Longitudinal spin physics with the PHENIX detector at RHIC

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Abstract. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has demonstrated the unique ability to collide beams of polarized protons at center of mass energies from $\sqrt{s}=62.4$ GeV to 500 GeV. The spin-dependent gluon distribution function of the proton, $\Delta g(x)$, can be determined from such collisions, through processes such as $p + p \rightarrow \pi + X$, $p + p \rightarrow \gamma + X$, $p + p \rightarrow \eta + X$, and others. The results of analyses for these kinds of processes in PHENIX will be presented, some of which provide strong constraints on the contribution of gluon spin to the spin of the proton.

Flavor-separated spin-dependent quark and antiquark distribution functions can also be extracted in polarized $p+p$ collisions, from parity-violation in the production of $W$ bosons, which we observe indirectly from their decay into leptons. Our progress in determining the $W$-production yield from our selection of $p + p \rightarrow e + X$ events will be presented.

1. Introduction
Polarized deep-inelastic scattering experiments conducted at SLAC, CERN, and DESY, revealed that quark and antiquarks carry roughly 25% of the spin of the proton [1]. This fraction is unexpectedly small, and understanding the remainder, which must come from the intrinsic spin of the gluons $\Delta q(x)$, and orbital angular momentum of the quarks $L_q$, and gluons $L_g$, presents an outstanding challenge to both theorists and experimentalists.

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has the unique ability to collide beams of highly polarized protons. This has provided experimentalists with a new tool to access, with leading order sensitivity, the gluon contribution to the spin of the proton [2]. In addition, in 2009 RHIC reached $pp$ center of mass energies of 500 GeV, where measurements of $\Delta u$, $\Delta \bar{u}$, $\Delta d$, and $\Delta \bar{d}$ are possible by exploiting parity-violation in the process $pp \rightarrow W^\pm + X$ [2]. This ability is important since $\Delta \bar{u}$ and $\Delta \bar{d}$, like $\Delta g$, are poorly known.

2. RHIC: The polarized proton collider
RHIC has two rings, each containing up to 120 bunches of polarized protons (though usually not all “buckets” are filled). In the interaction regions, a bunch from one ring collides with a bunch from the other ring, then these same bunches circulate in opposite directions 3833 m around the RHIC rings and collide again about 13 $\mu$s later [3].

To preserve the spin during acceleration and store, a pair of Siberian snakes are used in RHIC. Spin rotators can be used to rotate the spins from the stable vertical direction to the
radial or longitudinal directions at the interaction region. In the most recent $p+p$ run in 2009, RHIC ran at $\sqrt{s}=500$ GeV for 30 days, and achieved 35% polarization and a peak luminosity of $8.5 \times 10^{31}$ cm$^{-2}$s$^{-1}$, and store average of $5.5 \times 10^{31}$ cm$^{-2}$s$^{-1}$. RHIC also ran at $\sqrt{s}=200$ GeV, at 56% polarization. The polarization of the beams was measured every few hours using proton-carbon CNI polarimeters, which are calibrated using a polarized hydrogen gas jet target to better than 5% absolute accuracy. A summary of the polarized proton runs at RHIC is given in Table 1.

3. The PHENIX detector

The PHENIX detector (see Fig. 1) comprises two forward detectors and four spectrometer arms [4]. The forward detectors (beam-beam counter (BBC) and zero-degree calorimeter (ZDC)) determine the collision vertex position and time, are calibrated to determine the proton beam luminosity and polarization (ZDC plus some scintillators are used for this), and can form a minimum bias trigger. The four spectrometers have specialized functions. The east and west “central” arms have tracking, particle identification, and an electromagnetic calorimeter at pseudorapidity $|\eta| < 0.35$. The muon spectrometer arms are specialized for the detection of muons.

The east and west central arms are in a solenoidal field along the beam axis, and can identify electrons, photons, and charged hadrons in a pseudorapidity range $-0.35 < \eta < 0.35$ over $|\Delta \phi| = 90^\circ$ in azimuth. Tracking is provided by drift chambers (DC), time expansion chamber (TEC), and pad chambers (PC), while particle identification is possible with a time-of-flight system, (TOF) and ring-imaging Cerenkov (RICH). Of particular importance is the electromagnetic calorimeter (EMCal). Individual calorimeter towers are made of lead scintillator (PbSc) or lead glass (PbGl) and subtend $\Delta \eta \times \Delta \phi \approx 0.01 \times 0.01$. This fine segmentation allows the two photons from $\pi^0$ decay to be resolved up to $p_T$ of 12 GeV/c. Shower shape analysis extends this range beyond 20 GeV/c, and allows the two photon invariant mass peak from $\pi^0$ decay to be used for energy calibration. Fine segmentation is also important for distinguishing rare direct photon events from the background from photons originating from neutral meson decay. This allows the measurement of the theoretically clean (but statistically limited) direct-photon asymmetry [2].

The north and south muon arms subtend a pseudorapidity interval $1.2 < |\eta| < 2.4(2.2)$

Table 1. Summary of polarized proton runs at RHIC and integrated luminosity recorded by PHENIX.

| Run | Year    | $\sqrt{s}$ (GeV) | Polarization       | Recorded Luminosity |
|-----|---------|-------------------|--------------------|--------------------|
| 1,2 | 2001,2002 | 200   | 14%, Transverse | 0.15 pb$^{-1}$  |
| 3   | 2003     | 200   | 34%, Longitudinal | 0.35 pb$^{-1}$  |
| 4   | 2004     | 200   | 46%, Longitudinal | 0.12 pb$^{-1}$  |
| 5   | 2005     | 200   | 47%, Longitudinal | 3.4 pb$^{-1}$   |
|     |          |       | 47%, Transverse  | 0.4 pb$^{-1}$   |
| 6   | 2006     | 200   | 55%, Longitudinal | 7.5 pb$^{-1}$   |
|     | 62.4     | 50%, Longitudinal | 0.08 pb$^{-1}$ |
| 8   | 2008     | 200   | 44%, Transverse  | 5.2 pb$^{-1}$   |
| 9   | 2009     | 500   | 44%, Longitudinal | 11 pb$^{-1}$   |
|     | 200      | 56%, Longitudinal | 16 pb$^{-1}$   |
Beam and side views of the PHENIX detector respectively, with full azimuthal coverage. They have a hadron absorber, radial magnetic field, and cathode strip tracking chambers. Trigger electronics identify muons using layers of proportional tubes interspersed with hadron absorber. Of great interest to the spin program is the ability to trigger on muons from $J/\psi$ decay, and high energy muons from $W$ decay. The latter channel will allow the flavor separated measurement of the $u$ and $d$ polarized quark and antiquark distributions when an upgrade involving new planes of RPCs and new trigger electronics is complete.

In addition to its well-understood detectors, PHENIX has selective triggers for final states of interest to the spin program, including high $p_T$ neutral pions, electrons, and photons. These events can be recorded at rates above 5 kHz with the PHENIX data acquisition system. Data analysis is done in parallel at the RHIC Computing Facility and the CCJ facility at RIKEN in Wako, Japan.

4. Physics Results
PHENIX is sensitive to $\Delta g$ through measurements of the double helicity asymmetries in the production of particular final states, such as $\pi^0$. The asymmetries are defined:

$$A_{LL}^{\pi^0} = \frac{d\sigma^{++}/dp_T - d\sigma^{+-}/dp_T}{d\sigma^{++}/dp_T + 2d\sigma^{+-}/dp_T}$$
where $\sigma_{+} (\sigma_{-})$ is the production cross section for $\pi^0$ from $p + p$ collisions with like (unlike) proton helicities. In leading order this can be factorized as the sum of all partonic subprocesses $ab \to cX$ where parton $c$ fragments into the detected $\pi^0$. In this framework, $A_{LL}$ can be understood as the convolution:

$$A_{LL}^{\pi^0} = \frac{\sum_{abc} \Delta f_a \Delta f_b \sigma(ab\to cX) \hat{a}_{LL}(ab\to cX) D_{c\pi^0}}{\sum_{abc} \Delta f_a \Delta f_b \sigma(ab\to cX) D_{c\pi^0}},$$

where $f_a(\Delta f_a)$ are the unpolarized (polarized) parton distribution functions, and $D_{c\pi^0}$ is the fragmentation function of $c$ into $\pi$. The spin-averaged partonic scattering cross-section for $ab \to cX$ is denoted by $\hat{\sigma}$, and $\hat{a}_{LL}$ is the analyzing power; both of which are calculable at next-to-leading order (NLO) in perturbative QCD (pQCD) [2].

The $A_{LL}(pp \to \pi^0X)$ analyses have been PHENIX’ most sensitive probes of $\Delta g$ since we can trigger on, and reconstruct $\pi^0 \to 2\gamma$ with high efficiency. Also, at $\sqrt{s} = 200$ GeV, the cross-section is dominated by $qg$ scattering for $p_{T\pi} > 5$ GeV, so the process is directly sensitive to $\Delta g$.

In the analyses, the invariant mass spectrum is formed from all pairs of photons, and the asymmetry is formed around the $\pi^0$ mass peak in a window from 112-162 MeV. The background fraction, and asymmetry in the background, are estimated from sidebands around the mass peak. Background fractions vary from 16% in the $\pi^0 pT$ range of 2-3 GeV, to 6% in the 9-12 GeV range at $\sqrt{s} = 200$ GeV.

In 2006, PHENIX recorded 0.08 pb$^{-1}$ of $p + p$ collisions at $\sqrt{s} = 62.4$ GeV. This run was intended primarily to improve upon ISR results on inclusive pion cross-sections. At these low center of mass energies, NLO pQCD predictions of inclusive pion cross-sections tend to under-predict the observed yields. Including threshold resummation at next-to-leading-logarithm (NLL) accuracy improves the agreement with fixed target [5] and collider data [6]. The PHENIX measurement of the inclusive $\pi^0$ cross-section confirmed the necessity of such corrections [7]. In addition, a measurement of $A_{LL}(pp \to \pi^0X)$ at $\sqrt{s} = 62.4$ GeV [7], made with one week of data, excluded the GRSV scenarios $\Delta g(x) = \pm g(x)$ [8] (see Fig. 2). The NLL predictions for $A_{LL}$ are slightly smaller than for NLO pQCD. The asymmetry measurement also extended our sensitivity to $\Delta g(x)$ to higher $x$ in comparison to the measurements at $\sqrt{s} = 200$ GeV. While the collider luminosity is significantly worse at these low energies; the fact that the data can be used reliably in a global analysis, and the fact that the asymmetries become easier to measure (due to the approximate $xT$ scaling of the cross-sections and asymmetries) the author feels it can be advantageous to spend more running time at $\sqrt{s} = 62.4$ GeV in order to reduce the uncertainties on $\Delta g$.

From the 2005 and 2006 runs at $\sqrt{s} = 200$ GeV, PHENIX published results on $A_{LL}$ of $\pi^0$ [9] (see Fig. 3). The asymmetries are consistent with zero, and lie below the GRSV standard model (which reflected the best fit to polarized deep inelastic scattering (DIS) data). This favors a smaller $\Delta g(x)$, and smaller integral $\Delta g$. An estimate of the integral of $\Delta g(x)$ was made from these data in the framework of the GRSV model. We use the notation $\Delta g_{[a, b]}$ to denote the integral of $\Delta g(x)$ from $a < x < b$. The polarized DIS data were refit using a constraint on the value of $\Delta g_{[0, 1]}$, at a scale $\mu^2 = 0.4$ GeV$^2$, to extract a set of polarized parton distribution functions (PDFs) using the GRSV parametrization. From the resulting polarized PDFs, a prediction for $A_{LL}^{\pi^0}$ is made and compared with the measurement. The resulting $\chi^2$ is plotted as a function of $\Delta g_{GRSV}^{[0, 0.2, 0.3]}$, evolved to $\mu^2 = 4$ GeV$^2$, in Fig. 3. The curve is not parabolic since $\pi^0$ can be produced from $gg$, $gq$, and $qq'$ scattering. The former has quadratic sensitivity to $\Delta g$, leading to two minima in the $\chi^2$ curve. The $qq$ contribution is linear in $\Delta g$, breaking the symmetry. Including the statistical uncertainty, the results suggest $\Delta g_{GRSV}^{[0, 0.2, 0.3]} = 0.2 \pm 0.1(1\sigma)$ and $0.2^{+0.2}_{-0.8}(3\sigma)$ with an additional systematic uncertainty of
\( A_{LL} \) for \( \pi^0 \) at \( \sqrt{s} = 62.4 \) GeV as a function of \( p_T \), showing statistical uncertainties. (14\% uncertainty from beam polarization not shown.) Four GRSV NLO pQCD (solid curves) and NLL pQCD (dashed curves) are shown for comparison. Details are discussed in the text.

\[ \pm 0.1 \] arising from the experimental uncertainty in beam polarization and relative luminosity. Using other parametrizations yields similar results, suggesting the asymmetry data are sensitive primarily to the integral \( \Delta g[0.02,0.3] \) and not to the specific shape of \( \Delta g(x) \). A similar analysis showed that changes of a factor of 2 in the renormalization, factorization, and fragmentation scales used in the NLO pQCD prediction, lead to changes in the value of \( \Delta g_{GRSV}^{[0.02,0.3]} \) extracted of \( \pm 0.1(\pm 0.1) \) at \( \Delta \chi^2 = 1(9) \). This suggest that calculations beyond NLO, while extraordinarily difficult, would be of great value in reducing the uncertainty on \( \Delta g \).

The above results are consistent with a comprehensive global analysis of almost all polarized DIS and RHIC data [1, 10]. The RHIC data now pose the tightest constraint on \( \Delta g(x) \) in the range \( 0.05 < x < 0.2 \). The global analysis suggests a truncated first moment \( \Delta g^{[0.001,1]} = 0.013^{+0.702}_{-0.331} \) at \( Q^2 = 10 \) GeV\(^2\), and full first moment \( \Delta g^{[0.1]} = -0.084 \). These results are very interesting. First, they suggest that large, anomaly-inspired values for \( \Delta g \) are very unlikely. Second, the difference between the truncated and full first moment highlights the importance of extending the measurements at RHIC to lower \( x \). This may be possible in the near future as PHENIX’ barrel and forward silicon vertex detectors are installed, and a proposed forward calorimeter (covering \( 1 < \eta < 3 \)) is developed. These will increase the acceptance of the PHENIX detector substantially, and will allow new, correlated asymmetry measurements of \( \gamma \)-jet, hadron-jet, and jet-jet. These new observables will allow us to constrain the kinematics of the hard-scattered partons, and improve our sensitivity to \( \Delta g(x) \) at lower momentum fraction \( x \), perhaps to a few\( \times 10^{-3} \).

The PHENIX collaboration also has preliminary asymmetry results on several other inclusive channels. The \( A_{LL}^{\eta} \) measurement has a slightly different sensitivity to \( \Delta g \) than \( \pi^0 \) since the flavor content of the \( \eta \) is different. The asymmetry measured is consistent with 0, and is shown in Fig. 4 along with GRSV model predictions [8]. PHENIX’ measurement of \( A_{LL} \) of direct photons is shown also in Fig. 4. This asymmetry too is consistent with 0, and is heavily statistics limited. The virtues of this measurement are that it is dominated by \( qg \) scattering, and so is linear in
Figure 3. Left: $A_{LL}$ for $\pi^0$ at $\sqrt{s} = 200$ GeV as a function of $p_T$, showing statistical uncertainties (8.3% uncertainty from beam polarization not shown.) Right: $\chi^2$ profile as function of $\Delta g_{GRSV}$ using 2005 and 2006 $A_{LL}^{\pi^0}$ data.

$\Delta g$, and that the photon carries information about the hard scattering kinematics and is not the result of a fragmentation process.

In Fig. 5 is shown the $A_{LL}(pp \rightarrow h^+X)$ measured at $\sqrt{s} = 62.4$ GeV (where $h^+$ denotes a non-identified charged hadron ($\pi$,K,p)). These data were taken with the minimum bias trigger, with the momentum of the hadron measured using the drift chamber (DC). The PHENIX RICH has a threshold for $\pi^\pm$ of 4.7 GeV, so a RICH veto ensures the events are $h^+$ with $p_T < 4.7$ GeV. The GRSV model curves are shown on the plot. The GRSV max curve, corresponding to $\Delta g(x) = g(x)$ is not shown as it is clearly excluded by this data. Similar data exist for $h^–$.

At $\sqrt{s} = 200$ GeV, $A_{LL}(pp \rightarrow \pi^0X)$ has been measured at $p_T > 5$ GeV. Here we trigger on the EMCal, and look for associated tracks, measuring the particle momentum in the DC. The hadrons can be identified as pions as now they are above the RICH threshold. The charged pions are not as well measured as $\pi^0$ since PHENIX lacks a dedicated charged hadron trigger. Still, the channel is important because it has high analyzing power for $\Delta g$. This is apparent from two observations. First, at $p_T > 5$ GeV, $\pi$ production is dominated by $qg$ scattering, giving leading order sensitivity to $\Delta g$. Second, we can write $A_{LL}^{\pi^0} \propto \Delta g(x_1) \otimes (\Delta u(x_2)D_u^{\pi^0} + \Delta d(x_2)D_d^{\pi^0})$. Since $\Delta u$ is large and positive, if $\Delta g$ is positive, we expect $A_{LL}^{\pi^0} > 0$. Similarly, $A_{LL}^{\pi^+} \propto \Delta g(x_1) \otimes (\Delta d(x_2)D_u^{-\pi} + \Delta \bar{u}(x_2)D_d^{-\pi})$. Since $\Delta d$ is negative, this yields smaller asymmetries than for $\pi^+$. The asymmetry $A_{LL}^{\pi^0}$ will lie in-between. Thus we predict an ordering of the asymmetries $A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^0}$ if $\Delta g > 0$. We also observe that $A_{LL}^{\pi^+}$ has the largest analyzing power for $\Delta g$ of these channels.

Finally we note with great excitement that the $W$ programs at PHENIX and STAR have their first data from the RHIC run in 2009 at $\sqrt{s} = 500$ GeV. PHENIX accumulated roughly 10 pb$^{-1}$ of data during this 4 week run. The goals of the program (see [2, 11] for details), are to extract the flavor-separated spin-dependent quark distribution functions, in particular $\Delta \bar{u}$ and $\Delta d$. These have been measured in semi-inclusive DIS experiments (SMC, HERMES, and COMPASS) but with limited accuracy. The virtue of the RHIC program is that these quantities will be measured at very high momentum scales, without uncertainties due to fragmentation functions or possible higher-twist contributions.
With the recorded luminosity, PHENIX expects (before acceptance and efficiency cuts) \( \approx 200 \, e^+ \) from \( pp \rightarrow W^+ \rightarrow e^+\nu_e \) with \( p_T > 25 \, \text{GeV} \) in the central arms and \( \approx 35 \, e^- \).

Figure 4. (a) \( A_{LL} \) for \( \eta \) at \( \sqrt{s} = 200 \, \text{GeV} \) as a function of \( p_T \), showing statistical uncertainties and GRSV model predictions (8.3\% uncertainty in beam polarization not shown). (b) \( A_{LL} \) for direct photons at \( \sqrt{s} = 200 \, \text{GeV} \) as a function of \( p_T \), showing statistical uncertainties and GRSV model predictions.

Figure 5. \( A_{LL} \) for \( h^+ \) versus \( p_T \) measured at \( \sqrt{s} = 62.4 \, \text{GeV} \), showing statistical uncertainties, and GRSV model predictions.
with \( p_T > 25 \) GeV from \( pp \rightarrow W^- \rightarrow e^- \bar{\nu}_e \). In the asymmetry analysis, we look for \( p_T > 25 \) GeV in the calorimeter with an isolated, high-momentum charged track passing a time-of-flight cut. The resolution of the DC is sufficient to distinguish \( e^+ \) from \( e^- \) even at \( p_T > 40 \) GeV, allowing us to identify the parent as \( W^+ \) or \( W^- \). The main background is from \( e^\pm \) from photon conversion from \( \pi^0 \) decay (plus a contribution from converted direct photons), with additional contributions from energetic charged hadrons showering in the EMCal. Other backgrounds include \( e^\pm \) from heavy quark decay, cosmics, and accidentals. The process \( pp \rightarrow Z \rightarrow e^+e^- \) constitutes \( < 10\% \) background for \( W^+ \), and about 30% for \( W^- \). We have clear evidence for a \( W \) signal above these backgrounds. After all cuts, and considering detectors inefficiencies and dead regions, we expect an uncertainty on the single spin asymmetry \( \delta A_{L}^{W^+} \approx 0.3 \). With a few more successful runs, this uncertainty should reach a few percent.

5. Summary
Results from the RHIC spin experiments, PHENIX and STAR, now pose the tightest constraints on \( \Delta g(x) \), which is smaller than anticipated from polarized DIS experiments. There is still considerable uncertainty in \( \Delta g(x) \) in the low-\( x \) (\( x < 0.02 \)) region, which will be addressed by both experiments, though continued running and through upgrades in the future. The process \( pp \rightarrow W \rightarrow e\nu \) has been observed at PHENIX, and cross-section and single-spin asymmetry \( A_{L}^{W} \) analyses are nearing completion. These are very exciting and productive times for the spin program.

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