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Constraining the gluon polarization in polarized proton-proton collisions at RHIC

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The STAR experiment at the Relativistic Heavy-Ion Collider at Brookhaven National Laboratory is carrying out a spin physics program in high-energy polarized $\vec{p}+\vec{p}$ collisions at $\sqrt{s} = 200-500\,\mathrm{GeV}$ to gain a deeper insight into the spin structure and dynamics of the proton.
One of the main objectives of the spin physics program at RHIC is the extraction of the polarized gluon distribution function based on measurements of gluon initiated processes, such as hadron and jet production. The STAR detector is well suited for the reconstruction of various final states involving jets, π^0, $\pi^{\pm}$, $e^{\pm}$ and γ, which allows the measurement of several different processes. Recent results will be shown on the measurement of jet production and hadron production at $\sqrt{s} = 200\,\mathrm{GeV}$.

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1. Introduction

The spin structure and dynamics of the nucleon is one of the fundamental and unresolved questions in Quantum Chromodynamics (QCD). Various experimental programs have been conducted in the past to deepen our understanding on the proton spin. Deep-inelastic scattering (DIS) experiments have clearly established that the quark spin contribution is small and accounts for only $\approx 25\%$ of the proton spin [1].

High energy polarized $\vec{p}+\vec{p}$ collisions at $\sqrt{s} = 200-500\,\mathrm{GeV}$ at RHIC provide a unique way to probe the proton spin structure and dynamics using hard scattering processes [2]. The production of jets and hadrons is presently the prime focus of the gluon polarization studies. The first full NLO global analysis of polarized DIS data, as well as results obtained by the PHENIX [3] and STAR [4] experiments in polarized $\vec{p}+\vec{p}$ collisions at RHIC placed a strong constraint on the gluon spin contribution in the gluon momentum fraction range of $0.05 < x < 0.2$, and suggested that the gluon spin contribution is not large in that range [5]. Constraining the polarized gluon distribution function, Δg, through inclusive measurements has been, so far, the prime focus of the STAR physics analysis program of the Run 3/4 [6], Run 5 [4] and Run 6 [7] data samples. Inclusive measurements, such as inclusive jet production, integrate over a fairly large x region for a given jet transverse momentum region. While those measurements provide a strong constraint on the value of Δg integrated over a range in x, those measurements do not permit a direct sensitivity to the actual x dependence. This motivates the need for correlation measurements in polarized $\vec{p}+\vec{p}$ collisions.

2. Recent jet A_{LL} results

STAR reconstructs jets with the midpoint cone algorithm using clusters of charged track momenta measured with the STAR Time Projection Chamber (TPC) and tower energy deposits in the STAR Barrel Electromagnetic Calorimeter (BEMC) within a cone radius of $R \equiv \sqrt{\Delta\eta^2+\Delta\phi^2}$ [7]. The jet sample was required to be within a fiducial range of $-0.7 < \eta_{\mathrm{Detector}} < 0.9$ for the 2006 data sample with a cone radius of $R = 0.7$. The dominant fraction of jet events in the 2006 data sample is based on a jet patch (JP) trigger that required a minimum energy deposition for a group of towers over a region of $\Delta\eta \times \Delta\phi = 1.0 \times 1.0$. This trigger was taken in coincidence with a minimum-bias condition using the STAR Beam-Beam Counter (BBC). Figure 1 (a) shows the most recent inclusive jet cross section measured by the STAR collaboration as a function of p_T. The cross section is found to be in good agreement with NLO calculations (dark shaded band) [8] after including the impact of hadronization and underlying event effects (light shaded band). The latter have been evaluated using a PYTHIA and GEANT simulation. The largest systematic uncertainty is due to the jet energy scale, affecting the measured cross section at the level of 40%.

Throughout the following discussion, four gluon polarization scenarios have been used as input to NLO perturbative QCD calculations of A_{LL}. The GRSV standard case refers to a global analysis fit of polarized DIS data [9]. The case for a vanishing gluon polarization (GRSV-ZERO) and the case of a maximally positive (GRSV-MAX) or negative (GRSV-MIN) gluon polarization have also been considered. The GS-C [10] set of Δg is reflected by a large positive gluon polarization at low x, a node around $x \sim 0.1$ and a negative gluon polarization at large x at a scale of $Q^2 \sim 4\,\mathrm{GeV}^2$. Figure

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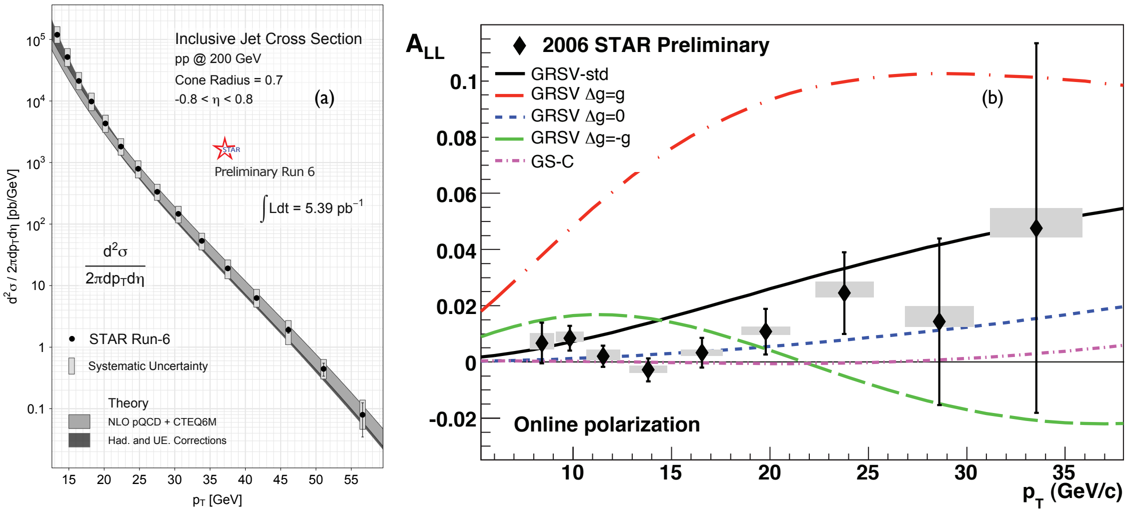

Figure 1: *Recent STAR 2006 inclusive jet result for cross-section (a) and A_{LL} (b).*

1 (b) shows the most recent STAR preliminary measurement of A_{LL} for inclusive jet production as a function of p_T based on the 2006 data sample of $4.7\,\mathrm{pb}^{-1}$. Typical beam polarization values during the 2006 data-taking period were $55-60\%$. The leading systematic uncertainty comes from the trigger and jet reconstruction biases. Differences between observed and true jet p_T are estimated using PYTHIA and GEANT simulations and result in corrections being applied to the jet p_T values. Additionally, the trigger conditions at STAR can artificially bias the analyzed data sample towards particular flavors of partonic collisions. A conservative systematic uncertainty is evaluated to account for this effect which incorporates all allowable gluon polarization scenarios. The A_{LL} curves in Figure 1 (b) are derived from NLO fits to world polarized DIS data by two separate theory groups, GRSV [9] and GS [10]. The currently measured result is consistent with a small gluon polarization scenario for the STAR kinematic range of $0.03 < x < 0.3$. This range accounts for $\sim 50\%$ of the total ΔG integral, i.e. $\Delta G = \int_0^1 \Delta g dx$, for GRSV-STD at a scale of $Q^2 = 100\,\mathrm{GeV}^2$ which is typical for the jet measurements presented here.

3. Recent neutral and charged pion A_{LL} results

Neutral pions are identified via the two-photon decay channel, which accounts for more than 98% of π^0 decays. Two primary sub-detectors, the STAR Barrel Electromagnetic Calorimeter (BEMC) and respective Shower Maximum Detector (SMD) are employed to reconstruct decay photons from mid rapidity neutral pions. Charged pion production is of particular interest since the difference of the longitudinal double-spin asymmetries for π^+ and π^- production, $A_{LL}(\pi^+)$ - $A_{LL}(\pi^-)$, tracks the sign of Δg, due to the opposite signs of the polarized distribution functions for up and down quarks. The STAR Time Projection Chamber (TPC) offers robust reconstruction and identification of charged pions up to a transverse momentum of 15 GeV/c. Particle identification is accomplished using measurements of ionization energy loss in the TPC.

Figure 2 (a) shows A_{LL} for neutral pion production at mid rapidity as a function of p_T based on the 2006 data sample [11]. This measurement is shown in comparison to NLO calculations

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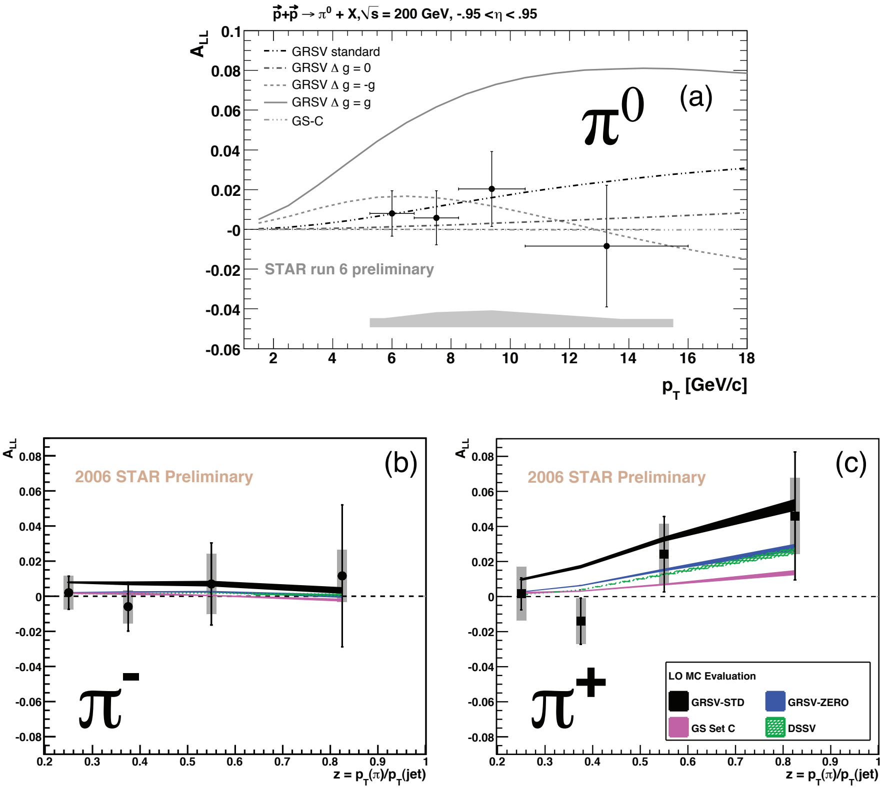

Figure 2: *Recent STAR 2006 A_{LL} neutral pion result (a) and STAR 2006 A_{LL} results for charged pion (π^- and π^+) / jet correlation measurements (b/c).*

assuming different gluon polarization scenarios [7, 11]. This measurement reaches to higher p_T values compared to previous measurements by PHENIX [12] and STAR [13]. At the present level of precision, the data excludes extreme gluon polarization scenarios. The STAR collaboration has also recently presented results for neutral pion production at forward rapidity based on the STAR Electromagnetic Endcap Calorimeter (EEMC) and the STAR Forward Pion Detector (FPD) [14].

Figure 2 (b) and (c) show STAR's preliminary result of A_{LL} for charged pion (π^- and π^+) / jet correlation measurements at mid rapidity. Charged pions are reconstructed opposite a jet that triggered the experiment. The data are shown versus $z \equiv p_T(\pi)/p_T(jet)$ and were obtained in 2006 [15]. Full NLO calculations for this observable have recently been released [16]. These calculations will provide the basis for charged pion results to be included in a global analysis. The data shown for charged pion production are compared to a LO MC evaluation of A_{LL} excluding extreme scenarios of Δg. The measurement of $A_{LL}(\pi^+)$ is of particular interest, since its analyzing power is large because of the large ug scattering contribution to the production cross section and sizable $\Delta u/u$. In the future, more precise measurements of $A_{LL}(\pi^+)$ have the potential for providing a better understanding of Δg.

4. Status and prospects of di-jet production

Correlation measurements such as those for di-jet production allow for a better constraint of the

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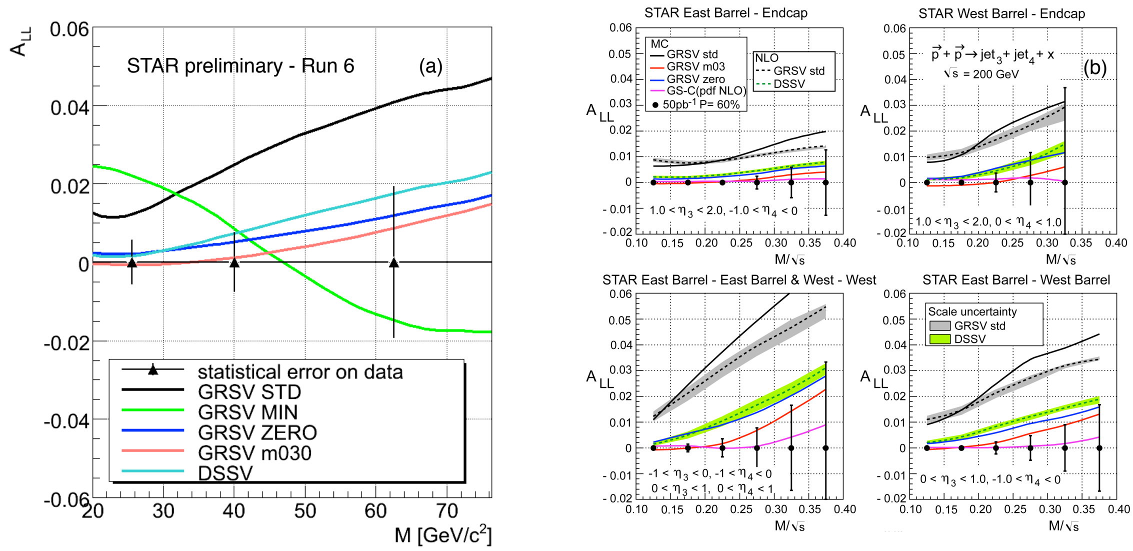

Figure 3: *(a) Statistical precision of the longitudinal double-spin asymmetry, A_{LL}, as a function of the di-jet invariant mass, M, for the 2006 RHIC data sample. (b) Longitudinal double-spin asymmetry, A_{LL}, for di-jet production as function of the ratio $M/\sqrt{s}$ for different topological combinations of the STAR BEMC and the STAR EEMC acceptance region.*

partonic kinematics and thus the shape of Δg. At LO, the di-jet invariant mass, M, is proportional to the product of the x values of the partons, $M = \sqrt{s}\sqrt{x_1 x_2}$, whereas the pseudo-rapidity sum of the final-state jets, $\eta_3 + \eta_4$, is proportional to the logarithm of the ratio of the x values, $\eta_3 + \eta_4 = \ln(x_1/x_2)$. Photon-jet coincidence measurements are expected to provide a theoretically clean way to extract Δg. The wide acceptance of the STAR experiment permits reconstruction of di-jet events with different topological configurations, i.e. different η_3/η_4 combinations, ranging from symmetric ($x_1 = x_2$) partonic collisions to asymmetric ($x_1 < x_2$ or $x_1 > x_2$) partonic collisions. This, together with the variation of the center-of-mass energy, is expected to constrain Δg over a wide range in x of approximately $\sim 2\cdot 10^{-3} < x < 0.3$ for di-jet and photon-jet events. The NLO framework for correlation measurements exists and therefore those measurements can be used in a global analysis [17].

Figure 3 (a) shows the statistical precision of the longitudinal double-spin asymmetry, A_{LL}, as a function of the di-jet invariant mass, M. Those uncertainties, extracted from the 2006 data sample, are compared to a LO MC evaluation of A_{LL} computed with a PYTHIA MC sample using different event weights to account for different polarized gluon distribution functions of GRSV [9] and DSSV [5]. The size of the statistical uncertainty at the highest invariant mass bin is at the level of the difference between GRSV-STD and DSSV.

Figure 3 (b) shows the expected precision for the longitudinal double-spin asymmetry, A_{LL}, for di-jet production as a function of $M/\sqrt{s}$ for different topological combinations of the STAR BEMC and the STAR Endcap Electromagnetic Calorimeter (EEMC) acceptance regions. Taking into account the different η ranges covered, and equivalently, the different $\cos\theta^*$ regions being probed, each panel represents a different range in x_1/x_2. At LO, $\cos\theta^*$ amounts to $\tanh\left(\frac{\eta_3-\eta_4}{2}\right)$. The upper left panel effectively probes asymmetric partonic collisions where predominantly a low-

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x gluon collides with a high-x quark at large invariant masses. The effective variation of x_1 and x_2 amounts to $0.2 < x_1 < 0.6$ and $0.07 < x_2 < 0.2$. In contrast, a kinematic region of larger x values is probed at predominantly symmetric partonic collisions such as the one shown in the lower right panel. The effective variation of x_1 and x_2 is roughly equal and given by the horizontal axis of the lower right panel. The projected uncertainties are shown for a luminosity of $50\,\mathrm{pb}^{-1}$ and a beam polarization of 60%. Those projected uncertainties are compared to a LO evaluation of A_{LL} and a full NLO A_{LL} calculation. Scale uncertainties are shown as a shaded band for DSSV and GRSV-STD reflecting a variation of the invariant mass M as a hard scale of $2M$ and $0.5M$. Asymmetric cuts are imposed for the LO MC and the NLO determination of $\min(\mathrm{p_T}) \geq 7\,\mathrm{GeV/c}$ and $\max(\mathrm{p_T}) \geq 10\,\mathrm{GeV/c}$. The result of a LO MC evaluation using GS-C [10] for Δg is also shown. GS-C is still consistent with the current inclusive jet results [7]. A cone radius of $R = 0.7$ has been used. Good agreement is found between a LO MC evaluation of A_{LL} and a full NLO calculation. Scale uncertainties are found to be small in comparison to the variation of the chosen polarized gluon distribution functions, in particular, at large values of M.

While inclusive measurements from STAR have provided important constraints on Δg, and will continue to do so, the impact of di-jet measurements, and potentially also future photon-jet measurements, on the x dependence should greatly enhance our understanding of Δg.

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