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Constraining the polarized gluon PDF in pp collisions at RHIC

F. Ellinghaus, for the PHENIX and STAR Collaborations
University of Colorado, Boulder, CO 80309, USA

The main focus of the physics program at PHENIX and STAR that makes use of RHIC's polarized proton beams is to figure out how and if at all the gluons inside protons are polarized, or to put it another way, do the spin 1 gluons prefer to have their spins aligned or anti-aligned with the spin of the proton, or do they just not care? This question is an important part of the more general question of how the constituents of protons, gluons and quarks, conspire to make up the overall spin 1/2 of the proton. Measurements of, e.g, jet and hadron, production cross-section differences between the two cases where the two polarized protons colliding have their spins aligned and anti-aligned are sensitive to the gluon polarization, which is encoded in the spin–dependent parton distribution function (PDF) for gluons, $\Delta g(x)$.

In the most naive model, the so-called constituent quark model, in which the protons consist of three static quarks, two of the three spin 1/2 quarks will align their spins with the spin of the proton, the third one is anti-aligned, and voila, the three quarks account for the spin 1/2 of the proton. However, after pioneering experiments at SLAC starting in the mid-1970's it was the European Muon Collaboration (EMC) at CERN in the late 1980's that found the contribution of the quark spins to the spin of the nucleon to be small and actually consistent with zero within the uncertainties [1]. The most recent results by the HERMES Collaboration at DESY [2] and the COMPASS Collaboration at CERN [3] show that the quarks contribute about 30% to the spin of the nucleon, leading to our current understanding that a substantial fraction of the proton's spin has to arise from the quark orbital angular momentum and/or the gluons.

The basic principle of these measurements is to use deep inelastic scattering (DIS) of longitudinally polarized leptons off longitudinally polarized nucleons, which are usually embedded in a gaseous or solid state target. The polarized lepton will interact with a quark inside the polarized nucleon via the exchange of a spin 1 virtual photon. This photon can only be absorbed by the quark when the spins of the quark and the photon are anti-aligned due to angular momentum conservation. The cross section for this process can be measured for the two cases where the spin of the leptons and the nucleons is aligned and anti-aligned, and depending on which cross section turns out to be bigger, one can learn if the quark spins tend to be aligned or anti-aligned with the spin of the nucleon. This cross section difference is usually measured as a function of Q^2, the negative four-momentum squared of the virtual photon, and of x, the fraction of the momentum of the (fast) proton carried by the struck parton, and it is given in terms of the so-called polarized structure function $\mathrm{g}_1(x, Q^2)$.

The possible contribution of the gluon spin $\Delta G(Q^2) = \int_0^1 dx \Delta g(x, Q^2)$ to the nucleon spin has first been studied in DIS. The problem with studying gluons in DIS is that the electromagnetic probe, the photon, cannot directly couple to the gluon since gluons carry no electric charge. An indirect way of accessing the polarized gluon PDF $\Delta g(x)$ is via next-to-leading order (NLO) fits to the above mentioned structure function $g_1(x, Q^2)$. The information on the polarized gluon PDF is contained in the dependence of g_1 on Q^2 at a given x, which is nearly constant. To be precise, it is the difference from the constant behavior, the so-called scaling violation, which contains the information. However, since all measurements of g_1 have been done at fixed-target experiments the range in Q^2 covered is very limited, leading to rather large uncertainties for $\Delta g(x)$. A more direct way to measure $\Delta g(x)$ at the DIS experiments is via a NLO process called photon-gluon fusion (PGF), in which the virtual photon and the gluon interact via the creation of a quark-antiquark pair. However, the available results so far suffer from the fact that the energy scale at the fixed-target experiments is rather low.

Thus, the motivation to study the gluon in pp collisions at the STAR and PHENIX experiments at RHIC (Relativistic Heavy Ion Collider) at BNL is quite natural. The involved energies are high and the gluon participates in leading order since the basic processes of interest are the scattering of quarks off gluons and of gluons off gluons. Similar to the case of g_1 the cross section difference is measured between the two cases where the two polarized

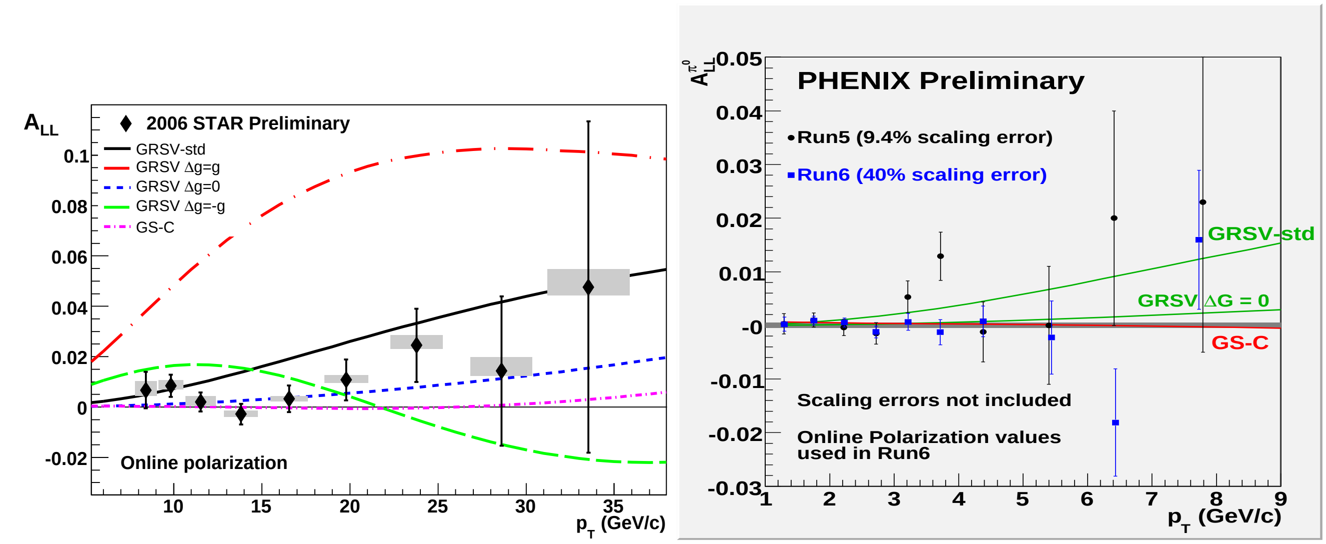


Figure 1: Double helicity asymmetry for mid-rapidity inclusive jet (left panel) production from the 2006 (preliminary, see Ref. [8] for final results from 2005 data) data and π^0 (right panel) production from the 2006 (preliminary[a]) and 2005 data [5] at $\sqrt{s} = 200$ GeV as a function of p_T. The results for the asymmetries are compared to pQCD calculations [10] based on different sets of polarized PDFs [11, 12]. See text for details.

protons colliding have their spins aligned and anti-aligned. To be precise, the difference divided by the sum, the so-called double helicity asymmetry

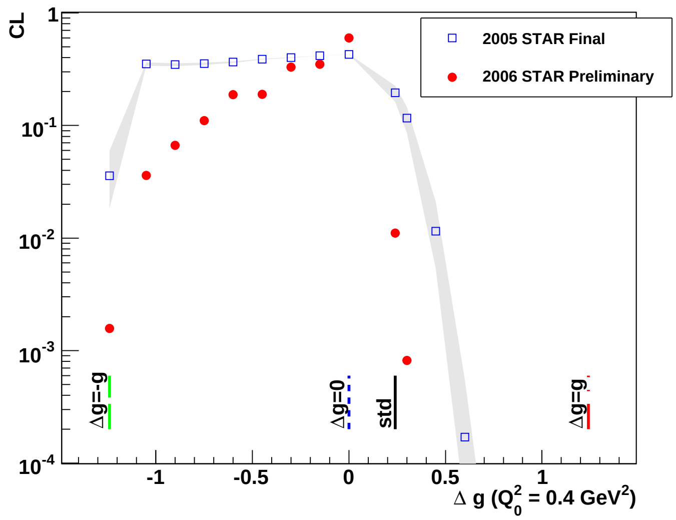
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\Delta\sigma}{\sigma}, \quad \text{with} \quad \Delta\sigma \propto \sum_{abc} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma}^{ab\to cX'} \otimes D_c^h, \tag{1}$$

is measured, where the cross section σ^{++} (σ^{+-}) describes the reaction where both protons have the same (opposite) helicity. The spin–dependent term is given on the rhs of Eqn. 1, where Δf_a, Δf_b represent the spin–dependent PDFs for quarks (u,d,s) and gluons, which, from the NLO fits to g_1 as mentioned above, are well known for quarks but not well known for gluons. The fragmentation functions D_c^h represent the probability for a certain parton c to fragment into a certain hadron h, and thus they are not needed in the case of jet production. The spin–dependent hard scattering cross sections $\Delta\hat{\sigma}$ have to be calculated using perturbative QCD. Thus, the applicability of perturbative QCD in the kinematic regime of the A_{LL} measurements is a crucial prerequisite. This has been checked by comparing the results from NLO pQCD calculations using the well known unpolarized PDFs for quarks and gluons with measured unpolarized cross sections for, e.g., the inclusive production of jets [4] or neutral pions [5]. Good agreement has been found giving confidence in proceeding with measurements of the double helicity asymmetry (Eqn. 1), which experimentally translates into

$$A_{LL} = \frac{1}{|P_B||P_Y|}\frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}, \quad \text{with} \quad R \equiv \frac{L_{++}}{L_{+-}}, \tag{2}$$

where N_{++} (N_{+-}) and L_{++} (L_{+-}) are the experimental yield N and luminosity L for the case where the beams have the same (opposite) helicity. The relative luminosity R is just the ratio of the two luminosities. The polarizations of the two colliding beams at RHIC are denoted by P_B and P_Y. The degree of polarization is determined from the combined information of a $\vec{p}C$ polarimeter [6], using an unpolarized ultra–thin carbon ribbon target, and from $\vec{p}\vec{p}$ scattering, using a polarized atomic hydrogen gas-jet target [7]. The average polarization value for the data from 2005 (2006) is 49% (57%).

[a]Final results are now available in Ref. [9].



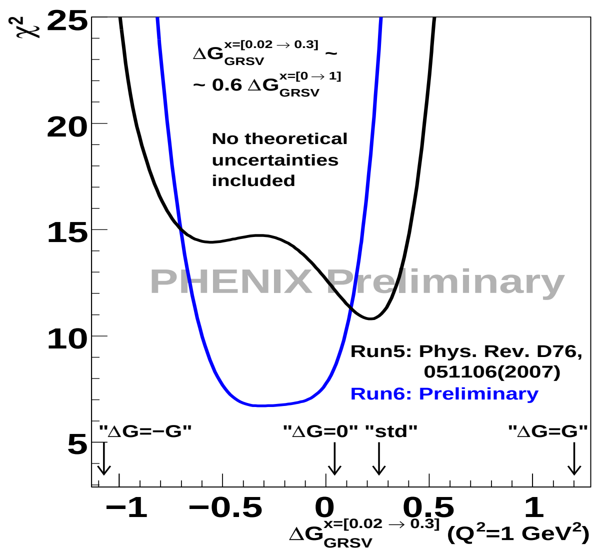


Figure 2: Confidence level of the STAR jet data (left panel) and χ^2 profile for the PHENIX π^0 data (right panel) resulting from a comparison to four GRSV [12] scenarios as well as for several other values of ΔG at the input scale [10].

The double helicity asymmetry as a function of the transverse momentum p_T for jet production at STAR and π^0 production at PHENIX are shown in Fig. 1. The results are compared to NLO pQCD calculations [10], using two sets of polarized PDFs. In addition to the GS-C PDFs [11], the GRSV PDFs [12] (GRSV-std) have been modified by assuming the polarized gluon PDF to be zero ($\Delta G = 0$), equal ($\Delta G = G$), or opposite ($\Delta G = -G$) to the unpolarized gluon PDF at the input scale. It is apparent from Fig. 1 that the maximum and minimum GRSV scenarios, which are not even shown anymore on the PHENIX plot, are ruled out by both experiments. While not excluded, GRSV-std is disfavored by the data as can be seen in Fig. 2, where for the STAR jet data (PHENIX π^0 data) the confidence level (χ^2 profile) is shown for the four GRSV scenarios as well as for several other values of ΔG at the input scale. Note that no uncertainties have been calculated for the GRSV set of PDFs, and that they in general are rather large for the poorly constrained $\Delta g(x)$ from the DIS data as discussed above (see, e.g., Ref. [13]), hence the RHIC results remain consistent with the results from DIS.

Based on Fig. 2 a small or maybe negative contribution of the gluon spin ΔG to the nucleon spin appears to be most likely; however, this is a model dependent result. The present inclusive measurements cannot determine x but are sensitive to the gluon contribution integrated over the range $0.05 < x < 0.2$. Thus, in case the gluon contribution is large outside the presently accessible x–range it could still account for all the "missing" spin, even though the contribution in the limited accessible x range is rather small. An example is the predicted asymmetry based on the GS-C PDF also shown in both panels of Fig. 1. It is consistent with the present data, but the GS-C PDF gives a large contribution of gluons to the nucleon spin due to the fact that it is large and positive at small x and becomes negative above $x \approx 0.1$. In other words, the gluon contribution is small in the measured region since it has a node, but the positive contribution at smaller x could account for all the spin due to the abundance of gluons at small x.

These features can also be seen in Fig. 3, which shows a recent NLO pQCD fit (DSSV [14]), including for the first time the pp data in addition to DIS and semi-inclusive DIS in the extraction of the polarized PDFs, a so-called global fit. In the x range accessible at RHIC the DSSV fit yields smaller values for $x\Delta g(x)$ than the earlier GRSV or DNS [15] fits with much reduced uncertainties. However, at smaller values of x the uncertainties are large and thus allow for a large $x\Delta g(x)$. A lower (higher) range in x can be probed running RHIC at higher (lower) energies. Results on π^0 production at PHENIX at $\sqrt{s} = 62.4$ GeV are already available [16], while running at $\sqrt{s} = 500$ GeV is foreseen to start in 2009. In addition, measurements at forward rapidity will allow access to a lower range in x. Also, with more data available in the future it is possible to advance from inclusive measurements, in which only one

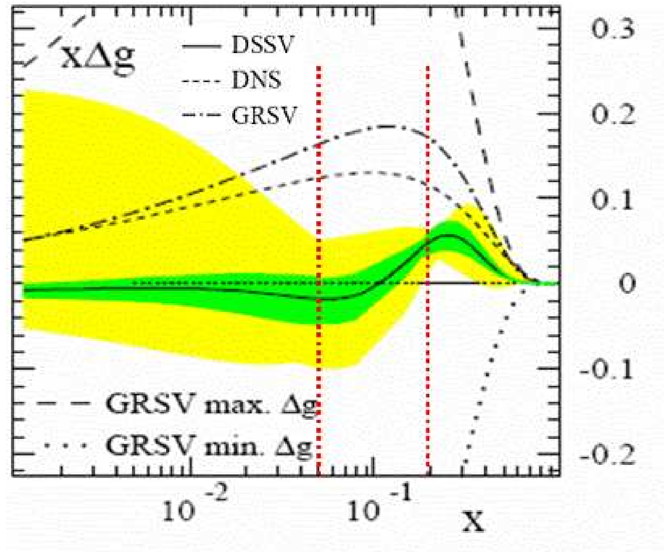


Figure 3: Polarized gluon PDF from a fit [14] that included for the first time the pp data (in addition to DIS and semi-inclusive DIS), compared to the earlier fits GRSV and DNS [15]. Alternative DSSV fits corresponding to $\Delta\chi^2 = 1$ ($\Delta\chi^2/\chi^2 = 2\%$) are given by the green (yellow) bands. Figure taken from Ref. [14].

particle in the final state is detected, to measurements in which two or more leading particles or jets are detected in the final state, allowing for a much better handle on the x-dependence. Since in DIS the momentum fraction x can be measured directly, a precise measurement of the functional from of the polarized gluon PDF $\Delta g(x)$ will be possible at a proposed polarized electron-proton collider called EIC [17], which would be able to overcome the difficulties arising from the low energy scale and limited Q^2 range at fixed-target experiments.

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