The status of the LHeC project and its impact on Higgs Physics

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Abstract. The LHeC is envisioned to collide electrons and protons concurrently with collisions at the LHC. The overall status of the project is summarized. This comprises a review of the accelerator facility, the Energy Recovery Linac, and the detector design.

The ATLAS and CMS collaborations at the Large Hadron Collider have observed a new particle consistent with a scalar boson and with a mass of about 125 GeV. The prospects of studying this newly discovered boson at the LHeC are reviewed. This includes ability to isolate the $H \to b\bar{b}$ decay with a large signal-to-background ratio of better than $S/B = 2$ and the model independent exploration of the CP-properties of the HVV, $V = W, Z$ couplings. The latter is a unique capability of ep collisions. The propescts of other decay channels will also be discussed. An enhanced instantaneous luminosity scenario of $L = 10^{34} cm^{-2} s^{-1}$ is considered. In this scenario the LHeC becomes a Higgs facility.

1. Introduction

With the discovery of a Higgs boson by the ATLAS and CMS collaborations [1, 2] a new era in particle physics has begun. While the Standard Model predicts the existene of a scalar field, the observation of this new particle opens a window of opportunity to search for new physics beyond. The exploration of the Higgs boson coupling to other particles in the Standard Model is sensitive to new interactions. The Large Hadron-electron Collider (LHeC) offers an excellent setup for precision measurement of these couplings.

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 maximum center of mass energy. As such, it has a rich and diverse physics programme of its own, as documented extensively in the recent conceptual design report (CDR) [3] and summarised in an initial submission by the LHeC Study Group to the European Strategy of Particle Physics (ESPP) discussion prior to the Cracow Symposium [4].

2. Accelerator Design

The LHeC envisions electron-proton (ep) and electron-ion (eA) collisions as a complement of the Large Hadron (pp and AA/p) collider. At the LHeC the lepton-quark interactions would reach the TeV scale. It is important to note that the LHeC is envisioned to run concurrently with LHC operations. The LHeC is designed not to disrupt operation of the LHC. In the CDR [3] two configurations were considered:

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Table 1. LHeC *ep* and *eA* collider parameters (from reference [5]). The numbers give the default CDR values, with optimum values for maximum *ep* luminosity in parentheses and values for the *ePb* configuration separated by a comma.

Parameter [unit]	LHeC	
species	e^-	p, $^{208}\mathrm{Pb}^{82+}$
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	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	
CM energy [TeV]	1300, 810	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1 (10), 0.2	

- Ring-Ring (RR) option. A ring with a new electron beam would be mounted on top of the proton tings of the LHC.
- Linac-Ring (LR) option. An Energy Recovery Linac (ERL) in race track configuration providing electrons to collide head on with a proton beam of the LHC.

Careful consideration of a number of factors led to choosing the LR option as the default one (see reference [5] and references therein) Each linac accelerates the beam to 10 GeV, which leads to a 60 GeV electron energy at the interaction point after three passes through the opposite linear structures of 60 cavity-cryo modules each. The arc radius is about 1 km, mainly determined by the synchrotron radiation loss of the 60 GeV beam which is decelerated for recovering the beam power after having passed the IP. The default tunnel circumference is 1/3 that of the LHC. The tunnel is designed to be tangential to IP2 or IP8 (see Section 3). Detailed civil engineering considerations are described in the CDR.

The preference for the LR option has been recently further reiterated in [6]. A propoposal for the constuction of a ERL faclity at CERN is materiallizing as an experimental facility for research and development in accelerator physics [6].

An important development is the recent progress to demonstrate the feasibility of reaching the instantaneous luminosity of $L = 10^{34} cm^{-2} s^{-1}$. While remaning a challenge, confidence among accelerator physicists at CERN remains healthy [6]. The target parameters to reach this goal are summarized in Tab. 1.

3. Status of Detector Design

detector with backward-forward assymetry, due to the beam configuration. It is a classical design with strong similarities to the ATLAS detector, except for the use of the return magnetid field for the measurement of the momenta of escaping muons [3].

The time schedule of the LHeC project is determined by the evolution of the the LHC project and the upgrade plans. One can expect that the detector would need to be ready within about $10-12$ years. A first installation study was made considering pre-mounting the detector at the surface, lowering and installing it at the pit. The LHC complex has eight caverns where detectors and infrastructure, such as the beam dump and the RF cavities are located. Based on these constraints Interaction Point, IP, number two[2] was considered in the CDR. Recently IP8 [3] has been considered as an alternative to IP2 [6]. Further studies are expected to make progress in the near term. In case of a possible installation in IP2 the detector should be small enough to fit into the L3 magnet structure of 11.2 m diameter, which is still resident in IP2 and would be available as mechanical support. Based on the design, as detailed in the CDR, it is estimated that the whole installation can be done in 30 months, which appears to be compliant with the operations currently foreseen in the LS3 shutdown in the early twenties.

A number of developments have taken place after the publishing of the CDR. These include improvements in the design of the beam-pipe and the tracking detectors. Discussions are ongoing in view of the strength of the Higgs boson physics at the LHeC to re-optimize the detector by de-emphasizing electromagnetic calorimetry in favor of hadronic calorimetry. The latter is essential for the reconstruction of the Higgs boson with the $b\bar{b}$ decay. The Wits group is contributing to the design of the hadronic calorimeter. Currently, a new generation of plastic scintillators are being tested using facilities in South Africa. This includes determination of radiation hardness, detailed understanding of the mechanisms of radiation damage and the optical properties. Results in this area are reported in separate proceedings [7, 8, 9].

4. Higgs Boson Production in High Energy *ep* Collisions

The leading production mechanism for the SM Higgs boson at the LHeC is

$$eq \to \nu_e H q' \quad \text{and} \quad eq \to eHq, \tag{1}$$

via the Vector Boson Fusion processes (VBF), as depicted in figure 1. It is remarkable that the Higgs boson production via VBF was first calculated for lepton-nucleon interactions (for a review of this question see [10] and references therein).

The production rate for the Charge Current, CC, process is larger than that of the Neutral Current, NC, process by about a factor of $4-6$. This is mainly due to the accidentally suppressed NC coupling to the electrons. Here we have used the package MadGraph [11] for the full matrix element calculations at tree-level, and adopted the parton distribution functions CTEQ6L1 [12]. We choose the renormalization and factorization scales to be at the W-mass, which characterizes the typical momentum transfer for the signal processes.

In order to appreciate the unique kinematics of the VBF process it is most intuitive to express the cross section in a factorized form. Consider a fermion f of a c.m. energy E radiating a gauge boson V ($s \gg M_V^2$), the cross section of the scattering $fa \to f'X$ via V exchange can be expressed as:

$$\sigma(fa \to f'X) \approx \int dx\; dp_T^2\; P_{V/f}(x, p_T^2)\; \sigma(Va \to X) \tag{2}$$

where $\sigma(Va \to X)$ is the cross-section of the $Va \to X$ scattering and $P_{V/f}$ can be viewed as the probability distribution for a weak boson V of energy xE and transverse momentum p_T. These expressions lead us to the following observations:

1 Unlike the QCD partons that scale like $1/p_T^2$ at the low transverse momentum, the final state quark f' typically has $p_T \sim \sqrt{1-x} M_V \le M_W$.

[2] The ALICE detector is currently located in IP2.
[3] The LHCb detector is currently located in IP8.

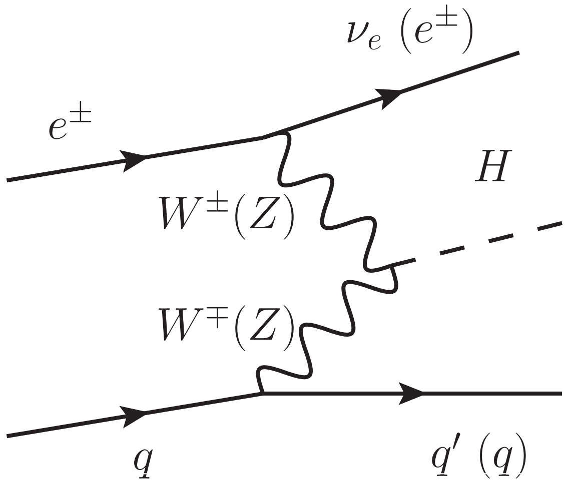

Figure 1. Leading order diagram for the production of a Standard Model Higgs boson in ep collisions for the charged current and neutral current processes.

2 Due to the $1/x$ behavior for the gauge boson distribution, the out-going parton energy $(1-x)\,E$ tends to be high. Consequently, it leads to an energetic forward jet with small, but finite, angle with respect to the beam.

3 At high p_T, $P^T_{V/f} \sim 1/p_T^2$ and $P^L_{V/f} \sim 1/p_T^4$, and thus the contribution from the longitudinally polarized gauge bosons is relatively suppressed at high p_T to that of the transversely polarized.

Items 1 and 3 clearly motivate a tagging for a forward jet to separate the QCD backgrounds [13, 14], while item 3 suggests a veto of central jets with high p_T to suppress the backgrounds initiated from the transversely polarized gauge bosons, and from other high p_T sources such as top quarks [15].

The mere identification as a Higgs boson is not enough, for it will leave open a host of other questions, such as whether this scalar is elementary or composite, CP-conserving or CP-violating. In general the tensor structure of the coupling to weak bosons needs to be investigated in order to assess whether the newly discovery boson is related to new physics. Collisions at the LHeC provide a unique opportunity to separate the HWW and HZZ vertices while allowing for the independent exploration of the azimuthal correlation of the scattered fermions [16]. This is a unique feature of ep collisions not present in pp and e^+e^- collisions. Deviations from the SM can be parametrized using two dimension-5 operators:

$$\Gamma_{\mu\nu} \propto \left[\lambda(p\cdot q g_{\mu\nu} - p_\nu q_\mu) + i\lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma\right], \tag{3}$$

where p and q are four momenta of the weak bosons, and λ and λ' are effective coupling strengths for the anomalous CP-conserving and the CP-violating operators, respectively.

5. Results

Studies reported in the LHeC CDR [3] based on a fast simulation of signal and background using the CC reaction 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. It is important to note that the

Table 2. Cross sections and rates of Higgs production in ep scattering with the LHeC. The cross sections are obtained with MADGRAPH5 (v1.5.4) using the p_T of the scattered quark as scale, CTEQ6L1 partons and $m_H = 125\,\text{GeV}$. The assumed branching ratios, Br, to different decays are given.

LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	$Br(H \to X)$	$N^H_{CC}\ e^-p$	$N^H_{NC}\ e^-p$	$N^H_{CC}\ e^+p$
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau\tau$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

instantaneous luminosity was assumed $L = 10^{33} cm^{-2}s^{-1}$. Given these promising results efforts are being made in order to consider a higher luminosity scenario, namely $L = 10^{34} cm^{-2}s^{-1}$. Various parameters assumed in Reference [3] have been re-assessed in order to achieve the desired instantaneous luminosity [5]. In this scenario the LHeC could be considered a Higgs facility on its own right. Table 2 gives estimates of Higgs boson cross-sections and yields for various production mechanisms and decay channels. With the high luminosity scenario the exploration of the $H \to b\bar{b}$ and the CP properties of the HWW coupling will enter into the realm of precision. Other decays, such as $H \to \tau\tau, VV, gg, c\bar{c}$ will become accessible with sizeable statistics.

The LHC is believed to display inferior sensitivity to couplings compared to that of a linear collider. 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.

6. Conclusions

The progress of the LHeC project is summarized. In the area of accelerator studies significant progress has been made in the definition of the project for the Electron Recovery Linac. This project, while broad in nature, is essential to the Ring-Linac option that is considered to be default at the LHeC. In the area of detector development progress has been made with regards to more detailed designs of the beam pipe and the tracking detectors. With regards to the location of the interation point, in addition to IP2, IP8 is also being considered. Currently, various activities are ongoing in facilities in South Africa to understand the performance and radiation resistance of a new generation of plastic scintillators for the LHeC hadronic calorimeter [7, 8, 9].

When considering the scenario of instantaneous luminosity $L = 10^{34} cm^{-2}s^{-1}$, the LHeC is rendered a Higgs facility. Here hundred of thousands of Higgs candidates could be reconstructed over a decade of data taking. This provides strong sensitivity to a number of couplings beyond the capabilities of the LHC and competitive with the ILC. The LHeC has the unique feature of being able to separate the HWW and HZZ coupling measurements.

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