SIGNALS OF NEW LEPTONS

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ABSTRACT

We discuss the production of heavy leptons at a future high–energy $e^+e^-$ linear collider with a center of mass energy of 500 GeV. Signals and backgrounds are analyzed for their single production in association with ordinary leptons.

1. Introduction

Many theories beyond the Standard Model (SM) lead to the existence of new fermions. In most of the cases these new fermions have non–canonical $\text{SU}(2) \times \text{U}(1)$ quantum numbers, e.g. the left–handed (LH) components are in weak isosinglets and/or the right–handed (RH) ones in weak isodoublets. Examples of such fermions [besides a fourth generation with a heavy neutrino] are the following [1,2]:

i) In the unifying group SO(10), which is one of the simplest and most economic extensions of the SM, the smallest anomaly–free fermion representation has dimension 16. It contains a right–handed neutrino in addition to the 15 Weyl fermions in one lepton–quark generation. These heavy neutrinos are of the Majorana type.

ii) In the exceptional group $\text{E}_6$, which is suggested as low energy limit of superstring theories, each generation of fermions lies in the 27 dimensional representation. Thus, in addition to the usual chiral fields, twelve new fields are needed to complete the representation. Among these, there will be two weak isodoublets of heavy leptons, a RH and a LH doublet, and two isosinglets of neutrinos which can be either of Dirac or Majorana type.

iii) Mirror fermions, whose chiral properties are opposite to those of ordinary fermions [i.e. the RH components in isodoublets and the LH ones in isosinglets] appear in many extensions of the SM. They provide a way to restore left–right symmetry at the scale of the electroweak symmetry breaking, and they naturally occur in lattice gauge theories.

These new fermions will mix with the ordinary fermions of the SM, and this mixing will give rise to new currents which determine to a large extent their decay properties and allow for new production mechanisms [2,3]. In this report, we briefly discuss the signals and backgrounds for the production of the new leptons at a high–energy $e^+e^-$ linear collider with a c.m. energy of 500 GeV [4]. A more complete discussion can be found in [3].
2. Production and Decay

If the new particles have non-zero electromagnetic and weak charges, they can be pair produced if their masses are smaller than the beam energy. In general the reactions are built-up by a superposition of photon and $Z$ boson exchanges [additional contributions could come from extra gauge bosons if their masses are not much larger than the c.m. energy of the collider]. The cross sections are large and, up to phase space suppression factors, of the order of the point-like QED cross section for muon pair production. At a 500 GeV $e^+e^-$ collider this gives cross sections $\sigma \sim 400$ fb which, with the expected integrated luminosity of $\sim 20$ fb$^{-1}$ [4], lead to several thousand events. This large number of events allows to probe masses up to the kinematical limit of 250 GeV and, due to the clean environment of $e^+e^-$ colliders, to investigate in detail the properties of these fermions.

The mixing allows an additional production mechanism for the new fermions: single production in association with their light partners. In the case of quarks [and for second and third generation new leptons if inter-generational mixing is neglected] the production process is mediated by $s$–channel gauge boson exchange; since the mixing angles are restricted to values smaller than $O(10^{-1})$ by present experimental data [1], the cross sections are rather small. But in the case of [the first generation] heavy leptons, additional $t$–channel exchanges, $W$ exchange for neutral leptons and $Z$ exchange for charged leptons are present, increasing the cross sections by several orders of magnitude. This results in large production rates which allow to probe lepton masses close to the total c.m. energy if the mixing angles are not prohibitively tiny. For instance, for a heavy neutrino with a LH mixing to the electron, the production cross section is of $O(1)$ pb at a 500 GeV collider if the neutrino mass is around 300 GeV and its mixing angle close to the bound $\theta_{\text{mix}} \simeq 0.1$.

Present experimental data imply that the masses of the new states are larger than $M_Z/2$ and for not too small mixing angles, larger than $M_W$; the mass range up to $m_F \sim M_Z$ can be probed at LEP200. The heavy fermions decay through mixing into massive gauge bosons plus their ordinary light partners; for masses larger than $M_W/M_Z$ the vector bosons will be on–shell and will decay into light quarks and leptons. Because the decay is suppressed by small mixing angles, the new fermions have very narrow widths: for $\theta_{\text{mix}} \sim 0.1$ and masses around 100 GeV the partial decay widths are less than 10 MeV. The charged current decay mode is always dominant and asymptotically the branching ratios are 1/3 and 2/3 for the neutral and charged current decays, respectively. To fully reconstruct the fermions from their final decay products, one needs the branching ratio of their decay into visible particles. For the decays of $N, E$ into charged leptons and $W/Z$ bosons which subsequently decay into two jets, the branching ratios are approximately 0.43 and 0.23, respectively [in the case of the $Z$ boson, one can also include the cleaner $e$ and $\mu$ decays, but the branching ratio is rather small: $\sim 6\%$ compared to $\sim 70\%$ for hadrons].

In the following, we will discuss the signals and the various backgrounds for the single production of charged and neutral heavy leptons [with a LH mixing to electrons] at a 500 GeV collider. The analysis will be based on an integrated luminosity of 50 fb$^{-1}$ which corresponds to $\sim 2$ years running of a standard $e^+e^-$ collider [4].
3. Signals and Backgrounds

The processes for the production of the charged and neutral heavy leptons \( E \) and \( N \) were simulated by incorporating in the PYTHIA [5] generator the matrix elements for the three body reactions: \( e^+e^- \rightarrow N\nu_e(E^\pm e^\mp) \rightarrow \nu_ee^\pm W^\mp(e^\pm e^\mp Z) \) and forcing the gauge bosons to decay hadronically; full hadronization was allowed to take place. All the resulting particles were then subjected to detector resolution and acceptance effects. The parameters for the detector were taken from the “standard” set of [6] but with angular acceptance up to \(| \cos \theta | < 0.98 \) for the electromagnetic and hadronic calorimeters as well as for the charged particle tracker. In the case of the neutral heavy lepton, the missing momentum vector was calculated and subsequently assumed to be the reconstructed neutrino momentum. The background processes were simulated using existing parameter options in PYTHIA.

In the case of the charged lepton \( E \), the signal consists of an \( e^+e^- \) pair and two jets. Other processes likely to produce such a configuration are: (i) \( e^+e^- \rightarrow e^+e^-Z \), with the \( Z \) decaying hadronically; the cross section is 3800 fb; (ii) \( e^+e^- \rightarrow ZZ \), with a cross section of 615 fb; (iii) \( e^+e^- \rightarrow t\bar{t} \), followed by \( t \rightarrow bW \) and leading to two electrons and 2 jets but with missing momentum; and (iv) \( \gamma\gamma \rightarrow e^+e^-q\bar{q} \) which has a large cross section but the jets have small invariant masses and the resulting events have the primary electrons going mostly along the beam pipe. In the case of the neutral lepton \( N \), the signal consists of an electron, a pair of jets and missing momentum. The backgrounds that one has to consider are: (i) \( e^+e^- \rightarrow e\nu W \) with a cross section of 5800 fb when the \( W \) decays hadronically; (ii) \( e^+e^- \rightarrow WW \) where one of the \( W \)’s decays hadronically and the other to an \( e\nu \) pair and the cross section in this case is 1140 fb; (iii) \( \gamma\gamma \rightarrow e(e)q\bar{q} \) where one of the electrons escapes observation.

The analysis proceeded by selecting among all “reconstructed” final state particles the \( e^-, e^+ \) with a momentum greater than 30 GeV. The following cuts were found to suppress considerably the background processes without affecting significantly the signals.

For the charged lepton: (1) One and only one \( e^+e^- \) pair. (2) \( 85 < M_{jj} < 105 \) GeV where the lower bound on the reconstructed \( Z \) mass was set intentionally high so as to avoid a possibility of confusing a \( Z \) with a \( W \). (3) \( |p_{l+}| > (E_{beam} - M_E^2/4E_{beam}) - 40 \) GeV and \( |p_{l-}| > \frac{2}{3}M_E - 133 \) GeV, with \( M_E \) the reconstructed mass; these kinematic constraints ensure energy-momentum conservation, with some tolerance for detector resolution effects. (4) A cut \( |M_{ll} - M_Z| > 12 \) GeV which is effective against the \( ZZ \) background. (5) Cuts \( \cos \theta_Z > -(M_E + 440)/720 \) and \( \cos \theta_Z < (2100 - M_E)/2000 \), which are necessary to reduce the background from \( e^+e^- \rightarrow e^+e^-Z \). (6) \( \cos \theta_{l\nu} < 0.5 \) since in the signal, the two leptons are mostly back–to–back. Cuts (3) and (5) apply to \( E^- \), similar ones apply for \( E^+ \).

In the case of neutral leptons, similar cuts where applied: (1) One and only one \( e^- \). (2) \( 70 < M_{jj} < 90 \) GeV for the reconstructed \( W \) mass. (3) \( |p_\nu| > (E_{beam} - M_N^2/4E_{beam}) - 40 \) and \( |p_l| > \frac{2}{3}M_N - 133 \). (4) A cut \( M_{ll} > 120 \) GeV, effective against the \( WW \) background. (5) \( \cos \theta_{l\nu} < 2.58 - M_N/240 \) reduces the background from \( e^+e^- \rightarrow e^-\nu W \). (6) \( \cos \theta_{l\nu} < 0.5 \); here also the two leptons from the signal are mostly back–to–back.
4. Results and Discussions

Fig. 1 shows the reconstructed invariant mass histograms for heavy leptons with masses of 250, 350 and 450 GeV and with mixing angles $\theta_{\text{mix}} = 0.05$ in the case of the charged lepton and $\theta_{\text{mix}} = 0.025$ for the heavy neutrino. For these values, one can see that the signal peaks stand out clearly from the background events, especially for heavy lepton masses not too close to the total c.m. energy of the collider. For the $\gamma\gamma$ and $t\bar{t}$ backgrounds, no events survived [in the former case, because it was not possible to generate a sufficient number of events, only an upper limit of $< 15$ surviving background events/5 GeV can be given]. The backgrounds from vector boson pair production have been suppressed to a very low level; the backgrounds from single $W$ and $Z$ production are relatively higher.

For smaller mixing angles, the signal cross sections have to be scaled down correspondingly. For lepton masses of the order of 450 GeV, only slightly smaller $\theta_{\text{mix}}$ values can be probed, while for masses around 350 GeV one can go down by at least a factor of two. The situation is much more favorable for heavy neutrinos than for charged leptons, the cross section being one order of magnitude larger. For instance, assuming a mass of 350 GeV and requiring that the ratio of the signal events to the square root of the background events be larger than unity, one can probe mixing angles down to $\theta_{\text{mix}} \sim 0.005$ for neutral leptons and $\theta_{\text{mix}} \sim 0.03 = 2$ for charged leptons.

In conclusion. Because the cross sections are large and the environment in $e^+e^-$ colliders is very clean, pair produced new leptons can be unambiguously detected up to masses close to the beam energy. For new leptons of the first generation, one can reach masses close to the total center of mass energy of the machine in the process of single production in association with ordinary electrons and neutrinos, provided that the mixing angles are not prohibitively tiny.

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References.

[1] See e.g. the talks given by J. Hewett and E. Nardi, these proceedings.

[2] See A. Djouadi, D. Schaile and C. Verzegnassi [conv.] et al., Report of the Working Group “Extended Gauge Models”, Proceedings of the Workshop “$e^+e^-$ Collisions at 500 GeV: The Physics Potential”, Report DESY 92-123B, P. Zerwas, ed.

[3] For details and for a complete set of references, see A. Djouadi, Prep. UdeM–LPN–TH –93–157, and G. Azuelos and A. Djouadi, Prep. UdeM–LPN–TH–93–158.

[4] See e.g. the talk given by B. Wiik, these proceedings.

[5] T. Sjöstrand, PYTHIA 5.6 and JETSET 7.3, Report CERN-TH.6488/92.

[6] P. Grosse-Wiesmann, D. Haidt and J. Schreiber, in the same proceedings as in Ref. [2].