Semi-inclusive Deep Inelastic Scattering and the Electron-ion Collider in China

The 3rd Workshop on Ultra-Peripheral Collision Physics
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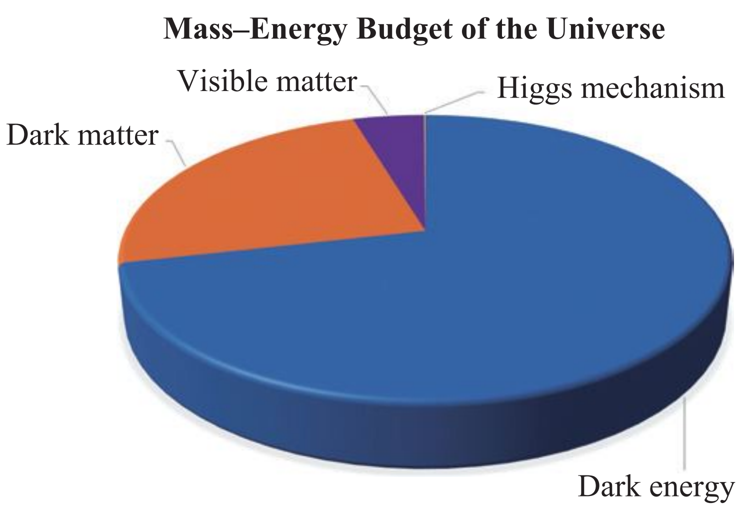
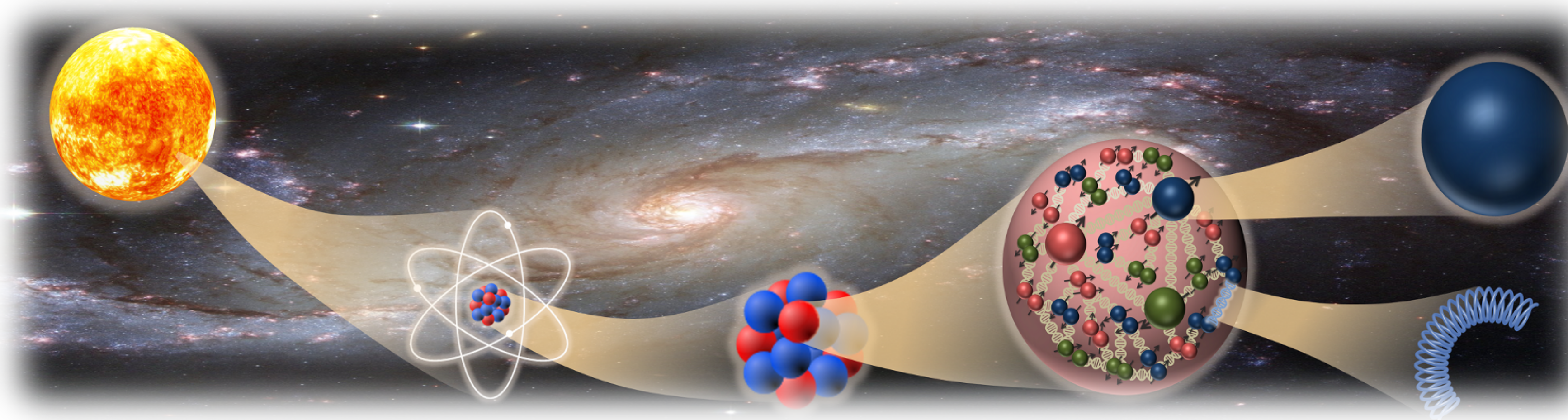
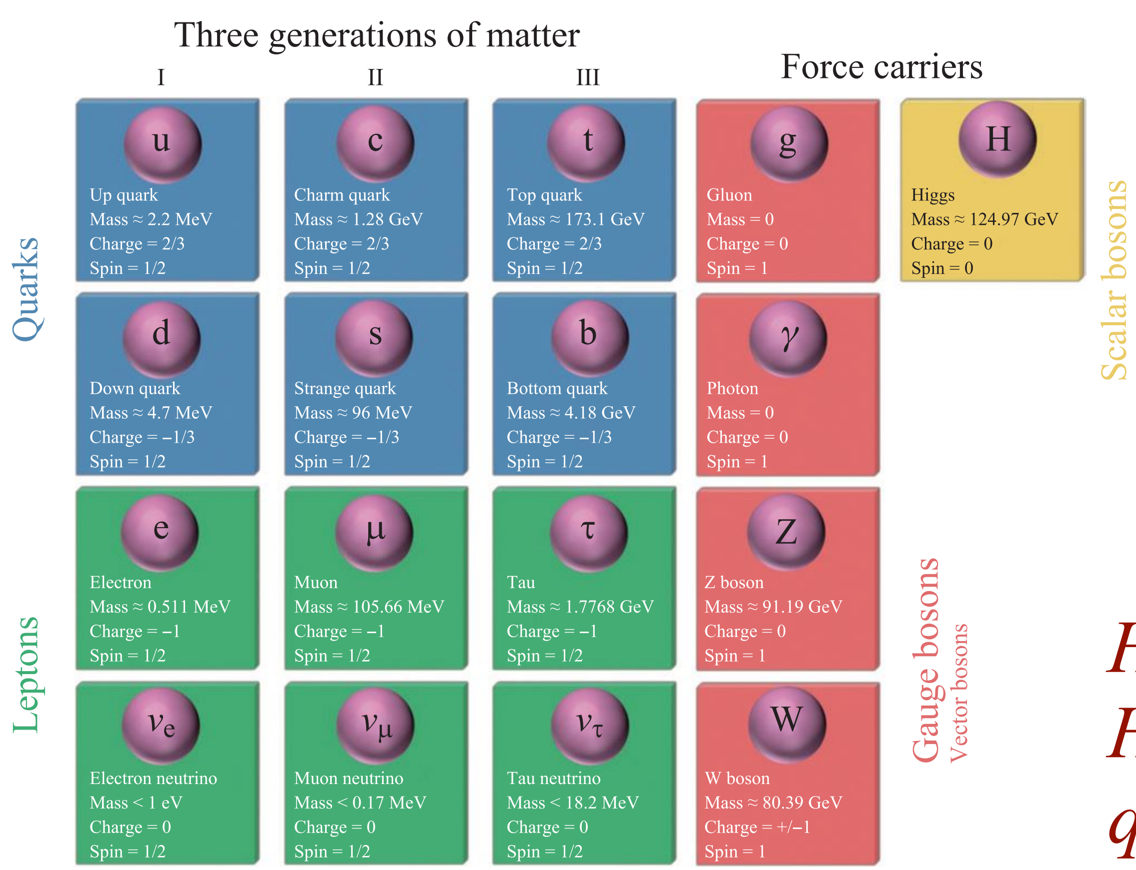
On behalf of EicC working groups and the TNT Collaboration

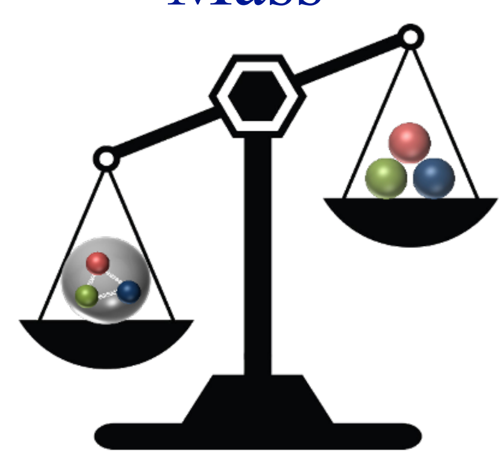
How much do we understand our world?



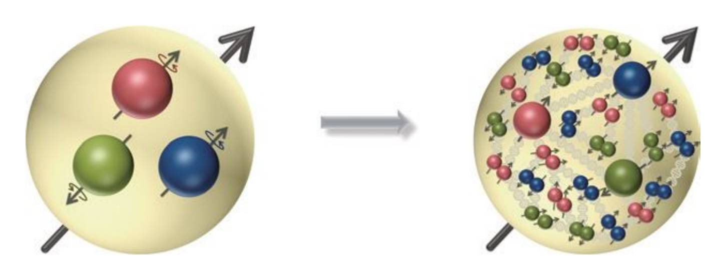




Mass



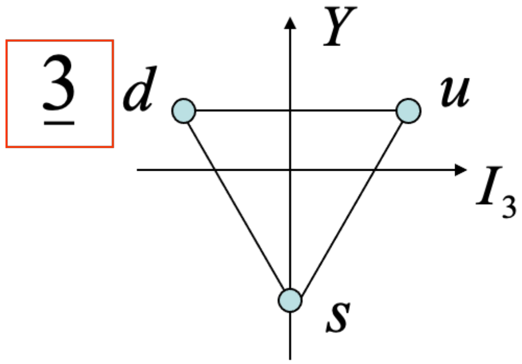
Spin

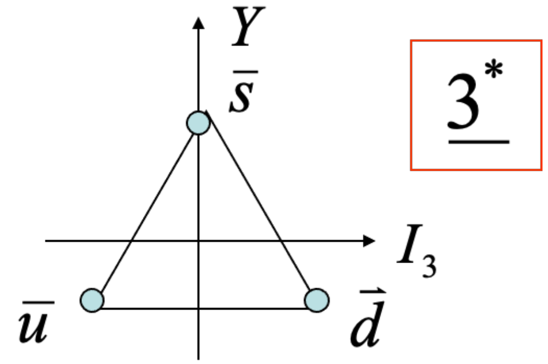


How do quarks and gluons make up a nucleon?
How can nucleon properties be explained at quarks and gluons degrees of freedom?

Proton Spin Structure in Naïve Quark Model

Quark model:

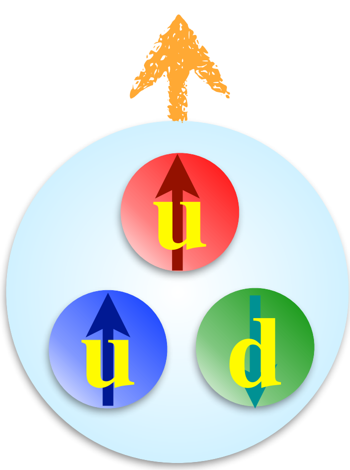




M. Gell-Mann, Phys. Lett. 8, 214 (1964);
G. Zweig, CERN Report No. TH-401 (1964).

ordinary baryons: $|qqq\rangle$, mesons: $|q\bar{q}\rangle$

Spin-flavor wave function of the proton:



$$|p_\uparrow\rangle = \frac{1}{\sqrt{18}}\Big[2\,|u_\uparrow d_\downarrow u_\uparrow\rangle + 2\,|u_\uparrow u_\uparrow d_\downarrow\rangle + 2\,|d_\downarrow u_\uparrow u_\uparrow\rangle - |u_\uparrow u_\downarrow d_\uparrow\rangle$$
$$- |u_\uparrow d_\uparrow u_\downarrow\rangle - |u_\downarrow d_\uparrow u_\uparrow\rangle - |d_\uparrow u_\downarrow u_\uparrow\rangle - |d_\uparrow u_\uparrow u_\downarrow\rangle - |u_\downarrow u_\uparrow d_\uparrow\rangle\Big].$$

$$\Delta u = u_\uparrow - u_\downarrow = \frac{4}{3} \qquad \Delta d = d_\uparrow - d_\downarrow = -\frac{1}{3}$$

The sum of quark spins gives the proton spin.

Lepton-Hadron Deep Inelastic Scattering

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

- 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:

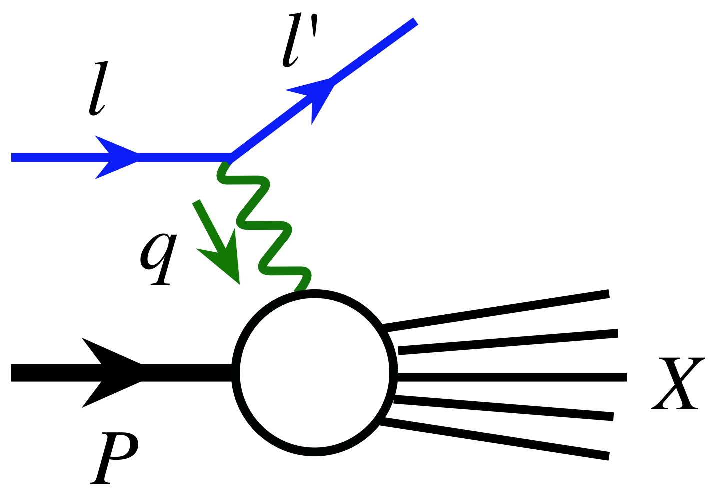
$$\sigma \propto H(Q) \otimes f_{i/P}(x, \mu^2)$$

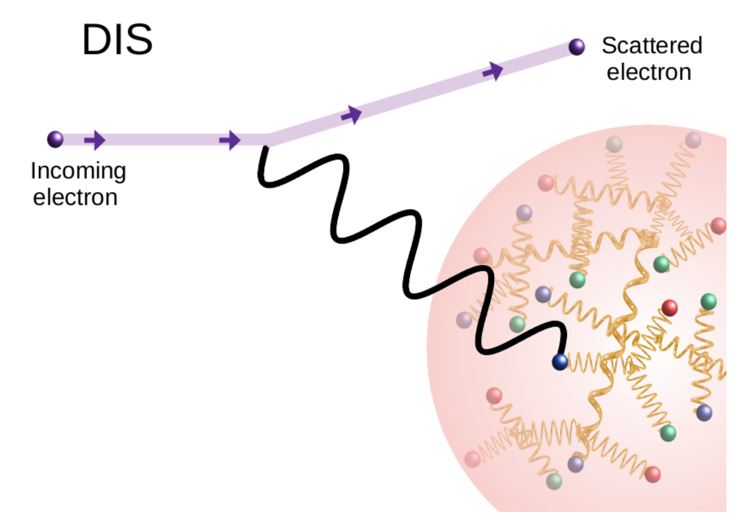
- overall corrections suppressed by $1/Q^n$
- indirectly "see" quarks, gluons and their dynamics
- predictive power relies on

— precision of the probe

— universality of $f_{i/P}(x, \mu^2)$

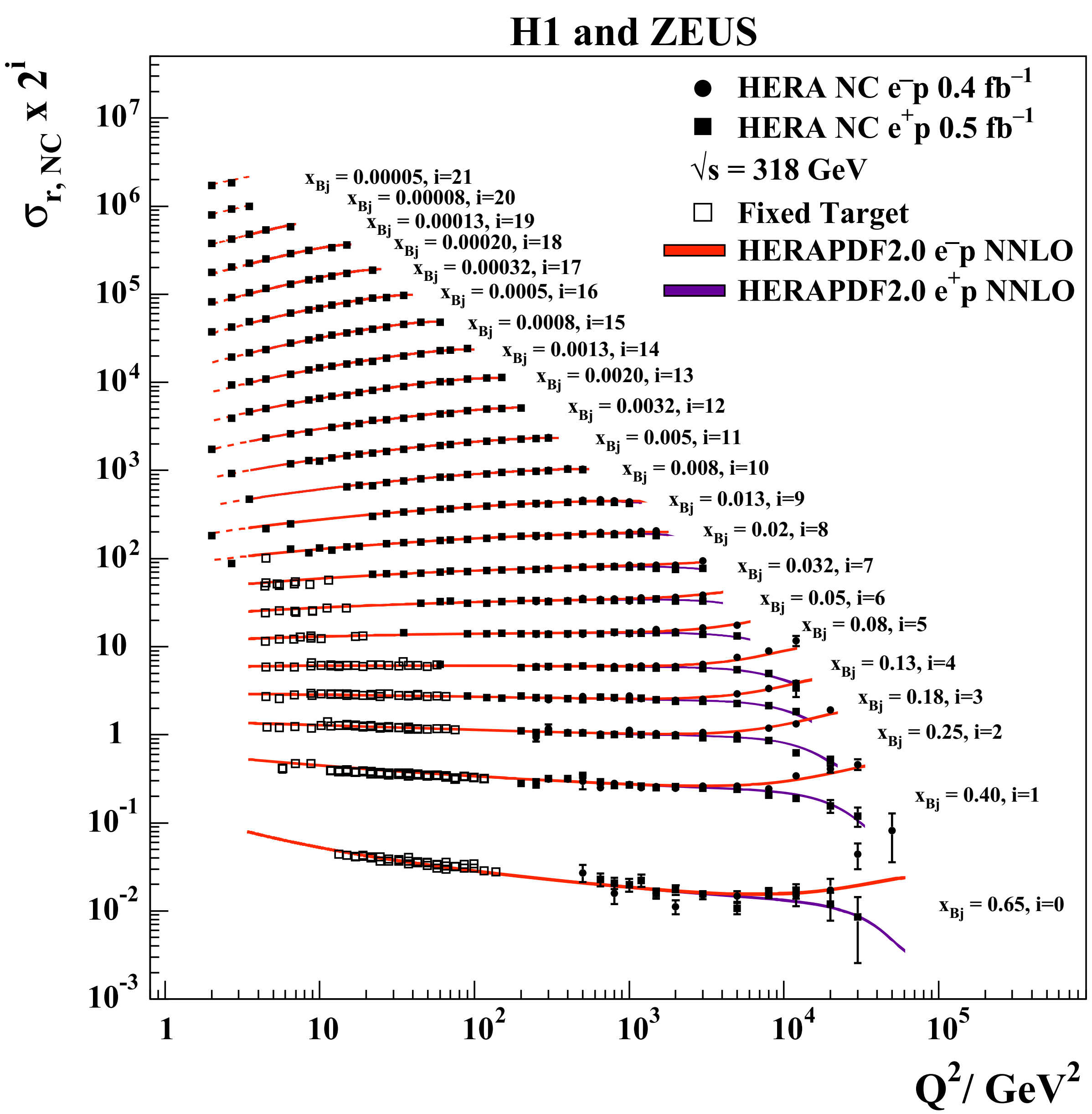
Modern "Rutherford" experiment.



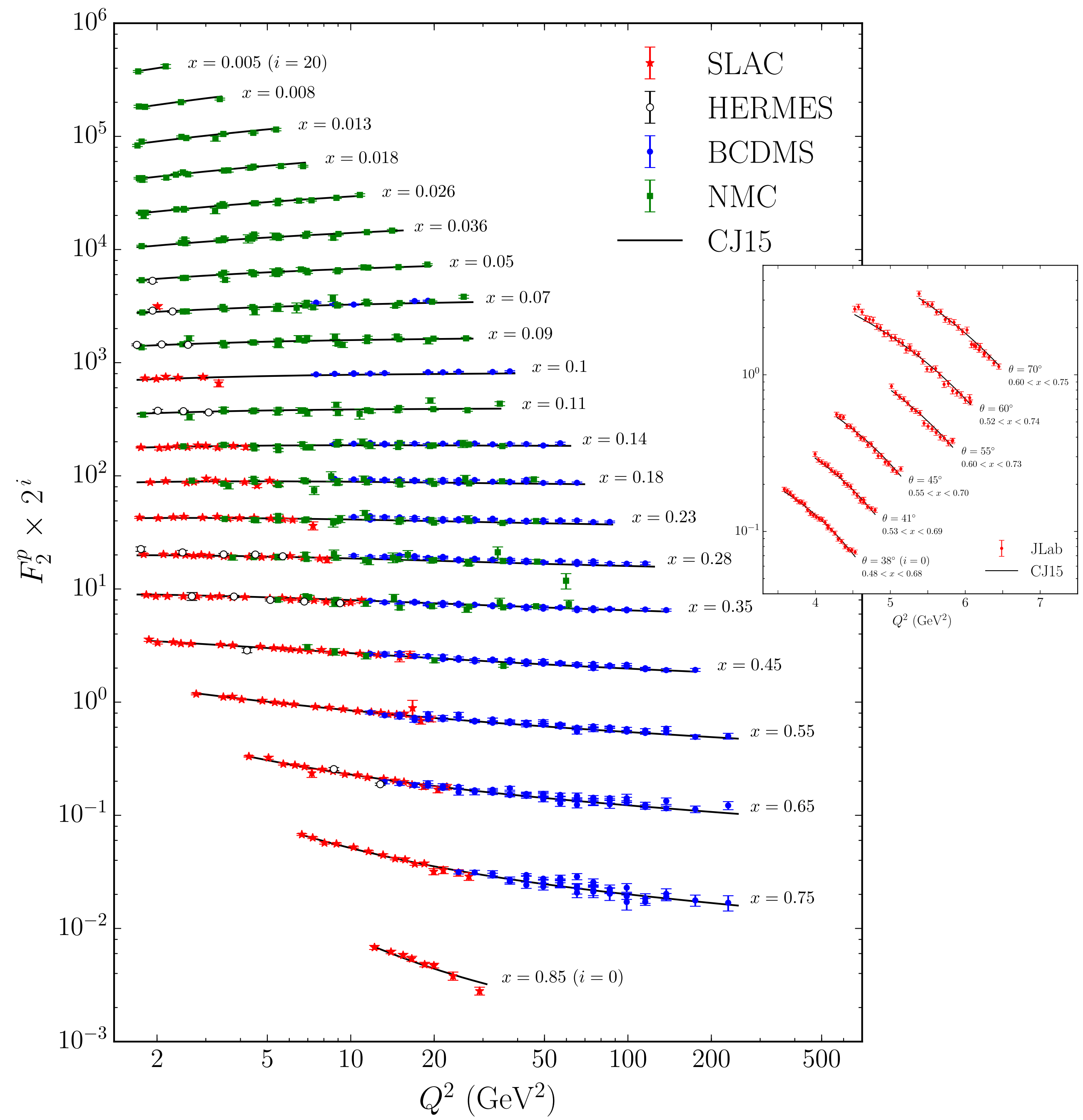


[Figure from DESY-21-099]

Lepton-Hadron Deep Inelastic Scattering

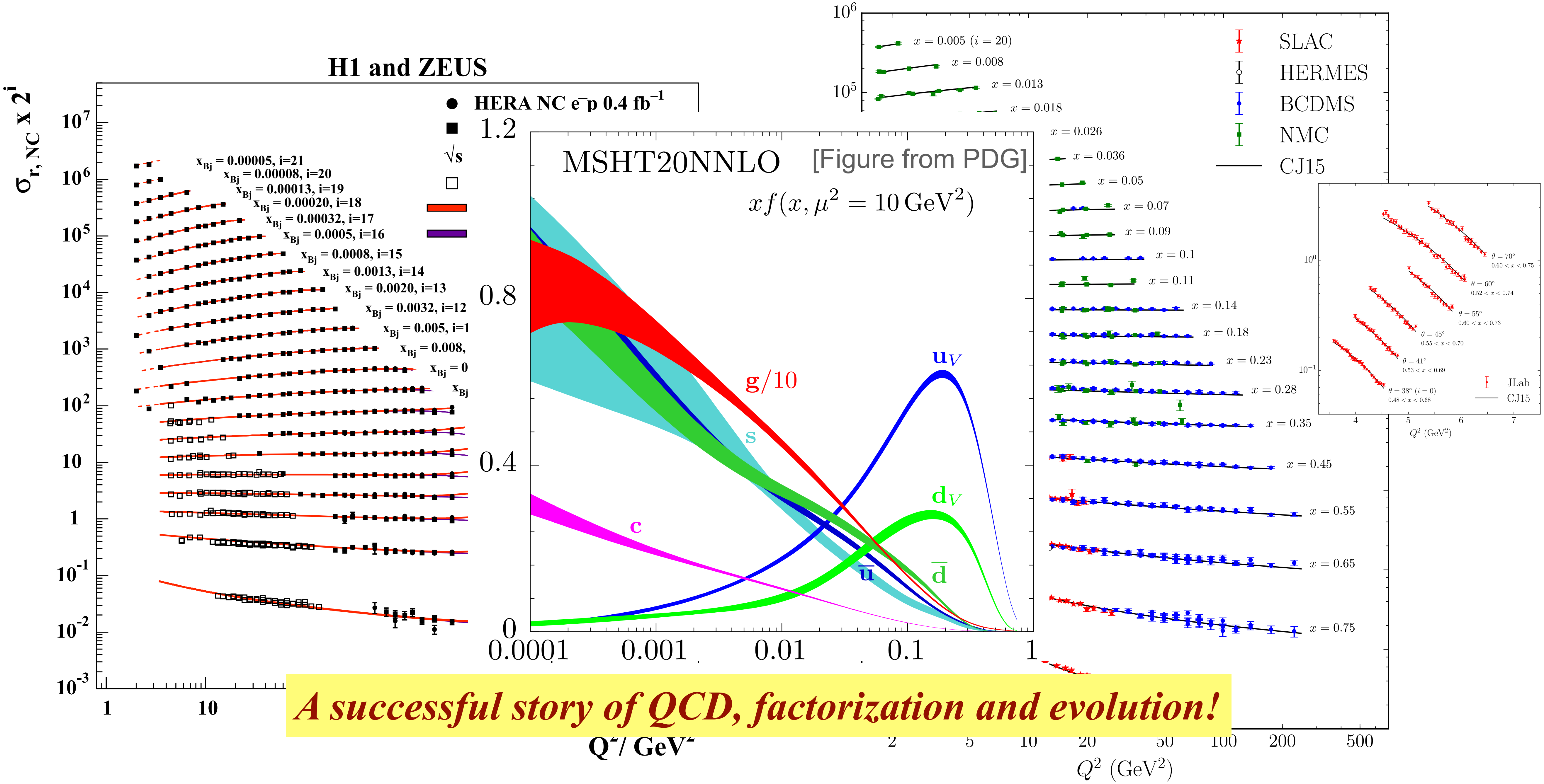


H. Abramowicz *et al.*, EPJC 78, 580 (2015).



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).

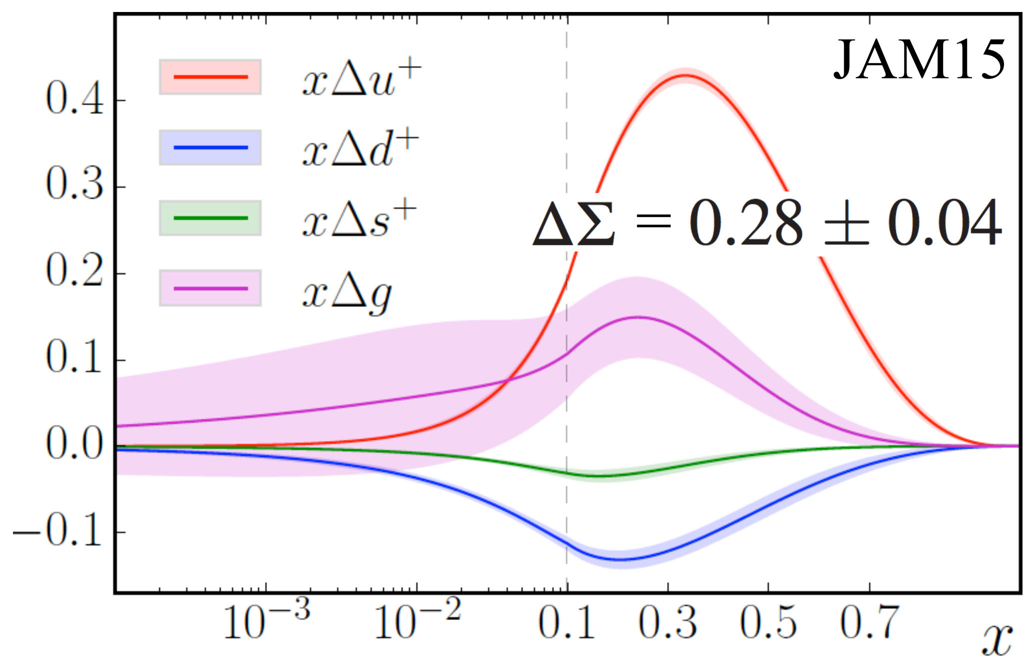
Nucleon Spin Structure

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).

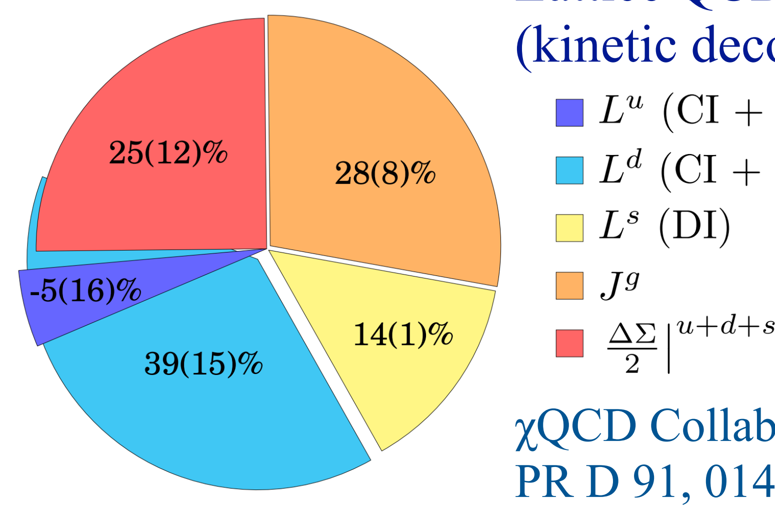
JAM17: $\Delta\Sigma = 0.36 \pm 0.09$

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)

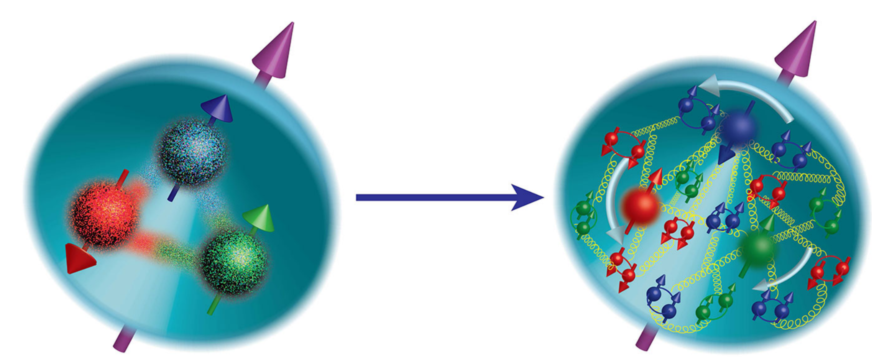


χQCD Collaboration, PR D 91, 014505 (2015).

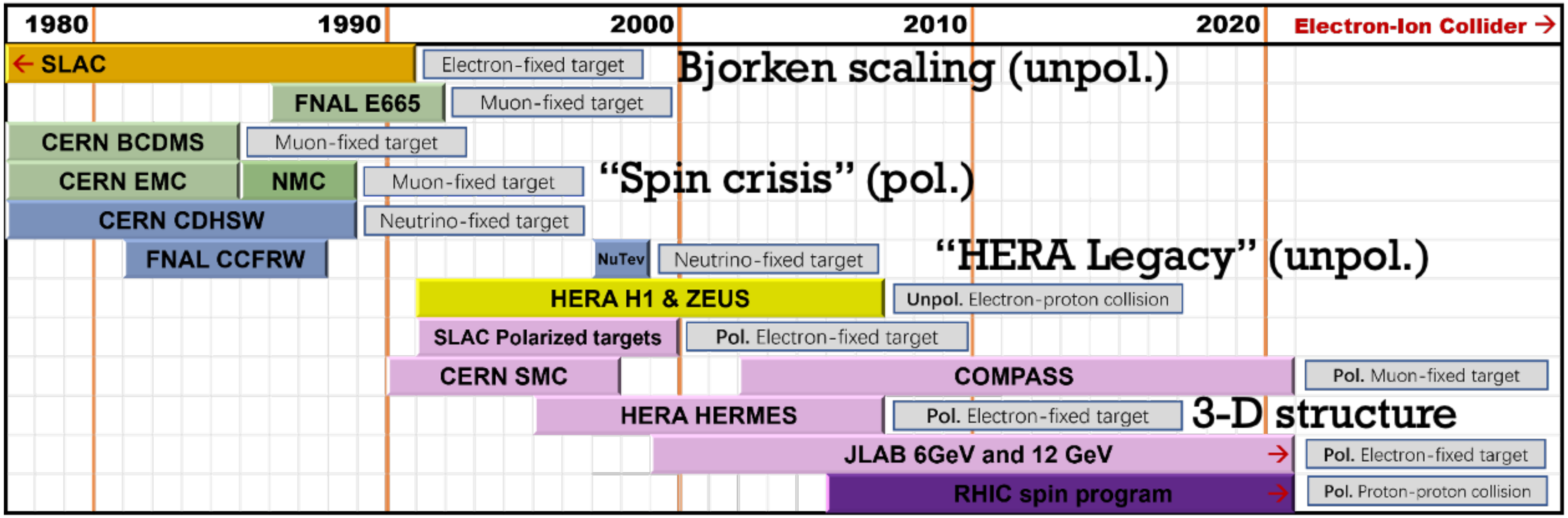
Gluon spin from LQCD: $S_g = 0.251(47)(16)$

50% of total proton spin

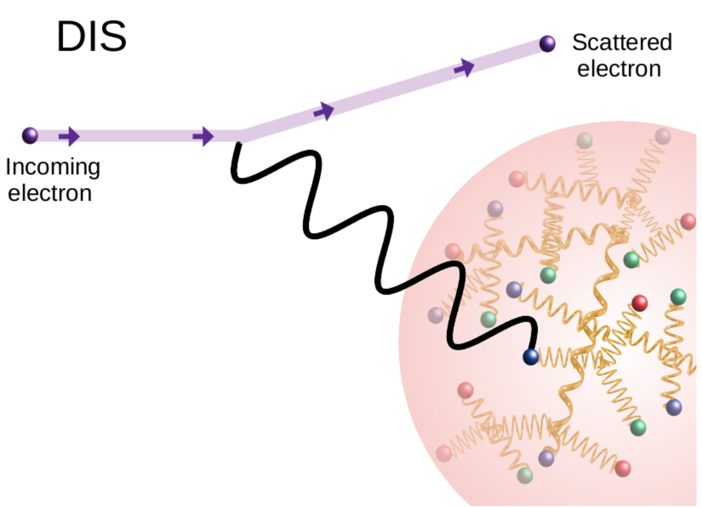
Y.-B. Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017).



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)

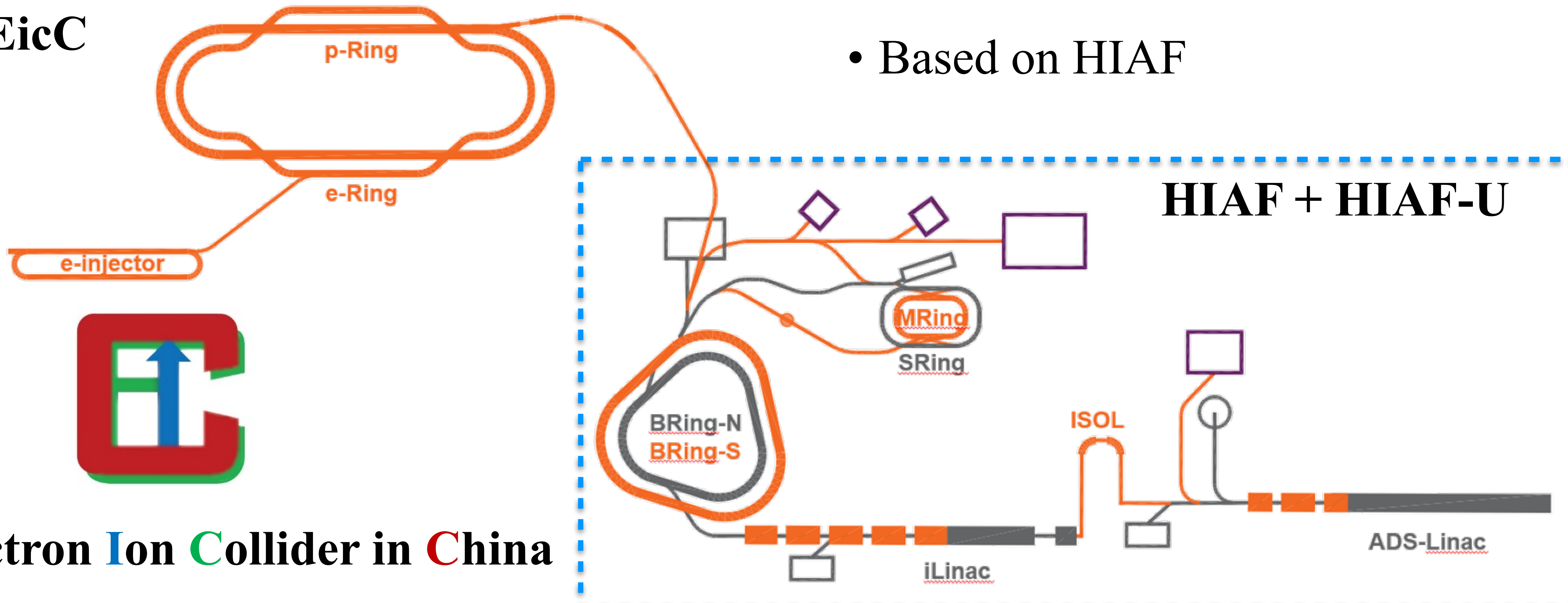
High Intensity heavy-ion Accelerator Facility

- 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 in 2025

Electron-ion Collider in China

EicC

- Based on HIAF



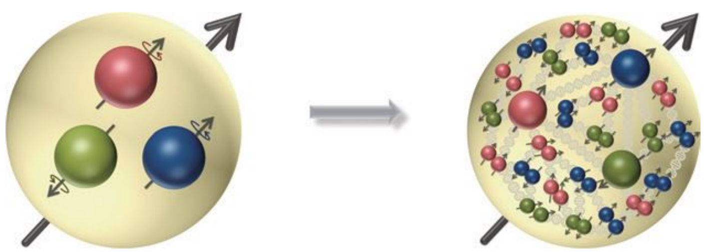
Electron Ion Collider in China

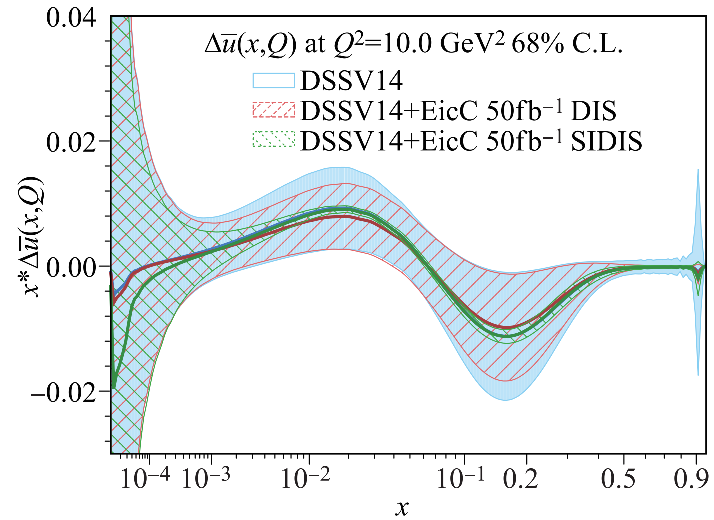
[Figure by EicC Accelerator WG]

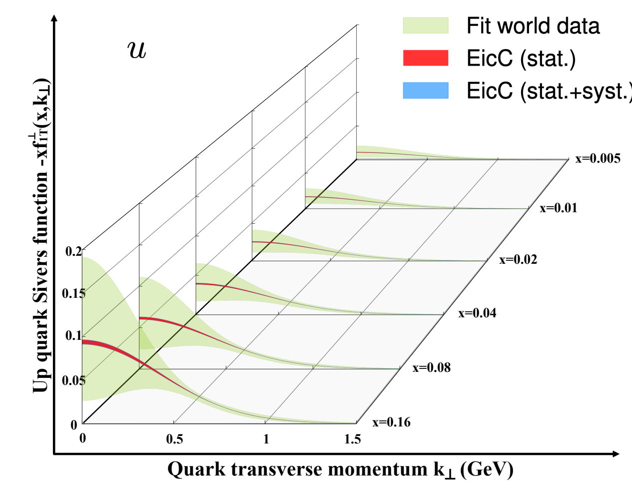
- energy in c.m.: 15 ~ 20 GeV
- luminosity: $\gtrsim 2 \times 10^{33}$ cm$^{-2} \cdot$ s^{-1}
- electron beam: 3.5 GeV, polarization ~ 80%
- proton beam: 20 GeV, polarization ~ 70%
- other available polarized ion beams: d, $^{3}He^{++}$
- available unpolarized ion beams: $^{7}Li^{3+}$, $^{12}C^{6+}$,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

Physics Highlights

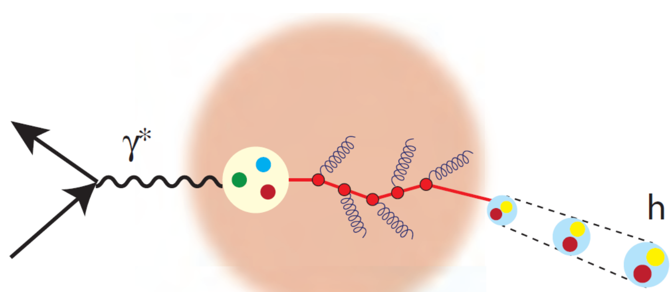
Partonic structure and three-dimensional landscape of the nucleon

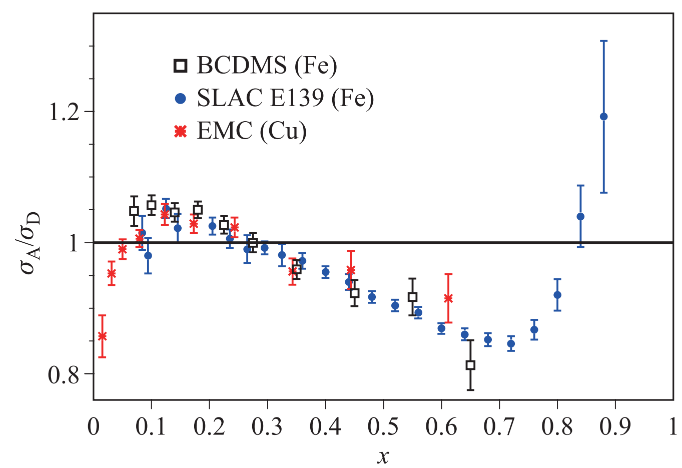


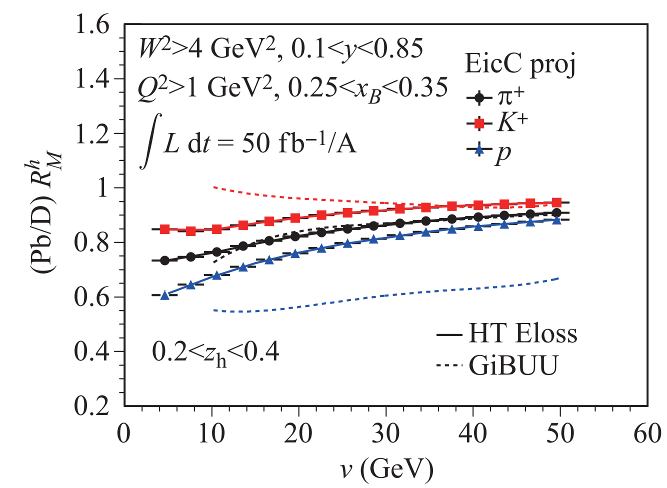




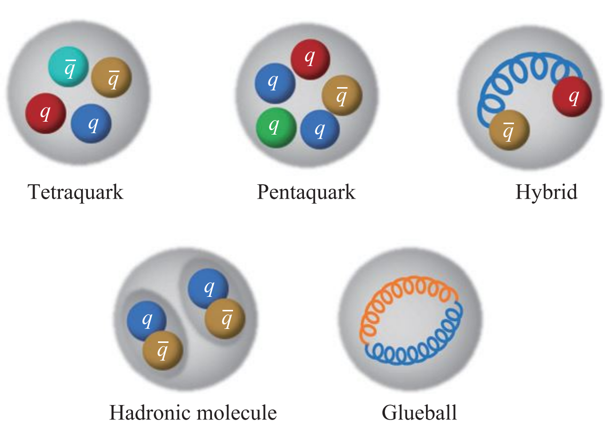
Partonic structure of nuclei

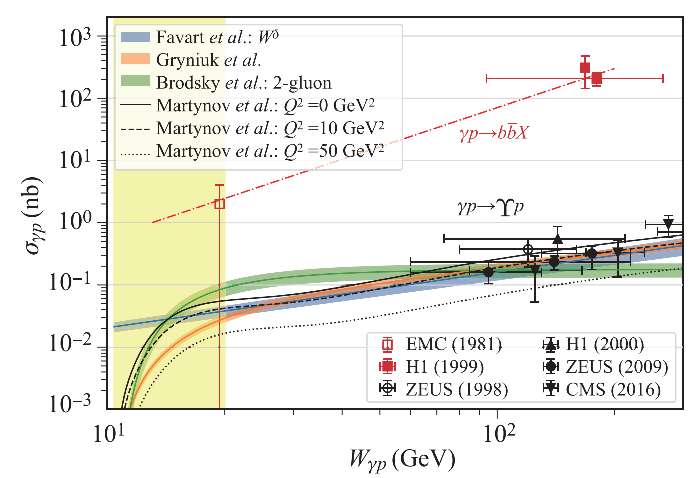


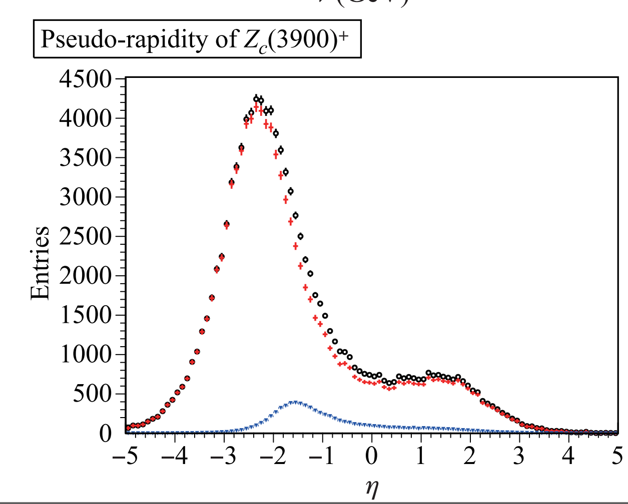




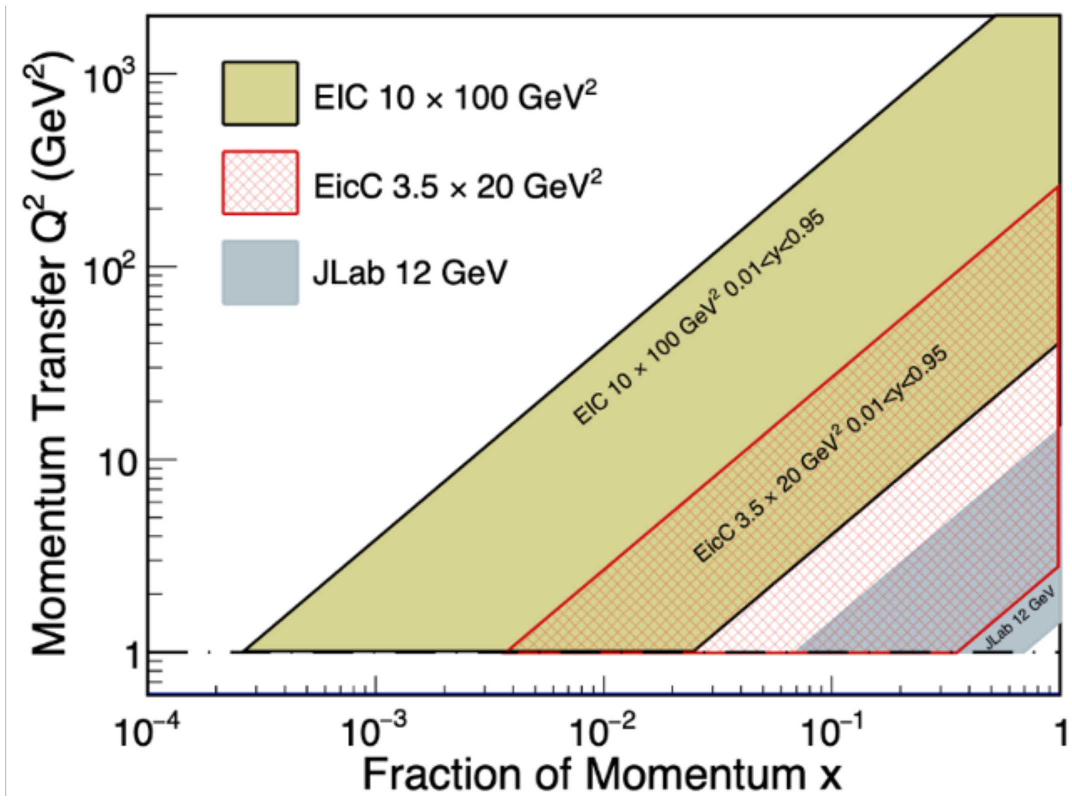
Exotic hadronic states







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

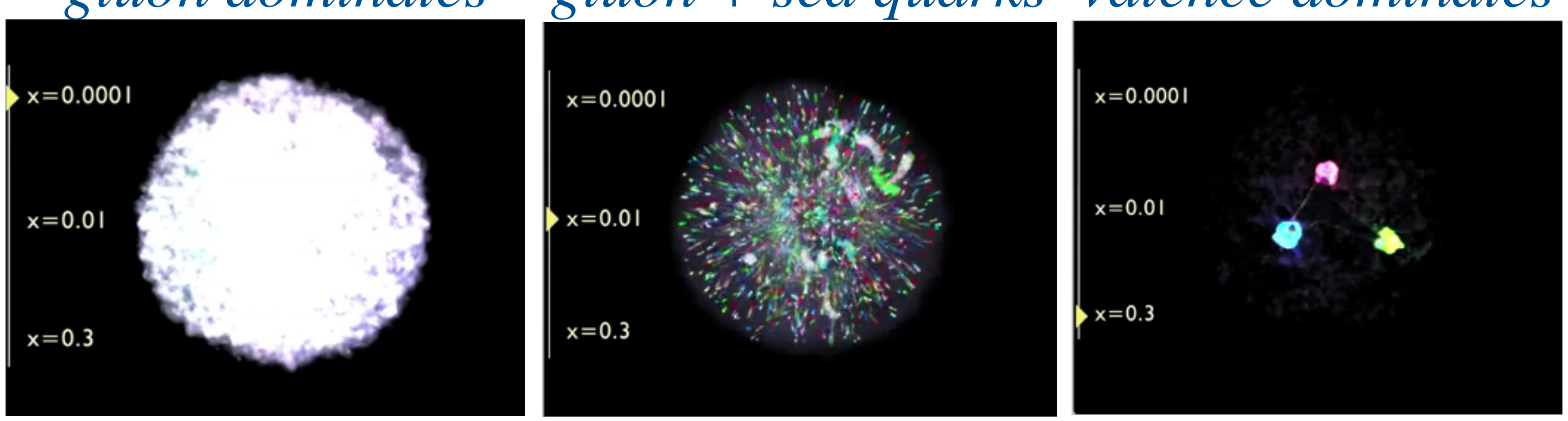
Combine with J/ψ production at JLab

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:

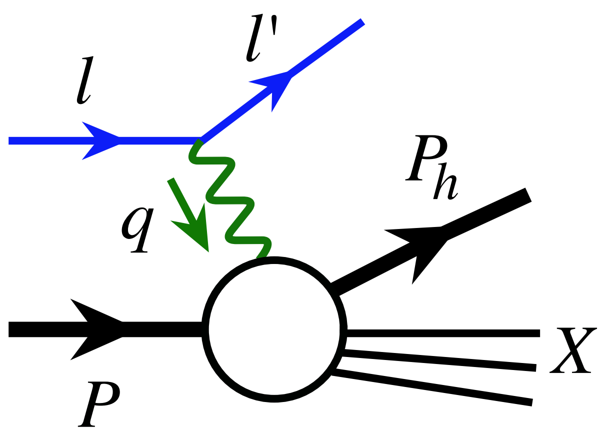
Parton distribution in nuclei at moderate x

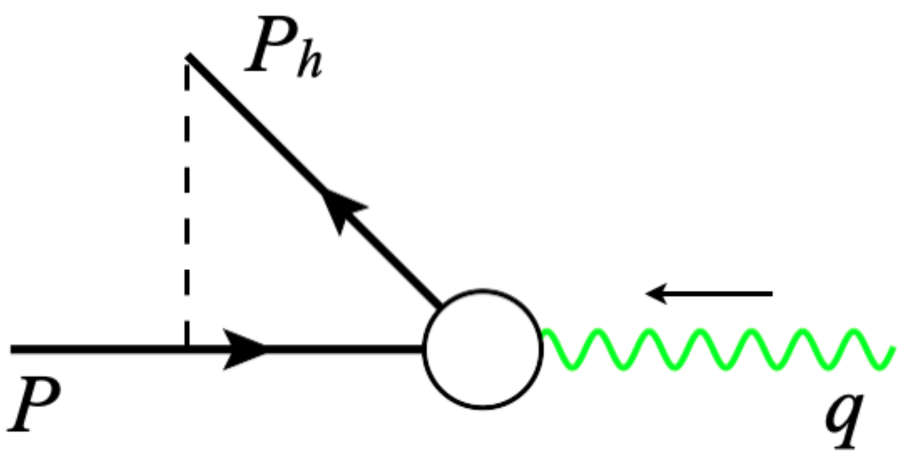
Fast parton/hadron interaction with cold nuclear matter

Semi-inclusive Deep Inelastic Scattering

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

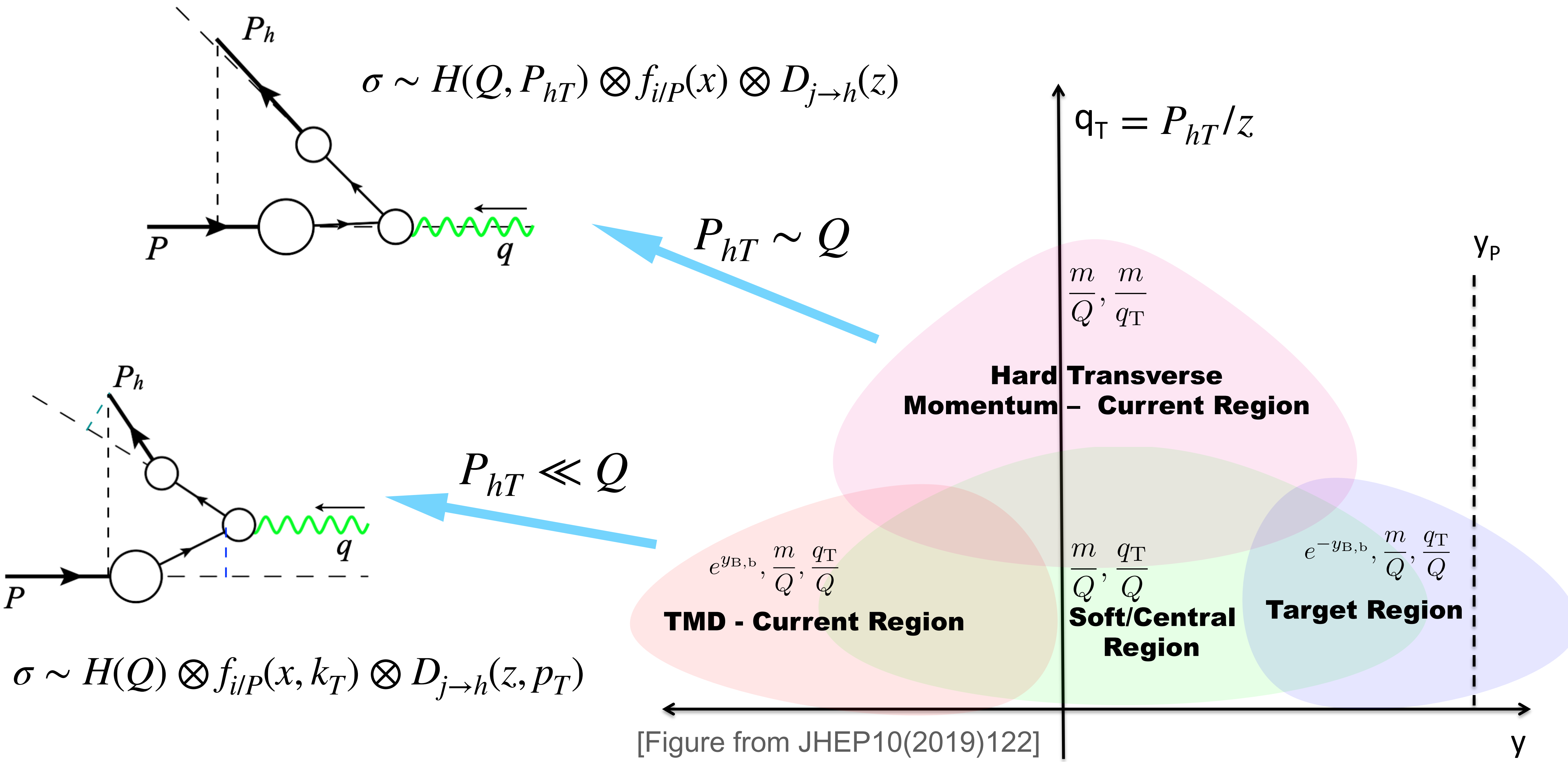
- enable us to explore the emergence of color neutral hadrons from colored quarks/gluons
- flavor dependence by selecting different types of observed hadrons: pions, kaons, …
- a large momentum transfer Q provides a short-distance probe
- an additional and adjustable momentum scale P_{hT}
- multidimensional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





SIDIS Kinematic Regions

Sketch of kinematic regions of the produced hadron



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

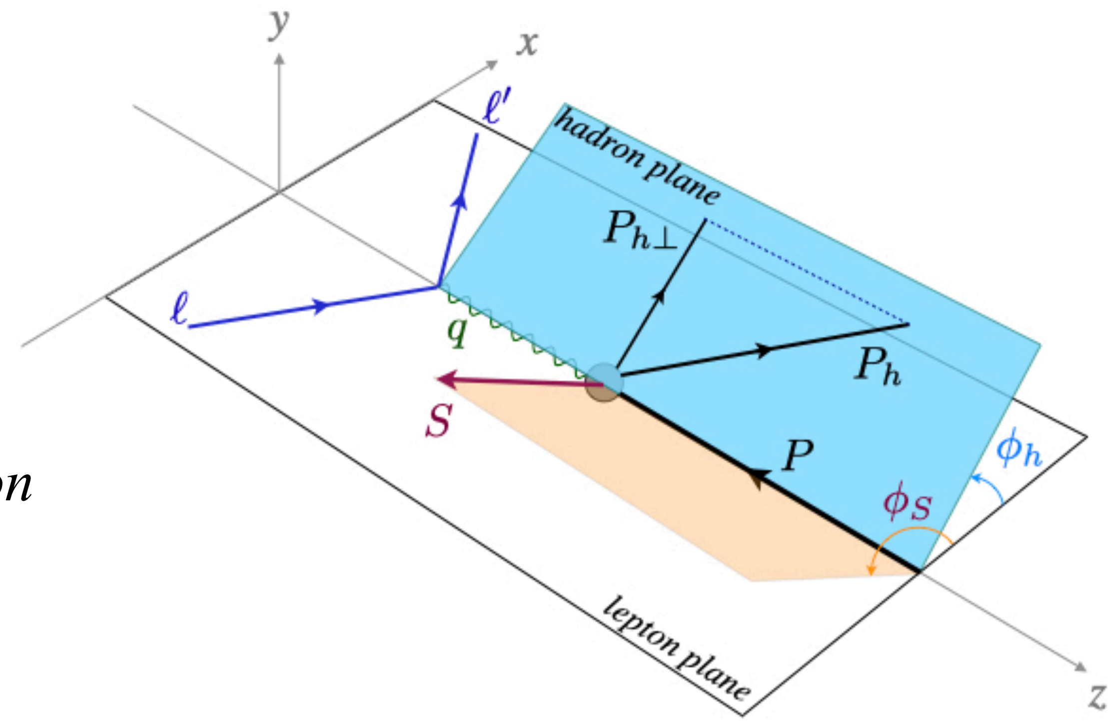
Structure Functions of SIDIS

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



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

$$= \frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x_B}\right)$$

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

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

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

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

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

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

$$x_B = \frac{Q^2}{2P\cdot q}$$

$$y = \frac{P\cdot q}{P\cdot l}$$

$$z = \frac{P\cdot P_h}{P\cdot q}$$

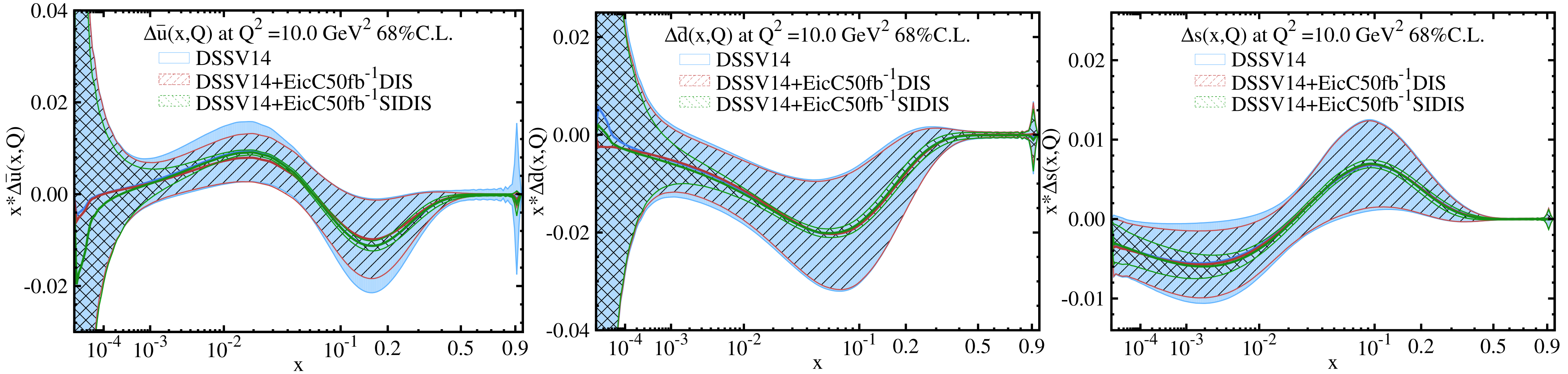
$$\gamma = \frac{2x_B M}{Q}$$

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: Helicity distribution

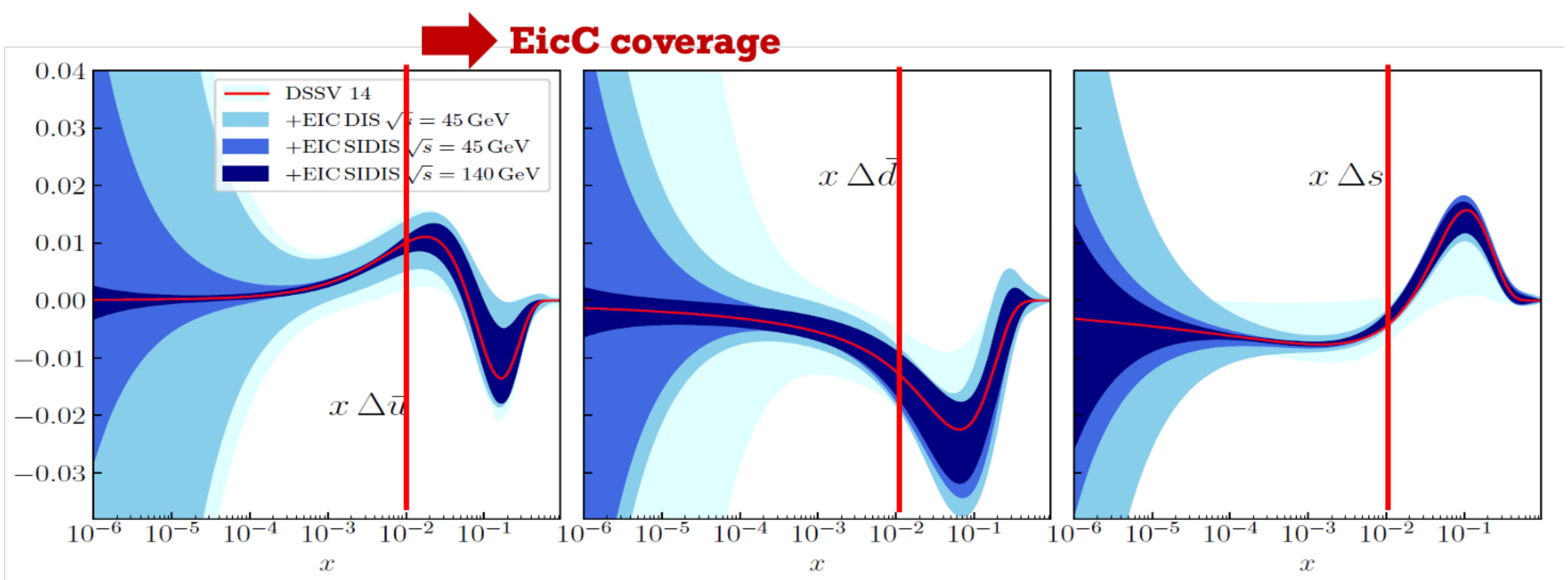
EicC:



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]

TMD Helicity Distributions

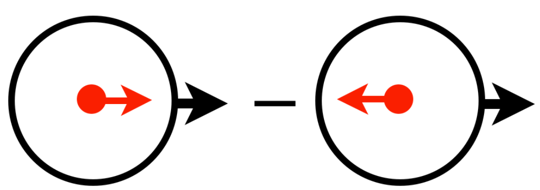
Longitudinal DSA in SIDIS

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

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

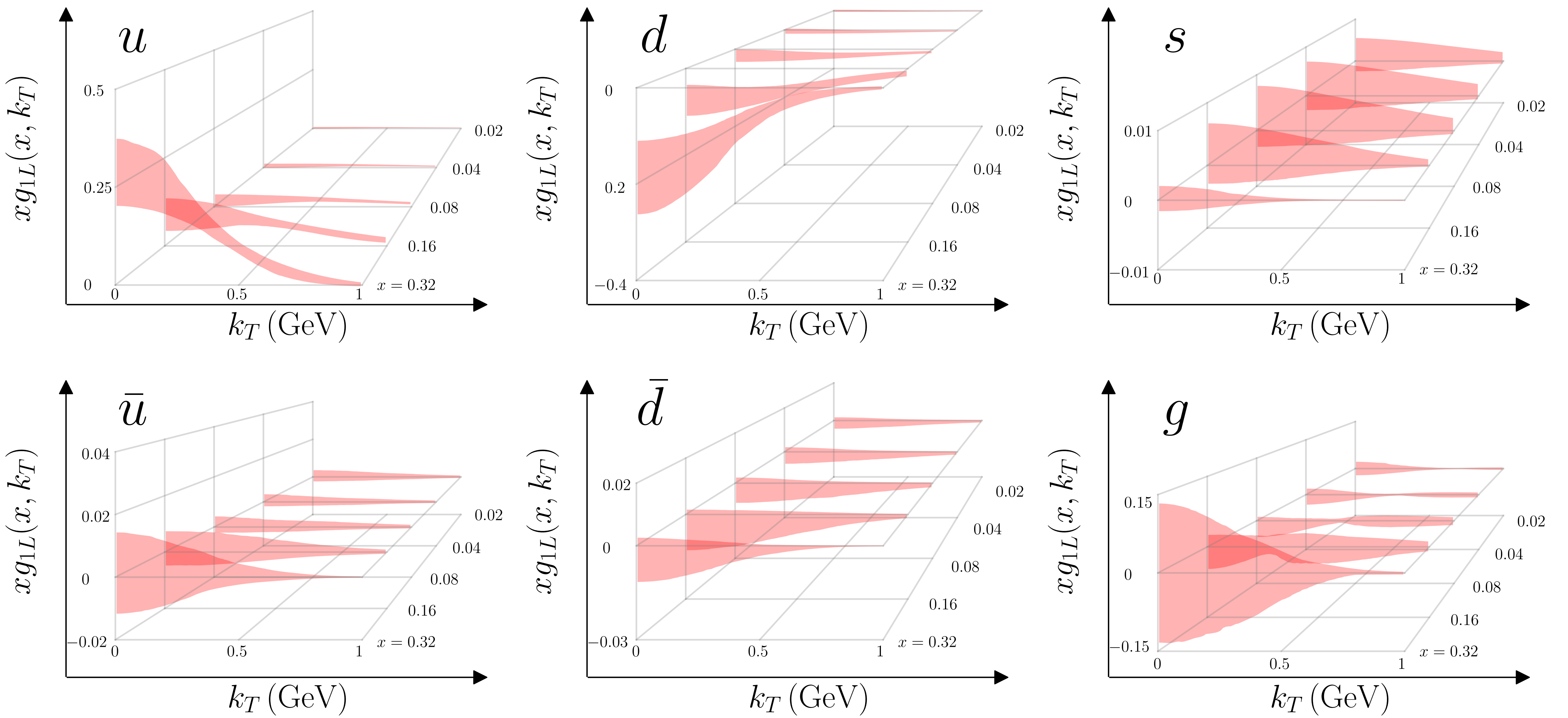
HERMES Collaboration, Phys. Rev. D 99 (2019) 112001.

JLab CLAS: proton (NH_3) target

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

First Extraction of TMD Helicity

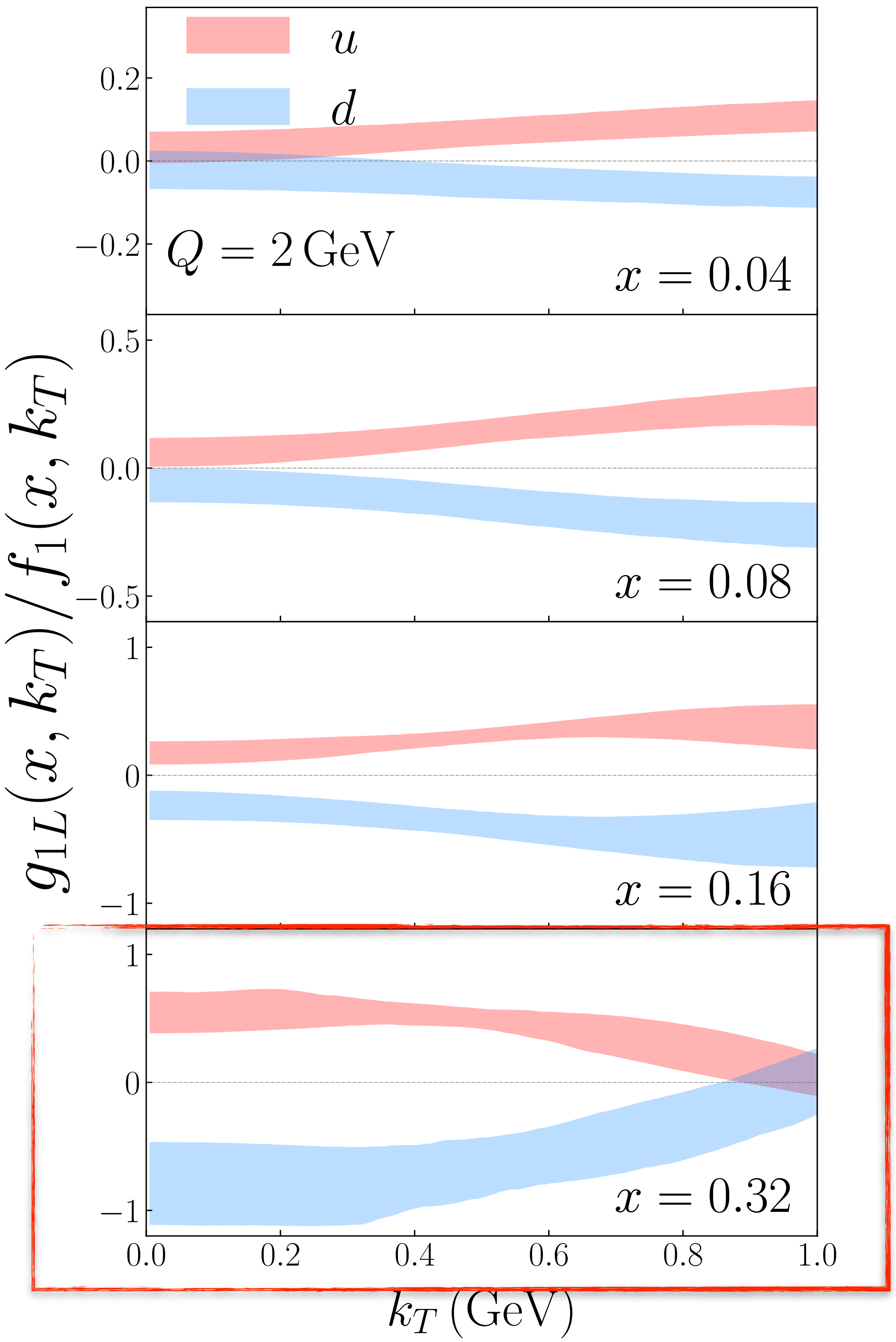
NLO+NNLL analysis results



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.

Transverse Momentum Dependent Polarization



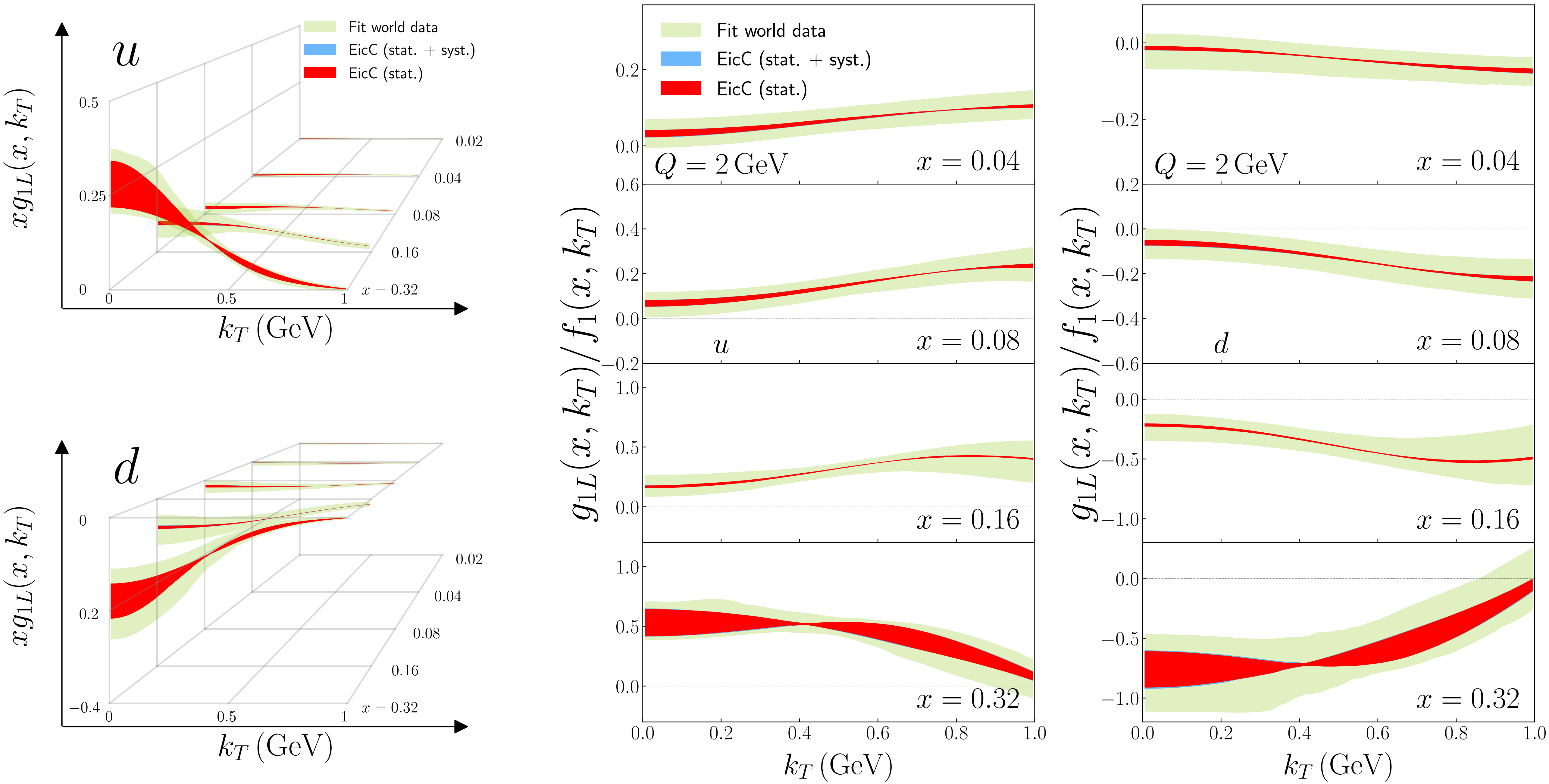
$g_{1L}(x, k_T^2)$ gives the absolute number density difference between spin-parallel and spin-antiparallel quarks.

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

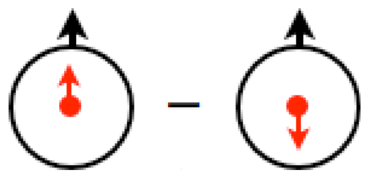
K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902.

EicC Impact: TMD Helicity



Transversity Distribution

Transversity distribution

h_1  (Collinear & TMD)

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

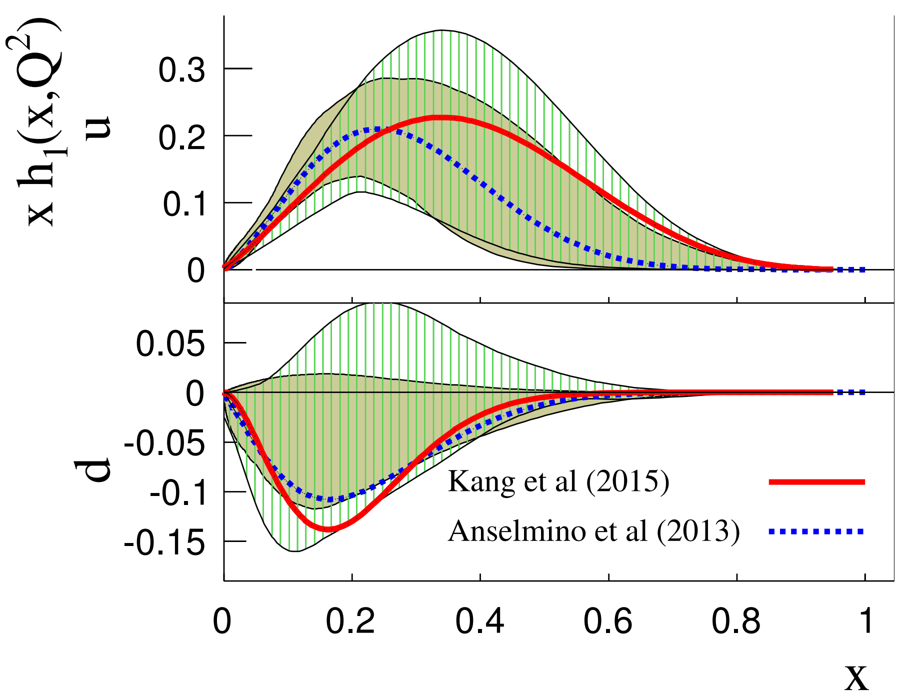
Chiral-odd:

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

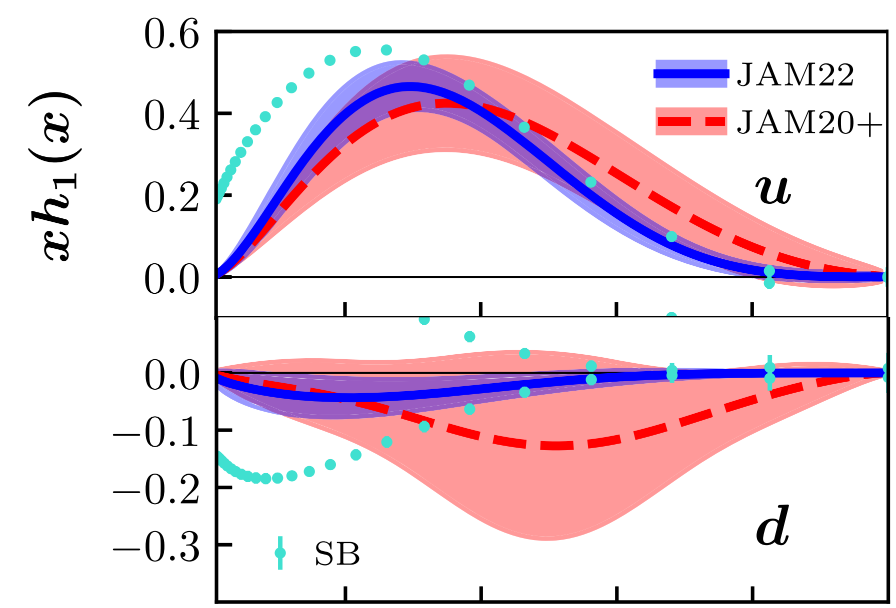
Effect in SIDIS:
transverse single spin asymmetry (Collins asymmetry)

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

Phenomenological extractions



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

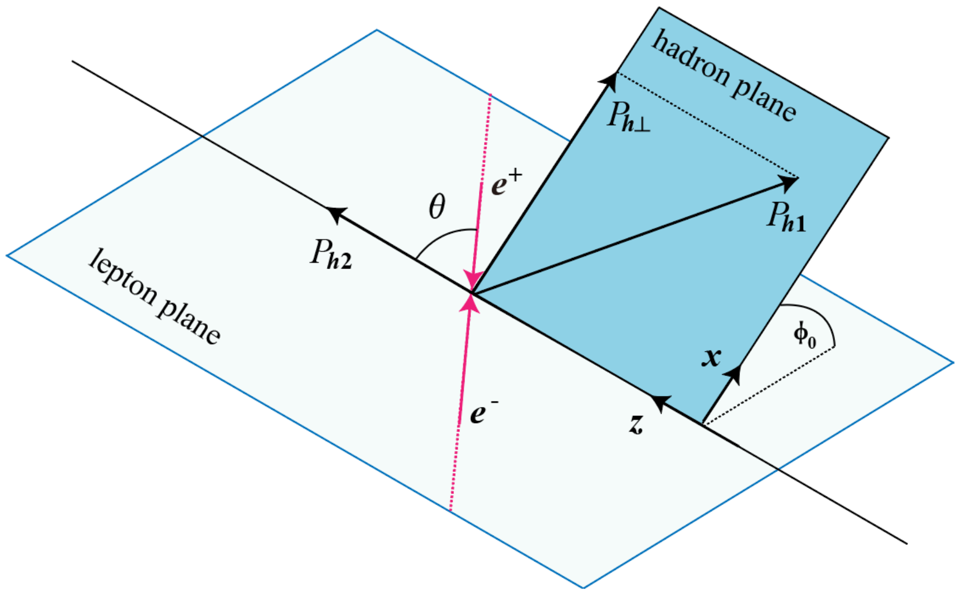


JAM Collaboration, PRD 104, 034014 (2022).

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, $P_{hT} \ll Q$ $\qquad F_{\rm Collins}^{h_1h_2} \sim H_1^{\perp h_1} \otimes H_1^{\perp h_2}$

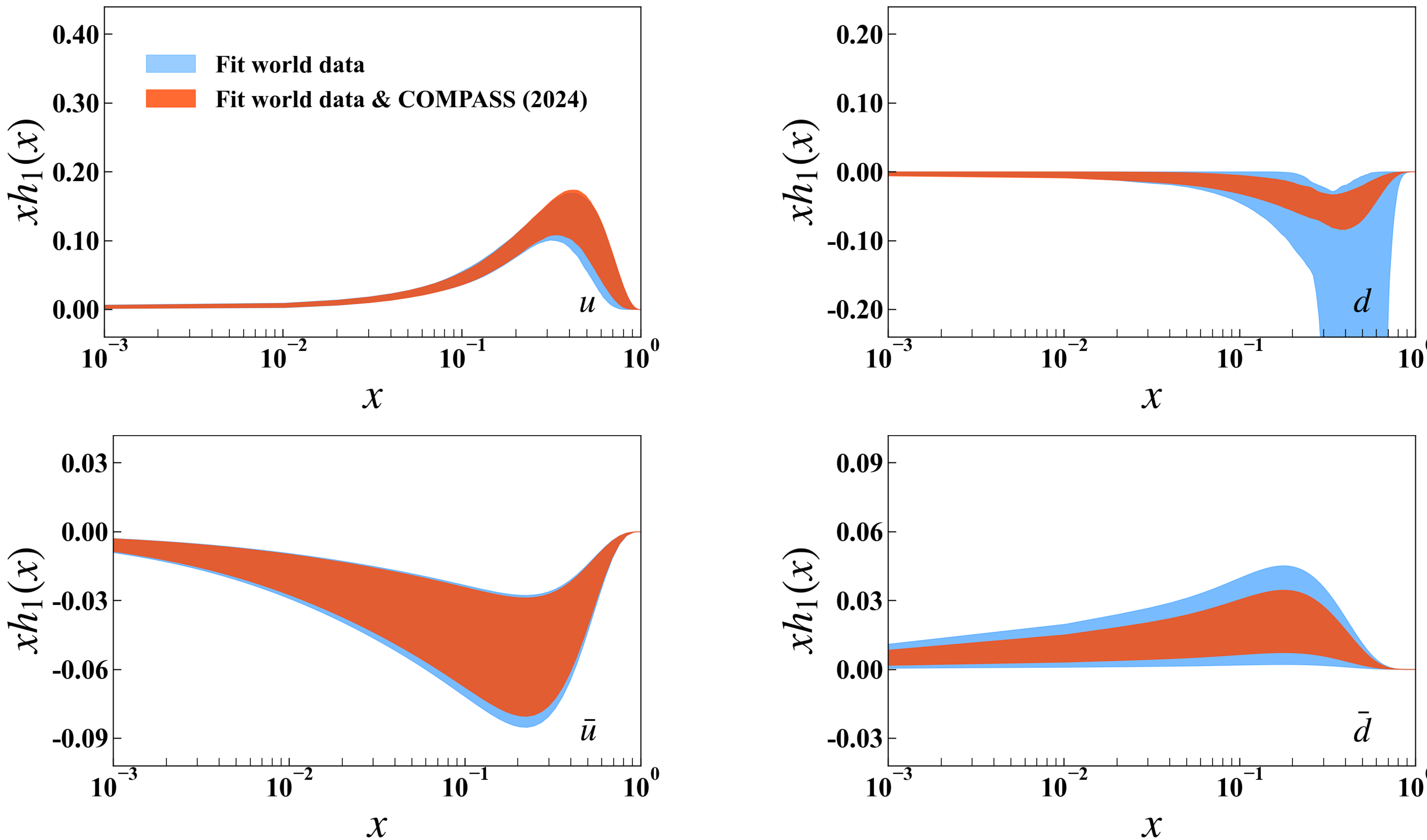
Experimental measurements:

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

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

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

Transversity Distributions

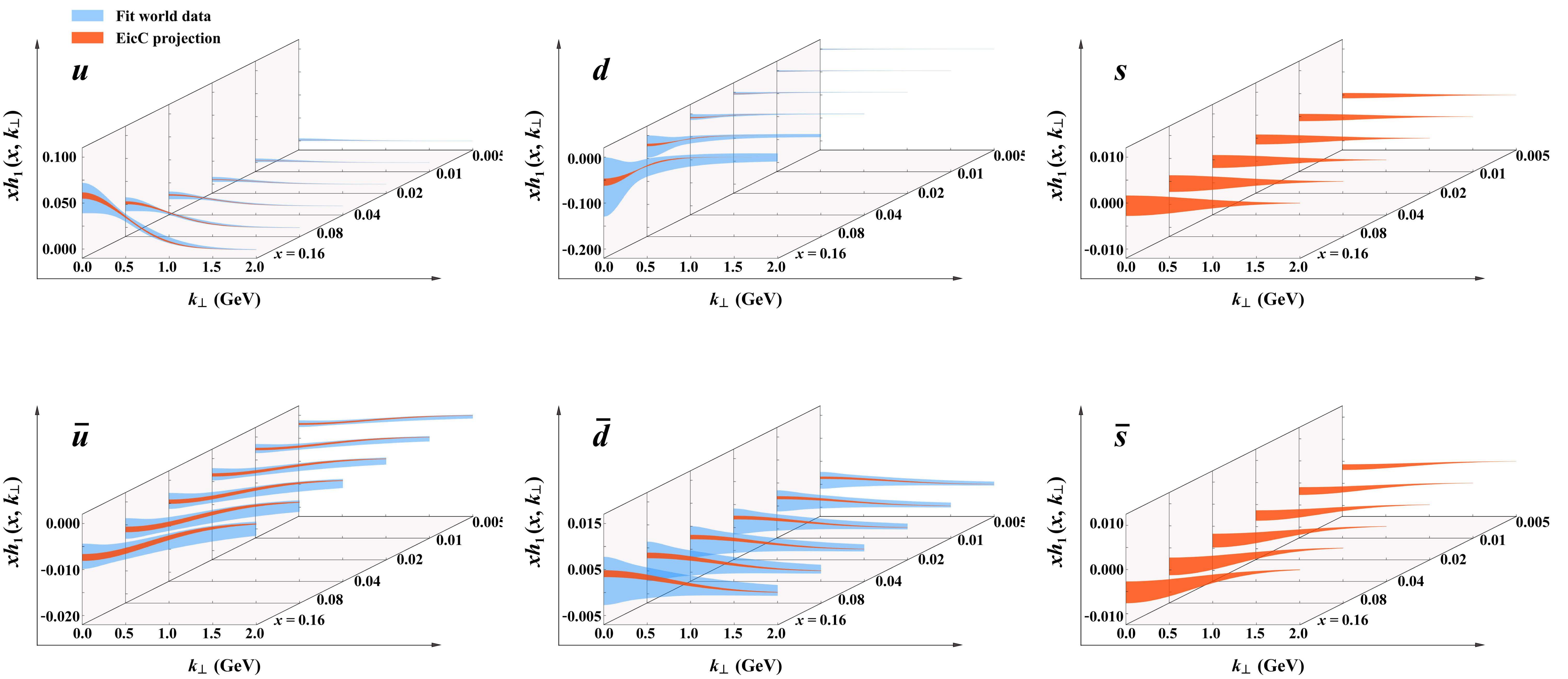


Without assuming zero sea quark transversity distributions

Existing world data favor negative $\bar{u}$ transversity distribution

C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, Phys. Rev. D 109 (2024) 056002, arXiv:2412.18324

EicC Impact on Transversity

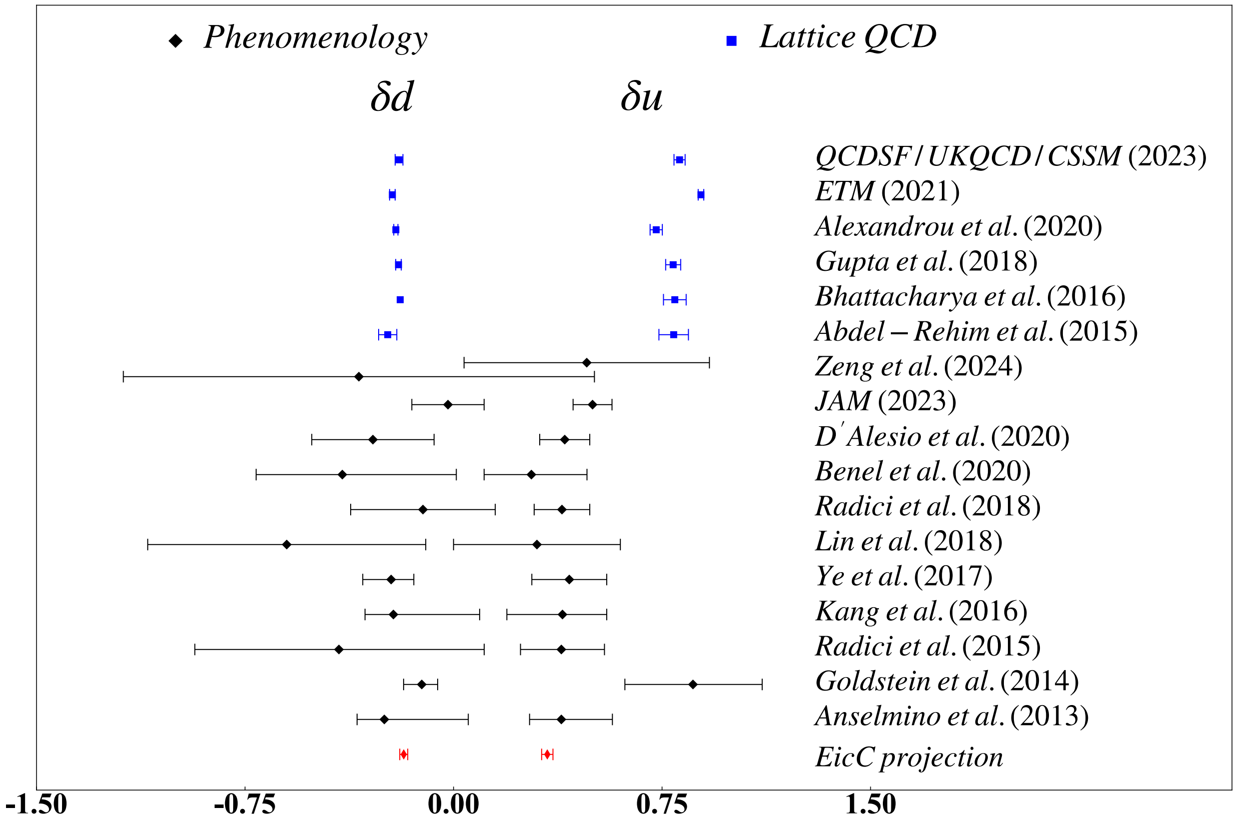


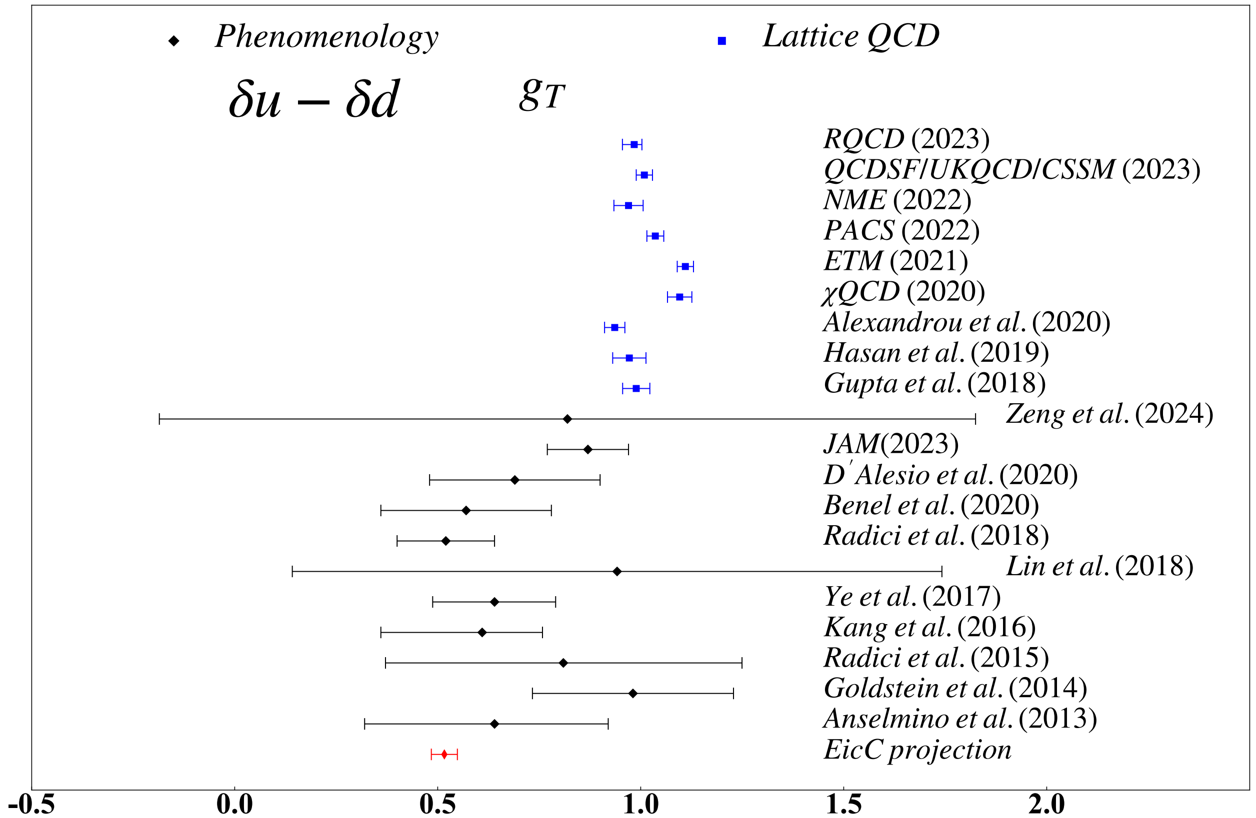
EicC Impact on Tensor Charge

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.

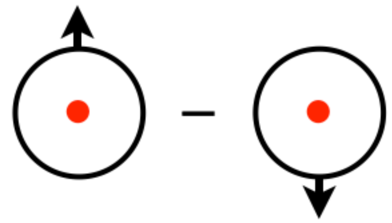




The Sivers Function

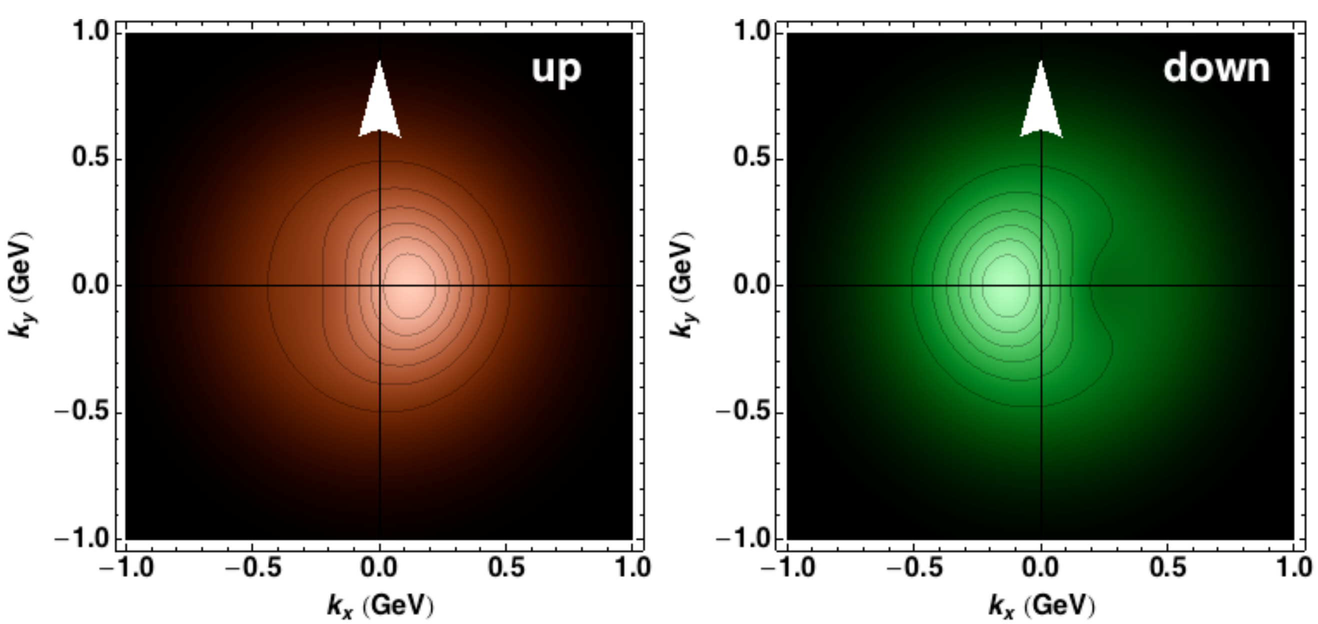
Sivers TMD distribution function

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



A naive T-odd distribution function

Transverse momentum distribution
distorted by nucleon transverse spin



[Figure from A. Bacchetta]

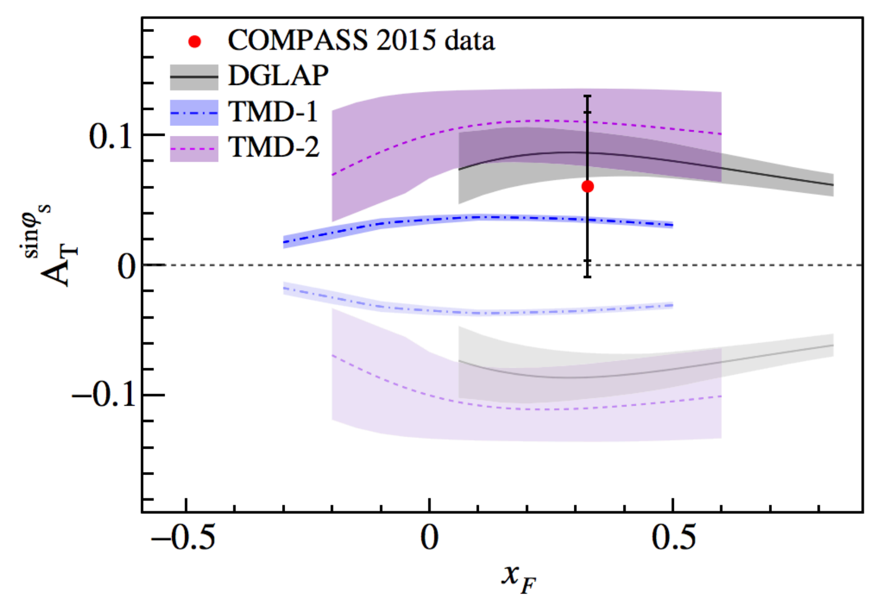
Effect in SIDIS:
transverse single spin asymmetry
(Sivers asymmetry)

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

sizable Sivers asymmetry observed
by HERMES, COMPASS, JLab

Sign change prediction:

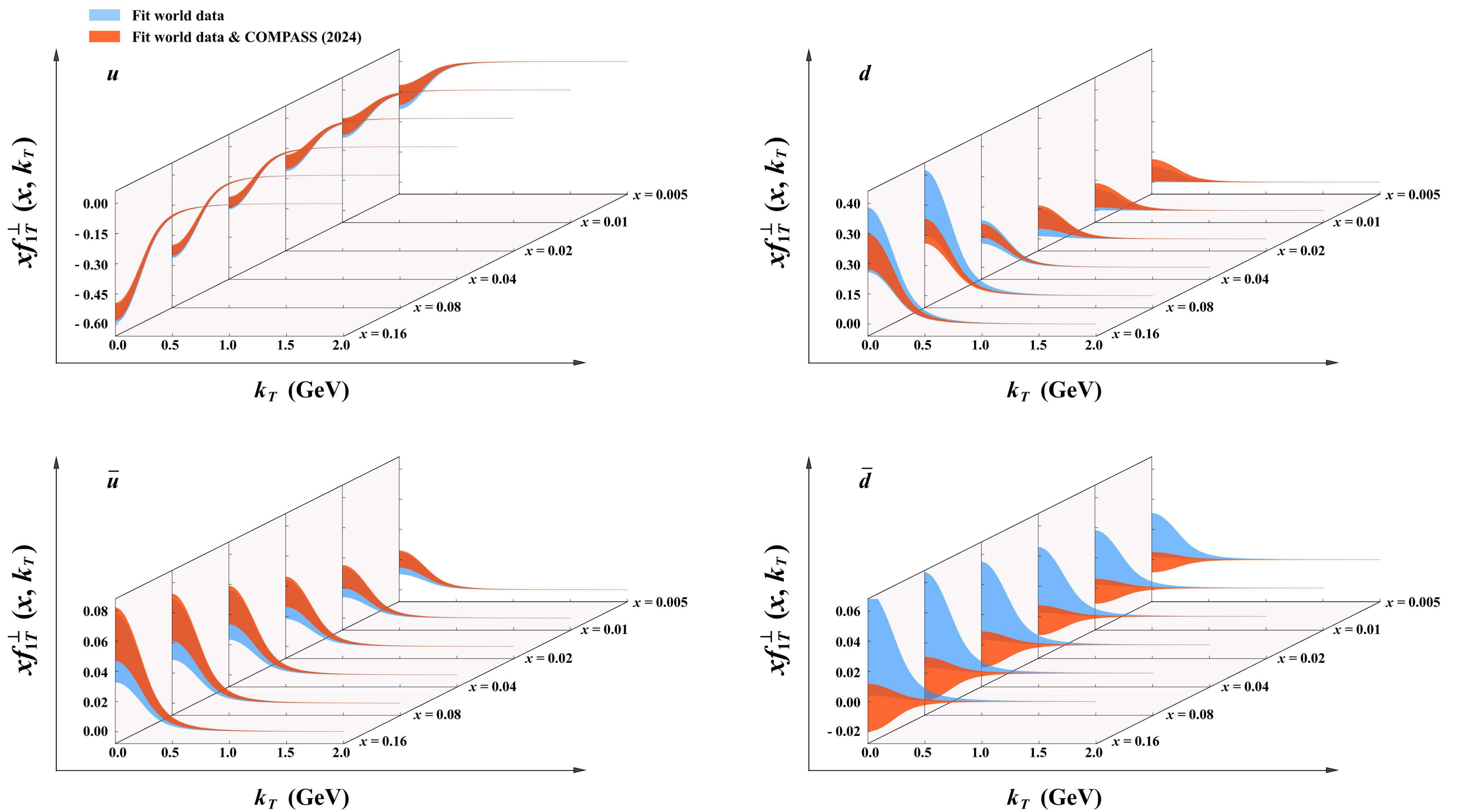
$$f_{1T}^{\perp}(x, k_T^2)\,|_{\text{SIDIS}} = -f_{1T}^{\perp}(x, k_T^2)\,|_{\text{DY}}$$



COMPASS Collaboration, PRL 119, 112002 (2017).

Sivers Functions

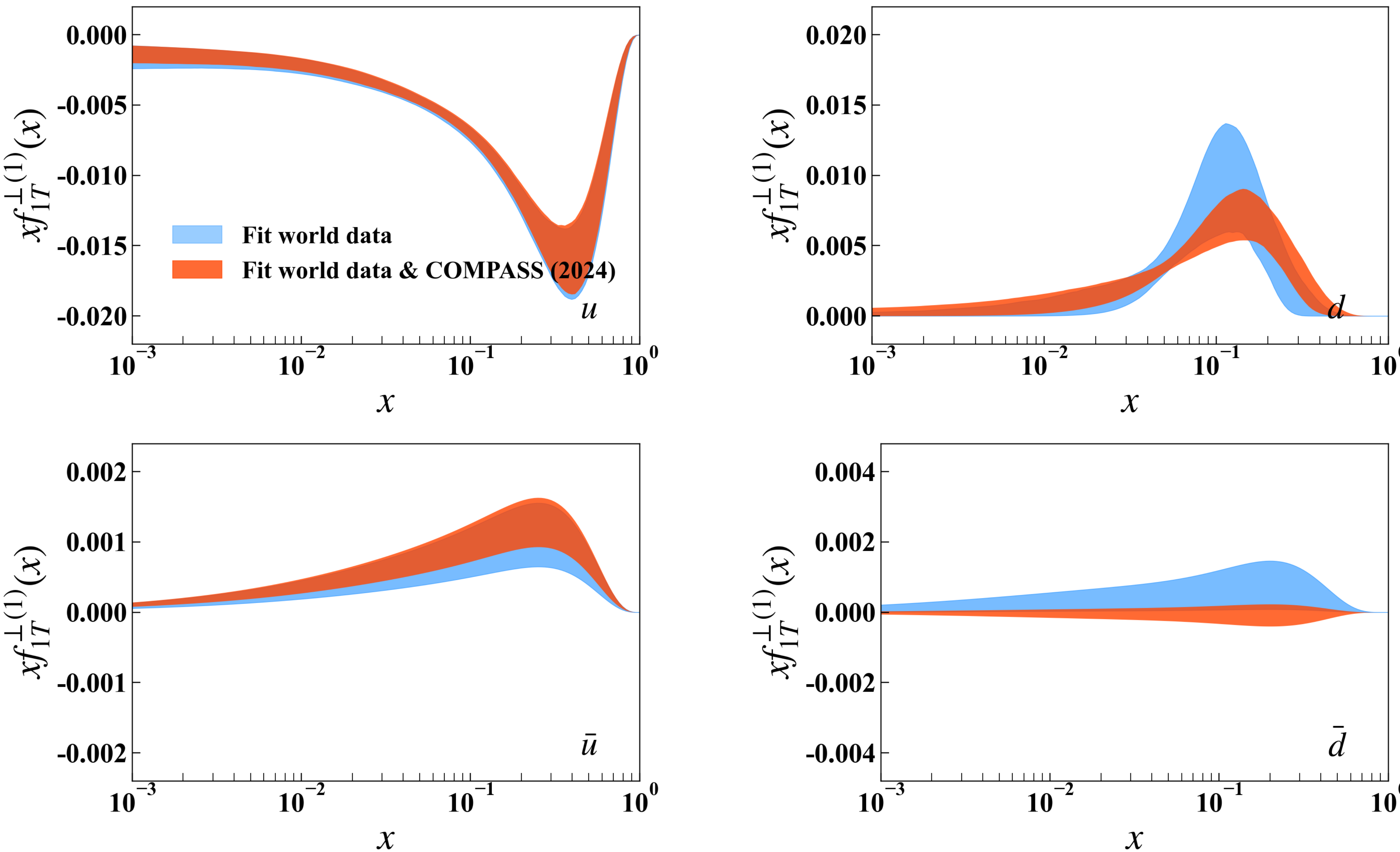
Global analysis of SIDIS, Drell-Yan, $W^{\pm}/Z^0$ production data



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

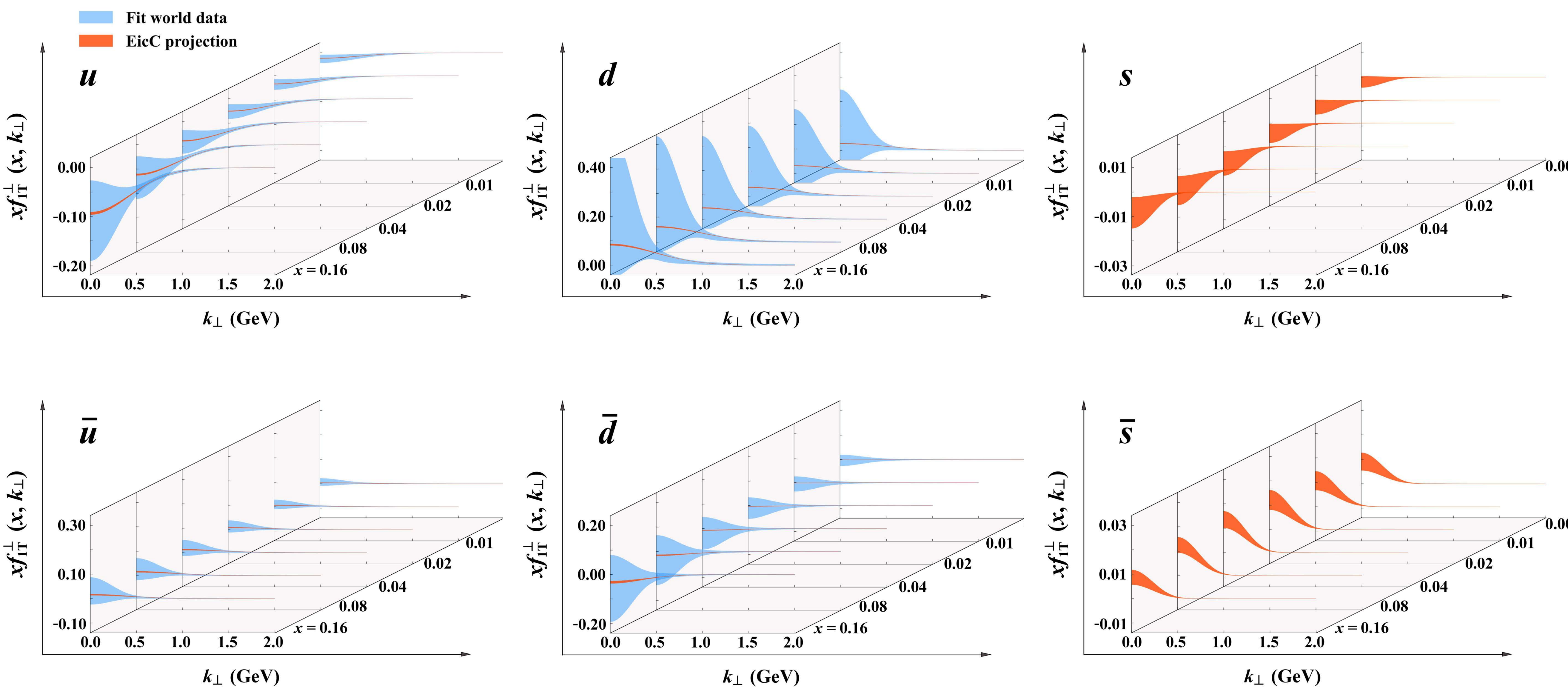
Sivers Functions

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



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

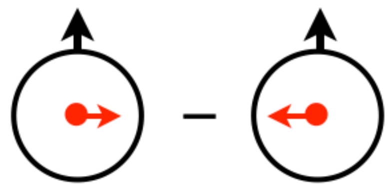
EicC Impact on Sivers Functions



Double Spin Asymmetry and Worm-gear

Trans-helicity worm-gear distribution

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

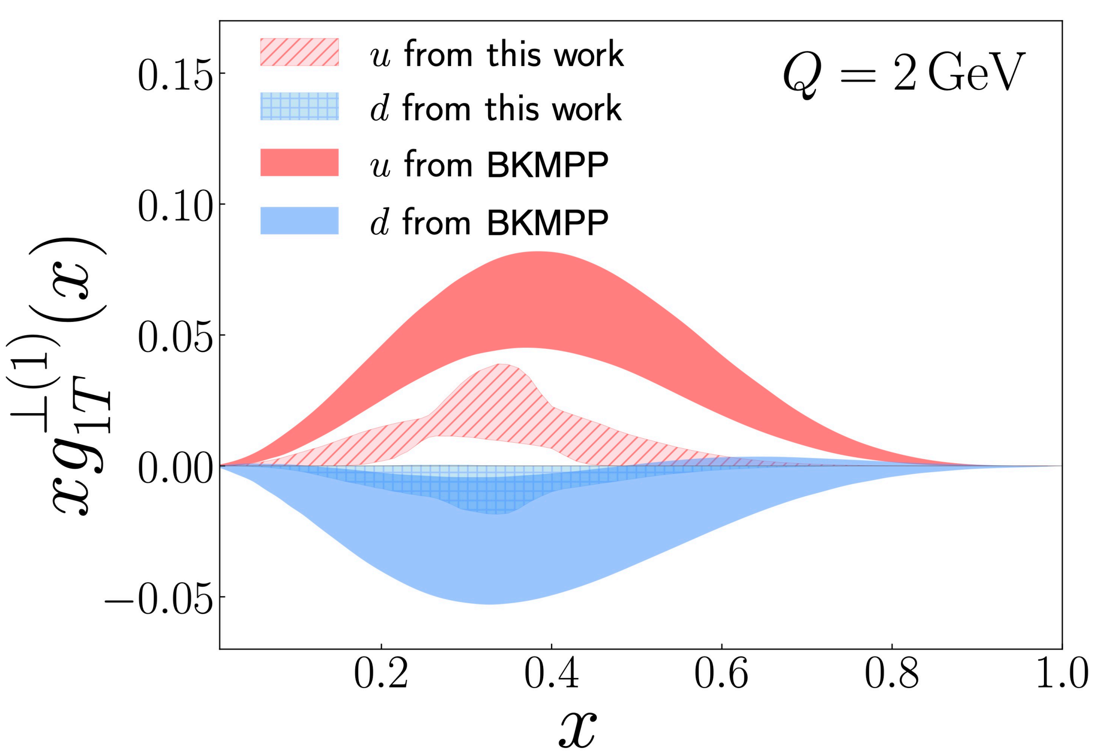


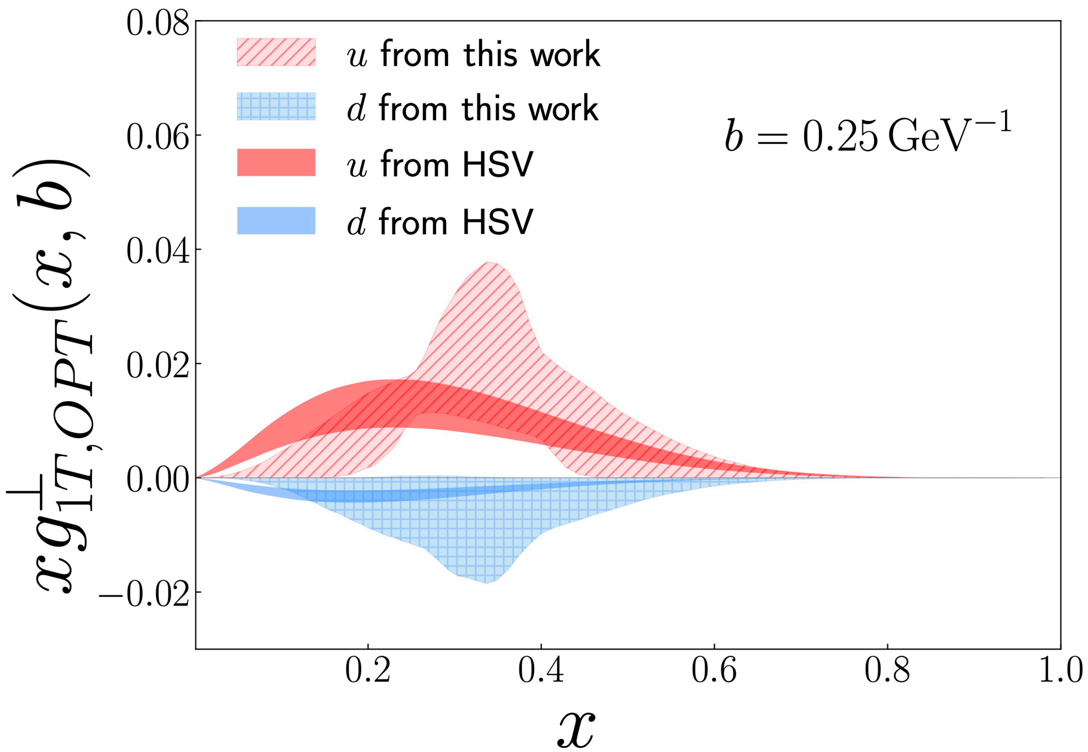
Effect in SIDIS:
A longitudinal-transverse double spin asymmetry

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

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

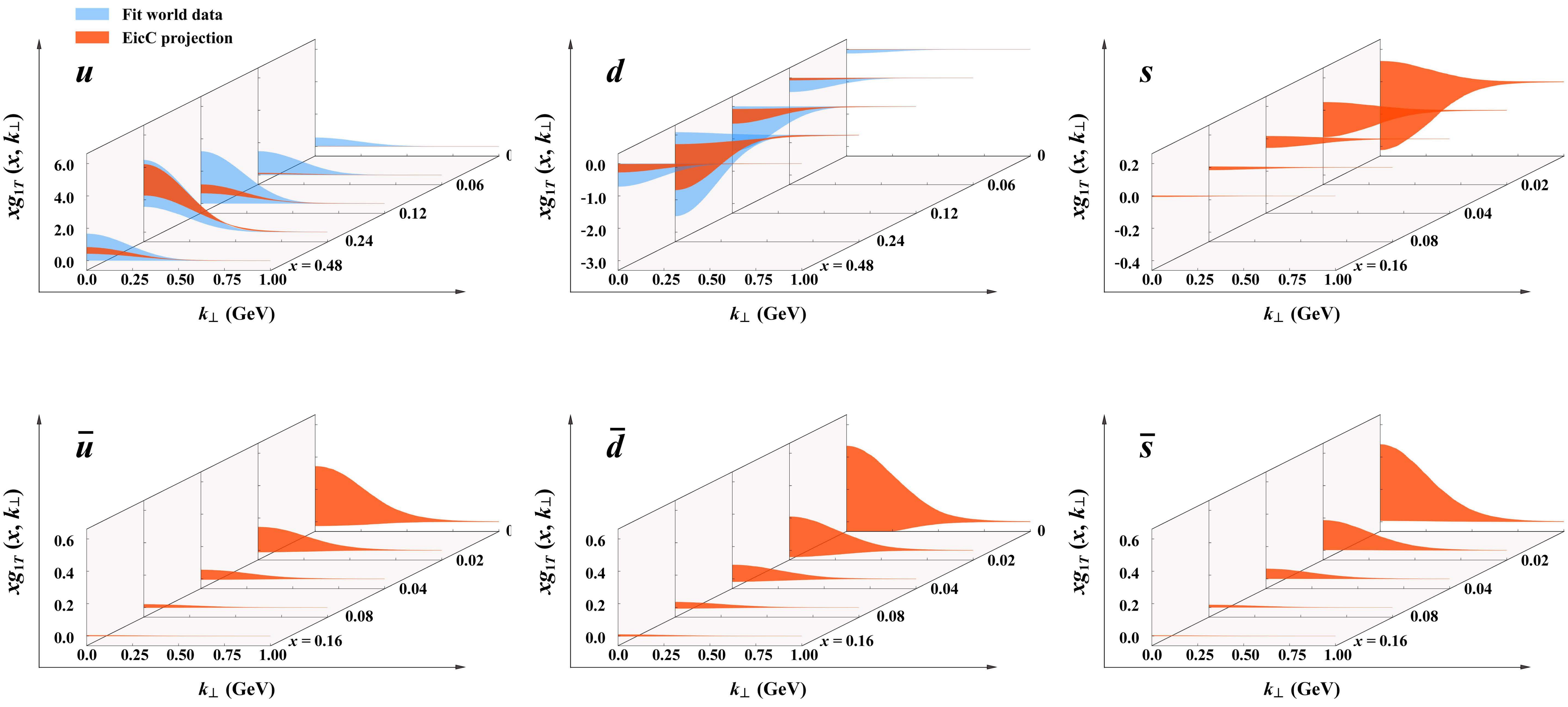
Phenomenological extraction





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

EicC Impact on Trans-helicity Distributions



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.
- 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 (not covered in this talk)
  - power corrections, higher twist effects, target fragmentation
  - radiative corrections, nuclear effects
  - …

Thank you!

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 ^3He

p and ^3He pol.: 70%

electron pol: 80%

Observables (examples):

Longitudinal double spin asymmetry $A_{LL} \Rightarrow g_{1L}$

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

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

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

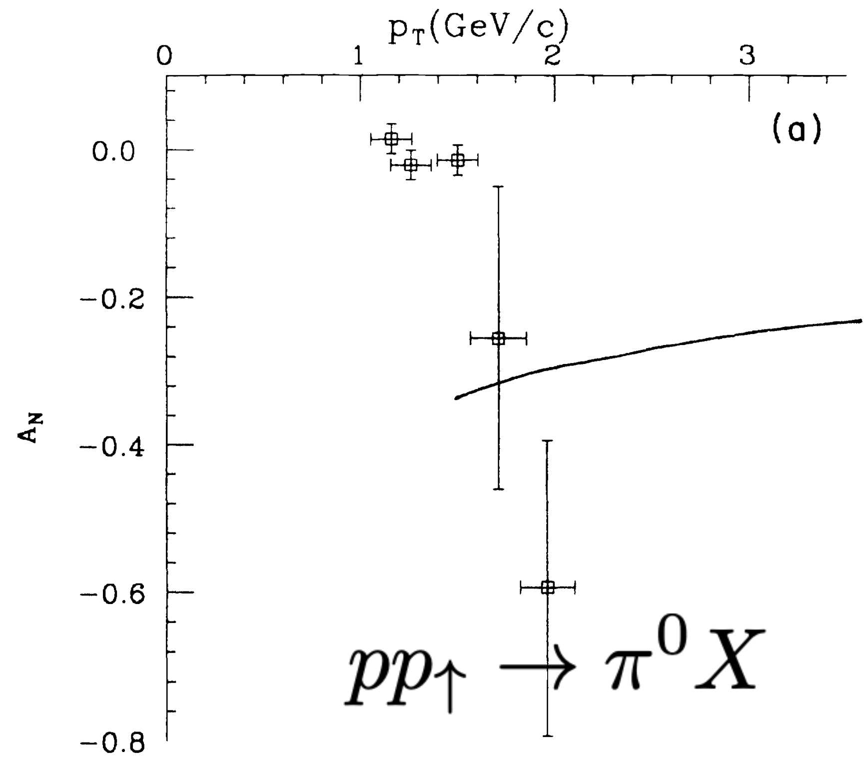
$$\mathscr{M} = \frac{(k^+ + m)^2 - k_T^2}{2k^+(k^0 + m)}$$

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

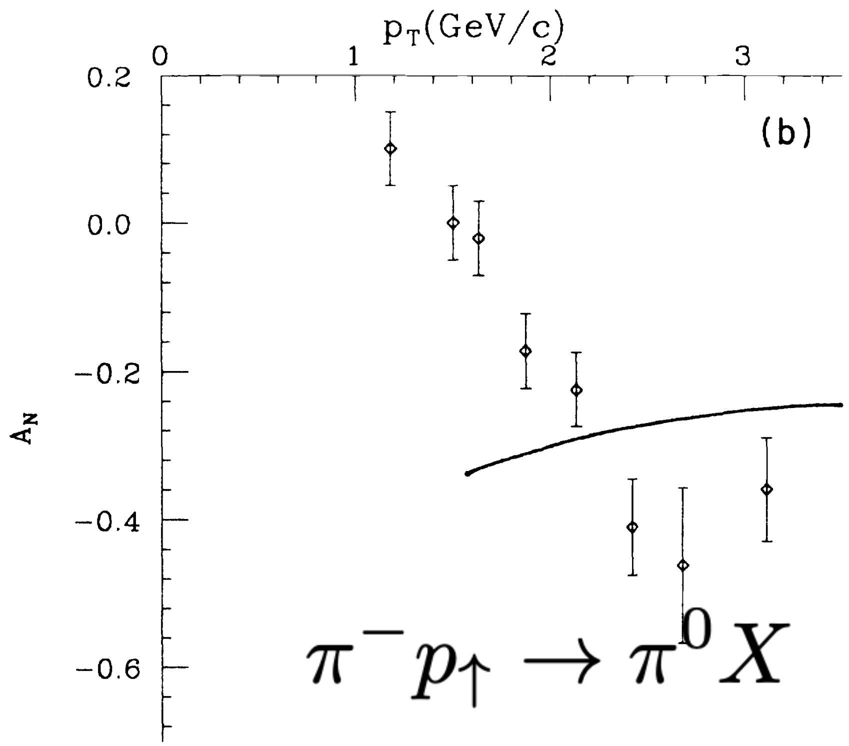
It predicts decreasing polarization with k_T, which should be tested by data.
This interpretation is based on a kinetic boost, but a complete boost including QCD dynamics is challenging.

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.

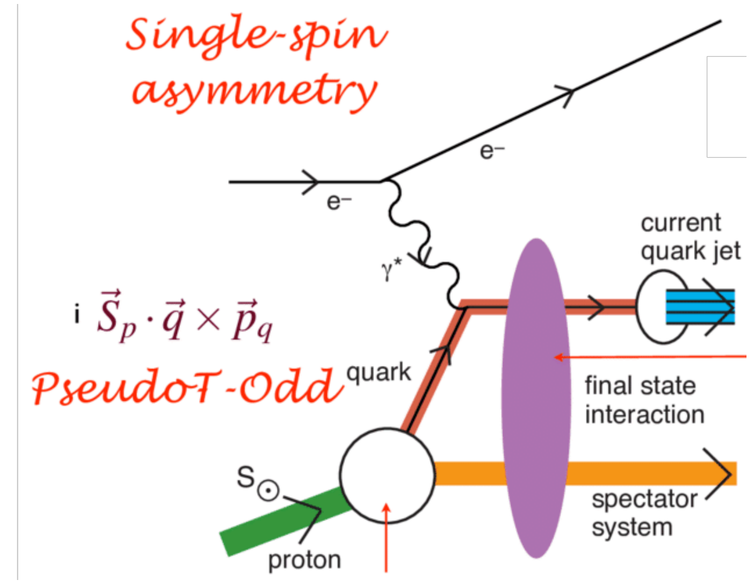
For the next decade, the "Sivers effect" was thought to vanish.

The Sivers Function: Early Story

Until an explicit model calculation showing …

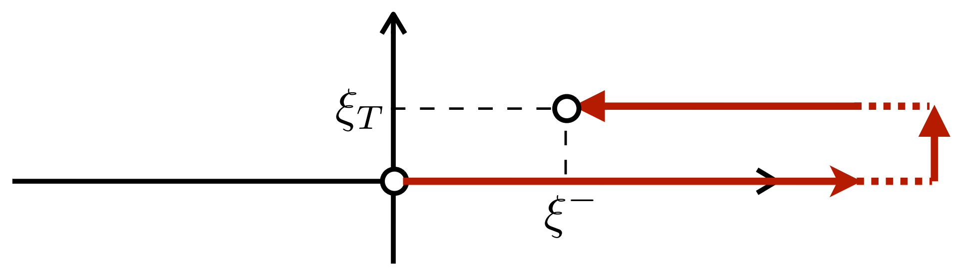
nonzero Sivers effects exist at leading twist
due to final-state interactions

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.

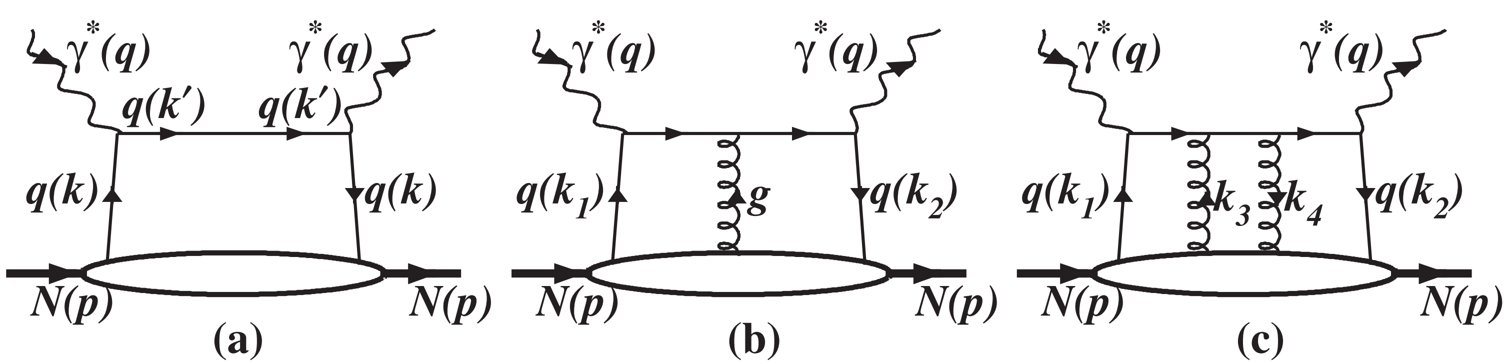
[Figure from A. Bacchetta]

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.



TMD Evolution

Evolution equations

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

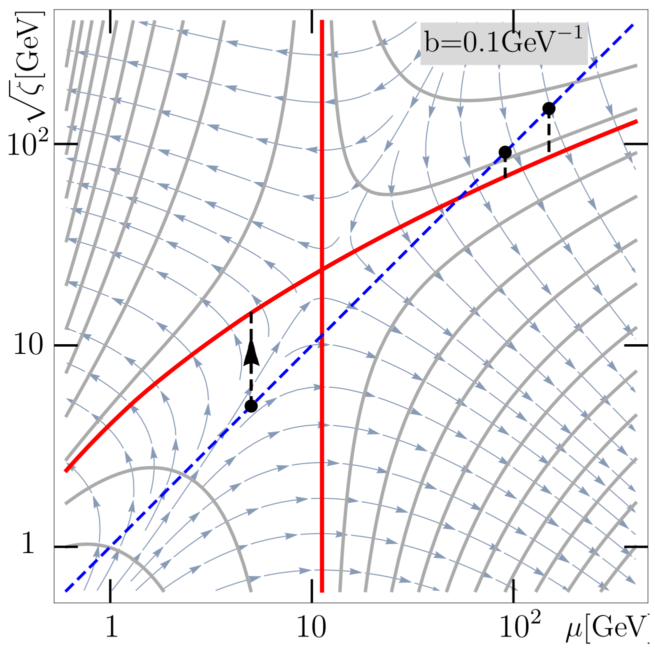
$$\zeta \frac{dF(x,b;\mu^2,\zeta)}{d\zeta} = -\mathcal{D}(\mu,b) F(x,b;\mu^2,\zeta)$$

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

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

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

ζ-prescription



equipotential lines:

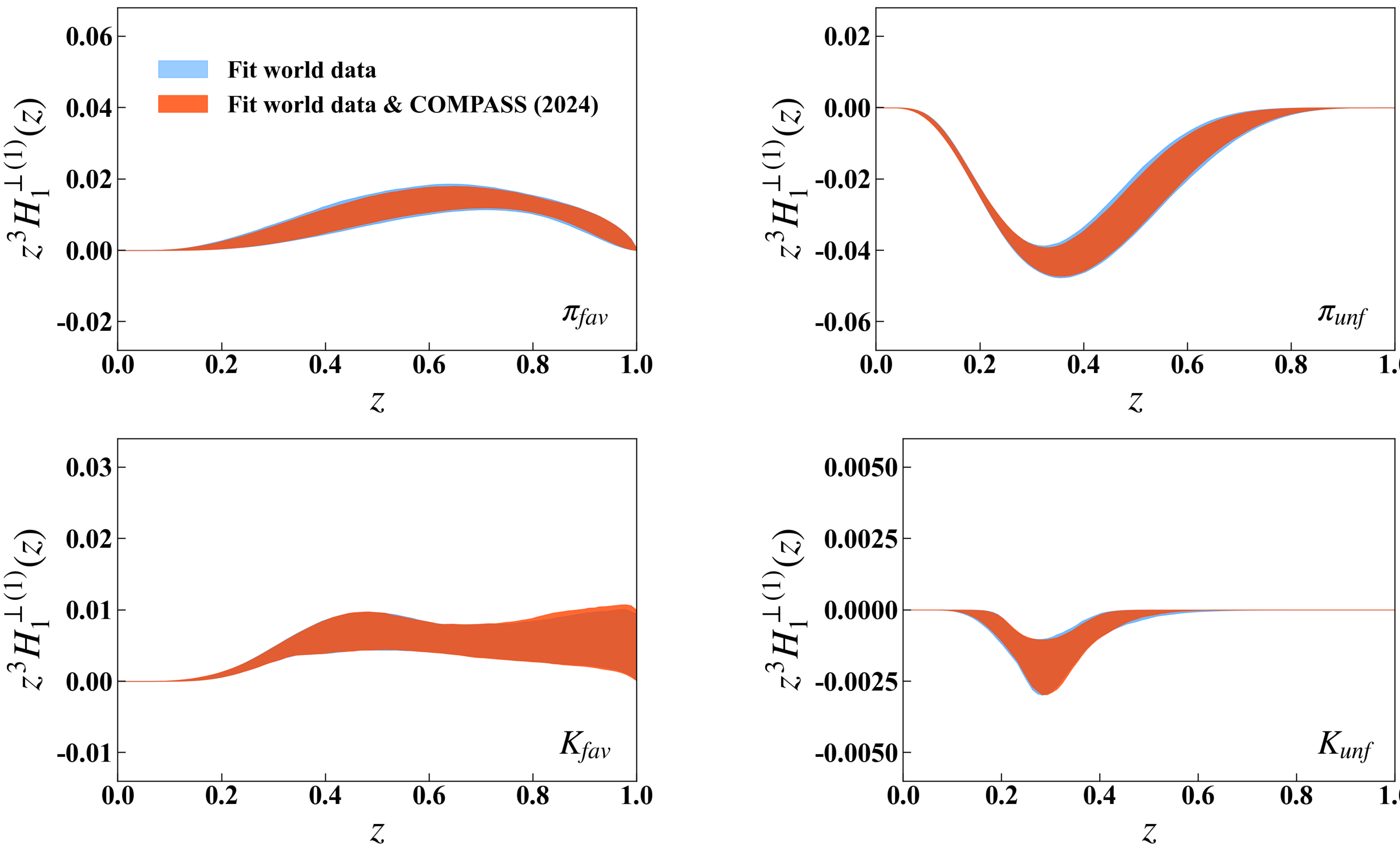
$$\frac{d\ln\zeta_\mu(\mu,b)}{d\ln\mu^2} = \frac{\gamma_F\left(\mu,\zeta_\mu(\mu,b)\right)}{2\mathcal{D}(\mu,b)}$$

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

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

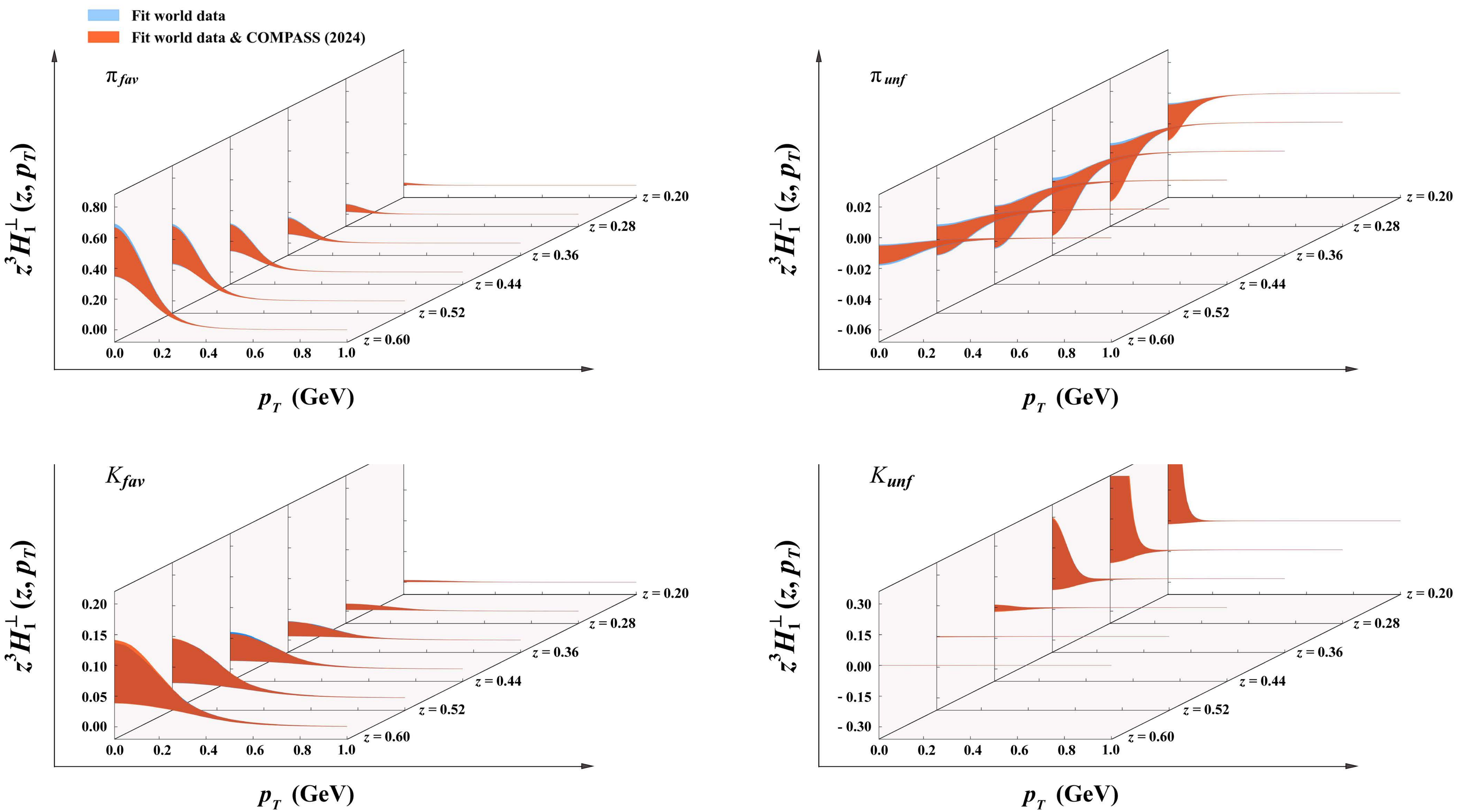
I. Scimemi, A. Vladmirov, JHEP 06 (2020) 137.

Collins Fragmentation Functions



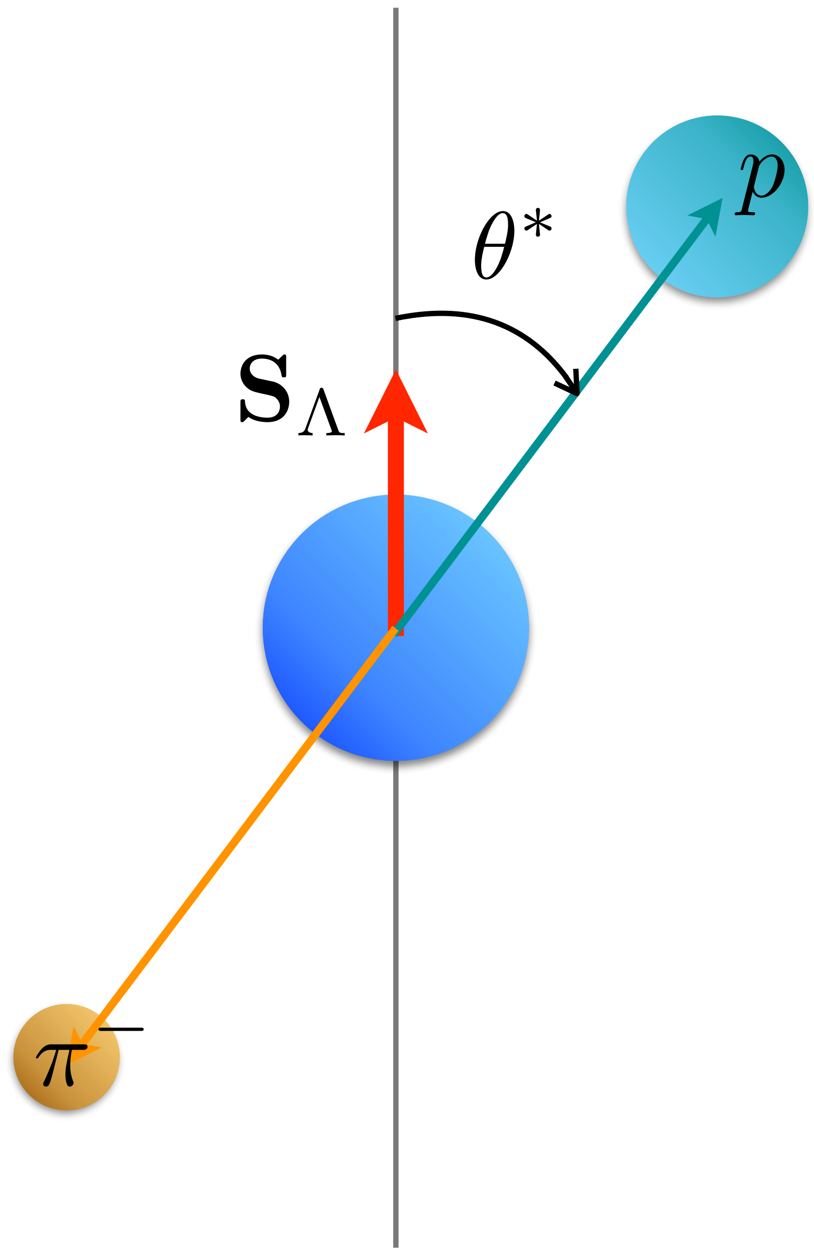
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, arXiv:2412.18324

Collins Fragmentation Functions



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

Analyze Λ Polarization



Decay channel: $\Lambda \to p\pi^-$

branch ratio: $64.1 \pm 0.5\%$

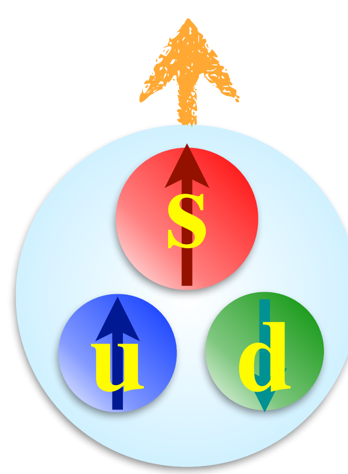
parity violating weak decay

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} \propto \mathcal{A}\,(1 + \alpha_\Lambda P_\Lambda \cos\theta^*)$$

decay parameter: $\alpha_\Lambda = 0.748 \pm 0.007$

[Current PDG value]

Allow to measure the spin (polarization) of the produced Λ



valence component: $|uds\rangle$

spin dominated by s quark

Sensitive to nucleon strange sea and its polarization via SIDIS