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Search for lepton flavour violation in Z^0 decays

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We have searched for lepton flavour violation in Z^0 boson decays into lepton pairs, $Z^0 \to \mu\tau$, $Z^0 \to e\tau$, and $Z^0 \to e\mu$. The data sample is based on an integrated luminosity of 10.4 pb^{-1} corresponding to 370 000 Z^0's produced. We obtain upper limits on the branching ratios of 4.8×10^{-5} for the $\mu\tau$, 3.4×10^{-5} for the $e\tau$ and 2.4×10^{-5} for the $e\mu$ decay modes at the 95% confidence level.

1. Introduction

In the standard model [1,2] lepton flavour is absolutely conserved. However, there is no gauge principle requiring this conservation law. Different models [3-7], beyond the standard model, allow processes which violate lepton flavour conservation. In theories where such violation arises through mixing with new particles [3,5], the branching ratio for such processes, e.g. $Z^0 \to \mu\tau$, can be as large as 10^{-4}. The observation of such decays would be a clear indication of physics beyond the standard model.

Previous experiments [8-13] have searched for lepton flavour violating decays and have reported negative results. In this paper we present the results obtained with the L3 detector at LEP for the channels $Z^0 \to \mu\tau$, $Z^0 \to e\tau$, $Z^0 \to e\mu$.

2. The L3 detector

The L3 detector covers 99% of 4π. The detector consists of a time expansion chamber (TEC), a high resolution electromagnetic calorimeter composed of BGO crystals, a ring of scintillation counters, a uranium and brass hadron calorimeter with propor-

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tional wire chamber readout, and an accurate muon chamber system. These detectors are installed in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction. The luminosity is measured with the help of two small-angle BGO calorimeters.

The central tracking chamber is a time expansion chamber which consists of two cylindrical layers of 12 and 24 sectors, with 62 wires measuring the R–ϕ coordinate. The single wire resolution is 58 μm averaged over the entire cell. The double-track resolution is 640 μm. The fine segmentation of the BGO detector and the hadron calorimeter allow us to measure the direction of jets with an angular resolution of 2.5°, and to measure the total energy of hadronic events from Z^0 decay with a resolution of 10.2%. The muon detector consists of 3 layers of precise drift chambers, which measure a muon's trajectory 56 times in the bending plane, and 8 times in the non-bending direction. The trigger efficiency for lepton pairs is greater than 99.9% in the barrel region [14,15]. A detailed description of each detector subsystem, and its performance, is given in ref. [16].

3. Preselection

For the present analysis we use the data sample based on an integrated luminosity of 10.4 pb^{-1} accumulated during the 1990 and early 1991 runs corresponding to the production of 370 000 Z^0's. The preselection cuts, used to select a data sample containing high energy dilepton events of all types, are the following:

(1) The total energy is greater than 30 GeV.

(2) The number of jets is 2 or 3.

(3) The number of tracks in the TEC is between 1 and 5, to help remove hadron events.

(4) The number of calorimeter clusters is less than 15, to help remove hadron events.

(5) The acolinearity angle between the two jets is smaller than 20°, to remove radiative events.

(6) $|\cos\theta|$ of the thrust axis is less than 0.7, so that the event is well contained in the detector.

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

4. Detector resolution

The expected signature of $Z^0 \to \mu\tau$ ($Z^0 \to e\tau$), is a beam energy muon (electron) opposite to the decay products of a τ. The main background arises from $\tau^+\tau^-$ events with one of the taus decaying into a muon (electron) which carries almost all the energy of the tau. Good muon (electron) momentum resolution is essential to reduce this background while retaining a high detection efficiency.

Muons are identified and their momentum measured in the muon chamber system surrounding the calorimeters. To be accepted, a muon track must have one track segment in each of the three layers of the muon chambers. The muon momentum resolution determined from dimuon events is 2.5% at 45 GeV as shown in fig. 1. This includes contributions from chamber resolution, multiple scattering and fluctua-

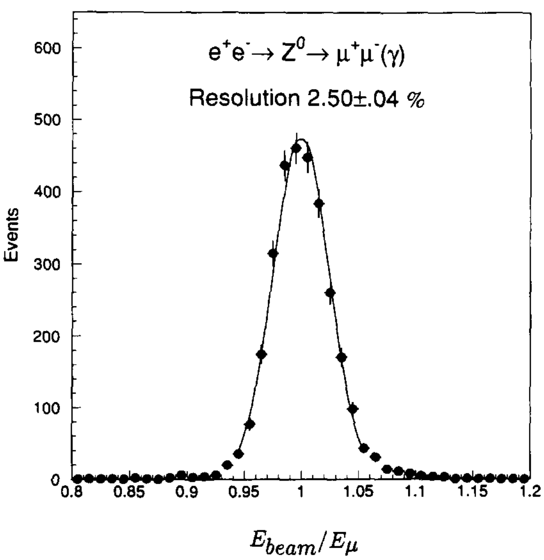

Fig. 1. Muon energy (E_μ) resolution from $Z^0 \to \mu\mu(\gamma)$ events.

tions of the energy loss in the calorimeter. Using dielectron events, the expected width of the electron energy distribution is determined to be 1.2%, which includes a substantial contribution from initial and final state radiation.

5. Monte Carlo simulation

In order to determine the acceptance for the three lepton flavour violating decay modes ($Z^0 \to \mu\tau$, $Z^0 \to e\tau$, $Z^0 \to e\mu$), events were generated using a modified version of the KORALZ [18] Monte Carlo generator. To estimate the background from $\mu^+\mu^-$, $\tau^+\tau^-$, e^+e^- and $q\bar{q}$ events, various Monte Carlo generators have been used [18–20]. All Monte Carlo events include a detailed simulation [21] [#1] of the L3 detector. The same analysis program is used for both the data and the Monte Carlo events.

6. $Z^0 \to \mu\tau$ channel

For $Z^0 \to \mu\tau$ we require one jet to be consistent with a beam energy muon and the other to be consistent with a τ decay. We have used the following selection:

For the μ candidate:

(1) The muon track must extrapolate to within 100 mm of the nominal vertex position in the transverse plane and 200 mm in the longitudinal plane.

(2) $0.97 < E_\mu / E_{\text{beam}} < 1.08$.

For the τ candidate, in order to reject dimuon background, we require:

(3) There is no track found in the muon detector.

(4) The energy in the electromagnetic calorimeter is greater than 0.8 GeV.

(5) The TEC track, for a τ candidate with purely electromagnetic energy, does not extrapolate to dead zones in the hadron calorimeter and the muon chambers. This rejects background from radiative dimuon events.

(6) The energy distribution in the hadron calorimeter is inconsistent with that of a muon.

[#1] GEANT version 3.13 (September 1989). The GHEISHA program is used to simulate hadronic interactions. See ref. [22].

The last requirement can be quantitatively expressed by the cut on the χ^2_μ variable:

$$\chi^2_\mu = \frac{\Sigma_{i=1}^{n} (E_i - \bar{E}_{\mu i})^2}{\sigma^2_{\mu i}(n-1)} > 5 .$$

E_i is the energy deposited in layer i of the hadron calorimeter, which has a total of 10 layers. $\bar{E}_{\mu i}$ and $\sigma_{\mu i}$ are the average value and standard deviation of energy deposited in layer i by a muon as determined from the dimuon events. Fig. 2 shows the χ^2_μ distribution for the $Z^0 \to \mu\mu$ events. The mean value of this χ^2_μ variable is about one. For a τ which decays hadronically, the mean value of this χ^2_μ variable is a few hundred. This also helps reject radiative dimuon events when the radiating μ goes into a crack in the muon chambers and is therefore not detected.

Fig. 3 shows the distribution of the muon energy after all cuts, except cut (2), have been applied. The importance of lepton resolution to reject the $\tau^+\tau^-$ background is evident from this figure.

The above cuts, together with the preselection, result in an overall detection efficiency of $(22.5 \pm 1.0)\%$ for $Z^0 \to \mu\tau$. One candidate from the data satisfies the cuts. From Monte Carlo studies we expect a total of 1.6 ± 0.9 background events (0.7 ± 0.7 from $\mu^+\mu^-$, 0.9 ± 0.5 from $\tau^+\tau^-$ and 0 from $q\bar{q}$). Using Poisson

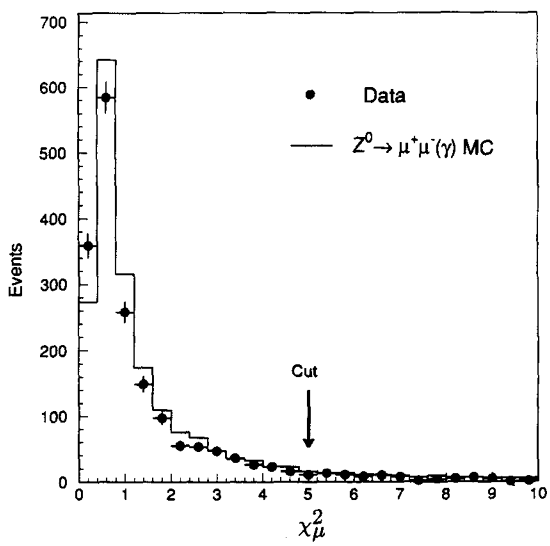

Fig. 2. The χ^2_μ distribution for $Z^0 \to \mu\mu$ data and $Z^0 \to \mu\mu$ Monte Carlo. The arrow indicates the cut. The mean value of this χ^2_μ variable for a τ decaying hadronically, is a few hundred.

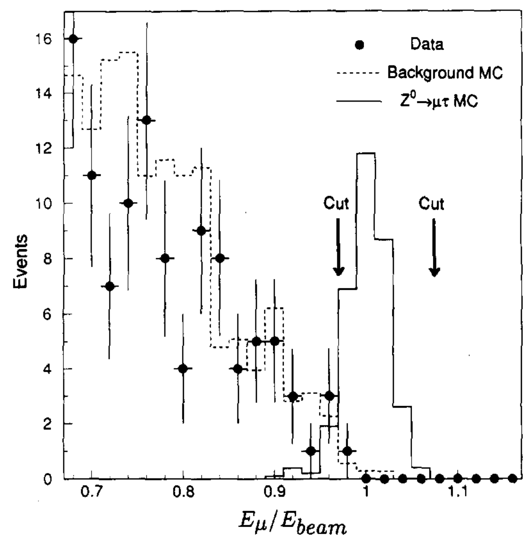

Fig. 3. The distribution of the muon energy (E_μ) for the data, Monte Carlo background, and signal $Z^0 \to \mu\tau$ Monte Carlo, after all cuts, but the muon energy cut (2), are applied. The normalization for the signal Monte Carlo is arbitrary. The arrows represent the cut on muon energy.

statistics we set a 95% CL upper limit of 4 events from the $Z^0 \to \mu\tau$ channel. This yields a 95% CL limit on the branching ratio of

$$\mathrm{Br}(Z^0 \to \mu\tau) < 4.8 \times 10^{-5} .$$

7. $Z^0 \to e\tau$ channel

For $Z^0 \to e\tau$ we require one jet to be consistent with a beam energy electron and the other to be consistent with a τ decay. We have used the following selection: For the electron candidate:

(1) There is an electromagnetic cluster (energy E_e) associated with a track in the TEC.

(2) $0.98 < E_e/E_{\mathrm{beam}} < 1.05$

(3) The electromagnetic shower profile should be consistent with that of an electron.

The last requirement can be quantitatively expressed by the cut on the χ_e^2 variable:

$$\chi_e^2 = \frac{\sum_{i=1}^{6}(E_i - \bar{E}_{ei})^2}{5\sigma_{ei}^2} < 3 .$$

To define the χ_e^2 variable the 6 most energetic crystals in the electromagnetic cluster are used. E_i is the energy deposited in one crystal of the electromagnetic cluster, $\bar{E}_{ei}$ and σ_{ei} are the average value and standard deviation of energy deposited in crystal i, determined from $Z^0 \to ee$ events. Crystals are ordered according to measured energy.

For the tau candidate:

(4) The energy in the electromagnetic calorimeter is less than 30 GeV in order to reject dielectron events.

(5) Jets associated with more than one TEC track and with more than 20 GeV of electromagnetic energy are required to have a total jet energy less than 0.93 E_{beam}. This cut removes four-lepton events, which have no missing energy.

(6) If the jet has only one track in the TEC, the energy in the last 6 layers of the hadron calorimeter is required to be greater than 0.13 of the sum of energy in hadron and electromagnetic calorimeters.

The last cut removes dielectron events where one electron passes close to the cracks in the electromagnetic calorimeter without depositing all its energy. Fig. 4 shows the distribution of the electron energy after all cuts except cut (2) have been applied.

This set of cuts, together with the preselection, yields an overall efficiency for the $e\tau$ events of $(24.2 \pm 1.0)\%$. We find no candidates remaining.

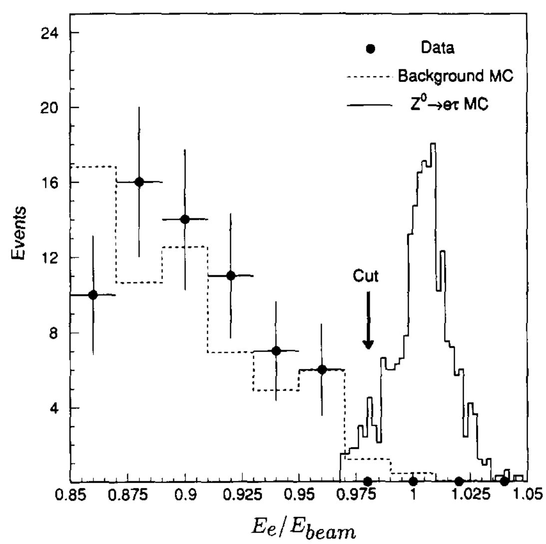

Fig. 4. The distribution of the electron energy (E_e) for the data, Monte Carlo background, and signal $Z^0 \to e\tau$ Monte Carlo, after all cuts, but the electron energy cut (2), are applied. The normalization for the signal Monte Carlo is arbitrary. The arrow represents the cut on electron energy.

Table 1
Limits on branching ratios.

	$Z^0 \to \mu\tau$	$Z^0 \to e\tau$	$Z^0 \to e\mu$
this experiment	4.8×10^{-5}	3.4×10^{-5}	2.4×10^{-5}
OPAL Collaboration [a]	35×10^{-5}	7.2×10^{-5}	4.6×10^{-5}
CLEO and ARGUS Collaborations [b]	7.4×10^{-5}	12×10^{-5}	
Sindrum Collaboration [c]			6.6×10^{-13}

[a] Ref. [11]. [b] Refs. [8,9]. [c] Ref. [13].

From Monte Carlo studies we expect a total of 0.8 ± 0.3 background events (0.8 ± 0.3 from $\tau^+\tau^-$, 0 from e^+e^- and 0 from $q\bar{q}$). Using Poisson statistics we set a 95% CL upper limit of 3 events from the $Z^0 \to e\tau$ channel. This yields a 95% CL limit on the branching ratio of

$$\mathrm{Br}(Z^0 \to e\tau) < 3.4 \times 10^{-5} .$$

8. $Z^0 \to e\mu$ channel

For $Z^0 \to e\mu$ we require one jet to be consistent with a beam energy electron and the other to be consistent with a beam energy muon. This type of event is more easily identified than those containing τ's and allows the following, less restrictive, selection criteria:

For the electron candidate:

(1) There must be an electromagnetic cluster (energy E_e) associated with a track in the TEC.

(2) $0.95 < E_e/E_{\mathrm{beam}} < 1.05$

(3) No muons are present in this hemisphere.

For the muon candidate:

(4) $0.93 < E_\mu/E_{\mathrm{beam}} < 1.08$

(5) The energy in the hadron calorimeter is less than 10 GeV.

Together with the preselection this gives an overall efficiency for the $e\mu$ channel of (34.7 ± 1.6)%.

We applied the above cuts to the sample of preselected events. We find no candidates remaining. All Monte Carlo ($\mu^+\mu^-$, $\tau^+\tau^-$, e^+e^-, and $q\bar{q}$) give 0 events. Using Poisson statistics we set a 95% CL upper limit of 3 events from the $Z^0 \to e\mu$ channel. This yields a 95% CL limit on the branching ratio of

$$\mathrm{Br}(Z^0 \to e\mu) < 2.4 \times 10^{-5} .$$

9. Conclusions

We have searched for lepton flavour violating decays in the channels $Z^0 \to \mu\tau$, $Z^0 \to e\tau$, and $Z^0 \to e\mu$. The candidates found (1, 0 and 0 respectively) are consistent with the expected background. We set the limits for these decay of: $\mathrm{BR}(Z^0 \to \mu\tau) < 4.8 \times 10^{-5}$, $\mathrm{BR}(Z^0 \to e\tau) < 3.4 \times 10^{-5}$, and $\mathrm{BR}(Z^0 \to e\mu) < 2.4 \times 10^{-5}$ at the 95% CL. Table 1 shows a comparison between these limits and previously obtained results. *In order to transform the low energy limits* [8,9,13] *from* τ *and* μ *decays into limits for* $Z^0 \to \mu\tau$, $Z^0 \to e\tau$ *and* $Z^0 \to e\mu$ *the procedure described in ref.* [23] *has been used. Note that in contrast to the LEP limits which are given at the 95% CL the low energy limits are at the 90% CL.*

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