

TMD Phenomenology and Opportunities at EicC

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

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How much do we understand our world? for \mathbf{H} and \mathbf{m} in \mathbf{h} at \mathbf{h} gluons in hard with large

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 $\sim 1/fm$
- collinear factorization: $\sigma \propto H(Q) \otimes \phi_{a/P}(x,\mu^2)$
- overall corrections suppressed by 1*/Qⁿ*
- indirectly "see" quarks, gluons and their dynamics
- predictive power relies on
- precision of the probe
- universality of $\phi_{a/P}(x,\mu^2)$

Modern "Rutherford" experiment.

(a) *Neutral current deep inelastic scattering.* (b) *Resolved photoproduction.* [Figure from DESY-21-099]

Lepton-Hadron Deep Inelastic Scattering Haan Inglastie U uup anuidsuu Jefferson Lab F^p ² data from the E00-116 experiment in $R = 14$, which corresponds to a 2.71 90% confidence level (C.L.) in the ideal Gaussian statistics. JUAUUTI HIZ Figs. 1–3, and all other data used in the fits, are listed in

H. Abramowicz *et al.*, EPJC 78, 580 (2015). reduced cross sections to gether with fixed-target data \mathcal{I}_1

Lepton-Hadron Deep Inelastic Scattering Haan Inglastie U uup anuidsuu Jefferson Lab F^p ² data from the E00-116 experiment in $R = 14$, which corresponds to a 2.71 90% confidence level (C.L.) in the ideal Gaussian statistics. JUAUUTI HIZ Figs. 1–3, and all other data used in the fits, are listed in

Nucleon Spin Structure

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

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

JAM17: $ΔΣ = 0.36 ± 0.09$

JAM Collaboration, PRL 119, 132001 (2017).

Proton spin puzzle
 $\frac{1}{1 - \frac{1}{1 - \frac{1}{$ fraction to the nucleon spin.

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

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

50% of total proton spin Y.-B. Yang *et al.* (χQCD Collaboration), PRL 118, 102001 (2017).

Semi-inclusive Deep Inelastic Scattering

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

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

p2 *, M*iT \overline{p} \mathbf{A} \overline{a} p2 f *ic* \mathbb{I} p2 *ey*ⁱ *,* k^T \bullet $\overline{\textbf{r}}$ **SIDIS Kinematic Regions**

m r d n Sketch of kinematic regions of the produced hadron

Q , p is the given factor of each size and shown. (The exact size and shape of each region of each region of each region of each region of \mathbb{R} may be very different from what is shown and depends on quantities like *Q* and the hadron

l $\overline{ }$

^Q ^l

^Q (499)

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 $\overline{)}$

^R ⇠ *^m*²

Small and Large Transverse Momentum 1 di↵(*s, b*; *p^c ^t*) = *diff* (*s, b*; *p^c ^t*) exp *{*2(*s, b*; *^p^c h*(*h*) Large Transverse Momentum *dq^T* **E** TRAINSVELSE IVIOINEL *^t*) (26) $\overline{}$ *n*! \mathbf{a} , \mathbf{b} , \mathbf{b} , \mathbf{c} , \mathbf{b} , \mathbf{b} , \mathbf{c} , *a***₁** $\frac{1}{2}$ *****c* $\frac{1}{2}$ *k* $\frac{1}{2}$ *k*₂ *k Q2 Q2***n** *Q2*^z *Q2***n** *Q2z ^Q*² (1 *^z*ˆN)*k*² **Q2**z∂N *Q2*^z N *Q*²n N *Q*²n N *Q*²n N *Q ^z*ˆN*Q*² ⁺

 $W(q_{\rm T},Q) = {\rm T}_{\rm TMD} \, d\sigma$ $=X(q_T/\lambda)[FO(q_T,Q)-ASY(q_T,Q)]$ $A = \frac{1}{2}$ $Y(\rho_m \Omega) = Y(\rho_m/\lambda) T_{m}$

 $\sqrt{440}$

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Early Story: the Sivers function

Transverse single spin asymmetry observed in experiments This formulation of the $\mathcal{L}_\mathcal{A}$ is the $\mathcal{L}_\mathcal{A}$ of the $\mathcal{L}_\mathcal{A}$ is the $\mathcal{L}_\mathcal{A}$ is the $\mathcal{L}_\mathcal{A}$

ata. *T*ur Symposium on riigh Energy Spi Data: J. Antille et al., Phys. Lett B94 (1980) 523. Data: 7th Symposium on High Energy Spin Physics (1986). s_p

p, a new distribution function ¤=O. 1. FIG. 2. BIG. 2.19) SSA a new distribution fun pp r *-faox* **at plabr200 GeV/c. D. Sivers proposed to explain such SSA a new distribution function** momentum:

 0.001 and 0.13 990) 83. *Sivers function* $\Delta^N G_{a/p(\uparrow)}(x, k_T; \mu^2)$

unction was T-odd and prohibited by QCD Energy, Division of High Energy Physics, Contract No. However it was soon shown this function was T-odd and prohibited by QCD

> Γ Colling Nuol Dhys D 206 σ . Comms, truel. Thys. D σ 0.3 1.41 **APPENDIX: 2** + **2 KINEMATICS** J. Collins, Nucl. Phys. B 396 (1993) 161. $\frac{1}{2}$

 i i naive form to estimate the size of (*E)* needed to characttect \degree was thought to vanish. \degree \overline{C} *For the next decade, the "Sivers effect" was thought to vanish.*

the hard-scattering $\mathcal{L}^{\mathcal{L}}$ model to demonstrate how the demonstrate how the how the

to the data, this simple exercise provides a starting point

Early Story: the Sivers function Fig. 1. The hadronic tensor *W"#* should be written as a sum matrix elements *&*^'s that are defined as

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d²*p^T* d²*k^T*

e
e² *a*

Leading Twist TMDs

SIDIS in Trento Convention

Fixed Target Experiments (Existing)

Electron-Ion Colliders (Future) b2+iBQMb Q7 i?2 T_BM; M/ i?2 2_BM;- b b?QrM BM i?2 $\bf I$ vullutid it t ir \mathcal{L} m/2T2Mi \mathcal{L} i \mathcal{L} /Bz2 \mathcal{L} Q^2 is a model in the set of the matrix \mathcal{L} is a model in the matrix \mathcal{L} $f''(z)$ Bb $f(z)$ \rightarrow $f''(z)$ $\mathbf{U} \mathbf{U} \mathbf{I} \mathbf{U}$ i?2 BM~m2M+2 Q7 σ*^x* M/ σ*^y* QM i?2 HmKBMQbBiv Bb H2bb i?M

the quantum world of the atomic nucleus and allow physicists and allow physicists and allow physicists access for the first access for the first and α

Complementary Kinematic Coverage

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

The Sivers Function

Sivers TMD distribution function

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

A naive T-odd distribution function

Transverse momentum distribution distorted by nucleon transverse spin

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

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Sign change prediction:

Measurements of the Sivers Asymmetry

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

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Measurements of the Sivers Asymmetry

 $HFDMFC$ Colleboration I High F_{POTX} phys 12 (2020) 010 (re enalyzed) t fit and the conduction, s. Then there f and f and g and g the calculated as HERMES Collaboration, J. High Energy Phys. 12 (2020) 010. (re-analyzed)

Measurements of the Sivers Asymmetry $\mathbf{F}_{\mathbf{S}}$ from target for \mathbf{S} from target for $\mathbf{F}_{\mathbf{S}}$ for $\mathbf{F}_{\mathbf{S}}$, and $\mathbf{F}_{\mathbf{S}}$

COMPASS Collaboration, Phys. Lett. B 673 (2009) 127; Phys. Lett. B 744 (2015) 250. $FONPACS$ $Collaboration$ $Phys$ I att R 673 (2000) 127. Phys I att R 744 (2015) 250 CONITASS CONDUCTRION,

Measurements of the Sivers Asymmetry \bar{z} and \bar{z} or \bar{z} from target for \bar{z}

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JLab HallA Collaboration, Phys. Rev. Lett. (2011) 072003; Phys. Rev. C 90 (2014) 055201. JLAO HAIIA COIIADOPATION, PHYS. REV. LETT. (2011) 072005; PHYS. REV. (2014) 055201 $(2011) 055201.$ J Lab HallA Collaboration, Phys. Rev. Lett. (2011) 072003; Phys. Rev. C 90 (2014) 05520

Extraction of the Sivers function

C. Zeng, T. Liu, P. Sun, Y. Zhao, Phys. Rev. D 106 (2022) 094039. represent the Eigent V 7han Phys Poul D 106 (2022) 004030

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via survivalues, in the truncated with the truncated services of t

FIG. 8. The Sivers function green bands represent to the fit the fit the fit the fit to world SIDIS data, the Eicc projections with only s uncertainties, and the blue bands represent the EicC projections including systematic uncertainties as described in the text. Γ^2 of Γ^-

 $f_{1T}^{\perp (1)}(x) = \pi \int d\mathbf{k}^2_{\perp} \frac{\mathbf{k}_{\perp}^{\perp}}{2M^2} f_{1T}^{\perp}(x, \mathbf{k}_{\perp}^2)$ $U = 2M²$ z $d\mathbf{k}^2$ ⊥ ${\bf k}_\perp^2$ $\frac{\mathbf{A}_{\perp}}{2M^2} f_{1T}^{\perp}(x, \mathbf{k}_{\perp}^2)$

Since TMDs are well defined at small transverse momen-

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

Sivers Asymmetry of *ρ0* **Production**

Data from COMPASS Collaboration, PLB 843 (2023) 137950.

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

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

Sivers Asymmetry of *ρ0* **Production**

Predictions at EicC kinematics:

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

Different predictions to be tested at EicC kinematics

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

Transversity Distribution

Transversity distribution

$$
\mathbf{h}_1 \quad \begin{pmatrix} \uparrow \\ \uparrow \end{pmatrix} - \begin{pmatrix} \uparrow \\ \uparrow \end{pmatrix} \quad \text{(Collinear & TMD)}
$$

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

Phenomenological extractions

Z.-B. Kang, A. Prokudin, P. Sun, F. Yuan, PRD 93, 014009 (2016). JAM Collaboration, PRD 104, 034014 (2022).

Chiral-odd:

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

Effect in SIDIS:

 $\frac{1}{2}$ and $\frac{1}{2}$ a transverse single spin asymmetry (Collins asymmetry)

 $\mathcal{H}_1(x,\mathbf{k}_\perp^2)\bigotimes\mathcal{H}_1^\perp(z,\mathbf{p}_\perp^2)$

Sea Quark Transversity

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EicC Impact on Transversity

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

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

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

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

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

Tensor Charge

Tensor charge

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

$$
\gamma_5 u(P, S) \qquad g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)] dx
$$

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

Tensor Charge RUDU OHAN SU

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

C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, PRD 109 (2024) 056002. $t(024)$ 056002. equation calculation calculation calculations in the calculation calculations α α calculations α C. Zeng, H. Dong, TL, F. Sun, T. Zhao, FKD

Tensor Charge T_{e} excracted the extraction of $\sum_{n=1}^{\infty}$ pared with the results from previous previous parallel and \mathbf{y}

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

C. Zeng, H. Dong, TL, P. Sun, Y. Zhao, PRD 109 (2024) 056002. \overline{S} \overline{S} can be \overline{S} and \overline{S} calculations \overline{S} logical extractions from data and determined the control of the control of the control of the control of the c
Control of the control of the contro $3024) 056002.$

Double Spin Asymmetry and Worm-gear

Trans-helicity worm-gear distribution

$$
g_{1T}^{\perp}(x, k_T)
$$
 \bigodot \bigodot \bigodot A longitudinal-transverse double spin asymmetry

- Longitudinally polarized quark density in a $\cos(\phi_1 \phi_2)$ *n*₁.0009+0.0009+1.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.0006 0.020 0.020 0.020 0.020 0.020 0.020 0.020 0.020 0.020 0.020 0.020 0.020 0.020 0.020 0.020 0 *n* ansversery polarized in 0*.*⁰⁰⁰⁹ 0*.*0077+0*.*⁰⁰⁰⁸
- Overlap between wave functions differing by one unit of orbital angular momentum Overlap between wave functions differing by 0*.*⁰⁰⁰²¹ *^d* ⁴*.*31+1*.*⁴⁷ 0*.*000 0001141 0001141 0.000341 0*.*⁰⁰⁰³² *^r^u* ⁰*.*0067+0*.*⁰⁰⁵⁰

Phenomenological extraction 0*.*⁰⁰⁰³⁷ ⁰*.*00038+0*.*⁰⁰⁰⁴⁵

Effect in SIDIS: A longitudinal-transverse double spin asymmetry

ty in a

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

K. Yang, TL, P. Sun, Y. Zhao, B.-Q. Ma, arXiv:2403.12795 FIG. 10. The first transverse moment of the worm-gear functions, *g*

The story is not ending …

Challenge at Large Transverse Momentum

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

Challenge at Large Transverse Momentum

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

Challenge at Large Transverse Momentum

Our proposal: power correction at high *Ph^T* , as sketched in Fig. 2 (right), is certainly

with *z* ⇠ *zh*, and the factorizable NLP contribution, as we show in this paper, could have the leading transition of \mathcal{L}_{max}

the power suppression in (1 *z*). While the production

 π^+ to π^+ to π^+

d pair is suppressed by inverse powers of *P^h^T* ,

h \overline{A} supposed hard parts at the power power \overline{A}

ge enough phase space to shower. In This paper is not the sec. In Sec. II, it is not the sec. In Sec. II, it is $\frac{1}{2}$ introduce the introduced the factor formalism for $\frac{1}{2}$ to the $\frac{1}{2}$ accuracy of P , provide a leading order calculation of P Need large enough phase space to shower ⇒ sufficiently high multiplicity

 π^+ is formally suppressed by π^+ is formally suppressed by order to π^+ is the suppressed by π^+ is the suppressed by π^+ is the suppressed by π^-

Near the edge of phase spa $\frac{1}{2}$ in $\frac{1}{2}$ is produced with pair is produced with $\frac{1}{2}$ in $\frac{1}{2}$ is produced with ⇒ low multiplicity

 π^+

NLP contribution: NLP contribution: corrections in comparison to the size of the size of the size of the size of the LP contributions of the LP con that could also be sensitive to the same quark-antiquark-antiquark-antiquark-antiquark-antiquark-antiquark-antiquark-

π⁺ π⁺ \mathbb{R}^n

 π ⁺_{*ii*} π ⁺

 $u \neq \pm \frac{a}{\infty}$ $\rightarrow \pm \frac{a}{u}$

 \overrightarrow{u} \overrightarrow{u} *d d*

 \mathbb{I} D \overrightarrow{C} *nus b*ctici charge to form the number. *π⁺ π⁺ π⁺ π⁺ u u u u* $\frac{1}{\sqrt{2}}$ *π d d d d u u u u d d d d u u u u d d d d Parton pair with the right quantum number* \oint_{∂} $\int u$ $u \neq \bigotimes$ u $B \sigma d$ ron μ *u* to μ . *has better chance to form the hadron.*

 π^+ _{*ll*} π^+

 π^+

π⁺ π⁺ π⁺ π⁺

power of 1*/P^h^T* [23, 33, 34]. With the factorization for-

 $\frac{1}{\sqrt{2}}$

 π^+ _{tio}n, π^+

 t direct production on t

Q ⇤QCD observed, SIDIS cross section with a large

 \mathcal{F} and outlooks are given in Sec. V. I. and outlooks are given in S

Tianbo Liu $\frac{u}{x}$ of the *u* ¯ as we will demonstrate below the trade of the trade

Callenge at Large Momentum suppressed by extra power of 1*/P^h^T* . To make this point even more more more and the fracetion informal contribution

Only consider the leading term — lower limit of NLP contribution. NLP contribution is more significant at lower collision energy. practical for now to make the "valence quark" approxi-0*.*2, and *P^h^T* = 1*.*0 GeV.

zh : [0*.*4*,* 0*.*6]

Evolution should be modified acco by ordered the cross section called \sim Evolution should be modified accordingly

also an opportunity for studying α and α power corrections α

have much lower collision energies than what COMPASS is than what COMPASS in the collision energies than what C

 \overline{m}

 $u \sim u$ \int_0^∞ $\frac{d}{dx}$ \int_0^∞ $\frac{$

Mh*/*dzhdP2hT (GeV

 $u \sim u$ *u* $\sqrt{000}$ *d* u

11 *II*

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

TL and J.W. Qiu, 2020

10¹

Mh*/*dzhdP2hT (GeV

 100

kinematic experienced by the parton \neq *kinematic experienced by the parton* 6= *kinematic reconstructed from observed momenta*

Challenges in traditional approach:

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

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

—— EIC Yellow Report

Radiative Corrections

Our proposal:

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

From radiative correction to radiation contribution:

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

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

R *adiative* Correction \mathbf{P}

$\overline{}$ *s* \mathbf{R} 0*.*0 0*.*1 0*.*2 0*.*3 0*.*4 0*.*5 0*.*6 0*.*0 0*.*1 0*.*2 0*.*3 0*.*4 0*.*5 0*.*6 Ω 0*.*0 0*.*1 0*.*2 0*.*3 0*.*4 0*.*5 0*.*6 Numerical estimation: Collins asymmetry

0*.*03

h

FIG. 17. RC e↵ects in SIDIS with LT *UT* $\frac{1}{2}$ **J** $\frac{1}{2}$ **TL, W. Melnitchouk, J.W. Qiu, N. Sato, 2021**

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FIG. 17. RC e↵ects in SIDIS with LT *UT*

0*.*0010

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;

 \cdots

 $-$ …

- SIDIS with polarized beam and target is a main process to study polarized TMDs
- Also an important approach to test/develop the theories/models
- EicC can significantly improve the precision of the determination of TMDs, especially for sea quarks, complementary to JLab12 and EIC-US.
- There are still challenges on the theoretical side
	- power corrections, higher twist effects
	- radiative corrections
	- target fragmentation

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TMD Evolution

Evolution equations

$$
\mu^{2} \frac{dF(x, b; \mu, \zeta)}{d\mu^{2}} = \frac{\gamma_{F}(\mu, \zeta)}{2} F(x, b; \mu, \zeta) \n\qquad \qquad -\zeta \frac{d\gamma_{F}(\mu, \zeta)}{d\zeta} = \mu \frac{d\mathcal{D}(\mu, b)}{d\mu} = \Gamma_{\text{cusp}}(\mu) \n\zeta \frac{dF(x, b; \mu, \zeta)}{d\zeta} = -\mathcal{D}(b, \mu) F(x, b; \mu, \zeta) \n\qquad \qquad \gamma_{F}(\mu, \zeta) = \Gamma_{\text{cusp}}(\mu) \ln\left(\frac{\mu^{2}}{\zeta}\right) - \gamma_{V}(\mu) \nF(x, b; \mu_{f}, \zeta_{f}) = \exp \left[\int_{P} \left(\gamma_{F}(\mu, \zeta) \frac{d\mu}{\mu} - \mathcal{D}(\mu, b) \frac{d\zeta}{\zeta} \right) \right] F(x, b; \mu_{i}, \zeta_{i}) \n\zeta - \text{prescription} \n\qquad\n\mu^{2} = \zeta = Q^{2} \qquad R[b; (\mu_{i}, \zeta_{i}) \rightarrow (Q, Q^{2})] = \left(\frac{Q^{2}}{\zeta_{\mu}(Q, b)} \right)^{-\mathcal{D}(Q, b)} \n\frac{d\ln \zeta_{\mu}(\mu, b)}{d\ln \mu^{2}} = \frac{\gamma_{F}(\mu, \zeta_{\mu}(\mu, b))}{2\mathcal{D}(\mu, b)} \n\mathcal{D}(\mu_{0}, b) = 0, \quad \gamma_{F}(\mu_{0}, \zeta_{\mu}(\mu_{0}, b)) = 0 \n\frac{d\zeta}{d\zeta} = \frac{Q^{2}}{\zeta_{Q}(b)} \tag{6.11}
$$

Tianbo Liu 46 Figure 2. In the ($\frac{40}{100}$ plane we show the force-lines of the TMD evolution field E at different values of the TMD evolution field E at different values of the force-lines of the TMD evolution field E at different va 山东大学(青岛)

SHANDONG UNIVERSITY

BaBar (2014) BaBar (2016)

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BESIII

Belle

Result: Collins Fragmentation Function Result: Collins Fragmentation Function HERMES [20] *P^h*? 24 0*.*9

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

Test New Physics Model: Split-supersymmetry

• In the unified framework of gaugino masses, sfermion mass at 10^9 GeV, tan β =1, sin φ =1

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

Transversity TMDs

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Collins TMD FFs

Hadron transverse momentum p_T (GeV)

Hadron transverse momentum p_T (GeV)

Hadron transverse momentum p_T (GeV)

Some More on Transversity

New data released by COMPASS

 $A \cup A$ $A \cup A$ SIDIS on transversely polarized deuteron target

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

Some More on Transversity

Preliminary results (without systematic uncertainties)

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

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

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

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

JLab HallA Collaboration, Phys. Rev. Lett. 108 (2012) 052001.

\int *Aw* Physics **Connection to New Physics**

Current upper limit on the neutron EDM (electric dipole moment) *b* /*B*(*a* + 1, *b* + 1) (23) (1 *x*) /*B*(*a* + 1, *b* + 1) (23)

C. Abel *et al.*, Phys. Rev. Lett. 124, 081803 (2020) Current upper limit on the proton EDM *P*, *S P*, *S i*_{*N*} *d*_{*i*}^{*n*} [|]*P*, *^S* ⁱ ⁼ *gq* $\frac{1}{2}$ Gran $d_p < 2.1 \times 10^{-25} e \text{ cm}$ B.K. Sahoo *et al.*, Phys. Rev. D 95, 012002 (2017). $\frac{1}{2}$ ¹(*x*) *hq*¯ ¹(*x*)] *dx* (25) $d_p = g_T^u d_u + g_T^d d_d + g_T^s d_s$ $d_n = g_T^d d_u + g_T^u d_d + g_T^s d_s$ $\int_T^s d_s$ d_u < 1.27 × 10⁻²⁴ *e* cm d_d < 1.17 × 10⁻²⁴ *e* cm $d_n < 1.8 \times 10^{-26} e \text{ cm } (90\% \text{ CL})$ $d(^{199}\text{Hg})$ < 7.4 × 10⁻³⁰ *e* cm (95% CL) B. Graner *et al.*, Phys. Rev. Lett. 116, 161601 (2016). *Constraint on quark EDMs* [|]*P*, *^S* ⁱ ⁼ *gq ^T ^u*¯(*P*, *^S*)*i*^µ⌫ \overline{a} $\prod_{i=1}^n$ \geq $\frac{1}{\sqrt{2}}$ h^{-30} \approx h^{-30} 1(*050/CI*) **D** George at al. Place B as Lett 116, 161 $\overline{\text{Ms}}$ $\alpha_q \sim e M_q / (4\pi/\sqrt{P})$ $\Lambda \sim 1$ sensitivity to new physics: $d_q \sim e m_q / (4 \pi \Lambda^2)$ $\Lambda \sim 1 \text{ TeV}$

> [±](`) + *N*(*P*) ! *l* [±](`⁰) + *h*(*Ph*) + *X*(*PX*) (28) **TL, Z. Zhao, H. Gao, Phys. Rev. D 97, 074018 (2018).**