Transverse Spin at PHENIX: Results and Prospects

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Abstract
The Relativistic Heavy Ion Collider (RHIC), as the world’s first and only polarized proton collider, offers a unique environment in which to study the spin structure of the proton. In order to study the proton’s transverse spin structure, the PHENIX experiment at RHIC took data with transversely polarized beams in 2001–02 and 2005, and it has plans for further running with transverse polarization in 2006 and beyond. Results from early running as well as prospective measurements for the future will be discussed.

1 Introduction
The Relativistic Heavy Ion Collider (RHIC) has opened up a new energy regime in which to study the spin structure of the proton. Polarization of more than 50% has so far been achieved for 100-GeV proton beams, with expectations that this value will rise to 70% in 2006 or 2007.

The PHENIX experiment, one of two large experiments at RHIC, specializes in the measurement of photons, electrons, and muons as well as high-transverse-momentum ($p_T$) probes in general over a limited acceptance, with good particle identification capabilities. It has a high rate capability and sophisticated trigger systems, allowing measurement of rare processes. The PHENIX detector consists of two mid-rapidity ($|\eta| < 0.35$) spectrometers, primarily for identifying and tracking charged particles as well as measuring electromagnetic probes, forward spectrometers for identifying and tracking muons ($1.2 < |\eta| < 2.4$), and interaction detectors.

Several polarization-averaged cross sections have been measured for 200-GeV collisions at RHIC and found to be in good agreement with next-to-leading-order (NLO) pQCD calculations. The ability of NLO pQCD to describe RHIC cross section data well and with little scale dependence provides a solid foundation for using it to interpret polarized data in a similar kinematic regime.
2 Current Results

Large transverse single-spin asymmetries (SSAs) have been observed in spin-dependent proton-proton scattering experiments spanning a wide range of energies, as well as in semi-inclusive deep-inelastic scattering. The origin of these asymmetries remains unclear, but several different mechanisms have been proposed, as described for example in Refs. [6]–[9].

From data collected in 2001–02 (0.15 pb$^{-1}$, $\langle P_{\text{beam}} \rangle \sim 15\%$), PHENIX measured the left-right transverse single-spin asymmetry ($A_N$) for neutral pion and charged hadron production at $x_F \sim 0.0$ up to a transverse momentum of 5 GeV/c from polarized proton-proton interactions at $\sqrt{s} = 200$ GeV. [4] As can be seen in Fig. 1, the asymmetries observed for production of both neutral pions and inclusive charged hadrons are consistent with zero within a few percent over the measured $p_T$ range.

![Figure 1: Mid-rapidity neutral pion and charged hadron transverse single-spin asymmetries. Points for positive hadrons have been shifted down by 50 MeV/c to improve readability. The error bars represent statistical uncertainties.](image)

The result is consistent with mid-rapidity results for neutral pions at $\sqrt{s} = 19.4$ GeV. [10] The present measurement is complementary to that of Ref. [3], which observed large asymmetries for forward neutral pions at $\sqrt{s} = 200$ GeV. Neutral pion production at forward rapidity is expected to originate from processes involving valence quarks, whereas particle production at mid-rapidity is dominated by gluon-gluon and quark-gluon processes. As evident from Fig. 2, $\pi^0$ production in the $p_T$ range covered by the recent PHENIX measurement is nearly half from gluon-gluon scat-
tering and half from gluon-quark scattering. As such, the asymmetry is not very sensitive to mechanisms involving quarks.

Figure 2: Relative fractional contributions of partonic processes to mid-rapidity $\pi^0$ production at $\sqrt{s} = 200$ GeV, calculated by W. Vogelsang.

In the forward direction at PHENIX, a large negative transverse SSA of approximately -11% in the production of neutrons from 200-GeV $p + p$ collisions has been observed. This measurement was made using the RHIC zero-degree calorimeters (ZDCs), hadronic calorimeters covering 2$\pi$ in azimuth and $4.7 < |\eta| < 5.6$. In 2005 there was a brief period of accelerator commissioning with polarized proton collisions at 410 GeV, and the large negative asymmetry in forward neutron production was found to persist.

The azimuthal asymmetry of forward charged particles was also measured at PHENIX using beam-beam counters (BBCs), which are quartz Čerenkov counters that cover 2$\pi$ in azimuth and $3.0 < |\eta| < 3.9$. The asymmetry for inclusive forward charged particles was consistent with zero. However, non-zero asymmetries were found in charged particle production from events in which a forward neutron was also detected in the ZDC. A significant negative asymmetry was observed for forward charged particles in neutron-tagged events, with a preliminary value of $(-4.50 \pm 0.50 \pm 0.22) \times 10^{-2}$. A smaller positive asymmetry was found for backward charged particles produced in neutron-tagged events, with a preliminary value of $(2.28 \pm 0.55 \pm 0.10) \times 10^{-2}$. The observed asymmetries for forward and backward charged particles in events with a forward neutron may suggest a diffractive process.
3 Prospective Future Measurements

Despite great theoretical progress in recent years, no single, clear formalism has emerged in which to interpret the currently available data. Further theoretical work and a variety of additional experimental measurements are necessary to understand current results and elucidate the transverse spin structure of the proton.

From a modest transverse-spin data sample taken in 2005 (0.16 pb$^{-1}$, $\langle P_{\text{beam}} \rangle \sim 48\%$), PHENIX has begun analysis to obtain improved mid-rapidity $A_N$ results for neutral pions and charged hadrons, expected to provide tighter constraints on the gluon Sivers function. Future higher-statistics samples for these particles at mid-rapidity will reach higher $p_T$ and provide greater sensitivity to transversity and the Collins effect.

There is also analysis underway to obtain first results for $A_N$ of single muons, largely from open charm decay but with significant contributions from light-hadron decays. The current $x_F$ reach for this measurement is up to $\sim 0.15$; higher $x_F$ values would become accessible with lower-energy running. A forward hadron $A_N$ measurement using the PHENIX muon spectrometers may be possible using decay muons and the charged hadrons that punch through the absorber in front of the muon tracker. Careful studies will be needed to understand the particle ratios in this sample.

In 2003 Boer and Vogelsang proposed a single transverse-spin di-jet measurement that could probe the gluon Sivers function. A non-zero Sivers function implies a spin-dependence in the $k_T$ distributions of the partons within the proton, which would lead to an observable spin-dependent asymmetry in $\Delta \phi$ of back-to-back jets. In 2006, PHENIX intends to perform a measurement similar to the one proposed, using di-hadrons instead of di-jets because of the limited detector acceptance. This analysis will study the spin-dependence of the azimuthal angle between nearly back-to-back $\pi^0$-hadron pairs, triggering on a decay photon from the $\pi^0$ in order to obtain a higher-statistics sample. Although dilution of the effect is anticipated for hadron rather than jet pairs, studies have shown that it should still be measurable. Fragmentation to the final-state hadrons must also be considered, and some contribution from the Collins mechanism may be present; however, as shown above in Fig. 4, for $p_T \lesssim 5$ GeV/c there is a large contribution to mid-rapidity $\pi^0$ production from gluon fragmentation, to which the Collins mechanism does not apply.

Measurement of $A_N$ for direct photons has also been proposed to probe the gluon Sivers function. Direct photon production is dominated by quark-gluon Compton scattering ($q+g \rightarrow \gamma + X$) over a wide range in photon $p_T$ at RHIC. Transverse SSAs of photons and jets in events with correlated photon-jet pairs would access the gluon and quark Sivers functions, respectively, with some ability to identify the $x$ values at which these functions were probed. PHENIX can currently measure $A_N$ of mid-rapidity direct photons. Future upgrades extending the azimuthal coverage for tracking to $2\pi$ in the inner region and adding forward electromagnetic calorimetry ($0.9 < |\eta| < 3.0$) are expected to expand the coverage for this measurement as well as make $\gamma$-jet and jet-jet measurements feasible.
Yet another proposal has been made to access the gluon Sivers function via mid- to moderate rapidity ($-0.2 < x_F < 0.6$) $D$ meson production at RHIC.\textsuperscript{15} PHENIX is currently capable of measuring open charm decays statistically via inclusive single electrons and muons. In the future, a silicon vertex detector upgrade will make it possible to identify $D$ mesons event by event. Note that $A_N$ measurements for charmonium production, also sensitive to the gluon, are already possible at PHENIX. However, the charmonium production mechanism is not as well understood.

The flavor separation of the Sivers function for $u$, $d$, $\bar{u}$, and $\bar{d}$ quarks via $A_N$ of forward or backward $W$ boson production, possible once RHIC achieves 500-GeV collisions, has been suggested by Schmidt.\textsuperscript{16} The processes of interest at PHENIX are $u + d \to W^+ \to \mu^+ + \nu_{\mu}$ and $d + \bar{u} \to W^- \to \mu^- + \bar{\nu}_{\mu}$. An upgrade to trigger on the high-$p_T$ muons from $W$ decays is expected in 2009. The trigger upgrade will also make open charm, charmonium, and Drell-Yan measurements cleaner.

The double transverse-spin asymmetry, $A_{TT}$, is another observable sensitive to transverse spin quantities. $A_{TT}$ for the Drell-Yan process would provide direct access to transversity. Although this asymmetry is expected to be at the sub-percent level for $\sqrt{s} = 200$ GeV, it could reach several percent for $\sqrt{s} < 100$ GeV. PHENIX already has an effective di-muon trigger for measuring Drell-Yan pairs; however, the trigger upgrade will improve backgrounds. To measure $A_{TT}$ it would be necessary to optimize the beam energy to balance luminosity against the size of the predicted asymmetry. A first direct measurement of transversity would be an exciting milestone.

### 4 Summary

The first transverse-spin results from PHENIX are now available, and further results from the brief transverse-spin run in 2005 are forthcoming. A longer period of running with transversely polarized beams is anticipated for 2006. Looking farther ahead, forward detector upgrades will improve access to the kinematic region where large asymmetries have been observed, and mid-rapidity upgrades will improve jet measurements.

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