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Search for Heavy Isosinglet Neutrinos in e^+e^- Annihilation at $130 < \sqrt{s} < 189$ GeV

The L3 Collaboration

Abstract

A search for heavy neutrinos that are isosinglets under the standard $SU(2)_L$ gauge group is made at center-of-mass energies $130 < \sqrt{s} < 189$ GeV with the L3 detector at LEP. Such heavy neutrinos are expected in many extensions of the Standard Model. The search is performed for the first generation heavy singlet neutrino, $\mathrm{N_e}$, through the decay mode $\mathrm{N_e} \to \mathrm{e} + \mathrm{W}$. We set upper limits on the mixing parameter between the heavy and light neutrino for the heavy neutrino mass range from 80 GeV to 185 GeV.

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Introduction

In the Standard Model all fundamental fermions have a right-handed component that transforms as an isosinglet except the neutrinos, which are observed only in left-handed form. However, isosinglet heavy neutrinos arise in many models that attempt to unify the presently known interactions into a single gauge scheme, such as Grand Unified Theories or Superstring inspired models [1]. Their existence is also predicted in many extended electroweak models such as left-right symmetric and see-saw models [2].

In e^+e^- annihilation isosinglet heavy neutrinos can be produced through their mixing with the light neutrinos (see Figure 1). Constraints on isosinglet neutrino mixing have been set by several experiments [3, 4]. Heavy singlet neutrinos have been searched for in leptonic decays of mesons and in neutrino beam experiments [3], leading to stringent upper limits on the square of the mixing amplitude, $|U_\ell|^2$, reaching 10^{-7} in the low mass region (m_{N} below 2 to 3 GeV). In addition, three LEP experiments [4] have set limits on $|U_\ell|^2$ of the order of 10^{-3} to 10^{-5} for the neutrino mass range from 3 GeV up to 80 GeV.

In this paper we report on a direct search for isosinglet heavy neutrinos with masses larger than the W mass.

Production and decay

In this search, one isosinglet neutral heavy lepton N_ℓ is assumed to be associated with each generation of light neutrinos via the mixing amplitude U_ℓ. We do not consider mixing of the light neutrinos with higher isodoublet states (sequential leptons) nor the possibility of mixing among light neutrinos (as discussed in Ref. [5]).

The mixing between the isosinglet neutral lepton and its associated isodoublet neutrino allows single production to occur in e^+e^- annihilation:

$$\mathrm{e}^+\mathrm{e}^- \rightarrow \mathrm{N}_\ell + \nu_\ell.$$

In contrast to sequential isodoublet neutral leptons where pair production is dominant (when kinematically allowed), here single production dominates. The corresponding pair production cross section is suppressed relatively to the single production cross section by an additional $|U_\ell|^2$ factor, which is expected to be small (from indirect searches at LEP1 and low-energy experiments $|U_\ell| \leq 0.1$ for m_{N} larger than 80 GeV [6]). The single production process proceeds through s-channel Z exchange for all generations. For the first generation, $\mathrm{N_e}$, when heavy neutrinos can couple to electrons, there is an additional contribution from t-channel W exchange (see Figure 1). Due to this additional contribution the production cross section for the first generation heavy neutrinos can be as high as 0.6 pb. Since the mixing amplitude is expected to be small, the production cross section for N_μ and N_τ is too small to be explored at LEP2. Therefore, in this paper we concentrate on the search for the first generation heavy singlet neutrino, $\mathrm{N_e}$.

Isosinglet heavy neutrinos decay via the neutral or charged weak currents through the mixing with a light lepton:

$$\mathrm{N_e} \rightarrow \mathrm{Z}\nu_\mathrm{e} \text{ or } \mathrm{N_e} \rightarrow \mathrm{We}.$$

For neutrino masses not far above the W mass, heavy neutrinos decay predominantly through the W boson due to phase space suppression of the decay into Z, while for large masses $Br(\mathrm{N_e} \rightarrow \mathrm{eW}) = 0.67$ and $Br(\mathrm{N_e} \rightarrow \mathrm{Z}\nu_\mathrm{e}) = 0.33$ [7].

Data sample and event simulation

We present the analysis of data collected by L3 [8] at LEP2 from 1995 to 1998. The search was performed using a luminosity of 12.1 pb^{-1} at $\sqrt{s}$ = 130 to 136 GeV, 21.1 pb^{-1} at $\sqrt{s}$ = 161 to 172 GeV, 55.2 pb^{-1} at $\sqrt{s}$=183 GeV, and 176 pb^{-1} at $\sqrt{s}$=189 GeV.

Using the full differential cross section [9], a dedicated Monte Carlo generator is constructed to simulate heavy singlet neutrino production and decay. Subsequent hadronic fragmentation and decay are simulated by the JETSET Monte Carlo program [10]. Initial and final state radiation is taken into account. In addition, we include the effects of the finite width of the produced W and Z bosons. For the search we considered the mass range of the heavy neutrino between 80 and 185 GeV. For the simulation of background from Standard Model processes, the following Monte Carlo programs are used: PYTHIA 5.7 [10] ($\mathrm{e^+e^-} \rightarrow q\bar{q}(\gamma)$, $\mathrm{Ze^+e^-}$, ZZ), KORALZ [11] ($\mathrm{e^+e^-} \rightarrow \tau^+\tau^-(\gamma)$), KORALW [12] ($\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}$), PHOJET [13] ($\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-q\bar{q}}$), DIAG36 [14] ($\mathrm{e^+e^-} \rightarrow \mathrm{e^+e^-}\tau^+\tau^-$), and EXCALIBUR [15] ($\mathrm{e^+e^-} \rightarrow \mathrm{f\bar{f}'f\bar{f}'}$).

The Monte Carlo events have been simulated in the L3 detector using the GEANT3 program [16], which takes into account the effects of energy loss, multiple scattering and showering in the materials.

Event signatures and selection

The most important backgrounds for heavy neutrino searches are $\mathrm{W^+W^-}$production with one hadronic and one leptonic W decay (96% of the background), $q\bar{q}(\gamma)$ (3.6%) and ZZ production (0.4%). Reducing the $\mathrm{W^+W^-}$ background requires full reconstruction of the heavy neutrino mass from its decay products. The only decay channel for which this is possible is $\mathrm{N_e} \rightarrow \mathrm{eW}$ with W → jets. Thus, the event signature is one isolated electron plus hadronic jets. This channel has the largest branching ratio varying between 68% and 45% depending on the heavy neutrino mass.

An electron is defined as a cluster in the electromagnetic calorimeter with an energy larger than 4 GeV matched to a track in the (R, ϕ) plane to within 10 mrad. The cluster shower profile should be consistent with the one expected for an electron, *i.e.* $0.97 < E_9/E_{25} < 1.03$, where E_9 and E_{25} are the sums of the lateral-energy-leakage-corrected energies of 9 and 25 BGO crystals centered on the most energetic one. The electron polar angle θ must be in the fiducial volume defined by $|\cos\theta| < 0.94$. The energy, excluding the electron energy, deposited in a 10° cone around the electron direction, is required to be smaller than 5 GeV.

Jets are reconstructed from electromagnetic and hadronic calorimeter clusters using the Durham algorithm [17] with a jet resolution parameter of $y_{cut} = 0.008$. The jet momenta are defined by the vectorial energy sum of calorimetric clusters.

The event selection requires at least two hadronic jets plus one isolated electron. The visible energy must be greater than 70 GeV and the number of reconstructed tracks must be greater than 6. The polar angle θ of the missing momentum should be in the range $25° < \theta < 155°$. The visible invariant mass m_{vis} of the event is reconstructed and, to improve the resolution, it is rescaled according to

$$m_{\mathrm{N}} = m_{vis} \frac{\sqrt{s}}{p_\nu + E} ,$$

where p_ν is the missing momentum of the event, and E is the visible energy. Figure 2 shows the rescaled invariant mass m_{N} of the events after all previous cuts have been applied. Two regions are defined. In region 1, where the heavy neutrino mass is close to the W mass, a significant fraction of W's produced in N_e decays are off-shell. In region 2, $m_N > 100$ GeV, the W's are produced on-shell. In this case to further improve the resolution on the mass measurement, the determination of jet energies and angles, and the missing momentum direction (both for the signal and the W^+W^- background), a kinematic fit is applied imposing four-momentum conservation and the constraint that the invariant mass of the hadronic jets is equal to the W mass. In total, 21 events are selected in region 1, while 26.2 are expected from the background. The corresponding numbers for region 2 are 464 and 463.3. Figure 3 shows the distribution of the invariant mass of the electron and missing momentum, $m_{e\nu}$, for events in region 2 after the kinematic fit has been applied. One can see a clear peak at 80 GeV coming from the W^+W^- background.

The final selection requires the invariant mass of the electron and missing momentum to be outside the W mass region. Applying the cut, $m_{e\nu} < 70$ GeV or $m_{e\nu} > 90$ GeV, rejects 70% of the background events. Figure 4 shows the invariant mass of the events accepted after the mass cut is applied. We observe a good agreement between data and expected background: 84 events pass the selection, while 88.7 are expected from the SM background.

Results

We calculate the 95% confidence level upper limit on the square of the mixing amplitude, $|U_e|^2$, following the procedure in reference [18]. In region 1 we use the total number of events found in data and MC background to set a limit. In region 2 the number of events in data and MC background for a given mass m_N is defined as the number of events which have a reconstructed mass in the range of $m_N \pm 2\sigma$, where mass resolution σ varies from 2 to 2.5 GeV over the mass range considered. The selection efficiency varies from 20% to 45% depending on the heavy neutrino mass and the center-of-mass energy. The systematic error, which is mainly due to the uncertainty in the energy calibration, the simulation and reconstruction of the heavy neutrinos, and the Monte Carlo statistics, is estimated to be 5% relative. To obtain limits, the selection efficiency has been reduced by one standard deviation of the total systematic error. Taking into account the luminosities, the selection efficiencies, the production cross sections and branching ratio $Br(N_e \rightarrow eW)$ for heavy singlet neutrinos at $\sqrt{s} = 133$ to 189 GeV, we obtain an upper limit on the square of the mixing parameter, $|U_e|^2$.

The results for the mixing amplitude, $|U_e|^2$, as a function of the mass are shown in Figure 5. These limits are the first results for masses of singlet heavy neutrinos greater than 80 GeV.

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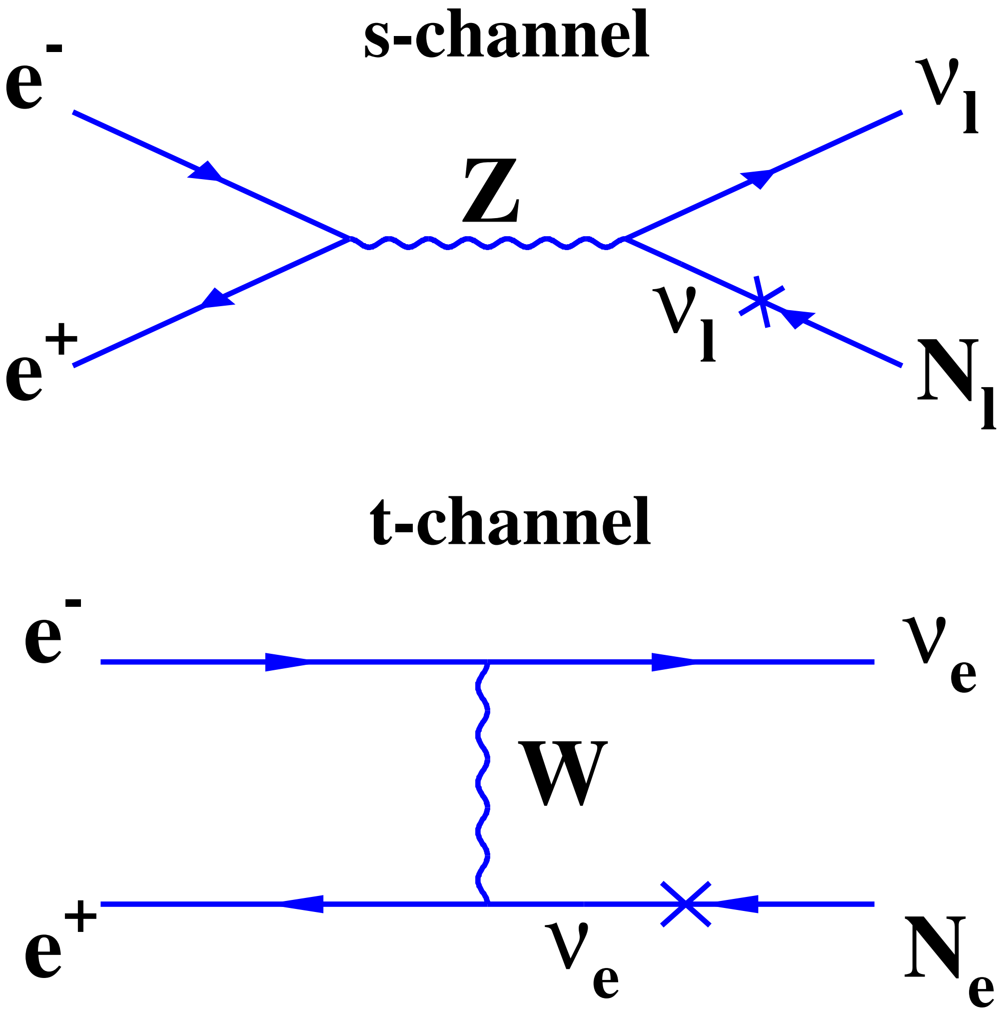

Figure 1: Feynman diagrams showing the production of isosinglet heavy neutrinos. Here the lepton ℓ denotes e, μ, or τ for s-channel production.

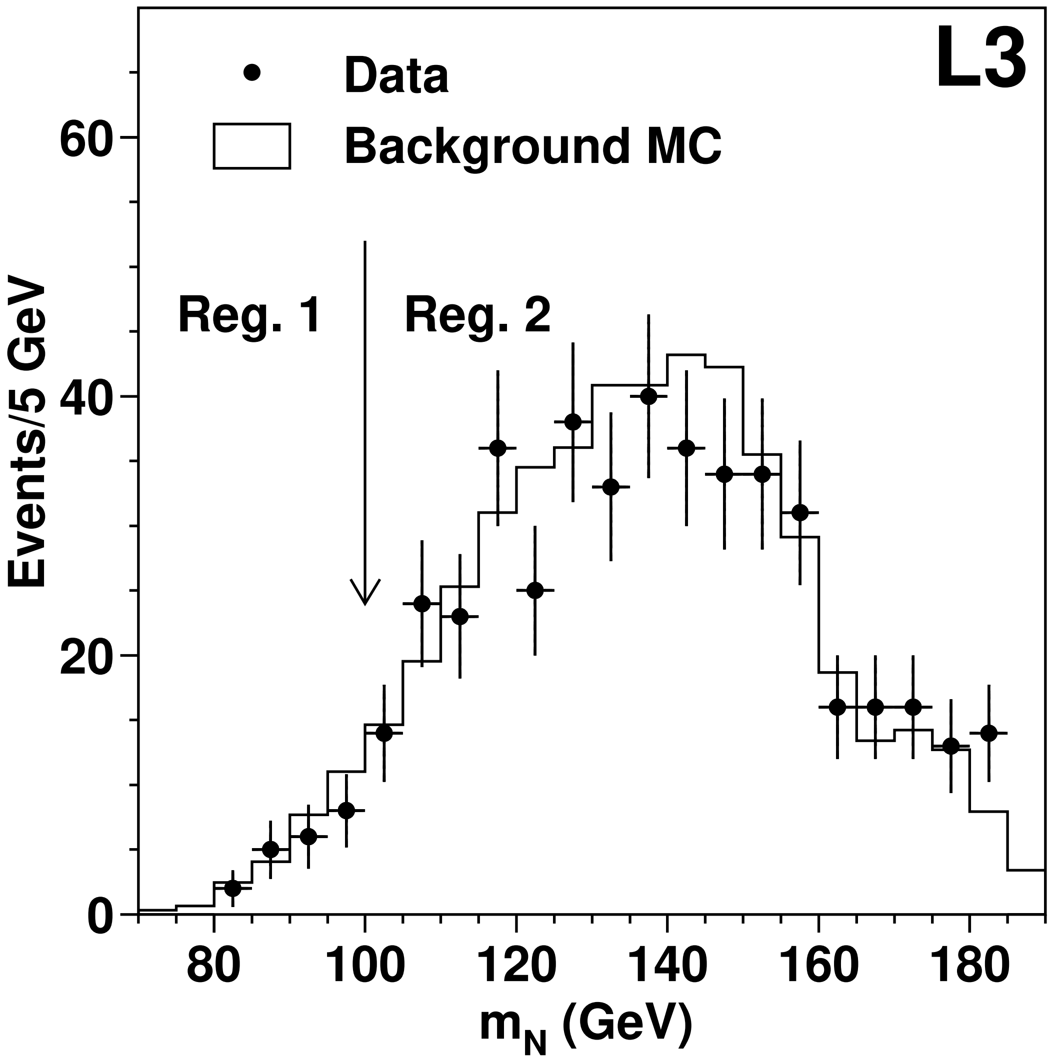

Figure 2: Distribution of the rescaled visible invariant mass, m_{N}, of the event. The points are the data and the solid histogram is the background. See text for definitions of Region 1 and Region 2.

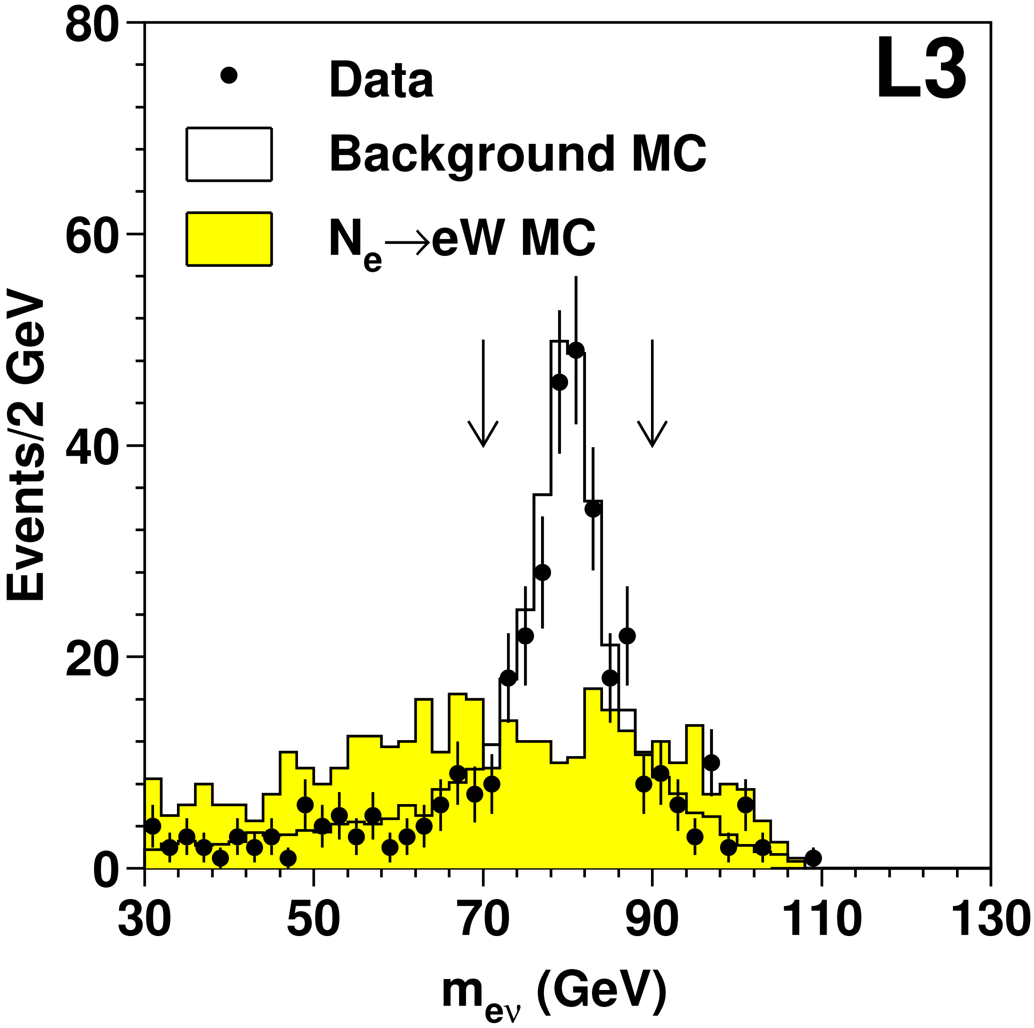

Figure 3: The invariant mass, $m_{e\nu}$, of the isolated electron and missing momentum. The points are the data taken at $\sqrt{s}$ = 189 GeV, the solid histogram is the background Monte Carlo. The shaded histogram is the predicted signal $e^+e^- \rightarrow \nu N$ for a 140 GeV heavy neutrino. The normalization for the signal Monte Carlo is arbitrary. The arrows indicate the value of the applied cut.

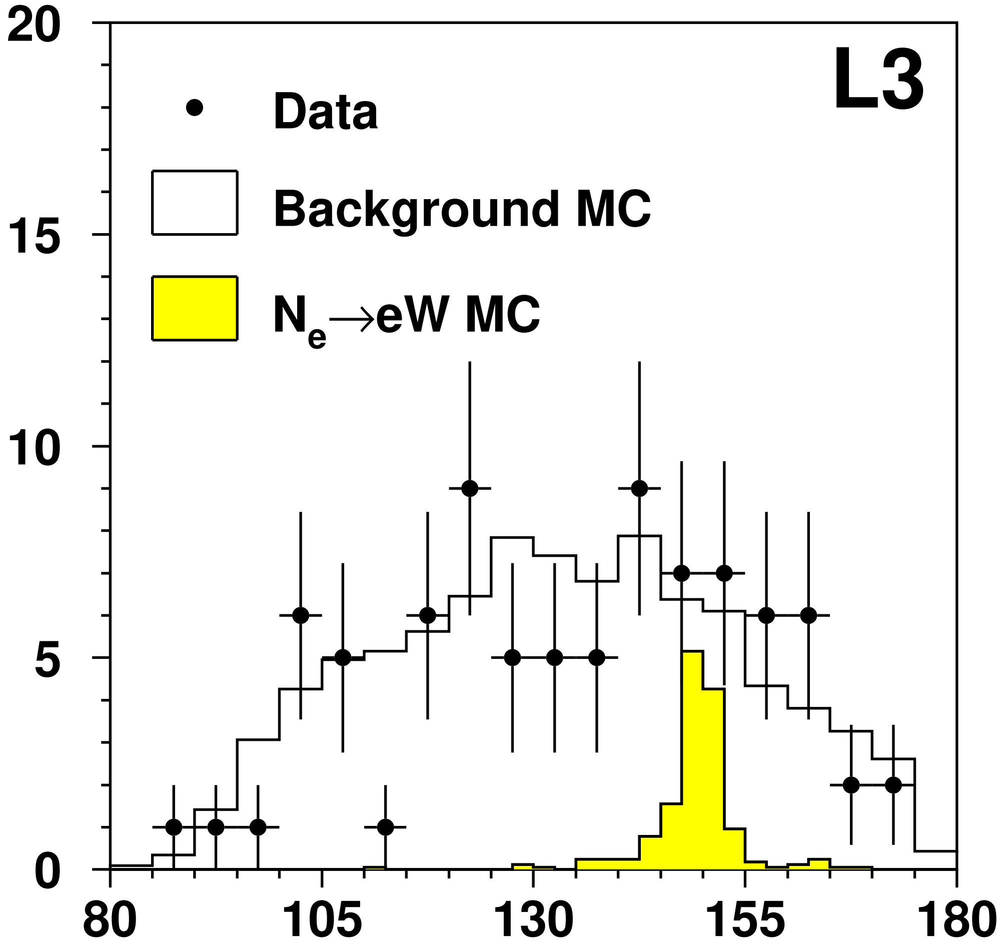

Figure 4: Distribution of the invariant mass of the event after the kinematic fit. The points are the data and the solid histogram is the background MC. The shaded histogram is the predicted signal $e^+e^- \rightarrow \nu N$ for a 150 GeV heavy neutrino. The normalization for the signal Monte Carlo is arbitrary.

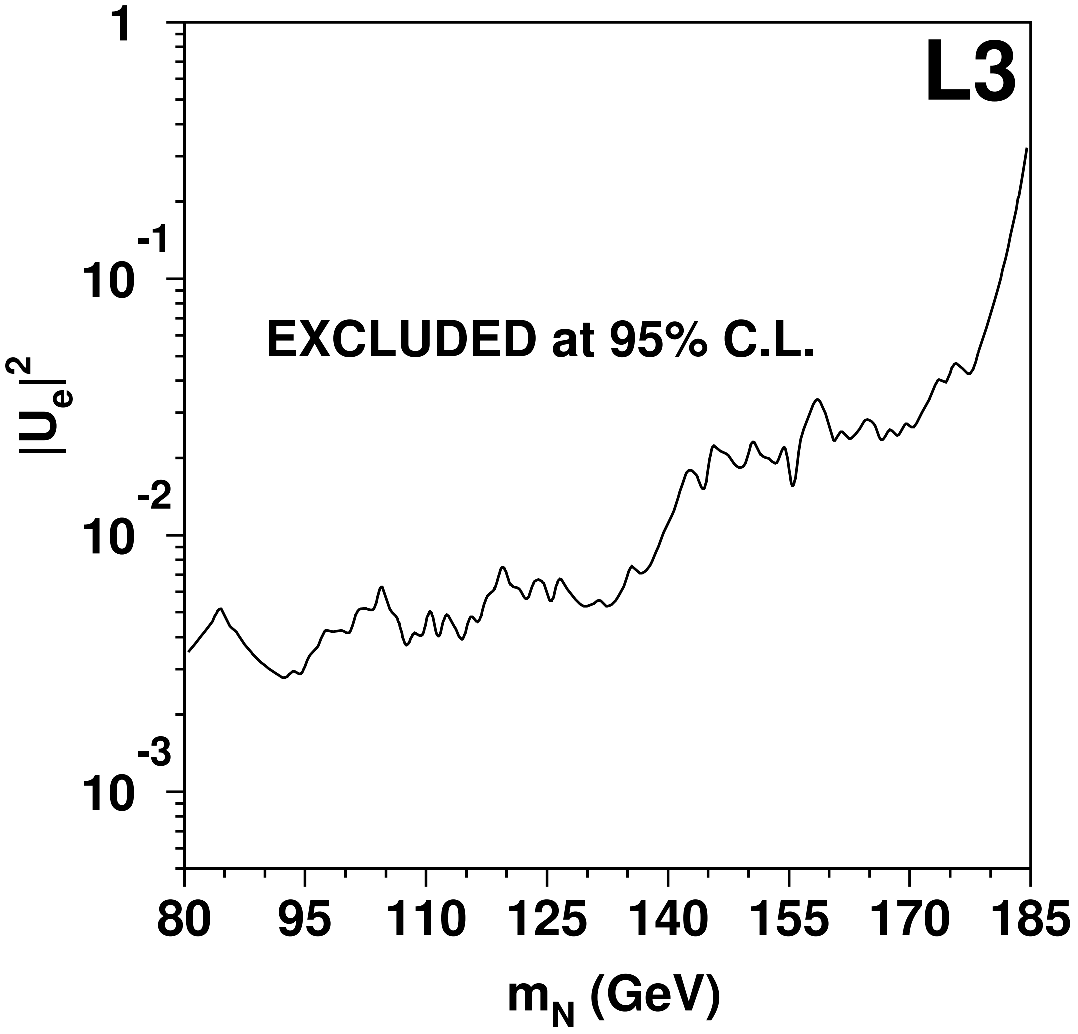

Figure 5: Upper limit at the 95% C.L. on the mixing amplitude as a function of the singlet heavy neutrino mass.