Abstract

The knowledge of the properties of the $\tau$ lepton has improved considerably in the last two years thanks to new and more precise measurements performed in $e^+e^-$ colliders operating at three different center of mass energies: the $\tau^+\tau^-$ production threshold region (BEPC), the $\Upsilon$ region (CESR) and the $Z$ (LEP). The first part of this article reviews some of these measurements. The approach followed is to emphasize the relative merits and the complementarity of $\tau$ physics at different energies. To do so, several representative examples are chosen. These are: the measurement of the $\tau$ mass at BEPC, studies of $\tau$ decay modes involving multiple $\pi^0$s at CESR, and several measurements at the LEP experiments (leptonic branching ratios -L3, decay modes involving strange particles -DELPHI, $\tau$ lifetime -OPAL and $\tau$ polarization -ALEPH). The second part summarizes the state-of-the art on the universality tests on the $\tau$ sector.

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Heidelberg, Germany, May, 1993
1 Introduction

Most of the present knowledge on the $\tau$ lepton comes from studies of its properties in $e^+e^-$ colliders. The $\tau$ was discovered [1, 2] in 1977 at SPEAR, an $e^+e^-$ collider operating at energies near the $\tau^+\tau^-$ production threshold. Further studies followed in other $e^+e^-$ colliders. DORIS ($\sqrt{s} \sim 10 GeV$), PEP and PETRA ($\sqrt{s} \sim 30 GeV$) and TRISTAN ($\sqrt{s} \sim 50 GeV$).

In the last two years there has been a very significant improvement on the knowledge of the properties of the $\tau$ lepton, due to new, more precise measurements, performed at or near three well known resonances. The $\psi$ region (BEPC), the $\Upsilon$ region (CESR and DORIS), and the $Z$ region (LEP) [3, 4]. Each of these regions offers a rich $\tau$ physics program, but the experimental issues (i.e. characterization of the $\tau$ signal, backgrounds) and accessible measurements are different (and often complementary) for the different center of mass energies. The two extremes are BEPC, where the $\tau$'s are almost at rest and the $\tau^+\tau^-$ production cross section is dominated by photon exchange, and LEP with highly boosted $\tau^+\tau^-$ events produced in $Z$ decays. The CESR collider operates in a region of intermediates energies that is not as well suited for $\tau$ physics than both the threshold and the $Z$, but its high luminosity provides a large data sample of more than 2 million $\tau^+\tau^-$ pairs.

The first part of this article (section 2) highlights $\tau$ physics near the $\psi$, the $\Upsilon$ and the $Z$. Some of the general issues are discussed (cross sections, characterization of a $\tau$ event, backgrounds) and examples of recent measurements are given. I discuss the new measurement of the $\tau$ mass at BEPC, a measurement best done at threshold. At CESR, the large data sample and the moderate boost allows the CLEOII detector to use their excellent electromagnetic calorimeter to measure $\tau$ decay modes involving several $\pi^0$'s. At LEP the large boost and the use of precise silicon vertex detector enables a measurement of the $\tau$ lifetime at the 1 % level, which I illustrate with the OPAL measurement. Besides, the clean $\tau^+\tau^-$ signature make it possible to select a largely unbiased data sample, and therefore, to measure the $\tau$ branching ratios independently of the luminosity. This is illustrated with the L3 measurement. Several $\tau$ decay mode involving kaons –historically a low energy measurement, have been measured by DELPHI using its Ring Imaging Cerenkov Detector. Finally, I discuss the ALEPH measurement of the $\tau$ polarization.

There are several approaches to $\tau$ physics. Present experimental data [6, 7] are consistent with a standard $\tau$ lepton. One can assume so and use the $\tau$ as a tool to investigate other questions. For instance, the semileptonic character of hadronic $\tau$ decays permits refined tests of perturbative QCD as well as of different aspects of strong interaction phenomena (resonance structure, Weinberg sum rules, gluon condensates, pion mass difference etc) [6, 8]. The other possible approach is to question the "standarness" of the $\tau$ lepton, either by looking for rare phenomena (i.e. forbidden decays) or by performing precision measurements that have the potential to be sensitive to "new physics". For example, precision measurements of the $\tau$ mass, lifetime and lepton branching ratios translate into tests of universality of the charged current. The universality of the neutral current can be tested from precision measurements of the $Z$ decay width, forward-backward asymmetry and $\tau$ polarization. In the second part of this paper (section 3), I review the present status of the universality tests in the $\tau$ sector. As a conclusion, section 4 presents a summary of
menta and the energies of the particles; b) good particle identification capabilities; c) OCR Output
detector. The main requirements are: a) good precision in the measurement of the mo
Independently of the region of operation, cr physics studies depend critically on a good
discussed in sections 2.2 to 2.4.

some of the characteristics of T physics at the 1/2 the T and the Z, that will be further

to the high selection efiiciencies possible at the Z energies. Tables 2 and 3 summarize
relatively small sample, the LEP experiments compete succesfully with CLEOII thanks
imposed by backgrounds with a large data sample. On the other hand, in spite of the
1) change by orders of magnitude. Indeed, the large physics potential of BEPC is limited
sections are not very different. However, the size of the data samples (also shown in Table
energies near the rb the T and at the Z resonances. Note that the production cross
Table 1 and Fig. 1 show the production cross sections of r+r" events at center of
mass energies.

Table 1: Production cross sections and data samples of $\tau^+\tau^-$ events at different center of
mass energies.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sigma(\tau^+\tau^-)(nb)$</th>
<th>$N_{\tau^+\tau^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEPC (3.6GeV)</td>
<td>2.4</td>
<td>$10^4$</td>
</tr>
<tr>
<td>CESR (10.6GeV)</td>
<td>0.9</td>
<td>$2.5 \times 10^6$</td>
</tr>
<tr>
<td>LEP (92GeV)</td>
<td>1.5</td>
<td>$2.0 \times 10^5$</td>
</tr>
</tbody>
</table>

the state-of-the-art and a small exercize in futurology.

$\tau$ physics is becoming a broad field and this article covers only a small portion of it.
The reader is referred to the literature for recent review articles [6, 7] and compilations
of latest results [3, 4, 5].

## 2 Tau Physics at the $\psi$ $\Upsilon$ $Z$ Resonances

### 2.1 General Issues

Table 1 and Fig. 1 show the production cross sections of $\tau^+\tau^-$ events at center of mass
energies near the $\psi$ the $\Upsilon$ and at the $Z$ resonances. Note that the production cross
sections are not very different. However, the size of the data samples (also shown in Table
1) change by orders of magnitude. Indeed, the large physics potential of BEPC is limited
at present by the reduced statistics, while CESR compensates the low selection efficiencies
imposed by backgrounds with a large data sample. On the other hand, in spite of the
relatively small sample, the LEP experiments compete succesfully with CLEOII thanks
to the high selection efficiencies possible at the $Z$ energies. Tables 2 and 3 summarize
some of the characteristics of $\tau$ physics at the $\psi$ the $\Upsilon$ and the $Z$, that will be further
discussed in sections 2.2 to 2.4.

Independently of the region of operation, $\tau$ physics studies depend critically on a good
detector. The main requirements are: a) good precision in the measurement of the mo-
menta and the energies of the particles; b) good particle identification capabilities; c)
Table 3: Impact of the $\tau$ boost.

<table>
<thead>
<tr>
<th>Region</th>
<th>$\beta\gamma ct (mm)$</th>
<th>Particle Id</th>
<th>$\pi^0$ Reconst.</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi$</td>
<td>$\sim 0$</td>
<td>low momenta dE/dx, TOF</td>
<td>low energy $\pi^0$'s large opening angle</td>
<td>No</td>
</tr>
<tr>
<td>$\Upsilon$</td>
<td>0.24</td>
<td>moderate momenta dE/dx, TOF</td>
<td>moderate energy moderate opening angle</td>
<td>Yes</td>
</tr>
<tr>
<td>$Z$</td>
<td>2.4</td>
<td>high momenta dE/dx, RICH</td>
<td>high energy small opening angle</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Figure 1: The cross section $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ in the energy range between threshold and $100 GeV$. 

Table 3: Impact of the $\tau$ boost.
dependence of $0,\ldots$ folded with a function describing the beam spread is fitted to Eq. 1. The threshold. At every point, the $T^+T^-$ production cross section is measured, and the energy

The most precise measurement of the $T$ mass is provided by an energy scan near $0.23\text{nb}$. The $T^+T^-$ cross—section at threshold (Fig. 2) has a finite value of around $0.23\text{nb}$. Due to the Coulomb interaction between the $T^+$ and the $T^-$, the $T^+T^-T^-T^-$ cross section to account for the effects of initial state radiation, coulomb interaction, final state radiation and vacuum polarization \[16, 17\].

Segmented electromagnetic calorimetry for $\pi^0$ reconstruction; d) good hadronic calorimetry and hermeticity. At high energies, a precise silicon microvertex detector is a must for $\tau$ lifetime measurements.

All LEP detectors and CLEOII have many of these features \[10, 9\] as shown in Table 4. The “Si VTX” entry in the table shows the configuration for the 1994 run.

### 2.2 $\tau$ Physics at the $\psi$

Close to threshold, the cross section for $\tau^+\tau^-$ pair production is given by

$$\sigma_{\tau\tau}(s, m_\tau) = \int_0^{\beta^*} dx F_R(x, s) \sigma_1(s \sqrt{1 - x}, m_\tau),$$

$$\sigma_1(s, m_\tau) = \sigma_0(s, m_\tau) \frac{F_R(\beta) F_F(\beta)}{[1 - H(\beta)]^2},$$

$$\sigma_0(s, m_\tau) = \frac{4\pi\alpha^2 \beta(\beta^2 - \beta^2)}{3s}$$

where $\beta$ is the velocity of the $\tau$ lepton and $F_R, F_F, F_\Pi$ modify the lowest order Born cross section to account for the effects of initial state radiation, coulomb interaction, final state radiation and vacuum polarization \[16, 17\]. Due to the Coulomb interaction between the $\tau^+$ and the $\tau^-$, the $\tau^+\tau^-$ cross-section at threshold (Fig. 2) has a finite value of around $0.23\text{nb}$.

The most precise measurement of the $\tau$ mass is provided by an energy scan near threshold. At every point, the $\tau^+\tau^-$ production cross section is measured, and the energy dependence of $\sigma_{\tau\tau}$ folded with a function describing the beam spread is fitted to Eq. 1. The

Table 4: Some detector properties relevant for $\tau$ physics.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Si VTX</td>
<td>3 layers</td>
<td>2 layers</td>
<td>3 layers</td>
<td>2 layers</td>
<td>2 layers</td>
</tr>
<tr>
<td></td>
<td>$r\phi - z$</td>
<td>$r\phi - z$</td>
<td>$r\phi - z$</td>
<td>$r\phi - z$</td>
<td>$r\phi - z$</td>
</tr>
<tr>
<td>Tracker</td>
<td>Drift chb</td>
<td>TPC</td>
<td>TPC</td>
<td>TEC + z-chb</td>
<td>JET chb</td>
</tr>
<tr>
<td></td>
<td>51 pts 200μ</td>
<td>8 pts 100μ</td>
<td>24 pts 100μ</td>
<td>37 pts 30 - 70μ</td>
<td>12 pts 50μ</td>
</tr>
<tr>
<td>($\delta E/E$)</td>
<td>CsI</td>
<td>Sandwich</td>
<td>HPC</td>
<td>BGO</td>
<td>Lead Glass</td>
</tr>
<tr>
<td>ang. seg (deg)</td>
<td>2.6%@100MeV</td>
<td>17%/\sqrt{E}</td>
<td>25%/\sqrt{E}</td>
<td>4%@200MeV</td>
<td>12%$/\sqrt{E}$</td>
</tr>
<tr>
<td>lon. seg</td>
<td>2.5</td>
<td>0.8</td>
<td>1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>$E_{\gamma}^{\min}$ (MeV)</td>
<td>no</td>
<td>3</td>
<td>9</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>250</td>
<td>500</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>HCAL</td>
<td>no</td>
<td>1.2m Fe</td>
<td>1m Fe</td>
<td>60 U plates</td>
<td>1m Fe</td>
</tr>
<tr>
<td>Part. Id.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOF</td>
<td>120ps</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>dE/dx</td>
<td>6.2 %</td>
<td>4.6 %</td>
<td>5.5 %</td>
<td>no</td>
<td>3.5 %</td>
</tr>
<tr>
<td>RICH</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>
The precision of this measurement is limited by the beam energy spread and stability rather than by statistics. Other nice features of $\tau$ physics near threshold are: a) the absence of backgrounds due to charm decays; b) the possibility of measuring backgrounds to $\tau^+\tau^-$ production, by taking data right below threshold; c) the low momenta involved, enabling good particle identification with conventional techniques like $dE/dx$ and TOF; d) the possibility to single-tag $\tau^+\tau^-$ events, based on the fact that below charm threshold only $\tau^+\tau^-$ events are characterized by prompt leptons and missing energy. Single tagging makes it possible to select an unbiased $\tau$ sample with negligible background ([18, 19]).

### 2.2.1 Measurement of the $\tau$ mass at BEPC

A recent measurement of the $\tau$ mass has been recently carried out at BEPC (Beijing) [20, 21]. An energy scan was performed very near threshold and the $\tau$ production cross section was measured as shown in Fig. 3. The $\tau^+\tau^-$ events where characterized by the signature

$$e^+e^- \rightarrow \tau^+\tau^- \rightarrow e + \mu + E_{\text{miss}}$$

The $\tau$ mass is obtained from a fit of the experimentally measured cross section to the formula

$$\sigma_{\tau\tau}(s, m_\tau) = \int ds'G_{\text{beam}}(s, s')\sigma_{\tau\tau}(s', m_\tau)$$

where $G_{\text{beam}}(s, s')$ characterizes the gaussian dispersion of the beam. The resulting measurement on $m_\tau$ improves by an order of magnitude the precision of the previous world average, dominated by a similar measurement at DELCO (SPEAR) [22]. This has been possible thanks to the small energy spread ($1.4\text{MeV}$) and the good energy stability ($0.18\text{MeV}$) of BEPC. The value,

$$m_\tau = 1776.9 \pm 0.2 \pm 0.2\text{MeV}$$

Figure 2: The cross section $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ near threshold [17]. The solid line is the Born approximation, while the dashed line includes all the radiative corrections (except initial-state effects).
of multiple $\tau^0 \rightarrow \gamma \gamma$ decays is possible thanks to the (relatively) large opening angle. The reconstruction of multiple $\pi^0 \rightarrow \gamma \gamma$ decays is possible thanks to the (relatively) large opening angle.

2.3 $\tau$ Physics at the $\Upsilon$

At $\sqrt{s} \sim 10.6 GeV$ the $\tau$'s have already a considerable boost in the laboratory frame, $\beta \sim 0.94$, flying an average distance of $\sim 230 \mu m$ before decaying. This boost is enough to characterize a $\tau^+\tau^-$ event as a back-to-back “jet” with low charged and neutral multiplicity and some missing energy and transverse momentum due to neutrinos. It also permits a measurement of the $\tau$ lifetime. On the other hand, the boost is small enough to allow a relatively large opening angle (Fig. 4) between the photons arising from $\pi^0$ decay, enabling the identification of decay modes involving many $\pi^0$'s.

The most serious problem at this energy are the backgrounds, that make it very difficult to select an unbiased $\tau$ sample. Typically, $\tau^+\tau^-$ events are selected requiring one $\tau$ to decay to a single charged particle and the other to 3 charged particles (plus some neutrals). To suppress backgrounds the events are required to be kinematically consistent with a $\tau^+\tau^-$ event (i.e, the 3 prong side must have an invariant mass smaller than the $\tau$ mass, there must be some missing transverse momentum, etc), but the low multiplicity of hadronic events at $10.6 GeV$, and the high cross section to produce charmed mesons that can mimic the $\tau$ signal result in low selection efficiencies (around 15 %) and high residual backgrounds (10 to 20 %) that forbid an unbiased selection. The charm background also makes single-tagging very hard. However, in the case of exclusive final states being studied, one can impose one $\tau$ to decay to a leptonic tag and the other to the exact topology of the final state being studied. An accurate measurement of the luminosity is necessary to determine absolute branching ratios.

2.3.1 Measurement of multi $\pi^0$ modes at CLEO

The CLEO-II detector at CESR has recently measured branching fractions for $\tau$ lepton decay into one-prong final states with multiple $\pi^0$ [23], $B_{\pi n \pi^0}, n = 1, 4$. The reconstruction of multiple $\pi^0 \rightarrow \gamma \gamma$ decays is possible thanks to the (relatively) large opening angle.
The low multiplicity back-to-back jet topology combined with the tag, reduces multitudes (plus any number of neutrals) and missing energy and transverse momentum. Backgrounds by requiring a lepton or 3-prong tag recoiling versus one single charged track.

The first step in the selection, summarized in Table 5, separates T-+-T- events from the other T* to decay to the exact topology being measured. The events were identified by imposing one T* between photons and the high efficiency, excellent energy resolution and fine segmentation of CLEO-II calorimeter, made of 7800 CsI (Tl) crystals located inside the magnet. This measurement –that includes the first observation of the decay mode h*47r°1/2, illustrates the techniques to select τ+τ- events at the energies of the Y, and the possibility of reconstructing up to eight photons in the final state, thanks to a combination of good detector and merciful kinematics.

The measurement is based on a data sample of about 610,000 T+T' pairs, corresponding to an integrated luminosity of 670pb^-1. The events were identified by imposing one τ to decay via a leptonic tag (τ —> e+ν_τν_τ) or a 3-prong tag (τ —> 3h'π°ν_τ) and the other τ to decay to the exact topology being measured.

The first step in the selection, summarized in Table 5, separates τ+τ- events from backgrounds by requiring a lepton or 3-prong tag recoiling versus one single charged track (plus any number of neutrals) and missing energy and transverse momentum.

The low multiplicity back-to-back jet topology combined with the tag, reduces multitudes (plus any number of neutrals) and missing energy and transverse momentum.

![Figure 4: The minimum angular separation between any two particles (charged and/or neutral) in e+e^- → τ+τ- events, where τ+ —> e+ν_τν_τ and τ- —> π^-3π°ν_τ [19].](image)

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Leptonic tag</th>
<th>3-prong tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged topology</td>
<td></td>
<td>1.vs.1</td>
</tr>
<tr>
<td>Tag</td>
<td></td>
<td>1.vs.3</td>
</tr>
<tr>
<td>Missing Energy</td>
<td></td>
<td>3-prongs</td>
</tr>
<tr>
<td>Missing P_1</td>
<td></td>
<td>E_{Ecal} &lt; 0.75E_{cm}</td>
</tr>
<tr>
<td>Visible Energy</td>
<td>E_{vis} &gt; 0.2E_{cm}</td>
<td>P_1 points into detector</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E_{vis} &gt; 0.3E_{cm}</td>
</tr>
</tbody>
</table>

Table 5: CLEO II criteria to select τ events with one τ decay to a leptonic or 3-prong tag and the other to one track and π°s [23].
many WO's, LEP energies are well suited for τ physics. In this section, several examples

### 2.4 τ Physics at the Z

Except for precision measurements of the τ mass and study of τ decay modes involving many π⁰'s, LEP energies are well suited for τ physics. In this section, several examples
<table>
<thead>
<tr>
<th>Mode</th>
<th>Tag</th>
<th>Eff (%)</th>
<th>$f_{ee}$(%)</th>
<th>$f_{had}$(%)</th>
<th>$f_{\tau}$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h^\pm\pi^0\nu_\tau$</td>
<td>$e$</td>
<td>$\sim 3$</td>
<td>$2.2 \pm 0.1$</td>
<td>$&lt; 0.1$</td>
<td>$4.3 \pm 0.1$</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\sim 3$</td>
<td>$2.3 \pm 0.1$</td>
<td>$&lt; 0.1$</td>
<td>$4.6 \pm 0.2$</td>
</tr>
<tr>
<td></td>
<td>$3h$</td>
<td>$\sim 3$</td>
<td>$2.0 \pm 0.1$</td>
<td>$2.6 \pm 0.1$</td>
<td>$3.4 \pm 0.2$</td>
</tr>
<tr>
<td>$h^\pm2\pi^0\nu_\tau$</td>
<td>$e$</td>
<td>$\sim 1.5$</td>
<td>$4.1 \pm 0.3$</td>
<td>$&lt; 0.4$</td>
<td>$3.6 \pm 0.2$</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\sim 1.5$</td>
<td>$3.7 \pm 0.3$</td>
<td>$&lt; 1.0$</td>
<td>$4.4 \pm 0.3$</td>
</tr>
<tr>
<td></td>
<td>$3h$</td>
<td>$\sim 1.5$</td>
<td>$2.9 \pm 0.2$</td>
<td>$5.1 \pm 0.4$</td>
<td>$3.0 \pm 0.2$</td>
</tr>
<tr>
<td>$h^\pm3\pi^0\nu_\tau$</td>
<td>$e$</td>
<td>$\sim 1.0$</td>
<td>$11 \pm 2$</td>
<td>$&lt; 6$</td>
<td>$12.4 \pm 1.7$</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\sim 1.0$</td>
<td>$11 \pm 2$</td>
<td>$&lt; 6$</td>
<td>$11.4 \pm 1.7$</td>
</tr>
<tr>
<td></td>
<td>$3h$</td>
<td>$\sim 1.0$</td>
<td>$14 \pm 2$</td>
<td>$22 \pm 3$</td>
<td>$6.6 \pm 1.2$</td>
</tr>
<tr>
<td>$h^\pm4\pi^0\nu_\tau$</td>
<td>$e$</td>
<td>$\sim 0.5$</td>
<td>$14 \pm 6$</td>
<td>$&lt; 10$</td>
<td>$5.7 \pm 3.2$</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\sim 0.5$</td>
<td>$15 \pm 6$</td>
<td>$&lt; 10$</td>
<td>$4.3 \pm 2.3$</td>
</tr>
<tr>
<td></td>
<td>$3h$</td>
<td>$\sim 0.5$</td>
<td>$45 \pm 27$</td>
<td>$&lt; 45$</td>
<td>$6. \pm 6$.</td>
</tr>
</tbody>
</table>

Table 7: Efficiencies and backgrounds for the $\pi^\pm\pi^0$ candidate sample of [23].

![Histogram](image)

Figure 5: Invariant $\pi^\pm\pi^0$ mass spectra. [23].

<table>
<thead>
<tr>
<th>$\tau^\pm \to h^\pm2\pi^0\nu_\tau$</th>
<th>$\tau^\pm \to h^\pm3\pi^0\nu_\tau$</th>
<th>$\tau^\pm \to h^\pm4\pi^0\nu_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{h\pi^0}/B_{h\pi^0}$</td>
<td>$0.345 \pm 0.006 \pm 0.016$</td>
<td>$0.041 \pm 0.003 \pm 0.005$</td>
</tr>
<tr>
<td>$Br(%)$</td>
<td>$8.21 \pm 0.15 \pm 0.47$</td>
<td>$0.98 \pm 0.07 \pm 0.12$</td>
</tr>
<tr>
<td>$0.006 \pm 0.002 \pm 0.002$</td>
<td>$0.15 \pm 0.04 \pm 0.05$</td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Summary of CLEO-II measurements of $\tau$ decay to multi-$\pi^0$ modes [23].
are considered to give a flavour of the rich variety of measurements accessible to LEP. The LEP experiments select a \( \tau^+\tau^- \) data sample with a total non-\( \tau \) background around 1.7 \%.

<table>
<thead>
<tr>
<th>Efficiency (%)</th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background (%)</td>
<td>1.5</td>
<td>1.7</td>
<td>1.5</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 9: Selection efficiencies and backgrounds for the four LEP experiments.

2.4.1 Selection of \( \tau \) Pair Events at LEP

At LEP energies, the reduced impact of the backgrounds to \( \tau^+\tau^- \) production permits an almost unbiased selection. Broadly speaking, the characterization of \( \tau^+\tau^- \) events is similar to the one at \( \Upsilon \) energies: two nearly back-to-back "jets" of one or more charged particles, often with additional neutral particles and some missing energy and transverse momentum. But nearby the \( Z \) backgrounds are easier to distinguish. There are four main backgrounds to consider. The first two are \( e^+e^- \rightarrow e^+e^- \) and \( e^+e^- \rightarrow \mu^+\mu^- \), which can be identified by the presence of two very high momenta, back-to-back particles with the full center-of-mass energy deposited in the electromagnetic calorimeter for \( e^+e^- \rightarrow e^+e^- \) events and very little for \( e^+e^- \rightarrow \mu^+\mu^- \). LEP detectors have good charged particle-tracking, muon particle identification and electromagnetic calorimetry, enabling them to effectively suppress those backgrounds. A third background comes from multihadron production. In Fig. 6 (from [9]) the energy dependence of the hadronic multiplicity is shown, illustrating how a cut on the hadronic multiplicity is much more efficient to separate \( \tau^+\tau^- \) events from QCD backgrounds at the \( Z \) than at lower energies. The fourth source of background comes from two-photon processes \( e^+e^- \rightarrow (e^+e^-)X \) where the final state electron and positron escape undetected at low angles and the system \( X \) is misidentified as a low visible energy \( \tau \) pair. At LEP this processes are very suppressed since they lack the \( Z \) resonance that enhances \( \tau^+\tau^- \) production. The consequence of the naturally reduced backgrounds to \( \tau^+\tau^- \) production at LEP is that high purity can be attained without sacrificing selection efficiency, and that selection requirements that strongly bias certain \( \tau \) decay modes are unnecessary. The efficiency (within the fiducial volume) and the remnant backgrounds in the \( \tau \) pair selection of the four LEP experiments are summarized in Table 9.
and \( \varphi_b \) is the azimuthal angle of the \( \pi^* \) decay product. The impact parameter is given

\[ b = L \sin \theta_\tau \sin(\phi - \phi_\tau) \]

(5)

where \( L \) is the decay length, \( \phi_\tau \) and \( \theta_\tau \) are the azimuthal and polar angle of the decaying \( \tau \), and \( \phi \) is the azimuthal angle of the \( \tau \) decay product. The impact parameter is given

\[ b = \frac{L}{\sin \theta_\tau} \sin(\phi - \phi_\tau) \]

as the distance of closest approach of the track extrapolation to the assumed production point in the \( \tau \varphi \) plane (see Fig. 7).

2.4.2 Measurement of the \( \tau \) Lifetime (OPAL)

At \( \sqrt{s} \approx 92 \text{GeV} \) the \( \tau \)'s have a large boost in the laboratory frame, \( \beta \approx 0.991 \), leading to a decay length of \( \beta \gamma c \tau \approx 2.3 \text{mm} \). The long \( \tau \) average decay lengths combined with the introduction of high precision silicon strip vertex detectors, make it possible a very precise determination of the \( \tau \) lifetime by the LEP experiments.

There are two basic methods to measure \( \tau_\tau \), i.e., the impact parameter method and the transverse decay length method. Both of them are used by the OPAL experiment to extract a very precise measurement of the \( \tau \) lifetime from their 1990, 1991 and 1992 data sample [24, 4].

OPAL has excellent tracking capabilities. The entire tracking system is immersed in a solenoidal magnetic field of 0.435T. It comprises a precision silicon microvertex detector [25], a vertex drift chamber, a large jet chamber and outer \( z \) chambers.

The \( \tau \) production point is taken as the average beam spot position reconstructed from charged tracks during a LEP fill. The average size of the beam spot is measured using the impact parameters of tracks with respect to the average beam spot position in collinear \( Z \rightarrow \mu^+\mu^- \) events, resulting in dimensions \( \sigma_x = 95 \pm 7 \mu m, \sigma_y = 14 \pm 3 \mu m \).

The first method to measure \( \tau_\tau \) uses the impact parameter, \( b \), of a \( \tau \) decay track, defined as the distance of closest approach of the track extrapolation to the assumed production point in the \( \tau \varphi \) plane (see Fig. 7),

\[ b = L \sin \theta_\tau \sin(\phi - \phi_\tau) \]

(5)

Figure 6: Charged particle multiplicity from the process \( e^+e^- \rightarrow \text{hadrons} \) and \( e^+e^- \rightarrow \pi^+\pi^- \) as a function of center-of-mass energies [9].
positive sign if it points into the same thrust hemisphere relative to the beam position in which it lies, and negative otherwise.

Neither the \( \tau \) production point, nor the flight direction are known. They are approximated respectively by the beam centroid and the charged track thrust axis. As a consequence of these approximations (plus the detector resolution) the "true" impact parameter distribution (basically an exponential distribution) becomes smeared. The measured distribution is broader than the true one due to finite tracking resolution and the beam size, and acquires also negative entries, introduced by the use of the thrust axis. However, it is still significantly positive-shifted and can be used, by comparison with Monte Carlo prediction to extract a measurement of \( \tau_r \),

\[
\tau_r = \tau_{MC} \times \frac{x_{meas}}{x_{MC}}
\]

where \( \tau_{MC} \) is the \( \tau \) lifetime assumed in the Monte Carlo generator, and \( x_{meas}, x_{MC} \) are the means of the measured and Monte Carlo impact parameter distributions respectively.

Fig. 8 shows the impact parameter distribution for those 1991 data which have silicon detector information. The dominant uncertainties of the one-prong impact parameter study are listed in Table 10 (for the 1992 data) and the results are shown in Table 11.

The second customary technique to measure \( \tau_r \) is the decay length method. The true \( \tau \) flight distance is measured from three-prong decays. Three-prong \( \tau \) decay candidates are selected from event hemispheres which contain exactly three tracks of charge \( \pm 1 \). A vertex fit is performed to the three charged tracks. As for the one-prong measurement, estimates of the production point and the \( \tau \) flight direction are taken from the average beam position and the charged track thrust axis, while the reconstructed vertex of the three charged tracks measures the actual \( \tau \) decay position (Fig 9).

In the OPAL analysis, 2609 (6645) candidates are found in the 1991 (1992) data. A least squares fit is performed to combine the beam position, the vertex position and the thrust axis to obtain the three-dimensional decay length and error. The full set of decay lengths is then subject to a maximum likelihood fit to determine the average decay length. The average decay length is then converted into a lifetime with a Lorentz factor which includes a correction to the average boost for the effects of initial state radiation. The
Figure 8: Impact parameter distribution for the 1991 OPAL data [24].
Table 10: Systematic error contributions for the 1992 OPAL one-prong $\tau_r$ measurements.

<table>
<thead>
<tr>
<th>Source</th>
<th>Error contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matching of MC and data track resolutions</td>
<td>0.1</td>
</tr>
<tr>
<td>beam position uncertainties</td>
<td>0.2</td>
</tr>
<tr>
<td>beam size uncertainties</td>
<td>0.4</td>
</tr>
<tr>
<td>event axis and direction biases</td>
<td>0.1</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>0.8</td>
</tr>
<tr>
<td>backgrounds</td>
<td>0.3</td>
</tr>
<tr>
<td>total systematic error</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 11: $\tau_r$ results for the OPAL one-prong measurements.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_r (fs)$</td>
<td>296.4 ± 7.1 ± 3.8</td>
<td>292.1 ± 4.4 ± 2.9</td>
</tr>
</tbody>
</table>

Figure 9: The decay length method
energy deposited in the electromagnetic calorimeter is required to be less than 85% of $Z \rightarrow e^+e^-$ backgrounds, events with two identified electrons are rejected and the total energy in the hadron calorimeter or tracks in the muon chambers are rejected. To remove parallel to the beam respectively. Hemispheres with hadronic or minimum ionizing show and BGO cluster must be smaller than 25 and 40mrad in the planes perpendicular and narrow) and be precisely associated with the charged track (the angle between track and a magnetic shower in the BGO and no hadronic energy behind. The shower is required to match with the expected characteristics of an electromagnetic shower (i.e., be symmetric and narrow) and be precisely associated with the charged track (the angle between track and BGO cluster must be smaller than 25 and 40mrad in the planes perpendicular and parallel to the beam respectively). Hemispheres with hadronic or minimum ionizing showers in the hadron calorimeter or tracks in the muon chambers are rejected. To remove $Z \rightarrow e^+e^-$ backgrounds, events with two identified electrons are rejected and the total energy deposited in the electromagnetic calorimeter is required to be less than 85% of

Electrons are seen in the L3 detector as a track in the inner chamber with an electromagnetic shower in the BGO and no hadronic energy behind. The shower is required to match with the expected characteristics of an electromagnetic shower (i.e., be symmetric and narrow) and be precisely associated with the charged track (the angle between track and BGO cluster must be smaller than 25 and 40mrad in the planes perpendicular and parallel to the beam respectively). Hemispheres with hadronic or minimum ionizing showers in the hadron calorimeter or tracks in the muon chambers are rejected. To remove $Z \rightarrow e^+e^-$ backgrounds, events with two identified electrons are rejected and the total energy deposited in the electromagnetic calorimeter is required to be less than 85% of

The systematic errors are summarized in Table 12 and the results are summarized in Table 13. The 1990-1992 combined $\tau$ lifetime for the OPAL experiment is

$$\tau_{\tau}(fs) = 290.8 \pm 2.8 \pm 2.4.$$  

### 2.4.3 Measurement of the Leptonic Branching Fractions (L3)

A precise determination of the leptonic branching ratios is of particular interest to test the universality of the $\tau$ couplings to the charged current. The value of the strong coupling constant $\alpha_s$ can also be determined by the ratio between the leptonic and hadronic branching ratios [26].

The L3 detector at LEP is particularly well suited to identify leptons thanks to its high resolution BGO electromagnetic calorimeter and its precise $\mu$-chambers [27]. The analysis summarized here, uses a total integrated luminosity of $31pb^{-1}$, yielding a total of 17274 $\tau^+\tau^-$ events [28].

Electrons are seen in the L3 detector as a track in the inner chamber with an electromagnetic shower in the BGO and no hadronic energy behind. The shower is required to match with the expected characteristics of an electromagnetic shower (i.e., be symmetric and narrow) and be precisely associated with the charged track (the angle between track and BGO cluster must be smaller than 25 and 40mrad in the planes perpendicular and parallel to the beam respectively). Hemispheres with hadronic or minimum ionizing showers in the hadron calorimeter or tracks in the muon chambers are rejected. To remove $Z \rightarrow e^+e^-$ backgrounds, events with two identified electrons are rejected and the total energy deposited in the electromagnetic calorimeter is required to be less than 85% of

<table>
<thead>
<tr>
<th>Source</th>
<th>Error contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>vertex drift chamber calibration</td>
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</tr>
<tr>
<td>silicon detector alignment</td>
<td>0.6</td>
</tr>
<tr>
<td>event axis and direction biases</td>
<td>0.5</td>
</tr>
<tr>
<td>backgrounds</td>
<td>0.4</td>
</tr>
<tr>
<td>Measurement biases</td>
<td>1.1</td>
</tr>
<tr>
<td>total systematic error</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 12: Systematic error contributions for the 1992 OPAL three-prong $\tau$ measurements.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{\tau}(fs)$</td>
<td>286.3 ± 7.4 ± 5.2</td>
</tr>
</tbody>
</table>

Table 13: $\tau$ results for the OPAL three-prong measurements.

The systematic errors are summarized in Table 12 and the results are summarized in Table 13. The 1990-1992 combined $\tau$ lifetime for the OPAL experiment is

$$\tau_{\tau}(fs) = 290.8 \pm 2.8 \pm 2.4.$$  

Electrons are seen in the L3 detector as a track in the inner chamber with an electromagnetic shower in the BGO and no hadronic energy behind. The shower is required to match with the expected characteristics of an electromagnetic shower (i.e., be symmetric and narrow) and be precisely associated with the charged track (the angle between track and BGO cluster must be smaller than 25 and 40mrad in the planes perpendicular and parallel to the beam respectively). Hemispheres with hadronic or minimum ionizing showers in the hadron calorimeter or tracks in the muon chambers are rejected. To remove $Z \rightarrow e^+e^-$ backgrounds, events with two identified electrons are rejected and the total energy deposited in the electromagnetic calorimeter is required to be less than 85% of
Figure 10: Distribution of three-prong decay lengths together with a maximum likelihood fit to the data that provides the average decay length (1991 OPAL data) [24].
the center of mass energy. A total of 5185 $\tau \rightarrow e\nu\nu_\tau$ candidates are selected in this way, with an efficiency of 83.5 % in the fiducial volume and an estimated total background of 3.3 %. Fig. 11:a shows the momentum distribution of the selected electrons.

Muons are seen as a track in the inner chamber, with minimum ionization in electromagnetic and hadronic calorimeter and good match with a track observed in the muon system. At least two layers of $\mu$ chambers must have hits. To reject $Z \rightarrow \mu^+\mu^-$ backgrounds, events where two $\mu$'s are identified are excluded. A total of 5028 candidates are selected in this way with an efficiency of 86 % in the fiducial volume and an estimated total background of 5.5 %. Fig. 11:b shows the momentum distribution of the selected muons.

The leptonic branching fractions are determined from the ratio of $\tau \rightarrow l\bar{\nu}_l\nu_\tau$ events to the total number of $\tau^+\tau^-$ events selected. Note that knowledge of the luminosity is not necessary, due to the unbiased selection. The results of the analysis are summarized in Table 14.

### 2.4.4 Measurement of Decay Modes Involving Kaons (DELPHI)

The decays of the $\tau$ lepton involving $K$ mesons are of particular interest to test the couplings of the $W$ to the hadronic current, since theoretical QCD calculation exist [8] predicting the (small) deviation from the naive expectation, $B(\tau \rightarrow K\nu_\tau)/B(\tau \rightarrow \pi\nu_\tau) \sim \tan^2 \theta_c$. A precise measurement of the exclusive branching ratio $B(\tau \rightarrow K\nu_\tau)$ allows to test these predictions. Furthermore, the study of decay modes involving several kaons on the final state (i.e, $\tau \rightarrow K\pi, K\pi\pi, K\bar{K}\pi$) would allow to measure the poorly known spectral functions involving the strange current.

At low center-of-mass energies $K$ identification is possible with conventional methods (dE/dx, TOF). Until very recently, the measurement of $\tau$ decays involving $K$ mesons were done at low energy (DELCO and TPC/27). The DELPHI experiment at LEP profits from the excellent $\pi/K$ separation capability of its Ring Imaging Cerenkov Detector (RICH) to measure the inclusive $B(\tau \rightarrow K\nu_\tau(\pi^0))$ as well as the exclusive $B(\tau \rightarrow K\nu_\tau) B(\tau \rightarrow K^*\nu_\tau)$ branching ratios [29].

The design of the RICH has been described in [30]. Particle identification is obtained over a large momentum interval using the combined information of a gas radiator ($C_5F_{12}$) ensuring $\pi/K$ separation in the high momentum region and a liquid radiator ($C_6F_{14}$) complementing the gas information at low momenta. The Čerenkov photons produced in both media are converted in a photosensitive gas, and the resulting photoelectrons drift towards a MWPC. The Barrel RICH used in this analysis is made out of 48 independent radiators, each equipped with a chamber. For one prong $\tau$ decays, with large average momentum, only the gas radiator is relevant.

| $\tau \rightarrow e\nu\nu_\tau$ | 83.5 | 2.3 | 1.0 | 17.86 ± 0.25 ± 0.23 |
| $\tau \rightarrow \mu\nu\nu_\tau$ | 86.0 | 2.3 | 3.2 | 17.26 ± 0.25 ± 0.23 |

Table 14: Summary of L3 measurements of $\tau$ decays to leptons [28].
Figure 11: Lepton momentum normalized to $E_{\text{beam}}$. Points are data, empty and hatched histograms are the total Monte Carlo expectation for the signal and the background: (a) Electrons; (b) Muons [28].
19

T polarization. Measuring the dependence of PT with cosθ provides nearly independent leptons, the T polarization can be measured using the T decay products as analysers of the and vga; are the vector and axial couplings of the Z to the lepton Z. Unlike the lighter

\[ A_z = Q_M/(v_l + g_\ell) \]

where

\[ A_z(1 + \cos^2 \theta) + A_x(2 \cos \theta) \]

\[ (1 + \cos^2 \theta) + A_x A_z(2 \cos \theta) \]

PTICOSGI Z _

\[ A_z(1 + \cos^2 \theta) + A_x(2 \cos \theta) \]

The dependence of the T polarization, PT, with the angle θ between both the Z and the final state leptons are polarized, with polarizations PT = −Ae and difference in the right- and left—handed couplings of the leptons to the neutral current, At LEP energies, the process e+e− → τ+τ− is dominated by Z exchange. Due to the difference in the right- and left-handed couplings of the leptons to the neutral current, both the Z and the final state leptons are polarized, with polarizations PT = −Ae and Pτ = −Ae respectively. The dependence of the τ polarization, Pτ, with the angle θ between the beam \( e^- \) and the \( \tau^- \) appears, at the Z peak, in the improved Born approximation as

\[ P_\tau(\cos \theta) = -\frac{A_z(1 + \cos^2 \theta) + A_x(2 \cos \theta)}{(1 + \cos^2 \theta) + A_z A_x(2 \cos \theta)} \]

where

\[ A_i = 2v_l a_l/(v_l^2 + a_i^2), \]

and \( v_l, a_l \) are the vector and axial couplings of the Z to the lepton \( l \). Unlike the lighter leptons, the τ polarization can be measured using the τ decay products as analysers of the τ polarization. Measuring the dependence of \( P_\tau \) with \( \cos \theta \) provides nearly independent

<table>
<thead>
<tr>
<th>( \tau \rightarrow K\nu_\tau )</th>
<th>( \tau \rightarrow K^*\nu_\tau )</th>
<th>( \tau \rightarrow K(\pi^0)\nu_\tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br (%)</td>
<td>0.93 ± 0.20</td>
<td>1.71 ± 0.63</td>
</tr>
</tbody>
</table>

Table 15: Summary of DELPHI measurements of \( \tau \) decays to Kaons [29].

Charged kaons with momenta between 4 and 30GeV can be identified using two different techniques. Below the Cerenkov light production threshold for \( K^- \) at 9GeV, the method, veto identification, requires no photoelectrons consistent with belonging to the Cerenkov ring produced by the track. Above the production threshold of Cerenkov photons by Kaons, the method used is the ring identification, which requires that the Cerenkov angle \( \theta_c \) of the reconstructed photoelectrons is consistent with the one expected for a Kaon of this momentum.

Samples of data (more than 12000 tracks from \( Z \rightarrow \mu^+\mu^- \) and \( \mu \) from \( \tau \) decays) were used to study the detector resolution and efficiency in detail. The resolution for a single photo electron was measured to be 4.5mrad. The average Cerenkov angle for the photo electrons associated to a track was computed and a proper set of selection criteria were applied to identify and remove photoelectrons coming from backgrounds sources (i.e, feedback photons, crosstalk in the MWPC) or those in which the value of the average Cerenkov angle was not properly computed. After the selection, an average resolution of 1.5mrad for high momentum muons was obtained.

Fig. 12 shows the average Cerenkov angle for different identified particles in the one prong \( \tau \) decay sample for the 1992 data. The population in the expected Kaon band is clearly discernible. The kaon production was obtained by fitting the percentage of kaon candidates to the total one prong sample, using a likelihood technique. The exclusive branching ratios \( \tau \rightarrow K\nu_\tau, \tau \rightarrow K^*\nu_\tau \) as well as the inclusive decay \( \tau \rightarrow K(\pi^0)\nu_\tau \) have been measured. Fig. 13 shows the clear signal of the \( K^* \) on the inclusive \( K\pi^0 \) sample. The results are summarized in Table 15.

2.4.5 Measurement of \( P_\tau \) (ALEPH)

At LEP energies, the process e+e− → τ+τ− is dominated by Z exchange. Due to the difference in the right- and left-handed couplings of the leptons to the neutral current, both the Z and the final state leptons are polarized, with polarizations \( P_Z = -A_e \) and \( P_\tau = -A_e \) respectively. The dependence of the \( \tau \) polarization, \( P_\tau \), with the angle \( \theta \) between the beam \( e^- \) and the \( \tau^- \) appears, at the Z peak, in the improved Born approximation as
Figure 12: The distribution of the Cerenkov angle as a function of the particle momentum for muons, pions and kaons [29].

Figure 13: $K \pi^0$ invariant mass distribution with the fitted background from misidentified pions hatched and the $K^*$ signal [29].
determinations of $A_e$ and $A_\tau$, testing the universality of the couplings of the $Z$ to electrons and $\tau$'s. The ALEPH experiment has used 18.8 $pb^{-1}$ of data, corresponding to a total of about 20,000 observed $\tau^+\tau^-$ events, at a center of mass energies near the $Z$ pole [31]. The ALEPH detector is well suited for this analysis, due to its good particle identification capabilities and hermeticity. The particle identification techniques and selection of the different $\tau$ decay modes are discussed in [31] and summarized in Table 16.

Two methods were used to measure $P_\tau$. In the first, single-$\tau$ method, the polarization is inferred from the kinematic distributions of single $\tau$ decays. In the second method, acollinearity method, the polarization is inferred from the angular correlation of the decay products of the two $\tau$'s in an event. Both methods use the $\tau$ decay modes $\tau \rightarrow e\nu_e\nu_e$, $\tau \rightarrow \mu\nu_\mu\nu_\mu$, $\tau \rightarrow \pi\nu_\tau$, $\tau \rightarrow \rho\nu_\tau$, and $\tau \rightarrow a_4\nu_\tau$, together constituting more than 80% of all $\tau$ decays.

In the single-$\tau$ method, $P_\tau$ is obtained by fitting to the observed kinematic distributions the admixture of left- and right-handed Monte Carlo $\tau$'s that minimizes the fit parameter. For the leptons and pion decays, only one measurable energy exists. Defining $x = E_{e,\mu,\pi}/E_{beam}$ the expected distribution [33], ignoring mass and radiative effects is,

$$W(x_i) = \frac{1}{3} \left[ (5 - 9x_i^2 + 4x_i^3) + P_\tau(1 - 9x_i^2 + 8x_i^3) \right]$$

(9)

with $x_i = x_{e,\mu}$ and

$$W(x_\pi) = 1 + P_\tau(2x_\pi - 1).$$

(10)

In the case of multipions decays the distribution has the same general expression:

$$W(\tilde{\xi}) = a(\tilde{\xi}) + P_\tau b(\tilde{\xi})$$

(11)

where $\tilde{\xi}$ is the set of observed momenta. It can be written in a form similar to the pion distribution [32]:

$$W(w) = f(w)(1 + P_\tau w)$$

(12)

by using the quantity $w(\tilde{\xi})$, defined by

$$w(\tilde{\xi}) = \frac{b(\tilde{\xi})}{a(\tilde{\xi})} = \frac{W_+(\tilde{\xi}) - W_-(\tilde{\xi})}{W_+(\tilde{\xi}) + W_-(\tilde{\xi})},$$

(13)

where $W_+(W_-)$ is the probability density of $\tilde{\xi}$ for positive (negative) helicity. In the case of lepton and pion decays, $w$ is equivalent to the energy distribution, but in the cases

<table>
<thead>
<tr>
<th>item</th>
<th>$e\nu$</th>
<th>$\mu\nu$</th>
<th>$\pi\nu$</th>
<th>$\rho\nu$</th>
<th>$a_4\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>candidates</td>
<td>3019</td>
<td>5677</td>
<td>3287</td>
<td>5279</td>
<td>2147</td>
</tr>
<tr>
<td>acceptance (%)</td>
<td>40</td>
<td>69</td>
<td>61</td>
<td>48</td>
<td>55</td>
</tr>
<tr>
<td>$\tau$ background (%)</td>
<td>0.7</td>
<td>2.5</td>
<td>6.0</td>
<td>6.3</td>
<td>7.9</td>
</tr>
<tr>
<td>non-$\tau$ background (%)</td>
<td>1.0</td>
<td>2.3</td>
<td>0.5</td>
<td>0.4</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 16: Performance of channel classification and background rejection in the ALEPH analysis [31].
Figure 14: Fit results for the individual channels. The points with error bars are the observed spectra, the shaded histogram in the total background. The dashed (dotted) histogram is the Monte Carlo contribution from right- (left-) handed $\tau$s. The solid line histogram indicates the sum of all Monte Carlo contributions [31].
$g(c) = F(c) + P_{\tau}(\cos \theta)G(c)$,

where the functions $F$ and $G$ reflect the kinematics of the particular $\tau$ decay channel (for a thorough discussion see [35]).

The parameters $A_\tau$ and $A_\epsilon$ can be extracted from the acollinearity distribution integrated over $\cos \theta$ and the forward-backward asymmetry as a function of the acollinearity, which at $s = M^2_\beta$ are given by [34, 35]

$$\frac{1}{\sigma} \frac{d\sigma}{dc} = F(\epsilon) - A_\epsilon G(\epsilon),$$

$$\frac{1}{\sigma} \frac{d\sigma}{dc} = F(\epsilon) + P_{\tau}(\cos \theta)G(\epsilon),$$

Table 17: Individual channel polarization results [31].

<table>
<thead>
<tr>
<th>decay channel</th>
<th>$P_{\tau}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow e\nu_e\bar{\nu}_\tau$</td>
<td>$-0.225 \pm 0.085 \pm 0.045$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\nu_\mu\bar{\nu}_\tau$</td>
<td>$-0.154 \pm 0.065 \pm 0.029$</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi\nu_\tau$</td>
<td>$-0.133 \pm 0.031 \pm 0.018$</td>
</tr>
<tr>
<td>$\tau \rightarrow a_1\nu_\tau$</td>
<td>$-0.114 \pm 0.063 \pm 0.034$</td>
</tr>
</tbody>
</table>

Table 18: Polarization parameters extracted from polar angle fit [31].

<table>
<thead>
<tr>
<th>parameter</th>
<th>result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_e$</td>
<td>$0.117 \pm 0.025 \pm 0.008$</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>$0.140 \pm 0.019 \pm 0.014$</td>
</tr>
<tr>
<td>$A_{e-\tau}$</td>
<td>$0.131 \pm 0.015 \pm 0.009$</td>
</tr>
</tbody>
</table>

Table 17 and Fig. 14 show the fit results for the individual channels. The angular dependence of the polarization is measured by extracting the polarization in nine regions of polar angle. The relation 7 is then fitted to these data, with $A_\tau$ and $A_e$ as parameters. One can allow them to vary independently providing a test of universality. Alternatively, a one fit parameter, with $A_e = A_\tau = A_{e-\tau}$, can be performed. The results of these fits are summarized in Table 18. Fig. 15 shows the data points entering the fit for the angular dependence of the polarization.

The dominant sources of systematics in these analysis are the absolute energy calibration, $\pi^0$ identification and Monte Carlo statistics.

A new method to extract $P_{\tau}$, proposed in [34] was also used. In this method, the polarization is determined by fitting a tree-level theoretical prediction for the acollinearity, to the observed distribution. The selected events have both $\tau$'s decaying to final states with a single charged track and the distributions are corrected for acceptance and radiative effects. The acollinearity is defined, using charged tracks only, as $\epsilon = \pi - \theta_{12}$, where $\theta_{12}$ is the opening angle between the tracks. The acollinearity distribution, for a given angle $\theta$, may be written

$$\frac{1}{\sigma} \frac{d\sigma}{dc} = F(\epsilon) + P_{\tau}(\cos \theta)G(\epsilon),$$

where the functions $F$ and $G$ reflect the kinematics of the particular $\tau$ decay channel (for a thorough discussion see [35]).

The parameters $A_\tau$ and $A_e$ can be extracted from the acollinearity distribution integrated over $\cos \theta$ and the forward-backward asymmetry as a function of the acollinearity, which at $s = M^2_\beta$ are given by [34, 35]

$$\frac{1}{\sigma} \frac{d\sigma}{dc} = F(\epsilon) - A_\epsilon G(\epsilon),$$

23
Figure 15: Measurement $P_\tau(\cos \theta)$ from the single-$\tau$ method. The solid (dashed) line shows the fit curve with (without) the assumption of $\tau - \epsilon$ universality [31].
of the propagator. These effects have been shown \[36\] to be small (or \(\approx \alpha(m_\tau) = 1/133.3\)) corrections not included in the Fermi coupling constant \(G_F\), and the non-local structure

\[
\left( T \rightarrow Z_1\right)(1/T) = (Z = e, \nu, t),
\]

For the leptonic modes, the \(T\) decay partial width is, assuming massless neutrinos,

\[
\Gamma(T \rightarrow l\bar{\nu}_l l'\bar{\nu}_{l'} ) = \frac{G_F^2 m_\tau^5}{192\pi^3} f(m_l^2/m_\tau^2) r \quad (l = e, \mu),
\]

where \(f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x\). The factor \(r\) takes into account radiative corrections not included in the Fermi coupling constant \(G_F\), and the non-local structure of the propagator. These effects have been shown \[36\] to be small (\(\alpha = \alpha(m_\tau) = 1/133.3\))

\[
\left( 1 + \frac{25}{4\pi} \right) \left( 1 + \frac{3 m_\tau^2}{5 M_W^2} \right) \approx 0.9960
\]

<table>
<thead>
<tr>
<th>parameter</th>
<th>result</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A_x)</td>
<td>0.154 \pm 0.079 \pm 0.002</td>
</tr>
<tr>
<td>(A_r)</td>
<td>0.147 \pm 0.056 \pm 0.011</td>
</tr>
<tr>
<td>(A_{x-r})</td>
<td>0.149 \pm 0.047 \pm 0.009</td>
</tr>
</tbody>
</table>

Table 19: Polarization parameters extracted from polar angle dependence of the acollinearity distribution \[31\].

\[
A_{FB}(\epsilon) = \frac{3}{4} A_r \frac{F(\epsilon) A_r - G(\epsilon)}{F(\epsilon) - G(\epsilon) A_r}.
\]

The acollinearity analysis uses only events at the \(Z\) peak in which both \(\tau\)'s decay into one charged track. The charged tracks are identified and the decay channel classified into two categories, called the "inclusive-pion" (one hemisphere identified as \(\tau \rightarrow \pi \nu_\tau\), no restriction on the other) and the "inclusive-lepton" (one hemisphere is identified as \(\tau \rightarrow e \nu_\tau\) or \(\tau \rightarrow \mu \nu_\tau\), and neither as \(\tau \rightarrow \pi \nu_\tau\), in order to avoid double-counting).

The corrected acollinearity distributions of the inclusive pion and inclusive lepton samples are shown in Fig. 16. \(P_\tau\) is obtained by fitting those distributions to Eq. 15. \(A_r\) and \(A_x\) are obtained from \(P_\tau\) measured in the forward and backward hemisphere. The results are summarized in Table 19.

Notice that the two methods described are not independent, since the kinematics of the decay products of a single \(\tau\) and the acollinearity of the two \(\tau\)'s are correlated. The systematic uncertainties in measuring angles are, however, largely independent of the systematics in the single-\(\tau\) method.

3 Tests of Universality on the \(\tau\) Sector

3.1 Leptonic \(\tau\) Decays and Couplings to the Charged Current

The Standard Model pictures the \(\tau\) as a sequential lepton which decays to its associate neutrino via the charged current,

\[
L_{cc} = \frac{g}{2\sqrt{2}} W^+_{\mu} \left[ \sum_\ell \bar{\nu}_\ell \gamma^\mu (1 - \gamma_5) l + \bar{u} \gamma^\mu (1 - \gamma_5) d_q \right] + h.c.
\]

For the leptonic modes, the \(\tau\) decay partial width is, assuming massless neutrinos,

\[
\Gamma(\tau \rightarrow l\bar{\nu}_l l'\bar{\nu}_{l'}) = \frac{G_F^2 m_\tau^5}{192\pi^3} f(m_l^2/m_\tau^2) r \quad (l = e, \mu),
\]

where \(f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x\). The factor \(r\) takes into account radiative corrections not included in the Fermi coupling constant \(G_F\), and the non-local structure of the propagator. These effects have been shown \[36\] to be small (\(\alpha = \alpha(m_\tau) = 1/133.3\))

\[
r = \left[ 1 + \frac{25}{4\pi} \left( \frac{25}{4} - \pi^2 \right) \right] \left[ 1 + \frac{3 m_\tau^2}{5 M_W^2} \right] \approx 0.9960
\]
Figure 16: Results of the fits to the normalized forward and backward cross sections as function of the acollinearity. The points with error bars are the data corrected for acceptance, background and radiative effects. Solid curves are the result of the fits. Dashed (dotted) curves are the contributions from right-(left-) handed $\tau$'s [31].
For a standard $\tau$ lepton, the relation between $\tau_\tau$ and $B_\tau(l = e, \mu)$ can be obtained from Eq. 18. $B_\tau$ can be taken as the average value between $B_\mu$ and $B_\mu$,

$$B_\tau = B_\mu + \frac{B_\mu}{f(m_\mu^2/m_\tau^2)}, \quad (20)$$

where, substituting constants in Eq. 18,

$$B_\mu = 3.47 \times 10^{-20} \times \tau_\tau(f s) \times m_\tau^5(MeV), \quad (21)$$

$$B_\mu = 3.38 \times 10^{-20} \times \tau_\tau(f s) \times m_\tau^5(MeV), \quad (22)$$

The above relations can be checked by measuring the leptonic branching ratios the $\tau$ lifetime and the tau mass. Figs. 17, 18, 19, 20, show the most precise recent measurements for the $\tau$ mass, lifetime and leptonic branching ratios [4]. Fig. 21 shows the world average of the leptonic branching ratio $B_\tau$ and the $\tau$ lifetime, together with the prediction from Eq. 21. The agreement between the data and the theoretical expectation is good, about one standard deviation apart. A look to Figs. 17, 18, 19, 20, also reveals that the data tend to be over consistent, a trend that creates some skepticism about the meaning of the world averages.

The ratio between $B_\mu$ and $B_\mu$ is a direct test of $\mu - e$ universality. Allowing the value of the coupling $g$ in Eq. 18 to depend on the lepton flavour considered (i.e, $g_\mu, g_\mu, g_\tau$) one has,

$$\frac{B_\mu}{B_\mu} = \left(\frac{g_\mu}{g_\mu}\right)^2 f(m_\mu^2/m_\tau^2), \quad (23)$$

From the averages $B_\mu$ and $B_\mu$ one obtains [4],

$$\left(\frac{g_\mu}{g_\mu}\right)_\tau = 1.009 \pm 0.0064 \quad (24)$$

Figure 17: The new measurements of $m_\tau$ together with the PDG 1990 [37] value.
Figure 18: The new measurements of $\tau_\tau$ together with the PDG 1990 [37] value.

Figure 19: The new measurements of $B_c$ together with the PDG 1990 [37] value.
Figure 20: The new measurements of $B_\mu$ together with the PDG 1990 [37] value.

Figure 21: Consistency between leptonic branching ratios mass and lifetime.
in good agreement with the universality hypothesis and with the most precise values obtained from $\pi \rightarrow e, \mu$ decays [4]

$$
\left( \frac{g_\mu}{g_e} \right)_\pi = 1.0014 \pm 0.0016
$$

(25)

To test $\tau - \mu$ universality, it is necessary to introduce the (precisely) measured values of the muon mass and lifetime. Ignoring the small radiative corrections

$$
\left( \frac{g_\tau}{g_\mu} \right)^2 = B l_{\mu} \frac{\tau_\mu}{\tau_\tau} \left( \frac{m_\mu}{m_\tau} \right)^5,
$$

(26)

then one obtains, assuming $e - \mu$ universality

$$
\frac{g_\tau}{g_\mu} = 0.9957 \pm 0.0060
$$

(27)

This result is consistent with the universality hypothesis within one standard deviation. Note that $\mu - \tau$ universality is tested with a precision 4 times worse than $e - \mu$ universality.

### 3.2 $\tau$ Production at the Z and Couplings to the Neutral Current

Near the Z pole, the study of the $\tau^+ \tau^-$ production cross-section allows to extract information on the lepton electroweak parameters. The Z coupling to the neutral lepton current is given by

$$
\mathcal{L}_{NC} = \frac{g}{4 \cos \theta_W} Z_\mu \sum_l \bar{l} \gamma^\mu (v_l - a_l \gamma_5) l
$$

(28)

where the weak charges are predicted to be the same for all leptons,

$$
v_e = v_\mu = v_\tau = -1 + 4 \sin^2 \theta_W
$$

(29)

$$
a_e = a_\mu = a_\tau = -1.
$$

(30)

For unpolarized beams, the differential $\tau$ production cross-section can be written, at lowest order at $\sqrt{s} \sim M_Z^2$,

$$
\frac{d\sigma}{d \cos \theta} \propto 1 + \cos^2 \theta + \frac{8}{3} A_{FB} \cos \theta,
$$

(30)

where $\theta$ is the polar angle of the produced $\tau$ and the forward-backward asymmetry, at the Z pole is related with the couplings $A_e, A_\tau$ defined in Section 2.5.5 as

$$
A_{FB} = \frac{3}{4} A_e A_\tau.
$$

(31)

Thus, $A_e, A_\tau$ can be determined independently from the measurement of the forward-backward asymmetry and from the measurement of the $\tau$ polarization as discussed in Section 2.4.4. Fig. 22 shows the LEP measurements of $A_\tau, A_e$ obtained from the measurement of the average $\tau$ polarization and its $\cos \theta$ dependence.

The Z decay width into $\tau^+$'s is another test of universality, since it is proportional to the sum of the squares of the vector and axial couplings,

$$
\Gamma_\tau = \frac{G_F M_Z^2}{6\sqrt{2}\pi} \left[ v_\tau^2 + a_\tau^2 \right];
$$

(32)
Figure 22: The Measurements of $A_r, A_e$ at LEP [38].

Figure 23: LEP results for the leptonic width [38].
Figs. 23 and 24 summarize the LEP averages for the decay width and the forward-backward asymmetry for the 3 lepton families.

Combining the measurements of the partial widths of the Z into leptons, the forward-backward asymmetry, the average \( \tau \) polarization and the angular dependence of the \( \tau \) polarization, the vector and axial couplings for \( e, \mu \) and \( \tau \) can be determined. The axial coupling squared is obtained from the leptonic width (see Eq. 32), while the ratio \( v_{l}/a_{l} \) is obtained from the asymmetries. The LEP results are given in Fig. 25. Fig. 26 show the one standard deviation contours in the \( a_{l} - v_{l} \) plane. The measured ratios of \( e, \mu \) and \( \tau \) couplings provide a test of universality:

\[
\begin{align*}
    a_{\mu}/a_{e} &= 1.0006 \pm 0.0026 & a_{e}/a_{\mu} &= 0.9990 \pm 0.0029; \\
    v_{\mu}/v_{e} &= 0.77 \pm 0.21 & v_{e}/v_{\mu} &= 1.00 \pm 0.13
\end{align*}
\]  

The axial coupling is consistent with universality of the axial coupling at better than 3 per mil level. The vector coupling is also consistent with universality but only at the 27 % level for the \( \mu - e \) case and 13 % for the \( \tau - e \) case. Note that adding the extra information from polarization studies allows to reduce the error on the vector coupling of the \( \tau \) by a factor two with respect to the \( \mu \). This is the only example of a \( \tau \) property known with better precision than the corresponding one for the muon.

4 Overview and Prospects

Our knowledge on the properties of the \( \tau \) lepton has improved dramatically in the last few years. The qualitative change of \( \tau \) physics can be appreciated in Table 20, which compares the status of several \( \tau \) measurements in the 1990 compilation of the Particle Data Group [37] with the more recent world averages [3, 4].
corresponds to the Standard Model predictions. The shaded area corresponds to the Standard Model predictions.

Figure 25: LEP results for the leptonic vector and axial coupling [38].

Figure 26: One standard deviation contours in the $g_V - g_A$ plane. The solid contour results from a fit assuming lepton universality ($g_V = v/2, g_A = a/2$) [38]. The shaded area corresponds to the Standard Model predictions.
High precision $\tau$ physics could also be performed in the B Factory [146, 47, 48]. The B Factory, with the possibility to perform a sensitive study of the properties of the $\tau - \nu_\tau$ vertex and in the precision of the measurement of most $\tau$ decay modes, together with the possibility to perform a sensitive study of the properties of the $\tau - \nu_\tau$ vertex.

Among the many improvements [118, 19] in $\tau$ physics that could be achieved in a $\tau$ collider, with a state-of-the-art detector. The salient features of the $\tau - Charm Factory$ would integrate a high-luminosity $e^+e^-$ collider, with a state-of-the-art detector. The salient features of the $\tau - Charm Factory$ for $\tau$ physics would be, firstly, high statistics (around $10^7$ $\tau$ pairs a year) and secondly very small systematic errors possible in the threshold region, as discussed in section 2. Among the many improvements [18, 19] in $\tau$ physics that could be achieved in a $\tau - Charm Factory$, are a one-order-of-magnitude increase in the sensitivity to a massive $\tau$ neutrino and in the precision of the measurement of most $\tau$ decay modes, together with the possibility to perform a sensitive study of the properties of the $\tau - \nu_\tau$ vertex [44, 45, 18, 19].

High precision $\tau$ physics could also be performed in the $B$ Factory [46, 47, 48].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1990</th>
<th>1993</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\tau (MeV)$</td>
<td>$1784.12^{+7}_{-3.6}$</td>
<td>$1776.9 \pm 0.3$</td>
<td>BES</td>
</tr>
<tr>
<td>$m_{\nu_\tau} (MeV)$</td>
<td>$&lt; 35$</td>
<td>$&lt; 31$</td>
<td>ARGUS</td>
</tr>
<tr>
<td>$\tau_\tau (fs)$</td>
<td>$303 \pm 8$</td>
<td>$294.7 \pm 3$</td>
<td>LEP, CLEO</td>
</tr>
<tr>
<td>$B_s(%)$</td>
<td>$17.7 \pm 0.4$</td>
<td>$17.88 \pm 0.15$</td>
<td>LEP, CLEO, ARGUS</td>
</tr>
<tr>
<td>$B_d(%)$</td>
<td>$17.8 \pm 0.4$</td>
<td>$17.42 \pm 0.17$</td>
<td>LEP, ARGUS</td>
</tr>
<tr>
<td>$B_\ell(%)$</td>
<td>$12.6 \pm 1.2$</td>
<td>$12.04 \pm 0.24$</td>
<td>LEP, ARGUS</td>
</tr>
<tr>
<td>$B_K(%)$</td>
<td>$0.68 \pm 0.19$</td>
<td>$0.89 \pm 0.12$</td>
<td>LEP</td>
</tr>
<tr>
<td>$B(h^{+}4\pi^0)(%)$</td>
<td>$-0.15 \pm 0.06$</td>
<td>$0.54 \pm 0.10$</td>
<td>CLEOII</td>
</tr>
<tr>
<td>$B(3h^{+}2\pi^0)(%)$</td>
<td>$-0.15 \pm 0.06$</td>
<td>$0.54 \pm 0.10$</td>
<td>CLEOII</td>
</tr>
<tr>
<td>$(g_\tau/g_u)$</td>
<td>$0.94 \pm 0.15$</td>
<td>$0.9957 \pm 0.0060$</td>
<td>CLEOII, LEP</td>
</tr>
<tr>
<td>$\Gamma_{\tau\tau}$</td>
<td>$83.62 \pm 4.8$</td>
<td>$83.50 \pm 0.45$</td>
<td>LEP</td>
</tr>
<tr>
<td>$AFB_{\tau\tau}$</td>
<td>$-0.0158 \pm 0.0018$</td>
<td>$0.139 \pm 0.014$</td>
<td>LEP</td>
</tr>
<tr>
<td>$P_\tau$</td>
<td>$-0.0158 \pm 0.0018$</td>
<td>$0.139 \pm 0.014$</td>
<td>LEP</td>
</tr>
<tr>
<td>$(a_\tau/a_e)$</td>
<td>$0.9990 \pm 0.0029$</td>
<td>$0.100 \pm 0.13$</td>
<td>LEP</td>
</tr>
<tr>
<td>$(v_\tau/v_e)$</td>
<td>$0.12 - 0.41$</td>
<td>$0.35 \pm 0.003$</td>
<td>LEP, CLEOII, ARGUS</td>
</tr>
</tbody>
</table>

Table 20: Recent improvements in $\tau$ physics.

Obviously, the on-going LEP experiments and CLEOII will improve present precision in the next few years. An interesting question in how far away are those experiments from reaching their systematic limit. Making prophecies about systematics is always risky business, since increased statistics and detector improvements often reduce systematic errors below pessimistic predictions. However, many of the most interesting measurements of the properties of the $\tau$ have already comparable statistical and systematic errors, and present experiments will not probably be able to achieve a spectacular improvement in measurements like the leptonic branching ratios, $\tau$ lifetime, $P_\tau$ etc. (for a very recent discussion see [39]). The tendency of LEP experiments (and CLEOII) to be somewhat overconsistent adds to the idea that the precision on the world average of many precise measurements (i.e., leptonic branching ratios, $\tau$ lifetime) will not be enormously reduced soon.

Further progress on $\tau$ physics could be achieved in future $e^+e^-$ colliders. Significantly, there is a proposed facility in each one of the energy regions discussed in this article.

The $\tau - Charm Factory$ [40, 41, 42, 43, 44] would integrate a high-luminosity $e^+e^-$ collider, with a state-of-the-art detector. The salient features of the $\tau - Charm Factory$ for $\tau$ physics would be, firstly, high statistics (around $10^7$ $\tau$ pairs a year) and secondly very small systematic errors possible in the threshold region, as discussed in section 2. Among the many improvements [18, 19] in $\tau$ physics that could be achieved in a $\tau - Charm Factory$, are a one-order-of-magnitude increase in the sensitivity to a massive $\tau$ neutrino and in the precision of the measurement of most $\tau$ decay modes, together with the possibility to perform a sensitive study of the properties of the $\tau - \nu_\tau$ vertex [44, 45, 18, 19].

High precision $\tau$ physics could also be performed in the $B$ Factory [46, 47, 48]. The
Fig. 27, where the error bars on the leptonic branching ratios and lifetime have been shown. The central value of $B_i$ and $\tau$ is left at its present value, but the error bars correspond to future projections.

The main goal of the $B$ Factory is the study of the $BB$ system, with the aim of understanding the origin of $CP$ violation. Like the $\tau$ - Charm Factory, the $B$ Factory proposes to integrate a state-of-the-art detector with a very high luminosity $e^+e^-$ collider operating on the $T$ region. The $B$ Factory could be symmetric (essentially an upgraded version of CLEOII/CESR), or asymmetric in order to have an easier separation of vertex of long-lived particles. An asymmetric option has recently been approved at SLAC, and can be operative by the end of the decade [48]. The design luminosity of the $B$ Factory implies also about $10^7 \tau$ pairs a year. In this region, however, $\tau$ physics is harder as discussed in section 2. An asymmetric $B$ Factory could [49] nevertheless, improve the precision in the $\tau$ lifetime by at least a factor two, and improve very much on the knowledge of the $\tau$ vertex.

The $Z$ Factory [50] is a high-luminosity version of LEP. I have tried to show in section 2 that the $Z$ resonance is an excellent place for $\tau$ physics. Topics like the study of the couplings of the $\tau$ to the neutral current or $\tau$ lifetime could be improved with increased statistics. The $Z$ Factory aims at about $3 \times 10^7$ $Z$ particles a year, resulting in about $10^6 \tau^{+}\tau^{-}$ a year, more than one order of magnitude less than the $\tau$ - Charm Factory and the $B$ Factory. This disadvantage should be at least partially compensated by the very efficient $\tau$ selection possible at the $Z$ pole.

Table 21 shows a comparison between the present and the projected sensitivity for some of the major properties of the $\tau$ lepton. One can see that the improvement on precision that future $e^+e^-$ colliders would bring to $\tau$ physics is still very large. I would like to conclude insisting on an all too obvious but often ignored idea. In a moment where no clues are available about where the new physics saint graal my be hidden, and with more than a decade to go before a possible $pp$ collider can explore the next high energy frontier, precision physics may well hold pleasant surprises for the brave and the curious. 

Fig. 27, where the error bars on the leptonic branching ratios and lifetime have been
Acknowledgments

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References


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