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Search for Unstable Sequential Neutral and Charged Heavy Leptons in e^+e^- Annihilation at $\sqrt{s} = 130$ and 136 GeV

The L3 Collaboration

Abstract

A search for unstable sequential neutral and charged heavy leptons has been made at center-of-mass energies 130 and 136 GeV with the L3 detector at LEP. The neutral leptons are assumed to decay via mixing to electrons and muons. No evidence for their existence was found. We exclude unstable Dirac neutrinos for masses below 59.3 (57.9) GeV and unstable Majorana neutrinos below 48.6 (47.2) GeV if the neutrino couples to the electron(muon) family. We exclude unstable charged heavy leptons for masses below 61 GeV for a wide range of the associated neutral lepton mass.

Introduction

Electron-positron colliders are well suited for the search for new heavy leptons, with masses up to the kinematic limit $m_{\mathrm{L}} \leq E_{\mathrm{beam}}$ [1]. The predicted production cross sections are large and final state particles can be identified cleanly. Heavy neutral and charged leptons that have not so far been observed are predicted by various models [2]. The sequential fourth generation neutral and charged leptons are the most natural extension. Previous results on this subject obtained at the Z resonance by LEP and SLC experiments can be found in [3, 4]. Here we report on a direct search for unstable sequential neutral heavy leptons (heavy neutrinos), L^0, of the Dirac or Majorana type, and charged heavy leptons, $L^{\pm}$. The data used in this analysis were collected with the L3 detector at LEP during November 1995 at increased center-of-mass energies, 130.3 and 136.3 GeV. The integrated luminosity is 5.1 pb^{-1}.

The L3 Detector

The L3 detector [5] consists of a silicon microvertex detector [6], a central tracking chamber (TEC), a high resolution electromagnetic calorimeter composed of bismuth germanate (BGO) crystals, a lead-scintillator ring calorimeter at low polar angles [7], a scintillation counter system, a uranium hadron calorimeter with proportional wire chamber readout, and an accurate muon chamber system. A forward-backward muon detection system extends the polar angle coverage of the muon chambers down to 24 degrees [8]. These detectors are installed in a 12 m diameter magnet which provides a solenoidal field of 0.5 T and an additional toroidal field of 1.2 T in the forward-backward region. The luminosity is measured with a forward-backward BGO calorimeters preceded by silicon trackers [9] situated on each side of the detector.

Production and Decays

Sequential heavy leptons are pair-produced [1)] through the s-channel: $\mathrm{e^+e^-} \rightarrow \gamma/\mathrm{Z} \rightarrow \mathrm{L^+L^-}$, $\mathrm{L^0\overline{L}^0}$ [10].

Heavy leptons are assumed to couple to the photon and the Z in the same way as ordinary leptons. The production cross section is reduced with respect to the standard lepton cross section by a phase-space factor T [10] :

$T = \beta(3-\beta^2)g_{\mathrm{V}}^2 + 2\beta^3 g_{\mathrm{A}}^2$ for charged leptons,

$T = \frac{1}{4}\beta(3+\beta^2)$ for Dirac neutrinos,

$T = \beta^3$ for Majorana neutrinos,

where $g_{\mathrm{A}} = I_3 = -1/2$ and $g_{\mathrm{V}} = I_3 - 2Q_{\mathrm{L}}\,\sin^2\theta_{\mathrm{W}} = -1/2 + 2\,\sin^2\theta_{\mathrm{W}}$ for charged sequential leptons and $\beta = \sqrt{1-4m^2/s}$ is the velocity of heavy lepton. The total cross sections are in the range 1–4 pb at masses well below the beam energy and fall as the mass of the lepton

[1)] The only exception is single heavy neutrino production $\mathrm{e^+e^-} \rightarrow \mathrm{L^0}\bar{\nu}_{\mathrm{e}}$ through t-channel W exchange. The cross section for this process depends on the degree of mixing between $\mathrm{L^0}$ and the electron generation. Single $\mathrm{L^0}$ production is not considered in this analysis.

approaches the beam energy. Due to the β^3 term the cross section for Majorana neutrinos falls more rapidly than the cross section for Dirac neutrinos.

We assume that the charged lepton decays through the charged current weak interaction, $\mathrm{L}^{\pm} \rightarrow \mathrm{L}^0 + \mathrm{W}^{\pm *}$, and that the associated neutral lepton is stable.

The decay of a neutral heavy lepton is expected to proceed via mixing with a light lepton (e or μ), analogous to the decay of a charged lepton through a virtual W boson: $\mathrm{L}^0 \rightarrow \ell^{\pm} + \mathrm{W}^{\mp *}$ [2].

The decay amplitude contains a mixing parameter U_ℓ [11] for the transition from L^0 to the light lepton ℓ. The neutral heavy lepton decay width (for the Dirac type) is given by

$$\Gamma(\mathrm{L}^0 \rightarrow \ell^{\pm} + \mathrm{W}^{\mp *}) = 9|U_\ell|^2 (m_{L^0}/m_\mu)^5/\tau_\mu$$

where τ_μ is the muon lifetime.

For Majorana neutrinos the decay width is a factor of two larger than for Dirac neutrinos, since the transitions $\mathrm{L}^0 \rightarrow \ell^+$ and $\mathrm{L}^0 \rightarrow \ell^-$ occur with equal probability. Therefore, both the lifetime and decay length of a Majorana neutrino are half those of a Dirac neutrino.

The mean decay length is a function of $|U_\ell|^2$ and the mass. It is given by [11]

$$\mathrm{L}_{\mathrm{L}^0} = \beta\gamma c \tau_{\mathrm{L}^0} \propto \beta |U_\ell|^{-2} m_{\mathrm{L}^0}^{\alpha},$$

where τ_{L^0} is the lifetime of the neutral heavy lepton and $\alpha \approx -6$. This implies that the decay can occur far from the interaction point if the particle has a low mass or a very small coupling. To ensure high detection and reconstruction efficiencies, the search is restricted to L^0's decaying within 1 cm of the interaction point. This limits the sensitivity to the mixing parameter:

$|U_\ell|^2 > 1.8 \times 10^{-10}$ for a Dirac neutrino at $m_{\mathrm{L}^0} = 50$ GeV,

$|U_\ell|^2 > 0.4 \times 10^{-10}$ for a Dirac neutrino at $m_{\mathrm{L}^0} = 60$ GeV.

Monte-Carlo Generation

The generation of heavy lepton production and decay was done by the TIPTOP [12] Monte-Carlo program. It incorporates initial state radiative corrections, the effects of the fermion spin on the decay distribution, and the W propagator for the case when the W is produced off-shell.

We have used the PYTHIA 5.7 [13] Monte-Carlo program to generate the following backgrounds (except $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}$, which was simulated with KORALW [14]) :

- $\mathrm{e^+e^-} \rightarrow f\bar{f}(\gamma)$
- $\mathrm{e^+e^-} \rightarrow \mathrm{Ze^+e^-}$
- $\mathrm{e^+e^-} \rightarrow \mathrm{ZZ}$
- $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}$

[2] In this search we consider that neutral heavy leptons couple to electron or muon families and we neglect the possibility of mixing between light leptons.

- $e^+e^- \to W^\pm e^\mp \nu$
- $e^+e^- \to e^+e^- q\bar{q}$ and $e^+e^-\tau^+\tau^-$

The number of events simulated for each background process corresponds to at least 10 times the luminosity of the collected data.

The Monte-Carlo events have been fully simulated in the L3 detector using the GEANT3 program [15], which takes into account the effects of energy loss, multiple scattering and showering in the materials. Monte-Carlo events were reconstructed in the same way as data.

Search for Unstable Neutral Heavy Leptons

The event topology used in the search for heavy neutrinos is two isolated leptons (e or μ)

$$e^+e^- \to L^0\overline{L}^0, \quad L^0 \to \ell^\pm + W^{\mp *}.$$

An electron is defined as a geometrical cluster in the electromagnetic calorimeter with an energy more than 4 GeV matched to a TEC track in the (R,ϕ) plane to within 20 mrad. The cluster shower profile should be consistent with that of an electron, *i.e.* we require $0.95 < E_9/E_{25} < 1.05$, where $E_{9(25)}$ is the corrected sum of energies of 9(25) BGO crystals around the most energetic one. The electron candidate must be in the fiducial volume defined by $|\cos\theta| < 0.94$.

Muons are identified and their momenta measured by the muon chamber system surrounding the calorimeters. We require that a muon track consists of track segments in at least two of the three layers of muon chambers, and that the muon track points back to the intersection region. The muon momentum must be greater than 4 GeV and it must be in the fiducial volume defined by $|\cos\theta| < 0.8$.

Jets are reconstructed using a two step algorithm [17] which groups the energy deposited in calorimeters into clusters before collecting the clusters into jets. The clustering algorithm normally reconstructs one cluster for each muon, electron or photon shower, and a few clusters for a hadronic decay of a single τ. Under the above definition of a jet, particles with only one cluster, like electrons, are also considered as jets.

Events satisfying the following criteria are selected :

1) The visible energy is greater than 60 GeV;

2) The number of reconstructed jets is greater than two;

3) The event contains at least two leptons with the same flavor (electrons or muons);

4) The event multiplicity (number of charged tracks) is greater than 5 for the electron decay mode and greater than 3 for the muon decay mode;

5) At least one lepton in the event is isolated. The isolation criterion is that the energy in a 30° cone around the electron candidate is less than 5 GeV. For muons, the energy in a 30° cone around the muon must be less than 8 GeV (in this case, we do not subtract the calorimetric energy loss of the muon). Figure 1 shows the energy in a 30° cone for electron candidates after all cuts except the last one are applied.

Cuts 1) and 2) remove mainly the two-photon background. Cut 4) reduces $\tau^+\tau^-$ background (this cut is tighter for the final state with an electron as $\tau^+\tau^-$ background is more serious than for the final state with a muon) and further removes two-photon background. Cut 5) removes the remaining $q\bar{q}(\gamma)$ background.

After applying all the above cuts no events are left in the data while we expect 0.9 (0.3) from the background Monte Carlo for the electron(muon) final state. The selection efficiency for the 50–65 GeV neutral heavy lepton mass range is 46.0%(40.3%) for final states with an electron(muon). The systematic error, which is mainly due to uncertainties on Monte-Carlo statistics, energy calibration factors and lepton identification, is estimated to be 7%. Systematics have been taken into account by lowering the number of expected events by one standard deviation of the total systematic error.

Taking into account the luminosity, the selection efficiency and the production cross section for a neutral heavy lepton we obtain an upper limit on the neutral heavy lepton mass. As no candidate events were found in data, the 95% C.L. exclusion limit corresponds to three expected events. We have excluded unstable Dirac neutrinos for masses below 59.3(57.9) GeV and unstable Majorana neutrinos below 48.6(47.2) GeV if the neutrino couples to the electron(muon) family.

Search for Unstable Charged Heavy Leptons

In our search for an unstable charged lepton we assume that the associated neutral lepton is stable. Ignoring mass corrections, the branching ratios for the leptonic decays $\mathrm{L}^\pm \rightarrow \mathrm{L}^0 + \ell^\pm + \nu_\ell$ ($\ell =$e,μ,τ) are each $\frac{1}{9}$ and the branching ratio for semi-leptonic decays $\mathrm{L}^\pm \rightarrow \mathrm{L}^0$ + hadrons is $\frac{2}{3}$. Including the tau leptonic decays ($\tau \rightarrow \mathrm{e}\nu_e\nu_\tau,\ \mu\nu_\mu\nu_\tau$) gives a total branching ratio to e or μ of 26%, and consequently 45% of $\mathrm{L}^+\mathrm{L}^-$ pairs are expected to decay into a final state containing at least one isolated electron or muon. From LEP results at the Z resonance [3] the mass of a stable neutral heavy lepton must be greater than 40 GeV. Therefore, in our search for a charged heavy lepton we assume that the mass of the associated neutral heavy lepton is greater than 40 GeV, which results in large missing energy and large transverse momentum imbalance.

The above signature of a charged heavy lepton is very similar to that of a chargino, when the chargino decays into a stable neutralino and a W boson. Therefore, for the charged heavy lepton we use a selection which has been developed for the chargino search [16], which is mainly based on the signatures of missing energy, transverse momentum imbalance, and isolated leptons. For a large difference ($\Delta m \geq 15$ GeV) between the masses of the charged lepton and the associated neutral lepton, the events are easy to trigger and select. Both trigger and selection efficiencies are lower in the Δm region below 15 GeV [16]; the events, which have low multiplicity and little energy deposition, are more difficult to distinguish from two-photon events. Figure 2 shows the combined trigger and selection efficiency as a function of Δm. This efficiency is largely independent of the charged heavy lepton masses in the range 50–60 GeV.

After applying the selection, no events are left in the data while 0.9 events are expected from background. The estimated systematic error varies from 5% for 20 GeV mass difference up to 13% for 5 GeV mass difference. The main sources of systematic error are uncertainty on energy calibration factors, uncertainty on jet angular resolution and Monte-Carlo statistics. Systematics have been taken into account by lowering the number of expected events by one standard deviation of the total systematic error.

Taking into account the luminosity, selection efficiency and the production cross section for a charged heavy lepton we obtain an upper limit on the charged heavy lepton mass. As no candidate events were found in data, the 95% C.L. exclusion limit corresponds to three expected events. Figure 3 shows 95% C.L. exclusion contour in the $m_{\mathrm{L}^\pm}$–m_{L^0} mass plane.

Conclusion

A search for unstable sequential neutral and charged heavy leptons has been made at center-of-mass energies 130.3 and 136.3 GeV with the L3 detector at LEP. The neutral leptons were assumed to decay via mixing to electrons and muons. No evidence for their existence was found. We exclude unstable Dirac neutrinos for masses below 59.3(57.9) GeV and unstable Majorana neutrinos below 48.6(47.2) GeV if the neutrino couples to the electron(muon) family. We exclude unstable charged heavy leptons for masses below 61 GeV for a wide range of the associated neutral lepton mass.

These limits for charged heavy leptons and Dirac heavy neutrinos are 13-15 GeV higher than previously published LEP results [3].

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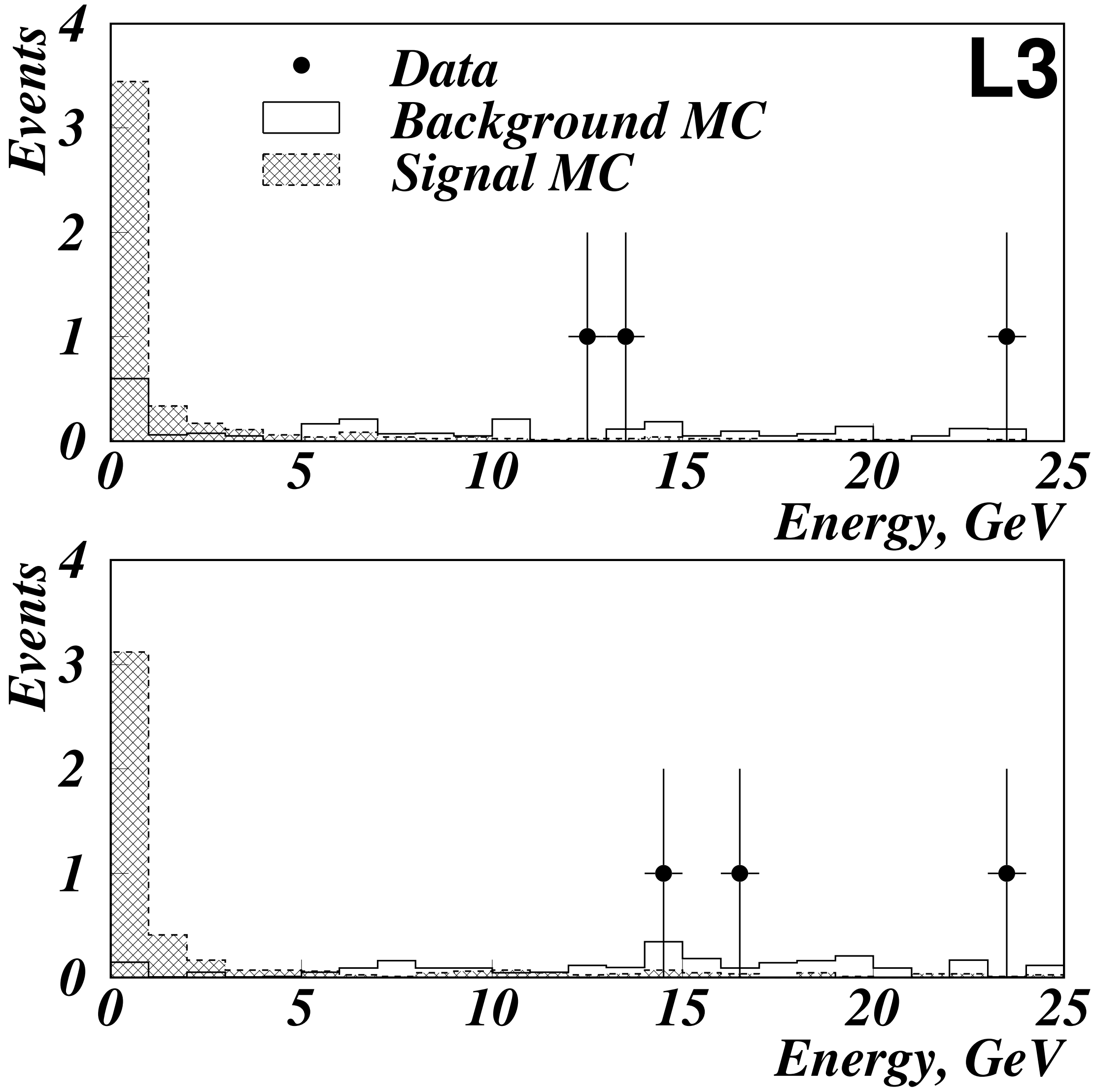
Figure Captions

Figure 1. Energy in 30° cone around the most energetic electron candidate (upper plot) and second most energetic electron candidate (lower plot). The dots are the data, the solid histogram is the background Monte Carlo. The dashed line is a predicted signal $e^+e^- \rightarrow L^0\overline{L}^0$, where L^0 is of the Dirac type with $m_{L^0} = 55$ GeV. Both histograms are normalised to the same luminosity as the data.

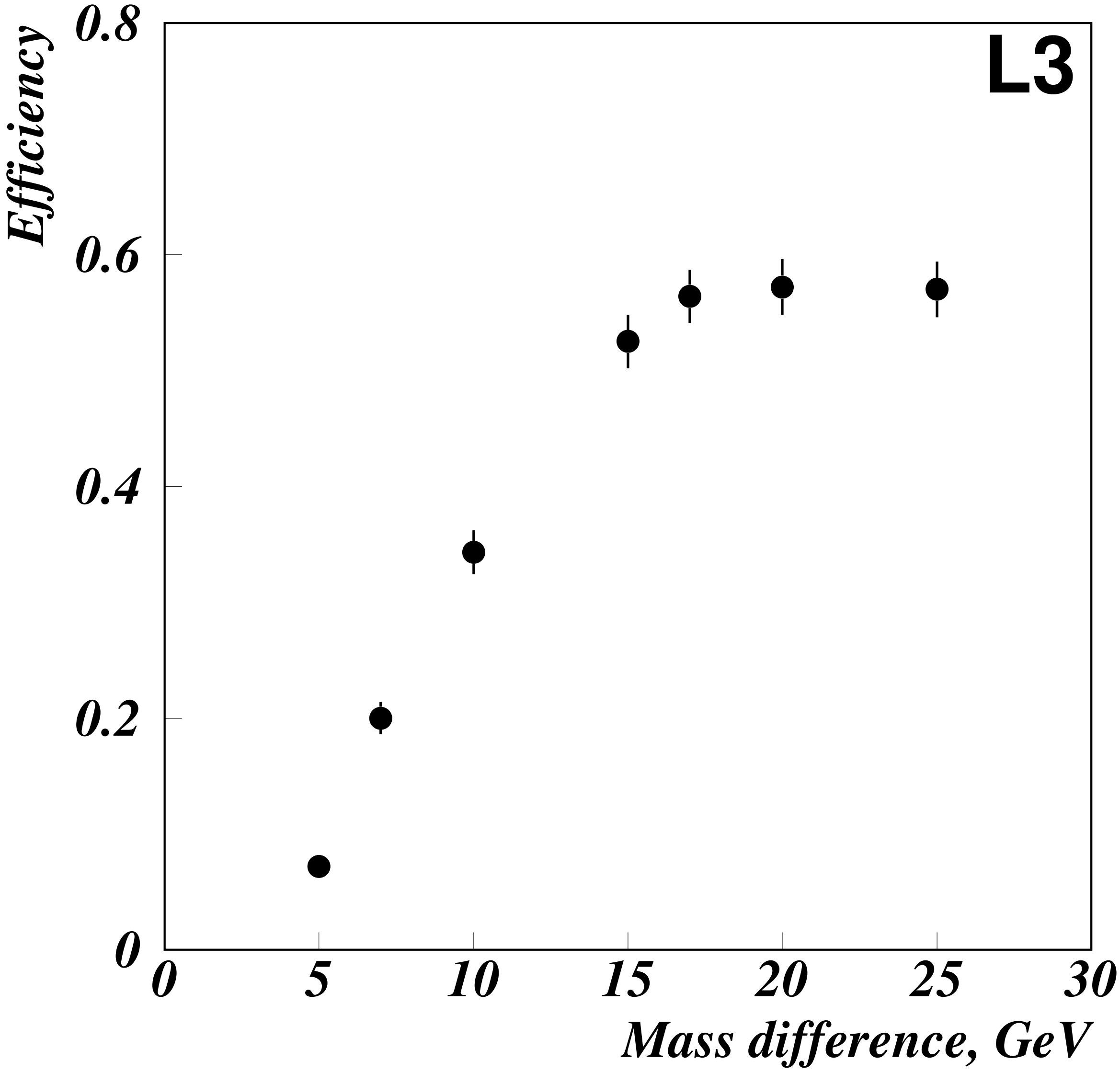
Figure 2. The combined trigger and selection efficiencies in all possible decay channels as a function of the mass difference Δm between the charged heavy lepton and the associated neutral lepton, for the decay $L^{\pm} \rightarrow L^0 + W^{\pm *}$.

Figure 3. The 95% confidence level limits on charged heavy lepton mass $m_{L^{\pm}}$ and the associated neutral heavy lepton mass m_{L^0} assuming L^0 is stable.



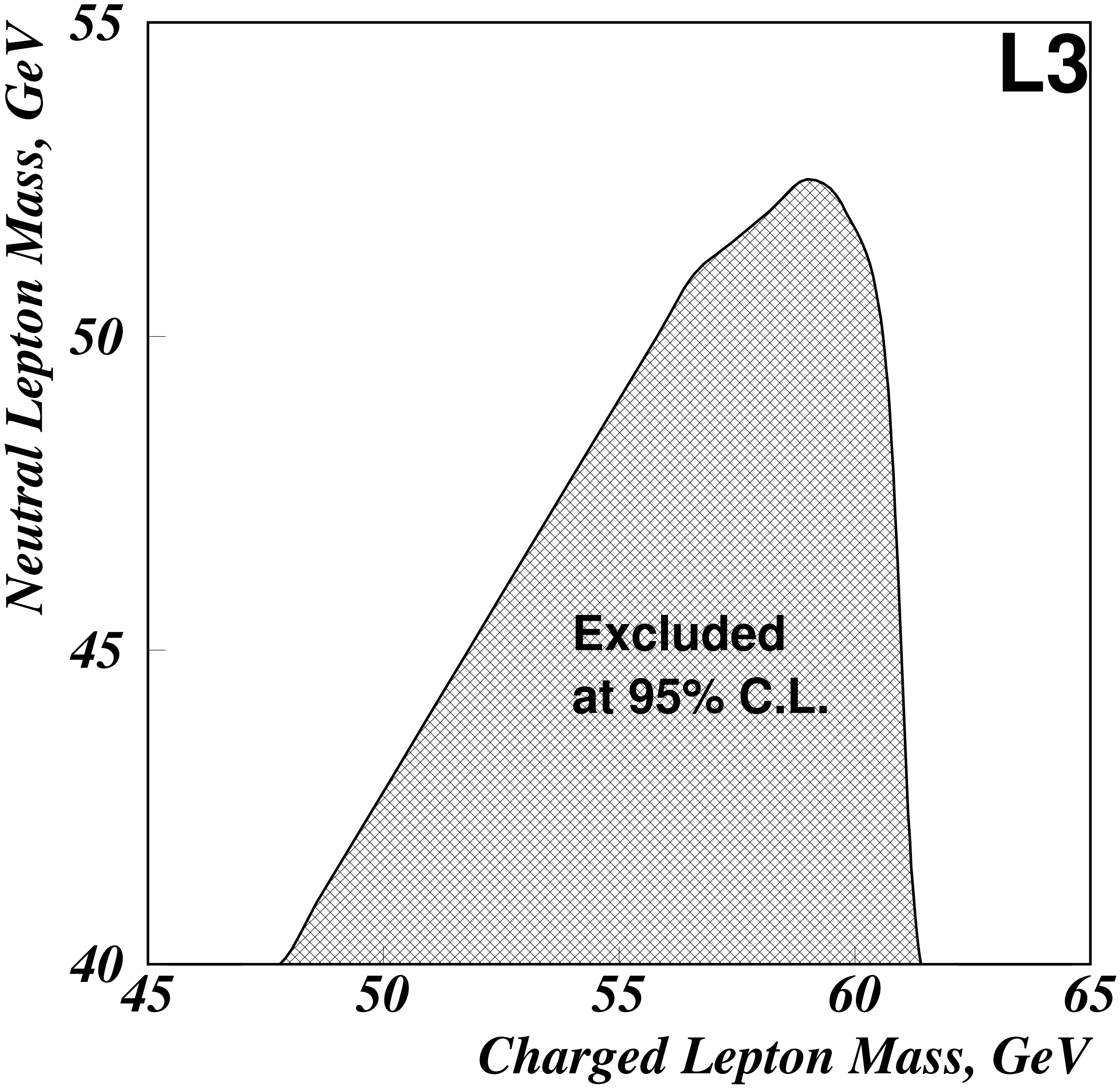
Events
Data
Background MC
Signal MC
L3
Energy, GeV
Events
Energy, GeV

Figure 1:



Efficiency
0.8
0.6
0.4
0.2
0
L3
0
5
10
15
20
25
30
Mass difference, GeV

Figure 2:



L3
Excluded
at 95% C.L.
Neutral Lepton Mass, GeV
Charged Lepton Mass, GeV
40
45
50
55
45
50
55
60
65

Figure 3: