Helicity Parton Distributions at an EIC*

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We present a quantitative assessment of the impact of a future EIC on determinations of helicity quark and gluon densities and their contributions to the proton spin. Our results are obtained by performing global QCD analyses at NLO accuracy based on realistic sets of pseudo-data for various conceivable center-of-mass system energies.

1 Motivation and Framework

Despite the impressive progress made both experimentally and theoretically in the past two decades, many fundamental questions related to the proton's helicity structure, including a quantitative understanding of the decomposition of the proton's spin, still remain unanswered. An accurate determination of the first moments of polarized quark and gluon densities entering the proton's spin sum rule or elucidating the flavor dependence of helicity PDFs to quantify, e.g., a potential SU(3) symmetry breaking in the light quark sea, cannot be achieved without considerably enlarging the kinematic coverage of spin-dependent data towards smaller momentum fractions x in the future. All the required measurements to address and answer these questions are unique to a polarized, high energy lepton-nucleon collider such as the proposed electron-ion collider (EIC) project [1].

To assess the impact of a future EIC in determining helicity PDFs we will consider two sets of energies conceivable at the first stage of the eRHIC option of an EIC [2] which is based on colliding an $E_e = 5\,\text{GeV}$ electron beam with the existing RHIC proton beam of $E_p = 100 - 250\,\text{GeV}$. Simulations based on pseudo-data generated with an electron energy of $20\,\text{GeV}$ are used to estimate the impact of a later stage of an EIC; for details, see [3]. The resulting c.m.s. energies $\sqrt{s}$ range from about $45\,\text{GeV}$ to $141\,\text{GeV}$ and allow one to access x values down to 5.3×10^{-4} and 5.3×10^{-5}, respectively, in DIS with $Q^2 > 1\,\text{GeV}^2$. Figure 1 illustrates the dramatically extended $x - Q^2$ coverage of an EIC for both stages as compared to existing fixed-target DIS experiments and data from polarized pp collisions.

We use the PEPSI MC generator [4] to produce fictitious EIC data for the inclusive and semi-inclusive DIS of longitudinally polarized electrons and protons with identified charged pions and kaons in the final-state. We demand a minimum Q^2 of $1\,\text{GeV}^2$, a squared invariant mass of the virtual photon-proton system larger than $W^2 = 10\,\text{GeV}^2$, and $0.01 \leq y \leq 0.95$.

*talk presented by M. Stratmann

The range of y is further restricted from below by constraining the depolarization factor of the virtual photon to be larger than 0.1. To ensure detection of the scattered lepton we require a minimum momentum of 0.5 GeV, and, in case of SIDIS, only hadrons with a momentum larger than 1 GeV and a fractional energy in the range $0.2 \leq z \leq 0.9$ are accepted. All particles detected in the final-state should be at least 1 degree away from the beam directions. The statistical accuracy of each DIS and SIDIS data set corresponds to a modest accumulated integrated luminosity of $10\,\text{fb}^{-1}$, equivalent to about one to two months of operations for the anticipated luminosities for eRHIC [2], except for the 5×100 GeV option which requires about a year of running.

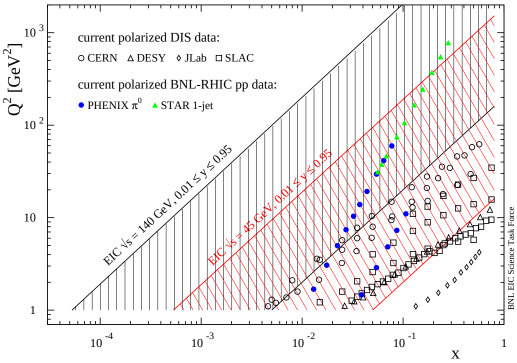

Figure 1: Kinematic range in x and Q^2 accessible with two different c.m.s. energies at an EIC for $0.01 \leq y \leq 0.95$.

Monte Carlo data for the ratio g_1/F_1 in DIS and SIDIS are generated in 4 [5] bins per decade in Q^2 [x] spaced logarithmically. As the actual pseudo-data used in our global analyses, we take the ratio g_1/F_1 computed at NLO accuracy using the DSSV+ [5] and MRST [6] polarized and unpolarized PDFs, respectively, and assign to each (x, Q^2)-bin the same relative statistical uncertainties as obtained with the MC event generator and assuming 70% beam polarizations. In addition, we randomize the pseudo-data in each bin within these one-sigma uncertainties. For the SIDIS data with identified charged pions and kaons we assign an additional, conservative 5 and 10% relative uncertainty to the EIC pseudo-data to reflect our current incomplete knowledge of parton-to-pion and parton-to-kaon fragmentation functions, respectively, based on uncertainty estimates for the DSS sets of FFs [7]. In total we add 234 data points for DIS and about 800 points for SIDIS to the existing DSSV+ global analysis framework [5] based on 570 DIS, SIDIS, and pp data. We note that the typical size of the double spin asymmetry $A_{LL} \simeq g_1/F_1$ at the lowest x values accessible at an EIC can be as small as a few times 10^{-4}, depending on the yet unknown behavior of $\Delta g(x, Q^2)$ in this kinematic regime. This size sets the scale at which one needs to control systematic uncertainties due to detector performance or luminosity measurements.

2 Impact of EIC DIS and SIDIS data

As an example, the l.h.s. of Fig. 2 illustrates our simulated data sets for inclusive polarized DIS at an EIC for three different c.m.s. energies assuming an integrated luminosity of $10\,\text{fb}^{-1}$. The solid lines are the result of the DSSV+ best fit, and the shaded bands illustrate the current uncertainty estimate. While DIS measurements for 20×250 GeV collisions are crucial to reach x values of a few times 10^{-5}, one can already cover momentum fractions down to 5×10^{-4} for $Q^2 \gtrsim 2.5\,\text{GeV}^2$ with c.m.s. energies envisioned in the first stage of eRHIC. Having available an as large as possible range in Q^2 for any given fixed value of x is of outmost importance for studying scaling violations $dg_1/d\log Q^2$ which, for small enough x, are closely related to the yet unknown polarized gluon density. Our projected SIDIS data for identified charged pions and kaons share the same x and Q^2 binning as the DIS data presented in Fig. 2.

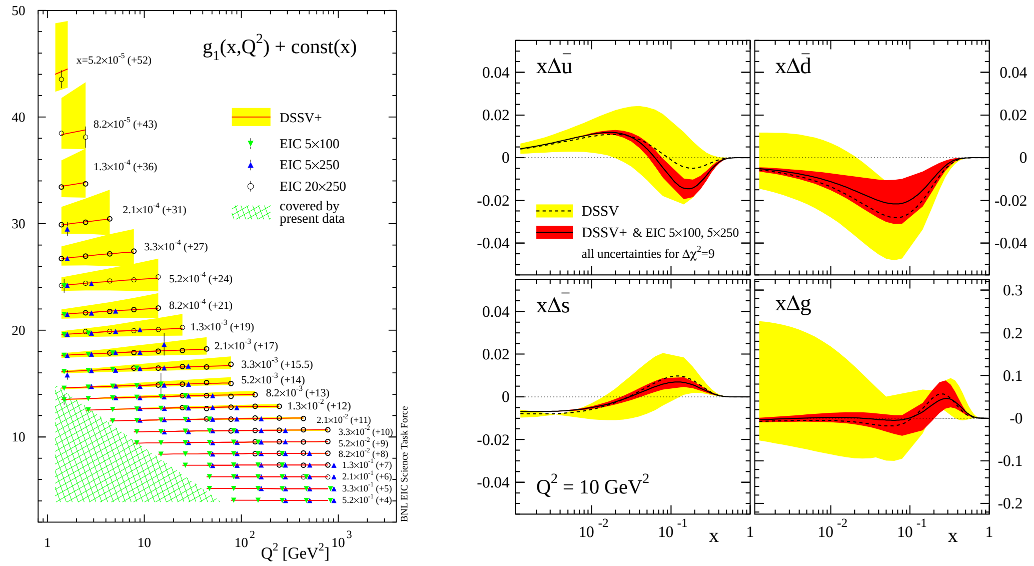

Figure 2: **left:** projected EIC data for $g_1(x, Q^2)$ for three different c.m.s. energies; constants are added to g_1 to separate the different x bins. The solid lines and shaded bands reflect our current knowledge [5]. **right:** impact of projected DIS and SIDIS data for 5×100 and 5×250 GeV collisions on the determination of helicity sea quark PDFs and the gluon. The outer bands illustrate present uncertainty estimates and the inner bands the improvements expected due to EIC data.

The r.h.s. of Fig. 2 demonstrates the impact of the projected combined EIC data for DIS and SIDIS on extractions of the polarized sea quark and gluon densities, utilizing only data which can be obtained with the initial stage of the eRHIC option. The outer bands in each panel refer to the present ambiguities for helicity PDFs as determined in the DSSV analysis [5]. The smaller, inner bands are obtained with the same global analysis framework, functional form for the PDFs, number of free fit parameters, and $\Delta\chi^2$ criterion but now include also the projected EIC data. As can be seen, the expected improvements are dramatic, in particular, for the polarized gluon density below $x \simeq 0.01$ but also for the individual sea quark flavors. More detailed studies and χ^2 profiles can be found in [3]. It should also be stressed that only the relative improvement of the uncertainties in Fig. 2, i.e., the differences between the inner and outer error bands, is of significance here since the generation of the pseudo-data requires to assume a certain set of polarized PDFs. Of course, only real EIC data will eventually reveal the actual functional form of the helicity PDFs at small x. We note, that at an EIC one can for the first time systematically study the validity of the leading twist pQCD framework assumed in global QCD analyses of helicity PDFs so far by varying the lower cut-off scale $Q_{\rm min}$ above which one starts to include data in the fit.

Finally, we look into what can be achieved for the first moments of the flavor singlet combination $\Delta\Sigma$ and the gluon helicity density Δg which both enter the proton spin rule. Figure 3 shows the correlated uncertainties for the truncated moments computed in the region $0.001 \leq x \leq 1$ with and without including projected EIC data sets. As can be seen, $\Delta g(Q^2, 0.001, 1)$ and

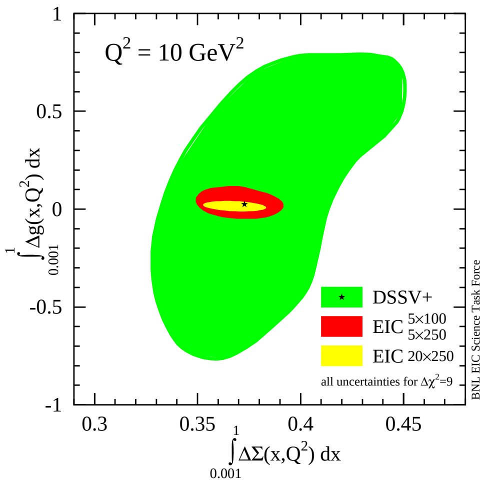

Figure 3: Correlated uncertainties for the first moments of the flavor singlet combination $\Delta\Sigma$ and the gluon helicity density Δg computed in the region $0.001 \leq x \leq 1$. The green, red, and yellow shaded areas are based on fits to current data and to projected EIC data with 5 GeV and 20 GeV electron beams, respectively. The symbol denotes the DSSV+ best fit.

$\Delta\Sigma(Q^2, 0.001, 1)$ can be constrained up to about ± 0.05 and ± 0.02, respectively, if 20×250 GeV data are included in the PDF analyses. However, already at the initial stage of an EIC a very significant reduction of uncertainties can be achieved. Quantifying the relevance of orbital angular momenta of quarks and gluons will be part of another suite of unique measurements at an EIC aiming at the nucleon's spatial structure [1].

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