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Nuclear and Particle Physics Proceedings 273–275 (2016) 1526–1531

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Heavy-ion physics with high-energy e-A scattering

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Abstract

In recent years the physics of heavy-ion collisions has seen a phenomenal increase of interest from both the experimental and theoretical particle physics community. In particular the field has been pushed forward by the proton-lead and lead-lead programs at the LHC, given the fact that they can provide information on both cold nuclear matter effects and the quark-gluon plasma. Unfortunately a clear distinction between hot and cold nuclear effects is hard to achieve at the LHC, and thus in the last decade the construction of electron-ion colliders have been proposed in order to shed light on this matter. In this talk we explore some of the possibilities for the study of heavy-ions that such facilities offer and compare with the potential of the LHC. Specifically, we focus on the proposed Large Hadron-electron Collider facility at CERN.

1. Introduction

After more than 100 years from the first scattering experiments [1, 2] and in spite of the increasing experimental precision and theoretical efforts, the behaviour of matter under the strong interaction is a standing puzzle. Nowadays, even though we count with the highly successful framework of pQCD [3] to explain the interaction of particles at the fundamental level and the understanding of the proton structure has seen an astonishing improvement [4, 5, 6, 7, 8, 9], the description of nuclear effects relies strongly on theoretical models or parameterizations that give an incomplete picture of the results.

The LHC proton-lead and lead-lead programs aim to the core of this problem, looking to disentangle cold and hot nuclear matter effects and to study the properties of the Quark-Gluon plasma, the de-confined state of the universe right after the Big Bang. However in nucleus-nucleus collisions the clean extraction of information from measurements is obscured by the interplay of many different effects both hot (i.e. from de-confined matter) and cold (i.e. from ordinary nuclear matter). In this respect, the proposed electron-ion colliders will have the power to study a kinematical region that overlaps with the currently reached at LHC, with the addition of avoiding hot nuclear matter effects and decreasing the technical complexity of the detections and posterior data analysis. In this talk we discuss part of the extensive physics program of the Large Hadron-electron Collider; for the full reach of the LHeC and technical details, we refer the reader to [10, 11].

2. Nuclear PDFs

The scattering amplitude for electron-proton scattering is a product of lepton and hadron currents times the propagator characteristic of the exchanged particle. The leptonic part of the cross section can be calculated exactly. The hadronic tensor, however, cannot and it is only possible to reduce it to a sum of structure functions, $F_i(x, Q^2)$. These are written in terms of parton distributions f_i that give the probability distribution of the parton of type i to carry a fraction x of the proton's longitudinal momentum. The parton distributions are not calculable and have to be determined by experiment but at the same time are proven to be universal,

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.247

i.e. independent of the type of hard scattering process. Their extraction must be done as precisely as possible, as no prediction can be done without them. In particular, the nuclear PDFs, known to differ from the ones in unbounded nucleus [12, 13], are loosely constrained due to the scarce diversity and limited kinematical coverage of available data.

The nuclear modification of structure functions has been extensively studied since the early 70's. It's characterization is typically done through the so-called nuclear modification factor which, for a given parton density f, reads:

$$R^A_f(x, Q^2) = \frac{f^A(x, Q^2)}{A f^N(x, Q^2)} . \quad (1)$$

Here the superscript A refers to a nucleus of mass number A and N denotes the nucleon (usually a proton). In the absence of nuclear effects, R should be equal to unity. Nevertheless, F_2, that is, the ratio of the structure function F_2 off a nucleus with respect to the same off a proton (or deuteron) presents a complex behaviour of enhancements ($R > 1$) for $x > 0.8$ and $0.1 < x < 0.3$ (anti-shadowing), and suppressions ($R < 1$) for $0.3 < x < 0.8$ and for $x < 0.1$ (shadowing). The latter is the dominant phenomenon at LHC energies as the kinematic region $x < 0.1$ determine the particle production. Nuclear PDF analyses at LO and NLO accuracy [14, 15, 16, 17] include data from NC and CC DIS and DY experiments, and the small amount of available pion and kaon production cross-sections at mid-rapidity in deuteron-gold collisions from RHIC. The bulk of the measurements is sensitive to the valence quark distributions and the constraints on the gluon, specially on the small-x region, are particularly poor. Therefore high-accuracy data on nuclear structure functions at smaller x, achievable at the LHeC, will be able to substantially reduce the uncertainties.

As can be seen in Figs. 1 and 2 the kinematical coverages of the LHC and LHeC overlap, extending the region known from fixed target experiments up to four orders of magnitude in Q^2 and five orders of magnitude in x. It is clear then that the LHeC has the potential to put the PDF knowledge on a qualitatively and quantitatively new and superior basis. This is due to the kinematic range, huge luminosity, availability of polarised electron and positron beams, both proton and deuteron beams, and to the anticipated very high precision of the cross section measurements. Therefore, the QCD fits, which will in time include the real LHeC data, will benefit from a massively improved and better constrained input information.

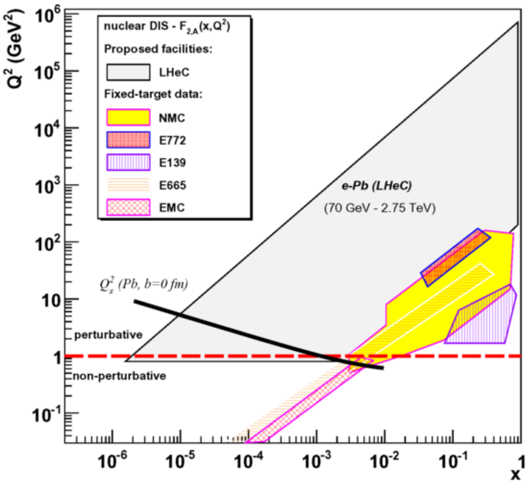

Figure 1: Kinematical coverage of the LHeC, taken from [10].

A quantitative estimation of the impact of LHeC cross-sections on nPDFs has been done in [18]. The simulation was performed using the LHC energy for the lead beam and three different energies for the electron beam with CTEQ6.6 proton PDFs and EPS09 nPDFs as baseline. All the technical details of the original EPS09 fit were preserved except for one additional gluon parameter that has been varied and the only additionally weighted data set considered was the PHENIX data on π^0 production at mid-rapidity in dAu collisions at RHIC. Then a new fit was done and the comparison with the original nuclear modification factors can be seen in Fig. 3. While there is no significant modification of the valence distributions, the improvement in the determination of sea quark and gluon densities at small x is evident. Furthermore, due to the fact that DGLAP evolution links large and small x, the LHeC will also provide additional information on the antishadowing and - with less precision - on the EMC-effect regions.

Information from the LHeC will complement that coming from pA collisions and self-calibrating hard probes in nucleus-nucleus collisions regarding the correct interpretation of the findings of the heavy-ion program at RHIC and at the LHC. Beyond the qualitative interpretation of such findings, the LHeC will greatly improve the quantitative characterization of the properties of QCD extracted from such studies. The importance of understanding initial state effects is not limited to the nuclear community. In fact proton PDFs extractions include DIS data with neutrino beams which, due to the smallness of the cross section, require the use of nuclear targets. The relevance of the corrections for nu-

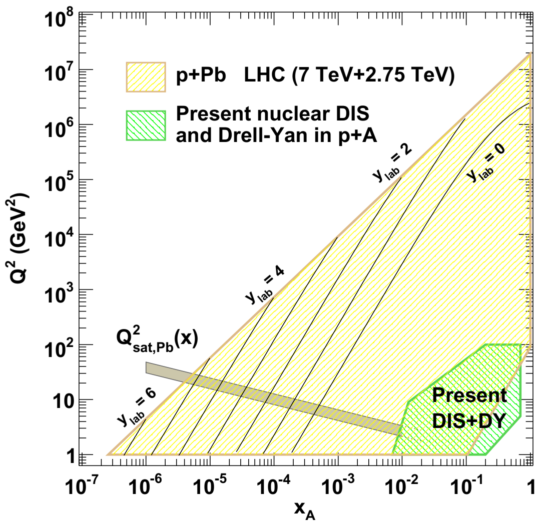

Figure 2: Same as 1, for the LHC proton-lead run; taken from [10].

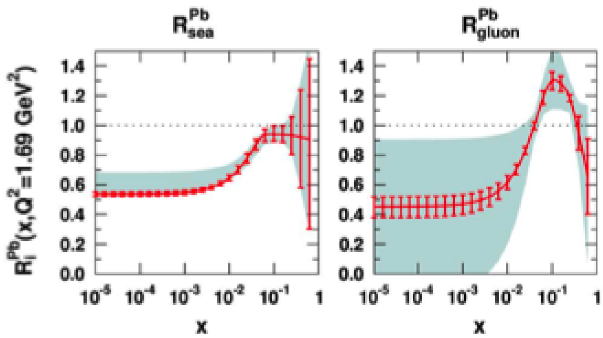

Figure 3: Estimation of the impact of LHeC data on the nuclear modification factor R for sea (left) and gluon (right).

clear effects is then established as they account for a significant source of uncertainty in the extraction of parton densities for the proton.

3. Physics at High Parton Densities

The partonic behaviour within the framework of collinear factorization is valid when momentum scales are sufficiently hard and the hadron can be described as a dilute set of partons. This condition of diluteness is not satisfied if the density of partons increases as it occurs if the number of partons increases (large structure function) or the interaction between the partons becomes strong (large α_s). From the experimental side, HERA data exhibit a strong rise towards low x at fixed Q^2, validating the idea that the proton becomes increasingly densely packed as we go to lower and lower x. Then non-linear evolution will eventually become relevant and the parton densities must *saturate*. In Fig. 4 we show schematically the situation.

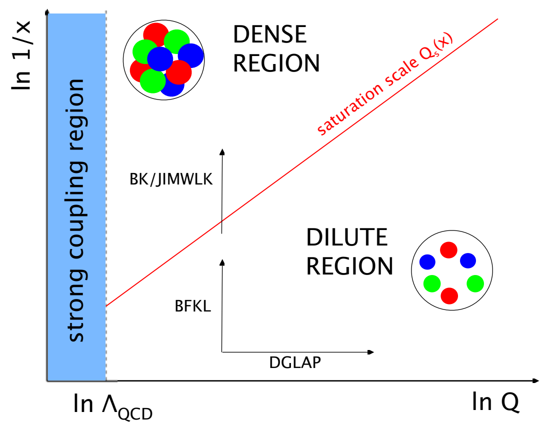

Figure 4: Picture of the saturation regime, taken from [10].

There is an approximately diagonal line in the $ln(Q^2)$-$ln(1/x)$ plane below which the parton distributions are dilute, and the standard QCD parton framework is valid. In that region the DGLAP equations give the correct description of parton dynamics. Near the line, however, non-linear QCD corrections gain relevance while in the region above the line partons are in a high-density state. Usually a dynamically generated *saturation scale*, growing with decreasing x (and, for nuclei, with increasing A) determines the separation of the two regimes. The LHeC opens the possibility of studying these dynamics, suggesting the accessibility of a parton-level understanding of the collective properties of QCD.

In order to analyse the regime of high parton densities at small x at the LHeC the two-pronged approach illustrated in Fig. 5 is proposed. Reaching the saturation regime of QCD can be done either by decreasing x (increase of the centre-of-mass energy) or increasing the matter density (increase A of the nucleus). This will allow to pin down and compare the small x and saturation phenomena in protons and nuclei and will offer an excellent testing ground for theoretical predictions. For a complementary perspective on the opportunities for novel QCD studies offered by the LHeC, see [19].

4. Diffractive vector meson production off nuclei

Exclusive diffractive processes are also promising as a source of information on the nuclear gluon density [20] and as the quasi-elastic scattering of photons

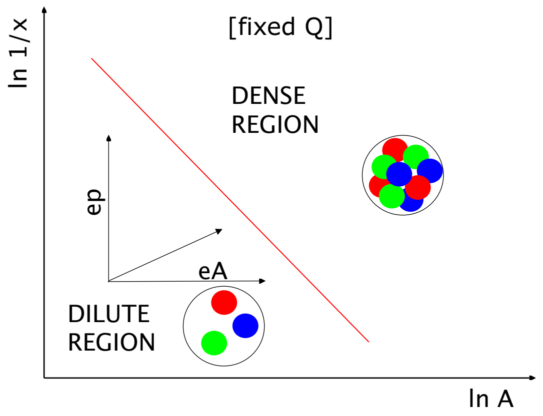

Figure 5: The different regions for the parton densities in the $ln(1/x)$-$ln(A)$ plane, for fixed Q^2. Plot taken from [10].

from nuclei at small x can be treated within the same dipole model framework as for ep scattering, the comparisons with the proton case become straightforward. The incorporation of nuclear effects into the dipole cross section can be made through the modification of the transverse gluon distribution and addition of the corrections due to Glauber rescattering from multiple nucleons [21, 20]. In the case of nuclei, the structure of in-

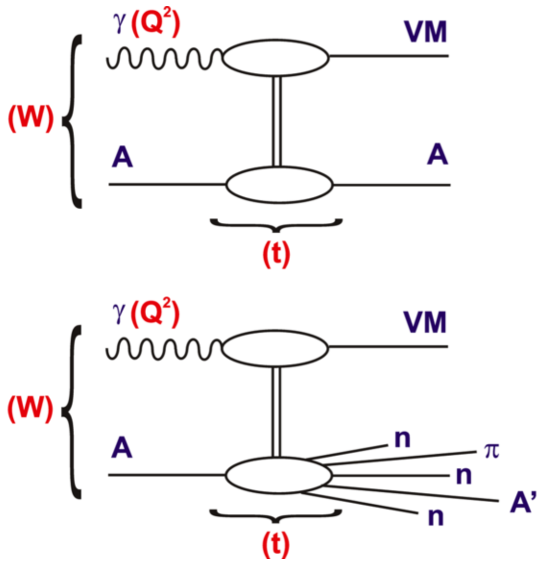

Figure 6: The different types of exclusive diffraction in the nuclear case: coherent (upper plot) and incoherent (lower plot). Figure taken from [10].

coherent diffraction with nuclear break-up is more complex than with a proton target and therefore more informative. The low-$|t|$ regime (upper plot in Fig. 6), will dominate up to a smaller value of $|t|$ than in the proton case due to the larger size of the nucleus. On the other side, the dissociation regime (Fig. 6, lower) shall present an intermediate regime in momentum transfer perhaps up to $|t| = 0.7GeV^2$, in which the nucleus breaks up into its constituents, and a large-$|t|$ regime where the nucleons will also break up. A quantitative analysis of this aspect of diffraction is crucial to complete the understanding of the transverse structure of nuclei. In Fig.

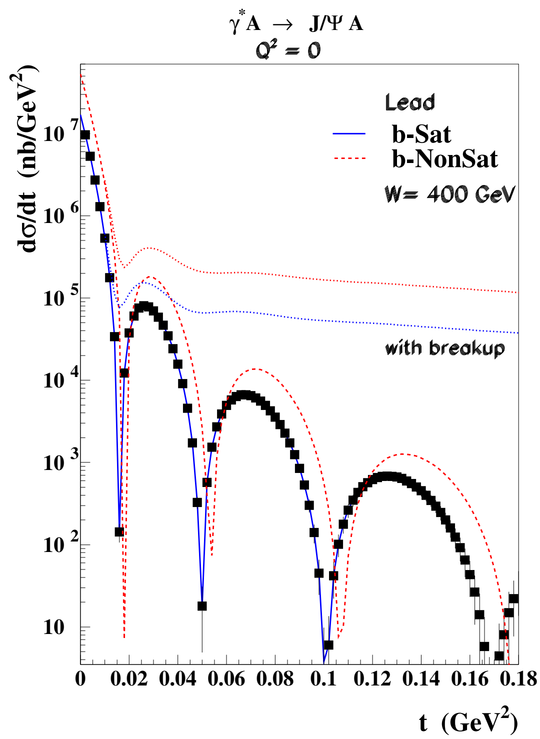

Figure 7: Pseudo data of the differential cross-section for the diffractive production of J/Ψ on a lead nucleus compared to the b-Sat model predictions for coherent production with (solid-blue) and without (dashed-red) saturation effects, and to the predictions for the incoherent case (dotted lines). Figure taken from [10].

7 we show the diffractive cross sections for exclusive J/Ψ production off a lead nucleus with (b-Sat) and without (b-NonSat) saturation effects. Both models predict the cross-section to be dominated by coherent production for $t \approx 0$, while the nuclear break-up contribution dominates for $|t|$ larger than $0.01GeV^2$, resulting in a relatively flat t distribution. Resolving the rich structure at large t should be then possible based on the measurement of the transverse momentum of the elastically produced J/Ψ according to $t = -p_T^2(J/\Psi)$.

5. Jets in photon-nucleus collisions

Regarding photoproduction in *eA* collisions, jets provide an abundant yield of high-energy probes of the medium. In Fig.8 we present the expected cross sections [22, 23, 24] for an electron beam of $50 GeV$ colliding with the LHC beams. The same integrated luminosity was assumed for *ep* and *eA* ($2 fb^{-1}$) and only jets with $E_{T\,jet} > 20 GeV$ were considered. The only uncertainty here included comes from the EPS09 [14] nuclear PDFs. From the predictions, yields of around 10^3 jets per GeV are expected with $E_{T\,jet} \approx 95$ (80) GeV in *ep* (*ePb*), for $\eta_{jet} < 3.1$. Initial nuclear effects are smaller than 10%. The two-peak structure in the jet-plot results from the sum of the direct plus resolved contributions, each of which produce a single maximum, located in opposite hemispheres. Positive jet values are dominated by direct photon interactions, whereas negative jet values are dominated by contributions from resolved photons. Such measurements are valuable as factorization checks and also for studying the nuclear modification of QCD radiation.

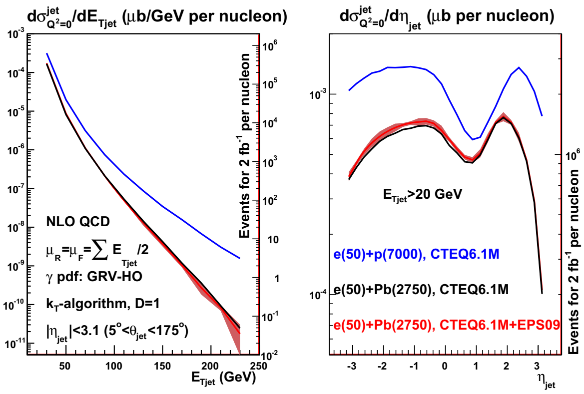

Figure 8: Estimation of the inclusive jet in photoproduction, differential in $E_{T\,jet}$ (left) and η_{jet} (right) for $e(50) + p(7000)$ (blue, top lines), $e(50) + Pb(2750)$ with no nuclear effects (black), and $e(50) + Pb(2750)$ with EPS09 nuclear modification (red). The photon, proton and nuclear PDFs are taken from GRV-HO [25], CTEQ6.1M [26] and EPS09 [14], respectively.

6. Summary

The LHeC constitutes a natural and affordable extension of the LHC, and an important improvement with respect to HERA exceeding its luminosity by a factor of 100 and reaching a maximum Q^2 of above $1TeV^2$ (maximum at HERA: $0.03TeV^2$). The LHeC proposes a broad physics program including a per mille accuracy measurement of α_s, the accurate mapping of the gluon field over five orders of magnitude in Bjorken x, the unbiased resolution of the quark contents of the nucleon and of the partonic structure of the photon. Moreover, it is expected to solve the puzzle of non-linear interaction dynamics at high density and whether there is a damping of the rise of the parton densities towards low x. With respect to the understanding of nuclear behavior it shall be a crucial tool, as it will give access to a kinematical region never reached before and help disentangle hot and cold nuclear matter effects. Finally, the reach of LHeC includes the precision study of New Physics, which shall be crucial to complement LHC results.

7. Acknowledgements

I thank N. Armesto for useful comments. This work was supported by European Research Council grant HotLHC ERC-2011-StG-279579; by Ministerio de Ciencia e Innovación of Spain under the Consolider-Ingenio 2010 Programme CPAN (CSD2007-00042); by Xunta de Galicia; and by FEDER.

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