PROCEEDINGS OF SCIENCE

Low x at LHeC/FCC-eh and its connections to ultrahigh energy neutrinos

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We discuss selected topics and prospects for low x physics at the Large Hadron-electron Collider and Future Circular Collider (electron-hadron option) as well as the connection and importance of such measurements for the ultrahigh energy neutrino physics.

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1. Introduction

The measurements of deep inelastic scattering of leptons on hadrons have provided crucial information about the structure of hadrons. The DIS experiments unraveled complex QCD structure of hadrons from the discovery of the partons by the SLAC experiment [1, 2], to the observation of the dramatic rise of the structure function at HERA with decreasing Bjorken x [3]. The complete understanding of the interactions in the Standard Model can only be achieved via series of complementary lepton-lepton, hadron-hadron and lepton-hadron collisions. The Large Hadron-electron Collider (LHeC) and Future Circular Collider- electron-hadron (FCC-eh) projects at CERN would open the window to the new, unprecedented regime of high energy and luminosity for deep inelastic lepton-proton and lepton-ion scattering.

The lepton-hadron, or lepton-nucleus collisions could be realized at LHC, by a linac-ring option, see [4]. In that scenario, an energy recovery linac is proposed, with a racetrack shape with two straight sections, where in each sections electrons can be accelerated up to 10 GeV. This set up can lead up to 60 GeV energy for the lepton, with three passes through the opposite cavity-cryo modules. Such scenario allows for the simultaneous running with proton-proton or heavy ion collisions at the LHC and as such would have low interference with the normal operation of the LHC. This option could be also utilized together with the FCC machine.

2. Low x physics

One of the most striking observations at HERA collider was the strong rise of the structure function F_2 with decreasing value of x. This was understood as a result of the growth of the gluon density due to the subsequent gluon splittings in the non-abelian gauge theory. Even though at present the structure function and the resulting gluon density can be successfully described through the DGLAP evolution (with sufficiently flexible initial conditions) the QCD theory predicts that at very low x, large logarithms appear that need to be resummed. In addition, the unlimited growth of the gluon density will lead to the enhanced probability of the recombination of gluons, a process which will tame growth of the gluon density for very low values of x. Including the recombination process will lead to the modification of the evolution equations of partons, by the terms which are non-linear in the parton density. It can be demonstrated that the unique feature of such non-linear modification of the high energy evolution equations is the emergence of the new scale, called saturation scale $Q_s(s)$ which separates the dilute and dense parton regime [5]. This scale depends on the energy $\sqrt{s}$ or the Bjorken x and it growths with the energy (or with decreasing x). Extensive phenomenology was done with the models which include the saturation at HERA, and they all point to the relatively low values of this scale, of the order of 1 GeV^2 at about $x \simeq 10^{-4}$. Unfortunately this is too low to make any firm statements about the partonic interpretation. The unique feature of the machine like LHeC is the possibility of extending the kinematic range such that the saturation scale should be in the perturbative regime and the tests on the validity of the saturation picture can be performed in a wider range of x Bjorken and Q^2.

In the nominal mode, the LHeC would scatter 7 TeV protons from the LHC with the 60 GeV electrons from the energy recovery linac, with the luminosity of the order of $10^{34}\,\frac{1}{cm^2 s}$. This energy range allows to probe x values down to 10^{-7} and Q^2 values down to fractions of GeV^2, provided the detector has electron acceptance down to 179°.

The LHeC can thus provide stringent constraints on the gluon and sea quarks distributions both at large and very low values of x, much beyond the current constraints imposed by the HERA collider. The details of the impact of the LHeC measurements on the parton distributions were presented in other contributions at this conference.

3. Diffraction

About 10% of all events observed at HERA collider were the diffractive events, which are characterized by the presence of the large rapidity gap. The LHeC could perform much more detailed studies of the diffraction in a wider kinematic range. Thus more detailed analysis of tests of factorization could be performed and diffractive parton distribution functions could be extracted with high precision. Since the LHeC could operate as an electron-ion collider one could also study the relation between diffraction in ep and shadowing in eA collisions. Leading proton tagging and large rapidity gap selection could be used to select the diffractive events, both methods are complementary with some region of common acceptance. A larger kinematic range for the collisions could allow for the new domain of the diffractive masses to be explored. In Fig. 1 the diffractive mass distribution is shown for LHeC with operating electron energy of 50 GeV and with integrated luminosity of 2 fb^{-1}. This distribution is compared to that probed at HERA. We see that the range in the diffractive masses is significantly enlarged, thus allowing for the diffractive production of high mass states such as beauty or W/Z bosons.

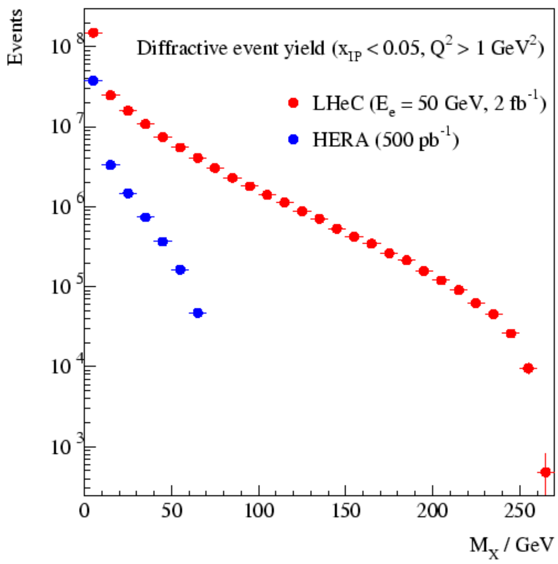

Figure 1: Simulated distributions in the invariant mass M_x according to the RAPGAP Monte Carlo model for samples of events obtainable with $x_{IP} < 0.05$. One year of high acceptance LHeC running at $E_e = 50$ GeV compared with HERA (full luminosity for a single experiment).

The inclusive diffraction will allow to extract the diffractive parton distribution functions in a wide range of β and x_{IP} and allow for the tests of the Pomeron vertex factorization. In addition to the inclusive diffraction exclusive diffractive processes can be measured wt the LHeC with greater accuracy and statistics. Among them are the exclusive diffractive production of the vector mesons. It has been argued that this process is an ideal tool for extraction of the dipole scattering amplitude and thus is also convenient for extracting the blackness of the interaction. In particular the measurement of the t (momentum transfer)-dependence in this process will allow to extract the information about the impact parameter profile of the dipole scattering amplitude. The large momentum transfer t probes on average small values of impact parameter where the density of the profile is the highest.

In Fig. 2 the integrated cross section for the photo production of the J/ψ is shown as a function of the energy of the photon-proton system. The vertical lines indicate different electron energies and thus indicate the limit of the range in W. The change in the slope of the different prediction indicate the onset of the unitarity corrections. Extending the kinematic range at FCC-he would provide extra lever arm in energy. Another sensitive test of the low x and saturation dynamics in this process, is provided by the measurement of the t dependence for different energies and for different vector mesons. It was observed in [6] that the t-profile of the elastic cross section has a characteristic dip in the presence of saturation. The position of the dip is dependent on the energy as well as on the mass of the vector meson and the virtuality of the photon if one considers DIS instead of the photo production. It turns out that the dip moves to lower values of t when the energy is increased. On the other hand, if the virtuality Q^2 of the photon is increased the dip moves to higher momenta. The details depend on the particular model, but the general tendencies are universal. Thus the measurement of the t - dependence and possible deviation of the slope in t could in principle provide a unique signal for the onset of the saturation in DIS.

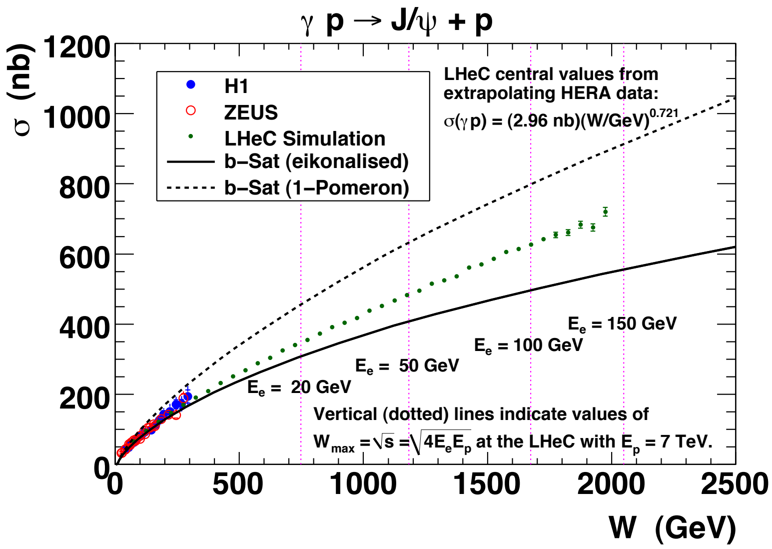

Figure 2: LHeC exclusive J/ψ photoproduction pseudodata, as a function of the $\gamma - p$ centre-of-mass energy W. The difference between the solid and dashed curves indicates the size of unitarity corrections according to the b-Sat dipole model.

4. Relation to ultrahigh energy neutrino physics

The LHeC measurements would provide an important input for the processes relevant to the neutrino observatories at high energies like IceCube [7]. At high neutrino energies, the cross section for the neutrino interaction is dominated by the deep inelastic scattering due to the growing parton densities. For the ultrahigh neutrino energies this requires the precise knowledge of the parton densities at very small x. This is illustrated in Fig. 3 where in the $(\ln 1/x, \ln Q^2)$ plane we show the dominant contribution to the neutrino DIS cross section for neutrino energy equal to $E_\nu = 10^{11}$ GeV. We see that the cross section is peaked around $Q^2 = M_W^2$ (due to the mass of the charged vector boson exchanged in weak interaction) and for x of the order of 10^{-7}. This is far beyond the current constraints from the collider experiments and thus the cross section can suffer from large uncertainties due to the errors in PDFs. Another process where the low x dynamics is essential,

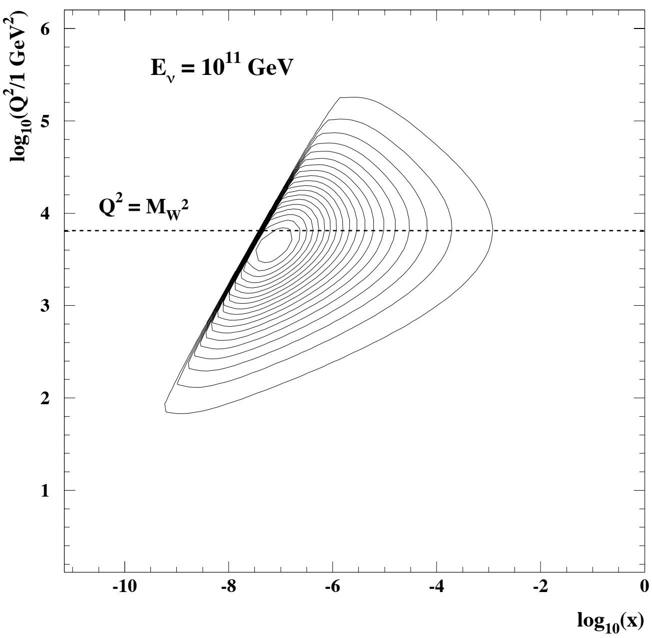

Figure 3: Two-dimensional projection of the total cross section for the charged current interaction of the neutrino with the nucleon. The energy of the incoming neutrino is $E_\nu = 10^{11}$ GeV.

is the prompt neutrino production in the atmosphere. The atmospheric neutrinos constitute an important source of the background for the astrophysical neutrinos at high energies [7]. They are produced in the processes of meson production in the interactions of high energy cosmic rays with the nuclei in the atmosphere. A high energy tail of the distribution of these neutrinos is dominated by the so called prompt neutrinos which originate from the decays of the charmed mesons. These mesons are produced very forward and their production cross section is driven by the small x gluon densities. In Fig. 4 we illustrate the resulting prompt neutrino flux from the interaction of cosmic rays in the atmosphere as a function of the neutrino energy. We see that it dominates the flux at highest energy tail. The PDF uncertainties in this cross section are the dominant uncertainties (not shown in the plot) and they can affect the strength of the measured signal of extraterrestrial neutrinos (for more discussion see [8]).

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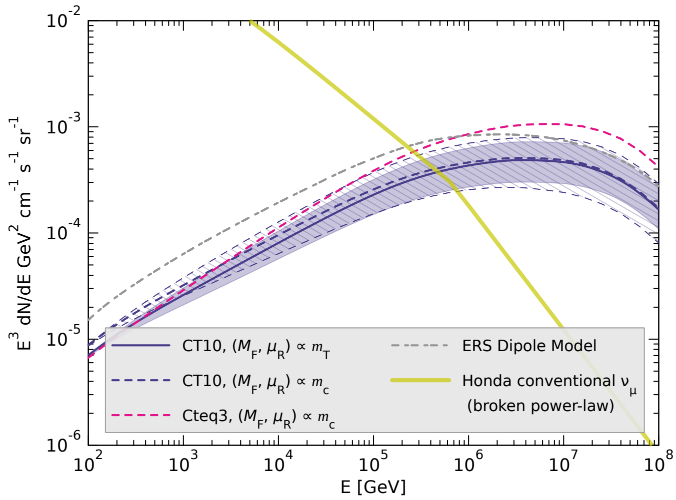

Figure 4: Prompt neutrino flux as a function of the neutrino energy together with the conventional component (yellow curve). The uncertainties are due to the renormalization and factorization scale variations in the calculation. Parton distribution function uncertainties are not included in the plot.

5. Summary

LHeC collider is the project which will offer a new realm in the measurements of the deep inelastic scattering both in terms of the luminosity and energy range. It will allow to measure the plethora of low x observables with unprecedented precision and in the new kinematic range thus allowing to test the novel QCD phenomena like parton saturation. It will provide the important constraints for the parton distribution functions needed not only for the LHC measurements and searches, but also important in the context of the ultrahigh energy neutrino physics explored at modern neutrino observatories.

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