Measurement of Transverse Spin Effects with the Forward Pion Detector at STAR in Polarized p+p Collisions at 200GeV

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The STAR collaboration presents preliminary measurements of A_N, the transverse single spin asymmetries in $p + p \rightarrow \pi^0 + X$ interactions at $\sqrt{s} = 200GeV/c$ with rapidity in the range from 3.3 to 3.7. The data were collected with the STAR FPD and FPD++ detectors during RHIC Run 6. With this much larger data set than that of earlier RHIC runs, a determination of the transverse momentum (p_T) dependence of A_N for narrow bins of the Feynman X_F out to $p_T > 3GeV/c$ is presented. While all the current theories predict that the asymmetry at fixed X_F should fall with p_T, this experimental measurement shows no reduction in asymmetry as a function of p_T. These asymmetries correspond to production in a regime where NLO PQCD calculations can successfully describe the spin summed cross sections.

1 Background

In this paper we present preliminary results from STAR for data taken during RHIC Run 6 on the transverse single spin asymmetries in the reaction

$$p + p \rightarrow \pi^0 + X.$$

Data were collected using the FPD [2] and FPD++ [3] detectors at STAR, which are located in the far forward regions relative to the two polarized proton beams.

The STAR results are part of broader effort involving electron or proton scattering from polarized nucleons for the study of spin observables associated with so called **T odd** processes. The calculations of single transverse asymmetries must provide non-vanishing amplitudes for helicity flip and non-flip. The T odd asymmetries require the interference between these amplitudes. One interfering amplitude must be out of phase from the other by 90^o for non-vanishing single transverse spin asymmetries to be possible. Neither a helicity flip nor the required phase difference is present in the lowest twist term of the perturbative calculation.

Such processes present a challenge for theory as they occur in regimes where the spin averaged cross sections can be calculated in leading twist PQCD but the transverse spin dependence of these cross sections vanishes in this leading twist, collinear factorization picture. The calculations of these transverse asymmetries then pushes theoretical calculations toward the more non-trivial questions in QCD.

The additional methods required to enable the calculation of non-zero transverse single spin asymmetries have been of three main types. In the **Sivers Effect** [4] a spin dependent transverse momentum is explicitly added to the more common longitudinal momentum dependence of the parton distribution functions. In the **Collins Effect** [5] a similar transverse spin dependence is associated with the transverse momentum dependence of fragmentation functions. Each of these methods generates a fixed p_T bias that is dependent upon transverse spin but should be independent of the hard scattering process. If factorization between the hard scattering process and parton distribution is valid, and this is not proven for these formulations, it is very difficult to avoid the conclusion that the asymmetry should fall with p_T. In particular, for a cross section that falls in proportion to a power of p_T, these arguments suggest that asymmetry would be expected to fall as $1/p_T$. Recent calculations of Collins and Sivers effects bear out this general observation [6].

The third alternative involves higher twist effects and these too, almost by definition, require the calculated asymmetry to fall at least as the inverse power of p_T [7]. So in the current view of how these transverse asymmetries can come about, the requirement that the single spin asymmetry should falls with p_T is quite universal.

2 The Measurement

The forward electromagnetic calorimetry in STAR has evolved through several stages as the spin program at RHIC has progressed. The first **pre-FPD** detector consisted of prototype lead/scintillator and lead glass modules placed about 7 meters from the interaction point in STAR both left and right of the beam. It was with this apparatus that the first published transverse single spin asymmetry π^0 data from RHIC were obtained [8].

In subsequent RHIC polarized proton runs, FPD modules were installed North and South of the beam (left and right), both east and west of the interaction region. Each of the left and right FPD detectors consisted of a 7x7 array of lead glass scintillators, each cell with transverse dimensions 3.8 cm x 3.8 cm. The central part of the FPD++ detector, used in this analysis, has the same fiducial transverse size as the FPD. Smaller arrays were placed above and below the beam line where, with vertically polarized beam, no up/down asymmetry is expected.

For this result, single π^0's are reconstructed in FPD modules east of the interaction region or in FPD++ modules west of the interaction region. The calibration of calorimeter cells was determined to an accuracy of about 2% by fitting with the π^0 mass distribution. Run 6 was by far the most successful run for transverse spin in STAR as is summarized in Table 1. The figure of merit for statistical significance of single spin measurements based on polarization and luminosity is about 50 times greater for Run 6 than for the previous runs combined.

Because of parity and rotational invariance, the transverse single spin asymmetry, defined by

$$A_N = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

can be measured either with a single detector location by changing the transverse beam polarization or with a single polarization and symmetrical measurement in a left detector vs right detector. The first method requires a careful measurement of the ratio of spin up to spin down luminosity. The second method requires a careful measurement of the left vs. right acceptance of the detectors.

With both the FPD or FPD++, we have symmetrical acceptance left and right of the beam. With the spin transverse quantization direction vertical, a superior method for calculating the asymmetry is called the cross ratio method. We define, for example, N_R+ as the observed number of events involving the right(R) detector with transverse spin (+). With this convention and taking the beam polarization to be P_{bm}, we calculate the cross ratio for asymmetry, which is defined as

$$A_N \equiv \frac{1}{P_{bm}} \frac{\sqrt{N_{L+}}\sqrt{N_{R-}} - \sqrt{N_{R+}}\sqrt{N_{L-}}}{\sqrt{N_{L+}}\sqrt{N_{R-}} + \sqrt{N_{R+}}\sqrt{N_{L-}}}.$$

	Run2	Run3	Run5	Run6
Det	pre FPD	FPD 6 mods	FPD 8 mods	East FPD West FPD++
P_{bm}	15%	30%	45%	60%
$\int Ldt$ pb^{-1}	0.15	0.25	0.1	6.8
$<\eta>$	3.8	± 3.3 ± 4.0	± 3.7 ± 4.0	-3.7 $+3.3$

Table 1: Transverse spin runs at STAR with forward calorimetry: 2001-2006.

The cross ratio method for calculating A_N is insensitive to both the ratio of luminosities for the two spin states and to the ratio of left to right acceptance.

The data presented here involves two detector settings with nominal acceptance around rapidities of $\eta = 3.3$ and $\eta = 3.7$. For previous measurements of A_N, a narrow range of acceptance in rapidity, implies a high degree of correlation between Feynman X_F and transverse momentum p_T. With good statistics over this range of rapidities, we are able to study the p_T dependence for fixed bins in X_F.

3 Results

The A_N values determined from Run 6 data are shown in Figure 1. It is seen that the transverse single spin asymmetry for π^0 production grows at large and positive X_F, where positive X_F corresponds to the forward direction for the polarized proton.

As expected, the asymmetry for forward production is large but for backward production, it is small or zero. As discussed above, current theories predict that the asymmetry should fall with increasing transverse momentum at fixed X_F. These predictions imply that smaller rapidity should be associated with smaller asymmetry when X_F is fixed. From the figure, these data indicate the opposite trend.

In Figure 2, the data have been divided into five X_F bins. Within each X_F bin, the dependence of A_N upon p_T is shown. While we observe that the asymmetry may be rising for p_T in the lower part of the p_T range shown, there is no evidence of the fall off with p_T that current theory predicts.

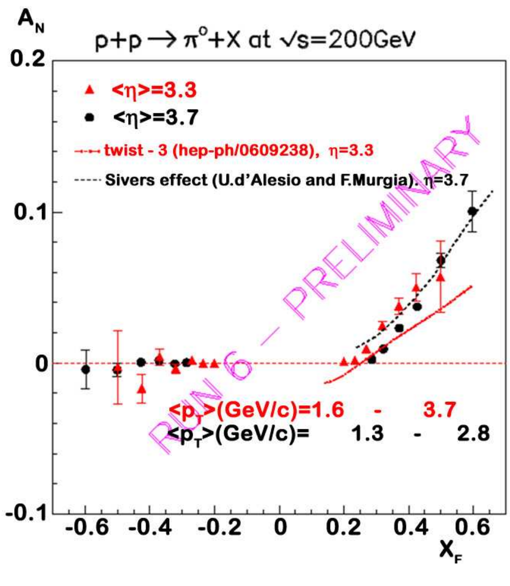

Figure 1: Single Transverse Spin π^0 Asymmetry.

4 Summary

These data are of higher p_T and X_F than the $0.04 < x_{\text{Bjorken}} < 0.3$ and $0.1 < p_{T,\pi} < 1$ GeV/c range associated with the semi-inclusive deep inelastic scattering (SIDIS) data recently used to determine Sivers moments.

Integrated over p_T, the X_F dependence of these SSA results can be explained by models of the Sivers type [6] or with collinear twist-3 calculations [7]. Both approaches, however, predict the falloff of asymmetry with p_T at fixed X_F by about one inverse power of p_T. Because we have verified that the corresponding spin averaged cross sections are in accordance with NLO PQCD calculations [2] and fall very nearly as power of p_T, a large class of models will predict a p_T^{-1} dependence of the asymmetry.

These new results pose exciting challenges to present day theory. Both naïve considerations of Sivers or Collins contributions to SSA from a spin dependent δk_T and detailed calculations predict an asymmetry that should fall with p_T in the regime of these data. It seems likely that more exotic implementations of these approaches may be required to fit this experimental result. Recently, interesting questions have been raised about the application of factorization theorems in processes related to this measurement [9]. The data presented here, in conjunction with recent transverse single spin asymmetry measurements from SIDIS experiments, should greatly constrain future PQCD related models.

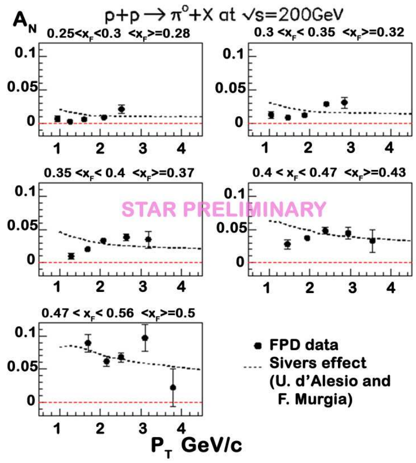

Figure 2: A_N vs p_T for bins in X_F.

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