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CONSTRAINING THE SIVERS FUNCTIONS USING TRANSVERSE SPIN ASYMMETRIES AT STAR

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Collisions of transversely polarized proton beams at RHIC have resulted in 0.8 pb^{-1} of integrated luminosity at center of mass energy of $\sqrt{s} = 200$ GeV.The STAR collaboration is pursuing multiple analyses to extract transverse single spin asymmetries, with one of the goals being to provide constraints on the Sivers functions. Results for mid-rapidity leading charged particle and forward π^0 asymmetries are presented as well as progress toward dijet measurements.

1 Introduction

The origin of significant transverse single spin asymmetries is not fully understood within the framework of Quantum Chromodynamics. Calculations to leading order in perturbative Quantum Chromodynamics (pQCD) predict these analyzing powers (A_N) to be zero. However, experimental data [1,2,3] indicates that A_N for inclusive particle production is on the order of 0.2 for the transverse momentum range $0.5 < p_T < 2.5$ GeV and Feynman x_F range of $0.2 < x_F < 0.8$, and is largely independent of center of mass energy. Unfortunately the discrepancy between data and theory is not accounted for by next-to-leading order pQCD calculations. In an effort to explain these large asymmetries theorists have developed models for the non-perturbative elements within the QCD-parton framework. Sivers[4] introduced a flavor dependent correlation between the proton spin ($\mathbf{S_p}$), momentum ($\mathbf{P_p}$) and transverse momentum ($\mathbf{k_T}$) of the partons inside. This correlation results in the following modification of the unpolarized parton distribution functions ($f = u, d, s...g$):

$$\hat{f}(x, \mathbf{k_T}, \mathbf{S_p}) = f(x, k_T) + \frac{1}{2}\Delta^N f(x, k_T)\frac{\mathbf{S_p}\cdot(\mathbf{P_p}\times\mathbf{k_T})}{|\mathbf{S_p}||\mathbf{P_p}||\mathbf{k_T}|}$$

The Sivers functions are represented as $\Delta^N f$ and x is the Bjorken scaling variable. Independently, Collins[5] postulated that a significant A_N could be produced by introducing a transverse momentum kick in the fragmentation functions which is correlated with the spin of the scattered parton, and therefore the spin of the proton. Finally, several theorists have explored the idea that higher twist effects in either the initial[6] or final[7] state may cause the observed analyzing powers. This contribution will focus largely on how the transverse proton spin asymmetries measured by the STAR Collaboration constrain the first of these models, the Sivers functions.

2 Transversely Polarized p-p Collisions in the STAR Detector at RHIC

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab is also the world's first polarized proton collider. In the 2002 proton run 0.3 pb^{-1} of

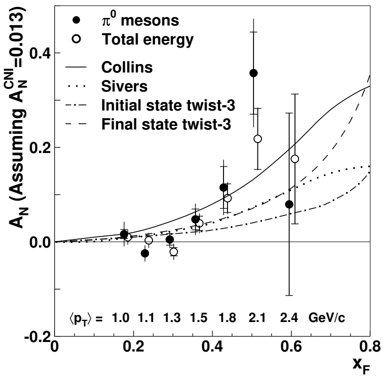

Figure 1. A_N versus x_F for π^0 mesons. The closed circles represent π^0's reconstructed using the SMD, while the open circles are for the total tower energy only and are shifted in x_F by 0.01. The model curves were evaluated at $p_T = 1.5$ GeV.

integrated luminosity was collected for transversely polarized proton collisions at $\sqrt{s} = 200$ GeV at an average polarization of 20%. In 2003 the integrated transverse luminosity and average polarization increased to 0.5 pb^{-1} and 30%, respectively. The luminosity at STAR is measured by the beam-beam counters (BBC) [8], which are segmented scintillator detectors mounted ± 370 cm from the interaction region which cover the psuedorapidity range of $3.3 < |\eta| < 5$. In addition to relative luminosity, BBC coincidences were used to suppress beam gas backgrounds as well as provide the minimum-bias trigger for the proton collisions. The Coulomb-Nuclear Interference (CNI) Polarimeter [9,10,11] was used to determine the average beam polarization for each RHIC store. It is necessary to know the CNI analyzing power, A_N^{CNI}, in order to extract the proton polarization. A_N^{CNI} has been measured for protons at energies of 24.3 GeV, the proton injection energy into RHIC, but not for the 100 GeV collision energy. For the analysis results presented here it was assumed that A_N^{CNI} does not change with $\sqrt{s}$, and therefore all measurements are quoted with the $A_N^{CNI} = 0.013$ measured at injection energy. A polarized gas jet target has been installed at RHIC and was operated during the 2004 proton run, with the goal of extracting a measurement of the proton polarization at 100 GeV. This in turn will allow the extraction of A_N^{CNI} at $\sqrt{s} = 200$ GeV, allowing for the rescaling of the measurements presented here if necessary.

3 Forward π^0 Asymmetry Results

During the 2002 proton run the prototype Forward Pion Detector (pFPD) [12], a Pb-scintillator sampling calorimeter composed of 12 towers and 2 shower maximum (SMD) layers, was located 750 cm from the STAR interaction region. The pFPD, spanning $3.1 < \eta < 4.3$, was situated to detect π^0's at large $x_F = \frac{2p_L}{\sqrt{s}}$, where p_L is the pion longitudinal momentum. From these data the π^0 meson analyzing power was measured:

$$A_N = \frac{1}{P_{beam}} \frac{N^+ - RN^-}{N^+ + RN^-}$$

$N^{+/-}$ is the number of pions detected when the polarization of the beam headed toward the pFPD was oriented up,(down) and R is the spin dependent relative luminosity, $R = L^+/L^- \approx 1.15$, as measured by the BBC. Figure 1 shows A_N

versus x_F for π^0 mesons reconstructed using the SMD (filled circles) as well as the total energy sum from the pFPD towers only (open circles). The close agreement shows that A_N is not sensitive to the π^0 identification algorithm. The statistical (point-to-point systematic) errors are represented by the inner (outer) bars.

Consistent with measurements at lower $\sqrt{s}$ the A_N for π^0 production is non-zero and increasing with p_T and x_F. Statistical uncertainty precludes any discrimination between the Sivers, Collins and twist-3 predictions[4,5,6,7] for A_N.

4 Leading Charged Particle Results

The midrapidity leading charged particle (LCP) A_N measurement is complementary to the forward π^0 asymmetry discussed above, and is in principle also sensitive to the Sivers, Collins and higher twist effects. The Collins contribution is highly suppressed in the LCP asymmetries because mid-rapidity observables occuring in the low p_T regime ($p_T < 5$ GeV), result from largely symmetric gluon-gluon collisions, and since the gluon transversity function is zero the gluon Collins function is zero as well. For the LCP analysis 5.2 M minbias triggers from the 2002 proton run were used to identifiy charged hadrons with $0.4 < p_T < 5$ GeV and $|\eta| < 1$ in the STAR TPC [13]. The analyzing power, plotted as a function of p_T and η in Figure 2, is consistent with zero. The data points are averaged over both colliding beams, with the error bars representing the statistical uncertainty of A_N and the CNI polarimeter added in quadrature. The measurement is statistically limited but clearly places an upper limit of $A_N \leq 5\%$ for mid-rapidity leading charged particles. These results are consistent with previous data and predictions by Anselmino and Murgia [14], which show A_N for inclusive charged and neutral pions going to zero as $x_F \to 0$.

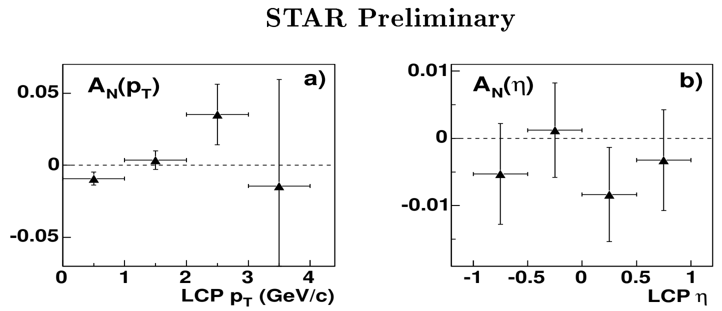

Figure 2. LCP A_N as a function of transverse momentum p_T and η. Error bars are a combination of statistical plus CNI polarimeter uncertainty.

5 Dijet Results

The STAR transverse spin asymmetry measurements confirm that A_N for inclusive particle production is sizable in the forward direction and small at midrapidity for $\sqrt{s} = 200$ GeV. However, it is difficult to extract only the Siver's functions from these measurements because A_N may result from any combination of the Sivers, Collins and higher twist effects. In an effort to isolate the Sivers functions, Boer and Vogelsang [15] have proposed the measurement of A_N for dijets binned as a function of the deviation ($\delta\phi$) from π of the difference in azimuthal jet angles ($\Delta\phi = \phi_{jet_1} - \phi_{jet_2}$), ie, $\delta\phi \equiv \pi - \Delta\phi$. Collinearly factorized pQCD assumes the parton momentum to be parallel with that of the proton. This results in $\delta\phi = 0$ for leading order calculations where gluon emission is neglected. However, higher order terms and intrinsic transverse momentum of the partons will cause a non-zero $\delta\phi$, which can then be correlated with the spin orientation of the proton, providing information about the Sivers function. Figure 3 shows the sensitivity of the dijet A_N prediction by Vogelsang and Boer to the gluon Sivers's functions.

The STAR detector is well designed for this measurement with both the TPC and Barrel Electromagnetic Calorimeter (BEMC) covering the midrapidity range of $|\eta| < 1$. A cone jet finder, with radius R $= \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$, collects the charged TPC tracks and neutral BEMC hits to reconstruct dijets from the high tower triggered 2003 proton data. Due to the partial construction of the BEMC in 2003 ($0 < \eta < 1$) the thrust axis of the first jet of the dijet pair was restricted to the fiducial area covered by both the TPC and BEMC ($0.2 < \eta < 0.65$). This jet sets the energy scale for the dijet pair and is required to have $E_T > 7$ GeV and include the trigger tower. The second jet is reconstructed from TPC tracks only and is allowed a thrust axis range of $|\eta| < 0.5$. Figure 4 shows the $\Delta\phi$ distribution for the reconstructed dijets, which is centered at π and has a finite width of $\sigma_{\Delta\phi} = 0.23 \pm 0.02$. Simulations (PYTHIA 6.2[16]) are used to estimate the contribution to the width from detector resolution effects and missing neutral energy in the 2nd jet. After incorporating these corrections, the width is a measure of the per-parton root mean square transverse momentum k_T, defined as $k_T = \langle E_T \rangle \sin \sigma_{\Delta\phi}$. Again using simulation, the energy scale of the first jet was determined to be $\langle E_T \rangle = 13.0 \pm 0.7$ GeV, resulting in a k_T measurement of $\sqrt{\langle k_T^2 \rangle} = 2.3 \pm 0.4 \pm^{0.67}_{1.11}$ GeV. Comparison to world data [17] on the average transverse momentum of the dimuon/diphoton/dijet pair, $\langle p_T \rangle_{pair} = \sqrt{\frac{\pi}{2} \langle k_T^2 \rangle}$, in Figure 5 shows good agreement with the established trend of increasing $\langle p_T \rangle_{pair}$ with $\sqrt{s}$.

Extraction of A_N requires the dijets in Figure 4 to be spin sorted in terms of $\delta\phi$. Preliminary analysis from the 2003 run suggests that the absolute statistical errors for this measurement are ± 0.1. Although this is too large to discriminate between the models shown in Figure 3, the gluon Sivers functions have never been measured and the absolute size of this asymmetry is unknown.

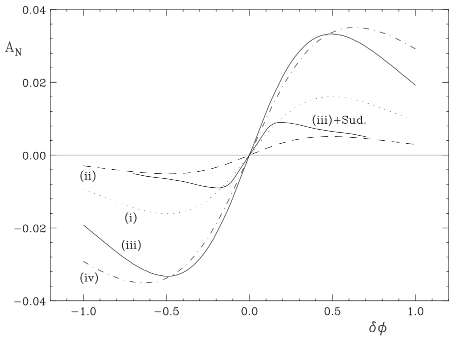

Figure 3. A_N for back-to-back dijets at $\sqrt{s} =$ 200 GeV for several gluon Sivers function models, $\Delta_g^N f_g(x)$. (i) $\Delta_g^N f_g = \frac{\Delta_d^N f_d + \Delta_u^N f_u}{2}$, (ii) $\Delta_g^N f_g = 0$, (iii) $\Delta_g^N f_g = \Delta_d^N f_d$, (iv) $\Delta_g^N f_g = \Delta_d^N f_d$ with increased gluonic k_T, (iii)+Sud. includes Sudakov effects

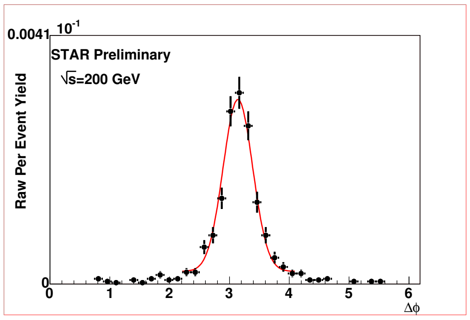

Figure 4. Dijet $\Delta\phi$ distribution for $\sqrt{s} = 200$ GeV with statistical error bars.

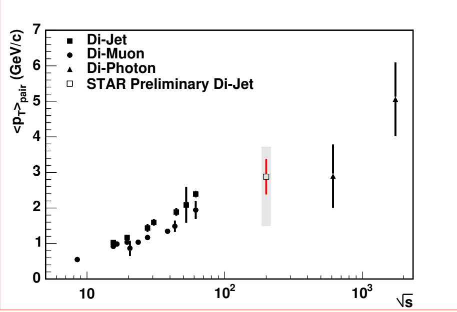

Figure 5. $\langle p_{T\,pair} \rangle$ versus $\sqrt{s}$ for world data set plus STAR. Statistical errors shown by black line and systematic by shaded bar.

6 Conclusions

The STAR detector design permits the measurement of transverse single spin asymmetries over a wide span of psuedorapidity, $-4.3 < \eta < 4.3$, allowing access to information about gluon Sivers functions at mid-rapidity as well as quark Sivers functions at high rapidity. The STAR detector also lends itself to jet reconstruction which permits the separation of the Collins and Sivers effects at all ranges of η. Transverse spin running has been and remains an integral part of the the STAR spin program, with plans for up to 4 pb^{-1} to be taken in the 2005 RHIC run. These data, taken with greatly expanded coverage for electromagnetic calorimetry and expected beam polarization of 40%, will increase the statistical precision of the above measurements and extend them into previously unmeasured η ranges.

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