Measurement of Transverse Single-Spin Asymmetries for Mid-rapidity Production of Neutral Pions and Charged Hadrons in Polarized p+p Collisions at $\sqrt{s} = 200$ GeV

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The transverse single-spin asymmetries of neutral pions and non-identified charged hadrons have been measured at mid-rapidity in polarized proton-proton collisions at \( \sqrt{s} = 200 \text{ GeV} \). The data cover a transverse momentum (\( p_T \)) range 0.5-5.0 GeV/c for charged hadrons and 1.0-5.0 GeV/c for neutral pions, at a Feynman-\( x_F \) (\( x_F \)) value of approximately zero. The asymmetries seen in this previously unexplored kinematic region are consistent with zero within statistical errors of a few percent. In addition, the inclusive charged hadron cross section at mid-rapidity from 0.5 < \( p_T < 7.0 \text{ GeV/c} \) is presented and compared to NLO pQCD calculations. Successful description of the unpolarized cross section above \( \sim 2 \text{ GeV/c} \) using NLO pQCD suggests that pQCD is applicable in the interpretation of the asymmetry results in the relevant kinematic range.

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The measurement of transverse single-spin asymmetries (SSAs) in proton-proton collisions and deep-inelastic lepton-nucleon scattering (DIS) probes the quark and gluon structure of transversely polarized nucleons. Large transverse SSAs have been observed in a number of spin-dependent proton-proton scattering experiments at energies ranging from $\sqrt{s} = 5 - 10$ GeV. Asymmetries approaching 30% were observed in inclusive pion production at transverse momentum ($p_T$) up to 1.2 GeV/c and Feynman-$x$ ($x_F$) up to 0.8 [1, 2]. At mid-rapidity and $x_T = \frac{2p_T}{\sqrt{s}}$, up to 0.8, asymmetries were also observed in inclusive $\pi^0$ and $\pi^+$ production but not in $\pi^-$ production [3, 7]. At higher center-of-mass energies of 20 and 200 GeV, $\pi^+$, $\pi^-$, and $\pi^0$ asymmetries were found to persist at large $x_F$ [8, 9, 10] while the asymmetry in $\pi^0$ production at mid-rapidity was found to be consistent with zero at $\sqrt{s} = 20$ GeV and for $p_T < 4$ GeV/c [9]. Non-zero transverse asymmetries have also been observed in semi-inclusive DIS experiments [10, 11, 12].

Three different mechanisms have been studied as the possible origin of transverse SSAs in hadron collisions at high energies: (1) Transversity distributions, the quark spin distributions in a transversely polarized proton, can give rise to SSAs in combination with spin-dependent fragmentation functions (FFs), e.g., the Collins function [13]. Spin-dependent FFs serve as analyzers for the transverse spin of the struck quark. (2) Quark and gluon distributions that are asymmetric in the transverse intrinsic parton momentum, $k_T$, first suggested by Sivers [14], can lead to SSAs. (3) Alternatively, interference between quark and gluon fields in the initial or final state can also generate SSAs [14, 15]. Sivers parton distributions can exist both for quarks and gluons, and a possible connection to orbital angular momentum of partons in the nucleon has been suggested [14, 17].

It is expected that SSAs measured at the Relativistic Heavy Ion Collider (RHIC) result from a combination of these three effects (see [5] and references therein). Model calculations leading to predictions for the Sivers and transversity distributions have been performed to describe existing data at forward rapidities. Precision measurements of SSAs in different regions of $x_F$ and $p_T$ and their QCD analysis may serve to quantify contributions from the competing mechanisms. In this Letter we present first measurements of transverse single-spin asymmetries at mid-rapidity and collider energies.

These data were collected during the 2001-2 polarized proton run at RHIC, in which approximately 0.15 $pb^{-1}$ of integrated luminosity were collected using the PHENIX detector. Two beams of 55 bunches of polarized protons, with approximately $5 \times 10^{10}$ protons per bunch, were injected into RHIC and accelerated to 100 GeV each.

Measurements of the unpolarized production of charged hadrons and of the spin-dependent production of both neutral pions and charged hadrons were made in the central arms of the PHENIX detector. These cover a pseudorapidity range of $|\eta| < 0.35$ and two azimuthal angle intervals of $\Delta \phi = 90^\circ$, offset 33.75° from vertical [15].

A minimum-bias (MB) collision trigger and the vertex position in the beam direction are provided by two beam-beam counters (BBCs) [16]. The BBCs, which cover $2\pi$ in azimuth and $3.0 < |\eta| < 3.9$, are sensitive to charged particles and select approximately half of the total inelastic proton-proton cross section. A $\pm 30$ cm event vertex cut was applied for all analyses, corresponding to the central arm acceptance. The approximate vertex resolution was 2 cm in the beam direction.

Charged-particle tracks from MB events were reconstructed using a drift chamber and pad chambers [20] as well as the collision vertex, which is the assumed point of origin because the tracking chambers are placed outside the magnetic field. Thus charged particles that do not originate at the vertex have incorrectly reconstructed momentum, leading to low-momentum, long-lived particle decays (e.g., $K^{\pm}$, $K^0_S$) and conversion electrons as the two main sources of background.

For the charged hadron cross section, approximately 17 million MB events were analyzed. The luminosity was measured as $N_{MB}/\sigma_{MB}$ with $\sigma_{MB} = 21.8$ mb [21], accounting for the fraction of the yield for which the MB condition was satisfied. Backgrounds were estimated and subtracted statistically following the method of [22]: conversion electrons were estimated using the different response of the ring-imaging Čerenkov detector (RICH) [23] to electrons and charged pions, and decay particles were estimated using the track bend in the residual magnetic field in the tracking detectors. Weak decays of short-lived particles, mainly $K_S^0$, $\Lambda$, and $\bar{\Lambda}$, remain, especially when they decay close to the vertex. Based on a Monte Carlo simulation, the reported cross section was reduced by 7% over the entire $p_T$ range to correct for these decays.

The unpolarized cross section for inclusive charged hadron production at mid-rapidity is presented in Fig. 1 and Table 1. The dominant systematic uncertainty for $p_T > 5$ GeV/c is from the background subtraction, while for $p_T < 5$ GeV/c it is due to the weak-decay correction. There is a 9.6% normalization uncertainty due to the luminosity measurement. In Fig. 1 the cross section is compared to a next-to-leading-order (NLO) pQCD calculation using the CTEQ6M [22] parton distribution functions and Kniehl-Kramer-Pötter FFs [20] and found to be consistent above $p_T \sim 2$ GeV/c. The unpolarized cross sections for mid-rapidity and forward production of neutral pions have also been measured in 200-GeV proton-proton collisions at RHIC [8, 21] and have been found to agree well with NLO pQCD calculations [24, 27, 28]. The agreement between all of these unpolarized measurements and the theoretical calculations indicates that NLO pQCD is applicable in interpreting
polarized data at $\sqrt{s} = 200$ GeV and provides a solid theoretical foundation for the study of the spin structure of the proton at RHIC.

The stable spin direction of the protons through acceleration and storage is vertical, and there is an approximately equal number of bunches filled with the spin of the protons up as there is down. With both beams polarized, single-spin analyses were performed by taking into account the spin states of one beam, averaging over those of the other. The beam polarization at 100 GeV was obtained using the same analyzing power ($A_N^{\text{C}}$) in proton-carbon elastic scattering in the Coulomb-nuclear interference region measured at 22 GeV (see [29] and references therein), near RHIC injection energy. The average beam polarization was 15±5%.

The left-right transverse single-spin asymmetry, $A_N$, can be extracted using

$$A_N = \frac{1}{P_b} \left( \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \right) = \frac{1}{P_b} \left( \frac{N^+ - R N^+}{N^+ + R N^+} \right),$$  

where $P_b$ is the beam polarization, $\sigma^+$ ($\sigma^-$) the production cross section when the protons in the bunch are polarized up (down), $N^+$ ($N^-$) the experimental yield from up- (down-) polarized bunches, and $R = \mathcal{L}^+/\mathcal{L}^-$ the relative integrated luminosity of bunches of opposite polarization sign. The above formula as written applies to yields observed to the left of the polarized beam. An overall minus sign is required for yields observed to the right of the polarized beam. Alternatively, we derive the asymmetry using

$$A_N = \frac{1}{P_b} \left( \frac{\sqrt{N_L^+ N_R^-} - \sqrt{N_L^- N_R^+}}{\sqrt{N_L^+ N_R^-} + \sqrt{N_L^- N_R^+}} \right),$$

which calculates a single value for the asymmetry taking into account yields from both the left ($N_L$) and right ($N_R$) sides of the polarized beam and provides a consistency check on the relative luminosity [30].

The BBCs were used to determine the relative luminosity ($R$ in Eq. 1) between bunches of opposite polarization sign fill-by-fill. A typical $R$ for the data sample analyzed here was approximately 1.09, measured to better than 10^{-3}. In the asymmetry analysis of charged hadrons, which utilized ~ 13M minimum-bias events, it was required that there be no hits in the RICH in order to eliminate electrons from photon conversions which mimic high-$p_T$ charged tracks. The momentum threshold for production of Čerenkov radiation by pions was 4.7 GeV/c, allowing the RICH veto to preserve nearly all charged pions. The electron contamination in the final data sample was less than 1%. The decay background from long-lived particles was less than 5%.

Neutral pions were reconstructed via their decay to two photons using finely segmented ($\Delta\phi \times \Delta\eta \approx 0.01 \times 0.01$) electromagnetic calorimeters (EMCal) [31]. Photon clusters were selected by their shower shape and a charged track veto. Approximately 18M events recorded by an
EMCal-based high-energy photon trigger in coincidence with the BBC collision trigger were analyzed \cite{21}. The trigger efficiency for neutral pions varied from \( \sim 24\% \) in the 1-2 GeV/c bin to \( \sim 78\% \) in the 4-5 GeV/c bin. Only triggered events were used in this analysis. The \( \pi^0 \) peak widths varied from 13.2 MeV/c\(^2\) in the 1-2 GeV/c bin to 10.6 MeV/c\(^2\) in the 4-5 GeV/c bin. The contribution from combinatorial background ranged from 34\% to 5\% across these bins; in order to avoid errors associated with peak extraction it was not subtracted.

The asymmetry for neutral pions and charged hadrons was determined for each fill using Eq. \ref{eq:3} then averaged over all fills. The contribution to the \( \pi^0 \) asymmetry by the background under the peak was estimated by calculating the asymmetry of 50-MeV/c\(^2\) regions on both sides of the signal, from 60-110 MeV/c\(^2\) and 170-220 MeV/c\(^2\) (see Table \ref{tab:3}). The asymmetry of the signal region and its uncertainty were then corrected using

\begin{equation}
A_N^\pi = \frac{A_{\text{Peak}}^\pi - r A_{\text{bg}}^\pi}{1 - r}, \quad \sigma A_N^\pi = \frac{\sqrt{\sigma A_{\text{Peak}}^\pi + r^2 \sigma A_{\text{bg}}^\pi}}{1 - r}
\end{equation}

where \( r \) is the fraction of background under the peak.

As the dominant systematic uncertainty is expected to be from the determination of the relative luminosity, systematic errors were evaluated by direct comparison of the asymmetry values calculated using Eq. \ref{eq:1} and Eq. \ref{eq:2}. Any potential effect should be the same for both the charged hadron and neutral pion analyses. No \( p_T \) dependence was expected or observed; therefore, we take the weighted average of the systematic uncertainties calculated for each bin, 0.002, as the overall, uniform systematic uncertainty.

The resulting asymmetries are plotted vs. \( p_T \) in Fig. \ref{fig:2} and shown in Tables \ref{tab:2} and \ref{tab:3}. The asymmetries are consistent with zero over the entire \( p_T \) momentum range.

In this Letter we have presented the first measurement of transverse-spin asymmetries \( A_N \) at mid-rapidity and high \( p_T \) at collider energies and the cross section for inclusive charged hadrons at mid-rapidity. NLO pQCD calculations have been found to reproduce experimental results for \( p_T > \sim 2 \) GeV/c not only for the cross section presented here but also for inclusive neutral pion and production, indicating that pQCD can be used to interpret the high-\( p_T \) asymmetries. The transverse SSAs observed for mid-rapidity production of both neutral pions and charged hadrons are consistent with zero within statistical errors of a few percent, measured over \( 0.5 < p_T < 5 \) GeV/c. The result is consistent with the mid-rapidity results for neutral pions at \( \sqrt{s} = 20 \) GeV \cite{3}. The present measurement is complementary to that of \cite{3}. The large asymmetries observed in neutral pion production at forward rapidity at \( \sqrt{s} = 200 \) GeV \cite{3} are expected to originate from partonic processes involving valence quarks (\( x > 0.1 \)), whereas the particle production at mid-rapidity presented here is dominated by gluon-gluon and quark-gluon processes (\( x < 0.1 \)). Our results are consistent with the pQCD expectation that quark-gluon correlations are suppressed at high \( p_T \) and mid-rapidity \cite{15,32}. A QCD analysis of the presented \( A_N \) may lead to constraints on gluon-Sivers contributions to observed transverse-spin phenomena. The present transverse single-spin asymmetries represent an early measurement in a rigorous program to study transverse proton spin structure at hard scales using a pQCD framework at RHIC.

### Table II: Neutral pion transverse single-spin asymmetry values and statistical uncertainties. An \( A_N \) scale uncertainty of \( \pm 35\% \) is not included.

| \( p_T \) (GeV/c) | \( \langle p_T \rangle \) (GeV/c) | \( r \) | \( A_{\text{Peak}}^\pi \) (%) | \( A_{\text{bg}}^\pi \) (%) | \( A_N^\pi \) (%) |
|-----------------|---------------------------|------|-----------------|-----------------|---------------|
| 1-2             | 1.45                      | 34   | -0.6±0.8        | -0.7±0.9       | -0.5±1.2      |
| 2-3             | 2.34                      | 12   | -1.4±1.7        | -3.1±3.4       | -1.2±2.0      |
| 3-4             | 3.36                      | 6    | 1.3±4.2         | 3.6±12.2       | -1.6±4.7      |
| 4-5             | 4.38                      | 5    | 7.0±10.1        | 42±39          | 5.2±10.9      |

### Table III: Charged hadron transverse single-spin asymmetry values and statistical uncertainties. An \( A_N \) scale uncertainty of \( \pm 35\% \) is not included.

| \( p_T \) (GeV/c) | \( \langle p_T \rangle \) (GeV/c) | \( A_{\text{Peak}}^h \) (%) | \( A_{\text{bg}}^h \) (%) |
|-----------------|---------------------------|-----------------|---------------|
| 0.5-1           | 0.70                      | -0.3±0.42       | -0.09±0.41    |
| 1-2             | 1.32                      | -0.12±0.82      | -0.54±0.78    |
| 2-5             | 2.56                      | -2.1±2.7        | -3.1±2.6      |

FIG. 2: Mid-rapidity neutral pion and charged hadron transverse single-spin asymmetry, \( A_N \), vs. transverse momentum. Points for positive hadrons have been shifted down by 50 MeV/c to improve readability. The error bars indicate statistical uncertainties.
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