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

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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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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 instantaneus 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 instantaneus luminosities $\mathcal{L} \sim 5.4 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$ will be possible. Integrated luminosities $\sim 1$ 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 ultra-peripheral collisions. This can be done in \(ePb\) 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\(^4\) for the glue are shown in

\(^4\)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.
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 $F_2^{HMQ}$) - 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.

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### References

θ > 1°
0.001 < y < 0.96
β < 1
ξ < 0.4

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 ξ < 0.4 (see text for details). Taken from [10].


[5] B. Holzer, Overview of the LHeC and FCC-he accelerator concepts, these proceedings.


