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Measurement of proton spin structure at RHIC-PHENIX

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Abstract. As the first polarized proton proton collider, RHIC provides a unique opportunity to address the spin components of the proton. Unlike deep inelastic scattering experiments, the gluon is the main player in $p+p$ collisions. The PHENIX detector is with relatively small acceptance, but with excellent particle identification capability and a fast data acquisition system. The primary goal of the PHENIX spin program is to measure the gluon spin component of the proton. In addition, there are a transverse spin physics program and a spin flavor decomposition program using the parity violating process. In this article, recent progress in PHENIX are presented.

Keywords: proton spin, polarized proton collisions
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1. Introduction

Proton is the most fundamental hadron with spin-half (in units of $\hbar$). It's a natural question how this proton spin is composed. In the past few decades, deep inelastic scattering experiments has led this field. The quark component are relatively well established. But in virtue of the electro-magnetic interaction, the gluon component (ΔG) is hard to access.

The primary goal of the spin program at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is to investigate the gluon spin component using polarized proton proton collider. Other two major topics are the transverse spin structure and (anti-) quark flavor decomposition with the parity violating process.

Since 2001, the RHIC performance has been improved. The major data sets accumulated by the PHENIX detector [1] are $\sim$ 10/pb for both longitudinal and transverse spin programs with the collision energy at $\sqrt{s} = 200$ GeV. The polarization has been achieved up to almost 60%.

2. Preparations for spin measurements

The most sensitive way to measure the spin effect is to measure the asymmetry between different spin configurations. At RHIC, an alternative spin direction every bunch (100ns cycle) minimizes the time dependent systematics of the detectors. Unlike most DIS experiments performed in the fixed target regime, the perturbative QCD (pQCD) is believed to work in high four-momentum transfer squared, Q^2. The measurement of unpolarized cross section is a confirmation of our theory baseline. We measured the cross section of π^0's [2] and direct photons [3] in the mid-rapidity region and both data are explained well by Next to leading order pQCD calculations. The factorization is one of our key elements to connect an asymmetry measured in the experiment with the spin components in the proton.

3. Longitudinal spin structure

To measure the gluon spin component in the proton, we started to measure double spin asymmetries (A_{LL}) in π^0 production. The partonic subprocess under π^0's production is dominated by (gluon+gluon) and (gluon+quark) in low p_T region ($p_T <\sim 15\text{GeV}/c$), and π^0's have an advantage in statistics and the PHENIX detector is suitable to collect the events with the trigger based on energy deposit in the electro-magnetic calorimeter. Figure 1(a) shows the measurement of A_{LL} in π^0 production. The uncertainty is down to 0.1%. The gray band in the inset shows our systematical uncertainties which is mainly come from the relative luminosity determination. The scale uncertainty of 8.3% from the absolute polarization measurment is not shown in the plot. To extract the ΔG from the A_{LL} measurement, a model which determines the shape of the gluon helicity distribution as a function of the gluon momentum fraction x, $\Delta g(x)$, is used. Based on the model, the A_{LL} curve as a function of p_T is extracted for each ΔG ($\equiv \int \Delta g(x)dx$) value. For a certain ΔG value, a χ^2 is calculated by comparing the curve with the measurement. Figure 1(b) shows the χ^2 for different ΔG values. Dotted lines and dashed lines show the χ^2 with range of uncertainties of the relative luminosity and the absolute polarization value. From the χ^2 distribution, we found $\Delta G_{GRSV}^{x=[0.02,0.3]}(\mu^2 = 4GeV^2) = 0.2 \pm 0.1(1\sigma)$ and $0.2^{+0.2}_{-0.8}(3\sigma)$ with an additional systematic uncertainty of ± 0.1. A scenario of large gluon polarization in the proton is excluded. It indicates small ΔG value, but the best fit value from various DIS experimental results are not totally excluded. The reason of a poor determination in the negative gluon polarization (anti-aligned to the proton spin) is because the gluon polarization comes into A_{LL} through the square due to dominant (gluon+gluon) subprocess in low p_T π^0's production.

Ideally, the direct photon process is the golden channel to probe gluon's. The main partonic subprocess is (gluon + quark) and no fragmentation function is necessary, which is much simpler than the case of π^0's. We have a preliminary result of the A_{LL} of the direct photon production shown in Fig.2. However this channel is suffered by vast background from π^0 decays in low p_T region, which reduces the statistical significance. As we go to higher p_T, the situation gets better, and

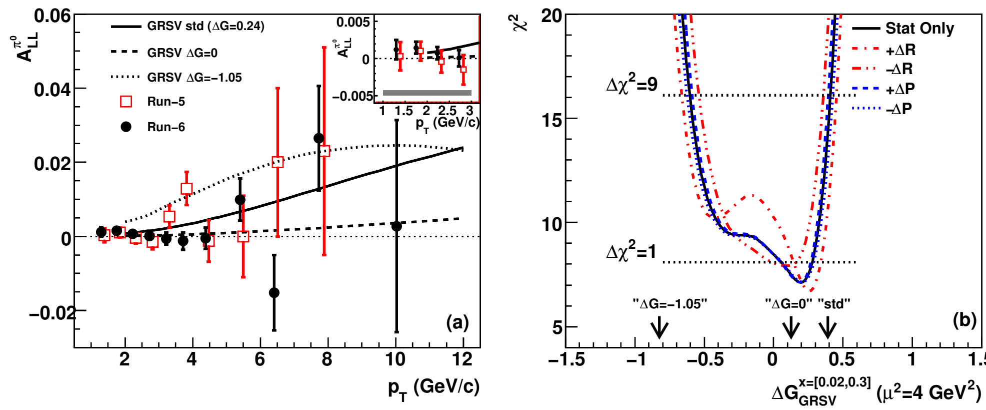

Fig. 1. (a) Asymmetry in π^0 production as a function of p_T. Error bars are statistical uncertainties. An 8.3scale uncertainty due to the uncertainty in beam polarization is not shown. The p_T independent uncertainty of 7×10^{-4} due to relative luminosity is shown only in the inset as a shaded bar. For comparison, we also show our Year-2005 result. NLO pQCD expectations based on different inputs for ΔG in the GRSV parameterization are plotted. (b) The χ^2 profile as a function of $\Delta G_{GRSV}^{[0.02,0.3]}$ using the combined Year-2005 and Year-2006 data considering only statistical uncertainty, or also varying by $\pm 1\sigma$ the two primary experimental systematic uncertainties, from beam polarizations ($\pm\Delta P$) and relative luminosity ($\pm\Delta R$).

the isolation cut works effectively to isolate the direct photon productions. More integrated luminosity is required for this channel.

Other inclusive channels like $\pi^{\pm}$, η, and charm particles are also informative because of different subprocesses involved.

The inclusive measurements are suitable for PHENIX, with a relatively small acceptance, but with a high rate data acquisition system. There are two major issues in inclusive measurements. The first one is there is essentially no power to determine the x dependence. The p_T of the particle is a representative of the parton x, but as shown in Fig. 3, it spreads widely. The second is the statistical uncertainty is so small that we almost reach to the systematical limit. The major systematics comes from the determination of the relative luminosity. It is originated from beam bunch characteristics. One way to reduce this systematics is to flip the spin direction in the middle of the store, so that each bunch keeps its characteristics but spin direction. This equipment is under development in 2009.

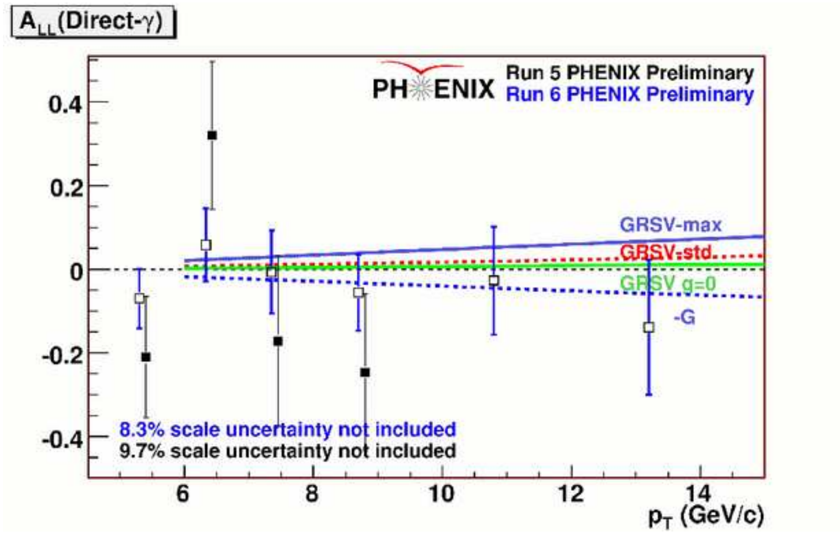

Fig. 2. Double helicity asymmetry (A_{LL}) of direct photon production from Year-2005(Run5) and Year-2006(Run6) data. The curves are theory calculations.

4. Transverse spin structure

The transverse spin structure of the proton is not a simple rotation of the longitudinal spin structure in the relativistic frame. Although there are several attempts to get a global picture involving both longitudinal and transverse, those topics are separated for now. At PHENIX, they are identified by the collision mode. The natural collision mode of the circular ring is transverse (vertical). It gets longitudinal direction with the spin rotators activated. The discovery of unexpected single spin asymmetry in reasonably high energy $p + p$ collisions [4] motivated to develop two main mechanisms : Sivers mechanism and Collins mechanism. At PHENIX, we are at the stage of collecting evidences of various single transverse spin asymmetries.

We observe a finite left-right single spin asymmetry (A_N) in π^0 production detected by the muon piston calorimeter (MPC). The MPC is located at the forward region ($3.1 < |\eta| < 3.7$). Figure 4 shows the A_N at the energy of $\sqrt{s} = 62.4$GeV. The magnitude of the asymmetry is as high as 10% at higher x_F region. Although the collision energy is different, the behavior and magnitudes of the asymmetry look similar to the previous experimental results.

Figure 5 shows the A_N of neutral pion's and charged particles in the mid-rapidity region. They are consistent to zero within 1% level. Since gluon's are dominant origin in the production and gluon's do not carry the transversity, this measurement constrains the size of the gluon Sivers [5]. PHENIX accumulated a large amount of data in 2008. We expect to set more precise limit on the gluon Sivers.

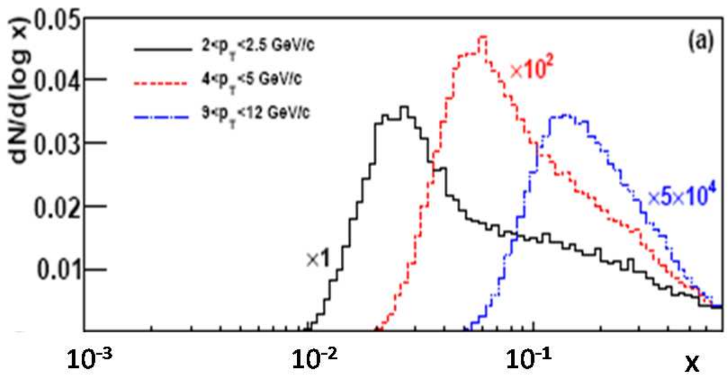

Fig. 3. Distribution of gluon x in three π^0 p_T bins from a NLO pQCD simulation.

The charm production is another good channel to probe the gluon Sivers. In J/ψ production, it is proposed that we can check its production mechanism if the gluon Sivers effect is non-zero [7].

The transversity effects possibly come out by being coupled with the interference fragmentation function (IFF) asymmetry. It was suggested a phase change in the invariant mass of two hadrons at the mass of ρ [6]. Figure 6 shows the measurement of $A_{UT}^{sin(\phi)}$ from Year-2006 data. In the central arm with radial transverse spin collision, $A_{UT}^{sin(\phi)}$ refers roughly the amplitude of sine ϕ modulation of two particle production; the ϕ is the angle of the plane made by two particles (the sign is determined as more charge to less charge particle.) to the horizontal plane. The result is consistent to zero within our statistical uncertainty.

In di-jet production, the quark and gluon Sivers effect introduces non-zero k_T with respect to the spin direction. However it was mentioned there is a possible cancellation between initial and final state interactions, or between u-quark and d-quark [8]. By choosing particular processes, like Drell-Yan (DY) or gamma-jet, it is able to avoid the cancellation effect. In DY process, the Sivers effect is predicted to appear with the opposite sign to the one seen in semi inclusive DIS experiments [9]. An alternative way to the DY process which requires a lot of integrated luminosity is proposed using the gamma-jet production [10]. With the gamma, we can avoid the final state interactions. This is one of topics of the PHENIX forward detector upgrade program.

5. Flavor separation (W boson program)

The parity violating process is a unique way to enable the quark flavor separation. In leading order, the sign of W-boson tells the original partonic process whether it is $(u+\bar{d})$ or $(d+\bar{u})$, and $\bar{u}$ and $\bar{d}$ have a positive helicity. So from the longitudinal

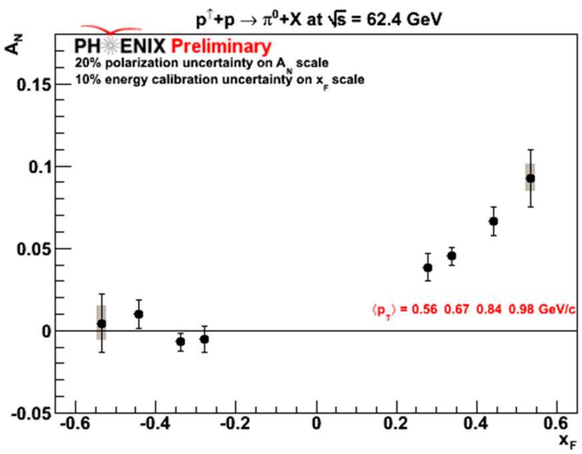

Fig. 4. Single transverse left-right asymmetries (A_N) of π^0 measured by the muon piston calorimeter in $\sqrt{s} = 62.4$GeV $p + p$ collisions.

single spin asymmetry (A_L), we can access to the spin component for each quark flavor. Compared to semi inclusive DIS experiments, the advantage of this approach is it doesn't rely on the fragmentation function. PHENIX detects a lepton from W-boson decay. In the forward muon arm, a new trigger system is required. The upgrade will be completed by 2011. In the central arm, the detectors and triggers are ready to collect electrons from W-boson. In 2009, RHIC provided the first 500GeV polarized $p + p$ collisions for this program. Data were successfully taken. PHENIX will show a proof of principle.

6. Other observable related to the spin

There are many other spin related observables. The Λ is a unique tool to analyze the spin transfer because of its self analyzing decay. J/ψ may work in a similar way. The difficulty in Λ's is they are hard to trigger with a simple electro-magnetic calorimeter based logic. A di-jet k_T difference in double helicity collisions may probe an angular momentum component in the proton. Currently our measurement shows no difference. A theoretical interpretation is necessary. In the very forward neutron production, the left-right single spin asymmetry (A_N) is measured [11].

7. Summary

In the longitudinal spin program, the primary goal is to find the gluon spin component in the proton. For now, the measurement indicates that the gluon carries

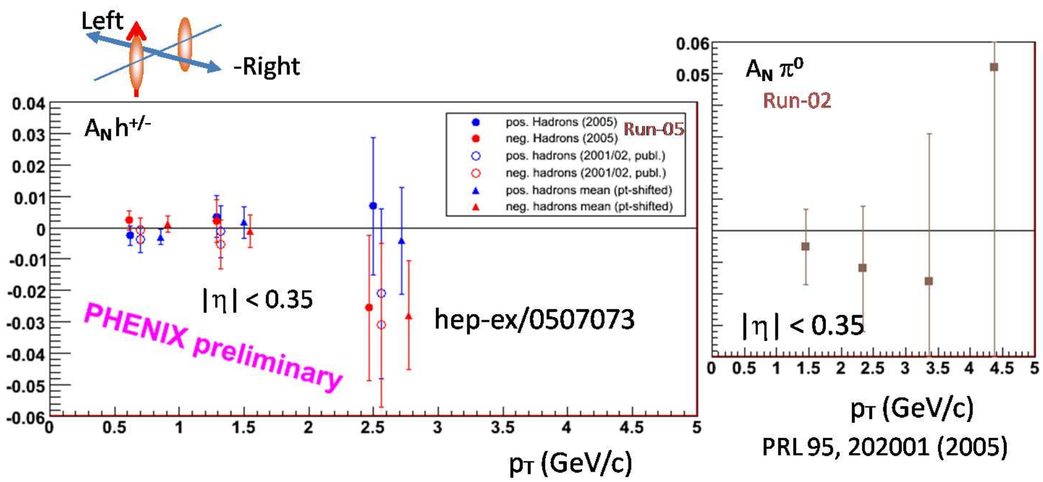

Fig. 5. Single transverse left-right asymmetries (A_N) of charged hadrons and π^0's measured by the central arms in $\sqrt{s} = 200$GeV $p + p$ collisions.

only a small fraction of the missing spin component. But the standard scenario is not ruled out statistically. PHENIX measurement is limited in a relatively large x region (0.02 to 0.3), and is insensitive to the shape of polarized PDF. In the transverse spin program, experimental results leads the field. For a few years, we need to collect more evidences on the table. The W-boson program (single longitudinal asymmetry in $\sqrt{s} = 500$GeV) is about to start. It provides a unique way to access the spin flavor decomposition. There are many other observables related to the spin. We may find unexpected results.

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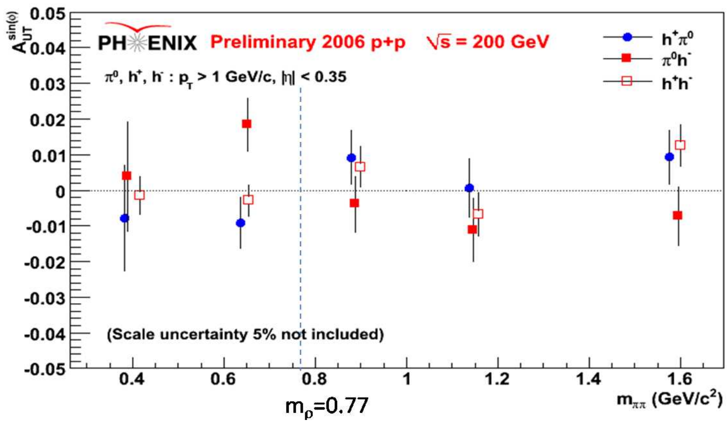

Fig. 6. The size of sine modulation of interference fragmentation as a function of the invariant mass of two hadrons measured by the central arms in $\sqrt{s} = 200$GeV $p + p$ collisions.

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