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Search for Lepton Flavour Violation in Z Decays

L3 Collaboration

Abstract

We have searched for lepton flavour violation in Z boson decays into lepton pairs using all data collected with L3 detector during the 1990, 1991 and 1992 runs on an event sample corresponding to 1,500,000 Z's produced. At the 95% confidence level the upper limits on the branching ratio for $Z \rightarrow e\mu$ is 0.6×10^{-5}, for $Z \rightarrow e\tau$ is 1.3×10^{-5} and for $Z \rightarrow \mu\tau$ is 1.9×10^{-5}.

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1 Introduction

In the Standard Model [1, 2] lepton flavour is conserved. However, there is no gauge principle requiring this conservation. Different models [3–9], beyond the Standard Model, allow processes which violate lepton flavour conservation. In theories where such violation arises through mixing with new particles [4,6], the branching ratios for such processes, e.g. $Z \rightarrow \mu\tau$, have been calculated to be as large as 10^{-4} in certain models. The observation of such decays would be a clear indication of physics beyond the Standard Model. Here a search for lepton flavour violation in Z decays into $e\mu$, $e\tau$ and $\mu\tau$ is reported using the data collected with L3 detector during the 1990, 1991 and 1992 runs on an event sample corresponding to 1,500,000 Z's produced. Direct searches for lepton flavour violation [10–17] have been performed previously by L3 and other experiments. Stringent constraints on violation of μ flavour exist from low-q^2 reactions, such as the absence of the decay $\mu \rightarrow eee$ [14], providing an upper limit [18] on $Br(Z \rightarrow e\mu)$ of 6.6×10^{-13}. Searches for neutrinoless τ decays $\tau \rightarrow eee$, $\tau \rightarrow \mu\mu\mu$ [12, 13] lead to much less stringent limits on $Br(Z \rightarrow e\tau)$ and $Br(Z \rightarrow \mu\tau)$.

2 The L3 Detector

The fiducial solid angle of the L3 detector [19] is 99% of 4π. The detector consists of a time expansion chamber (TEC) for tracking charged particles, a high resolution electromagnetic calorimeter of BGO crystals, a barrel of scintillation counters, a hadron calorimeter with uranium absorber and proportional wire chamber readout and a muon spectrometer. The luminosity is determined from small-angle Bhabha scattering using BGO electromagnetic calorimeters in the polar angle ranges θ and $\pi - \theta$ between 24.93 and 69.94 mrad. All subdetectors are installed inside a 12m diameter solenoidal magnet which provides a uniform 0.5 T field along the beam direction. A detailed description of each detector subsystem, and its performance, is given in [11,19].

3 Signature and Background

The expected experimental signature of $Z \rightarrow e\mu$, $Z \rightarrow \mu\tau$ and $Z \rightarrow e\tau$ is an electron or muon with an energy close to the beam energy recoiling against a different type of lepton or hadrons from tau decay. Background arises from Standard Model leptonic final states and can be divided into two classes : (i) incorrectly reconstructed e^+e^- and $\mu^+\mu^-$ events; (ii) $\tau^+\tau^-$ events with one or both of the taus decaying into a muon or electron which carries almost all the energy of the tau. Good muon and electron energy resolution is essential to reduce the latter background while retaining a high detection efficiency. The energy resolution for electrons determined from Bhabha events is 1.3% at 45 GeV, while the muon momentum resolution determined from dimuon events is 2.5%.

About 300000 Monte Carlo events were generated to study Standard Model backgrounds from e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ and four-fermion channels using various Monte Carlo generators [20–23]. A modified version of the KORALZ [20] Monte Carlo program was used to generate signal events.

4 Preselection and Lepton Identification

The preselection cuts, used to select a data sample containing high energy dilepton events of all types, are the following:

- The total energy is greater than 30 GeV.
- The number of jets is 2.
- The number of tracks in the TEC is between 1 and 6, to remove hadron events.
- The number of calorimeter clusters is less than 15, to remove hadron events.
- The acolinearity angle between the two jets is smaller than 20°, to remove radiative events.

Jets are reconstructed using a two step algorithm [24] 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.

An electron is defined as a geometrical cluster in the electromagnetic calorimeter with an energy more than 2 GeV matched with a TEC track in the (R, ϕ) plane within 10 mrad. The cluster shower profile should be consistent with that of an electron, i.e. we require $0.97 < E_9/E_{25} < 1.025$, where $E_{9(25)}$ is the corrected sum of energies of 9(25) BGO crystals around the most energetic one, and $\chi^2 < 2$, where χ^2 is obtained by fitting the shape of the cluster to the mean electron shower profile. The electron candidate must be in the fiducial volume defined by $|\cos\theta| < 0.9$.

Muons are identified and their momenta 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 chamber layers. The accepted muon track must extrapolate back to within 100 mm of the nominal vertex position in the transverse plane and 200 mm in the longitudinal plane. The muon candidate energy must be greater than 3 GeV and it must be in the fiducial volume defined by $|\cos\theta| < 0.75$.

5 $\mathrm{Z} \to e\mu$ Channel

For the $\mathrm{Z} \to e\mu$ channel we require one jet to be consistent with a beam energy electron and the other one to be consistent with a beam energy muon. This type of event is essentially free of background and allows a less restrictive selection cut on lepton energy than Z $\rightarrow e\tau$ and Z $\rightarrow \mu\tau$ channels. Fig. 1 shows the normalised electron energy versus the normalised muon momentum for the data events selected. Signal events will populate the region where both normalised energies are close to unity. We require that for the electron candidate the normalised energy should be greater than 0.96 ($\approx 3\ \sigma$) and for the muon candidate greater than 0.92 ($\approx 3\ \sigma$). No events lie within this region giving the 95% confidence level limit on the signal of three events. We apply the above cuts to the sample of the signal and Standard Model background ($\tau^+\tau^-$, e^+e^- and $\mu^+\mu^-$) Monte Carlo events. We find no events in the Standard Model Monte Carlo sample. The efficiency of the analysis as determined by the signal Monte Carlo is 32.0 $\pm$ 1.0%. This error includes the uncertainty due to the Monte Carlo statistics. The additional systematic error due to the corrected number of hadronic Z decays used for normalization and due to the uncertaintes in the detector calibration constants is estimated to be 1.5% [25]. This yields a 95% confidence level limit on the branching ratio of

$$Br(\mathrm{Z} \rightarrow e\mu) < 0.6 \times 10^{-5}.$$

6 Z $\rightarrow e\tau$ Channel

For Z $\rightarrow e\tau$ we require one jet to be consistent with a beam energy electron and the other one to be consistent with a τ decay. We consider the following τ decays :

- $\tau \rightarrow \mu\nu\bar{\nu}$
  We require that the τ-jet consists of one muon with an energy greater than 3 GeV.
- $\tau \rightarrow e\nu\bar{\nu}$
  We require that the τ-jet consists of one electron with an energy less than 30 GeV. The hadronic energy, contained in the τ jet, should be less than 0.5 GeV. To reject the Z $\rightarrow ee(\gamma)$ background we require that the acoplanarity angle between TEC tracks associated with the electron and the τ be more than 3.2 mrad. Fig. 2 shows the distribution of this variable for Z $\rightarrow ee(\gamma)$ as well as Z $\rightarrow e\tau$ events.
- $\tau \rightarrow$ 1 prong
  We require that the τ-jet, containing only one TEC track, has a total energy more than 3 GeV and electromagnetic energy less than 30 GeV. The hadronic energy contained in the τ jet should be greater than 0.5 GeV. To reject Z $\rightarrow ee(\gamma)$ events, where one electron passes close to the cracks in the electromagnetic calorimeter and therefore deposits some energy in the hadron calorimeter, we require that the energy in the hadron calorimeter beyond its first 25 X_0 be greater than 10% of the total jet energy. The above cut on the acoplanarity angle between two TEC tracks is also applied.
- $\tau \rightarrow$ 3 or 5 prongs
  We require that the τ-jet contains at least two TEC tracks, has a total energy more than 3 GeV, has an electromagnetic energy less than 30 GeV and an energy deposition in the hadron calorimeter more than 1 GeV. To remove four-fermion events,

which have no missing energy, we require that energy in the hadronic calorimeter be less than $0.85 \times (E_{beam} - E_{ECAL})$.

Figure 3 shows the distribution of the electron energy after all cuts but the electron energy cut have been applied. To reject the remaining $Z \rightarrow \tau\tau$ background we require that the energy of the electron should be more than $0.985 \times E_{beam}$. After all cuts this yields an efficiency for the $Z \rightarrow e\tau$ channel of $23.8 \pm 0.9\%$.

Table 1 shows the estimated acceptance for the $Z \rightarrow e\tau$ channel for the different τ decay modes together with the number of surviving events after all cuts.

Channel	Acceptance (%)	Expected	Seen
$\tau \rightarrow e\nu\bar{\nu}$	4.0 ± 0.4	0	0
$\tau \rightarrow \mu\nu\bar{\nu}$	7.1 ± 0.5	0.7 ± 0.4	0
$\tau \rightarrow$ 1 prong	8.5 ± 0.5	1.1 ± 0.4	2
$\tau \rightarrow$ 3 or 5 prongs	4.2 ± 0.4	1.0 ± 0.3	0

Table 1: Acceptance, expected background events and number of events seen in the data for the $Z \rightarrow e\tau$ channel for different τ decay modes.

We find two events in the data, while we expect 2.8 ± 0.7 events from $Z \rightarrow \tau\tau$ and $Z \rightarrow ffff$ Monte Carlo. We set a 95% C.L. upper limit of 4.7 events for the $Z \rightarrow e\tau$ channel, yielding a 95% C.L. limit on the branching ratio of

$$Br(Z \rightarrow e\tau) < 1.3 \times 10^{-5}.$$

7 $Z \rightarrow \mu\tau$ Channel

For $Z \rightarrow \mu\tau$ we require one jet to be consistent with a beam energy muon and the other one to be consistent with a τ decay. We consider the following τ decays :

- $\tau \rightarrow \mu\nu\bar{\nu}$
  Due to the background from dimuon events, this decay channel is not considered.

- $\tau \rightarrow e\nu\bar{\nu}$
  We require that the τ-jet consists of one electron with energy greater than 5 GeV. The hadronic energy, contained in the τ jet, should be less than 0.5 GeV. To reject the $Z \rightarrow \mu\mu(\gamma)$ background we require : (i) the acoplanarity between TEC tracks associated with the muon and the τ to be greater than 3.2 mrad; (ii) there are no track segments in the muon chambers in the hemisphere opposite to the μ candidate.

- $\tau \rightarrow 1$ prong
  We require that the τ-jet contains only one TEC track, has a total energy more than 5 GeV and an electromagnetic energy less than 35 GeV. The hadronic energy contained in the τ jet should be greater than 0.5 GeV. To reject the $Z \rightarrow \mu\mu(\gamma)$

background, the shower profile of the τ jet in the hadron calorimeter should be inconsistent with that of a muon [10]. Cuts (i) and (ii) from the previous decay channel are also applied.

- $\tau \rightarrow 3$ or 5 prongs
  We require that the τ-jet contains at least two TEC tracks and has a total energy greater than 5 GeV. There must be no track segments in muon chambers in the hemisphere opposite to the μ candidate.

Figure 4 shows the distribution of the muon energy after all cuts but the electron energy cut have been applied. To reject the remaining $\mathrm{Z} \rightarrow \tau\tau$ background we require that the energy of the muon should be more than $0.97 \times E_{beam}$. After all cuts this yields an efficiency for the $\mathrm{Z} \rightarrow \mu\tau$ channel of $22.0 \pm 0.9\%$.

Table 2 shows the estimated acceptance for the $\mathrm{Z} \rightarrow \mu\tau$ channel for the different τ decay modes together with the number of surviving events after all cuts.

Channel	Acceptance (%)	Expected	Seen
$\tau \rightarrow e\nu\bar{\nu}$	5.0 ± 0.4	1.8 ± 0.8	1
$\tau \rightarrow$ 1 prong	11.8 ± 0.6	3.4 ± 0.8	3
$\tau \rightarrow$ 3 or 5 prongs	5.2 ± 0.5	0.7 ± 0.3	1

Table 2: Acceptance, expected background events and number of events seen in the data for the $\mathrm{Z} \rightarrow \mu\tau$ channel for different τ decay modes.

We find 5 events in data, while we expect 5.9 ± 1.2 events from $\mathrm{Z} \rightarrow \tau\tau$, $\mathrm{Z} \rightarrow \mu\mu$ and $\mathrm{Z} \rightarrow ffff$ Monte Carlo. We set a 95% C.L. upper limit of 6.2 events for the $\mathrm{Z} \rightarrow \mu\tau$ channel, yielding a 95% C.L. limit on the branching ratio of

$$Br(\mathrm{Z} \rightarrow \mu\tau) < 1.9 \times 10^{-5}.$$

8 Conclusion

We have searched for lepton flavour violating decays of the Z boson, obtaining the limits :

$$Br(\mathrm{Z} \rightarrow e\mu) < 0.6 \times 10^{-5}$$

$$Br(\mathrm{Z} \rightarrow e\tau) < 1.3 \times 10^{-5}$$

$$Br(\mathrm{Z} \rightarrow \mu\tau) < 1.9 \times 10^{-5}.$$

These limits are approximately 5 times better than previously published LEP results [15–17].

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Figure Captions

Fig. 1 Muon energy versus electron energy for selected $\mathrm{Z} \to e\mu$ candidate events. The shaded area represents the region corresponding to the signal events.

Fig. 2 The distribution of acoplanarity angle between two opposite TEC tracks in the dilepton events. The points are data, the histogram corresponds the $\mathrm{Z} \to ee(\gamma)$ Monte Carlo events and the dashed line shows the distribution for the signal $\mathrm{Z} \to e\tau$ Monte Carlo events. The normalisation for the signal distribution is arbitrary. The arrows indicate the cuts.

Fig. 3 The distribution of electron energy after all cuts but the electron energy cut have been applied in the $\mathrm{Z} \to e\tau$ selection.

Fig. 4 The distribution of muon energy after all cuts but the muon energy cut have been applied in the $\mathrm{Z} \to \mu\tau$ selection.

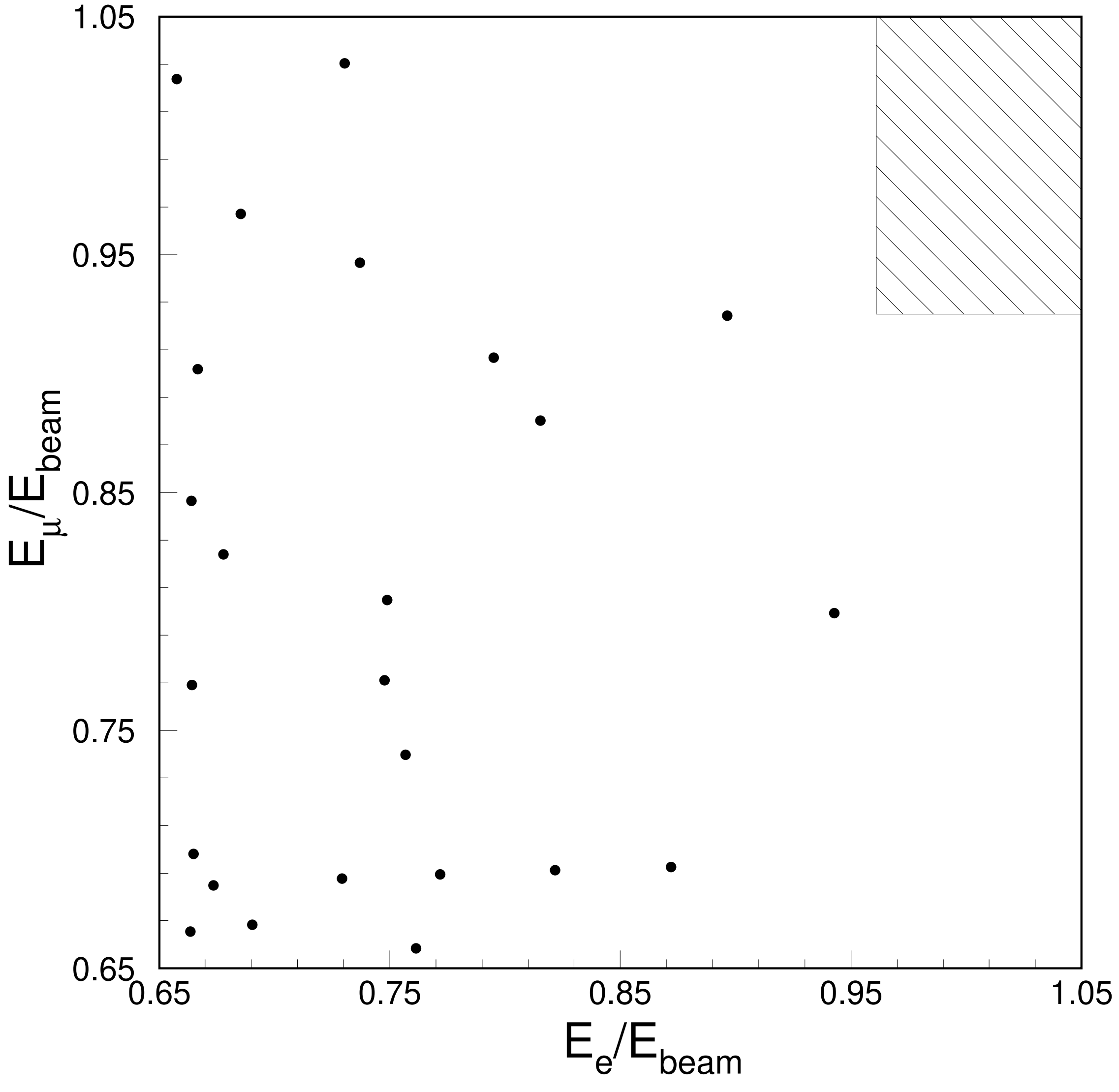
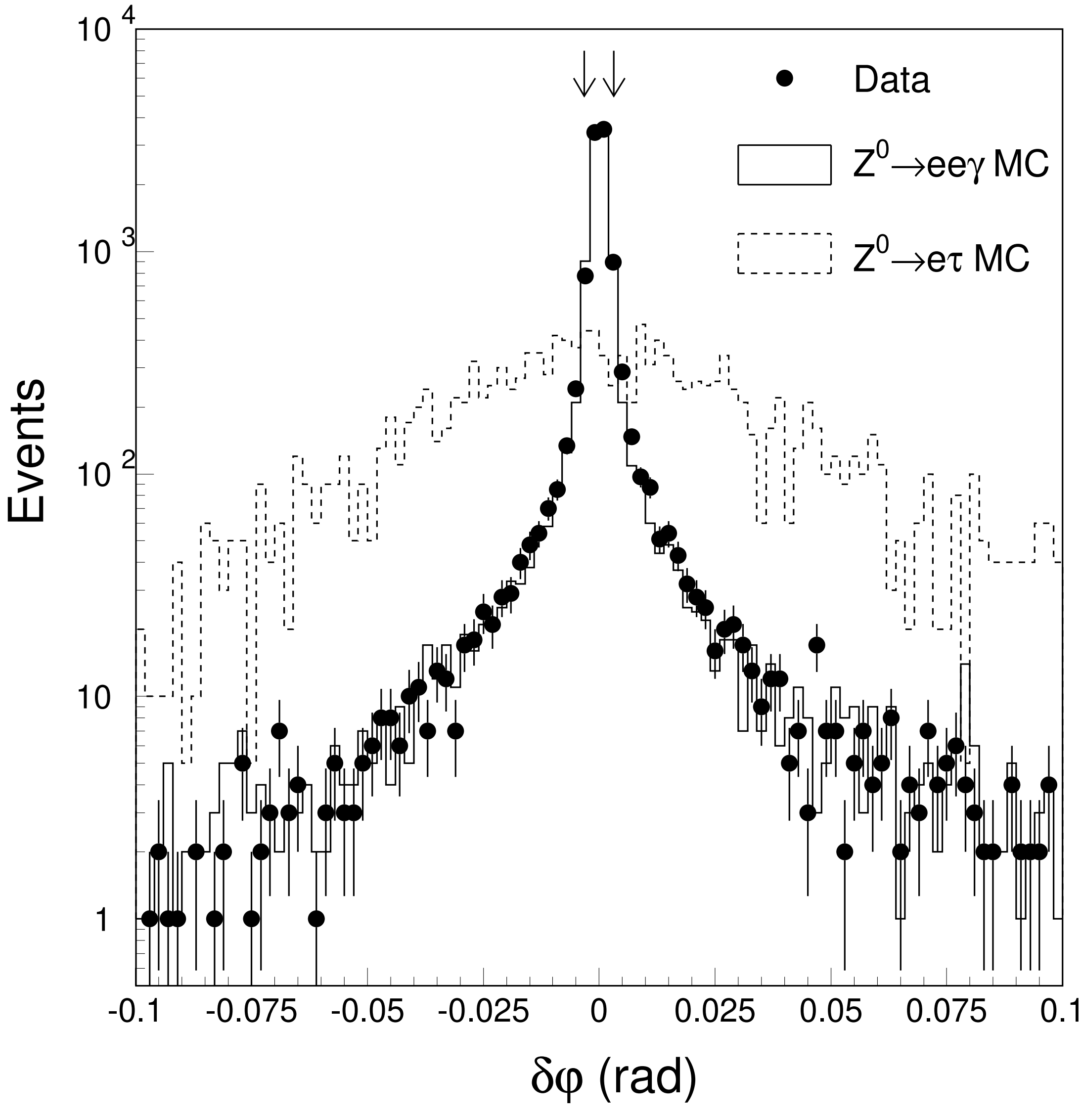
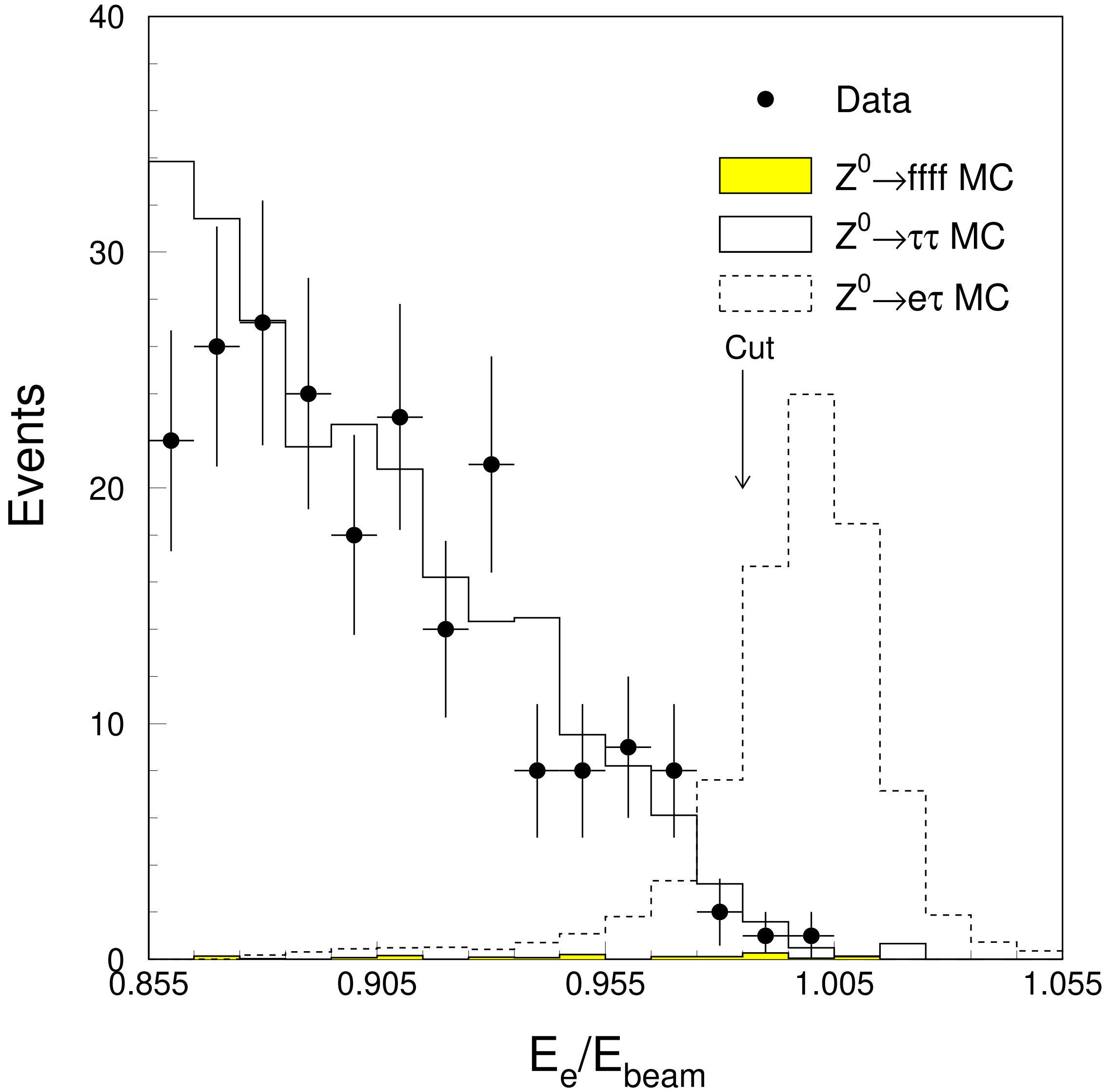


Figure 1:



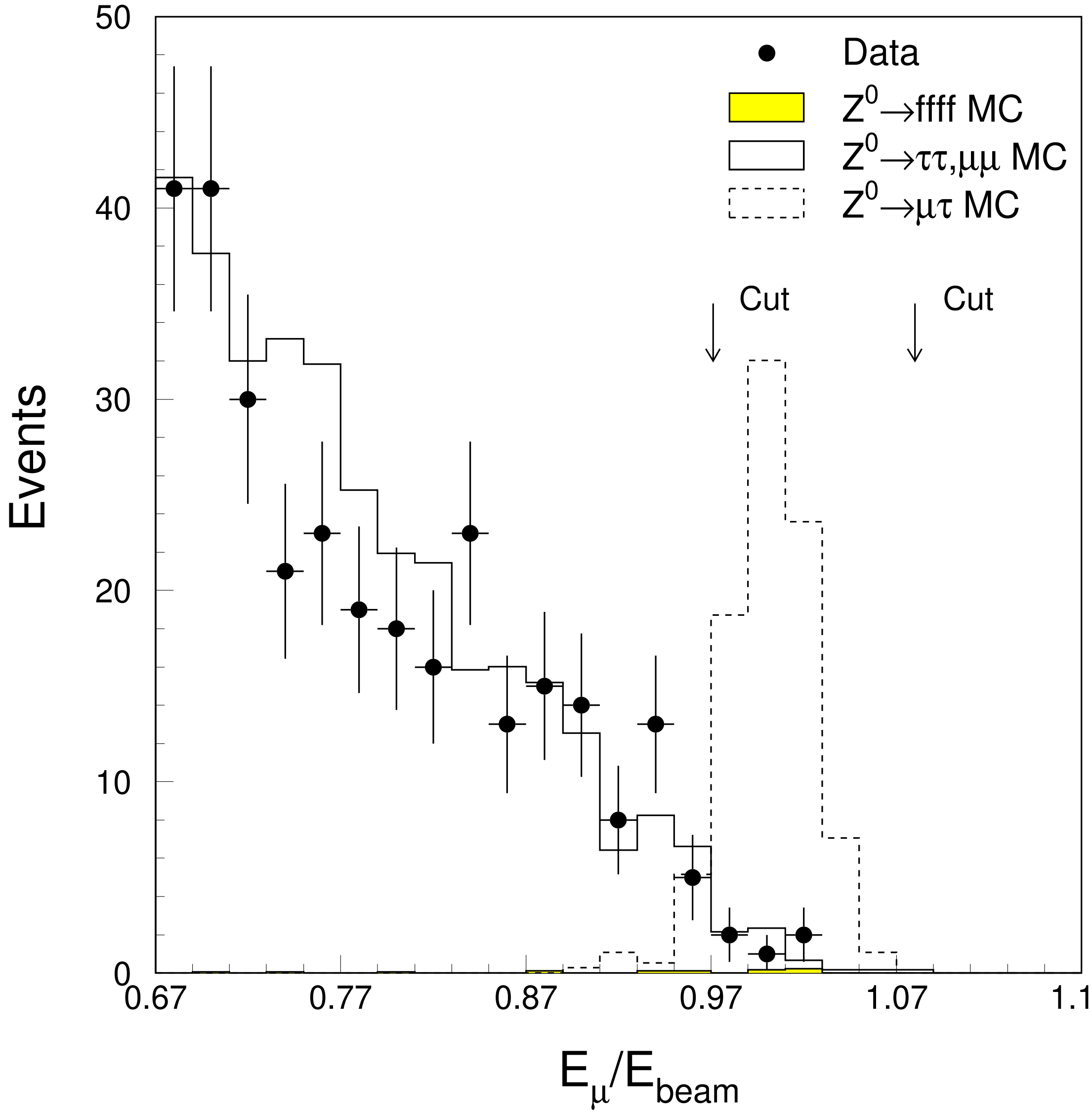
Events
Data
$Z^0 \rightarrow ee\gamma$ MC
$Z^0 \rightarrow e\tau$ MC
$\delta\varphi$ (rad)

Figure 2:



Data
$Z^0 \rightarrow ffff$ MC
$Z^0 \rightarrow \tau\tau$ MC
$Z^0 \rightarrow e\tau$ MC
Cut
Events
E_e/E_{beam}
0
10
20
30
40
0.855
0.905
0.955
1.005
1.055

Figure 3:



Data
Z0→ffff MC
Z0→ττ,μμ MC
Z0→μτ MC
Cut
Cut
Events
0
10
20
30
40
50
0.67
0.77
0.87
0.97
1.07
1.17
Eμ/Ebeam

Figure 4: