Evidence for Polarization of Gluons in the Proton

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We discuss the impact of recent high-statistics Relativistic Heavy Ion Collider data on the determination of the gluon polarization in the proton in the context of a global QCD analysis of polarized parton distributions. We find evidence for a nonvanishing polarization of gluons in the region of momentum fraction and at the scales mostly probed by the data. Although information from low momentum fractions is presently lacking, this finding is suggestive of a significant contribution of gluon spin to the proton spin, thereby limiting the amount of orbital angular momentum required to balance the proton spin budget.

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Introduction.—The gluon helicity distribution function $\Delta g(x)$ of the proton has long been recognized as a fundamental quantity characterizing the inner structure of the nucleon. In particular, its integral $\Delta G \equiv \int_0^1 dx \Delta g(x)$ over all gluon momentum fractions x may in $A^+ = 0$ light-cone gauge be interpreted as the gluon spin contribution to the proton spin [1]. As such, ΔG is a key ingredient to the proton helicity sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g, \qquad (1)$$

where $\Delta\Sigma$ denotes the combined quark and antiquark spin contribution and $L_{q,g}$ are the quark and gluon orbital angular momentum contributions. For simplicity, we have omitted the renormalization scale Q and scheme dependence of all quantities.

It is well known that the quark and gluon helicity distributions can be probed in high-energy scattering processes with polarized nucleons, allowing access to $\Delta\Sigma$ and ΔG. Experiments on polarized deep inelastic lepton-nucleon scattering (DIS) performed since the late eighties [2] have shown that relatively little of the proton spin is carried by the quark and antiquark spins, with a typical value $\Delta\Sigma \sim 0.25$ [2–4]. The inclusive DIS measurements have, however, very little sensitivity to gluons. Instead, the best probes of Δg are offered by polarized proton-proton collisions available at the BNL Relativistic Heavy Ion Collider (RHIC) [5]. Several processes in pp collisions, in particular jet or hadron production at high transverse momentum p_T, receive substantial contributions from gluon-induced hard scattering, hence, opening a window on Δg when polarized proton beams are used.

The first round of results produced by RHIC until 2008 [5] were combined with data from inclusive and semi-inclusive DIS in a next-to-leading order (NLO) global QCD analysis [3], hereafter referred to as "DSSV analysis". One of the main results of that analysis was that the RHIC data—within their uncertainties at the time—did not show any evidence of a polarization of gluons inside the proton. In fact, the integral of Δg over the region $0.05 \leq x \leq 0.2$ of momentum fraction primarily accessed by the RHIC experiments was found to be very close to zero. Other recent analyses of nucleon spin structure [4] did not fully include RHIC data; as a result Δg was left largely unconstrained.

Since the analysis [3], the data from RHIC have vastly improved. New results from the 2009 run [6,7] at center-of-mass energy $\sqrt{s} = 200$ GeV have significantly smaller errors across the range of measured p_T. This will naturally put tighter constraints on $\Delta g(x)$ and may extend the range of x over which meaningful constraints can be obtained. A striking feature is that the STAR jet data [6] now exhibit a double-spin asymmetry A_{LL} that is clearly nonvanishing over the whole range $5 \lesssim p_T \lesssim 30$ GeV, in contrast to the previous results. Keeping in mind that, in this regime, jets are primarily produced by gluon-gluon and quark-gluon scattering, this immediately suggests that gluons inside the proton might be polarized. At the same time, new PHENIX data for π^0 production [7] still do not show any significant asymmetry, and it is of course important to reveal whether the two data sets provide compatible information. In this Letter, we assess the impact of the 2009 RHIC data sets on

Δg in the context of a new NLO global analysis of helicity parton densities.

Global analysis and new and updated data sets.—As just described, the key ingredients to our new QCD analysis are the 2009 STAR [6] and PHENIX [7] data on the double-spin asymmetries for inclusive jet and π^0 production. At the same time, we also update some of the earlier RHIC results used in [3] and add some new DIS data sets by the COMPASS experiment. More specifically, we now utilize the final PHENIX π^0 data from run 6 at $\sqrt{s} = 200$ GeV [8] and 62.4 GeV [9], the final STAR jet results from run 5 and run 6 [10], and the recent inclusive [11] and semi-inclusive [12] DIS data sets from COMPASS. As far as the impact on Δg is concerned, the data sets [6,7] clearly dominate. The COMPASS data sets will primarily affect the quark and antiquark helicity distributions as reported in [13].

The method for our global analysis has been described in detail in [3] and will not be presented here again. It is based on an efficient Mellin-moment technique that allows one to tabulate and store the computationally most demanding parts of a NLO calculation prior to the actual analysis. In this way, the evaluation of the relevant spin-dependent pp cross sections [14] becomes so fast that it can be easily performed inside a standard χ^2 minimization analysis. As a small technical point, we note that STAR has moved to the "anti-k_t" jet algorithm [15] for their analysis of the data from the 2009 run. In order to match this feature, we use the NLO expressions derived in [16] for the polarized case. As in our previous DSSV analysis [3], standard Lagrange multiplier (LM) and Hessian techniques are employed in order to assess the uncertainties of the polarized parton distributions determined in the fit.

We adopt the same flexible functional form as in [3] to parametrize the NLO helicity parton densities at the initial scale $Q_0 = 1$ GeV, for instance,

$$x\Delta g(x, Q_0^2) = N_g x^{\alpha_g}(1-x)^{\beta_g}(1+\eta_g x^{\kappa_g}), \qquad (2)$$

with free parameters N_g, α_g, β_g, η_g, and κ_g. Note that this parametrization allows for a node in the distribution, as realized by the central gluon density of the DSSV analysis [3]. We enforce positivity $|\Delta f|/f \leq 1$ of the parton densities, using the unpolarized distributions $f(x, Q^2)$ of [17], from where we also adopt the running of the strong coupling. We use the same set for computing the spin-averaged cross sections in the denominators of the spin asymmetries.

Results of global analysis.—Figure 1 shows our new result for the gluon helicity distribution $\Delta g(x, Q^2)$ at $Q^2 = 10\ \mathrm{GeV}^2$. The solid line presents the updated central fit result, with the dotted lines corresponding to additional fits that are within the 90% confidence level (C.L.) interval. In defining this interval, we follow the strategy adopted in Ref. [17]. These alternative fits may be thought of as spanning an uncertainty band around Δg within this

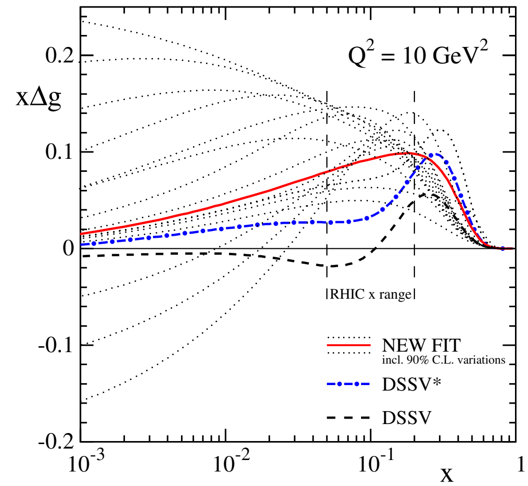

FIG. 1 (color online). Gluon helicity distribution at $Q^2 = 10\ \mathrm{GeV}^2$ for the new fit, the original DSSV analysis of [3], and for an updated analysis without using the new 2009 RHIC data sets (DSSV*, see text). The dotted lines present the gluon densities for alternative fits that are within the 90% C.L. limit. The x range primarily probed by the RHIC data is indicated by the two vertical dashed lines.

tolerance and for the adopted functional form (2). The dotted-dashed curve represents the result of a fit—henceforth labelled as "DSSV*"—for which we only include the updates to the various RHIC data sets already used for the original DSSV analysis [3] (dashed line); i.e., we exclude all the new 2009 data [6,7]. The new COMPASS inclusive [11] and semi-inclusive [12] DIS data sets have little impact on Δg and are included in the DSSV* fit.

The striking feature of our new polarized gluon distribution is its much larger size as compared to that of the DSSV analysis [3]. For $Q^2 = 10\ \mathrm{GeV}^2$, it is positive throughout and clearly away from zero in the regime $0.05 \leq x \leq 0.2$ predominantly probed by the RHIC data, as is demonstrated by the alternative fits spanning the 90% C.L. interval. In contrast to the original DSSV gluon distribution, the new Δg does not show any indication of a node in the RHIC x range [18]. It is interesting to notice that the DSSV* fit, without the new 2009 but with updated earlier RHIC data sets, already tends to have a positive Δg. This trend is then very much strengthened, in particular, by the 2009 STAR data [6].

Figure 2 shows the comparison to the new STAR jet data [6] obtained with our new set of spin-dependent distributions. As in the analysis itself, we have chosen both the factorization and renormalization scales as p_T. STAR presents results for two rapidity ranges, $|\eta| < 0.5$ and $0.5 < |\eta| < 1$. It is evident that the new fit describes the data very well in both ranges. We also illustrate the uncertainties corresponding to our analysis, using the LM method with a tolerance $\Delta\chi^2 = 1$ unit (inner bands) and 90% C.L. (outer bands). The result for our previous

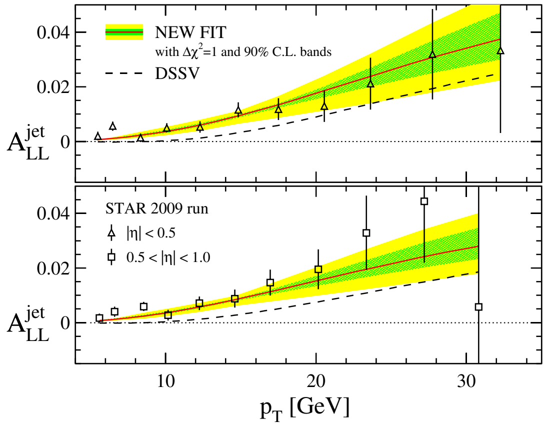

FIG. 2 (color online). Latest STAR data [6] for the double-spin asymmetry in jet production for two rapidity ranges compared to the results of our new and original [3] analyses. The inner and outer bands correspond to $\Delta\chi^2 = 1$ unit and 90% C.L., respectively.

DSSV analysis [3] is also shown. As one can see, it falls considerably short of the data in the region $10 \lesssim p_T \lesssim 20$ GeV, where it barely touches the new uncertainty band. This precisely demonstrates the fact mentioned earlier that the 2009 jet data [6] tend to exhibit a somewhat higher asymmetry than previously, resulting in larger gluon polarization in the new fit. Comparing to the results of [3], one finds that the uncertainty bands for our new fit have become significantly narrower than for the DSSV one. The new analysis, including updates and new data, is within the uncertainty estimate for the old DSSV fit [3].

Figure 3 shows corresponding comparisons to the PHENIX data for A_{LL} in π^0 production at $\sqrt{s} = 62.4$ and 200 GeV [7,9]. In contrast to jet production, the asymmetries are consistent with zero within uncertainties. As a result, they are still perfectly described by a calculation based on the original DSSV analysis with its small gluon polarization exhibiting a node. Within our new analysis, here, we also obtain a larger spin asymmetry that still describes the data very well. In this sense, the new STAR and PHENIX data sets are mutually consistent.

It is worth pointing out in this context that the RHIC jet and pion data sets probe $\Delta g(x)$ at different scales Q, owing to the different ranges in transverse momentum accessed. As a result, the scale evolution of $\Delta g(x)$ plays a role here, a point that we will elaborate on now. Figure 4 shows the variation of the total χ^2 of the fit as a function of the truncated first moment in the RHIC x range, $\int_{0.05}^{0.2} dx \Delta g(x, Q^2)$, for various values of Q^2. The solid curve corresponds to $Q^2 = 10$ GeV^2, which once more demonstrates that the truncated moment is clearly positive at this scale within our estimated 90% C.L. variations indicated at the base of the plot. As one can see, towards lower scales the central value of the moment decreases and its uncertainty increases. The observed relatively strong scale dependence is reminiscent of that known for the full first moment [19]. It is a significant factor for the consistency between the PHENIX π^0 data taken at lower scales and the STAR jet data at higher scales. In the original DSSV analysis [3], the χ^2 was dominated by data at lower scales, hence, resulting in the nearly vanishing Δg. A feature related to these observations is that our new gluon distribution is peaked at relatively high x at the input scale, in fact, just above the RHIC region. Evolution then pushes the distribution toward lower x, making it compatible with the STAR data which probe it at much higher scales.

Ultimately, one is interested, of course, in a reliable determination of the full integral ΔG entering in (1). RHIC

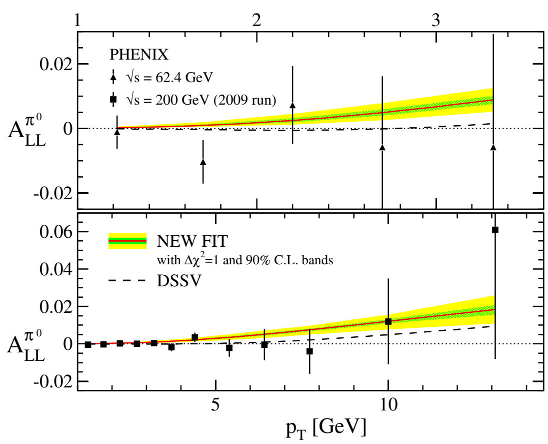

FIG. 3 (color online). As in Fig. 2, but comparing to the PHENIX data [7,9] for the double-spin asymmetry in π^0 production at $\sqrt{s} = 62.4$ GeV (upper panel) and $\sqrt{s} = 200$ GeV (lower panel).

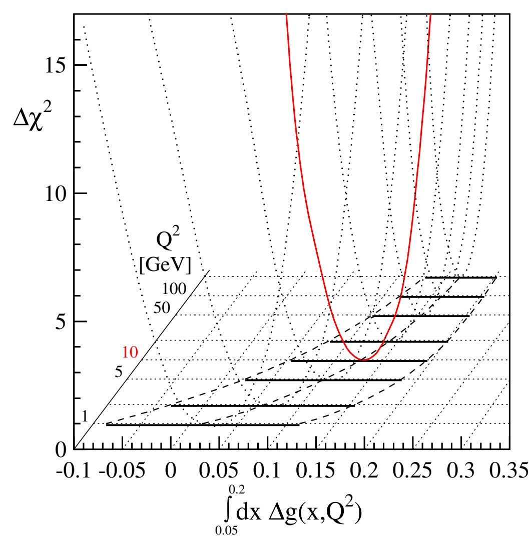

FIG. 4 (color online). Change of the $\Delta\chi^2$ profile of the truncated first moment of Δg in the RHIC x range with Q^2. The solid lines at the base of the plot indicate the 90% C.L. interval.

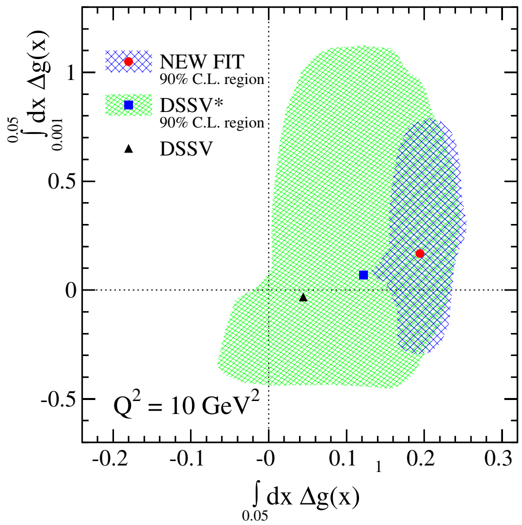

FIG. 5 (color online). 90% C.L. areas in the plane spanned by the truncated moments of Δg computed for $0.05 \le x \le 1$ and $0.001 \le x \le 0.05$ at $Q^2 = 10\ \text{GeV}^2$. Results for DSSV, DSSV*, and our new analysis, with the symbols corresponding to the respective values of each central fit, are shown.

data mainly probe the region $0.05 \le x \le 0.2$, but the more precise 2009 results help to constrain $\Delta g(x)$ better down to somewhat lower values $x \simeq 0.02$. Here, some very limited information on Δg is also available from scaling violations of the DIS structure function g_1 which is, of course, fully included in our global QCD analysis. Overall, the constraints on $\Delta g(x)$ in, say, the regime $0.001 \le x \le 0.05$ are much weaker than those in the RHIC region, as can be inferred from Fig. 1. Very little contribution to ΔG is expected to come from $x > 0.2$.

Figure 5 shows our estimates for the 90% C.L. area in the plane spanned by the truncated moments of Δg calculated in $0.05 \le x \le 1$ and $0.001 \le x \le 0.05$ for $Q^2 = 10\ \text{GeV}^2$. Results are presented both for the DSSV* and our new fit. The symbols in Fig. 5 denote the actual values for the best fits in the DSSV, DSSV*, and the present analyses. We note that for our new central fit the combined integral $\int_{0.001}^{1} dx \Delta g(x, Q^2)$ accounts for over 90% of the full ΔG at $Q^2 = 10\ \text{GeV}^2$. Not surprisingly, the main improvement in our new analysis is to shrink the allowed area in the horizontal direction, corresponding to the much better determination of $\Delta g(x)$ in range $0.05 \le x \le 0.2$ by the 2009 RHIC data. Evidently, the uncertainty in the smaller-x range is still very significant, and better small-x probes are badly needed. Data from the 2013 RHIC run at $\sqrt{s} = 510\ \text{GeV}$ may help here a bit. In the future, an electron-ion collider would provide the missing information, thanks to its large kinematic reach in x and Q^2 [20].

Conclusions and outlook.—We have presented a new global analysis of helicity parton distributions, taking into account new and updated experimental results. In particular, we have investigated the impact of the new data on A_{LL} in jet and π^0 production from RHIC's 2009 run. For the first time, we find that the jet data clearly imply a polarization of gluons in the proton at intermediate momentum scales, in the region of momentum fractions accessible at RHIC. This constitutes a new ingredient to our picture of the nucleon. While it is too early to draw any reliable conclusions on the full gluon spin contribution to the proton spin, our analysis clearly suggests that gluons could contribute significantly after all. This in turn also sheds a new light on the possible size of orbital angular momenta of quarks and gluons. We hope that future experimental studies, as well as lattice-QCD computations that now appear feasible [21], will provide further information on $\Delta g(x)$ and eventually clarify its role for the proton spin. We plan to present a full new global analysis with details on all polarized parton distributions once the 2009 RHIC data have become final and additional information on the quark and antiquark helicity distributions, in particular from final data on W boson production at RHIC, has become available. Also, on the theoretical side, a new study of pion and kaon fragmentation functions should precede the next global analysis of polarized parton distributions.

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