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Energy Frontier Electron-Ion Physics with the LHeC and FCC-eh

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Energy-frontier DIS can be realised at CERN through an energy recovery linac that would produce 60 GeV electrons to collide with the HL-LHC or later HE-LHC (LHeC) or eventually the FCC hadron beams (FCC-eh). It would deliver electron-lead collisions with centre-of-mass energies in the range $0.8-2.2$ TeV per nucleon, and luminosities exceeding 5×10^{32} cm^{-2}s^{-1}. In this talk we will present novel ways for the accurate determination of nuclear PDFs, in a hugely extended space of x and Q^2, and the resulting constraints for the theory of parton dynamics in nuclei. We will then discuss diffractive physics and, finally, the possibilities for establishing the existence of a new non-linear regime of QCD at small x beyond the dilute regime described by collinear factorisation. Furthermore, we will comment on the possibilities at the LHeC and FCC-eh for analysing the transverse partonic structure of hadrons and nuclei and its corresponding fluctuations, with expected strong, direct implications on our understanding of the results obtained in present and future high-energy heavy-ion programmes.

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Parton distribution functions (PDFs) of the proton are largely constrained by the unique *ep* collider HERA at a centre of mass energy ($\sqrt{s}$) of around 300 GeV [1]. No such an *eA* collider exists for constraining nuclear PDFs (nPDFs). The current nPDFs are mainly constrained with fixed target ℓA DIS and *pA* Drell-Yan data at high x and low Q^2 [2]. Therefore our current knowledge on nPDFs is very limited. The gluon density of the proton at low x dominates and increases as x decreases. There is indication that at low x and Q^2, the fixed order QCD may no longer be able to describe the data [3]. It is expected that at sufficiently lower x the parton density becomes so large that a non-linear regime is reached. Non-linear effects would tame the growth of parton densities from power-like to logarithmic, a phenomenon known as "saturation". For reaching such low x regime, one needs higher energy collider such as LHeC or FCC-eh. The dense regime can also be reached with heavy ion beam since the enhancement of the saturation scale Q_s is A dependent [4].

With an electron or a positron beam of 60 GeV colliding with a heavy ion (lead) beam of 2.75 and 19.7 TeV at $\sqrt{s} = 0.8$ and 2.2 TeV at LHeC and FCC-eh, respectively, these colliders will provide a huge extension towards both low x and high Q^2 with respect to the current kinematic range [4]. The large kinematic reach at the TeV scale makes these colliders well positioned to reach conclusive evidence for the existence of a new saturation region of QCD [5]. Quantitative understanding of the nuclear behaviour is also needed for the *AA* and quark-gluon plasma studies.

The nPDFs $f_i^A(x,Q^2)$ are defined for a nucleus A with Z protons and N $(= A - Z)$ neutrons with $f_i^A(x,Q^2) = \frac{Z}{A} f_i^{p/A}(x,Q^2) + \frac{N}{A} f_i^{n/A}(x,Q^2)$, where $f_i^{p/A}$ are the nPDFs of a bound proton and the neutron contents $f_i^{n/A}$ are obtained from $f_i^{p/A}$ via isospin symmetry. As revealed by DIS experiments, the bound nPDFs are not the same as those of a free proton, but are modified in a nontrivial way. The modification in the global nPDFs analysis assumes the following relation between the bound nPDFs and free-proton PDFs $R_i^A(x,Q^2) = f_i^{p/A}(x,Q^2)/f_i^p(x,Q^2)$, and it has a functional form characterised by small-x shadowing at low x and anti-shadowing at medium x and EMC-like effect at high x as shown in Figure 1 of Ref. [2].

The impact of LHeC measurements was studied [6] by using samples of pseudodata corresponding to an integrated luminosity of 10 fb^{-1} and 1 fb^{-1} at $\sqrt{s} = 1.3$ and 0.8 TeV for the *ep* and *e*Pb collisions, respectively. The improvement on the nPDFs at $Q^2 = 10$ GeV^2 is shown in Figure 1. The improvement on the $\bar{d}$ nPDF is significant and the largest effect is on the gluon density with its uncertainty being reduced by a factor of 5. Similar analysis showing the impact of the LHeC and FCC-eh pseudodata on the nPDFs has also been conducted [7] using xFitter [8].

In addition to the dominant inclusive neutral and charged current DIS processes used above, the diffractive process is believed to be the most precise probe of non-linear dynamics in QCD since the associated colour neutral exchange corresponds to a pair of gluons in comparison with a single gluon exchange in the bulk of non-diffractive processes. At HERA, the relative fraction of the diffractive cross sections with respect to the inclusive DIS cross section was observed to be around 14%. The fraction is increased up to 25% at *eA* colliders according to saturation (colour glass condensate) models [9]. In addition to the enhanced sensitivity to saturation effects, the LHeC/FCC-eh will provide a widely extended kinematic coverage for diffractive events. Their study at the LHeC/FCC-eh will allow the extraction of diffractive parton densities for a larger range in Q^2 than at HERA, and will thus provide crucial tests of parton dynamics and flavour decomposition in diffraction as well as of the factorisation theorems. An analysis using pseudodata

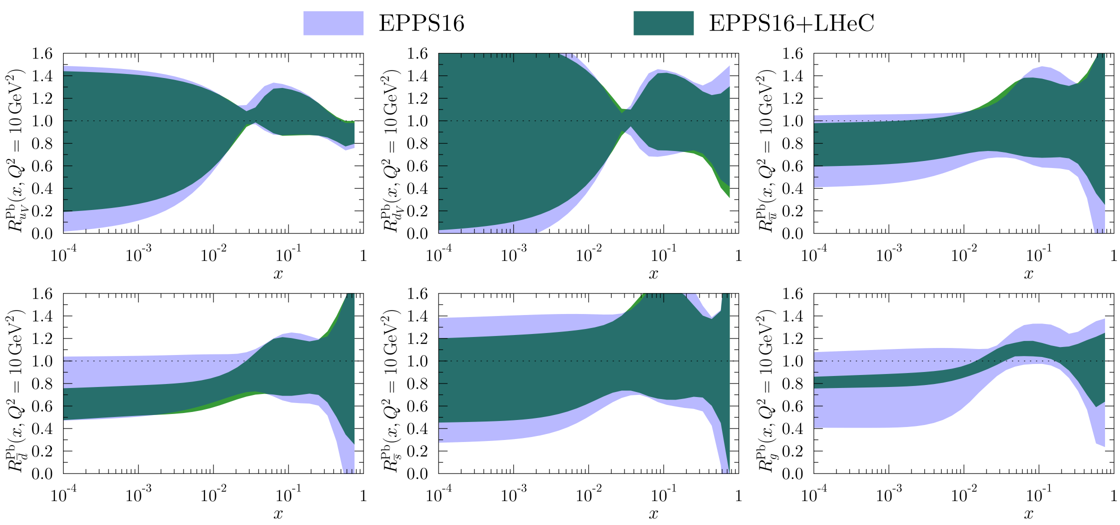

Figure 1: Impact of LHeC pseudodata on EPPS16 nPDFs at $Q^2 = 10$ GeV^2 [6].

samples has been performed and the results are shown in Ref. [10]. The high energy involved also enables the production of diffractive states with large masses which could include W and Z bosons as well as states with heavy flavours or even exotic states with quantum number 1^- [4].

Exclusive diffractive processes are also promising as a source of information on the gluon density in the nucleus [11]. The production has two distinct types: the coherent type where the nucleus scatters elastically and remains in its ground state, and the incoherent type where the nucleus dissociates into its constituent nucleons or other states. A quantitative study of the production will improve our understanding of the transverse structure of nuclei. The expected coherent and incoherent differential cross sections for the diffractive production of J/Ψ on the lead nucleus as a function of the momentum transfer squared t are shown in Figure 2 (left) with (b-Sat) and without (b-NonSat) saturation effects [4]. The cross section for $t \sim 0$ is dominated by coherent production, whereas the nuclear break-up contribution becomes dominant for $t \geq 0.01$ GeV^2, leading to relatively flat distribution. The coherent cross section exhibits a characteristic multiple-dip structure at these relatively large t values, the details of which are sensitive to gluon saturation effects. The pseudodata for the coherent process shown in the figure correspond to a modest integrated luminosity of order 10 pb^{-1}. Saturation effects can be studied in a very clean way using the t-averaged gluon density obtained from the forward coherent cross section. Figure 2 (right) shows this cross section as a function of the $\gamma^* p$ centre of mass energy W for different nuclei. The cross section varies substantially as a function of W and the nuclear mass number A. It is also very sensitive to shadowing or saturation effects due to the fact that the differential cross section at $t = 0$ has a quadratic dependence on the gluon density and proportional to the ratios of the gluon densities squared [4].

To conclude, an energy frontier eA collider LHeC/FCC-eh will allow unprecedented study of matter in a new regime of QCD. It provides new capabilities to study the saturation region, measure the gluonic structure of nuclei and investigate colour propagation using the nucleus as an analyser. The eA program at a collider is also an experimental challenge since it was never conducted, there

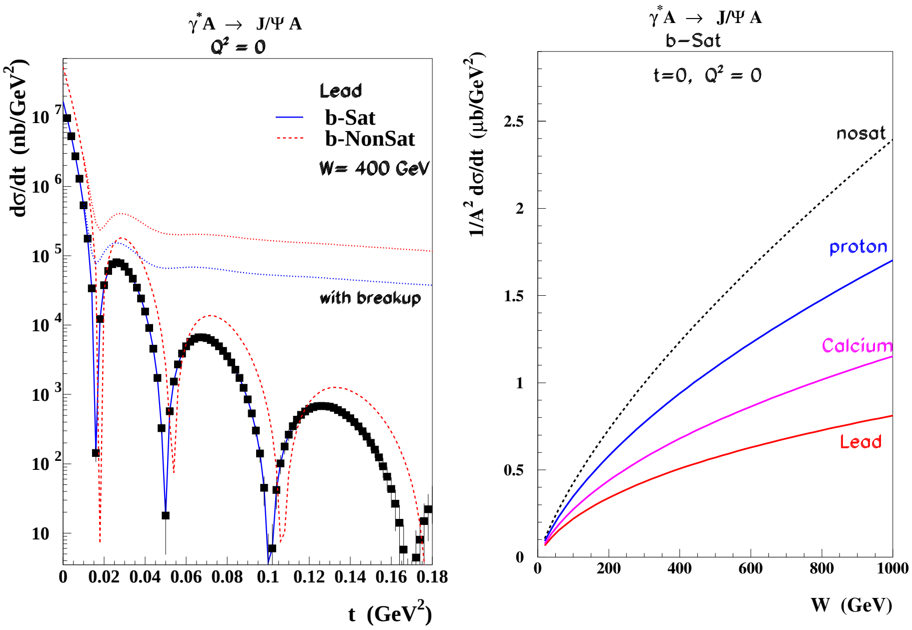

Figure 2: Differential cross section as a function of the momentum transfer squared t (left) and energy dependence of the coherent photoproduction on a proton and different nuclei (right). The figures are from [4].

will be new difficulties compared to an ep collider, and it puts further constraints on the design of the detector, the interaction region and forward instrumentations.

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