Spin physics with STAR

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Abstract

The STAR collaboration aims to study polarized proton-proton collisions at RHIC. The emphasis of the spin run this year is on transverse single spin asymmetries. Beyond 2001, we aim to determine directly and precisely the gluon polarization, as well as the polarizations of the u, $\bar{u}$, d and $\bar{d}$ quarks in the proton by measuring in addition longitudinal and double spin asymmetries. Furthermore, we aim to measure for the first time the quark transversity distributions. These measurements will improve substantially the knowledge and understanding of the spin structure of the nucleon.

1 Introduction

Over the past decade, the inclusive spin asymmetries $A_{1(2)}$ and structure functions $g_{1(2)}$ of the nucleon have been measured in Deep Inelastic Scattering (DIS) experiments at CERN [1, 2], SLAC [3] and DESY [4]. The data lead one to conclude that only a small fraction of the nucleon spin is carried by quark spins. The gluon polarization is determined indirectly from next-to-leading order QCD analyses of the scale dependence of the data, and is found to be relatively small to within large uncertainties [2]. Semi-inclusive measurements [5, 6] demonstrate that the polarization of the valence u quark is positive and that the polarization of the valence d quark is negative. The data do not resolve the flavor composition of quark spin densities in the sea. Only under the assumption of SU(2) flavor/isospin symmetry of the light sea is the polarization of the sea quarks/anti-quarks determined, and found consistent with zero to within large experimental uncertainties.

The largely open questions of which fraction of the nucleon spin originates from gluon polarization and which fraction results from sea-quark polarization will be addressed in the present generation of spin experiments, including STAR at the Relativistic Heavy Ion Collider (RHIC).

For this purpose, RHIC will accelerate and collide intense beams ($\mathcal{L} = 8 \times 10^{31} - 2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) of highly polarized (70%) protons, to projected integrated luminosities of 320 (800) pb^{-1} at $\sqrt{s}$ =200 (500) GeV over the upcoming years [7].

STAR (Solenoid Tracker At RHIC) will measure the cross-section asymmetries in collisions with either beam or both beams polarized in longitudinal (L) and tranverse (T) directions.

These so-called single and double spin asymmetries can be denoted by:

$$A_{L,T} = \frac{1}{P} \cdot \frac{R_- - R_+}{R_- + R_+}, \quad A_{LL,LT,TT} = \frac{1}{P_1\, P_2} \cdot \frac{(R_{++} + R_{--}) - (R_{+-} + R_{-+})}{(R_{++} + R_{--}) + (R_{+-} + R_{-+})}, \qquad (1)$$

where the symbols P denote the respective beam polarizations, the symbols R denote the observed number of events normalized to the luminosity of the beam crossing, and the subscripts $(+)$ and $(-)$ denote the spin directions with respect to the L, T axes. These measurements thus require knowledge of the relative luminosities for $(+)$ versus $(-)$, and for $(++)$ and $(--)$ versus $(+-)$ and $(-+)$ collisions, in addition to knowledge of the absolute beam polarizations.

The asymmetries give insight into the nucleon spin structure. Specifically, STAR will study:

1. the gluon polarization from the measurements of A_{LL} (i) in inclusive high p_T (prompt) photon production $\vec{p}\vec{p} \to \gamma + X$, (ii) in jet(s) production $\vec{p}\vec{p} \to \text{jet(s)} + X$, (iii) from the prompt photon in coincidence with jet production $\vec{p}\vec{p} \to \gamma + \text{jet} + X$, and (iv) possibly from heavy quark production $\vec{p}\vec{p} \to e^+ + e^- + X$,

2. the flavor decomposition of the quark spin densities in the nucleon sea from measurements of A_L in W production, $\vec{p}p \to W + X \to e + X$,

3. the quark transversity distributions from A_{TT} (i) in di-jet production $\vec{p}\vec{p} \to \text{di} - \text{jet} + X$, and (ii) in Z^0 production $\vec{p}\vec{p} \to Z^0 \to e^+ + e^- + X$,

in addition to higher twist effects in forward, inclusive π^0 production [8,9] and transfer of the beam polarization into the final state, as examined in reference [10] for Λ production.

After a short overview of the STAR detector systems crucial to the spin measurements, the goal of this year's spin program is described in some detail, followed by a discussion of future measurements of the gluon polarization and the flavor decomposition of the quark spin densities in the nucleon sea.

2 STAR detector

The STAR detector design facilitates the identification and measurement of jets, electrons, photons, and neutral pions.

Its key component is a Time Projection Chamber (TPC) [11] with full azimuthal coverage, placed inside a uniform solenoidal 0.5 T magnetic field. The TPC thus provides tracking for charged particles with pseudorapidities $|\eta| < 1.5$, and is well suited for the reconstruction of hadronic jets.

Photons and electrons are identified using a lead-scintillator Electromagnetic Calorimeter (EMC) with preshower layers, and measured to an energy resolution $\Delta E/E \simeq 0.02 + 0.16/\sqrt{E}$. The construction and integration of the EMC in STAR is proceeding in stages. The modules installed to date (2001) cover $0 < \eta < 1$ and $\Delta\phi = 4\pi/5$. Future additions will extend the coverage to $-1 < \eta < 2$ for the full range in azimuth. Each calorimeter module is equipped with a Shower Maximum Detector (SMD) at a depth of about 5 radiation lengths, which provides the high spatial resolution in the shower profile needed to resolve pairs of nearby photons characterizing π^0 decay.

The last detector subsystem discussed here is the Forward Pion Detector (FPD). The FPD consists of one prototype module of the EMC with its associated SMD, and three similarly shaped Pb-glass detectors positioned around the beampipe at a distance of 750 cm from the interaction point. Its primary purpose is the measurement of the transverse single spin asymmetries in inclusive π^0 production.

Further detail on these and other STAR detector subsystems is provided in reference [12,13].

3 Single transverse spin asymmetries from $\vec{p} + p \rightarrow \pi^0 + X$

The E704 collaboration at FNAL has measured [14] the single transverse spin asymmetries for the production of leading charged and neutral pions up to large Feynman $x_F \simeq 2E_\pi/\sqrt{s}$, $0.0 < x_F < 0.8$, and small transverse momenta $0.5 < p_T < 2.0\,\mathrm{GeV}$ in pp collisions at $\sqrt{s} = 20\,\mathrm{GeV}$. The asymmetries are found to be large and are described by models [8,9] of higher twist effects, which predict that the asymmetries persist at RHIC energies $\sqrt{s} = 200\,\mathrm{GeV}$.

The STAR collaboration aims to measure the single transverse asymmetry for neutral pions using the FPD, described above, for $0.2 < x_F < 0.6$ and $1 < p_T < 4\,\mathrm{GeV}$ during this year's spin running [13]. The SMD of the FPD allows the reconstruction of the opening angle $\phi_{\gamma_1\gamma_2}$ between the decay photons, as well as a crude partition of the energy of the photon pair measured in the FPD prototype EMC module. The invariant mass $M_{inv}^2 = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos\phi_{\gamma_1\gamma_2})$ thus reconstructed is shown in Figure 3 (left side).

The raw trigger rate from the FPD for the nominal luminosity of $5 \times 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is estimated from PYTHIA [15] simulations to be about 10 Hz for an energy threshold of 26 GeV. Figure 3 (right side) shows the projected data for 50% beam polarization from one week of running with regular data taking conditions. The continuous (dashed) line shows the model [9] asymmetry for neutral (charged) pions. Although the asymmetries for charged pions are expected to be even larger than the asymmetry for neutral pions, the observable asymmetry with the FPD is largest for π^0 since π^+ and π^- cannot be distinguished and $A(\pi^+) \simeq -A(\pi^-)$.

The measurement of the single transverse spin asymmetry in π^0 production is the main goal of this year's STAR spin physics program. The measurement will be the first at $\sqrt{s} = 200\,\mathrm{GeV}$, and will prove STAR's ability to measure spin asymmetries in the RHIC environment. If the asymmetry is confirmed to be large, the $\vec{p}p \rightarrow \pi^0 + X$ process may provide an experimental method to *in-situ* determine the beam polarization vector at the STAR interaction region [13].

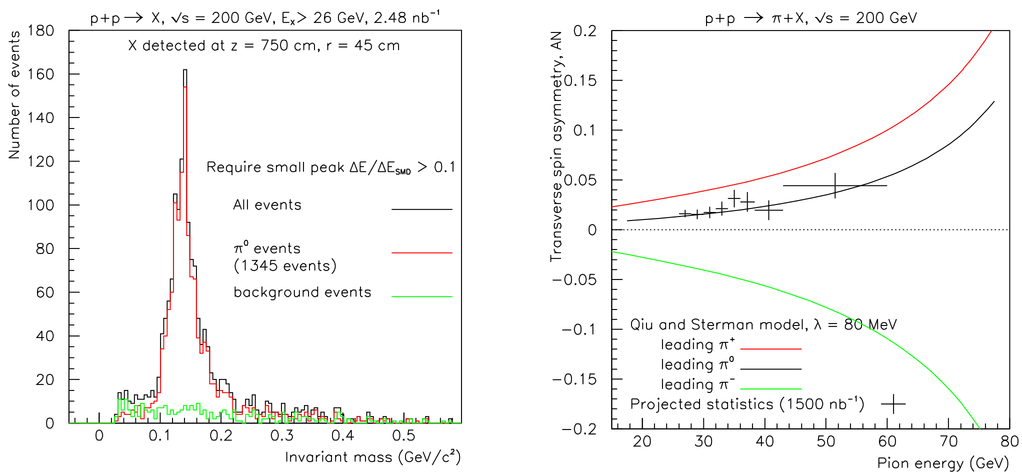

Figure 1: (Left) GEANT simulation of the di-photon invariant mass distribution reconstructed with the STAR EMC in pp collisions at $\sqrt{s} = 200$ GeV simulated[13] with PYTHIA; (Right) The single transverse asymmetry A_N for $\vec{p}p \rightarrow \pi + X$ at $\sqrt{s} = 200$ GeV as a function of the pion energy at a fixed transverse momentum of 1.5 GeV. The lines are theoretical predictions for neutral pion (continuous line) and charged pions (dashed lines). The expected statistical precision of the 2001 STAR measurements with the Forward neutral Pion Detector are indicated by the data points[13].

4 Gluon polarization from $\vec{p} + \vec{p} \rightarrow \gamma +$ jet $+X$

Prompt photon production has been the classical tool to determine the unpolarized gluon distribution for moderate and large values of x. At leading order, the photon production in pp collisions is dominated by the gluon Compton process $q + g \rightarrow \gamma + q$. PYTHIA-based simulations [15,16] show that only about 10% of the production originates from other processes, predominantly from the annihilation $q + \bar{q} \rightarrow \gamma + g$. Restricting ourselves to the Compton process, the double longitudinal spin asymmetry A_{LL} can be written at leading order as:

$$A_{LL} \simeq \frac{\Delta G(x_g, Q^2)}{G(x_g, Q^2)} \times A_1^p(x_q, Q^2) \times \hat{a}_{LL}^{\mathrm{Compton}}, \tag{2}$$

where the proton asymmetry A_1^p is known from inclusive DIS [1–4] and the partonic asymmetry $\hat{a}_{LL}^{\mathrm{Compton}}$ can be calculated in perturbative QCD. The QCD scale Q^2 is on the order of the p_T^2 for the prompt photon, and the fraction $x_q(x_g)$ of the hadron momentum carried by the quark (gluon) can be reconstructed on an event-by-event basis when the photon and the jet are detected in coincidence,

$$x_g^{\rm recon} = min(x_1, x_2), \qquad x_q^{\rm recon} = max(x_1, x_2), \tag{3}$$

$$x_{1(2)} = \frac{p_{T,\gamma}}{\sqrt{s}} \left[\exp\left(\pm\eta_\gamma\right) + \exp\left(\pm\eta_{\rm jet}\right)\right], \tag{4}$$

where η_γ and $\eta_{\rm jet}$ denote the observed photon and jet pseudorapidities, $p_{T,\gamma}$ is the observed transverse momentum of the photon, and the jet energy needs not be determined. This reconstruction works well for $x_q^{\rm recon} > 0.2$ [16]. The measurement of A_{LL} thus forms a direct determination of $\Delta G(x)/G(x)$. To estimate the precision of the future STAR measurement,

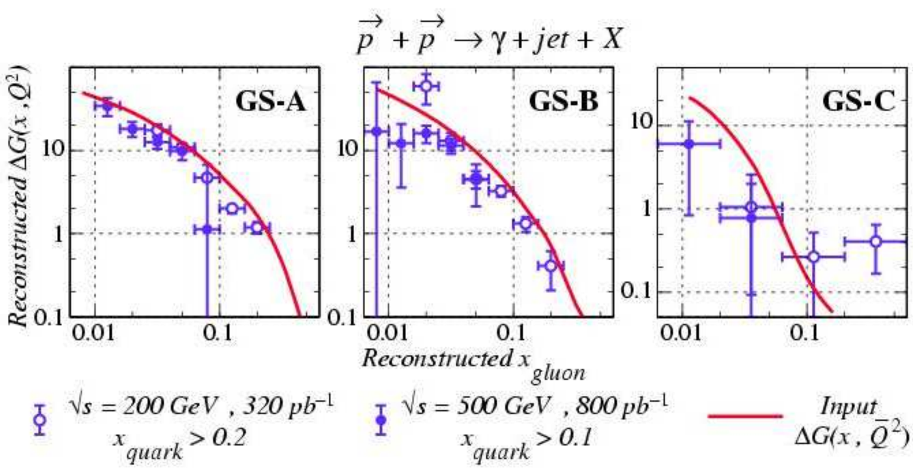

Figure 2: The estimated sensitivity of the future STAR measurements of $\Delta G(x)$ at an average Q^2 of $100\,\mathrm{GeV}^2$ from the $\vec{p}\vec{p} \to \gamma + \mathrm{jet} + X$ channel for three parametrizations of $\Delta G(x)$, as outlined in the text.

three parametrizations from reference [17] (GS-A, GS-B, and GS-C) of the largely unknown gluon distribution $\Delta G(x)$ were used. At the initial scale $Q_0^2 = 4$ GeV^2, their integrals $\Delta G = \int_0^1 \Delta G(x) \mathrm{d}x$ evaluate to $\Delta G(GS-A) = 1.7$, $\Delta G(GS-B) = 1.6$, and $\Delta G(GS-C) = 1.0$. The continuous lines in Figure 2 show the distributions evolved to $Q^2 = 100\,\mathrm{GeV}^2$.

The data points show the values of ΔG reconstructed with Eq. (2) for integrated luminosities of $320\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 200\,\mathrm{GeV}$ and $800\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 500\,\mathrm{GeV}$. The measurement for two values of $\sqrt{s}$ is essential to cover a relatively wide region in x_g, $0.01 < x_g < 0.3$. The slight underestimation of the model values of ΔG results mostly from (i) the neglect of the annihilation contribution to the observed asymmetry A_{LL} in Eq. (2), and (ii) a small sample of analyzed events with incorrectly reconstructed kinematics ($x_q^{\rm recon} \neq x_q$ and $x_g^{\rm recon} \neq x_g$), and this may be corrected for by simulation [16]. Backgrounds, predominantly high p_T fragmentation photons and photons from π^0, η^0 decays, potentially dilute A_{LL}. These backgrounds will be suppressed by requiring a large radius for the isolation cone, and by identifying and rejecting pairs of decay photons with the SMD.

The integral $\Delta G = \int_0^1 \Delta G(x)\,{\rm d}x$ from the STAR measurements of A_{LL} in $\vec{p}\vec{p} \to \gamma + {\rm jet} + X$ is expected to be determined to a precision better than ± 0.5. The knowledge of ΔG may be further improved by combining this result with the results from less favorable channels and from other experiments.

5 Single spin asymmetries in W production

STAR aims to decompose the quark spin densities in the nucleon sea by measuring the parity violating single spin asymmetries for W production in $\vec{p} + p \to W + X \to e + X$ collisions at $\sqrt{s} = 500\,{\rm GeV}$. At these energies, the W is produced predominantly through $q\bar{q}$ annihilation — a valence-sea process in pp collisions — which makes the W an ideal probe.

The leading order W production asymmetries read for $Q^2 = M_W^2$ [18]:

$$A_L^{W^+} = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}, \quad A_L^{W^-} = \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}, \tag{5}$$

where the transverse momentum of the W is neglected and the W production process is assumed to be dominated by the annihilation of light quarks [19]. The fractions $x_{1,2}$ of the hadron momentum carried by the struck quarks are related to the rapidity y_W of the W according to [20]

$$x_1 = \frac{M_W}{\sqrt{s}} \exp{(y_W)} \quad \text{and} \quad x_2 = \frac{M_W}{\sqrt{s}} \exp{(-y_W)}, \tag{6}$$

which thus needs to be reconstructed. The rapidity y_W can be determined from the observed rapidity y_e of the electron [21].

The top part of Figure 3 shows evaluations of the asymmetry based on the leading order polarized [22] and unpolarized [23] parton distributions. The continuous lines correspond to the 'Standard Scenario' [22] of flavor symmetric light sea quark and antiquark distributions at the initial QCD scale.

The dashed lines correspond to the 'Valence Scenario' [22], in which $SU(3)$ flavor symmetry is broken and the light sea densities are different ($\Delta\bar{u} \neq \Delta\bar{d} \neq \Delta\bar{s}$). The bottom part of Figure 3 compares the 'Standard Scenario' asymmetries with their intuitive, approximate forms [18]:

$$\begin{array}{llllll} A_L^{W^+} & \simeq & -\frac{\Delta\bar{d}}{\bar{d}}, & A_L^{W^-} & \simeq & -\frac{\Delta\bar{u}}{\bar{u}}, & \text{for } y_W \leq & -1, \\ A_L^{W^+} & \simeq & \frac{\Delta u}{u}, & A_L^{W^-} & \simeq & \frac{\Delta d}{d}, & \text{for } y_W \geq & 1. \end{array} \tag{7}$$

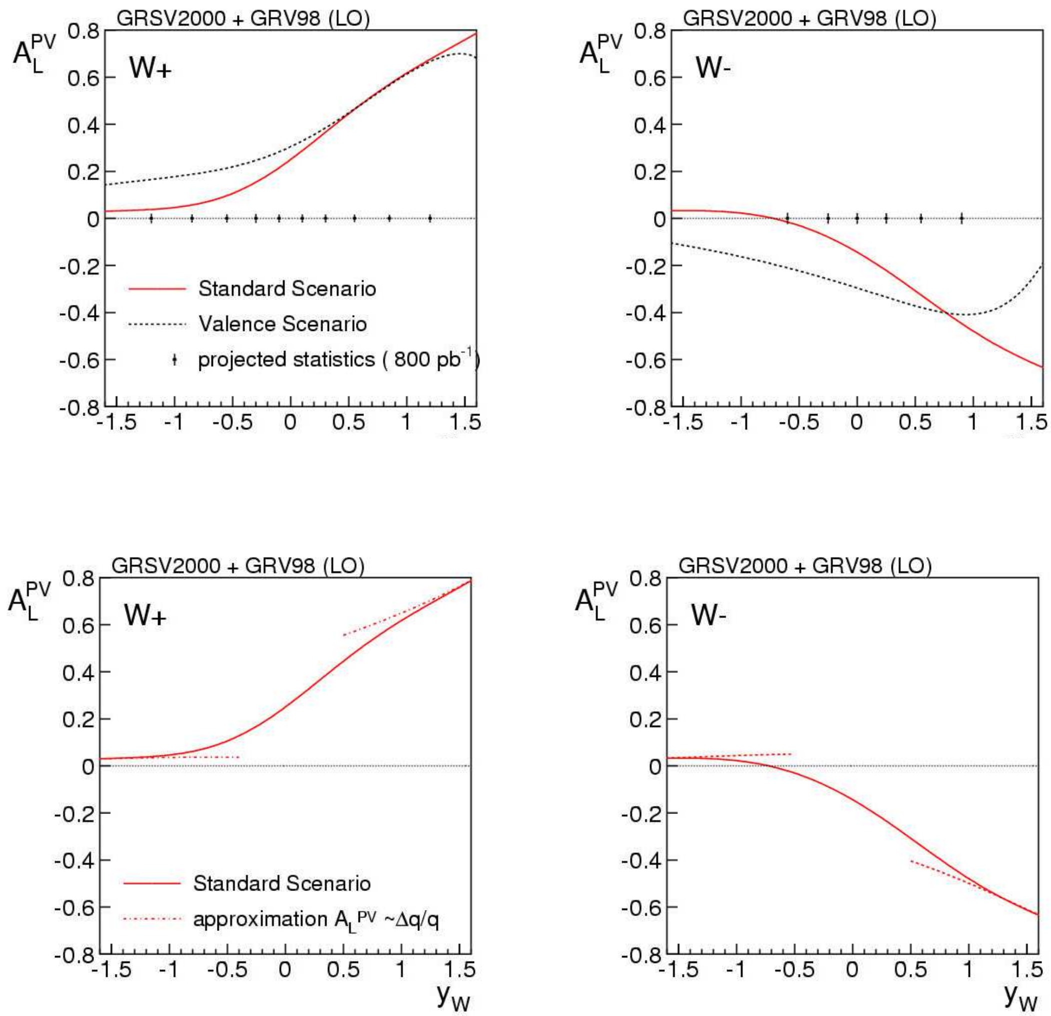

Figure 3: Top half: $A_L^W(y_W)$ for W^+ (left) and for W^- (right) for a flavor symmetric distribution of the light sea quark and antiquark polarizations (continuous line) and for a flavor asymmetric distribution (dashed line). The points indicate the projected precision of the STAR measurements for $800\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 500\,\mathrm{GeV}$. Bottom half: the asymmetries $A_L^W(y_W)$ for a flavor symmetric distribution of the light sea quark and antiquark polarizations (continuous lines) together with the intuitive approximations $A_L^W \simeq \Delta q/q$ (dashed lines), cf. Eq.(7).

The points in Figure 3 show the projected statistical precision of future STAR measurements at $\sqrt{s} = 500\,\mathrm{GeV}$. These projections are based on an integrated luminosity of $800\,\mathrm{pb}^{-1}$ and account for preliminary data selections used to reliably relate the rapidities y_e and y_W. Potentially large hadronic backgrounds will be rejected with the Preshower and SMD subsystems of the EMC, whereas backgrounds from heavy quark and Z^0 leptonic decays are estimated to be manageably small. The measurements – while demanding – are thus expected to verify various symmetry scenarios and to aid the flavor decomposition of quark spin densities in the nucleon sea.

6 Summary

The STAR collaboration is about to start its spin physics measurements, and aims in its initial running period of about five weeks for the measurement of the single transverse spin asymmetry in the production of neutral pions, using a recently installed and successfully commissioned Forward neutral Pion Detector.

During future running periods the aim of the spin measurements is to determine the polarization ΔG of gluons in the nucleon, the flavor composition of the nucleon sea, and the yet unexplored quark transversity distributions. STAR's unique ability to measure ΔG through coincident detection of direct photons and jets from $\vec{p}\vec{p}$ collisions is expected to yield a particularly competitive measurement of ΔG over a wide kinematic range, $0.01 < x_g < 0.3$. Furthermore, the high beam energies at RHIC open a window to study the flavor composition of quarks in the nucleon through weak-interactions.

RHIC starts colliding polarized protons in December 2001, thereby opening a new era in high energy spin physics — stay tuned!

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