Highlights of the PHENIX Transverse Spin Physics

Ming X. Liu
P-25 MS H846, Los Alamos National Laboratory, Los Alamos, NM 87545
mliu@lanl.gov

Abstract. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory delivers the world highest energy polarized proton-proton collisions at a center of mass energy up to 500GeV and provides a unique opportunity to study the spin structure of the proton at high-energy scale. In recent years, there has been tremendous experimental and theoretical progress toward understanding the physics with transversely polarized beams (or targets). The scope of research in transverse physics involves from measurements of nucleon structure and parton distribution functions to the studies of QCD dynamics in high-energy polarized DIS and p+p collisions.

During the 2006 and 2008 RHIC runs, the PHENIX experiment took a significant amount of transversely polarized p+p collision data at the center of mass energies of 62 and 200 GeV, with integrated luminosity of 8 pb$^{-1}$ at 200GeV and beam polarization of 45%(run8) and 57%(run6). In this report, I highlight the latest results from the PHENIX experiment, followed by a brief discussion of the future prospects of transverse physics with the PHENIX upgrade detectors, particularly on the importance of the unique measurements of open charm, J/Psi and Drell-Yan productions.

1. Introduction

Spin has been playing a key role in our understanding of fundamental interactions since the day it was postulated. Today, we are facing with two major puzzles in spin physics: (1) the challenge of “too small”, i.e., the nucleon spin puzzle. It was believed that the spin was carried by the quarks that make up the proton. However, experiments in the 1980’s led to the startling discovery that quarks contribute very little to the proton spin, setting off the “proton spin crisis”. Where the rest of the proton spin coming from remains a major challenge to our understanding of the nucleon structure. Currently, there are several candidates that could make up the difference, such as the gluons’ spin, and/or the quark and gluon’s orbital angular momentum, and we need to determine them experimentally; (2) the challenge of “too big”, i.e., the unexpectedly large transverse left-right single spin asymmetries (TSSA, $A_N$) in transversely polarized high energy p+p (and e+p) collisions. Prior to the early Fermilab E704 experimental measurements, it was believed based on pQCD arguments that transverse single spin asymmetry should be very small in high-energy p+p collisions, $A_N \sim \frac{m}{\sqrt{s}} \sim 10^{-3}$, while the experimental data showed asymmetry as large as 40%. Spin measurements have historically produced surprising results and are a stringent test to theories as spin is an intrinsically relativistic and quantum mechanical aspect of particle interactions. This “too big” challenge is the focus of my discussion here.
Since the beginning of RHIC-Spin, very interesting results on transverse single spin asymmetries and cross sections have been measured by the RHIC experiments (BRAHMS, PHENIX and STAR) in a very wide kinematic range in polarized p+p collisions. All three experiments have observed and confirmed significant non-zero TSSAs in inclusive single particle productions in the forward rapidities. In the middle and backward rapidities, TSSAs are consistent with zero within the experimental uncertainty. The BRAHMS experiment has measured TSSAs for charged hadrons, including pion, Kaon, proton and antiproton at very forward rapidities (y~3.0 and 3.3). The STAR collaboration has measured $T_0 TSSA$ as a function of $x_F$ and $p_T$, up to $p_T \sim 4.5$ GeV. The PHENIX experiment has measured TSSA in pion and inclusive charged hadron production as a function of $x_F$ and $p_T$ in the central and forward rapidities and confirmed previous results from other experiments. PHENIX also carried out the first unique measurements of TSSAs in open heavy quark and J/Psi production at $\sqrt{s}=200$ GeV.

At RHIC energies, the NLO pQCD calculations have been applied successfully to describe the unpolarized cross section of pion production. For the TSSA physics, two different approaches have been used to explain the observed large TSSAs in the forward rapidity: one is based on the postulated transverse momentum dependent (TMD) functions, such as the nucleon spin and parton transverse momentum correlation functions (Sivers functions) and spin dependent fragmentation functions (Collins functions), to generate the asymmetries; the other one utilizes the collinear factorization scheme and the asymmetry is generated from the initial and/or final state soft gluon interactions, the so called Twist-3 approach. Both models are used successfully to fit the observed pion TSSA $v.s. x_F$ at RHIC. However, the observed somewhat flat $p_T$ dependence of TSSA $A_N$ at high $p_T$ remains as a challenge for both TMD and Twist-3 models, as both models expect smaller $A_N$ at larger $p_T$ in the high $p_T$ region. At present, serious doubts are still lingering over the issues in QCD spin physics, such as the applicability of QCD-factorization under the current experimental conditions and the completeness of our understanding of the mechanisms that generate the transverse single-spin asymmetries. We expect future high statistic precision data from RHIC will provide a definite answer to many puzzles we have now.

2. The PHENIX experiment

The PHENIX experiment is designed for optimal measurements of rare probes \[1\]. In this report, we present the highlights of transverse spin asymmetry measurements using the PHENIX detectors at RHIC and also discuss the future plans.

2.1. PHENIX Highlights – $A_N$ at central and forward rapidity in light hadron production

PHENIX central arm detectors have excellent capability of tracking, particle identification and photon and electron energy measurements in the pseudo-rapidity range of $|\eta| < 0.35$. In 2006 and 2007, the forward Muon Piston Calorimeters (PMC) were installed to both south and north muon magnets, expanding the coverage of photon measurement to forward pseudo-rapidity $3.1 < |\eta| < 3.7$ with full azimuth. Figure 1 shows the $\pi^0$ and inclusive charged hadron TSSAs measured in the central rapidity $|\eta| < 0.35$. The results could indicate that the gluon’s contribution is small in the probed kinematic range \[2\].
The new MPC detectors measure inclusive photons in the very forward rapidity where large TSSAs were observed at lower energies and also by other RHIC experiments (BRAHMS and STAR) in light hadron productions. Very significant none-zero TSSAs have been measured in $\pi^0$ production by the MPC at lower energy of $\sqrt{s} = 62$ GeV. The results are consistent with BRAHMS and STAR observations, see Figure 2.

Figure 2. The measured $A_N$ as a function of $x_F$ in pi0 production in the forward rapidity at the center of mass energy of $\sqrt{s} = 62$ GeV.
2.2. PHENIX Highlights – $A_N$ in heavy quark production and the role of gluons

Besides the traditional light hadron probes, RHIC-Spin opens up new channels, such as heavy quark and Drell-Yan, that had never been possible in previous fixed target experiments. In particular, the PHENIX forward muon arms provide a unique probe to study the TSSA in open heavy quark and heavy quarkonium production, and in the future, the Drell-Yan production in the forward rapidity.

At RHIC energies, heavy quarks are predominantly produced via gluon-gluon interaction. Since gluon has zero transversity thus no Collins effect, we expect heavy quark asymmetries are sensitive to the gluon’s Sivers function, which is currently not well constrained by DIS experiments. So open charm and beauty through high pT single muon production in the forward rapidity could be an excellent probe of the gluon’s Sivers function at RHIC. Figure 3 shows the first measurement of TSSA in inclusive prompt muon production as a function of muon pT in the forward rapidity $1.4 < \eta < 1.9$. Although statistically limited, the data already put a constraint on the gluon’s Sivers function and excluded the maximum gluon Sivers function scenario. The blue curve corresponding to the open charm prompt muon $A_N$ with maximum gluon Sivers function. It should be noted that the measured prompt muons come from both open charm and open beauty contributions. With upgrade silicon vertex detectors, it is possible to separate these two contributions in the future.

Transverse spin physics could also provide new information about QCD dynamics. It is proposed recently that the TSSA of J/psi is sensitive to J/Psi’s production mechanisms\[3\]. In p+p collisions, if J/Psi is produced via color octet channel, the initial and final states effects will cancel each other, as a results, the TSSA will be zero. However, if the production is dominated by color singlet channel, we could have none zero $A_N$. The situation is opposite in the polarized DIS process. It is nice to see that transverse spin physics could have an impact on a much broader aspects in QCD study. The PHENIX preliminary results from Run6 are statistically limited to draw any strong conclusion, but these combined with Run8 results will provide much improved constraint.

![Figure 3](image.png)

Figure 3. Left: At RHIC, heavy quarks are predominantly produced by gluon-gluon interaction. Right: measured prompt muon $A_N$ as a function of pT in the forward rapidity $1.4 < \eta < 1.9$.

It is also important to note that the physics of TSSA in the gluonic sector could be more complicated and interesting. In the TMD approach, there is only one gluon Sivers function that could contribute to TSSA, thus, in the open charm production, both charm and anti-charm are expected to have identical TSSA $A_N$. However, the Twist-3 approach, there are two independent tri-gluon functions that could generate TSSAs, and depending on how these two functions coupled to quark and anti-quark, TSSAs could be very different in open charm and anti-charm production\[4\], see Figure 4.
Figure 4. Twist-3 model calculations of the TSSA as a function of rapidity for $D^0$ and $\bar{D}^0$-bar production in p+p collisions at $\sqrt{s}=200$ GeV. Different from TMD model where is only one gluon Sivers function, in the Twist-3 approach, the two independent tri-gluon functions could yield quite different TSSAs in charm and anti-charm production, a distinct experimental signature that can be tested at RHIC in the future.

2.3. Future Transverse Physics with PHENIX upgrade detectors

With upcoming detector upgrades for both PHENIX and STAR experiments and expected much improved accelerator performance, RHIC-Spin program will provide a great opportunity for new studies of polarized nucleon structure and the QCD dynamics. The silicon vertex detectors in PHENIX will allow us to cleanly identify and separate leptons from heavy quark and Drell-Yan decays. A lepton from a heavy quark (or light hadron) decay normally has a significantly displaced secondary vertex from the primary interaction point, while leptons from Drell-Yan process are prompt, see Figure 4.

Figure 4. PHENIX Silicon vertex detectors will precisely measure the impact parameter of a lepton to the primary collision vertex point and identify a lepton from long-lived light hadron (pion), short-lived open heavy quark and prompt Drell-Yan decay.

The future Drell-Yan $A_N$ measurement is particularly important at RHIC\textsuperscript{[5]}. There is a fundamental prediction of QCD that $A_N$ of Drell-Yan should have an opposite sign of the $A_N(p^\tau)$ observed in the polarized DIS experiment. See Figure 5. Its verification or disproval will be an important milestone in our understanding of QCD spin physics.
We expect the future high precision measurements of open heavy quark, J/Psi and Drell-Yan transverse SSAs will shed new light on our understanding of the origin of TSSAs, nucleon structure as well as the QCD dynamics, and could have a strong impact on the future EIC physics program.

3. Conclusion and outlook

The PHENIX experiment at RHIC has produced exciting physics results with transversely polarized proton beams. Significant none-zero asymmetries have been observed in the forward rapidity in $\pi^0$ production; in the middle and backward rapidities, the asymmetries are consistent with zero within experimental uncertainty in light hadron productions. PHENIX has also produced the first measurements of open heavy quark and J/Psi TSSAs in the electron and muon channels, and much improved measurements are expected with the upgrade silicon vertex detectors in the near future. Currently the PHENIX silicon vertex detector upgrade projects are in good progress, and part of the detectors will be installed as early as 2011. PHENIX upgrades also open up new physics opportunity, such as the Drell-Yan TSSA measurement that could provide a crucial test of a new fundamental prediction of QCD.

With upcoming detector upgrades for both PHENIX and STAR experiments and expected much improved accelerator performance, RHIC-Spin program will provide a great opportunity for new studies of polarized nucleon structure and the QCD dynamics.

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