SINGLE PRODUCTION OF EXCITED LEPTONS AT THE LHeC

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Single production of excited electrons (e^*) at the future Large Hadron-Electron Collider (LHeC) through both gauge (GM) and contact (CI) interactions is studied. Subsequent decays of excited electrons to ordinary electron and photon via gauge and contact interactions are considered. Expected sensitivity to e^* production in electron-proton collisions at the LHeC at high centre of mass energies of TeV scale will be addressed and compared to the recent results obtained using the data accumulated from the three large colliders LEP, HERA and Tevatron, as well as to the expected sensitivities of the LHC and ILC.

1 Introduction

The three-family structure and mass hierarchy of the known fermions is one of the most puzzling characteristics of the Standard Model (SM) of particle physics. Attractive explanations are provided by models assuming composite quarks and leptons [1]. The existence of excited states of fermions (F^*) is a natural consequence of compositeness models. Despite extensive searches at the highest energies presently available with existing colliders, no evidence for the existence of such particles was found and upper constraints on the coupling constant f/Λ were derived. With higher centre of mass energies available now in pp collisions at the LHC and at future ILC and LHeC colliders, prospects for finding the lowest excited states of the spectrum will be enlarged, if such particles exist at all.

Single production of excited leptons at the LHC ($\sqrt{s}$ up to 14 TeV) may happen via the reactions $pp \to e^{\pm}e^* \to e^+e^-V$ and $pp \to \nu e^* + \nu^* e^{\pm} \to e^{\pm}\nu V$. Experimental signatures expected from the production of excited leptons in pp collisions will be diffcult to separate from the large background of strong interaction processes. However, the LHC would be able to tighten considerably the current constraints on these possible new states and to probe excited lepton masses of up to 1 TeV [2]. A sensibility similar to the LHC could be reached at the ILC [3], with different e^+e^-, $e\gamma$ and $\gamma\gamma$ collisions modes and a centre of mass energy of $\sqrt{s} \geq 500$ GeV.

Recent results of searches for excited fermions [4,5,6] at HERA using all data collected by the H1 detector demonstrated that ep colliders are very competitive to pp or e^+e^- colliders for these kind of exotic processes. Indeed limits set by HERA extends at high mass beyond the kinematic reach of LEP searches [7,8] and to lower f/Λ values than present Tevatron results [9] using 1 fb^{-1} of data. Therefore a future LHeC machine, with a centre of mass energy of 1 TeV up to 2 TeV, much more higher than the previous ep collider HERA, would be an ideal instrument to search for excited fermions. This has motivated us to examine excited electron production at a future

LHeC collider and compare it to the potential of other types of colliders at the TeV scale, the LHC and the ILC.

2 Excited Fermion Models

Compositeness models attempt to explain the hierarchy of masses in the SM by the existence of a substructure within the fermions. Several of these models [10,11,12] predict excited states of the known fermions, in which excited fermions are assumed to have spin 1/2 and isospin 1/2 in order to limit the number of parameters of the phenomenological study. They are expected to be grouped into both left- and right-handed weak isodoublets with vector couplings. The existence of the right-handed doublets is required to protect the ordinary light fermions from radiatively acquiring a large anomalous magnetic moment via F^*FV interaction (where V is a γ, Z or W).

Interactions between excited and ordinary fermions may be mediated by gauge bosons, as described by the effective Lagrangian:

$$\mathcal{L}_{GM} = \frac{1}{2\Lambda}\bar{F}_R^{*}\sigma^{\mu\nu}\left[g\,f\frac{\vec{\tau}}{2}\vec{W_{\mu\nu}} + g'\,f'\,\frac{Y}{2}\,B_{\mu\nu} + g_s\,f_s\,\frac{\vec{\lambda}}{2}\,\vec{G_{\mu\nu}}\right]F_L \;+\; h.c., \tag{1}$$

where Y is the weak hypercharge, g_s, $g = \frac{e}{\sin\theta_W}$ and $g' = \frac{e}{\cos\theta_W}$ are the strong and electroweak gauge couplings, where e is the electric charge and θ_W is the weak mixing angle; $\vec{\lambda}$ and $\vec{\tau}$ are the Gell-Mann matrices and the Pauli matrices, respectively. $G_{\mu\nu}$, $W_{\mu\nu}$ and $B_{\mu\nu}$ are the field strengh tensors describing the gluon, the $SU(2)$, and the $U(1)$ gauge fields. f_s, f and f' are the coupling constants associated to each gauge field. They depend on the composite dynamics. The parameter Λ has units of energy and can be regarded as the compositeness scale which reflects the range of the new confinement force.

In addition to gauge mediated (GM) interactions, novel composite dynamics may be visible as contact interactions (CI) between excited fermions and ordinary fermions. Such interactions can be described by an effective four-fermion Lagrangian [12]:

$$\mathcal{L}_{CI} = \frac{4\,\pi}{2\Lambda^2}j^{\mu}j_{\mu}\,, \tag{2}$$

where Λ is here assumed to be the same parameter as in the gauge interaction Lagrangian (1) and j_μ is the fermion current

$$j_\mu = \eta_L\bar{F}_L\gamma_\mu F_L + \eta'_L\bar{F^*}_L\gamma_\mu F^*_L + \eta"_L\bar{F^*}_L\gamma_\mu F_L + h.c. + (L{\to}R). \tag{3}$$

By convention, the η factors of left-handed currents are set to one, while the factors of right-handed currents are considered to be zero.

3 Simulation and Results

In the following study, excited electron production and decays via both GM and CI e^* are considered. For GM interactions, the e^* production cross section under the assumption $f = -f'$ becomes much smaller than for $f = +f'$ and therefore only the case $f = +f'$ is studied.

Considering pure gauge interactions, excited electrons could be produced in ep collisions at the LHeC via a t-channel γ or Z bosons exchange. The Monte Carlo (MC) event generator COMPOS [13] is used for the calculation of the e^* production cross section and the simulation of signal events. The COMPOS generator uses the narrow width approximation (NWA) for the calculation of the production cross section and takes into account the natural width of the excited electron for the e^* decay. The NWA is valid for e^* masses and the couplings f/Λ relevant to this analysis, as the total e^* width remains less than 10% of the e^* mass. Figure 1(a) shows the total e^* production cross sections for different design options of the LHeC, operating thus at different centre of mass energies. These results are obtained with the assumption $f = +f'$ and $M_{e^*} = \Lambda$ and are compared to production cross section at HERA and also at the LHC [2]. In the mass range accessible by the LHeC, the e^* production cross section is clearly much higher than at the LHC. For comparison, the production cross sections of excited neutrinos at the LHeC is also schown in figure 1(b).

Considering gauge and contact interactions together, formulae for the e^* production cross section via CI and of the interference term between contact and gauge interactions have been incorporated into COMPOS [4,14]. For simplicity, the relative strength of gauge and contact interactions are fixed by setting the parameters f and f' of the gauge interaction to one. Comparisons of the e^* production cross section via only gauge interactions and via GM and CI together, as a function of the e^* mass, are presented in figure 2(a) for $M_{e^*} = \Lambda$ and figure 2(b) for $\Lambda = 10$ TeV, respectively. These results for the LHeC at $\sqrt{s} = 1.4$ TeV are compared to the cross section at an LHC operating at $\sqrt{s} = 14$ TeV. These plots demonstrate that at the LHeC the ratio of the contact and gauge cross section decreases as Λ and M_{e^*} increases, differently than for the LHC where contact interactions may be an important source of production of excited electrons. Figure 3 shows the evolution of the relative branching ratio (BR) of e^* decays via contact and gauge interactions as a function of the e^* mass and of the compositness scale Λ. In the mass range accessed at the LHeC, e^* decays are dominated by gauge decays, provided that Λ is large enough. Therefore, only gauge decays are looked for in the present study.

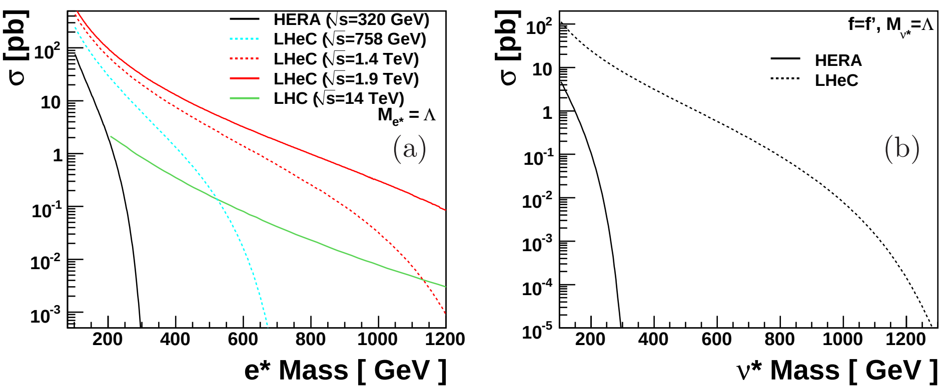

Figure 1: The e^* production cross section for different design scenarios of the LHeC electron-proton collider, compared to the cross sections at HERA and at the LHC (a). Comparison of theproduction cross sections for ν^* at HERA and at the LHeC (b). Results for both e^* and ν^* are obtained with the assumptions $f = +f'$ and $M(e^*, \nu^*) = \Lambda$.

In order to estimate the sensitivity of excited electron searches at the LHeC, the e^* production followed by its decay in the channel $e^* \to e\gamma$ is considered. This is the key channel for excited electron searches in *ep* collisions as it provides a very clear signature and has a large branching ratio. Only the main sources of backgrounds from SM processes are considered here, namely neutral currents (NC DIS) and QED-Compton ($e\gamma$) events. Other possible SM backgrounds are negligible. The MC event generator WABGEN [15] is used to generate these background events. Figure 4 compares the e^* production cross section to the total cross section of SM backgrounds. Background events dominate in the low e^* mass region. Hence to enhance the signal, candidate events are selected with two isolated electromagnetic clusters with a polar angle between 5° and 145° and transverse energies greater than 15 GeV and 10 GeV, respectively.

To translate the results into exclusion limits, expected upper limits on the coupling f/Λ are derived at 95% Confidence Level (CL) as a function of excited electron masses.

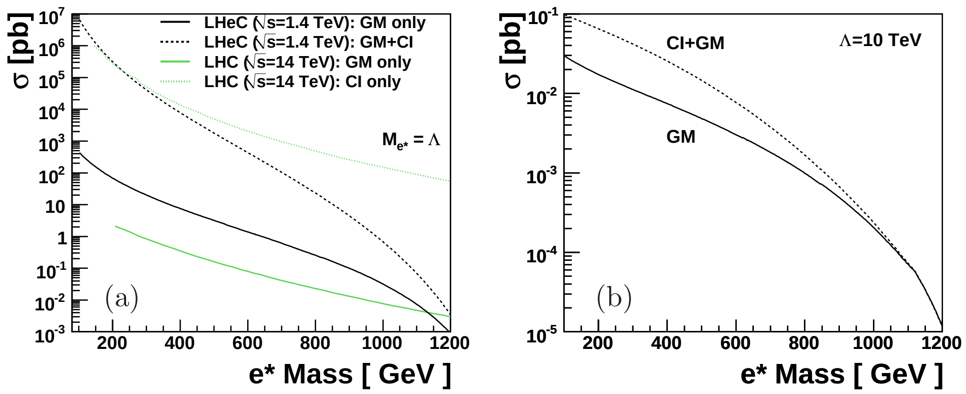

Figure 2: Comparison of the e^* production cross section via gauge and contact interactions. In figure (a), the results for the LHeC ($\sqrt{s} = 1.4$ TeV) and for the LHC ($\sqrt{s} = 14$ TeV) are compared. Production cross sections for a fixed Λ value of 10 TeV are shown in figure (b) for the LHeC.

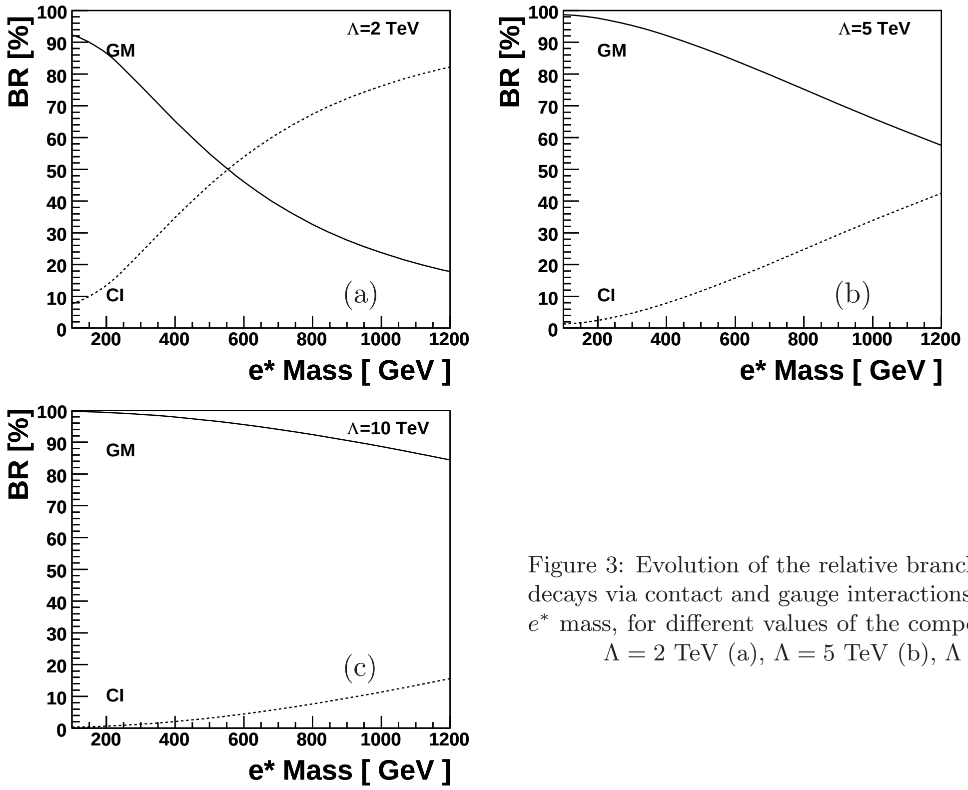

Figure 3: Evolution of the relative branching ratio (BR) of e^* decays via contact and gauge interactions, as a function of the e^* mass, for different values of the compositeness scale Λ: for $\Lambda = 2$ TeV (a), $\Lambda = 5$ TeV (b), $\Lambda = 10$ TeV (c).

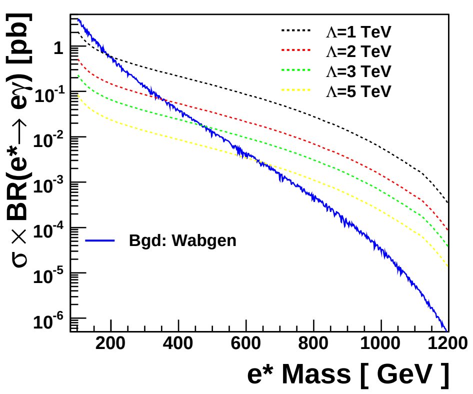

Figure 4: Electromagnetic production cross section for e^* ($e^* \to e\gamma$) for different values of Λ.

In case of gauge interaction, the attainable limits at the LHeC on the ratio f/Λ are shown in figure 5 for excited electrons, for the hypothesis $f = +f'$ and different integrated luminosities $L = 10$ fb^{-1} for $\sqrt{s}$ up to 1.4 TeV and $L = 1$ fb^{-1} for $\sqrt{s}$ up to 2 TeV. They are compared to the upper limits obtained at LEP [7,8], HERA [4] and also to the expected sensitivity of the LHC [2]. Considering the assumption $f/\Lambda = 1/M_{e^*}$ and $f = +f'$, excited electrons with masses up to 1.2(1.5) TeV, corresponding to centre of mass energies of $\sqrt{s} = 1.4(1.9)$ TeV of the LHeC, are excluded. Under the same assumptions, LHC ($\sqrt{s} = 14$ TeV) could exclude e^* masses up to 1.2 TeV for an integrated luminosity of 100 fb^{-1}. In the accessible mass range of LHeC, above result demonstrates that expected sensitivity of the LHeC to the e^* searches is more stringent than the expected result from LHC.

If e^* production is considered via gauge and contact interaction together, an upper limit on $1/\Lambda$ is also obtained, under the assumption $f = +f' = 1$. Possible e^* decays by either gauge or contact interactions are taken into account and the efficiency of the analysis to e^* CI decays is conservatively assumed to be zero. The limit on f/Λ as a function of the e^* mass is displayed in the figure 6. No large change of the LHeC sensitivity is observed if e^* CI production is also considered.

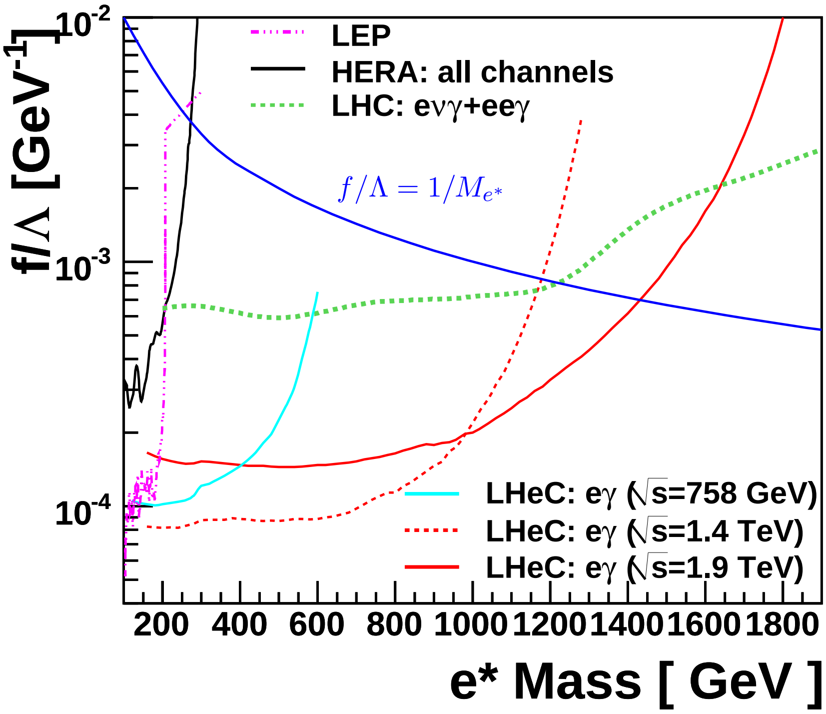

Figure 5: Sensitivity to excited electron searches for different design scenarios of the LHeC electron-proton collider, compared to the expected sensitivity of the LHC ($\sqrt{s} = 14$ TeV, $L = 100$ fb^{-1}). Different integrated luminisities at the LHeC ($L = 10$ fb^{-1} for $\sqrt{s}$ up to 1.4 TeV and $L = 1$ fb^{-1} for $\sqrt{s}$ up to 2 TeV) are assummed. The curves present the expected exclusion limits on the coupling f/Λ at 95% CL as a function of the mass of the excited electron with the assumption $f = +f'$. Areas above the curves are excluded. Present experimental limits obtained at LEP and HERA are also represented.

4 Conclusion

Searches for excited leptons and quarks have been performed using the data accumulated from the LEP, HERA and Tevatron colliders and have been unsuccessful so far. Studies about the sensitivity to e^* production at the LHC and the future ILC collider have been done in [2,3]. The

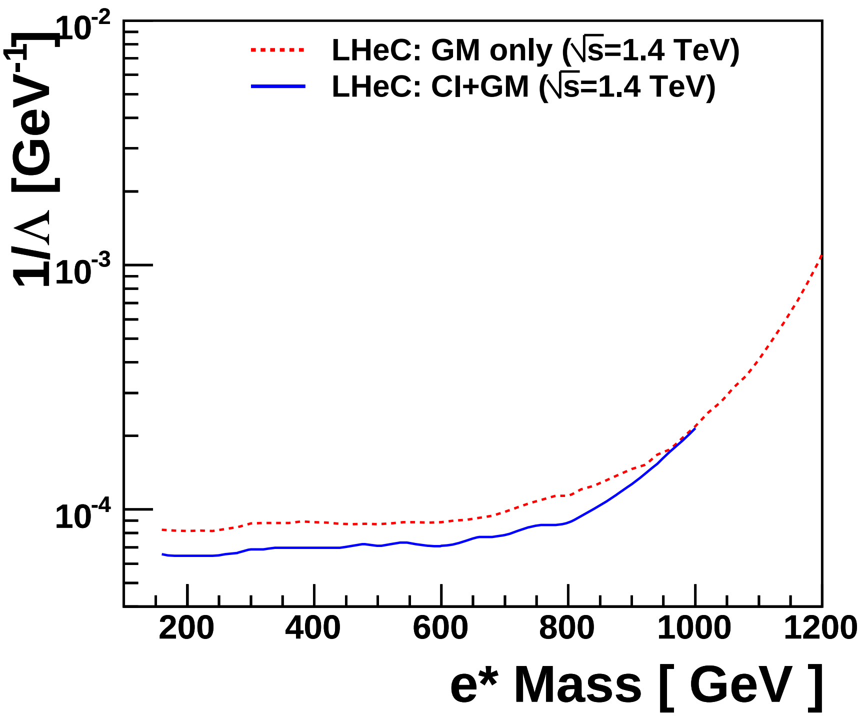

Figure 6: Expected exclusion limits at 95% CL on the inverse of the compositeness scale $1/\Lambda$ as a function of the mass of the excited electron for an integrated luminosity of 10 fb^{-1} ($\sqrt{s} = 1.4$ TeV) at LHeC. The excluded domain obtained by considering an e^* production via gauge mediated interactions only and under the assumption $f = +f' = 1$ is represented by the area above the dashed curve. Area above the plain curve corresponds to the additional domain excluded if gauge and contact interactions are considered together for e^* production. Areas above the curves are excluded.

LHC would be able to tighten considerably the current constraints on these possible new states and to probe excited lepton masses up to 1 TeV for a center of mass energy $\sqrt{s} = 14$ TeV and an integrated luminosity $L = 100$ fb^{-1}. In particular, preons exchange may lead to contact interactions between quarks and leptons and may be an important source of production of excited lepton at the LHC. A sensibility similar to the LHC could be reached at the ILC.

We have presented the results of excited single electrons production with subsequent electromagnetic decay. Production and decays of e^* through both gauge and contact interactions were studied. From our study, for excited electrons at the TeV scale, the expected sensitivity of a future LHeC collider is more stringent than others colliders so far. An electron-proton collider in the TeV region would therefore remain an ideal machine to search for excited electrons. Singly produced excited electrons could be accessible up to a mass of 1.2 to 1.5 TeV at the LHeC for centre of mass energies of $\sqrt{s} = 1.4$ TeV and an integrated luminosity $L = 10$ fb^{-1} to $\sqrt{s} = 1.9$ TeV and $L = 1$ fb^{-1}, respectively. The expected limit improves only slightly when e^* production via GM and CI together is considered, demonstrating that the gauge interaction mechanism is dominant for excited electron processes in electron-proton collisions.

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