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Measurement of Target Spin (in)dependent Asymmetries in Dimuon Production in Pion-Nucleon Collisions at COMPASS

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Abstract

The exploration of the transverse spin structure of the nucleon is one of the main topics of the COMPASS phase-II experiment. In 2015 and 2018 COMPASS performed Drell–Yan (DY) measurements using a 190 GeV π^- beam interacting with a transversely polarized NH_3 target and unpolarized W target. The azimuthal asymmetries in DY with transversely polarized NH_3 target are sensitive to various transverse momentum dependent parton distribution functions. Preliminary results on the Sivers asymmetry are consistent with the QCD prediction for a sign-change of Sivers functions in DY. The angular coefficients λ, μ and ν that describe the unpolarized part of the DY cross section have been extracted from the data collected with W target. The preliminary results on the angular coefficients indicate the violation of the Lam–Tung relation, consistent with the observation in earlier DY experiments with pion beams.

1 Introduction

Studying the nucleon spin structure provides a unique way to understand the internal partonic structure and their correlations in the nucleon. Data from the European Muon Collaboration (EMC) [1] first suggested puzzling result that the intrinsic spin of quarks inside the proton only contributes little to the total spin of the proton. Nowadays, a good understanding of the longitudinal spin structure of proton is achieved, while new challenges in measuring and interpreting the transverse single spin asymmetries have arisen. This reflects the importance of understanding the multi-dimensional tomographic nucleon structure.

The formalism of Transverse Momentum Dependent parton distribution functions (TMDs) can be used to investigate the nucleon spin structure in terms of its transverse degrees of freedom. The correlation among the transverse spin of nucleon and quark and also the transverse momentum of quark are encoded in different TMDs. In the leading-twist approximation, there are in total eight TMDs of the proton. The so-called Sivers function is the correlation between transverse momentum of quark and transverse spin of nucleon; the Boer–Mulders function is the correlation between transverse spin of quark and its transverse momentum, just to mention two of the most discussed TMDs in recent years.

The TMDs can be accessed via the Semi-Inclusive Deep Inelastic Scattering (SIDIS) process or the DY process. The SIDIS can access TMDs via various combinations of beam and target polarizations, and the cross section are the convolution of TMDs of the target hadron and the fragmentation functions of the struck quark. The DY process accesses TMDs from hadron-hadron collisions (either unpolarized, singly or doubly polarized), and the cross sections are the convolutions of TMDs of the two hadrons participating in the reaction.

Assuming factorization and universality of TMDs, the TMDs extracted from two different processes should be the same. However, the Sivers functions $f_{1T}^{q\perp}(x,k_T)$ and the Boer–Mulders functions $h_1^{q\perp}(x,k_T)$ are naive time-reversal odd TMDs, thus they are predicted to undergo a sign reversal between the space-like SIDIS process and the time-like DY process:

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

$$h_1^{q\perp}(x,k_T)\,|_{\mathrm{DY}} = -h_1^{q\perp}(x,k_T)\,|_{\mathrm{SIDIS}} \tag{2}$$

The prediction of the sign reversal of these two TMDs, based on the gauge invariance of QCD, is of fundamental importance in hadron physics and remains to be tested.

2 The Drell–Yan Process

The DY process occurring in hadron-hadron collisions is the annihilation of a quark and anti-quark forming a virtual photon which then decays into a lepton pair. It is an important tool to access the Parton Distribution Functions (PDFs) of the colliding hadrons. The DY azimuthal asymmetries are commonly defined using two coordinate systems: the target rest frame (TF) and the Collins–Soper (CS) virtual-photon rest frame [2]. These frames are sketched in Fig. 1.

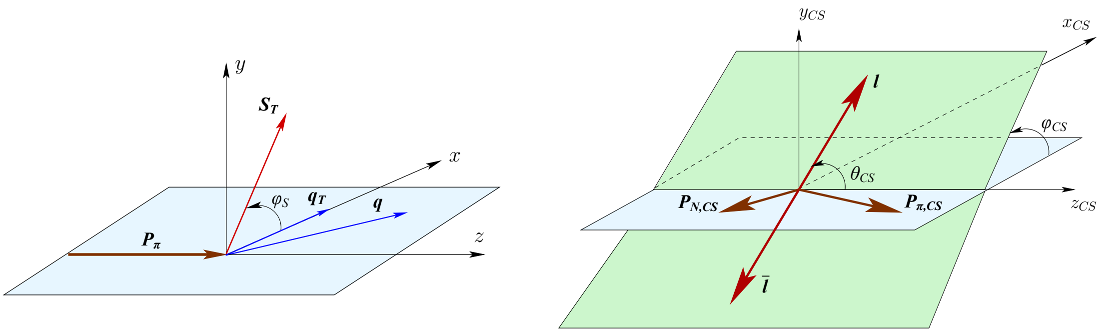

Figure 1: Left panel: target rest frame. Note that z-axis (x-axis) is chosen along the beam momentum (along q_T). Right panel: the Collins–Soper frame. The x and z axes are within the hadron plane formed by the pion and nucleon momenta (P_π and P_N). The z-axis bisects the momentum vectors of the two colliding hadrons.

When the polarizations of the produced leptons are summed over, the differential cross section of pion-induced DY production off a transversely polarized nucleon can be expressed as [2, 3]:

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}q^4\mathrm{d}\Omega} &\propto \hat{\sigma}_U \\
&\times\Big\{1 + A_U^1 \cos^2\theta_{\mathrm{CS}} + \sin 2\theta_{\mathrm{CS}} A_U^{\cos\varphi_{\mathrm{CS}}} \cos\varphi_{\mathrm{CS}} + \sin^2\theta_{\mathrm{CS}} A_U^{\cos 2\varphi_{\mathrm{CS}}} \cos 2\varphi_{\mathrm{CS}} \\
&\quad + S_T\Big[(A_T^{\sin\varphi_{\mathrm{S}}} + \cos^2\theta_{\mathrm{CS}} \tilde{A}_T^{\sin\varphi_{\mathrm{S}}}) \sin\varphi_{\mathrm{S}} \\
&\quad + \sin 2\theta_{\mathrm{CS}} \Big(A_T^{\sin(\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}})} \sin(\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}}) + A_T^{\sin(\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})} \sin(\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})\Big) \\
&\quad + \sin^2\theta_{\mathrm{CS}} \Big(A_T^{\sin(2\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}})} \sin(2\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}}) + A_T^{\sin(2\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})} \sin(2\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})\Big)\Big]\Big\}
\end{aligned}
\tag{3}
$$

Here $\hat{\sigma}_U = (F_U^1 + F_U^2)$, where F_U^1, F_U^2 are the polarization and azimuth-independent structure functions. The subscripts U and T represent the unpolarized and the transverse polarization dependent asymmetries, respectively. In Eq. (3), the differential cross section of DY process contains five target Transverse-Spin-dependent Asymmetries (TSAs) and three Unpolarized Angular Coefficients (UACs). The asymmetries A_U and A_T are defined as the ratio of the corresponding structure functions to the sum of the unpolarized ones ($\hat{\sigma}_U$). They are the amplitudes of the respective modulations involving the polar and azimuthal angle of the lepton momentum in the CS frame (θ_{CS} and φ_{CS}) and the azimuthal angle of the target spin vector in the target rest frame (φ_{S}) [2, 3].

2.1 Transverse-Spin-Dependent Asymmetries

In twist-2 approximation, Eq. (3) simplifies, and can be written as:

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}q^4\mathrm{d}\Omega} \propto \hat{\sigma}'_U \times \Big\{&1 + D_{\sin^2\theta_{\mathrm{CS}}} A_U^{\cos 2\varphi_{\mathrm{CS}}} \cos 2\varphi_{\mathrm{CS}} + S_T\Big[D_{1+\cos^2\theta_{\mathrm{CS}}} A_T^{\sin\varphi_{\mathrm{S}}} \sin\varphi_{\mathrm{S}} \\
&+ D_{\sin^2\theta_{\mathrm{CS}}} \sin^2\theta_{\mathrm{CS}} \Big(A_T^{\sin(2\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}})} \sin(2\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}}) + A_T^{\sin(2\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})} \sin(2\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})\Big)\Big]\Big\}
\end{aligned}
\tag{4}
$$

where

$$
\hat{\sigma}'_U = (F_U^1 + F_U^2)(1 + A_U^1 \cos^2\theta_{\mathrm{CS}}) \tag{5}
$$

At the leading-order (LO) perturbative QCD within the leading-twist approximation, $F_U^2 = 0$ and $A_U^1 = 1$. Here the depolarization factors $D_{f(\theta_{\mathrm{CS}})}$, depending only on the lepton polar angle, are defined as:

$$
D_{f(\theta_{\mathrm{CS}})} = \frac{f(\theta_{\mathrm{CS}})}{1 + A_U^1 \cos^2\theta_{\mathrm{CS}}} \tag{6}
$$

In Eq. (4), one UAC term $A_U^{\cos 2\varphi_{\mathrm{CS}}}$ and three TSAs terms $A_T^{\sin\varphi_{\mathrm{S}}}$, $A_T^{\sin(2\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}})}$ and $A_T^{\sin(2\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})}$ appear. The term $A_U^{\cos 2\varphi_{\mathrm{CS}}}$ is related to the Boer–Mulders TMD of the nucleon ($h_1^{q\perp}$), while $A_T^{\sin\varphi_{\mathrm{S}}}$, $A_T^{\sin(2\varphi_{\mathrm{CS}}+\varphi_{\mathrm{S}})}$ and $A_T^{\sin(2\varphi_{\mathrm{CS}}-\varphi_{\mathrm{S}})}$ refer to the nucleon's Sivers TMD ($f_{1T}^{q\perp}$), Pretzelosity TMD ($h_1^{q\perp}$) and Transversity TMD (h_1^q), respectively.

2.2 Unpolarized DY Angular Coefficients

In the literature the three UACs in Eq. (3) are often expressed alternatively as:

$$
\lambda = A_U^1, \quad \mu = A_U^{\cos\varphi_{\mathrm{CS}}}, \quad \nu = 2A_U^{\cos 2\varphi_{\mathrm{CS}}} \tag{7}
$$

These angular coefficients have attracted much attention on both theoretical and experimental sides in recent decades. The unpolarized part of the DY differential cross section in $\mathrm{d}\Omega = \mathrm{d}(\cos\theta_{\mathrm{CS}})\,\mathrm{d}(\varphi_{\mathrm{CS}})$ can be written as follows:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta_{\mathrm{CS}}+\mu\sin 2\theta_{\mathrm{CS}}\cos\varphi_{\mathrm{CS}}+\frac{\nu}{2}\sin^2\theta_{\mathrm{CS}}\cos 2\varphi_{\mathrm{CS}}\right] \tag{8}$$

In the naive DY model, the virtual photon formed by the annihilation of quark and antiquark is transversely polarized, meaning that the lepton angular distribution varies as $1+\cos^2\theta_{\mathrm{CS}}$ (i.e. $\lambda = 1$, $\mu = 0$, $\nu = 0$). Beyond the naive DY model, which ignores the intrinsic transverse momenta of partons and QCD effects, λ can deviate from 1 and μ, ν can have non-zero values. Nevertheless, the Lam–Tung relation [4], $1-\lambda = 2\nu$, was expected to be valid and insensitive to QCD corrections. It came as a major surprise when the Lam–Tung relation was found to be significantly violated in pion-induced DY experiments [5,6].

An explanation for the violation of the Lam–Tung relation was proposed by considering the contribution of a non-perturbative Boer–Mulders TMD [7], which is important in the region of low transverse momentum of the lepton pair.

The DY UACs were studied by several pion-induced DY experiments in the past. NA10 [8] at CERN performed a series of pion-induced DY measurements for three beam energies (140, 194 and 286 GeV). A large sample of DY events for dimuon masses $M_{\mu\mu} > 4.05$ GeV/c^2 was collected using the 194 GeV beam and a tungsten target. DY measurements were also performed by the E615 collaboration at Fermilab, using 252 GeV π^- beam scattering off a tungsten target. The results, presented in Ref. [6], were obtained from the analysis of DY events with $M_{\mu\mu} >$ 4.05 GeV/c^2.

3 COMPASS-II Experiment

COMPASS is a fixed-target experiment at the CERN SPS M2 beam line. It aims at studying hadron structure and hadron spectroscopy with high intensity muon and hadron beams. The first measurement of polarized DY was performed by COMPASS in 2015, with a beam of negative pions and a transversely polarized proton target. After this successful measurement, another DY data-taking occurred in 2018.

4 Data Analysis and Preliminary Results of DY Asymmetries

The preliminary results of DY TSAs and UACs presented here are based on DY data collected by COMPASS in 2018. The 190 GeV/c π^- beam interacted with two NH_3 target cells transversely polarized in opposite directions, followed by an aluminum target and, further downstream, a tungsten beam plug which also served as a target. Events with two muons originating from the target region fired the physics trigger, being recorded for analysis. The reconstructed vertices are formed by one incoming beam track and an outgoing opposite-sign muon pair. The vertex distribution along the beam direction (z-vertex) is presented in Fig. 2 left panel. The event selection criteria are nearly identical to those used in the COMPASS DY TSAs analysis [9]. The obtained dimuon mass spectrum is shown in Fig. 2 right panel, for events from the NH_3 target. In the chosen invariant mass range, between 4.3 and 8.5 GeV/c^2, the DY purity is estimated to be about 96%. The contamination in the DY sample from other physics sources is estimated by Monte-Carlo (MC) simulation. A stricter invariant mass cut of $4.7 < M_{\mu\mu}$ (GeV/c^2) < 8.5 and a z-vertex cut $-30 < z\ (cm) < -10$ were adopted for W target (i.e. only the first 20 cm of the tungsten beam plug are considered as target).

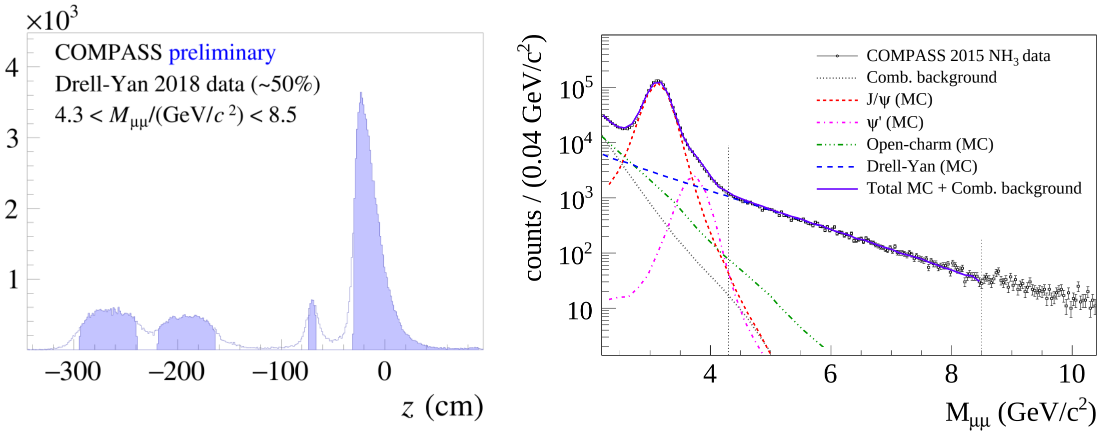

Figure 2: Left panel: The reconstructed vertex distribution along the beam axis for dimuon events. The shaded areas from left to right represent the locations of NH_3 (two cells), Al, and W targets. Right panel: The dimuon invariant mass distribution from NH_3 target in 2015 data set, where the value of contamination is adopted for 2018 data analysis.

4.1 Result of Transverse-Spin-Dependent Asymmetries

The results obtained from the COMPASS 2015 data set were published already in 2017 [9]. Fig. 3 left panel shows the published result on the Sivers asymmetry. Preliminary results of an enlarged sample that includes the 2015 data and ∼ 50% of the data collected in 2018 are shown in Eq. (4) right panel, for all five TSAs entering Eq. (3). The averaged Sivers asymmetry from 2015 data is found to be above 0 at about one standard deviation of the total uncertainty. The asymmetry is compared with the theoretical predictions from standard DGLAP and two different TMD evolution approaches [10–12] adopting the sign-change hypothesis for the Sivers TMD PDFs. The result shows that this first measurement of the DY Sivers asymmetry is consistent with the predicted sign change of Sivers function. The preliminary result combining the 2015 and partial 2018 data with an improved statistics confirm the preference for the Sivers sign change hypothesis.

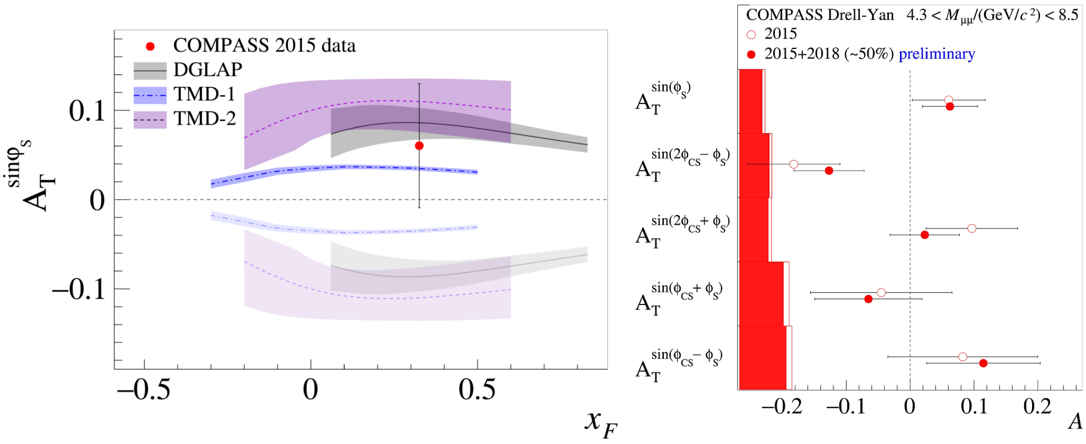

Figure 3: Left panel: The averaged Sivers asymmetry from COMPASS 2015 data and the theoretical predictions from DGLAP [10], TMD-1 [11] and TMD-2 [12]. Right panel: The averaged values for each of the 5 TSAs from COMPASS 2015 and partial 2018 data.

4.2 Result of Unpolarized DY Angular Coefficients

The extracted angular coefficients, λ, μ, ν and the amount of the violation of the Lam–Tung relation, $2\nu-(1-\lambda)$, from the tungsten target are plotted as a function of dimuon transverse momentum (q_T) in Fig. 4. The COMPASS preliminary results are compared with the results from NA10 [8] and E615 [6]. The data are also compared with NLO pQCD calculation using the DYNNLO code [13]. In general the COMPASS results for λ and ν are consistent with results from NA10 and E615, while the COMPASS result for μ is of opposite sign with respect to that of the two earlier experiments. This apparent discrepancy in sign is caused by the difference in the definition of y-axis direction in these experiments [14]. Fig. 4 also shows that the violation of the Lam–Tung relation is clearly observed in COMPASS, in qualitative agreement with NA10 and E615. The COMPASS result on ν is found to deviate from the prediction of NLO pQCD calculation, indicating possible non-pQCD contributions, such as the convolution of the Boer–Mulders functions from the two colliding hadrons.

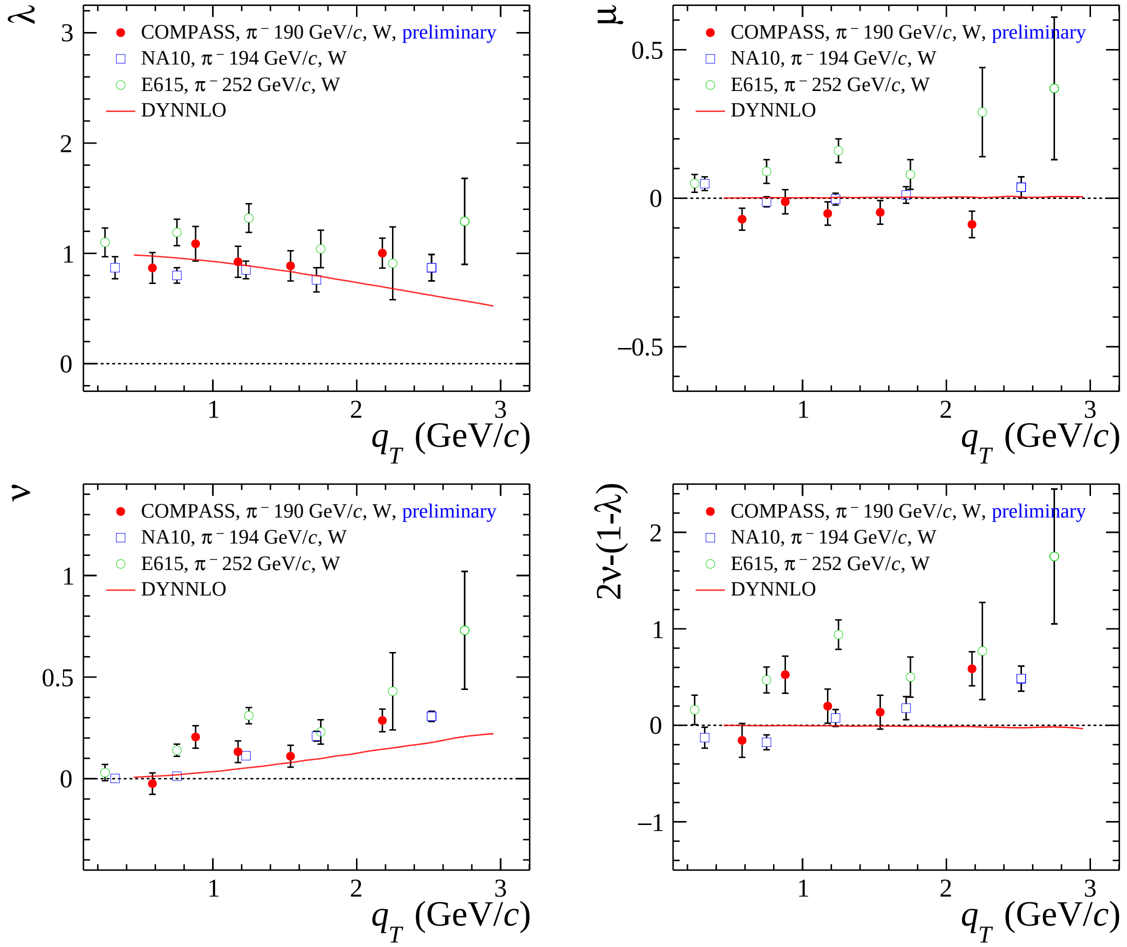

Figure 4: DY angular coefficients (λ, μ and ν) and the violation of Lam–Tung relation, $2\nu-(1-\lambda)$, versus q_T in the CS frame for the π^-+ W reaction from COMPASS. Data from NA10 and E615, as well as NLO pQCD calculations using the DYNNLO code, are also shown for comparison.

5 Conclusion

The COMPASS experiment studies the spin and partonic structure of the nucleon via SIDIS and Drell–Yan channels employing muon and pion beams impinging on different polarized and unpolarized targets. In 2017 COMPASS published the results of Sivers asymmetry from the first ever polarized DY measurement. We present preliminary results including part of the DY data collected in the 2018 run. The combined result on the Sivers asymmetry with improved statistics continues to favor the sign-reversal prediction for the Sivers function in DY. Preliminary results on the angular coefficients for unpolarized $\pi + W$ collision confirm the violation of Lam–Tung relation in pion-induced DY, in qualitative agreement with earlier observation from NA10 and E615. A comparison between the COMPASS preliminary results on the ν coefficient with pQCD calculation suggests possible contributions from other non-pQCD sources, such as the Boer–Mulders functions.

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