The polarised gluon density $\Delta G(x)$ from di-jet events at high energy $ep$-colliders

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We present the potential to determine the polarised gluon density from boson-gluon fusion processes with di-jet events at future high energy $ep$-colliders. These include HERA at DESY operated with polarised electrons and protons, polarised protons from HERA colliding on polarised electrons from a future linear collider, and polarised protons from RHIC at BNL colliding on electrons from a future electron accelerator.

Introduction

The origin of the spin in the proton is still a subject of debate. The last generation of deep inelastic scattering (DIS) experiments has confirmed that the quarks account for only 30% of the proton spin. Next-to-leading order (NLO) QCD fits of the $g_1$ structure function and semi-inclusive data suggest that the contribution of the gluon to the spin could be large [1]. A first attempt of a direct measurement of the polarised gluon distribution, $\Delta G$, using leading charged particles [2] is not in conflict with this suggestion. In general, it has been concluded that major progress in our understanding of the spin structure can be made with clear and unambiguous direct measurements of $\Delta G$.

Polarized $ep$-colliders are particularly suited for this task. It has been demonstrated by the present unpolarized studies at HERA that the large centre of mass system (CMS) energy allows for several processes to be studied which show a clear sensitivity to the gluon distribution in the proton. Consequently one could expect that a powerful method to access $\Delta G$ is the measurement of di-jet rate asymmetries at high energy colliders of polarised electrons and protons. In LO two diagrams can lead to di-jet events (Fig. 1): the photon-gluon fusion (PGF) and the QCD-Compton process. The PGF is directly sensitive to the gluon density, while the QCD-Compton process is sensitive to the quark densities and constitutes the background.

Several feasibility studies on extracting the polarised gluon density $\Delta G$ from di-jet events at HERA in LO have been performed during the last years and are summarized in [3–5]. These studies established the di-jet process as a prime candidate to access the polarised gluon directly. Extracting $\Delta G$ at HERA in NLO has been studied as well [6]. The studies have been extended to eRHIC and THERA. In this paper we summarize the main results of these studies. In Section 1 we recall the results for HERA. Section 2 describes a first look at the potential of a combination of HERA and a possible future linear collider at DESY. In

Figure 1. Feynman diagrams for PGF and QCD-Compton processes.
Section 3 we show in a somewhat greater detail what could be achieved at BNL, if a new accelerator for polarised electrons would be build, and its electrons would collide with the polarised protons from RHIC.

1. HERA as an $\vec{e}\vec{p}$-collider

At HERA 820 (920) GeV protons collide with 27.5 GeV electrons, providing a center-of-mass energy $\sqrt{s} \approx 300(320)$ GeV. Studies of upgrading HERA to a fully polarised electron-proton collider are discussed in [4,5]. The potential of an extraction of $\Delta G$ in LO, assuming that both beams are 70% polarised, is shown in Figure 2. The different assumptions for the particle density functions are the Gehrmann-Stirling (GS) sets A and C [8], and the instanton-gluon distribution [9].

$\Delta G$ at HERA for a luminosity of $500 \text{pb}^{-1}$ was used, which allowed to include hadronisation and detector effects. Higher order effects were partly taken into account by unpolarised parton showers. The cuts chosen for this analysis are: $5 < Q^2 < 100 \text{GeV}^2$, $0.3 < y < 0.85$, and two jets with a $p_t > 5 \text{GeV}$ are required in the pseudo-rapidity region of $|\eta_{\text{jet}}| < 2.8$. Furthermore a cut on the invariant mass of the two jets, $s_{ij} > 100 \text{GeV}$, is applied. Fig. 3 demonstrates that the polarised gluon is measurable in the $x$-range (of the gluon) of 0.002 < $x$ < 0.2. Note that this measurement allows the determination of the shape of $\Delta G(x)$. Furthermore it reaches $x$-values lower than any other measurement in future so far, and (for a GS-A type of gluon) will measure about 75% of the first $\Delta G(x)$ from di-jets at NLO, shown on top of the GS-A parton density curve, for two values of integrated luminosity. The expected value for the beam polarisation is taken into account. GS-C is shown for reference.

![Figure 2. Sensitivity to $\Delta G/G$ (a) and $x\Delta G$ (b) at HERA for a luminosity of 500 pb$^{-1}$ and three different assumptions for the shape of $\Delta G(x)$. The error bars represent statistical errors. The shaded band gives an estimate of the systematic errors.](image)

![Figure 3. The statistical precision of a measurement of $x\Delta G(x)$ from di-jets at NLO, shown on top of the GS-A parton density curve, for two values of integrated luminosity. The expected value for the beam polarisation is taken into account. GS-C is shown for reference.](image)
measurability now becomes $0.005 < x < 0.5$, the measurement will be less precise than in LO, but still has a very significant discrimination power, even already for a luminosity of 200 pb$^{-1}$.

![Figure 4. Asymmetries measured using a 800 GeV $e^-$ beam of TESLA on a 820 GeV $p$ beam from HERA, for two selected $Q^2$ regions (top/bottom). On the left hand side the low-$x$ region is expanded and the newly reachable low-$x$ domain is shown by the hatched region of the plot.](image)

2. THERA: combining HERA and TESLA

THERA is a proposal to collide a 250 to 800 GeV electron beam, delivered by a linear collider such as TESLA, on the 920 GeV proton beam of HERA. A di-jet study has been made in LO with MEPJET to check the reach of THERA. The result is shown in Fig. 4 for jet selection cuts as for (LO) HERA, and for the optimistic case of having a 800 GeV electron beam on 820 GeV protons. The plot is shown for a polarisation of the beams of 100%. At the lowest $x$-values the asymmetries get very small, i.e. of order of $10^{-3}$, and become unmeasurable even with a statistics of 1 fb$^{-1}$. But with a statistics in that ball-park, one can hope to measure $\Delta G(x)$ about one order of magnitude lower in $x$ of the gluon compared to HERA: the reach at THERA is $0.0005 < x < 0.1$.

3. eRHIC: adding electrons to RHIC

Recently, it has been suggested to add an electron ring or electron LINAC to the RHIC rings. The latter are presently being commissioned to provide a polarised proton beam of 250 GeV. The polarised electron beam energy would be around 10 GeV, leading to a total CMS energy of 100 GeV for this facility, baptised eRHIC, or EIC (Electron Ion Collider). The reachable luminosity is expected to be very high for this collider, of the order of 4 fb$^{-1}$/year.

A LO MEPJET study was made for eRHIC. The jet selection cuts have been optimized for reaching largest sensitivity: two jets with a $p_t > 3$ GeV are required in the pseudo-rapidity region of $-3.5 < \eta_{jet} < 4$ and $s_{ij} > 100$ GeV is required. The region in $\eta$ used is larger than for HERA and THERA, and will be a challenge for the detector design. With HERA-like cuts some of the precision is lost, but the measurement is still very significant.

Fig. 6 shows the asymmetries as function of $x_g$ for both HERA and eRHIC, and the expected error bars for 1 fb$^{-1}$, calculated with 100% polarisation. Fig. 7 shows the statistical precision reachable for data samples with different luminosity, calculated with MEPJET, and assuming 70% polarisation for both beams. The figure also shows the sensitivity to the gluon distribution. Clearly a good separation power between different models for $\Delta G$ is preserved. The polarised gluon can be measured in the region $0.02 < x < 0.3$. For larger values the asymmetries to the QCD compton background are dominating and its use will depend on how well one can control this contribution.

In Table 1 we present the $x$-values of possible measurements of $\Delta G$ and the corresponding
sensitivities for two different values of the \( p_t \) cut of the jets. Hadronisation and detector effects are taken into account as correction factors determined by comparing MEPJET and PEPSI results, as studied for HERA. These corrections inflate the errors by 40-60%. Lowering the jet \( p_t \) is in particular important for reaching higher sensitivities in the low-\( x \) region.

Finally we present a table with the sensitivities for HERA and for eRHIC of measurable points with statistical errors, after taking into account effects of NLO, hadronisation and detector smearing. All effects are computed as correction factors to the LO MEPJET results, determined from the detailed HERA studies with PEPSI and NLO MEPJET/DISENT. The result of the \( x \)-values of the possible data points and their error is given in Table 1. For eRHIC the values correspond to the \( p_t \)-jets cut: \( p_t > 5 \) GeV. These numbers can be used e.g. in general QCD fits to \( g_1 \) data, by using the di-jet cross sections as a constraint on the gluon, as done e.g. in [15] for a LO study on a polarised HERA.

### Table 1
Possible measurements (\( x \)-values) and corresponding sensitivities to \( \Delta G \) at eRHIC in LO, for 4 \( \text{fb}^{-1} \), for two different cuts on the \( p_t \) of the jets. Beam polarisations of \( P_e \cdot P_p = 50\% \) are assumed.

| \( p_t \) > 3 GeV | \( p_t \) > 5 GeV |
|------------------|------------------|
| \( x \)          | \( \delta(x \Delta G) \) | \( x \)          | \( \delta(x \Delta G) \) |
| 0.017            | 0.057            | 0.017            | 0.332            |
| 0.024            | 0.032            | 0.024            | 0.208            |
| 0.033            | 0.025            | 0.033            | 0.063            |
| 0.047            | 0.023            | 0.047            | 0.045            |
| 0.065            | 0.022            | 0.065            | 0.036            |
| 0.090            | 0.020            | 0.090            | 0.030            |
| 0.13             | 0.020            | 0.13             | 0.028            |
| 0.18             | 0.019            | 0.18             | 0.026            |
| 0.25             | 0.019            | 0.25             | 0.025            |

4. Summary

In summary di-jet measurements at a future polarised ep-collider will give important information on the shape and magnitude of the polarised gluon distribution of the proton. For all three ep-collider versions studied, these measurements are found to be feasible. The global result is shown in Fig. 7, for HERA and eRHIC and compared to results from other planned or possible future polarised experiments: pp-scattering at RHIC [16] (STAR, \( \sqrt{s} = 200 \) GeV, \( L = 320 \) pb\(^{-1} \)), \( pp \)-scattering in COMPASS [17], and pp-scattering in HERA-N [18], i.e. using the polarised protons of HERA on a polarised fixed target. All
Table 2
Possible measurements ($x$-values) and corresponding sensitivities to $\Delta G$ at eRHIC and HERA in NLO ($P_e \cdot P_p = 50\%$).

| HERA (500 pb$^{-1}$) | eRHIC (4 fb$^{-1}$) |
|---------------------|---------------------|
| $x$ | $\delta(x\Delta G)$ | $x$ | $\delta(x\Delta G)$ |
| 0.005 | 0.200 | 0.024 | 0.180 |
| 0.014 | 0.112 | 0.033 | 0.110 |
| 0.047 | 0.140 | 0.047 | 0.084 |
| 0.15 | 0.200 | 0.065 | 0.068 |
| 0.45 | 0.092 | 0.090 | 0.060 |

measurements are shown at LO. Clearly eRHIC can produce the (statistically) most precise measurements, and HERA covers the range to lowest possible $x$-values which can only be beaten by HERA, if it would be able to deliver sufficient luminosity.

In all di-jet measurements at $ep$-colliders appear to be a decisive tool to analyse and settle the question on $\Delta G$.

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Figure 7. Summary of the sensitivity of future measurements of $\Delta G/G$ for HERA (500 fb$^{-1}$) and eRHIC (4 fb$^{-1}$) compared with other experiments (see text).