Topics in the Relation of the LHeC and the LHC

Bruce Mellado for the LHeC Study Group

University of the Witwatersrand, School of Physics, Private Bag 3, Wits 2050, Johannesburg, South Africa

E-mail: Bruce.Mellado@wits.ac.za

Abstract. The LHeC is envisioned to collider electrons and protons concurrently with proton-proton collisions at the LHC. The present report is based on the recently published conceptual design report of the LHeC and on contributions to the European strategy debate in emphasizing the role of the LHeC to complement and complete the high luminosity LHC programme. The report focusses on the importance of high precision PDF and α_s determinations for the physics of the Higgs boson and beyond the Standard Model.

1. Introduction

Deep inelastic lepton-hadron scattering is the cleanest and most precise probe of parton dynamics in protons and nuclei. The LHeC is the only current proposal for TeV-scale lepton-hadron scattering and the only medium-term potential complement to the LHC pp, AA and pA programme at the energy frontier. As such, it has a rich and diverse physics programme of its own, as documented extensively in the recent conceptual design report (CDR) [1] and summarised in an initial submission by the LHeC Study Group to the European Stratey of Particle Physics (ESPP) discussion prior to the Cracow Symposium [2]. The focus of this second submission to the ESPP is a further exploration of the relationship between the LHeC and the LHC. Specifically, by improving the understanding of the LHC initial state through tighter constraints on parton densities and providing information on many other aspects of strong interactions, the LHeC extends the capabilities of the LHC programme substantially.

The LHeC offers the prospect of synchronous operation of a new ep (and eA) facility with the GPDs in the high luminosity phase of the LHC (HL-LHC). The physics programme of the GPD experiments on this timescale, as illustrated in the ATLAS and CMS contributions to the ESPP process, is centered around two major objectives: i) the most precise and complete exploration possible of the newly discovered Higgs-like particle and ii) maximising the sensitivity of the continuing search for new particles and symmetries or extra dimensions in the few TeV range of mass. This document investigates the potential impact of precision LHeC results on these objectives, as we understand them at present, recognising that the situation will evolve with time and deserves continuous further study. It also recalls the importance of the deep inelastic electron-ion scattering for the completion of the LHC heavy ion programme. The mutual relations between the LHeC and the LHC are of course much deeper than can be covered in a brief communication such as this.

As documented in detail in [1], the parton density (PDF) determinations offered by the LHeC are substantially superior to the possibilities using LHC data alone and, for the first time, provide a full flavour decomposition essentially free of assumptions. The LHeC also promises

a broad and unique programme of further strong interaction physics, such as the exploration of a newly accessed high density, low coupling regime at low x and a new level of precision and hugely extended kinematic coverage on the partonic structure of nuclei. Combined with competitive sensitivity to new physics in channels where initial state lepton quantum numbers are an advantage, the LHeC represents a cost effective means of fully exploiting the LHC and substantially extending its physics programme.

Following the discovery by ATLAS [3] and CMS [4] of a new boson with a mass of about 126 GeV, the future focus of the field will be firstly on determining whether this particle is the Standard Model Higgs boson or something more exotic and secondly on extending the sensitive range for discovery of other new particles as far as possible. ATLAS and CMS have reported exclusion limits for a wide range of massive new particles in the $1-2$ TeV range. With no strong evidence for new effects so far, the need to further extend such searches to the largest masses possible is paramount. The increased beam energy following LS1 will provide a first major step in this direction. Beyond that, further progress is limited by luminosity, due to the fast-falling cross sections as higher and higher x PDFs are involved (especially for gluon initiated processes), and by the uncertainities on those PDFs. To fully exploit the new particle discovery range of the LHC, both a luminosity upgrade and tighter external PDF constraints are therefore required.

The future exploration of the Higgs boson sector at the LHC, for example by measuring relative couplings and testing the CP structure, may similarly become limited by theory uncertainties derived from PDF measurements once the very high luminosities possible at HL-LHC have been accumulated [5]. This is particularly true for the 'working horse' channels in which the Higgs boson decays to $\gamma\gamma$ or four charged leptons. Whilst LHC inclusive W and Z production data will somewhat improve constraints on the quark densities of the proton at the electroweak scale, they will have a limited impact on the gluon density, which is more pertinent to Higgs boson physics, given the dominant gg production mechanism.

2. The LHeC Linac-Ring Collider

The LHeC aims at colliding the high-energy protons and heavy ions circulating in the LHC with 60-GeV polarized electrons and possibly also positrons. The LHeC is realized by adding to the LHC a separate 9-km racetrack-shaped recirculating superconducting (SC) energy-recovery linac (ERL). The key components of the LHeC are the two 1-km 10-GeV SC linacs of the ERL, comparable in scale to the 17.5-GeV SC linac of the European XFEL presently under construction. The LHeC ERL provides a design lepton beam current of 6.4 mA at the ep collision point, which is taken to be at IP2 of the LHC. Aside from the IP2 interaction region, the LHeC underground infrastructure is fully decoupled from the existing LHC tunnel. Two of the access shafts could be located on the CERN Prevessin site.

The LHeC is designed to operate with simultaneous LHC pp (or AA) collisions. LHeC operation is fully transparent to the other LHC experiments thanks to the low lepton bunch charge and resulting minuscule beam-beam tune shift experienced by the protons, together with the choice of the LHeC circumference to be equal to a third of the LHC's in order to allow for ion-clearing gaps in the ERL without perturbing LHC steady-state operation.

LHeC has been designed under the constraint that the total electrical power for the LHeC lepton branch should not exceed 100 MW (about half the present maximum CERN site power). The LHeC electrical power budget is dominated by the RF and by the cryo power for the two 1-km long SC linacs. The cryo power required and, therefore, also the size of the cryoplants (as well as the maximum lepton current) are directly linked to the unloaded quality factor of the cavities, Q_0. With a Q_0 of 2.5×10^{10}, the total main-linac cryopower amounts to 23 MW. The RF power needed for RF microphonics control is about 24 MW, and the extra-RF power needed for compensating SR losses at 6.4-mA current also to 23 MW. The remaining components, like injectors or arc magnets, require a few MW each.

parameter [unit]	LHeC	
species	e	p, ^{208}Pb^{82+}
beam energy (/nucleon) [GeV]	60	7000, 2760
bunch spacing [ns]	25, 100	25, 100
bunch intensity (nucleon) [10^{10}]	0.1 (0.2), 0.4	17 (22), 2.5
beam current [mA]	6.4 (12.8)	860 (1110), 6
rms bunch length [mm]	0.6	75.5
polarization [%]	90 (e^+ none)	none, none
normalized rms emittance [μm]	50	3.75 (2.0), 1.5
geometric rms emittance [nm]	0.43	0.50 (0.31)
IP beta function $\beta^*_{x,y}$ [m]	0.12 (0.032)	0.1 (0.05)
IP spot size [μm]	7.2 (3.7)	7.2 (3.7)
synchrotron tune Q_s	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)	
lepton disruption parameter D	6 (30)	
crossing angle	0 (detector-integrated dipole)	
hourglass reduction factor H_{hg}	0.91 (0.67)	
pinch enhancement factor H_D	1.35 (0.3 for e^+)	
CM energy [TeV]	1.3, 0.81	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1 (10), 0.2	

Table 1. LHeC parameters. The numbers give the default values with optimum values for maximum ep luminosity in paranthesis and values for the ePb configuration separated by a komma.

Together with rather conservative assumptions for most parameters, the 100 MW power limit yields the LHeC ep target luminosity of 10^{33} cm^{-2}s^{-1}. However, extensions to significantly higher luminosity, e.g., 10^{34} cm^{-2}s^{-1}, are possible by a combination of improvements, namely (1) by considering a normalized proton beam emittances of 2 μm (as achieved in 2011/12 LHC operation) instead of 3.75 μm; (2) by a further reduction of the proton IP beta function from 0.1 m down to 0.05 m, which should be possible by using a variant of the so called ATS optics; (3) by increasing the proton bunch intensity from 1.7×10^{11} to the HL-LHC 25 ns target value of 2.2×10^{11} [for the 50-ns HL-LHC scenario it would be even 3.3×10^{11} with a possible further factor 2.5 increase of luminosity, to more than 2×10^{34} cm^{-2}s^{-1}]; and (4) by doubling the lepton beam current, which should be possible without exceeding the 100-MW power limit if the unloaded Q_0 value of the SC RF cavities can be raised to 4×10^{10} (as it is assumed for the similar eRHIC design). Table 1 shows LHeC parameters, including, in parentheses, values for a higher-luminosity variant.

The LHeC represents an interesting possibility for further efficient exploitation of the LHC infrastructure investment. The development of a CW SC recirculating energy-recovery linac for LHeC would prepare for many possible future projects, e.g., for an International Linear Collider, for a neutrino factory, for a proton-driven plasma wake field accelerator, or for a muon collider. With some additional arcs, using 4 instead of 3 passes through the linacs, a machine like the LHeC ERL (without energy recovery) could also operate as a Higgs boson factory $\gamma\gamma$ collider (SAPPHiRE).

3. Parton Distributions

3.1. Valence and Sea Quarks

The LHeC is in a unique position to unravel all quark densities in the proton with a complete quark flavour separation for the first time and with unprecented precision. The huge phase space covered matches the needs of the LHC and includes the extreme values of Bjorken x, lowest, $x \simeq 10^{-5}$, where saturation may set in and largest, near to 1, which determine the multi-TeV BSM cross sections at the LHC. The detailed shape measurements of the various parton distributions, for example of the strange density versus Q^2 and x, imply that the nowadays large uncertainties due to PDF parameterisations in pQCD fits will be drastically reduced. A complete base of PDFs as the LHeC promises to deliver will at many places lead to possibly sizeable deviations of the now canonical PDF pattern. This is a necessary input for future LHC measurements, as precision Higgs boson coupling and cross section determinations. There are also expectations that discoveries are made in the conventional PDF pattern, as by possible observations of anti-quarks to be different from their sea quarks or an intrinsic heavy flavour part. Since the momentum is conserved, and shared between quarks and gluons, any deviation affects the overall pattern, which reflects on other parts of physics. Moreover, a crucial variety of non-canonical PDFs will be accessed: generalised, unintegrated, diffractive, neutron, photon and nuclear parton distributions.

The basis of LHC physics and discoveries BSM is QCD at high orders and the accurate knowledge of the classic PDFs. In the following, based on [1], some brief remarks are made on the unique potential of the LHeC in the determination of the complete set of quark densities, while the mapping of the gluon density is described subsequently below.

- **Valence quarks:** The knowledge of the valence quark distributions, both at large and at low Bjorken x, as derived in the current world data QCD fit analyses is amazingly limited. An impressive improvement is expected from the LHeC. A NLO QCD fit to simulated inclusive neutral and charged current LHeC data (see [1]) shows that the uncertainty of the down valence quark distribution at, for example, $x = 0.7$ can be reduced from a level of $50 - 100\%$ to about 5%. This will be crucial for searches of new physics at the LHC at the high energy frontier, in order to verify any excess (or deficiency) compared to the SM prediction. Direct access to valence quarks down to low $x \sim 0.001$ can be obtained at LHeC from the NC, Z exchange related $e^{\pm}p$ cross section difference, which can resolve possible sea-antiquark differences.

- **Light sea quarks:** The measurement of the structure functions $F_2 \propto 4U + D$, in ep and $F_2 \propto U + D$, in eD is the basis for determining the light sea quark densities in the nucleon. LHeC will extend greatly the HERA kinematic coverage to much lower x and to higher scales Q^2. From NC and CC measurements and comparing ep with eD data, the up and down sea quark densities will be unfolded, which nowadays are assumed to be equal at $x < 0.01$.

- **Strange:** Several long-standing questions are related to the strange quark density in the proton: how much is it suppressed with respect to the other two light quarks? Is there an asymmetry between the strange and anti-strange density? The knowledge of the strange-quark density itself is important for many processes, for instance for the precision measurement of the W boson mass. Information on the strange quark density is available from several experiments, in particular from previous Neutrino DIS experiments, but overall there is no real understanding of the strange quark distribution. The strange quark distribution is accessible at LHeC in charged current scattering through the subprocesses $W^+ s \to c$ (for positron beams) and $W^- \bar{s} \to \bar{c}$ (for electron beams), with charm tagging in the final state. The LHeC simulation studies show that for the first time accurate measurements of the s and $\bar{s}$ densities can be performed over a large kinematical phase space in x and Q^2.

- **Charm:** Information on the charm content in the proton can be accessed at LHeC by measuring the inclusive charm production cross section in neutral current DIS. At low scales $Q^2 \sim m_c^2$ (with m_c being the charm quark mass) one has to treat the charm production fully massive, i.e. the charm quarks can be only dynamically produced in the reaction $\gamma g \to c\bar{c}$ and thus are themselves no active flavours in the proton. However, at large scales $Q^2 \gg m_c^2$ one can treat the charm quarks as massless partons, which are contributing to the sea. The charm quark mass m_c is a crucial parameter: it regulates the ratio of charm and light quarks in the sea and thus affects predictions for almost any quark driven process at the LHC. At LHeC one expects much more precise and kinematically extended measurements of inclusive charm production compared to HERA. This will allow to map for the first time the transition from the massive to the massless regime. Simulations show that one can use the data for a m_c determination at a precision of two permille. With very good forward charm tagging one can also test the hypothesis of an intrinsic charm component in the proton wave function, which could appear at high $x \simeq 0.2$.

- **Beauty:** Simulation studies show that one expects at LHeC precise measurements of inclusive beauty production in DIS. For large squared momentum transfer $Q^2 \gg m_b^2$ (with m_b being the beauty quark mass) these measurements can be directly translated into an effective beauty quark density in the proton. There is a huge interest in these densities, since in many scenarios of new physics the beauty quarks are the original particles. For instance in the minimal supersymmetric extension of the standard model the production of the neutral Higgs boson A is driven by $b\bar{b} \to A$. While at HERA the inclusive beauty production results were statistically limited to about 20% precision, very accurate results can be expected at the LHeC.

- **Top:** The production of top quarks can be studied at the LHeC for the first time in DIS experiments. The dominant process is single top (or anti-top) production in Wb to t fusion. The unique top physics program that can be performed at the LHeC includes possibly the consideration of a quark density for the top, from NC, a high precision measurement of the top mass from its decay and cross section. Top physics at the LHeC is a promising subject for further study.

In summary, while the LHC data can add information to certain aspects of the quark densities in the proton using specific reactions (e.g. Drell Yan), it remains reserved for the LHeC to uniquely resolve the complete quark and antiquark structure of the proton, for all quark flavours, over the largest kinematic range ever and last but not least with the best theoretical understanding.
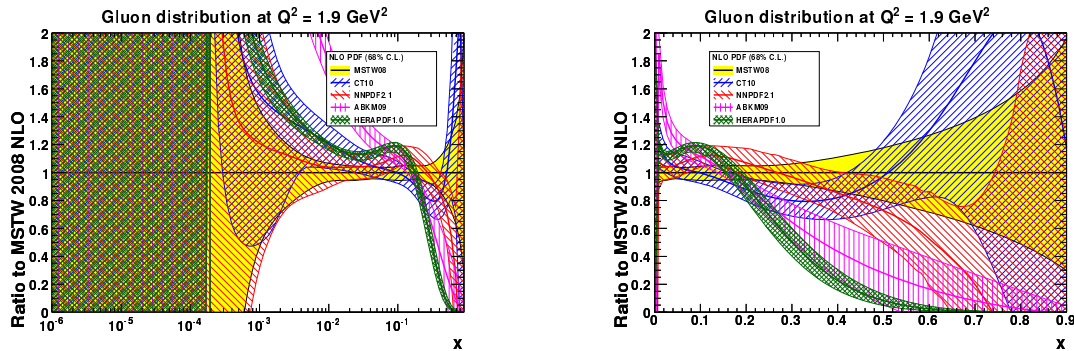
3.2. Gluon Distribution

As has been summarised in the CDR, there are many fundamental reasons for the necessity to understand the gluon distribution and the gluon-parton interactions deeper than hitherto. Half of proton's momentum is carried by gluons. Gluon self-interaction is responsible for the creation of baryonic mass. In pp scattering at the LHC, the Higgs particle is predominantly produced by gluon-gluon interactions. Gluino pair production, predominantly proceeds via $gg \to g \to \tilde{g}\tilde{g}$ production and is hugely uncertain at high masses. On the other hand the rise of the gluon density towards low Bjorken $x < 10^{-5}$ is expected to be tamed and a new phase of hadronic matter to be discovered, in which gluons interact non-linearly while α_s is smaller than 1.

From the simulations as described one derives a typical uncertainty for the gluon density to be reduced to about 3, 1, 5 % at $x = 5 \cdot 10^{-6}$, 0.005, 0.5, respectively. These values of Bjorken x mark the low value for saturation to be discovered, the central rapidity value for Higgs boson production and about the high mass limit for gluino pair production. Obviously, see Figure 1, the potential of the LHC for the determination of the gluon density over $5 - 6$ orders of magnitude in x, simultaneously with all quark PDFs and α_s, is striking. It has to be compared with the
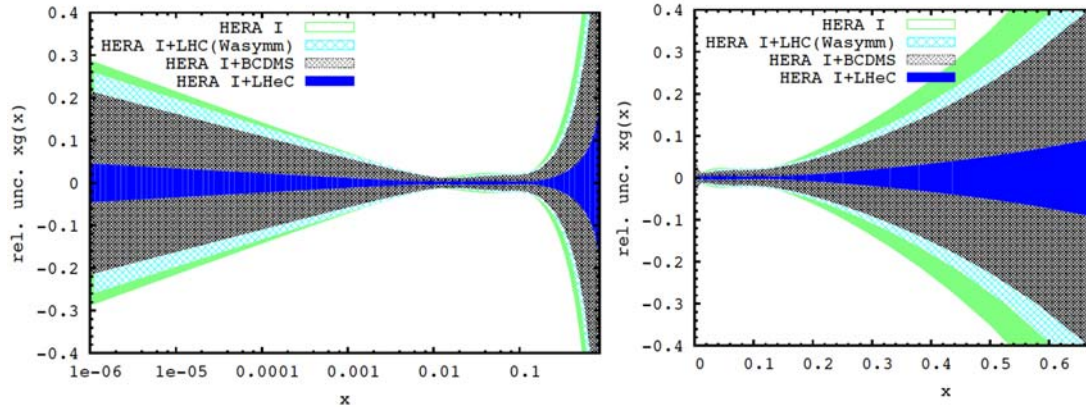
Figure 1. Relative uncertainty of the gluon distribution at $Q^2 = 1.9\,\text{GeV}^2$, as resulting from an NLO QCD fit to HERA (I) alone (green, outer), HERA and BCDMS (crossed), HERA and LHC (light blue, crossed) and the LHeC added (blue, dark). Left: logarithmic x scale, right: linear x scale.

Figure 2. Ratios to MSTW08 of gluon distribution and uncertainty bands, at $Q^2 = 1.9\,\text{GeV}^2$, for most of the available recent PDF determinations, taken from [1]. Left: logarithmic x scale, right: linear x scale.

current status of huge uncertainty on xg at low and high x as is illustrated in Figure 2.

4. Higgs Boson Measurements

In the Standard Model, the breaking of the electroweak $SU(2)_L \times U(1)_Y$ symmetry gives mass to the electroweak gauge bosons via the Brout-Englert-Higgs mechanism, while the fermions obtain their mass via Yukawa couplings with a scalar Higgs field. With the observation of a Higgs-like boson by the ATLAS [3] and CMS [4] collaborations with a mass around 126 GeV, a new research field has opened in particle physics. The measurement of the couplings of the newly found boson to the known fundamental particles will be a crucial test of the SM and a window of opportunity to establish physics beyond the SM.

At the LHeC, a light Higgs boson could be uniquely produced and cleanly reconstructed either via HZZ coupling in neutral current DIS or via HWW coupling in charged current DIS. Those vector boson fusion processes have sizeable cross sections, O(100) fb for 126 GeV mass, and they can be easily distinguished, which is a unique advantage in comparison to the VBF

Higgs production in pp scattering. The observability of the Higgs boson signal at the LHeC was investigated in the CDR [1] using initially the dominant production and decay mode, i.e. the CC reaction $e^-p \to H(\to b\bar{b}) + \nu + X$, for the nominal 7 TeV LHC proton beam and electron beam energies of 60 and 150 GeV. Simple and robust cuts are identified and found to reject effectively e.g. the dominant single-top background, providing an excellent S/B ratio of about 1 at the LHeC, which may be further refined using sophisticated neural network techniques. At the default electron beam energy of 60 GeV, for 80 % e^- polarisation and an integrated luminosity of 100 fb^{-1}, the Hbb coupling is estimated to be measurable with a statistical precision of about 4 %, which is not far from the current theoretical uncertainty. Typical coupling measurements, as for $\gamma\gamma$ or $4l$, are of about 10 % precision with the HL-LHC, while the specific $b\bar{b}$ coupling will be particularly difficult to measure due to high combinatorial backgrounds in pp.

The LHC is said to be inferior to a linear collider in its coupling measurement prospects. Part of this statement comes from large uncertainties, which are related to the imperfect knowledge of the PDFs and theory parameters. The LHeC, with its high precision PDF and QCD programme, will render many of these uncertainties unimportant. Currently, for example, an uncertainty of the $H \to \gamma\gamma$ cross section due to PDFs is quoted of nearly 10 % [6], based on the variation of the cross section predictions from different PDFs. This will be very much reduced with the LHeC: an iHix calculation of the NLO Higgs cross section for MSTW08, NNPDF2.3 and HERAPDF1.5 leads to intrinsic uncertainties of 1.7, 1.2 and 2.2 %, respectively, with a maximum deviation of 6.9 %. The full experimental LHeC uncertainty, however, is 0.2 %. The main advantage will be that the precision LHeC data, possibly combined with HERA, will replace essentially all previous data sets and thus lead to a much better agreement between various PDF determinations, besides the huge reduction in uncertainty with the LHeC.

A sizeable uncertainty is also related to the strong coupling constant, a difference in α_s of ± 0.005 corresponding to an about 10 % cross section uncertainty, see e.g. [7] or [8]. Obviously, the large improvement in the determination of α_s with the LHeC will reduce this uncertainty strongly too. Essentially with such a high quality data set as the LHeC, one will simultaneously determine the coupling and the PDFs, and control their correlations at a very high level. In [9] a systematic evaluation has been presented of the effect of the heavy quark masses and of α_s on the uncertainties of the Higgs boson branching fractions in various channels. One finds partially large effects as 6 % from M_c on the $H \to c\bar{c}$ branching or 5.6 % from α_s on $H \to gg$. These will certainly be much reduced. It is for future studies to more systematically analyse the striking potential of the LHeC to remove or reduce the QCD uncertainties of the Higgs boson cross sections and couplings. There will also be improvements related to QCD measurements at the LHC. Their level of precision, however, especially for the gluon, α_s and heavy quark QCD cannot compete with the genuine DIS process.

It has also been observed [1], that the LHeC can specifically explore well the CP structure of the HWW coupling by separating it from the HZZ coupling and the other signal production mechanisms. Any determination of an anomalous HWW vertex will thus be free from possible contaminations of these. Compared to the pp situation, ep lacks the complications due to underlying event and pile-up driven backgrounds. In Ref. [10] it has been recently pointed out that the kinematics of the scattered quarks depend strongly on the CP structure of the HWW. This not only affects the azimuthal angle difference between the scattered quqarks but also their transverse momenta, separation in rapidity and other relevant quantities. The analysis performed in [1] needs to be re-assessed to take this into account.

The few initial studies performed so far will be pursued further given that the Higgs boson is now likely to indeed exist. For the projected analyses, this first concerns using the appropriate LHeC detector simulation, and optimising further its design. For the accelerator design it is obvious that a luminosity in excess of 10^{33} cm^{-2}s^{-1} is very desirable, see the discussion on machine parameters in Section 2. The then possible precision measurements of rarer (τ, Z,

W, perhaps photon) decay channels, of the CP angular distributions, for both the HWW and HZZ couplings, and NC initiated production would make the LHeC, by design a QCD machine, a collider to study the Higgs boson and mechanism of very remarkable and complementary potential.

5. Summary

The LHeC is a new ep collider of unprecedent kinematic range, luminosity and precision in deep inelastic scattering. This leads to the first ever complete measurement of PDFs, including, for example, the strange density. It furthermore extends to very high Bjorken x in ep and to so large Q^2 that no nuclear or higher twist corrections affect the high x PDF determinations. A much deeper understanding of quark-gluon dynamics is needed and in sight, exemplified by the potential of the LHeC to measure $\alpha_s(M_Z^2)$ to per mille accuracy.

The LHeC is designed to operate synchronously with the HL-LHC. Preparations have begun, following the detailed design concept report and a corresponding mandate from CERN, supported by ECFA and NuPECC, to prototype critical components and to carry out more detailed studies, as of the interaction region and high luminosity optics, in major international collaborations with CERN. As has been indicated here, there is a potential for the LHeC to achieve luminosities in excess of $10^{33}\,\mathrm{cm^{-2}s^{-1}}$.

There are two major questions for the HL-LHC to investigate, the properties of the 126 GeV boson, which likely is the Higgs particle, and the search for maximum mass particles, of several TeV in direct production mode. It has been argued here that the LHeC can assist the transformation of the LHC into a precision Higgs facility, with its own coupling and CP measurements based on clean WW fusion in ep, and with its ultra-precise PDF, heavy quark and α_s determinations, which will reduce the theoretical uncertainties of Higgs measurements in pp to a negligible level. It is similarly apparent that the discovery potential of new particles at high masses at the HL-LHC is severely limited by the deviations and uncertainties of the predictions based on currently available PDF sets and as well the uncertainties of input parameters such as the heavy quark masses and α_s. For the Higgs the prominent decay $H \to b\bar{b}$ and for SUSY gluino pair production have been used as first representative examples.

References

[1] J. L. Abelleira Fernandez *et al.* [LHeC Study Group], "A Large Hadron Electron Collider at CERN" J.Phys.G. **39**(2012)075001, arXiv:1206.2913.

[2] LHeC Study Group, Contribution (No 147) to the Cracow meeting on the ESPP, "A Large Hadron Electron Collider at CERN", LHeC-Note-2012-004 GEN, CERN, August 2012.

[3] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 1 [arXiv:1207.7214 [hep-ex]].

[4] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716** (2012) 30 [arXiv:1207.7235 [hep-ex]].

[5] ATLAS Collaboration, Contributions to the ESPP, "Physics at High Luminosity LHC with ATLAS", CERN, August 2012 and Update October 2012.

[6] J. Baglio, A. Djouadi and R. M. Godbole, Phys. Lett. B **716** (2012) 203 [arXiv:1207.1451 [hep-ph]].

[7] J. Rojo, Talk at the PDF4LHC Workshop, 8th of October, 2012, CERN.

[8] J. Baglio and A. Djouadi, JHEP **1103** (2011) 055 [arXiv:1012.0530 [hep-ph]].

[9] A. Denner, S. Heinemeyer, I. Puljak, D. Rebuzzi and M. Spira, Eur. Phys. J. C **71** (2011) 1753 [arXiv:1107.5909 [hep-ph]].

[10] A. Djouadi, R. M. Godbole, B. Mellado and K. Mohan, arXiv:1301.4965 [hep-ph].