Search for Excited Neutrinos from Z^0 Decays

The L3 Collaboration

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ABSTRACT

We have searched for the excited electron neutrino produced from Z^0 decays in the channel $e^+e^- \rightarrow \nu\nu^*$ using the L3 detector at LEP. The decays $\nu^* \rightarrow eW$ and $\nu^* \rightarrow \nu\gamma$ have been investigated. We have determined an upper limit on the $Z\nu\nu^*$ coupling as a function of m_{ν^*} up to the Z^0 mass.

L3 Preprint #0021

2 October 1990

1. Introduction

The Standard Model [1] has been very successful in describing data on electroweak interactions, including all LEP results. However, it leaves many fundamental questions unexplained such as the lepton-quark spectrum, mass generation, the Higgs mechanism and the large number of arbitrary parameters. One possibility, which could explain the number of families and make the fermion masses and weak mixing angles calculable, would be to assume that quarks, leptons and gauge bosons are all composite [2] with an associated energy scale Λ. One natural consequence of compositeness models is the existence of excited states, l^*, of the known leptons l.

The excited charged leptons, known as e^*, μ^* and τ^*, have already been excluded for masses below $M_Z/2$. The upper limits of Zll^* and γll^* couplings are obtained up to M_{l^*} close to M_Z [3]. There are theoretical suggestions [4] for the existence of excited neutrinos ν^*. In particular the excited electron neutrino, could be the lightest excited particle. In this paper we will present the search for the excited neutrinos using the L3 detector at LEP.

The excited neutrinos are supposed to be the isospin-$\frac{1}{2}$ partners of the excited charged leptons and have spin $\frac{1}{2}$. We assume that the excited neutrinos are of the Dirac type and so have the same couplings with the vector bosons as normal neutrinos.

In e^+e^- collisions excited neutrinos can be produced in pairs ($e^+e^- \longrightarrow \nu^*\bar{\nu}^*$) or singly ($e^+e^- \longrightarrow \nu\nu^*$) via γ or Z^0 annihilation or the exchange of $W^\pm$. Obviously in the first process only ν^* masses less than or equal to the beam energy can be explored. From our measurement of the Z^0 width, pair produced heavy neutrinos have been excluded for masses below 43.2 GeV [5] independently of the decay modes. Therefore, in the following we shall assume that excited neutrinos have masses above 43 GeV and are only produced singly. We restrict our search to the excited electron neutrino assuming that it is the lightest excited particle.

2. The Production and Decays of ν^*

The effective Lagrangian for the excited neutrinos at vertex $Vl\nu^*$ can be written as [6]:

$$L_{eff} = \sum_{V=\gamma,Z,W} \frac{e\lambda^V}{\Lambda}\bar{\Psi}_{\nu^*}\sigma^{\mu\nu}(1-\gamma_5)\Psi_l\partial_\mu V_\nu + h.c.$$

where Λ is the composite mass scale and λ^V, $V = (\gamma, Z, W)$, are the coupling constants, which can be written as:

$$\lambda^\gamma = \frac{1}{4}(f - f'),\quad \lambda^Z = \frac{1}{4}(f\,cot\theta_W + f'\,tan\theta_W),\quad \lambda^W = \frac{f}{2\sqrt{2}sin\theta_W},$$

where f and f' are the free parameters for SU(2) and U(1) respectively.

The cross section for ν^* production can then be calculated. Since the Z^0 contribution is dominant within the beam energy range of LEP, we can neglect the γ and $W^{\pm}$ contributions (less than 1%) and write down the total cross section as follows:

$$\sigma = \frac{\pi\alpha^2}{3s}(\frac{\lambda^Z}{\Lambda})^2(s - m_{\nu^*}^2)^2(s + 2m_{\nu^*}^2)\frac{(1 - 4sin^2\theta_W)^2 + 1}{sin^2 2\theta_W}\frac{1}{(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2}.$$

We can also rewrite the coupling as:

$$\frac{\lambda^Z}{\Lambda} = \frac{\sqrt{2}}{4}\frac{f_Z}{m_{\nu^*}} = \frac{\sqrt{2}}{4}\frac{f cot\theta_W + f' tan\theta_W}{m_{\nu^*}}$$

to have the normalization used by H. Terazawa et al. [7].

An excited neutrino can decay into a γ, a virtual Z^0, or a virtual W, or even a real W if m_{ν^*} is greater than m_W. We have studied the following two different cases:

(1) We impose an additional condition $f = f'$, then the $\gamma\nu\nu^*$ coupling vanishes and $\nu^* \longrightarrow \nu Z$ and $\nu^* \longrightarrow eW$ are the only decay modes allowed. Since the branching ratio of the W channel decay is 71% [4], independently of ν^* mass, and its signatures are much clearer than those of the Z channel decays, we will investigate only the W channel decays. The visible final state is an electron plus two jets if the W decays hadronically (branching ratio $\sim$ 68%) or an electron plus another lepton (e, μ, or τ) if the W decays leptonically (branching ratio $\sim$ 32%).

(2) If the $\gamma\nu\nu^*$ coupling exists, that is, if the neutrino has a magnetic moment [8], then $f \neq f'$ and the decay $\nu^* \longrightarrow \nu\gamma$ would have a branching ratio in excess of 99% [4]. Hence the W and Z channel decays are negligible. The event signature is a single energetic photon.

All the above processes have been simulated by a Monte Carlo program according to the differential cross section obtained from the above Lagrangian. An angular distribution of $1 + cos\theta$ has been assigned to the ν^* decay [6]. The subsequent hadronic fragmentation and decays have been simulated by the JETSET Monte Carlo program [9]. The effect of initial state radiation is not included in the Monte Carlo generator but it is taken into account in our cross section calculations later. All generated events have been passed through the L3 detector simulation [10] which includes the effects of energy loss, multiple scattering, interactions and decays in the detector and the beam pipe.

3. The L3 Detector

The L3 detector and its performance in the detection of muons, electrons, photons and hadronic jets is described in detail elsewhere [11]. It consists of a central tracking and vertex chamber (TEC), a BGO electromagnetic calorimeter, a ring of plastic scintillation counters, two scintillator and lead endcaps as veto counters, a hadron calorimeter made of uranium and proportional wire chambers and a high precision muon chamber system. These detectors are installed inside a 12 m inner diameter magnet which provides a uniform field of 0.5 T along the beam direction. The luminosity is measured by detecting small angle Bhabha events. The BGO covers the polar angle from 42.3° to 137.7°, the same angular region is covered by the TEC. The veto counters cover from 7° to 37° and from 143° to 173°, the muon chambers from 36° to 144°, and the hadron calorimeter from 5.5° to 174.5°.

The data used in these searches were taken with the L3 detector at LEP in 1990 during an energy scan of the Z^0 resonance at center of mass energies between 88.3 and 94.3 GeV. The integrated luminosity used for the single photon analysis is 3.8 pb^{-1}, and for the lepton and hadron analysis 3.3 pb^{-1}.

Two main trigger conditions are used in this analysis. One requires a cluster in the BGO calorimeter with an energy greater than 3 GeV matching with a TEC track. The second one requires a cluster in the BGO with an energy greater than 6 GeV. The efficiencies of both conditions have been checked to be better than 99% using redundant triggers.

4. Search for ν^* via W boson decay

Our analysis uses a jet cluster algorithm [12] which groups neighbouring calorimeter energy depositions. The algorithm normally reconstructs one jet for a single isolated electron, photon, muon, high energy tau or a hadronic jet.

In our analysis an electron is identified as an electromagnetic shower with a matched track in the vertex chamber within 5° in the r-ϕ plane. If the shower is not matched with a TEC track, it is identified as a photon. The requirement on the electromagnetic shower profile is that the energy sum of 9 crystals divided by the energy sum of 25 crystals (centered around the shower maximum) must be larger than 0.95.

We define an acoplanarity angle in the $r-\phi$ plane normal to the beam direction.

For the leptonic decays of W bosons, we select events by applying the following criteria :

(1) There must be two and only two jets with energies greater than 5 GeV, amongst which at least one is identified as a single electron.

(2) The acoplanarity angle between these two jets must be greater than 25°.

(3) The total number of tracks in the TEC must be less than 7.

(4) The muon momentum, when W or τ decays to muon, must be less than 40 GeV. This muon must satisfy a momentum-dependent vertex cut and a scintillator timing cut.

(5) The thrust angle θ must satisfy $|cos\theta| < 0.7$.

Cut (1) rejects hadron, hard radiative Bhabha, $\mu^+\mu^-\gamma$ and $\tau^+\tau^-\gamma$ events; cut (2) rejects hadron, Bhabha, $\mu^+\mu^-$, $\tau^+\tau^-$ and 2γ events; cut (3) again rejects hadron events; cut (4) rejects cosmic muons and radiative $\mu^+\mu^-$ events and cut (5) ensures that events are mainly in the central region of the detector covered by the BGO barrel. Figure 1 shows the acoplanarity angle of the two jets for the data and the Monte Carlo simulation of ν^*events with $m_{\nu^*} = 70\ GeV$.

No events survive the above cuts. We have used Monte Carlo simulation to estimate the background from hadron [9], Bhabha [13], $\mu^+\mu^-$ [14] and $\tau^+\tau^-$ [14] events. For the corresponding luminosity, we find 0.8 events from Bhabha, 0.6 events from $\tau^+\tau^-$ and negligible background from the others.

The acceptance for ν^* events, estimated from Monte Carlo simulation, is about 32% depending slightly on the ν^* mass. Statistical and systematic errors have been taken into account by lowering the efficiency by 10%. This includes the error on the luminosity, selection and Monte Carlo simulation.

For the hadronic decays of W bosons, we select events by applying the following criteria :

(1) There must be three jets with energies greater than 5 GeV, amongst which one and only one is identified as a single electron. The energy measured exclusive of these three jets must be less than 10 GeV.

(2) The electron must be isolated from any other jet by at least 25°.

(3) The acoplanarity angle between the two non–electron jets must be greater than 20°.

(4) Muons, if present, must satisfy a momentum dependent vertex cut and a scintillator timing cut.

(5) The thrust angle θ must satisfy $|cos\theta| < 0.7$.

(6) The energy deposition in the Hadron Calorimeter Endcap must be less than 15 GeV.

Cut (1) rejects two jet hadron events, Bhabha, $\mu^+\mu^-$ and $\tau^+\tau^-$ events; cut (2) rejects hadron events; cut (3) rejects hadron, Bhabha, $\mu^+\mu^-$, $\tau^+\tau^-$ and 2γ events; cut (4) rejects cosmic muons; cut (5) and cut (6) ensure that events are mainly in the central region of the detector covered by the BGO barrel. Figure 2 shows the electron energy distribution for data and for the ν^* Monte Carlo with $m_{\nu^*} = 70\ GeV$.

No events are left after the above cuts. Backgrounds from hadrons, Bhabha, $\mu^+\mu^-$ and $\tau^+\tau^-$ are again estimated by Monte Carlo simulation. For the corresponding luminosity, we find 1.7 events from hadrons while other sources of background are negligible.

The acceptance for ν^* events, estimated from Monte Carlo simulation, is about 19% depending slightly on the ν^* mass. Statistical and systematic errors have been taken into account by lowering the efficiency by 10%. This includes the error on the luminosity, selection and Monte Carlo simulation.

Since no events are found in either the leptonic or hadronic decay channels, we can set limits on the coupling constant summing the two channels; using Poisson statistics the 95% C.L. limit corresponds to 3 events expected.

Summing both channels weighted by their branching ratio and acceptance, we give an upper limit of the coupling constant f_Z/m_{ν^*} at 95% C.L. as a function of m_{ν^*} up to the mass of Z^0 as shown in Fig. 3.

If one assumes that the $Z\nu\nu^*$ coupling is the same as the $Z\nu\nu$ coupling, the excited neutrino is excluded with a mass less than 91 GeV at the 95% C.L.

5. Search for ν^* via photon decay

In this case, only one energetic photon can be seen in the detector. We select events by requiring the following criteria:

(1) There must be a photon in the BGO, within the polar angle $45° < \theta < 135°$, with energy greater than 10 GeV. The remaining energy must be less than 20% of the total energy in BGO.

(2) The aspect ratio of the ellipse defined by the transverse projection of the photon shower in the BGO must be greater than 0.27 at 10 GeV, rising linearly to 0.5 at 45 GeV.

(3) There must be no tracks in the Muon Chambers.

(4) There must be less than 4 local shower maxima in the BGO with energy greater than 100 MeV.

(5) There must be no tracks in the TEC.

(6) The energy of the most energetic cluster in the Hadron Calorimeter must be less than 3 GeV.

(7) The energy of the most energetic cluster in the Veto Counters must be less than 1 GeV.

(8) The energy of the most energetic cluster in the Luminosity monitor must be less than 5 GeV.

Cut (1) rejects events from $e^+e^- \longrightarrow \nu\nu\gamma$ and $e^+e^- \longrightarrow ee\gamma$; cut (2) rejects bremsstrahlung photons in the BGO originating from cosmic rays; cut (3) rejects cosmic muons; other cuts reject all backgrounds from e^+e^- collisions.

No events are left after the above cuts. We have used Monte Carlo simulation to estimate the background from $e^+e^- \longrightarrow \nu\nu\gamma$ [15], $e^+e^- \longrightarrow e^+e^-\gamma$ [16] and $e^+e^- \longrightarrow \gamma\gamma\gamma$ [17]. For the corresponding luminosity, we find 0.5 events from $\nu\nu\gamma$ and no events from others.

The acceptance for ν^* events, estimated from Monte Carlo simulation, is about 69% depending slightly on the ν^* mass. Statistical and systematic errors have been taken into account by lowering the efficiency by 10%, this includes the error on the luminosity, selection and Monte Carlo simulation.

By taking into account the luminosity and acceptance, we give an upper limit of the coupling constant f_Z/m_{ν^*} at 95% C.L. as a function of m_{ν^*} up to the Z^0 mass as shown in Figure 3. The ALEPH result [18] is also shown in the plot by taking into account the relation between the two couplings:

$$f_Z = 2\sqrt{2}\lambda$$

where λ is the coupling used by ALEPH.

If one assumes that the $Z\nu\nu^*$ coupling is the same as the $Z\nu\nu$ coupling, the excited neutrino is excluded with a mass less than 91 GeV at the 95% C.L.

6. Conclusions

We have searched for the lightest excited particle, the excited electron neutrino, produced from Z^0 decay in the channel $e^+e^- \rightarrow \nu\nu^*$ using the L3 detector at LEP.

The excited neutrino dominant decay would be $\nu^* \rightarrow eW$ if the $\gamma\nu\nu^*$ coupling does not exist, $\nu^* \rightarrow \nu\gamma$ if the $\gamma\nu\nu^*$ coupling does exist. We studied both these channels, considering either the leptonic or hadronic decay of the W boson in the first case, and we determined upper limits for the $Z\nu\nu^*$ coupling as functions of m_{ν^*} up to the Z^0 mass.

Independently on the existence of the $\gamma\nu\nu^*$ coupling, the excited neutrino is excluded at the 95% C.L. with a mass less than 91 GeV if the $Z\nu\nu^*$ coupling is the same as the $Z\nu\nu$ coupling.

Acknowledgments

We wish to thank CERN for its hospitality and help. We want particularly to express our gratitude to the LEP division: it is their excellent achievements which made this experiment possible. We acknowledge the effort of all engineers and technicians who have participated in the construction and maintenance of this experiment. We acknowledge the support of all the funding agencies which contributed to this experiment.

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FIGURE CAPTIONS

Figure 1. The acoplanarity angle of the two jets for data and ν^* Monte Carlo with $m_{\nu^*} = 70\ GeV$.

Figure 2. The energy distribution of the electron for data and ν^* Monte Carlo with $m_{\nu^*} = 70\ GeV$.

Figure 3. The upper limit of the coupling constant f_Z/m_{ν^*} at 95% C.L. as a function of m_{ν^*} for both $\nu^* \to eW$ and $\nu^* \to \nu\gamma$ decays from L3. The upper limit for $\nu^* \to \nu\gamma$ from ALEPH is also shown. The excluded region is above and left of the curves.

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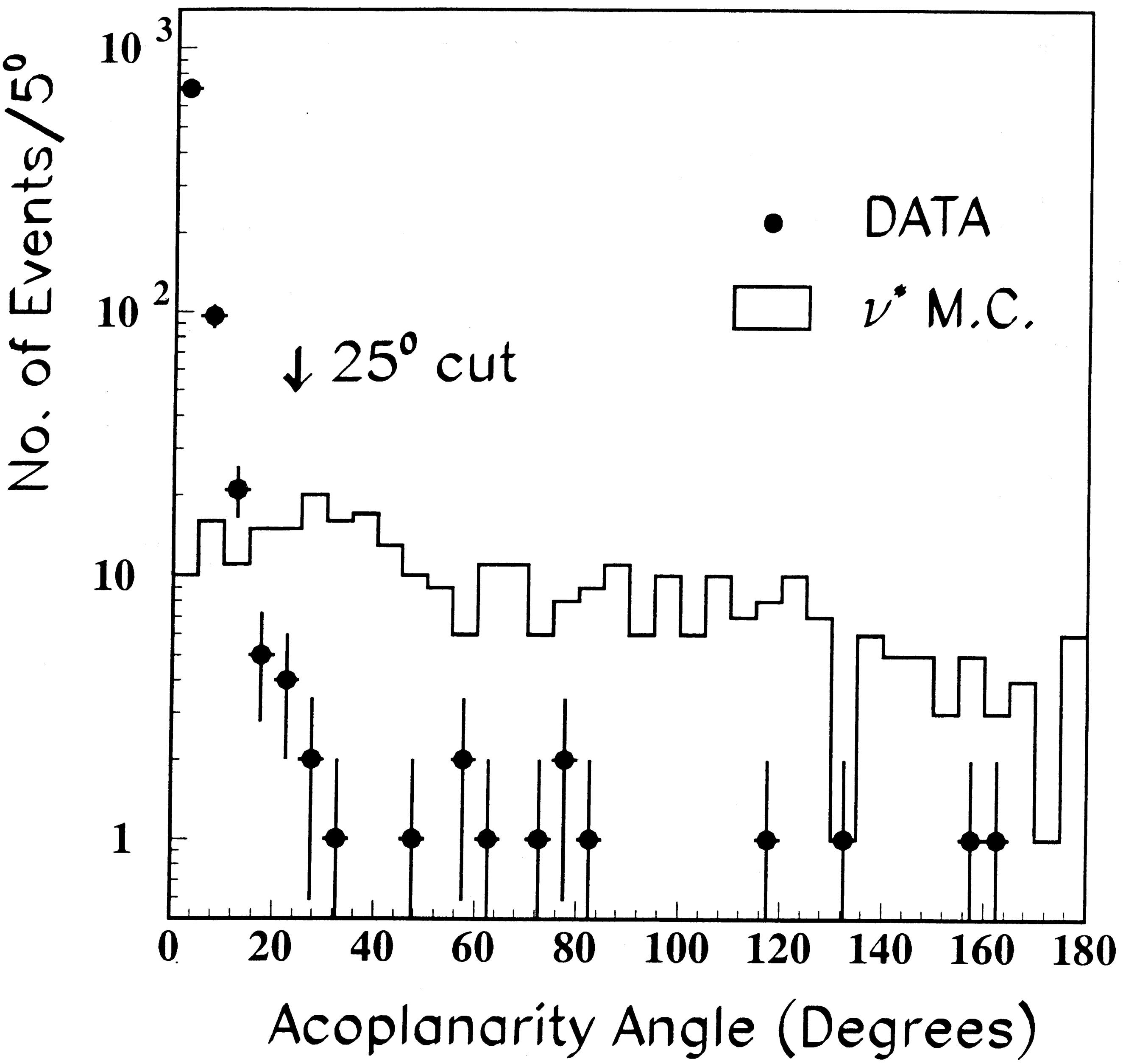
§ Supported by the German Bundesministerium für Forschung und Technologie



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10 2
10
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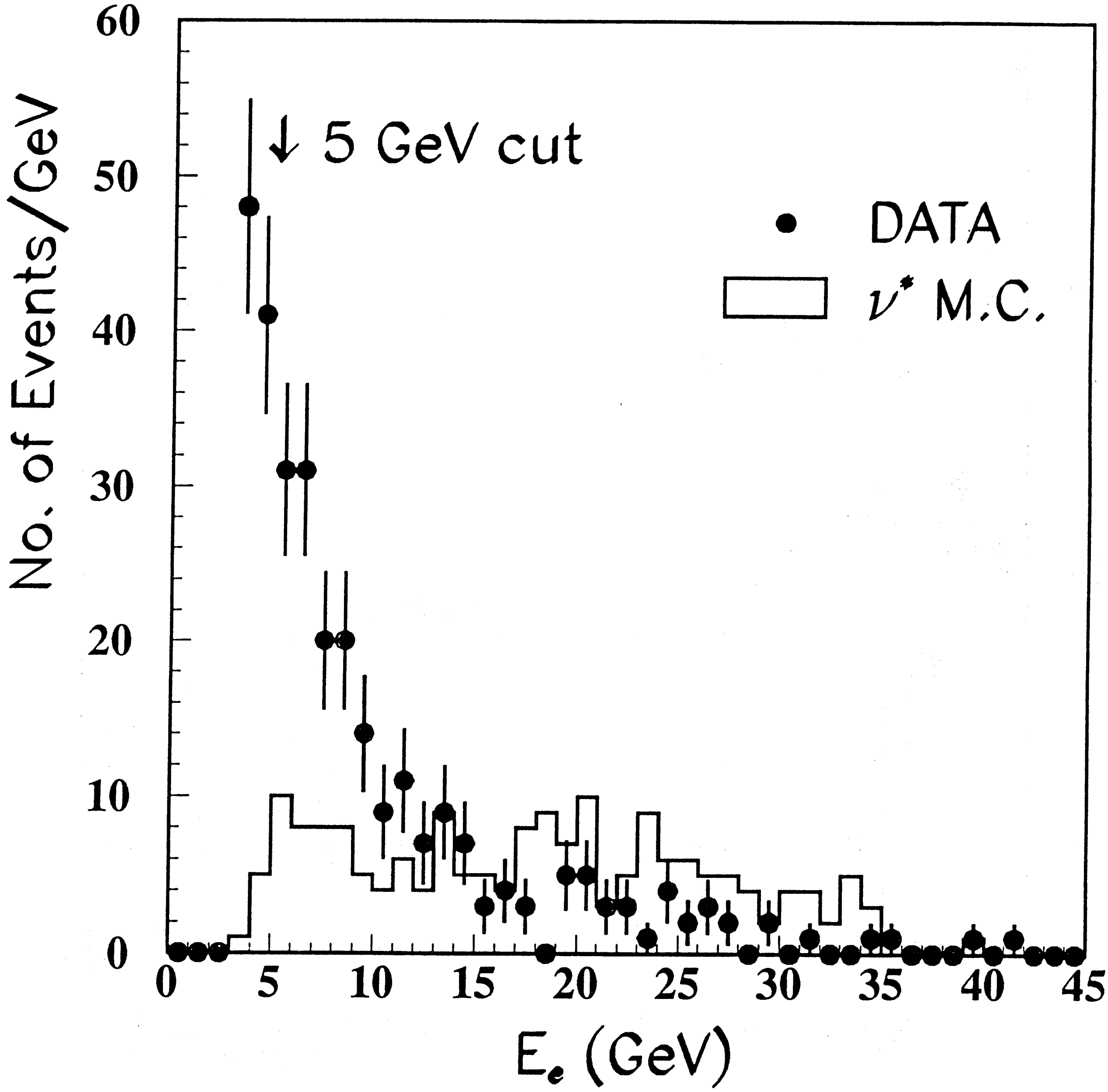
60
80
100
120
140
160
180
Acoplanarity Angle (Degrees)

Figure 1



No. of Events/GeV
E_e (GeV)
↓ 5 GeV cut
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60
0
5
10
15
20
25
30
35
40
45

Figure 2

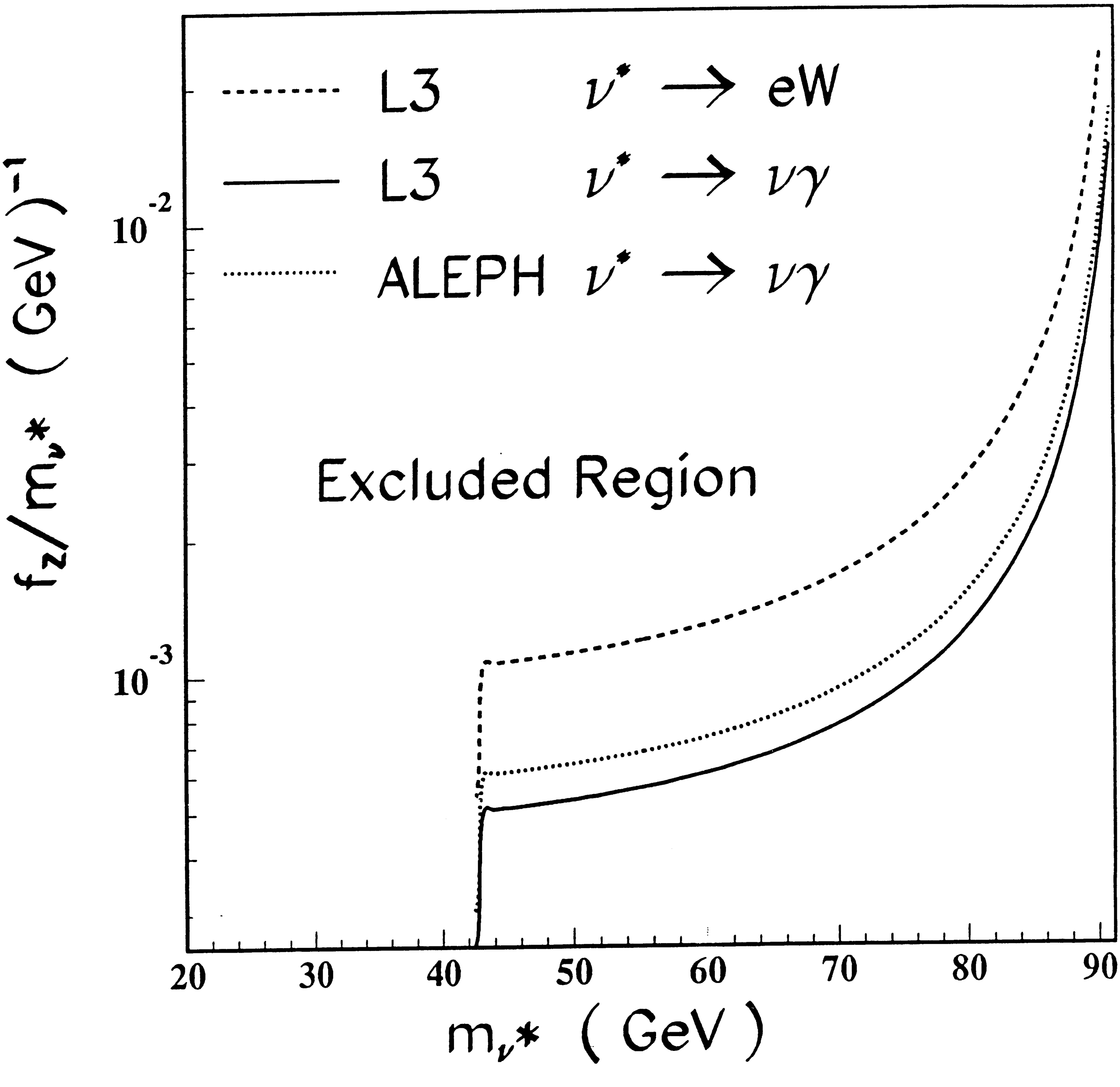

Figure 3

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