Nucleon Three-dimensional Spin Structures

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In collaboration with:

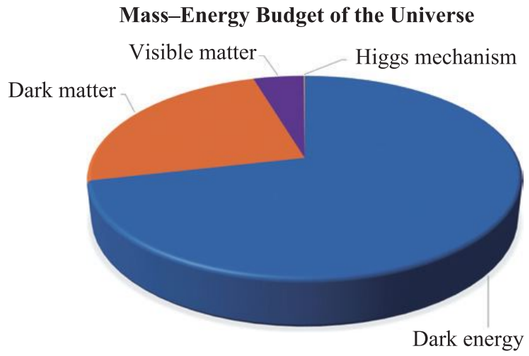
Hongxin Dong, Zuo-tang Liang, Bo-Qiang Ma, Peng Sun, Ke Yang, Chunhua Zeng, Xiaoyan Zhao, Yuxiang Zhao, Ya-jin Zhou, Yiyu Zhou

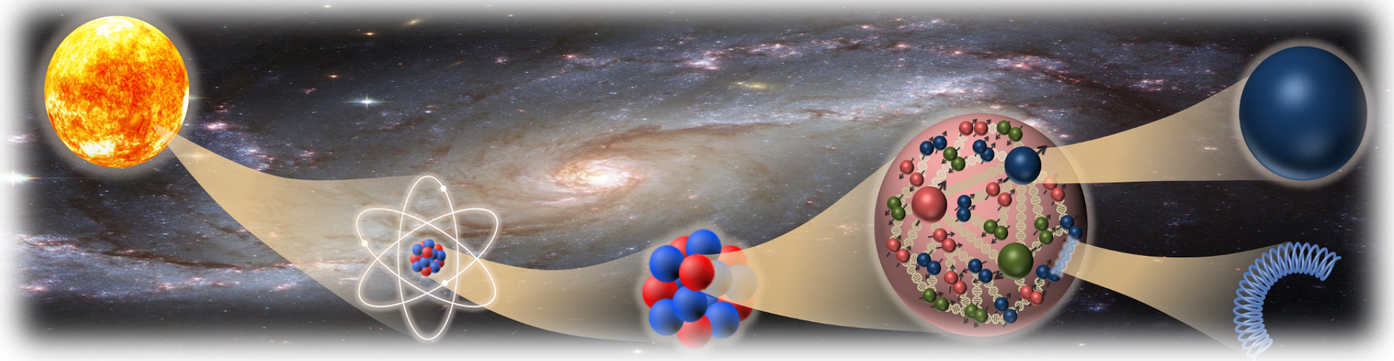
Flavour Physics Lecture 味物理讲座

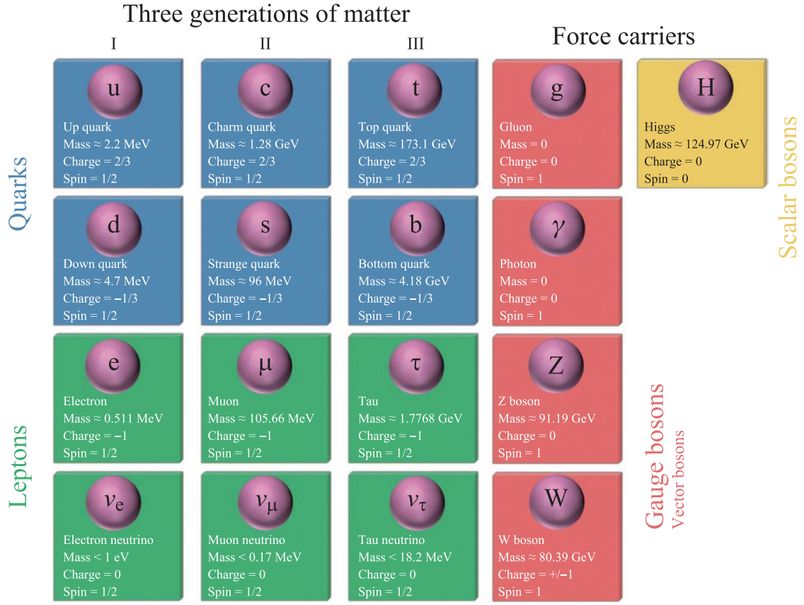
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SCNT Southern Center for Nuclear-Science Theory

How much do we understand our world?



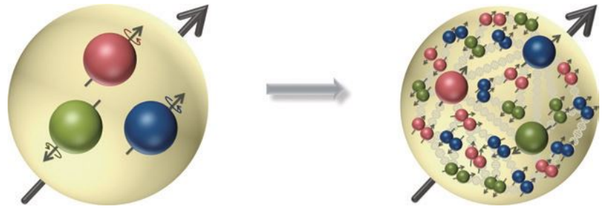




Mass



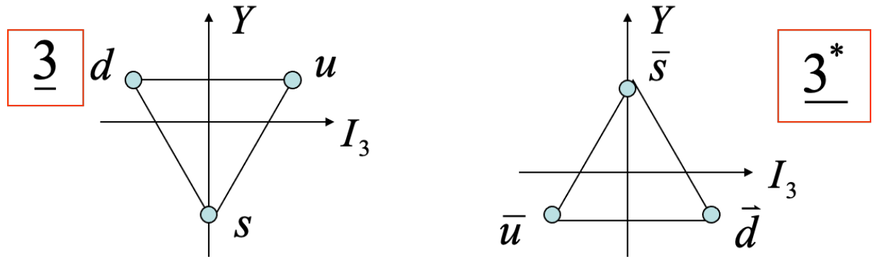
Spin



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:



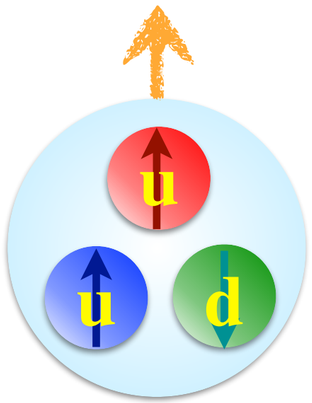
M. Gell-Mann, Phys. Lett. 8, 214 (1964);
G. Zweig, CERN Report No. TH-401 (1964).

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

Spin-flavor wave function of the proton:

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

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



Naïve quark model: the sum of quark spins gives the proton spin!

Lepton-Hadron Deep Inelastic Scattering

Inclusive DIS at a large momentum transfer:

- 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:

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

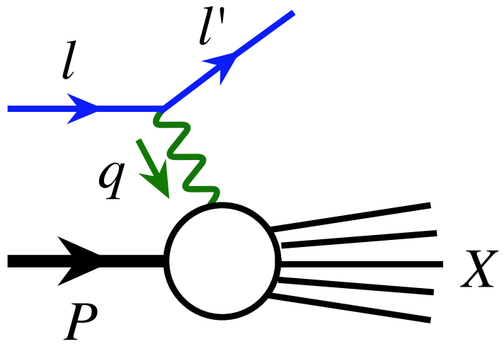
- overall corrections suppressed by $1/Q^n$
- indirectly "see" quarks, gluons and their dynamics
- predictive power relies on

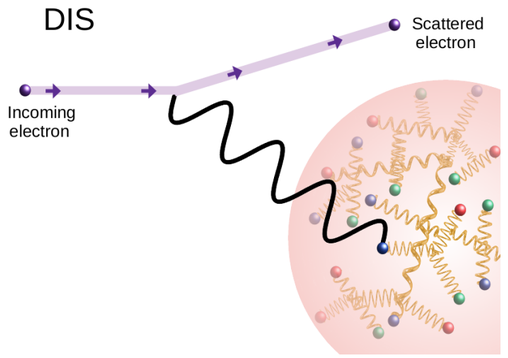
— precision of the probe

— universality of $f_{i/P}(x, \mu^2)$

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

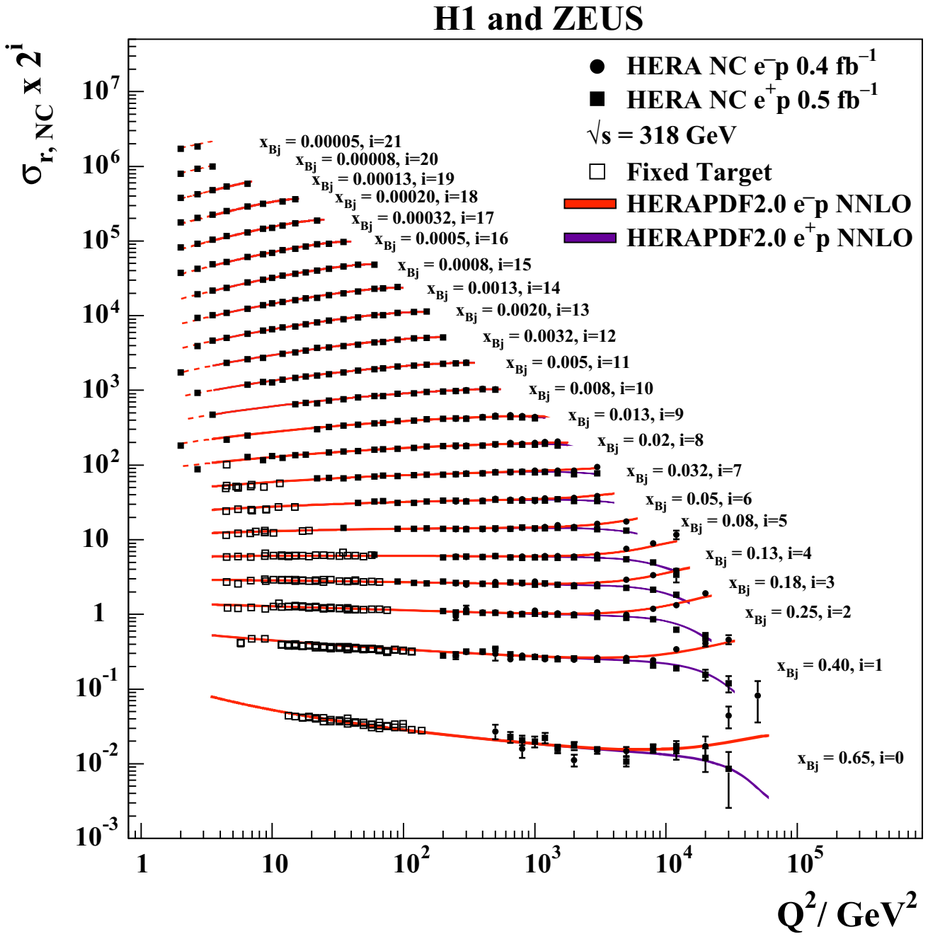
Modern "Rutherford" experiment.



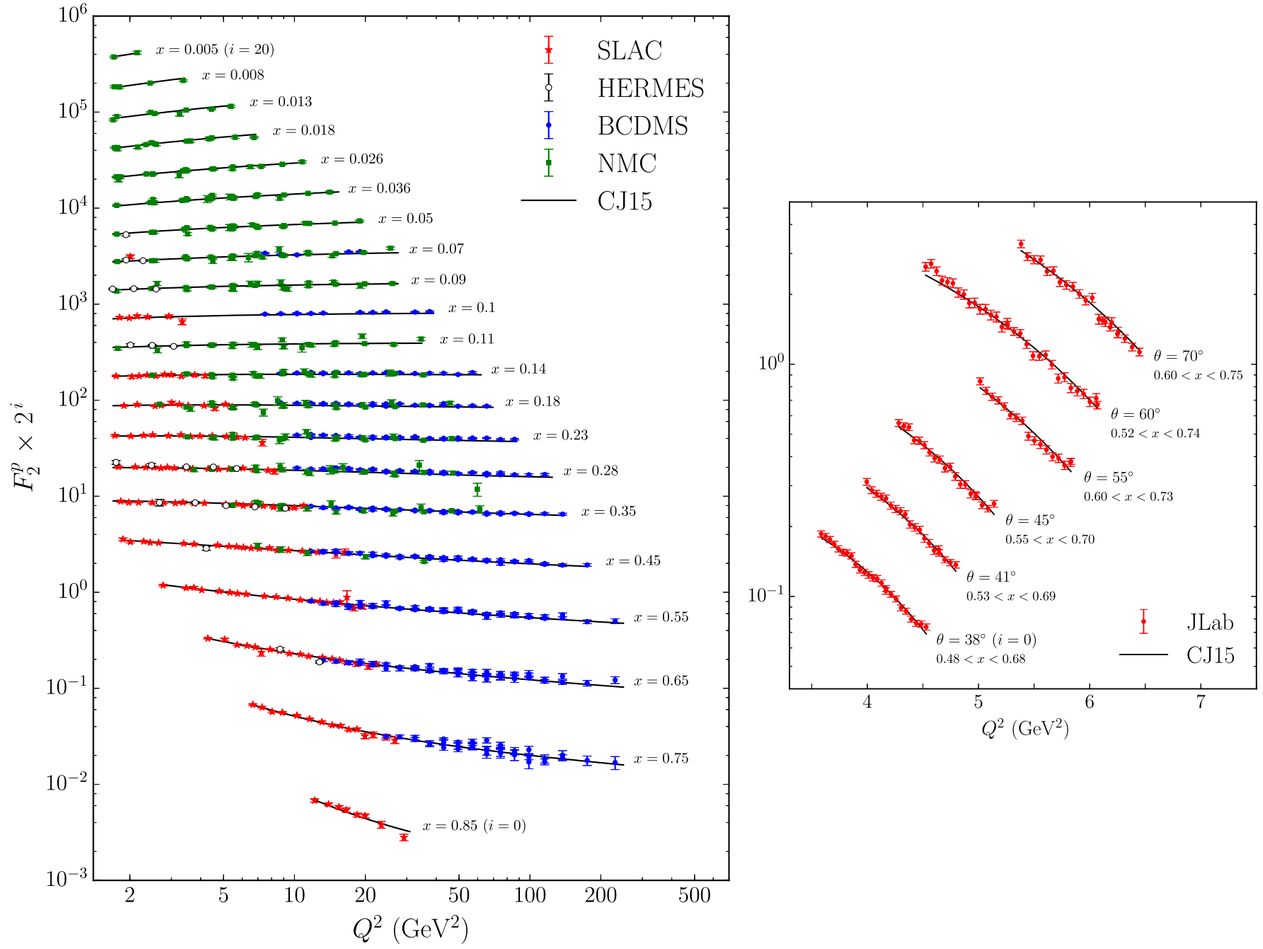


[Figure from DESY-21-099]

Lepton-Hadron Deep Inelastic Scattering

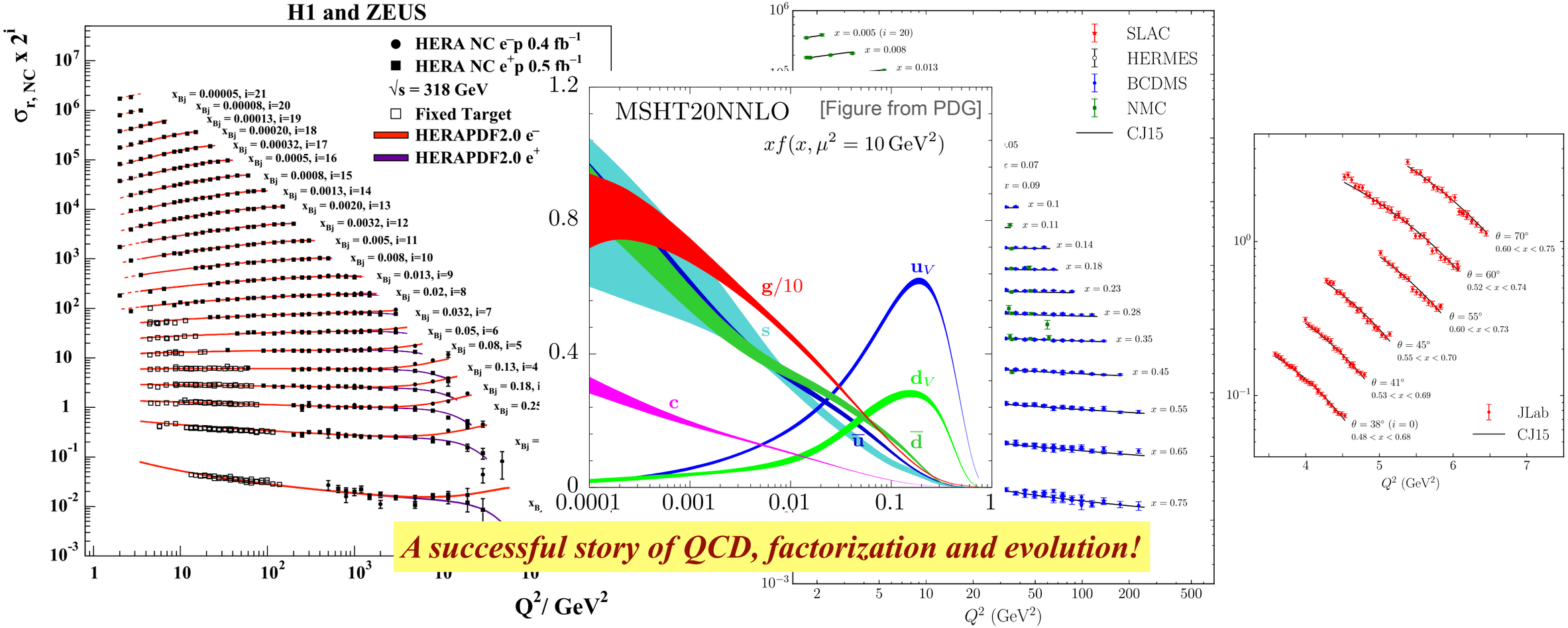


H. Abramowicz *et al.*, EPJC 78, 580 (2015).



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

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

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

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

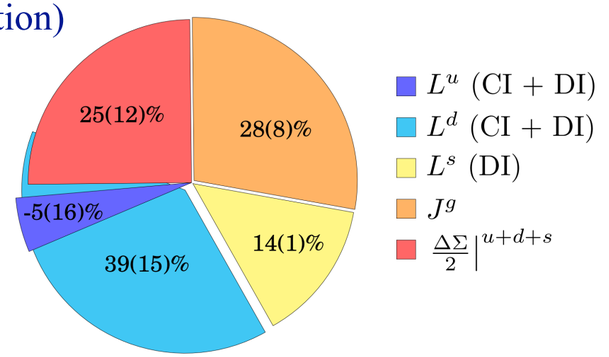
Spin decomposition

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

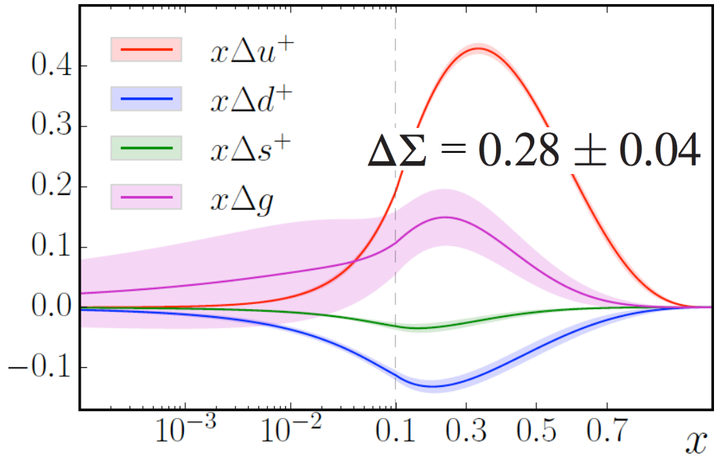
$$= \frac{1}{2}\Delta\Sigma + L_{q,\text{kin}} + J_g$$

R.L. Jaffe, A. Manohar, NPB 337, 509 (1990).
X. Ji, PRL 78, 610 (1997).

Lattice QCD
(kinetic decomposition)



χQCD Collaboration, PRD 91, 014505 (2015).



JAM Collaboration, PRD 93, 074005 (2016); PRL 119, 132001 (2017).

Gluon spin from LQCD:

$$S_g = 0.251(47)(16)$$

50% of total proton spin

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

Wigner Rotation Effect

Melosh-Wigner rotation

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

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

$$\chi_T^{\uparrow} = w\left[\left(k^+ + m\right)\chi_F^{\uparrow} - \left(k^1 + ik^2\right)\chi_F^{\downarrow}\right] \qquad k^+ = k^0 + k^3$$

$$\chi_T^{\downarrow} = w\left[\left(k^+ + m\right)\chi_F^{\downarrow} + \left(k^1 - ik^2\right)\chi_F^{\uparrow}\right] \qquad w = \left[2k^+\left(k^0 + m\right)\right]^{-1/2}$$

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

The effect on quark polarization

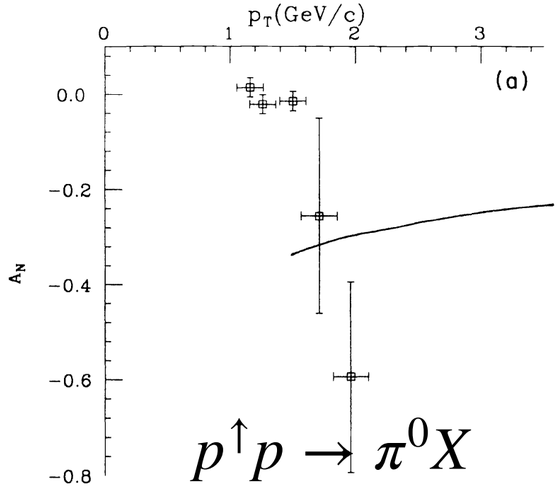
$$\Delta q = \int \mathrm{d}^3\mathbf{k}\mathscr{M}\left[q^{\uparrow}(k) - q^{\downarrow}(k)\right] \qquad \mathscr{M} = \frac{(k^+ + m)^2 - k_T^2}{2k^+(k^0 + m)}$$

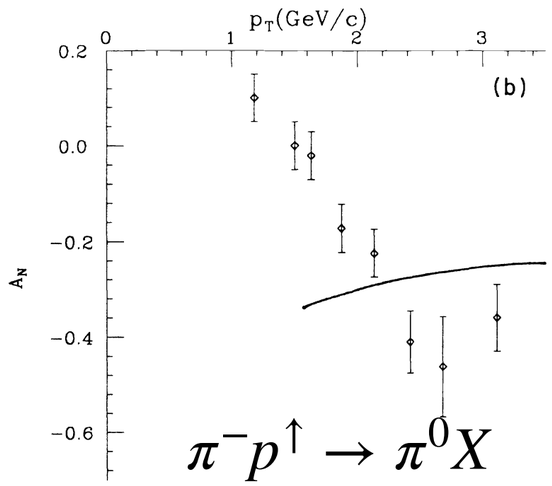
B.-Q. Ma, J. Phys. G 17 (1991) L53-L58; B.-Q. Ma, Q.-R. Zhang, Z. Phys. C 58 (1993) 479.

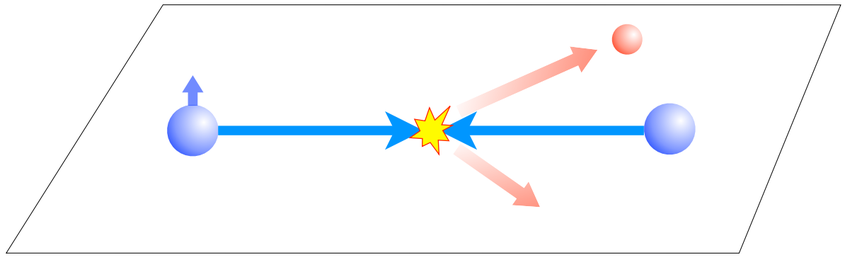
It predicts decreasing polarization with k_T, which should be tested by data.
This interpretation is based on a kinetic boost, but a complete boost including QCD dynamics is challenging.

Transverse Single Spin Asymmetry: 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.

Transverse Single Spin Asymmetry: Early Story

Until an explicit model calculation showing …

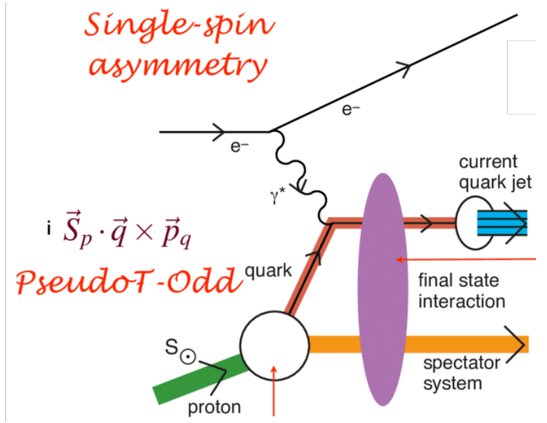
Nonzero Sivers effects exist at leading twist due to final-state interactions

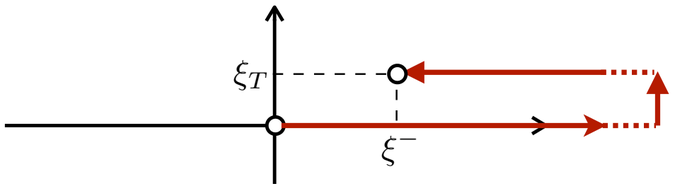
S.J. Brodsky, D.S. Hwang, I. Schmidt, Phys. Lett. B 530 (2002) 99.

Sivers function can exist due to nontrivial gauge link

$$\Phi_{ij}\left(x,p_T\right)=\int\frac{\mathrm{d}\xi^-\mathrm{d}^2\xi_T}{(2\pi)^3}e^{ip\cdot\xi}\langle P\,|\,\bar{\psi}_j(0)\mathcal{U}^{n_-}_{(0,+\infty)}\mathcal{U}^{n_-}_{(+\infty,\xi)}\psi_i(\xi)\,|\,P\rangle\Big|_{\xi^+=0}$$

J.C. Collins, Phys. Lett. B 536 (2002) 43.





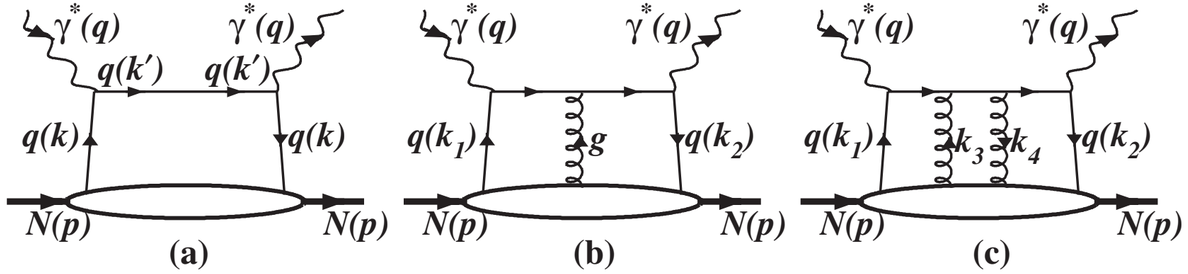
[Figure from A. Bacchetta]

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

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

Collinear expansion

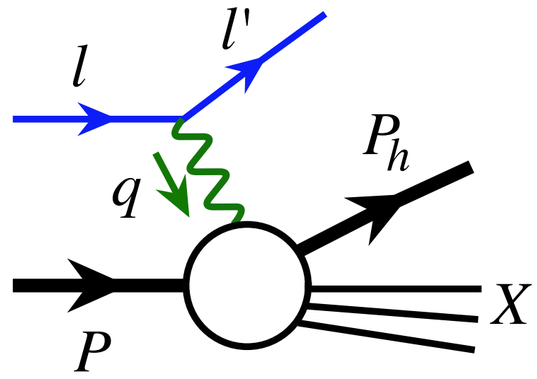
Z.T. Liang and X.N. Wang, Phys. Rev. D 75 (2007) 094002.

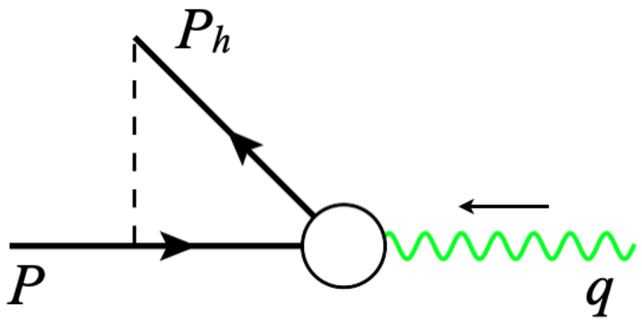


Semi-inclusive Deep Inelastic Scattering

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

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

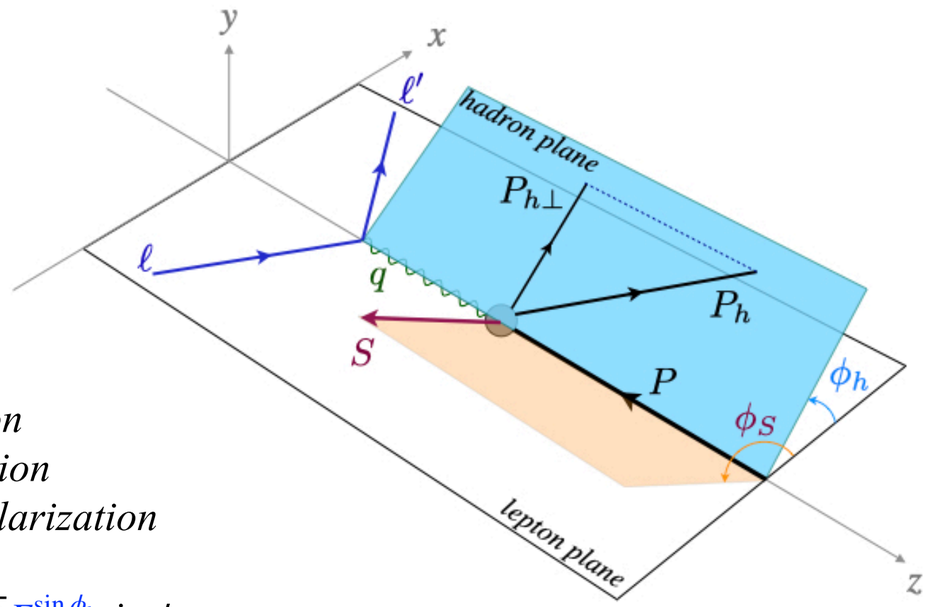




Semi-inclusive Deep Inelastic Scattering

SIDIS process

$$l + N \to l' + h + X$$



Differential cross section
in terms of 18 structure functions

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{hT}^2\,\mathrm{d}\phi_h\,\mathrm{d}\phi_S} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)$$

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

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

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

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

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

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

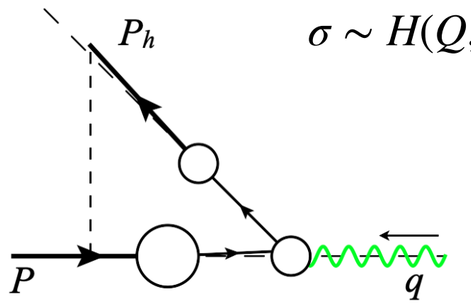
$$F_{AB,C}(x_B, z, P_{hT}^2, Q^2)$$

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

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

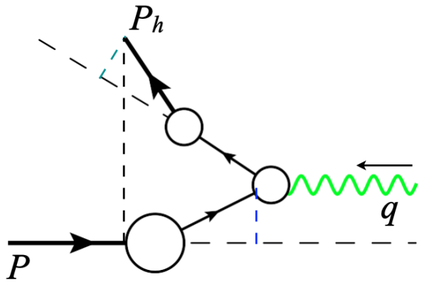
SIDIS Kinematic Regions

Sketch of kinematic regions of the produced hadron



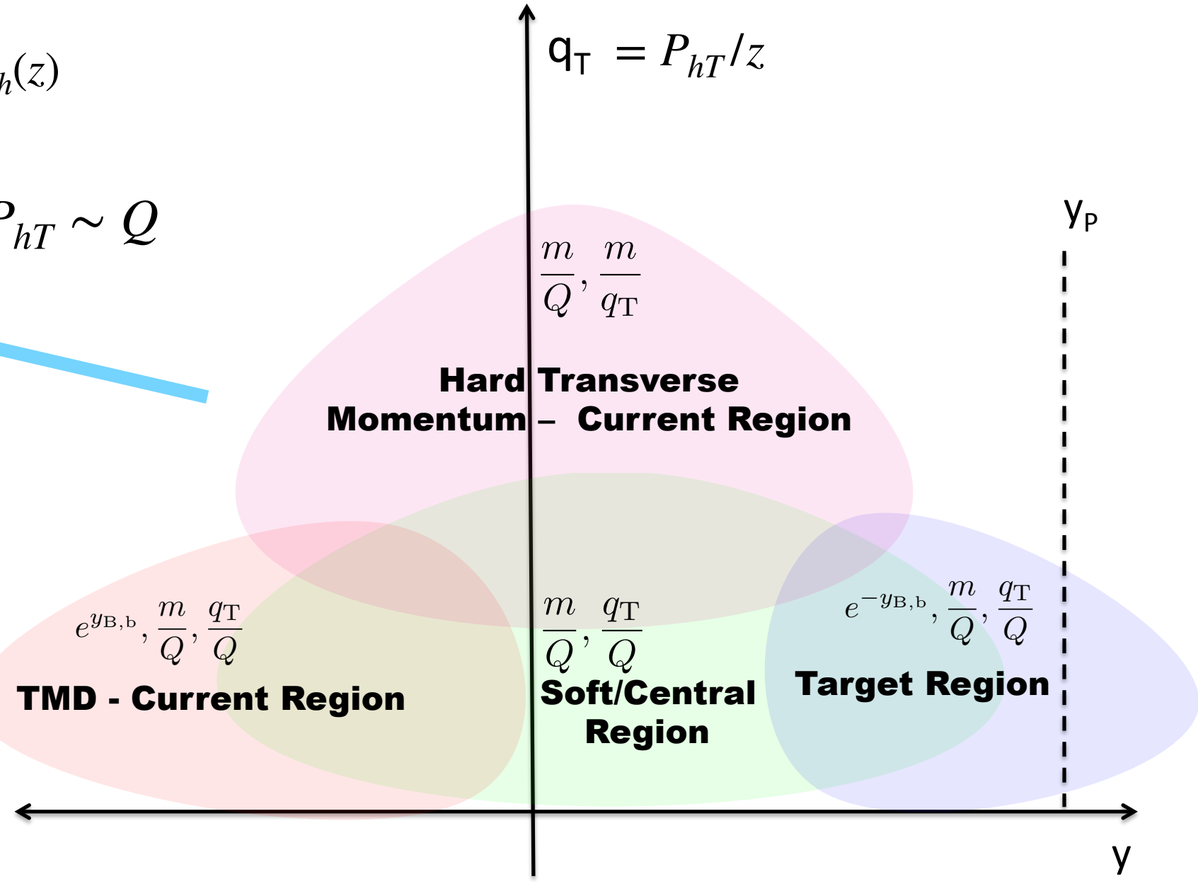
$$\sigma \sim H(Q, P_{hT}) \otimes f_{i/P}(x) \otimes D_{j\to h}(z)$$

$$P_{hT} \sim Q$$



$$P_{hT} \ll Q$$

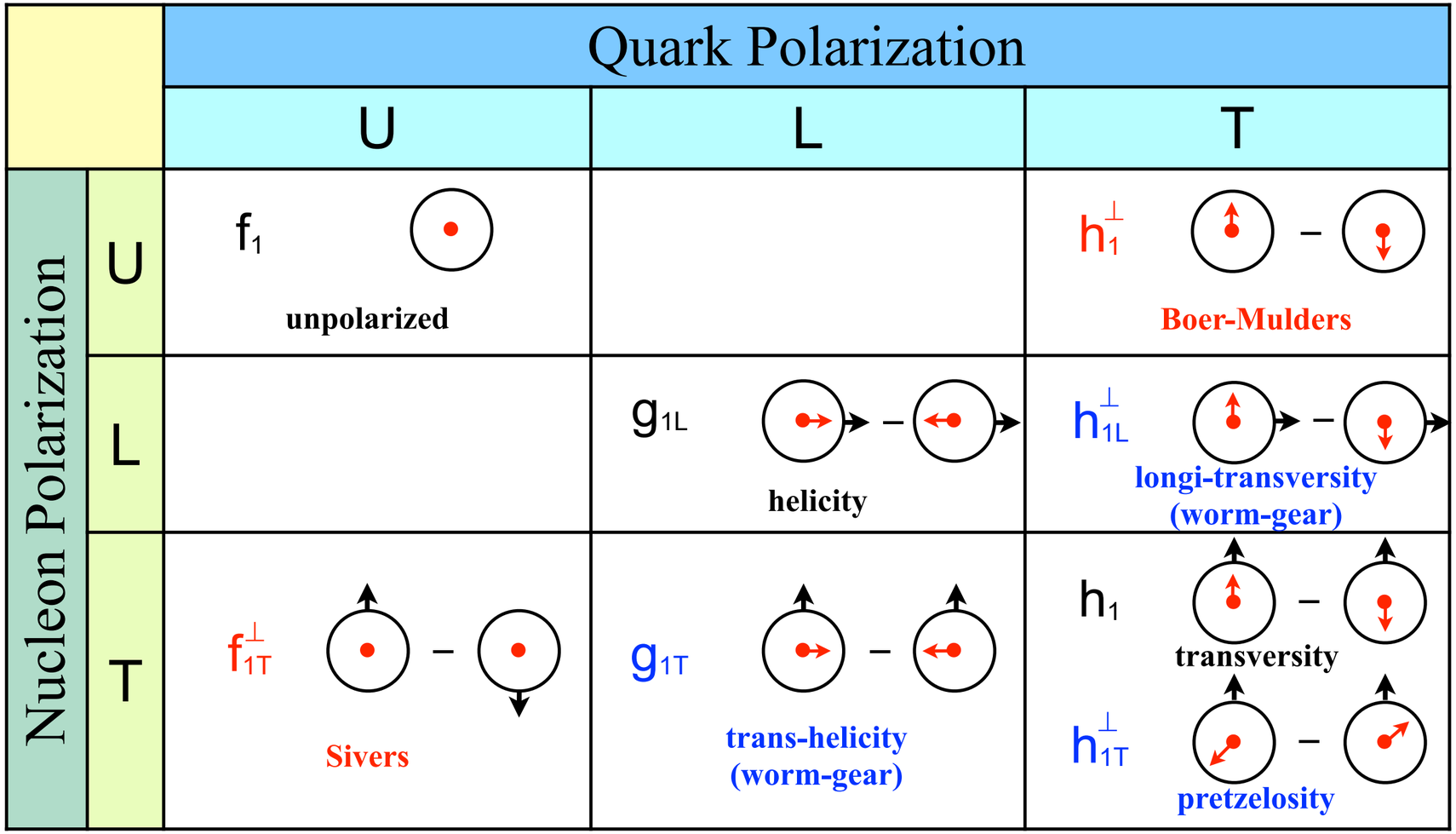
$$\sigma \sim H(Q) \otimes f_{i/P}(x, k_T) \otimes D_{j\to h}(z, p_T)$$



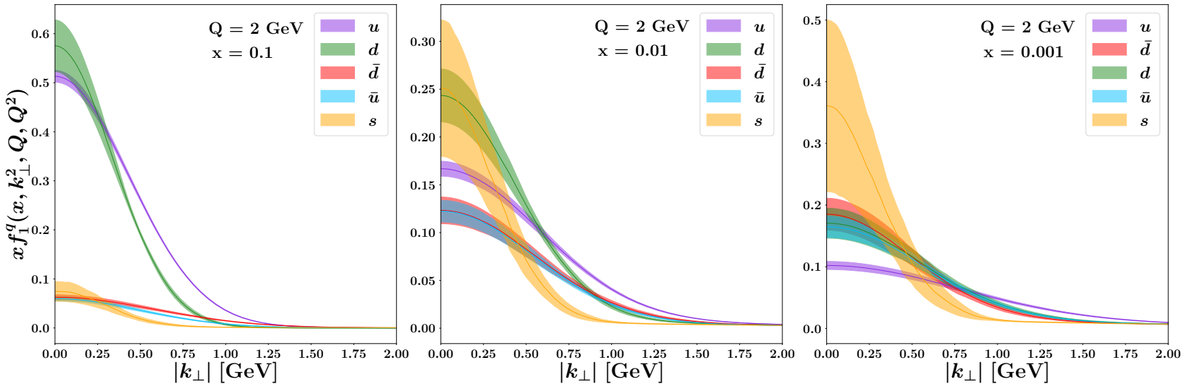
P_{hT} is defined in the photon-hadron frame

[Figure from JHEP10(2019)122]

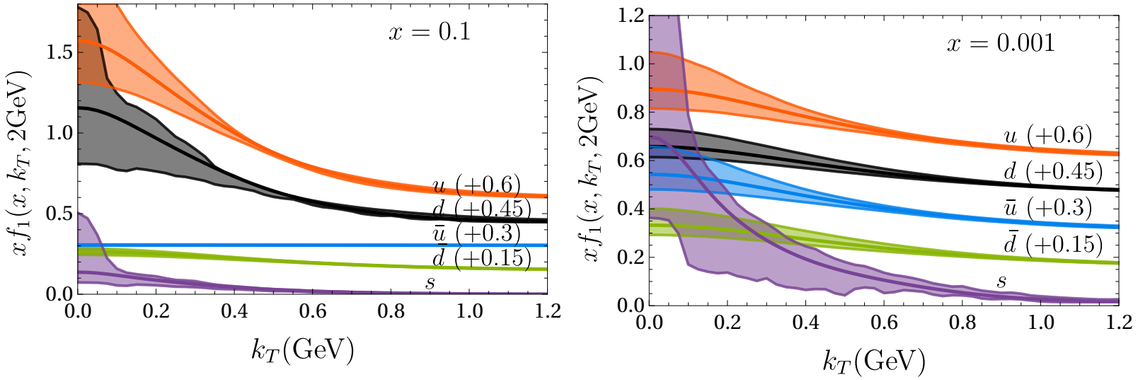
Leading Twist TMD PDFs



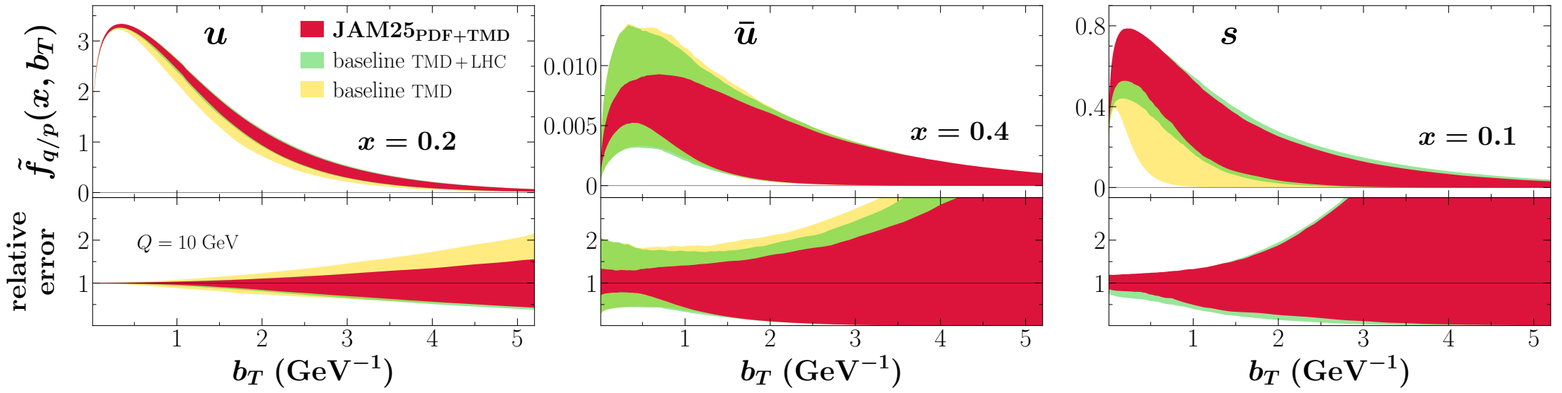
Unpolarized TMD PDFs



A. Bacchetta *et al.* (MAP Collaboration), JHEP 08 (2024) 232.



V. Moos, I. Scimemi, A. Vladimirov, P. Zurita, JHEP 11 (2025) 134.



P.C. Barry *et al.* (JAM Collaboration), PRL 137 (2026) 171902.

Longitudinal Double Spin Asymmetry

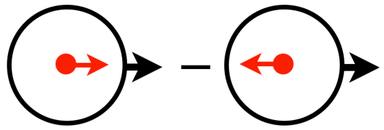
Longitudinal DSA in SIDIS

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

In TMD region:

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

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

g_{1L} 

(both collinear and TMD)

Several global analyses of collinear helicity
but TMD helicity was missing for a long time!

P_{hT} dependent DSA measurements

JLab CLAS: proton (NH_3) target — CLAS Collaboration, Phys. Lett. B 782 (2018) 662.

COMPASS: deuteron (D_2) targets — COMPASS Collaboration, Eur. Phys. J. C 78 (2018) 952.

HERMES: proton (H_2) and deuteron (D_2) targets — HERMES Collaboration, Phys. Rev. D 99 (2019) 112001.

Experimental Data Sets

SIDIS Longitudinal DSA data:

Collaboration	Lepton beam	Target	Detected hadron	Data points
HERMES	27.6 GeV $e^{\pm}$	H_2	π^+	80
			π^-	80
		D_2	π^+	80
			π^-	80
			K^+	79
			K^-	78
CLAS	6 GeV e^-		π^0	21

Target and hadron mass corrections:

$$x_S \equiv -\frac{q^+}{P^+} = \frac{2x}{\gamma^2}\left[\sqrt{1+\gamma^2\left(\frac{q_T^2}{Q^2}\right)}-1\right] \qquad z_S \equiv \frac{P_h^-}{q^-} = z\frac{x_S}{x}\frac{1+\sqrt{1-\varsigma^2}}{2\left(1-q_T^2/Q^2\right)} \qquad \varsigma = \frac{\gamma M_h}{zQ}$$

Low transverse momentum selection: $\delta = \frac{q_T}{Q} < 0.5$

TMD Evolution

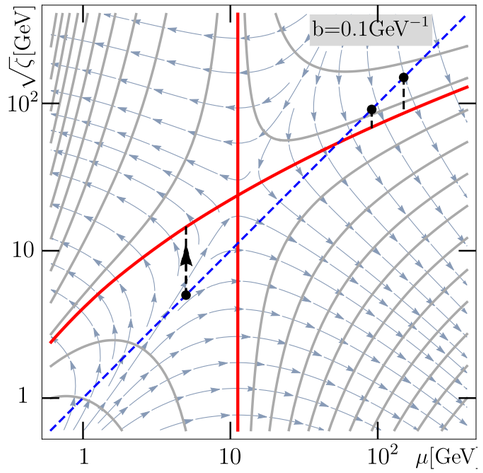
Evolution equations

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

$$\zeta\frac{dF(x,b;\mu^2,\zeta)}{d\zeta}=-\mathscr{D}(\mu,b)F(x,b;\mu^2,\zeta) \qquad \gamma_F(\mu,\zeta)=\Gamma_{\rm cusp}(\mu)\ \ln\frac{\mu^2}{\zeta}-\gamma_V(\mu)$$

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

ζ-prescription



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

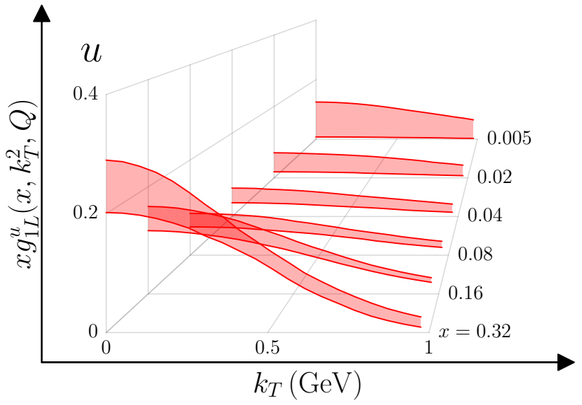
equipotential lines: $\dfrac{d\ln\zeta_\mu(\mu,b)}{d\ln\mu^2}=\dfrac{\gamma_F\left(\mu,\zeta_\mu(\mu,b)\right)}{2\mathscr{D}(\mu,b)}$

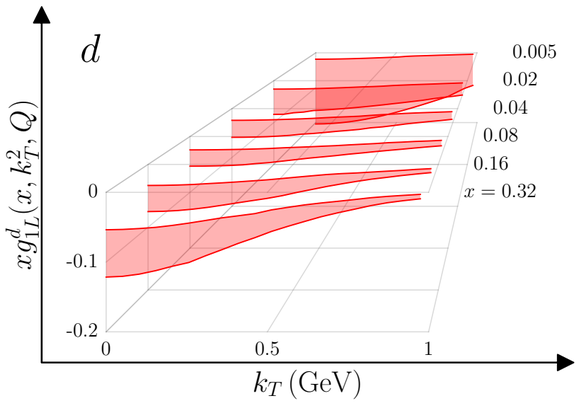
$$\mathscr{D}\left(\mu_0,b\right)=0,\quad \gamma_F\left(\mu_0,\zeta_\mu\left(\mu_0,b\right)\right)=0$$

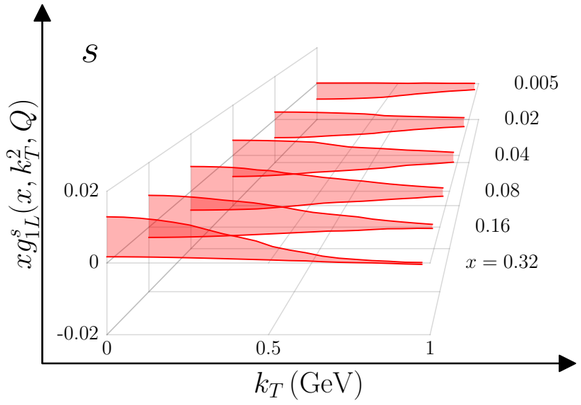
$$F\left(x,b;Q,Q^2\right)=\left(\frac{Q^2}{\zeta_Q(b)}\right)^{-\mathscr{D}(Q,b)}F(x,b),\quad \mu_f^2=\zeta_f=Q^2$$

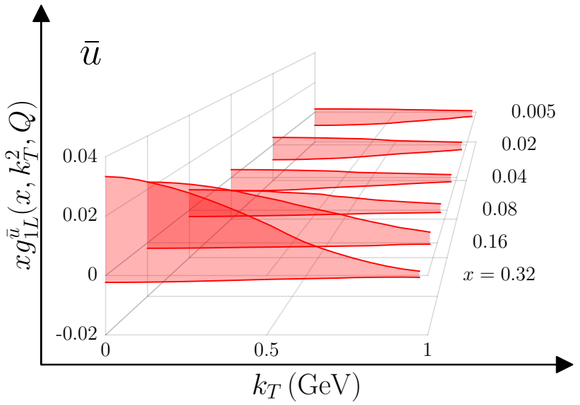
Extracted TMD Helicity Distributions

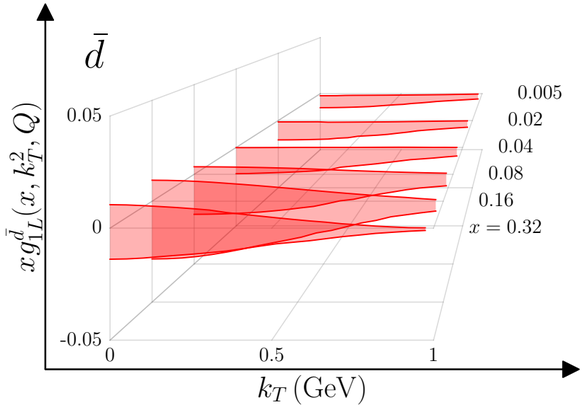
NNLO+NNLL

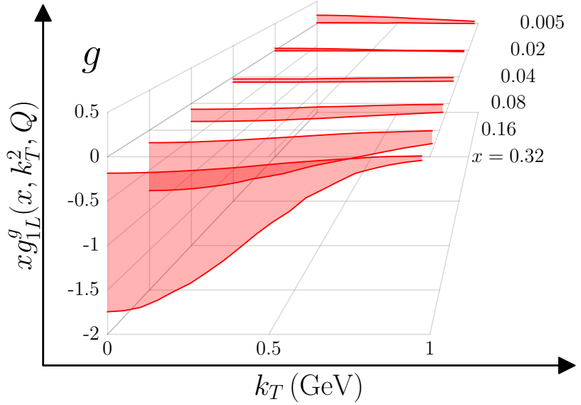












K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902;

updated analysis: K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

Transverse Momentum Dependent Polarization

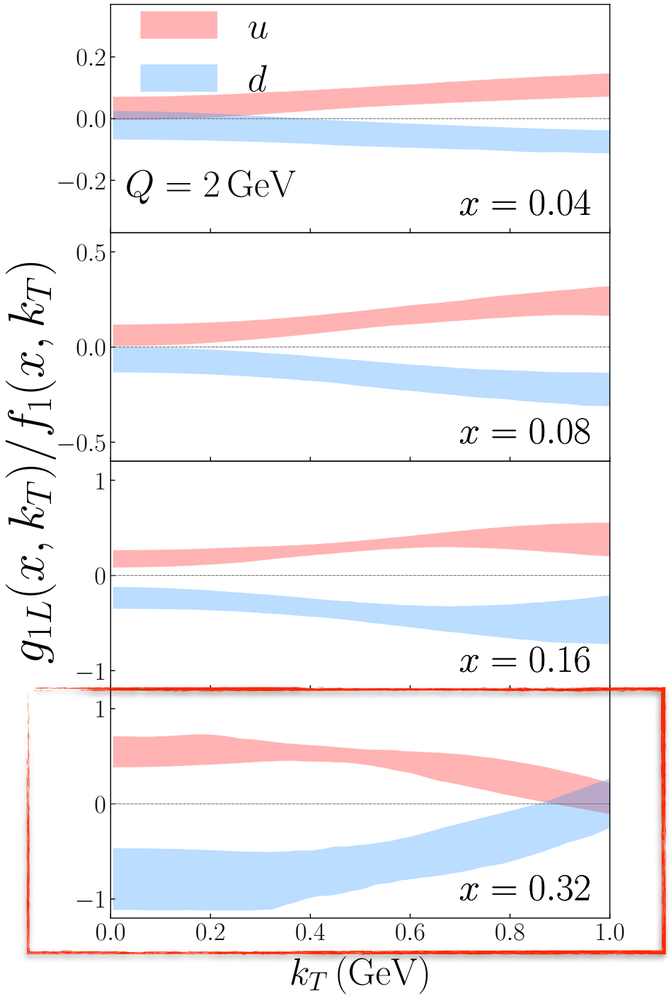
$g_{1L}(x, k_T^2)$ gives the absolute number density difference between spin-parallel and spin-antiparallel quarks.

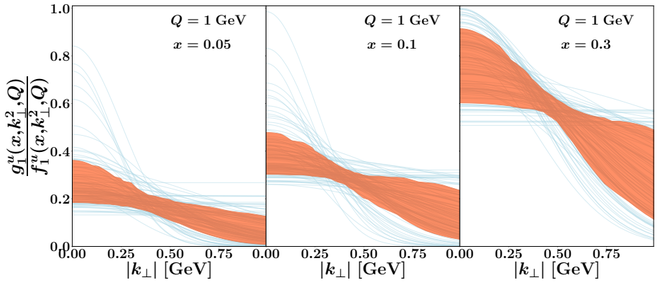
The ratio $g_{1L}(x, k_T^2)/f_1(x, k_T^2)$ measures the polarization rate of quarks.

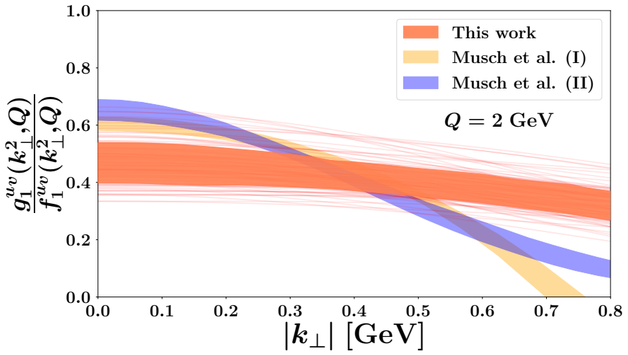
- At large x, where valence components dominate, the polarization decreases with increasing k_T
  Qualitatively consistent with kinetic Wigner rotation effects
- At low x, where the valence component is no longer adequate, distributions are highly driven by complex QCD dynamics

K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. Lett. 134 (2025) 121902; arXiv:2409.08110.

updated analysis: K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

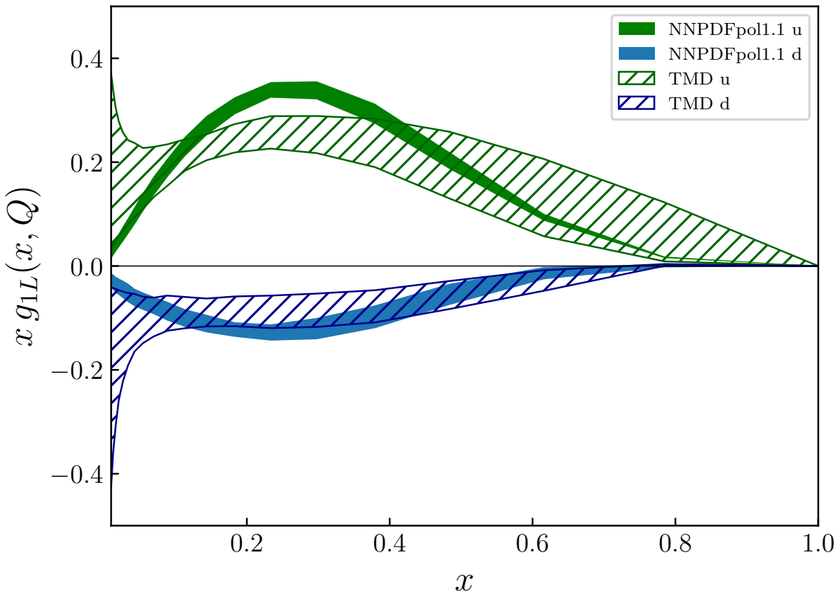


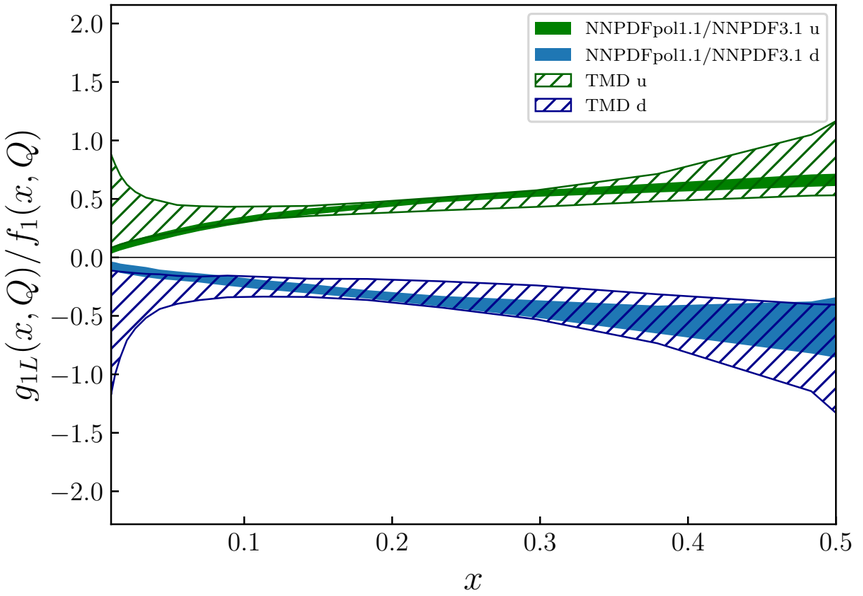




A. Bacchetta *et al.* (MAP Collaboration), Phys. Rev. Lett. 134 (2025) 121901; arXiv:2409.18078.

TMD vs. Collinear Helicity Distributions

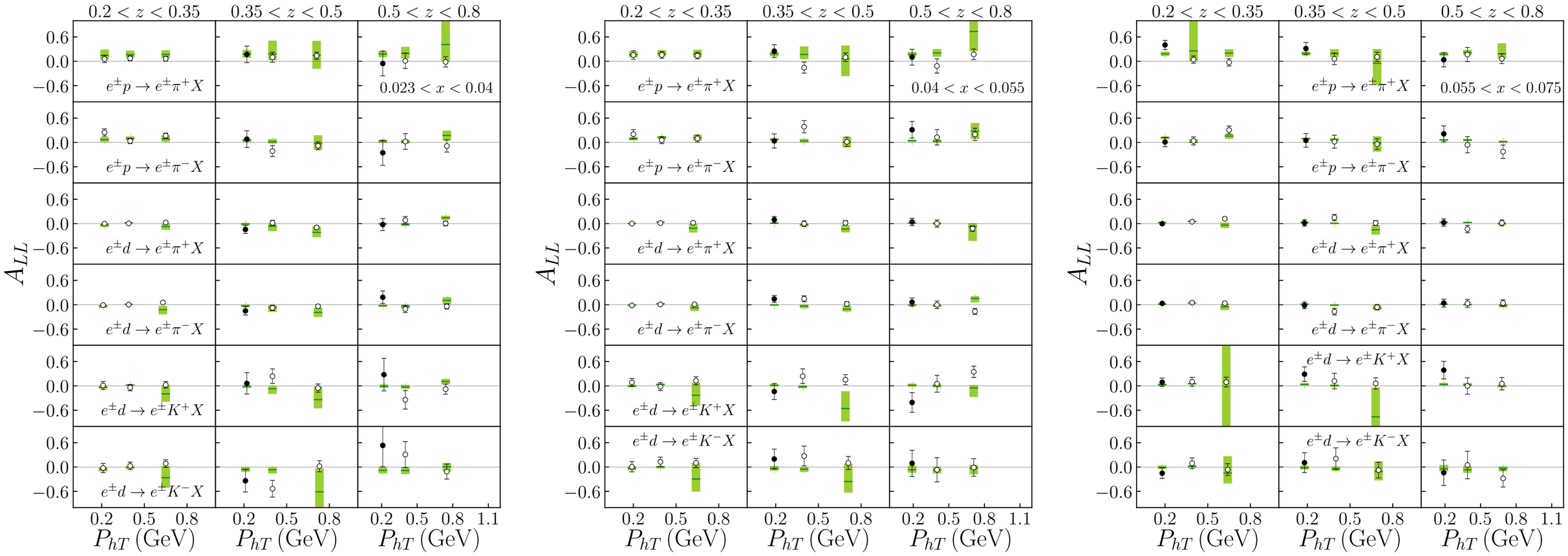




Transverse momentum integrated distributions: $g_{1L}(x,Q) = \pi \int_0^{Q^2} \mathrm{d}k_T^2\; g_{1L}\left(x, k_T^2, Q, Q^2\right)$

K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

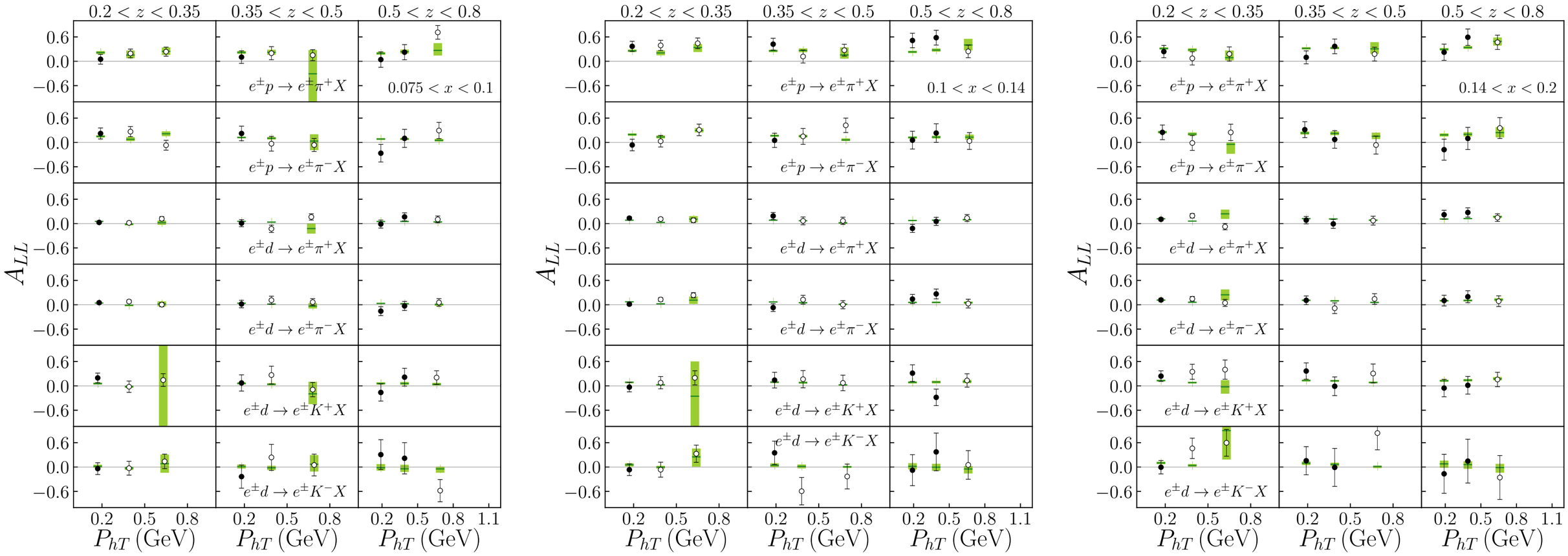
Comparison with Data



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

K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

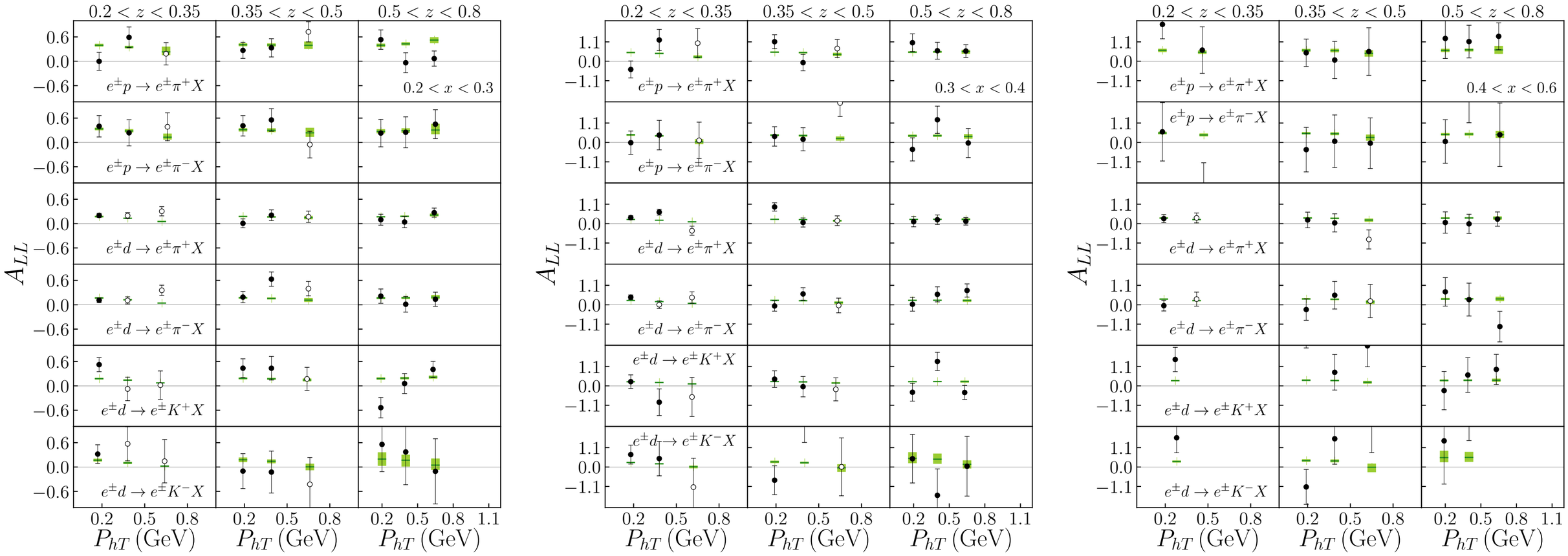
Comparison with Data



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

K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

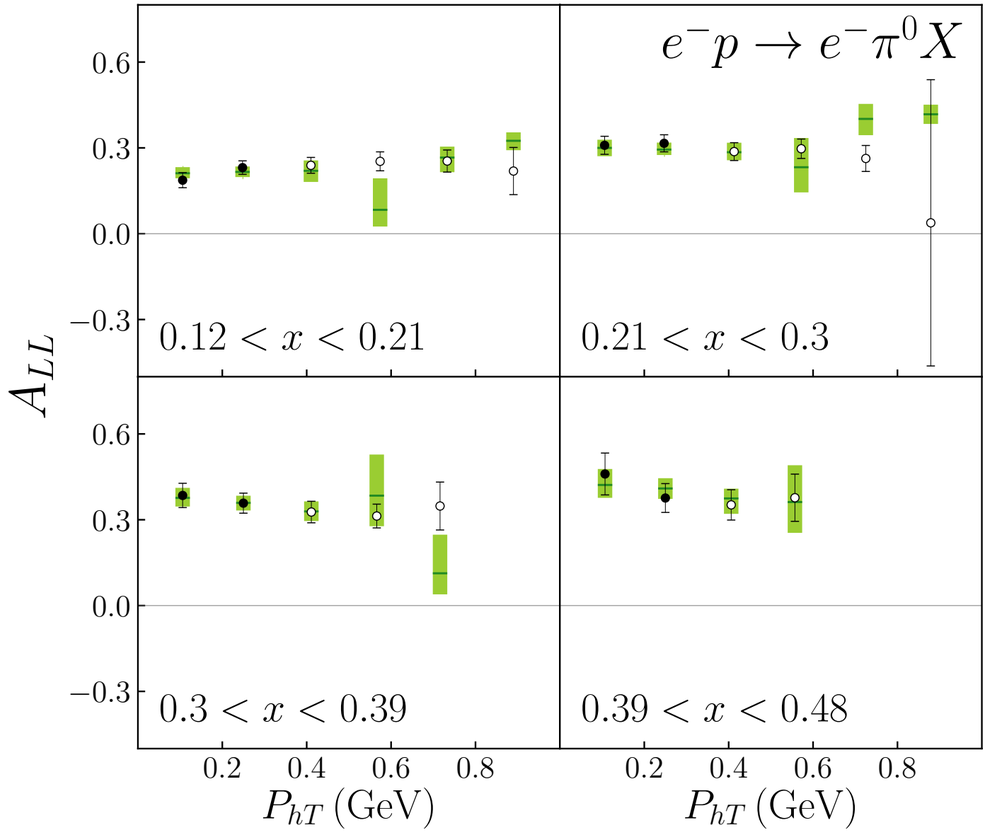
Comparison with Data



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

K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

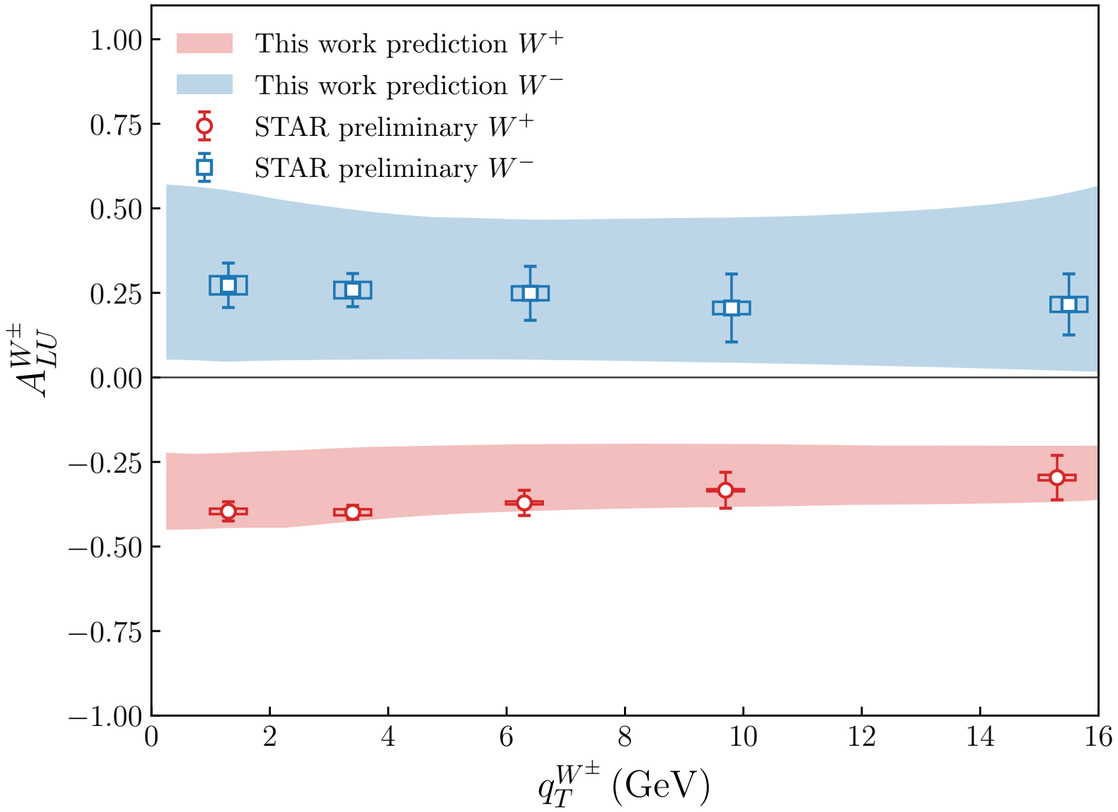
Comparison with Data



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

K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

Prediction of $W^{\pm}$ SSA $A_{LU}^{W^{\pm}}$ in pp Collisions



Uncertainty bands propagated from extracted TMD helicity from SIDIS.

K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

Azimuthal Modulation of Longitudinal DSA

Azimuthal modulation of A_{LL} in SIDIS

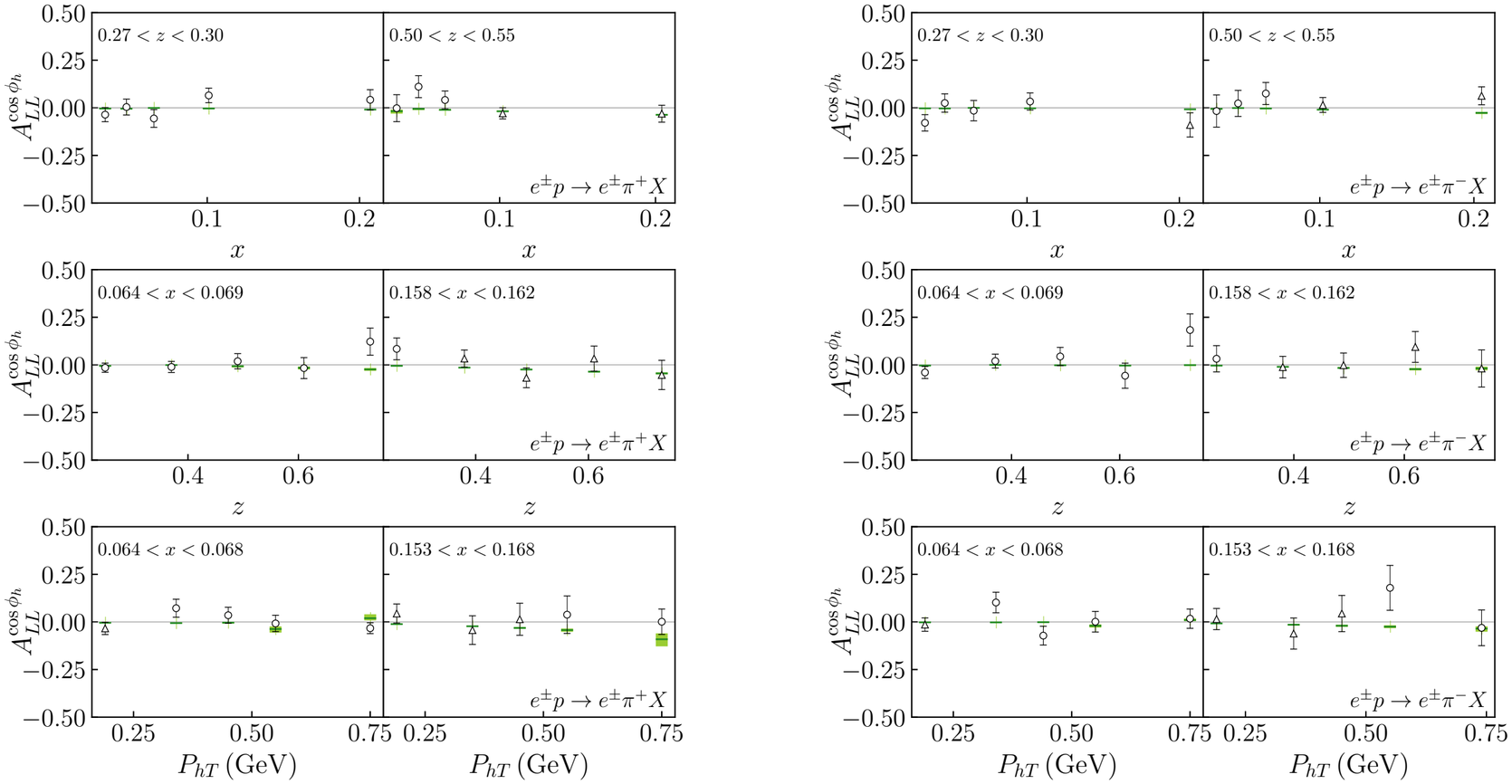
$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\Bigg\{ -z^2 M_h \mathscr{B}_1\left[xe_L, H_1^{\perp(1)}\right] + \frac{z^2 M_h^2}{M}\mathscr{B}_1\left[g_{1L}, \frac{\tilde{D}^{\perp(1)}}{z}\right]$$
$$-M\mathscr{B}_1\left[xg_L^{\perp(1)}, D_1\right] - M_h\mathscr{B}_1\left[h_{1L}^{\perp(1)}, \frac{\tilde{E}}{z}\right]\Bigg\}$$

up to subleading power in $1/Q$

Relation from QCD equation of motion: $xg_L^{\perp} = x\tilde{g}_L^{\perp} + g_{1L} + \frac{m}{M}h_{1L}^{\perp}$

Neglecting twist-three contributions (Wandzura-Wilczek approximation): $F_{LL}^{\cos\phi_h} \approx -\frac{2M^2}{Q}\mathscr{B}_1\left[g_{1L}^{(1)}, D_1\right]$

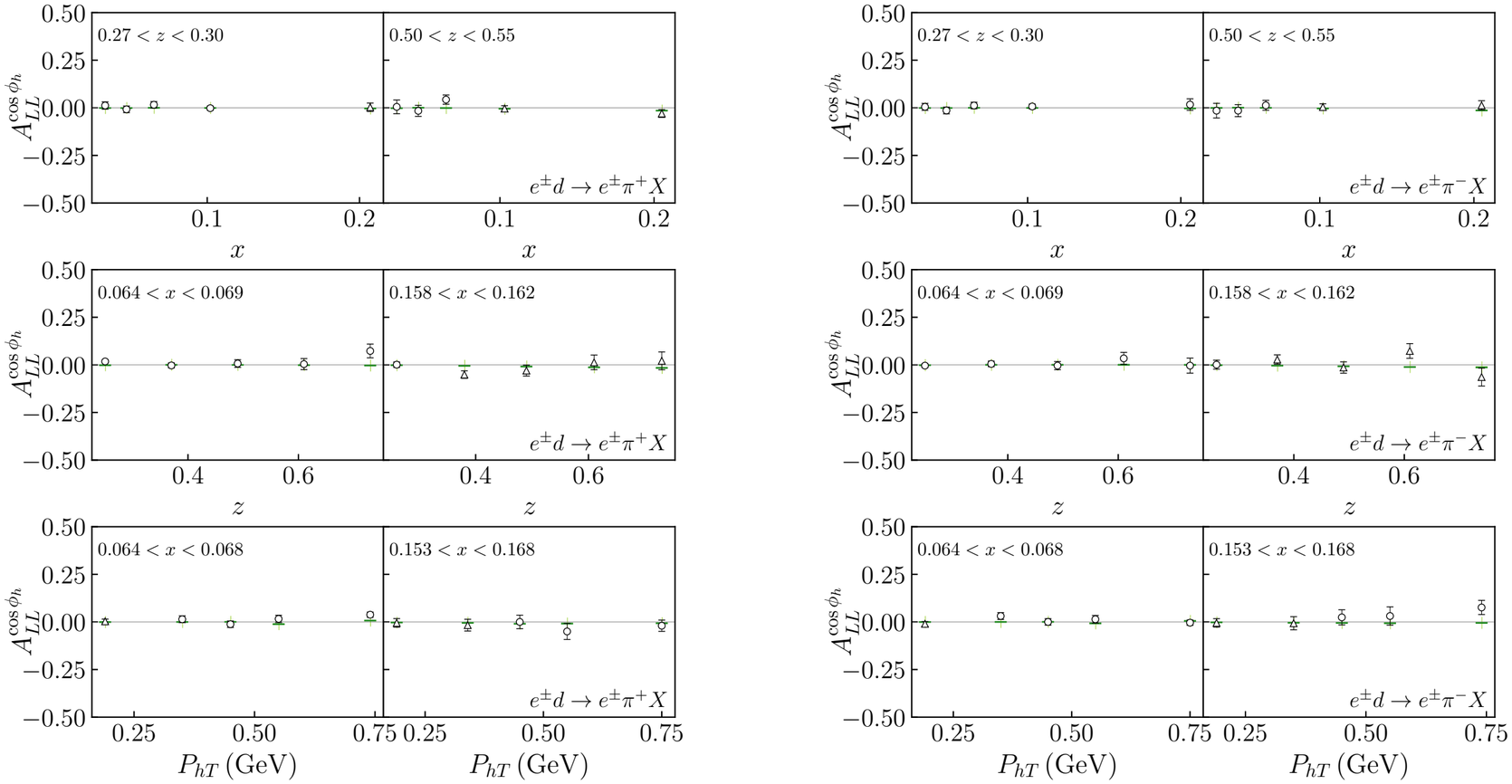
Comparison with $A_{LL}^{\cos\phi_h}$ Data



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

K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

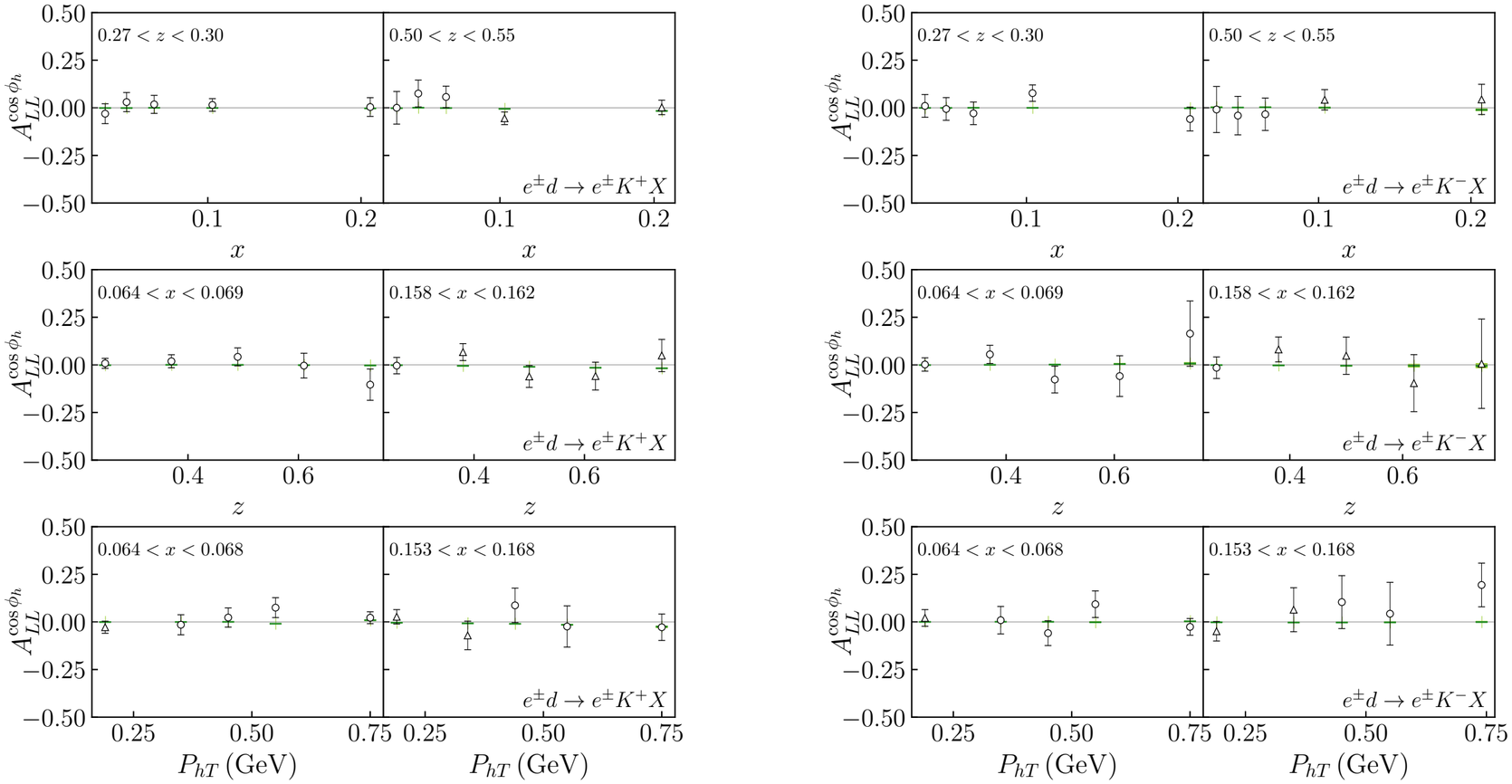
Comparison with $A_{LL}^{\cos\phi_h}$ Data



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

K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

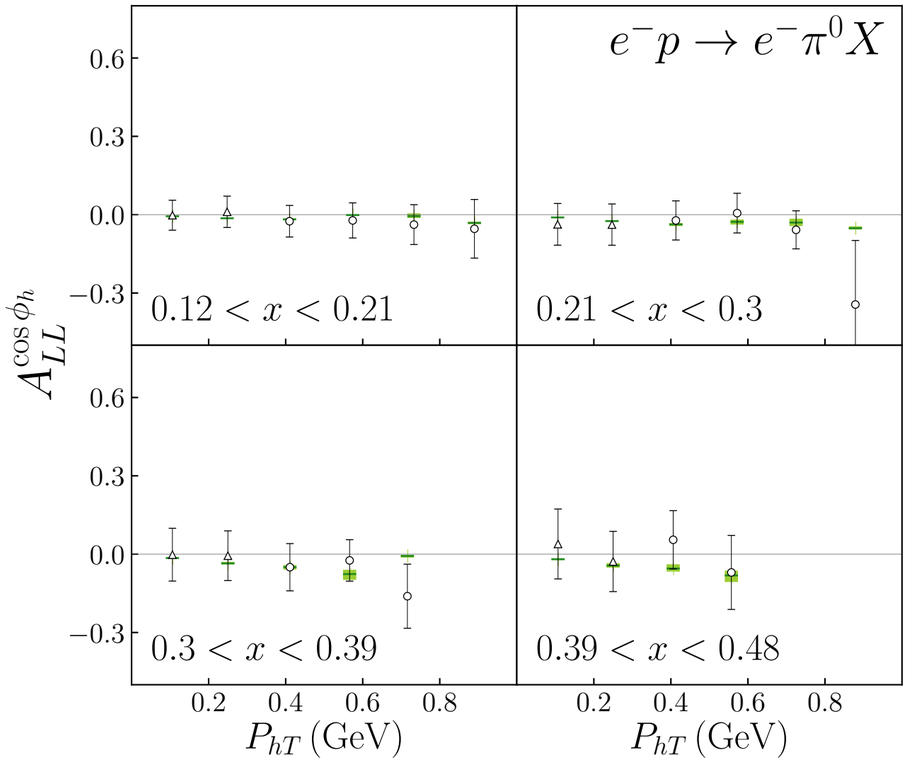
Comparison with $A_{LL}^{\cos\phi_h}$ Data



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

K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

Comparison with $A_{LL}^{\cos\phi_h}$ Data

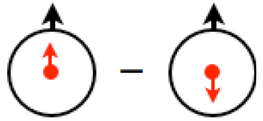


Data: CLAS Collaboration, Phys. Lett. B 782 (2018) 662.

K. Yang, TL, B.-Q. Ma, P. Sun, Y. Zhao, Y. Zhou, arXiv:2610.31290.

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:

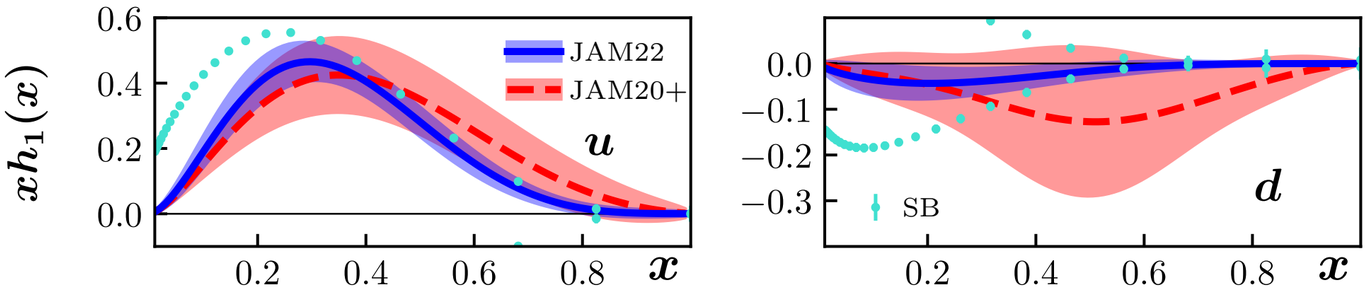
No mixing with gluons
Valence dominant
Couple to another chiral-odd function.

Effect in SIDIS:

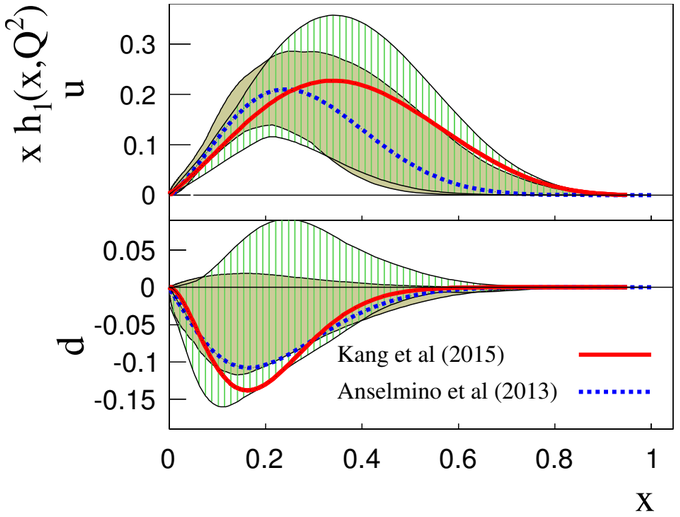
transverse single spin asymmetry (Collins asymmetry)

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

Phenomenological extractions



JAM Collaboration, PRD 106, 034014 (2022).



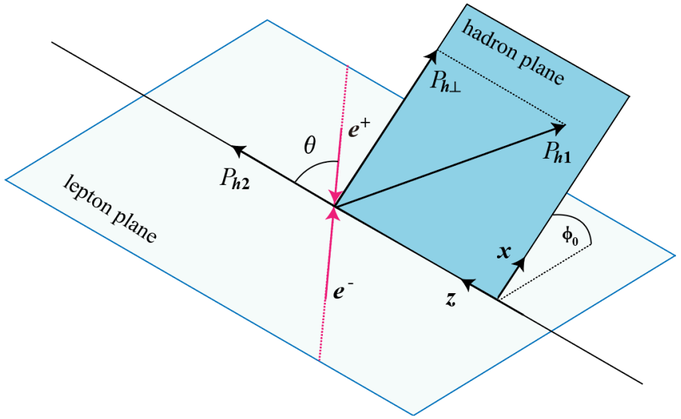
Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, PRD 93, 014009 (2016).

Assuming vanishing transverse polarization of sea quarks in early analysis!

Complementary Process

Semi-inclusive e^+e^- annihilation:

$$e^+e^- \to h_1 h_2 X$$



$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}z_1\,\mathrm{d}z_2\,\mathrm{d}^2\boldsymbol{P}_{h\perp}\,\mathrm{d}\cos\theta} = \frac{3\pi\alpha^2}{2Q^2} z_1^2 z_2^2 \left[\left(1+\cos^2\theta\right) F_{UU}^{h_1 h_2} + \sin^2\theta \cos\left(2\phi_0\right) F_{\text{Collins}}^{h_1 h_2} \right]$$

In TMD region: h_1 and h_2 are near back-to-back, $P_{hT} \ll Q$

$$F_{\text{Collins}}^{h_1 h_2} \sim H_1^{\perp h_1} \otimes H_1^{\perp h_2}$$

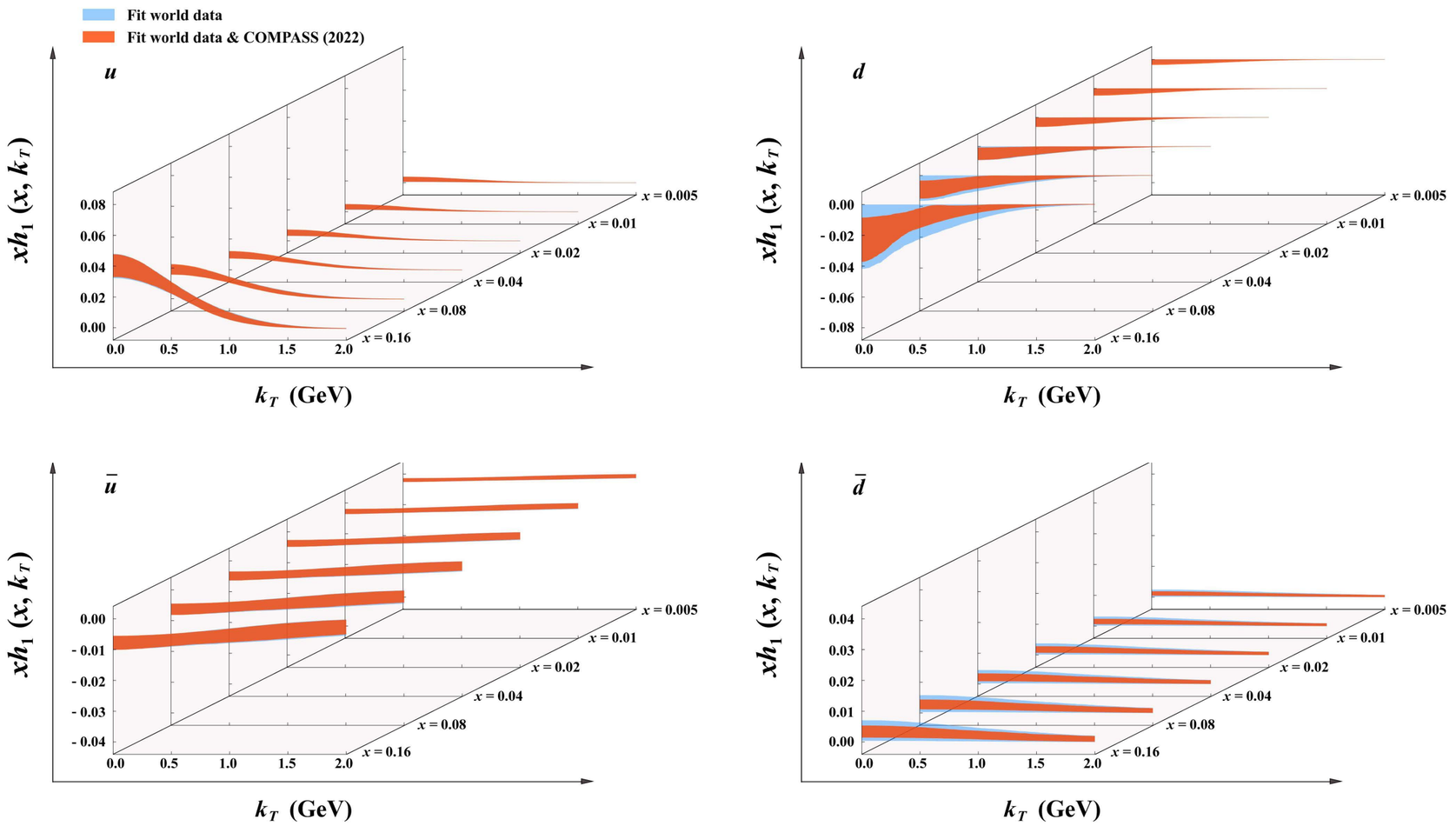
Experimental measurements:

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.

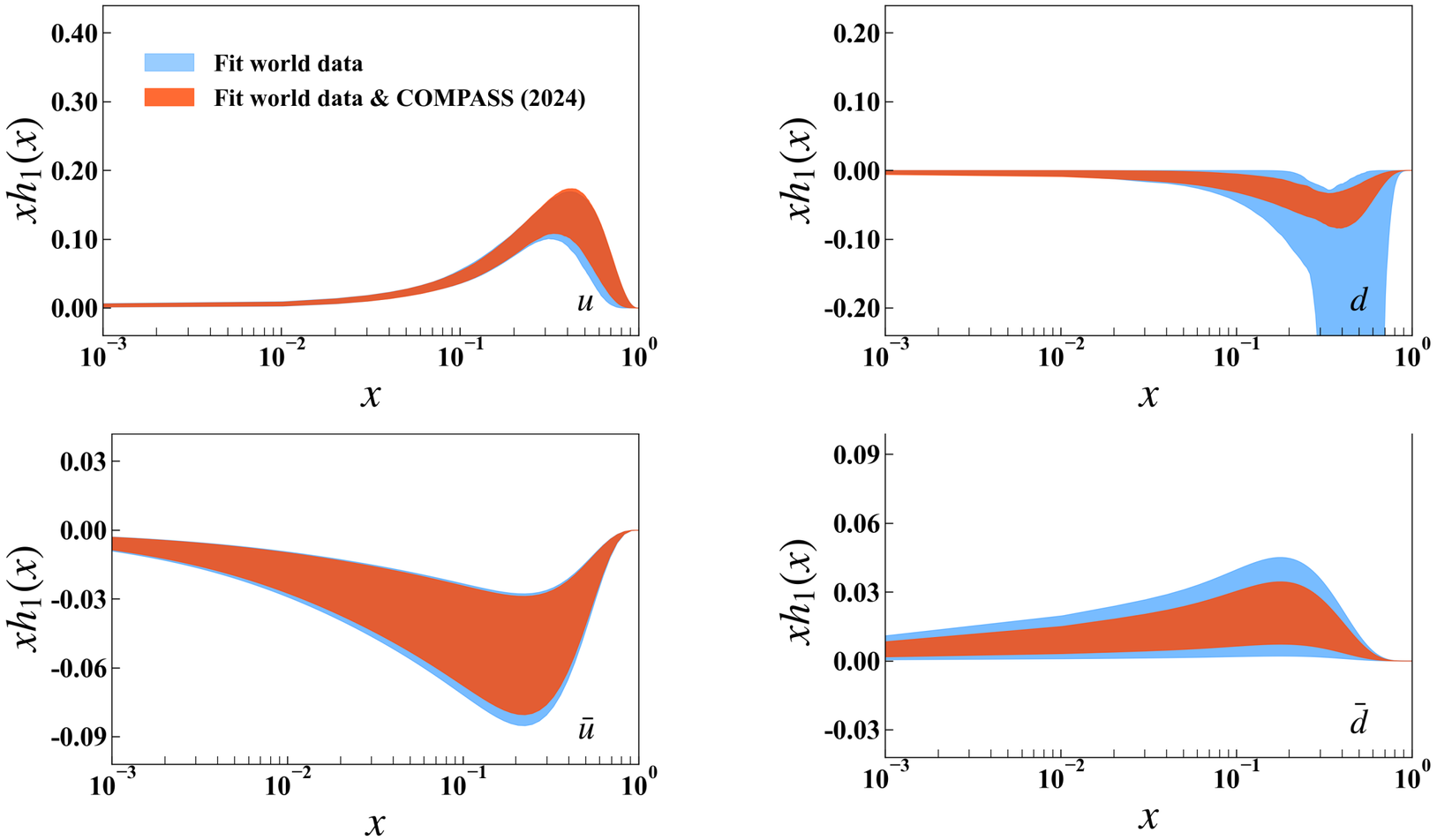
BESIII: $\sqrt{s} = 3.68\ \text{GeV}$ Phys. Rev. Lett. 116 (2016) 042001.

Transversity Distributions



C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, PRD 109 (2024) 056002; arXiv:2412.18324.

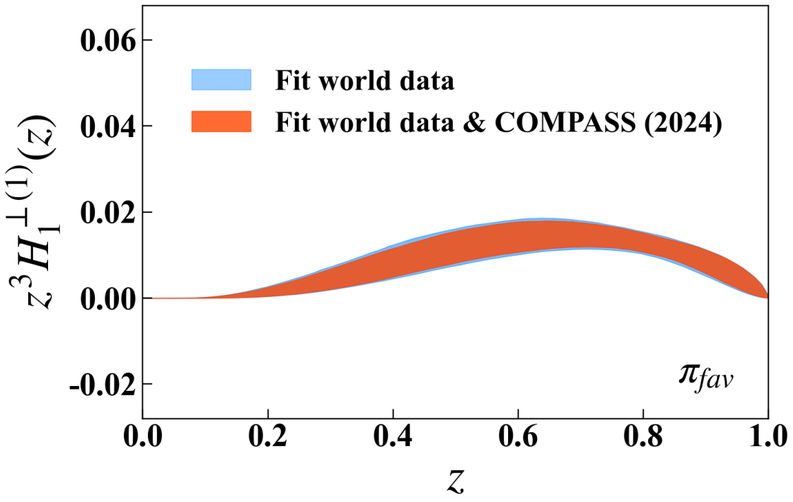
Transversity Distributions

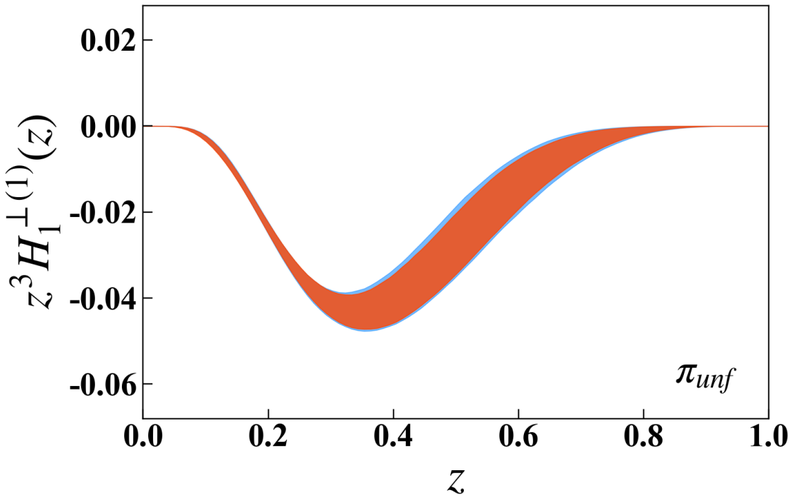


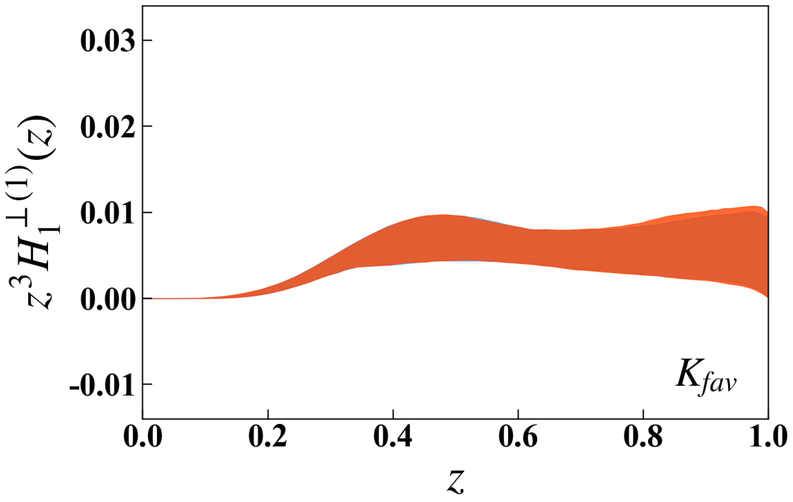
Find $\bar{u}$ favors *negative* transverse polarization

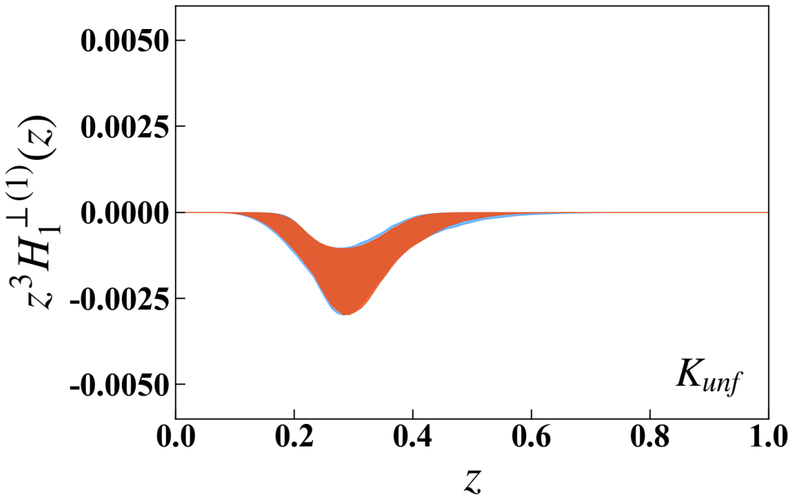
C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, PRD 109 (2024) 056002; arXiv:2412.18324.

Collins Fragmentation Functions









C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, PRD 109 (2024) 056002; arXiv:2412.18324.

Collinear Transversity Distributions in Dihadron SIDIS

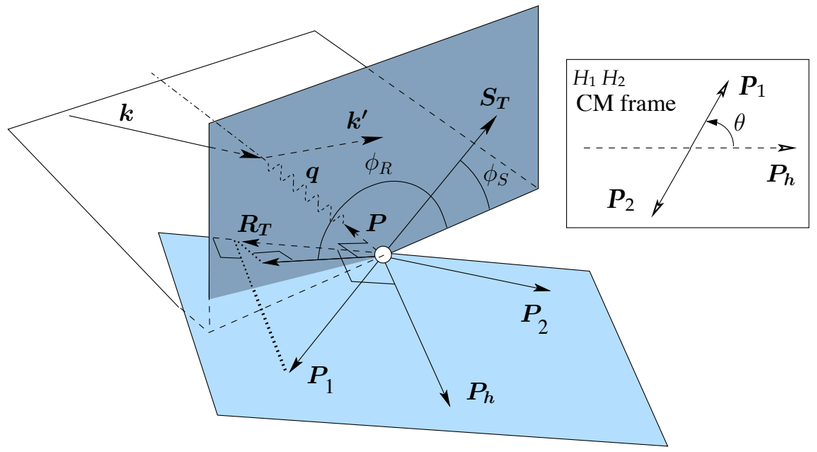
Dihadron SIDIS

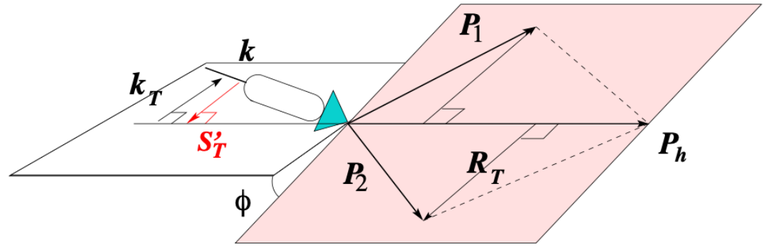
$$l + N \to l' + h_1 h_2 + X$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}\phi_S\,\mathrm{d}z\,\mathrm{d}\phi_R\,\mathrm{d}M_h^2\,\mathrm{d}\cos\theta} =$$

$$\frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\left\{F_{UU} + S_T\,\varepsilon\,\sin(\phi_R+\phi_S)F_{UT}^{\sin(\phi_R+\phi_S)}\right\}$$

$$F_{UT}^{\sin(\phi_R+\phi_S)} \sim h_1 \otimes H_1^{\sphericalangle}$$





h_1: collinear transversity distribution function

$H_1^{\sphericalangle}$: a chiral-odd dihadron fragmentation function

describing the correlation between quark transverse polarization and the azimuthal orientation of the hadron pair plane

M. Radici, R. Jakob, and A. Bianconi, Phys. Rev. D 65 (2002) 074031;
A. Bacchetta, A. Courtoy, M. Radici, JHEP 03 (2013) 119.

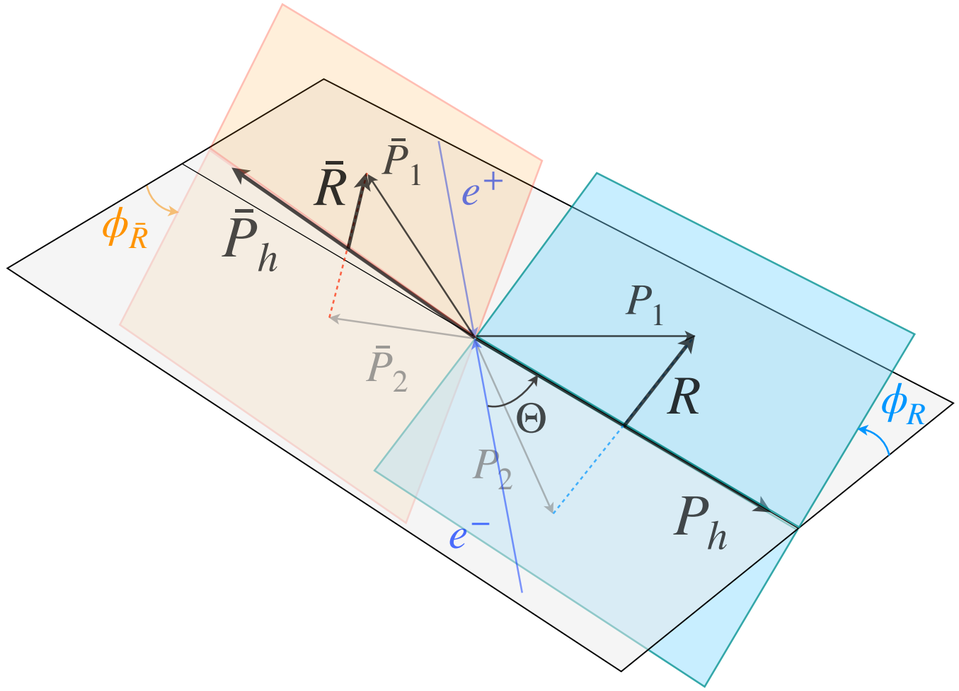
Complimentary Processes

Artru-Collins asymmetry in e^+e^- annihilation

$$e^+ + e^- \to h_1 h_2 + h_1' h_2' + X$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z\,\mathrm{d}\bar{z}\,\mathrm{d}M_h^2\,\mathrm{d}\bar{M}_h^2\,\mathrm{d}\cos\Theta\,\mathrm{d}\cos\theta\,\mathrm{d}\cos\bar{\theta}\,\mathrm{d}\phi_R\,\mathrm{d}\phi_{\bar{R}}}$$

$$= \frac{3\alpha^2}{8\pi^2 Q^2}\left[\left(1+\cos^2\Theta\right)F_{UU}^{1} + \sin^2\Theta\,\cos\left(\phi_R+\phi_{\bar{R}}\right)F_{UU}^{\cos(\phi_R+\phi_{\bar{R}})} + \cdots\right]$$

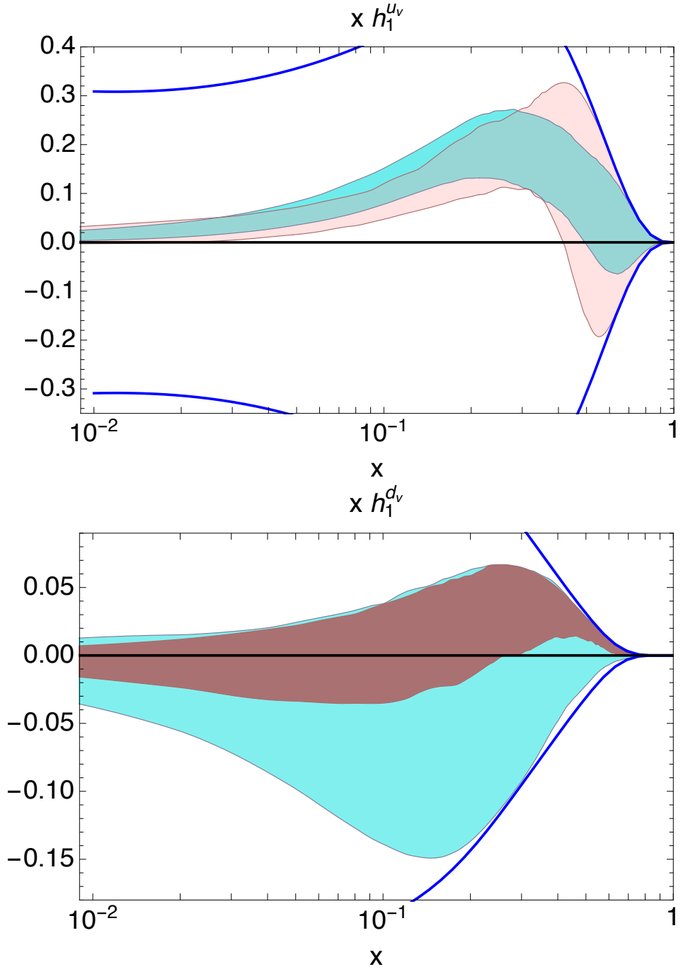


$$F_{UU}^{1} \sim D_1^{q\to h_1 h_2} \otimes D_1^{\bar{q}\to h_1' h_2'}$$

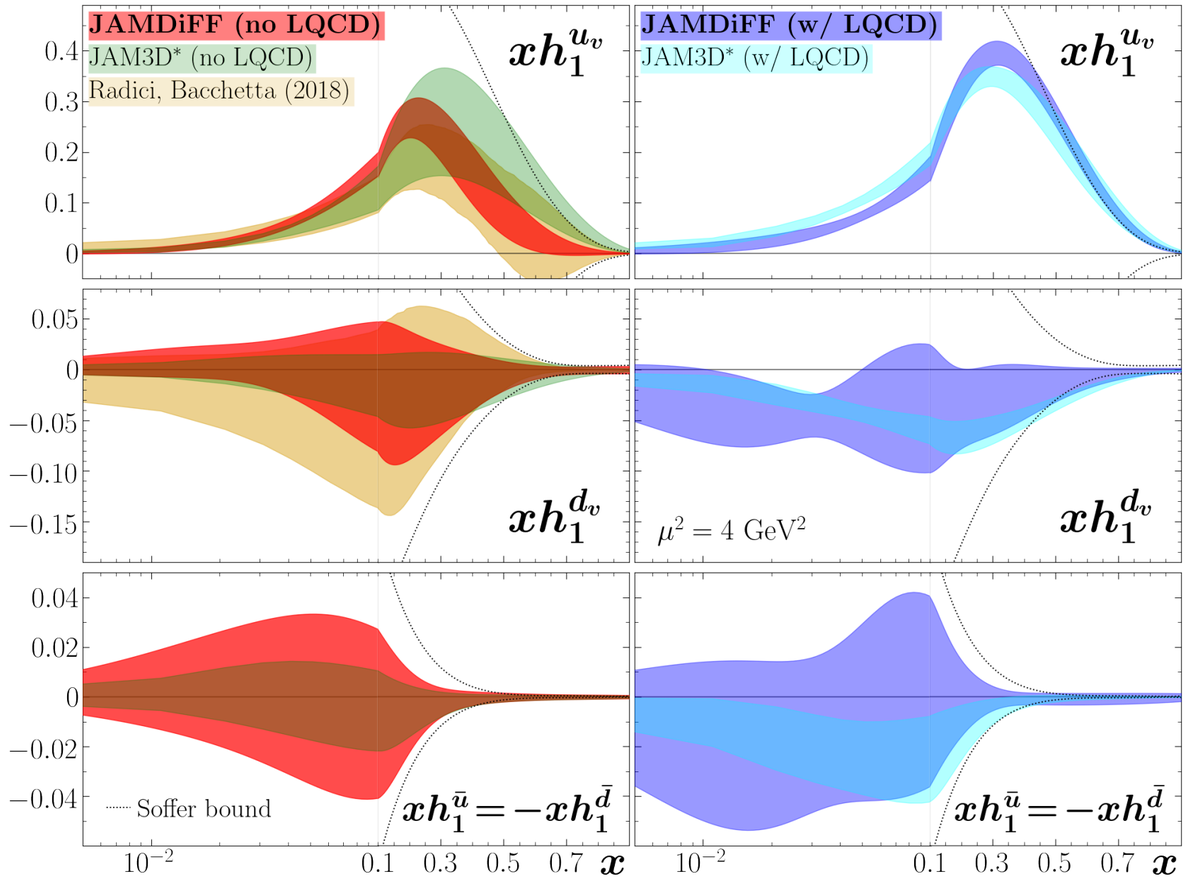
$$F_{UU}^{\cos(\phi_R+\phi_{\bar{R}})} \sim H_1^{\sphericalangle\, q\to h_1 h_2} \otimes H_1^{\sphericalangle\, \bar{q}\to h_1' h_2'}$$

X. Artru, J.C. Collins, Z. Phys. C 69 (1996) 277; D. Boer, R. Jakob, M. Radici, Phys. Rev. D 67 (2003) 094003.

Collinear Transversity Distributions

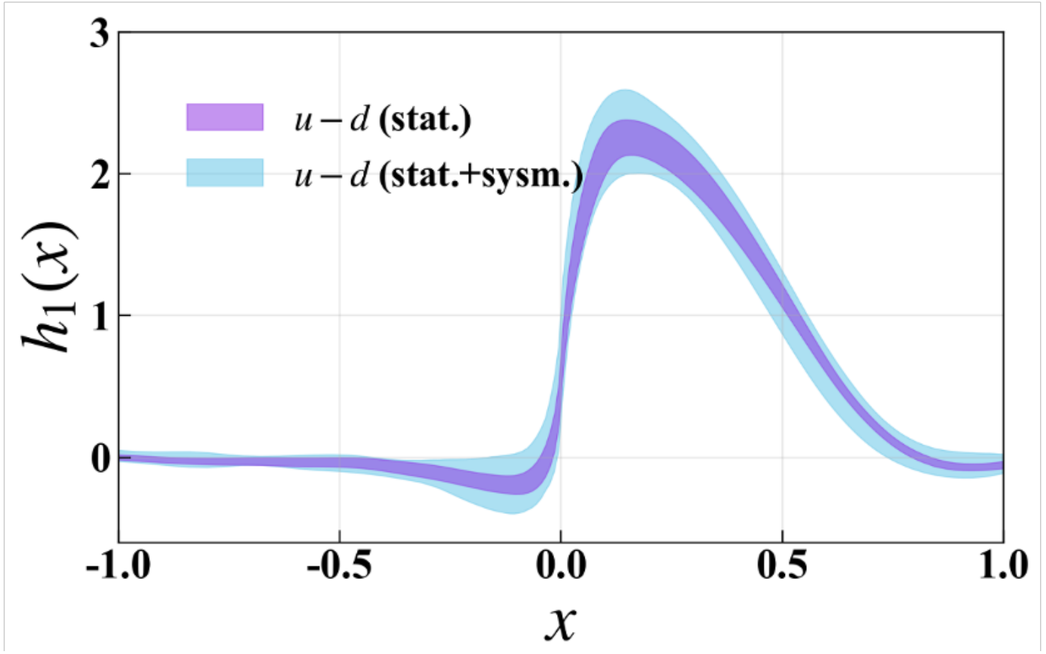


M. Radici and A. Bacchetta, Phys. Rev. Lett. 120 (2018) 192001.

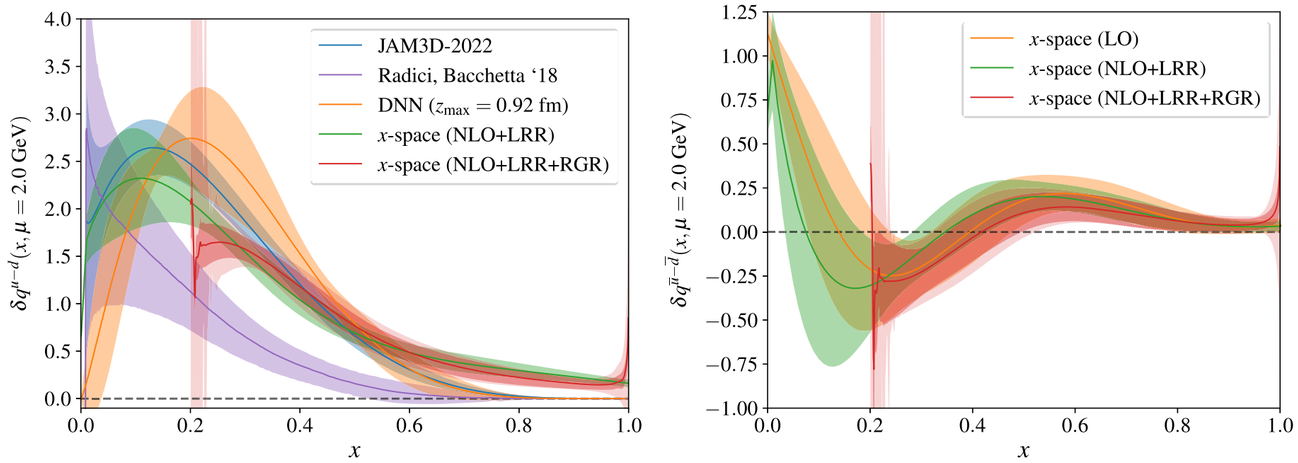


C. Cocuzza *et al.* (JAM Collaboration), Phys. Rev. Lett. 132 (2024) 091901; Phys. Rev. D 109 (2024) 034024.

Transversity Distribution from Lattice QCD



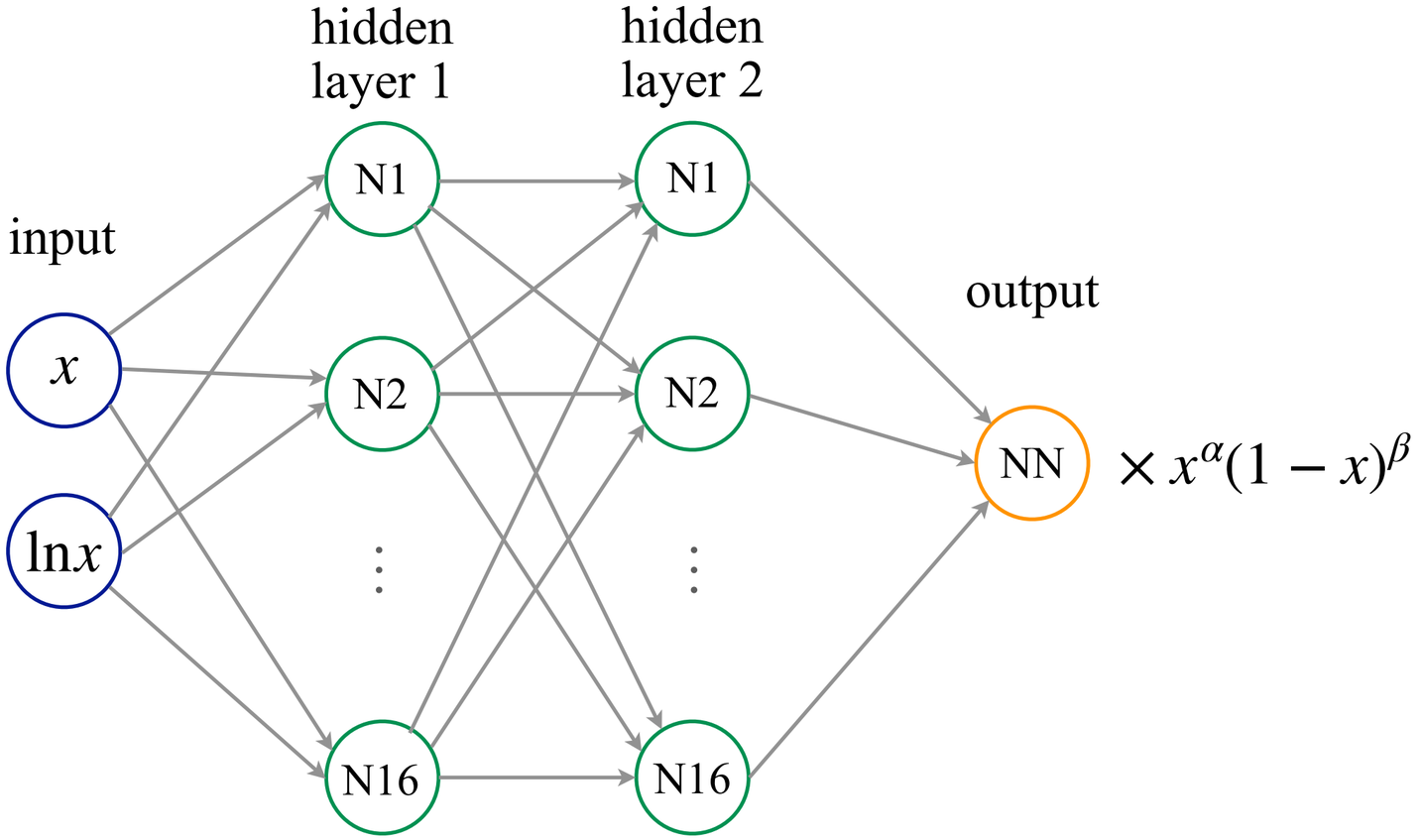
Lattice Parton Collaboration, Phys. Rev. Lett. 131 (2023) 261901.



X. Gao *et al.*, Phys. Rev. D 109 (2024) 054506.

NN Parametrization

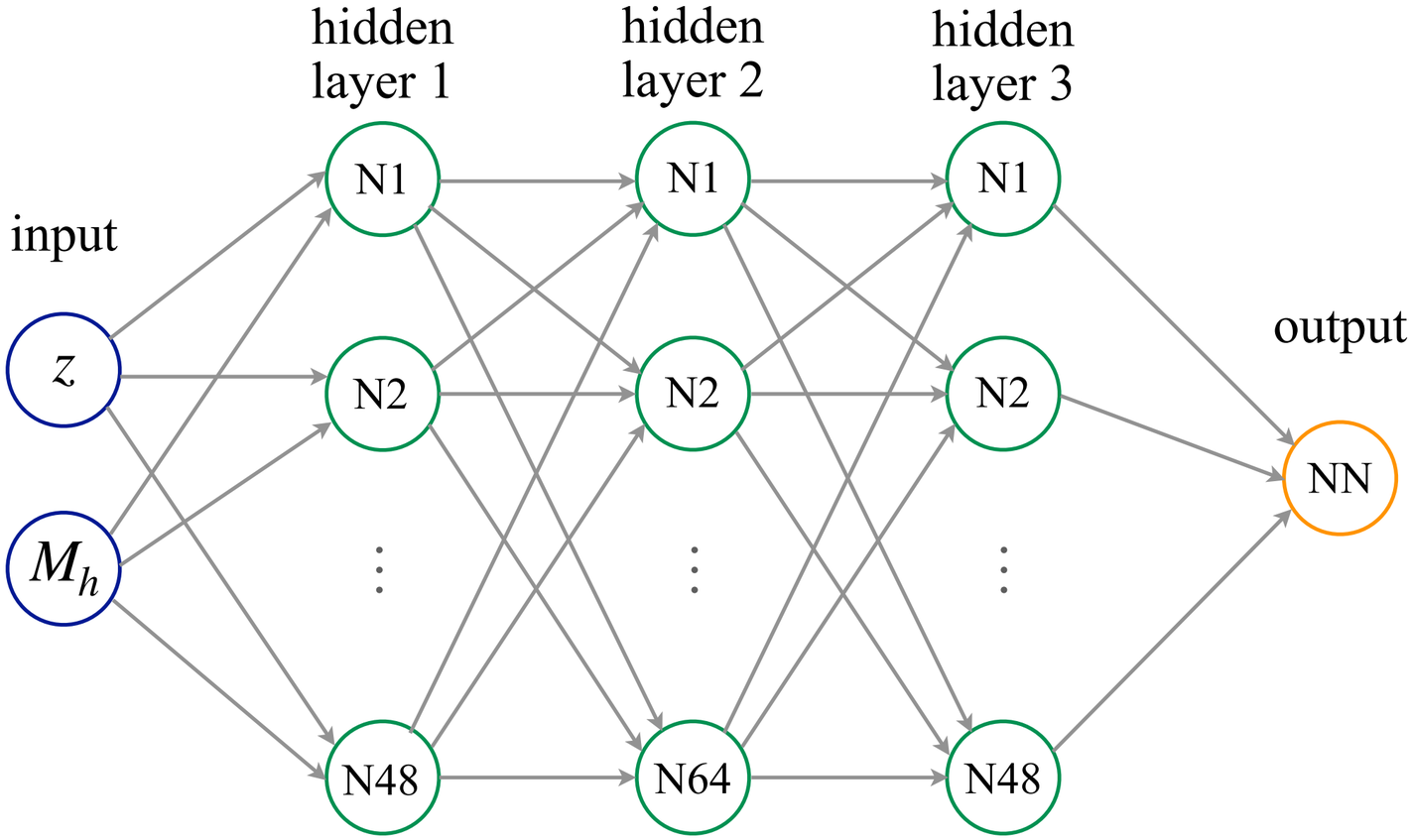
Parametrization of transversity distributions h_1:



tested with various architectures: number of layers, number of neurons, activation functions, optimization algorithms

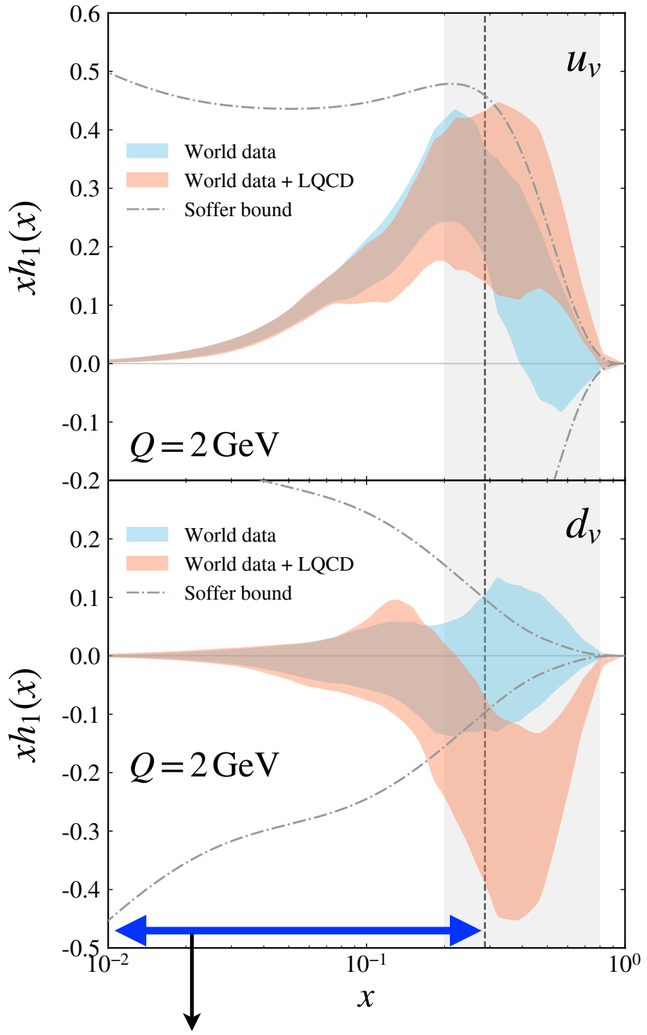
NN Parametrization

Parametrization of dihadron fragmentation functions D_1 and $H_1^{\sphericalangle}$

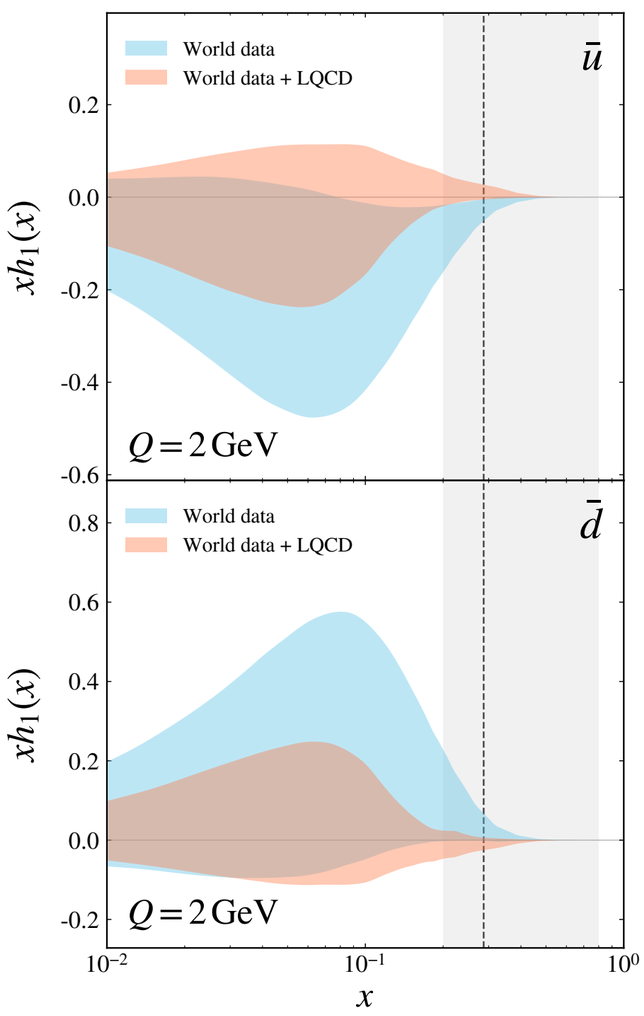


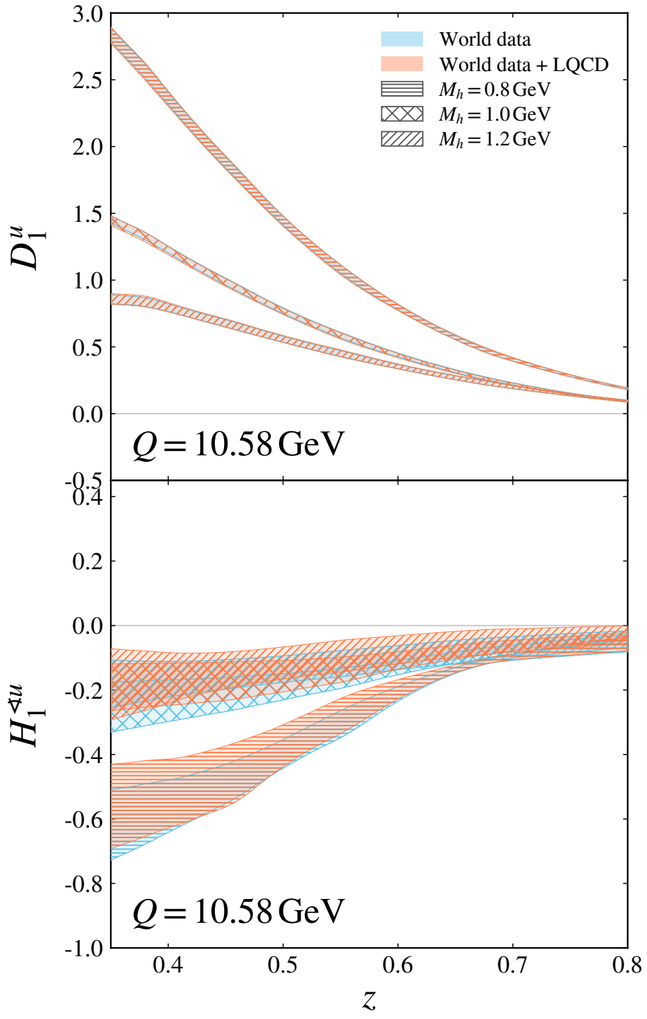
tested with various architectures: number of layers, number of neurons, activation functions, optimization algorithms

Extracted Transversity Distributions and DiFFs



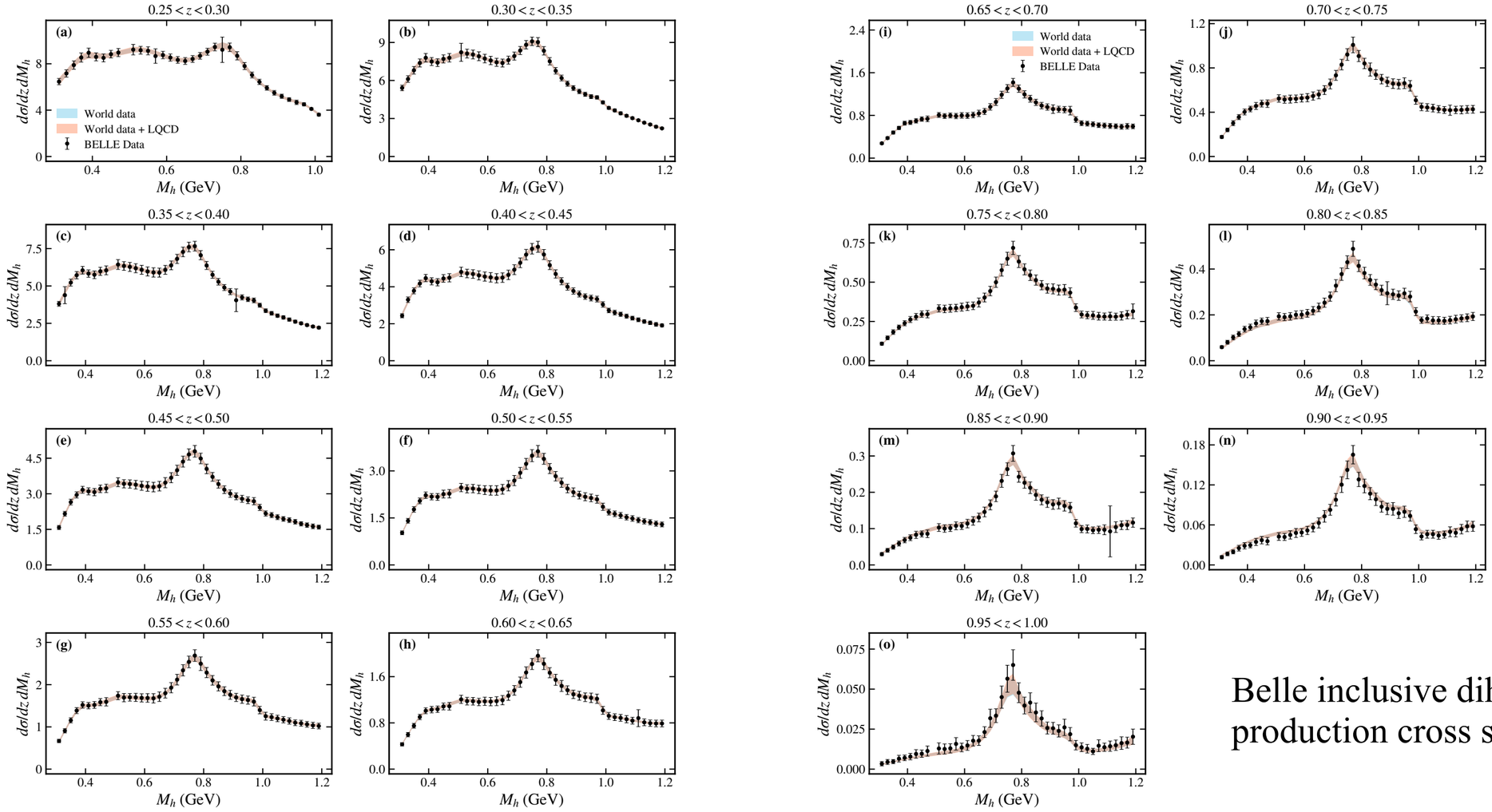
directly covered by SIDIS data





H. Dong, Y. Huang, TL, X. Shen, P. Sun, X. Xiong, J. Zhang, Y. Zhao, Y. Zhou, R. Zhu, axXiv:2611.12745

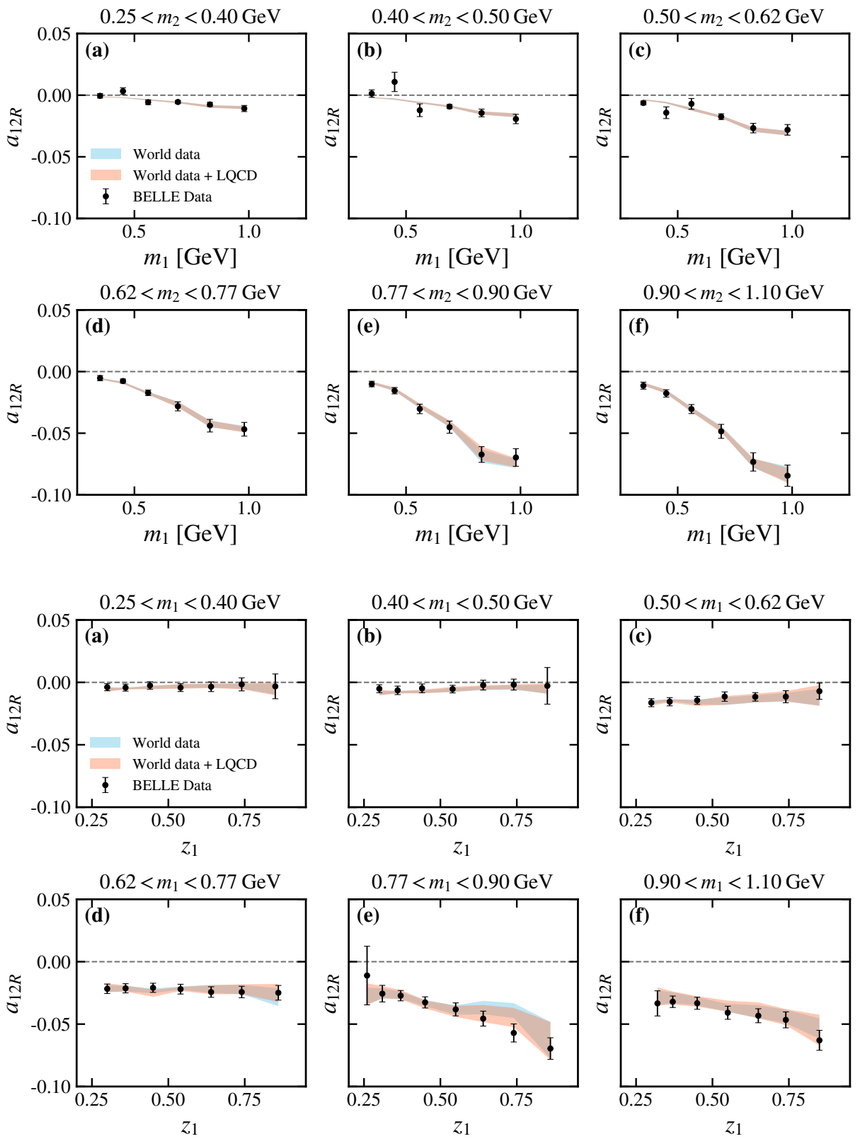
Comparison with Data

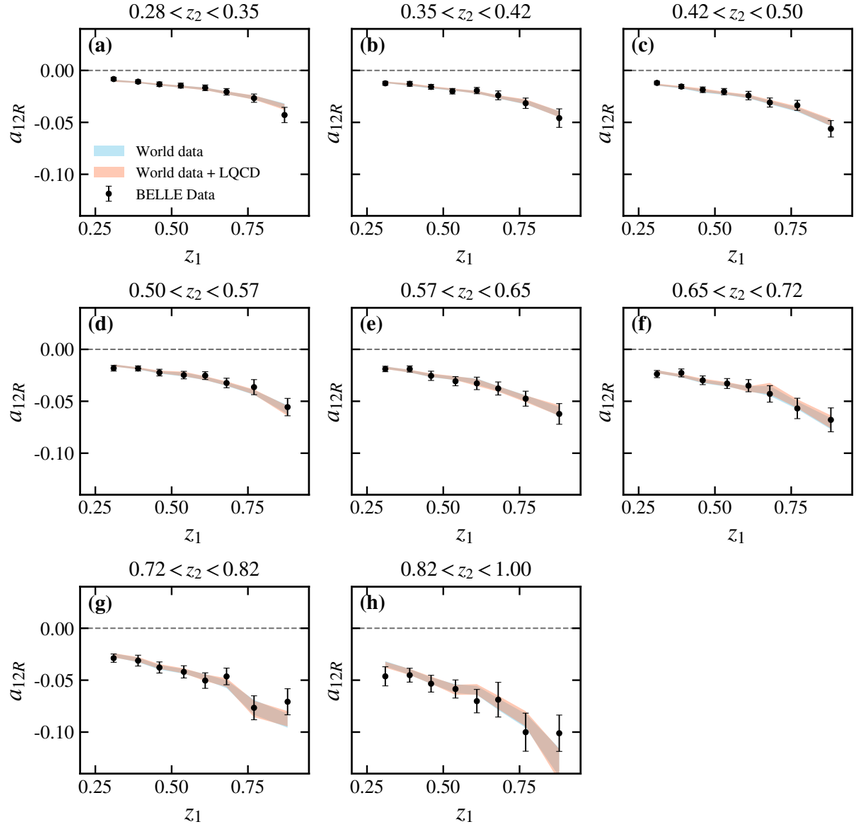


Belle inclusive dihadron production cross section data

Data: Belle Collaboration, Phys. Rev. D 96 (2017) 032005.

Comparison with Data

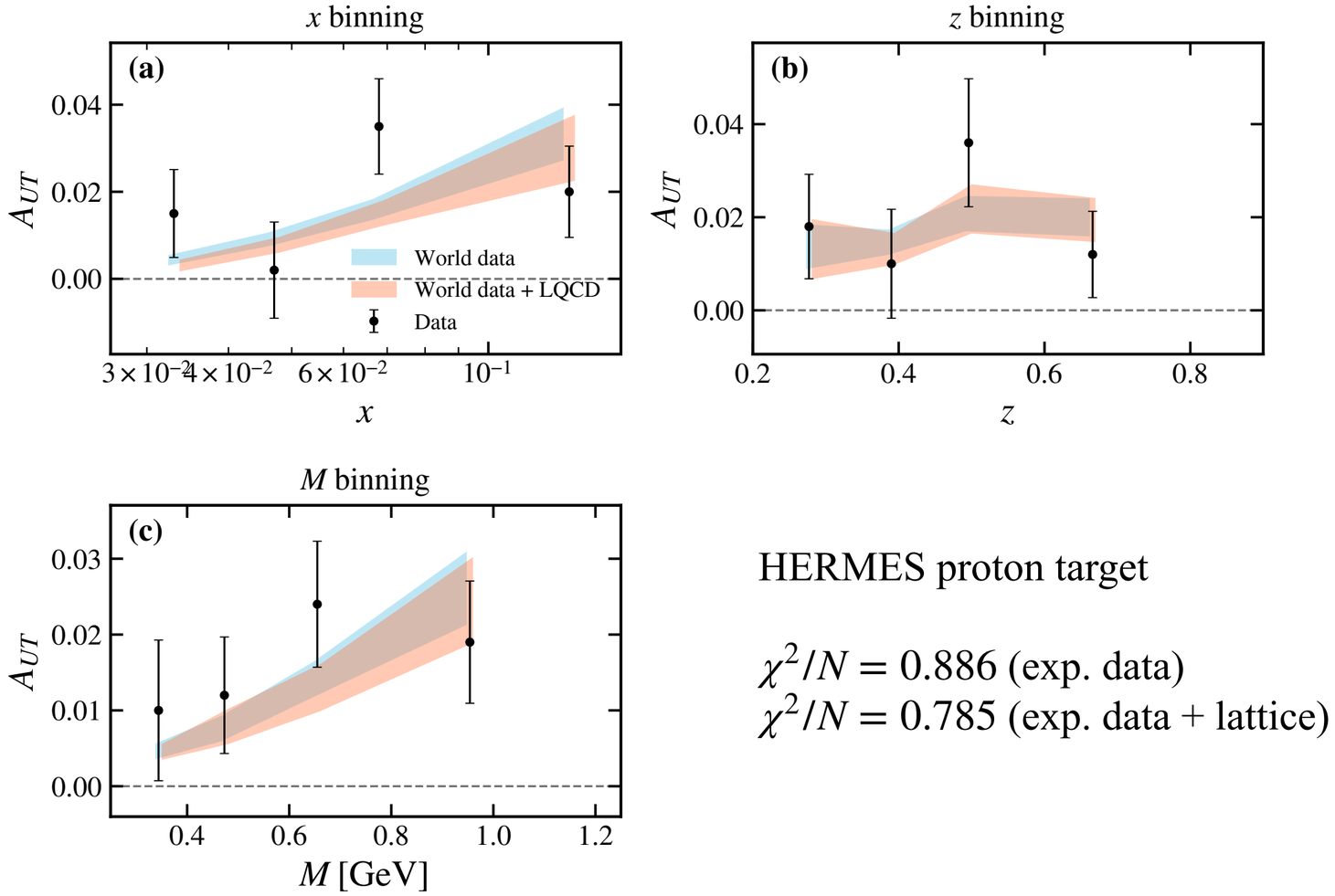




Belle dihadron pair Artru-Collins asymmetry data

Data: Belle Collaboration, Phys. Rev. Lett. 107 (2011) 072004.

Comparison with Data

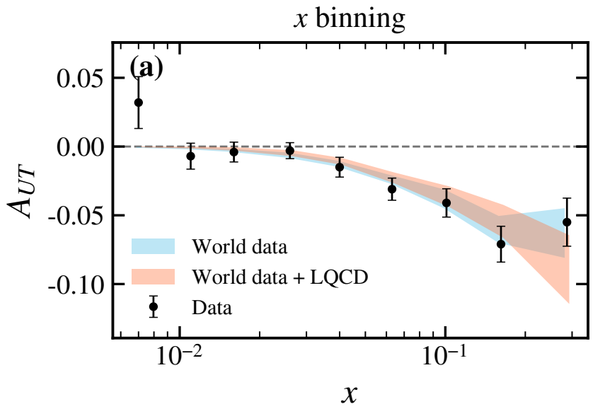


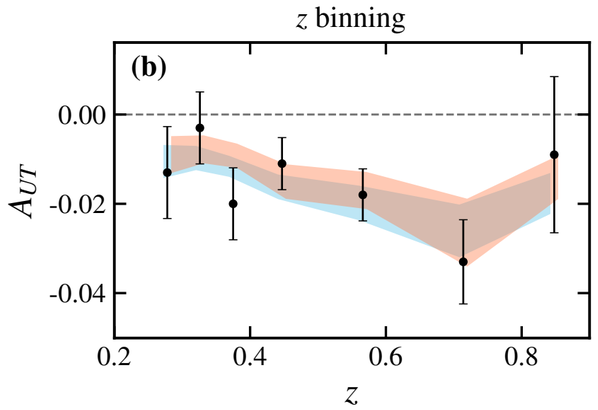
HERMES proton target

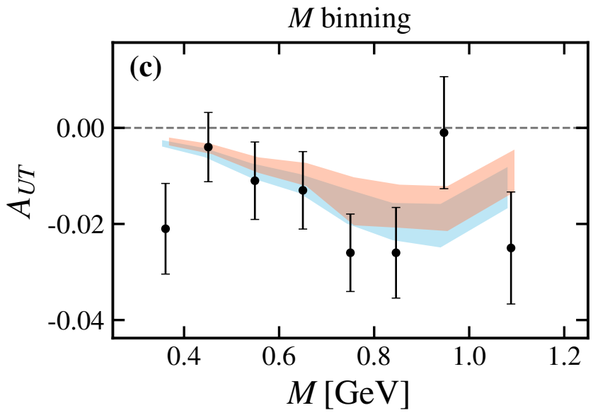
$\chi^2/N = 0.886$ (exp. data)
$\chi^2/N = 0.785$ (exp. data + lattice)

Data: HERMES Collaboration, JHEP 06 (2008) 017.

Comparison with Data



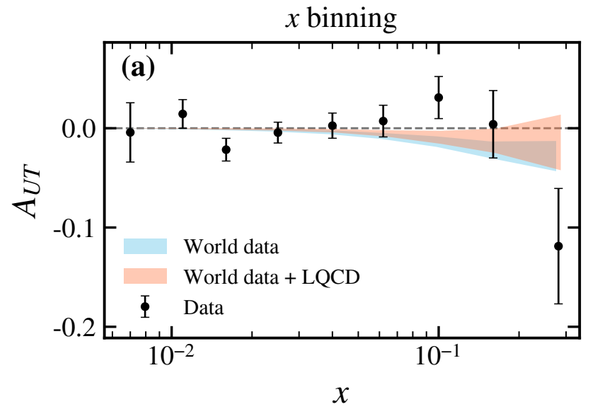


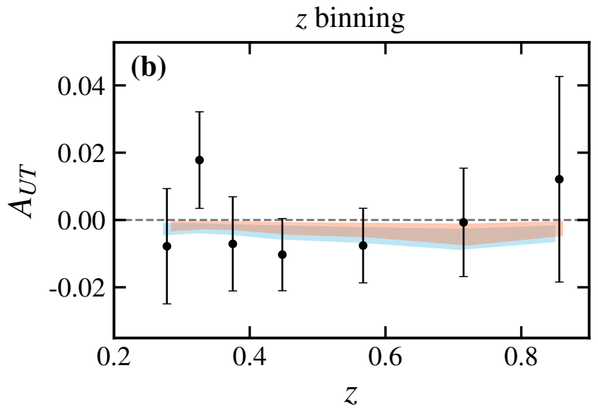


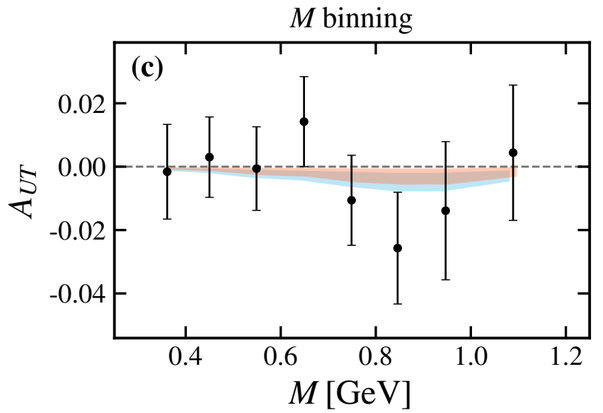
COMPASS proton target

$\chi^2/N = 0.762$ (exp. data)
$\chi^2/N = 0.920$ (exp. data + lattice)

Data: COMPASS Collaboration, Phys. Lett. B 736 (2014) 124.





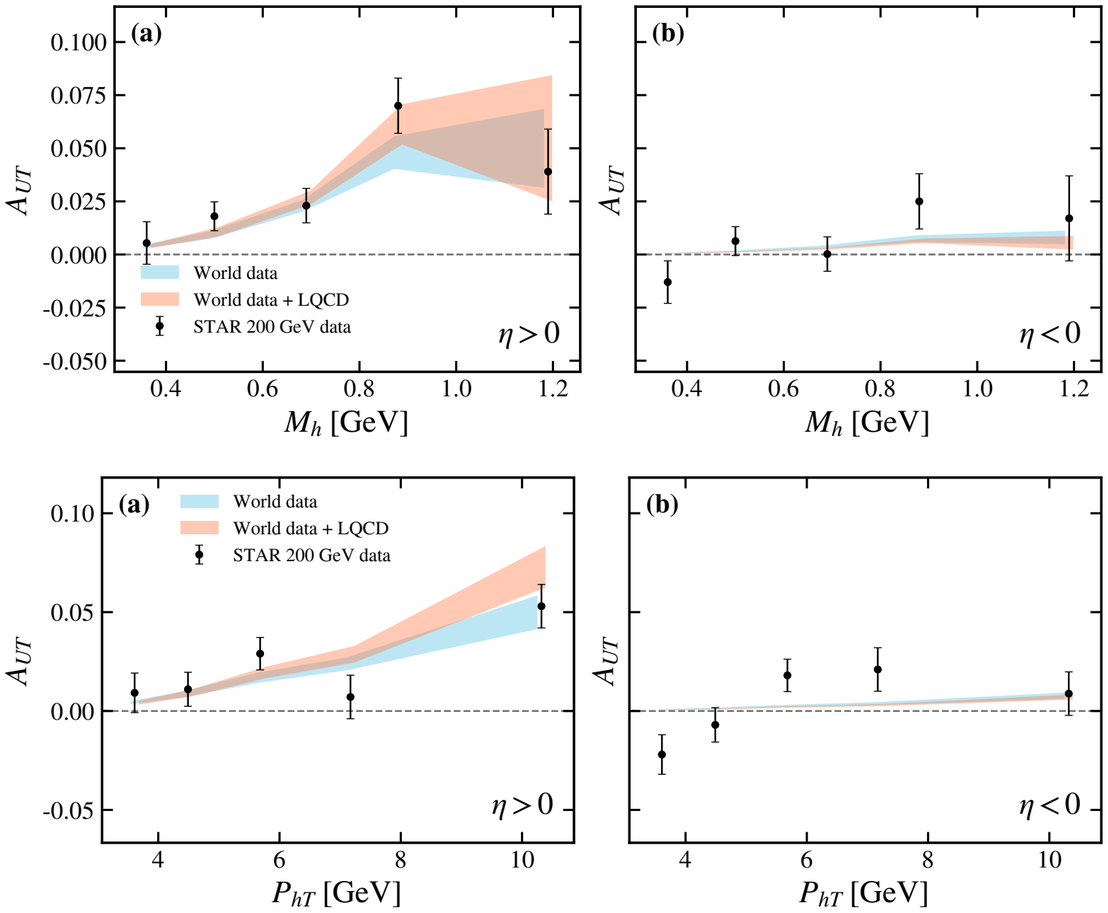


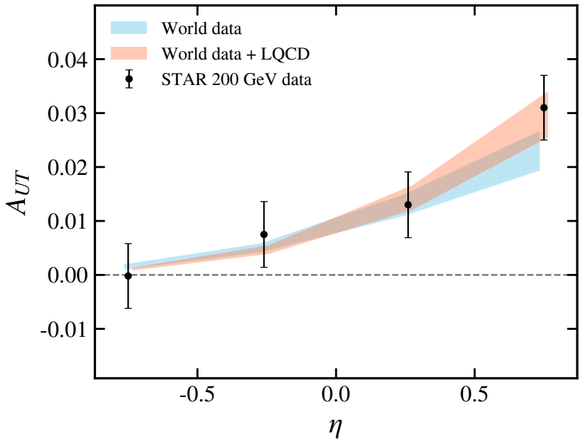
COMPASS deuteron target

$\chi^2/N = 0.804$ (exp. data)
$\chi^2/N = 0.834$ (exp. data + lattice)

Data: COMPASS Collaboration, Phys. Lett. B 845 (2023) 138155.

Comparison with Data



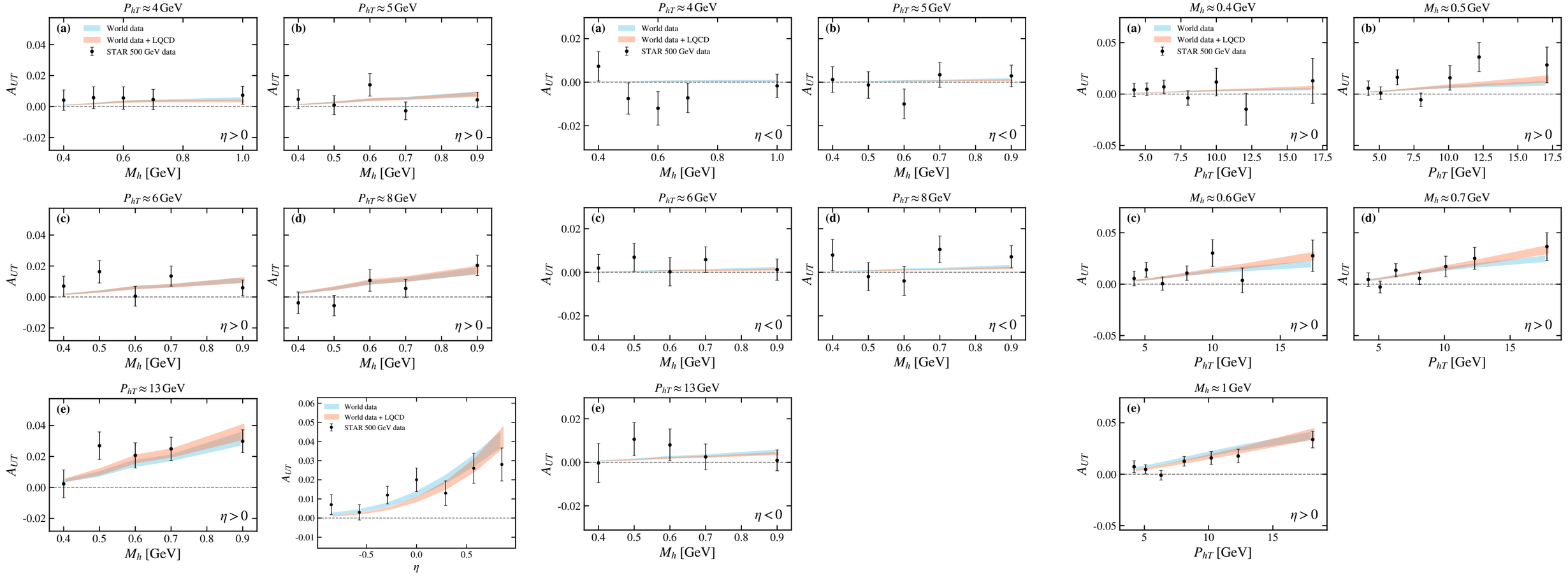


STAR 200 GeV pp

$\chi^2/N = 1.172$ (exp. data)
$\chi^2/N = 1.239$ (exp. data + lattice)

Data: STAR Collaboration, Phys. Rev. Lett. 115 (2015) 242501.

Comparison with Data



STAR 500 GeV pp

$\chi^2/N = 0.884$ (exp. data)
$\chi^2/N = 0.855$ (exp. data + lattice)

Data: STAR Collaboration, Phys. Lett. B 780 (2018) 332.

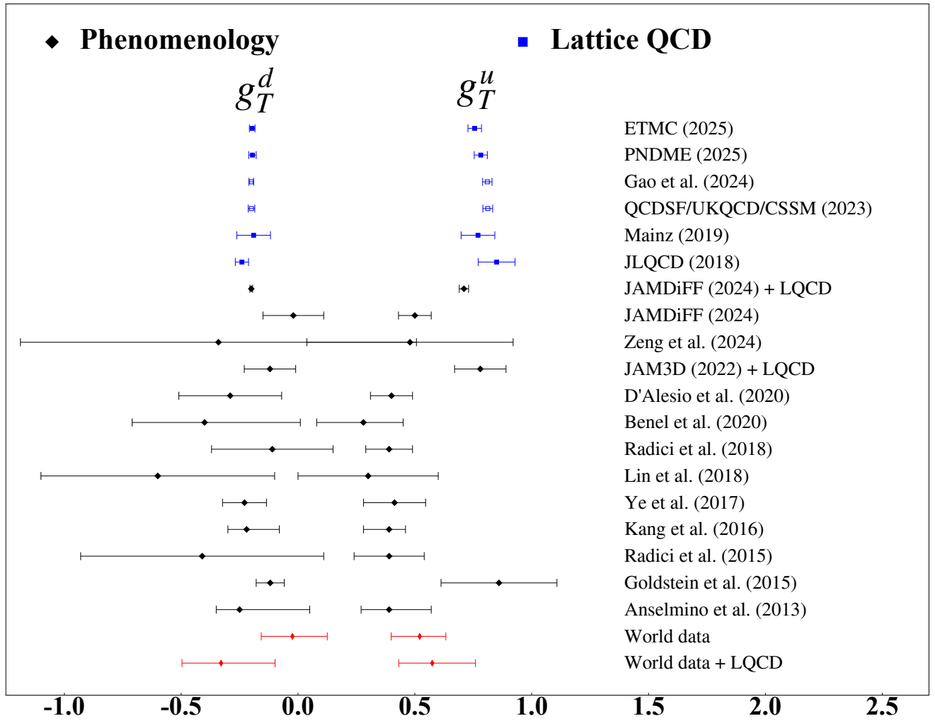
Tensor Charge

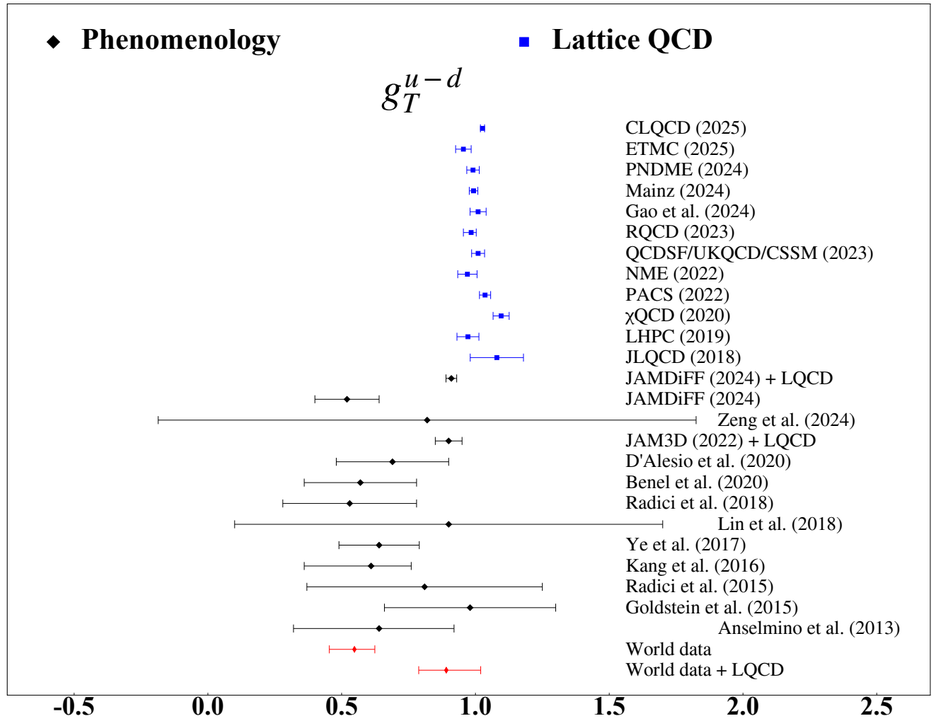
Tensor charge

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

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

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



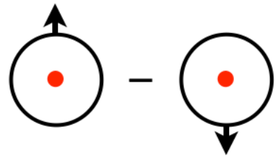


H. Dong, Y. Huang, TL, X. Shen, P. Sun, X. Xiong, J. Zhang, Y. Zhao, Y. Zhou, R. Zhu, axXiv:2611.12745

The Sivers Function

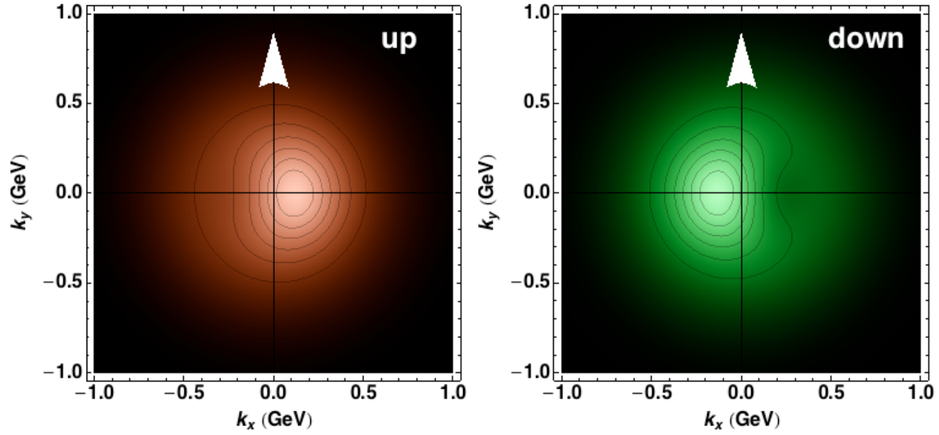
Sivers TMD distribution function

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



A naive T-odd distribution function

Transverse momentum distribution
distorted by nucleon transverse spin



[Figure from A. Bacchetta]

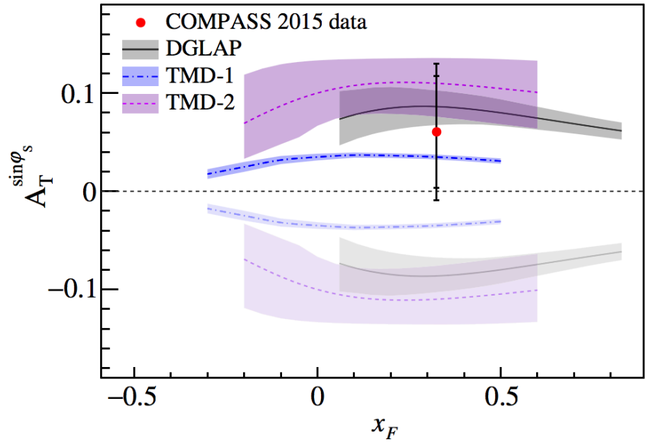
Effect in SIDIS:
transverse single spin asymmetry (Sivers asymmetry)

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

sizable Sivers asymmetry observed
by HERMES, COMPASS, JLab

Sign change prediction:

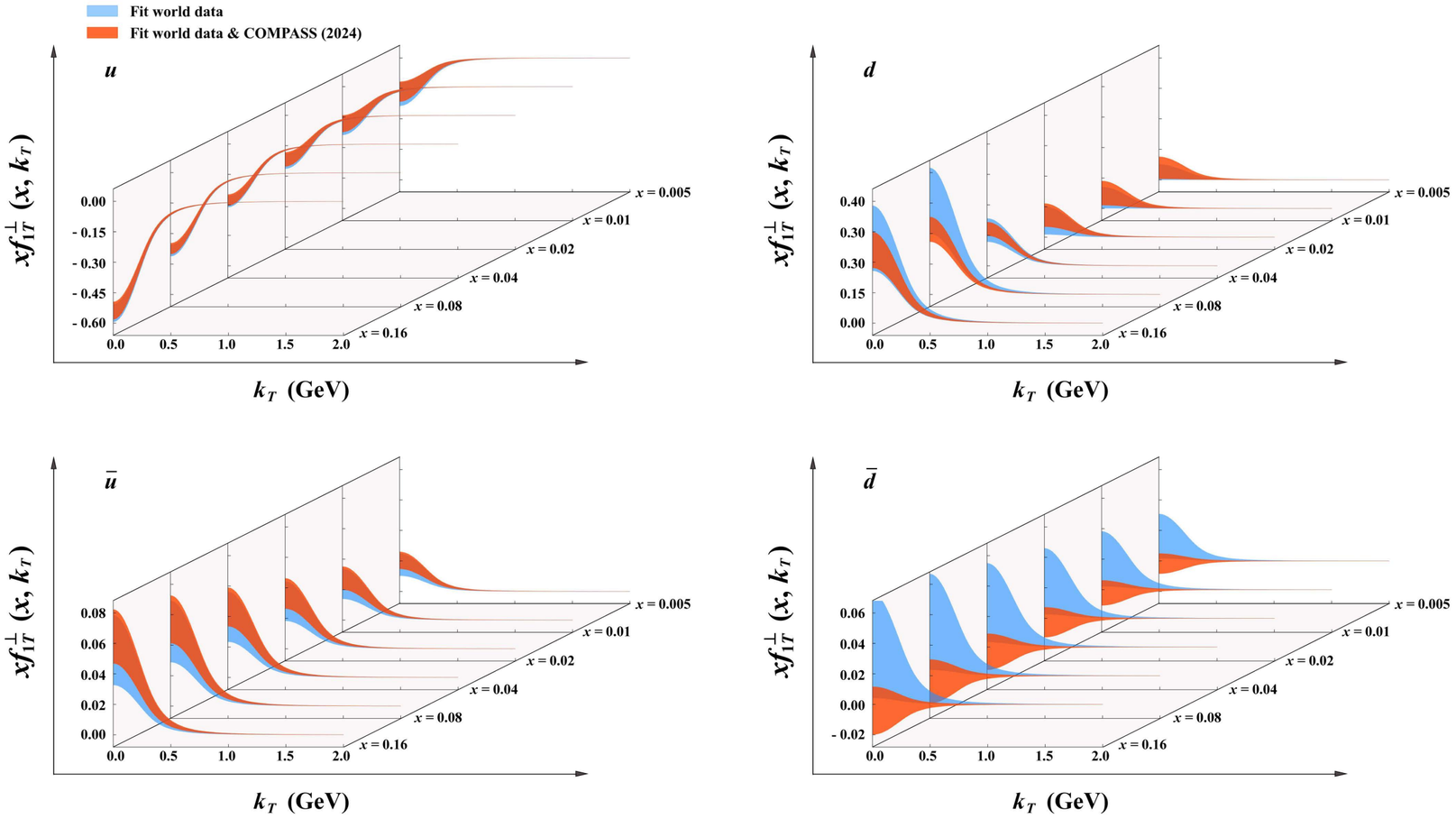
$$f_{1T}^{\perp}(x, k_T^2)\,|_{\text{SIDIS}} = -\,f_{1T}^{\perp}(x, k_T^2)\,|_{\text{DY}}$$



COMPASS Collaboration, PRL 119, 112002 (2017).

Extracted Sivers Functions

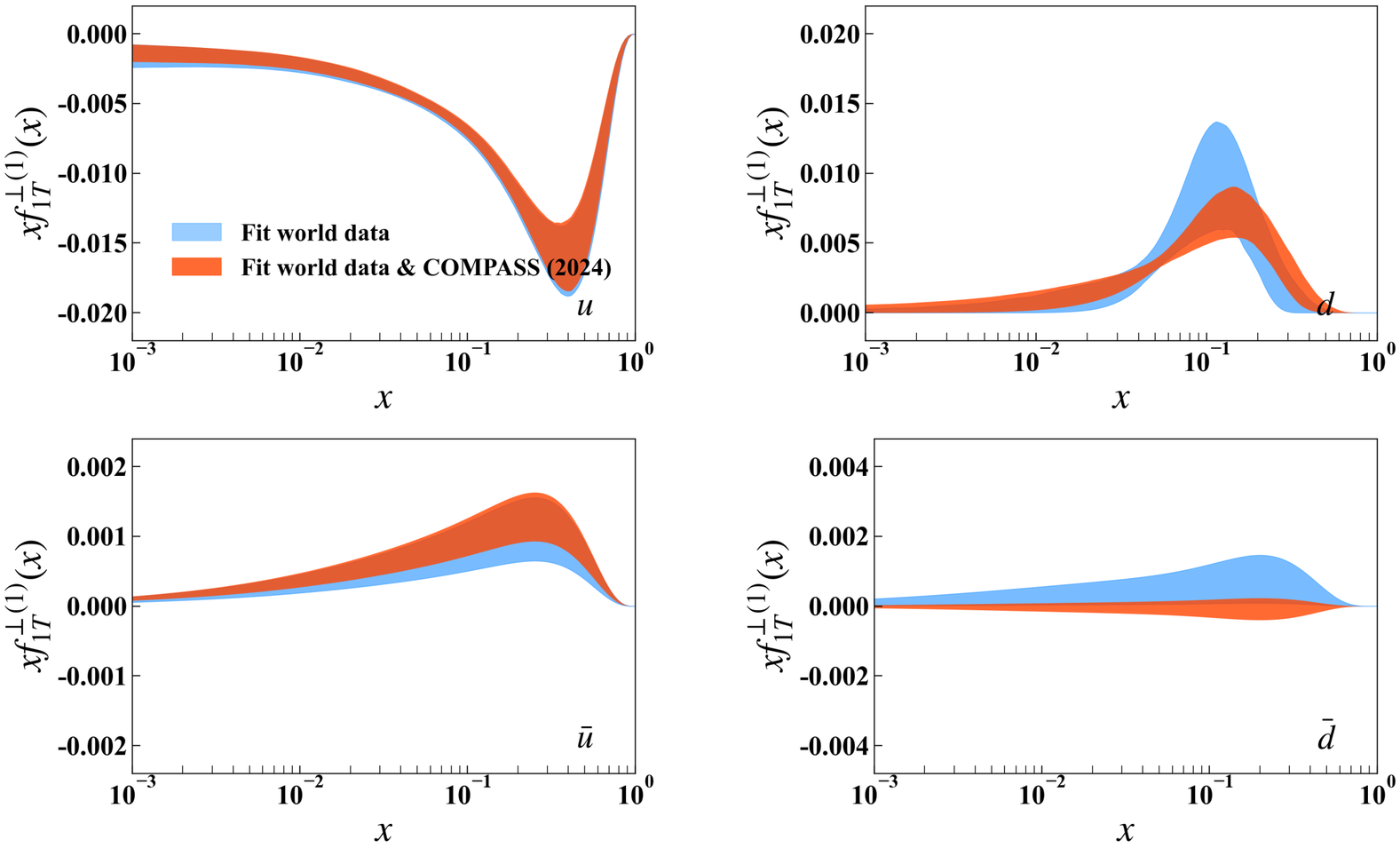
Global analysis of SIDIS, Drell-Yan, $W^{\pm}/Z^0$ production data



C. Zeng, TL, P. Sun, Y. Zhao, PRD 106 (2022) 094039; arXiv:2412.18324.

Extracted Sivers Functions

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

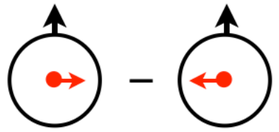


C. Zeng, TL, P. Sun, Y. Zhao, PRD 106 (2022) 094039; arXiv:2412.18324.

Double Spin Asymmetry and Worm-gear

Trans-helicity worm-gear distribution

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



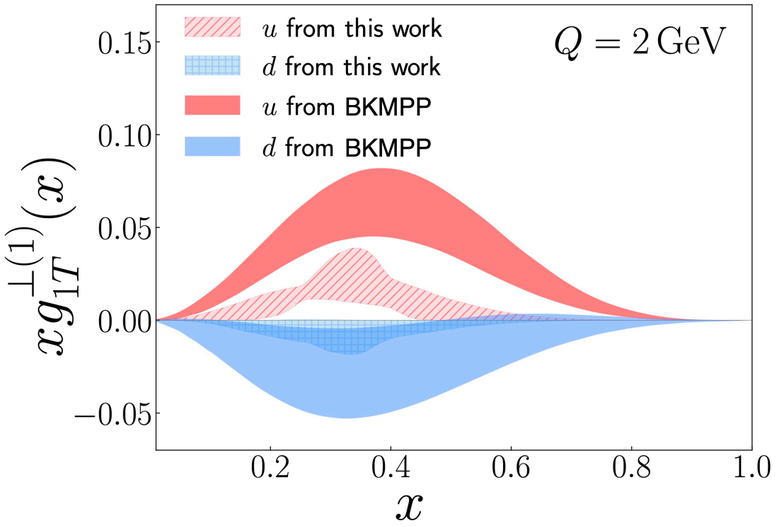
- Longitudinally polarized quark density in a transversely polarized nucleon
- Overlap between wave functions differing by one unit of orbital angular momentum

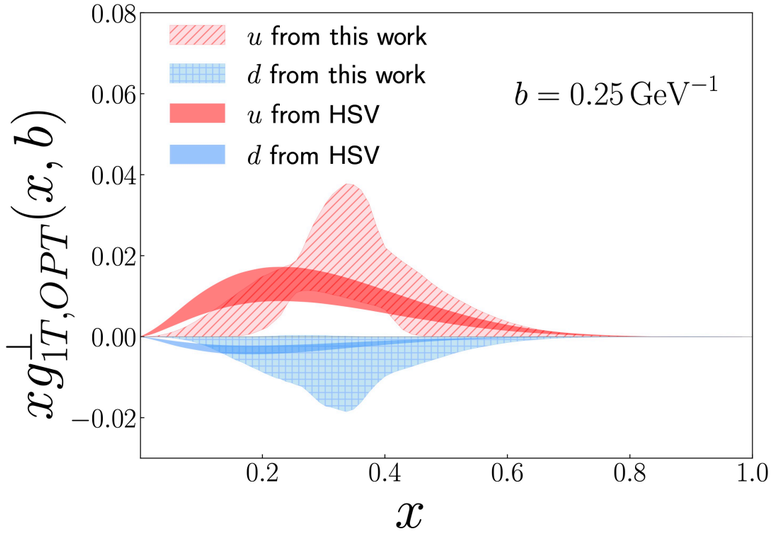


Effect in SIDIS:
A longitudinal-transverse double spin asymmetry

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

Phenomenological extraction



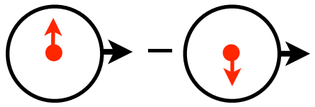


K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, Phys. Rev. D 110 (2024) 034036.

Longitudinal SSA and Worm-gear

Longi-transversity worm-gear distribution

$$\frac{S_L k_T^{\alpha}}{M} h_{1L}^{\perp}(x, k_T^2)$$



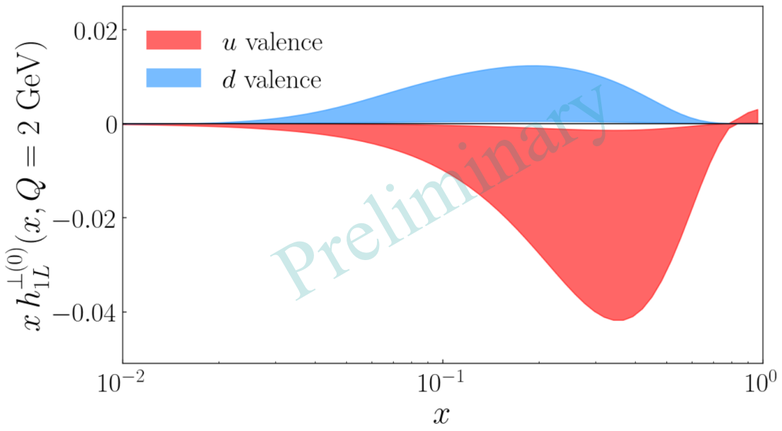
- Transversely polarized quark density in a longitudinally polarized nucleon
- Overlap between wave functions differing by one unit of orbital angular momentum

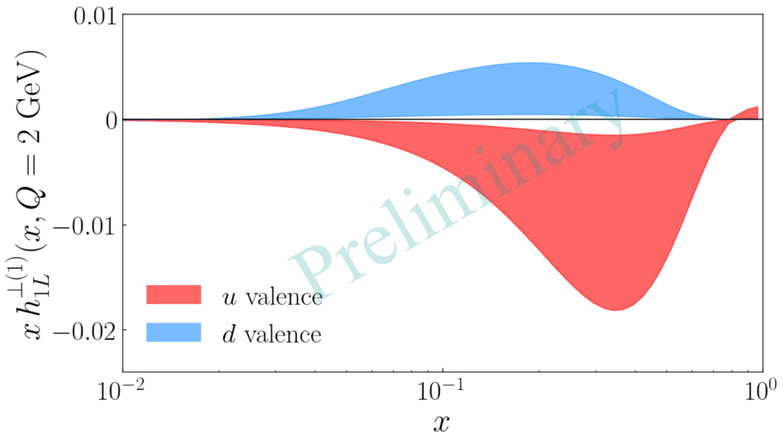


Effect in SIDIS:
A longitudinal target single spin asymmetry

$$A_{UL}^{\sin 2\phi_h} \sim h_{1L}^{\perp} \otimes H_1^{\perp}$$

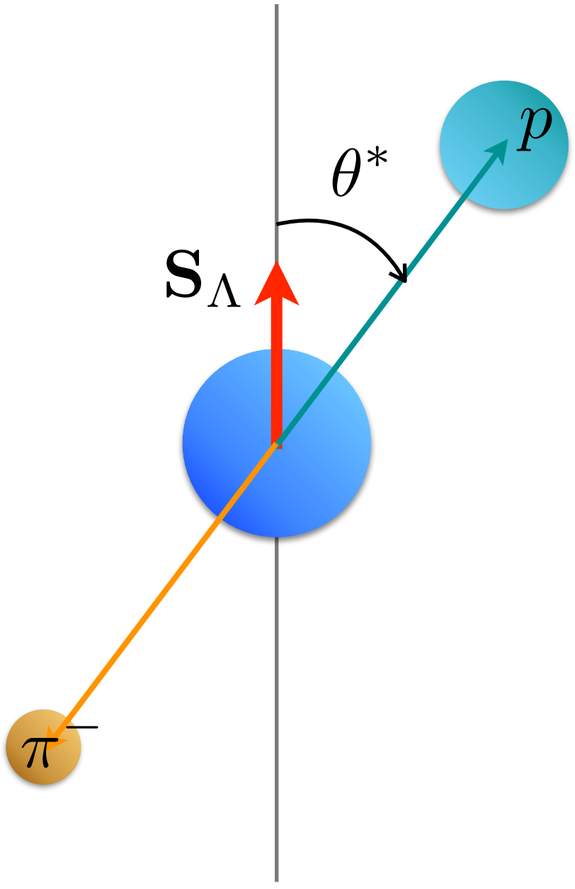
First extraction





W. Chen, K. Yang, TL, P. Sun, Y. Zhao, in preparation, 2026

Analyze Λ Polarization

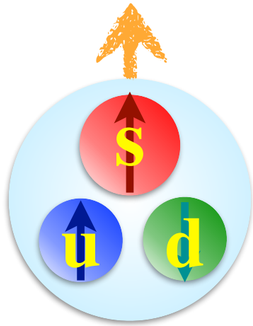


Decay channel: $\Lambda \to p\pi^-$

branch ratio: $64.1 \pm 0.5\%$

parity violating weak decay

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



decay parameter: $\alpha_\Lambda = 0.748 \pm 0.007$ [Current PDG value]

BESIII Collaboration, Nature Phys. 15 (2019) 631; Phys. Rev. Lett. 129 (2022) 131801.

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

valence component: $|uds\rangle$

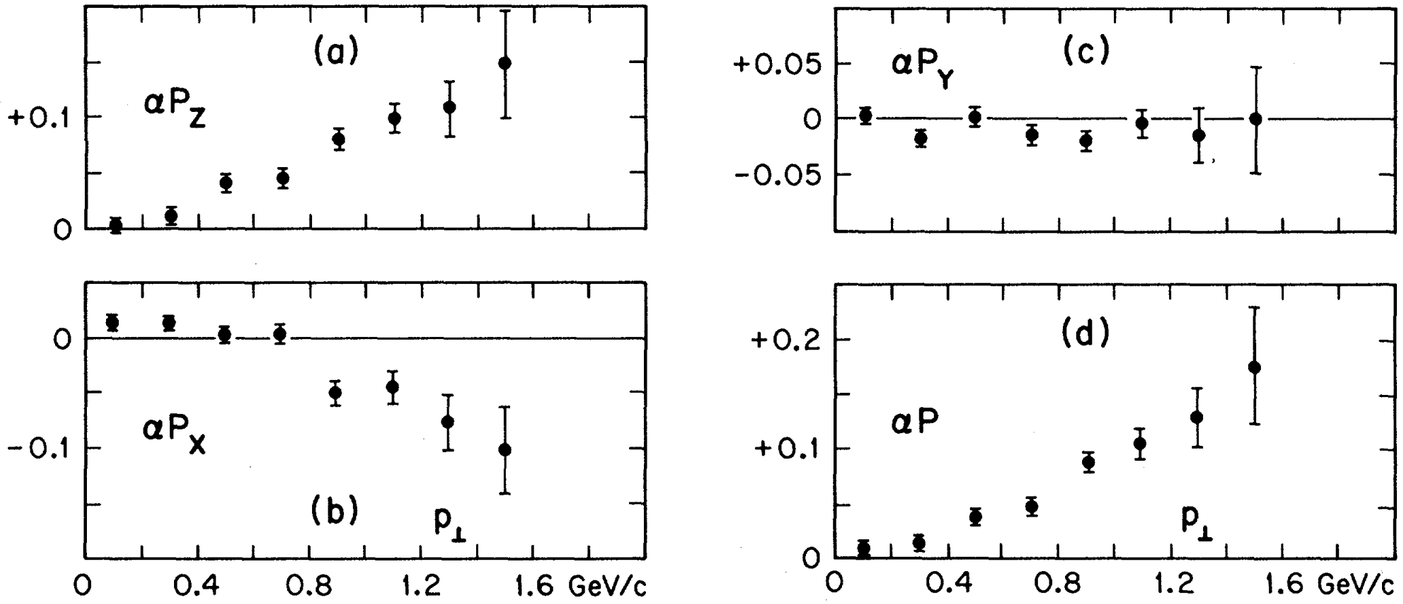
spin dominated by *s* quark

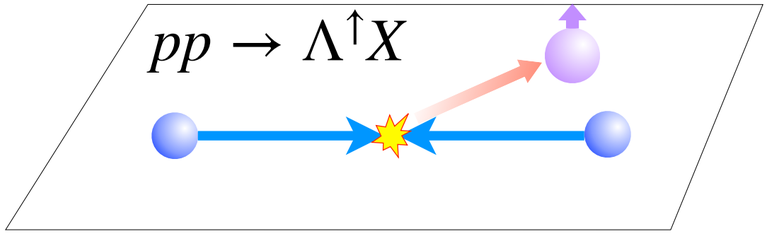
Sensitive to nucleon strange sea and its polarization via SIDIS

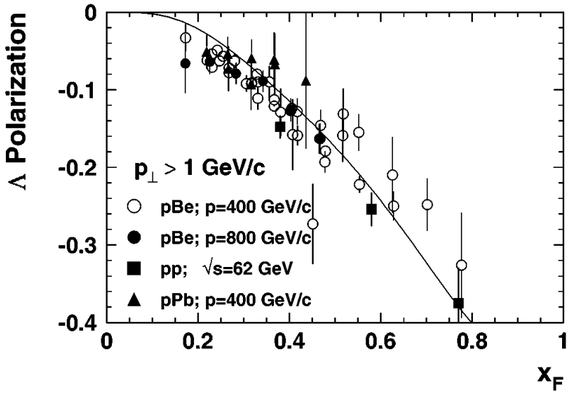
Unexpected Transverse Λ Polarization

Measurement of "spontaneous" Λ polarization

$p + \mathrm{Be} \rightarrow \Lambda + X$ 300 GeV proton beam







G. Bunce *et al.*, Phys. Rev. Lett. 36 (1976) 1113.

pQCD predicted negligible polarization at that time!

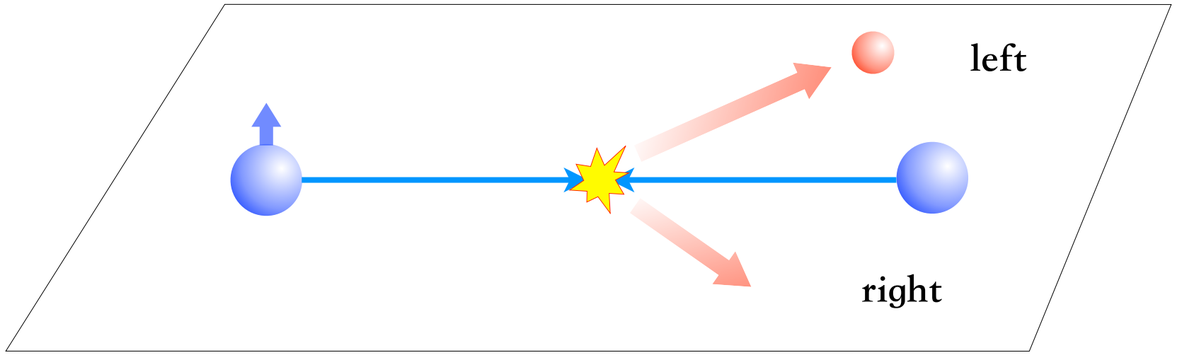
Liang-Boros Model

VOLUME 79, NUMBER 19 PHYSICAL REVIEW LETTERS 10 NOVEMBER 1997

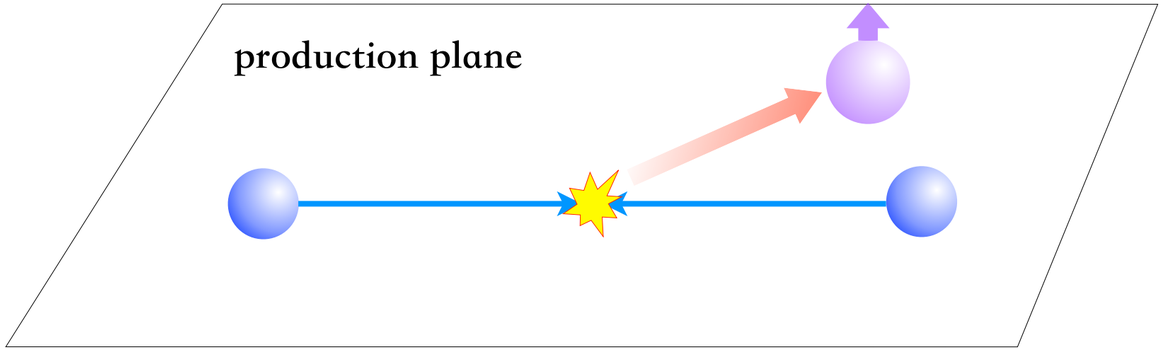
Hyperon Polarization and Single Spin Left-Right Asymmetry in Inclusive Production Processes at High Energies

Liang Zuo-tang[1] and C. Boros[2,3]
[1]*Department of Physics, Shandong University, Jinan, Shandong 250100, China*
[2]*Institut für Theoretische Physik, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany*
[3]*Special Research Centre for the Subatomic Structure of Matter, University of Adelaide, Adelaide, Australia 5005*
(Received 16 May 1997)

The polarization of hyperons observed in unpolarized hadron collisions is closely related to the left-right asymmetries observed in single spin inclusive hadron production.



transverse spin selects transverse momentum

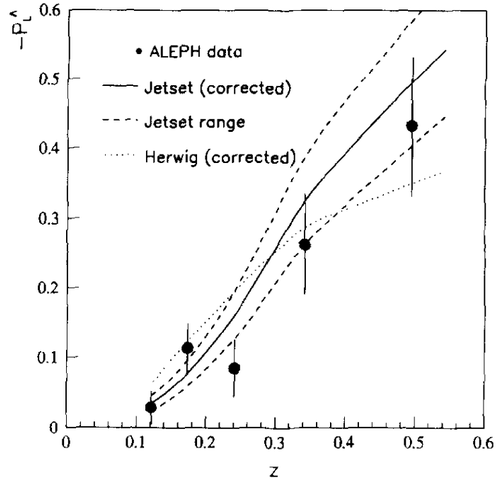


transverse momentum selects transverse spin

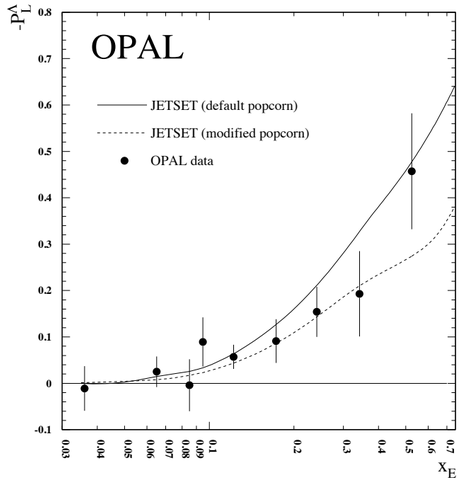
Correlation between quark transverse momentum and transverse spin!

Semi-inclusive e^+e^- Annihilation

Longitudinal spin transfer: $e^+e^- \to Z^0 \to \Lambda X$



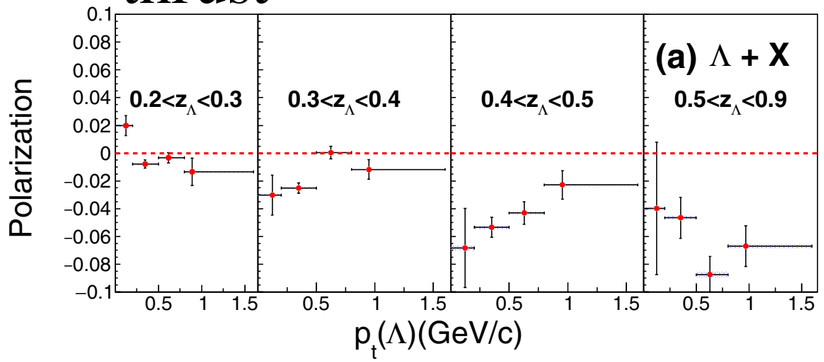
ALEPH Collaboration, Phys. Lett. B 374 (1996) 319.



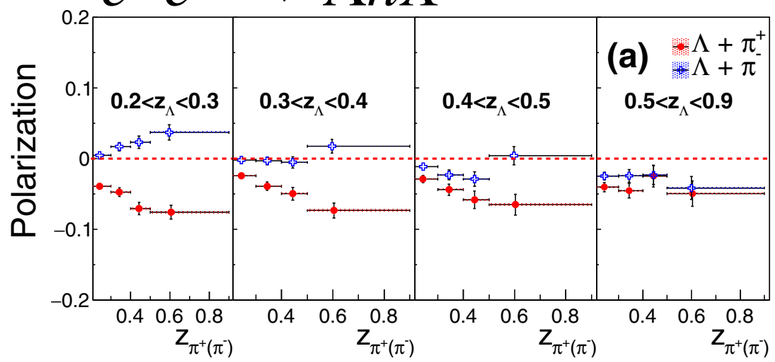
OPAL Collaboration, Eur. Phys. J. C 2 (1998) 49.

"Spontaneous" transverse polarization:

thrust



$e^+e^- \to \Lambda hX$



Belle Collaboration, Phys. Rev. Lett. 122 (2019) 042001.

SIDIS with Polarized Λ

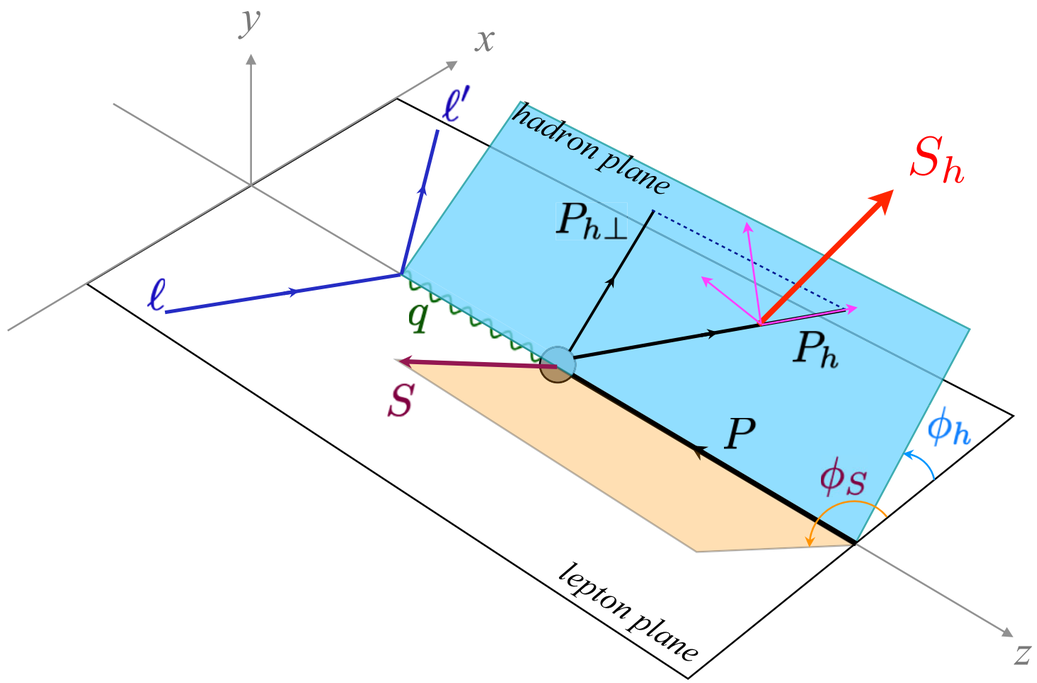
$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_B\mathrm{d}y\mathrm{d}z\mathrm{d}\phi_h\mathrm{d}\phi_s\mathrm{d}P_{h\perp}^2}$$

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

$$\times\Big[\mathcal{F}_{U,U} + S_{hL}\mathcal{F}_{U,L} + \left|S_{hT}\right|\mathcal{F}_{U,T}$$

$$+S_L\left(\mathcal{F}_{L,U} + S_{hL}\mathcal{F}_{L,L} + \left|S_{hT}\right|\mathcal{F}_{L,T}\right)$$

$$+\left|S_T\right|\left(\mathcal{F}_{T,U} + S_{h_L}\mathcal{F}_{T,L} + \left|S_{hT}\right|\mathcal{F}_{T,T}\right)\Big]$$



$\mathcal{F}_{A,B}$

A: target nucleon polarization
B: produced hadron (Λ) polarization

TMD Fragmentation Functions

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		D_1 = Unpolarized		$H_1^\perp$ = Collins
Polarized Hadrons	L		G_1 = Helicity	$H_{1L}^\perp$ = Worm-gear
	T	$D_{1T}^\perp$ = Sivers-type	$G_{1T}^\perp$ = Worm-gear	H_1 = Transversity $H_{1T}^\perp$ = Pretzelosity

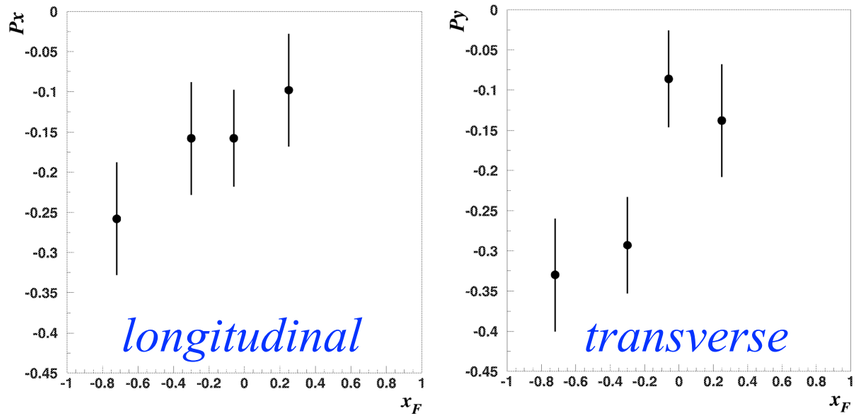


[Figure from TMD Handbook]

Λ Polarization Lepton-Hadron Scattering

Neutrino scattering experiments

G.T. Jones *et al.* Birmingham-Bonn-CERN-London-Munich-Oxford, Z. Phys. C 28 (1985) 23.
WA59 Collaboration, Z. Phys. C 53 (1992) 207.
E632 Collaboration, Phys. Rev. D 50 (1994) 6691.
NOMAD Collaboration, Nucl. Phys. B 588 (2000) 3.
NOMAD Collaboration, Nucl. Phys. B 605 (2001) 3.



NOMAD Collaboration, Nucl. Phys. B 588 (2000) 3.

TABLE VI. Λ Polarization. The x axis is along the W boson direction in the Λ rest frame. The other two axes are perpendicular to the W, with the y axis being transverse to the production plane, and the z axis inside the production plane.

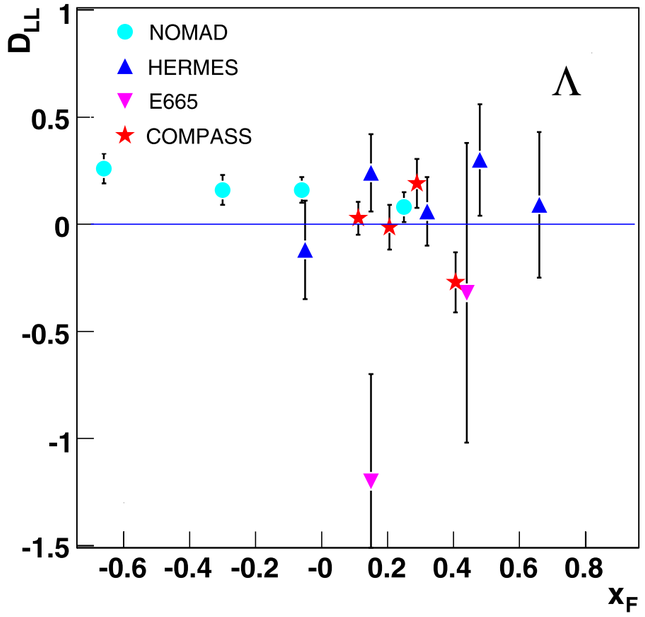
Reaction [Ref.]	P_x	P_y	P_z
ν-Ne [This expt.]	-0.38 ± 0.16	-0.04 ± 0.17	-0.17 ± 0.18
$\bar{\nu}$-Ne [15]	-0.56 ± 0.13	-0.02 ± 0.13	0.08 ± 0.13
ν-p [26]	-0.10 ± 0.14	-0.02 ± 0.16	0.12 ± 0.15
$\bar{\nu}$-p [26]	-0.24 ± 0.17	-0.05 ± 0.16	-0.20 ± 0.17
ν-Ne, $x_F < 0$ [This expt.]	-0.43 ± 0.20	-0.06 ± 0.19	-0.45 ± 0.19
$\bar{\nu}$-Ne, $x_F < 0$ [15]	-0.63 ± 0.13	-0.02 ± 0.14	0.12 ± 0.14
ν-p, $x_F < 0$ [26]	-0.29 ± 0.18	-0.09 ± 0.19	0.19 ± 0.18
$\bar{\nu}$-p, $x_F < 0$ [26]	-0.38 ± 0.18	0.02 ± 0.18	-0.17 ± 0.18
K^0 control sample [This expt.]	-0.02 ± 0.08	0.10 ± 0.08	-0.10 ± 0.08

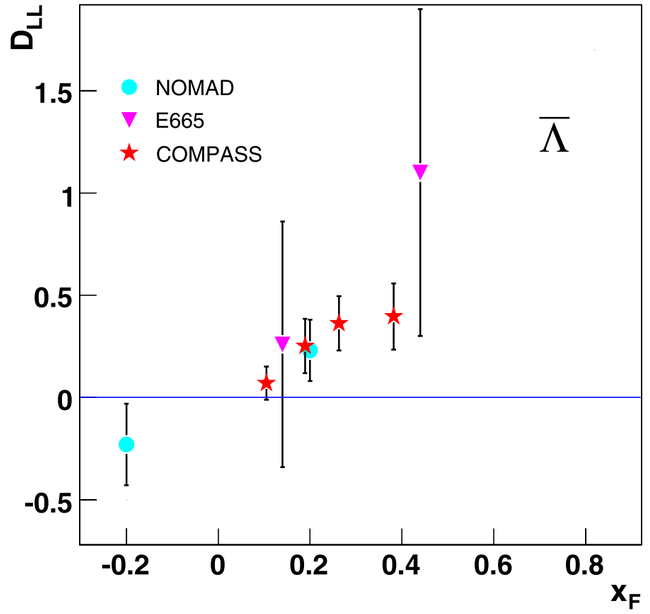
E632 Collaboration, Phys. Rev. D 50 (1994) 6691.

Spin Transfer with Polarized e/μ Beam

Longitudinal polarized e/μ beam on unpolarized target

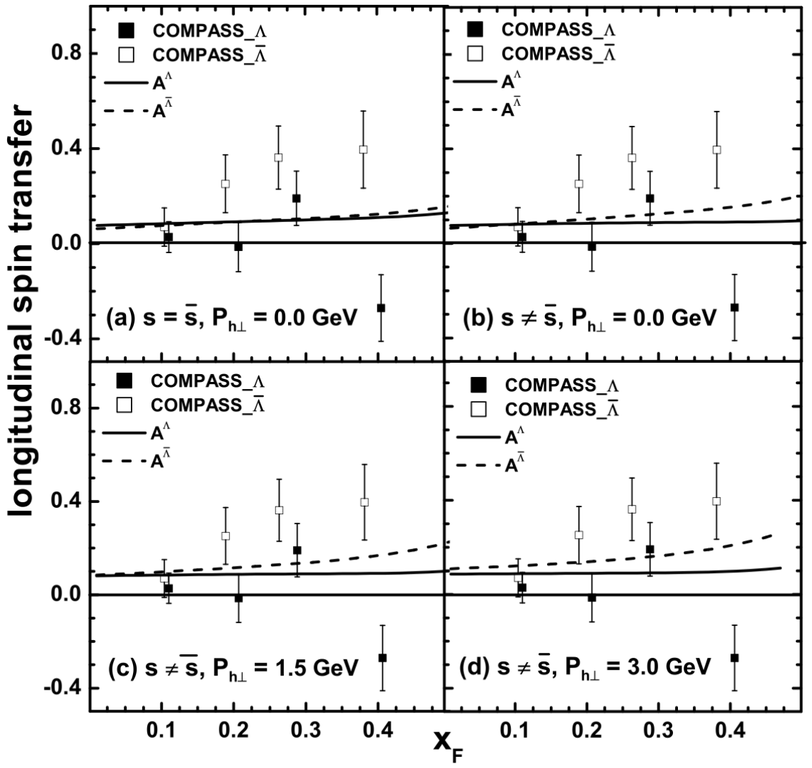
E665 Collaboration, Eur. Phys. J. C 17 (2000) 263.
HERMES Collaboration, Phys. Rev. D 74 (2006) 072004.
COMPASS Collaboration, Eur. Phys. J. C 64 (2009) 171.



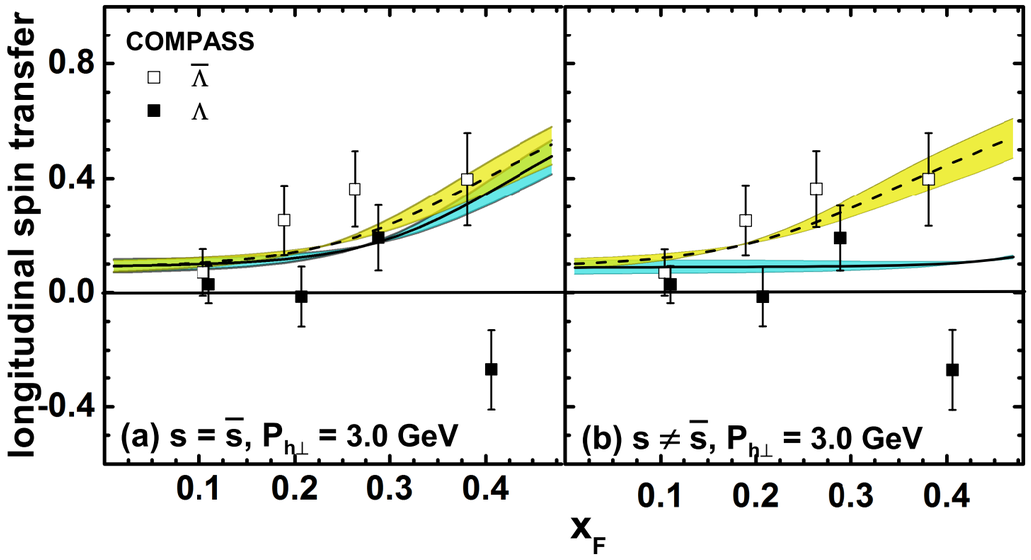


Small spin transfer to Λ, but large spin transfer to $\bar{\Lambda}$

Spin Transfer to Λ and $\bar{\Lambda}$



Y. Chi, X. Du, B.-Q. Ma, Phys. Rev. D 90 (2014) 074003.



X. Du, B.-Q. Ma, Phys. Rev. D 95 (2017) 014029.

Nucleon strange sea asymmetry may be a possible origin of the Λ - $\bar{\Lambda}$ difference.
Sensitive to the flavor separation of fragmentation functions.

Longitudinal Spin Transfer

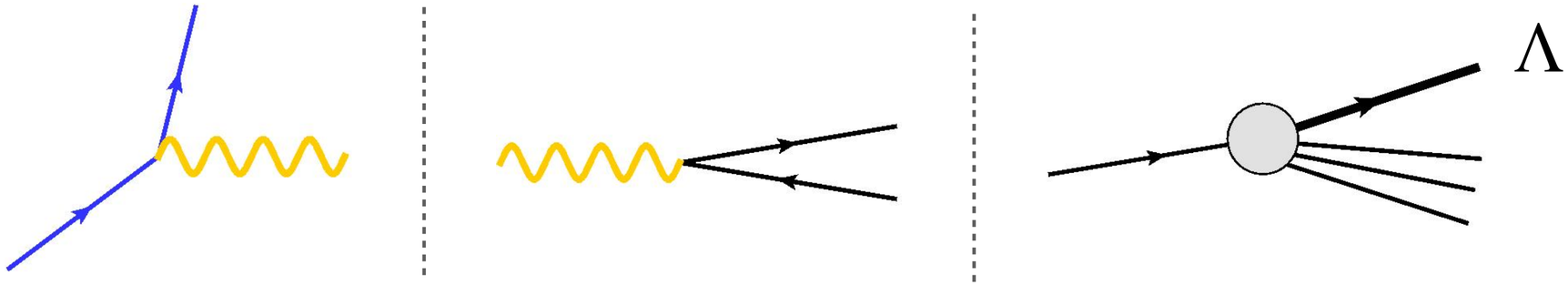
Longitudinal polarized lepton beam on unpolarized nucleon target

$$D_{LL}^{\Lambda} = \frac{G_{U,L}\left(x, Q^2, z\right)}{F_{U,U}\left(x, Q^2, z\right)}$$

$$G_{U,L} \sim f_1(x) \otimes G_1(z)$$

$$F_{U,L} \sim f_1(x) \otimes D_1(z)$$

Illustration of D_{LL}^{Λ} :



emission of polarized photon

preference to pick quark with certain helicity

quark spin transfer to Λ

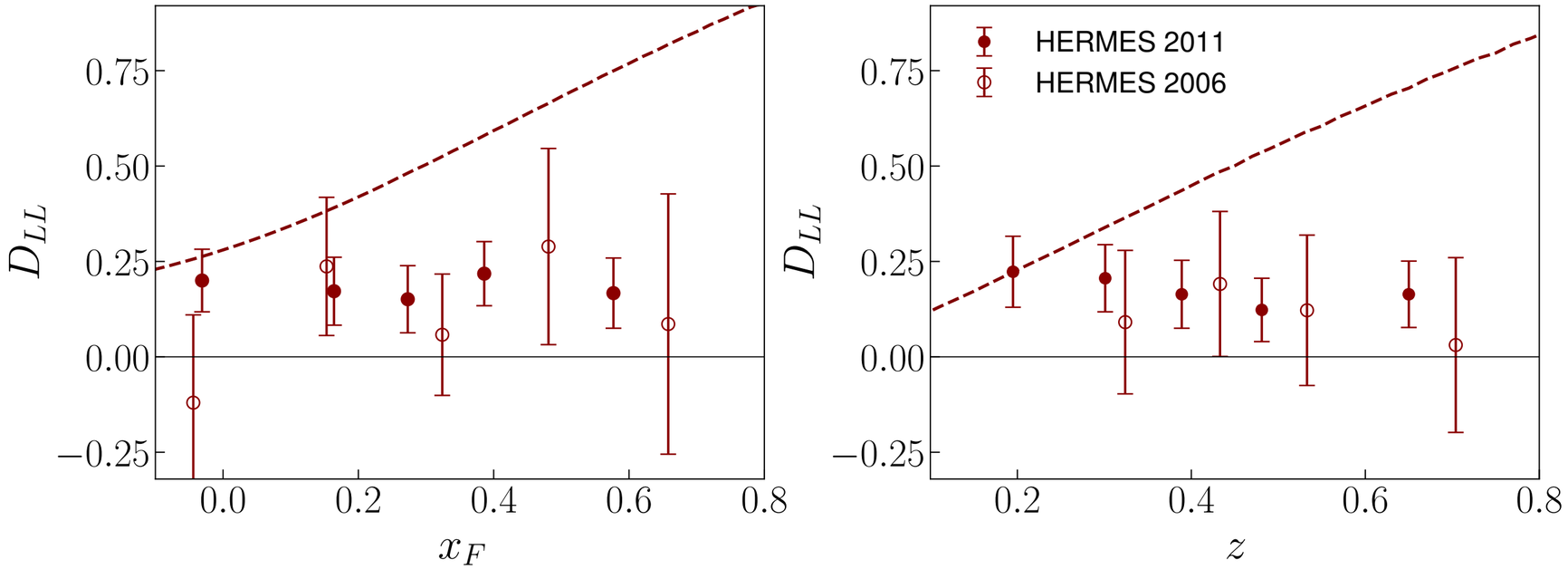
Longitudinal Spin Transfer

Longitudinal polarized lepton beam on unpolarized nucleon target

$$D_{LL}^{\Lambda} = \frac{G_{U,L}\left(x, Q^2, z\right)}{F_{U,U}\left(x, Q^2, z\right)}$$

$$G_{U,L} \sim f_1(x) \otimes G_1(z)$$

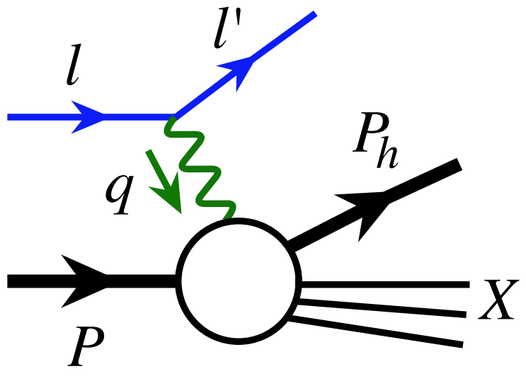
$$F_{U,L} \sim f_1(x) \otimes D_1(z)$$



Theory curves based on JR14 PDF parametrization and DSV FF

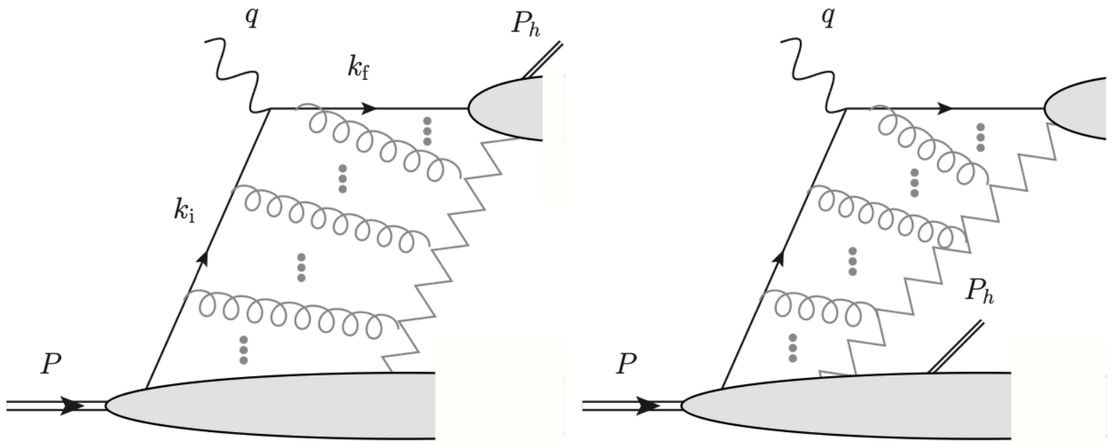
Tension between data and theory with current fragmentation mechanism

How is the Λ Produced in SIDIS?

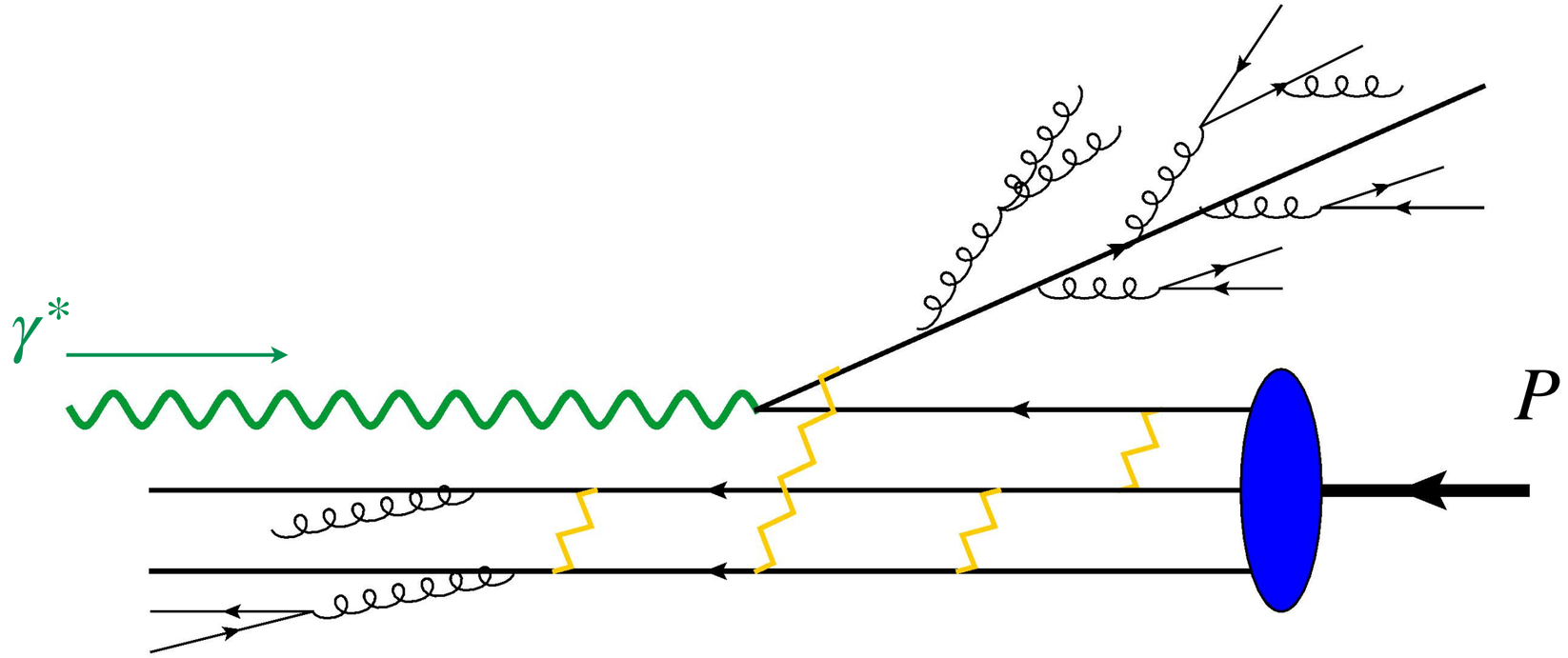


What we know:
A hadron, e.g. Λ, is observed in the final state,
with momentum P_h (and polarization S_h)

What we do not know:
Whether it was produced from the struck quark/parton,
the remnant of the target, or …?

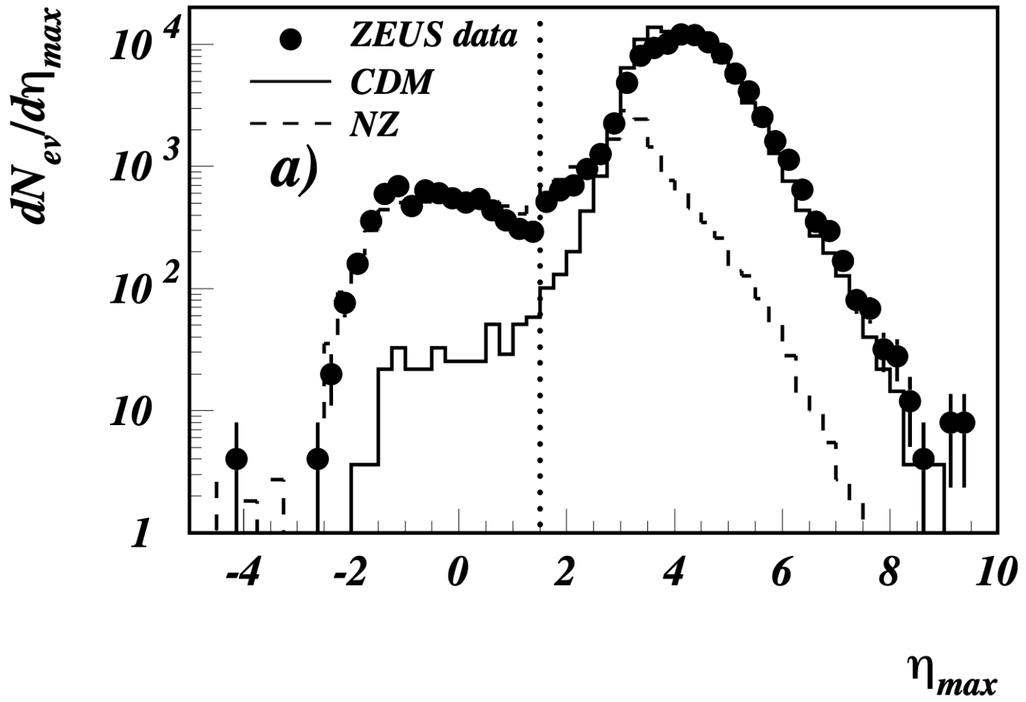


SIDIS Kinematic Regions

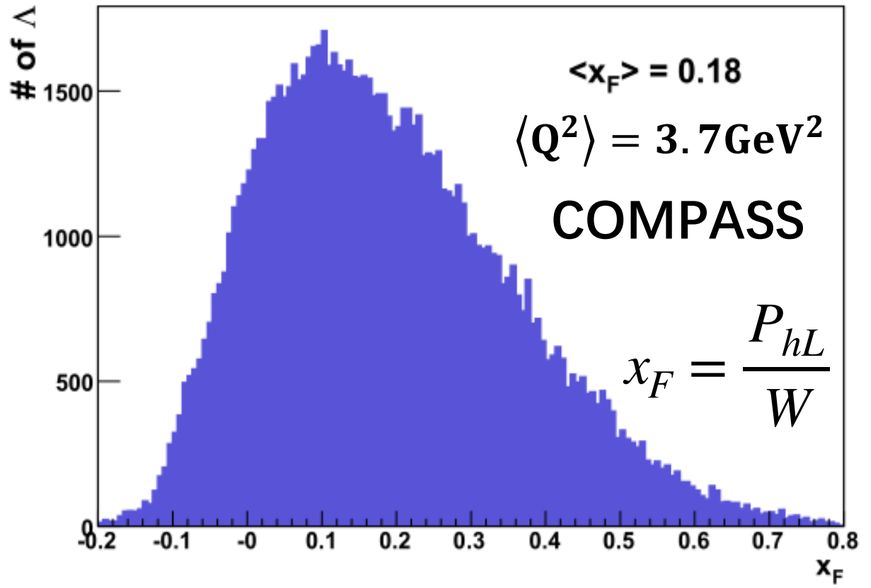


At high energy limit: enough phase space for shower, to match the quantum number of hadrons.
Energy is mostly transferred to the struck quark, produced hadrons dominated by current fragmentation.

Events Distribution



Such expected separations were observed at high energies.



No clear separation between current and target regions at relatively low energies!

Some Attempt to Separate CF and TF

"R" criteria:

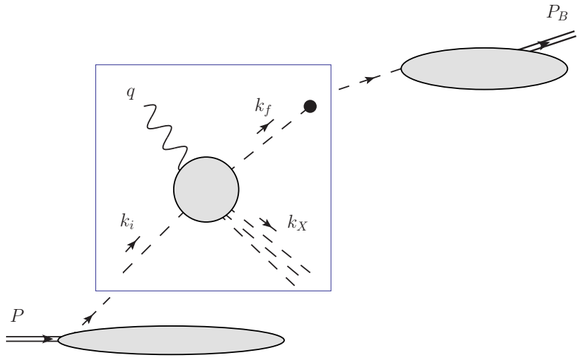
General hardness ratio: $R_0 \equiv \max\left(\frac{k_i^2}{Q^2}, \frac{k_f^2}{Q^2}\right)$

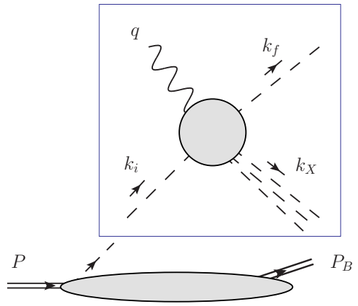
Collinearity ratio: $R_1 \equiv \left|\frac{P_h \cdot k_f}{P_h \cdot k_i}\right|$

R_1 small for current region
R_1^{-1} small for target region

Transverse hardness ratio: $R_2 \equiv \left|\frac{(k_f - q)^2}{Q^2}\right|$

R_2 small for TMD region



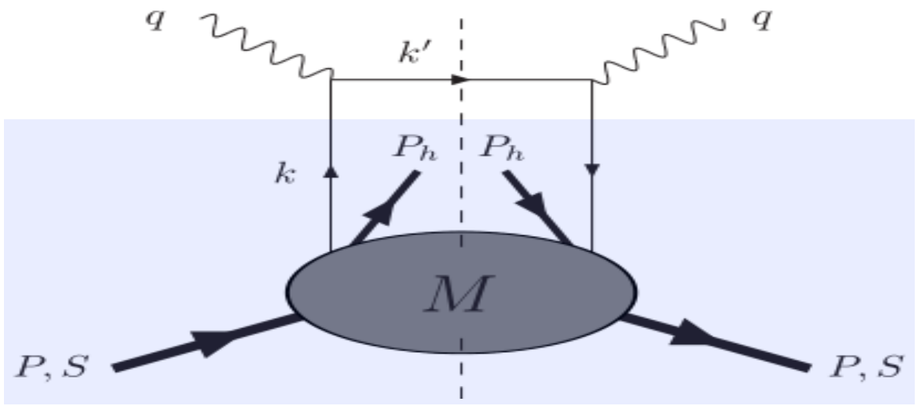


M. Boglione, A. Dotson, L. Gamberg, S. Gordon, J. O. Gonzalez-Hernandez, A. Prokudin, T.C. Rogers, N. Sato, JHEP 10 (2019) 122.

But it relies on partonic level information we want to extract / determine!

Fracture Functions

Correlation function



$$\mathscr{M}_{ij}\left(k;P,S;P_\Lambda,S_\Lambda\right)=\sum_X\int\frac{d^4\xi}{(2\pi)^4}e^{ik\xi}\langle P,S|\bar{\Psi}_j(0)\Big|P_\Lambda,S_\Lambda;X\rangle\left\langle P_\Lambda,S_\Lambda;X\right|\Psi_i(\xi)|P,S\rangle$$

decomposition with Dirac matrices:

$$\mathscr{M}=\frac{1}{2}\left(\mathcal{S}I+\mathcal{V}_\mu\gamma^\mu+\mathcal{A}_\mu\gamma^\mu\gamma_5+i\mathcal{P}\gamma_5+i\mathcal{T}_{\mu\nu}\sigma^{\mu\nu}\gamma_5\right)$$

leading-twist terms can be projected by: $\gamma^+,\quad \gamma^+\gamma_5,\quad i\sigma^{i+}\gamma_5$

M. Anselmino, V. Barone, A. Kotzinian, Phys. Lett. B 699 (2011) 108.

Target vs. Current on D_{LL}^{Λ}

Questions:

Whether TF can compete with CF contributions?

What is the expected effect by TF on D_{LL} measurement?

Quark densities in the nucleon:

$u, d > \bar{u}, \bar{d} > s, \bar{s}$



Current fragmentation:

favored channels: u, d, s

In the target nucleon remnant:

- *ud, us, ds* pairs have better chance to produce Λ than *u, d, s*
- considering quark densities in the nucleon, *ud* pair is expected the dominant channel

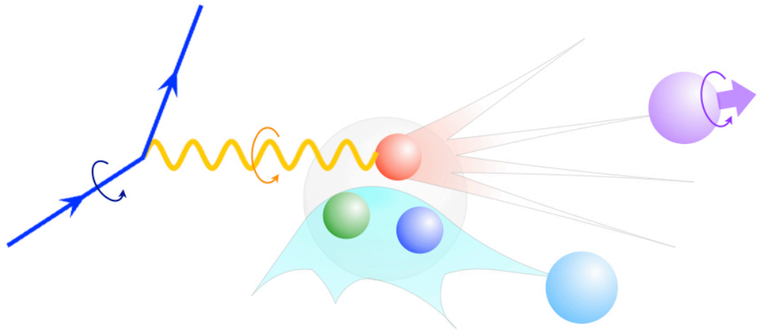
X. Zhao, Z.-t. Liang, TL, Y.-j. Zhou, Phys. Rev. Lett. 134 (2025) 231901.

Target vs. Current on D_{LL}^{Λ}

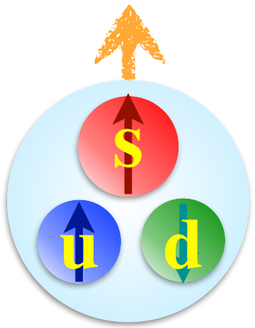
Questions:

Whether TF can compete with CF contributions?

What is the expected effect by TF on D_{LL} measurement?



Spin-flavor wave function



$$\Lambda^{\uparrow} = \frac{1}{\sqrt{3}}(ud)_{0,0}s^{\uparrow} + \frac{1}{\sqrt{12}}(us)_{0,0}d^{\uparrow} - \frac{1}{\sqrt{12}}(ds)_{0,0}u^{\uparrow}$$
$$+\frac{1}{2}\left(\sqrt{\frac{2}{3}}(us)_{1,1}d^{\downarrow} - \sqrt{\frac{1}{3}}(us)_{1,0}d^{\uparrow}\right) - \frac{1}{2}\left(\sqrt{\frac{2}{3}}(ds)_{1,1}u^{\downarrow} - \sqrt{\frac{1}{3}}(ds)_{1,0}u^{\uparrow}\right)$$

In the target nucleon remnant:

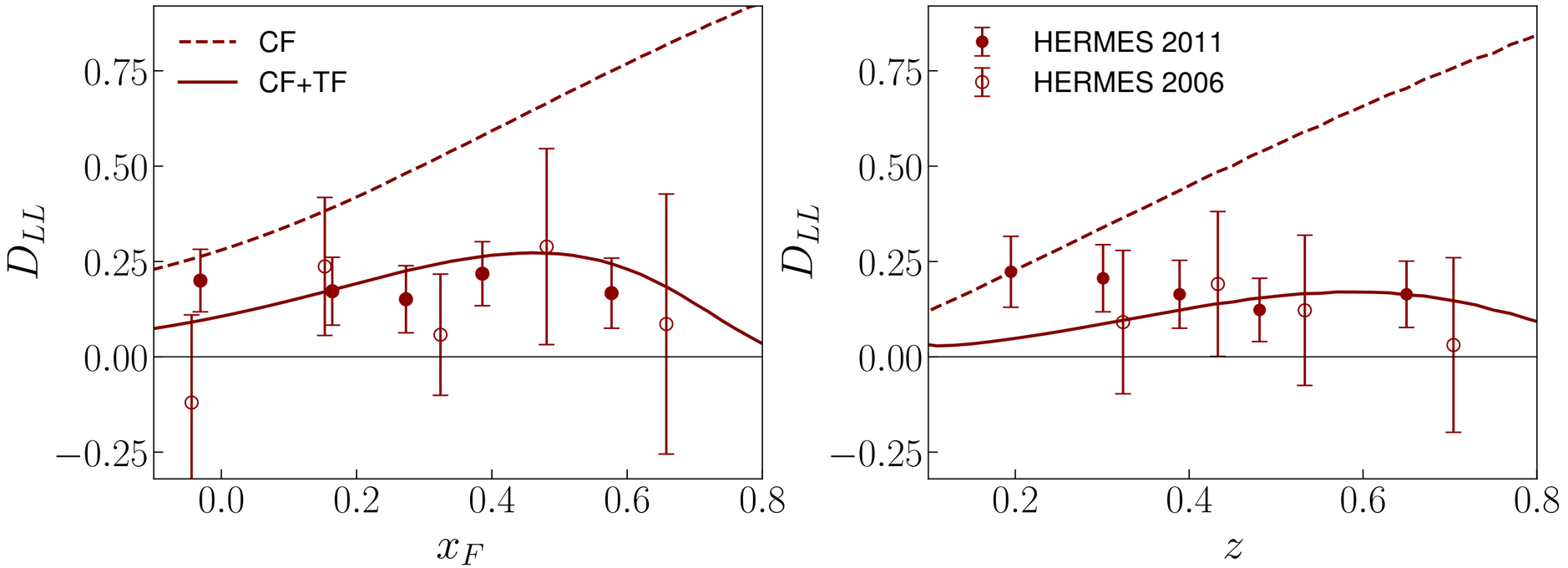
- the target remnant is not directly polarized by the virtual photon
- but can indirectly learn the polarization as constrained by the nucleon wave function
- *ud* pair in a isoscalar state is more likely to produce Λ and will be unpolarized

Expect: the target fragmentation will dilute/suppress the overall measured D_{LL}

X. Zhao, Z.-t. Liang, TL, Y.-j. Zhou, Phys. Rev. Lett. 134 (2025) 231901.

Spin Transfer Estimation

Compare with HERMES data



HERMES Collaboration, Phys. Rev. D 74 (2006) 072004; J. Phys. Conf. Ser. 295 (2011) 012114.

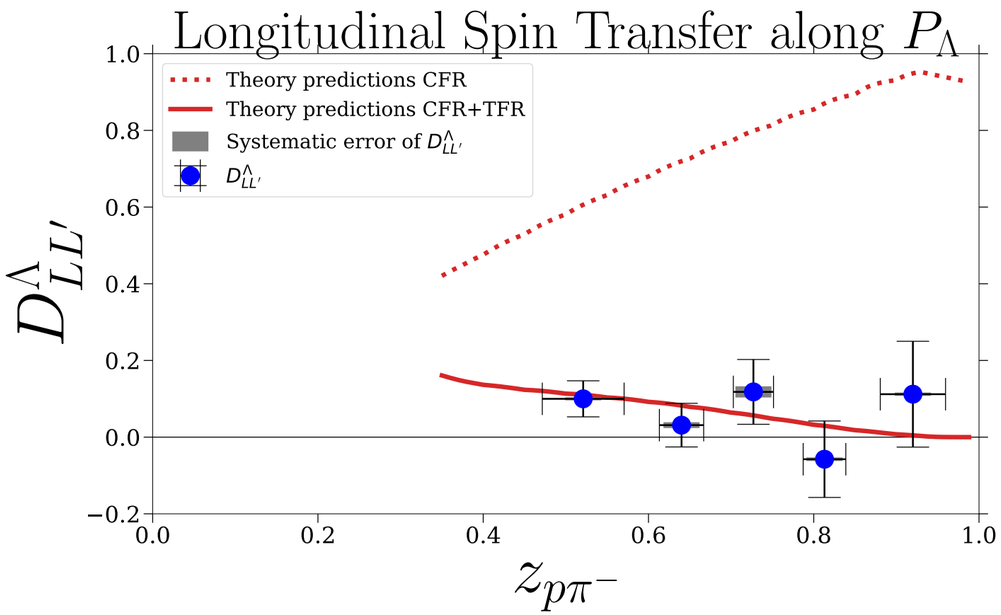
Longitudinal spin transfer D_{LL} to Λ is significantly suppressed by target fragmentation contributions, even at large x_F or z.

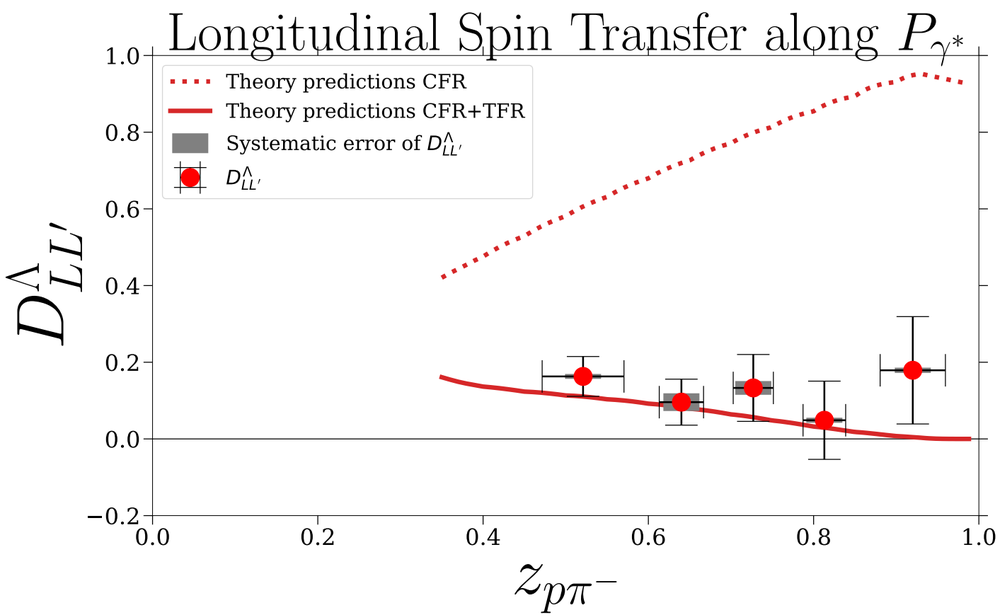
Including only the leading TF channel can describe the data well.

X. Zhao, Z.-t. Liang, TL, Y.-j. Zhou, Phys. Rev. Lett. 134 (2025) 231901.

Spin Transfer Estimation

Reconfirmed by recent JLab CLAS measurement





M. McEneaney *et al.* (CLAS Collaboration), arXiv:2509.05758

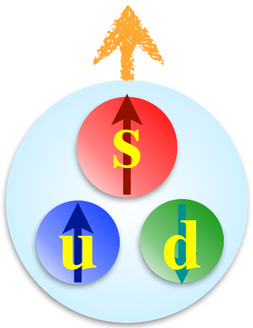
Theory predictions (CFR+TFR) from

X. Zhao, Z.-t. Liang, TL, Y.-j. Zhou, Phys. Rev. Lett. 134 (2025) 231901.

At lower energies, the suppression effect becomes more significant!

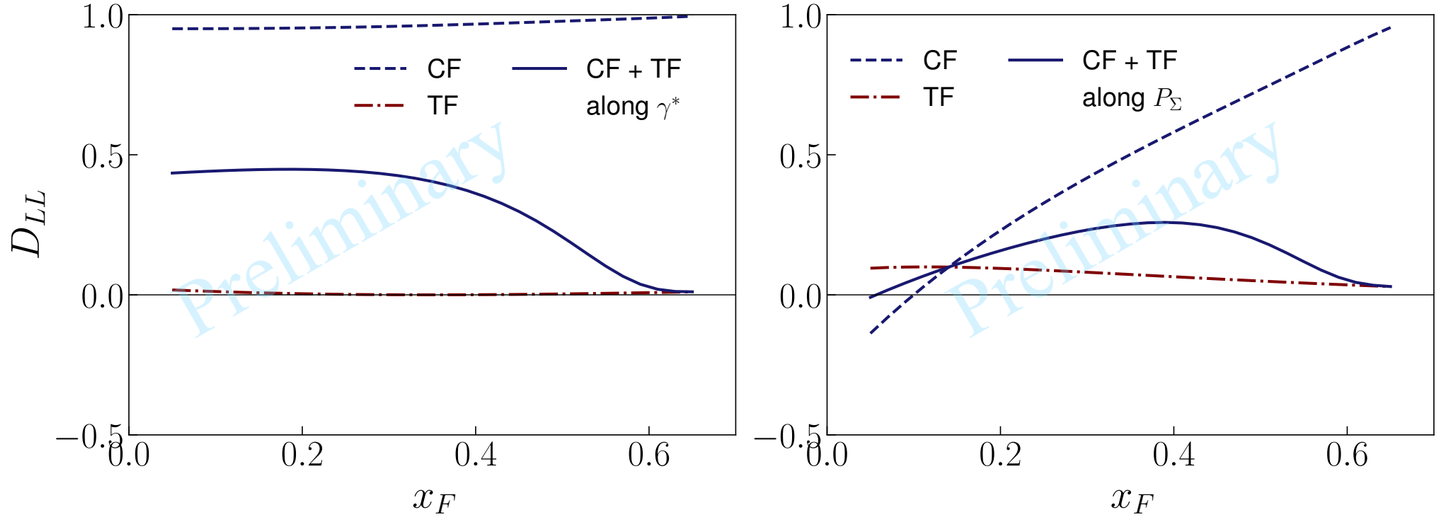
Spin Transfer to Σ^0 Hyperon

Spin-flavor wave function



$$\Sigma^{0\uparrow} = \frac{1}{3}(ud)_{1,0}s^{\uparrow} - \frac{1}{6}(us)_{1,0}d^{\uparrow} - \frac{1}{6}(ds)_{1,0}u^{\uparrow} - \frac{\sqrt{2}}{3}(ud)_{1,1}s^{\downarrow} + \frac{1}{3\sqrt{2}}(us)_{1,1}d^{\downarrow}$$
$$+\frac{1}{3\sqrt{2}}(ds)_{1,1}u^{\downarrow} - \frac{1}{2}(us)_{0,0}d^{\uparrow} - \frac{1}{2}(ds)_{0,0}u^{\uparrow}$$

Longitudinal spin transfer prediction at JLab energy



X. Zhao, TL, Y.-j. Zhou, in preparation, 2026

Summary

- Quark transverse momentum distribution is important in understanding nucleon spin structures
- Helicity distribution
  - in the valence region, quark polarization rate decreases with increasing transverse momentum, supporting the feature of kinetic Wigner rotation effect;
  - sea quark TMD helicity distributions are still almost unknown and polarized pp collisions may provide constraints.
- Transversity distribution
  - sea quarks may have nonzero transverse polarization;
  - positivity bounds need to be tested.
- Lattice QCD can provide complementary information, especially when lacking precise data
- Spin is also a sensitive observable to deepen our understanding of hadronization mechanism.
- At existing fixed-target SIDIS experiments, one cannot clearly separate the current and target fragmentation regions of Λ production events.
- Target fragmentation plays an important role in understanding spin-transfer and related observables.

Thank you!

Backup

Imposing a Bound?

Question:

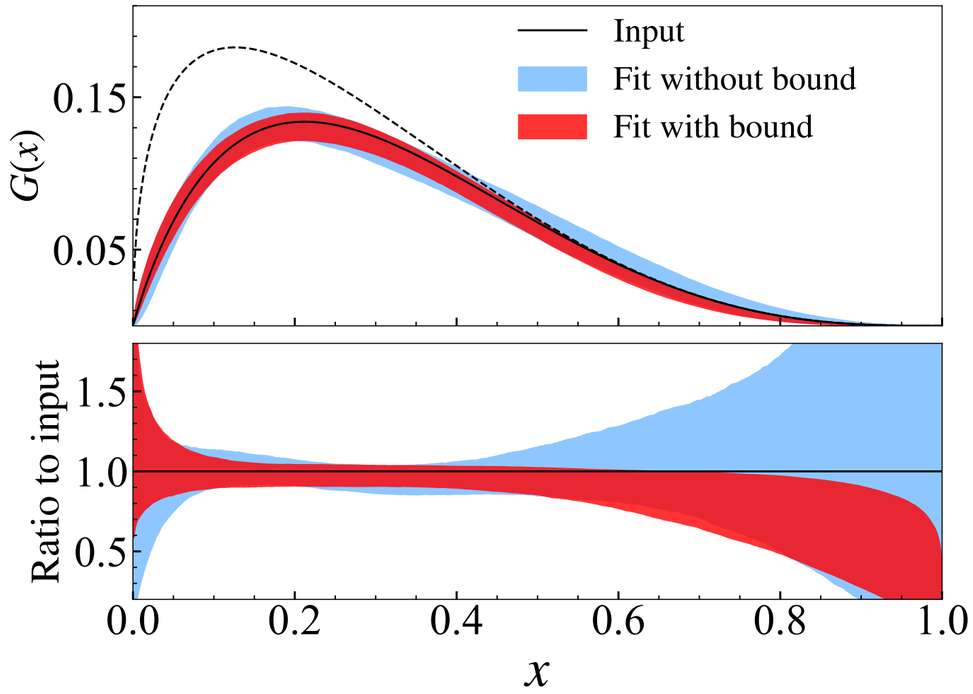
Whether we should impose the bound $|g_1(x)| \leq f_1(x)$ in the fit?
Similar situations in many other quantities.

A toy model test:

Input some "pol" function $G(x)$
and "unpol" function $F(x)$
Generate asymmetry "data"

Fit the "data" with or without
imposing the bound $G(x) \leq F(x)$

Imposing a bound in the fit may bias the fit result!

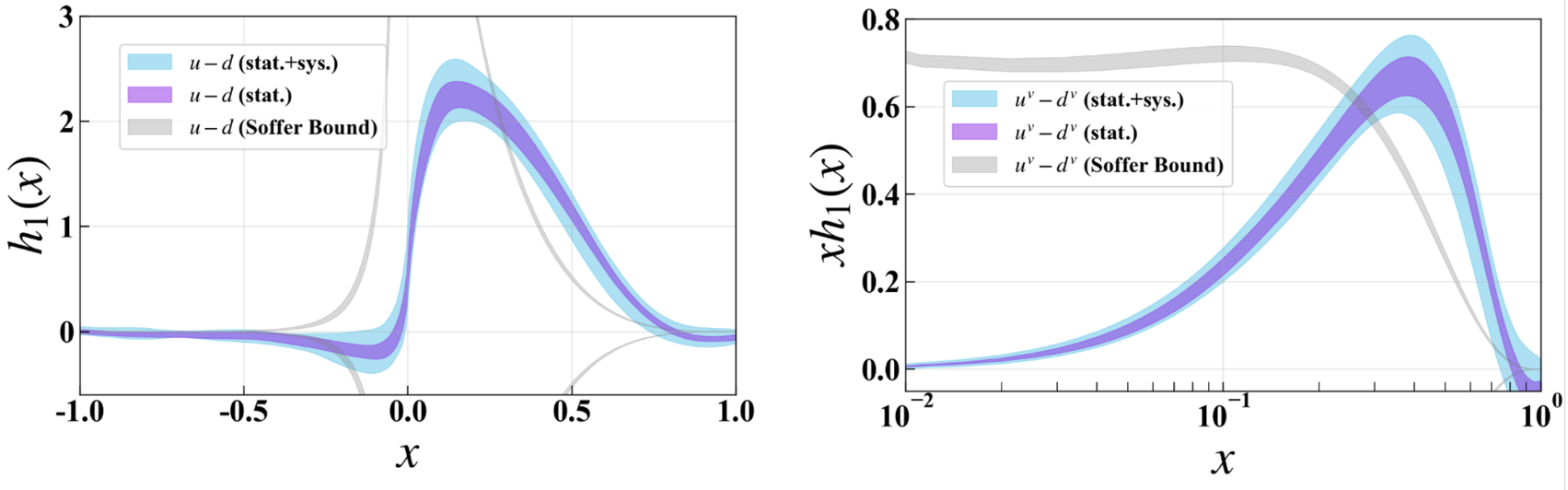


About Soffer's Bound

Soffer's bound on transversity distributions

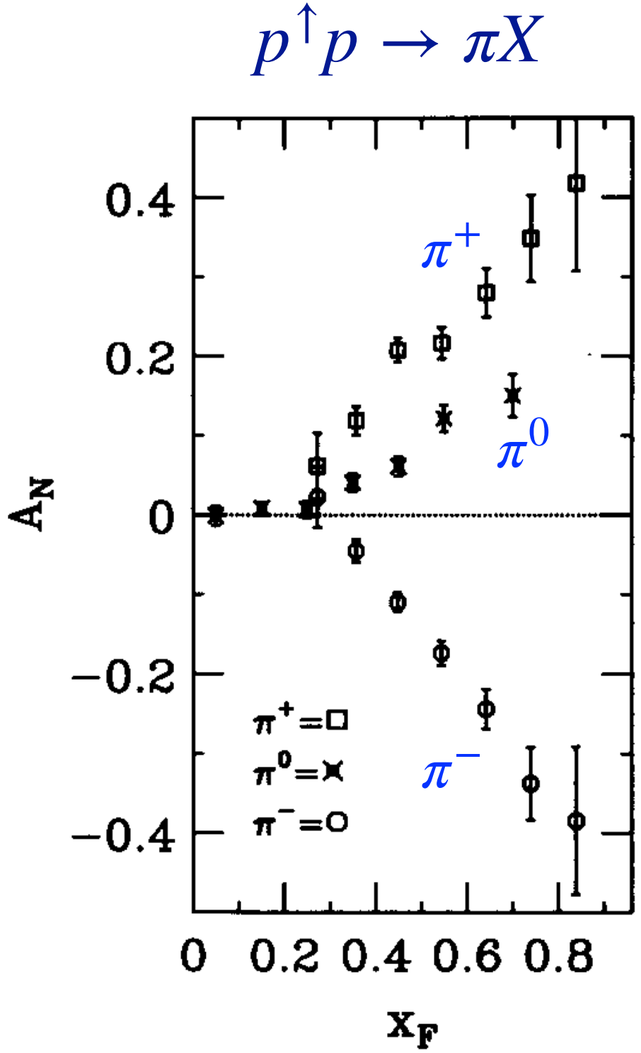
$$|h_1(x)| \leq \frac{1}{2}[f_1(x) + g_1(x)]$$

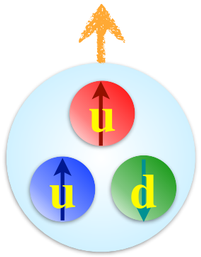
It is broken in existing lattice QCD calculations



Lattice results from: LPC Collaboration, Phys. Rev. Lett. 131 (2023) 261901.

Liang-Boros Model





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

u夸克向上(与质子同向)极化，d夸克向下(与质子反向)极化

强子产额 $\pi^+(u\bar{d})$ 倾向左侧，$\pi^-(d\bar{u})$ 倾向右侧

初态自旋向上u夸克倾向向左，自旋向下d夸克倾向向右

末态u, d夸克相对于产生面倾向于自旋向上

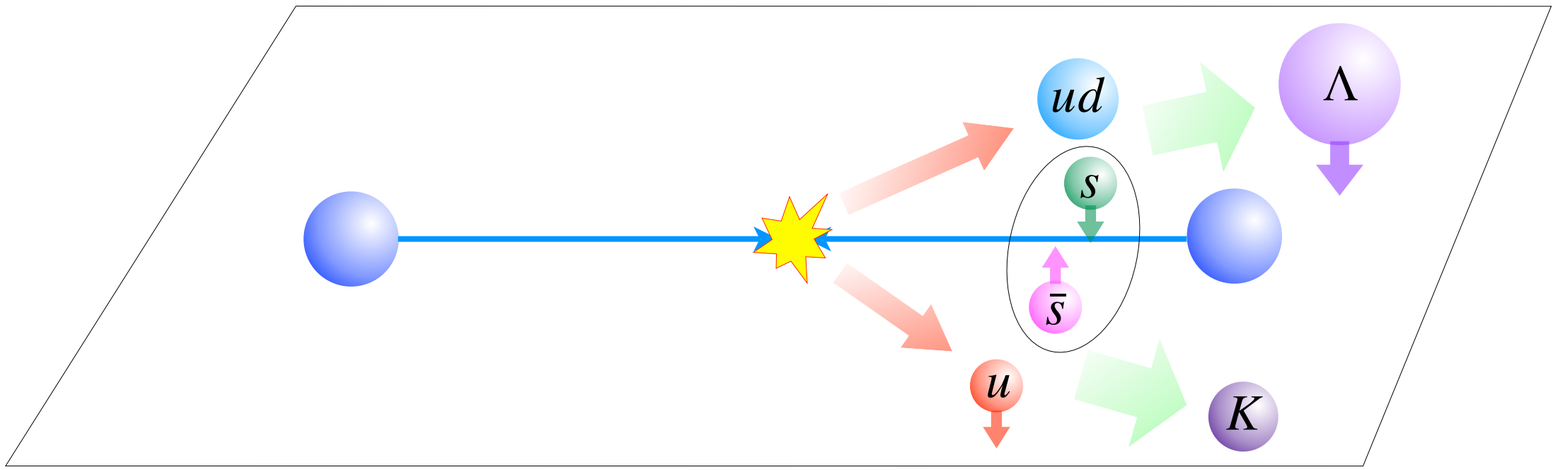
Liang-Boros Model

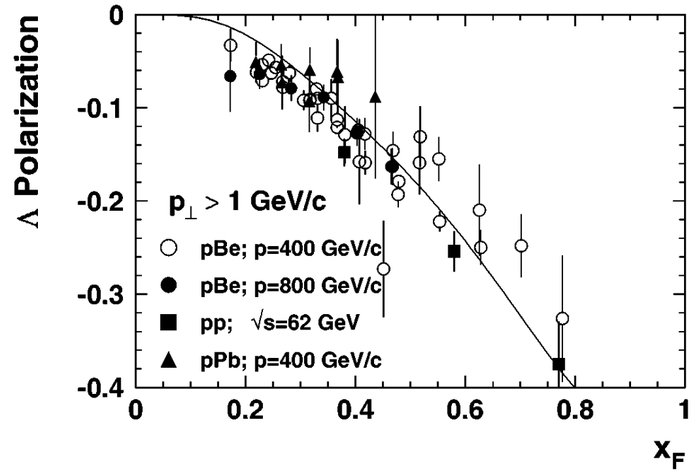
ud 双夸克碎裂为 Λ 的反应道，在 Λ 产生的另一侧有倾向于自旋向下的夸克

海中的 s 与 $\bar{s}$ 横向自旋反关联

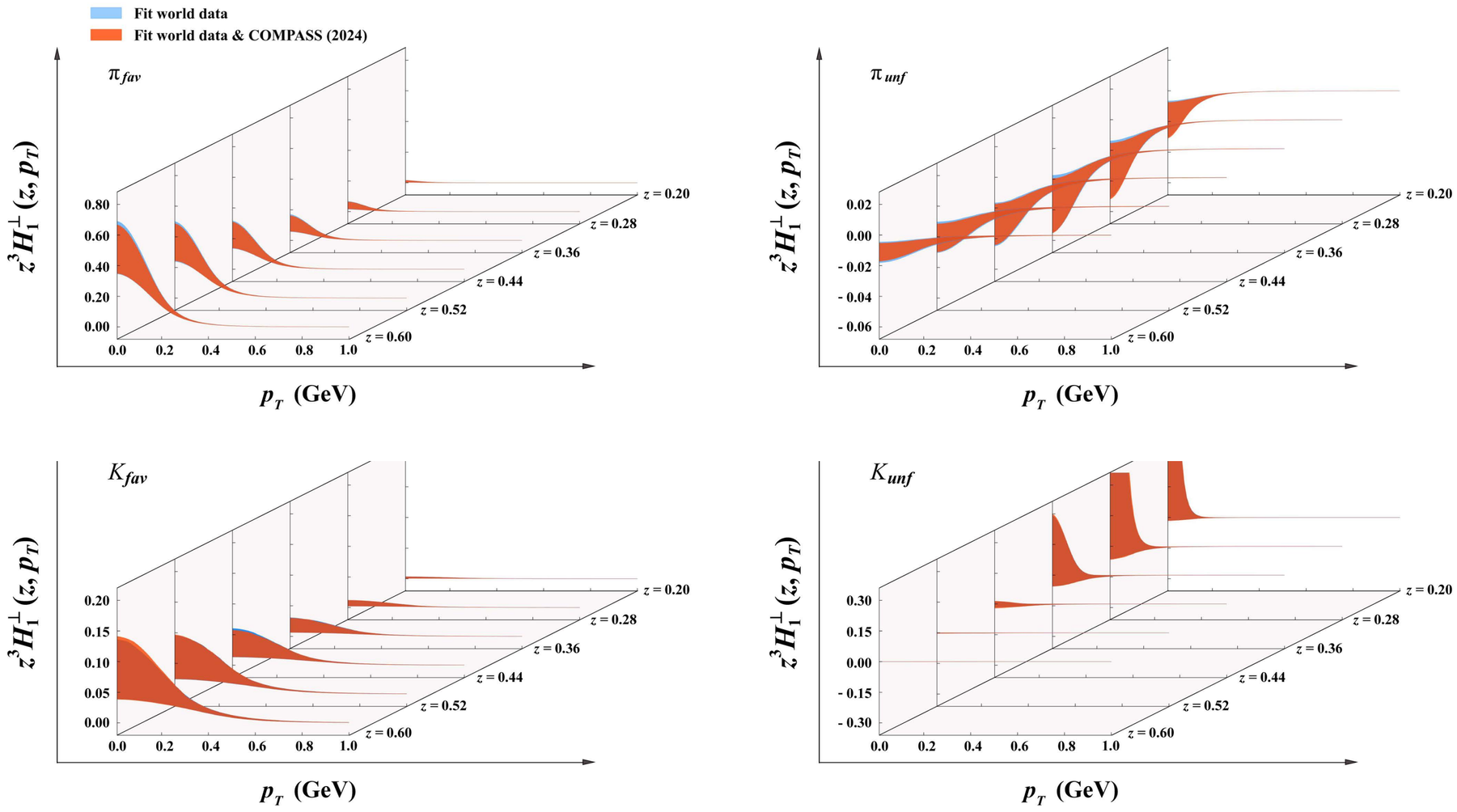
伴随 K 介子产生倾向挑选自旋向上的 s 夸克

与 ud 双夸克组合的 s 夸克更多为自旋向下，自旋转移为 Λ 超子向下极化





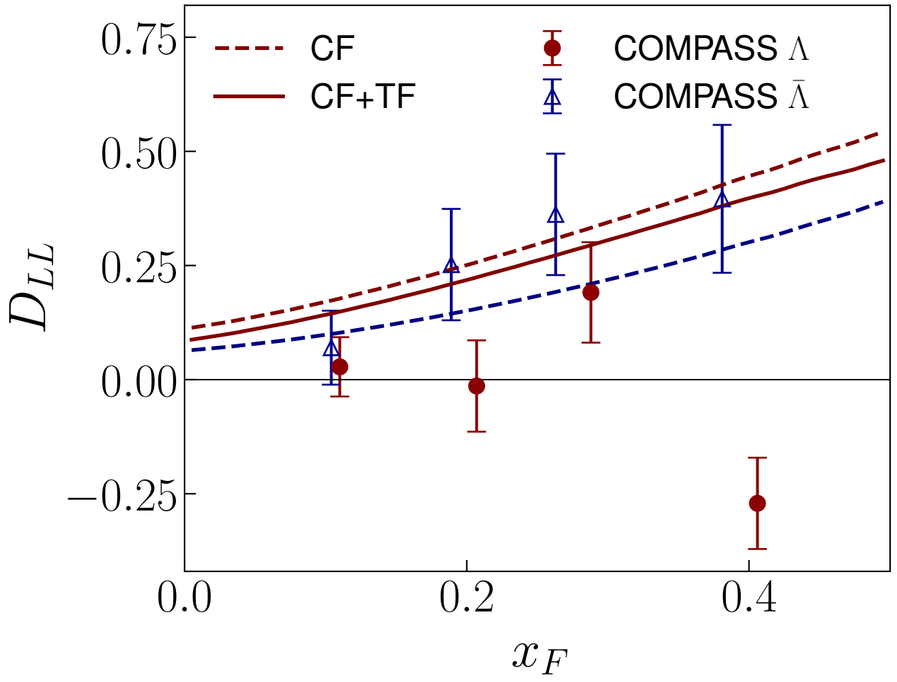
Collins Fragmentation Functions



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

Spin Transfer Estimation

Compare with COMPASS data



COMPASS Collaboration, Eur. Phys. J. C 64 (2009) 171.

- The suppression effect reduces at higher energies, as expected.
- Including the leading TF channel alleviates the tension, but still deviates from data.
- Need detailed analysis including more channels.

- For $\bar{\Lambda}$ production, target fragmentation cannot compete with current fragmentation.
- Only current fragmentation can describe the data.

X. Zhao, Z.-t. Liang, TL, Y.-j. Zhou, Phys. Rev. Lett. 134 (2025) 231901.