PROCEEDINGS OF SCIENCE

Dimuon production with a transversely-polarized target in pion-induced collisions at COMPASS

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The COMPASS experiment, located in the North Area of CERN, has the study of nucleon structure as one of its primary physics goals. In 2015 and 2018, COMPASS collected Drell-Yan and J/ψ production data from the collisions of a 190 GeV π^- beam with a transversely-polarized proton target and a tungsten target. Dimuon angular distributions provide valuable information about the transverse momentum dependent parton distribution functions (TMD PDFs) of the nucleon. Transverse-spin dependent azimuthal asymmetries (TSAs) are of particular interest because they can be used to test the predicted sign change of the Sivers TMD PDF when measured in Drell-Yan compared to semi-inclusive deep inelastic scattering. Additionally, TSAs in J/ψ production may give access to gluon TMD PDFs and also improve our understanding of the charmonium production mechanism.

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[*] Speaker

1. Transverse Momentum Dependent PDFs and the Drell-Yan Process

The study of the transverse momentum dependent structure of nucleons and other hadrons is an active area of research. Transverse momentum dependent parton distribution functions (TMD PDFs) describe correlations between the transverse momentum and spin of partons and their parent hadron. At leading twist, there are eight such TMD PDFs. Two processes that are able to access these TMD PDFs are Semi-Inclusive Deep Inelastic Scattering (SIDIS) and Drell-Yan (DY) scattering.

The DY cross-section with a transversely polarized proton target can be written in terms of azimuthal asymmetries that are related to various TMD PDFs:

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}q^4\mathrm{d}\Omega} \propto \hat{\sigma}_U \{1 &+ \cos^2\theta_{CS}\, A_U^1 + \sin(2\theta_{CS})\, A_U^{\cos\phi_{CS}} \cos\phi_{CS} + \sin^2\theta_{CS}\, A_U^{\cos 2\phi_{CS}} \cos 2\phi_{CS} \\ &+ S_T \left[\left(A_T^{\sin\phi_S} + \cos^2\theta_{CS}\, \tilde{A}_T^{\sin\phi_S}\right)\sin\phi_S\right. \\ &+ \sin 2\theta_{CS}\left(A_T^{\sin(\phi_{CS}+\phi_S)}\sin(\phi_{CS}+\phi_S) + A_T^{\sin(\phi_{CS}-\phi_S)}\sin(\phi_{CS}-\phi_S)\right) \\ &+ \left.\sin^2\theta_{CS}\left(A_T^{\sin(2\phi_{CS}+\phi_S)}\sin(2\phi_{CS}+\phi_S) + A_T^{\sin(2\phi_{CS}-\phi_S)}\sin(2\phi_{CS}-\phi_S)\right)\right]\Big\}\,. \end{aligned} \tag{1}$$

Here, S_T denotes the target transverse spin. The reference frames defining the angles in Eq. 1 are shown in Fig. 1. The asymmetries denoted by A_T are transverse spin dependent asymmetries (TSAs). Of particular interest are $A_T^{\sin(2\phi_{CS}+\phi_S)}$ related to the proton pretzelosity TMD $h_{1T}^{\perp}$, $A_T^{\sin(2\phi_{CS}-\phi_S)}$ related to the proton transversity TMD h_1, and $A_T^{\sin\phi_S}$ related to the proton Sivers TMD $f_{1T}^{\perp}$. The Sivers TMD is time-reversal odd, unlike transversity and pretzelosity. Because of this, the Sivers function is predicted by QCD to have opposite sign when measured in DY compared to SIDIS. Confirming this prediction experimentally is important for verifying the TMD framework of QCD. For more information and references on TMD PDFs, see [1].

The asymmetries denoted by A_U are spin-independent asymmetries. They are often written as $\lambda \equiv A_U^1$, $\mu \equiv A_U^{\cos\phi_{CS}}$, and $\nu \equiv 2A_U^{\cos 2\phi_{CS}}$. The so called Lam-Tung relation $1- = 2\nu$ is predicted to hold up to NLO in perturbative QCD (pQCD). However, previous DY experiments have shown this relation to be violated. They have also shown ν to differ from the pQCD predictions [2]. These disagreements with pQCD can be explained by considering a non-perturbative Boer-Mulders TMD $h_1^{\perp}$, which is also time-reversal odd like the Sivers TMD [3]. For this reason ν ($A_U^{\cos 2\phi_{CS}}$) is often referred to as the Boer-Mulders asymmetry.

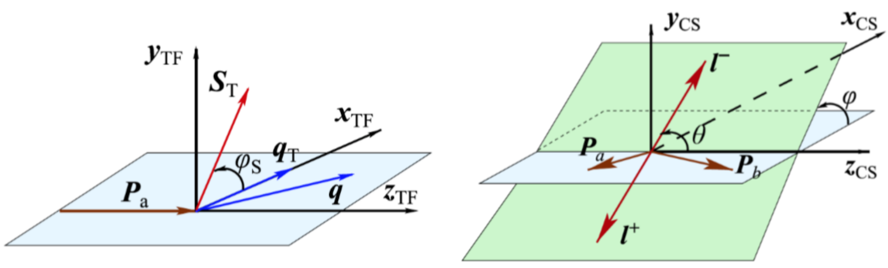

Figure 1: The target rest frame (left) and Collins-Soper frame (right).

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2. COMPASS experiment and data collection

COMPASS is a fixed target experiment in the North Area of CERN. It uses secondary hadron beams or tertiary muon beams obtained from the SPS-extracted proton beam. COMPASS has taken both SIDIS and DY data with essentially the same spectrometer. The SIDIS measurements involved 160 or 200 GeV/c longitudinally polarized muon beams colliding with transversely or longitudinally polarized proton or deuteron targets. The DY data-taking, which occurred in 2015 and 2018, involved a 190 GeV/c π^- beam colliding with a transversely polarized proton target.

The polarized target during the DY runs was composed of two 55 cm long cells filled with solid state ammonia. The protons in each NH_3 cell were polarized in opposite directions, so that acceptance variation effects were minimized in the total data sample. Since the signature of a DY event is a lepton pair, a hadron absorber was added just downstream of the polarized target. The absorber contained both an aluminum target and a tungsten target. A distribution of reconstructed vertices of dimuon events along the beam direction in 2018 data is shown in the left panel of Fig. 2.

A multi-step event selection procedure is implemented to isolate dimuon DY candidates. The right panel of Fig. 2 shows the invariant mass distribution of dimuon events from the NH_3 target in 2015, along with Monte-Carlo simulated contributions from various processes. The invariant mass range $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$ is chosen for the DY TSA analysis to minimize background. The background in this range is estimated to be 4%. In the spin-independent analysis of DY events from the tungsten target, the stricter mass cut of $4.7 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$ GeV/c^2 is used. These mass ranges will be referred to as 'high-mass Drell-Yan'.

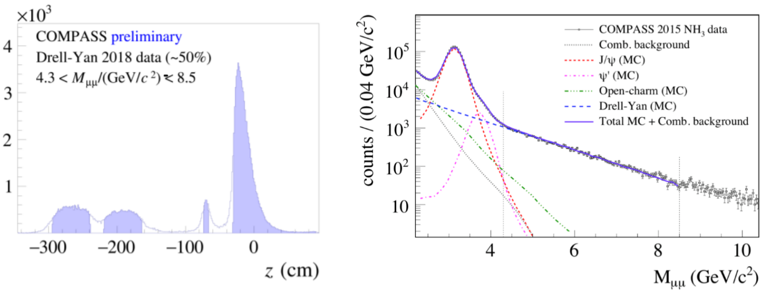

Figure 2: Left: The distribution of events in 2018 COMPASS data based on the reconstructed z-vertex position. The shaded regions from left to right are the positions of the two ammonia cells, the aluminum target, and the tungsten target. Right: The invariant dimuon mass distribution in 2015 data, with contributions from different processes estimated using Monte-Carlo [4]. The combinatorial background is evaluated using like-sign muon pair data.

3. COMPASS DY azimuthal asymmetry results

The newest COMPASS results for the spin-independent quantities ν and $2\nu - (1 - \lambda)$ are shown in Fig. 3. These quantities are extracted from the angular-dependence analysis of high mass dimuons originating in the first 20 cm of the tungsten target. The results are shown along with the NLO pQCD prediction calculated using DYNNLO code [2] and the previous results of the NA10 [5] and E615 [6] experiments. Within error bars, the COMPASS results agree reasonably well with NA10 and E615 in both cases. The results for ν tend to be systematically above the pQCD prediction, suggesting the presence of a non-zero Boer-Mulders effect. The Lam-Tung relation is shown to be

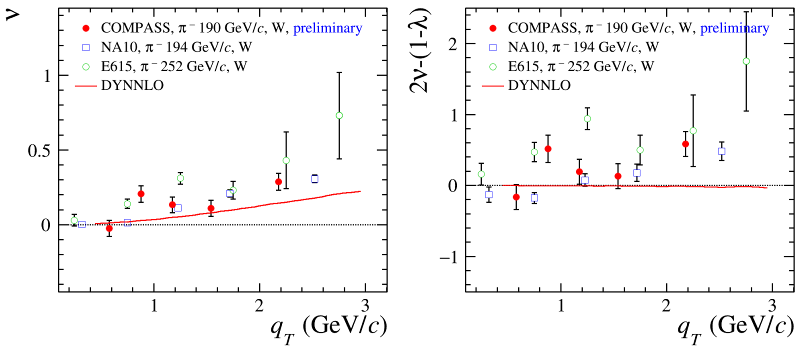

Figure 3: COMPASS results for ν (left) and the Lam-Tung violation quantity $2\nu-(1-\lambda)$ (right) as a function of the virtual photon transverse momentum q_T, extracted from DY events originating in the tungsten target. The previous results from NA10 and E615 are also shown for comparison, along with the pQCD prediction calculated using DYNNLO code (statistical error bars small enough to be invisible).

violated by the current experimental results. The extraction of spin-independent asymmetries from COMPASS NH_3 data is ongoing.

The most recent COMPASS TSA results, extracted from high mass DY dimuons produced in the polarized NH_3 target, are shown in the left panel of Fig. 4. The figure shows the published results from the 2015 data sample [4], and the more recent results that add about half of the 2018 data sample. The results show a Sivers TSA $A_T^{\sin(\phi_S)}$ about 1σ above zero, a transversity TSA $A_T^{\sin(2\phi_{CS})-\phi_S)}$ about 2σ below zero, and a pretzelosity TSA $A_T^{\sin(2\phi_{CS})+\phi_S)}$ less than 1σ above zero. The analysis of the rest of the 2018 data sample is ongoing and will improve the statistical precision of the results. The current COMPASS DY Sivers TSA measurement is consistent with the sign change prediction. This can be seen when comparing the sign of the Sivers TMD based on COMPASS DY TSA results to that from COMPASS SIDIS TSA results in a similar kinematic range [7]. (The angle conventions mean that Sivers TSAs with the same sign in both processes points to a Sivers TMD PDF with opposite sign.) The right panel of Fig. 4 also demonstrates that the sign change is favored by comparing the published COMPASS DY result to phenomenological predictions using DGLAP and two different TMD evolution schemes (see [4] and the references therein).

4. Azimuthal asymmetries in J/ψ production

In addition to true DY events, COMPASS data contains dimuons coming from the decay of the J/ψ meson. The right panel of Fig. 2 shows that there are over an order of magnitude more J/ψ events than high mass DY events. Extracting TSAs from these events is a worthwhile endeavor. There are two leading-order processes by which J/ψ can be produced in hadron-hadron collisions: quark-antiquark annihilation and gluon-gluon fusion. The first process is sensitive to quark TMDs, and the extraction of TSAs from these events would provide complementary information to that from DY. The second process is sensitive to gluon TMDs, which are still poorly known. Additionally, there is a significant feed-down contribution to the J/ψ peak from higher states like $\psi(2S)$ and the χ_c states. In order to know how to interpret J/ψ TSA results, the production mechanism must be understood. Ref. [8] predicts a large Sivers asymmetry in COMPASS J/ψ production assuming quark-antiquark annihilation as the only relevant process. However, more recent studies [9] suggest

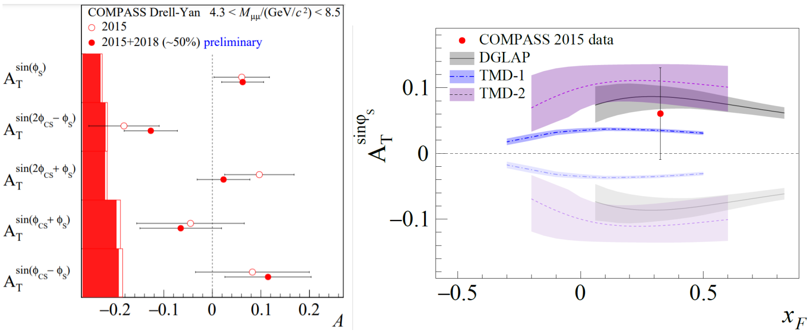

Figure 4: Left: Average TSA results from COMPASS DY data. The full 2015 data sample and half of the 2018 sample was used in this preliminary extraction. Right: The published COMPASS Sivers TSA result from 2015 data, along with phenomenological curves predicted by DGLAP and two TMD evolution schemes [4]. The darker curves in the upper half of the plot are the curves if the sign change prediction holds.

that gluon-gluon fusion should be dominant at COMPASS kinematics. Comparing the TSA results extracted from the data to these predictions can give insight into the J/ψ production mechanism. The extraction of TSAs from J/ψ events in the COMPASS 2015 and 2018 data samples is ongoing.

5. Summary

Azimuthal asymmetries in COMPASS DY data give access to TMD PDFs and spin-orbit correlations in the proton and the pion. The most recent extraction of spin-independent asymmetries from COMPASS DY data hint at a non-zero Boer-Mulders effect and violation of the Lam-Tung relation. The current results from TSA extraction favor the Sivers sign change prediction between DY and SIDIS. Ongoing analyses with larger data sets will improve the statistical precision of both the spin-independent and TSA results. In addition, the results of the ongoing TSA extraction from J/ψ events should offer insight into the J/ψ production mechanism at COMPASS and possibly give information about poorly known gluon TMDs.

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