Forward Transverse Single Spin Asymmetries at PHENIX

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Abstract. Recent measurements of single transverse spin asymmetries in proton-proton collisions measured by the PHENIX experiment at RHIC are presented. The focus is on the single particle left-right asymmetry $A_N$ for $\pi^0$ at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 62.4$ GeV and the measurement of di-hadron correlations at $\sqrt{s} = 200$ GeV which are produced by the fragmentation of a transversely polarized quark via the Interference Fragmentation Function (IFF) $H_1^<$ and thus provide a probe for the quark transversity distribution function.

1. Introduction

The single transverse spin asymmetry $A_N$ for pions in proton-proton collisions was first discovered more than 30 years ago at the ZGS. Even though it is a fairly simple observable, the left-right asymmetry of count-rates with respect to the spin direction of the polarized proton in the process $p + p^\uparrow \rightarrow \pi + X$, where $\pi$ can be charged or neutral, our understanding of the mechanism(s) leading to this asymmetry is still not complete. The asymmetry persists all the way up to RHIC energies with a center of mass energy of up to 200 GeV. At these energies it is reasonable to use a factorized picture to explain the asymmetries. If transverse momentum dependence of parton distribution functions (PDFs) and fragmentation functions (FFs) is introduced, there are two mechanisms which can generate left-right asymmetries at leading order in the hard part and leading twist in the soft part of the interaction. The first one, called the Sivers effect, is related to the transverse momentum dependence of PDFs. Proposed first by Sivers [1], an azimuthal asymmetry is generated by the spin dependence of the intrinsic transverse momentum of the quarks within the transversely polarized nucleon described by the Sivers function $f_{1T}^{1T}(x, k_T^2)$. Here $x$ is the fractional momentum of the nucleon carried by the parton and $k_T$ its intrinsic transverse momentum. The Sivers function is naive time reversal odd, therefore a phase shift in the amplitude is needed for the asymmetry to survive. In models for the Sivers function the phase shift is generated by a final state interaction. In a simple model by Burkhard [3], the Sivers function is connected to quark orbital angular momentum, a missing part of the spin puzzle [3]. The idea is, that orbital angular momentum will lead to a red- or blueshift of the quark that participates in the hard scattering. Due to spin-orbit coupling the OAM will be spin dependent. Since the PDFs are strongly dependent on the momentum fraction $x$ of the nucleon that the quark carries, this shift leads to a spin dependent asymmetry in impact parameter space. The attractive strong force will then translate the impact parameter space asymmetry into a momentum space asymmetry of the produced hadrons, a mechanism which Burkhard termed “Chromodynamic lensing”. The second effect leading
to single transverse spin asymmetries is known as the Collins effect. Here a spin dependent transverse momentum dependence of the fragmentation function is assumed. The spin dependent transverse momentum dependence of the fragmentation of a transversely polarized quark into unpolarized mesons can be described by the Collins fragmentation function $H_T^\perp(z, \kappa_T^2)$ [2], with $z$ being the fractional momentum of the fragmenting parton the hadron carries and $\kappa_T$ the intrinsic transverse momentum of the produced hadron with respect to the parton. This function is chiral odd and couples to the transversity distribution function $h_1(x)$, which is also a chiral odd quantity. In fact, since in QCD chiral odd amplitudes are heavily suppressed, using a chiral odd fragmentation function like the Collins FF or the Interference Fragmentation Function [4] have so far been the only successful ways to access the transversity distribution. Therefore $h_1(x)$ is the least well known of the three leading twist PDFs which are equally important to describe the spin structure in a collinear picture [5].

Both, Sivers and Collins effect have been very successful at describing azimuthal asymmetries in semi-inclusive deep inelastic scattering (SIDIS). Here the two effects can be separated because the parton kinematics can be reconstructed from the scattered lepton. Given universality and factorization, the SIDIS results can be used to explain the asymmetries in p+p collisions. In the collinear case a benchmark for the validity of a factorized approach has been the agreement of the measured cross-sections for pions with the theoretical predictions using PDFs and FFs. Using leading log resummation this agreement works well down to a center of mass energy of 62.4 GeV for $\pi^0$'s [6]. However, if intrinsic transverse momentum is taken into account, it was shown that TMD factorization does not work without modification by process dependent soft factors [11]. The most prominent example is probably the sign flip of the Sivers effect in Drell-Yan and SIDIS [7]. At the time of this writing it is not clear, if the universality for TMD PDFs can be saved. If factorization is broken, it will be up to the experiments to determine how large the effect is.

At large transverse momenta, the phase shift necessary to produce the SSAs can be generated in the hard part by including an additional parton exchange with the nucleon. Since the spin asymmetry is now dependent on the interaction with two partons in the polarized nucleon, the nucleon structure has to be described by twist three correlation functions [8, 9]. It has been shown that the observed asymmetries are well described by a fit based on a model for the twist three correlation functions [10]. If one assumes that contributions from the Collins effect are small, both, Sivers and twist three functions should describe the asymmetries in the kinematic regions in which they are thought to be valid. For Sivers, these are large momentum transfers and small transverse momenta, so there are two momentum scales involved, whereas the twist three mechanism has only one hard scale. In the kinematic region of overlap, it has been shown explicitly for the Drell Yan process that both lead to the same result [12]. Since twist three effects have an intrinsic $1/p_T$ dependence, it is expected that $A_N$ exhibits this behavior at high $p_T$. However this has not been observed yet. Additional interest in $A_N$ has arisen from the discovery that using a relation between the quark gluon correlation function $q,F$ and the first moment of the Sivers function, there is a sign mismatch between $T_{q,F}$ extracted from p+p collisions and the moment of the Sivers function extracted from fits to SIDIS data [13]. The reason is not understood yet, but may hint either at an incomplete understanding or a strong kinematic dependence of the Sivers function. It appears thus that the measurement of the transverse SSA $A_N$ provides access to a multitude of effects, which also makes it interpretation difficult. This article presents the PHENIX measurement for the transverse spin asymmetry $A_N$ for neutral pions at $\sqrt{s} = 62.4$ GeV and $\sqrt{s} = 200$ GeV in the forward region. The forward and backward regions in this context are defined with respect to the momentum of the polarized proton. Hadrons scattered into the forward region come from fragmenting valence quarks and thus lead to a strong analyzing power. We look at various kinematic dependences, especially at the $p_T$ dependence to find the onset of the $1/p_T$ behavior. By showing all relevant kinematic
dependences of the analyzing power, we hope to learn more about the origin of $A_N$ and give data for the check of theoretical model calculations. In addition to the measurement of $A_N$ we also present the measurement of the di-hadron correlations in the central region. Using recent results by the Belle collaboration, using di-hadron correlations which probe the product of transversity distribution to the interference fragmentation function, might lead to the first extraction of transversity from proton-proton data. Thus a new kinematic regime can be accessed, a crucial step towards determining the tensor charge. In addition, the extraction uses only collinear factorization which is different for the Collins effect. Other advantages compared to using the Collins effect is that for the relevant invariant mass range of the produced pion pairs the evolution factorization which is different for the Collins effect. Other advantages compared to using the polarization of 48%. We also sampled 0.7 pb$^{-1}$ at $\sqrt{s} = 200$ GeV with 54% polarization. In 2008 we had only 200 GeV running with a delivered integrated luminosity of 1.1 pb$^{-1}$ but a lower transverse polarization of 46%. The results for the forward transverse SSA $A_N$ presented here are from $\pi^0$'s detected in the Muon Piston calorimeters (MPC) [16], located 220 cm on both sides of the interaction region. The calorimeter uses PbWO$_4$ crystals, due to the small Moliere radius of 2.0 cm. The crystals have a surface area of $2.2 \times 2.2$ cm$^2$ and a radiation length of $20X_0$. They are read out by avalanche photo diodes (APDs). With the two detectors a pseudorapidity range of $3.1 < |\eta| < 3.9$ is covered. In the central region $0.35 < \eta < 0.35$ PHENIX is instrumented by two arms each covering $\pi/2$ of the azimuth. The detectors used for di-hadron analysis are the pad- and wire-chambers for unidentified charged tracks and the electromagnetic calorimeters in each arm to reconstruct neutral pions.

2. The PHENIX Detector
The PHENIX detector is described in detail in [15]. It is located at the Relativistic Heavy Ion Collider (RHIC) at BNL. The data presented here was taken in the years 2006 and 2008. In 2006, PHENIX sampled a delivered luminosity of $4.6 \times 10^{-3}$pb$^{-1}$ at $\sqrt{s} = 62.4$ GeV with a transverse polarization of 48%. We also sampled 0.7 pb$^{-1}$ at $\sqrt{s} = 200$ GeV with 54% polarization. In 2008 we had only 200 GeV running with a delivered integrated luminosity of 1.1 pb$^{-1}$ but a lower transverse polarization of 46%. The results for the forward transverse SSA $A_N$ presented here are from $\pi^0$'s detected in the Muon Piston calorimeters (MPC) [16], located 220 cm on both sides of the interaction region. The calorimeter uses PbWO$_4$ crystals, due to the small Moliere radius of 2.0 cm. The crystals have a surface area of $2.2 \times 2.2$ cm$^2$ and a radiation length of $20X_0$. They are read out by avalanche photo diodes (APDs). With the two detectors a pseudorapidity range of $3.1 < |\eta| < 3.9$ is covered. In the central region $0.35 < \eta < 0.35$ PHENIX is instrumented by two arms each covering $\pi/2$ of the azimuth. The detectors used for di-hadron analysis are the pad- and wire-chambers for unidentified charged tracks and the electromagnetic calorimeters in each arm to reconstruct neutral pions.

3. $A_N$ measurement for reconstructed pions in MPC at $\sqrt{s} = 62.4$ GeV
Figure 1 shows the results for $A_N$ measured in the 62.4 GeV run in 2006. We divided the dataset into two of roughly equal size by selecting pions with $\eta > 3.5$ and $\eta < 3.5$. In the backward region, where sea-quarks in the polarized proton are probed, the asymmetries are very small. This is expected, since both, Sivers function and transversity are only significant in the valence quark region. For hadrons scattered in the forward direction with respect to the polarized proton momentum the asymmetries rise with $x_F$ for the same reason. At high $x_F$ for $\eta < 3.5$ the asymmetries reach a maximum. Compared with the data points at $\eta > 3.5$, for fixed $x_F$ the $p_T$ has to be higher to reach lower $\eta$. This is also evident in the average $p_T$ for each bin noted in the figure. Thus differences between the two different pseudorapidity bins could be attributed to the $p_T$ dependence of the asymmetries which leads to falling asymmetries at high $p_T$ as expected in the twist three framework.

4. $A_N$ from clusters in the MPC at $\sqrt{s} = 200$ GeV
With the given crystal size of the MPC, the two photon decay of the $\pi^0$ leads to merged clusters for pion energies $> 20$ GeV. Translated into the variable $x_F = 2p_L/\sqrt{s}$ this means that at 62.4 GeV clusters will be merged for $x_F > 0.65$ and for 200 GeV already at $x_F > 0.2$. At leading order in the parton picture $x_F$ can be interpreted as the difference in the momentum fractions $x$ the partons participating in the hard scattering carry. Figure 4 shows the distribution of $x$ for the participating partons in the central and forward region of PHENIX. From these distributions it also becomes obvious why only forward measurements can access valence quarks at high $x$. At the position of the MPC, the pion energy at which the clusters are merging corresponds to
transverse momenta $p_T$ of greater than 2 GeV/c. Since the high $p_T$ region is of special interest to investigate the predicted $1/p_T$ shape of $A_N$ we decided to analyze asymmetries for clusters with an energy greater than 25 GeV and determine the cluster content from Monte Carlo simulations. We used the Pythia [17] generator with k-factors adjusted, so that the cross sections for pions and direct photons measured at RHIC are truthfully reproduced. The simulation of the MPC was done in Geant3 [18]. The result is shown in figure 6. A majority of the clusters originate from neutral pions, at low $p_T$ more than 90%. At higher $p_T$ the fraction of clusters coming from direct photons at LO rises and the fraction of pion induced clusters falls to 60%. The resulting values for the asymmetry $A_N$ for the 200 GeV data are shown in figure 2. Again, we divided the data in two different $\eta$ ranges, here at $\eta = 3.3$ to provide for two datasets of roughly equal size. The asymmetries follow the same trend as the results from reconstructed pions at 62.4 GeV. In fact the datapoints are compatible with the ones at 62.4 GeV if scaled with $\sqrt{s}$ i.e. by using the dimensionless variable $x_F$. Surprisingly, as shown in fig. 5 this is true for asymmetries down to 19.4 GeV as measured by the E704 collaboration [19], even though at these energies the frameworks for the mechanisms to produce the SSAs introduced above, are no longer valid. Figures 3 and 7 explore the $p_T$ behavior at 200 GeV some more. At high $p_T$ a trend for falling asymmetries can be observed. However, due to the large error bars and the contamination of the cluster asymmetries by other sources of photons the trend is not significant.
Figure 4. Distribution of the Bjorken scaling variable \( x \) of the parton fragmenting into the detected hadron for \( A_N \) measured forward in the MPC and in the central arm. Curves for different bins in \( p_T \) are shown.

Figure 5. World results for \( A_N \) at different \( \sqrt{s} \). The asymmetries seem only to dependent on \( x_F \).

Figure 6. Results for the decomposition of the clusters used to compute \( A_N \). Most clusters come from \( \pi^0 \)'s but at high \( p_T \) the fraction of direct photon grows. The contributions from charged hadrons (\( h^+, h^- \)) is negligible.

5. Di-hadron correlation measurements in the central region to access transversity

Using di-hadron correlations to access transversity in proton-proton collisions has first been proposed by Baccheta and Radici [20]. In events where two hadrons with different charges are produced within a jet cone, the azimuthal asymmetry of the difference vector \( \vec{R} \) between the two hadron momentum vectors around the momentum sum vector with respect to the spin axis is measured. Since the sign of the asymmetry is fixed by the charge ordering, it is not possible to compute this asymmetry for particles with equal charge. At PHENIX this requirement means, that the analysis is restricted to the central region where charged particle tracking and neutral particle detection is available. We use \( \pi^0 \)'s reconstructed in the EMCs and unidentified charged track reconstructed in the pad and drift chambers. A minimum \( p_T \) of 1 GeV/c is required. In order to select tracks from the same jet, we use pairs in the same arm. As a reminder, each arm covers \( -0.35 < \eta < 0.35 \) and \( \pi/2 \) in azimuth. Figures 8 and 9 show the results in bins of the invariant mass \( m_{\text{INV}} \) of the hadron pair and the combined transverse momentum, respectively. We choose this binning because the recent results of the Belle collaboration for the
IIFF of $(\pi^+/\pi^-)$ pairs shows a strong dependence on the invariant mass of the hadron pair [21]. Since the measured asymmetry is a product of transversity and IFF $A_{RS} \propto h_1(x) \cdot H_1^< (z, m_{\text{Inv}})$ we can expect a strong dependence on $x$, $m_{\text{Inv}}$ and the fractional momentum of the fragmenting parton $z$ the produced hadron pair carries. However, $x$ and $z$ are not accessible. The fractional momentum $x$ is correlated to $p_T$, but, as seen in fig. 4 at small rapidities it is not possible to select valence quarks with a $p_T$ cut. The measured asymmetries are small, however they exhibit the linear behavior expected in this range for $m_{\text{Inv}}$. This can be explained by $u$-quark dominance in SIDIS and the opposite sign for $u$- and $d$-quark transversity. This might also cause the sign difference in the slopes for $\pi^0$ combinations with positive and negative hadrons. But since the fragmentation function has not been measured yet and there are no SIDIS results available for these combinations, this interpretation is speculative.

**Figure 7.** $p_T$ dependence of the 200 GeV cluster $A_N$ measured in the MPC

**Figure 8.** Results for the di-hadron asymmetry $A_{RS}$ in $m_{\text{Inv}}$ binning of the produced hadron pair

**Figure 9.** Results for the di-hadron asymmetry $A_{RS}$ in $p_T$ binning of the produced hadron pair
6. Summary and Outlook

Transverse spin asymmetries in proton proton collisions provide insights into the transverse spin structure of the proton in a kinematic regime not accessible in SIDIS. Thus measuring these asymmetries is also important in the context of the predicted sign flip of the Sivers function in SIDIS and DY. Due to the presence of two color charges in the initial state they also challenge our understanding of TMD factorization. At PHENIX we measured transverse spin asymmetries in the hard scattering regime. We investigated multiple kinematic dependencies to help identify the underlying mechanism. A focus is the shape of $A_N$ at high $p_T$. To disentangle Collins and Sivers effect contributions and measure transversity in proton-proton collisions, we measured the di-hadron asymmetry $A_{RS}$ in the central region. In the future these measurements will be extended into the PHENIX muon arms in which muons from charged hadron decay can be measured. Since they cover a more forward region of $1.2 < |\eta| < 2.4$ and the full azimuth, it is expected that the magnitude of the asymmetry will be larger.

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