Perspective on Tau Studies at a Tau-Charm Factory[*]

PATRICIA R. BURCHAT

Santa Cruz Institute for Particle Physics
University of California, Santa Cruz, California, 95064

ABSTRACT

A high luminosity storage ring operating at center-of-mass energies in the range 3 - 5 GeV would allow high-statistics studies of the τ lepton. To take full advantage of the large data samples, the systematic errors must be greatly reduced compared to those for existing τ measurements. The size of uncertainties on current measurements and the desired precision of future measurements of τ properties are discussed. A τ physics program at a τ-charm factory is outlined and briefly compared to that at a $B\bar{B}$ factory.

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A tau-charm factory with a luminosity of 10^{33} cm^{-2} s^{-1} would produce τ pairs at a rate of more than one per second for center-of-mass energies above about 3.6 GeV. This would lead to samples of more than 10^7 τ pairs per year resulting in measurements of tau properties with very small statistical uncertainties, typically less than a few tenths of a percent for the major decay modes. This can be compared to typical uncertainties of $(2-30)\%$ on current measurements[1] of τ properties as shown in Table 1. In column (a), I list the fractional error calculated from the formal error on the world average assuming all systematic errors are independent and adding the statistical and systematic errors in quadrature. In column (b), I list the fractional systematic error for the measurement with the smallest systematic error. If the systematic errors for different experiments are correlated, it is this number which really reflects the precision of our knowledge of the measurement. To truly improve our knowledge of τ properties and to take full advantage of future large data samples, we must substantially decrease the systematic errors on our measurements.

Another factor which determines the size of systematic errors for which we should aim is the precision which is theoretically interesting. In this regard, there are properties for which there are no definite theoretical predictions, which we would like to measure as precisely as possible (for example, forbidden decay modes, a nonzero neutrino mass, or a nonzero electric dipole moment), and others for which there are definite predictions, which we would like to measure to the precision of the theoretical predictions (for example, the purely leptonic branching fractions or the Michel parameters). Some precise measurements, such as the τ mass, are not interesting by themselves but are necessary for other measurements such as the ν_τ mass.

As an example of a theoretical prediction, I will discuss briefly the size of corrections to predictions for τ decay rates. For the purely leptonic decay modes $\tau^- \to \nu_\tau l^- \bar{\nu}_l$, the lowest order decay rate, assuming an infinite W mass and a negligible $l^\pm$ mass, is given by

$$\Gamma(\tau^- \to \nu_\tau l^- \bar{\nu}_l) = \frac{G_F^2 m_\tau^5}{192\pi^3}.$$

The correction for the finite W mass[2] is 0.03%. The first order electroweak correction[2] is 0.43% and the phase space correction[3] for $\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu$ is 2.7%. Hence, we would like to measure the leptonic branching fraction to at least the precision of the electroweak corrections, a few tenths of a per cent.

The semihadronic decay rate suffers from much larger and more uncertain corrections.[4] The ratio of the total semihadronic decay rate to the decay rate for

Table 1. Measured properties of the τ lepton and the fractional error for (a) the world average and (b) the individual measurement with the smallest systematic error.

Property	World Average	Fractional Error	
		(a)	(b)
Branching Fractions			
Exclusive:			
$\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e$	$(17.7 \pm 0.4)\%$	2%	3%
$\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu$	$(17.7 \pm 0.4)\%$	2%	3%
$\tau^- \rightarrow \nu_\tau \pi^-$	$(10.9 \pm 0.6)\%$	6%	7%
$\tau^- \rightarrow \nu_\tau \rho^-$	$(22.8 \pm 1.0)\%$	4%	6%
$\tau^- \rightarrow \nu_\tau \pi^- \pi^+ \pi^-$	$(6.7 \pm 0.4)\%$	6%	10%
$\tau^- \rightarrow \nu_\tau \pi^- 2\pi^0$	$(6.7 \pm 0.4)\%$ (predicted)		
$\tau^- \rightarrow \nu_\tau \pi^- \pi^+ \pi^- \pi^0$	$(5.0 \pm 0.5)\%$	10%	16%
$\tau^- \rightarrow \nu_\tau \pi^- 3\pi^0$	1.0% (predicted)		
$\tau^- \rightarrow \nu_\tau 5\pi^\pm (\pi^0)$	$(0.11 \pm 0.03)\%$	30%	25%
$\tau^- \rightarrow \nu_\tau K^-$	$(0.6 \pm 0.2)\%$	30%	10%
$\tau^- \rightarrow \nu_\tau K^{*-}$	$(1.6 \pm 0.3)\%$	20%	25%
Inclusive:			
$\tau \rightarrow$ 1 prong $+ X$	$(87.0 \pm 0.3)\%$	0.3%	0.3%
Rare Decays	$< 3 \times 10^{-5}$ (best limit)		
Mass	(1784 ± 3) MeV	0.2%	
Lifetime	$(3.04 \pm 0.09) \times 10^{-13}$ s	3%	3%
Michel parameter ρ	0.73 ± 0.07	10%	4%
ν_τ mass	< 35 MeV		

$\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e$

$$R_H \equiv \frac{\Gamma(\tau^- \rightarrow \nu_\tau \text{ hadrons})}{\Gamma(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e)}$$

is equal to three (the number of colors) in lowest order. The electroweak correction[2] is (2.36 ± 0.50)%, significantly larger than the 0.43% correction for purely leptonic decays. Nonperturbative QCD corrections are estimated[5] to be positive and in the range (1- 3)%. Perturbative QDC corrections have recently been calculated[6] to order α_s^3. Unfortunately, the coefficient of the $(\alpha_s/\pi)^3$ correction is large (104.0) compared to that of the $(\alpha_s/\pi)^2$ correction (5.20). In addition, the precise value of α_s at this energy is not known. (Initial measurements of R_H can be used to measure $\alpha_s(m_\tau)$.)

More precise predictions can be made for some of the exclusive hadronic final states such as $\tau^- \rightarrow \nu_\tau \pi^-$ and $\tau^- \rightarrow \nu_\tau K^-$ (from the $\pi^\pm$ and $K^\pm$ lifetimes), and $\tau^- \rightarrow \nu_\tau \rho^-$ (from the conserved vector current hypothesis and experimental data for $\sigma(e^+e^- \rightarrow 2\pi)$). To compare measurements of these branching fractions from a τ-charm factory with theoretical predictions, we will probably need a new compilation of predictions, including electroweak corrections, with theoretical and experimental uncertainties specified.

The desire for systematic errors about one order of magnitude lower than those for current experiments leads to some stringent detector requirements. Low backgrounds and very clean particle identification help to reduce systematic errors. The former can be achieved in tau decays in a way which is not biased toward particular decay modes by tagging on the missing energy carried away by the neutrinos in the event if the detector has very good solid angle coverage. In addition, the detector must be sensitive to neutrons and K_L^0's in $q\bar{q}$ events which can mimic the missing energy signal. At center-of-mass energies just above the threshold for τ pair production, τ's are produced nearly at rest and therefore the maximum momentum of any decay product is approximately $m_\tau/2$. Hence, we need very good separation of electrons, muons, charged pions and kaons with momentum less than about one GeV. Near threshold, the particle identification problem is helped by the fact that the two-body decays $\tau^- \rightarrow \nu_\tau \pi^-$ and $\tau^- \rightarrow \nu_\tau K^-$ lead to almost monoenergetic but slightly separated pion and kaon momenta.

A possible τ physics program would involve data collection at three different center-of-mass energies (in addition to a scan near threshold to determine the tau mass precisely): just above threshold to take advantage of the good pion/kaon/lepton momentum separation; near 3.68 GeV (just below the ψ') where the cross section is larger, but still below the threshold for $D\bar{D}$ production; and at $\approx$ 4.2 GeV where the cross section is maximum. At the lowest energy, one would study the branching fractions for $\tau^- \rightarrow \nu_\tau \pi^-$, $\tau^- \rightarrow \nu_\tau K^-$, $\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e$ and $\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu$, the Michel parameter ρ and the ν_τ mass through the endpoint of the leptonic decay spectrum, and the Michel parameter ξ through angular correlations. Above threshold one can set better limits on the ν_τ mass through the decay $\tau^- \rightarrow \nu_\tau 5\pi^\pm$ and measure the Michel parameter δ through energy correlations.

Both the τ-charm and $B\bar{B}$ factories are proposed to deliver $\mathcal{O}(10^7)$ τ pairs per year to be compared with existing data samples of $\mathcal{O}(10^4)$ τ pairs for experiments at SPEAR, PEP and PETRA, and $\mathcal{O}(10^5)$ τ pairs for experiments at CESR and DORIS. Either factory would obviously provide significantly larger data samples than existing facilities. One question which arises is which is better suited for τ physics: a τ-charm factory or a $B\bar{B}$ factory. Some τ properties can only be studied at one facility or the other. Two examples are the τ mass (which can only be measured precisely near threshold) and the τ lifetime (which can only be measured if the τ has a significant decay length in the laboratory frame). Other τ properties, such as branching fractions, ν_τ mass and Michel parameters, can, in principle, be studied at either facility. To compare the facilities requires detailed (time-consuming) Monte Carlo studies. Probably the most detailed studies for both a τ-charm and $B\bar{B}$ factory have been done for the Michel parameters.[7][8] The conclusion is that the τ-charm factory is superior for the ρ parameter but the two facilities are roughly comparable for the remainder of the parameters with the τ-charm factory having a slight advantage. For the ν_τ mass and exclusive branching fractions, detailed studies have been conducted for the τ-charm factory[7] but not the $B\bar{B}$ factory. An advantage of the τ-charm factory for searches for rare decays of the τ is the fact that one can also collect data below the $\tau^+\tau^-$ threshold to measure backgrounds from sources other than $\tau^+\tau^-$.

In conclusion, to take advantage of the large samples of τ pairs expected at a τ-charm factory, the systematic errors must be reduced by about one order of magnitude compared to current measurements. This will require very hermetic detectors with excellent particle identification below about one GeV. More detailed studies need to be done for the $B\bar{B}$ factory before a comparison can be made with a τ-charm factory for τ studies.

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