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# TAU PHYSICS PROSPECTS AT THE TAU-CHARM FACTORY AND AT OTHER MACHINES

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ABSTRACT

The prospects for tau physics at future high-luminosity facilities are briefly discussed. Although important (and often complementary) contributions will be made from other machines, the unique experimental environment near threshold makes the Tau-Charm Factory the best experimental tool for $\tau$ physics.

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# TAU PHYSICS PROSPECTS AT THE TAU-CHARM FACTORY AND AT OTHER MACHINES

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**Abstract**
The prospects for tau physics at future high-luminosity facilities are briefly discussed. Although important (and often complementary) contributions will be made from other machines, the unique experimental environment near threshold makes the Tau-Charm Factory the best experimental tool for $\tau$ physics.

The physics programme of the Tau-Charm Factory ($\tau$cF) was established in the 1989 SLAC workshop [1]. At that time, the experimental knowledge on the $\tau$ was quite poor [2], and the main part of the physics community was not giving much attention to that (still exotic) lepton. The situation has completely changed since then. ARGUS and CLEO have substantially increased their $\tau^+\tau^-$ data sample, and the four LEP collaborations have demonstrated the potential of this machine for making clean $\tau$ physics. Moreover, a small, but very important, contribution has been accomplished at the Beijing collider. The growing interest on the $\tau$ particle has been reflected in several specialized reviews [3, 4], which have emphasized the unique properties of this heavy lepton for testing the Standard Model, and in the first two workshops [5, 6] devoted entirely to the $\tau$. The qualitative change of $\tau$ physics can be appreciated in Table 1, which compares the status of several $\tau$ measurements in the 1990 compilation of the Particle Data Group [7] with the more recent world averages [6, 8]; the main experimental sources of the improvements are also indicated.

Obviously, our knowledge on the $\tau$ lepton properties is going to be further improved in the next few years. To get a proper feeling on the quantitative impact of the $\tau$cF in this field, one should analyze the precisions that can be reached with present facilities. Moreover, the possible contributions of other future machines should also be considered. Figure 1 shows the energy and luminosity of present and future $e^+e^-$ colliders in the energy range 1 GeV $\leq E_{\mathrm{c.m.}} \leq$ 100 GeV. All machines above $\sqrt{s} = 2m_\tau$ produce $\tau$'s and can make significant contributions to $\tau$ physics.

Figure 1: Luminosity/Energy plot of present and future $e^+e^-$ colliders, in the energy range 1 GeV $\leq E_{\mathrm{c.m.}} \leq$ 100 GeV.

The different running energies have their own advantages and problems; thus, a given collider can be very good for measuring some parameter and totaly insensitive to other properties of the $\tau$. The luminosity is clearly an important ingredient, but not always the decisive one. There are three energy regions worth while to be considered: the $\tau^+\tau^-$ threshold (BEPC, $\tau$cF), the $\Upsilon$ region (DORIS, CESR, BF) and the $Z$ peak (LEP, ZF).

LEP has the great advantage of producing $\tau$'s with a sizeable boost and low backgrounds. It is obviously the best machine for lifetime measurements. Adding the 1990–1992 data sample of the four LEP experiments ($2 \times 10^5$ $\tau$ pairs) an accuracy of about 3 fs has been obtained [9]: $\tau_\tau|_{\mathrm{LEP}} = 293.5 \pm 2.8$ fs. In spite of having accumulated a much larger statistics ($2 \times 10^6$ $\tau$ pairs), the CLEO result [8], $\tau_\tau|_{\mathrm{CLEO}} = 296 \pm 10$ fs, is less precise; a smaller average flight path and larger hadronic backgrounds make difficult to achieve a better sensitivity [10]. At threshold, to measure the lifetime is clearly not possible.

The $\tau$-mass measurement requires completely different experimental conditions. With only 7 ($\tau^+\tau^- \to e^\pm\mu^\mp + 4\nu$) events, taken at threshold, BES [11] has been able to achieve an unbelievable

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Table 1: Recent improvements in $\tau$ physics. [(a) 95% C.L.; (b) 90% C.L.]

| Parameter | 1990 [7] | 1993 [6,8] | Experiment |
|---|---|---|---|
| $m_\tau$ (MeV) | $1784.1^{+2.7}_{-3.6}$ | $1777.0 \pm 0.3$ | BES |
| $m_{\nu_\tau}$ (MeV) | $< 35$ (a) | $< 31$ (a) | ARGUS + BES |
| $\tau_\tau$ (fs) | $303 \pm 8$ | $294.7 \pm 3.0$ | LEP, CLEO |
| $B_e$ (%) | $17.9 \pm 0.4$ | $17.88 \pm 0.15$ | LEP, CLEO, ARGUS |
| $B_\mu$ (%) | $17.8 \pm 0.4$ | $17.42 \pm 0.17$ | LEP, ARGUS |
| $B(h^-\nu_\tau)$ (%) | $12.6 \pm 1.2$ | $12.04 \pm 0.24$ | LEP, ARGUS |
| $B_1$ (%) | $86.13 \pm 0.33$ | $85.23 \pm 0.19$ ? | LEP ($84.80 \pm 0.23$) |
| $B(3\pi^\pm 2\pi^0\nu_\tau)$ (%) | – | $0.54 \pm 0.10$ | CLEO |
| $B(\pi^-\pi^0\eta\nu_\tau)$ (%) | $< 1.1$ (a) | $0.17 \pm 0.02$ | CLEO |
| $B(\mu^-\gamma)$ | $< 5.5 \times 10^{-4}$ (b) | $< 4.2 \times 10^{-6}$ (b) | CLEO |
| $B(e^-e^+e^-)$ | $< 3.8 \times 10^{-5}$ (b) | $< 3.5 \times 10^{-6}$ (b) | CLEO |
| $\rho_e$ | $0.64 \pm 0.06$ | $0.717 \pm 0.038$ | ARGUS |
| $\rho_\mu$ | $0.84 \pm 0.11$ | $0.762 \pm 0.046$ | ARGUS |
| $\xi_l$ | – | $0.90 \pm 0.18$ | ARGUS |
| $h_{\nu_\tau}$ | – | $-1.25 \pm 0.26$ | ARGUS |
| $\tilde{d}^Z_\tau(M_Z)$ (e cm) | – | $< 3.7 \times 10^{-17}$ | LEP |
| $\mu(\nu_\tau)$ ($\mu_B$) | $< 4 \times 10^{-6}$ (b) | $< 5.4 \times 10^{-7}$ (b) | BEBC |
| $B(Z \to \tau\tau)$ (%) | $3.33 \pm 0.13$ | $3.36 \pm 0.02$ | LEP |
| $B(Z \to \tau e)$ | – | $< 1.3 \times 10^{-5}$ (a) | LEP |
| $B(Z \to \tau\mu)$ | – | $< 1.9 \times 10^{-5}$ (a) | LEP |
| $\alpha_s(m_\tau)$ | 0.12 – 0.41 | $0.35 \pm 0.03$ | LEP, CLEO, ARGUS |
| $\sum_{\text{excl.}} B_i$ (%) | $93.5 \pm 2.4$ | $100.3 \pm 1.3$<br>$91.0 \pm 3.3$ ? | ALEPH<br>ARGUS |

accuracy of 0.5 MeV: $m_\tau = 1776.9 \pm 0.5$ MeV. A recent update, including more channels, has further improved the precision to 0.3 MeV [8]. ARGUS and CLEO, with many orders of magnitude more data, have only reached precisions of 2.8 and 1.8 MeV, respectively [8], using clever kinematic tricks.

Between these two extreme cases (lifetime and mass), nearly all aspects of $\tau$ physics (except the $Z\tau^+\tau^-$ couplings) can be addressed in any of the three energy regions; with slightly different strategies, because of the different kinematics (and background) conditions. Nevertheless, the sensitivity to a given measurement can change with the centre-of-mass energy (or with the symmetric/asymmetric configuration of the machine [10]). The potential information provided by different facilities should then be regarded as complementary. Tau physics can and should be done at any (existing or planned) $e^+e^-$ collider above threshold.

Present experiments can still increase their sensitivities and better (in some cases new) results should be expected in the near future; however, they are soon going to reach their systematic limits [9, 10, 12–14]. Further improvements in $\tau$ physics require new high-precision machines working in the high-statistics regime. As shown in Fig. 1 three high-luminosity colliders have been proposed, one in each of the three energy regions discussed before: the $\tau$cF, the $B$ Factory (BF) and the $Z$ Factory (ZF). Table 2 shows the number of $\tau^+\tau^-$ pairs that would be produced by these facilities. The highest production rate corresponds to the $\tau$cF, but the differences are not very large. Note that these numbers would further increase if higher luminosities are achieved. A next generation BF could reach $\mathcal{L} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and a high-luminosity $\tau$cF with $\mathcal{L} = 5 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$ has already been considered at this workshop [15, 16].

Table 2: Comparison of $\tau$ yearly data samples at the Z, B and $\tau$-charm factories.

| Collider | ZF | BF | $\tau$cF |
|---|---|---|---|
| Luminosity ($\text{cm}^{-2}\text{s}^{-1}$) | $2 \times 10^{32}$ | $10^{33}$ | $10^{33}$ |
| $N_{\tau^+\tau^-}$ | $0.3 \times 10^7$ | $0.9 \times 10^7$ | $0.5 \times 10^7$ (3.57 GeV)<br>$2.4 \times 10^7$ (3.67 GeV)<br>$3.5 \times 10^7$ (4.25 GeV) |

The larger statistics is, however, not the main advantage of the $\tau$cF. With the sharp increase in statistics foreseen in these facilities, the attainable precision will be limited by backgrounds and systematic errors. To achieve precise –$\mathcal{O}(0.1\%)$– measurements of $\tau$ branching ratios, for instance, the normalization, detection efficiencies and backgrounds must each be known at the 0.1% level. The decisive advantage that makes the $\tau$cF the best experimental tool for $\tau$ physics, is its capability of tightly controlling the backgrounds and systematic errors.

The threshold region provides a unique environment, where backgrounds are both small and experimentally measurable. By adjusting the beam energy above or below the $\tau^+\tau^-$ threshold, the backgrounds can be directly measured, avoiding any need for Monte Carlo simulations with their inevitable uncertainties. Moreover, the data samples are very pure because they are free of heavier flavour backgrounds. $b$ contaminations are completely absent and, running below the charm threshold, one can collect $\tau$ events that are completely free of $c$ backgrounds.

Furthermore, at the $\tau$cF it would be possible –for the first time at any machine– to single-tag $\tau^+\tau^-$ events; i.e. by observing the decay of one $\tau$, its partner would be cleanly tagged, without any pre-selection of its decay mode. This completely avoids normalization uncertainties, which turns out to be crucial to achieve very precise measurements of branching ratios. Single-tagging requires a clean signature from a single $\tau$ decay. With the capability of the $\tau$cF to produce $\tau$'s without heavy flavours contamination, there are several distinct signatures [13]: $e + E_{\text{miss}}$, $\mu + E_{\text{miss}}$, and (at 3.57 GeV) monochromatic-$\pi + E_{\text{miss}}$. Detailed studies indicate backgrounds of between $10^{-3}$ (at 3.57 GeV) and $10^{-4}$ (at 3.67 GeV) for the $e + E_{\text{miss}}$ trigger, which has a $\tau^+\tau^-$ event detection efficiency of 24%. For comparison, the typical background contaminations in present samples of double-tagged $\tau^+\tau^-$ events at $B$ or $Z$ Factory energies are about 5%. The lowest backgrounds achieved in LEP data are about 1%, while retaining adequate detection efficiency. This corresponds to a $q\bar{q}$ rejection of $\approx 4 \times 10^{-4}$, to be compared with $\approx 10^{-5}$ at the $\tau$cF.

The threshold region has also several kinematic advantages that result from the low particle velocities, such as monochromatic spectra for two-body decays. Due to the Coulomb interaction, the $\tau^+\tau^-$ production cross-section has a finite value of 0.20 nb [17] at threshold, which makes feasible to collect a copious sample of $\tau^+\tau^-$ events almost at rest. Running just above the $\tau^+\tau^-$ threshold at 3.57 GeV, the one-prong decays $\tau^- \to l^-\bar{\nu}_l\nu_\tau, \pi^-\nu_\tau, K^-\nu_\tau$ are kinematically separated (Fig. 2a). In contrast, at higher energies the distributions completely overlap (Fig. 2b) and the particle identification requirements –especially between $\pi$ and $K$– are more severe [18]. Measurements of $\tau$ branching ratios can then be done much more precisely at threshold.

Figure 2: Momentum spectra from one-prong $\tau$ decays at centre-of-mass energies of a) 3.57 GeV (1.5 MeV above the $\tau^+\tau^-$ threshold) and b) 10 GeV.

Figure 3 clearly illustrates the power of this kinematic constraint to search for exotic two-body decays like $\tau^- \to l^-X$ ($l = e, \mu$; $X =$ Majoron, familon, flavon, ...), which, at threshold, lead to the distinctive signature of monochromatic leptons (Fig. 3a) [19]. In contrast, the sensitivity is much weaker at higher energies since the lepton spectrum from the $l^-X$ decay is broad, spreading over the full spectrum of the standard $l^-\bar{\nu}_l\nu_\tau$ decay (Fig. 3b). For $\tau^- \to e^-X$ ($\tau^- \to \mu^-X$), the expected branching-ratio sensitivity at the $\tau$cF is better than $10^{-5}$ ($10^{-3}$) for one-year's data [19], to be compared with the present limits of 1-2%. The experimental sensitivity could be improved a further order-of-magnitude if the monochromator optics is successful. Sensitivity to still-lower branching ratios would require improvements in the $\pi e$ rejection of the $\tau$cF detector, e.g. with a fast RICH.

Figure 3: The combined electron spectra (solid histograms) from the standard decay $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ mixed with a hypothetical 1% two-body decay $\tau \to eX$ at centre-of-mass energies of a) 3.57 GeV and b) 10 GeV [19]. The particle $X$ is a massless Goldstone boson. The dashed histograms show conventional (V-A) fits to the combined spectra. Each plot contains 200k $\tau^- \to e^- \bar{\nu}_e \nu_\tau$, corresponding to two months' data at 3.57 GeV.

At threshold, the experimental data require small radiative corrections since the $\tau$'s are almost at rest and radiation can only bring them closer to rest. At higher-energies, the important role of initial-state QED bremsstrahlung results in large radiative corrections, which unavoidably introduce additional contributions into the final errors. This effect is particularly important for high-precision measurements of the Michel parameters in leptonic $\tau$ decays. In the recent ARGUS measurement [20] of the $\xi$ parameter, $|\xi| = 0.90 \pm 0.13 \pm 0.10$, initial-state radiation is the second main source of uncertainty with a $\pm 0.06$ contribution to the final systematic error (background subtraction gives $\pm 0.08$). Furthermore, the Lorentz boost smears the final charged-lepton energy spectrum and causes the parameters $\rho$ and $\eta$ to be strongly correlated. Clearly, the Lorentz structure of $\tau$ decays can be more accurately analyzed in the threshold region, where the $\tau$cF operates.

Another important advantage of the $\tau$cF energy region is the existence of two precisely-known energy points, the $J/\psi$ and $\psi'$, which provide a very high-rate ($\sim 1$ kHz) signal to calibrate and monitor the detector performance. This allows for a tight control of the systematic errors, making possible, for instance, to maintain the momentum-scale error of the $\tau$cF detector below 0.1% [15].

In addition to excellent momentum measurements, there are advantages [15] for photon detection and particle identification near threshold. Since particles are produced isotropically, the detection inefficiency caused by charged and neutral pileup is minimized. This is especially important for decays involving several neutral particles. The very good photon resolution of the $\tau$cF detector would increase the sensitivity to the $\tau$-neutrino mass, by allowing an optimal use of high-multiplicity $\tau$ decays containing neutrals, such as $\tau^- \to \nu_\tau 2\pi^- \pi^+ 2\pi^0$ [12,13]. Moreover, the kinematic limit of particles from $\tau$ decays at rest is 1.8 GeV, making the identification of $\pi$, $K$ and $p$ easier than at higher-energy machines.

The unique purity of the $\tau$cF data would offer the opportunity to perform a high-precision global analysis of (inclusive and exclusive) semi-leptonic $\tau$-decay modes, including kinematical quantities more subtle than the simple invariant-mass distribution of the hadronic final state [14]. The cleanness of the (bias-free) data, the excellent $\pi/K$ separation and the very good efficiency for neutral modes, would enourmously simplify the QCD analysis of current spectral functions, removing the Monte Carlo based unfolding procedure which is needed, at higher energies, to correct for detector effects [14].

Thus, the $\tau$cF experiment would benefit from a very high statistics, low and measurable backgrounds, and reduced systematic errors. The coincidence of all these features near threshold creates an ideal facility for precision $\tau$ studies. Table 3 gives an illustrative list of expected sensitivities [13, 18, 19, 21–23] at the $\tau$cF for some typical $\tau$ parameters. In all cases the improvements with respect to the present precisions are substantial. Note, that a BF (or ZF) with a similar data sample could obviously reach a comparable statistical precision for many of these observables. However, for most measurements, only the $\tau$cF is likely to achieve comparable systematic errors, thereby reaching the overall precisions indicated in Table 3.

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Table 3: Examples of the expected precision at the $\tau$cF for some $\tau$ parameters. Some improved estimates from preliminary analyses are indicated within brackets.

| Parameter | Present accuracy | $\tau$cF sensitivity |
|---|---|---|
| $m_\tau$ | 0.3 MeV | 0.1 MeV |
| $m_{\nu_\tau}$ | $< 31$ MeV | 2 MeV |
| $B_{e,\mu}$ | 1% | 0.1% |
| $B_\pi$ | 3% | 0.1% |
| $B_K$ | 34% (12%) | 0.5% |
| $\|g_\tau/g_\mu\|$ | 0.6% | 0.1% |
| $\|g_\mu/g_e\|$ | 0.6% | 0.1% |
| $\rho_{e,\mu}$ | 6% | 0.3% (0.03%) |
| $\xi_l$ | 20% | 3% (0.2%) |
| $h_{\nu_\tau}$ | 22% | 0.3% |
| $\eta_\mu$, $\delta_l$ | – | $\pm 0.03$ ($\pm 0.002$) |
| $\xi'_\mu$ | – | 15% |
| $B(\tau^- \to \pi^-\eta\nu_\tau)$ | $< 3 \times 10^{-4}$ | $10^{-6}$ |
| $B(\tau^- \to l^- X)$ | $< 2\%$ | $10^{-5}$ |
| $B(\tau^- \to 3l^\pm)$ | $< 10^{-5}$ | $10^{-7}$ |
| $B(\tau^- \to \mu^-\gamma)$ | $< 4 \times 10^{-6}$ | $10^{-7}$ |
| $a_\tau^\gamma$ | $< 0.1$ | 0.001 |
| $d_\tau^\gamma$ | $< 6 \times 10^{-6}$ e cm | $10^{-7}$ e cm |

## References

[1] *Proc. Tau-Charm Factory Workshop* (SLAC, California, 1989), ed. L.V. Beers, SLAC-Report-343 (1989).

[2] B.C. Barish and R. Stroynowski, Phys. Rep. 157 (1988) 1;
K.K. Gan and M.L. Perl, Int. J. Mod. Phys. A3 (1988) 531;
C. Kiesling, *$\tau$ Physics*, in *High Energy Electron-Positron Physics*, eds. A. Ali and P. Söding, Advanced Series on Directions in High Energy Physics, Vol. 1 (World Scientific, Singapore, 1988), p. 177.

[3] A. Pich, *Tau Physics: Present Status and Future Prospects*, in *Physics at LEP*, eds. M. Aguilar-Benítez and M. Cerrada (World Scientific, Singapore, 1990) p. 323; Mod. Phys. Lett. A5 (1990) 1995; *Tau Physics*, in *Heavy Flavours*, eds. A.J. Buras and M. Lindner, Advanced Series on Directions in High Energy Physics, Vol. 10 (World Scientific, Singapore, 1992) p. 375; *Tau Physics and Tau-Charm Factories*, Nucl. Phys. B (Proc. Suppl.) 31 (1993) 213.

[4] M. Perl, Rep. Prog. Phys. 55 (1992) 653;
K. Riles, Int. J. Mod. Phys. A7 (1992) 7647;
A.J. Weinstein and R. Stroynowski, Ann. Rev. Nucl. Part. Sci. 43 (1993) 3700.

[5] *Proc. Workshop on Tau Lepton Physics* (Orsay, 1990), eds. M. Davier and B. Jean-Marie (Editions Frontières, Gif-sur-Yvette, 1991).

[6] *Proc. Second Workshop on Tau Lepton Physics* (Columbus, Ohio, 1992), ed. K.K. Gan, (World Scientific, Singapore, 1993).

[7] M. Aguilar-Benítez et al., *Review of Particle Properties*, Phys. Lett. B239 (1990) 1.

[8] E. Fernández, *Tau Physics*, plenary talk at the EPS-93 Conference (Marseille, 1993).

[9] A. Kounine, *Tau and Charm Physics at LEP*, these proceedings.

[10] A.J. Weinstein, *Tau and Charm Physics Prospects at CESR/DORIS and B Factories*, these proceedings.

[11] J.Z. Bai et al. (BES), Phys. Rev. Lett. 69 (1992) 3021.

[12] D.F. Cowen, *The CLEO-II Limit on the Tau Neutrino Mass and Prospects for Its Improvement*, these proceedings.

[13] J.J. Gómez-Cadenas, Sensitivity of Future High-Luminosity $e^+e^-$ Colliders to a Massive $\tau$ Neutrino, these proceedings.

[14] F. Le Diberder, *QCD Tests in Tau Decays*, these proceedings.

[15] J. Kirkby, *Detector and Computing Aspects*, these proceedings.

[16] J. Le Duff, *Summary of the Machine Working Group*, these proceedings.

[17] M. Perrotet, *An Improved Calculation of* $\sigma(e^+e^- \to \tau^+\tau^-)$ *Near Threshold*, these proceedings;
M.B. Voloshin, *Topics in* $\tau$ *Physics at a Tau-Charm Factory*, Univ. Minnesota preprint TPI-MINN-89/33-T (1989).

[18] J.J. Gomez-Cadenas, *Beautiful* $\tau$ *Physics in the Charm Land*, in [1], p. 48

[19] M.C. González-García, *Exotic Tau Decays at Tau and B Factories*, these proceedings;
R. Alemany et al., *Searching for Exotic* $\tau$ *Decays*, CERN-PPE/93-49.

[20] H. Albrecht et al. (ARGUS), *A Determination of Two Michel Parameters in Purely Leptonic Tau Decays*, DESY 93-108.

[21] A. Stahl, *The Lorentz Structure of the Charged Weak Current in* $\tau$ *Decays*, these proceedings.

[22] W. Fetscher, *Universality of the Charged Leptonic Weak Interaction*, these proceedings; Phys. Rev. D42 (1990) 1544.

[23] A. Pich, *Perspectives on Tau-Charm Factory Physics*, these proceedings.