PDFs, α_s and Low-x Physics and at Future DIS Facilities

LHeC/FCC-eh: Future (energy frontier) Electro-Proton and Electron-Hadron Colliders

The LHeC/FCC-eh PDF & Low x Study Group:[1]

Conveners: N. Armesto, D. Britzger, C. Gwenlan, M. Klein, P. Newman, F. Olness, A. Stasto, *with the working group.*[2]

ABSTRACT

In this LOI, we briefly outline how Parton Distribution Functions (PDFs) and Low x studies at future high energy deep inelastic scattering (DIS) facilities relate to topics and projects relevant for the Snowmass planning process. These results are detailed in a newly released Conceptual Design Report (CDR). [1]

I. OVERVIEW

Future DIS Facilites: The Large Hadron electron Collider (LHeC) and Future Circular Collider in electron-hadron mode (FCC-eh) facilities provide unique opportunities for advancing the physics of DIS to the energy and intensity frontier by colliding a novel, high energy, intense electron beam with high energy proton and ion beams.

While the following discussion will focus on the LHeC, essentially all the results carry forward to the FCC-eh, which is designed to utilise the same Energy Recovery Linac (ERL) technology, and would further extend the rich physics program of the LHeC to even higher center-of-mass energies.

Energy & Luminosity: With a 50 GeV electron beam, the center-of-mass energy of ep collisions will be 1.2 TeV at the HL-LHC, 1.7 TeV at an HE-LHC, and, for 60 GeV, 3.5 TeV at an FCC-he. The luminosity for ep of $10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ could provide $\sim 50\,\text{fb}^{-1}$ during an initial 3-year run; this data would be equivalent to 50 times the entire accumulated HERA data set.

II. PHYSICS GOALS

Standard Model & Beyond: The LHeC/FCC-he facilities enable a far reaching physics program on a variety of topics including parton structure of the proton and heavier nuclei, QCD dynamics, electroweak and top-quark physics. The high centre of mass energy, the extended $\{x, Q^2\}$ kinematic reach, the cleanliness of the neutral and charged current processes and final states, and the high luminosity goal can thus contribute to the search for new physics beyond the Standard Model by dramatically reducing the uncertainties of the PDFs entering the calculations of the relevant cross sections for signals and backgrounds.

Fundamental Character of QCD: The kinematic reach and intense luminosity of an LHeC will also allow the investigation of fundamental questions of the QCD theory including whether QCD may break down in extreme kinematic regions, be embedded in a higher gauge symmetry, or if unconfined color might be observed.

Implications for other Experiments: By making incisive tests of the QCD Quark Parton Model (QPM) in extreme kinematic regimes, an LHeC can not only provide tools for interpreting hadroproduction data, but also yield a new understanding of strong interaction dynamics and the underlying hadronic substructure.

These features will benefit complementary measurements at the HL-LHC, EIC, DUNE, FCC, as well as ultra-high-energy astrophysical studies.

III. UNIQUE PHYSICS OBJECTIVES

The physics program of the LHeC is unprecedented for the following reasons:

PDFs from a single data set: For the first time, the partonic structure of the proton (and nuclei) can be completely resolved in a single experiment. Using neutral and charged current cross section measurements of $\{F_2, F_3\}$, as well as heavy quark production, the PDFs can be extracted across a huge DIS kinematic range of $x = [10^{-6}, 0.9]$ and $Q^2 = [1, 10^6]$ GeV^2.

Nuclear PDFs: Additionally, the high luminosity ensures the proton data is sufficient to extract the flavor components without the use of fixed-target DIS data which typically involves nuclear corrections.

While the LHeC can completely resolve the proton PDF flavors without using any nuclear data, the option of an LHC heavy ion beam allows exploration of individual nuclear PDFs.

Large x: The very high luminosity leads to ample statistics in the large x region at so high Q^2 that higher twist effects become negligible. This region is especially important for constraining BSM signatures with large mass scales at the LHC.

Small x: At small x the gluon and sea quark densities, as discovered at HERA, rise so much that non-linear and possibly saturation effects may become manifest. This can be studied for the first time reliably in ep, and eA, at the LHeC, at so high Q^2 that the strong coupling is small. This may replace the DGLAP evolution by BFKL type equations with major consequences for future hadron collider physics at HL-LHC and beyond.
[Also see the separate "LHeC/FCC-he Small-x" LOI.]

Up and Down PDFs: The high energy allows weak

[1] We thank the many members of the working group who contributed to the results of the CDR.[1] A compilation of meetings are presentations can be found at: http://www.physics.smu.edu/olness/lhec/

[2] Contacts: Claire Gwenlan c.gwenlan@physics.ox.ac.uk
Fred Olness olness@smu.edu

probes $(W^{\pm}, Z)$ to dominate the interaction at larger Q^2 values which permits the up and down sea and valence quark distributions to be resolved in the full range of x; no additional data will be required. Additionally, the possibility to run a positron beam greatly enhances the precision determination of the (negatively charged) down quark PDF.

Gluon PDF: The gluon PDF is poorly known, both in the low x and high x regions; the medium x gluon is critical for Higgs production channels, while large x is crucial for new physics searches. The LHeC constrains the gluon to per cent accuracy for all x, using a variety of measures primarily the $\partial F_2/\partial \ln Q^2$ as well as the longitudinal structure function F_L.

Strange PDF: Determining the strange quark PDF is a long-standing puzzle, and measurements ranging from fixed-target to collider experiments have not resolved this important question. The high energy and luminosity of the LHeC, however, allows the precise extraction of the strange PDF directly using the charged current charm production process $(W s \to c)$.

Charm, Bottom & Top: The production of heavy quarks introduces a new paradigm where the quark mass is neither heavy or light. Hence, we encounter the challenging multi-scale dilemma and must address a variety of questions including: are heavy quarks like charm and bottom radiatively generated or is there also an intrinsic heavy quark component in the proton?; to what extent do the universality and factorisation theorems work in the presence of heavy quarks?

The LHeC can resolve these issues with a variety of precision measurements with a complete composition of the proton flavour by flavour which includes F_2^c and F_2^b. These are obtained through charm and beauty tagging with high precision in NC ep scattering. A thorough PDF analysis of the LHeC data thus can be based on the inclusive NC/CC cross sections and tagged $\{s, c, b\}$ data. In addition, one may also use DIS jets and low energy data with a precision measurement of F_L.

Finally, the LHeC provides the first access to top quark production in a DIS environment and allow the production of single top production $(W b \to t)$, top pair production $(g \to t\bar{t})$, and even investigation of the top quark PDF.

TMDs & GPDs: Beyond the collinear PDFs, semi-inclusive measurements of jets and vector mesons, and especially Deeply Virtual Compton Scattering (DVCS), a process established at HERA, will shed light on also the transverse structure of the proton in a new kinematic range. These measurements allow us to access the Wigner distribution $W(x, \mathbf{k_T}, \mathbf{b_T})$; one can think of it as the "master" parton distribution. If we integrate the Wigner distribution over the transverse momentum, we obtain a Generalized Parton Distribution (GPD) $f_{\rm GPD}(x, \mathbf{b_T})$, while if we integrate over the impact parameter we obtain a Transverse Momentum Dependent (TMD) PDF $f_{\rm TMD}(x, \mathbf{k_T})$. Thus, by expanding the scope of our investigations beyond collinear PDFs to include GPDs and TMD PDFs we can extract more detailed information on the partons which comprise the hadron.

Strong Coupling Constant α_s: The determination of the strong coupling α_s and the gluon PDF are tightly coupled. The measurement of inclusive NC and CC DIS cross sections allows for the simultaneous determination of the PDFs and $\alpha_s(m_Z)$ with a precision of $\delta\alpha_s(m_Z) = \pm 0.00022\,(\exp \bigoplus \mathrm{pdf})$. The measurement of jet production cross sections, which exhibit a direct sensitivity to α_s already at leading-order in perturbative QCD, promise an uncertainty of $\delta\alpha_s(m_Z) = \pm 0.00016\,(\exp \bigoplus \mathrm{pdf})$, and together with inclusive DIS data of $\delta\alpha_s(m_Z) = \pm 0.00013\,(\exp) \pm 0.00010\,(\mathrm{pdf})$ The large kinematic reach of the LHeC allows the measurement of the running $\alpha_s(\mu_R)$ over 6 decades in Q^2 using inclusive jet production. Many other channels, observables and processes can be studied for further α_s-determinations as well, for instance, event shape observables, heavy-quark production, multi-jet production cross section, jet production in photoproduction, and more.

IV. OPEN QUESTIONS AND PROJECTS:

While extensive work has already been described in the updated CDR report, [1] there are a number of outstanding questions and projects that require additional investigation and computation. We list a few examples below.

- N^{3}LO Evolution and massive matrix elements.
- NNLO for differential heavy quark production.
- Impact of resummation on hadronic observables.
- Small-x treatments in both ep and eA.
- Implications of the above for SM and BSM precision measurements.

Collaboration and cooperation on these tasks is welcome.

V. CONCLUSION

The LHeC/FCC-he offers a unique physics program that will vastly expand our knowledge of the hadronic structure of matter and the associated forces. In effect, this provides the most powerful and highest resolution "microscope" to resolve the structure of matter at unprecedented scales. These results also exploit synergies with measurements at complementary facilities (HL-LHC, EIC, FCC, etc.,) which can be used collectively to transform our understanding of hadronic matter.

The study of topics discussed above is ongoing, and we welcome participation and contributions.

REFERENCES

Additional details and a complete set of references can be found in the 2020 Conceptual Design Report (CDR):

[1] P. Agostini et al.(LHeC, FCC-he Study Group), "The Large Hadron-Electron Collider at the HL-LHC," (2020), arXiv:2007.14491 [hep-ex].