Low x and Diffractive Physics at a Large Hadron Electron Collider

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The prospect of a high energy *ep* and *eA* collider (an LHeC) involving an LHC hadron beam and a new electron accelerator is discussed. The low x physics possibilities of such a facility are explored in particular.

1 The LHeC Project

Energy-frontier physics will be dominated for the foreseeable future by the proton and heavy ion beams of the LHC, whose unprecedented energy and intensity herald a new era in the field. In the context of a CERN-ECFA-NuPECC commissioned workshop [1, 2], the fledgling LHeC project is investigating whether these hadron beams could be exploited as part of a new high performance electron-proton (*ep*) and electron-ion (*eA*) 'Large Hadron electron Collider' [3–6]. Through its unique sensitivity to the lepton-quark vertex, this could be complementary to the LHC *pp*, *pA* and *AA* programmes and to a possible pure lepton future collider in revealing physics at the TeV energy scale. The large achievable luminosities in particular set the LHeC aside from previously evaluated possible future high energy *ep* colliders [7]. Work is ongoing to assess the physics potential of an LHeC, as well as its accelerator, interaction region and detector requirements and the impact on the existing LHC programme.

Two basic configurations are under study [8]. A new electron ring based on slim (20 cm × 10 cm) dipole magnet elements, carried on top of the LHC proton ring, yields the largest luminosities. With 50 GeV beam electrons at 50 MW power consumption, an electron ring could deliver 5×10^{33} cm^{-2}s^{-1}, a factor of 100 beyond the highest luminosity achieved at HERA. An alternative solution is a linear electron accelerator arriving tangentially. A luminosity of 5×10^{32} cm^{-2}s^{-1} could be achievable for 50 GeV electron energy and 50 MW power, assuming an LHC luminosity upgrade. Linac energies up to 150 GeV are under consideration, which might be possible if energy recovery techniques may be applied. The possibility also exists of replacing the protons with, in the first instance, lead ions. Other heavy ion species and deuterons are also under consideration.

2 Overview of the LHeC Physics Programme

An overview of LHeC physics can be found for example in [9]. The accessible kinematic plane for *ep* collisions assuming a 7 TeV proton and a 140 GeV electron beam is compared with previous experiments in Figure 1a. The coverage is extended compared with HERA towards low Bjorken x at fixed Q^2 or towards high Q^2 at fixed x by the ratio of squared centre of mass energies $s_{\text{LHeC}}/s_{\text{HERA}} \sim 20$. With sufficient luminosity to overcome the basic $1/Q^4$ cross

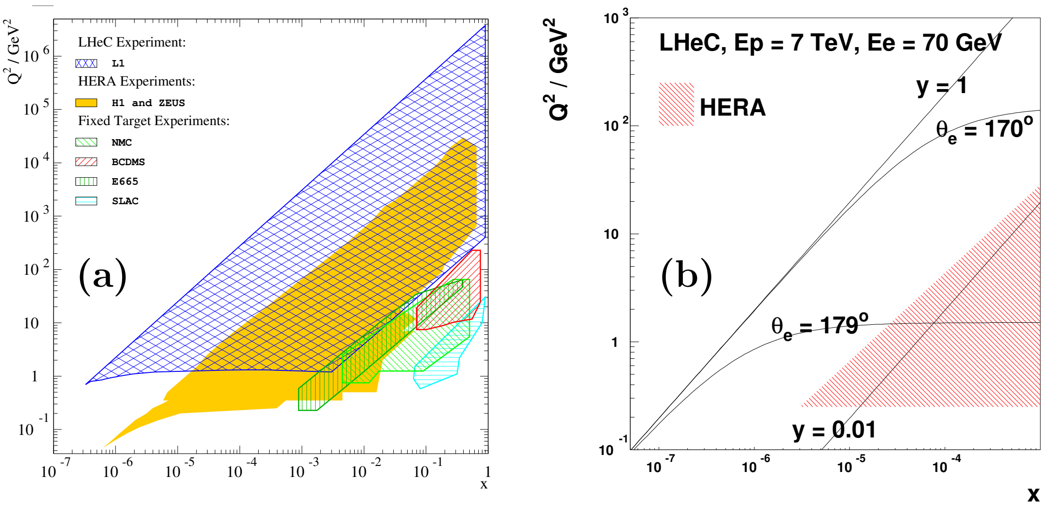

Figure 1: (a) Kinematic plane for ep collisions, showing the coverage of fixed target experiments, HERA and an LHeC. (b) Zoomed view of the low x corner of the kinematic plane, showing the acceptances for two different cuts on electron scattering angle θ_e at the LHeC.

section dependence, squared 4-momentum transfers $Q^2 \sim 10^6$ GeV^2 are accessible, probing distance scales below 10^{-19} m. As well as sensitivity to new physics [10], an LHeC would allow a full flavour decomposition of the parton distribution functions (PDFs) of the proton and would clarify many issues at the highest x [8]. It would permit measurements of the strong coupling constant and the light quark electroweak couplings to unprecedented precision [11]. As discussed in more detail in Sections 4.1 and 4.3, the ultra-high parton density region $x \lesssim 10^{-4}$ will be accessed for the first time at sufficiently large Q^2 for perturbative QCD techniques to be applied. When the LHC runs with heavy ions, the LHeC becomes the first ever eA colliding beam machine (Section 4.2).

Accessing the full available phase space brings challenges in the detector and interaction region design [12], as illustrated for the example of the scattered electron kinematics with a 70 GeV beam in Figure 1b. If the electron detection acceptance extends to scatterings through a 1° angle ($\theta_e = 179°$), full coverage of the region $Q^2 > 1$ GeV^2 is obtained, reaching below $x = 10^{-6}$. In contrast, with detector components restricted to $\theta_e < 170°$, there is little acceptance for $Q^2 < 100$ GeV^2 or $x < 10^{-4}$. Optimising the luminosity by including beam focusing elements close to the interaction region [3], similar to those installed for the HERA-II upgrade, must therefore be evaluated against the corresponding loss of small angle detector acceptance. In order to obtain good sensitivity to both high cross section low-x physics and rare high transverse momentum processes, a two stage programme may be necessary.

3 Low x Physics and Electron-Hadron Scattering

At sufficiently large Q^2 in the low x region, the 'asymptotically free' quarks of DIS meet a high background density of partons, and various novel effects are predicted. Ultimately, unitarity constraints become important and a 'black body' limit is approached [13], in which the cross section reaches the geometrical bound given by the transverse proton size. This limit is characterised by new effects such as Q^2 dependences which differ fundamentally from the usual logarithmic variations and diffractive cross sections approaching 50% of the total [14]. Applying the black body bound to the inelastic cross section for the interaction of a colour dipole, formed from a $\gamma^* \rightarrow q\bar{q}$ splitting, leads to an approximate constraint on the gluon density $xg(x, Q^2) < Q^2/\alpha_s$ [15], comparable to expectations for the gluon at the lowest LHeC x values. "Parton saturation" effects are therefore expected in the low x region at the LHeC.

Although no conclusive saturation signals have been observed in parton density fits to existing HERA data, hints have been obtained by fitting the data to dipole models [16–20], which are applicable at very low Q^2 values, beyond the range in which quarks and gluons can be considered to be good degrees of freedom. The typical conclusion [19] is that HERA data in the perturbative regime do not exhibit any evidence for saturation. However, when data in the $Q^2 < 1$ GeV^2 region are included, only models which include saturation effects are successful. Similar conclusions have been reached by studying the change in fit quality in the NNPDF NLO QCD PDF fit framework as low x and Q^2 data are progressively omitted [21].

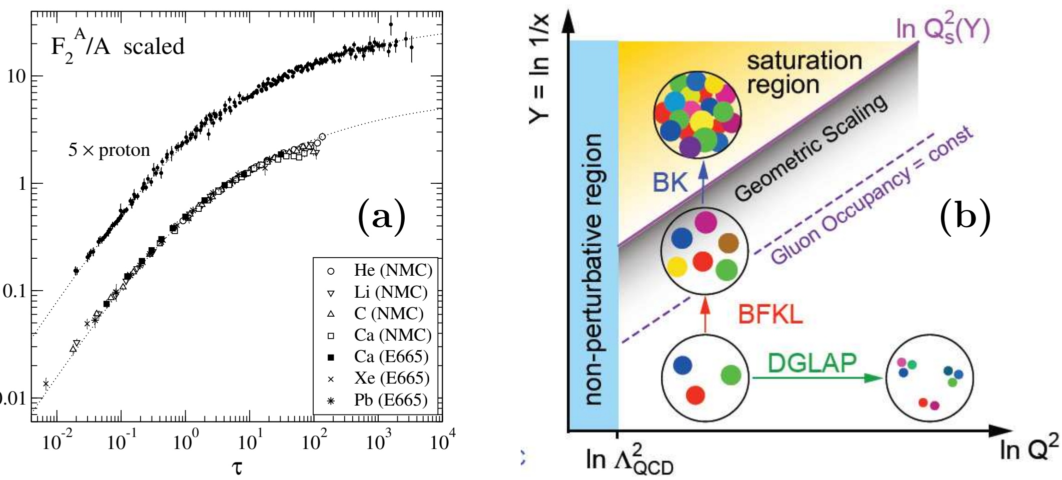

Figure 2: (a) Geometric scaling plot for protons and for nuclei (see text for details). (b) Illustration of the DIS kinematic plane, showing the transition to the saturation region.

The 'geometric scaling' [22] feature of the data reveals that to good approximation the low x cross section is a function a single variable $\tau = Q^2/Q_s^2(x)$, where $Q_s^2 = Q_0^2\ x^{-\lambda}$ is an x dependent 'saturation scale'. This parameterisation works well for scattering from both protons and heavy ions, as shown in Figure 2a [23]. An interpretation of this feature is that the cross section is invariant along lines of constant 'gluon occupancy' or 'blackness'. As illustrated in Figure 2b, such lines are diagonals in the $\ln 1/x$ v $\ln Q^2$ kinematic plane, due to two competing effects in the growth of the blackness: increasing parton densities as x decreases and dilution of the system as Q^2 grows and the resolution improves. When viewed in detail, there is a change in behaviour in the geometric scaling plot, Figure 2a, near $\tau = 1$, which has been interpreted as a transition to the saturation region shown in Figure 2b. However, data with $\tau < 1$ exist only at very low, non-perturbative, Q^2 values to date, precluding a partonic interpretation.

Whether or not the low Q^2 HERA saturation signal is confirmed, a central aim of the LHeC programme is to observe how unitarisation impacts on the proton structure. Understanding the mechanisms involved in terms of parton dynamics, for example the gluon recombination process $gg \to g$ [24], should be possible in the low x and moderate Q^2 region at the LHeC.

4 Simulated LHeC Low x Performance

This section describes some first explorations of low x physics possibilities with an LHeC. It is by no means exhaustive. Among the important topics which are under study, but are not covered here are forward jets and their relation to parton cascade dynamics and Deeply Virtual Compton Scattering (DVCS). More details on these and other topics may be found at [1, 2].

4.1 Inclusive ep Cross Sections

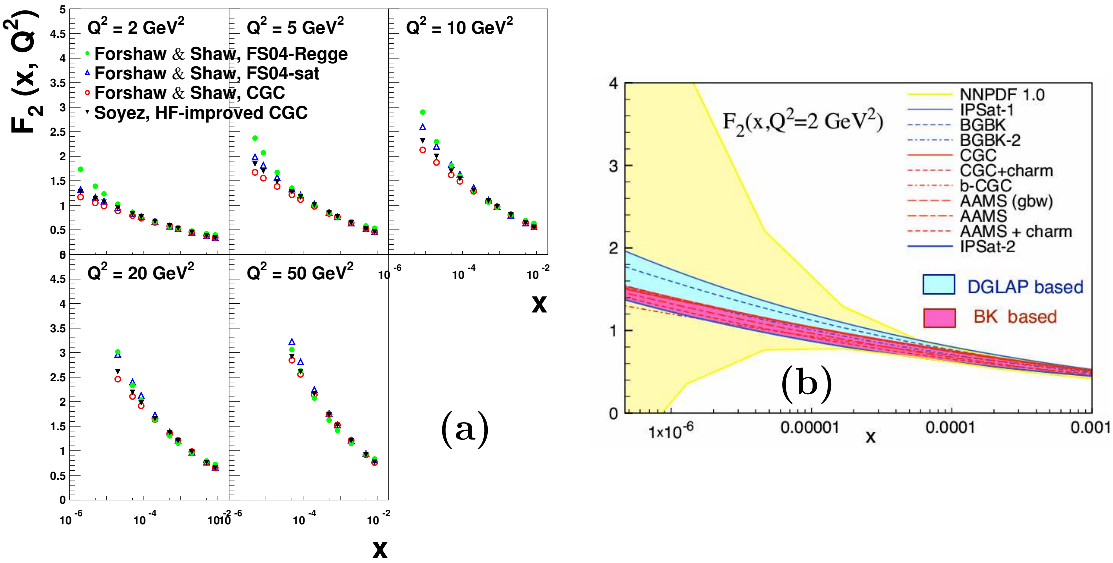

Figure 3: Extrapolations into the LHeC low x region of a variety of models of the inclusive structure function F_2. (a) Simulated data points in four dipole models at several Q^2 values. (b) A wide range of dipole model predictions at $Q^2 = 2$ GeV^2, also compared with the extrapolation uncertainty band from the NNPDF QCD fit to current data.

Figure 3a shows extrapolations of four dipole models constrained by fits to HERA data to predict the structure function $F_2(x, Q^2)$ in the LHeC kinematic range, which is shown in the form of simulated measurements [25]. At the lowest x and Q^2, there is a clear distinction between the 'FS04-Regge' model [19], which does not include saturation, and all others [19, 20], which include saturation effects as estimated from low Q^2 HERA data. However, any such sensitivity is lost by around $Q^2 = 50$ GeV^2, emphasising the importance of low angle scattered electron acceptance.

Figure 3b [26] shows a wider selection of dipole models, all of which include unitarisation effects, at a low scale, $Q^2 = 2$ GeV^2. The predictions have been grouped into two classes, according to whether the low x saturation is generated from eikonalisation of two gluon exchange within a DGLAP framework or from the non-linear BK equation [27] or Colour-Glass

Condensate [28] approach. It is interesting to note that the range of variation among these dipole models with QCD-based input is substantially smaller than the full range which is formally allowed by extrapolating the reasonable approach to parameterisation uncertainties in the NNPDF PDF fit [29]. The expected experimental precision (Figure 3a) is certainly good enough to distinguish between many of the different models.

Whilst such extrapolations of dipole fits to HERA data give encouraging indications, the unequivocal establishment of parton saturation at the LHeC is likely to be challenging. Two studies using very different approaches to PDF fitting are in progress [30, 31]. They both subject LHeC pseudo-data derived from saturating dipole models to NLO DGLAP fits, to determine whether saturation effects could be masked, for example by the flexibility in the parton parameterisations. It is not yet clear whether a breakdown of pure DGLAP dynamics may be visible with F_2 data alone. If not, the two ongoing analyses agree that the addition of F_L data as a second observable in the fits would prove conclusive.

4.2 Inclusive eA Cross Sections

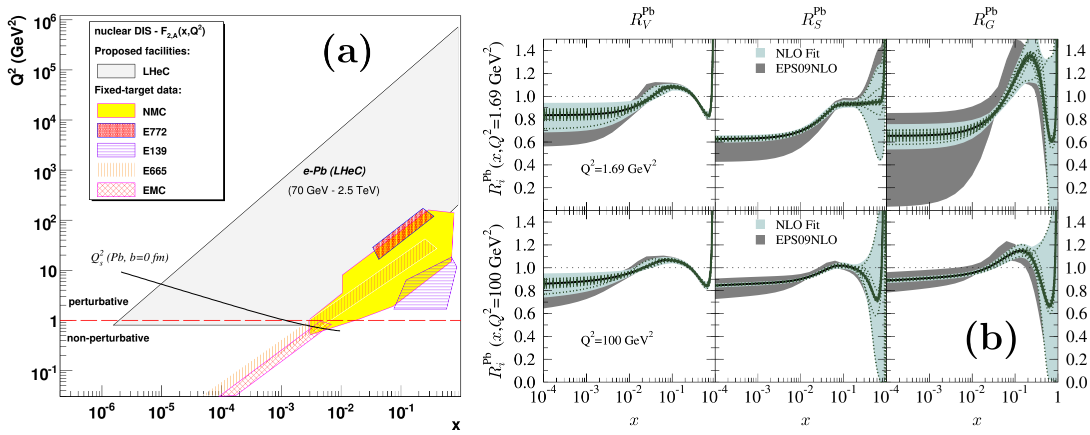

Figure 4: (a) Kinematic plane for eA collisions, showing existing fixed target coverage and the potential LHeC range. (b) Nuclear ratios (see text) as extracted in the framework of the EPS09 nuclear PDF fits. Uncertainty bands are shown with ("NLO Fit") and without ("EPS09NLO") the addition of the LHeC pseudo-data.

Since eA collisions have previously been achieved only in fixed target experiments, the parton distributions of nuclei are completely unknown at low x. Indeed, as illustrated in Figure 4a [32], the LHeC offers an extension in the kinematic range by around four orders of magnitude towards lower x at fixed Q^2 or towards higher Q^2 at fixed x. The LHeC is thus unique in its sensitivity to the initial state of heavy ion (AA) collisions in the LHC energy range.

The small x nuclear gluon density g_A at central impact parameters is enhanced relative to that (g_N) in a nucleon by a factor $(g_A/\pi R_A^2)/(g_N/\pi R_N^2) \simeq A^{1/3} g_A/A g_N \simeq A^{1/3}$ [14]. Scattering from nuclei thus offers enhanced sensitivity to unitarisation phenomena compared with ep collisions, if such effects can be unfolded from nuclear shadowing corrections due to the coherent scattering of the lepton from more than one nucleon. Figure 4a includes an estimate of the critical saturation line for electron-lead collisions. There is a substantial low x region within the LHeC acceptance below this line. The prospects of unfolding and understanding saturation effects when ep and eA data are considered together are very strong.

The influence of simulated LHeC data on fits to nuclear PDFs has been evaluated in the framework of the EPS09 NLO QCD analysis of existing nuclear data [33]. Figure 4b [34] illustrates this in the form of the nuclear ratio, (e.g. $R^A(x, Q^2) = F_2^A(x, Q^2)/AF_2^p(x, Q^2)$ for the total quark contribution), for the specific case of lead ($A = 207$, $A^{1/3} \sim 6$). If only existing fixed target eA and pA Drell-Yan / leading pion data are included, the uncertainties on the valence quark (R_V), sea quark (R_S) and gluon (R_G) ratios are all large, the gluon at low x and Q^2 being particularly problematic. Adding LHeC data resolves the low x region in a manner which is sensitive to saturation effects [34]. More detail on the potential synergies between eA, pA and AA scattering can be found in [35].

4.3 Diffraction

Non-inclusive observables promise to enhance the LHeC sensitivity to non-linear evolution and saturation phenomena. Diffractive channels are promising, due to the underlying exchange of a pair of gluons. The cleanest processes experimentally are Deeply-Virtual Compton Scattering (DVCS, $ep \to e\gamma p$) and exclusive vector meson production ($ep \to eVp$), which have both played a major role at HERA [36]. Simulations of LHeC elastic vector meson photoproduction ($Q^2 \sim 0$) have yielded encouraging results, especially for the J/ψ, as illustrated in Figure 5a [37, 38]. With acceptance for the muon decay products extending to within 1° of the beampipe,[1] invariant photon-proton masses W of well beyond 1 TeV are accessible, extending substantially beyond HERA coverage and clearly distinguishing between models in which saturation effects are present and where they are absent [18]. Similar studies of elastic J/ψ photoproduction in LHeC eA collisions have been proposed as a direct means of extracting the nuclear gluon density [39].

First studies [37] have been made of LHeC possibilities with the inclusive diffractive DIS process, $ep \to eXp$. Similarly to fully inclusive DIS, fractional struck quark momenta relative to the diffractive exchange, $\beta = x/x_{I\!P}$, a factor of around 20 lower than at HERA are accessible at the LHeC. Large improvements in diffractive parton densities (DPDFs) [40] are possible from NLO DGLAP fits to diffractive structure function, dijet and heavy flavour data. The extended phase space towards large Q^2 at fixed x increases the lever-arm for extracting the diffractive gluon density and opens the possibility of significant weak gauge boson exchange, which would allow a quark flavour decomposition for the first time. Figure 5b shows a comparison between HERA and the LHeC in terms of the invariant masses M_X which could be produced in diffractive processes with $x_{I\!P} < 0.05$ (RAPGAP Monte Carlo model [41]). Diffractive masses up to several hundred GeV are accessible, such that diffractive final states involving beauty quarks and W and Z bosons, or even exotic states with 1^- quantum numbers, could be produced.

Leading twist diffraction has been related [13, 42] to the leading twist component of the nuclear shadowing phenomenon. Measuring diffractive DIS together with nuclear structure functions (Section 4.2) in the LHeC range therefore tests the unified picture of complex strong interactions and leads to a detailed understanding of the shadowing mechanism, possibly essential in interpreting saturation signatures in eA interactions.

[1]This is likely to be achievable, even if tracking and calorimetry extend only to within 10° of the beampipe.

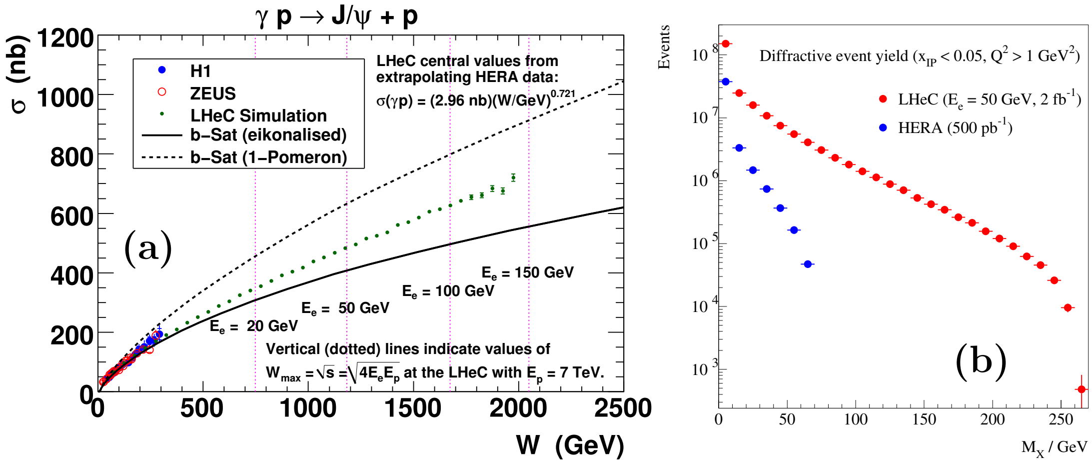

Figure 5: (a) An LHeC simulation of elastic J/ψ photoproduction cross section data for a 150 GeV electron beam, compared with HERA data and dipole model predictions with ("b-Sat - eikonalised") and without ("b-Sat - 1 pom") non-linear effects. (b) Comparison between expected LHeC and HERA diffractive mass (M_X) distributions.

5 Summary

An investigation of the possible exploitation of the LHC proton beams for *ep* physics is well underway in the framework of the LHeC project. If realised, an LHeC facility would become an integral part of the quest to fully understand the new Terascale physics which will emerge as the LHC era unfolds. Integral to this, the prospects for understanding the influence of unitarity constraints on low x physics in terms of new parton dynamics are particularly promising. Further evaluations of the full physics potential and the various detector, interaction region and accelerator lay-out options are ongoing. Frequent updates on the progress towards a Conceptual Design Report can be found at [4].

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