PROCEEDINGS OF SCIENCE

Transverse Momentum Dependent Transverse Spin Asymmetries in COMPASS Drell-Yan data

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Gaining a deeper understanding of the nucleon structure remains one of the longstanding challenges of current hadron physics. This work presents an analysis of transverse-spin dependent azimuthal asymmetries in the Drell–Yan process, $\pi^- + p^\uparrow \rightarrow \gamma^* + X \rightarrow \mu^+ + \mu^- + X$, based on data collected by the Common Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) Collaboration in 2015 and 2018. The data were obtained using a 190 GeV negative pion beam scattered off transversely polarised NH_3 target. The analysis introduces a new method of weighting asymmetries by powers of the dimuon pair transverse momentum relative to the beam. This technique provides direct access to certain k_T^2 moments of the transverse-momentum dependent parton distribution functions. These findings represent one of the most significant experimental advances in spin physics in recent years and are expected to remain a key reference point until new data from CLAS12, EIC, and LHCspin are available.

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1. Introduction

The three-dimensional structure of hadrons reflects both the longitudinal and intrinsic transverse motion of partons, as well as their spin. At leading twist in perturbative QCD, the nucleon is described by eight transverse-momentum dependent (TMD) parton distribution functions (PDFs) which characterize the distributions of partons longitudinal and transverse momenta and encode their correlations with both nucleon and quark spins. Among them, the Sivers, Boer–Mulders, pretzelosity, and transversity distributions are of particular interest in this analysis.

The Sivers function, $f_{1T}^{\perp q}(x, \boldsymbol{k}_T)$, describes the correlation between the intrinsic transverse momentum of unpolarised quarks and the transverse polarization of the nucleon. A nonzero Sivers function indicates a preferred transverse momentum direction of quarks in a polarised nucleon, arising from partonic orbital angular momentum. The Boer–Mulders function, $h_1^{\perp q}(x, \boldsymbol{k}_T)$, describes the correlation between a quark's transverse momentum and its transverse spin inside an unpolarised hadron. It reflects an imbalance between quarks of opposite transverse spin orientations, leading to a net transverse quark polarization even in an unpolarised nucleon. The transversity distribution, $h_1^q(x, \boldsymbol{k}_T)$, measures the difference between quarks polarised parallel and antiparallel to the nucleon's transverse spin. Closely related, the pretzelosity distribution, $h_{1T}^{\perp q}(x, \boldsymbol{k}_T)$, encodes correlations between the transverse polarization of the nucleon and that of the quark, as well as the quark intrinsic transverse momentum. In quark models such as the MIT bag model, pretzelosity is connected to the difference between helicity and transversity distributions, highlighting relativistic effects in the nucleon [1].

TMD PDFs can be probed through measurements of specific azimuthal asymmetries in processes such as the Drell–Yan reaction, where a quark and an antiquark annihilate to produce an oppositely charged lepton pair in hadron–nucleon collisions ($\mathrm{h} + \mathrm{N}^{\uparrow} \to \ell^+ + \ell^- + \mathrm{X}$). The cross section for this process can be factorised into a convolution of two components: the hard-scattering partonic cross section, which is calculable in perturbative QCD, and non-perturbative functions, namely the PDFs.

2. Asymmetries in Drell-Yan process

In COMPASS experiment, the leading order Drell–Yan process occurs through the annihilation of a quark from proton (p) and antiquark from pion (π^-) into a virtual photon, which then produces a pair of oppositely charged leptons. The general expression for the differential cross section at leading twist for a transversely polarised target is given by [2]:

$$\begin{aligned}\frac{\mathrm{d}\sigma_{\mathrm{DY}}}{\mathrm{d}^4 q\, \mathrm{d}\Omega} = &\frac{\alpha^2}{Cq^2}\Bigg\{(1+\cos^2\theta)A_{\mathrm{U}}^{1} + \sin^2\theta\, \cos 2\varphi_{\mathrm{CS}}\, A_{\mathrm{U}}^{\cos 2\varphi_{\mathrm{CS}}} + |\boldsymbol{S}_{\mathbf{T}}|\Bigg[(1+\cos^2\theta)\sin\varphi_{\mathrm{S}}\, A_{\mathrm{T}}^{\sin\varphi_{\mathrm{S}}} \\ &+ \sin^2\theta\, \sin(2\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}})A_{\mathrm{T}}^{\sin(2\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}})} + \sin^2\theta\, \sin(2\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})A_{\mathrm{T}}^{\sin(2\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})}\Bigg]\Bigg\},\end{aligned} \tag{1}$$

where q is a virtual photon momentum, θ is a polar angle of the muon momentum ($\boldsymbol{l}^-$) in the Collins–Soper frame shown in, and a kinematic factor $C = 4\sqrt{(P_\pi \cdot P_{\mathrm{N}})^2 - M_\pi^2 M_p^2}$, with P_π, P_{N}

representing the four-momenta of the pion and nucleon. Meanwhile, φ_{CS} refers to the azimuthal angle of $\boldsymbol{l}^-$ in the Collins–Soper frame, while φ_{S} denotes the azimuthal angle of the target polarization vector $\boldsymbol{S}_{\mathbf{T}}$ in the target frame. Asymmetries in Eq. (1) originate from convolutions of specific TMD PDFs. Extracting these convolutions typically requires assuming a particular $\boldsymbol{k}_{\mathbf{T}}$-dependence. Alternatively, one can weight the spin-dependent part of the cross-section with powers of the outgoing particle transverse momentum, $q_{\mathrm{T}} = \boldsymbol{k}_{\mathbf{T},\boldsymbol{\pi}} + \boldsymbol{k}_{\mathbf{T},\mathbf{p}}$. Integrating the structure functions over q_{T} with these weights significantly simplifies the convolutions. The resulting q_{T}-weighted transverse-spin dependent azimuthal asymmetries (WTSAs) can then be expressed as simple products of proton and π^- TMD PDFs, or certain moments of these distributions defined as:

$$f_h^{(n)}(x) = \int \mathrm{d}^2\boldsymbol{k}_{\mathbf{T}} \left(\frac{k_{\mathrm{T}}^2}{2M_{\mathrm{h}}^2}\right)^n f(x, k_{\mathrm{T}}^2), \tag{2}$$

where M_{h} is the mass of the hadron. The Sivers, pretzelosity, and transversity asymmetries discussed in this paper are subsequently expressed as follows:

$$\begin{aligned}
A_{\mathrm{T}}^{\sin\varphi_{\mathrm{S}}\frac{q_{\mathrm{T}}}{M_{\mathrm{p}}}} &= -2\frac{\sum_{\mathrm{q}} e_{\mathrm{q}}^2\left[f_{1,\pi^-}^{\bar{\mathrm{q}}}(x_\pi)\, f_{1\mathrm{T,p}}^{\perp(1)\mathrm{q}}(x_{\mathrm{N}}) + (\mathrm{q} \leftrightarrow \bar{\mathrm{q}})\right]}{\sum_{\mathrm{q}} e_{\mathrm{q}}^2\left[f_{1,\pi^-}^{\bar{\mathrm{q}}}(x_\pi)\, f_{1,\mathrm{p}}^{\mathrm{q}}(x_N) + (\mathrm{q} \leftrightarrow \bar{\mathrm{q}})\right]},\\
A_{\mathrm{T}}^{\sin(2\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}})\frac{q_{\mathrm{T}}^3}{2M_\pi M_{\mathrm{p}}^2}} &= -6\frac{\sum_{\mathrm{q}} e_{\mathrm{q}}^2\left[h_{1,\pi^-}^{\perp(1)\bar{\mathrm{q}}}(x_\pi)\, h_{1\mathrm{T,p}}^{\perp(2)\mathrm{q}}(x_N) + (\mathrm{q} \leftrightarrow \bar{\mathrm{q}})\right]}{\sum_{\mathrm{q}} e_{\mathrm{q}}^2\left[f_{1,\pi^-}^{\bar{\mathrm{q}}}(x_\pi) f_{1,\mathrm{p}}^{\mathrm{q}}(x_N) + (\mathrm{q} \leftrightarrow \bar{\mathrm{q}})\right]},\\
A_{\mathrm{T}}^{\sin(2\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})\frac{q_{\mathrm{T}}}{M_\pi}} &= -2\frac{\sum_{\mathrm{q}} e_{\mathrm{q}}^2\left[h_{1,\pi^-}^{\perp(1)\bar{\mathrm{q}}}(x_\pi)\, h_{1,\mathrm{p}}^{\mathrm{q}}(x_N) + (\mathrm{q} \leftrightarrow \bar{\mathrm{q}})\right]}{\sum_{\mathrm{q}} e_{\mathrm{q}}^2\left[f_{1,\pi^-}^{\bar{\mathrm{q}}}(x_\pi) f_{1,\mathrm{p}}^{\mathrm{q}}(x_N) + (\mathrm{q} \leftrightarrow \bar{\mathrm{q}})\right]}.
\end{aligned} \tag{3}$$

In this expression, f_1, h_1 represent the unpolarised quark number density and the transversity distribution, while $f_{1\mathrm{T,p}}^{\perp(1)}, h_1^{\perp(1)}, h_{1\mathrm{T}}^{\perp(2)}$ are not TMD PDFs themselves but correspond to the first moments of the Sivers and Boer–Mulders, and the second moment of pretzelosity distribution.

3. Results

The COMPASS Drell–Yan data, collected in 2015 and 2018, were obtained using a 190 GeV/c π^- beam from the CERN SPS, scattered off a solid NH$_3$ target with ~73% of transversely polarised hydrogen nuclei. The target consisted of two longitudinally aligned cylindrical cells with opposite vertical polarisation, allowing simultaneous measurement of both spin orientations. The WTSAs were measured in the dimuon mass range $M_{\mu\mu} \in (4.0, 9.0)$ GeV/c^2 and evaluated in one-dimensional bins of the nucleon and pion Bjorken variables (x_{N}, x_π), the dimuon Feynman variable (x_{F}), the transverse momentum (q_{T}), and the dimuon mass ($M_{\mu\mu}$).

The Sivers asymmetries (first row in Fig. 1) are approximately one standard deviation above zero, consistent with the unweighted COMPASS asymmetries in the Drell–Yan process [3] and with theoretical predictions [4]. The pretzelosity WTSAs (second line in Fig. 1) are measured around one standard deviation below zero. Due to the small size of the pretzelosity TMD PDFs and kinematic suppression, these asymmetries are predicted to be very small [4]. The cubic weighting in q_{T} emphasizes large-q_{T} regions where the TSAs are negative, driving the observed negative

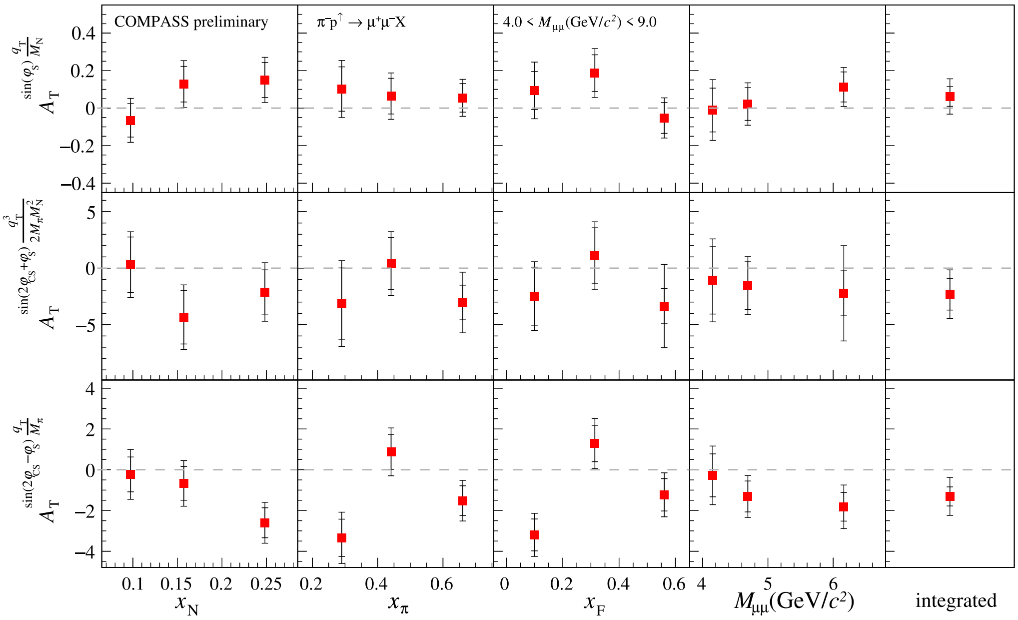

Figure 1: Kinematic dependences of the Sivers, pretzelosity, and transversity WTSAs (top to bottom). Inner error bars represent statistical, while outer total experimental uncertainties.

values, unlike other asymmetries that depend linearly on q_T and are unaffected. The transversity WTSAs, shown in third line of Fig. 1, are negative with a significance of roughly two standard deviations, in line with theoretical predictions [4], though the magnitude exceeds that of the Sivers TSA [3].

4. Summary

The COMPASS measurement of transverse-spin asymmetries in Drell-Yan process, using transverse-momentum weighting, provides new insights into nucleon structure by allowing direct extraction of TMD PDFs. The q_T-weighted transverse-spin asymmetries for Sivers and transversity agree with theory and analogical Drell-Yan measurement performed by COMPASS Collaboration [3], while pretzelosity shows a negative shift due to the applied weight.

References

[1] H. Avakian, A. V. Efremov, P. Schweitzer, P. and F. Yuan, Phys. Rev. D **78**, 114024 (2008).

[2] S. Arnold, A. Metz and M. Schlegel, Phys. Rev. D **79**,034005 (2009).

[3] COMPASS Collaboration, Phys. Rev. Lett. **133**, 071902 (2024).

[4] S. Bastami *et al.*, JHEP **02**, 166 (2021).