Longitudinal Spin Physics at RHIC and a Future eRHIC

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Recent highlights from the spin program at the Relativistic Heavy Ion Collider (RHIC), focusing on the gluon contribution to the proton spin and the polarization of the light flavor sea, are presented. The impact of these data on recent global fits by the DSSV and NNPDF groups is also discussed. Finally, this note examines the constraints on the longitudinal spin structure of the proton which would be possible with a proposed eRHIC facility.

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1 Introduction

Although Quantum Chromodynamics (QCD) has been the accepted theory of strong interactions for over forty years, many of its aspects remain poorly understood. For example, it is still not clear how the dynamic interactions between the fundamental units of QCD, quarks and gluons, give rise to the observed spin of the proton. There is a similar lack of understanding about the mechanism which is responsible for the generation of the ‘sea’ of light flavor quarks and anti-quarks inside the proton. These puzzles have motivated a number of theoretical and experimental efforts, including the spin program at the Relativistic Heavy Ion Collider (RHIC).

These proceedings will detail recent results from the two main experiments at RHIC, STAR and PHENIX, which give insight on the puzzles presented above as well as present future plans. Section 2 focuses on the latest constraints from RHIC on the intrinsic gluon spin contribution to the proton’s helicity and section 3 details recent W boson results, which provide a unique probe of the polarized sea quark distributions. Section 4 briefly discusses the impact that a future upgrade to RHIC (eRHIC), in which one of the proton/ion rings is replaced with an electron ring, could have on our understanding of the proton spin structure. Finally, a summary will be given in Section 5.

2 Gluon Contribution to the Proton Spin

The proton spin can be decomposed into contributions from the quark and gluon helicities and the orbital angular momenta of these partons:

\[ < S_p > = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L \]

\[ \Delta \Sigma = \int_0^1 (\Delta u + \Delta d + \Delta \bar{u} + \Delta \bar{d} + \ldots) dx \]

\[ \Delta G = \int_0^1 \Delta g(x, Q^2) dx \]

where \( \Delta \Sigma \) is the contribution from the spins of the quarks and anti-quarks, \( \Delta G \) is the contribution from the gluon spin, and \( L \) is the contribution from angular momentum from the partons.

Fixed-target polarized deep inelastic scattering (DIS) experiments have shown that quark and anti-quark helicities contribute roughly 30% to the spin of the proton in the range \( 0.001 \leq x \leq 1.0 \) [1]. This finding naturally lead to the question of how the remaining sources of angular momentum, the gluon helicity and parton orbital
angular momenta, contribute to the proton spin. The orbital angular momenta of the various partons is difficult to access experimentally and won’t be discussed further, but information about the gluon helicity contribution can be obtained by measuring scaling violations of the polarized structure function $g_1(x, Q^2)$ which is accessible in polarized DIS. Because these scaling violations are logarithmic in $Q^2$, a large range is needed to adequately constrain the gluon helicity contribution. Unfortunately, the $Q^2$ range of current polarized DIS data is not large enough to significantly constrain the gluon helicity contribution to the proton spin.

The need for better constraints on $\Delta G$ was a primary motivation for the spin program at RHIC. Proton-proton collisions probe gluon information at leading order via quark-gluon and gluon-gluon hard scattering, and because RHIC can provide polarized proton beams, information on the gluon polarization is accessible. The observable sensitive to $\Delta G$ in polarized $pp$ collisions is the longitudinal double spin asymmetry $A_{LL}$ where the $LL$ signifies that both beams are longitudinally polarized. $A_{LL}$ is defined as:

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \quad (2)$$

where $\sigma^{++}$ and $\sigma^{+-}$ represent the cross sections for some observable when the protons have the same or opposite helicity, respectively. The two main experiments at RHIC, STAR and PHENIX, have measured $A_{LL}$ using a number of different final states, but the most precise results are from inclusive jets at STAR and inclusive $\pi^0$s at PHENIX.

Both collaborations have recently released results from polarized $pp$ data taken in 2009 at $\sqrt{s} = 200$ GeV [2, 3]. The inclusive jet $A_{LL}$ from STAR is shown in the left panel of figure 1 as a function of parton jet $p_T$ for two pseudorapidity ranges, which emphasize different partonic kinematics. Due to an increase in sampled integrated luminosity as well as several advancements in triggering, data acquisition, and analysis techniques, these data are a factor of 3 to 4 more precise than the previous results from the 2006 data set [4]. These results are compared to a number of next-to-leading order (NLO) global analyses and lie above the original DSSV extraction [1], which included RHIC results from the 2005 and 2006 runs.

The latest $\pi^0A_{LL}$ results from the PHENIX Collaboration are shown in the right panel of figure 1 and combine data taken in 2005, 2006, and 2009. The results are again compared to the central values of a number of NLO global analyses and found to be consistent with the GRSV-zero [5] and original DSSV scenarios. These data are also consistent with the STAR results presented above.
While the $A_{LL}$ defined in equation 2 is sensitive to $\Delta G$, there is not a direct correspondence due to the convolution of different subprocess contributions and probed gluon momentum fractions, both of which depend on the transverse momentum of the final state. It is therefore necessary to include the RHIC $A_{LL}$ data in an NLO ‘global analysis’ which can treat these effects consistently in the extraction of $\Delta G$. The DSSV collaboration was the first group to carry out a global analysis which incorporated $pp$ data from RHIC as well as the world’s DIS and semi-inclusive DIS data. Their first results, which included RHIC data taken in 2005 and 2006, gave a value of $\Delta g(x, Q^2)$ in the range $0.05 \leq x \leq 0.2$ equal to $0.005^{+0.129}_{-0.164}$ \cite{1} \cite{2}. Recently, the DSSV group performed a new analysis incorporating the 2009 jet and $\pi^0 A_{LL}$ results from STAR and PHENIX and found the first non-zero value for $\Delta g(x, Q^2)$. The new result is shown in figure 2 and the best fit value for $\Delta g(x, Q^2)$ is $0.20^{+0.06}_{-0.07}$ in the range $0.05 \leq x \leq 1.0$ \cite{7}. It is also apparent that while the uncertainties for $x \geq 0.05$ have improved significantly, the $x$ range below 0.05 is still largely unconstrained.
Figure 2: Best fit values of the integral of $\Delta g(x, Q^2 = 10\text{GeV}^2)$ for the original and new DSSV extractions (see [7] for details of the data sets). The x-axis is the integral over $0.05 \leq x \leq 1.0$ and the y-axis is over $0.001 \leq x \leq 0.05$.

The NNPDF collaboration has also begun to incorporate RHIC data into their global analysis. The NNPDF technique differs from most other global analyses in that it uses a flexible neural network to determine the parton distribution functions (PDFs) as opposed to a fixed functional form. Recently, a new polarized PDF set was created which includes the STAR jet and $W$ data. This set was generated using a re-weighting technique which allows new data to be added to an existing NNPDF analysis without having to rerun the entire neural network procedure [8]. The new polarized PDF set gives a value for the integral of $\Delta g(x, Q^2)$ equal to $0.23 \pm 0.06$ in the range $0.05 \leq x \leq 1.0$, fully consistent with the DSSV result.

3 Sea Quark Polarization

While the sum over the quark and anti-quark helicity distributions, $\Delta \Sigma$, is most important for the spin sum rule in equation [1], the flavor separated helicity distributions can also provide important information about proton structure and QCD. The polarized anti-quark distributions are of particular interest as they can discriminate between several different models describing the generation of the proton sea and give insight into non-perturbative aspects of QCD. Until recently, most constraints on the flavor separated polarized quark and anti-quark PDFs have come from semi-inclusive DIS (SIDIS), in which an identified hadron is detected along with the scattered elec-
tron. The uncertainty on the flavor separated polarized PDFs comes largely from the uncertainty on the fragmentation functions, which encode the probability of a quark or anti-quark of a given flavor to fragment into a specific hadron, as well as the limited $x$ coverage of the SIDIS data.

The production of real $W$ bosons in polarized $pp$ collisions at RHIC provides a probe of the flavor separated quark and anti-quark polarized PDFs which is complementary to the SIDIS measurements as they do not rely on fragmentation functions and probe much higher $Q^2$. At RHIC, $W$ bosons are produced primarily via $u + \bar{d}$ and $d + \bar{u}$ s-channel scattering and are detected in the charged lepton plus neutrino decay channel (where only the charged lepton is measured). The polarized PDFs are accessed by measuring a longitudinal single-spin asymmetry $A_L$:

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

where $\sigma^+$ and $\sigma^-$ are the cross sections for $W$ production from collisions where the polarized proton beam had positive or negative helicity, respectively (the spin orientation of the other beam is averaged over). The $A_L$ is plotted as a function of the pseudorapidity of the emitted charged lepton and different pseudorapidity regions are more sensitive individual flavors of quark and anti-quark.

The STAR collaboration has recently released $W^\pm A_L$ results for data taken in 2011 and 2012 \cite{9}. The asymmetry, shown in figure 3, is presented as a function of lepton pseudorapidity in six bins and compared to several theoretical models. The $W^+$ asymmetries agree well with the theoretical models but there is some tension between data and theory for the $W^-$ asymmetries at negative lepton pseudorapidities. This region has enhanced sensitivity to the polarized $\bar{u}$ distributions.

The PHENIX collaboration has released preliminary $A_L$ results for the process $W^\pm + Z^0 \rightarrow e^\pm + \nu$ in the pseudorapidity range $\eta < |0.35|$ from years 2011, 2012, and 2013 \cite{10}. These data agree well with the recent STAR results presented above. In addition to the mid-rapidity results, PHENIX has also presented asymmetries at larger pseudorapidities than the current STAR results using the $W$ to muon decay channel from data taken in 2013. Work is continuing on reducing the systematic uncertainties for these results.

As with the extraction of $\Delta G$ from double spin asymmetries, constraints on individual quark and anti-quark PDFs from $W$ data require a global analysis. Both the DSSV and NNPDF groups have included the most recent STAR $W$ results in their latest global analyses \cite{8}. A comparison of the original DSSV (which did not contain RHIC $W$ data) and the latest NNPDF extractions of the polarized light anti-quark...
Figure 3: $A_L$ from $W^\pm$ production plotted as a function of the decay lepton pseudo-rapidity compared with several theoretical models. Data from 2011 and 2012 were combined using a profile likelihood method and error bars on the points represent the 68% confidence intervals.

PDFs can be seen in figure 4. As expected, the addition of the new STAR $W$ results significantly changes the $\Delta u$ distribution while only slightly changing $\Delta d$.

Figure 4: Comparison of the most recent polarized NNPDF and original DSSV PDF sets.
4 Possibilities at a Future eRHIC

As the results in the preceding sections show, the RHIC Spin Program has yielded a wealth of information about the polarized structure of the proton. While $pp$ scattering has the advantage of accessing gluon information at leading order, the fact that both beam and target are composite objects means that precise determination of the partonic kinematics is very difficult. This increases the uncertainty on the $x$ dependence of the extracted polarized PDFs. Because a lepton has no internal structure, the partonic kinematics can be accessed much more precisely in DIS. As mentioned above, fixed target DIS experiments do not have the kinematic reach needed to constrain $\Delta G$, but a much wider kinematic range would be available at a polarized $ep$ collider. There is a great deal of interest among the nuclear physics community for building such a machine and one proposed realization would consist of replacing one of the current RHIC rings with an electron ring to form an eRHIC\[11].

An eRHIC would allow for collisions of electrons and polarized protons, as well as heavier nuclei. Such a machine would marry the wide kinematic range possible in colliders with the precision of DIS and would be the ultimate laboratory for the exploration of QCD. A future eRHIC will have a large and diverse scientific mission\[12], one part of which will be the precise determination of $\Delta G$ and the quark and anti-quark PDFs discussed in the sections above.

The golden channel for measuring $\Delta G$ at an eRHIC will be scaling violations of the polarized structure function $g_1(x, Q^2)$. The collider will allow a much wider lever arm in $Q^2$ for a given value of $x$ than the current fixed target DIS experiments. In addition, the proposed high luminosity will greatly improve the statistical error on each point. The left panel of figure 5 presents the estimated precision on the integral of $\Delta g(x, Q^2)$ between $x_{\text{Min}}$ and unity as a function of $x_{\text{Min}}$ for several expected eRHIC energies and integrated luminosities. The uncertainties from the most recent DSSV extraction are shown for comparison and the power of eRHIC to improve the constraints on $\Delta G$ is obvious.

The proposed eRHIC machine will also be able to probe the flavor separated (un)polarized quark and anti-quark PDFs in two complimentary ways: SIDIS and virtual $W$ production\[13, 11, 12]. As any eRHIC detector is likely to have particle identification abilities, the standard SIDIS measurements currently carried out at fixed target experiments will be available at an eRHIC. These measurements will benefit from improved fragmentation function determinations which should be available by the time an eRHIC turns on. An eRHIC should contribute to the improvement of these fragmentation functions as well. The second method for accessing the quark and anti-quark PDFs involves charged-current DIS in which a virtual $W$ boson is
exchanged instead of the usual photon. These charged-current events access different polarized structure functions which encode unique combinations of quark and anti-quark PDFs. In addition, because the $W$s are virtual, a range of $Q^2$ values can be probed and an overlap between the $W$ and SIDIS measurements will be possible. The right panel of figure 5 shows the expected $x - Q^2$ coverage of the charged-current measurements in the eRHIC kinematic range. As with the extraction of $\Delta G$, the large kinematic range and high statistics possible with an eRHIC is expected to greatly reduce the uncertainty on the flavor separated quark and anti-quark PDFs.

5 Summary

The RHIC Spin Program has given great insight into the polarized structure of the proton. Recent jet and pion asymmetries have been incorporated into NLO global analyses and give evidence for the first non-zero gluon contribution to the spin of the proton, albeit over a restricted $x$ range. The $W$ program has also yielded tighter constraints on the polarized quark and anti-quark PDFs, having a particularly significant effect on the $\Delta u$ distribution. There are plans to build a polarized electron-ion collider which would become the premier facility for the exploration of QCD. Such a machine would allow precision determinations of both the gluon contribution to the proton spin and the flavor separated quark and anti-quark distribution functions.
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