PROCEEDINGS OF SCIENCE

# The gluon Sivers asymmetry measurements at COMPASS

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The Sivers effect describes the correlation between the spin of the nucleon and the orbital motion of partons. For gluons it has been measured at COMPASS via $J/\Psi$ production and via high-$p_T$ hadron pair production in Semi-Inclusive Deep Inelastic Scattering of a 160 GeV/$c$ muon beam off transversely polarised proton and deuteron targets by determining the amplitude of the modulation of the Sivers angle $\phi^{Siv}$ distribution. Both the approach using $J/\Psi$ channel and high-$p_T$ hadron pair selection will be described in detail and the results given.

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## 1. Introduction

The Sivers effect is connected to the correlation of the transverse motion of partons in the nucleon and the nucleon spin. In the view of the spin puzzle it is of particular interest to measure the Sivers effect for gluons as a signature of possible gluon orbital motion in the nucleon.

The transverse momentum dependent parton distribution functions (PDFs) of the nucleon have been studied in semi-inclusive DIS off transversely polarised targets since many years. Strong emphasis has been put on extracting Sivers and Collins asymmetries, which were published by the COMPASS and HERMES collaborations using deuteron [1] and proton [2, 3, 4, 5] targets.

In order to extract the Sivers asymmetry for gluons from COMPASS data, a model of muon-nucleon scattering is applied. As a framework for SIDIS description in this paper we use the LEPTO model [6], in which three hard processes incoherently contribute: photon-gluon-fusion (PGF) $\gamma^{*}g \to q\bar{q}$, QCD Compton (QCDC) $\gamma^{*}q \to qg$ and the leading process (LP) $\gamma^{*}q \to q$. Their relative weights are calculated according QCD cross-sections with infrared and collinear cutoffs. After each hard process the final state quarks, gluon and target remnant form strings which are hadronising into final state hadrons. The above-mentioned analysis by the COMPASS collaboration are dominated by the leading process, the absorption of a virtual photon by a quark. In order to measure the Sivers effect for gluons, a method of obtaining the asymmetry of the PGF process is needed. It is also possible to tag PGF events by the $J/\Psi$ production.

## 2. The gluon Sivers asymmetry measurement via $J/\Psi$ production at COMPASS

The Sivers asymmetry in $J/\Psi$ production in scattering of muons off transversely polarised protons $\mu^{+} + p^{\uparrow} \to \mu' + J/\Psi + X$ is measured in two $z$-bins in the COMPASS 2010 data. Events with three muons in the final state are selected. The invariant mass distributions of the muon pairs of opposite signs are shown in Figure 1 separately for the two $z$-bins together with the boundaries of the signal band and two side-bands, which are used to evaluate the asymmetry of the background. The signal to background and signal to total ratios were calculated to be $N_{sig}/N_{bg} = 4.3, N_{sig}/N_{tot} =$

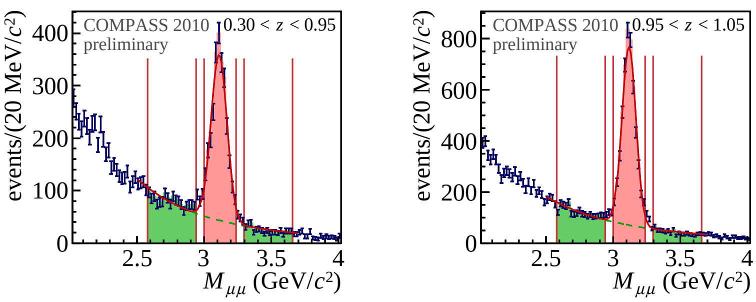


Figure 1: Dimuon invariant mass in the two z-intervals. Left: inclusive events , right: exclusive events. The boundaries of the side-bands and the signal band are denoted by vertical red lines. The red fit to the data is the normal distribution plus background in the form $AN(M_{\mu\mu}, \mu, \sigma) + BM_{\mu\mu}^{C}$. The dotted green line is the background estimation $BM_{\mu\mu}^{C}$.

0.8 for the first bin in $z$ and $N_{sig}/N_{bg} = 5.2, N_{sig}/N_{tot} = 0.8$ for the second. The Sivers asymmetry is the amplitude of the modulation $\sin(\phi_{p_T} - \phi_S)$, where $p_T$ is the transverse (with respect to the virtual photon) momentum of the reconstructed $J/\Psi$. It is assumed that the background asymmetry is the same as the side-band asymmetry and is subtracted. The results is shown in Fig.2 (right).

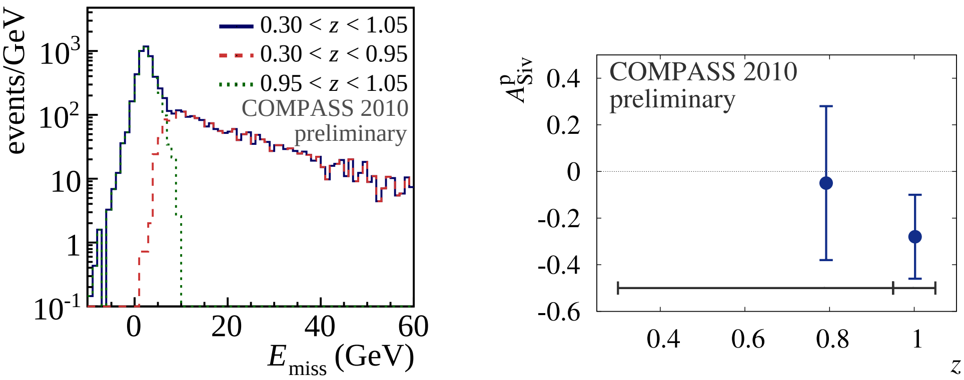


Figure 2: Missing energy spectrum (left) and the final Sivers asymmetry in the two $z$ bins (right).

The obtained asymmetries, $A^p_{Siv} = -0.05 \pm 0.33$ for $z \in [0.3; 0.95]$ and $A^p_{Siv} = -0.28 \pm 0.18$ for $z \in [0.95; 1.05]$, show the tendency to the negative sign but the statistical error is large and it is difficult to draw any resolute conclusion.

## 3. Sivers asymmetry in two hadron production

In order to extract the gluon asymmetry from PGF events a sample of events with two hadrons in the final state is used. The Sivers Asymmetry can then be written as

$$A_T^{2h}(\vec{x}, \phi_{Siv}) = \frac{d^7\sigma(\vec{x}, \phi_{Siv}) \uparrow - d^7\sigma(\vec{x}, \phi_{Siv}) \downarrow}{d^7\sigma(\vec{x}, \phi_{Siv}) \uparrow + d^7\sigma(\vec{x}, \phi_{Siv}) \downarrow}, \tag{3.1}$$

where $\vec{x} = (x_{Bj}, Q^2, p_{T1}, p_{T2}, z_1, z_2)$ and $\uparrow$ ($\downarrow$) labels the polarisation of the target cell. Then the number of events in a $\phi_{Siv}$ bin is given by $N(\vec{x}, \phi_{Siv}) = \alpha(\vec{x}, \phi_{Siv})\left(1 + fP_T A^{Siv}(\vec{x}) \sin\phi_{Siv}\right)$. Here $f$ is the dilution factor, $P_T$ is the target polarisation and $\alpha$ is an acceptance-dependent factor. The Sivers asymmetry $A_T^{2h}(\vec{x}, \phi_{Siv})$ is factorised into the amplitude $A^{Siv}(\vec{x})$ and the modulation $\sin\phi_{Siv}$.

As said before the model with only PGF, QCDC and LP processes is successful in describing the unpolarised data. The LP is dominating the cross-section; the other two can be enhanced, however, by selecting hadrons with high $p_T$. Introducing the processes fractions $R_j$ ($j = PGF, QCDC, LP$) the amplitude of the Sivers asymmetry can be expressed in terms of the amplitudes of the three contributing processes:

$$A^{Siv} = R_{PGF} A^{Siv}_{PGF} + R_{QCDC} A^{Siv}_{QCDC} + R_{LP} A^{Siv}_{LP}. \tag{3.2}$$

The weighted method used in this analysis was already applied to extract the gluon polarisation from the longitudinal double-spin asymmetry in the SIDIS measurement of single hadron production [7]. Both the deuteron runs (two target cells) and for the proton run (three target cells) four target configurations can be introduced. Decomposing the Sivers asymmetry into the asymmetries of the contributing processes (Eq. (3.2)) and introducing the Sivers modulation $\beta_j^t(\phi_{Siv}) = R_j f P_T^t \sin\phi_{Siv}$ specific for the process $j$ the number of events is given by

$$N^t(\vec{x},\phi_{Siv}) = \alpha^t(\vec{x},\phi_{Siv})\Big(1+\beta^t_{PGF}(\phi_{Siv})A^{Siv}_{PGF}(\vec{x}) + \beta^t_{QCDC}(\phi_{Siv})A^{Siv}_{QCDC}(\vec{x}) + \beta^t_{LP}(\phi_{Siv})A^{Siv}_{LP}(\vec{x})\Big), \tag{3.3}$$

where $t = 1,2,3,4$ denotes the target configuration. For each process a statistical weighting factor is introduced which is chosen to be $\omega_j \equiv \beta_j/P_T$. Each of the four equations (3.3) is weighted three times with $\omega_j$ depending on the process $j$(PGF, QCDC, LP) and integrated over $\phi_{Siv}$ and $\vec{x}$ giving twelve observed quantities $q_j^t$:

$$\begin{aligned} q_j^t &= \int d\vec{x}d\phi_{Siv}\omega_j(\phi_{Siv})N^t(\vec{x},\phi_{Siv}) \approx \sum_{i=0}^{N^t}\omega_i^j \\ &= \tilde{\alpha}_j^t\Big(1+\{\beta^t_{PGF}\}_{\omega_j}\{A^{Siv}_{PGF}\}_{\beta^t_{PGF}\omega_j} + \{\beta^t_{QCDC}\}_{\omega_j}\{A^{Siv}_{QCDC}\}_{\beta^t_{QCDC}\omega_j} + \{\beta^t_{LP}\}_{\omega_j}\{A^{Siv}_{LP}\}_{\beta^t_{LP}\omega_j}\Big), \end{aligned} \tag{3.4}$$

where $\tilde{\alpha}^t = \int d\vec{x}d\phi_{Siv}\alpha^t(\vec{x})\omega(\phi_{Siv})$ is the weighted acceptance-dependent factor and the weighted mean is defined as:

$$\{\beta_k^t\}_{\omega_j} = \frac{\int d\vec{x}d\phi_{Siv}\alpha^t(\vec{x})\omega_j(\vec{x},\phi_{Siv})\beta_k^t(\vec{x},\phi_{Siv})}{\int d\vec{x}d\phi_{Siv}\alpha^t(\vec{x})\omega_j(\vec{x},\phi_{Siv})} \approx \frac{\sum_i^{N^t}\beta_j^{t,i}\omega_j^i}{\sum_i^{N^t}\omega_j^i}, \tag{3.5}$$

where $k,j \in \{PGF,QCDC,LP\}$. The weighted acceptance-dependent factors cancel assuming their ratio is the same before and after the polarisation reversal, $(\tilde{\alpha}_j^1\tilde{\alpha}_j^4)/(\tilde{\alpha}_j^2\tilde{\alpha}_j^3) = 1$.

## 4. Monte Carlo optimisation and Neural Network training

The analysis which has been performed is very similar to the one described in [7]. In this analysis the package NetMaker [8] is used. The package provides NN training with custom input, output and target vector. The NN has been trained with a Monte Carlo sample with process identification. As an input vector six kinematic variables have been chosen, $x_{Bj}, Q^2, p_{T1}, p_{T2}, p_{L1}, p_{L2}$. The latter two are the longitudinal components of the hadron momenta. The trained neural network is applied to the data by taking the vector of the aforementioned six variables. Hence, the simulated distribution of these variables need to be in agreement with their distributions in the data samples. Figure 3 shows the comparison between the experimental and MC data for the proton case. The same comparison is performed for the proton data.

The main goal of of NN parameterisation is an estimation of $R_j$. In the present analysis one has to estimate simultaneously the fractions of the three processes. The NN returns three $R_j$ values for each process adding up to one. Studies on MC data show that the average $R_j$ values from the NN and the true fractions $R_j$ from the MC process ID are consistent.

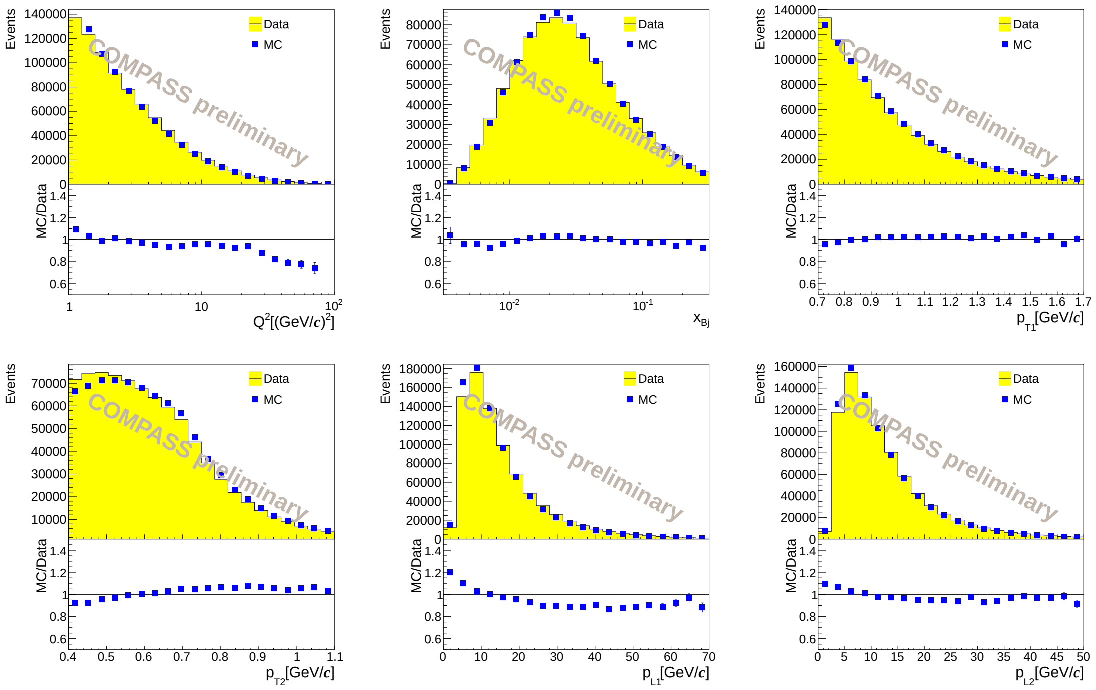


Figure 3: Comparison of kinematic variables distributions from experimental and MC2010 high-$p_T$ proton data, respectively.

## 5. Results

The method presented in Sect. 3 with the use of trained NNs has been applied to the two data sets. The gluon contribution to the Sivers asymmetry is shown in Fig. 4 together with the contribution of the two other two hard processes. The result of the analysis of the deuteron data is $A_{PGF}^{Siv,d} = -0.14 \pm 0.15(stat.) \pm 0.06(syst.)$ measured at $\langle x_g \rangle = 0.13$. It is consistent with the results for proton data, $A_{PGF}^{Siv,p} = -0.26 \pm 0.09(stat.) \pm 0.08(syst.)$ obtained at $\langle x_g \rangle = 0.15$ within one standard deviation of the total uncertainty (obtained as linear combination of the statistical and systematic uncertainty). This compatibility is expected as presumably the transverse motion of gluons is the same in deuteron and proton.

While the gluon contribution to the Sivers asymmetry is found to be consistent with zero for the COMPASS deuteron data its value for the proton data is below zero by more than two standard deviations. This result is interesting comparing to the recent analysis of the PHENIX data, [9], which show compatibility with zero of the gluon Sivers effect for protons.

The positive value obtained for for high-$p_T$ sample of the COMPASS proton data for the asymmetry of the leading process, can be compared with the COMPASS results for the SIDIS single hadron measurement [3]. There, the asymmetry for negative hadrons is found to be about zero and that for positive hadrons above zero, so that for the two-hadron final state a positive value may be expected.

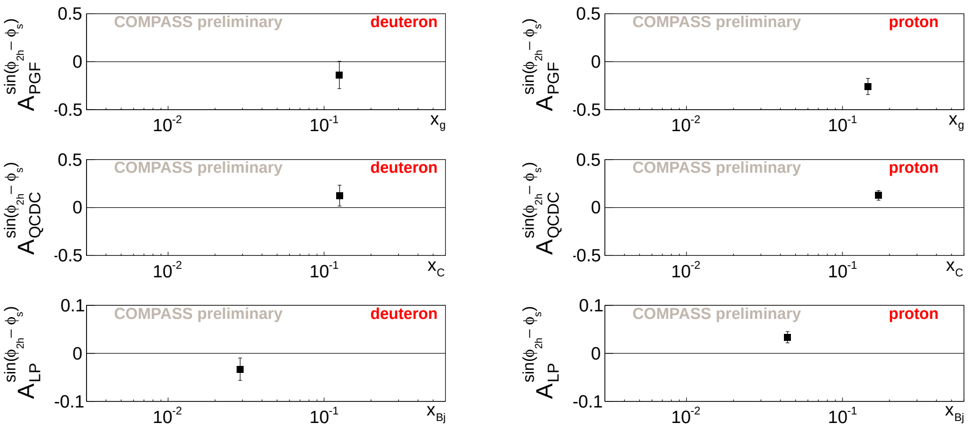


Figure 4: Sivers two-hadron asymmetry extracted for Photon-Gluon fusion (PGF), QCD Compton (QCDC) and Leading Process (LP) from the COMPASS high-$p_T$ deuteron (left) and proton (right) data.

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