The RHIC Spin Program Overview

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Abstract. After more than a decade of RHIC running as a polarized proton collider, we summarize recent achievements of the RHIC spin program and their impact on our understanding of the nucleon’s spin structure, i.e. the individual parton (quarks and gluons) contributions to the helicity structure of the nucleon, and to understand the origin of the transverse spin phenomena. Open questions are identified and a suite of future measurements with polarized beams at RHIC to address them is laid out.

1. Introduction
This presentation is majorly based on our recently published paper [1], where we summarized the achievements of the RHIC spin physics program for more than a decade of RHIC operation as a polarized proton collider, and outlined the near and longer term plans and experimental upgrades to further advance spin studies at RHIC.

One of the main goals of the RHIC spin program has been the studies of different contributions to the proton spin 1/2, for which it was found from the previous experiments that only small fraction can be attributed to the spins of quarks and anti-quarks. Another set of puzzles is associated with transverse spin effects, which can not be explained by collinear perturbative QCD (pQCD) at leading twist, which requires extension of the theory to higher twist (multi-parton correlations), or introduction of transverse momentum dependencies correlated with nucleon or parton spin. Parton transverse momentum distributions correlated with proton spin are connected with parton orbital momentum in the nucleon – the least known piece in the nucleon spin decomposition at the moment.

2. Helicity Structure of the Proton
The spin structure of the proton has been measured since 1980s in polarized lepton-nucleon deep-inelastic scattering (DIS) experiments, which revealed that only ~1/3 of the proton spin can be attributed to the spins of quarks and anti-quarks [2] indicating that the proton spin must be largely carried by the spin of the gluons and/or orbital angular momentum of the quarks and gluons. Since then, the main goal of spin physics has been to elucidate the role of gluon spin ($\Delta g$) as well as flavor separated contribution of quark and anti-quark spin ($\Delta q$ and $\Delta \bar{q}$) in the proton spin. Getting access to the orbital angular momentum remains a challenging task from both theoretical and experimental point of view, which will be a major part of the new 12 GeV program at Jefferson Laboratory and at future Electron-Ion Collider. DIS experiments have been providing data to constrain $\Delta g$ from the scaling violation in inclusive polarized scattering [3] and from semi-inclusive measurements of high transverse momentum ($p_T$) hadron pairs [4] and heavy flavor production [5] to utilize the photon-gluon
process. The flavor separated contribution of quarks and anti-quarks to the proton spin is determined in semi-inclusive DIS using fragmentation processes, which correlate final state hadron with quark flavor.

Polarized proton-proton collisions at RHIC provide complementary approach to study proton spin structure. Gluon-spin contribution is accessed through the hard scattering directly involving gluons. Flavor decomposition of quark and anti-quark polarization can elegantly be obtained from the measurements of $W$ bosons, which couple left-handed quarks and right-handed anti-quarks: $u_L d_R \rightarrow W^+$ and $d_L u_R \rightarrow W^-$. This approach is free of uncertainties in fragmentation functions (FF), if $W$s are measured through their leptonic decays.

2.1. Polarized gluon contribution

Gluon polarization within the proton is probed through the measurements of double helicity asymmetry, $A_{LL}$, in different production channels involving gluon dominated hard scattering processes. $A_{LL}$ is defined as the difference between cross sections for colliding bunches with the same helicity and opposite helicity, divided by the sum. The most statistically abundant channels are inclusive pion and jet production. Fig.1 and 2 show the recent updates for $\pi^0$ and jet production.

![Figure 1](image1.png)

**Figure 1.** $A_{LL}$ vs. $x_T$ for inclusive $\pi^0$-mesons production at mid-rapidity in $p+p$ collisions at $\sqrt{s}=200$ GeV [9] and 510 GeV [10], compared to predictions from three recent NLO global analyses [11,12,8] (blue curves for $\sqrt{s}=200$ GeV and red curves for 510 GeV).

![Figure 2](image2.png)

**Figure 2.** $A_{LL}$ vs. $x_T$ for inclusive jet production at mid-rapidity in $p+p$ collisions at $\sqrt{s}=200$ GeV [13] and 510 GeV (preliminary), compared to predictions from three recent NLO global analyses [11,12,8] (blue curves for $\sqrt{s}=200$ GeV and red curves for 510 GeV).

Extraction of $\Delta g$ is based on a next-to-leading order (NLO) pQCD framework, which was proved to well describe RHIC unpolarized cross section data [6]. The DSSV group has found from their global analysis that the integral of $\Delta g(x,Q^2=10 \text{ GeV}^2)$ in the region $x > 0.05$ is $0.20^{+0.06}_{-0.07}$ at 90% C.L. [7], consistent with the NNPDFpol1.1 fit [8].

Despite this very important achievement, providing the evidence of sizable gluon polarization within the proton, uncertainties for $\Delta g(x)$ remain significant in the presently unmeasured small $x$ region, see Fig. 3, and prevent a reliable determination of the full integral. Fig.3 also demonstrates the expected improvement of the fit results after inclusion of the data from 2012-2015 RHIC runs (being analyzed), which include data collected in forward rapidity region at $\sqrt{s} = 510$ GeV. These data will extend the kinematic reach in $x$ towards values of a few times $10^{-3}$ where $\Delta g$ is unconstrained so far.
2.2. Polarized sea quark distribution

The production of $W^\pm$ bosons in longitudinally polarized proton-proton collisions serves as an elegant tool to access valence and sea quark helicity distributions at a high scale $Q^2 \sim M_W$ and without the need of FF as in semi-inclusive DIS. $W$ boson production, coupling left-handed quarks and right-handed anti-quarks, provide us with direct access to (anti-)quark preferred helicity state within the longitudinally polarized proton by measuring the parity violating single helicity asymmetry $A_L$. While the valence quark helicity densities are already well known at intermediate $x$ from DIS, the sea quark helicity PDFs are only poorly constrained. The latter are of special interest due to the differing predictions in various models of nucleon structure (see [14] for a review), which are all able to describe the asymmetry of the unpolarized light quark sea.

**Figure 3.** The running integral for $\Delta g$ as a function of $x_{\text{min}}$ at $Q^2 = 10$ GeV$^2$ as obtained in the DSSV global analysis framework. The inner and outer uncertainty bands at 90% C.L. are estimated with and without including the combined set of projected pseudo-data for preliminary and future RHIC measurements up to Run-2015, respectively.

**Figure 4.** $A_L$ for $W^\pm$ production as a function of lepton pseudorapidity $\eta_\ell$ measured by PHENIX [15] in comparison to theory predictions based on inclusive and semi-inclusive DIS data.

**Figure 5.** $A_L$ for $W^\pm$ production as a function of lepton pseudorapidity $\eta_\ell$ measured by STAR [16] in comparison to theory predictions based on inclusive and semi-inclusive DIS data.
Fig. 4 and 5 show the recently released results by PHENIX and STAR collaborations. STAR data covering wider rapidity range prefer $W$ decay lepton asymmetries, which are systematically larger than the theory predictions based on inclusive and semi-inclusive DIS data directly indicating more positive $\bar{u}$ helicities, while the $W^+$ asymmetries are roughly compatible with theory curves. As a consequence these results provide an indication of the flavor symmetry being also broken for the polarized light quark sea with $\Delta \bar{u}$ being positive than $\Delta \bar{d}$ being negative. A positive $\Delta \bar{u} - \Delta \bar{d}$ asymmetry would favor the chiral quark soliton model, the Pauli blocking ansatz and statistical models, while disfavoring any cloud based models. The PHENIX analysis of $W$ production through muon decays in forward region, $1.2<|\eta|<2.4$, as well as STAR analysis of the highest integrated luminosity 2013 RHIC run are ongoing. After inclusion these results in the global analysis of polarized PDFs, the considerable improvement in $u$ and $d$ helicity distributions are expected in the accessed $x$ range above 0.05. The uncertainty on the flavor asymmetry for the polarized light quark sea $\Delta \bar{u} - \Delta \bar{d}$ will be further reduced and a measurement on the $2\sigma$ level will be possible, see Fig. 6.

![Figure 6. The polarized light sea-quark asymmetry $x(\Delta \bar{u} - \Delta \bar{d})$ computed with NNPDFpol1.1 and NNPDFpol1.1+ PDFs at $Q^2 = 10 \text{ GeV}^2$, projected to data already collected at RHIC for $W$ program, compared to various models of nucleon structure (see Ref. [14] for a review).](image)

3. Transverse Spin Phenomena

Surprisingly large single-transverse spin asymmetries $A_N$ (SSA) in fixed target $pp \rightarrow \pi X$ pion production have been observed experimentally since more than 30 years ago (see e.g. [17]). $A_N$ relates to left-right asymmetry in particle production in the experiments with one beam transversely polarized colliding on unpolarized target or another beam. Measurements at RHIC have extended the observations from the fixed-target energy range to the collider regime, up to and including the highest center-of-mass energies to date in polarized $pp$ collisions. Fig. 7 summarizes the measured asymmetries in $\pi^0$ production from different experiments as function of Feynman-$x_F$.

The surprisingly large asymmetries seen are nearly independent of $v/s$ over a very wide range. To understand the observed SSAs one has to go beyond the conventional leading twist collinear parton picture in the hard processes. Two theoretical formalisms have been proposed to generate sizable SSAs in the QCD framework: transverse momentum dependent (TMD) parton distribution functions (PDF) and FF, which provide the full transverse momentum information, and the collinear quark-gluon-quark correlations at Twist-3 level in the initial state and the fragmentation process, which provide information about the average transverse momentum. At RHIC the $p_T$-scale is sufficiently large (see Fig. 8) to make a formalism using collinear quark-gluon-quark correlation functions applicable to calculate the transverse single spin asymmetries. Here, various underlying mechanisms can contribute and need to be disentangled to understand the experimental observations in detail, in
particular the $p_T$-dependence.

**Figure 7.** Transverse single spin asymmetry measurements for neutral pions at different center-of-mass energies as function of Feynman-$x$.

**Figure 8.** Transverse single spin asymmetry measurements for neutral pions at $\sqrt{s} = 500$ GeV as a function of $p_T$.

It has been shown that both initial state TMD and multi-parton dynamics (Twist-3 approach) provide equivalent descriptions of transverse asymmetries in an overlap region at intermediate transverse momenta and that the $k_\perp$ moment of a quark’s TMD Sivers function is related to the corresponding Twist-3 quark-gluon correlation function $T_qF(x,x)$ [18]. It was also found that the $k_\perp$ moment of the Sivers function, extracted from data for single-spin asymmetries in semi-inclusive deep-inelastic scattering, has opposite sign from that of $T_qF(x,x)$, extracted from single-inclusive hadron production in $pp$ collisions [19]. One of explanations of such a “sign mismatch” problem could be that Sivers effect is not dominantly responsible for the observed single-spin asymmetries in $pp$ collisions. The bigger contribution may come from either fragmentation or some other effects.

Recently, it has been proposed that in the collinear, Twist-3 factorization approach a significant portion of the sizable inclusive pion asymmetries seen at forward pseudorapidity is due to Twist-3 FFs coupled to transversity [20]. This calculation is the first one which showed, similar to the experiment, a flat $p_T$-dependence for $A_\chi$ (Fig. 8).

Another interesting observation from RHIC is $A_\chi$ for “electromagnetic” jets (jets with its energy measured only in the electromagnetic calorimeter) in the pseudo-rapidity range $2.5<\eta<4$, see Fig.9. With increasing number of photons in the “electromagnetic jet” (increasing “jettiness” of the event) the asymmetry becomes smaller. Jets with an isolated $\pi^0$ have the largest asymmetry consistent with the asymmetry in inclusive $\pi^0$ events. Also, requiring an additional correlated away-side jet the asymmetry for isolated forward $\pi^0$ mesons becomes smaller. These observations indicate that the underlying subprocess causing a significant fraction of the large transverse single spin asymmetries in the forward direction may be of diffractive nature.

The main goal of the further RHIC-Spin program is to disentangle the different processes responsible for the large $A_\chi$ asymmetry in $pp$ collisions. We identify jet, direct photons, heavy flavor, and also $W, Z$ boson and Drell-Yan measurements as ones sensitive to initial state effect and described by Sivers/Twist-3 parton correlation functions. Final state effects can be probed through hadron azimuthal asymmetry within a jet, coupling transversity to TMD Collins FF [21], and hadron pair azimuthal asymmetry coupling transversity to the so-called “interference fragmentation function” (IFF) [22] in the framework of collinear factorization. Diffractive processes will be identified using Roman Pots by tagging one or both scattered protons. The first data with Roman Pots installed for STAR experiment was collected in RHIC 2015 run.
Studying Sivers effect in pp collisions is of particular interest due to its fundamental role for testing our understanding of QCD factorization. It was predicted that due to initial or final state effects from gluon exchange, Sivers function is not universal in different processes [23]. Very interesting prediction comes for the comparison of Drell-Yan production and semi-inclusive DIS, for which the Sivers function is predicted to have opposite sign [24]. The other channels like W and Z boson production also show high sensitivity to the predicted sign change. The first data on W and Z AN from the limited data sample was already released by STAR [25]. A factor of 15-30 more data is expected from the dedicated RHIC run in 2017.

Transverse single spin asymmetries in direct photon production provide a different path to access this sign change through the formalism utilizing the Twist-3 parton correlation functions. For the 2015 polarised pp run both PHENIX and STAR installed preshowers in front of their forward electromagnetic calorimeters. The collected data in 2015 RHIC run will enable a measurement of the SSA for direct photons.

Measurements of Collins and IFF asymmetries give us access to transversity distribution, which is currently poorly known. Fig. 10 and 11 show the first observation of non-zero Collins and di-hadron asymmetries in pp collisions. While the measurements of transversity through the Collins FF need TMD factorization to hold in pp scattering, di-hadron asymmetries utilize collinear factorization. Thus, not only can more precise measurements of these effects in pp improve our knowledge of transversity, such measurements are/will be invaluable to test the longstanding theoretical questions, such as the magnitude of any existing TMD factorization breaking.

Colliding of transversely polarized protons with nuclei at RHIC opens a new avenue in both spin and heavy ion physics. Kang and Yuan [26] showed that comparison of AN measurements in p+A and p+p collisions may be sensitive to gluon saturation effects in nuclei. First data from p+Au and p+Al collisions were already collected by both PHENIX and STAR collaborations in 2015, and the results are expected soon.

Data from RHIC 2015 run also allowed extending the forward neutron AN measurements from p+p to p+Al and p+Au collisions. An unexpected A-dependence of the asymmetry was observed [27], which awaits for theoretical interpretation.
Figure 10. $A_{UT}^{\sin(\phi_k-\phi_\ell)}$ vs. $z$ for charged pions in jets at $0 < \eta < 1$ from $p+p$ collisions at $\sqrt{s} = 200$ GeV and 500 GeV by STAR.

Figure 11. $A_{UT}^{\sin\phi}$ as a function of $M_{\pi^+\pi^-}$ (upper panel) and corresponding $p_{T\pi^+\pi^-}$ (lower panel), at $\sqrt{s}=200$ GeV and 500 GeV by STAR for $-1 < \eta < 1$.

4. Future upgrades
Both collaborations, PHENIX and STAR, are actively developing their future upgrade programs, with the main focus on forward capabilities. STAR collaboration plans to construct Forward Calorimeter System and Forward Tracking System. PHENIX collaboration initiated even more ambitious project. The current PHENIX detector setup will be decommissioned in 2016, and a new detector system will be built based on superconducting solenoid from the decommissioned BaBar experiment at SLAC, with electromagnetic and hadronic calorimetry and tracking in the barrel region $-1<\eta<1$. The open geometry of the detector allows for the addition of a forward spectrometer, covering $1<\eta<4$, and consisting of hadronic calorimeter and tracking system. Part of the current PHENIX detector systems (e.g. forward silicon tracker and muon identification systems) will be re-used in the new detector setup.

The suggested physics program centers on a comprehensive set of measurements of jet, hadron and Drell-Yan lepton pair production in transversely spin-polarized $p+p$ and $p+A$ collisions, with the emphasis on low and high region of Bjorken $x$, exploiting the unique capability of the RHIC collider to provide beams of protons with high polarization in addition to a variety of unpolarized nuclear beams.

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