Physics opportunities in electron-hadron collisions at the future eRHIC

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Our understanding of the structure of nucleons is described by the properties and dynamics of quarks and gluons in the theory of quantum chromodynamics. With advancements in theory and the development of phenomenological tools we are preparing for the next step in subnuclear tomographic imaging at a future electron-ion collider. A large range of center-of-mass energies ($\sqrt{s} \approx 45 - 150$ GeV) in combination with extremely high luminosities ($> 10^{33}$ cm^{-2}s^{-2}) will open a unique opportunity for very high precision measurements, allowing for a detailed investigation of the proton and nuclear hadronic substructure in multi-dimensions. In addition, highly polarized nucleon ($P \approx 70\%$) and electron ($P \approx 80\%$) beams can probe the parton polarizations in previously unexplored kinematic regions and with unprecedented accuracy, as well as address the role of orbital angular momentum with respect to the nucleon spin. This talk will summarize the eRHIC physics case for electron-proton collisions, the expected impact over the current knowledge and some of the technical challenges of such a versatile experimental endeavor.

1 Introduction

The BNL proposal for a future Electron-Ion Collider, eRHIC [1], is a major new research facility that builds on the existing RHIC accelerator complex to advance the long-term vision for Nuclear Physics to discover and understand the emergent phenomena of QCD, i.e. the creation of mass and spin of the visible matter. Its design concept incorporates new and innovative accelerator techniques to provide a cost-effective design to add a polarized electron beam colliding with the full array of RHIC hadron beams at a luminosity beyond 10^{33}cm^{-2}s^{-1}.

Such a facility will address directly and with high precision questions that relate to our fundamental understanding of QCD:

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
- Where does the saturation of gluon densities set in?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

eRHIC will address the above questions with the highest, unprecedented precision and at one facility.

2 electron-proton scattering at eRHIC

eRHIC will open up the unique opportunity to go far beyond our current largely one-dimensional picture of the nucleon. It will enable partonic "tomographic images", providing essential insight into QCD dynamics inside hadrons. Moreover it can unravel how the proton spin derives from its constituents: the quarks and the gluons, a formidable challenge that goes directly to the heart of exploring and understanding the QCD dynamics of matter.

2.1 Proton's helicity structure

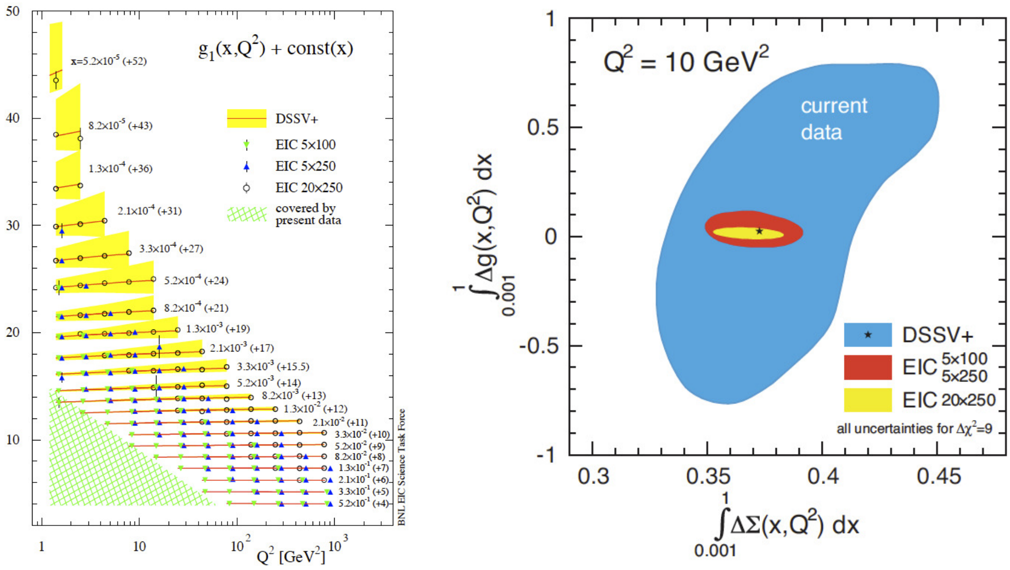

Figure 1: (*left*)Projected eRHIC data for the structure function g_1 for different combinations of electron and proton beam energies; (*right*) Correlated uncertainties for the flavor singlet combination $\Delta\Sigma$ and the gluon helicity density Δg.

Helicity-dependent parton densities encode the information to what extent quarks and gluons with a given momentum fraction x tend to have their spins aligned with the spin direction of a nucleon and are related to how the spin of a nucleon is composed of the spins and orbital angular momenta of quarks and gluons. The integrals of helicity PDFs over all momentum fractions x at a resolution scale Q^2, $\Delta f(Q^2) = \int_0^1 \Delta f(x, Q^2)dx$, provide information about the contribution of a given parton flavor f to the spin of the nucleon. A precise determination of the polarized gluon $\Delta g(x, Q^2)$ and quark $\Delta q(x, Q^2)$ distribution functions in a broad kinematic regime is a primary goal of eRHIC.

Current determinations of Δg suffer from both a limited $x - Q^2$ coverage and fairly large theoretical scale ambiguities in polarized p+p collisions for inclusive (di)jet and pion production [2]. Several channels are sensitive to Δg in e+p scattering at collider energies such as DIS jet or charm production, but QCD scaling violations in inclusive polarized DIS have been identified as the golden measurement.

Figure 1(*left*) illustrates the simulated data sets for inclusive polarized DIS at eRHIC for the three different choices of c.m. energies. The error bars reflect the expected statistical accuracy for a integrated luminosity of 10fb^{-1} and assuming 70% beam polarizations.

The simulated data are used in a fit to study 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 sum rule $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + \Sigma_q L_q^z + L_g^z$, with $L_{q,g}^z$ denoting the contribution from orbital angular momentum (not accessible in inclusive DIS). Figure 1(*right*) shows how eRHIC will greatly reduce the uncertainties, in particular for Δg which is largely unconstrained so far.

2.2 Multidimensional imaging of quarks and gluons

With its wide range in energy, nuclear beams and high luminosity, eRHIC will offer an unprecedented opportunity for precision measurements, allowing us to study the momentum and space-time distribution of gluons and sea quarks in nucleons and nuclei.

One of the main goals will be a precise determination of the Generalized Parton Distribution functions (GPDs), which describe the distribution of quarks and gluons in the nucleon with respect to both position and momentum. Moreover, GPDs allow us to study how the orbital motion of quarks and gluons in the nucleon contributes to the nucleon spin, completing the spin sum role (see Sec. 2.1).

A golden measurement toward the determination of the whole set of GPDs is Deeply Virtual Compton Scattering (DVCS), which is the exclusive production of a real photon. This theoretical and experimentally clean process is sensitive to both quarks and gluons (via evolution).

Presently available DVCS measurements provide some limited information on GPDs and more precise data, in a wider phase space and including transversely polarized target spin asymmetry, are required to pin them down [3].

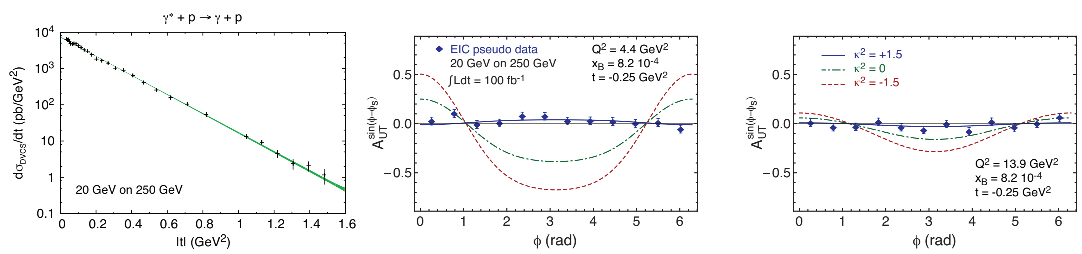

Figure 2: Expected uncertainties for a DVCS $|t|$-differential cross section (*left*) measurement in a particular x, Q^2 bin, and for A_{UT} (*center-right*) compared to theory model with large positive (*solid*), vanishing ($dot - dashed$), and large negative (*dashed*) E^{sea} contributions.

An access to GPDs requires a large data set with small errors. As an example of the precision achievable at eRHIC, Fig. 2 (*left*) shows the expected uncertainty for a measurement of the DVCS $|t|$-differential cross section in a particular x, Q^2 bin. Figure 2(*center-right*) shows the expected uncertainty for the transverse target-spin asymmetry (A_{UT}) as a function of the azimuthal angle ϕ between the production and the scattering planes for a particular $x_{Bj}, Q^2, |t|$ bin, compared to theoretical expectations. The simulation proves that eRHIC can perform accurate measurements of cross sections and asymmetries in a very fine binning and with a very low statistical uncertainty.

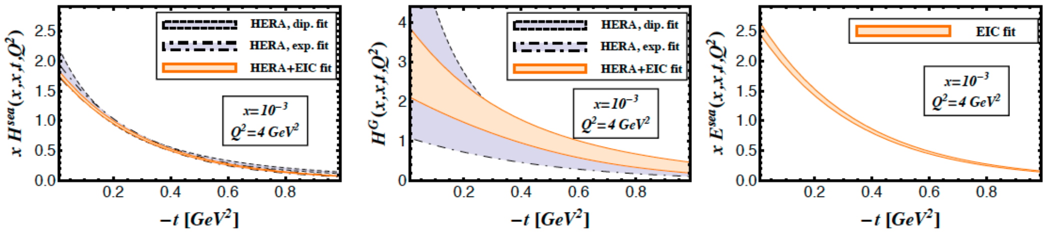

Figure 3: Extraction of GPD H for sea quarks ($left$) and gluons ($center$) and GPD E for sea quarks ($right$) in a particular x, Q^2 bin. The violet band is the uncertainty obtained excluding the eRHIC pseudo-data to the global fit procedure.

A global fit, including the eRHIC simulated data together with all the data presently available has been done. Figure 3 shows how eRHIC can largely improve the knowledge on GPD H for gluons. Moreover, a precise measurement of the transversely polarized target spin asymmetry A_{UT}, which allows for a decomposition of GPD H and E contributions, leads to the accurate extraction of GPD E, which at the moment remains almost unconstrained [3], providing an estimate of the angular momentum carried by sea quarks.

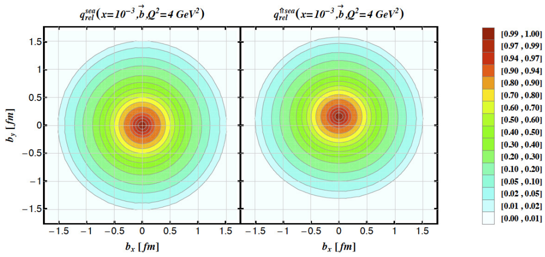

Figure 4: Tomographical picture of the sea-quuarks distribution in the impact parameter space for an unpolarized ($left$) and a polarized ($right$) proton beam.

Fourier-transforming the GPDs, it is possible to obtain the quarks and gluons distributions in the impact parameter space. Fig. 4 shows an example of a tomographic (2+1 D) picture of the see-quarks distribution as resulting from eRHIC pseudo-data analysis, in a particular bin, for the case of an unpolarized and a polarized proton-beam. The shift observed in the polarized case comes from the GPD E contribution.

References

[1] E.C. Aschenauer *et al.*, “eRHIC Design Study: An Electron-Ion Collider at BNL”, arXiv:1409.1633

[2] E.C. Aschenauer, “The RHIC Spin Program: Achievements and Future Opportunities, arXiv:1304.0079

[3] E.C. Aschenauer, S. Fazio, K. Kumericki, and D. Mueller, JHEP 09 (2013) 093