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The possibility of detecting single heavy Dirac and Majorana neutrinos at LEP II is investigated in detail. We study the process $e^+e^- \longrightarrow \nu_\ell \, \ell \, q_i \, \bar{q}_j$ as a clear signature for heavy neutrinos. Numerical estimates for cross sections and distributions for the signal and the background are calculated and a Monte Carlo reconstruction of final state particles after hadronization is presented.

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The recently accumulated data at LEP offers a unique opportunity for the search of new particles. At center of mass energies around 200 GeV and integrated luminosities of a few hundreds of inverse picobarns this experimental facility can be employed, for instance, in the search of new heavy Dirac and/or Majorana neutrinos. The L3 Collaboration [1] has recently published results on the search of new possible excited charged and neutral leptons. Their experimental data was compared with a specific model of new excited leptons interacting with the Standard Model gauge bosons and new limits were found. Single production of new possible charged leptons according to Standard Model extentions is also under study at the Delphi Collaboration [2]. A natural question is then: what are the consequences of these results for other models of new heavy leptons? This is particularly important for new heavy neutrinos. The Super-Kamiokande results [3] provide increasing evidence for light neutrino oscillations and non zero neutrino masses. A possible explanation of the smallness of neutrino masses is the "see-saw" mechanism, which implies new heavy neutrino states, with extremely small mixing angles. However, there are theoretical models which decouple the mixing angles from the mass relations [4]. This is the case if in the general mass matrix one imposes some internal symmetry that makes the matrix singular. Then the mixing parameters are bounded only by its phenomenological consequences. Another possible scenario for heavy neutrinos is in grand unified extensions of the Standard Model such as $SO(10)$, E_6, as well as in mirror models. This new heavy neutrinos could be of the Dirac type. In this case we have no simple connection between mixing angles and mass ratios.

We are then lead to consider the possibility of new heavy neutrino states of Majorana and Dirac types, with a mixing angle with light neutrinos limited only by it's phenomenological consequences. There are experimental bounds on heavy neutrino masses indicating that, if they exist, their masses must be greater than 80-100 GeV [5,6] and mixings between heavy and light neutrinos are expected to be small. There is some model dependence on these results, but from radiative corrections [7] there is also no indication of new physics in this region. The high precision measurements of the Z properties at LEP/SLC indicates that the mixing of the presently known fermions and possible new heavy states is known to be small, of the order of $\sin^2\theta_{\rm mix} = 10^{-2} - 10^{-3}$. A recent estimate [8] gives $\sin^2\theta_{\rm mix} < 0.0052$ with 95% C.L. This limit value is used throughout this paper for all curves and distributions. Single production of new heavy neutrinos, according to some Standard Model extentions, in electron-positron colliders offers a unique possibility for a search in the neutrino mass region $M_N = (\sqrt{s}/2, \sqrt{s})$. Since there are no new interactions in this kinematical region, after mixing the relevant part of the Lagrangian at LEP II energies is given by:

$$\mathcal{L}_{nc} = -\frac{g}{4c_W} sin\theta_{\rm mix} Z_\mu \overline{\psi_N} \gamma^\mu \left(1-\gamma_5\right) \psi_{\nu_\ell} + h.c.. \quad (1)$$

and

$$\mathcal{L}_{cc} = -\frac{g}{2\sqrt{2}} sin\theta_{\rm mix} W_\mu \overline{\psi_N} \gamma^\mu \left(1-\gamma_5\right) \psi_\ell + h.c. \quad (2)$$

where $\ell =$ e, μ , τ and N is the new heavy neutrino. For Dirac neutrinos we impose lepton number conservation and for Majorana neutrinos we must allow lepton number violation. There is some model (singlets, doublets, mirror neutrinos) dependence on the N-N-Z vertex but

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for the light-to-heavy neutrino vertex this dependence disappears [9].

We are interested in the process $e^+e^- \longrightarrow \nu_\ell\, \ell\, q_i\, \bar{q}_j$ since it gives a clear signature for heavy neutrinos and has a higher cross section than the pure leptonic final states. As we will shown below in this paper, it also allows a clear separation between the signal and the Standard Model background.

In Fig. 1 we show the first order Feynmam diagrams that display the exchange of a single new heavy neutrino for the above process. In Fig. 2 we show the corresponding Standard Model diagrams that contribute for the same final state. We must also include in the Standard Model calculation, which is our background, all the diagrams of Fig. 1 with the heavy neutrinos replaced by light neutrinos. The single heavy Dirac neutrino for the electron family dominates the associated muon (and tau) family production since in the first case we have s and t channel exchanges, whereas in the last cases we have only s channel contribution. For single heavy Majorana one has to sum over final neutrino and anti-neutrino production and do the correct sum over the three lepton families. Another point to be taken into account is the fact that the final state light neutrino is an experimentally undetected particle. So we must sum over all possible combinations whenever necessary.

In the search for new particles a fundamental point to be clarified is the relation between the heavy neutrino signal and the Standard Model background. This point was recently studied for future electron-positron colliders [9] at $\sqrt{s}$ =500 GeV and new electron-muon colliders [10,11] where single production of new heavy neutrinos was shown to be more important than pair production [12,13].

In the present work we have done a detailed study of the process $e^+e^- \longrightarrow \nu_\ell\, \ell\, q_i\, \bar{q}_j$. Calculations for cross sections and distributions are straightforward, although rather lengthly. We have at our disposal efficient algebraic programs like CompHep [14] that can perform this kind of calculations. Hadronization of quarks can also be done with the well known program Phytia [15].

The total cross section for $e^+e^- \longrightarrow \nu_\ell\, \ell\, q_i\, \bar{q}_j$ at LEP II energy of $\sqrt{s}$ = 190 GeV is shown in Fig. 3. From this figure on we have summed over the final state charged leptons e^-, e^+, μ^-, μ^+ and employed the general detector cuts $E_\ell > 20$ GeV and $-0.95 < cos\theta_\ell < 0.95$, where θ_ℓ is the angle of the final charged lepton relative to the initial electron. The Standard Model background clearly dominates the signal. For both Dirac and Majorana production we have a maximum near M_N =120 GeV. We turn now our attention to distributions and cuts that can improve the signal to background ratio. In order to make our calculations closer to experiment, we have hadronized all final state quarks. In the next figures we have hadronized the quarks using the Pythia program [15]. All distributions are shown for the Majorana heavy neutrino. For the Dirac case we have a very similar pattern.

In Fig. 4 we display the invariant charged lepton + neutrino mass distribution. We note that the left scale applies to the Standard Model background and the right one applies to the signal curves for M_N =100, 120, 150 GeV. The background events are strongly concentrated at the W mass value. This suggests a first cut in the region 75 GeV $< M_{\rm inv(charged\ lepton\ +\ neutrino)} >$ 85 GeV.

Another interesting variable is the total invariant visible charged lepton + hadrons mass distribution shown in Fig. 5. The background has its maximum at 160 GeV and the signal is peaked at the heavy neutrino mass M_N =120 GeV. An important point for this distribution comes from the fact that in the models we are considering the heavy neutrino has a very narrow width. If this distribution is shown with large bins, the signal is spread and lost. If the bin is narrow, the signal is very clear. Fig. 5 shows this effect for 1 GeV and 5 GeV bins.

The invariant hadronic mass is also peaked at the W mass for the background since the main contribution comes from the diagram shown in Fig. 2e and spreads for the signal. We have then used the cut 70 GeV $< M_{\rm hadrons} <$ 90 GeV. Another useful cut comes from the angular correlation between θ_ℓ, and the reconstructed final state hadronic angle relative to the initial electron, $\theta_{hadrons}$. In the next figures we have chosen the value $(\cos\theta_\ell - 1)^2 + (\cos\theta_{\rm hadrons} + 1)^2 > (0.6)^2$.

In Figs. 6, 7 and 8 we show the invariant visible mass (charged leptons + hadrons) versus missing (neutrino) energy for background and signal (in arbitrary units) for M_N =100, 120, 150 GeV. In figures 6a, 7a and 8a we have done only the general detector cuts. For M_N =100 GeV the signal is already separated from the background but for higher masses this is no longer possible. The more general cuts discussed above can improve the signal to background ratio. Besides these cuts we have done in Fig. 6b the cut $E_{\rm charged\ lepton} <$ 40 GeV. The background is clearly below the signal. In Fig. 7b, for M_N =120 GeV, besides the above cuts we have done $E_{\rm charged\ lepton} <$ 60 GeV. Here again the signal dominates the background. In Fig. 8b, for M_N =150 GeV, we have employed 40 GeV $< E_{\rm charged\ lepton} <$ 80 GeV.

In Tables I and II we give the total number of events for Majorana and Dirac heavy neutrinos for an integrated luminosity of 200 pb^{-1}. This is shown for the general detector cuts and for the more restrictive cuts discussed above. They clearly do not affect the signal. Finally, from Figs. 6b, 7b and 8b we must do additional cuts in the final state missing energy $\not{E}$ and final visible energy $M_{visible}$, in order to reduce even further the background to an acceptable level and increase the signal to background ratio.

The present work shows that the recent LEP II data can test the possibility of new Dirac and/or Majorana neutrinos with mass in the region $M_N = (\sqrt{s}/2, \sqrt{s})$ and mixing angles with light neutrinos in the range $10^{-2} - 10^{-3}$. This was calculated for an integrated luminosity of 200 pb^{-1}. The process $e^+e^- \longrightarrow$ "charged lepton + missing energy + hadrons" can give a clear signature for heavy neutrinos. For the models that we considered an important point is that the heavy neutrino width is very narrow and distributions must be done with narrow bins.

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Figure Captions

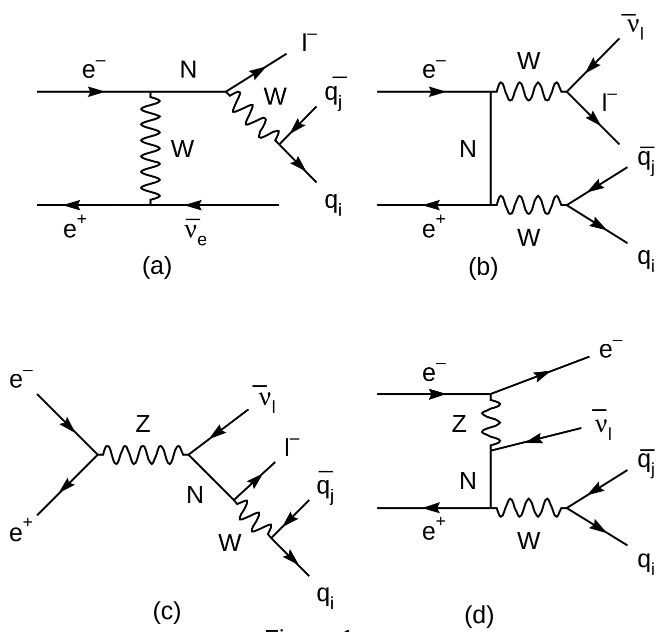
1. Signal Feynman diagrams for heavy Majorana and Dirac neutrino contribution to $e^+e^- \longrightarrow \nu_\ell \, \ell \, q_i \, \bar{q}_j$.
2. Standard model Feynman diagrams for $e^+e^- \longrightarrow \nu_\ell \, \ell \, q_i \, \bar{q}_j$.
3. Total cross section for the Standard Model background, Dirac and Majorana heavy neutrinos at $\sqrt{s} = 190$ GeV and $\sin^2\theta_{mix} < 0.0052$ with 95%.
4. Invariant mass distribution for the system charged lepton + neutrino.
5. Invariant mass distribution for the final visible particles (charged lepton + hadrons), for M_N= 120 GeV. The first figure is done with 5 GeV bins and the second one is done with 1 GeV bins. Both are in arbitrary units.
6. Invariant visible mass (charged leptons + hadrons) versus missing energy (neutrino) for background and signal for $M_N = 100$ GeV (in arbitrary units). Fig. 6a was done with the general detector cuts and Fig. 6b was done with the additional cuts as discussed in the text.
7. Same as figure 6 for $M_N = 120$ GeV.
8. Same as figure 6 for $M_N = 150$ GeV.

TABLE I. Expected number of events for Majorana

	♯ Detector cuts
M_N=100 GeV	21.2
M_N=120 GeV	29.6
M_N=150 GeV	18.8

TABLE II. Expected number of events for Dirac

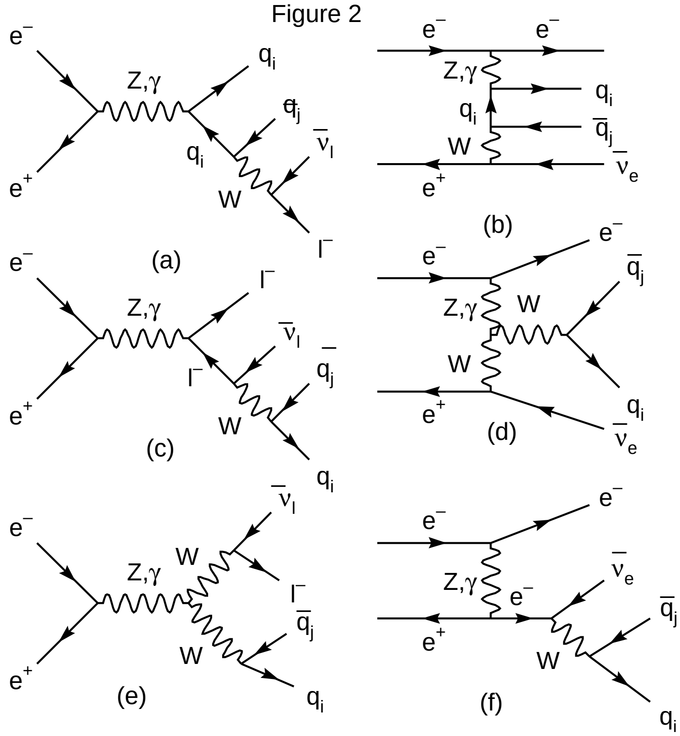
	♯ Detector cuts
M_N=100 GeV	31.1
M_N=120 GeV	42.6
M_N=150 GeV	26.5



e−
N
l−
W
q̄j
W
qi
e+
ν̄e
(a)
ν̄l
e−
W
l−
N
q̄j
e+
W
qi
(b)
e−
Z
ν̄l
l−
N
q̄j
e+
W
qi
(c)
e−
e−
Z
ν̄l
N
q̄j
e+
W
qi
(d)

Figure 1

Figure 2



e^-
e^+
Z,γ
q_i
$\bar{q}_j$
$\bar{\nu}_l$
W
l^-
(a)
e^-
e^-
Z,γ
q_i
q_i
$\bar{q}_j$
W
$\bar{\nu}_e$
e^+
(b)
e^-
e^+
Z,γ
l^-
l^-
$\bar{\nu}_l$
$\bar{q}_j$
W
q_i
(c)
e^-
e^-
Z,γ
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W
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$\bar{q}_j$
q_i
(f)