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Highlights from PHENIX transverse spin program at RHIC

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Summary. — In recent years, there has been exciting development in both experimental and theoretical studies of transverse spin phenomena in high energy polarized p+p and polarized DIS collisions. In the p+p frontier, the polarized p+p collider at RHIC provides a unique opportunity to investigate the novel physics that causes the large spin effects seen in the transversely polarized p+p collisions over the past 30 years, particularly in the forward rapidity. Since the beginning, PHENIX has been conducting a very active transverse spin physics program to study Sivers, Collins and other novel spin effects at RHIC, including measurements of transverse single spin asymmetry (TSSA) in light and heavy quark productions, leading neutron TSSA in the very forward rapidity, and di-hadron (and "jet") spin correlations in a wide kinematics range, just to name a few. In 2012, PHENIX collected transversely polarized 200 GeV p+p data with a record high luminosity of $9.24\,\text{pb}^{-1}$, with an average beam polarization of 58%. In this talk, I highlight the recent results from the PHENIX experiment, and also briefly discuss the near-term prospects of new transverse spin measurements only possible with the latest (forward) silicon vertex detectors, (F)VTX, and the upcoming forward MPC-EX upgrade detectors.

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1. – Introduction

Spin has been playing a key role in our understanding of fundamental interactions since the day it was postulated. Spin dependent observables have historically produced surprising results and provided a stringent test to theories of particle interactions. Today, we are still facing with two longstanding puzzles in spin physics: First, the challenge of "Too-Small", *i.e.*, the well know missing nucleon spin puzzle. In early days, it was believed that the spin of the proton were dominantly 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 still remains a major challenge to our understanding of the nucleon structure, and is under extensive experimental and theoretical investigation today. There are several candidates that could make up the difference, such as the contributions from gluons spin and/or the quark and gluon orbital angular momentum; Second, the challenge of "Too-Big", *i.e.*, the unexpectedly large transverse left-right single spin asymmetries (A_N) observed in transversely polarized high energy p+p (and e+p) collisions. Prior to the early Fermilab E704 experimental measurements, it was believed based on naive pQCD arguments that transverse single spin asymmetry should be very small in high-energy p+p collisions, $A_N \sim m_q/\sqrt{s} \sim 10^{-3}$, while the experimental data showed that the asymmetry is as large as $\sim 40\%$. It is interesting to note that these two puzzles could be closely related if there is significant parton orbital motion inside the proton.

Since the beginning of RHIC operation, several interesting large transverse single spin asymmetries have been discovered [1]. All three RHIC-spin experiments (BRAHMS, PHENIX and STAR) 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 ($y \sim 3.0$ and 3.3). The STAR collaboration has measured π^0 and η TSSA as function of x_F and p_T. The PHENIX experiment has measured TSSA in pion and inclusive charged hadron production as function of x_F and p_T in the central, forward and backward rapidities. PHENIX has also carried out the first exploratory measurements of TSSAs in open heavy quark and J/ψ production at $\sqrt{s} = 200\,\text{GeV}$.

2. – The PHENIX experiment

The PHENIX experiment is designed for optimal measurements of rare probes [2]. Here we highlight the latest transverse spin physics studies from the PHENIX experiment at RHIC.

2·1. *PHENIX Highlights (I): A_N in central and forward rapidities in light hadron productions.* – PHENIX central arm detectors have excellent capability of charged particle 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 Calorimters (MPC) were installed to both south and north muon magnets, expanding the coverage of photon measurement to forward and backward pseudo-rapidity $3.1 < |\eta| < 3.9$ with full azimuth. Significant TSSAs have been observed in the forward rapidity with MPC detectors in transversely polarized p+p collisions. Figure 1 show the π^0, η and inclusive Electromagnetic cluster (mostly from π^0 decays) TSSAs measured in the forward rapidity $3.1 < \eta < 3.9$ by MPC detectors.

To explain the observed large TSSAs in the forward rapidity in p+p and DIS collisions, two independent theoretical approaches have been developed: one is based on the postulated transverse momentum dependent (TMD) functions. In this model, the asymmetry is generated by the correlation functions of nucleon spin and parton transverse momentum (Sivers functions) and/or spin dependent fragmentation functions (Collins functions); 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 *vs.* x_F at RHIC.

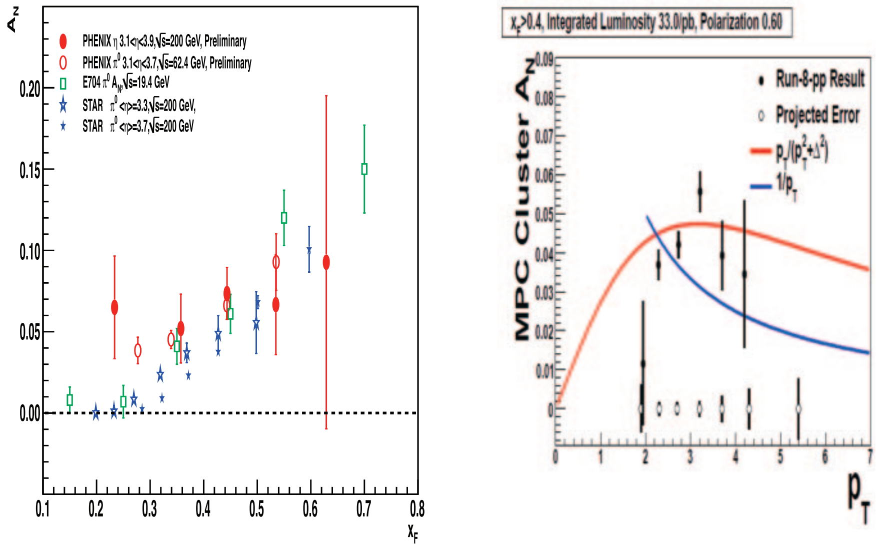

Fig. 1. – Transverse single spin asymmetry of π^0 as a function of Feynman-x (left) at various center-of-mass energies, from fixed target to RHIC experiments; and TSSAs for EM clusters (mostly π^0) as a function of cluster p_T measured by the PHENIX experiment in the forward rapidity (right).

At RHIC energies, unlike in the previous fixed target low energy experiments, the NLO pQCD calculations have been applied successfully to describe the unpolarized cross section of pions and jet production, and the collinear Twist-3 approach is expected applicable to RHIC spin asymmetry observables. However, here for the inclusive forward hadron productions, various underlying mechanisms, including the Sivers and the Collins effects, can contribute and need to be disentangled to understand the experimental observations in detail, in particular the p_T-dependence. 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. At present, serious doubts are still lingering over the issues in 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 large transverse single-spin asymmetries. We expect future high precision data from RHIC will provide a definite answer to many puzzles mentioned above.

2·2. *PHENIX Highlights (II): A_N at forward rapidity in heavy hadron production.* – Besides the light hadron probes, PHENIX also has an excellent capability to measure rare probes, such as heavy quarks and direct photons, 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 via muon channels, and in the future, the Drell-Yan production in the forward rapidity.

Heavy quarks are predominantly produced via gluon-gluon interaction in p+p collisions at RHIC energies. Since gluon has zero transversity thus no Collins effect, a nonezero heavy quark asymmetry is a sensitive probe to the gluon Sivers functions, which is not well constrained by current experimental data. Measurements of open charm and

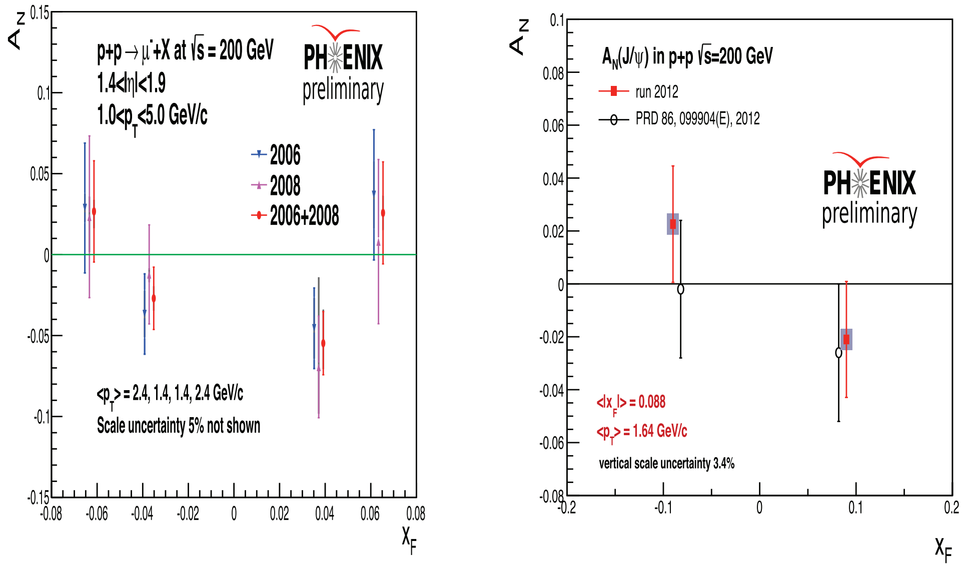

Fig. 2. – Transverse single spin asymmetry measured for muons (μ^-) from open heavy quark (left) and J/ψ (right) decays as function of muon's Feynman-x.

open beauty through high p_T single muons in the forward rapidity could be used to study the gluon Sivers functions. Figure 2 show the first measurements of TSSA in inclusive prompt muon (mostly from open charm decays) as a function of muon $x_F = p_z/2\sqrt{s}$ in the forward and backward rapidities $1.4 < |\eta| < 1.9$. Although statistically limited, the data already put a constraint on the gluon Sivers function and excluded the maximum gluon Sivers function scenario. Due to detector limitations, current open charm measurements are limited to μ^- only. We expect the latest (forward) silicon vertex upgrade detectors (F)SVTX that were completed in 2012 will allow us to carry out a much improved measurements of both μ^+ and μ^- (mostly from charm and anti-charm decays, respectively) TSSAs. It is worth to note that for charm and anti-charm, TSSAs could be significantly different as suggested by Kang [3] and Koike [4] *et al.*

Also it was realized only recently that transverse spin asymmetry could be used to study QCD dynamics in particle production, for *e.g.*, the long standing puzzle over J/ψ production mechanisms. It was proposed by Yuan [5] that the TSSA of J/ψ is sensitive to J/ψ production mechanisms. For *e.g.*, in p+p collisions, if J/ψ is produced via color octet channel, the initial and final states effects will cancel each other, and as a results, the TSSA will be zero. However, if the production process is dominated by color singlet channel, one could have none-zero A_N. The situation is opposite in the polarized DIS process. Figure 2 show the latest PHENIX results of J/ψ A_N from Run6, Run8 and Run12 data sets [6]. The data are currently statistically limited to draw strong physics conclusion, but we expect future high luminosity runs will provide much improved constraint.

2·3. *Future transverse spin physics in PHENIX*. – With the latest PHENIX upgrade detectors and expected much improved accelerator performance, RHIC-Spin program will provide a great opportunity for new studies of polarized nucleon structure and the

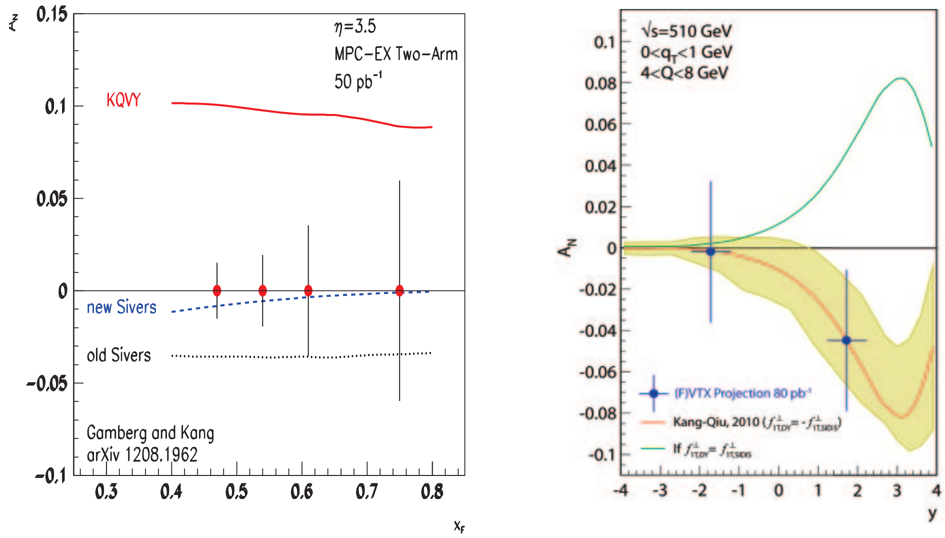

Fig. 3. – Projected transverse single spin asymmetry measurements of direct photon (with MPC-EX) and Drell-Yan (FVTX dimuons) in the forward rapidity.

QCD dynamics. The PHENIX experiment just completed the (forward) silicon vertex detectors upgrade in 2012. These new precision silicon vertex detectors will allow us to cleanly identify and separate leptons, for the first time, from heavy quark and Drell-Yan decays: a lepton from a heavy quark (and light hadron) decay normally has a significantly displaced secondary vertex from the primary interaction point, while leptons from Drell-Yan process are prompt.

PHENIX is also in a process of upgrading the forward calorimeters (MPC-EX upgrade) with preshower detectors that will allow the identification of direct photons and neutral pions up to energies of 80 GeV at $3.1 < |\eta| < 3.9$. Figure 3 show the projected experimental sensitivities of direct photon and Drell-Yan Sivers asymmetries.

The future Drell-Yan TSSA A_N measurement is particularly important at RHIC [7]. There is a fundamental prediction of QCD that A_N of Drell-Yan should have an opposite sign of the A_N observed in the polarized DIS experiment, see fig. 3, the green curve in the right-hand plot corresponds to Drell-Yan A_N if the sign does not change with respective to the DIS results. Its verification or disproval will be an important milestone in our understanding of QCD dynamics in spin physics.

3. – Conclusions 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 π^0, η and leading neutron productions; in the middle and backward rapidities, the asymmetries are consistent with zero within experimental uncertainty in light hadron productions. PHENIX has also carried out the first exploratory measurements of open heavy quark and J/ψ TSSAs in the electron and muon channels, and much improved measurements are expected with the latest silicon vertex detectors that were successfully commissioned recently. The new silicon vertex detectors (F)SVTX will allow us to perform Drell-Yan measurements in the forward and backward rapidities in transversely polarized p+p collisions, and such measurement could provide a crucial test of a new fundamental prediction of QCD. The upcoming PHENIX MPC-EX upgrade that is scheduled for 2015 run, will open up new physics opportunity for high p_T π^0 and direct photon TSSAs measurements in the forward rapidity. With expected much improved accelerator performance, PHENIX Spin program will provide a great opportunity for new studies of polarized nucleon structure and the QCD dynamics.

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