

# Lepton Flavour Violation in $\tau$ decays at $B_{\text{A}}B_{\text{AR}}$

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**Abstract.** Recent results from  $\tau$  physics studies at *BABAR* are presented with an emphasis on Lepton Flavour Violation measurements.

## 1. Introduction

Lepton flavour conservation differs from other conservation laws in the Standard Model (SM) because it is not associated with an underlying conserved current symmetry. Lepton Flavour Violation (LFV) has been observed in the neutrino sector but combining the information on neutrino mixing and masses with the Standard Model can only produce LFV of the order of  $10^{-54}$ , an undetectable amount. However, many extensions to the SM predict enhanced LFV in tau decays with respect to muon decays with branching fractions up to the current experimental limits [2]. Observation of LFV in tau decays would be a clear signature of physics beyond the SM, while non-observation would provide further constraints on theoretical models. While stringent limits exist on the branching fractions  $\mathcal{B}(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$  [1], these do not exclude  $\mathcal{B}(\tau \rightarrow \mu\gamma)$  at the sensitivities of the current *B*-meson Factories.

The *BABAR* *B*-meson Factory produces almost as many  $\tau$  pairs as *B* pairs. The *BABAR* detector (described in detail in Ref. [3]) operates at the Stanford Linear Accelerator Center the PEP-II asymmetric-energy  $e^+e^-$  storage ring. The luminosity is recorded at centre-of-mass (CM) energies ( $\sqrt{s}$ ) of 10.58 GeV and 10.54 GeV.

The analyses follow a similar strategy. Each analysis looks for the production of  $\tau$  pairs where one of the  $\tau$  decays to either a 1-prong ( $\tau^- \rightarrow l^- \nu_\tau \nu_\mu, \pi^- \nu_\tau, \rho^- \nu_\tau$ ) or 3-prong ( $\tau^- \rightarrow 2h^- h^+ (n\pi^0) \nu_\tau$ ) final state which covers roughly 99% of the  $\tau$  branching fraction. The event is divided into two hemispheres in the CM frame based on the plane perpendicular to the thrust axis from the tracks in the event. Each hemisphere is assumed to contain the decay products of a single  $\tau$  lepton. The analysis procedure selects events with 1-prong or 3-prong in one hemisphere (tag hemisphere) and tracks from the other  $\tau$  in the other hemisphere (signal hemisphere). A cut on the event thrust is applied to reject light quark production  $e^+e^- \rightarrow q\bar{q}$  ( $q = \{u, d, s, c, b\}$ ) and  $b\bar{b}$  backgrounds. Particle identification is applied to the tracks and the total event charge is required to be zero. The  $\tau$  is reconstructed from tracks and neutral deposits not in the tag hemisphere according to the analysis under consideration. Charged particles are required to have a minimum momentum and come from the beam spot. Tracks coming from photon conversions are rejected. Neutral energy deposits must be consistent with the pion and criteria are applied to reject photons where necessary.

The backgrounds come from a number of sources. Other  $\tau$  decays where a particle is missed or added can be eliminated by careful construction of the signal mode. Bhabhas and di-muon

events can be removed through criteria based on the event thrust, co-linearity of the tracks in the CM frame, the momentum of the two leptons in the CM frame and the reconstructed  $\tau$  mass. Hadronic events from  $q\bar{q}$  production can be suppressed through the event thrust, the topology of the decay and an excess of neutral energy. Two photon events have large missing energy and small transverse momentum that can be used to reject them.

Monte Carlo (MC) simulation is used to evaluate the background contamination and selection efficiency. The methods for extracting the signal yield vary depending on the analysis. Some analyses use a cut-based approach while others use a Maximum Likelihood (ML) technique. A signal box with a width of 2 to 3  $\sigma$  is defined in terms of two independent variables:  $\Delta E = E_\tau - \sqrt{s}/2$  and either the mass difference between the reconstructed tau and the true tau mass,  $\Delta M = M_{\text{rec}} - M_\tau$ , or the energy-constrained tau mass,  $m_{\text{EC}}$ , extracted from a kinematic fit with  $E_\tau$  constrained to  $\sqrt{s}/2$ . The expected number of events is calculated by fitting the background event distributions outside the signal region and extrapolating into the signal box. The resolution on  $\Delta E$  and  $m_{\text{EC}}$  or  $\Delta M$  is around 45 MeV and 10 MeV/ $c^2$ , respectively. The systematic errors on the signal efficiencies include contributions from uncertainties in the reconstruction efficiency of charged tracks and neutral deposits; the uncertainty associated with the particle identification on the signal and tag side; the luminosity measurement and the  $\tau$  pair cross-section determination; and the uncertainty on decay branching ratios.

## 2. $\tau^\pm \rightarrow e^\pm \gamma$ [4]

The data sample consists of 210.6 fb $^{-1}$  recorded at  $\sqrt{s} = 10.58$  GeV and 21.6 fb $^{-1}$  at  $\sqrt{s} = 10.54$  GeV. Events with two or four well-reconstructed tracks inconsistent with coming from a photon conversion are selected. The signal-side hemisphere is required to contain at least one  $\gamma$  with a CM energy greater than 500 MeV, and one track identified as an electron. Backgrounds arising from radiation are reduced by requiring that the total CM energy of all non-signal  $\gamma$  candidates in the signal-side hemisphere be less than 200 MeV. To suppress non- $\tau$  backgrounds with significant radiation along the beam directions, the polar angle ( $\theta_{\text{miss}}$ ) of the missing momentum associated with the neutrino(s) in the event is required to lie within the detector acceptance ( $-0.76 < \cos \theta_{\text{miss}} < 0.92$ ). A correlation between the missing mass ( $m_\nu^2$ ) and the scaled missing transverse momentum ( $p_{\text{miss}}^T/\sqrt{s}$ ) in the non- $\tau$  backgrounds is used to suppress them.

The resolution of the  $e\gamma$  mass is improved by assigning the point of closest approach of the  $e$  track to the  $e^+e^-$  collision axis as the origin of the  $\gamma$  candidate and by using a kinematic fit with  $E_{e\gamma}$  constrained to  $\sqrt{s}/2$ .  $m_{\text{EC}}$  and  $\Delta E$  are independent variables apart from small correlations arising from initial and final state radiation. We optimise the selection to obtain the smallest expected upper limit at 90% CL in a background-only hypothesis for observing events inside a  $\pm 2\sigma$  rectangular box signal box defined by:  $|\Delta E - \langle \Delta E \rangle| < 2\sigma(\Delta E)$  and  $|m_{\text{EC}} - m_\tau| < 2\sigma(m_{\text{EC}})$ . For the final background estimate, we use the  $m_{\text{EC}}$  distribution of data events inside the  $\pm 2\sigma(\Delta E)$  band. The signal efficiency is  $(4.7 \pm 0.3)\%$  and we find one event in the signal box for an expected background of  $1.9 \pm 0.4$  events. We set an upper limit employing the same technique used in our search for  $\tau^\pm \rightarrow \ell^\pm \ell^+ \ell^-$  [5] where the background levels were also small. This procedure gives an upper limit of  $\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \gamma) < 6.0 \times 10^{-8}$  at 90% CL.

## 3. $\tau^\pm \rightarrow \mu^\pm \gamma$ [6]

The data sample consists of 210.6 fb $^{-1}$  recorded at  $\sqrt{s} = 10.58$  GeV and 21.6 fb $^{-1}$  at  $\sqrt{s} = 10.54$  GeV. The analysis follows the broad lines of the  $\tau^\pm \rightarrow e^\pm \gamma$  analysis with the difference that it separates the tag-side decays into six categories according to the number of tracks, lepton identification and photon energy. A neural net is constructed to reduce backgrounds in each category with five observables used as input: the missing mass of the event, the highest CM

**Table 1.** Summary of efficiency estimates, the number of background events ( $N_{\text{bgd}}$ ), the number of observed events ( $N_{\text{obs}}$ ), and the 90% CL upper limit on the branching fraction ( $\mathcal{B}$ ) for each decay mode. The results are preliminary for  $\tau^- \rightarrow l^+ l^- l^+$ .

Mode	Efficiency [%]	$N_{\text{bgd}}$	$N_{\text{obs}}$	UL	Mode	Efficiency [%]	$N_{\text{obs}}$	UL
$e^- e^+ e^-$	$8.9 \pm 0.2$	$1.33 \pm 0.25$	1	$4.3 \cdot 10^{-8}$	$\tau^\pm \rightarrow e^\pm \pi^0 (\pi^0 \rightarrow \gamma\gamma)$	$2.83 \pm 0.25$	0	$1.4 \cdot 10^{-7}$
$\mu^- e^+ e^-$	$8.3 \pm 0.6$	$0.89 \pm 0.27$	2	$8.0 \cdot 10^{-8}$	$\tau^\pm \rightarrow \mu^\pm \pi^0 (\pi^0 \rightarrow \gamma\gamma)$	$4.75 \pm 0.37$	1	$1.1 \cdot 10^{-7}$
$\mu^+ e^- e^-$	$12.4 \pm 0.8$	$0.30 \pm 0.55$	2	$5.8 \cdot 10^{-8}$	$\tau^\pm \rightarrow e^\pm \eta (\eta \rightarrow \gamma\gamma)$	$3.59 \pm 0.24$	0	$2.8 \cdot 10^{-7}$
$e^+ \mu^- \mu^-$	$8.8 \pm 0.8$	$0.54 \pm 0.21$	1	$5.6 \cdot 10^{-8}$	$\tau^\pm \rightarrow e^\pm \eta (\eta \rightarrow \pi^+ \pi^- \pi^0)$	$3.17 \pm 0.32$	0	$5.5 \cdot 10^{-7}$
$e^- \mu^+ \mu^-$	$6.2 \pm 0.5$	$0.81 \pm 0.31$	0	$3.7 \cdot 10^{-8}$	$\tau^\pm \rightarrow e^\pm \eta$	$\mathcal{B}\epsilon = 2.12 \pm 0.20$	0	$1.9 \cdot 10^{-7}$
$\mu^- \mu^+ \mu^-$	$5.5 \pm 0.7$	$0.33 \pm 0.19$	0	$5.3 \cdot 10^{-8}$	$\tau^\pm \rightarrow \mu^\pm \eta (\eta \rightarrow \gamma\gamma)$	$7.03 \pm 0.53$	1	$1.6 \cdot 10^{-7}$
$e^- K^+ K^-$	$3.77 \pm 0.16$	$0.22 \pm 0.06$	0	$1.4 \cdot 10^{-7}$	$\tau^\pm \rightarrow \mu^\pm \eta (\eta \rightarrow \pi^+ \pi^- \pi^0)$	$3.67 \pm 0.32$	0	$4.8 \cdot 10^{-7}$
$e^- K^+ \pi^-$	$3.08 \pm 0.13$	$0.32 \pm 0.08$	0	$1.7 \cdot 10^{-7}$	$\tau^\pm \rightarrow \mu^\pm \eta$	$\mathcal{B}\epsilon = 3.59 \pm 0.41$	1	$1.3 \cdot 10^{-7}$
$e^- \pi^+ K^-$	$3.10 \pm 0.13$	$0.14 \pm 0.06$	1	$3.2 \cdot 10^{-7}$	$\tau^\pm \rightarrow e^\pm \eta' (\eta' \rightarrow \pi^+ \pi^- \eta)$	$3.75 \pm 0.27$	0	$5.9 \cdot 10^{-7}$
$e^- \pi^+ \pi^-$	$3.30 \pm 0.15$	$0.81 \pm 0.13$	0	$1.2 \cdot 10^{-7}$	$\tau^\pm \rightarrow e^\pm \eta' (\eta' \rightarrow \rho^0 \gamma)$	$2.98 \pm 0.28$	0	$4.5 \cdot 10^{-7}$
$\mu^- K^+ K^-$	$2.16 \pm 0.12$	$0.24 \pm 0.07$	0	$2.5 \cdot 10^{-7}$	$\tau^\pm \rightarrow e^\pm \eta'$	$\mathcal{B}\epsilon = 1.53 \pm 0.16$	0	$2.6 \cdot 10^{-7}$
$\mu^- K^+ \pi^-$	$2.97 \pm 0.16$	$1.67 \pm 0.29$	2	$3.2 \cdot 10^{-7}$	$\tau^\pm \rightarrow \mu^\pm \eta' (\eta' \rightarrow \pi^+ \pi^- \eta)$	$5.87 \pm 0.46$	0	$3.8 \cdot 10^{-7}$
$\mu^- \pi^+ K^-$	$2.87 \pm 0.16$	$1.04 \pm 0.18$	1	$2.6 \cdot 10^{-7}$	$\tau^\pm \rightarrow \mu^\pm \eta' (\eta' \rightarrow \rho^0 \gamma)$	$3.90 \pm 0.46$	0	$3.7 \cdot 10^{-7}$
$\mu^- \pi^+ \pi^-$	$3.40 \pm 0.19$	$2.99 \pm 0.41$	3	$2.9 \cdot 10^{-7}$	$\tau^\pm \rightarrow \mu^\pm \eta'$	$\mathcal{B}\epsilon = 2.18 \pm 0.26$	0	$2.0 \cdot 10^{-7}$
$e^+ K^- K^-$	$3.85 \pm 0.16$	$0.04 \pm 0.04$	0	$1.5 \cdot 10^{-7}$				
$e^+ K^- \pi^-$	$3.19 \pm 0.14$	$0.16 \pm 0.06$	0	$1.8 \cdot 10^{-7}$				
$e^+ \pi^- \pi^-$	$3.40 \pm 0.15$	$0.41 \pm 0.10$	1	$2.7 \cdot 10^{-7}$				
$\mu^+ K^- K^-$	$2.06 \pm 0.11$	$0.07 \pm 0.10$	1	$4.8 \cdot 10^{-7}$				
$\mu^+ K^- \pi^-$	$2.85 \pm 0.16$	$1.54 \pm 0.25$	1	$2.2 \cdot 10^{-7}$				
$\mu^+ \pi^- \pi^-$	$3.30 \pm 0.18$	$1.46 \pm 0.27$	0	$0.7 \cdot 10^{-7}$				

momentum of the tag-side track(s),  $\mu$  helicity angle, missing transverse momentum and the invariant mass squared of the missing neutrino.

To obtain the branching ratio, we perform an extended unbinned ML fit to the  $m_{\text{EC}}$  data distribution after all requirements but that on  $m_{\text{EC}}$  have been applied. The signal efficiency is  $(9.4 \pm 0.6)\%$ . The fit gives  $\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \gamma) = (-5.6^{+8.3}_{-6.3}) \times 10^{-8}$ , which corresponds to  $-2.2^{+3.2}_{-2.4}$  signal and  $143 \pm 12$  background events. In keeping with established  $\tau^\pm \rightarrow \mu^\pm \gamma$  studies, we derive a frequentist upper limit at 90% CL of  $\mathcal{B}(\tau^\pm \rightarrow \mu^\pm \gamma) < 6.8 \times 10^{-8}$ .

#### 4. $\tau^- \rightarrow l^+ l^- l^+$ [7]

The data sample consists of  $339.2 \text{ fb}^{-1}$  recorded at  $\sqrt{s} = 10.58 \text{ GeV}$  and  $36.7 \text{ fb}^{-1}$  at  $\sqrt{s} = 10.54 \text{ GeV}$ . Candidate signal events consist of one tau decay yielding three charged particles, while the second tau decay yields one charged particle. All possible lepton combinations consistent with charge conservation are considered, leading to six distinct decay modes. Signal events are required to have an invariant mass and total energy in the 3-prong hemisphere consistent with a parent tau lepton. These quantities are calculated from the observed track momenta assuming the corresponding lepton masses for each decay mode.

The expected background rates for each decay mode are determined by fitting a set of probability density functions (PDFs) to the observed data in the  $(\Delta M, \Delta E)$  plane in a grand sideband (GSB) region which is defined as the rectangle bounded by the points  $(-600 \text{ MeV}/c^2, -700 \text{ MeV})$  and  $(400 \text{ MeV}/c^2, 400 \text{ MeV})$ , excluding the signal region. The number of events observed and the preliminary 90% CL upper limits are shown in Table 1.

#### 5. $\tau^- \rightarrow l^\mp h^\pm h'^-$ [8]

The data sample consists of  $221.4 \text{ fb}^{-1}$  recorded at a luminosity-weighted centre-of-mass energy of  $\sqrt{s} = 10.58 \text{ GeV}$ . Candidate signal events are required to have a 1-3 topology, where one tau decay yields one charged particle (1-prong), while the other tau decay yields three charged particles (3-prong). One of the charged particles found in the 3-prong hemisphere must be

identified as either an electron or muon candidate. The  $(\Delta M, \Delta E)$  quantities and the expected background rates are calculated as for the  $\tau^- \rightarrow l^+ l^- l^+$  [7] (see above). Rectangular signal regions are defined separately for each decay mode in the  $(\Delta M, \Delta E)$  plane. The number of events observed and the 90% CL upper limits are shown in Table 1.

#### 6. $\tau^- \rightarrow l^\mp \pi^0, l^\mp \eta, l^\mp \eta'$ [9]

The data sample consists of  $339 \text{ fb}^{-1}$  recorded at a centre-of-mass energy near  $\sqrt{s} \sim 10.58 \text{ GeV}$ . The signature of the signal process is the presence of an  $\ell P^0$  pair having an invariant mass consistent with  $m_\tau = 1.777 \text{ GeV}/c^2$  and a total energy equal to  $\sqrt{s}/2$  in the CM frame, along with other particles in  $e^+e^- \rightarrow \tau^+\tau^-$  events having properties consistent with a  $\tau$  lepton decay. Two neutral decay modes ( $\pi^0 \rightarrow \gamma\gamma$  and  $\eta \rightarrow \gamma\gamma$ ) and three charged decay modes [ $\eta \rightarrow \pi^+\pi^-\pi^0$  ( $\pi^0 \rightarrow \gamma\gamma$ ),  $\eta' \rightarrow \pi^+\pi^-\eta$  ( $\eta \rightarrow \gamma\gamma$ ), and  $\eta' \rightarrow \rho^0\gamma$ ] are reconstructed. Events with two or four well reconstructed tracks and zero total charge are selected. The signal-side hemisphere is required to contain one or three tracks and two photon candidates with energy  $E_\gamma > 50 \text{ MeV}$  for the  $\pi^0 \rightarrow \gamma\gamma$ ,  $\eta \rightarrow \pi^+\pi^-\pi^0$  ( $\pi^0 \rightarrow \gamma\gamma$ ) and  $\eta' \rightarrow \pi^+\pi^-\eta$  ( $\eta \rightarrow \gamma\gamma$ ) channels, and  $E_\gamma > 100 \text{ MeV}$  for the  $\eta \rightarrow \gamma\gamma$  channel. For the  $\eta' \rightarrow \rho^0\gamma$  channel, the single photon candidate is required to have  $E_\gamma > 100 \text{ MeV}$ . Events with additional photon candidates in the signal hemisphere with  $E_\gamma > 100 \text{ MeV}$  are rejected. To reduce combinatorial backgrounds, a minimum  $P^0$  momentum is required and a criteria is placed on the  $P^0$  mass; both criteria are mode-dependent. The track unassociated with any of the  $P^0$  daughters is required to have a momentum  $> 0.5 \text{ GeV}/c$  and is identified as an electron or muon, but not as a kaon. The origin of the photon(s) is assigned to the point of closest approach of the lepton track to the  $e^+e^-$  collision axis for neutral  $P^0$  decays, or to the common vertex in the signal-side hemisphere for the charged  $P^0$  decays. Rectangular signal regions are defined separately for each decay mode in the  $(m_{\text{EC}}, \Delta E)$  plane. The number of events observed and the 90% CL upper limits are given in Table 1.

### 7. Conclusion and Acknowledgements

The results from the current generation of  $B$ -meson Factories are already beginning to constrain the parameter space of models that go beyond the Standard Model. By the end of their data-taking, the current generation of  $B$ -meson factories will have produced nearly 2 billion  $\tau$  pair decays. The physics potential of this legacy has only just begun to be exploited.

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### References

- [1] MEGA Collaboration, M.L. Brooks *et al.*, Phys. Rev. Lett. **83**, 1521 (1999).
- [2] E. Ma, Nucl. Phys. B Proc. Suppl. **123**, 125 (2003).
- [3] BABAR Collaboration, B. Aubert *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **479**, 1 (2002).
- [4] BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **96**, 041801 (2006).
- [5] BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **92**, 121801 (2004).
- [6] BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **95**, 041802 (2005).
- [7] BABAR Collaboration, B. Aubert *et al.*, submitted to Phys. Rev. Lett. [arXiv:hep-ph/0708.3650].
- [8] BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **95**, 191801 (2005).
- [9] BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **98**, 061803 (2007).