

# Measurement of $q_T$ -weighted TSAs in 2015 COMPASS Drell–Yan data

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## Abstract

In the polarised Drell–Yan experiment at the COMPASS facility at CERN the beam of negatively-charged pions with 190 GeV/ $c$  momentum and intensity about  $10^8$  pions/s interacted with transversely polarised  $\text{NH}_3$  target. Muon pairs produced in Drell–Yan process (DY) were detected. Recently, the first ever Transverse Spin Asymmetries (TSAs) measurement in DY has been presented by COMPASS. A complementary analysis of the TSAs weighted by powers of the dimuon transverse momentum  $q_T$  are presented. In the Transverse Momentum Dependent (TMD) PDF formalism, the  $q_T$ -weighted TSAs can be written in terms of products of the TMD PDFs of two colliding hadrons, unlike the conventional TSAs, which are their convolutions over quarks transverse momenta. The results are compared in a straightforward way with the weighted Sivers asymmetry in the SIDIS process, released by COMPASS in 2016.

## 1 Introduction

The hadron structure can be described at leading twist by eight Transverse Momentum Dependent (TMD) Parton Distribution Functions (PDFs), which depend on the fraction  $x$  of the hadron momentum carried by the parton and the transverse component of the parton momentum  $\mathbf{k}_T^2$ . They have been probed in Semi-Inclusive Deep Inelastic Scattering (SIDIS), where the cross-section contains convolutions of the TMD PDFs and fragmentation functions [1].

Comparison of SIDIS with the Drell–Yan process (DY), giving access to convolutions of TMD PDFs of the two colliding hadrons [2], can provide a test of the PDFs universality. In fact, two PDFs (the Sivers and Boer–Mulders functions) are predicted to bear opposite signs when extracted from SIDIS and DY [3]. Recently, COMPASS has done a pioneering measurement of the Transverse Spin Asymmetries (TSAs) in DY [4]. A complementary analysis of the same data, using the formalism of transverse momentum  $q_T$  weighted TSAs [5, 6], is presented.

The convolutions of TMDs are usually solved assuming a certain functional form of their dependence on  $\mathbf{k}_T^2$  (e.g. Gaussian). In SIDIS, it can be avoided using the TSAs weighted with powers of the outgoing hadron transverse momentum  $P_T$  [7, 8, 9]. Preliminary  $P_T$ -weighted TSAs from HERMES [10] were used to estimate the  $q_T$ -weighted Sivers asymmetry expected in DY experiments [5]. Similarly, in Sec. 3 we use the recent COMPASS measurement of the  $P_T/z$ -weighted Sivers asymmetry [11] to get a projection, which we compare with our DY results.

## 2 Transverse momentum weighted asymmetries in Drell–Yan process

We study the Drell–Yan reaction with 190 GeV/ $c$  pion beam and  $\text{NH}_3$  target with the H nuclei transversely polarised  $\pi^- p^\uparrow \rightarrow \mu^- \mu^+ X$ . At Leading Order (LO), the reaction proceeds via annihilation of a quark-antiquark pair into a virtual photon with momentum  $q$ , which decays into the dimuon. The LO cross-section contains five orthogonal modulations in  $\phi$  and  $\phi_S$  – the azimuthal angles of the muon momentum in the Collins–Soper frame and of the target spin vector  $\mathbf{S}_T$  in the target rest frame with  $z$ -axis along the beam momentum and  $x$ -axis

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along dimuon transverse momentum  $\mathbf{q}_T$ , respectively [12]. The structure functions  $F_{U,T}^X$  can be written as convolutions of TMD PDFs over the intrinsic transverse momenta of the two colliding partons  $\mathbf{k}_{\pi T}$  and  $\mathbf{k}_{N T}$  [2]. When the structure functions are integrated over  $q_T$  with properly chosen weights, the convolutions can be disentangled<sup>1</sup>:

$$\int d^2\mathbf{q}_T F_U^1 = \frac{1}{3} \sum_q e_q^2 [f_{1,\pi}^{\bar{q}}(x_\pi) f_{1,N}^q(x_N) + f_{1,\pi}^q(x_\pi) f_{1,N}^{\bar{q}}(x_N)] \quad (1)$$

$$\int d^2\mathbf{q}_T \frac{q_T}{M_p} F_T^{\sin\phi_S} = -\frac{2}{3} \sum_q e_q^2 [f_{1,\pi}^{\bar{q}}(x_\pi) f_{1T,p}^{\perp(1)q}(x_N) + (q \leftrightarrow \bar{q})], \quad (2)$$

$$\int d^2\mathbf{q}_T \frac{q_T^3}{2M_\pi M_p^2} F_T^{\sin(2\phi+\phi_S)} = -\frac{2}{3} \sum_q e_q^2 [h_{1,\pi}^{\perp(1)\bar{q}}(x_\pi) h_{1T,p}^{\perp(2)q}(x_N) + (q \leftrightarrow \bar{q})], \quad (3)$$

$$\int d^2\mathbf{q}_T \frac{q_T}{M_\pi} F_T^{\sin(2\phi-\phi_S)} = -\frac{2}{3} \sum_q e_q^2 [h_{1,\pi}^{\perp(1)\bar{q}}(x_\pi) h_{1,p}^q(x_N) + (q \leftrightarrow \bar{q})], \quad (4)$$

where the sums run over quarks and antiquarks  $q$ ;  $e_q$  are fractional electric charges;  $M_{\pi,p}$  are the pion and proton masses; and  $f^{(n)}$  or  $h^{(n)}$  are the  $n$ -th  $k_T^2$ -moments of the TMD PDFs,  $f^{(n)}(x) = \int d^2\mathbf{k}_T [k_T^2/(2M^2)]^n f(x, k_T^2)$ . We measure the  $q_T$ -weighted TSAs, defined as

$$A_T^{\sin\Phi W_\Phi} = \frac{\int d^2\mathbf{q}_T W_\Phi F_T^{\sin\Phi}}{\int d^2\mathbf{q}_T F_U^1}, \quad \Phi = \phi_S, 2\phi + \phi_S, 2\phi - \phi_S \quad (5)$$

where  $W_\Phi$  denotes the weights. The weighted TSAs are obtained by fit of the so-called modified double ratio  $R(\Phi) \propto A_T^{\sin\Phi W_\Phi} \sin\Phi$ . The ratio is constructed from event counts and sums of event weights coming from two oppositely-polarised target cells and from two sub-periods divided by polarisation reversal to cancel the acceptance  $a(\Phi)$ . It is calculated using eight bins in  $\Phi$  and one or three bins in four kinematic variables. As in the standard TSA analysis [4] we use the dilution factor to correct the asymmetries for the target composition, so the TSAs refer to proton.

The data have been collected in 2015 in nine data-taking periods (each having two sub-periods). The event sample is almost the same as in the TSA analysis [4]. The same invariant mass range  $M \in [4.3, 8.5] \text{ GeV}/c^2$  is used. The sharp cuts on  $q_T$  are replaced by cut on individual muon transverse momenta  $l_T < 7 \text{ GeV}/c$ . About 39000 dimuons pass the event selection. We estimate the background to be at the level of up to 4% [4]. Several possible systematic effects have been investigated. The major contribution comes from the effect of variation of the data-taking conditions within a given period, estimated by measurement of false asymmetries. They are calculated from events with sub-periods or target cells of origin changed in such a way that the physics asymmetries cancel. The combined systematic uncertainty is about 0.7 times the statistical one. In addition, there are normalisation uncertainties of about 5% from the polarisation measurement and dilution factor calculation. The results are shown on Fig. 1, the  $q_T$  distribution on Fig. 2.

### 3 Transverse momentum weighted Siverts asymmetry in SIDIS and Drell–Yan

To get a projection for the expected  $q_T$ -weighted Siverts asymmetry in DY, we use the corresponding  $P_T/z$ -weighted asymmetry in SIDIS  $\mu p^\uparrow \rightarrow \mu' h X$ , measured by COMPASS for positive and negative hadrons  $h$  with  $z > 0.2$  [11]. It can be written as [9, 11]:

$$A_{U,T}^{\sin(\phi_h - \phi_s) \frac{P_T}{z M}}(x, z, Q^2) = \frac{\int d^2\mathbf{P}_T \frac{P_T}{z M} F_{U,T}^{\sin(\phi_h - \phi_s)}}{\int d^2\mathbf{P}_T F_{U,U,T}^1} = 2 \frac{\sum_q e_q^2 f_{1T,p}^{\perp(1)q}(x, Q^2) D_{1,q}^h(z, Q^2)}{\sum_q e_q^2 f_{1,p}^q(x, Q^2) D_{1,q}^h(z, Q^2)}, \quad (6)$$

where we use the standard SIDIS variables,  $F$  indicate the SIDIS structure functions [1], and  $D_{1,q}^h(z)$  is the fragmentation function of  $q$  into hadron  $h$ . In writing explicitly the asymmetry, we only consider u, d, and s quarks and the corresponding antiquarks  $\bar{q}$  within the proton;

<sup>1</sup>We use the same Siverts function sign as in Ref. [11, 13] and opposite to Ref. [1, 2] and the Trento convention [14].

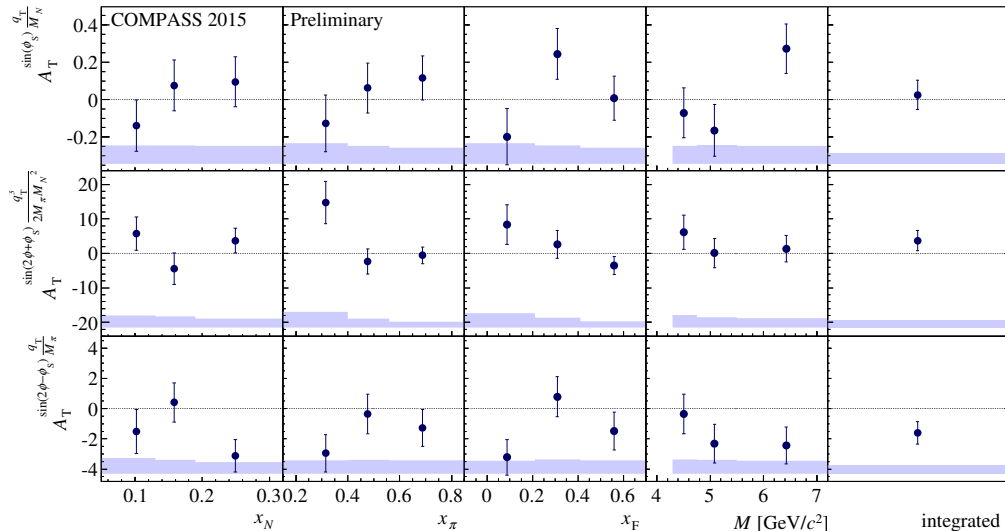


Figure 1: The  $q_T$ -weighted TSAs. The systematic uncertainty is denoted by blue bands. Normalisation uncertainties of about 5% (from polarisation and dilution factor) are not shown.

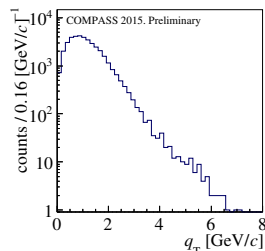


Figure 2: Distribution of  $q_T$  in the selected Drell–Yan events.

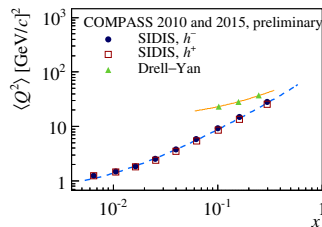


Figure 3: Mean  $Q^2$  of the events in the Drell–Yan analysis and SIDIS analysis [11].

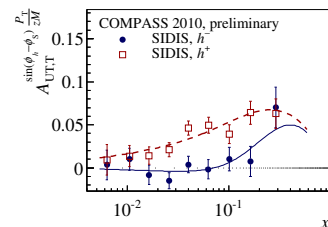


Figure 4: The weighted Siverson asym. in SIDIS [11], fitted. Statistical errors only.

we assume vanishing Siverson function of sea quarks; and, like in Ref. [13], we integrate the fragmentation functions over the available range in  $z$ .

We take the unpolarised PDFs from the CTEQ 5D global fit [15], implemented in the LHAPDF library [16] and the charged hadron fragmentation functions from the DSS 07 LO global fit [17]. As in [13], we use the collinear evolution of the PDFs and FFs, taken at the mean  $Q^2$  at each  $x$  (plotted on Fig. 3), as  $x$  and  $Q^2$  are correlated. We parametrise the first  $k_T^2$ -moment of the Siverson function as  $x f_{1T}^{\perp(1)q}(x) = a_q x^{b_q} (1-x)^{c_q}$ . The asymmetries for positive and negative hadrons in bins of  $x$  are simultaneously fitted (Fig. 4).

To get the projection for the  $q_T$ -weighted asymmetry in DY, we use Eq. (2, 5), we assume the change-of-sign prediction [3] and valence quark dominance. The asymmetry simplifies to  $A_T^{\sin \phi_S q_T/M_p}(x_N, Q^2) \approx 2 f_{1T,p}^{\perp(1)u}(x_N, Q^2) / f_{1,p}^u(x_N, Q^2)$ . We identify the  $x_N$  with the Bjorken  $x$  from SIDIS and we use the same unpolarised PDF, taken at the mean  $Q^2$  of the DY events used in the analysis (Fig. 3). No evolution of  $f_{1T,p}^{\perp(1)u}$  between the SIDIS and DY kinematics is considered. The result, compared with the measured asymmetries (Sec. 2), is shown on Fig. 6. A projection for combined analysis of 2015 and 2018 data is shown as well, assuming the statistics in 2018 to be 1.5 times larger than in 2015. The  $1\sigma$  error-bands account only for the uncertainty of the fit and the statistical errors of the experimental data. Variation of PDF and FF sets has been found to lead to differences of about 0.02.

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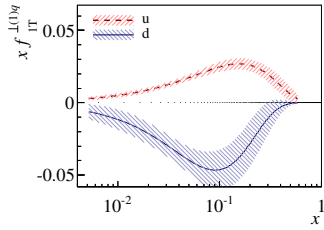


Figure 5: The Siverson PDF first  $k_T^2$ -moment as a function of  $x$  and  $Q^2(x)$ . The  $1\sigma$  error-bands account only for the uncertainty of the fit and the statistical errors of the data.

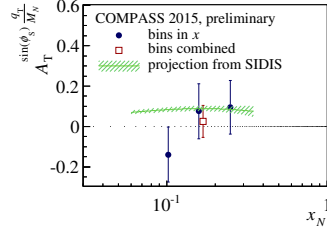


Figure 6: Weighted Siverson asymmetry in Drell–Yan from 2015 data and the projection from corresponding asymmetry in SIDIS. Only statistical errors are shown.

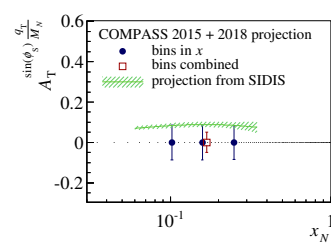


Figure 7: A projection for combined analysis of 2015 and 2018 data. The statistics in 2018 is assumed 1.5 times larger than in 2015. Only statistical errors are shown.

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