Precision QCD and electroweak physics at LHeC

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A brief review is presented of the precision QCD and electroweak physics potentials at a possible future Large Hadron electron Collider (LHeC). All presented results are taken from the recently released conceptional design report [1] (CDR), in which further references can be found.

1 Introduction

The $e^{\pm}p$ collider LHeC with (about) 60 GeV times 7 TeV beam energies, an integrated luminosity of 1-100 fb^{-1}, and lepton beam polarisation up to $\pm$ 0.9, is one of the most interesting options for future particle physics colliders. The LHeC would provide ample opportunities to continue and extend precision QCD and electroweak studies much beyond what has been achieved at HERA. Among other things the LHeC will reveal all kind of facets of the proton structure, as represented by the Parton Distribution Functions (PDF), which parametrise the quark and gluon densities in the proton. This will be crucial for the understanding (and predictions) of LHC results. The large asymmetry of the two beam energies necessitates an excellent forward hadron calorimetry and calibration in order to explore the full kinematic phasespace up to large values of the *Bjorken* scaling variable $x \simeq 0.8$. The next sessions describe some selected physics studies from the CDR.

2 Proton structure and α_s

A set of neutral (γ, Z-exchange) and charged current (W-exchange) pseudodata have been simulated. The simulations were performed according to accelerator and detector scenarios that seem realistic and include also expected systematic uncertainties. At HERA, the exchange of the W and Z weak gauge bosons contributed only in a small phase space of highest accessible boson virtualities Q^2. In contrast the LHeC will be the first genuine "electroweak electron proton collider" machine. The integrated neutral (NC) and charged current (CC) event rates obtained from the simulations are about two order of magnitude larger at LHeC than at HERA and values of Q^2 are reached of up to $Q^2 \sim 10^6$ GeV. For the NC case, precise data are expected from smallest $x \approx 0.000008$ to largest $x \approx 0.8$. In a seizable fraction of the Q^2 phase space the photon and Z^0 exchanges are 1:1. Running with two lepton beam charges (electrons and positrons) and positive and negative lepton longitudinal polarisations will be crucial for electroweak precision physics as well as for the exploration of the proton structure. For the latter the Z and W exchanges assist the photon exchange for a complete *quark flavour* *decomposition*. Subtracting the NC cross sections for positron beams from those for electron beams isolates the $\gamma - Z$ interference term, as expressed by the structure function $xF_3^{\gamma Z}$, and provides direct information on the valence quarks from $x \sim 0.001$ to $x \sim 0.8$. The CC data for electron beams with W^- exchange and those for positron beams with W^+ exchange allow to unfold the u, d and also the $\bar{u}, \bar{d}$ densities in the proton. The longstanding question: "is the strange sea equal to the anti-strange sea?" can be answered by studying the charged current processes $W^+ s \to c$ and $W^- \bar{s} \to \bar{c}$ and tagging the charm (or anti-charm) quark in the final state. Studies with corresponding pseudodata indicate that a precise measurement of strange and anti-strange densities in the proton is possible over a wide range in Q^2 and x.

The knowledge of the gluon density is crucial at the LHC, for instance for the SM Higgs production which is dominated by the gg fusion process. The current knowledge comes mainly from the observed scaling violations of the structure function F_2 at HERA (as visible in the inclusive NC data). It is rather precise in the region relevant for Higgs production at LHC but diverges towards smaller values of gg centre-of-mass energy.

Figure 1 show the projected error bands of selected PDFs: valence quarks and gluon, as determined from a Next-to-Leading Order (NLO) QCD analysis of inclusive NC and CC data. The results using the LHeC simulated pseudodata in addition to real HERA data are compared to those using only HERA or using HERA and fixed target data from BCDMS. A huge improvement in precision and also an extension of effective coverage to much smaller x values and towards large values $x \sim 0.8$ is demonstrated. Among other things this will be helpful to pin down the not so well known ratio u/d for $x \to 1$. One nice feature (not shown here) is that, using the LHeC data, one can relax many assumptions that were made for PDF fits to the HERA data alone, for instance $\bar{u} = \bar{d}$ for $x \to 0$. Relaxing this constraint, the PDF error bands for fitting the HERA data alone increase drastically, showing the insensitivity of the HERA data, while those for LHeC plus HERA stay reasonably small, due to the much better flavour decomposition capabilities at LHeC. The u/d flavour decomposition at LHeC can be further improved with the planned deuteron runs.

Inclusive deep inelastic NC data allow a precision determination of the strong coupling constant α_s, mainly via the scaling violations of F_2. Projections show that it will be possible, by fitting simultaneously LHeC and HERA data to reach a precision of 1 permille, which is a factor ~ 10 better than fitting only HERA data.

3 Jet and heavy flavour production

Jets are produced in ep collisions in leading order $o(\alpha_s)$ via the Boson Gluon Fusion (BGF) process $\gamma^* g \to q\bar{q}$, and the QCD compton process $\gamma^* q \to qg$. Here q and g denote initial (from the proton) or outgoing hard partons, the latter producing jets. The BGF process rate is proportional to the product of the gluon density and α_s, while the QCD compton is proportional to the product of the quark densities and α_s. Thus the analysis of jet production helps to disentangle the gluon density and α_s. The jet data at LHeC cover a kinematic range up to 500 GeV transverse momenta (compared to ~ 100 GeV at HERA). This will allow to study for the first time with good precision the running od α_s to such high scales where the onset of *top loop diagrams* are expected to influence the running behaviour. This will provide a unique test of the SM strong interactions. Currently the precision of predictions for jet productions in ep collisions is limited to order $o(\alpha_s^2)$. At the time of the LHeC, order $o(\alpha_s^3)$ calculations should be available which will be crucial to exploit the full physics potential of jet measurements at

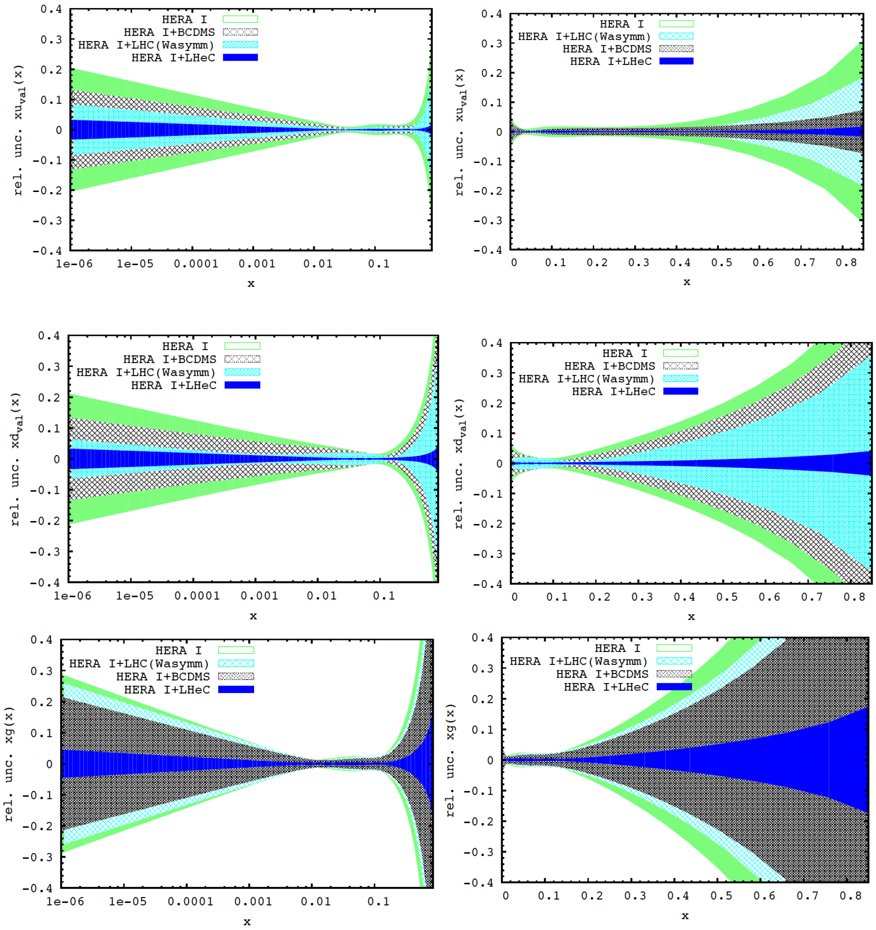

Figure 1: Uncertainty of selected parton distributions, at $Q^2 = 1.9\,\mathrm{GeV}^2$, as resulting from an NLO QCD fit to selected data (see text). Top: up valence quark; Middle: down valence quark; Down: gluon; left: logarithmic x, right: linear x.

the LHeC.

Charm and beauty quarks are produced in *ep* collisions in leading order via the BGF process $\gamma^* g \to c\bar{c}$ (or $b\bar{b}$). This process provides direct sensitivity to the gluon density in the proton. Charm and beauty production contribute up to 35% and 9% of the inclusive deep inelastic scattering cross sections. Thus a direct measurement of this contribution, represented by the structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$, is of great importance for the understanding of the whole proton structure in terms of light quarks, heavy quarks and gluons. Projections for $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ have been obtained using RAPGAP Monte Carlo simulations and are shown in Figure 3. They indicate a huge phase space extension and improvement in precision compared to representative HERA results which are also shown. The extension to low x values will be important for the study of the gluon density, while the mapping from low to high Q^2 for the precision determination of the charm and beauty quark masses and more generally for the treatment of mass

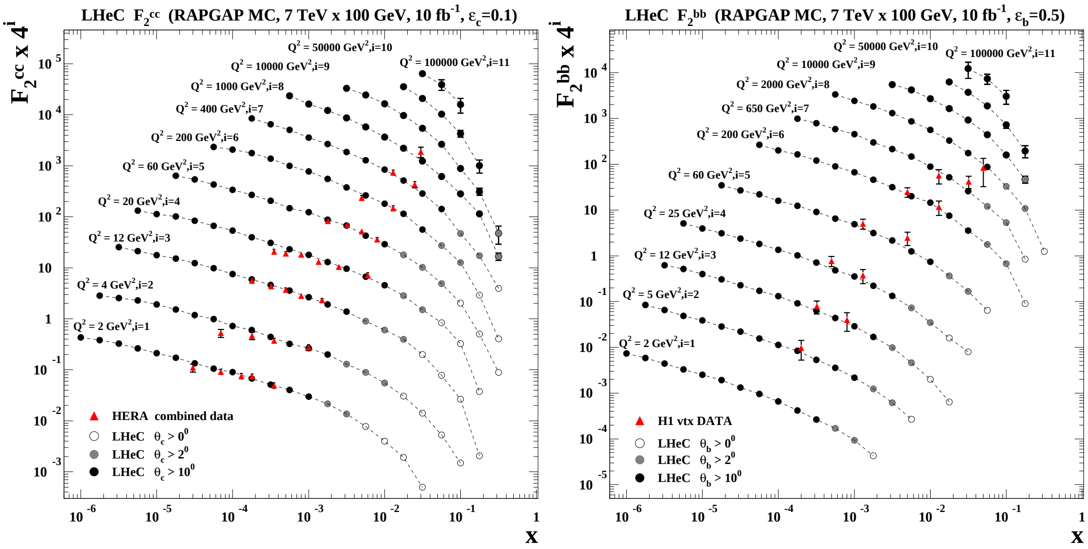

Figure 2: LHeC Projections for structure functions F_2^{cc} (left) and F_2^{bb} (right), compared to HERA data, shown as a function of x for various Q^2 values.

dependent terms in pQCD. With very good forward charm and beauty tagging capabilities of the LHeC detector, it will be possible to reach large x-values $x \geq 0.1$ where one can test the hypothesis of an *intrinsic* charm (or beauty) component in the proton wave function.

At LHeC one can also study for the first time at an *ep* collider top production, which is dominated by the reaction $bW^+ \to t$ (and $\bar{b}W^-\bar{t}$). In general LHeC will be the first multiflavour factory *ep* collider, allowing to do studies related to all six quark flavours.

4 Electroweak measurements

The LheC provides a rich potential for electroweak precision measuremnts from which here only a few are reported. Studies with $e^{\pm}p$ NC and CC pseudodata of positive and negative lepton beam polarisations show that there is a good sensitivity to determine the light quark axial and vector couplings to the Z boson. It will be possible to provide from these data a few relatively precise points for the running of the Weinberg angle $\sin^2\theta_W(\mu)$, for scales μ between 10 and 400 GeV, which are complementary and/or extend determinations from other type of experiments and colliders.

The interesting prospects of Higgs production were presented in another talk [2].

References

[1] The LHEC study group, "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", arXiv:1206.2913v1.

[2] Rohini Godbole, "Higgs CP properties and the LHeC", these proceedings.