New Physics at Large Scales at an LHeC

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An electron beam upgrade of the LHC, a large hadron-electron collider operating at c.m.s. energies in the range of 1-2 TeV, is expected to add valuable information on new particles anticipated to be discovered at the LHC and perhaps an LHeC. This report summarises initial studies on physics at large scales for a range of LHeC settings.

1 Motivation

In spite of the impressive success of the Standard Model (SM) in explaining the electroweak precision data, particle physics remains challenged by its understanding of the electroweak symmetry breaking (EWSB) mechanism and the particle's masses generation. It is one of the major goals of the Large-Hadron Collider (LHC) to probe EWSB and to find experimentally the Higgs boson and thus complete the SM. However, there are strong theoretical arguments that the SM is incomplete and further clarity into the dynamics of EWSB should be achieved [1]. Numerous extensions of the SM at the electroweak scale are proposed like the minimal supersymmetric extension of the SM, models with warped extra dimensions, little Higgs models with T-parity. Due to its c.m.s. energy of 14 TeV, some of the new particles and interactions predicted can be expected to be discovered and studied at the LHC, see e.g. [2] for recent in depth discussions.

A large hadron-electron collider (LHeC) [3] is one of the proposed upgrade options using the nominal or upgraded LHC 7 TeV protons and 20-150 GeV longitudinally polarised electrons or positrons. Its salient task is to explore the proton structure and new QCD phenomena in the kinematic domain of LHC physics with great precision. Thus an LHeC would represent the next generation of an electron-proton (ep) collider, expanded by about two orders of magnitude in luminosity ($\approx 10^{33}$ cm^{-2}s^{-1}) and phase space in comparison to HERA [4]. The LHeC design parameters of c.m.s. energies in the range of 1 to 2 TeV in electron/positron-proton collisons with integrated luminosities around 10 to 100 fb^{-1} will access a wide range of new physics at the terascale. Electron-proton colliders are in particular ideal machines for searches of new particles which mediate quark-lepton transitions [5].

Following a possible discovery at LHC, LHeC can provide independent information to constrain the underlying theory e.g. for electron-quark resonances and contact interactions, study of super-particles (sleptons, photinos) and new leptons (exited and exotic fermions) properties of a light SM Higgs boson, couplings of a new heavy gauge boson Z'. This report [6] sketches preliminary studies exploring some of the self-evident physics cases at large scales using a range of LHeC settings discussed recently [7, 8].

2 Proton structure and new high-mass particles

At the LHC new heavy states with mass M may be produced in Drell-Yan processes. This corresponds to very large Q^2, $M^2 \approx Q^2$, where Q^2 is the negative four-monentum squared of the exchanged gauge boson in deep inelastic (DIS) ep scattering, and moreover to high fractions of the proton momentum carried by the struck quark, Bjorken-$x \to 1$. Despite the enormous gain in knowledge of the proton's parton distribution functions (PDFs) obtained at HERA [4] which are essential for cross section predictions at the LHC [9] as of W, Z production at the rapidity plateau around $x \approx 0.006$, PDFs are not well known in the high x region. This limited knowledge would not inhibit the discovery of clear "peak-like" objects like a new massive Z' or W' boson at the LHC, but could be a severe limitation on the determination of the particle's properties. In particular its couplings to the various fields of SM are mandatory for an interpretation w.r.t. the underlying new physics model, however, only rough limits are expected to be obtained at high partonic c.m.s. energies where the uncertainties due to PDFs are greatest. Here an LHeC can contribute twofold. With the LHeC one can obtain independent coupling information on a Z' boson with masses up to $\lesssim 1.5$ TeV employing polarisation-dependent cross section and charge asymmetries with an integrated luminosity of 100 fb^{-1} per $e^{\pm}$ sample of 80% polarisation [10]. Moreover the LHeC can precisly determine the flavour content of the proton in the kinematic domain of the LHC [11]. This is particularly important if searches on new physics rely on the determination of a smooth cross section enhancement in comparison to SM predictions.

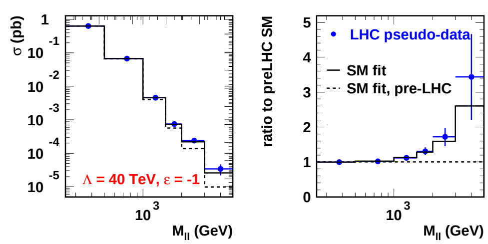

Figure 1: Mass spectrum of LHC Drell-Yan pseudo-data including a contact interaction term of $\Lambda = 40$ TeV (dots) in comparison to a present SM prediction (dashed) and a new SM expectation obtained from a fit including the pseudo-data (full line). The error bars correspond to 300 fb^{-1} integrated luminosity [12].

A potential interplay of the PDF knowledge and the presence of new physics in the Drell-Yan mass spectrum at the LHC is illustrated in Fig. 1. In a generic approach, Drell-Yan pseudo-data were simulated [12] where the new physics was embedded in a "contact interaction" term depending on an effective new physics mass scale Λ and parameters $\epsilon = \pm 1$ for either constructive or destructive interference of new physics and SM amplitudes. In a next step it was studied, if the Drell-Yan pseudo-data, when added to a standard NLO QCD fit of present DIS data, can be accommodated by modified PDFs. High mass Drell-Yan data involve quark and anti-quark distributions at Bjorken-$x \gtrsim 0.1$ with a PDF uncertainty of about 20% using current PDFs (e.g. CTEQ6 set) for masses up to 4 TeV. For higher masses and depending on the model, it may be difficult for LHC pp data alone to determine simultaneously the scale Λ and the type of the interference versus PDF effects: the example interaction shown in Fig. 1 can be fully accommodated by a new SM fit and modified PDFs. Combining this LHC pp pseudo-data and LHeC $e^{\pm}p$ cross section data at high-Q^2, however, can unambigously determine the type of interference and distinguish between PDF and new physics effects.

3 Leptoquarks and excited fermions

Leptoquarks (LQ) are hypothetical bosons carrying both lepton and baryon numbers which occur naturally in many unifying theories, but also in models of quark-lepton substructure. They are color triplets which would be dominantly pair produced via the strong interaction in pp collisons, and singly produced via the quark-lepton-LQ Yukawa coupling (λ_{LQ}) in quark-lepton collisions. Due to the control of the eq initial state with the charge and polarisation of the e beam, an ep collider is ideally suited for studies of first-generation LQs. These are usually classified in the Buchmüller-Rückl-Wyler model (BRW) [5]. Such particles can be also appear as super-particles (squarks) in R-parity violating SUSY models. In ep collisions, LQs can be produced directly up to the c.m.s. energy, $\sqrt{s_{ep}}$, as (narrow) s-channel resonances appearing as peaks in the neutral (NC) and charged current (CC) cross sections. Beyond this limit, the production mechanism is contact-interaction-like. At LHeC using 70 GeV (140 GeV) $e^{\pm}$ beams with integrated luminsities of 100 (10) fb^{-1} and 10 (1) fb^{-1} per sample, expected limits for all 14 BRW LQs were estimated [13] which are comparable to the expected LHC limits for couplings λ_{LQ} about 0.1. However, if LHC discovers a LQ with mass $\lesssim \sqrt{s_{ep}}$, the LQ properties like fermion number (counting produced final state electrons/positrons for a given lepton beam charge), type (determine LQ spin via angular distribution) and chiral couplings (using lepton beam polarisation) could be clearly identified at an LHeC if the unknown coupling is not too small [3, 14]. The searches for LQs are a particularly interesting case of a promising interplay between LHC (pp) and LHeC (ep) potentials worthwhile to be studied in more detail, i.e. to understand also better the single LQ production in pp, which is possible but with much lower cross section.

The four-fermion contact interaction approach can be used to constrain indirectly other extensions of the SM effectively. The LHeC will be sensitive to CI mass scales of the order of 50 TeV [13] assuming that uncertainties of SM expectations are well under control, e.g. PDF and new physics effects can be disentangled. It will be sensitive to the mass scales of extra dimensions of the order of 4-5 TeV and can resolve substructures below 10^{-19} m according to calculations in the classical form-factor approximation [13].

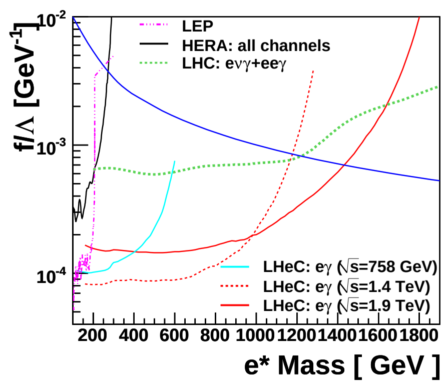

Figure 2: LHeC sensitivity for f/Λ ratio of excited electrons using 10 fb^{-1} (1 fb^{-1}) for 70/20 GeV (140 GeV) electron beams [15] in comparison to LEP and expected LHC limits [16]. LHeC analysis includes SM background from NC DIS and Compton processes.

Many theories beyond the SM lead naturally to new fermions. The existence of excited states of leptons and quarks is a characteristic signal of substructure in the fermion sector. If discovered, they would provide convincing evidence of a new scale of matter which cannot be much smaller than the compositness scale Λ which must be assumed of $\mathcal{O}(1)$ TeV at last. Production and decay of such new particles can be described in gauge-mediated (GM) and contact-interaction (CI) models. In ep, excited electron (e^*) and neutrino (ν^*) decay channels can be examined where CI contributions are usually negligible. A preliminary GM $e^* \rightarrow e\gamma$ analysis [15] shows that the LHeC with c.m.s. energy of 1.4-1.9 TeV is sensitive to much smaller ratios f/Λ (electroweak gauge coupling f) than LHC [16] for some M_{e^*} ranges, see Fig. 2. Furthermore, a determination of e^* quantum numbers would be possible at LHeC similarly to the methods applicable for LQs. The LHeC of c.m.s. energy of 2 TeV would have a clear discovery potential for higher e^* masses, M_{e^*}.

4 Single and anomalous top production

Top decays open plenty of room for new physics beyond the SM searches. However, the world sample for top decays remains modest. In hadron-hadron collisions, single top production is rare in comparison to the $t\bar{t}$ pair production and difficult to analyse due to high backgrounds. Recently, a first observation of single top quark production at Tevatron improved earlier LEP limits for $t \rightarrow ug$ and $t \rightarrow cg$ branching fractions [1]. The LHeC has the potential to explore SM top and anti-top quark properties employing the charge of the incident lepton beam: single top (anti-top) will be produced uniquely in CC DIS using an positron (electron) beam. The production is dominated by the Wtb vertex where the tree level SM cross section with $\mathcal{O}(10)$ pb is sizeable [11, 17]. More detailed studies are needed to quantify the promising LHeC capabilities regarding the exploration of dedicated top and anti-top quark properties, e.g. cross sections, couplings and polarisation.

Due to the large top mass close to the EWSB scale, a wide class of BSM models predict Flavour Changing Neutral Current (FCNC) mechanism for single top production. The LHeC, like HERA [4], is mainly sensitive to the anomalous $tu\gamma$ vertex. An LHeC preliminary analysis performed in the framework of a general effective Lagrangian proposed by HERA [17] (neglecting c-quark contributions), estimates the expected FCNC top rate for an assumed coupling $\kappa_{tu\gamma}$ =0.01 in comparison to SM background, single top and W, productions. Coupling limits of about 0.01 are in reach for LHeC using 7000 GeV protons scattering off 70 GeV (140 GeV) electrons with integrated luminosities of 100 fb^{-1} (10 fb^{-1}). At the LHC, a sensitivity of $\kappa_{tu\gamma}$ =0.007 with 100 fb^{-1} is expected. This comparison should be scrutinized further to understand details of used conventions, considered background and systematics.

5 Light SM Higgs

The Higgs boson, a weakly interacting spin-zero particle, is the agent of SM EWSB. Global fits of EW precision data favour a light Higgs mass, M_H, and exhibit some tension with direct searches [1]: the lower bound of 114.4 GeV from LEP, and an excluded mass range of 160-170 GeV from Tevatron. At the LHC, SM Higgs bosons will be mainly produced via gluon-gluon fusion. In ep collisions, W^+W^- (CC DIS) and ZZ (NC DIS) fusion are by far the most copious sources of SM Higgs; M_H dependent LO cross sections are shown in Fig. 3 left [18] using `Madgraph` [23] in very good agreement with results [14, 19] from `CompHEP` [22].

If a light SM Higgs, $100 < M_H < 150$ GeV, will be discovered at the LHC, it will be extremely challenging to determine e.g. the $H \rightarrow b\bar{b}$ coupling due to overwhelm-

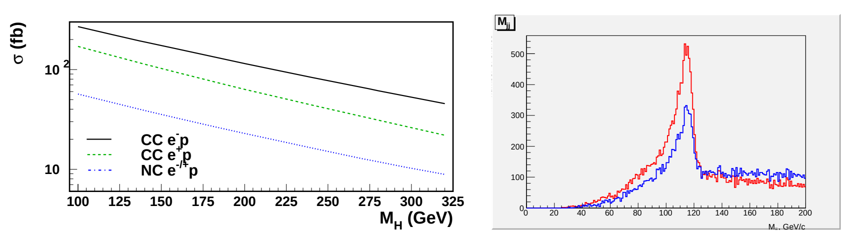

Figure 3: Left: LHeC LO SM Higgs cross sections vs Higgs mass using 140x7000 GeV^2 $e^{\pm}p$ beams [18]. Right: Invariant dijet mass distributions of a 120 GeV SM Higgs CC DIS sample with 209 fb^{-1} for 150x7000 GeV^2 e^-p beams selecting 2 jets with lowest rapidity (red) or highest p_T (blue) [20].

ing QCD backgrounds despite the high branching fractions of 90-10% in this M_H range. Measurements of Higgs-fermion couplings are needed to gain further evidence of EWSB theory since global EW fits have no sensitivity here without the assumption that the Higgs-Yukawa coupling is set to the fermion masses [1]. Two studies [20] [19, 21] are ongoing to investigate the LHeC potential to measure in particular the Hbb coupling focussing on light SM Higgs production in WW fusion in the presence of SM CC dijet production background. Independent, new analysis chains using either `Madgraph/MadEvent` [23] [20] or `CompHEP` [22] [19, 21], and `PYTHIA` for the decay, found consistent results for expected $S/\sqrt{B} \approx 3$ searching for Higgs in the invariant dijet mass spectrum, see Fig. 3 right [20] for an illustration of the Higgs signal in dependence on selection criteria. Adding b-tagging is expected to deliver a crucial improvement of the $S/\sqrt{B}$ ratio. A first look on b-tagging by flight length looks very promising with a b-tagging efficiency of about 95% assuming a 100 μm vertex reconstruction performance in the transverse direction [21].

References

[1] For a state-of-the-art report on EW theory, see e.g. C. Quigg, arXiv:0905.3187 [hep-ph].

[2] CERN Theory Instiute, *From the LHC to a Future Collider Search*, 9-27 February 2009, CERN, Switzerland. `http://indico.cern.ch/conferenceDisplay.py?confId=40437`

[3] J. B. Dainton, M. Klein, P. Newman, E. Perez and F. Willeke, JINST **1** (2006) P10001 [arXiv:hep-ex/0603016]. For further material, see `http://www.lhec.org.uk`

[4] For a recent HERA collider physics review, see e.g. M. Klein and R. Yoshida, Prog. Part. Nucl. Phys. **61** (2008) 343 [arXiv:0805.3334 [hep-ex]].

[5] W. Buchmüller, R. Rückl, D. Wyler, Phys. Lett. B **191** (1987) 442 [Erratum-ibid. B **448** (1999) 320].

[6] Slides:
`http://indico.cern.ch/contributionDisplay.py?contribId=211&sessionId=19&confId=53294`

[7] 1st ECFA-CERN LHeC Workshop, 1-3 September 2008, Divonne-les-Bains, France.
`http://indico.cern.ch/conferenceDisplay.py?confId=31463`

[8] LHeC Working Group Meetings preceding the DIS 2009, 25 April 2009, Madrid, Spain.
`http://indico.cern.ch/conferenceOtherViews.py?view=cdsagenda&confId=55684`

[9] See e.g. Proceedings of *HERA and the LHC. A workshop on the implications of HERA for LHC physics*, 2004-2008. `http://www.desy.de/~heralhc/`

[10] T. G. Rizzo, Phys. Rev. D **77**, 115016 (2008) [arXiv:0804.0081 [hep-ph]].

[11] M. Klein, *Parton Distributions at the LHeC*, Prepared for International DIS2007 Workshop, Munich, Germany, 16-20 Apr 2007. For an update, see also O. Behnke, these proceedings.

[12] E. Perez, *Physics beyond the standard model at LHeC*, Prepared for International DIS2007 Workshop, Munich, Germany, 16-20 Apr 2007; E. Perez, *Drell-Yan, new physics and high x PDFs*, Prepared for [7].

[13] A. F. Zarnecki, arXiv:0809.2917 [hep-ph].

[14] E. Perez, *Introduction*, Prepared for [7].

[15] N. Trinh and E. Sauvan, *Excited Fermions*, Prepared for [7].

[16] O. J. P. Eboli, S. M. Lietti and P. Mathews, Phys. Rev. D **65** (2002) 075003 [arXiv:hep-ph/0111001].

[17] G. Brandt, *Single Top Production*, Prepared for [7].

[18] U. Klein, *Higgs cross sections at LHeC*, Prepared for [7].

[19] M. Kuze et al., *Backgrounds to Higgs production at the LHeC*, Prepared for [7].

[20] U. Klein, *Production of an SM HIgss at an LHeC*, Prepared for [8].

[21] M. Ishitsuka et al., *Simulation Study of Higgs to bbar Mode in LHeC*, Prepared for [8].

[22] E. Boos *et al.* [CompHEP Collaboration], Nucl. Instrum. Meth. A **534**, 250 (2004) [arXiv:hep-ph/0403113]. Home page: `http://comphep.sinp.msu.ru/`

[23] J. Alwall, P. Artoisenet, S. de Visscher, C. Duhr, R. Frederix, M. Herquet and O. Mattelaer, AIP Conf. Proc. **1078** (2009) 84 [arXiv:0809.2410 [hep-ph]]. Home page: `http://madgraph.hep.uiuc.edu/`