Recent PHENIX results in polarized proton collisions

Kieran Boyle
Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY, 11794
E-mail: kboyle@grad.physics.sunysb.edu

Abstract. A major focus of the PHENIX experiment at the Relativistic Heavy Ion Collider is the study of proton spin structure using polarized proton beams. In longitudinally polarized proton collisions, PHENIX is able to study the gluon spin contribution to the proton spin. $A_{LL}$ results from 2005 and 2006 have been shown to constrain $g$. With an increased figure of merit, due to higher luminosity and polarization, new probes have become available, such as $\pi^\pm$ and $\eta$. Earlier results for single spin asymmetries using transverse polarization have been shown. A significant transverse data set in 2006 will soon yield results.

1. Introduction
The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory studies the spin structure of the proton with longitudinally and transversely polarized proton collisions. With longitudinally polarized proton collisions, the gluon spin contribution to the spin of the proton, $\Delta g$, can be studied. By measuring a double longitudinal spin asymmetry, $A_{LL}$, in the production at mid-rapidity ($|\eta|<0.35$) of hadrons such as $\pi^0$, $\pi^\pm$ and $\eta$, both the sign and magnitude of $\Delta g$ can be constrained. By examining $A_{LL}$ at different center of mass energies ($\sqrt{s}$), we can extend the $x$ range covered at PHENIX. With transversely polarized proton collisions, we can study the possible causes of single spin asymmetries in p+p collisions seen at large $x_F$. Previous PHENIX measurements at central rapidity may give constraints on the gluon Sivers function. A new electromagnetic calorimeter (MPC) in the forward region extends the ability of PHENIX to study transverse spin asymmetries.

2. Detector
The PHENIX detector [1] was built for high rate data taking with good resolution and particle identification at the cost of acceptance ($|\eta|<0.35$, $\Delta \phi = 2 \times 90^\circ$ for the central arms). The Electromagnetic Calorimeter was specifically designed for very good energy and spatial resolution and, in combination with a high $p_T$ photon trigger, is used to measure photon, $\pi^0$, and $\eta$ yields. Combined with tracking of charged particles and a Ring Imaging Čerenkov (RICH) Detector, charged pion yields are also measurable.

3. Constraining $\Delta g$
The quark spin contribution to the spin of the proton has been found to be only about 25% by various fixed target polarized DIS (pDIS) experiments. A major goal of the RHIC spin program is to measure $\Delta g$ through longitudinally polarized proton collisions.
In polarized proton collisions, assuming a partonic interaction $a+b\rightarrow c+X$, where $a$, $b$, and $c$ are quarks or gluons, we can define a double longitudinal spin asymmetry

$$A_{LL} = \frac{\sigma_{++}-\sigma_{+-}}{\sigma_{++}+\sigma_{+-}} = \frac{\sum_{a,b,c=q,g} \Delta f_a \otimes \Delta f_b \otimes \Delta \hat{\sigma} \otimes D_{h/c}}{\sum_{a,b,c=q,g} f_a \otimes f_b \otimes \hat{\sigma} \otimes D_{h/c}}.$$  

(1)

Here, $\sigma_{++}$ ($\sigma_{+-}$) is the cross section for same (opposite) helicity collisions, $f$ ($\Delta f$) are the (polarized) parton distribution functions (PDF), $\sigma$ ($\Delta \hat{\sigma}$) is the (polarized) partonic cross section calculable in pQCD, and $D_{h/c}$ is the fragmentation function (FF) for $c$ fragmenting into the specified hadron. Measuring $A_{LL}$ and using measured values for polarized quark PDFs, unpolarized PDFs and FF functions, $\Delta g$ can be constrained.

$A_{LL}$ is measured experimentally using

$$A_{LL} = \frac{1}{|P_1||P_2|} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}, \quad R = \frac{L_{++}}{L_{+-}}.$$  

(2)

where $P_1$ and $P_2$ are the beam polarizations of the two RHIC rings, $N$ is the probe yield, $L$ is the luminosity, and $R$ is defined as the relative luminosity.

For 2005 (2006), the recorded luminosity was 3.4 pb$^{-1}$ (7.5 pb$^{-1}$) and the average polarization was 47% (62%). An uncertainty in the polarization leads to a 40% relative scale uncertainty in the final $A_{LL}$. Calibration of the polarimeter with an absolute hydrogen jet polarimeter is expected to significantly decrease this uncertainty.

In RHIC, the stable polarization direction is vertical. Thus the beam polarization must be rotated parallel to the beam momentum axis when entering the PHENIX interaction area. By measuring the amplitude of a single transverse spin asymmetry in forward neutrons [2], the remaining transverse polarization component can be determined. For 2005, both beams were found to be almost 99% longitudinally polarized.

To measure relative luminosity (Eq. 2), we use beam-beam counters [2]. In PHENIX for the 2005 (2006) run, uncertainty in relative luminosity was $\delta R=1.0 \times 10^{-4}$ ($\delta R=1.1 \times 10^{-4}$) corresponding to a $\delta A_{LL}|_R=2.3 \times 10^{-4}$ ($\delta A_{LL}|_R=1.5 \times 10^{-4}$). This is less than the statistical

Figure 1. (a) $\pi^0$ $A_{LL}$ vs. $p_T$ at $\sqrt{s}=200$ GeV from 2005 (blue circles) and 2006 (red triangles). (b) $\pi^0$ $A_{LL}$ vs. $x_T$ with $\sqrt{s}=62$ GeV (large black circles) from 2006 and $\sqrt{s}=200$ GeV (small blue circles) from 2005. Error bars are only statistical. Model curves [5] are plotted assuming different $\Delta g$ values assuming an input scale of $Q^2=0.4$ GeV$^2$. 

Second Meeting of the APS Topical Group on Hadronic Physics IOP Publishing
Journal of Physics: Conference Series 69 (2007) 012034 doi:10.1088/1742-6596/69/1/012034
uncertainty for both 2005 and 2006 data. The lower uncertainty in $A_{LL}$ in 2006 is due to large polarization.

Figure 1a shows $\pi^0$ $A_{LL}$ vs. $p_T$ from 2005 (blue circles) as well as high $p_T$ data from 2006 (red triangles) using a high $p_T$ photon filter [4]. More data from 2006 at lower $p_T$ is expected when data production is finished. The $\pi^0$ cross section measured by PHENIX at midrapidity at $\sqrt{s}=200$ GeV has been shown to be well described by pQCD [3], allowing us to use pQCD to interpret $A_{LL}$ in terms of $\Delta g$. Four pQCD calculation [5] are plotted assuming different polarized PDFs, $\Delta g=g$ (GRSV-max), $\Delta g=-g$, $\Delta g=0$ and $\Delta g=GRSVstd$ (the best fit to the world data as of [5]), at an input scale of $Q^2=0.4$ GeV$^2$. The data clearly disagree with $\Delta g=g$. A $\chi^2$ test, neglecting theoretical uncertainties, shows the data also disfavor $\Delta g=-g$. The full 2006 data set may allow differentiation between $\Delta g=0$ and $\Delta g=GRSVstd$.

The data in Fig. 1a cover an $x$ range of 0.07 to 0.2. By measuring $A_{LL}$ for different center of mass energies, this $x$ range can be extended. In 2009, RHIC expects to run at $\sqrt{s}=500$ GeV, extending the measured low $x$ region. In 2006, a short data set was taken with $\sqrt{s}=62.4$ GeV allowing a constraint at higher $x$. Data at different $\sqrt{s}$ can be compared using $x_T$, defined as

$$x_T = \frac{2p_T}{\sqrt{s}}.$$ (3)

In Fig. 1b [6], the results for $\pi^0$ $A_{LL}$ from $\sqrt{s}=62$ GeV (large black circle) and $\sqrt{s}=200$ GeV (small blue circles) are plotted. Models assuming $\Delta g=g$ and $\Delta g=GRSVstd$ are also plotted for both center of mass values. Interpretation of this result requires that the data is described by pQCD. Therefore, it is important to check that $\pi^0$ cross section is described by pQCD at $\sqrt{s}=62$ GeV. This analysis is ongoing, and upon completion, will allow further discussion of this $A_{LL}$ result by comparing it with the pQCD calculations.

Similar to the ordering of fragmentation functions for $u$ quarks to pions ($D_{\pi^-}^u < D_{\pi^0}^u < D_{\pi^+}^u$), $A_{LL}$ for pions is also expected to be ordered (if $\Delta g>0$, then $A_{LL}^{\pi^-} < A_{LL}^{\pi^0} < A_{LL}^{\pi^+}$). Figure 2a [7] shows $A_{LL}$ from 2005 for positive (blue squares) and negative (red circles) charged pions, compared with $A_{LL}^{\pi^0}$ from 2006. Figure 2b shows the results from 2005 for $\eta$ $A_{LL}$ [8]. Interpretation of this result in terms of $\Delta g$ require better understanding of the $\eta$ fragmentation function. Both of these results will have great significance when the 2006 longitudinal data set, which had a figure of merit roughly 7.5 larger than the 2005 data set, is analyzed.
4. Transverse Spin

Unexpectedly large single transverse spin asymmetries (SSA) were measured in proton proton collisions with $\sqrt{s}=20$ GeV at large $x_F$ [9]. These large asymmetries were found to remain at $\sqrt{s}=200$ GeV [10]. A number of possible causes for this have been described such as the Sivers effect, transversity, and higher twist effects.

PHENIX has measured $\pi^0$ and hadron SSA at mid-rapidity ($|\eta|<0.35$) [11] and found results consistent with zero. As the production process for hadrons in the measured $p_T$ range is dominated by gluon-gluon interactions, these results may constrain the gluon Sivers effect [12].

In 2006, a large transverse data set with a figure of merit 23 times larger than previous runs was taken allowing measurements at higher $p_T$ and with additional probes. Also, a new electromagnetic calorimeter was installed covering a rapidity range of 3.1<$|\eta|<$3.65. An asymmetry has been seen in this detector during a short transverse run at $\sqrt{s}=62$ GeV [13].

5. Conclusion

Large luminosity and polarization in longitudinally polarized proton collisions at RHIC in 2005 and 2006 have allowed PHENIX to constrain $\Delta g$, ruling out maximal gluon polarization models, by measuring $\pi^0$ $A_{LL}$ at $\sqrt{s}=200$ GeV. Measurements of $\pi^0$ $A_{LL}$ at $\sqrt{s}=62$ GeV will allow PHENIX to probe a higher $x_T$ region. Other complementary analyses, such as $\pi^\pm$ and $A_{LL}$ will benefit from the larger figure of merit in 2006. Previous PHENIX SSA results may constrain the gluon Sivers effect. With a new electromagnetic calorimeter in the forward region, and a substantially more significant data set in 2006, new results from transversely polarized proton collisions are expected soon.

[1] Adcox K et al. 2003 Nucl. Inst. Meth. A 499 469
[2] Adler S S et al. 2004 Phys. Rev. Lett. 93 202002
[3] Adler S S et al. 2003 Phys. Rev. Lett. 91 241803
[4] Boyle K 2006 Proc. of the 16th Int. Spin Physics Symp. (Kyoto, Japan)
[5] Glück M, Reya E, Stratmann M, Vogelsang W 2001 Phys. Rev. D 63 094005
[6] Aoki K 2006 Proc. of the 16th Int. Spin Physics Symp. (Kyoto, Japan)
[7] Morreale A 2006 Proc. of the 16th Int. Spin Physics Symp. (Kyoto, Japan)
[8] Ellinghaus F 2006 Proc. of the 16th Int. Spin Physics Symp. (Kyoto, Japan)
[9] Adams D L et al. 1991 Phys. Lett. B 264 462
[10] Adams J et al. 2004 Phys. Rev. Lett. 92 171801
[11] Adler S S et al. 2005 Phys. Rev. Lett. 95 202001
[12] Anselmino M, D’Alesio U, Melis S, Murgia F 2006 Phys. Rev. D 74 094011
[13] Chiu M 2006 Proc. of the 16th Int. Spin Physics Symp. (Kyoto, Japan)