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eA and high parton densities at the LHeC and FCC-he

Néstor Armesto[a,b,*]

[a] *Instituto Galego de Física de Altas Enerxías IGFAE, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia-Spain*
[b] *On behalf of the LHeC/FCC-he Study Group*

E-mail: nestor.armesto@usc.es

Electron-nucleus collisions at the Large Hadron-electron Collider and the Future Circular Collider in electron-hadron mode promise to revolutionise our understanding of the parton structure of nuclei and of Quantum Chromodynamics (QCD) at high energies. They will extend the $x - Q^2$ phase space available in deep inelastic scattering (DIS) by four orders of magnitude down in x and up in Q^2. They will offer precision that is not achievable elsewhere, specifically compared to hadron-nucleus collisions. In this contribution we focus on the possibilities for the determination of nuclear parton densities, for unraveling a new non-linear regime of QCD at small values of x, and for studies on diffraction, as contained in [1–3] plus some new studies.

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*Speaker

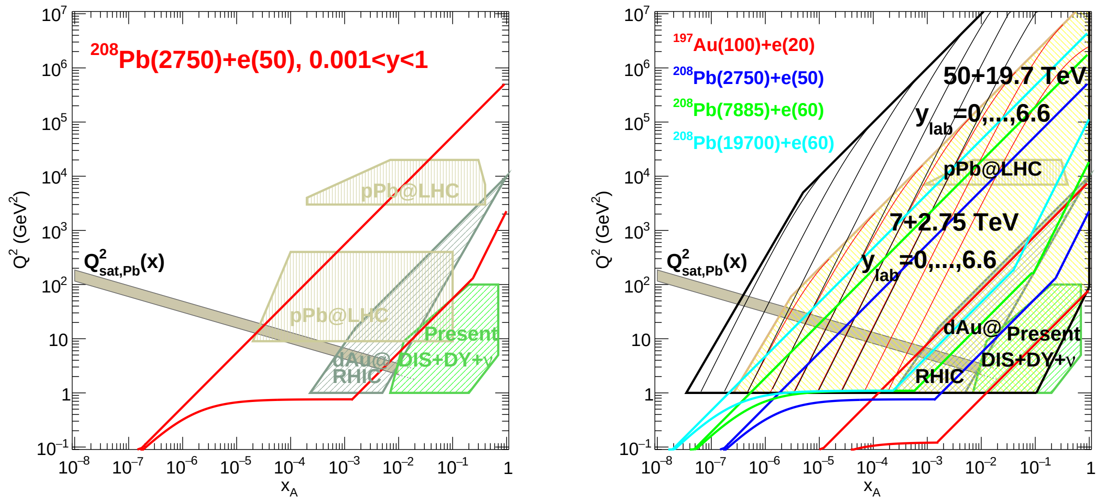

Figure 1: *Left*: Kinematic plane studied in *e*Pb collisions at the LHeC (solid red lines) together with the regions explored in present analyses: DIS and DY fixed target data (hatched area in green), hadron production in dAu collisions at RHIC (hatched area in grey) and Run 1 dijet and EW boson studies in *p*Pb collisions at the LHC (hatched upper region in brown). Also shown in the hatched upper region in brown are the expected coverage from dijets in Run 2 and from EW bosons in future Runs, and in the hatched lower region in brown the expectations from Run 2 D-meson analyses and from DY and photon studies in future LHC Runs. *Right*: Comparison of the kinematic regions in the $x-Q^2$ plane explored by datasets (charged lepton and neutrino DIS, DY, *d*Au at RHIC and *p*Pb at the LHC) used in present nPDF analyses [4], with the ones achievable at the Electron Ion Collider EIC (red), the LHeC (ERL against the HL-LHC beams, dark blue) and two FCC-he versions (with Pb beams corresponding to proton energies of 20 TeV - green and 50 TeV - light blue). The areas delimitated by thick brown and black lines show the regions accessible in *p*Pb collisions at the LHC and the FCC-hh (50 TeV) respectively, while the thin lines represent constant rapidities from 0 (right) to 6.6 (left) for each case. Acceptance is taken to be $1^\circ < \theta < 179^\circ$, and $0.01(0.001) < y < 1$ for the EIC (all other colliders). The saturation scale Q_{sat} shown here for indicative purposes only. Taken from [2, 3].

1. Introduction

The Large Hadron-electron Collider (LHeC) [1, 2] is a proposed upgrade of the HL-LHC. 50 – 60 GeV electrons from an energy recovery linac would collide with the LHC nuclear beams providing electron-nucleus collisions with $\sqrt{s_{NN}} \sim 0.8$ TeV and per nucleon instantaneous luminosities $\mathcal{L} \sim 7 \cdot 10^{32}$ cm^{-2}s^{-1}. If such electrons are collided with the FCC nuclear beams (FCC-he), $\sqrt{s_{NN}} \sim 2.2$ TeV and per nucleon instantaneous luminosities $\mathcal{L} \sim 5.4 \cdot 10^{33}$ cm^{-2}s^{-1} will be possible. Integrated luminosities ~ 1 fb^{-1} per year are well within reach.

The $x-Q^2$ kinematic region achievable in DIS on nuclei with such machines is shown in Fig. 1, where it is compared with the one contained in present and future sets of nuclear parton densities (nPDFs) and with the ultimate kinematic regions at the corresponding hadron-nucleus colliders. The extension with respect to present DIS knowledge is by 4 – 5 orders of magnitude down in x and up in Q^2. With respect to hadron-nucleus colliders, the respective kinematic regions greatly overlap but DIS offers a clean experimental environment (low multiplicity, no pileup, fully constrained kinematics) and a more controlled theoretical setup (many first principles calculations in collinear and non collinear frameworks). Therefore, the LHeC and the FCC-he will result in a leap in our understanding of QCD in nuclei. Besides, recently a joint interaction region for both electron-hadron and hadron-hadron collisions at the LHC has been investigated [3]. The possibilities for QCD with a detector in such interaction region are enormous, with the impact of studies of electron-nucleus (eA) on heavy-ion collisions (AA) focused on different aspects:

- The understanding of the parton structure of nuclei (nuclear parton densities nPDFs) and the dynamics at small x. Both aspects dominate particle production in the hard and soft sectors in hadronic and nuclear collisions. The LHeC and FCC-he will allow a precise determination and complete flavour decomposition of parton densities inside proton and single nuclei, down to the small-x values relevant for the LHC or FCC-hh.

- The clarification of the mechanism of particle production at small x which determines the initial conditions for eventual thermalisation and use of relativistic hydrodynamics. This is particularly relevant in view of the small system problem, whose dynamical explanation, initial or final state, is still unclear. Besides, the transverse profile and fluctuations of partons inside nucleons and nuclei can be best determined in eA.

- The understanding of the dynamics in the nuclear medium of hard probes, jets and quarkonia (including exotica) that will be abundantly produced up to large transverse momenta in a very clean environment, key for their use to precisely extract the properties of the quark gluon plasma in AA.

- At the LHC one can study photoproduction on proton and nuclei through ultraperipheral collisions. This can be done in ep/eA with much smaller systematic uncertainties, and with the additional possibility of changing the virtuality going to larger Q^2.

In this contribution we focus on the possibilities at the LHeC and FCC-he for the determination of nPDFs, and for studies on small-x physics and diffraction. We discuss material contained in [1–3], where we refer the reader for further information, plus some newer ideas [5–7].

2. Nuclear Parton Densities

With experimental measurements in the kinematic region shown in Fig. 1, we have investigated the possibilities for constraining nPDFs. Pseudodata for neutral (NC) and charged (CC) current DIS in ePb collisions have been generated [2] using a code validated with the Monte Carlo of the H1 Collaboration, and used for two types of analyses. First, NC (inclusive and cham) and CC LHeC pseudodata have been included in a global fit based on EPPS16 [4] whose results show a large reduction of uncertainties, and a sizable effect of charm on the glue at small x. On the other hand, we note the limitation on the u/d decomposition inherent to almost isospin symmetric nuclei (the u/d difference is suppressed by $2Z/A - 1$).

Second, ePb pseudodata have been used for determining Pb-only PDFs, with the goal of estimating the uncertainties coming solely from the achievable experimental precision. The method, that employs *xFitter* [8], is very similar to that used in ep [6]. The results[1] for the glue are shown in

[1]Here the nuclear modification factor for parton density $f(x, Q^2)$ is defined as the ratio of the density in a proton inside the nucleus over that in a free proton.

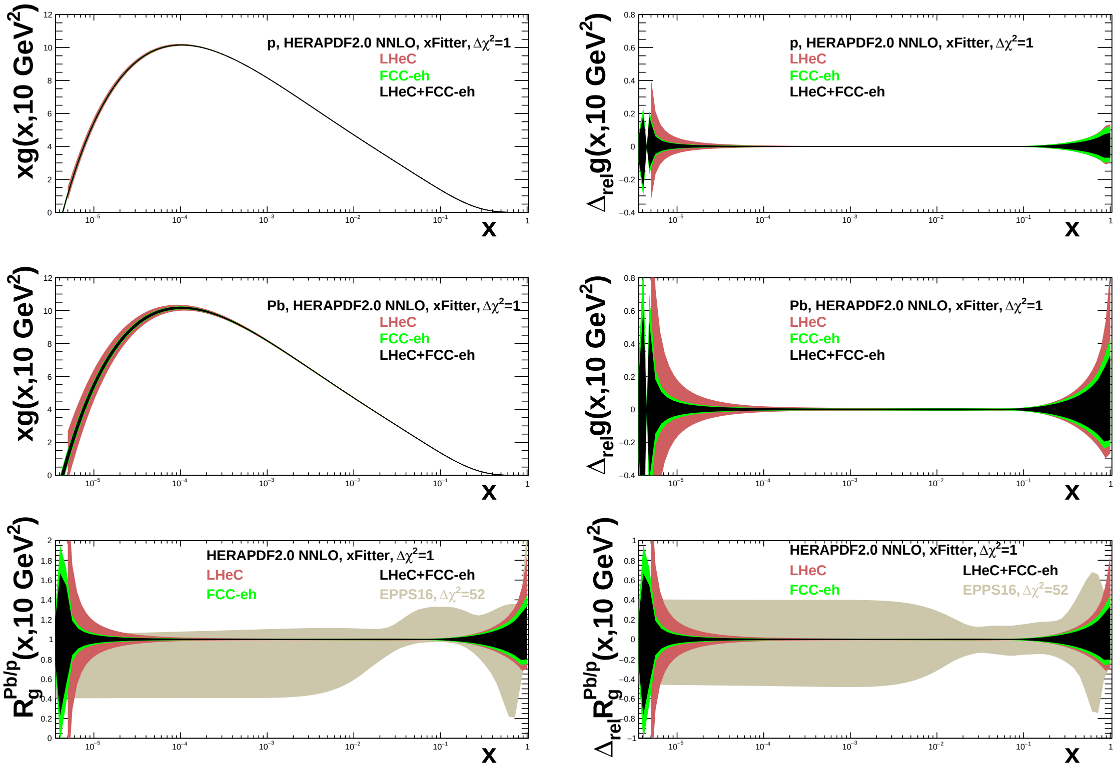

Figure 2: Distributions (left) and their relative uncertainties (right) of the gluon density in a free proton (top), in a proton in Pb (middle) and the corresponding nuclear modifications factor (bottom) in an analysis of ep and ePb LHeC and FCC-he NC plus CC pseudodata using *xFitter* [8] (both a single set of pseudodata for LHeC or FCC-he, or all combined), compared to the results of EPPS16 [4]. Taken from [2].

Fig. 2. We observe large improvements at all x (glue), but note the different tolerances between the analysis for a single nucleus and global fits like EPPS16. A fit to a single nucleus is possible, with no need of parametrisations of the initial conditions for QCD evolution that interpolate between different nuclei and introduce additional uncertainties. The precise nPDFs that are expected would allow, when used for predictions in pA, for precise tests of factorisation. As work to be done, the determination of c, b nPDFs, of strangeness through c-tagged CC, and the use more flexible functional forms, particularly at small x.

3. Further topics

In this Section we discuss the possibilities for studies on small-x physics and on diffractions. For other topics, please see in [1, 2].

3.1 Small-x physics

Fixed order perturbation theory implemented in linear evolution in collinear factorisation is expected to fail in DIS at small values of x. There, a new kind of evolution is required that demands the resummation of large logarithms of $1/x$ and, eventually, non-linear evolution leading to a saturation of parton densities. In the existing frameworks, saturation is a density effect enhanced by both decreasing x and increasing the size of the analysed hadron or nuclei. Therefore, eA collisions are essential to check the explanation of an eventual departure from fixed order perturbation theory and to distinguish it from resummation schemes implemented within linear evolution.

Studies in ep [1, 2] showed that kinematic reach - lever arm in Q^2 at small x to look for the tension between observables (F_2 and F_L or F_2^{HQ}) - is required to search for these new dynamics. Several analyses confirm that linear evolution cannot accommodate saturation even at NNLO or NNLO+NLLx. Varying nuclear size will be needed to definitively disentangle resummation from non-linear dynamics. The pioneering study in [9] was done for EIC kinematics which turned out to be limited for obtaining definitive conclusions. In the recent study [7] reweighting techniques where used to compare predictions from saturation and linear frameworks that were forced to coincide along a region close to that where saturation effects are expected to become important. The difference in Q^2 evolution between the two approaches leads to differences in results for F_2 (F_L) of a few ($\sim$ 10) % in ep and of $\sim$ 10 ($\sim$ 50) % for Au or Pb, in perturbative regions at small x accessible at the LHeC or FCC-he.

3.2 Diffraction

In eA, the separation between coherent and incoherent diffraction, where the nucleus remains intact and dissociates respectively, is a challenging problem. Diffraction offers large possibilities for giving differential information on proton and nucleus structure beyond standard PDFs. Diffractive PDFs give the conditional probability of measuring a parton in the hadron with the hadron remaining intact ($\sim$ 10 % of events at HERA were diffractive). Diffractive PDFs have never been measured in nuclei. The interplay between multiple scattering and survival probability of the colourless exchange (rapidity gap) and the relation between diffraction in ep and nuclear shadowing, with implications on multiple parton interactions and central exclusive production in hadronic colliders, make this subject of great interest. At the LHeC/FCC-he, diffractive PDFs are extractable in nuclei with the same accuracy as in proton (see [10]) in the kinematic region shown in Fig. 3, which largely extends that already examined in ep at HERA and the one eventually studied in nuclei at the EIC.

Acknowledgements

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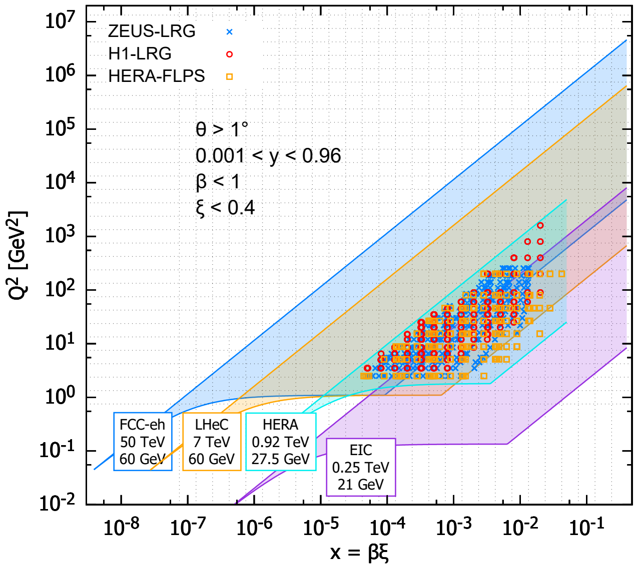

Figure 3: Kinematic phase space for inclusive diffraction in (x, Q^2) for the EIC (magenta region), the LHeC (orange region) and the FCC-he (dark blue region) as compared with the HERA data. The acceptance limit for the electron in the detector design has been assumed to be 1°, and we take $\xi < 0.4$ (see text for details). Taken from [10].

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