LHeC and FCC-eh: Small-x Physics at Energy Frontier Electron-Proton and Electron-Nucleus Colliders[1]

N. Armesto, M. Bonvini, C. Gwenlan, M. Klein, H. Mäntysaari, P. R. Newman, F. Olness, P. Paakkinen, H. Paukkunen, A. M. Stasto, P. Zurita, with the LHeC and FCC-eh Study Group

ABSTRACT

In this LoI, we briefly outline selected small-x physics studies at future deep inelastic scattering (DIS) facilities at the energy frontier, the LHeC and the FCC-eh, of relevance for high-energy physics in general and, thus, to the Snowmass 2021 planning process.

I. OVERVIEW: FUTURE ENERGY FRONTIER DIS FACILITES

The Large Hadron-electron Collider (LHeC) is a proposed upgrade of the HL-LHC [1, 2]. An energy recovery linac (ERL) in racetrack configuration will accelerate electrons to 50 GeV which will collide with the proton and ion beams from HL-LHC. The facility will be able to provide collisions with per-nucleon center-of-mass system (cms) energies $\sqrt{s_{NN}} \sim 0.2 - 1.2$ TeV and per nucleon instantaneous luminosities $\mathcal{L} \sim 10^{34(33)}$ cm^{-2}s^{-1} in ep (ePb) collisions. Such ERL can be later used to provide 60 GeV electrons to collide with the FCC hadron beams (Future Circular Collider in electron-hadron mode, FCC-eh), resulting in per-nucleon cms energies up to $\sqrt{s_{NN}} \sim 3.5$ (2.2) TeV and similar instantaneous luminosities in ep (ePb).

These large cms energies and luminosities, leading to an increase of up to two (four) orders of magnitude down in x and up in Q^2 in ep (ePb) with respect to DIS experiments performed up to date, allow for a wide physics programme on QCD (both precision and discovery), top, EW, Higgs and BSM, with strong synergies with pp, pA and AA collisions at the HL-LHC and the FCC. Several LoIs devoted to these aspects have been submitted to Snowmass 2021. In this one we address the possibilities offered by energy frontier DIS machines to explore the high-energy regime of QCD.

II. PHYSICS GOALS

Dynamics at small x: The behavior of QCD at high energies is largely unknown [3]. It is directly linked to the evolution in Q^2 and x of partonic densities (PDFs) at small values of x. While fixed-order perturbation theory, in the form of fixed order matrix elements and DGLAP evolution (available up to NNLO), works very well and is the basis for present available PDF sets, resummation at low x may be required to better describe HERA data at moderate Q^2 and the smallest available x [4, 5]. Besides, theoretical studies point to the eventual dominance of non-linear effects at high energies or small x that are not included neither in fixed-order nor in resummation schemes. Such non-linear effects, whose weak coupling but non perturbative realization is the Color Glass Condensate (CGC) [3, 6], are unavoidable in a quantum field theory and are related to fundamental QFT properties like unitarity. The CGC is an effective field theory at high energy where the field strengths and occupation numbers become as large as possible and parton densities *saturate*. It addresses a new regime of QCD and may be of relevance for our understanding of even more fundamental open problems like confinement. Besides, different factorization schemes exist, which are beyond standard collinear factorization, for example k_T [7] or TMD [8]. In some cases, such schemes can be related at small x, see e.g. [9] and refs. therein for the relation between TMD and CGC factorizations.

Implications for other Experiments: Understanding the high energy regime of QCD is of great importance at hadronic colliders, specifically at the (HL-)LHC. On the one hand, QCD uncertainties and backgrounds dominate precision measurements of SM parameters at the LHC (electroweak mixing angle, W boson mass,...) and BSM searches. It should be noted that at high energies, the production of large mass objects becomes dominated by small-x PDFs. And dynamics beyond standard fixed-order perturbation theory give large effects, for example order 10% in the cross section for Higgs production by gluon fusion at the FCC [10]. On the other hand, production in the forward region is dominated by small-x dynamics. The understanding of high-energy QCD is one of the aims of

[1] Contacts: Néstor Armesto nestor.armesto@usc.es
Paul Newman Paul.Newman@cern.ch
Anna Stasto ams52@psu.edu

the LHC physics program and has given some of the most striking observations in pp and pA collisions like the ridge phenomenon in such small systems. Furthermore, particle production in the forward region and the small-x dynamics are crucial for high-energy astroparticle physics. For example, the development of cosmic ray air showers, key for determining the energy and composition of the primary particles colliding with the atmosphere, is dominated by the forward region. And both the signal and the backgrounds for neutrino measurements in cosmic ray experiments is dominated by small-x dynamics, see for example [11]. Finally, the kinematic region accessible to the LHeC and the FCC-eh is complementary to that of the EIC [12] and lower energy experiments, e.g. those at JLab.

III. UNIQUE CAPABILITIES OF PROPOSED FACILITIES

The small x physics program of the LHeC and the FCC-eh [1, 2] is unprecedented for the following reasons:

Unprecedented kinematic range in (x, Q^2): The mentioned extension of the x-Q^2 plane that can be accessed provides a large lever arm in Q^2 at both small x (for large enough Q^2 to be in the perturbative region) and large x (knowledge of PDFs at large x is required in forward particle production in pp collisions, and large x in DIS is linked to large Q^2 - thus providing strong constraints on DGLAP evolution). The small x coverage is required to establish deviations from fixed-order perturbation theory due to small x resummation and the presence of genuine non-linear QCD effects, while the large x coverage sets the the frame to establish the quantitative relevance of new dynamics through tensions in DGLAP-based fits.

Several observables for each collision system: Several observables will be measured in neutral and charged current events: structure functions F_2, F_3 and F_L without and with heavy flavor tagging, semi-inclusive particle production and correlations, jets, and their diffractive counterparts (both through the identification of rapidity gaps and of leading hadrons). Therefore, many possibilities for constraining the strong dynamics will become available.

Proton and nuclei in a single experimental setup: All the mentioned observables will be studied in ep and in eA collisions in a single experimental setup and with similar precision. Linear and non-linear effects are expected to behave differently in ep and eA, the latter being ruled by the density that can be increased by both decreasing x and increasing the mass number of the hadron. It becomes highly plausible that disentangling non-linear dynamics will only be possible through a combination of measurements in both collision systems.

IV. OPEN QUESTIONS AND PROJECTS

While extensive work has already been described in the CDR reports [1, 2], there are a number of outstanding questions and projects that require additional detailed investigation and computation. We list a few examples below:

- Compatibility of DGLAP evolution with new low-x dynamics (saturation and resummation) in ep and in eA.
- Discriminating resummation from saturation through the simultaneous study of ep and eA.
- Search for a combination of observables with highest sensitivity to novel QCD dynamics.
- Observables beyond inclusive structure functions: jets, diffraction,...
- Complementarity of DIS with other collision systems to discriminate the small-x dynamics.

Reweighting techniques [13] and, when required, full fits [14–17] will be used for the first three items. Collaboration and cooperation on all these tasks is welcome.

V. CONCLUSION

The large cms energies and luminosities achievable at the LHeC and FCC-eh lead to a large extension of the DIS x-Q^2 kinematic domain presently available. Such extension, together with the cleanness of DIS events and the availability of different theoretical frameworks, and the possibility of studying both ep and eA collisions, make it an ideal experimental setup for unraveling the high-energy behavior of QCD. Establishing such behavior is most interesting both on its own and by its implications on hadronic colliders. In this LoI we indicated several studies that can be done within the Snowmass 2021 framework.

[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].

[2] J.L. Abelleira Fernandez *et al.* (LHeC Study Group), "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector," J. Phys. G **39**, 075001 (2012), arXiv:1206.2913 [physics.acc-ph].

[3] Yuri V. Kovchegov and Eugene Levin, *Quantum chromodynamics at high energy*, Vol. 33 (Cambridge University Press, 2012).

[4] Richard D. Ball, Valerio Bertone, Marco Bonvini, Simone Marzani, Juan Rojo, and Luca Rottoli, "Parton distributions with small-x resummation: evidence for BFKL dynamics in HERA data," Eur. Phys. J. C **78**, 321 (2018), arXiv:1710.05935 [hep-ph].

[5] Hamed Abdolmaleki *et al.* (xFitter Developers' Team), "Impact of low-x resummation on QCD analysis of HERA data," Eur. Phys. J. C **78**, 621 (2018), arXiv:1802.00064 [hep-ph].

[6] Francois Gelis, Edmond Iancu, Jamal Jalilian-Marian, and Raju Venugopalan, "The Color Glass Condensate," Ann. Rev. Nucl. Part. Sci. **60**, 463–489 (2010), arXiv:1002.0333 [hep-ph].

[7] S. Catani, M. Ciafaloni, and F. Hautmann, "High-energy factorization and small x heavy flavor production," Nucl. Phys. B **366**, 135–188 (1991).

[8] John Collins, *Foundations of perturbative QCD*, Vol. 32 (Cambridge University Press, 2013).

[9] Tolga Altinoluk, Renaud Boussarie, and Piotr Kotko, "Interplay of the CGC and TMD frameworks to all orders in kinematic twist," JHEP **05**, 156 (2019), arXiv:1901.01175 [hep-ph].

[10] Marco Bonvini, "Small-x phenomenology at the LHC and beyond: HELL 3.0 and the case of the Higgs cross section," Eur. Phys. J. C **78**, 834 (2018), arXiv:1805.08785 [hep-ph].

[11] Atri Bhattacharya, Rikard Enberg, Yu Seon Jeong, C. S. Kim, Mary Hall Reno, Ina Sarcevic, and Anna Stasto, "Prompt atmospheric neutrino fluxes: perturbative QCD models and nuclear effects," JHEP **11**, 167 (2016), arXiv:1607.00193 [hep-ph].

[12] A. Accardi *et al.*, "Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all," Eur. Phys. J. A **52**, 268 (2016), arXiv:1212.1701 [nucl-ex].

[13] Hannu Paukkunen and Pia Zurita, "PDF reweighting in the Hessian matrix approach," JHEP **12**, 100 (2014), arXiv:1402.6623 [hep-ph].

[14] S. Alekhin *et al.*, "HERAFitter," Eur. Phys. J. C **75**, 304 (2015), arXiv:1410.4412 [hep-ph].

[15] Daniel de Florian, Rodolfo Sassot, Pia Zurita, and Marco Stratmann, "Global Analysis of Nuclear Parton Distributions," Phys. Rev. D **85**, 074028 (2012), arXiv:1112.6324 [hep-ph].

[16] K. Kovarik *et al.*, "nCTEQ15 - Global analysis of nuclear parton distributions with uncertainties in the CTEQ framework," Phys. Rev. D **93**, 085037 (2016), arXiv:1509.00792 [hep-ph].

[17] Kari J. Eskola, Petja Paakkinen, Hannu Paukkunen, and Carlos A. Salgado, "EPPS16: Nuclear parton distributions with LHC data," Eur. Phys. J. C **77**, 163 (2017), arXiv:1612.05741 [hep-ph].