Recent results from the STAR spin program at RHIC

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Abstract. The STAR experiment uses polarized p+p collisions at RHIC to determine the contributions to the spin of the proton from gluon spin and from orbital angular momentum of the quarks and gluons. Selective STAR measurements of the longitudinal double spin asymmetry for inclusive jet and inclusive hadron production are presented here. In addition, we report measurements of the transverse spin asymmetry for di-jet production at mid-rapidity and the transverse single-spin asymmetry for forward $\pi^+$ production.

The quark and anti-quark contributions to the spin of the proton measured with polarized deep-inelastic scattering (DIS) fixed target experiments amount to only $\leq 30\%$ \cite{1}. Consequently, the rest of the spin of the proton must come from the gluons and the orbital angular momentum of both quarks and gluons. However, the gluon polarization, $\Delta g$, is poorly constrained from scaling violations in the DIS data \cite{2}, and more precise and direct measurements are needed. Polarized p+p collisions at the Relativistic Heavy Ion Collider (RHIC) provide a very suitable environment, rich with strongly interacting probes, to measure $\Delta g$ directly and precisely. There are many processes where the gluon participates directly. In addition, the high c.m. energy, $\sqrt{s} = 200$ GeV, and high $p_T$ make next-to-leading order (NLO) perturbative Quantum Chromodynamics (pQCD) analysis more reliable. The spin program of the Solenoid Tracker at RHIC (STAR) experiment \cite{3} aims, in the short term, to utilize these advantages to measure $\Delta g$ using inclusive jet and inclusive hadron production measurements in longitudinally polarized p+p collisions. In addition, the STAR experiment uses transversely polarized p+p collisions to gain insights into the orbital angular momentum of the partons.

The STAR collaboration previously observed a sizable analyzing power, $A_N$, for forward $\pi^+$ production at large $x_F$ \cite{4}, similar to previous observations at lower energies \cite{5}. The previous STAR results were in qualitative agreement with several different model predictions \cite{4} and could not differentiate between them, so higher precision measurements of $A_N$ as a function of both $x_F$ and $p_T$ were needed. New $A_N$ measurements with higher luminosity and polarization were performed in 2006 \cite{6}. Figure 1 shows preliminary results for $A_N$ as a function of $x_F$ (left panel) and as a function of $p_T$ for different $x_F$ bins (right panel), along with model predictions. The results in the left panel are consistent with the previous results \cite{4} in having large $A_N$ for high $x_F$, and provide sufficient accuracy to discriminate between different dynamics. The right panel shows that the $p_T$ dependence of $A_N$ is not well described by Sivers based calculations \cite{7,8}, which predict that $A_N$ should decrease as you go higher in $p_T$ for all $x_F$ bins.

The STAR experiment also probed the Sivers effect by measuring the di-jet opening angle in transversely polarized p+p collisions \cite{9} since Boer and Vogelsang \cite{10} suggested that $A_N$ for the distribution in relative azimuthal angle, $\zeta$, between the di-jet pairs could provide

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access to the Sivers effect [11]. Figure 2 shows preliminary results from 2006 data for $A_N$, for both beams, as a function of $\eta_1 + \eta_2$, where $\eta_1$ and $\eta_2$ are the pseudo-rapidities for the two jets. The measurement was done over $\eta \in [-1, 2]$ and for $|\zeta - 180^\circ| \leq 68^\circ$. $A_N$ is extracted from the cross ratio of the spin-sorted $\zeta$ distribution in which “left” and “right” yields were deduced from $\zeta > 180^\circ$ and $\zeta < 180^\circ$, respectively. $A_N^{\pm}$, shown in Figure 2, are consistent with zero - much smaller than the Sivers asymmetry that was observed in semi-inclusive deep inelastic scattering (SIDIS) by HERMES [12].

The STAR collaboration uses the measurement of the longitudinal double spin asymmetry, $A_{LL}$, for inclusive jet and inclusive hadron production to constrain $\Delta g$. $A_{LL}$ is directly sensitive to the polarized gluon distribution function in the proton through gluon-gluon and gluon-quark sub-processes [13]. We reported the unpolarized inclusive jet cross section from data taken in 2003 and 2004 [14], and preliminary results for the unpolarized inclusive $\pi^0$ cross section [15], and both show satisfactory agreement with NLO pQCD calculations over many orders of magnitude. The agreement suggests the applicability of pQCD to describe the polarization observables in this kinematic region.

In Figure 3, the left panel, we present preliminary results of the first STAR $A_{LL}$ measurement of inclusive $\pi^0$ production at mid-rapidity with statistical errors and the systematics band [15]. The systematics band does not include the normalization uncertainty due to the polarization measurement. In addition to the GRSV standard curve, which is based on the best fit to DIS data, different $\Delta g$ scenarios from maximally positive to maximally negative and passing zero $\Delta g$ are also shown in this and the following figures [16, 17]. This measurement is consistent with previously reported $A_{LL}$ for inclusive jets [14] in disfavoring the maximum positive $\Delta g$. 

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**Figure 1.** Left panel: $A_N$ as a function of $x_F$ at $\langle \eta \rangle = 3.3$ (triangles) and $\langle \eta \rangle = 3.7$ (circles) with statistical uncertainties. The lines are Twist-3 [8] and Sivers effect [7] based calculations. Right panel: $A_N$ as a function of $p_T$ for different $x_F$ bins along with Sivers effect based calculations.

**Figure 2.** Comparison of STAR results for $A_N^{+}$ (left) and $A_N^{-}$ (right) as function of $\eta_1 + \eta_2$ with predictions [11], based on two models of quark Sivers functions deduced from fits to HERMES SIDIS results [12].
The right panel shows the mean momentum fraction carried by the $\pi^0$ in its associated jet. This plot shows that the $\pi^0$ carries a very large fraction, 70%, of its associated jet momentum. Corrections for jet acceptance and reconstruction efficiency may reduce this fraction by $\sim 10\%$.

Fig. 3. Left panel: $A_{LL}$ for inclusive $\pi^0$ production with statistical errors and the systematic band. Right panel: Mean momentum fraction of the $\pi^0$ in their associated jet as a function of $p_T$ and the corresponding mean jet $p_T$. The data points are not corrected for jet acceptance or reconstruction efficiency.

Preliminary results from 2005 of very promising $A_{LL}$ measurements of inclusive $\pi^+$ and $\pi^-$ are shown in Figure 4 [18]. The error bars are statistical errors, and the associated bands indicate the systematics, which don’t include the scale uncertainty due to the polarization measurement. Several $\Delta g$ scenarios for these processes are also shown. The ordering of the measurements of $A_{LL}$ between $\pi^+$ and $\pi^-$ is sensitive to the sign of $\Delta g$. For now, this measurement is limited by statistics. We are currently working on 2006 data where we have higher luminosity and polarization.

Fig. 4 shows $A_{LL}$ for inclusive $\pi^-$ in the left panel and inclusive $\pi^+$ in the right one with statistical errors, and point-to-point systematic bands. The asymmetries are compared to theoretical predictions.

In addition, the STAR collaboration studied longitudinal spin transfer of $\Lambda(\bar{\Lambda})$ in polarized...
p+p collisions [19] and inclusive $\pi^0$ production using the STAR Endcap Calorimeter as proof of principle measurements in 2005.

In summary, we reported on preliminary di-jet Sivers $A_N$ measurement from 2006, and all measured $A_N$ are statistically consistent with zero, several factors smaller than expected from SIDIS. In addition, we reported on 2006 $A_N$ measurements of forward $\pi^0$ with higher statistics and polarization, which show inconsistency with Twist-3 / Sivers calculations; $A_N$ does not decrease with $p_T$ in all $x_F$ bins.

In the longitudinal spin program, we reported on several preliminary $A_{LL}$ measurements of inclusive hadrons and jets at mid-rapidity from 2005 data. The results are consistent in the region of kinematic overlap and provide improved constraints on the gluon spin contribution to the proton spin. They exclude large and positive gluon spin contributions.

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Figure 5. $A_{LL}$ for inclusive jet production at $\sqrt{s} = 200$ GeV versus jet $p_T$ with statistical error bars. The bands indicate the systematic uncertainties, which do not include the scale uncertainty due to polarization measurement. The curves are theoretical calculations [13] based on NLO pQCD.