Rare tau decays from BABAR

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Abstract The BaBar experiment has now completed data taking and with an integrated luminosity of 531 fb^{-1} of e$^+$e$^-$ collision data has recorded some 480 million tau-pair events. Various studies of suppressed, rare and forbidden decays of the tau have been conducted, including searches for high-multiplicity decays, for second-class hadronic weak currents, and for lepton-flavour violation.

Key words particle physics, tau leptons, rare decays

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1 Introduction

The BaBar experiment finished taking data in 2008, with a final data set comprising 531 fb^{-1} of e$^+$e$^-$ collision data taken mostly at or just below the $\Upsilon(4S)$ resonance. Small amounts of data were also taken at the $\Upsilon(2S)$ and $\Upsilon(3S)$. The principal aim of the experiment was the study of CP-violation in B-meson pairs produced in $\Upsilon(4S)$ decays, which work contributed to the award of the 2008 Nobel Prize to Kobayashi and Maskawa. The cross-section for tau-lepton pair production at BaBar is 0.9 nb, not far below that for B$\overline{\mathrm{B}}$ production, and varying only slowly with the e$^+$e$^-$ energy. Thus, over the data-taking period of the experiment, some 480 million tau-pair events were also recorded.

The BaBar detector [1] was well equipped to record and measure tau-pair events. It included: a silicon vertex tracker and a drift chamber within a solenoidal magnetic field of 1.5 T; a ring-imaging Cherenkov detector for particle identification, complementing the dE/dx capabilities of the tracking detectors; a thallium-doped, caesium iodide electromagnetic calorimeter for photon and electron identification; and an instrumented iron flux return for muon identification.

To select tau-pair events, one generally boosts to the e$^+$e$^-$ centre-of-mass frame where, in the absence of initial-state or final-state radiation, the tau leptons would be back to back, each carrying half of the available energy. Since the taus have a relatively large boost, the events have large thrust and can be divided into two hemispheres using the plane perpendicular to the thrust axis. A one-prong or three-prong system in one hemisphere, with effective mass less than the tau mass, together with missing energy carried by one or two neutrinos, would be evidence of a standard tau decay. Such a signature would tag the the opposite hemisphere as containing a tau candidate for further study.

2 Rare and suppressed tau decays

In the Standard Model (SM), the τ^- decays weakly, mediated by a virtual W$^-$ boson which couples to a fermion pair. In $\tau^- \to X^-\nu_\tau$ the system X$^-$ has spin 0 or 1 and may be $e^-\overline{\nu}_e$, $\mu^-\overline{\nu}_\mu$ or $\overline{u}d'$ where $d' = d\times\cos\theta_C + s\times\sin\theta_C$ and θ_C is the Cabibbo angle.

The mass of the tau is sufficiently large, at 1.8 GeV, to produce a large number of possible hadronic final states. At the same time, the mass is low enough to limit the number of final-state particles to a tractable number, and high-multiplicity states are suppressed by the limited phase space.

Various selection rules apply to the hadronic systems produced via the $\overline{u}d'$ quark pair: final states of spin-0 are disfavoured by helicity suppression, although less so for the more massive s quark. On the other hand, Cabibbo suppression disfavours the $\overline{u}s$ production. The structure of the hadronic weak interactions imposes further constraints on the quan-

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tum numbers of the system X. First-class hadronic weak currents (FCC) have spin, parity and G parity quantum numbers given by $J^{PG}=0^{++}$, 0^{--}, 1^{+-} and 1^{-+}. The second-class current (SCC) amplitudes are suppressed by a factor $(m_u-m_d)/(m_u+m_d)$ and have $J^{PG}=0^{+-}$, 0^{-+}, 1^{++} and 1^{--}. Thus, second-class currents are allowed in the SM because of the up-down quark mass difference (violation of isospin symmetry), but are expected to have branching fractions $<10^{-5}$. Finally, the phase space is limited by the mass of the tau, which limits the number of final-state hadrons that may be produced in the tau decays. A review of the factors influencing hadronic tau decays may be found in [2].

Decays that are forbidden in the Standard Model could be allowed by new physics, and there is a great deal of interest in searches for such decays, particularly in the lepton-flavour violating (LFV) channels. Many potential lepton-flavour violating decays have extremely clean topologies with very small backgrounds. (Experimentally, the second-class current hadronic decays have relatively low reconstruction efficiencies and have large backgrounds from other tau decays and from continuum $e^+e^-\to q\overline{q}$ production; as a consequence measured limits for SCC are several orders of magnitude above those for the potentially much rarer LFV processes.) Other possible rare decays may involve violation of baryon number as well as lepton number.

2.1 Tau decays suppressed by phase space

In principle, observation of high-multiplicity tau decays, for example to seven or more pions, could provide useful information on the tau neutrino mass. However, effective chiral Lagrangian theory [3] predicts branching fractions of order 10^{-11}, increasing to order 10^{-10} if the decays are mediated by hadronic resonance production. These rates would be well below the current experimental sensitivity.

2.2 Second-class currents

As discussed above, weak (V−A) non-strange hadronic currents are classified according to values of spin-parity and G-parity, J^{PG}. The first-class currents dominate hadronic τ^- decays, giving rise to the $\pi^-\nu_\tau$ ($J^{PG}=0^{--}$), $a_1^-\nu_\tau$ (1^{+-}) and $\rho^-\nu_\tau$ (1^{-+}) decay modes. Another first-class current mode could have $J^{PG}=0^{++}$, but no single meson can have such quantum numbers.

The second-class currents have an amplitude proportional to the mass difference between the up and down quarks, and observation of such a mode could provide useful data on this mass difference. The most promising channels to study have: $J^{PG}=0^{+-}$, for example $\tau^-\to\eta\pi^-\nu_\tau$ (possibly dominated by $a_0(980)^-$) and $\tau^-\to\eta'\nu_\tau$; and $J^{PG}=1^{++}$, such as $\omega\pi$ in an s-wave or d-wave configuration (possibly dominated by $b_1(1235)^-$). Other second-class current channels include $J^{PG}=0^{-+}$ for which no single meson can exist, or 1^{--} as for the $\pi_1(1400)^-$.

The branching fractions for the second-class current modes are expected be smaller than or of order 10^{-5}. Given the sizes of the tau samples now available at the B factories, it would seem at first sight that such small branching fractions could be measured. However, as has been pointed out, low signal efficiencies, large backgrounds and large uncertainties on the backgrounds make these measurements rather difficult.

3 Searches for phase-space suppressed high-multiplicity tau decays

BaBar has published results on several high-multiplicity tau decay modes [4, 5], involving seven or more pions. In searching for evidence for such decays, the use of the pseudomass helps separate the backgrounds, particularly from the continuum $q\overline{q}$ events, from any potential signal. No evidence was seen for any signal, and upper limits were set at 90% confidence level as follows:

$$BF(\tau^-\to4\pi^-3\pi^+\nu_\tau)<4.3\times10^{-7};$$

$$BF(\tau^-\to4\pi^-3\pi^+\pi^0\nu_\tau)<2.5\times10^{-7};$$

$$BF(\tau^-\to3\pi^-2\pi^+2\pi^0\nu_\tau)<3.4\times10^{-6};$$

$$BF(\tau^-\to2\omega\pi^-\nu_\tau)<5.4\times10^{-7}.$$

These results gave the first limit on the $2\omega\pi^-\nu_\tau$ channel and improvements by more than an order of magnitude over the previous limits in the other channels.

4 Searches for second-class currents

4.1 The channel $\tau^-\to\omega\pi^-\nu_\tau$

The decay mode $\tau-\to\omega\pi^-\nu_\tau$ has a branching fraction of 2%, dominated by the first-class current with $J^{PG}=1^{-+}$ (the $\rho^-\nu_\tau$ mode). This dominant channel requires the ω and π^- to be in a relative p-wave. In terms of an angular analysis of the decay products, this results in a $\sin^2\theta_{\omega\pi}$ distribution for the angle, in the ω rest frame, between the normal to the $\omega\to\pi^+\pi^-\pi^0$ decay plane and the direction of the other π^-. Any second-class current contribution, such as from $\mathrm{b}_1(1235)^- \to \omega\pi^-$ with $J^{PG} = 1^{++}$ would be in an s-wave and/or a d-wave. By fitting the observed distribution of $\sin^2\theta_{\omega\pi}$, one can extract a limit on any SCC contribution.

BaBar has used a sample of 347.3 fb^{-1} of data to set an upper limit on the SCC contribution to the decay mode $\tau^- \to \omega\pi^-\nu_\tau$ [6]. Fig. 1 shows the fit to the distribution of $\cos\theta_{\omega\pi}$. The data are consistent with the $\sin^2\theta$ distribution that would be expected from a pure FCC process. A limit on the SCC-mediated part of the $\tau^- \to \omega\pi^-\nu_\tau$ branching fraction has been set at $< 1.4\times10^{-4}$ at the 90% confidence level, giving an improvement by almost an order of magnitude over the previous limit.

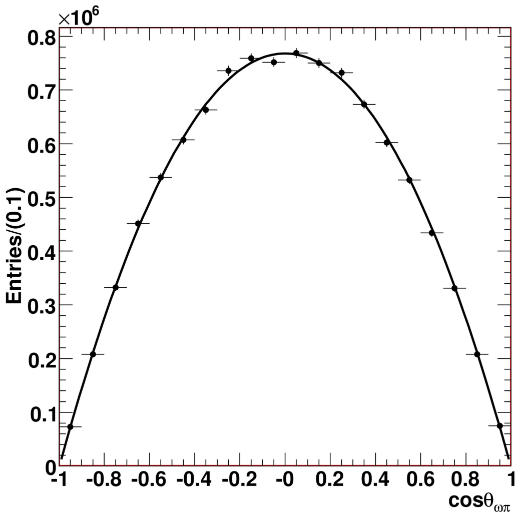

Fig. 1. The distribution of $\cos\theta_{\omega\pi}$ (as described in the text) in the BaBar data. The line shows a fit to obtain a limit on any possible contribution not arising from the $\sin^2\theta$ distribution expected from the first-class current.

4.2 The channel $\tau^- \to \eta'\pi^-\nu_\tau$

An $\eta\pi^-$ or $\eta'\pi^-$ system in tau decay has $J^{PG} = 0^{+-}$ or 1^{--} and can only be produced via a second-class current. Analysis of the $\tau^- \to \eta\pi^-\nu_\tau$ channel suffers from large backgrounds, particularly from $\tau^- \to \eta\pi^-\pi^0\nu_\tau$, and neither BaBar nor Belle has so far published studies of this mode.

BaBar has analysed a sample of 384 fb^{-1} of data in a study the decay mode $\tau^- \to \eta\pi^-\pi^-\pi^+\nu_\tau$, with η decaying via $\gamma\gamma$. For the SCC sub-channel $\tau^- \to \eta'\pi^-\nu_\tau$, with $\eta' \to \eta\pi^+\pi^-$, they obtain a limit $BF(\tau^- \to \eta'\pi^-\nu_\tau) < 7.2\times10^{-6}$ at 90% confidence level [7].

5 Searches for lepton-flavour violating tau decays

In the Standard Model, lepton-flavour violation can arise through neutrino oscillations, although the size of any effect in tau decays must be many orders of magnitude below experimental sensitivity. Therefore, any observation of LFV would be an unambiguous signature for new physics. Furthermore, such observations would be complementary to indirect detection of new physics at the LHC. Many models with new physics incorporate LFV at rates that could be within experimental reach, currently down to about 10^{-8} in tau decays. Some examples are: SUSY Higgs [8]; heavy Majorana neutrinos [9]; non-universal Z' bosons [10]; SUSY SO(10) [11]; minimal supergravity with the Seesaw mechanism [12]; and the Standard Model extended with heavy singlet Dirac neutrinos [13].

Figure 2 shows a summary of the many measurements of limits on LFV tau decay modes, as compiled by the Heavy Flavor Averaging Group (HFAG) [14], which now includes the tau properties under its remit.

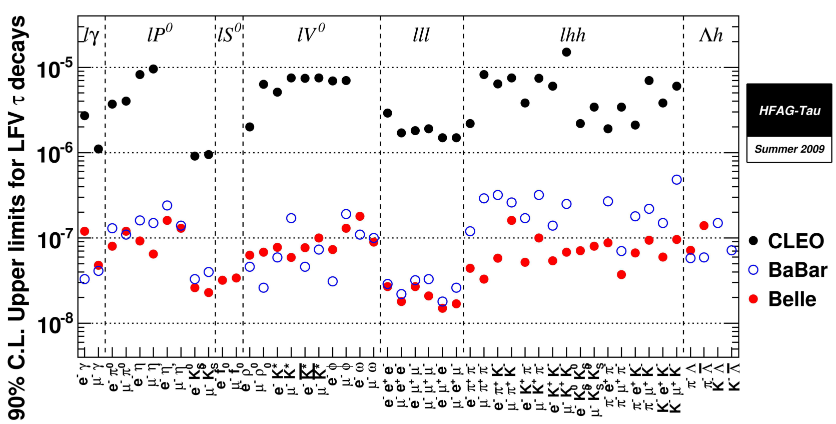

Fig. 2. Upper limits on lepton-flavour violating tau decays, compiled by the Heavy Flavor Averaging Group.

The figure shows the scale of the improvements that have been made by the B Factory experiments over the previous limits set by the CLEO experiment.

5.1 Event selections and analysis for LFV

In the process $e^+e^- \to \tau^+\tau^-$, the signal for LFV in one of the tau decays would be a fully reconstructed τ system, since such decays generally do not involve neutrinos. Therefore, the invariant mass of the decay products would be equal, within measurement errors, to the tau mass, and the energy in the centre-of-mass system would be equal to the beam energy. Conventionally then one tags a tau-pair event as previously described and then studies the non-tag hemisphere using the quantities M_{EC} and ΔE, where M_{EC} is the reconstructed mass using the beam energy as a constraint (which is more precisely measured than the energies of the tau decay products), and ΔE is the reconstructed energy minus the beam energy, in the CM frame. Monte Carlo samples are used to define the "signal box" and to study the expected backgrounds, although sideband regions around the signal boxes may also be used to assess levels of background in the signal region. Generally, such searches are conducted blind, with the numbers of data events in the signal boxes remaining unknown until all cuts and selections have been finalized. Fig. 3 shows, as an example, a $\Delta E - M_{\mathrm{EC}}$ plot for the BaBar search for $\tau^- \to e^-\gamma$ [15]. One can also define the quantity $\Delta M = M_{\mathrm{EC}} - M_\tau$ where M_τ is the nominal tau mass.

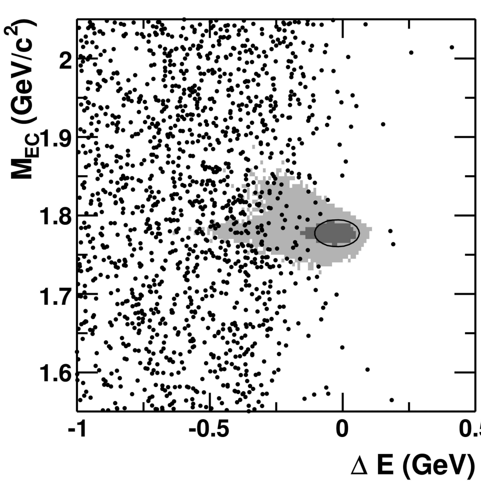

Fig. 3. The $\Delta E - M_{\mathrm{EC}}$ plot for the $\tau^- \to e^-\gamma$ search in BaBar. The data are shown as dots while contours that would contain 90% and 50% of any signal, as determined by Monte Carlo simulations, are shown as the light- and dark-shaded regions. The ellipse indicates the 2 σ region for a signal. It can be seen that there are no events within the 2 σ ellipse.

Backgrounds in the LFV searches arise generally from the following sources: continuum $q\overline{q}$ events are approximately uniform in ΔM and have $\Delta E < 0$; $\tau^+\tau^-$ and two-photon events generally have both ΔM and ΔE less than zero; Bhabha and di-muon events have a uniform ΔM distribution. Any signal candidates would of course be expected near $\Delta M = 0$ and $\Delta E = 0$. Other backgrounds may be important for specific search channels.

5.2 The channels $\tau^- \to e^-\gamma$ and $\tau^- \to \mu^-\gamma$

BaBar has looked for evidence for $\tau^- \to e^-\gamma$ and $\tau^- \to \mu^-\gamma$ using 482 million tau-pairs [15]. The dominant background in these searches comes from tau-pair events that include the radiation of a high-energy photon and in which one of the tau-leptons decays to a charged lepton plus a neutrino. For the two channels, $e^-\gamma$ and $\mu^-\gamma$, zero and two events were observed within the signal regions, compared with background expectations of 1.6 ± 0.4 and 3.6 ± 0.7 events respectively. Since the searches yielded no evidence for any signals, upper limits were set on the appropriate branching fractions as:

$$BF(\tau^- \to e^-\gamma) < 3.3 \times 10^{-8},$$

$$BF(\tau^- \to \mu^-\gamma) < 4.4 \times 10^{-8},$$

both at 90% confidence level, taking full account of systematic errors.

5.3 The channels $\tau^- \to l^-l^-l^+$, where $l = e$, μ

In an update of an earlier analysis, BaBar has recently made significant improvements in its limits for the lepton-flavour violating decay of the tau into three leptons [16].

Table 1. Numbers of expected background events (N_{bgd}), numbers of observed events (N_{obs}) and branching fraction upper limits at 90% confidence lever ($\mathrm{UL}_{90}^{\mathrm{obs}}$) for six three-lepton LFV decay modes. All upper limits are in units of 10^{-8}.

mode	N_{bgd}	N_{obs}	$\mathrm{UL}_{9}^{\mathrm{obs}}0$
$e^-e^+e^-$	0.12 ± 0.02	0	2.9
$e^-e^+\mu^-$	0.64 ± 0.19	0	2.2
$e^-\mu^+e^-$	0.34 ± 0.12	0	1.8
$e^-\mu^+\mu^-$	0.54 ± 0.14	0	3.2
$\mu^-e^+\mu^-$	0.03 ± 0.02	0	2.6
$\mu^+\mu^-\mu^+$	0.44 ± 0.17	0	3.3

Improved event selection methods using a neural network, together with better particle identification techniques for electrons and muons and higher integrated luminosity, of 468 fb^{-1}, have all contributed to significant lowering of the upper limits for six possible three-lepton decay modes. The limits have been improved by factors of $2-3$ with an increase in the integrated luminosity of only 25%. The new results are presented in Table 1.

5.4 The channels $\tau^- \to l^- K^0_S$, where $l^- = e^-$, μ^-

The branching fractions for $\tau^- \to l^- K^0_S$ have been estimated in models that extend the Standard Model with heavy singlet Dirac neutrinos [13] and in supersymmetric models with R-parity violation [17]. Generally, the expected branching fractions are significantly below the experimental sensitivity for large fractions of the parameter space. However, it is nevertheless important to continue pushing down the limits on such modes to constrain as much as possible the new physics possibilities.

BaBar used a sample of 469 fb^{-1} to perform the searches [18]. After all cuts and selections, the numbers of events from backgrounds appearing in the signal regions were expected to be 0.59 ± 0.25 for $\tau^- \to e^- K^0_S$ and 0.30 ± 0.18 for $\tau^- \to \mu^- K^0_S$. After unblinding, one event was seen in each channel, and upper limits on the branching fractions were determined to be:

$$BF(\tau^- \to e^- K^0_S) < 3.3 \times 10^{-8};$$

$$BF(\tau^- \to \mu^- K^0_S) < 4.0 \times 10^{-8}.$$

6 Conclusions

BaBar completed data-taking in April 2008, and has a final data set containing almost 10^9 tau-lepton decays. The Heavy Flavor Averaging Group now includes tau physics, and is able to combine the results of BaBar and Belle. BaBar's analyses of most of the rare decay channels are now complete or nearing completion. Some unique results have been obtained in searches for second-class weak hadronic currents and for high-multiplicity hadronic tau decays. Even as Belle continues to accumulate luminosity, many of BaBar's results from searches for lepton-flavour violation remain competitive (as may be seen in Fig. 2), and provide very useful limits on models of new physics. Further progress in rare tau decays should continue to be made in the remaining BaBar analyses and in the ongoing work at Belle. Beyond that, there are some possibilities at the LHC, but a super B factory or a tau-charm factory would be needed to produce another major advance in the searches for rare tau decays.

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