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Searches for Heavy Neutrinos from Z Decays

DELPHI Collaboration

Abstract

We have searched for possible fourth family heavy neutrinos, pair produced in Z^0 decays, in a sample of about 112 000 hadronic Z^0 final states collected with the DELPHI detector. For all mixing matrix elements we exclude a new Dirac neutrino lighter than 44.5 GeV at a 95 % confidence level, if the neutrino couples to the electron or muon family, and lighter than 44.0 GeV, if the neutrino couples to the tau family. Depending on the values of the mixing matrix element and to which lepton family the neutrino couples, we obtain mass limits up to 46.2 GeV. For all mixing matrix elements we exclude a new Majorana neutrino lighter than 39.0 GeV, if it couples to the electron or the muon family, and lighter than 38.2 GeV, if it couples to the tau family. Depending on the values of the mixing matrix element and to which lepton family the neutrino couples, we obtain mass limits up to 44.7 GeV. We also exclude stable new Dirac neutrinos lighter than 45.0 GeV and new Majorana neutrinos lighter than 39.5 GeV.

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1 Introduction

Heavy neutral leptons that have not so far been observed are predicted by various theories[1]. A sequential fourth generation neutrino is the most natural extension. From indirect measurements of the invisible width, Γ_{inv}, of the Z^0-resonance the number of light neutrinos can be estimated. A combination of the results from the LEP experiments[2]gives $N_\nu = 2.99 \pm 0.05$ (the width associated with a massless neutrino in the Standard Model is taken to be 166.5 ± 0.5 MeV). This assumes however that the lifetime of the neutrino is long enough for it to escape the apparatus before decaying. If the neutrino has a shorter lifetime a direct search is the best way to look for it.

The LEP collider at CERN provides a good opportunity to search for heavy neutrinos because of the large cross sections at the Z^0 resonance. Here we present results of a direct search for neutrinos with mass up to the half of the Z^0 mass, using data taken with the DELPHI detector. We also use Γ_{inv} to exclude long-lived neutrinos and Γ_{tot} to exclude neutrinos independently of the mixing matrix element. It has been proposed that right-handed neutrinos mix with the known neutrinos and reduce the measurable invisible width[3]but this possibility is not taken into account here. We restrict the analysis to massive neutrinos, L^0, belonging to a new electroweak doublet $\binom{L^-}{L^0}$, which mixes with the three known lepton doublets, just as the quark doublets mix in the Standard Model.

We consider both the case in which the neutrino is a Dirac particle and the case in which it is a Majorana particle. The neutrino, L^0, is in general a superposition of all neutrino mass eigenstates:

$$L^0 = \sum_l U_{lL} \nu_l{}', \tag{1}$$

where $\nu_l{}'$ is $\nu_e{}'$,$\nu_\mu{}'$,$\nu_\tau{}'$ or $L^{0\prime}$ and U_{lL} is the mixing matrix. The neutrinos can be pair produced in LEP via the Z^0 boson and decay through a flavour changing charged current reaction

$$L^0 \to l^- W^{+*}. \tag{2}$$

Flavour changing neutral currents are forbidden by the GIM-mechanism[4], and are not considered here. The lifetime of the Dirac neutrino in terms of its leptonic branching ratio and the muon lifetime, τ_μ, is given by

$$\tau_{L^0} = \left(\frac{m_\mu}{m_{L^0}}\right)^5 \frac{\tau_\mu \sum_{l \neq L} \mathrm{Br}(L^0 \to l^- e^+ \nu_e)}{f \sum_{l \neq L} |U_{lL}|^2}, \tag{3}$$

where f is a phase-space suppression factor for final states particles, which differs appreciably from unity when the mass difference between the neutrino and its decay products is small[5]. The lifetime of a Majorana neutrino is half of the lifetime for the corresponding Dirac neutrino, since the decays $L^0 \to l^- W^{+*}$ and $L^0 \to l^+ W^{-*}$ occur with equal probability for a Majorana neutrino. The phase-space factor f is assumed to be equal to unity in the whole mass range considered in the direct search. The expected cross section for the pair production is

$$\sigma_{L^0 \bar{L}^0} = \sigma_{\nu\bar{\nu}} T(\beta), \tag{4}$$

where

$$T(\beta) = \beta^3 \qquad \text{(Majorana)}$$
$$T(\beta) = \frac{\beta}{4}\left(3 + \beta^2\right) \text{(Dirac)}, \tag{5}$$

assuming the same couplings to the Z^0 as for the light neutrinos. $\sigma_{\nu\bar{\nu}}$ is the cross section for pair production of a massless neutrino and $\beta(=\sqrt{1-\frac{4m_{L^0}^2}{s}})$ is the velocity of the produced particle. The branching ratios for the different decay channels of a pair of heavy neutrinos are given in table 1, assuming that the doublet mixes with only one of the known lepton doublets ($l = e, \mu$ or τ).

2 The Detector

The DELPHI detector is described in detail in ref. [6]. Here we summarize the main features of the tracking detectors used in this analysis. Charged tracks are measured in the solenoidal 1.2 Tesla magnetic field with three cylindrical detectors. The Inner Detector (ID) covers polar angles from the beam axis between 29^o and 151^o (with an inner radius (r_{in}) of 12 cm and an outer radius (r_{out}) of 28 cm), the Time Projection Chamber (TPC) covers angles between 21^o and 159^o (r_{in} = 30 cm, r_{out} = 122 cm) and the Outer Detector (OD) covers angles between 42^o and 138^o (r_{in} = 198 cm, r_{out} = 206 cm).

The trigger is based on the tracking detectors, the electromagnetic calorimeters and a layer of scintillation counters situated inside the magnet coil in the barrel region and between the two layers of the muon chambers in the forward region.

Detailed information on the trigger can be found in ref. [6]and [7]. The trigger efficiency for a hadronic Z^0 event with a polar event axis between 20^o and 160^o is $\geq$ 99.7%[7].

3 Analysis Using Widths

The Minimal Standard Model (MSM) prediction for the total width of the Z^0-resonance is $\Gamma_{tot}^{SM} = 2484 \pm 11$ MeV †, if α_s is taken to be 0.110 ± 0.006[9], the mass of the Higgs to be between 50 GeV and 1 TeV, the top mass $= 139 \pm 38$ GeV[10]and the Z^0 mass $= 91.177 \pm 0.0022$ GeV[7]. The data taken by DELPHI give $\Gamma_{tot}^{exp} = 2465 \pm 19 \pm 5$ MeV[7]. From this, we can estimate the largest partial width which can exist beyond the total width of the known quarks and leptons. Using a Gaussian distribution, renormalized to the physical region, we calculate an upper limit for the new partial width so that the area between the bound (here the MSM prediction) and the limit is 95 % of the physical region[11]. We then obtain $\Gamma_{L^0} < 33\text{MeV} = 0.20\Gamma_\nu$ at a 95 % confidence level, and can thereby exclude all neutrinos with a mass less than 44.0 GeV in the Dirac case and 36.9 GeV in the Majorana case. This is independent of the mixing matrix element and the 33 MeV limit for the width is valid for all new particles.

Secondly by assuming $\Gamma_{inv}^{SM} = 500 \pm 2$MeV[7](the MSM prediction of the width of three massless neutrinos), and combining this with a measurement of the invisible width of the Z^0-resonance using DELPHI data, $\Gamma_{inv}^{exp} = 488 \pm 7 \pm 12$MeV[7]. We can estimate the largest invisible width there can exist beyond the known three neutrinos using the approach above and conclude that $\Gamma_{L^0} < 21\text{MeV} = 0.12\Gamma_\nu$.

If the L^0 events do not contribute to either Γ_{had} or to any Γ_l‡then they must contribute to the Γ_{inv}. The probability, ϵ_{inv}, that an L^0-event would not be selected by our hadronic

†The value of the total width was calculated using the formulae of ref. [8]. The error is due to the uncertainty in the top mass and the Higgs mass and the experimental errors in the measurement of α_s and the Z^0 mass.

‡No L^0 event contributes to Γ_τ because this width was measured using a topology of one charged particle in one hemisphere and n in the other, while L^0 events are characterized by at least two charged particles in each hemisphere.

Z^0 event criteria given below, and hence contributes to the Γ_{inv} is

$$\epsilon_{inv} = 1 - \frac{\epsilon_{L^0}(r)}{\epsilon_h}, \tag{6}$$

where ϵ_h is the efficiency to select a hadronic Z^0 event (in DELPHI 93.5 $\pm$ 1.0 % [12]) and ϵ_{L^0} the efficiency to select a heavy neutrino event as a hadronic Z^0 event, which is a function of the mean decay length, r, of the neutrino. This probability was studied with DELSIM, the DELPHI full detector simulation and the result is shown in figure 1. For a heavy neutrino with a mean decay length of more than 400 cm the probability is $\approx$ 100 %. In ref. [7] slightly different selection criteria were used for hadronic Z^0 events than in this analysis, but the resulting differences were smaller than the errors of figure 1.

We exclude, with 95 % confidence, neutrinos with a mass less than 45.0 GeV in the Dirac case and 39.5 GeV in the Majorana case with a decay length more than 400 cm. We also exclude smaller mean decay lengths than 400 cm for neutrinos with smaller masses using the information of the fit in figure 1. The results are shown as the curves labelled Γ_{inv} and Γ_{tot} in figures 5and 6.

4 Direct Search

The topology used in the direct search for heavy neutrinos, was two isolated charged particles and at least two jets in the event. First the event was required to pass the selection for a hadronic Z^0 according to the following selection criteria[12]. Only charged particles with the following characteristics are used

- polar angle, θ, between 20^o and 160^o,
- momentum between 0.1 GeV/c and 50 GeV/c,
- track length above 30 cm,
- projection of the impact parameter in the xy-plane below 4 cm,
- z coordinate at the origin below 10 cm,
- relative error on momentum measurement below 100 %.

An event is required to have at least 3 charged particles in one hemisphere ($\theta > 90^o$ or $\theta < 90^o$) and the sum of the transverse momentum squared of all particles relative to the beam axis must be greater than 9 GeV^2/c^2. The efficiency for selecting a hadronic Z^0 event is 93.5 %[12]and a background of about 1.3 % of leptonic Z^0 final states (tau pairs) and 0.2 % of non-Z^0 events (beam-gas interaction and two photon events) remain after applying these criteria[12].

The isolation of a particle is specified by the isolation parameter ρ. First the particle is removed, and the jets are constructed from the remaining particles. A particle is considered to be isolated if the ρ of the particle is bigger than 2.15 GeV$^{1/2}$, where ρ is computed from the jet which is closest to the particle track and

$$\rho = \sqrt{2E_{particle}\,(1 - cos\theta_{particle,jet})}. \tag{7}$$

Furthermore it is required that the angle between the closest jet and the particle track has to be greater than 45 degrees ($cos\theta_{particle,jet} < 0.71$) and the momentum of the particle greater than 4 GeV/c. These cuts were made to optimize the ratio between the signal and the background.

A heavy neutrino candidate should contain two isolated particles and all the other particles should form at least two jets, defined by the Lund cluster algoritm LUCLUS[13], using the default value of the resolution parameter ($d_{join} = 2.5$ GeV).

For a given number of hadronic Z^0 final states, N_h, the corresponding number of heavy neutrino events, N_{L^0}, is

$$N_{L^0} = \frac{\epsilon N_h \Gamma_{L^0}}{\epsilon_h \Gamma_h + \epsilon_{L^0} \Gamma_{L^0}} \quad , \tag{8}$$

where ϵ is the total efficiency to select a heavy neutrino event as a heavy neutrino candidate. Γ_h is the total width associated with the five known quarks and Γ_{L^0} the width associated with the heavy neutrino. The real data sample used consisted of 112 368 hadronic Z^0 events collected by DELPHI in 1990 and table 2 show how they are distributed over the different centre of mass energies. The expected number of heavy neutrino events as a function of the neutrino mass is shown in figure 2.

The efficiency, ϵ, depends on the mass of the neutrino, m_{L^0}, and the decay length of the neutrino, r $(= \gamma\beta c\tau_{L^0})$, as the mass of the neutrino determines the isolation of the lepton produced and the decay length determines the efficiency to select the event as a hadronic Z^0. A study of the selection efficiency with different m_{L^0} and r was made, using the DELPHI full detector simulation, and analyzing the Monte Carlo events through the same chain as the real data. The results of this study are shown in figures 3and 4.

We estimate from a sample of simulated $q\bar{q}$ events, comparable in size to the real data, that there is in the real data a background of 78 ± 10 events fulfilling the selection criteria.

In the real data sample we found 94 events fulfilling the selection criteria of two isolated particles and at least two jets. This gives as a hypothetical signal of $+16 \pm 14$. No peak was found in the reconstructed invariant mass spectrum of the candidates. Using the same method as before, we can exclude all mass regions in which we expect to have a signal of more than 40 events.

From equations (4), (5) and (8) we get a constraint for $T(\beta)$, from which the upper mass limits for both Majorana and Dirac neutrinos were determined. We calculate using eq. (8) for each neutrino mass the selection efficiency, ϵ, for which 40 events would pass our selection criteria. The corresponding mean decay length is obtained by using the information of the fits in figures 3and 4. The limits obtained are shown in figures 5and 6as a function of the mixing matrix element squared, $|U_{lL^0}|^2$, and m_{L^0}. They are labelled according to which lepton family the neutrino mixes with.

5 Results and Conclusions

No evidence for the existence of a heavy neutrino was found in the analysis. Dirac neutrinos coupling to the electron and muon families were excluded for all mixing matrix elements with a mass less than 44.5 GeV, and those coupling to the tau with a mass less than 44.0 GeV. For Dirac neutrinos also neutrinos with very small mixing matrix elements were excluded up to 45.0 GeV, and for mixing matrix elements squared bigger than 10^{-11} up to 46.2 GeV for neutrinos coupling to the electron and muon families and up to 45.7 GeV for neutrinos coupling to the tau family. For Majorana neutrinos coupling to the electron and muon families the mass limit is 39.0 GeV, and coupling to the tau family the mass limit is 38.2 GeV. Depending on the values of the mixing matrix element and to which lepton family the neutrino couples, we obtain mass limits up to 44.7 GeV for neutrinos coupling to the electron and muon families and up to 43.6 GeV for neutrinos coupling to the tau family. The limits in the case where the new heavy neutrino mixes arbitrarily with all known doublets are the same as if the neutrino couples to the tau family. The regions excluded by this analysis in the mixing matrix element squared versus mass of the neutrino plane are shown in figures 5(Dirac) and 6(Majorana). The mass limits given for a Dirac neutrino agree with other LEP result [14][15]and results from SLC[16]and the limit where all mixing matrix elements are excluded is higher in this analysis than in any other. For a Majorana neutrino the limits from the direct search are not as high as those of the L3 Collaboration[15]but the limit where all mixing matrix elements are excluded is considerably higher in this analysis.

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decay channel	$\mathrm{Br}(L^0\bar{L}^0 \to channel)$	$\frac{R}{T(\beta)} = \frac{\Gamma_\nu * \mathrm{Br}(L^0\bar{L}^0 \to channel)}{\Gamma_h}$
$L^0\bar{L}^0 \to llq\bar{q}'q\bar{q}'$	0.461	0.0440
$L^0\bar{L}^0 \to llq\bar{q}'l'\nu'$	0.436	0.0416
$L^0\bar{L}^0 \to lll'\nu'l'\nu'$	0.103	0.0098
all channels	1.000	0.0955

TABLE 1:The different decay channels of the heavy neutrino, their branching ratios and relative cross section compared with the total hadronic cross section (observe the kinematic factor $T(\beta)$ of eq. (5) in the expression for R).

$\sqrt{s}$ *(GeV)*	N_h
88.223	1586
89.224	3620
90.222	6711
91.225	82587
92.220	8715
93.221	5620
94.218	3529
total	112368

TABLE 2:The number of the hadronic Z^0 final states, N_h, taken at different centre of mass energies, $\sqrt{s}$.

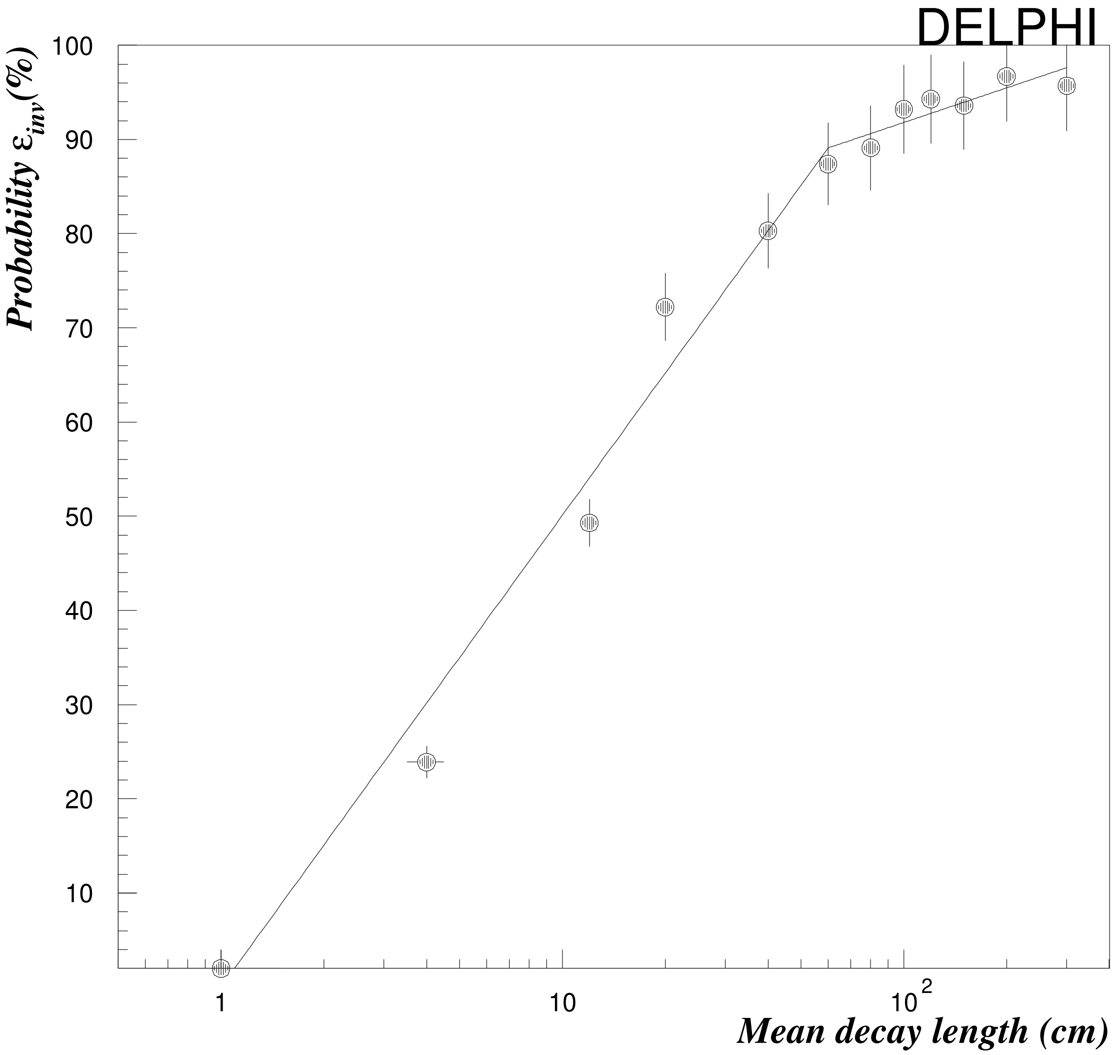

Figure 1: The probability that a heavy neutrino event contributes to the Γ_{inv} as a function of the logarithm of the mean decay length of the neutrino.

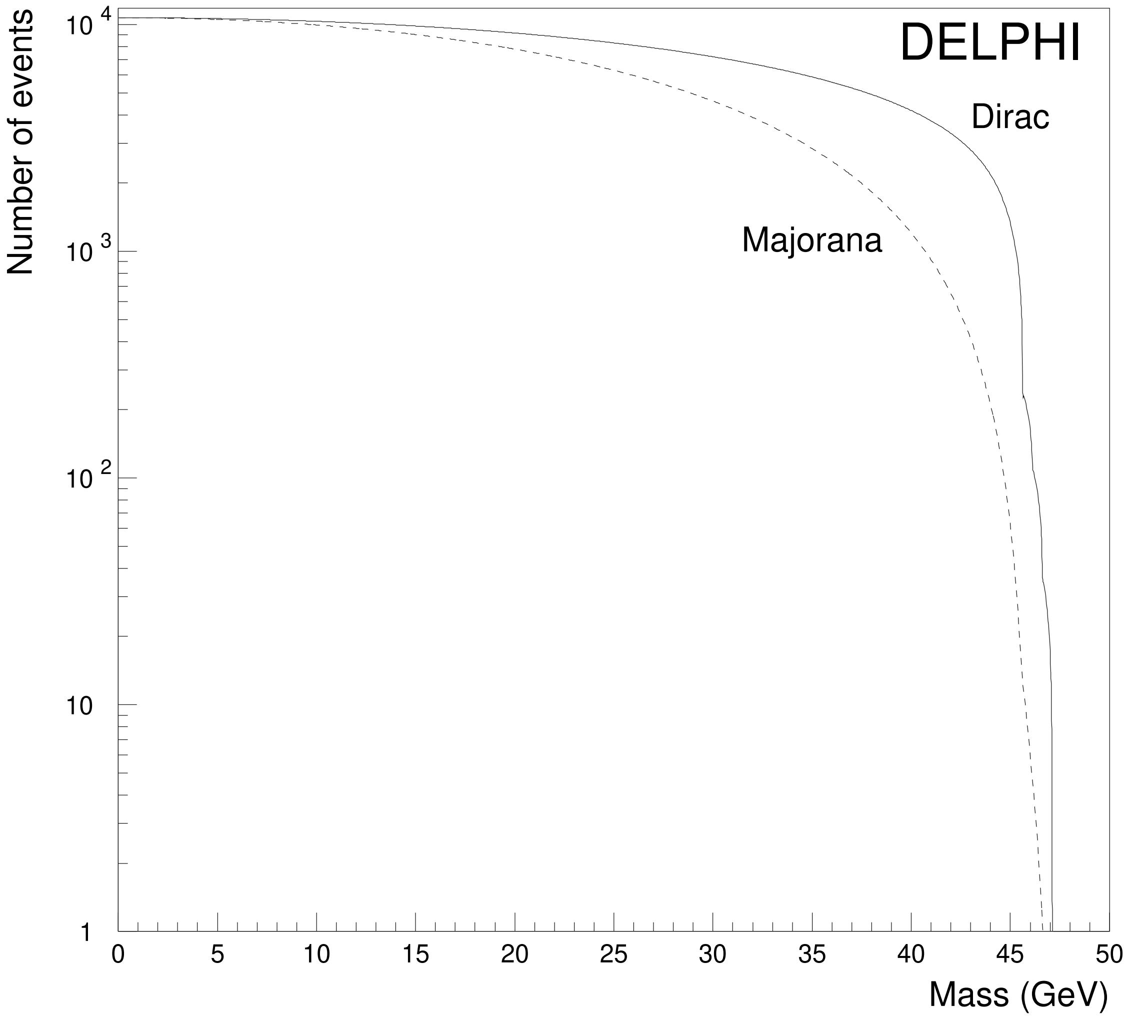

Figure 2: The number of produced heavy neutrino events as a function of the mass of the neutrino.

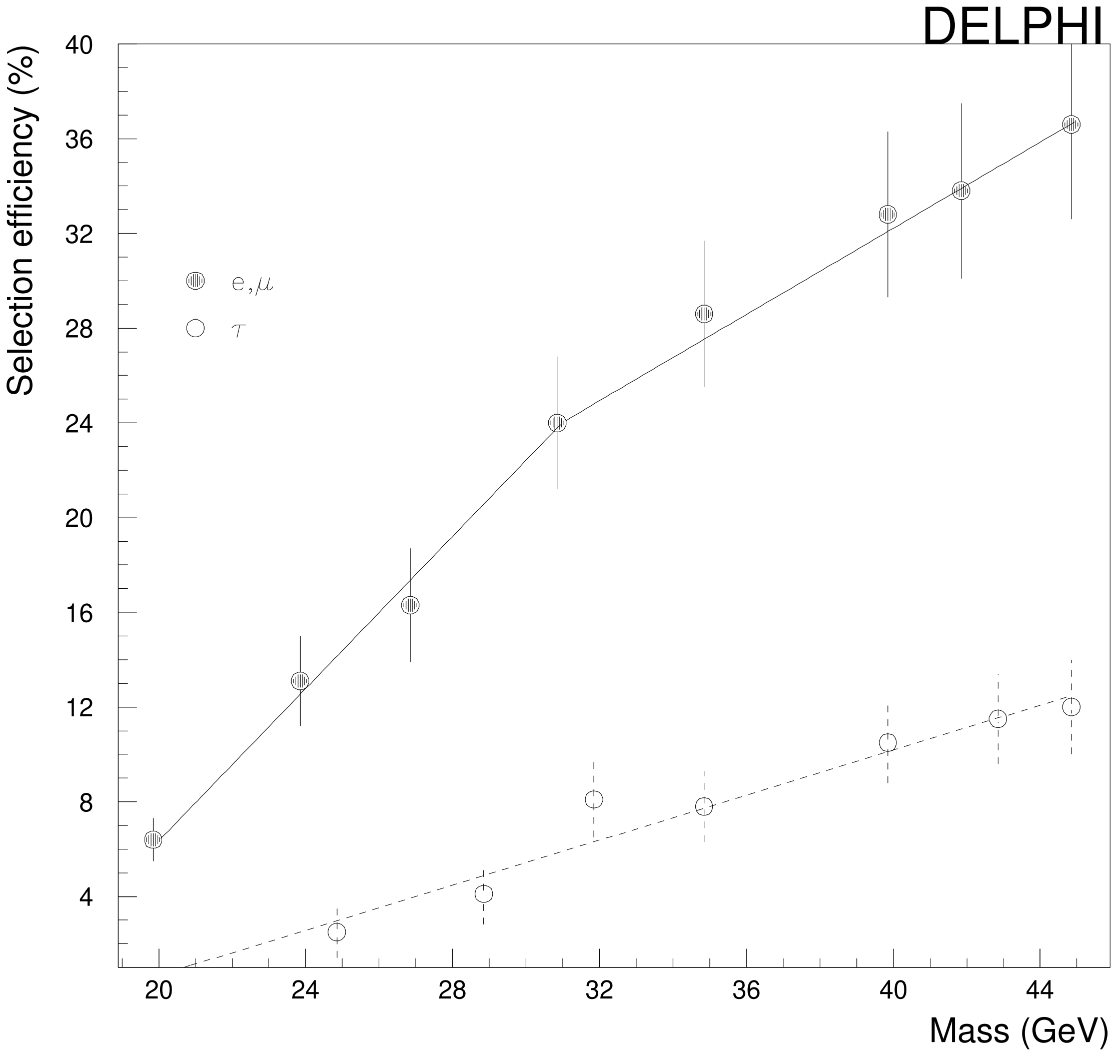

Figure 3: The selection efficiency for a heavy neutrino event as a function of the mass (r= 0.01 cm).

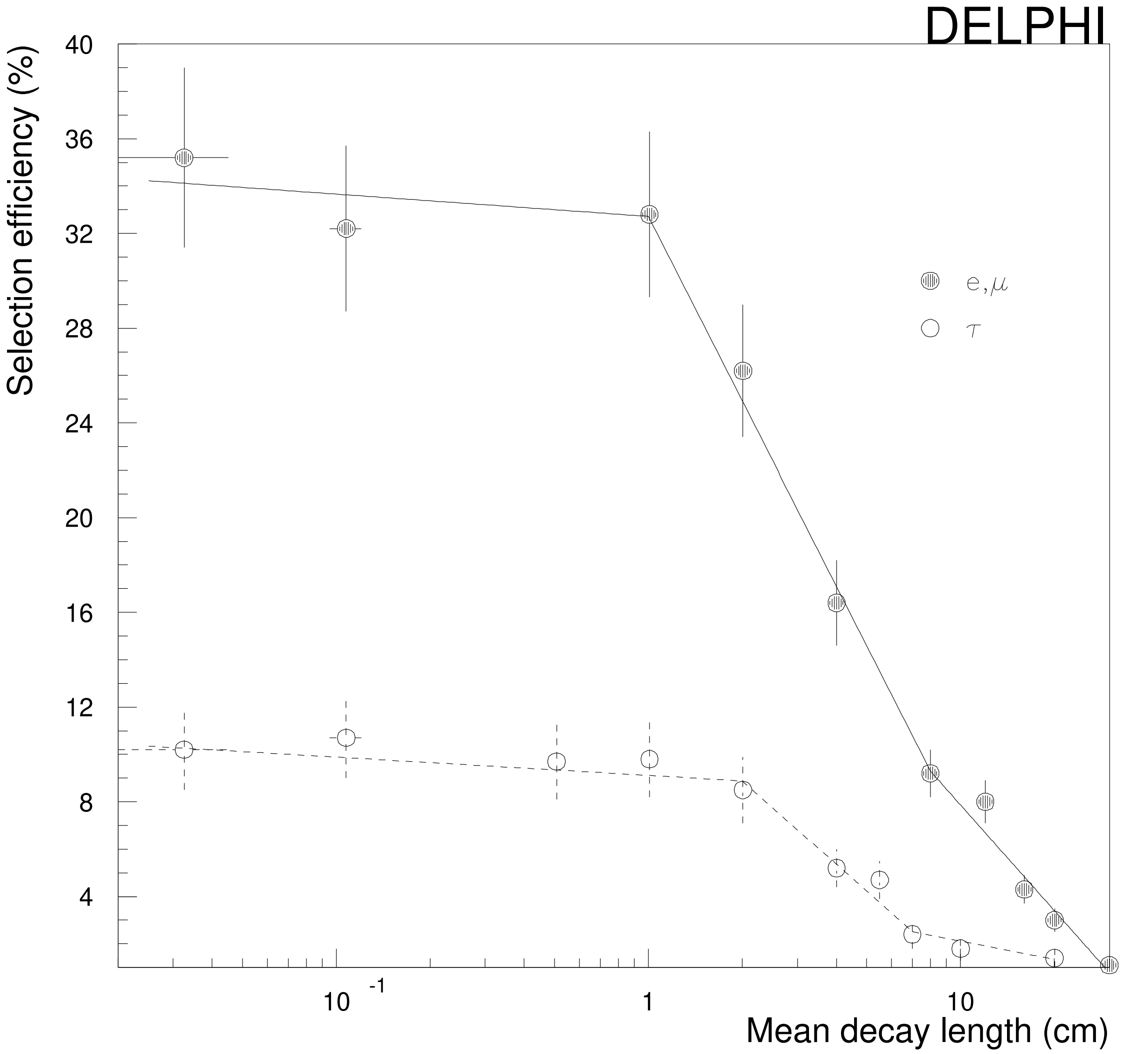

Figure 4: The selection efficiency for a heavy neutrino event as a function of the logarithm of the mean decay length ($m_L = 40$ GeV).

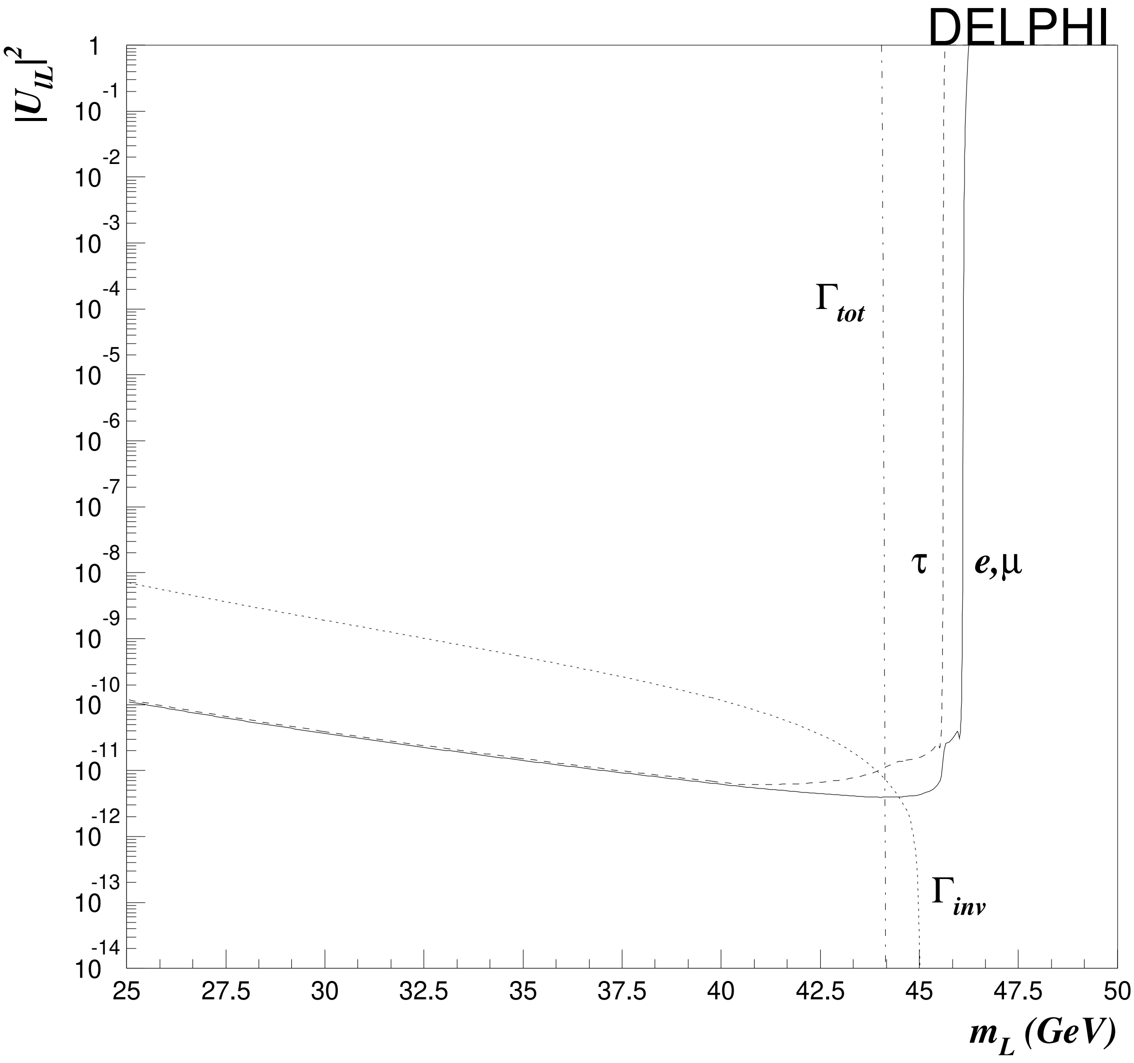

Figure 5: The 95 % CL limits on $|U_{lL}|^2$ as a function of m_L for e, μ and τ mixing for a Dirac neutrino, assuming mixing with one family.

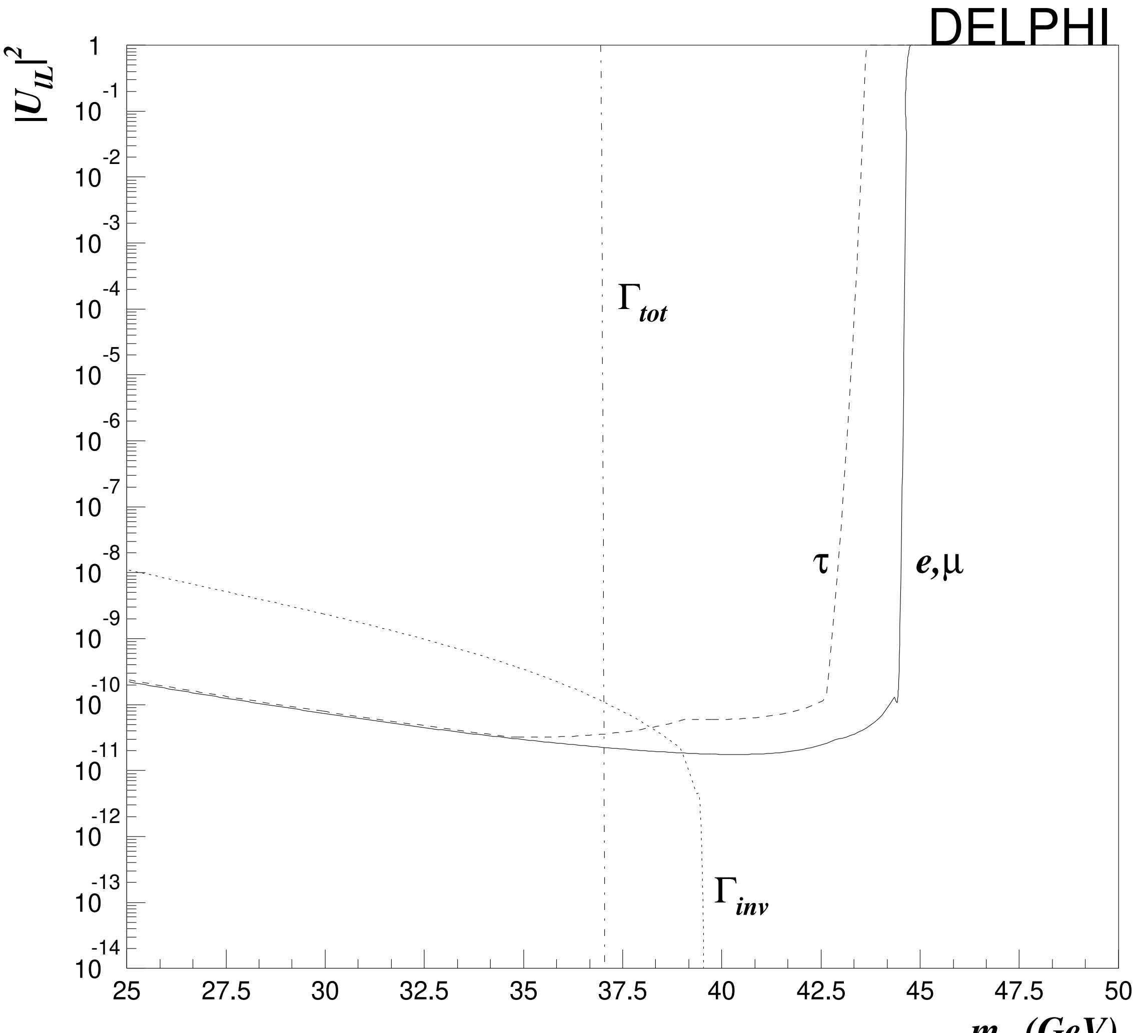

Figure 6: The 95 % CL limits on $|U_{lL}|^2$ as a function of m_L for e, μ and τ mixing for a Majorana neutrino, assuming mixing with one family.