Tau decays at the B-factories

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Since 1999, the B-factories collaborations *BABAR* and Belle have accumulated and studied large samples of tau lepton pairs. We summarize in the following the most interesting recent results.

1. Introduction

Today progress in tau physics proceeds mostly at the two B-factories *BABAR* and Belle, where unprecedented statistics of tau pair events produced in e^+e^- annihilations have been recorded.

Both experiments rely on "B-factories" operating at a centre-of-mass energy at and around the $\Upsilon(4s)$ peak (10.58 GeV). *BABAR* operates at the PEP-II complex at SLAC, which collides 9 GeV electrons against 3.1 GeV positrons, and has recorded about $531\,\mathrm{fb}^{-1}$ of data by May 2008. Belle operates at the KEKB B-factory in Japan, which collides 8 GeV electrons against 3.5 GeV positrons, and has recorded about $831\,\mathrm{fb}^{-1}$ of data by May 2008.

The *BABAR* [5] and Belle [1] detectors share several similarities and both include a silicon microvertex detector, a drift chamber, a 1.5 T solenoidal superconducting magnet, an electromagnetic calorimeter based on Cesium Iodide crystals, and a segmented muon detector in the magnet return yoke. The two experiments differ in the particle identification strategy: Belle uses an aerogel threshold Cherenkov detector together with time-of-flight and tracker dE/dx, whereas *BABAR* relies on a ring-imaging Cerenkov detector supplemented by the dE/dx in the trackers.

With a total data set now exceeding $1.1\,\mathrm{ab}^{-1}$ of integrated luminosity and a $e^+e^- \to \tau^+\tau^-$ cross-section at 10.58 GeV of 0.919 nb [18], B-factories recorded more than 10^9 tau pairs and contributed significant progress to the tau lepton physics.

2. Searches for Lepton Flavor Violation

2.1. Common analysis features

Most tau LFV decay searches at the B-factories look for low track multiplicity events that have 1 against 1 or 3 tracks in the center-of-mass system reference frame (CM). The thrust axis is used to define two hemispheres: one of them must be consistent with a tau LFV decay, while the other one must be compatible with a known tau decay. The LFV tau decay products are expected to match, within the experimental resolution, both the tau mass and the expected tau energy, i.e. half the CM energy. Analyses must account for the fact that initial and final state radiation processes decrease the amount of reconstructed energy, and that radiation in decay and Bremsstrahlung from the decay products decrease both the reconstructed energy and the reconstructed mass. The energy is reconstructed with a typical resolution of 50 MeV and, when constraining the reconstructed energy to half the CM energy, the invariant mass is reconstructed with a resolution of about 10 MeV. LFV decays are detected by an excess of events over the expected background within typically 2 or 3 standard deviations of the expected energy and mass.

The amount of expected background is usually estimated assuming that each background source has a mass and energy distribution as modeled by the Monte Carlo simulation, and then obtaining the normalization of all background sources by fitting the resulting total background distribution to the data events in the sidebands of the signal region. The signal efficiency is estimated with a Monte Carlo simulation and usually lies between 2% and 10% depending on the decay channel. Typical cumulative efficiency components include 90% for trigger, 70% for geometrical acceptance and reconstruction in the detector, 70% for reconstructing the selected track topology, 50% for particle identification, 50% for additional selection requirements before checking the reconstructed energy and mass, and 50% for requiring consistency with the expected energy and mass. The selection efficiency and background suppression are optimized to give the best "expected upper limit" assuming that the data contain no LFV signal. The optimization procedure and all systematic studies are completed while remaining "blind" to data events in the signal box in the energy-mass plane, in order to avoid experimenter biases.

When the expected background in the signal region is of order one or less, the number of signal events is normally set to the number of observed events minus the background, while in presence of sizable background the numbers of background and signal events are concurrently determined from a fit to the mass distribution of events that have total energy compatible with the expected one.

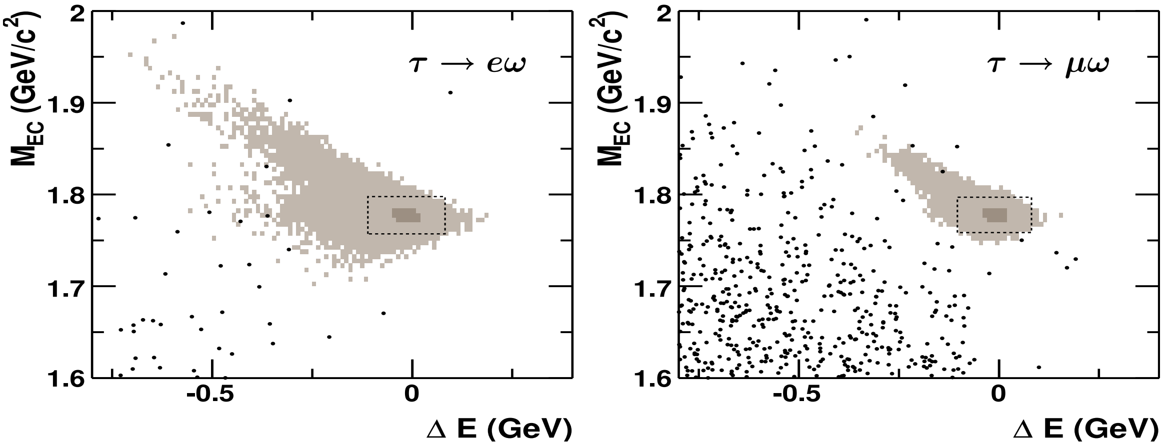

Figure 1: The dots represent data candidate events for the lepton-flavor-violating $\tau \to \ell\omega$ decay in the reconstructed energy-mass plane. The gray areas indicate where 90% of the signal events would be expected according to the simulation. The rectangular regions indicate where an excess of signal candidates is searched for.

2.2. Results

LFV decays can be grouped in the following categories: tau to lepton-photon ($\tau \to \ell\gamma$, where $\ell = e, \mu$), tau to three leptons or one lepton and two charged hadrons ($\tau \to \ell_1\ell_2\ell_3$, $\tau \to \ell h_1 h_2$), tau to a lepton and a neutral hadron ($\tau \to \ell h^0$, where $h^0 = \pi^0, \eta, \eta', K^0_s$, *etc.*).

BABAR has recently published results on a search for the lepton-flavor-violating decays $\tau \to \ell\omega$ ($\ell = e, \mu$), based on the analysis of 384 fb^{-1} of data[16]. Candidate ω mesons are reconstructed using the decay into $\pi^+\pi^-\pi^0$; simulated signal events are selected with an efficiency of 2.96% (2.56%) for the electron (muon) channel. The signal is searched by requiring that the reconstructed tau candidate has the correct mass (M_{RECO}) and the expected energy ($E_{\mathrm{RECO}} \simeq \sqrt{s}/2$) in the CM. The actual reconstructed quantities are smeared by the detector resolution and shifted by radiation and Bremsstrahlung (see Figure 1). The amount of expected background is estimated by determining the shape of the two-dimensional probability density function (PDF) of each background component on simulated events or in control samples extracted from data for background sources like Bhabha events whose simulation is practically unfeasible. The normalization of all background component PDFs are then determined with a fit on the data sidebands surrounding the signal region in the $M_{\mathrm{RECO}} - E_{\mathrm{RECO}}$ plane. No events are found while 0.35 (0.73) are expected for the electron (muon) channel, and upper limits are determined according to the Cousin and Highland prescription [21] with no Feldman and Cousin ordering in the range as follows: $\mathcal{B}(\tau \to e\omega) < 11 \cdot 10^{-8}$ and $\mathcal{B}(\tau \to \mu\omega) < 10 \cdot 10^{-8}$ at 90% confidence level (CL).

Recently, *BABAR* and Belle have published [10, 34] improved results on tau to three leptons LFV searches, based on enlarged event samples of 400 fb^{-1} and 535 fb^{-1} respectively. The two analyses have similar signal efficiencies (5.5%−12.5% for the different channels) although different strategies are adopted to define the signal regions in the energy-mass plane: Belle uses ellipses large enough to contain 90% of signal events, while *BABAR* uses rectangular signal boxes optimized to obtain the lowest expected upper limit in case of no signal. The Belle selection is significantly more effective in suppressing the background, which is expected to be 0.01−0.07 events in all channels but the three electron one, where 0.4 events are expected due to Bhabha contamination. The background in the signal region is estimated from the mass distribution sidebands, assuming it is constant, using looser selection criteria to get reasonable samples close to the signal region. No details are given on how the extrapolation is done for the full selection. *BABAR* expects 0.3−1.3 background events, i.e. of order one, since the selection is optimized for the best expected upper limit, at the risk of getting background events in the signal region. Belle observes no candidate signal events in 535 fb^{-1} of data in all modes, and calculates upper limits using Feldman and Cousin ordering [20, 34] in the range $[2.0-4.1] \cdot 10^{-8}$, depending on the mode. *BABAR* observes from 0 to 2 events in 376 fb^{-1} of data, and calculates upper limits according to Cousin and Highland prescription [21] with no Feldman and Cousin ordering in the range $[4-8] \cdot 10^{-8}$.

BABAR has published new results on tau LFV decays into a lepton and a pseudoscalar meson π^0, η, η' [12]. In these analyses both the $\eta \to \gamma\gamma$ and the $\eta \to 3\pi$ decay modes are used, and η' candidates decaying both to $\eta 2\pi$ and $\gamma 2\pi$ are considered. The expected background per channel is between 0.1 and 0.3 events. Summing over all ten modes, 3.1 background events are expected, and 2 events are observed.

Belle has published improved results on tau LFV decays into a lepton and a vector meson V^0 [35], with $V^0 = \phi$, ω, K^{*0} or $\bar{K}^{*0}$, using 543 fb^{-1} of data. No

Table I Summary of 90% CL upper limits on tau LFV decays from the B-factories. An asterisk indicates a preliminary result. h and h' denote a charged pion or kaon. Banerjee's combination of a subset of these channels is also included. For *BABAR*, V^0 includes just the ω vector meson.

Channel	Belle		*BABAR*	
	UL90 (10^{-8})	Lumi (fb^{-1})	UL90 (10^{-8})	Lumi (fb^{-1})
$\mu\gamma$	5	535	6.8	232
$e\gamma$	12	535	11	232
$\mu\eta$	6.5	401	15	339
$\mu\eta'$	13	401	13	339
$e\eta$	9.2	401	16	339
$e\eta'$	16	401	24	339
$\mu\pi^0$	12	401	15	339
$e\pi^0$	8	401	13	339
$\ell\ell\ell$	2–4	535	4–8	376
$\ell hh'$	20–160	158	10–50	221
ℓV^0	5.9–18	543	10–11	384
μK_S	4.9	281		
eK_S	5.6	281		
$\mu f_0(980) \to \mu\pi^+\pi^-$	3.2*	671		
$ef_0(980) \to e\pi^+\pi^-$	3.4*	671		
$\Lambda\pi, \overline{\Lambda}\pi$	7.2–14	154	5.8–5.9*	237
$\Lambda K, \overline{\Lambda}K$			7.2–15*	237
$\sigma_{\ell\tau}/\sigma_{\mu\mu}$			400–890	211

(* preliminary)

excess of signal events over the expected background is observed, and upper limits on the branching fractions are obtained in the range $(5.9{-}18)\cdot 10^{-8}$ at 90% CL.

Belle has also reported on a LFV search for $\tau \to \ell f_0(980)$ followed by $f_0(980) \to \pi^+\pi^-$ [30]: no events are observed on a negligible expected background, obtaining 90% CL limits in the range $3.3{-}3.4 \cdot 10^{-8}$ for the complete decay chain. This channel is sensitive to Higgs mediated LFV processes like $\tau \to \ell\eta$.

BABAR reported in the past also on a less conventional search for LFV in tau production ($e^+e^- \to \ell\tau$) [13], finding no signal.

The above results and additional B-factories LFV results [6–9, 27, 31–33, 37] are summarized in Table 2.2.

2.3. Prospects

While Belle plans to run until it will collect $1\,\mathrm{ab}^{-1}$ of data, *BABAR* has ended data-taking with a total collected luminosity of about $530\,\mathrm{fb}^{-1}$. In case of no signal, the expected upper limits on the number of selected signal events will improve depending of the amount of irreducible background in each channel:

- when the expected background is large ($N_{\mathrm{BKG}} \gg 1$), the expected upper limit is $N_{90}^{\mathrm{UL}} \approx 1.64\sqrt{N_{\mathrm{BKG}}}$;
- when the expected background is small ($N_{\mathrm{BKG}} \ll 1$), using [21] one gets $N_{90}^{\mathrm{UL}} \approx 2.4$.

Reducing the background below few events does not much improve the expected limit if significant efficiency is lost in the process, therefore optimized searches often enlarge the acceptance until $N_{\mathrm{BKG}} \approx 1$. For the cleaner channels, analyses can be optimized for an increased data sample to keep $N_{\mathrm{BKG}} \approx 1$ without loosing a significant part of the signal efficiency: in this best case scenario, the expected upper limits will scale as $N_{\mathrm{BKG}}/\mathcal{L}$ i.e. as $1/\mathcal{L}$. On the other hand, if no optimization is possible, just keeping the current analyses will provide upper limits that scale as $\sqrt{N_{\mathrm{BKG}}}/\mathcal{L}$, i.e. as $1/\sqrt{\mathcal{L}}$.

Beyond the current B-factories facilities, there are proposals for super B-factories [19] that would permit a 100 fold increase in the size of the tau pairs sample: this would allow probing tau LFV decays at the $10^{-9}{-}10^{-10}$ level.

3. V_{us} measurement with tau decays

V_{us} measurements relying on kaon decays are limited by theory uncertainties to a relative precision of 0.5%–0.6% (see for instance ref. [3]). On the other hand, the V_{us} determination from the inclusive branching ratio of the tau to final states with net strangeness equal to one ($\tau \to X_s\nu$) is presently dominated from experimental uncertainties, and theory uncertainties can be estimated as low as 0.23% [26].

Recently, the *BABAR* and Belle experiments have published measurements that improve the former knowledge of the tau branching fractions into $\mathcal{B}(\tau^- \to K^-\pi^0\nu_\tau)$ [11], $\mathcal{B}(\tau^- \to \overline{K}^0\pi^-\nu_\tau)$ [23], $\mathcal{B}(\tau^- \to K^-\pi^-\pi^+\nu_\tau)$ [14], and $\mathcal{B}(\tau^- \to K^-\phi\nu_\tau)$ [14, 29]. The information has been combined to obtain the most up-to-date measurement of $\mathcal{B}(\tau \to X_s\nu) =$ [17]: 2.8447 ± 0.0688. When the experimental measurement of $\mathcal{B}(\tau^- \to K^-\nu_\tau)$ is replaced with the prediction based on the more precise $K_{\mu 2}$ measurement and assuming $\tau - \mu$ universality ([26], $\mathcal{B}(\tau \to X_s\nu) = 2.8697 \pm 0.0680$ [17].

Following ref. [22], assuming $\mu{-}e$ universality, we use the tau branching fraction measurements to electron and muon to obtain $\mathcal{B}(\tau \to e\bar{\nu}_e\nu_\tau)^{\mathrm{uni}} = \mathcal{B}_e^{\mathrm{uni}} = (17.818 \pm 0.032)\%$, $R_{\tau,\mathrm{hadrons}} = (1 - \mathcal{B}_e - \mathcal{B}_\mu)/\mathcal{B}_e^{\mathrm{uni}} = 3.640 \pm 0.010$. Considering strange and non-strange tau decays, $R_{\tau,\mathrm{hadrons}} = R_{\tau,\text{non-}s} + R_{\tau,s}$, where $R_{\tau,s} = \mathcal{B}(\tau \to X_s\nu)/\mathcal{B}_e^{\mathrm{uni}}$. With the above we can measure:

$$|V_{us}| \;=\; \sqrt{R_{\tau,s}\Big/\left[\frac{R_{\tau,\text{non-}s}}{|V_{ud}|^2} - \delta R_{\tau,\mathrm{th}}\right]}, \qquad (1)$$

where $\delta R_{\tau,th} = 0.240 \pm 0.032$ [25]. With $V_{ud} = 0.97418(27)$ [4], we obtain $|V_{us}^{\tau}| = 0.2168 \pm 0.0028$. Unitarity predicts $|V_{us}^{\text{uni}}| = \sqrt{1 - |V_{ud}|^2} = 0.2259 \pm 0.0001$: the two values differ by 3.06σ. On the other hand, $|V_{us}|$ obtained from kaon measurements is about twice more precise and consistent with unitarity [3].

4. Other results

Several other results have been published with B-factories data, and only a selection of the most recent ones is briefly mentioned in the following.

Belle has measured the tau mass [2] using $\tau \to 3\pi\nu_\tau$ with a pseudo-mass technique. Although systematic errors are larger than at threshold experiments, the tau mass can be measured separately for oppositely charged tau leptons, permitting a CPT test that found no violation.

Belle has reported preliminary measurements of several branching fractions of the tau to final states including the η meson [28]. The measurements, including the invariant mass distributions, are generally consistent with the theory and adequately modeled by the Tauola simulation [36].

BABAR has measured $\mathcal{B}\tau \to 3\pi\eta\nu$ [15] and has searched for the decay $\tau \to \eta'(958)\pi\nu$, which proceeds through a second-class current and is expected to be forbidden in the limit of isospin symmetry. No evidence has been found and a 90% CL upper limit at $7.2 \cdot 10^{-6}$ has been obtained [15].

Belle has precisely measured the branching fraction and the invariant mass distribution of the decay $\tau^- \to \pi^- pi^0 \nu_\tau$ using $72.2\,\text{fb}^{-1}$ of data [24]. The unfolded invariant mass spectrum is used to obtain the parameters for the $\rho(770)$, $\rho'(1450)$, and $\rho''(1700)$ meson resonances and to estimate the hadronic (2π) contribution to the anomalous magnetic moment of the muon ($a_\mu^{\pi\pi}$).

5. Conclusions

The B-factories advanced considerably our knowledge on tau lepton physics. Searches for new physics effects have not found deviations from the Standard Model expectations, and a number of upper limits have been published to constrain new physics models. The measurement of $|V_{us}|$ with tau decays is promising because of the small estimated error from theory, but significant work is needed to further improve the precision on the most abundant Cabibbo-suppressed tau decays. The first results from the B-Factories produce a low $|V_{us}|$ value, which is about 3σ away from the unitarity constraint derived from the precise experimental measurement of $|V_{ud}|$.

Acknowledgments

I would like to thank the organizers of the HQL 2008 conference for their hospitality and their patience in waiting for the delivery of this contribution.

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