Global analysis of Sivers and Collins asymmetries within TMD factorization

Chunhua Zeng

Institute of Modern Physics

November 11, 2024

Collaborators:
Hongxin Dong, Tianbo Liu, peng Sun, Yuxiang Zhao

Contents

Introduction

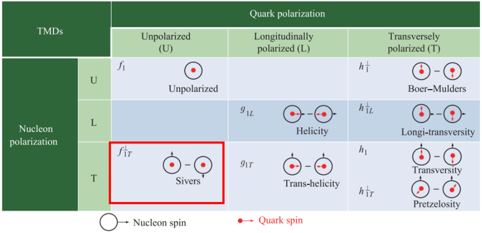
- The three-dimensional structure of the nucleon can be described by TMD PDFs.
- In leading twist, there are eight TMD PDFs.

TMDs		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally polarized (L)	Quark polarization: Transversely polarized (T)
Nucleon polarization	U	f_1 Unpolarized		$h_1^\perp$ Boer–Mulders
Nucleon polarization	L		g_{1L} Helicity	$h_{1L}^\perp$ Longi-transversity
Nucleon polarization	T	$f_{1T}^\perp$ Sivers	g_{1T} Trans-helicity	h_1 Transversity; $h_{1T}^\perp$ Pretzelosity

Nucleon spin   Quark spin

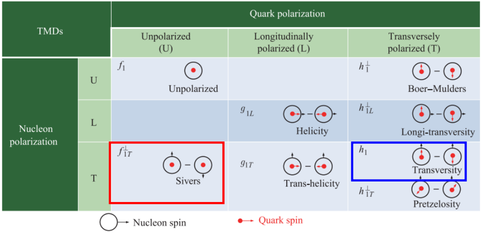
Introduction

- The three-dimensional structure of the nucleon can be described by TMD PDFs.
- In leading twist, there are eight TMD PDFs.



- $f_{1T}^{\perp}$(Sivers): Describes an unpolarized quark inside a transversely polarized hadron.

- The three-dimensional structure of the nucleon can be described by TMD PDFs.
- In leading twist, there are eight TMD PDFs.



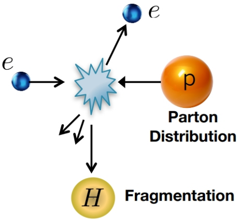
- $f_{1T}^{\perp}$(Sivers): Describes an unpolarized quark inside a transversely polarized hadron.
- h_1(Transversity): Describes a transversely polarized quark inside a transversely polarized hadron.

Introduction

TMDs can be studied experimentally through SIDIS, SIA, and DY processes.

Introduction

TMDs can be studied experimentally through SIDIS, SIA, and DY processes.



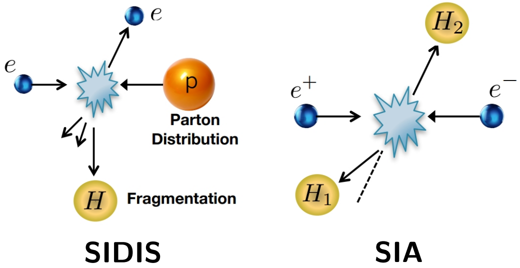
SIDIS

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

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1 \otimes H_1^{\perp}$$

Introduction

TMDs can be studied experimentally through SIDIS, SIA, and DY processes.



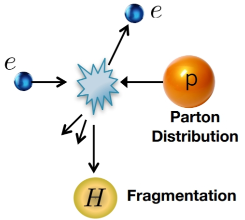
$$A_{UT,T}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp} \otimes D_1$$

$$A_0^{UL} \propto H_1^{\perp} \otimes H_1^{\perp}$$

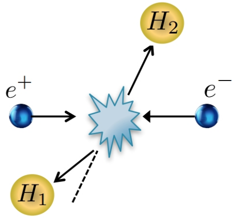
$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1 \otimes H_1^{\perp}$$

Introduction

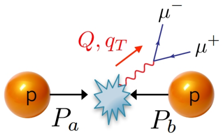
TMDs can be studied experimentally through SIDIS, SIA, and DY processes.



SIDIS



SIA



$$q_T \ll Q$$

DY

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

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1 \otimes H_1^{\perp}$$

$$A_0^{UL} \propto H_1^{\perp} \otimes H_1^{\perp}$$

$$A_{UT}^{\sin\phi} \propto f_{1T}^{\perp} \otimes f_1$$

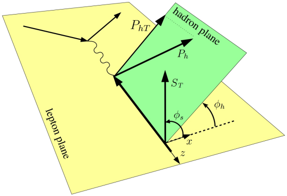
Contents

SIDIS: $l(l)+p(P)\to l(l')+h(P_h)+X$

The SIDIS cross section can be written as

$$\frac{d\sigma}{dxdydzd\phi_h d\phi_s dP_{h\perp}^2}=\frac{\alpha_{em}^2}{xyQ^2}(1-y+\frac{1}{2}y^2)\{F_{UU,T}+ S_T[\sin(\phi_h-\phi_s)F_{UT,T}^{\sin(\phi_h-\phi_s)}+\varepsilon\sin(\phi_h+\phi_s)F_{UT}^{\sin(\phi_h+\phi_s)}]+\ldots\},$$

The Sivers and Collins asymmetries for SIDIS process are



The SIDIS process in $\gamma^* p$ center of mass frame.

$$A_{UT,T}^{\sin(\phi_h-\phi_s)}=\frac{F_{UT,T}^{\sin(\phi_h-\phi_s)}}{F_{UU,T}}=\frac{\hat{\sigma}_{eq\to e'q'}\otimes f_{1T}^{\perp}\otimes D_1]}{\hat{\sigma}_{eq\to e'q'}\otimes f_1\otimes D_1}$$

$$A_{UT}^{\sin(\phi_h+\phi_s)}=\frac{F_{UT}^{\sin(\phi_h+\phi_s)}}{F_{UU,T}}=\frac{\hat{\sigma}_{eq\to e'q'}\otimes h_1\otimes H_1^{\perp}}{\hat{\sigma}_{eq\to e'q'}\otimes f_1\otimes D_1}$$

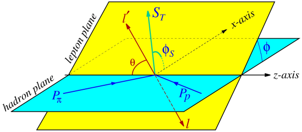
- $f_{1T}^{\perp}$: Sivers function
- h_1: Transversity function
- $H_1^{\perp}$: Collins function

DY: $h_1(P_1, S_1) + h_2(P_2, S_2) \rightarrow \gamma^* \rightarrow l^+ l^-$

The DY cross section can be written as

$$\frac{d\sigma}{d^4 q d\Omega} = \frac{\alpha_{em}^2}{\mathscr{F} Q^2}\{(1+cos^2\theta)F_{UU}^1 + S_T(1-cos^2\theta)\sin\phi_s F_{UT}^{sin\phi_s} + ...\},$$

The Sivers transverse-spin-dependent asymmetries for DY process are



The DY process in the Collins-Soper frame .

$$A_{UT}^{\sin\phi_s} = \frac{F_{UT}^{\sin\phi_s}}{F_{UU}^1} = \frac{\hat{\sigma}_{q\bar{q}\rightarrow l\bar{l}} \otimes f_{1T}^{\perp} \otimes f_1}{\hat{\sigma}_{q\bar{q}\rightarrow l\bar{l}} \otimes f_1 \otimes f_1}$$

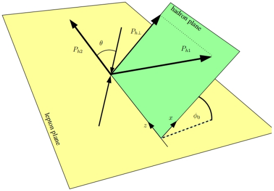
- $f_{1T}^{\perp}$: Sivers function

SIA: $e^+(P_{e^+}) + e^-(P_{e^-}) \to h_1(P_{h_1}) + h_2(P_{h_2}) + X$

In the limit of small transverse momentum $P_{h\perp}$, the cross section as predicted by TMD factorization reads

$$\frac{d^5\sigma}{dz_{h1}dz_{h2}d^2P_{h\perp}d\cos\theta} = \frac{N_c\pi\alpha_{em}^2}{2Q^2} z_{h1}^2 z_{h2}^2 \left[(1+\cos^2\theta)F_{UU} + \sin^2\theta\cos(2\phi_0)F_{UU}^{\cos 2\phi_0}\right].$$

The collins asymmetries for SIA process are



The SIA process in the frame of z axis along one of the detected hadrons.

$$A_0^{UL} \propto \frac{F_{UU}^{\cos 2\phi_0}}{F_{UU}} = \frac{\hat{\sigma}_{e\bar{e}\to q\bar{q}} \otimes H_1^\perp \otimes H_1^\perp]}{\hat{\sigma}_{e\bar{e}\to q\bar{q}} \otimes D_1 \otimes D_1}$$

- $H_1^\perp$: Collins function

Choice of unpolarized TMD

At small value of b, the TMD distribution could be related to collinear distributions

$$f_{1,f\leftarrow h}(x,b;Q,Q^2) = \sum_{f'} \int_x^1 \frac{dy}{y} C_{f\leftarrow f'}(y,b,\mu_{\mathrm{OPE}}^{\mathrm{PDF}}) \times f_{1,f'\leftarrow h}\left(\frac{x}{y},\mu_{\mathrm{OPE}}^{\mathrm{PDF}}\right) f_{\mathrm{NP}}(x,b) R(Q,b),$$

$$D_{1,f\to h}(z,b;Q,Q^2) = \frac{1}{z^2}\sum_{f'} \int_z^1 \frac{dy}{y} y^2 \mathbb{C}_{f\to f'}(y,b,\mu_{\mathrm{OPE}}^{\mathrm{FF}}) \times d_{1,f'\to h}\left(\frac{z}{y},\mu_{\mathrm{OPE}}^{\mathrm{FF}}\right) D_{\mathrm{NP}}(z,b) R(Q,b).$$

$f_{\mathrm{NP}}(x,b)$, $D_{\mathrm{NP}}(z,b)$ and the non-perturbative parts of the evolution factor $R(Q,b)$ are obtained from the fitting results in SV19 with ζ-prescription.

- SV19: JHEP06(2020)137

parametric form

Sivers function:(13 prameters for u, d, $\bar{u}$, $\bar{d}$)

Transversity function:(13 prameters for u, d, $\bar{u}$, $\bar{d}$)

Collins function:(22 prameters for π_{fav}, π_{unf}, K_{fav}, K_{unf})

parametric form

Sivers function:(13 prameters for u, d, $\bar{u}$, $\bar{d}$)

$$f_{1T;q\leftarrow p}^{\perp}(x,b) = N_q \frac{(1-x)^{\alpha_q} x^{\beta_q} (1+\epsilon_q x)}{n(\beta_q,\epsilon_q,\alpha_q)} \exp\left(-r_q b^2\right) f_{1,q}(x)$$

Transversity function:(13 prameters for u, d, $\bar{u}$, $\bar{d}$)

$$h_{1;q\leftarrow p}(x,b) = N_q \frac{(1-x)^{\alpha_q} x^{\beta_q} (1+\epsilon_q x)}{n(\beta_q,\epsilon_q,\alpha_q)} \exp\left(-r_q b^2\right) f_{1,q}(x)$$

Collins function:(22 prameters for π_{fav}, π_{unf}, K_{fav}, K_{unf})

parametric form

Sivers function:(13 prameters for u, d, $\bar{u}$, $\bar{d}$)

$$f_{1T;q\leftarrow p}^{\perp}(x,b) = N_q \frac{(1-x)^{\alpha_q} x^{\beta_q}(1+\epsilon_q x)}{n(\beta_q,\epsilon_q,\alpha_q)} \exp\left(-r_q b^2\right) f_{1,q}(x)$$

Transversity function:(13 prameters for u, d, $\bar{u}$, $\bar{d}$)

$$h_{1;q\leftarrow p}(x,b) = N_q \frac{(1-x)^{\alpha_q} x^{\beta_q}(1+\epsilon_q x)}{n(\beta_q,\epsilon_q,\alpha_q)} \exp\left(-r_q b^2\right) f_{1,q}(x)$$

Collins function:(22 prameters for π_{fav}, π_{unf}, K_{fav}, K_{unf})

$$H_{1;q\to h}^{\perp}(z,b) = \frac{1}{z^2} N_q \frac{(1-z)^{\alpha_q} z^{\beta_q}(1+\epsilon_q z)}{n(\beta_q,\epsilon_q,\alpha_q)} \times \exp\left(-\frac{\eta_{1q} z + \eta_{2q}(1-z)}{\sqrt{1+\eta_{3q}(b/z)^2}} \frac{b^2}{z^2}\right)\left(1+\eta_{4q}\frac{b^2}{z^2}\right)$$

Contents

Data selection:SIDIS data

Measurement: Collins and Sivers asymmetries

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1 \otimes H_1^{\perp}, \qquad A_{UT,T}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp} \otimes f_1$$

Data selection:SIDIS data

Measurement: Collins and Sivers asymmetries

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1 \otimes H_1^{\perp}, \qquad A_{UT,T}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp} \otimes f_1$$

- HERMES:The data to be presented during the 2002–2005 running period at the HERA lepton storage ring.
  1. J. High Energy Phys. 12 (2020) 010
- COMPASS: The data to be presented during the 2002–2005, 2007, 2010 and 2022 running period at CERN.
  1. Phys. Lett. B 673 (2009) 127–135
  2. Phys. Lett. B 744 (2015) 250–259
- JLab: Performed in Jefferson Lab (JLab) Hall A from 2008/11 to 2009/02.
  1. Phys. Rev. Lett. 107, 072003 (2011)
  2. Phys. Rev. C 90, 055201 (2014)

Data selection:SIDIS data

Measurement: Collins and Sivers asymmetries

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1 \otimes H_1^{\perp}, \qquad A_{UT,T}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp} \otimes f_1$$

- HERMES:The data to be presented during the 2002–2005 running period at the HERA lepton storage ring.
  1. J. High Energy Phys. 12 (2020) 010
- COMPASS: The data to be presented during the 2002–2005, 2007, 2010 and 2022 running period at CERN.
  1. Phys. Lett. B 673 (2009) 127–135
  2. Phys. Lett. B 744 (2015) 250–259
  3. Phys. Rev.Lett. 133 (2024) 101903.

  High precision
- JLab: Performed in Jefferson Lab (JLab) Hall A from 2008/11 to 2009/02.
  1. Phys. Rev. Lett. 107, 072003 (2011)
  2. Phys. Rev. C 90, 055201 (2014)

Data selection: SIDIS data

Data set	Target	Beam	Data points	Reaction
HERMES	H_2	27.6 GeV $e^{\pm}$	172(192)	$e^{\pm}p \to e^{\pm}\pi^{+}X$ $e^{\pm}p \to e^{\pm}\pi^{-}X$ $e^{\pm}p \to e^{\pm}K^{+}X$ $e^{\pm}p \to e^{\pm}K^{-}X$
COMPASS2009	^{6}LiD	160 GeV μ^{+}	75(104)	$\mu^{+}d \to \mu^{+}\pi^{+}X$ $\mu^{+}d \to \mu^{+}\pi^{-}X$ $\mu^{+}d \to \mu^{+}K^{+}X$ $\mu^{+}d \to \mu^{+}K^{-}X$
COMPASS2015	NH_3	160 GeV μ^{+}	75(104)	$\mu^{+}p \to \mu^{+}\pi^{+}X$ $\mu^{+}p \to \mu^{+}\pi^{-}X$ $\mu^{+}p \to \mu^{+}K^{+}X$ $\mu^{+}p \to \mu^{+}K^{-}X$
COMPASS2024	^{6}LiD	160 GeV μ^{+}	38(52)	$\mu^{+}d \to \mu^{+}h^{+}X$ $\mu^{+}d \to \mu^{+}h^{-}X$
JLab2011	^{3}He	5.9 GeV e^{-}	8(8)	$e^{-}n \to e^{-}\pi^{+}X$ $e^{-}n \to e^{-}\pi^{-}X$
JLab2014	^{3}He	5.9 GeV e^{-}	5(5)	$e^{-\,3}\text{He} \to e^{-}K^{+}X$ $e^{-\,3}\text{He} \to e^{-}K^{-}X$

Data selection: SIDIS data

Data set	Target	Beam	Data points	Reaction
HERMES	H_2	27.6 GeV $e^{\pm}$	172(192)	$e^{\pm}p \to e^{\pm}\pi^{+}X$
				$e^{\pm}p \to e^{\pm}\pi^{-}X$
				$e^{\pm}p \to e^{\pm}K^{+}X$
				$e^{\pm}p \to e^{\pm}K^{-}X$
COMPASS2009	^{6}LiD	160 GeV μ^{+}	75(104)	$\mu^{+}d \to \mu^{+}\pi^{+}X$
				$\mu^{+}d \to \mu^{+}\pi^{-}X$
				$\mu^{+}d \to \mu^{+}K^{+}X$
				$\mu^{+}d \to \mu^{+}K^{-}X$
COMPASS2015	NH_3	160 GeV μ^{+}	75(104)	$\mu^{+}p \to \mu^{+}\pi^{+}X$
				$\mu^{+}p \to \mu^{+}\pi^{-}X$
				$\mu^{+}p \to \mu^{+}K^{+}X$
				$\mu^{+}p \to \mu^{+}K^{-}X$
COMPASS2024	^{6}LiD	160 GeV μ^{+}	38(52)	$\mu^{+}d \to \mu^{+}h^{+}X$
				$\mu^{+}d \to \mu^{+}h^{-}X$
JLab2011	^{3}He	5.9 GeV e^{-}	8(8)	$e^{-}n \to e^{-}\pi^{+}X$
				$e^{-}n \to e^{-}\pi^{-}X$
JLab2014	^{3}He	5.9 GeV e^{-}	5(5)	$e^{-}\,^3\text{He} \to e^{-}K^{+}X$
				$e^{-}\,^3\text{He} \to e^{-}K^{-}X$

For validity of the TMD factorization, Only small δ data are selected:

$$\delta = P_{h\perp}/z/Q < 1. \tag{1}$$

Data selection: DY data

Measurement: Sivers asymmetries

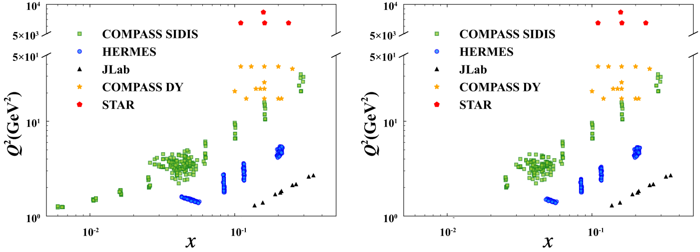
$$A_{UT}^{sin\phi} \propto f_{1T}^{\perp} \otimes f_1$$

- COMPASS: The dimuon production data were collected in 2015 and in 2018 at CERN.
  1. Phys. Rev. Lett. 133 (2024) 071902
- STAR: The data sample was collected in 2011($W^{\pm}$) and 2011-2013,2017(Z^0) at RHIC.
  1. Phys. Rev. Lett. 116 (2016) 132301
  2. Phys. Lett. B854 (2024) 138715

Data set	Reaction	Data points
COMPASS	$\pi^- + p^\uparrow \to \gamma^* + X$	15(15)
STAR.W+	$p^\uparrow + p \to W^+ + X$	8(8)
STAR.W-	$p^\uparrow + p \to W^- + X$	8(8)
STAR.Z	$p^\uparrow + p \to \gamma^*/Z + X$	1(1)

Data selection

The kinematic distributions of the data for SIDIS, Drell-Yan in $x - Q^2$ planes without(495) and with(405) δ cut .



Data seleciton SIA data

Measurement: Collins asymmetries

$$A_0^{UL} \propto H_{1T}^{\perp} \otimes H_{1T}^{\perp}$$

- Belle:
  1. Phys. Rev. D 78, 032011 (2008); 86, 039905(E) (2012).
- BABAR:
  1. Phys. Rev. D 90, 052003 (2014).
  2. Phys. Rev. D 92, 111101 (2015).
- BESIII:
  1. Phys. Rev.Lett. 116, 042001 (2016).

Data set	Energy	Data points	Reaction
BELLE2008	10.58 GeV	16(16)	$e^+e^- \to \pi\pi X$
BABAR2014	10.6 GeV	45(45)	$e^+e^- \to \pi\pi X$
BABAR2015	10.6 GeV	48(48)	$e^+e^- \to \pi\pi X$
			$e^+e^- \to \pi K X$
			$e^+e^- \to K K X$
BESIII2016	3.65 GeV	11(11)	$e^+e^- \to \pi\pi X$

Contents

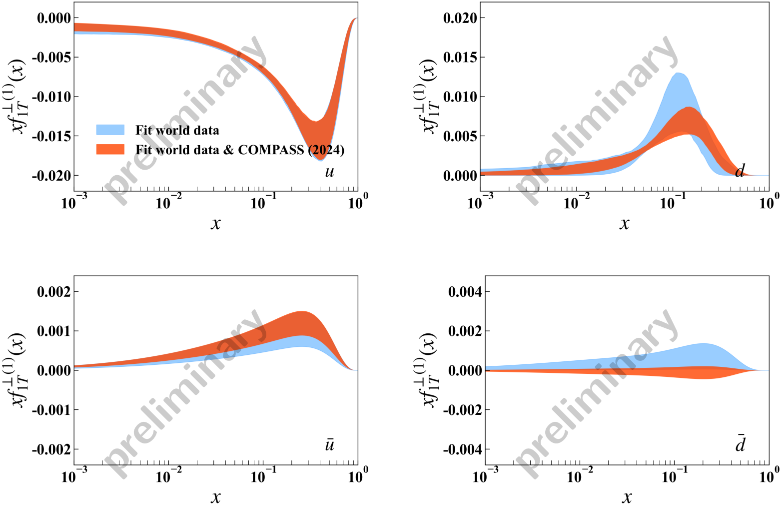
The χ^2 values for different datasets

SIDIS	N	χ^2/N Sivers	χ^2/N Collins
COMPASS09	75	1.10	0.98
COMPASS15	75	2.26	1.11
COMPASS24	38	0.83	1.07
HERMES	172	1.21	1.12
JLab	11	0.93	1.09
all	373	1.35	1.08

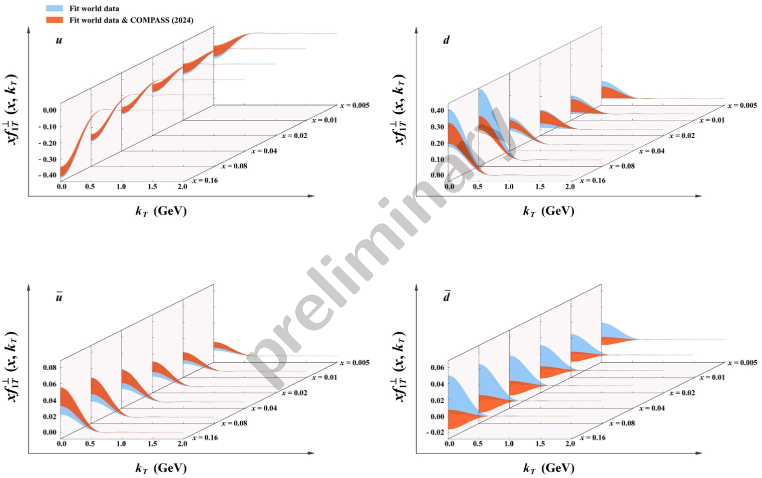
SIA	N	χ^2/N
Belle	16	0.79
Babar2014	45	1.04
Babar2015	48	0.79
BESIII	11	2.24
all	120	1.01

DY	N	χ^2/N
COMPASSDY	15	0.79
Star	17	1.91
all	32	1.38

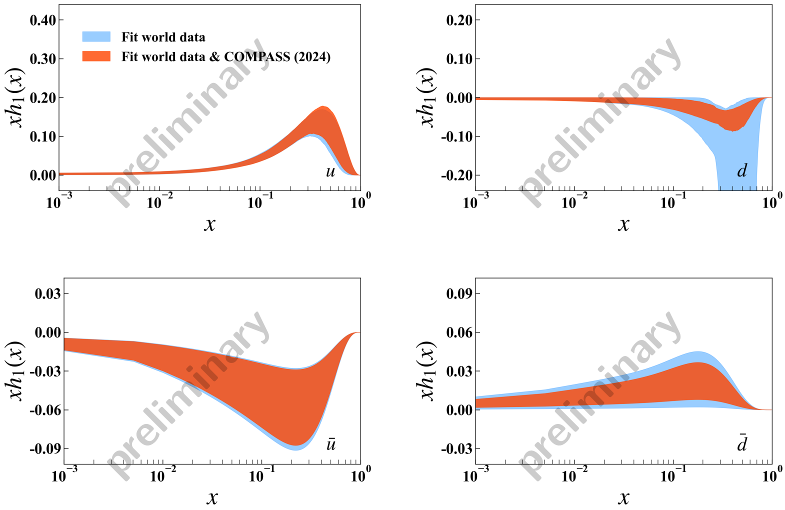
Sivers function with error bands



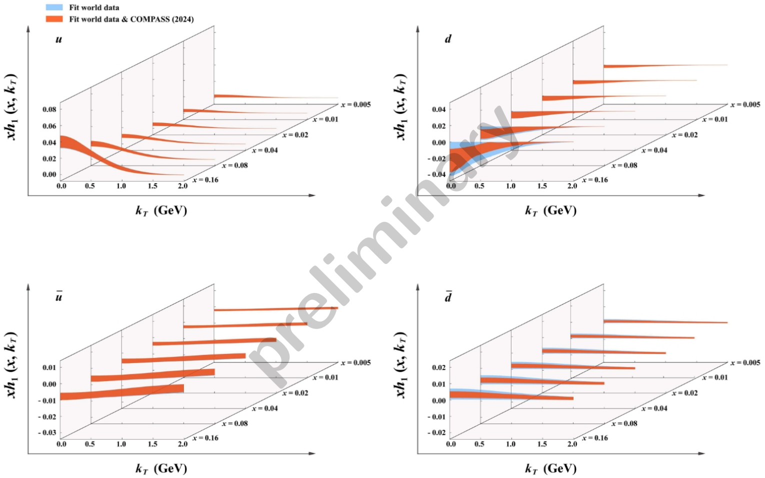
Sivers function with error bands



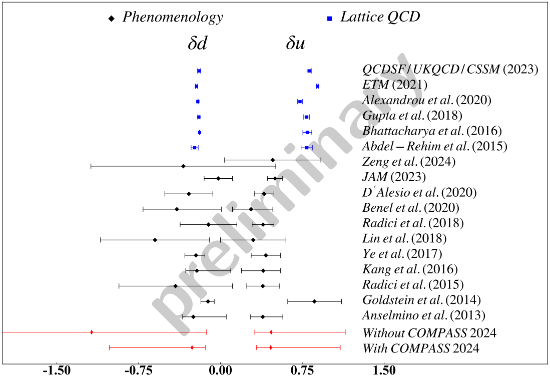
Transversity with error bands



Transversity with error bands



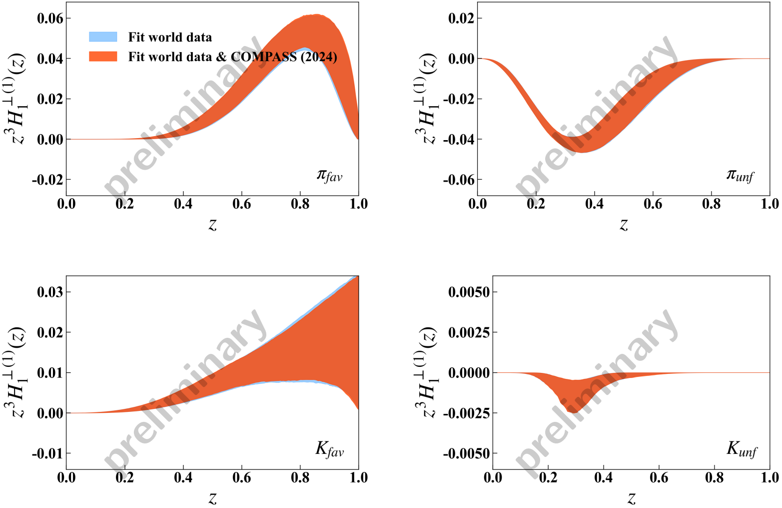
Comparison of tensor charge



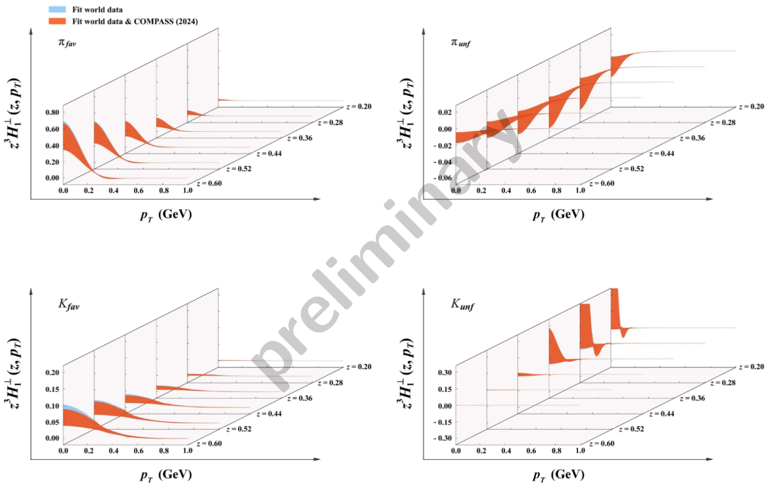
The tensor charge is defined as

$$\delta u = \int_0^1 dx\left(h_u(x) - h_{\bar{u}}(x)\right), \qquad \delta d = \int_0^1 dx\left(h_d(x) - h_{\bar{d}}(x)\right)$$

Collins function with error bands



Collins function with error bands



Contents

Summery

1. we present a global analysis of Sivers function, transversity and Collins functions encompasses the latest data sets from SIDIS as recently reported by the COMPASS Collaborations.

2.Upon integrating this new data into our fitting, the accuracy of the d, $\bar{d}$ quark extraction for both transversity and Sivers distribution is notably improved, as well as the tensor charge.