Transverse-spin asymmetries in COMPASS Drell-Yan data

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Studies of the transverse-spin dependent azimuthal asymmetries in the Drell-Yan process provide insight into the spin-dependent structure of the nucleon and test the limited universality of its transverse momentum dependent parton distributions, which are also studied in deep inelastic scattering. In 2015 and 2018, the COMPASS Collaboration at CERN conducted measurements of the $\pi^- \mathrm{p} \rightarrow \mu^+\mu^- \mathrm{X}$ reaction using a 190 GeV/c pion beam and a transversely polarized $\mathrm{NH_3}$ target. The results of this analysis were presented, including findings obtained with a novel approach that weights the asymmetries by powers of the transverse momentum of the dimuon system relative to the beam. This method overcomes the convolution over the intrinsic transverse momentum and provides straightforward access to certain k_T^2 moments of the transverse momentum dependent parton distribution functions.

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1. Introduction

Decades of theoretical studies and experiments have significantly advanced our understanding of the internal structure of nucleons. However, comprehending the nucleon structure in terms of quarks and gluons remains a major challenge. Investigating the three-dimensional distribution of partons within hadrons in momentum space involves key reactions such as semi-inclusive hadron production in deep-inelastic lepton-nucleon collisions (SIDIS, $\ell N \to \ell' h X$) and the Drell-Yan process, where a quark and antiquark from hadron-nucleon collisions annihilate to produce oppositely charged lepton pairs (DY, $hN \to \ell\ell' X$). In both SIDIS and DY, the cross section is factorized into two components: hard-scattering parton cross sections, calculable using perturbative methods, and nonperturbative functions including parton distribution functions (PDFs) and fragmentation functions (FFs). In the collinear framework, where the parton transverse momentum k_{T} is integrated out, the nucleon structure is described by three PDFs, each dependent on the hadron momentum fraction carried by a parton x and the squared 4-momentum transfer Q^2. However, a three-dimensional view of nucleons incorporates both the longitudinal and transverse motion of partons within (un)polarized hadrons, as well as their spin degrees of freedom. Under the twist-2 approximation of perturbative QCD, there are eight transverse momentum dependent (TMD) PDFs of the nucleon that describe the distributions of longitudinal and transverse momenta of partons and their correlations with nucleon and quark spins. These PDFs can be investigated through the measurement of transverse-spin asymmetries (TSA) in SIDIS and the DY process. The COMPASS experiment at CERN provides a unique opportunity to investigate the transverse-spin structure of the nucleon within a comparable kinematic region using both SIDIS and DY methods.

2. Transverse-spin asymmetries in Drell–Yan process

At leading order (LO), the DY reaction proceeds via the annihilation of a q–q̄ pair into a virtual photon. The cross section at leading twist and LO, for a transversely polarised target, is

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

where q is a virtual photon momentum, θ is a polar angle of the muon momentum $\boldsymbol{l}^-$ in the Collins–Soper frame, and C is a kinematic factor given by $C = 4\sqrt{(P_\pi \cdot P_{\mathrm{N}})^2 - M_\pi^2 M_{\mathrm{p}}^2}$, with P_π, P_{N} representing the four-momenta of the pion and nucleon. The cross section consists of five terms, each with an orthogonal modulation in φ_{CS} or φ_{S} – the azimuthal angles of $\boldsymbol{l}^-$ in the Collins–Soper (Fig. 1) or target frame (Fig. 2) and of the target polarisation vector $\boldsymbol{S}_{\mathrm{T}}$ in the target frame, respectively. Each term includes a structure function, $F_{\mathrm{U/T}}^X$. These structure functions are expressed as flavour sums of convolutions of TMD PDFs over the intrinsic momenta of the two annihilating quarks, one originating from the pion $\boldsymbol{k}_{\mathbf{T},\boldsymbol{\pi}}$ and one from the proton $\boldsymbol{k}_{\mathbf{T},\mathbf{p}}$. The standard

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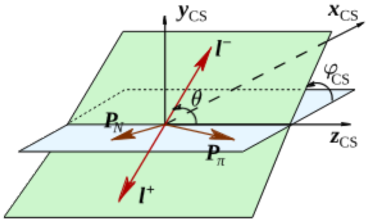

Figure 1: Angles φ_{CS} and θ in the Collins–Soper frame.

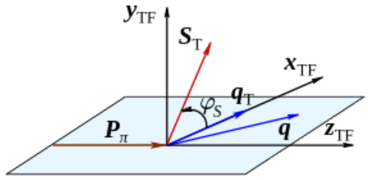

Figure 2: The angle φ_S in the target frame.

TSA, which are the amplitudes of the azimuthal modulations of the cross section in terms of the structure functions, can be expressed as

$$A_T^{\sin\varphi_S} = \frac{F_T^{\sin\varphi_S}}{F_U^1}, \qquad A_T^{\sin(2\varphi_{CS}\pm\varphi_S)} = \frac{F_T^{\sin(2\varphi_{CS}\pm\varphi_S)}}{2F_U^1}. \tag{2}$$

Accessing TMD PDFs from TSA involves handling convolutions over partonic transverse momenta. This is straightforward for F_U^1, as it requires integration over transverse momentum. For other modulations, the typical approach is to assume a functional form, often a Gaussian, for the PDF dependence on $\boldsymbol{k}_T$. Alternatively, integrating the structure functions over $\boldsymbol{q}_T = \boldsymbol{k}_{T,\pi} + \boldsymbol{k}_{T,p}$ with carefully chosen weights W_X simplifies the convolutions, similar to the approach used for F_U^1. The transverse momentum-weighted transverse-spin asymmetries (WTSA), specifically Sivers, pretzelosity, and transversity, are expressed as simple products

$$A_T^{\sin\varphi_S \frac{q_T}{M_p}} = \frac{\int d^2\boldsymbol{q}_T \frac{q_T}{M_p} F_T^{\sin\varphi_S}}{\int d^2\boldsymbol{q}_T F_U^1} = -2\frac{\sum_q e_q^2\left[f_{1,\pi^-}^{\bar{q}}(x_\pi)\, f_{1T,p}^{\perp(1)q}(x_N) + (q\leftrightarrow\bar{q})\right]}{\sum_q e_q^2\left[f_{1,\pi^-}^{\bar{q}}(x_\pi)\, f_{1,p}^{q}(x_N) + (q\leftrightarrow\bar{q})\right]},$$

$$A_T^{\sin(2\varphi_{CS}+\varphi_S)\frac{q_T^3}{2M_\pi M_p^2}} = \frac{\int d^2\boldsymbol{q}_T \frac{q_T^3}{2M_\pi M_p^2} F_T^{\sin(2\varphi_{CS}+\varphi_S)}}{\int d^2\boldsymbol{q}_T F_U^1} = -6\frac{\sum_q e_q^2\left[h_{1,\pi^-}^{\perp(1)\bar{q}}(x_\pi)\, h_{1T,p}^{\perp(2)q}(x_N) + (q\leftrightarrow\bar{q})\right]}{\sum_q e_q^2\left[f_{1,\pi^-}^{\bar{q}}(x_\pi) f_{1,p}^{q}(x_N) + (q\leftrightarrow\bar{q})\right]},$$

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)\frac{q_T}{M_\pi}} = \frac{\int d^2\boldsymbol{q}_T \frac{q_T}{M_\pi} F_T^{\sin(2\varphi_{CS}-\varphi_S)}}{\int d^2\boldsymbol{q}_T F_U^1} = -2\frac{\sum_q e_q^2\left[h_{1,\pi^-}^{\perp(1)\bar{q}}(x_\pi)\, h_{1,p}^{q}(x_N) + (q\leftrightarrow\bar{q})\right]}{\sum_q e_q^2\left[f_{1,\pi^-}^{\bar{q}}(x_\pi) f_{1,p}^{q}(x_N) + (q\leftrightarrow\bar{q})\right]}, \tag{3}$$

here, $f_1, h_1, f_{1T,p}^{\perp(1)}, h_1^{\perp(1)}, h_{1T}^{\perp(2)}$ denote the transverse momentum-weighted PDFs of the pion π^- and proton p: the number density, transversity, first moment of Sivers and Boer-Mulders, and second moment of pretzelosity. The moments of the TMD PDFs are defined as

$$f_h^{(n)}(x) = \int d^2\boldsymbol{k}_T \left(\frac{k_T^2}{2M_h^2}\right)^n f(x, k_T^2), \tag{4}$$

where M_h is the mass of the hadron.

3. Data analysis and results

The results presented in this article are based on data collected by COMPASS in 2015 and 2018. A 190 GeV/c π^- beam from the CERN SPS was scattered off a solid-state NH_3 target,

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with approximately 73% of the hydrogen nuclei transversely polarized. The target comprised two longitudinally aligned cylindrical cells, polarized vertically in opposite directions, allowing simultaneous data collection for both spin orientations. A detailed description of the COMPASS

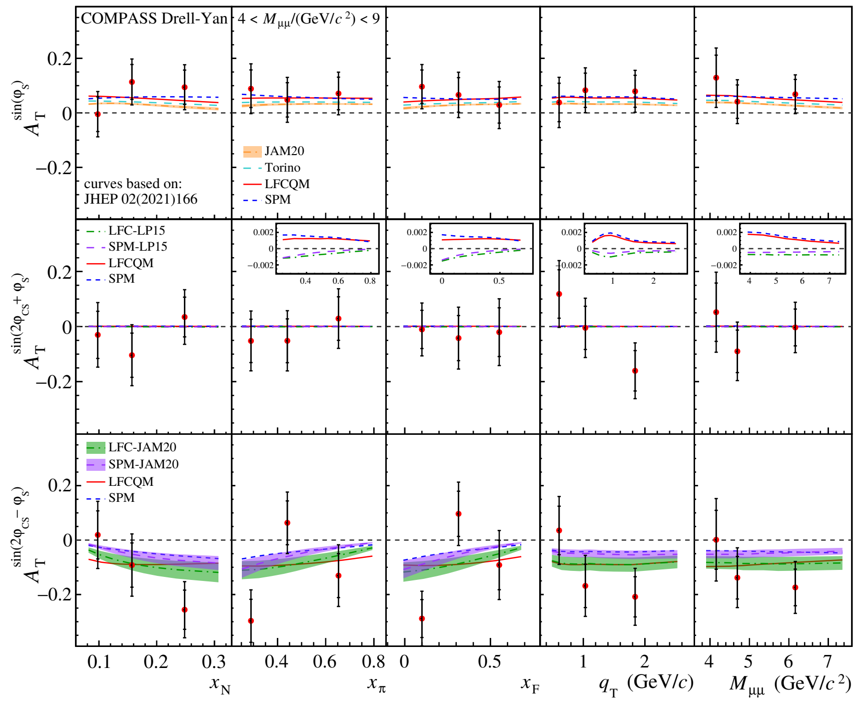

Figure 3: Kinematic dependences of the Sivers, pretzelosity, and transversity TSA (top to bottom). Inner (outer) error bars represent statistical (total experimental) uncertainties [2].

spectrometer can be found in Ref. [1]. The standard TSA were measured for the dimuon mass range $4.0 < M_{\mu\mu}$ (GeV/c^2) < 9.0 [2], and the WTSA for $4.3 < M_{\mu\mu}$ (GeV/c^2) < 8.5. Event selection was similar for both analyses, with the only difference being that the WTSA analysis did not include cuts on the transverse dimuon momentum ($q_T > 0.4$ GeV/c). Instead, a limit on the individual muon transverse momentum $\boldsymbol{l}_T < 7$ GeV/c in the laboratory frame was applied. TSA are evaluated in one-dimensional kinematic bins as functions of x_N, x_π, dimuon Feynman variable x_F, q_T, and $M_{\mu\mu}$. In Fig. 3, the combined results for the three TSA, $A_T^{\sin\varphi_S}$, $A_T^{\sin(2\varphi_{CS}+\varphi_S)}$, and $A_T^{\sin(2\varphi_{CS}-\varphi_S)}$, are shown. The final COMPASS results on the TSA are compared with recent theoretical predictions [3]. In Fig. 4, WTSA $A_T^{\sin\varphi_S \frac{q_T}{M_p}}$, $A_T^{\sin(2\varphi_{CS}+\varphi_S)\frac{q_T^3}{2M_\pi M_p^2}}$, $A_T^{\sin(2\varphi_{CS}-\varphi_S)\frac{q_T}{M_\pi}}$, are presented as functions of x_N, x_π, x_F, $M_{\mu\mu}$, and integrated over all mentioned variables. The Sivers TSA and WTSA are predicted to be positive across the entire kinematic range, consistent with the COMPASS data in Fig. 3 and Fig. 4. The average Sivers TSA is approximately 1.5 standard deviations above zero, while the WTSA effect is slightly smaller, about 1 standard deviation. Transversity asymmetries are expected to be negative and slightly larger in absolute value than the Sivers TSA. The measured average value for the transversity TSA is below zero, with a significance of about 2 standard deviations. Pretzelosity asymmetries are predicted to be very small due to the magnitude of pretzelosity TMD PDFs and

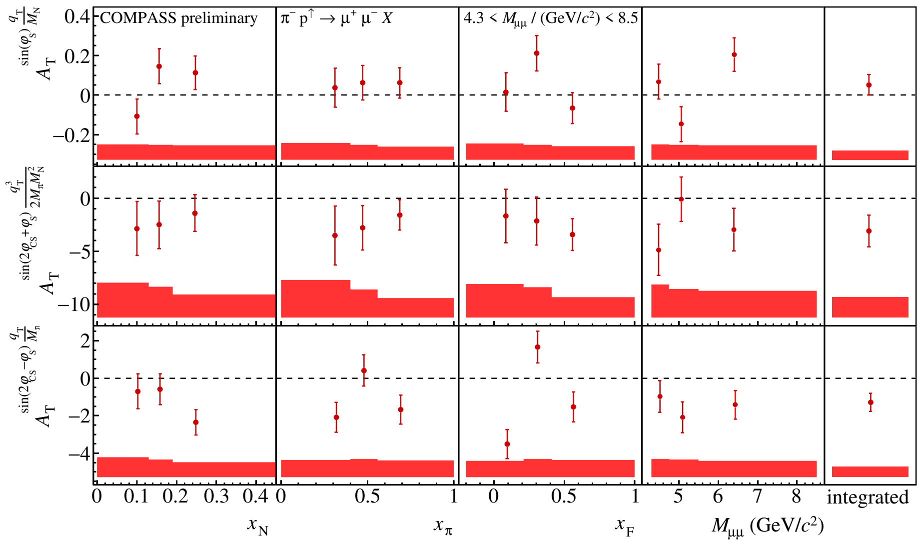

Figure 4: Kinematic dependences of the Sivers, pretzelosity, and transversity WTSA. Error bars (error bands) represent statistical (total experimental) uncertainties.

kinematic suppression factors [3]. The TSA average values are indeed small and consistent with zero within uncertainties. For the WTSA, the asymmetry is approximately 1 standard deviation negative, influenced by the cubic dependence on q_T, shifting values strongly negative. This effect does not impact the other asymmetries, as their q_T dependence is linear. Transversity is expected to be negative but larger in absolute value compared to the Sivers TSA [3]. The average values for both TSA and WTSA are below zero with a significance of about 2 standard deviations.

4. Conclusions

The newly published TSA results, along with preliminary WTSA results from COMPASS 2015 and 2018 data, are presented. The TSA analysis aligns with theoretical predictions. For WTSA, the Sivers and transversity results match theoretical expectations, while the pretzelosity value is negatively shifted due to the weighting method. These results provide further insights into accessing TMD PDFs and studying the nucleon spin structure.

References

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