized beam and target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

Thank you!

Backup

Conceptual Design of the EicC Detector





[Figure by EicC Detector WG]

TMD Evolution

Evolution equations

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

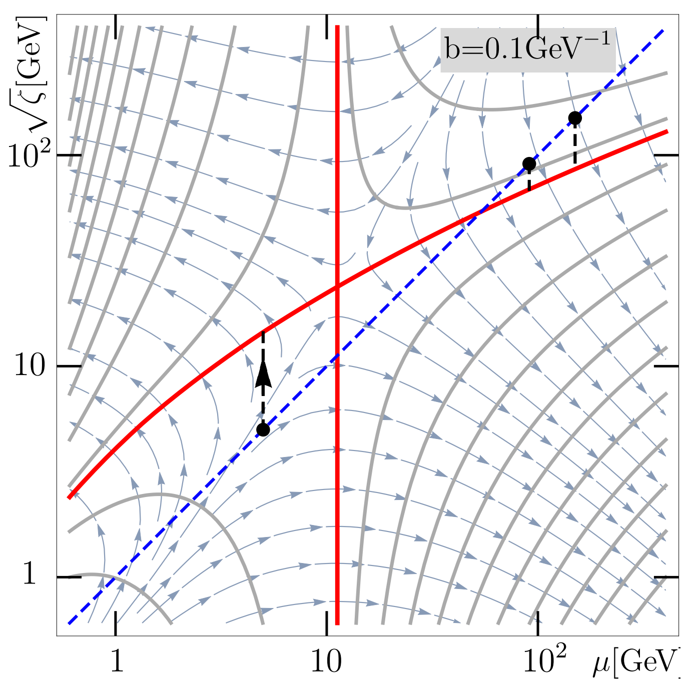
$$\zeta \frac{dF(x,b;\mu,\zeta)}{d\zeta} = -\mathcal{D}(b,\mu) F(x,b;\mu,\zeta)$$

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

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

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

ζ-prescription



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

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

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

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

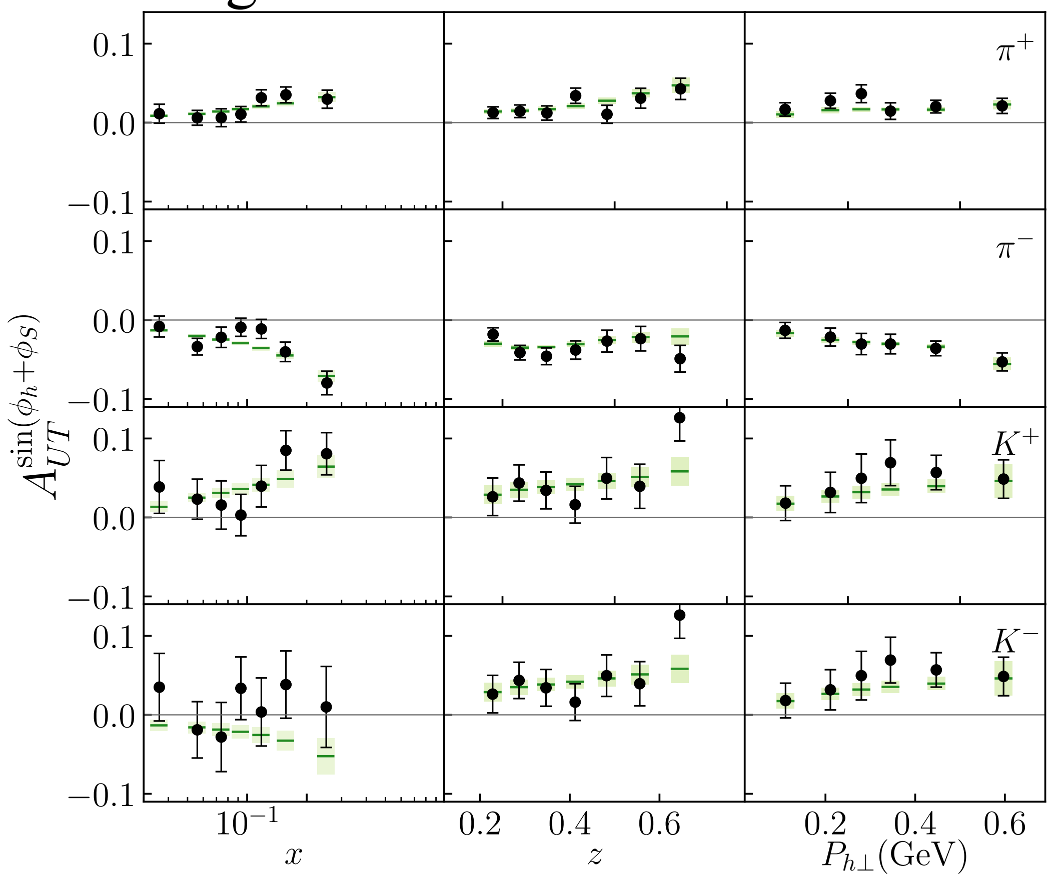
EicC Impact: Transversity and Collins

Baseline: a simultaneous fit of world SIDIS and e+e- data

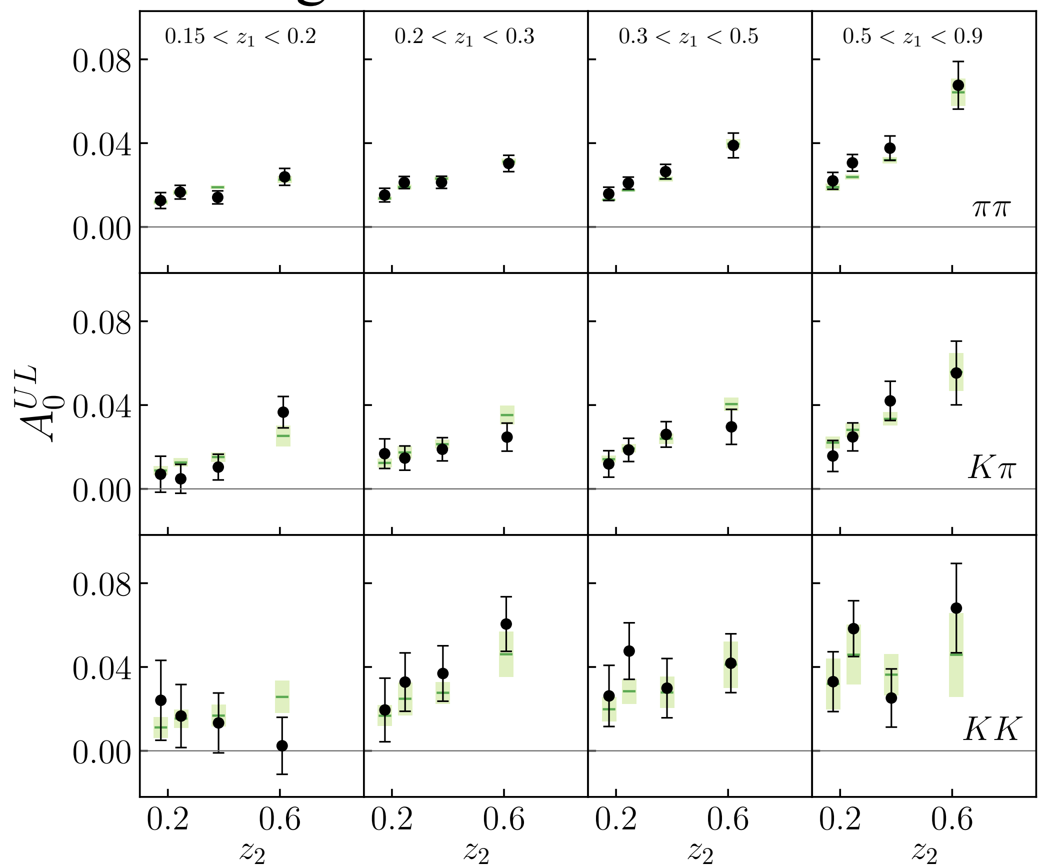
- SIDIS data from HERMES, COMPASS, JLab
- SIA data from BESIII, BaBar, Belle
- Include TMD evolution
- Include sea-quark transversity distributons

Comparison with data:

e.g.: HERMES SIDIS data

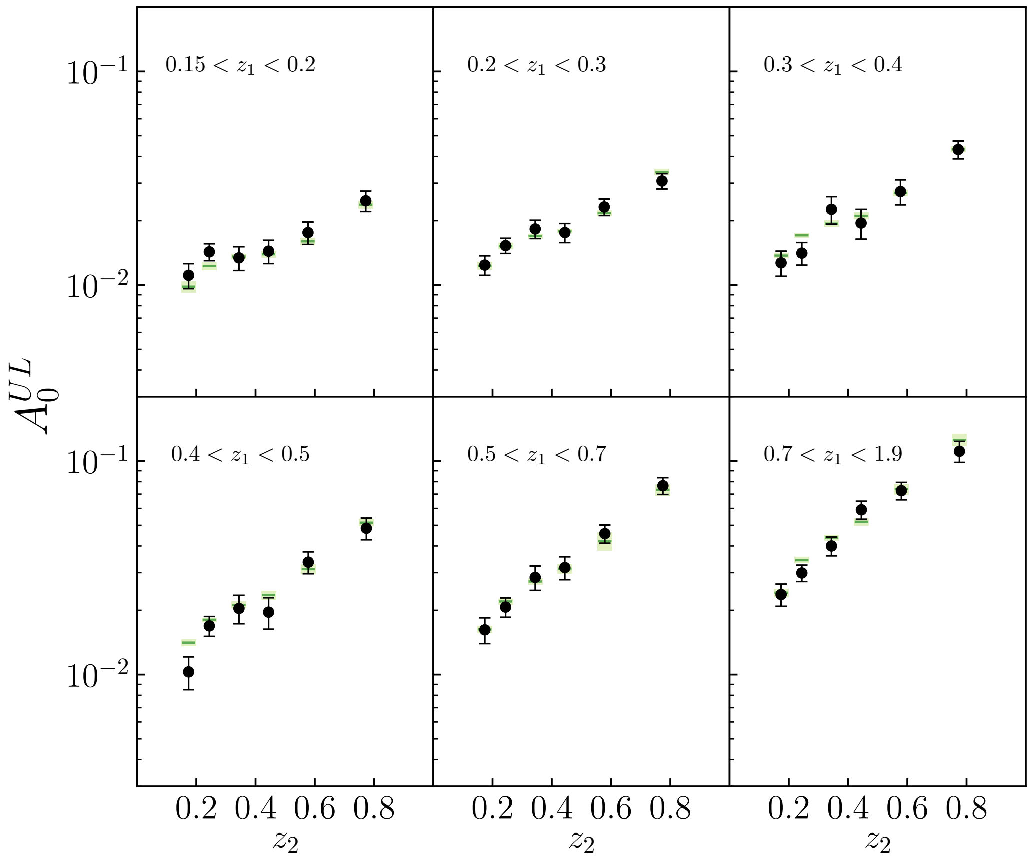


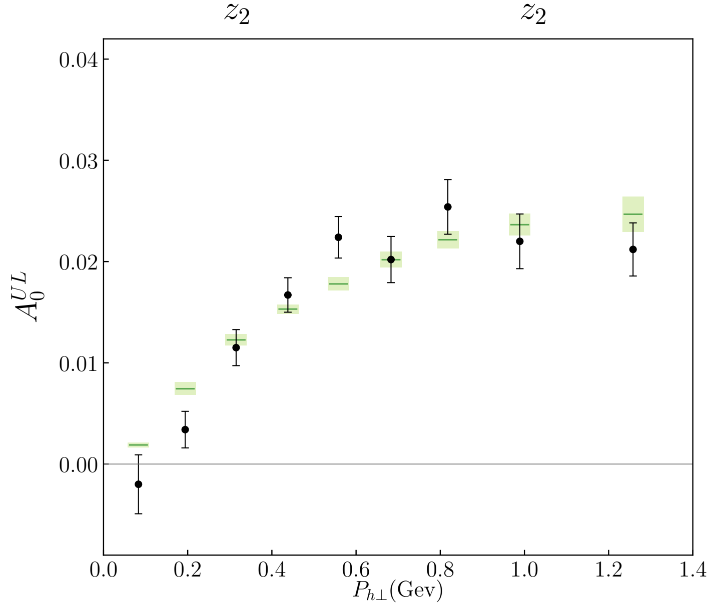
e.g.: BaBar SIA data



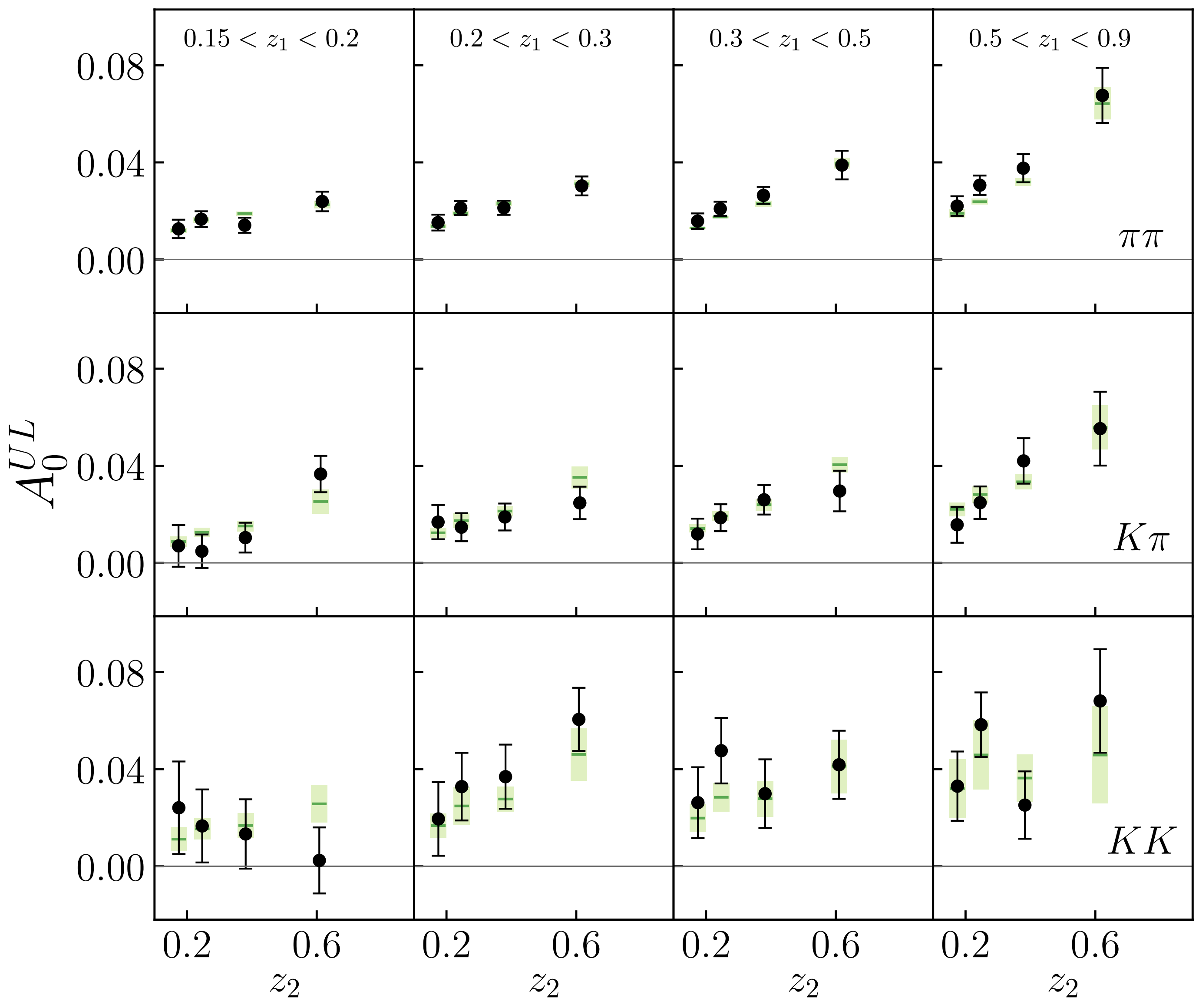
Comparison with Data

BaBar (2014)



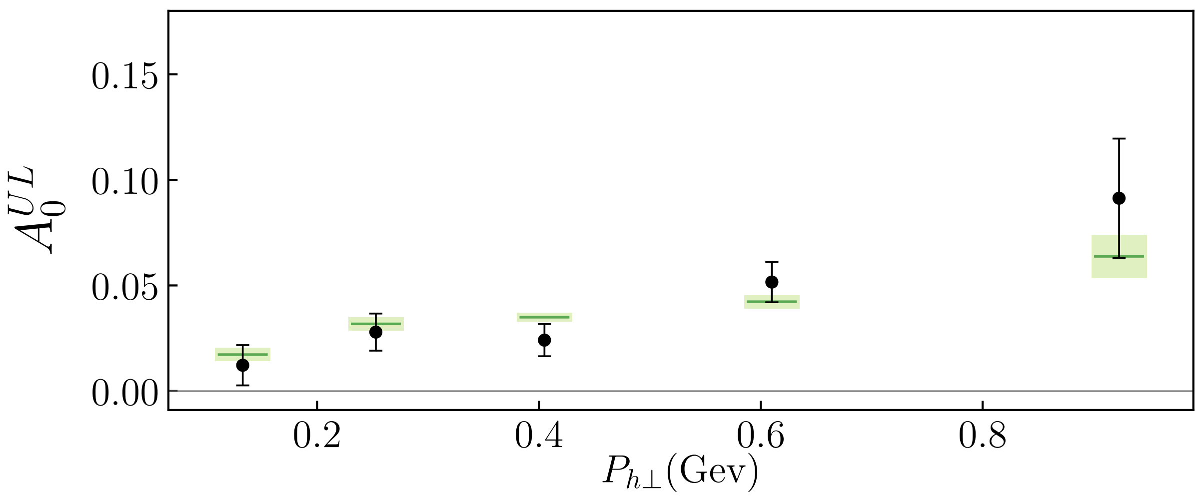


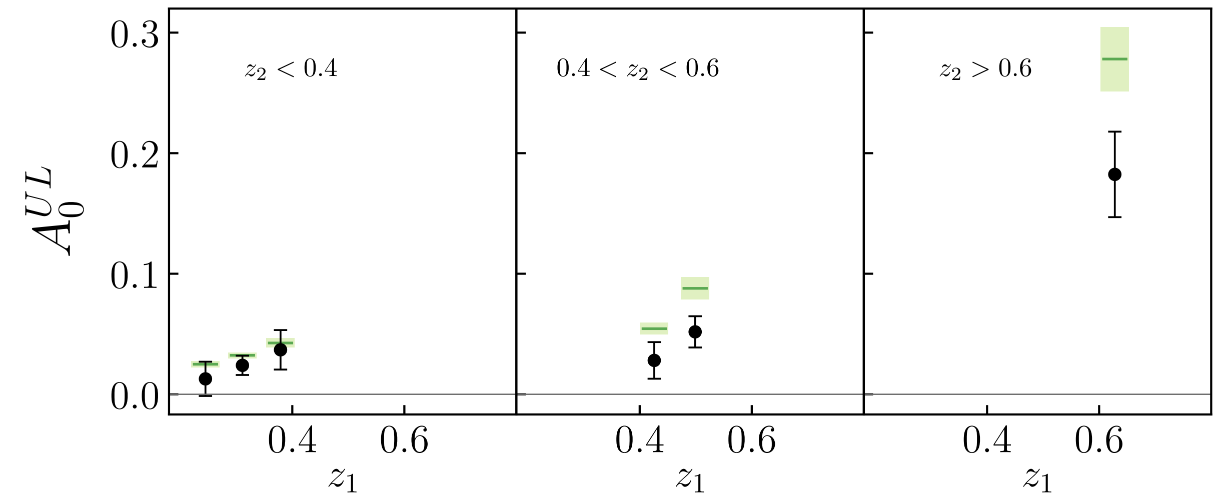
BaBar (2016)



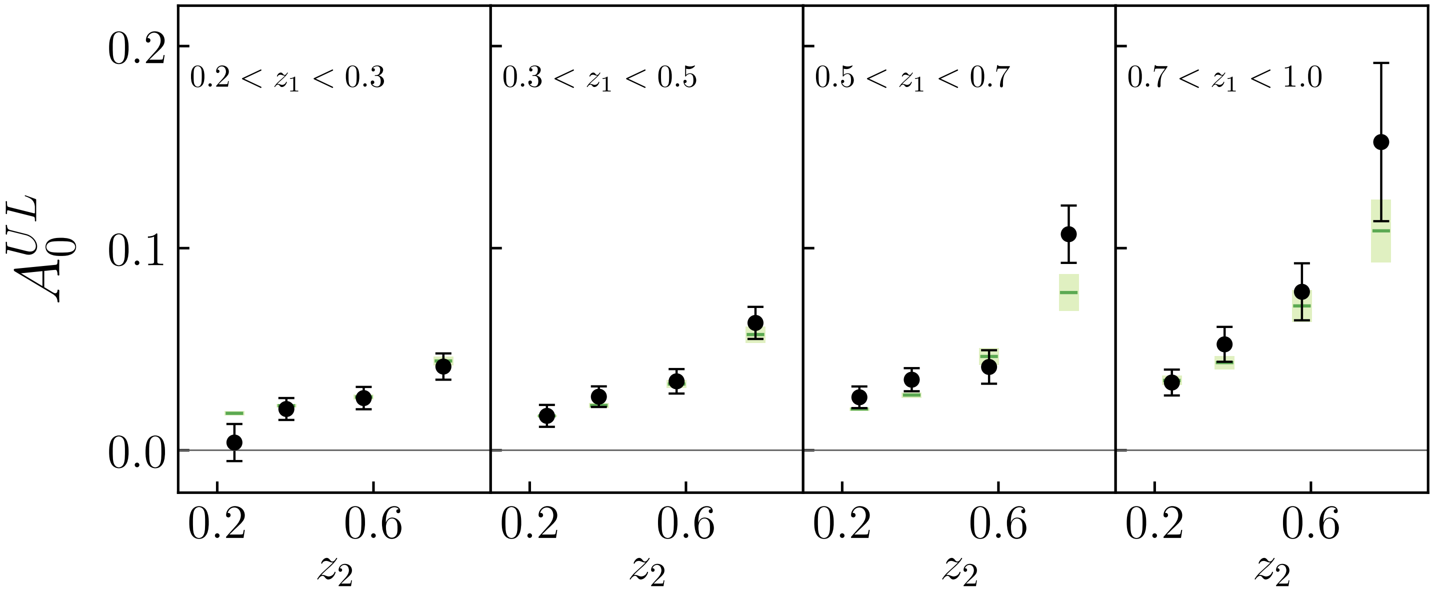
Comparison with Data

BESIII

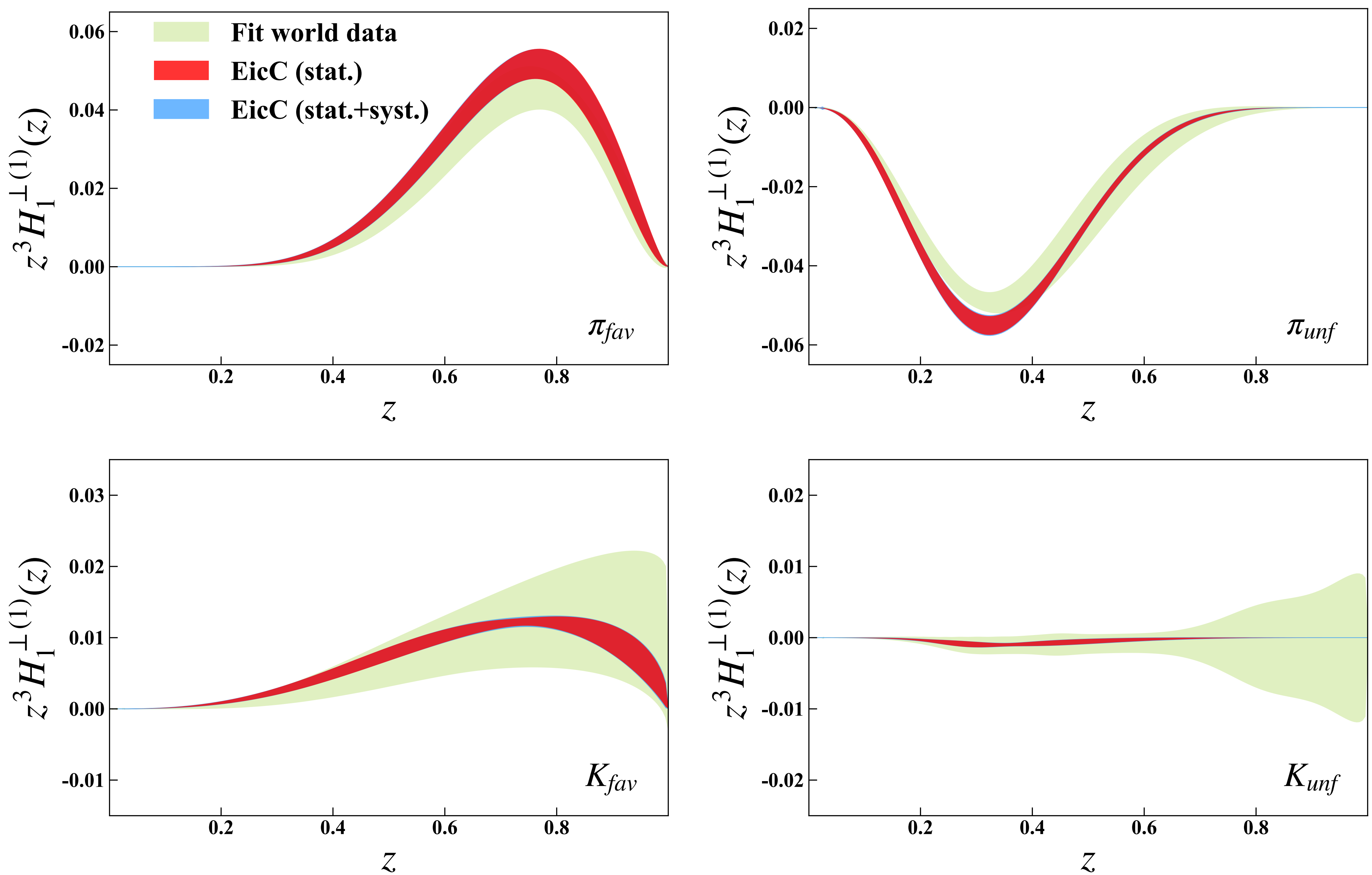




Belle

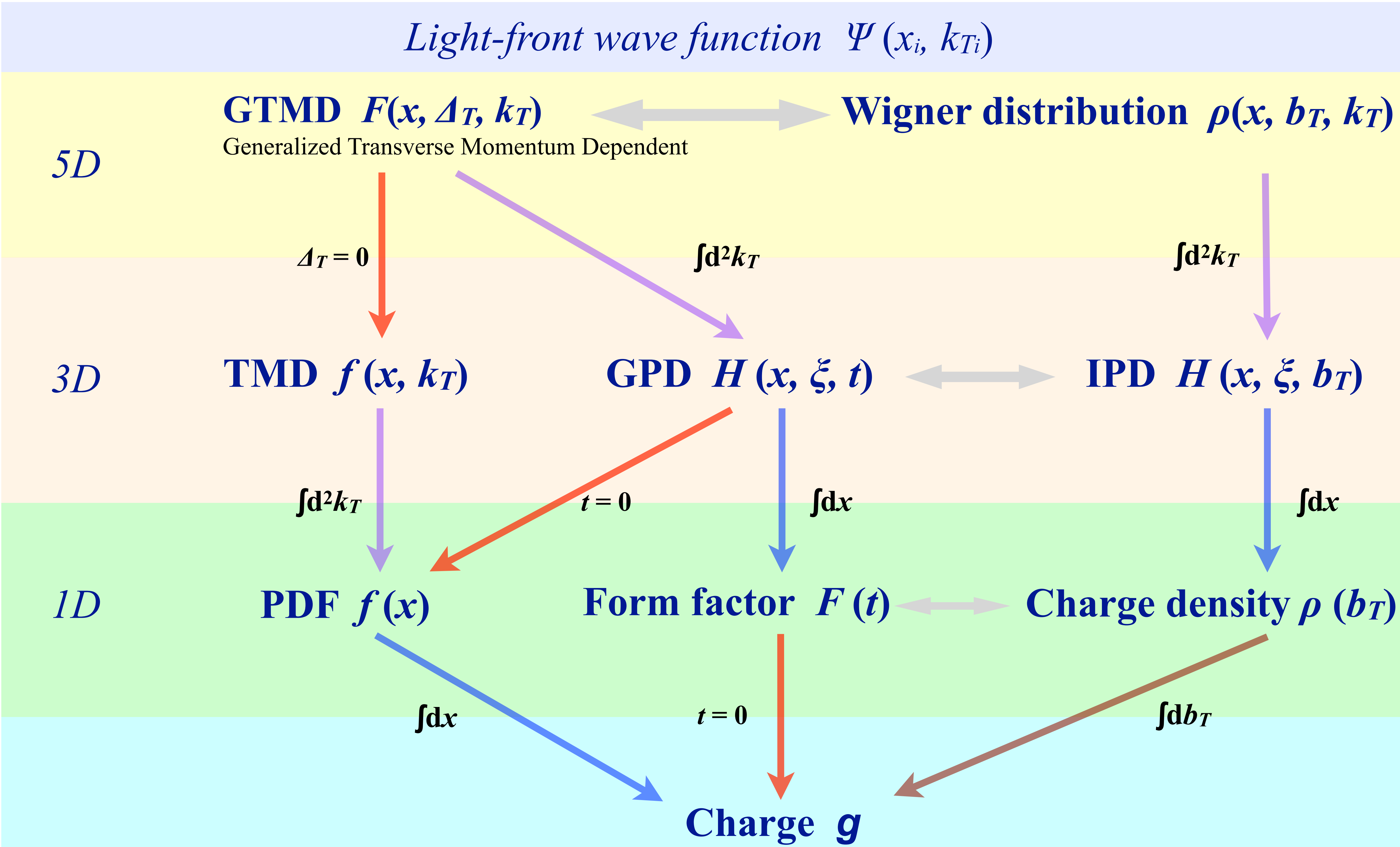


Result: Collins Fragmentation Function



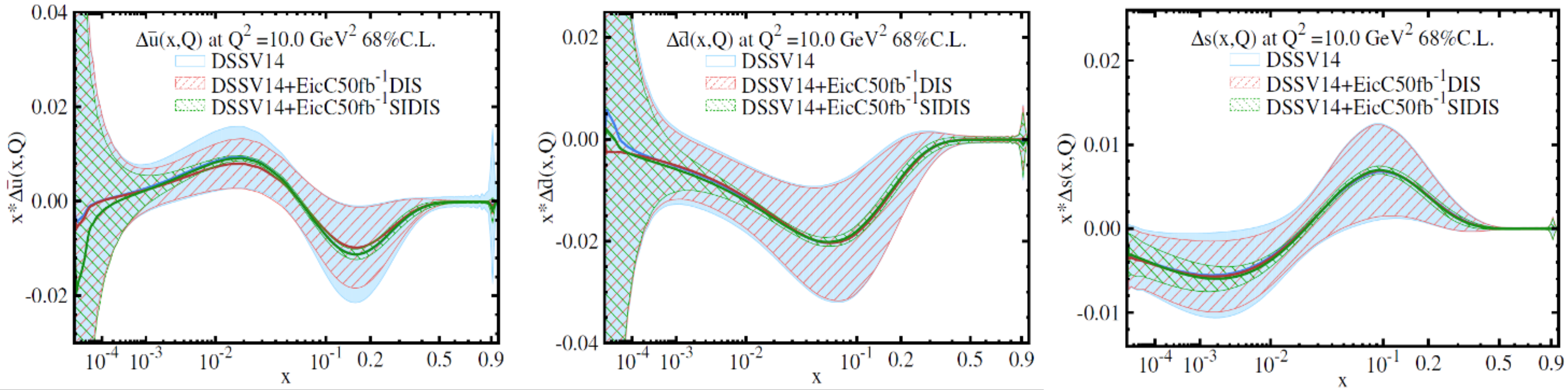
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2310.15532

Unified View of Nucleon Structure



EicC Impact: Helicity distribution

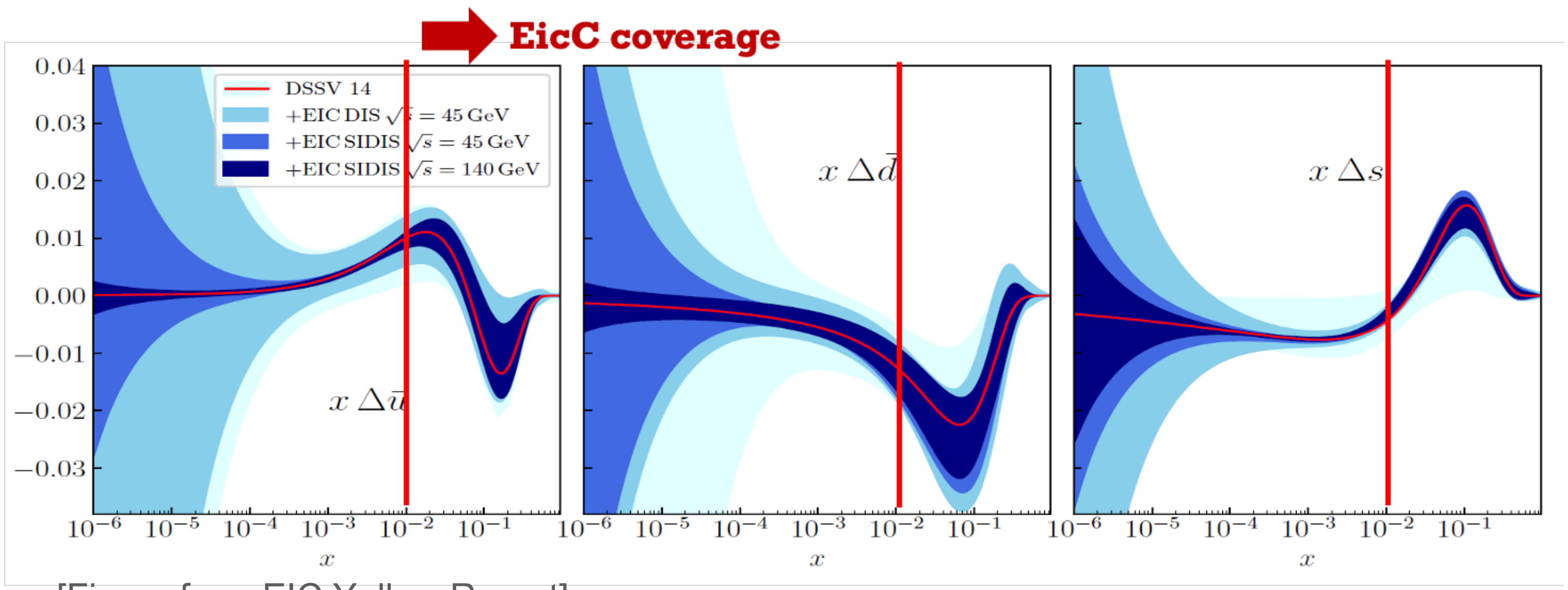
EicC:



D.P. Anderle, T.J. Hou, H. Xing, M. Yan, C.-P. Yuan and Y. Zhao, JHEP 08 (2021) 034.
Also included in the EicC White paper.

complementary

EIC-US:



[Figure from EIC Yellow Report]