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Physics of the Higgs Boson at the LHeC

Bruce Mellado*
University of the Witwatersrand, 1 Jan Smuts Avenue, Johannesburg 2000, South Africa
E-mail: Bruce.Mellado@wits.ac.za

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 $S/B = 1$ 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. An enhanced instantaneous luminosity scenario of $L = 10^{34} cm^{-2}s^{-1}$ is considered. In this scenario the LHeC becomes a Higgs factory.

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*Speaker.

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1. Introduction

In the Standard Model, SM, of electro-weak, EW, and strong interactions, there are four types of gauge vector bosons (gluon, photon, W and Z) and twelve types of fermions (six quarks and six leptons) [1, 2, 3, 4]. These particles have been observed experimentally. At present, all the data obtained from the many experiments in particle physics are in agreement with the Standard Model. In the Standard Model, there is one particle, the Higgs boson, that is responsible for giving masses to all the elementary particles [5, 6, 7, 8]. In this sense, the Higgs particle occupies a unique position.

In July 2012 the ATLAS and CMS experiments reported the discovery of a boson, a Higgs-like particle with a mass $m_H \approx 125$ GeV based on the data accumulated during 2011 and part of 2012 periods [9, 10]. The Tevatron experiments have reported an excess of events consistent with this observation in the decay to bottom and anti-bottom quarks [11]. It is also relevant to note that no additional Higgs bosons with couplings as in the Standard Model have been observed in the range of $m_H < 600$ GeV.

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) [12] 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 [13].

2. Higgs Boson Production in High Energy ep Collisions

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

$$eq \to \nu_e H q' \quad \text{and} \quad eq \to eHq, \tag{2.1}$$

via Vector Boson Fusion processes (VBF), as depicted in Fig. 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 [14] 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 [15] for the full matrix element calculations at tree-level, and adopted the parton distribution functions CTEQ6L1 [16]. 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:

$$\sigma(fa \to f'X) \approx \int dx\, dp_T^2\, P_{V/f}(x, p_T^2)\, \sigma(Va \to X) \tag{2.2}$$

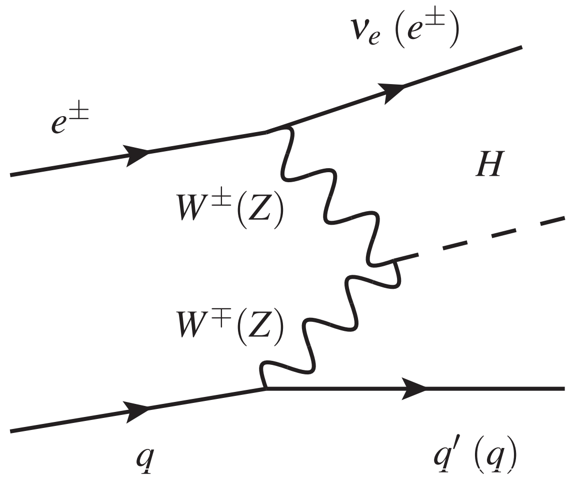

Figure 1: Leading order diagram for the production of a Standard Model Higgs boson in ep collisions for the charged current and neutral current processes.

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 $p_T \sim \sqrt{1-x}M_V \leq M_W$.

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 [17, 18], 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 [19].

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 [20]. 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:

$$\Gamma_{\mu\nu} \propto \left[\lambda(p \cdot q g_{\mu\nu} - p_\nu q_\mu) + i\lambda' \varepsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma\right], \tag{2.3}$$

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.

3. Results

Studies reported in the LHeC CDR [12] 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 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 Ref. [12] have been re-assessed in order to achieve the desired instantaneous luminosity [21]. In this scenario the LHeC could be considered a Higgs factory on its own right. Table 1 gives estimates of Higgs boson candidates. 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 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.

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Table 1: 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	$Br(H \to X)$	$\mathrm{N}^H_{CC}\ e^-p$	$\mathrm{N}^H_{NC}\ e^-p$	$\mathrm{N}^H_{CC}\ e^+p$
$H \to b\bar{b}$	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

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