Tau Lepton Leptonic Branching Fractions from L3

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We have measured the branching fractions of the τ lepton into electrons and muons with the L3 detector at LEP. The sample used in analysis has been collected during 1991, 1992 and 1993 around the Z peak, with an integrated luminosity of 61 pb^{-1}. A preliminary result yields:

$$\mathrm{BR}(\tau^- \to \mathrm{e}^-\overline{\nu}_e\nu_\tau) = (17.69 \pm 0.17 \pm 0.08)\% \quad (1)$$

$$\mathrm{BR}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau) = (17.36 \pm 0.17 \pm 0.07)\% \quad (2)$$

where the first error is statistical and the second one is systematic.

1. Introduction

LEP, the Large Electron Positron collider, is a suitable place for the study of the tau lepton. The $\mathrm{Z} \to \tau^+\tau^-(\gamma)$ decay has a clear signature due to the presence of neutrinos and the low multiplicity and high boost of the decay products. It usually produces two very collimated back-to-back jets with few particles and missing energy-momentum. Its high center of mass energy makes the hadronic background small.

A precise determination of the leptonic branching ratios of the τ, $\mathrm{B_e} \equiv \mathrm{BR}(\tau^- \to \mathrm{e}^-\overline{\nu}_e\nu_\tau)$ and $\mathrm{B}_\mu \equiv \mathrm{BR}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$ has a major physical interest:

- A measurement of the ratio $\mathrm{B}_\mu/\mathrm{B_e}$ allows is a test of $e-\mu$ universality:

$$\frac{B_\mu}{B_e} = 0.973\left(\frac{g_\mu}{g_e}\right)^2 \quad (3)$$

  where g_l is the coupling constant in the $\mathrm{W}^- \to \mathrm{l}^-\overline{\nu}_\mathrm{l}$ vertex. The value should be compared with the most precise one coming from $\pi \to e\nu_e$ decays [1].

- Combined with the measurement of the τ lifetime, a very sensitive test of the $\tau-\mu$ universality is performed through the relation:

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}B_e\left(\frac{m_\mu}{m_\tau}\right)^5 \quad (4)$$

  where τ_l and m_l are the lifetime and mass of the lepton l.

- Assuming universality in the leptonic sector the previous formula stands as a test of consistency between τ_τ, $\mathrm{B_e}$ and the present value of m_τ [2]. A value of m_τ may also be derived using the linear relation between τ_τ and $\mathrm{B_e}$.

- A very precise value of the strong coupling constant, α_s, is determined from the ratio between hadronic and leptonic branching fractions of the τ. Assuming $e-\mu$ universality:

$$R^\tau_{HAD} = \frac{B_H}{B_e} = \frac{1}{B_e} - 1.973 \quad (5)$$

This way is affected by small theoretical uncertainties [3] which make it competitive with other measurements based on topologies of hadronic events.

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The L3 detector has been described in detail elsewhere [4]. Here we summarize the selection, analysis and preliminary results for the B_e and B_μ branching fractions.

2. Selection of $Z \rightarrow \tau^+\tau^-(\gamma)$ events

Decays of the Z into $\tau^+\tau^-(\gamma)$ events are triggered in the L3 detector by energy, charged tracks and muon triggers. The combined efficiency of each independent trigger is very high, leading to a combined trigger efficiency greater than 99.9% for the sample that will be used in the following.

The event is divided in two hemispheres according to the plane perpendicular to the thrust axis. Only events having the polar angle of the thrust inside the "fiducial volume" $\mid cos(\theta_{th}) \mid < 0.72$ will be considered. Hadronic events are supressed cutting on charged and neutral multiplicity and requiring no more than one charged track outside a region of 20 degrees around the azimuthal projection of the thrust axis. $Z^0 \rightarrow e^+e^-(\gamma)$ and $Z^0 \rightarrow \mu^+\mu^-(\gamma)$ events are rejected if the energy deposit in the BGO or the momentum measured in the muon chambers is greater than 80% of the beam energy for any hemisphere. To be less sensitive to energy resolution and detector inefficiencies an acoplanarity cut ($>$ 10 mrad) is also imposed (figure 1). These two cuts reduce somehow the signal efficiency but eliminate dangerous backgrounds in a safer way.

Events with low energy in the calorimeters ($<$ 8 GeV) and low transverse momentum imbalance ($<$ 3 GeV) are mostly due to non-resonant four fermion processes ("two photon" events) and cosmic rays and are therefore rejected. Another cut on acollinearity ($<$ 0.3) is applied to kill any event with high longitudinal imbalance. A further cosmic rejection is made by eliminating events with activity in the muon chambers but bad scintillator timing (outside a 5 ns window with respect to the beam crossing).

The integrated luminosity after subtraction of the periods where the complete detector was not properly working is 61 pb^{-1}. A total of 31606 $Z \rightarrow \tau^+\tau^-(\gamma)$ events were selected with an efficiency of 70% in the fiducial volume. The background in this sample was estimated to be 0.8% from $Z \rightarrow \mu^+\mu^-(\gamma)$, 0.1% from $Z \rightarrow e^+e^-(\gamma)$, 0.3% from $Z \rightarrow q\bar{q}(\gamma)$ and 0.3% from "two photon" events.

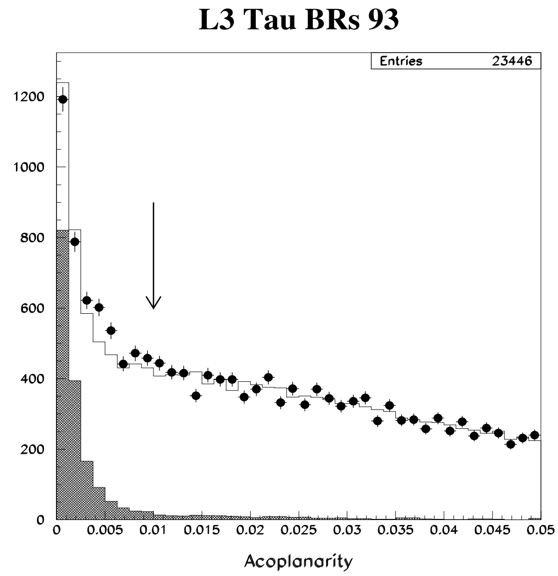

Figure 1. Acoplanarity (1993 data) between the two most energetic back-to-back tracks in the event. All cuts to select $\tau\tau$ events have been already applied, except the one shown in the figure. Points are data and histogram is Monte Carlo. The white area is the $\tau\tau$ signal and the coloured one is the background. The left part of the plot is dominated by dimuons and bhabhas from the Z.

3. Selection of $\tau^- \rightarrow e^-\overline{\nu}_e\nu_\tau$ events

Electrons are seen in the L3 detector as a track in the inner chamber with an electromagnetic shower in the BGO and small or no hadronic energy behind. This shower must have the characteristics of an electromagnetic particle shower: it must be symmetric and narrow. In order to match this requirement the energy deposit in the "square" of 9 crystals around the most energetic point must be greater than 95% of the total energy in 25 crystals: $E_9/E_{25} > 0.95$. In addition the χ^2 value of the fit to the expected electromagnetic sharing between those 9 crystals must be less than 6.

To remove hadronic decays a precise matching between the TEC track and the shower is needed: the angular difference between the charged track and the cluster must be less than 10 mrad in the bending plane and less than 20 mrad in the longitudinal projection(figure 2. The χ^2 of matching between the TEC momentum and the BGO energy is required to be less than 6. In addition, candidates are asked for having less than 20% of its energy in the hadron calorimeter and no muon chamber activity.

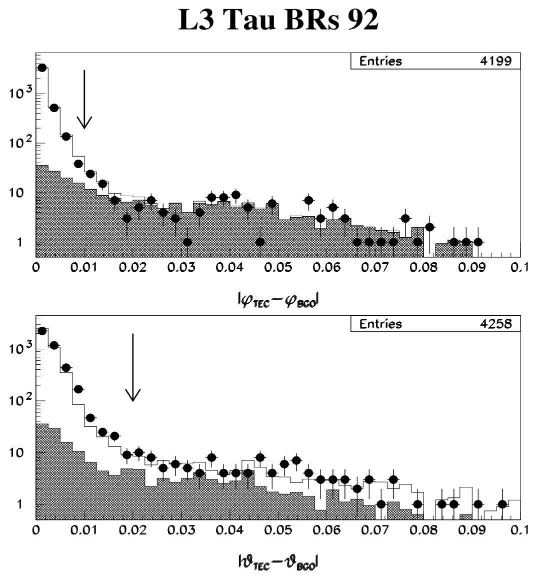

Figure 2. Angular difference between the TEC track predictions and the BGO cluster in transverse (a) and longitudinal (b) projections (1992 data). Events passed all cuts for electron identification but the cut shown on the plot. Points are data and histogram is Monte Carlo. The white area is the $\tau \to e$ signal and the coloured one is the background, dominated by other tau decays.

After these cuts we find 9857 electron candidates with an efficiency of 85% on the $\tau\tau$ sample, a total efficiency of 60% in the fiducial volume and a background of 2.4% from other tau decays, 0.2% from Z $\to e^+e^-(\gamma)$, 0.05% from Z $\to \mu^+\mu^-(\gamma)$ events and 0.8% from "two–photon" processes.

4. Selection of $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ events

Typical muons are seen in the L3 detector as a track in the TEC chamber, with minimum ionization in electromagnetic and hadronic calorimeters and a track in the muon system. In the case of signal in the muon chambers, we require a segment track in at least two of the three possible layers. The associated energy in the hadron calorimeter must be either less than 4 GeV or less than the energy measured by the muon chambers to remove punch-through and hadronic decays.

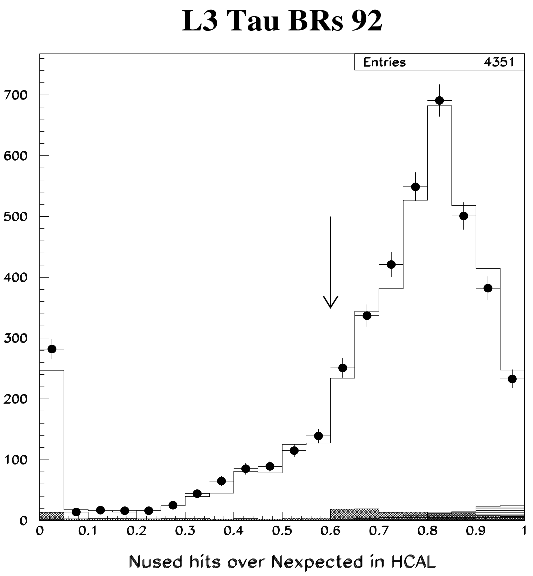

Figure 3. Number of used hits over the number of expected hits in the L3 hadron calorimeter. Events passed all cuts for muon identification. Points are data and histogram is Monte Carlo. The white area is the $\tau \to \mu$ signal and the coloured one is the background (dominated by other tau decays).

Table 1
Definition of the efficiencies used for the determination of the leptonic branching fractions.

EFFICIENCY TYPE	Meaning	
	Selected hemisphere	Opposite hemisphere
ϵ_{SS}	$\tau \to l$	$\tau \to l$
ϵ_{SB}	$\tau \to l$	$\tau \to$ background
ϵ_{BS}	$\tau \to$ background	$\tau \to l$
ϵ_{BB}	$\tau \to$ background	$\tau \to$ background
ϵ_{NN}	non $- \tau$	non $- \tau$

In order to minimize systematic uncertainties due to dead cells and edge effects in the muon spectrometer, decays are also selected if their shower development in the hadronic calorimeter is consistent with that of a minimum ionization particle, that is, they must leave less than 4 GeV in the hadron calorimeter and more than 60% of the expected proportional tubes along the particle direction must give a signal (figure 3).

With this selection we find 10246 muon candidates with an efficiency of 90% on the $\tau\tau$ sample and a total efficiency of 62% in the fiducial volume. We estimate to 3.5% the background coming from hadronic decays of the τ, to 2.5% the one coming from $Z^0 \to \mu^+\mu^-(\gamma)$ events and to 0.4% the one coming from "two–photon" processes.

5. Determination of the branching fractions

The leptonic branching ratios of the τ decay are determined from the ratio of the number of $\tau \to l\nu\nu$ events to the total number of $\tau^+\tau^-$ selected events. We have choosed this option instead of normalizing to the expected number of $\tau^+\tau^-$ events from luminosity because:

- Many of the experimental systematic discrepancies are negligible in the previous ratio (TEC inefficiencies, for instance).
- Using the experimentally measured $\tau^+\tau^-$ cross section will not help statistically and introduces additional systematic effects to be studied.
- Using the theoretical cross section introduces a dependence on α_s:

$$\frac{\Delta\sigma_{\tau^+\tau^-}}{\sigma_{\tau^+\tau^-}} \approx \frac{2}{\pi}\,\frac{\Gamma_H}{\Gamma_Z}\,\Delta\alpha_s(m_Z^2) \tag{6}$$

that is, a 0.5% bias for a variation of $\Delta\alpha_s = 0.01$. This is not nice for an expected accuracy of that order of magnitude. Moreover, if we want to use our B_l value for a precise determination of α_s the method must be abandoned.

We will define ϵ_{SS}, ϵ_{SB}, ϵ_{BS}, ϵ_{BB} and ϵ_{NN} to be the efficiencies of selecting a candidate as a function of the event configuration. A clear explanation of their meaning is presented in table 1. We determine B_l from the following relations:

$$R_l = \frac{\epsilon_{\tau\tau} + \epsilon_{NN}\ (\sigma_{NN}/\sigma_{\tau\tau})}{\epsilon'_{\tau\tau} + \epsilon'_{NN}\ (\sigma_{NN}/\sigma_{\tau\tau})} \tag{7}$$

$$\epsilon_{\tau\tau} = \epsilon_{SS}\ B_l^2 + (\epsilon_{SB} + \epsilon_{BS})\ B_l(1 - B_l) \tag{8}$$

$$+\epsilon_{BB}\ (1 - B_l)^2 \tag{9}$$

$$\epsilon'_{\tau\tau} = \epsilon'_{SS}\ B_l^2 + (\epsilon'_{SB} + \epsilon'_{BS})\ B_l(1 - B_l) \tag{10}$$

$$+\epsilon'_{BB}\ (1 - B_l)^2 \tag{11}$$

where ϵ' stands for the efficiencies in the sample of selected taus before lepton identification cuts and $\sigma_{NN}/\sigma_{\tau\tau}$ takes into account the different cross sections of the non-$\tau^+\tau^-$ processes. The quantity R_l is what is really measured:

$$R_l = \frac{\text{Number of selected leptonic decays}}{\text{Number of selected } \tau \text{ hemipheres}} \tag{12}$$

The advantage of this approach is that the measured value does not depend at all on the input value present in the Monte Carlo for B_l. In addition, any correlation between hemispheres due to cuts is automatically taken into account.

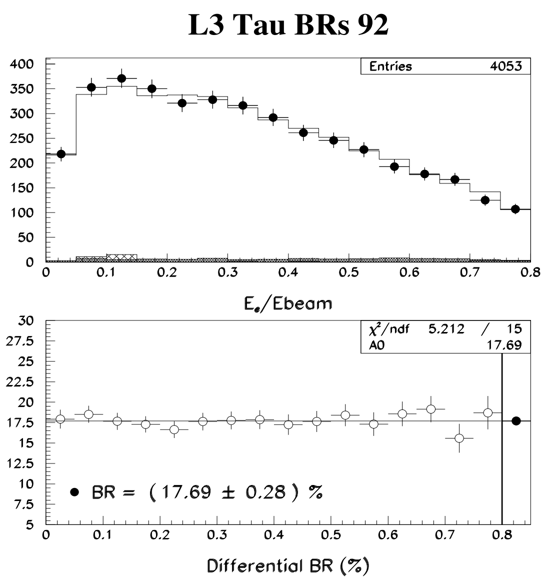

Figure 4. Electron energy normalized to the beam energy at the Z peak in 1992. We determine the differential branching ratio to isolate possible biases in the identification as a function of the energy. The χ^2 of the fit to a constant value is reasonable. Points are data, empty and coloured histograms are the total MC expectation and the background contributions, respectively.

Tables 2 and 3 contain the measured values of B_e and B_μ after taking into account efficiency corrections and background subtraction. Since the behaviour of the detector is different for each year, values have been determined year by year with a real Monte Carlo simulation of dead channels and resolutions. The relative backgrounds are not the same at all energies ($Z \rightarrow ee$ is a good example), thus forcing another splitting for 1993. We have neglected this effect in 1991, where the statistics is low and there are too many energy points. The first error shown is purely statistical

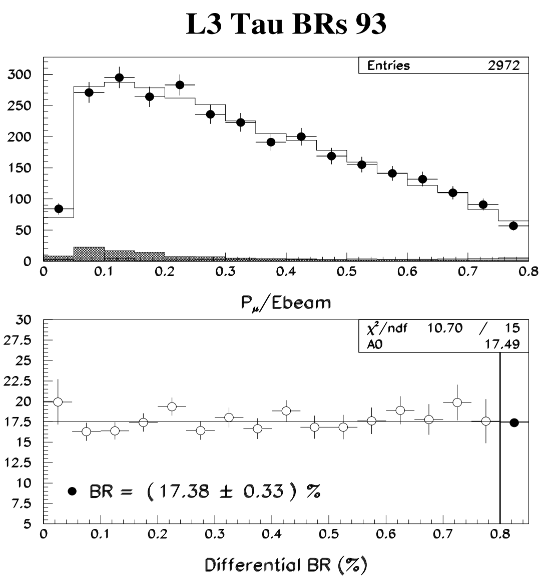

Figure 5. Muon momentum normalized to the beam energy at the Z peak in 1993. We determine the differential branching ratio to isolate possible biases in the identification as a function of the energy. The χ^2 of the fit to a constant value is reasonable. Points are data, empty and coloured histograms are the total MC expectation and the background contributions, respectively.

and the second is systematic due to the available Monte Carlo statistics. The final value was determined averaging all independent results and taking into account correlations (Monte Carlo events are identical at generator level for 1991, 1992 and 1993 at 91 GeV).

The energy and momentum distributions for electrons and muons are shown in figures 4 and 5, together with the differential determination of the branching ratio on a bin by bin basis.

6. Systematic uncertainties

Many discrepancies between data and simulation, like detector inefficiencies and acceptances, affect in the same way the numerator and the denominator of R_l. The background from $Z \rightarrow \mu\mu$

Table 2
L3 values for the branching ratio of the τ lepton into electrons. The first error is statistical and the second one is the statistical error due to the limited Monte Carlo statistics.

Year	Energy (GeV)	BR($\tau^- \to e^- \overline{\nu}_e \nu_\tau$) (%)
1991	**88-94**	**17.42 ± 0.42 ± 0.07**
1992	**91.2**	**17.69 ± 0.27 ± 0.08**
1993	**91.2**	**17.41 ± 0.31 ± 0.07**
1993	**89.4**	**18.91 ± 0.73 ± 0.15**
1993	**93.0**	**18.31 ± 0.62 ± 0.16**
Average		**17.69 ± 0.17 ± 0.06**

Table 3
L3 values for the branching ratio of the τ lepton into muons. The first error is statistical and the second one is the statistical error due to the limited Monte Carlo statistics.

Year	Energy (GeV)	BR($\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$) (%)
1991	**88-94**	**16.79 ± 0.43 ± 0.08**
1992	**91.2**	**17.84 ± 0.27 ± 0.08**
1993	**91.2**	**17.38 ± 0.32 ± 0.07**
1993	**89.4**	**17.50 ± 0.73 ± 0.14**
1993	**93.0**	**15.97 ± 0.63 ± 0.15**
Average		**17.36 ± 0.17 ± 0.06**

and Z $\to ee$ is so small than it gives a negligible systematic error. The only sizeable effects come from discrepancies at the level of leptonic cuts They will be discussed in the following.

In the case of electrons we have selected a sample of high energy electrons from the Z. This is done by applying all cuts that were used for selecting $\tau^+\tau^-$ events (see section 2) except those rejecting Z $\to ee$. On this sample we compare data and Monte Carlo efficiencies in those hemispheres with a very high energy electron on the opposite side (more than 0.97 times the beam energy). After some ad-hoc corrections due to the existence of dead crystals not included in the simulation there is a reasonable agreement (see figure 6). The remaining differences are known to be due to TEC chamber inefficiencies and BGO effects that do not seem to be energy dependent, leading to the global factors of the table 4. Their weighted statistical error will be considered as a systematic error (0.2%). A further check was to apply all identification cuts on a sample of electrons at low energy. We found also a 0.1% discrepancy in the range from 1 GeV to 4 GeV, to be added in quadrature to the previous estimate.

Table 4
Correction factors for the efficiency of the cuts identifying electrons at 45 GeV. The error quoted is the statistical error in the determination from Z $\to ee$ events.

Year	Correction factor for electrons
1991	**1.0230 ± 0.0031**
1992	**1.0233 ± 0.0018**
1993	**1.0253 ± 0.0022**

To study the muon efficiency we have selected a sample of dimuons using events with TEC momentum greater than 20 GeV and calorimetric energy less than 5 GeV on both hemi-

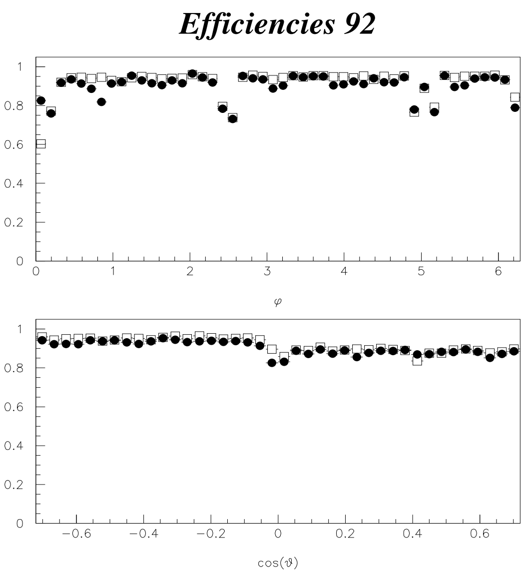

Figure 6. Efficiency of the identification cuts for electrons from a Z $\rightarrow$ ee sample (1992 data). Black dots are data and white squares are Monte Carlo.

spheres. This selection is almost independent of the hadronic calorimeter and the muon spectrometer behaviours and acts as a probe at the common edges of both subdetectors. The discrepancies between data and Monte Carlo for identifying a muon are found to be statistically inconsistent (table 5) by at most 0.23% and will be considered as a systematic error.

Variations of signal and background efficiencies in formula (7) could have an influence on the final result. The effect is dangerous in the case of Z $\rightarrow$ ee and Z $\rightarrow$ $\mu\mu$, where any excess of events gets possibly selected at the end (they are also leptons). This is why we have made very taugh cuts for these backgrounds. On the other hand, these cuts reject more signal than background events in the $\tau\tau$ sample, changing the relative efficiencies. One way of checking that there is agreement between data and MC consists in keeping all dileptons in the denominator of R_l while rejecting them only in the numerator. Comparing with the usual method, we found that the global discrepancy is consistent with the change in statistics. Therefore we will not assign any systematic error.

Antiselection of bhabhas and dimuons by means of energy and acoplanarity cuts shows no discrepancy between data and MC within statistical errors.

For "two photon" events and cosmics we have made an antiselection based on their typical properties: transverse energy balance, low energy. We found that the observed cross section could be wrong by $\pm$ 20%. This yields a systematic effect of 0.1% for B_μ and 0.2% for B_e.

We have also determined the differential branching ratio as a function of the lepton energy (see figures 4 and 5). It is rather constant, giving a reasonable χ^2 for all cases. This confirms the hypothesis that any inefficiency must be a global factor and that backgrounds from Z $\rightarrow$ ee and Z $\rightarrow$ $\mu\mu$ have been correctly taken into account. There is no signal of any structure due to the value of the τ polarization that has been introduced in the simulation.

Adding all these systematic contributions in quadrature we estimate an additional relative systematic error of 0.25% in B_μ and of 0.28% for B_e. Combined with the values and statistical errors of tables 2 and 3, we get the following preliminary result:

$$B_e = (17.69 \pm 0.17 \pm 0.08)\% \quad (13)$$
$$B_\mu = (17.36 \pm 0.17 \pm 0.07)\% \quad (14)$$

7. Interpretation of the results

The measured ratio of muonic to electronic branching fractions is (statistical and systematic uncertainties in B_e and B_μ can be taken as uncorrelated):

$$\frac{B_\mu}{B_e} = 0.981 \pm 0.014 \quad (15)$$

Using formula (3) we get:

$$\frac{g_\mu}{g_e} = 1.004 \pm 0.007 \quad (16)$$

Table 5
Data and MC efficiencies on a reference dimuon sample, which has been selected using only TEC and calorimetric energy information. They are found to be 0.23% systematically different.

Year	**Efficiency on Data (%)**	**Efficiency on MC (%)**
1991	**96.35 ± 0.26**	**96.05 ± 0.05**
1992	**96.07 ± 0.15**	**96.02 ± 0.05**
1993	**96.59 ± 0.13**	**96.14 ± 0.04**
All	**96.35 ± 0.09**	**96.11 ± 0.04**

in good agreement with $e-\mu$ universality of the weak charged current. We will then assume universality to extract a value of B_e from B_μ:

$$B_e = 1.028\ B_\mu = (17.85\ \pm\ 0.18)\% \tag{17}$$

The average with the "direct" measurement of B_e gives:

$$B_e \quad = \quad (17.77\ \pm\ 0.12)\% \tag{18}$$

(19)

Using the value of m_τ from BEPC [2] and the lifetime of the τ lepton measured by our experiment [5]:

$$m_\tau \quad = \quad (1777.0\ \pm\ 0.2\ \pm\ 0.2)\ \mathrm{MeV/c^2} \tag{20}$$

$$\tau_\tau \quad = \quad (296.4\ \pm\ 6.4\ \pm\ 4.4)\ \mathrm{fs} \tag{21}$$

we determined the ratio of the τ coupling constant to the μ one. From (2) we get:

$$\frac{g_\tau}{g_\mu} = 0.989\ \pm\ 0.013 \tag{22}$$

where good agreement with universality is observed again. Assuming that this ratio is 1, we show consistency with a τ mass:

$$m_\tau = (1769.3\ \pm\ 9.6)\ \mathrm{MeV/c^2} \tag{23}$$

Finally, the measurement of the electronic branching fraction can also be translated into a value for the ratio of hadrons to leptonic decays of the τ. Using expression (5) leads to:

$$R^\tau_{HAD} = 3.656\ \pm\ 0.039 \tag{24}$$

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