

1 RHIC Spin program & polarized gluon distribution

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One of the main motivations for the RHIC spin program is to precisely determine the contribution of gluonic spin, $\Delta g(x)$, to the proton spin over a wide range in gluon momentum fraction x . This is one possible piece of the “Spin Crisis” [1] or “Puzzle” presented by determinations from DIS [2] that the quarks contribute at most 1/3rd of the proton’s spin. RHIC exploits high p_T final states originating from collisions of polarized protons that directly involve the gluons. The spin dependence in the partonic subprocesses are often large, giving good sensitivity to the gluon spin and the large acceptance of the detectors offers access to a wide range of the gluon momentum fraction x .

Since the last update, the impact of our data to date has become much more clear. Many earlier fits solely to DIS data with moderate to large gluon contributions are incompatible with RHIC and new DIS data. This is best demonstrated in a recently released NLO global fit [3] to all data, DIS, SIDIS and RHIC inclusive π^0 and jet data, on an equal footing. The best fit in this analysis has a node in the x region addressed by the RHIC measurements to date pointing toward the need for sensitivity to the x dependence $\Delta g(x)$. Moreover substantial contributions to the integral ΔG are still possible at lower x , indicating the need to extend measurements in that direction as well.

RHIC is uniquely situated in the next 5 years to address these issues. Basing our plans on realistic assumptions that would give 50 pb^{-1} recorded at 200 GeV in the early portion of the coming 5 years, with opportunities for additional data in the out years, and significant integrated luminosity at 500 GeV for the W program very important contributions can be made to our understanding of the Δg . The statistics on the inclusive jet and π^0 channels will be improved by about a factor of 4. However these data tend to integrate over broad ranges in x . New in the coming 5 years will be the opportunity to perform measurements sensitive to the shape of $\Delta g(x)$. This will provide important constraints on the functional form assumed in global analyses, thereby reducing the theoretical uncertainty in extracting the gluon polarization and reducing the uncertainty in the determination of the integral contribution, ΔG , that arises from extrapolation outside the measured region. For $0.02 < x < 0.3$ our best information will come from di-jet correlations. These will be backed up by important independent information from γ -jet correlations, albeit with lower statistical precision. To reach $x \simeq 0.01$ and below, we will exploit new calorimetry at forward rapidity using γ correlations with mid-rapidity jets in addition to measurements at 500 GeV. Thus over the next 5 years we expect to be able to map out $\Delta g(x)$ with relevant precision in the range of a few 10^{-3} to 0.3.

To achieve this goal we require progress with polarized beams consistent with improvements described in section xx. With the completion of the FMS and DAQ1000 at STAR no further upgrades are required although it is expected that addition of the Forward Gem Tracker will be beneficial to detecting jets and photons in the covered region. PHENIX will greatly improve their capabilities with the VTX tracking and Nose Cone Calorimeter upgrades.

In the following we expand on the above by presenting the most recent data, demonstrating its important impact on the first global (hadronic plus (SI)DIS) fits, and describing how our future measurements will provide important leaps in our understanding of the role

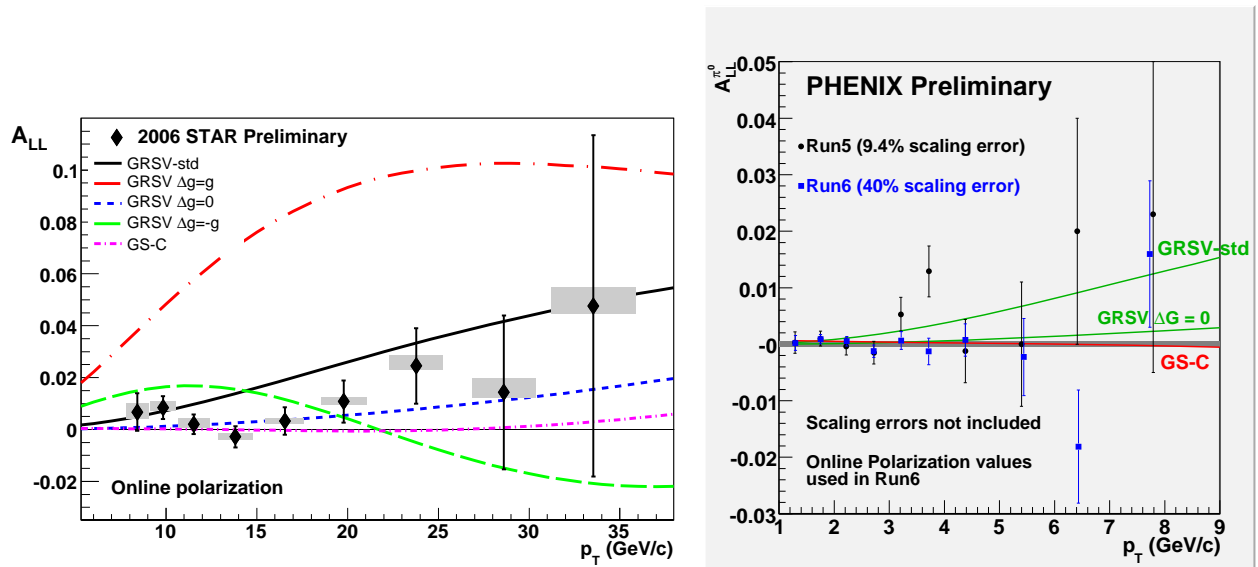


Figure 1: A_{LL} for 2006 inclusive jet data from STAR (left) and π^0 data from PHENIX (right). The theoretical curves are based on different models of gluon polarization from GRSV [4] including their best fit "GRSV-std" and the GS-C fit [5] characterized by a node vs. x but still a large integral Δg resulting from its low x dependence. Also shown is a simple model with $\Delta G=0$ at the input scale. In the left hand figure two extreme assumptions about Δg , maximally aligned ($\Delta g=g$) and anti-aligned ($\Delta g=-g$) at the input scale, are also shown.

of the gluon's spin in the proton.

1.1 Recent Results

1.1.1 Inclusive π^0 s and jets

The 200 GeV run in 2006 produced about 8 pb^{-1} of integrated luminosity with longitudinal polarization resulting in large improvement on the inclusive measurements made by the two experiments in previous years. Shown in Fig. 1 are the double spin asymmetries A_{LL} for inclusive jets at STAR and inclusive π^0 s at PHENIX. The curves correspond to theoretical calculations of A_{LL} for a range of gluon polarization distribution functions [4][5], as described in the figure caption.

The first full-fledged global analysis at next-to-leading order accuracy of all currently available spin-dependent data, including the 2006 RHIC preliminary results for inclusive jets and π^0 s, was completed very recently by DSSV [3]. The resulting polarized gluon density is depicted in the upper left panel of Fig. 2 together with estimates of the typical uncertainties involved in the analysis procedure based on a common approach using "Lagrange multipliers". The DSSV result is compared to previous fits of GRSV [4] and DNS [6], which are now outside the uncertainties estimated by DSSV. The impact RHIC data have on the determination of $\Delta g(x)$ is clearly visible in the upper right panel where the partial contributions $\Delta\chi_i^2$ of the individual data sets for variation of the truncated integral of Δg computed in the range Δg for $0.05 < x < 0.2$ are shown. RHIC data currently provide the best limit on negative values of this integral and are comparable to DIS for positive values. For $x \lesssim 0.05$ the

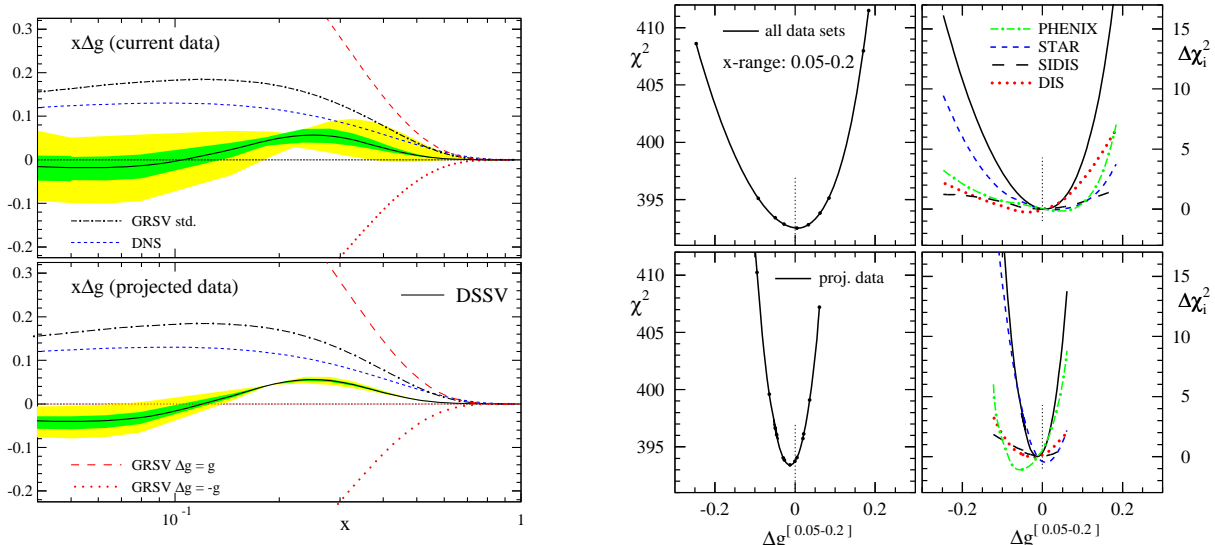


Figure 2: *Upper row: $x\Delta g$ ($Q^2 = 10 \text{ GeV}^2$) from the global NLO QCD analysis by DSSV [3] (left) and partial contributions $\Delta\chi^2_i$ of the fitted data sets to the total χ^2 for variation of the integral Δg computed in the range $0.05 < x < 0.2$ (right). The uncertainty bands correspond to $\Delta\chi^2 = 1$ (green) and $\Delta\chi^2/\chi^2 = 2\%$ (yellow). Also shown are results for $\Delta g(x)$ from previous GRSV [4] and DNS [6] fits. Lower panels: same as above when the RHIC data errors are scaled down by a factor of 4 as expected from the next long RHIC pp run at 200 GeV (50 pb^{-1} with a polarization of 60%).*

uncertainties in $\Delta g(x)$ are still sizable, and the full integral, $\int_0^1 \Delta g(x) dx$, which represents the contribution of gluons to the spin of the nucleon, is still not determined. Additional constraints from measurements over an extended x range, especially at lower x where the unpolarized distribution $g(x)$ is large, in addition to constraints on the functional form of $\Delta g(x)$ will be necessary to determine the full integral ΔG .

1.1.2 Other experiments

The broad interest in understanding the nucleon's spin structure has led to a world-wide experimental program in polarized DIS. The efforts of the COMPASS experiment at CERN, the recently completed HERMES experiment at DESY, and many experiments at Jefferson Laboratory are well documented elsewhere [7] and we provide only a brief update on the status of ΔG studies from these lepton scattering experiments.

First and foremost, deep inelastic lepton scattering provides information on the polarized gluon distribution via scaling violations of the structure function g_1 . The results from COMPASS, HERMES, Jlab and earlier experiments are an integral part of a global analysis [3] and their combined impact on determining $\Delta g(x)$ is also shown in the upper right panel of Fig. 2. The analysis of DIS data is well developed and there are many practitioners [4, 6, 8, 9, 10]. These most recent fits show considerable progress but still substantial uncertainty in the shape of $\Delta g(x)$ and sign of the integral ΔG remain.

The HERMES and COMPASS experiments have also pursued $\Delta g(x)$ via photon-gluon

fusion detected as high p_T hadron pairs [11, 12, 13, 14] and, in the case of COMPASS, open charm production [15]. These are leading order extractions and are thus not included in the DSSV global analysis. The $\Delta g(x)/g(x)$ results are consistent with zero to within uncertainties of 0.1 for $x = 0.2-0.3$.

The overall conclusion is that results from lepton scattering experiments and the RHIC program are in agreement. Large contributions from the gluonic spin to the proton spin in the range directly examined so far, $0.02 < x < 0.3$, are unlikely. However the possibility of an interesting x dependence for $\Delta g(x)$ and the importance of the lower x range have been brought to the fore.

1.2 Δg and RHIC spin: next five years 2009-2013

With upgrades newly completed or already under construction, planned increases in luminosity and runs at 500 GeV, RHIC and its two experiments, STAR and PHENIX, are uniquely positioned to add significant new constraints on the magnitude and functional form of $\Delta g(x)$. In this section we describe these new capabilities, measurements and their expected impact.

1.2.1 Semi-inclusive Channels

As the luminosity of RHIC grows, the already large STAR detector acceptance and the wider acceptance windows becoming accessible to PHENIX due to its detector upgrades (Si VTX tracker and Nose Cone Calorimeter) will allow measurements of two ‘‘particle’’ correlations such as jet-jet, hadron-hadron and photon-jet coincident events. The probed range, $\sim 2 \times 10^{-3} < x < \sim 3 \times 10^{-1}$, far exceeds that of any other experiment in the near future. At leading order the hard scattering subprocess kinematics can be calculated on an event by event basis. This leads to addressing one of the goals mentioned earlier, i.e. that of extracting $\Delta g(x)$ directly. Of course such LO extractions must be followed up with full theoretical work associated with evaluation of cross sections and asymmetries at next to leading order, but they do illustrate that individual measured points in the correlations are sensitive to a narrow range of gluon x and the points taken together map out the x dependence $\Delta g(x)$.

With realistic expectations on luminosity our best knowledge regarding $\Delta g(x)$ in the range $0.02 < x < 0.3$ will come from the di-jet channel with γ -jets supplying important independent information with less statistical precision. Using 2-body kinematics the di-jet data can be plotted vs. a number of different kinematic variables with cuts applied based on others providing near double differential distributions. In Fig. 3 we show the expected statistics for di-jets at $\sqrt{s} = 200$ GeV/ c^2 plotted vs. their invariant mass, $M_{inv} = \sqrt{x_1 x_2 s}$. Note that each panel presents a different combination of EM calorimeter sections contributing to the di-jet yield. Thus each panel represents a different selection of (x_1/x_2) and $\cos\theta^*$ and each point is sensitive to $\Delta g(x)/g(x)$ over a small range in x . For example the first 3 points in the lower left panel of Fig. 3 where $(\eta_3 + \eta_4) = 1$ represent approximately non-overlapping x bins centered at 0.076, 0.10 and 0.13. A leading order estimate considering the average quark polarization and $\cos\theta^*$ along with some dilution from gg and qq scattering leads to an estimate that these points each determine the gluon polarization $\Delta g(x)/g(x)$ to $\sim 0.02-0.03$. The 30-40 GeV/ c^2 bin in the upper and lower right panels correspond to an x of 0.06 and 0.16 respectively. Note that the asymmetries are often larger than for inclusive jets and that

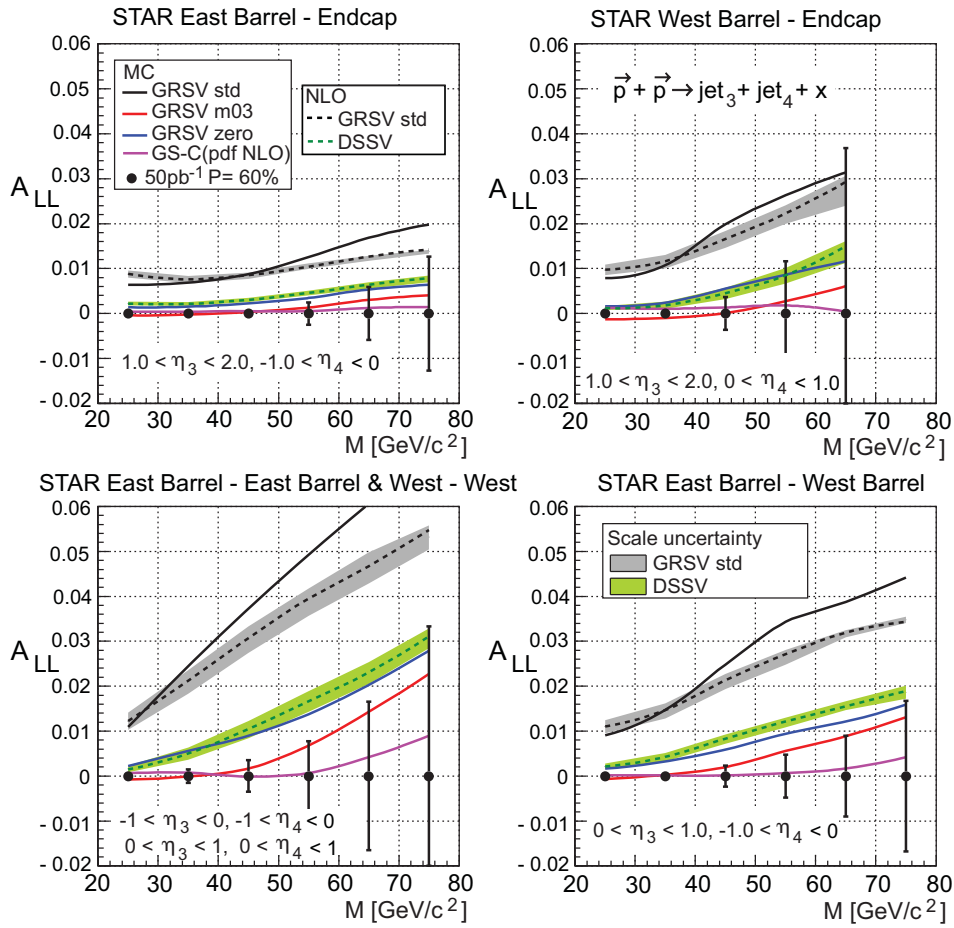


Figure 3: A_{LL} vs. M_{inv} for di-jets for $\sqrt{s} = 200 \text{ GeV}/c^2$ based on an integrated luminosity of 50pb^{-1} and a polarization of 60%. Individual plots represent di-jets shared between various regions of the STAR EM calorimeters. The curves represent various PDFs, GRSV-std, GRSV=0 GRSV=-0.3 and GS-C discussed previously. In addition NLO calculations[17] for two of the PDFs are also shown.

there is sensitivity on the scale of the currently allowed range as represented by solutions such as GRSV=0 and GS-C. Also shown are NLO calculations [17] for DSSV and GRSV-std with scale uncertainties. These give strong encouragement that scale uncertainties are not a serious problem and that a LO analysis by the experiments can be a useful tool. We emphasize that the goal of the measurements is not to simply distinguish between models, but to lead to an extraction of $\Delta g(x)$ where the functional form of $\Delta g(x)$ is constrained by the data.

In the forward region, a combination of a rise in the underlying partonic asymmetry correlates with a rise in the back angle qg Compton scattering cross section making it a very competitive measurement of the gluon polarization. With completion of the FMS in the past year STAR now has EM calorimetric coverage in pseudo-rapidity from $-1 < \eta < 4$. The relationship $(\eta_3 + \eta_4) = \ln(x_1/x_2)$ illustrates that correlations between direct photons in the FMS ($\eta = 3.3$) and jets at mid-rapidity ($-1 < \eta < 2$) can be used to probe gluons with

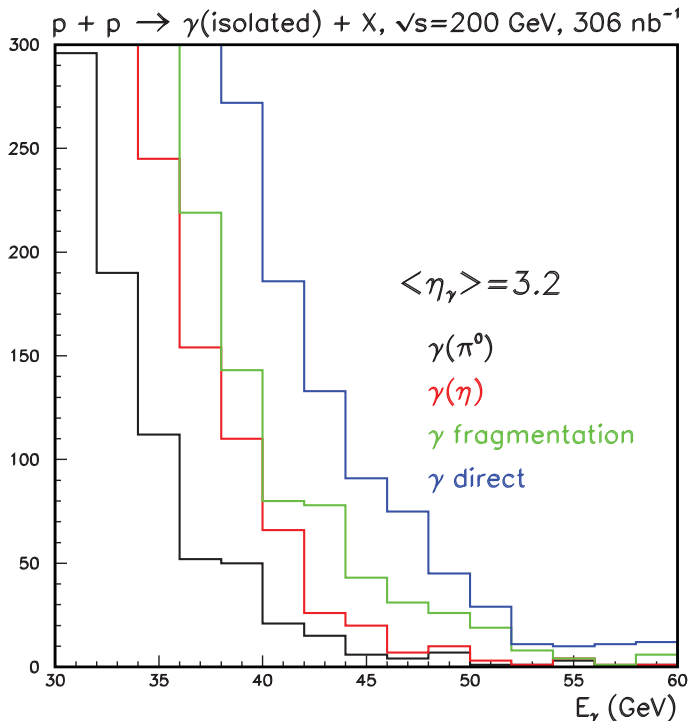


Figure 4: *Simulation of inclusive forward photon spectrum. Direct photon candidates are detected in a small fiducial volume within the FMS $3.1 < \eta < 3.4$. The remainder of the large area FMS $2.5 < \eta < 4$ is used as a veto to require that the candidate be isolated. Only candidates above $35 \text{ GeV}/c^2$ are considered to avoid the increasing fragmentation background for lower energy. The signal to background ratio is already 2:1 with these simple cuts.*

x values as low as a few $\times 10^{-3}$ with highly polarized valence quarks. The direct-photon jet channel and its experimental issues of suppressing fragmentation photon background and detecting the low p_T ($\sim 2.5 \text{ GeV}/c$) jet at mid-rapidity are identical to that described in Sect. xx on transverse studies of sign dependence of the color charge. Initial studies indicate that a signal to background ratio of 2:1 is achievable before considering the coincidence with the awayside jet as shown in Fig. /reffig:gamFMS. This should allow measurements of the gluon polarization for $x < 0.02$ at a level that can provide constraints within the range allowed by current fits in a run of 50 pb^{-1} . More detailed simulations and studies of data taken in run 8 are required before more quantitative sensitivities can be provided.

The γ -jet channel also has important contributions to make at higher x despite the statistical advantages of the di-jets in the relevant mid-rapidity regions. The direct photons will provide independent information where the entrance channel is dominated by qg , the exit channel does not have strong final state interactions, and where theoretical concerns such as scale variations are in better control. It is well recognized that extracting the γ -jet signal from the prolific number of di-jets is a challenging problem as illustrated in early simulations [18]. Considerable progress using full detector simulations and data from 2006 have been made in understanding this problem, but we have not yet reached the stage where quantitative sensitivity projections can be made. However, sufficient yield is produced with

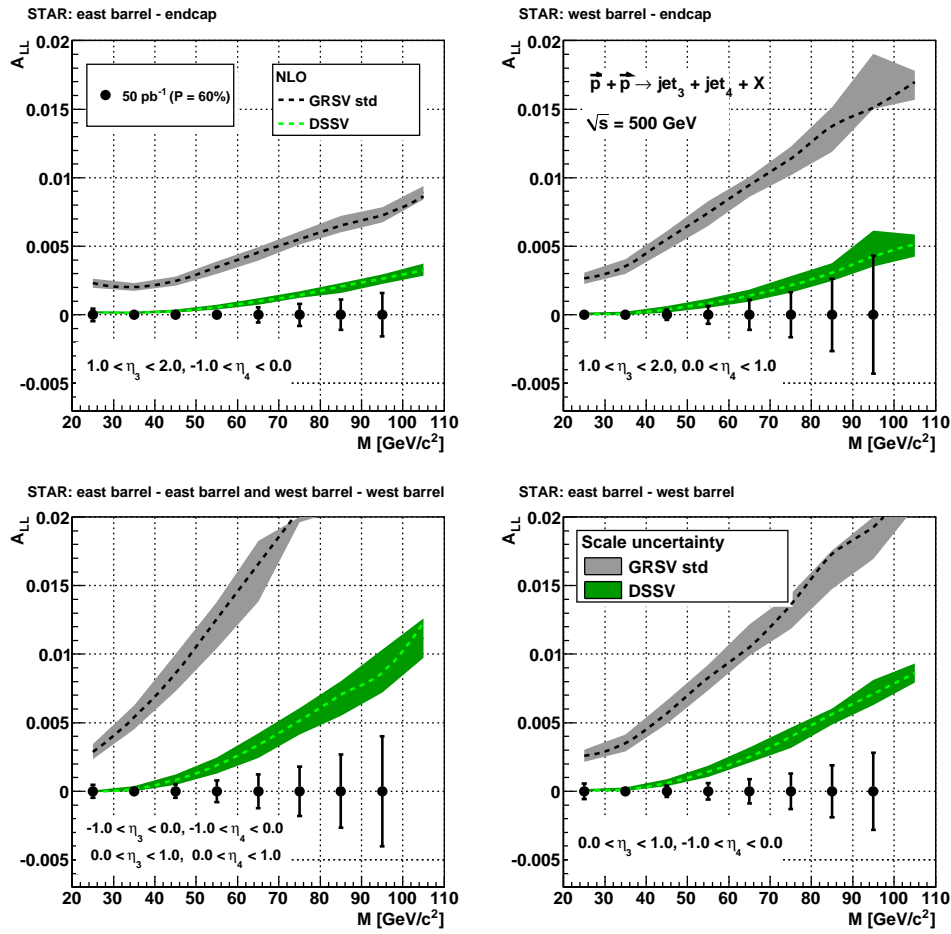


Figure 5: A_{LL} vs. M_{inv} for di-jets for $\sqrt{s} = 500 \text{ GeV}/c^2$ based on an integrated luminosity of 300 pb^{-1} and polarization of 70%. Individual plots represent di-jets shared between various regions of the STAR EM calorimeters. The curves represent various PDFs, GRSV-std, GRSV=0 GRSV=-0.3 and GS-C discussed previously. In addition NLO calculations[17] for two of the PDFs are also shown.

the luminosities expected in the next few years to make measurements with physics impact in the γ -jet channel assuming high efficiency and reasonable background suppression are proven. The measurements will greatly benefit from higher statistics to come later in the 5 year period when the experiments return to collect large luminosity at 200 GeV for HI comparison data after the tracking upgrades are in place. Even then the measurements will still be statistics limited and additional running could be pursued beyond the 5 year time frame based on the status at that time.

The programs for di-jets and γ -jets will be extended to 500 GeV for both STAR and PHENIX. At this energy a given p_T will correspond to an x lower by a factor of 2.5. It is expected that luminosity requirements will be driven by the W program and sufficient statistics for $\Delta g(x)$ from these two body channels will not drive the luminosity request. Projections for di-jet measurements at STAR for 300 pb^{-1} at $\sqrt{s} = 500 \text{ GeV}/c^2$ are shown

in Fig. 5.

1.2.2 Inclusive Channels

Inclusive channels, with π^0 s and jets being the most sensitive, have been the workhorse of the program to date. The increased luminosity expected in the coming years will permit these channels to provide far more precise information about ΔG as illustrated in Fig. 6. The impact of including approximately another 50 pb^{-1} of inclusive π^0 data from PHENIX and jet data from STAR in a global fit are shown in the lower portion of Fig. 2. The projected uncertainty in the integral of ΔG over the range $0.05 < x < 0.2$ is a factor of 2.4 smaller than at present.

There are two principal inclusive channels, charged pions and direct photons, whose impact has been limited by statistics with the luminosities delivered so far. With an additional $20\text{-}30 \text{ pb}^{-1}$ these will start to play an interesting role.

The quark-gluon subprocess starts to dominate for midrapidity pion production at $p_T > 5 \text{ GeV}/c$, leading to an approximately linear dependence of the asymmetries on ΔG . The preferred fragmentation of π^+ from an up quark and π^- from a down quark and the fact that Δu and Δd have opposite signs lead to an ordering of the pion asymmetries depending on the sign of ΔG [16]. Thus charged pion A_{LL} measurements at high p_T will provide enhanced sensitivity to the sign of ΔG compared to neutral pions alone.

Direct photon production is dominated by quark-gluon Compton scattering. The spin asymmetry is hence linear in gluon polarization and the quark polarization has already been measured accurately in the past DIS experiments. Thus the direct photon process should be an ideal independent and complementary method for the measurement of the polarized gluon distribution. However, due to low figure of merit of this process and the other measurements available to us we do not expect at this time to press for the large luminosities required to make this channel fully statistically competitive.

In the next few years the p-p running will turn to 500 GeV. It is fully expected that the inclusive channels will again provide the first results at this energy. A given p_T will naturally probe lower x for the gluon and thus assist in our effort to constrain $\Delta g(x)$. However, the inclusive channels will be dominated by gluon-gluon scattering in a momentum range where the unpolarized gluon density is quite large. Thus, the asymmetries are quite small. In Fig. 6 are shown estimates of inclusive π^0 statistics expected at PHENIX for 200 GeV and 500 GeV. Integrated luminosities of 50 pb^{-1} and 300 pb^{-1} respectively are assumed along with realistic estimates of trigger efficiencies based on previous runs. The comparison of the asymmetries at the two energies demonstrate that they approximately obey x_T scaling.

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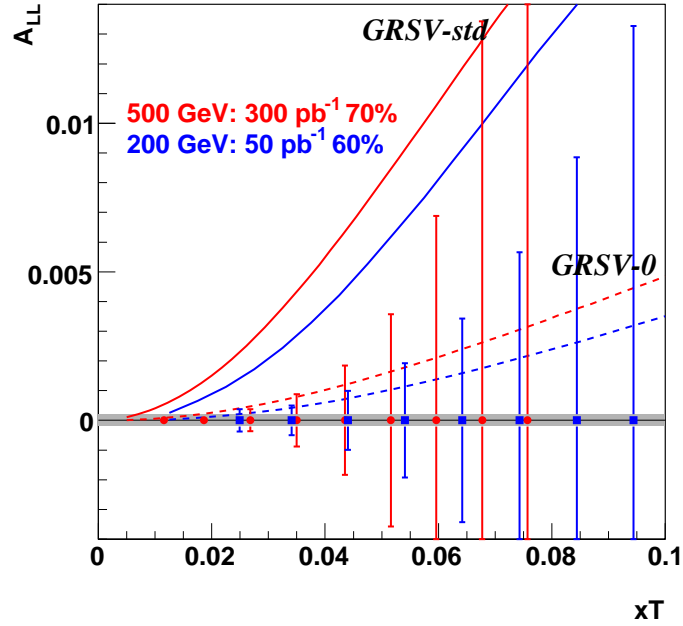


Figure 6: *PHENIX* estimated statistics for A_{LL} vs x_T for inclusive π^0 s at 200 GeV (50 pb^{-1} with a polarization of 60%) and 500 GeV (300 pb^{-1} with a polarization of 70%).

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