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A Search for Lepton Flavour Violation in Z^0 Decays

DELPHI Collaboration

Abstract

A search for lepton flavour violation through the decays $Z^0 \to e\mu, e\tau$ and $\mu\tau$ was made with the DELPHI detector at LEP, using a sample corresponding to an integrated luminosity of 11.2 pb^{-1}. The number of candidates was consistent with the estimated background. The upper limit on the branching ratio (at 95% confidence level) for $Z^0 \to e\mu$ was 3.2 10^{-5}, for $Z^0 \to e\tau$ was 10.8 10^{-5} and for $Z^0 \to \mu\tau$ was 13.5 10^{-5}.

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1 Introduction

Lepton flavour conservation is a feature of the Minimal Standard Model. Extensions to this model suggest that lepton flavour violation may arise either from one loop contributions from new particles (neutral heavy leptons, SUSY partners, leptoquarks etc.) or through mixing of the standard sector with new particles [1]. The latter case may induce $Z^0 \to ll'$ branching ratios as large as 10^{-4} .

Low energy experimental results [2] are mainly based on the failure to observe the neutrinoless $\mu \to$ eee and $\tau \to$ eee or $\tau \to \mu\mu\mu$ decays and indirectly give upper limits on the $Z^0 \to$ eμ, $Z^0 \to$ eτ and $Z^0 \to \mu\tau$ branching ratios. UA1 [3] has reported the result of a direct search based on a small sample of Z^0.

Here a search for lepton flavour violation in Z^0 decays into eμ, eτ and $\mu\tau$ is reported using data collected with the DELPHI detector at LEP during the 1990 and 1991 runs on an event sample corresponding to an integrated luminosity of 11.2 pb^{-1}. Direct searches for lepton flavour violation have also been performed by other LEP collaborations [4].

2 The Apparatus

The DELPHI detector is described in detail elsewhere [5]. The relevant components of the apparatus for this analysis, which was restricted to the barrel region, are: the Microvertex Detector (VD), Inner Detector (ID), Time Projection Chamber (TPC) and Outer Detector (OD), all for reconstructing the tracks of charged particles; the Time Of Flight detector (TOF) for the trigger; the barrel electromagnetic calorimeter - High density Projection Chamber (HPC); the Hadron Calorimeter (HCAL) and the Barrel Muon Chambers (MUB).

The VD consists of three layers of silicon microstrip detectors at radii of 6.3, 9 and 11 cm. The innermost layer was added for 1991 data taking; this resolved most ambiguities in pattern recognition and improved the momentum reconstruction. The OD, an array of proportional tubes located at a radius of 198 cm, reconstructs charged particle tracks very close to the HPC, thus giving an accurate matching of the extrapolated trajectory with an electromagnetic shower. The MUB system was used for μ identification and covers polar angles between 52° and 128°. A momentum resolution of 3.4% (8.0%) was obtained in the 1991 (1990) data sample for μ from $Z^0 \to \mu^+\mu^-$ decays. The electromagnetic energy resolution for e from $Z^0 \to e^+e^-$ using the HPC was 8.3% (11.0%) in the 1991 (1990) data sample. The HCAL energy resolution was $100\%/\sqrt{E(GeV)}$.

The trigger system consisted of several independent triggers based on the tracking chambers (ID, TPC and OD), MUB, HCAL and the scintillator counters of TOF and HPC. The average efficiency of the trigger for the selected barrel regions was found to be greater than 99% independent of lepton flavour and of polar angle.

3 Data Selection

A sample of low multiplicity events was selected. Further criteria were then applied to search for lepton flavour violating events with two jets (as defined below) with different lepton flavour.

In the following subsections the criteria for selecting single e, μ and τ jets will be discussed. The efficiencies of these selections were calculated relative to reference samples of events with two leptons, which were chosen with looser criteria. The efficiencies were also compared with those obtained using Monte Carlo simulations, generating the $Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$ and $Z^0 \to \tau^+\tau^-$ events through the BABAMC [6], DYMU3 [7] and KORALZ [8] programs and passing them through the DELSIM [9] program to simulate the detector response.

Events were used when LEP beam conditions were stable and when TPC, OD, MUB, HPC and HCAL were fully efficient. The tracking chambers measured the charged particle momentum, p, and the HPC the electromagnetic energy, E_{em} of the charged or neutral particles.

Particles were selected if their reconstructed trajectories were within the barrel region with polar angle, θ, between 43° and 137°. Their azimuthal angle had to be more than 2° from the TPC sector borders and the region near the TPC high voltage plane with θ between 88° and 92° was also excluded. Their azimuthal position extrapolated to the HPC had to be more than 3.5 cm from the HPC sector borders. The impact parameter of the charged particles with respect to the average interaction point was required to be less than 2.5 cm in the directions perpendicular to the beam and 5 cm in the direction parallel to the beam.

The following jet algorithm was used to define single leptons (including τ) which minimizes any difficulties arising from photon radiation or wrong association of tracks with calorimeter depositions. Initially the jet was defined as the most energetic charged or neutral particle in the event. The most energetic unused particle within 20° of this jet was then included and the four momentum of the jet redefined as the sum of the two. This was repeated for all charged and neutral particles in the event. After this the second jet was formed in the same way with the unused particles and this was repeated until no particles were left. Hereafter variables will refer to jets unless otherwise specified.

The initial selections for any two leptons required events to have between 2 and 6 charged particles making 2 jets, each with charge equal to ± 1 and collinear within 10°, with any number of additional neutral jets. Poorly reconstructed particles were avoided by rejecting events with total electromagnetic energy (E_{em}^{tot}) or absolute momentum sum for charged particles (p^{tot}) above 125 GeV. To exclude hard photons far away from both jet directions, events were rejected if they had $\{E_{em}^{tot} - (E_{em}^1 + E_{em}^2)\}$ above $0.05\sqrt{s}$, where E_{em}^i is the electromagnetic energy of jet i. To reduce background from beam gas interactions and two photon processes, p^{tot} had to be above $0.05\sqrt{s}$.

3.1 $Z^0 \to e^+e^-$ reference sample and single e identification

From the lepton pair sample, $Z^0 \to e^+e^-$ events were selected by requiring two to four reconstructed charged particles with at least two reconstructed track elements in the OD. The extra particles, in addition to the e^+ and e^-, allow for electromagnetic effects such as an early radiation from one of the e. Furthermore, each jet had to be an e jet defined in terms of the large electromagnetic energy measured in the HPC. Hence one jet had to have E_{em} between 0.6 and 1.4 of the beam energy, and the other, E_{em} between 0.3 and 1.4 of the beam energy.

Using these criteria 5996 $Z^0 \to e^+e^-$ events with two e candidates were selected. Figure 1 shows the electromagnetic energy of jets belonging to this sample.

The e jet to be used in the search for the lepton flavour violating processes $Z^0 \to e\mu$ and $Z^0 \to e\tau$ was selected requiring a jet containing just one energetic charged particle, $0.9 < E_{em}/E_b < 1.4$, p/p_b greater than 0.7, and a total energy deposition in the HCAL less than 1 GeV, where E_b and p_b are the beam energy and the beam momentum. The quality of the match between the observed longitudinal shower profile and that of an e of the same energy, was defined with a χ^2-like variable for the showers associated to a charged particle as:

$$\chi_e^2 = \sum_i (F_i - < F_i >)^2/\sigma_i^2$$

where the sum runs over the nine longitudinal layers of the HPC; F_i is the fraction of the total shower energy deposited in layer i, $< F_i >$ and σ_i are the mean and the root mean square deviation of the distribution of the energy fraction deposited in layer i by an e with energy equal to the shower energy. The values of $< F_i >$ and σ_i were determined as a function of the e energy using showers from $Z^0 \to e^+e^-$, $Z^0 \to e^+e^-\gamma$ and photon conversions. The e jet was required to satisfy χ_e^2 below 80.

The efficiency of the e jet selection was computed within the $Z^0 \to e^+e^-$ reference sample and was found to be $\varepsilon_e = (66\pm1)\%$. This efficiency has also been calculated using Monte Carlo simulation [6,9] and the two results were found to be in good agreement.

3.2 $Z^0 \to \mu^+\mu^-$ reference sample and single μ identification

The $Z^0 \to \mu^+\mu^-$ event sample was selected from the lepton pairs by requiring two or more reconstructed track elements in the OD, $0.7 < p/p_b < 1.4$ for one jet and $0.6 < p/p_b < 1.4$ for the other. Also the polar angle of the jets had to be between 52° and 128°, within the geometrical acceptance of the MUB, and there had to be a hit associated to a charged particle in each jet in at least one layer of the MUB. Since most μ give minimum ionization in the calorimeters, E_{em}/E_b had to be less than 0.3, and the total equivalent energy deposition in the HCAL to be less than 15 GeV but the sum of the energies deposited in the third and fourth layers of the HCAL to be greater than zero. Finally, to reject the cosmic-ray background, the impact parameter of both μ candidates with respect to the average interaction point had to be below 2 mm in the plane perpendicular to the beams and 1 cm in the direction parallel to the beams.

The selections above led to 3520 $Z^0 \to \mu^+\mu^-$ events. The p_b/p distribution for these jets is shown in Figure 2.

A μ jet was used in the search for the lepton flavour violating processes $Z^0 \to e\mu$ and $Z^0 \to \mu\tau$ if it had just one energetic charged particle with an associated hit in one or more layers of the MUB, $0.9 < p/p_b < 1.4$, E_{em}/E_b less than 0.1, an energy deposit in the third and fourth layer of the HCAL greater than 0.25 GeV, and a total hadronic energy less than 12 GeV. Since the background to $Z^0 \to e\mu$ was negligible (see section 4), the search for $Z^0 \to e\mu$ was made in the whole barrel region, including the region not covered by the MUB where no hit in the MUB was required for the μ jet.

Using the $Z^0 \to \mu^+\mu^-$ reference sample the μ jet selection was found to have an efficiency of $\varepsilon_\mu^{\mu\tau} = (82 \pm 2)\%$, taking into account the correlation between the selection criteria of the reference sample and the single jet, within the geometrical acceptance of MUB. This efficiency has also been computed using Monte Carlo simulations [7,9] and found to be equal to the one obtained from data within the statistical error. In the whole barrel region the efficiency was computed with Monte Carlo simulations [7,9] and found to be $\varepsilon_\mu^{e\mu} = (82 \pm 2)\%$

3.3 $Z^0 \to \tau^+\tau^-$ reference sample and single τ identification

The τ single jet identification had to be treated differently in the searches for $Z^0 \to e\tau$ and $Z^0 \to \mu\tau$ decays. For $Z^0 \to e\tau$, only the decays $\tau \to \mu\nu_\mu\nu_\tau$ and $\tau \to$hadrons were considered because if the decay $\tau \rightarrow e\nu_e\nu_\tau$ was allowed, the background from $Z^0 \rightarrow e^+e^-$ events would increase substantially. Conversely, in the search for $Z^0 \rightarrow \mu\tau$ where a background of radiative $Z^0 \rightarrow \mu^+\mu^-$ pairs would fake the $\tau \rightarrow \mu\nu_\mu\nu_\tau$ decay, only $\tau \rightarrow e\nu_e\nu_\tau$ and $\tau \rightarrow$hadrons were considered. Thus the search for $Z^0 \rightarrow e\tau$ was made in the whole barrel while the search for $Z^0 \rightarrow \mu\tau$ was restricted to polar angles between 52° and 128°, within the MUB acceptance.

In the following, the selections for $Z^0 \rightarrow e\tau$ and $Z^0 \rightarrow \mu\tau$ decays are described separately.

3.3.1 τ selection criteria for $Z^0 \rightarrow e\tau$

The $Z^0 \rightarrow \tau^+\tau^-$ reference sample used to study the τ jet in $Z^0 \rightarrow e\tau$, was selected according to the following criteria: acollinearity greater than 1°, at least two reconstructed track elements in the OD for each event, p^{tot} less than $0.85\sqrt{s}$ and E^{tot}_{em} less than $0.75\sqrt{s}$. A total of 3069 $Z^0 \rightarrow \tau^+\tau^-$ decays were selected.

Two decay modes for single τ were considered : $\tau \rightarrow \mu\nu_\mu\nu_\tau$ and $\tau \rightarrow$hadrons. A candidate jet had to have p/p_b below 0.6, and at least one associated cluster in the HCAL, while if the jet had θ between 43° and 52° (or between 128° and 137°) then the total energy deposition in the HCAL had to be above 0.5 GeV.

In addition a $\tau \rightarrow \mu\nu_\mu\nu_\tau$ candidate had to have just one charged particle and E_{em}/E_b below 0.05, while if the jet had θ between 52° and 128° it had to have one or more associated hits in the MUB.

A $\tau \rightarrow$hadrons candidate had to have one or three charged particles, E_{em}/E_b below 0.7, χ^2_e greater than 80 (or no shower in the HPC associated to any charged particle), and if the jet had θ between 52° and 128° it had to have no associated hits in the MUB.

The efficiency of the τ jet selection for either decay was computed using the $Z^0 \rightarrow \tau^+\tau^-$ reference sample and found to be $\varepsilon^{e\tau}_\tau = (44 \pm 1)\%$. It was also computed using Monte Carlo simulations [8,9] and they were found to be in agreement within statistical errors.

3.3.2 τ selection criteria for $Z^0 \rightarrow \mu\tau$

The $Z^0 \rightarrow \tau^+\tau^-$ reference sample used to study the τ jet in $Z^0 \rightarrow \mu\tau$ decays was selected according to the same criteria as in $Z^0 \rightarrow e\tau$, adding the requirement that θ be between 52° and 128°, within the MUB acceptance. A total of 2357 $Z^0 \rightarrow \tau^+\tau^-$ decays were selected.

Two decay modes for single τ were considered : $\tau \rightarrow e\nu_e\nu_\tau$ and $\tau \rightarrow$hadrons.

A $\tau \rightarrow e\nu_e\nu_\tau$ candidate had to have just one charged particle with χ^2_e below 80, E_{em}/E_b between 0.05 and 0.9, p/p_b below 0.7, and in the HCAL the total energy had to be below 0.5 GeV with no energy in the last 3 layers.

A $\tau \rightarrow$hadrons candidate had to have one or three charged particles, E_{em}/E_b below 0.7, p/p_b below 0.7, χ^2_e greater than 80 (or no shower in the HPC associated to any charged particle), at least one associated cluster in the HCAL, and no associated hits in the MUB.

The efficiency of the selection of τ decay to either type of jet computed using the $Z^0 \rightarrow \tau^+\tau^-$ reference sample was $\varepsilon^{\mu\tau}_\tau = (42 \pm 1)\%$ in agreement with the one obtained using Monte Carlo simulations [8,9] within statistical errors.

4 Search for lepton flavour violation

4.1 Candidates

A candidate event for lepton flavour violation is a Z^0 decaying into two charged leptons of different flavour, $Z^0 \to e\mu$ or $Z^0 \to e\tau$ or $Z^0 \to \mu\tau$. These events had to have two jets, each a possible single lepton, passing the initial selections for events with two leptons as defined in section 3.

No candidate was found for $Z^0 \to e\mu$, five were found for $Z^0 \to e\tau$ and six for $Z^0 \to \mu\tau$. Of the five $Z^0 \to e\tau$ candidates, three of the τ decays gave a charged π, one gave 3 charged π and one a μ. Of the $Z^0 \to \mu\tau$ candidates, three τ decayed to give a charged π, one gave 3 charged π and two an e.

Impact parameters of particles with respect to the average interaction point belonging to e, μ and τ jets of candidate events were consistent with the ones respectively found in $Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$ and $Z^0 \to \tau^+\tau^-$ reference samples. Candidate events were visually scanned and no particular feature which allowed their rejection was observed.

4.2 Background estimation

In order to estimate the background to the lepton flavour violation signal originating from leptonic Z° decays, samples of simulated $Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$ and $Z^0 \to \tau^+\tau^-$ decays were generated with the programs mentioned above[6–8]. The generated events were passed through the DELSIM [9] program to simulate the detector response and then processed through the same program chain as the data.

The main background to $Z^0 \to e\tau$ and $\mu\tau$ arises from one of the τ in $Z^0 \to \tau^+\tau^-$ giving a high momentum e or μ. Another source of background is radiating e (in $Z^0 \to e^+e^-$ events) or μ (in $Z^0 \to \mu^+\mu^-$ decays) passing the selections for a τ decay to hadrons. No such backgrounds were found for $Z^0 \to e\mu$.

The number of candidates is compatible with the total number of background events as seen in Table 1. Figure 3 shows for the search $Z^0 \to e\tau$ the distribution of E_{em}/E_b for the e jets with no requirements on E_{em}, compared to the spectrum for simulated $Z^0 \to \tau^+\tau^-$ and $Z^0 \to e^+e^-$ events. The E_{em}/E_b distribution for $Z^0 \to e^+e^-$ events is indicated by the Gaussian. Figure 4 shows for the search $Z^0 \to \mu\tau$ a similar plot of p/p_b for the μ jets with no requirements on p, compared to the spectrum for simulated $Z^0 \to \tau^+\tau^-$ and $Z^0 \to \mu^+\mu^-$ decays. The p/p_b distribution for $Z^0 \to \mu^+\mu^-$ events is indicated by the Gaussian.

4.3 Upper limits on branching ratios

Poisson statistics with the central values obtained for background [10] were used to find the upper limit on the number of predicted lepton flavour violating events. The background to each channel was computed as the sum of backgrounds arising from $Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$ and $Z^0 \to \tau^+\tau^-$ decays and Table 1 shows the values of background to the various channels and the statistical error on it. Upper limits on the numbers of produced $Z^0 \to e\mu$, $e\tau$ and $\mu\tau$ at 95% confidence level are given in Table 1. To obtain the corresponding limit on the branching ratios for Z^0 decays (to $e\mu$ for instance) the following formula was used:

$$\mathrm{BR}(Z^0 \to e^-\mu^+ + e^+\mu^-) < N_{e\mu} BR(Z^0 \to e^-e^+)/\varepsilon_e \varepsilon_\mu^{e\mu} N_{e^+e^-}$$

where:

$N_{e\mu}$	upper limit on $e\mu$ events
ε_e	single e efficiency
$\varepsilon_\mu^{e\mu}$	single μ efficiency in the barrel region
$N_{e^+e^-}$	number of $Z^0 \to e^+e^-$ events within the geometrical acceptance corrected for selection efficiencies, $Z^0 \to \tau^+\tau^-$ contamination and t-channel contribution. The efficiency, calculated using Monte Carlo simulated events [6], was found to be $(88 \pm 2)\%$. The $Z^0 \to \tau^+\tau^-$ contamination was computed using Monte Carlo simulations [8,9]. The t-channel contribution was calculated from reference [6] and found to be 15% in the angular region used in the search for $Z^0 \to e\tau$ and 10% for $Z^0 \to \mu\tau$. $N_{e^+e^-} = 5747 \pm 75$ in the whole barrel and $N_{e^+e^-} = 4549 \pm 67$ in the MUB acceptance region.
$BR(Z^0 \to e^+e^-)$	was recently measured combining the results of the four LEP collaborations [11] : $(3.345 \pm 0.02)10^{-2}$.

The normalization obtained from $N_{e^+e^-}$ was compared with the one obtained from $Z^0 \to \mu^+\mu^-$ and Bhabha events at small polar angle and was found to be equal within statistical errors. Upper limits on the branching ratios are given in Table 2, where the limits obtained in other experiments are also shown [4].

5 Summary and conclusion

A search for lepton flavour violation in Z^0 decays at LEP showed no evidence for a signal. Upper limits (at 95% confidence level) on branching ratios are 3.2 10^{-5} for $Z^0 \to e\mu$, 10.8 10^{-5} $Z^0 \to e\tau$ and 13.5 10^{-5} for $Z^0 \to \mu\tau$.

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Figure captions

- Figure 1: Electromagnetic energy scaled to beam energy for the jets belonging to the $Z^0 \to e^+e^-$ reference sample.
- Figure 2: Inverse momentum scaled to the beam momentum for the jets belonging to the $Z^0 \to \mu^+\mu^-$ reference sample.
- Figure 3: Electromagnetic energy scaled to beam energy, for the e jet when the cut on E_{em} is removed from the selections for $Z^0 \to e\tau$, for data (dots). The solid line is Monte Carlo simulated $Z^0 \to \tau^+\tau^-$ and $Z^0 \to e^+e^-$ events that have passed the same cuts. The Gaussian indicates the measured resolution of electromagnetic energy for e from $Z^0 \to e^+e^-$ which hence is the expected distribution for any $Z^0 \to e\tau$ signal.
- Figure 4: Momentum scaled to beam momentum, for the μ jet when the cut on p is removed from the selections for $Z^0 \to \mu\tau$, for data (dots). The solid line is Monte Carlo simulated $Z^0 \to \tau^+\tau^-$ and $Z^0 \to \mu^+\mu^-$ events that have passed the same cuts. The Gaussian indicates the measured resolution of momentum for μ from $Z^0 \to \mu^+\mu^-$ which hence is the expected distribution for any $Z^0 \to \mu\tau$ signal.

Table 1 : Number of candidate events, background contribution and upper limit on predicted number of events for $Z^0 \to e\mu$, $Z^0 \to e\tau$ and $Z^0 \to \mu\tau$.

Z^0 decay mode	$e\mu$	$e\tau$	$\mu\tau$
Number of candidates	0	5	6
e^+e^- background	0	1.6±1.1	0
$\mu^+\mu^-$ background	0	0	1.5±0.6
$\tau^+\tau^-$ background	0	5.7±1.3	5.3±1.2
Upper limit of predicted events at 95% CL	3.0	5.4	6.3

Table 2 : Upper limits on branching ratios for $Z^0 \to e\mu$, $Z^0 \to e\tau$ and $Z^0 \to \mu\tau$.

	$BR(Z^0 \to e\mu)$	$BR(Z^0 \to e\tau)$	$BR(Z^0 \to \mu\tau)$
Low energy exp. at 90% CL	$7.5\ 10^{-13}$	$10.0\ 10^{-5}$	$6.0\ 10^{-5}$
OPAL at 95% CL	$4.6\ 10^{-5}$	$7.2\ 10^{-5}$	$35.0\ 10^{-5}$
L3 at 95% CL	$2.4\ 10^{-5}$	$3.4\ 10^{-5}$	$4.8\ 10^{-5}$
ALEPH at 95% CL	$2.6\ 10^{-5}$	$12.0\ 10^{-5}$	$10.0\ 10^{-5}$
DELPHI at 95% CL	$3.2\ 10^{-5}$	$10.8\ 10^{-5}$	$13.5\ 10^{-5}$

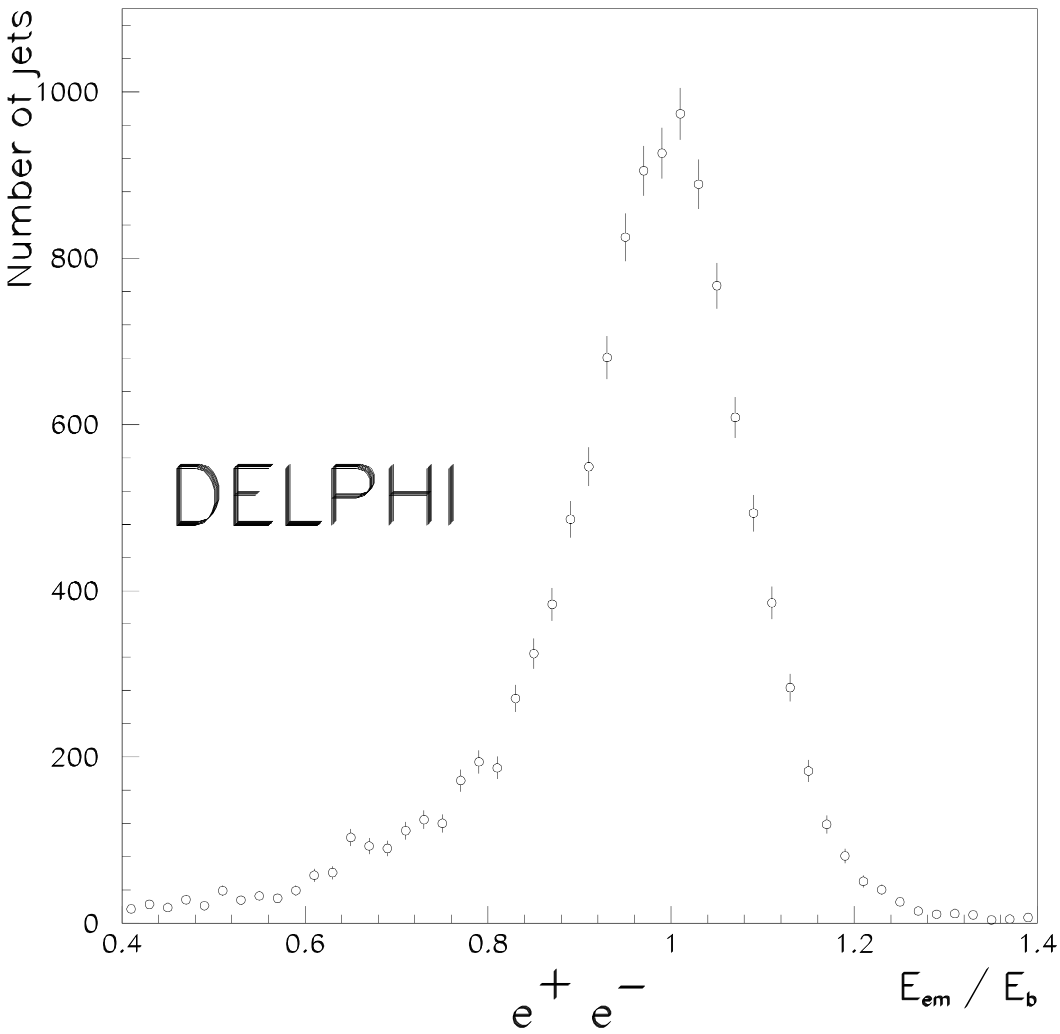

Figure 1: Electromagnetic energy scaled to beam energy for the jets belonging to the $Z^0 \to e^+e^-$ reference sample.

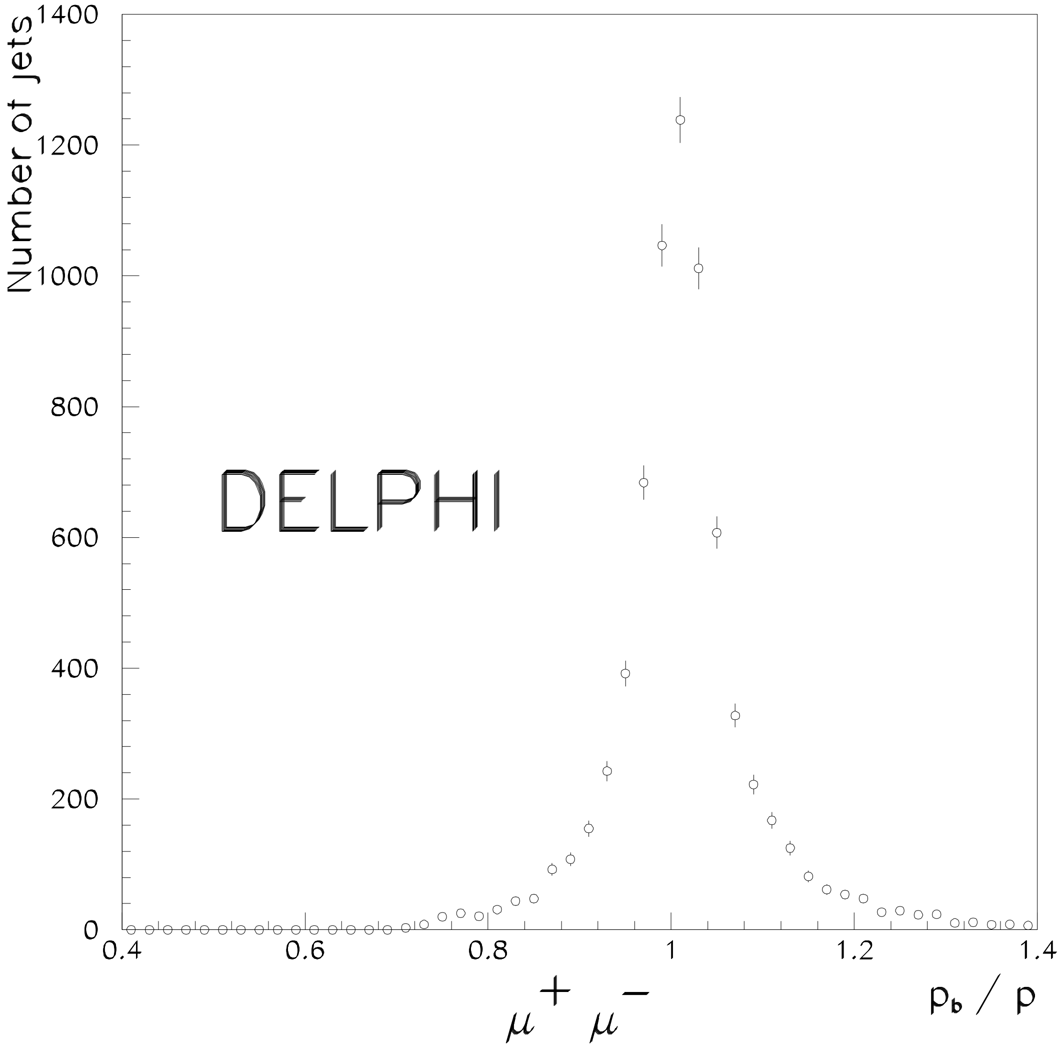

Figure 2: Inverse momentum scaled to the beam momentum for the jets belonging to the $Z^0 \to \mu^+\mu^-$ reference sample.

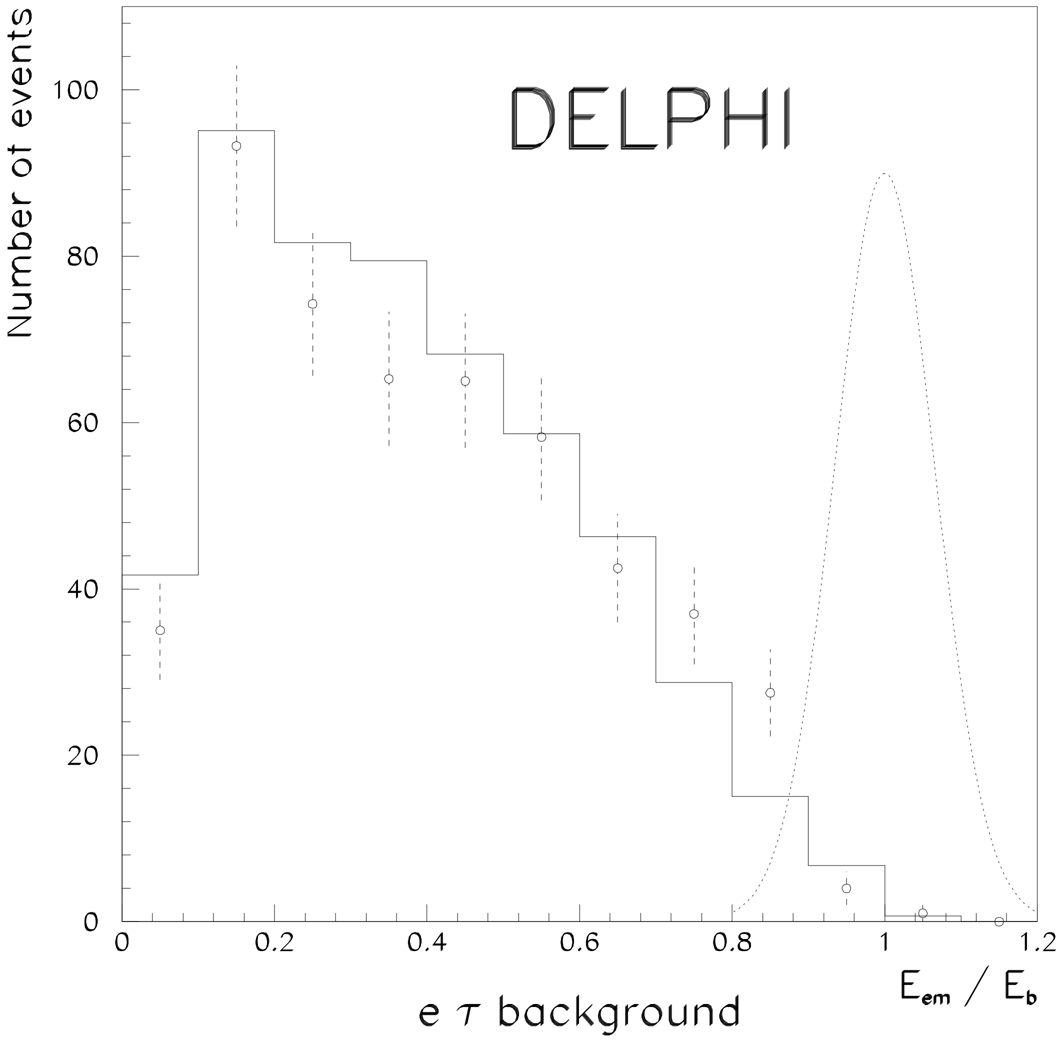

Figure 3: Electromagnetic energy scaled to beam energy, for the e jet when the cut on E_{em} is removed from the selections for $Z^0 \to e\tau$, for data (dots). The solid line is Monte Carlo simulated $Z^0 \to \tau^+\tau^-$ and $Z^0 \to e^+e^-$ events that have passed the same cuts. The Gaussian indicates the measured resolution of electromagnetic energy for e from $Z^0 \to e^+e^-$ which hence is the expected distribution for any $Z^0 \to e\tau$ signal.

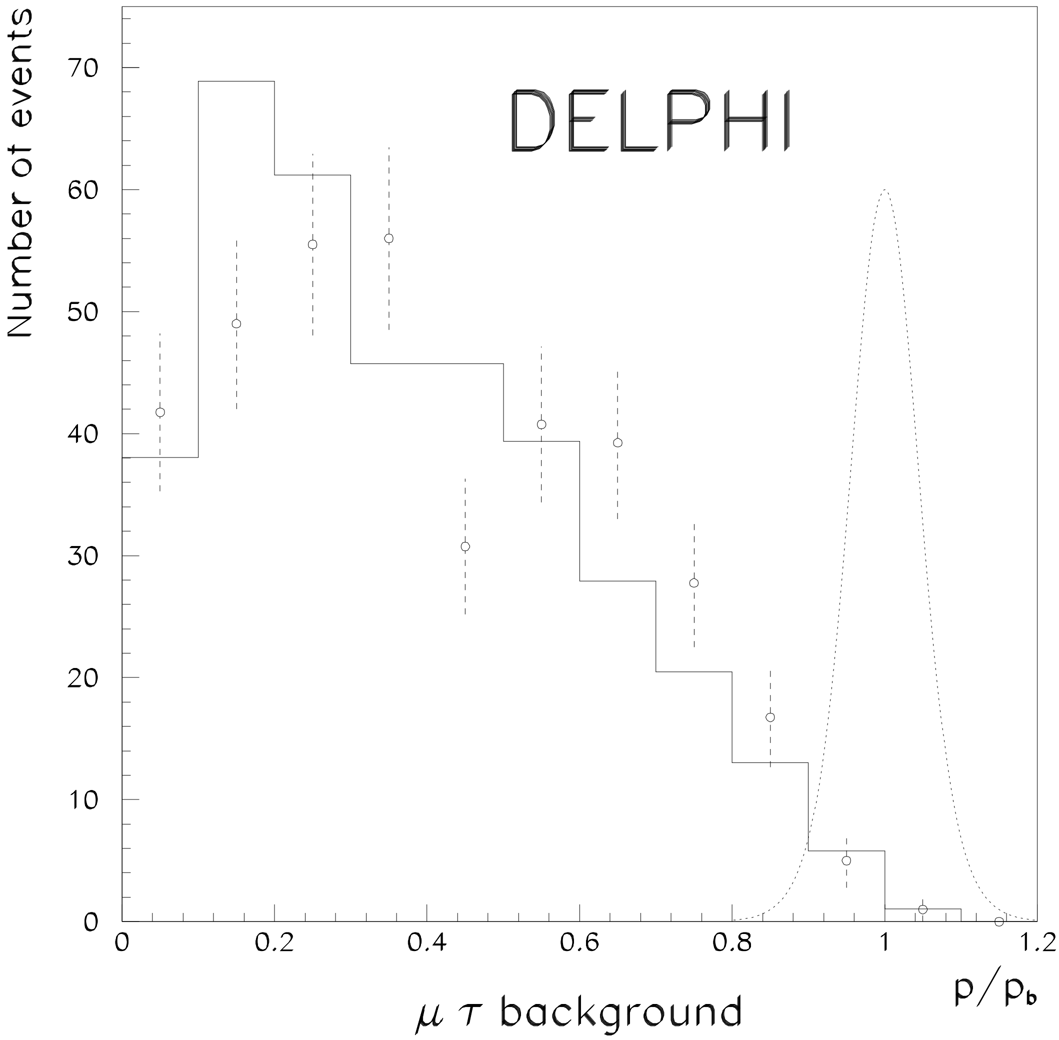

Figure 4: Momentum scaled to beam momentum, for the μ jet when the cut on p is removed from the selections for $Z^0 \to \mu\tau$, for data (dots). The solid line is Monte Carlo simulated $Z^0 \to \tau^+\tau^-$ and $Z^0 \to \mu^+\mu^-$ events that have passed the same cuts. The Gaussian indicates the measured resolution of momentum for μ from $Z^0 \to \mu^+\mu^-$ which hence is the expected distribution for any $Z^0 \to \mu\tau$ signal.