Exploring the Proton's Spin at PHENIX

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Abstract

In late 2001 the first polarized proton collisions at the Relativistic Heavy Ion Collider (RHIC) took place. The PHENIX experiment at RHIC has a broad program to investigate the spin structure of the proton. This program will be described, and first results will be presented.

1 Introduction

Far from the point particle it was once believed to be, the proton has proven to be an extremely complex entity. A very rich structure has gradually been uncovered over the past 40 years of research. A thorough comprehension of proton structure, in particular its spin structure, remains the goal of extensive ongoing study. The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is in a position to make significant contributions to further understanding the origin of the proton's spin.

2 History of Proton Structure

2.1 The Quark-Parton Model

In the 1960s, in deep-inelastic scattering (DIS) experiments at SLAC analogous to the famous Rutherford scattering experiment that led to the discovery of the atom's hard core, it was found that protons also had "hard" subcomponents [1, 2]. These hard subcomponents came to be known as partons. It took some time before the experimentally observed partons inside the proton came to be identified as the theoretically hypothesized quarks, but eventually the quark-parton model of the proton came into being. As experimental work progressed and higher-energy lepton beams were used as probes, the proton came to reveal a much more intricate structure than that of the three so-called "valence" quarks. These other subcomponents are now known to be sea quarks and gluons.

2.2 The Spin Structure of the Proton

For many years it was assumed that the proton's spin of $\frac{1}{2}\hbar$ was due to the spins of the three spin-$\frac{1}{2}$ valence quarks, with two oriented in one direction and one in the other. In the late 1980s, however, the EMC experiment at CERN [3] discovered that only $12 \pm 16\%$ of the proton's spin was carried by quarks. This surprising result became known as the "proton spin crisis". Subsequent experimental work, mostly through DIS, has continued to explore this problem for more than 25 years, yet there remains much to be understood. In particular, the magnitude and even sign of the gluon spin's contribution to the spin of the proton remains to be determined, the flavor breakdown of the sea quarks' contributions is largely unknown, and the contribution from orbital angular momentum of both quarks and gluons has yet to be probed.

3 The Relativistic Heavy Ion Collider (RHIC)

3.1 RHIC Physics

RHIC is the most versatile hadronic collider in the world. It is capable of colliding heavy ions up to $\sqrt{s} = 200$ GeV/nucleon and polarized protons up to $\sqrt{s} = 500$ GeV, as well as asymmetric species. Collision of asymmetric species is possible due to independent rings with independent steering magnets. In the first four years of running, RHIC has provided gold collisions at four different energies, deuteron-gold collisions, and polarized proton-proton collisions, with plans for copper collisions in the upcoming year. The flexibility of RHIC allows for an extremely diverse physics program. The heavy-ion physics program investigates strongly-interacting matter under extreme conditions of density and temperature. Systematic variations of nuclear matter with collision species and energy are being examined, and nucleon structure in a nuclear environment is being studied.

The polarized proton program seeks a better understanding of the proton's spin structure, in particular contributions from the gluons and sea quarks. By studying hadronic collisions rather than deep-inleastic scattering, RHIC experiments may directly observe gluon-scattering processes. As a collider, RHIC can provide collisions at much higher energy than can be achieved in fixed-target measurements. As a result hard processes, describable by perturbative QCD (pQCD), can be studied, and new probes such as W bosons will eventually become available. The application of factorization to pQCD processes is of particular importance because it allows one to separate out parton distribution functions (pdf's), partonic hard-scattering cross sections, and fragmentation functions (FF's). Partonic hard-scattering cross sections are directly calculable in pQCD, while pdf's and FF's must be determined experimentally. RHIC experiments have access to a wealth of data from other experiments on pdf's and FF's, allowing them to check the applicability of pQCD calculations to their unpolarized data and subsequently utilize factorized pQCD to determine various polarized pdf's more accurately.

The unpolarized cross sections for mid-rapidity production (see Figure 1) as well as forward production of neutral pions have been measured in 200-GeV proton-proton collisions at RHIC and have been found to agree well with next-to-

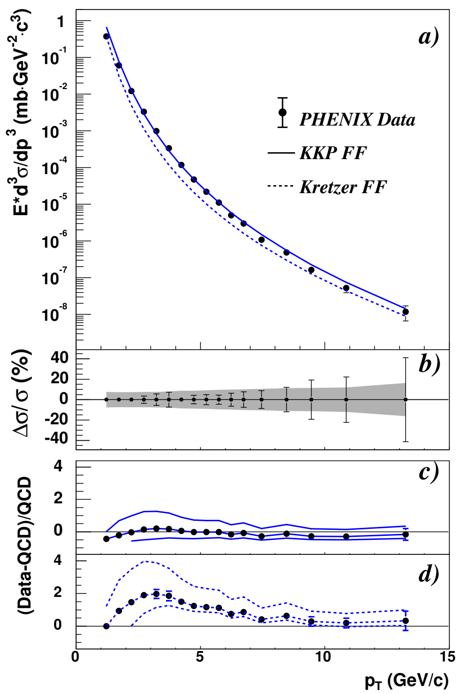

Figure 1: PHENIX results (points) for the invariant differential cross section for inclusive neutral pion production at 200 GeV. In panel *b)* the relative statistical (points) and point-to-point systematic (band) errors are shown.The curves are the results from NLO pQCD calculations using two different sets of fragmentation functions. See [4] for more details.

leading order (NLO) pQCD calculations [4, 5]. In addition, as shown in Figure 2, there are preliminary results from PHENIX for mid-rapidity production of inclusive charged hadrons which also demonstrate consistency with NLO pQCQ. This agreement indicates that NLO pQCD will be applicable in interpreting polarized data from RHIC as well and provides a solid theoretical foundation for the spin physics program.

3.2 RHIC as a Polarized Proton Collider

RHIC is the first high-energy polarized proton collider in the world. This achievement is possible due to the development of a variety of technologies to create, maintain, and measure the beam polarization throughout acceleration and storage.

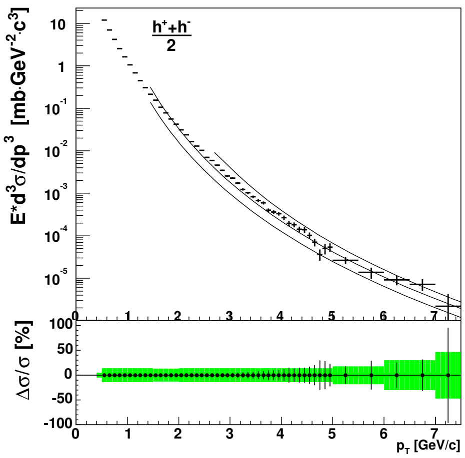

Figure 2: Preliminary PHENIX results (points) for the invariant differential cross section for inclusive charged hadron production at 200 GeV. In the bottom panel the relative statistical (points) and point-to-point systematic (band) errors are shown. The curves indicate NLO pQCD calculations by W. Vogelsang, using renormalization scales of $\frac{p_T}{2}$, p_T, and $2p_T$.

RHIC-AGS complex For proton-proton running, the path traveled by the protons is through a linac, a booster, the Alternating Gradient Synchrotron (AGS), and finally RHIC. The polarized source reliably provides a polarization of approximately 80%. The polarization in the AGS is maintained via careful tuning to avoid depolarizing resonances during acceleration and a partial Siberian snake. Siberian snakes, helical magnets developed at Novosibirsk, rotate the spin vector of the proton 180° such that any effects of depolarizing resonances will effectively be averaged out on the next turn around the ring. In 2005 a full-length, superconducting Siberian snake will be installed, completing the array of equipment related to running polarized protons in RHIC. Once the superconducting snake is installed, RHIC should be capable of reaching its design beam polarization of 70% at a beam energy of 250 GeV. In RHIC, there are two Siberian snakes installed in each ring. Very little polarization loss has been observed in the RHIC rings through acceleration and storage.

Polarimetry The RHIC-AGS complex utilizes various polarimeters to determine the beam polarization at different points along its path. In particular, there are proton-carbon (pC) polarimeters in both the AGS and RHIC which make use of Coulomb nuclear interference (CNI) [6]. A filament of carbon is inserted into the proton beam, and the left-right (azimuthal) asymmetry of recoil carbon atoms from $p^{\uparrow}C \rightarrow p^{\uparrow}C$ elastic scattering is measured. The analyzing power, $A_N \approx 0.015$, originating from the anomalous magnetic moment of the proton is exploited. The polarization of the beam can be determined from the following set of equations, in which N_L (N_R) is the number of recoil carbon atoms observed to the left (right) of the beam :

$$P_{Beam} = \frac{\varepsilon_{LR}}{A_N}, \varepsilon_{LR} = \frac{N_L - N_R}{N_L + N_R}$$

The uncertainty on the polarization measurement from the CNI polarimeters is currently approximately 30%, and the analyzing power must be further calibrated for improved polarization measurements.

In the spring of 2004, a hydrogen-jet polarimeter [7] was commissioned. A polarized hydrogen gas jet target is inserted into the beam, and the left-right asymmetry in p-p elastic scattering is measured in the CNI regime. The hydrogen-jet polarimeter will be used to calibrate the pC polarimeters and is expected to reduce the uncertainty on the polarization from ~30% to 5%.

Spin direction The naturally stable spin direction is transverse to the proton's momentum, in the vertical direction. Spin-rotator magnets immediately outside the STAR and PHENIX interaction regions are used to achieve longitudinal spin. These magnets were not commissioned until 2003, so during the 2001-2 run only data with transverse spin were taken. A detector which exploits previously measured forward-neutron azimuthal asymmetries in transverse-spin collisions is used to confirm the longitudinal component of the spin at the PHENIX interaction region.

3.3 The PHENIX Experiment

There are four major experiments at RHIC: two larger experiments, PHENIX and STAR, and two smaller ones, BRAHMS and PHOBOS. PHENIX, STAR, and BRAHMS all have spin physics programs. The four experiments have capabilities that overlap in many areas, making it possible to corroborate new results, but also areas of specialization which make the experiments complementary.

The PHENIX collaboration is comprised of approximately 480 participants from 12 different nations. The PHENIX detector [8] consists of two central spectrometer arms to track charged particles and detect electromagnetic processes, two forward spectrometer arms to identify and track muons, and three global detectors to determine when a collision occurs. The central arms cover a pseudo-rapidity range of $|\eta| < 0.35$ and $90°$ in azimuth each, while the forward arms cover $1.2 < |\eta| <$ ~2.2 and 2π in azimuth. PHENIX was specifically designed to have a high rate capability and high granularity as well as good mass resolution and particle-identification capabilities.

3.4 The Spin Physics Program at PHENIX

The first polarized proton collisions at RHIC were achieved in December 2001. In the 2001-2002 run, an average beam polarization of 15% was achieved, and

150 nb^{-1} of transverse-spin data were collected by PHENIX. In 2003, the average polarization reached 27%, and 220 nb^{-1} of longitudinal-spin data were taken. 2004 was principally a commissioning run to improve the polarization in the AGS and to commission the hydrogen jet polarimeter. During four days of data taking at the end of the commissioning period 75 nb^{-1} with an average polarization of approximately 40% were collected. There has been tremendous progress in machine performance over the first three years of running polarized protons at RHIC, and an extensive spin run of approximately 10 weeks with close to 50% polarization is anticipated in 2005. Proton running up until this point has been at $\sqrt{s} = 200$ GeV; 500-GeV runs are planned for the future.

PHENIX has a broad spin physics program. The principal areas of investigation are the gluon polarization (ΔG), flavor separation of the sea quark polarization ($\Delta\overline{u}$, $\Delta\overline{d}$), and transverse spin physics. PHENIX will be able to access a number of channels which probe ΔG through double longitudinal-spin asymmetries. These channels include pion production, for which results have already been published (see below), prompt photon production, dominated by gluon Compton scattering, heavy flavor production, mainly from gluon-gluon fusion, and jet production. When RHIC begins running 500-GeV protons, PHENIX will have access to W bosons, which will be identified via their leptonic decay mode. Because W$^+$ (W$^-$) production will be almost entirely from $u+\overline{d}$ ($\overline{u}+d$) and Δu and Δd are already well known, it will be possible to single out $\Delta\overline{u}$ and $\Delta\overline{d}$ from measurement of the single longitudinal-spin asymmetry of W production. The transverse spin physics program at PHENIX seeks to understand the transverse spin structure of the proton. This structure will be explored through a variety of measurements, including single transverse-spin asymmetries, for which there are already results (see below), jet correlations, the double transverse-spin asymmetry of the Drell-Yan process, and the interference fragmentation of pion pairs.

3.5 Recent Spin Physics Results

From the first two years of polarized proton collisions at RHIC, PHENIX has results on the single transverse-spin asymmetry of neutral pions and charged hadrons as well as the double longitudinal-spin asymmetry of neutral pions [9], [10].

3.5.1 Single Transverse-Spin Asymmetry of Neutral Pions and Charged Hadrons

The single transverse-spin asymmetry in the yield of a particular particle is given by

$$A_N = \frac{1}{P_{beam}} \left(\frac{N_L - N_R}{N_L + N_R} \right)$$

where N_L (N_R) is the particle yield to the left (right) of the polarized beam.

Large single transverse-spin asymmetries on the order of 20-30% have been observed in a number of experiments [11, 12, 5], ranging in energy from $\sqrt{s} = 20$-

200 GeV. The large asymmetries seen have stimulated more careful study by the theoretical community of polarized cross sections, in particular their dependence on the intrinsic transverse momentum of the partons (k_T) (see e.g. [13]).

Over the years, a number of models based on pQCD have been developed to predict these k_T dependencies and to explain the observed asymmetries. Among these models are the Sivers effect [14], transversity and the Collins effect [15], and various models which attribute the observed asymmetries to higher-twist contributions (see e.g. [16]). The Sivers effect hypothesizes that the asymmetries are due to spin-dependent intrinsic partonic momentum; the Collins effect suggests that they stem from a spin-dependent transverse momentum kick in the fragmentation process. The Collins effect requires transversity, the degree to which quarks in a transversely polarized proton are transversely polarized, to be non-zero in order to produce a non-zero asymmetry.

In Figure 3 preliminary PHENIX data on the transverse single-spin asymmetry of inclusive charged hadrons as well as neutral pions is shown as a function of p_T. The data were taken with the central arms and thus represent a pseudorapidity coverage of $|\eta| < 0.35$, corresponding to $x_F = \frac{p_L}{\sqrt{s}/2} \approx 0$. The single transverse-spin asymmetries observed for production of both neutral pions and inclusive charged hadrons at $x_F \approx 0$ are consistent with zero over the measured transverse momentum range. A small asymmetry in this kinematic region follows the trend of previous results, which indicate a decreasing asymmetry with decreasing x_F [11, 17, 5]. As a significant fraction of neutral pion production in this kinematic region comes from gluon scattering, any contribution to the asymmetry from transversity and the Collins effect, requiring a scattered quark, would be suppressed, while contributions from the Sivers effect or other mechanisms would remain a possibility. Further theoretical study of the results will have to be performed in order to interpret their full implications for the transverse spin structure of the proton. Future measurements reaching higher p_T will be dominated instead by quark scattering and a better probe of transversity and the Collins effect. See [9] for further discussion of these results.

3.5.2 Double Longitudinal-Spin Asymmetry of Neutral Pions

From the 2003 data-taking period, PHENIX obtained its first results probing ΔG, the gluon spin contribution to the spin of the proton. The double longitudinal-spin asymmetry of neutral pions was measured at mid-rapidity. The double longitudinal-spin asymmetry is given by

$$A_{LL} = \frac{1}{|\langle P_1 P_2 \rangle|} \left(\frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \right)$$

where P_1 and P_2 are the beam polarizations, N_{++} (N_{+-}) is the particle yield from same-helicity (opposite-helicity) bunch crossings and R is the relative luminosity between same- and opposite-helicity crossings. In Figure 4, the double-longitudinal asymmetry of neutral pions is shown as a function of p_T. The curves indicate two theoretical calculations based on NLO pQCD. The data

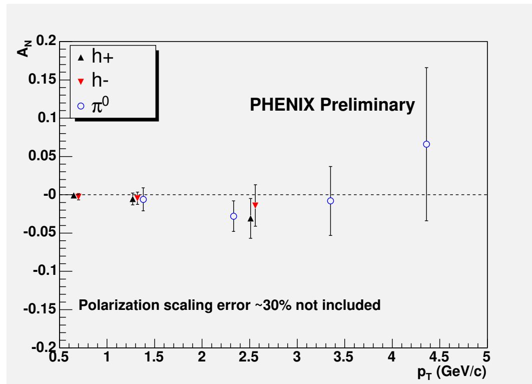

Figure 3: Preliminary PHENIX results as a function of transverse momentum for the single transverse-spin asymmetry of inclusive charged hadrons and neutral pions at mid-rapidity ($x_F \approx 0$). The positive charged hadron points are shifted 50 MeV/c to the left for readability. See [9] for more details.

points do not suggest a large contribution from gluon spin. For further details regarding the analysis and these results, see [10].

As mentioned above, in the current kinematic range π^0 production has a significant contribution from g-g scattering. This gluon dominance makes the $A_{LL}^{\pi^0}$ measurement quite sensitive to the polarized gluon pdf; however, because the polarized gluon pdf enters the factorized cross section twice at approximately equal values of x_{Bj}, it is not straightforward to determine the sign of ΔG from this measurement. Further theoretical discussion of these results and the sign of ΔG can be found in [18]. Future measurements of the double longitudinal-spin asymmetry of charged pions, produced largely via g-q scattering, will provide an additional handle on the magnitude of ΔG and allow determination of its sign.

4 Conclusions

RHIC, as a polarized hadron collider, provides a wealth of new opportunities to study the spin structure of the proton. The accelerator has already demonstrated success, and the RHIC community is looking forward to many more years of running with further improvements in luminosity and polarization as well as at higher energy. The PHENIX experiment has a broad program to investigate this structure, with particular focus on the gluon's contribution to the spin of the proton, the flavor decomposition of the sea quarks' contributions, and the transverse spin structure of the proton. First results are already available, indicating that the small single transverse-spin asymmetries seen at $x_F \approx 0$ at lower energies remain small at RHIC energies and that ΔG is not

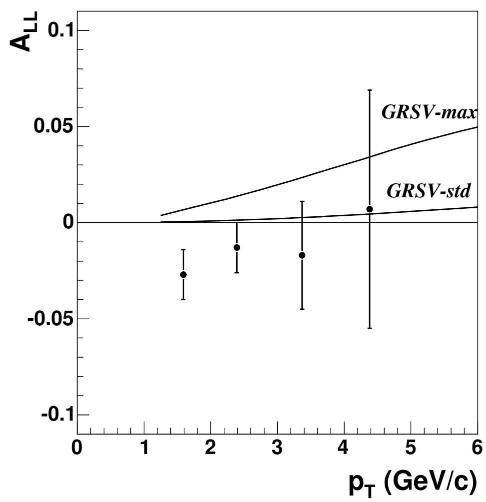

Figure 4: PHENIX results for the double longitudinal-spin asymmetry of inclusive neutral pions at mid-rapidity. A scale uncertainty of ±65% is not included. Two theoretical calculations based on NLO pQCD are shown for comparison with the data. See [10] for more details.

large. The spin structure of the proton continues to be a field of study of great interest with much still to be explored.

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