Longitudinal Spin Physics at STAR

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An overview of recent longitudinal spin physics results from the STAR Collaboration focusing on gluon and sea quark polarization measurements is presented. The impact of these results on global analyses by the DSSV and NNPDF groups is also discussed.

1 Introduction

While Quantum Chromodynamics (QCD) is accepted as the theory which governs the strong interaction, many of its aspects remain poorly understood. For example, it is not clear how the spin of the proton is built up from the spins and angular momenta of its constituent quarks and gluons. There is a similar lack of understanding on the dynamic origin of the low momentum 'sea' of light quarks and anti-quarks inside the proton. Gaining insight into these puzzles was a primary motivation behind the spin program at the Relativistic Heavy Ion Collider (RHIC). These proceedings will highlight recent results compiled using data taken with the STAR detector at RHIC which shed light on these outstanding questions.

2 Gluon Contribution to the Proton Spin

The total spin of the proton can be broken down into contributions from the helicities and angular momenta of its quarks and gluons:

$$< S_P >= \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L \tag{1}$$

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

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

where $\Delta\Sigma$ is the contribution from the spins of the quarks and anti-quarks, ΔG is the contribution from the gluon spin, and L is the contribution from parton orbital angular momentum.

Deep inelastic scattering (DIS) experiments with polarized fixed targets have shown that quark and anti-quark helicities account for only about 30% of the spin of the proton in the momentum fraction range $0.001 \leq x \leq 1.0$ [1] meaning that the majority of the proton spin must be carried by orbital angular momentum or gluon helicity. The gluon helicity contribution can be obtained by measuring scaling violations of the $g_1(x, Q^2)$ structure function, which is accessible in polarized DIS. Unfortunately, the Q^2 coverage of existing polarized fixed target DIS data is too limited to significantly constrain the gluon contribution to the proton spin.

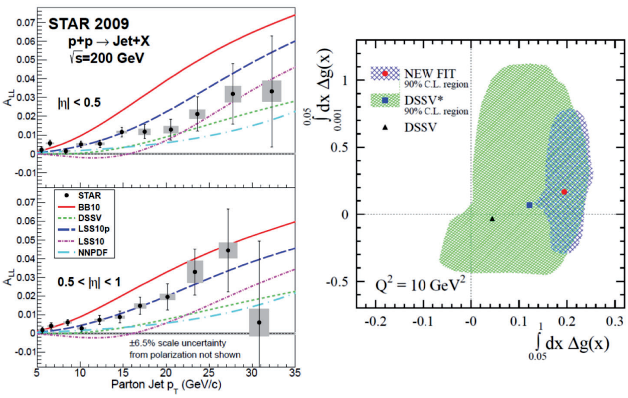

Figure 1 – (Left) STAR inclusive jet A_{LL} vs parton jet p_T for mid-rapidity (upper panel) and forward rapidity (lower panel) jets. Results are compared to the central values of several global analyses (error bands omitted for clarity). (Right) Best fit values of the integral of $\Delta g(x)$ for the original and new DSSV extractions. The x-axis is the integral over $0.05 \leq x \leq 1.0$ and the y-axis is over $0.001 \leq x \leq 0.05$.

With its ability to collide polarized protons, RHIC can probe gluon polarization at leading order via quark-gluon and gluon-gluon hard scattering. The observable sensitive to ΔG in longitudinally polarized pp collisions is the longitudinal double spin asymmetry A_{LL}. A_{LL} is defined as:

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \tag{2}$$

where σ^{++} and σ^{+-} represent the cross sections for some final state when the protons have the same or opposite helicity, respectively. To date, the most precise A_{LL} measurements from STAR have utilized inclusive jet final states. The inclusive jet A_{LL} obtained from data taken in 2009 at $\sqrt{s} = 200$ GeV [2] is shown in the left panel of figure 1. The transverse momenta of the jets were corrected to parton level and the sample was divided into two pseudorapidity ranges, which emphasize different partonic kinematics. The data are compared to a number of global analyses and lie above the DSSV extraction from 2008 [1], which included RHIC results from the 2005 and 2006 runs and found a gluon polarization consistent with zero.

The 2009 STAR inclusive jet results, along with inclusive π^0 results from the PHENIX collaboration [3], have been included in the latest next-to-leading order global analyses from the DSSV [4] and NNPDF [5] groups. The most recent DSSV best fit value for the integral of $\Delta g(x)$ over two x ranges is presented in the right panel of figure 1 along with two older fits. The result of the integration of $\Delta g(x)$ over the range $0.05 \leq x \leq 1.0$ is $0.20^{+0.06}_{-0.07}$, which is the first non-zero value to be extracted. While the 2009 data reduced the uncertainty in the $0.05 \leq x \leq 1.0$ range, the low x region is still largely unconstrained. The DSSV result is in good agreement with the recent extraction from the NNPDF collaboration, which uses a flexible neural network in their PDF fits, and finds a value for the integral of $\Delta g(x)$ to be 0.23 ± 0.06 over the range $0.05 \leq x \leq 1.0$ [6].

Recently, STAR has begun measuring A_{LL} using di-jet final states. Because the correlated two-jet system captures more information from the initial hard scattering, di-jets can place tighter constraints on partonic quantities such as x. Figure 2 presents the preliminary STAR di-jet A_{LL} from 2009 and 2012 taken at $\sqrt{s} = 200$ and 510 GeV, respectively. The data points are plotted as a function of di-jet invariant mass divided by $\sqrt{s}$ so they can be shown on the same scale. Theoretical predictions using the newest DSSV and NNPDF polarized PDF sets are

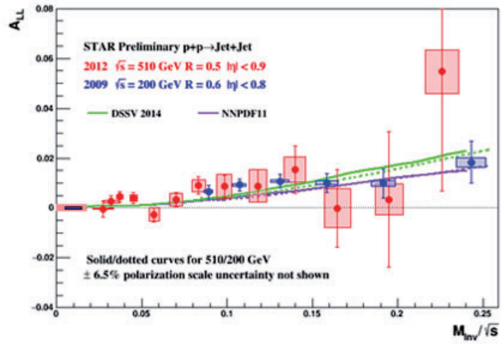

Figure 2 – Di-jet A_{LL} as a function of invariant mass divided by $\sqrt{s}$ for $\sqrt{s}$ = 200 (blue) and 500 (red) GeV together with theoretical predictions.

also shown. The 510 GeV data extend to lower $M/\sqrt{s}$ (which corresponds to lower x) while the 200 GeV data gives better precision at higher values. The asymmetries agree very well in the overlapping mass range.

3 Sea Quark Polarization

When considering the contribution to the total spin of the proton, it is the sum of quark and anti-quark helicity distributions which is relevant, as shown in equation 1. The flavor separated quantities can also provide important insight on proton structure, such as the origin of the light quark sea. It was originally thought that the sea arose via gluon splitting which should result in equal numbers of $\bar{u}$ and $\bar{d}$ quarks, however, subsequent Drell-Yan experiments [7,8] would show an excess of $\bar{d}$ over $\bar{u}$. Many models exist [9] which describe the $\bar{d}/\bar{u}$ ratio relatively well. While these models tend to show similar behavior for the unpolarized ratio, their predictions differ for some spin dependent observables, making measurements of the polarized anti-quark distributions particularly interesting.

RHIC provides a unique and elegant mechanism for the study of the individual quark and anti-quark helicity distributions via the production of real W bosons from polarized pp collisions. At RHIC, W bosons are produced primarily via $u + \bar{d}$ and $d + \bar{u}$ s-channel scattering and, at STAR, are detected in the electron (positron) plus neutrino decay channel. The polarized PDFs are probed by measuring a longitudinal single-spin asymmetry A_L:

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \tag{3}$$

where σ^+ and σ^- 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 asymmetry is often presented as a function of the pseudorapidity of the charged decay lepton, and, due to the $V - A$ structure of the weak interaction and the kinematics of W decay, the regions of large positive or negative pseudorapidity are sensitive to specific quark or anti-quark flavors.

Figure 3 presents the STAR $W^{\pm} A_L$ results from data taken in 2011 and 2012 [10] as a function of the pseudorapidity of the charged decay lepton. The data are compared with several theoretical models and the overall agreement is good, especially for W^+. However, there is some tension between data and theory in the negative pseudorapidity W^- region where the $\Delta\bar{u}$ distribution dominates. In fact, preliminary analysis by the DSSV group finds that the most recent

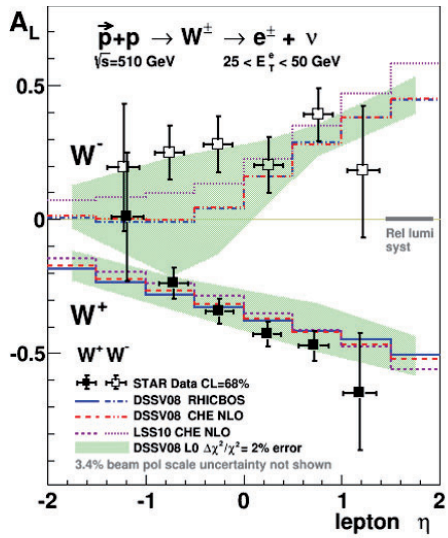

Figure 3 – A_L from $W^{\pm}$ production plotted as a function of the decay lepton pseudorapidity compared with several theoretical models. Data from 2011 and 2012 were combined using a profile likelihood method and error bars on the points represent the 68% confidence intervals.

STAR data changes the sign of the best fit of the integral of $\Delta\bar{u}$ over the region $0.05 \leq x \leq 1.0$ compared to previous extractions [11].

4 Summary

The STAR longitudinal spin program has greatly enhanced the understanding of the polarized structure of the proton. The inclusion of STAR jet results into global analyses give evidence for the first non-zero gluon contribution to proton spin and W boson asymmetries have significantly constrained polarized quark and anti-quark PDFs. With several high-statistics data sets being analyzed, STAR is poised to provide even greater constraints on these quantities in the future.

References

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