Tau physics results from BaBar

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Abstract Since 1999, the BABAR collaboration has accumulated and studied large samples of tau lepton pairs. The main physics results are reported.

Key words tau, tau lepton, lepton flavour violation, tau decays

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1 Introduction

Since 1999, the BaBar and Belle B-factories have analyzed an unprecedented amount of tau pairs and have been the major contributors to the progress of the experimental tau lepton physics.

The BaBar experiment operates at the PEP-II complex at SLAC, which collides 9 GeV electrons against 3.1 GeV positrons to produce a centre-of-mass energy of 10.58 GeV on the $\Upsilon(4s)$ peak, just above the threshold for producing B-mesons. By the end of 2007, BaBar has collected about $500\,\text{fb}^{-1}$of data; with a $e^+e^- \to \tau^+\tau^-$ cross-section at 10.58 GeV of 0.919 nb[1], this corresponds to about 450 million tau pairs.

The BaBar detector is described in detail elsewhere[2]. Charged-particle momenta are measured with a 5-layer double-sided silicon vertex tracker and a 40-layer helium-isobutane drift chamber inside a 1.5-T superconducting solenoidal magnet. The transverse momentum resolution is parameterized as $\sigma_{p_T}/p_T = (0.13\cdot p_T[\text{GeV}/c]\oplus 0.45)\%$. An electromagnetic calorimeter consisting of 6580 CsI(Tl) crystals is used to identify electrons and photons, a ring-imaging Cherenkov detector is used to identify charged hadrons, and the instrumented magnetic flux return (IFR), equipped with limited streamer tubes and resistive plate chambers, is used to identify muons.

2 Lepton flavour violation searches

The typical tau LFV decay search at the B-factories selects low track multiplicity events that have 1 against 1 or 3 tracks in the center of mass (c. m.) frame. The thrust axis is used to define two hemispheres, each one is then examined for consistency with a tau LFV decay, while the other one must be compatible with a known tau decay. Unlike known tau decays, which include at least one neutrino, the reconstructed products of a LFV tau decay are expected to match the tau mass and half the c.m. energy within the experimental resolution. It is worth noting that physics effects also limit the experimental accuracy in reconstructing the parent tau energy and mass from its decay products: initial and final state radiation affect the tau energy itself before the decay, while radiation in decay and Bremsstrahlung from the decay products change the reconstructed energy and invariant mass. The energy is reconstructed with a typical resolution of 50 MeV and, when using a total energy constraint to half the c.m. energy, the invariant mass is reconstructed with a resolution of about 10 MeV. Selected events around the expected energy and mass within 2 or 3 standard deviations are then investigated, looking for an excess over the expected background.

The amount of expected background is normally estimated using the distribution shapes from the Monte Carlo simulation normalized to the observed events in a two-dimensional sideband region around the signal region in the energy-mass plane. 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%

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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 maintaining the experimenter "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.

2.1 Results

LFV decays can be grouped in the following categories: tau to lepton-photon ($\tau \to l\gamma$, where $l = e, \mu$), tau to three leptons or one lepton and two charged hadrons ($\tau \to l_1 l_2 l_3$, $\tau \to l h_1 h_2$), tau to a lepton and a neutral hadron ($\tau \to l h^0$, where $h^0 = \pi^0$, η, η', K^0_s, etc.).

To date, all searches for Lepton Flavour Violation is tau decay (or production) have been negative, and 90% CL limits have been set on the rate of the examined processes. In the following, some details are given for the most recent results, and a table with all the BABAR searches is reported.

BABAR has reported improved results on tau to three leptons LFV searches[3] using an enlarged event sample of 376 fb^{-1}. Signal events are searched in a rectangular region around the expected mass and energy in the $\Delta M - \Delta E$ plane. The selection criteria and the signal region size are optimized to obtain the lowest expected upper limit in case of no signal. The shape of the $\Delta M - \Delta E$ distribution for all expected background components is estimated on simulated data. For each channel, a simultaneous fit on the data sidebands is used to determine the normalization of all background components in order to estimate the expected background in the signal region in the range of 0.3−1.3 events. From 0 to 2 events are observed in 376 fb^{-1} of data. Upper limits at 90% CL are set according to the Cousin and Highland prescription[4] in the range $[3.7—8.0] \times 10^{-8}$.

BABAR has recently reported results on the search for $\tau \to l\omega$[5] where $l = e, \mu$. Again the selection criteria and the signal region size are optimized to obtain the lowest expected upper limit in case of no signal. The expected background is estimated like for the three lepton search with a two-dimensional fit to the sidebands: 0.35 ± 0.6 events are expected for the electron channel, and 0.73 ± 0.3 for the muon one. No events are observed in data corresponding to 384 fb^{-1}, and 90% CL upper limits are set to 1.1×10^{-7} for $\tau \to e\omega$ and to 1.0×10^{-7} for $\tau \to \mu\omega$.

BABAR has published results on tau LFV decays into a lepton and a pseudoscalar meson π^0, η, η'[6]. 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 in a collected sample of 339 fb^{-1}. The obtained 90% CL limits are in the range $[1.1—2.4] \times 10^{-7}$.

BABAR reported also on less conventional searches of tau LFV decays into $\Lambda\pi$[7] and of LFV in tau production ($e^+e^- \to l\tau$)[8], finding no signal.

Table 1 summarizes the BABAR results on LFV searches[9].

Table 1. List of BABAR 90% CL upper limits (UL90) on tau LFV decays, with the respective events sample integrated luminosity. An asterisk indicates a preliminary result. h and h′ denote a charged pion or kaon. The last line reports the upper limit on the ratio of a LVF cross-section and the $e^+e^- \to \mu^+\mu^-$ one.

channel	UL90(10^{-7})	Int. L/fb^{-1}
$\mu\gamma$	0.7	232
$e\gamma$	1.1	232
$\mu\eta$	1.5	339
$\mu\eta'$	1.3	339
$e\eta$	1.6	339
$e\eta'$	2.4	339
$\mu\pi^0$	1.5	339
$e\pi^0$	1.3	339
lll	0.4—0.8	376
lhh′	1—5	221
$\mu\omega$	1.1	384
$e\omega$	1.0	384
$\Lambda\pi, \overline{\Lambda}\pi$	5.8—5.9*	237
$\Lambda K, \overline{\Lambda}K$	7.2—15*	237
$\sigma_{l\tau}/\sigma_{\mu\mu}$	40—89	211

2.2 Prospects

The BABAR data-taking schedule has recently been revised and will and with approximately 500 fb^{-1} of data. 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:

1) when the expected background is large ($N_{BKG} \gg 1$), the expected upper limit is $N^{UL}_{90} \approx 1.64\sqrt{N_{BKG}}$;

2) when the expected background is small ($N_{\rm BKG} \ll 1$), using[4] one gets $N_{90}^{\rm UL} \approx 2.4$.

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 $N_{\rm BKG} \approx 1$. For the cleaner channels, analyses can be optimized for an increased data sample to keep $N_{\rm BKG} \approx 1$ without loosing a significant part of the signal efficiency: in this best case scenario, the expected upper limits will scale as $N_{\rm BKG}/\mathcal{L}$ i.e. as $1/\mathcal{L}$. On the other hand, if no optimization is possible, applying the same analysis will provide upper limits that scale as $\sqrt{N_{\rm BKG}}/\mathcal{L}$, i.e. as $1/\sqrt{\mathcal{L}}$.

It is conceivable that all BaBar searches can be completed on the final collected data sample with expected background of order one in the signal region, at approximately constant efficiency, by suitably adapting the selection.

3 Strange spectral functions

The rate and the visible invariant mass distribution of the hadronic tau decays into strange final states can be used to determine the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix element $|V_{\rm us}|$, either simultaneously together with the strange quark mass, $m_{\rm s}$, or relying on an independent determination of $m_{\rm s}$[10—16]. In either case, the $|V_{\rm us}|$ determination is competitive with respect to alternative determinations based on kaon and hyperon decays[17—19]. Using the updated knowledge of $m_{\rm s}(2\ {\rm GeV}) = 94 \pm 6\ {\rm MeV}/c^2$ from lattice calculations[20], $|V_{\rm us}|$ has been determined with relatively small theoretical uncertainties[21—23], using available measurements of branching fractions of all τ decays into final states containing an odd number of kaons.

BaBar has provided results on tau branching fractions to strange final states that improve the above $|V_{\rm us}|$ determinations:

$$\mathcal{B}(\tau^- \to K^- \pi^0 \nu_\tau) = (0.416 \pm 0.003 \pm 0.018)\%^{[24]},$$

$$\mathcal{B}(\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau) = (8.83 \pm 0.01 \pm 0.13)\%^{[25]},$$

$$\mathcal{B}(\tau^- \to K^- \pi^- \pi^+ \nu_\tau) = (0.273 \pm 0.002 \pm 0.009)\%^{[25]},$$

$$\mathcal{B}(\tau^- \to K^- \pi^- K^+ \nu_\tau) = (0.1346 \pm 0.0010 \pm 0.0036)\%^{[25]},$$

$$\mathcal{B}(\tau^- \to K^- K^- K^+ \nu_\tau) = (1.58 \pm 0.13 \pm 0.12) \times 10^{-5\,[25]}.$$

where the uncertainties are statistical and systematic, respectively, and the charge-conjugate modes are implied. These results are more precise than the previously published measurements[26], and have been used to update the $|V_{\rm us}|$ prediction[27] (see Fig. 1).

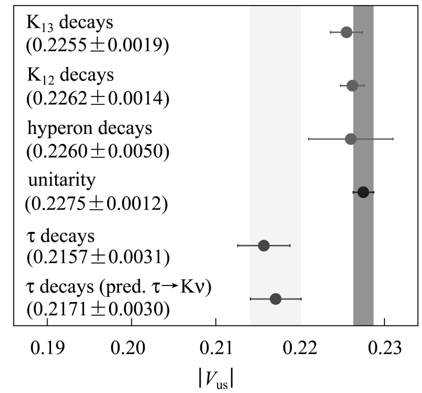

Fig. 1. Comparison of different estimates of $|V_{\rm us}|$. The bottom $|V_{\rm us}|$ determination uses $\mathcal{B}(\tau^- \to K^- \nu_\tau) = (7.15 \pm 0.03) \times 10^{-3}$, obtained from theoretical predictions using the much better known $K^- \to \mu^- \nu_\mu(\gamma)$ decay rate and assuming $\tau-\mu$ universality.

4 Other hadronic tau decays

Preliminary results obtained with 384 fb^{-1}are available[28] for:

$$\mathcal{B}(\tau^- \to \eta \pi^- \pi^- \pi^+ \nu_\tau) = (1.60 \pm 0.08 \pm 0.10) \times 10^{-4},$$

$$\mathcal{B}(\tau^- \to \eta'(958) \pi^- \nu_\tau) < 7.3 \times 10^{-6}\ (90\%\ {\rm CL}).$$

The last decay proceeds through a second-class current and is expected to be forbidden in the limit of isospin symmetry.

Preliminary results based on 210 fb^{-1}have been reported[29] for:

$$\mathcal{B}(\tau^- \to \pi^- \pi^- \pi^+ \pi^0 \nu_\tau) = (4.39 \pm 0.01 \pm 0.21) \times 10^{-2},$$

$$\mathcal{B}(\tau^- \to \pi^- \omega \nu_\tau) = (1.97 \pm 0.01 \pm 0.10) \times 10^{-2}.$$

BaBar has improved the existing measurements for tau decays into 5 charged pions:[30]

$$\mathcal{B}(\tau \to 5\pi \nu_\tau) = (8.56 \pm 0.05 \pm 0.42) \times 10^{-4},$$

$$\mathcal{B}(\tau \to f_1(1285) \pi \nu_\tau) = (3.9 \pm 0.7 \pm 0.5) \times 10^{-4}.$$

Furthermore, tau decays into seven pions have been searched for, and upper limits have been set for:[31, 32]

$$\mathcal{B}(\tau \to 7\pi(\pi^0)\nu_\tau) < 3.0 \times 10^{-7}\ (90\%\ {\rm CL}),$$

$$\mathcal{B}(\tau \to 7\pi\nu_\tau) < 4.3 \times 10^{-7}\ (90\%\ {\rm CL}),$$

$$\mathcal{B}(\tau \to 7\pi\pi^0\nu_\tau) < 2.5 \times 10^{-7}\ (90\%\ {\rm CL}),$$

$$\mathcal{B}(\tau \to 5\pi 2\pi^0\nu_\tau) < 3.4 \times 10^{-6}\ (90\%\ {\rm CL}),$$

$$\mathcal{B}(\tau \to 2\omega\pi\nu_\tau) < 5.4 \times 10^{-7}\ (90\%\ {\rm CL}).$$

5 Tau lifetime

The tau lepton lifetime is known up to 0.3%[26] and is the least precisely known quantity when one compares the charged weak current coupling of the tau with the one of the electron and the muon:

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5\frac{f_{e\mu}r^\mu_{EW}}{f_{e\tau}r^\tau_{EW}}, \quad (1)$$

$$\left(\frac{g_\tau}{g_e}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5\frac{f_{e\mu}r^\mu_{EW}}{f_{\mu\tau}r^\tau_{EW}}. \quad (2)$$

In the above expressions, τ_l corresponds to lepton lifetimes, m_l to lepton masses, $\mathcal{B}$ to branching fractions; $f_{\alpha\beta} = f(m_\alpha^2/m_\beta^2)$ with $f(x) = 1-8x+8x^3-x^4-12x\ln x$ are phase space factors[33], $r^l_{EW} \approx 1$ correspond to electro-weak radiative corrections[33]. The present data are consistent with the universality of the leptonic charged-current couplings to the 0.2% level[34].

BaBar has presented a preliminary measurement of the tau lifetime with an error comparable to the present world average:

$$\tau_\tau = 289.4 \pm 0.9 \pm 0.9 \text{ fs}^{[35]}. \quad (3)$$

The measurement uses about 80 $\text{fb}^{-1}$of data and is based on an extremely pure (99.4%) yet scarcely efficient (0.2%) selection of 1 against 3-prong events in the c.m. system, where the 1-prong track is an identified electron. Electron identification is used because it is more efficient and less contaminated with hadrons with respect to muon tagging. The selected tau candidates are about 300 000 and include about 0.2% hadronic background, 0.4% Bhabha background and a negligible amount of two-photon events.

The measurement is based on the reconstruction of the decay length of the tau that decayed into the 3-prong tracks. Using a novel technique aimed at minimizing the systematic dependence on the detector alignment, the tau decay vertex is first computed in a transverse plane with respect to the beam axis. The transverse decay length is computed in this plane by projecting the vector from the luminous region center to the tau decay vertex along the 3-prong total momentum direction (which approximates the tau flight direction). The tau decay length is finally reconstructed by projecting the transverse decay length onto the 3-prong total momentum direction.

The mean decay length is determined with an average, in order to minimize systematic effects from alignment and detector material modeling. The mean lifetime is determined using the Monte Carlo prediction of the average tau momentum, using the KKMC generator[36], which includes complete 2nd order radiative corrections. The measurement offset that originates from tracking errors correlations[37] and from approximating the tau momentum direction with that of the 3-prong total momentum is subtracted using the Monte Carlo simulation.

Finally, the contribution of background is subtracted. While hadronic background is simulated, a statistically adequate Monte Carlo simulation of Bhabha events is impractical because the relevant cross-section is about 20 times the tau production cross section ($\approx$ 1 nb), therefore a data control sample is used to estimate both the Bhabha contamination and its decay length distribution.

Systematic uncertainties come mainly from the reliability of the measurement bias subtraction using Monte Carlo, from detector alignment, from the mean tau momentum Monte Carlo simulation, and from background subtraction. This measurement includes a study of the effects of detector misalignment. Decay length shifts with respect to a perfectly aligned detector are measured on simulated Monte Carlo events by refitting tracks from coordinates taken on a detector that is purposefully distorted. Six representative distortions are applied by displacing the silicon vertex detector wafer positions according to the distortions that are observed in reconstructed data.

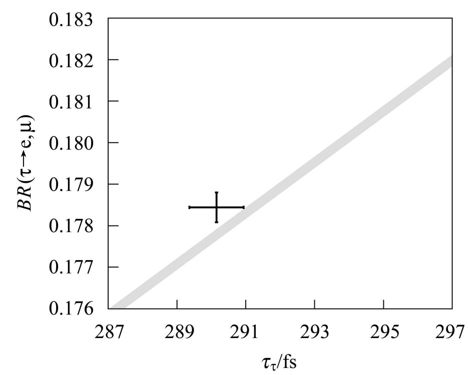

Fig. 2. Check of the Standard model (SM) prediction of universal leptonic couplings to the W (right) combining the present tau lifetime world average with the BABAR preliminary result. The thickness of the oblique line represents the uncertainty of the SM constraint, and is dominated by the uncertainty on the tau mass.

In the recent years, this preliminary measurement contributes the largest experimental improvement for the coupling ratio expressions (1) and (2). The measurement is the most precise single experiment determination of the tau lifetime to date[38]. Combining the BaBar 2004 result with the present world average and assuming no systematic error correlations we obtain

$$\tau_\tau = 290.15 \pm 0.79 \text{ fs} . \quad (4)$$

Using the present world averages, we present an updated check of lepton universality in Fig. 2 and updated determinations of the coupling ratios

$$\frac{g_\mu}{g_\tau} = 0.9982 \pm 0.0020 , \quad \frac{g_e}{g_\tau} = 0.9980 \pm 0.0020 , \quad (5)$$

$$\frac{g_{e,\mu}}{g_\tau} = 0.9981 \pm 0.0017 , \quad (6)$$

where $g_{e,\mu}$ is determined assuming $g_e = g_\mu$ holds for the theory.

In the recent past, LEP experiments improved considerably the experimental precision on the tau lifetime profiting from ideal conditions in most respects but statistics: there high momentum tracks had small impact parameter errors due to multiple scattering, tau events had a distinctive topology that permitted a pure and efficient selection against backgrounds, vertex detectors provided precise tracking close to the origin and systematic uncertainties from detector misalignment were reduced thanks to the complete and uniform acceptance in the azimuthal angle[37]. B-factories appear to be the only facilities where the tau lifetime measurement can be improved in the near future and they can overcome with statistics the disadvantages related to increased multiple scattering, to low momenta particles and to less favourable physics conditions for an efficient and pure selection.

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