# Search for Lepton Flavor Violating $\tau$ Decays into Three Leptons with 719 Million Produced $\tau^+\tau^-$ Pairs

# Belle Collaboration

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#### Abstract

We present a search for lepton-flavor-violating  $\tau$  decays into three leptons (electrons or muons) using 782 fb<sup>-1</sup> of data collected with the Belle detector at the KEKB asymmetric-energy  $e^+e^-$  collider. No evidence for these decays is observed and we set 90% confidence level upper limits on the branching fractions between  $1.5 \times 10^{-8}$  and  $2.7 \times 10^{-8}$ .

#### 1 Introduction

Lepton flavor violation (LFV) appears in various extensions of the Standard Model (SM). In particular, lepton-flavor-violating  $\tau^- \to \ell^- \ell^+ \ell^-$  (where  $\ell = e$  or  $\mu$ ) decays are discussed in various supersymmetric models [1,2,3,4,5,6,7,8], models with little Higgs [9,10], left-right symmetric models [11] as well as models with heavy singlet Dirac neutrinos [12] and very light pseudoscalar

bosons [13]. Some of these models with certain combinations of parameters predict that the branching fractions for  $\tau^- \to \ell^- \ell^+ \ell^-$  decays can be as large as  $10^{-7}$ , which is in the range already accessible in high-statistics B factory experiments.

Searches for lepton flavor violation in  $\tau^- \to \ell^- \ell^+ \ell^-$  (where  $\ell = e$  or  $\mu$ ) decays have been performed since 1982 [14], starting from the pioneering experiment MARKII [15]. In the previous high-statistics analyses, Belle (BaBar) reached 90% confidence level upper limits on the branching fractions of the order of  $10^{-8}$  [16,17], based on samples with about 535 (376) fb<sup>-1</sup> of data. Here, we update our previous results with a larger data set (782 fb<sup>-1</sup>), collected with the Belle detector at the KEKB asymmetric-energy  $e^+e^-$  collider [18], taken at the  $\Upsilon(4S)$  resonance and 60 MeV below it. We apply the same selection criteria as in the previous analysis, but optimized for the new data sample.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL), all located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside the coil is instrumented to detect  $K_{\rm L}^0$  mesons and to identify muons (KLM). The detector is described in detail elsewhere [19].

Leptons are identified using likelihood ratios calculated from the response of various subsystems of the detector. For electron identification, the likelihood ratio is defined as  $\mathcal{P}(e) = \mathcal{L}_e/(\mathcal{L}_e + \mathcal{L}_x)$ , where  $\mathcal{L}_e$  and  $\mathcal{L}_x$  are the likelihoods for electron and non-electron hypotheses, respectively, determined using the ratio of the energy deposit in the ECL to the momentum measured in the SVD and CDC, the shower shape in the ECL, the matching between the position of charged track trajectory and the cluster position in the ECL, the hit information from the ACC and the dE/dx information in the CDC [20]. For muon identification, the likelihood ratio is defined as  $(\mathcal{P}(\mu) = \mathcal{L}_{\mu}/(\mathcal{L}_{\mu} + \mathcal{L}_{\pi} + \mathcal{L}_{K}))$ , where  $\mathcal{L}_{\mu}$ ,  $\mathcal{L}_{\pi}$  and  $\mathcal{L}_{K}$  are the likelihoods for muon, pion and kaon hypotheses, respectively, based on the matching quality and penetration depth of associated hits in the KLM [21].

In order to optimize the event selection and to estimate the signal efficiency, we use Monte Carlo (MC) samples. The signal and the background (BG) events from generic  $\tau^+\tau^-$  decays are generated by KORALB/TAUOLA [22]. In the signal MC, we generate  $\tau^+\tau^-$  pairs, where one  $\tau$  decays into three leptons and the other  $\tau$  decays generically. All leptons from  $\tau^- \to \ell^-\ell^+\ell^-$  decays are assumed to have a phase space distribution in the  $\tau$  lepton's rest frame [23]. Other backgrounds including  $B\bar{B}$  and  $e^+e^- \to q\bar{q}$  (q=u,d,s,c) processes, Bhabhas,  $e^+e^- \to \mu^+\mu^-$ , and two-photon processes are generated

by EvtGen [24], BHLUMI [25], KKMC [22], and AAFHB [26], respectively. All kinematic variables are calculated in the laboratory frame unless otherwise specified. In particular, variables calculated in the  $e^+e^-$  center-of-mass (CM) system are indicated by the superscript "CM".

#### 2 Event Selection

We search for  $\tau^+\tau^-$  events in which one  $\tau$  decays into three leptons (signal  $\tau$ ), while the other  $\tau$  decays into one charged track, any number of additional photons, and neutrinos  $(\tan \tau)^2$ . Candidate  $\tau$ -pair events are required to have four tracks with zero net charge. The following  $\tau^-$  decays into three leptons are searched for:  $e^-e^+e^-$ ,  $\mu^-\mu^+\mu^-$ ,  $e^-\mu^+\mu^-$ ,  $\mu^-e^+e^-$ ,  $\mu^-e^+\mu^-$ , and  $e^-\mu^+e^-$ . Since each decay mode has a different mix of backgrounds, the event selection is optimized mode by mode. We optimize the selection criteria to improve the prospect of observing evidence of a genuine signal, rather than to minimize the expected upper limits, as detailed later.

The event selection starts by reconstructing four charged tracks and any number of photons within the fiducial volume defined by  $-0.866 < \cos \theta < 0.956$ , where  $\theta$  is the polar angle relative to the direction opposite to that of the incident  $e^+$  beam in the laboratory frame. The transverse momentum  $(p_t)$  of each charged track and energy of each photon  $(E_{\gamma})$  are required to satisfy the requirements  $p_t > 0.1 \text{ GeV}/c$  and  $E_{\gamma} > 0.1 \text{ GeV}$ , respectively. For each charged track, the distance of the closest approach with respect to the interaction point is required to be within  $\pm 0.5$  cm in the transverse direction and within  $\pm 3.0$  cm in the longitudinal direction.

The particles in an event are then separated into two hemispheres referred to as the signal and tag sides using the plane perpendicular to the thrust axis, as calculated from the observed tracks and photon candidates [27]. The tag side contains a charged track while the signal side contains three charged tracks. We require all charged tracks on the signal side to be identified as leptons. The electron (muon) identification criteria are  $\mathcal{P}(e) > 0.9$  ( $\mathcal{P}(\mu) > 0.9$ ) for momenta greater than 0.3 GeV/c (0.6 GeV/c). The electron (muon) identification efficiency for our selection criteria is 91% (85%) while the probability of misidentifying a pion as an electron (muon) is below 0.5% (2%).

To ensure that the missing particles are neutrinos rather than photons or charged particles that pass outside the detector acceptance, we impose additional requirements on the missing momentum  $\vec{p}_{\text{miss}}$ , which is calculated by

<sup>&</sup>lt;sup>2</sup> Unless otherwise stated, charge-conjugate decays are implied throughout this paper.

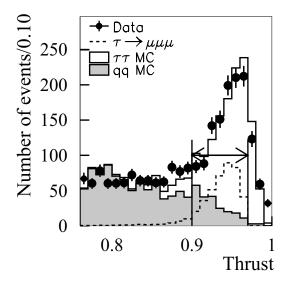


Fig. 1. Distribution of the thrust magnitude T for the  $\tau^- \to \mu^- \mu^+ \mu^-$  selection. The points with error bars are data, and the open histogram shows the BG estimated by MC. The shaded histogram is the BG from  $e^+e^- \to q\bar{q}$ . The dashed histogram is signal MC. The region indicated by the arrow between the two vertical lines is selected.

subtracting the vector sum of the momenta of all tracks and photons from the sum of the  $e^+$  and  $e^-$  beam momenta. We require that the magnitude of  $\vec{p}_{\rm miss}$  be greater than 0.4 GeV/c and that its direction point into the fiducial volume of the detector.

To reject  $q\bar{q}$  background, the magnitude of thrust (T) should lie in the range 0.90 < T < 0.97 for all modes except for  $\tau^- \to e^- e^+ e^-$  for which we require 0.90 < T < 0.96. The T distribution for  $\tau^- \to \mu^- \mu^+ \mu^-$  is shown in Fig. 1. We also require  $5.29 \text{ GeV} < E_{\text{vis}}^{\text{CM}} < 9.5 \text{ GeV}$ , where  $E_{\text{vis}}^{\text{CM}}$  is the total visible energy in the CM system, defined as the sum of the energies of the three leptons, the charged track on the tag side (with a pion mass hypothesis) and all photon candidates.

Since neutrinos are emitted only on the tag side, the direction of  $\vec{p}_{\rm miss}$  should lie within the tag side of the event. The cosine of the opening angle between  $\vec{p}_{\rm miss}$  and the charged track on the tag side in the CM system,  $\cos\theta_{\rm tag-miss}^{\rm CM}$ , is therefore required to lie in the range  $0.0 < \cos\theta_{\rm tag-miss}^{\rm CM} < 0.98$ . The requirement of  $\cos\theta_{\rm tag-miss}^{\rm CM} < 0.98$  suppresses Bhabha,  $\mu^+\mu^-$  and two-photon backgrounds since an undetected radiated photon results in a missing momentum in the same ECL cluster as the tag-side track [28]. The reconstructed mass on the tag side using a charged track (with a pion mass hypothesis) and photons,  $m_{\rm tag}$ , is required to be less than 1.78 GeV/ $c^2$ .

Conversions  $(\gamma \to e^+e^-)$  are a large background for the  $\tau^- \to e^-e^+e^-$  and  $\mu^-e^+e^-$  modes. We require  $M_{ee} > 0.2 \text{ GeV}/c^2$ , to reduce these backgrounds further. For the  $\tau^- \to e^-e^+e^-$  and  $\tau^- \to e^-\mu^+\mu^-$  modes, the charged track

Table 1 Selection criteria for the missing momentum  $(p_{\text{miss}})$  and missing mass squared  $(m_{\text{miss}}^2)$  for each mode. The units for  $p_{\text{miss}}$  and  $m_{\text{miss}}^2$  are GeV/c and  $(\text{GeV}/c^2)^2$ , respectively.

Mode	Hadronic tag	Leptonic tag	
$\tau^- \to \mu^- \mu^+ \mu^-$	$p_{\text{miss}} > -3.0 \ m_{\text{miss}}^2 - 1.0$	$p_{\rm miss} > -2.5 \ m_{\rm miss}^2$	
$\tau^- \to \mu^- e^+ e^-$	$p_{\text{miss}} > 3.0 \ m_{\text{miss}}^2 - 1.5$	$p_{\text{miss}} > 1.3 \ m_{\text{miss}}^2 - 1.0$	
$\tau^- \to e^- \mu^+ \mu^-$			
$\tau^- \to e^- e^+ e^-$	$p_{\text{miss}} > -3.0 \ m_{\text{miss}}^2 - 1.0$	$p_{\rm miss} > -2.5 \ m_{\rm miss}^2$	
	$p_{\rm miss} > 4.2 \ m_{\rm miss}^2 - 1.5$	$p_{\rm miss} > 2.0 \ m_{\rm miss}^2 - 1.0$	
$\tau^- \to e^+ \mu^- \mu^-$	not applied	not applied	
$\tau^- \to \mu^+ e^- e^-$			

on the tag side is required not to be an electron. We apply the requirement  $\mathcal{P}(e) < 0.1$  since a large background from two-photon and Bhabha events still remains. Furthermore, we reject the event if the projection of the charged track on the tag side is in gaps between the ECL barrel and endcap. To reduce backgrounds from Bhabha and  $\mu^+\mu^-$  events with extra tracks due to interaction with the detector material, we require that the momentum in the CM system of the charged track on the tag side be less than 4.5 GeV/c for the  $\tau^- \to e^-e^+e^-$  and  $\tau^- \to \mu^-e^+e^-$  modes.

Finally, to suppress backgrounds from generic  $\tau^+\tau^-$  and  $q\bar{q}$  events, we apply a selection based on the magnitude of the missing momentum  $p_{\rm miss}$  and missing mass squared  $m_{\rm miss}^2$  for all modes except for  $\tau^- \to e^+\mu^-\mu^-$  and  $\mu^+e^-e^-$ . We do not apply this requirement for these two modes since their backgrounds are much smaller. We apply different selection criteria depending on whether the  $\tau$  decay on the tag side is hadronic or leptonic: the number of emitted neutrinos is two (one) when the  $\tau$  decay on the tag side is leptonic (hadronic). Therefore, we separate events into two classes according to the track on the tag side: leptonic or hadronic. The selection criteria are listed in Table 1.

For the optimization, we examine the relation between the number of events  $(N_{\text{obs.}}^{99})$ , which would need to be observed to obtain 99% confidence level (CL) evidence, and the number of expected BG events  $(N_{\text{BG}})$ . We find that better sensitivity is obtained for smaller  $N_{\text{BG}}$ , provided that the signal efficiency does not drop drastically. For example, when we reduce  $N_{\text{BG}}$  from 1 to 0.1,  $N_{\text{obs.}}^{99}$  decreases from 5 to 2, as calculated with the POLE program [29]. This is equivalent to an improvement of the effective efficiency by a factor of 2.5.

For the case of  $\tau \to \mu\mu\mu$  we obtain an expected BG of  $0.13 \pm 0.06$  with an efficiency of 7.6% for the event selection described above. In this case, the

branching fraction obtained from  $N_{\text{obs.}}^{99}$  is  $\mathcal{B}_{99} = 1.8 \times 10^{-8}$ , and the upper limit for the branching fraction at the 90% CL is  $\mathcal{B}_{90}^{\text{UL}} < 2.1 \times 10^{-8}$  for zero observed events. When we relax the selection criteria by removing the requirements on  $p_{\text{miss}}$ - $m_{\text{miss}}^2$ , the momentum and mass of the tag side,  $\cos \theta_{\text{tag-miss}}^{\text{CM}}$ , thrust, and so on, we obtain an expected BG of  $0.42\pm0.17$  with an efficiency of 8.9%, so that  $\mathcal{B}_{99} = 2.3 \times 10^{-8}$  and  $\mathcal{B}_{90}^{\text{UL}} < 1.6 \times 10^{-8}$  for zero observed events. For the relaxed selection criteria, in the Feldman-Cousins approach [30] the upper limits on the branching fractions are small when the number of observed events fluctuates below the number of expected background events. As mentioned above, we optimize the selection criteria to obtain good sensitivity for signal discovery. Therefore, we choose the selection criteria described above to minimize  $\mathcal{B}_{99}$  with the signal region defined below.

The following main background sources remain after the event selection, which are estimated from the MC and data: Bhabha and  $\gamma\gamma \to e^+e^-$  for  $\tau^- \to e^-e^+e^-$ ,  $\gamma\gamma \to \mu^+\mu^-$  for  $\tau^- \to \mu^-e^+e^-$  and  $e^-\mu^+\mu^-$ ,  $\tau$ -pairs and  $q\bar{q}$  for  $\tau^- \to \mu^-\mu^+\mu^-$ ,  $e^-\mu^+e^-$  and  $\mu^-e^+\mu^-$ .

#### 3 Signal and Background Estimation

The signal candidates are examined in two-dimensional plots of the  $\ell^-\ell^+\ell^-$  invariant mass  $(M_{3\ell})$ , and the difference between the summed energy and the beam energy in the CM system  $(\Delta E)$ . A signal event should have  $M_{3\ell}$  close to the  $\tau$ -lepton mass and  $\Delta E$  close to zero. We define an elliptical signal region in the  $M_{3\ell}$ - $\Delta E$  plane, which is optimized using the signal MC, to have a minimum area containing 90% of the signal after all the selections.

In order not to bias our choice of selection criteria, we blind the data in the signal region and estimate the signal efficiency and the number of background events from the MC and the data outside the signal region. Figure 2 shows scatter-plots for the data and the signal MC distributed over  $\pm 20\sigma$  on the  $M_{3\ell} - \Delta E$  plane. We observe no events for  $\tau^- \to \mu^- e^+ e^-$ ,  $e^- \mu^+ e^-$ ,  $\mu^- e^+ \mu^-$ , one event for  $\tau^- \to \mu^- \mu^+ \mu^-$ , two events for  $\tau^- \to e^- e^+ e^-$  and three events for  $\tau^- \to e^- \mu^+ \mu^-$ , outside the signal region. The  $\gamma$  conversion veto effectively reduces the background for  $\tau^- \to e^- e^+ e^-$ .

The final estimate of the number of background events is based on the data with looser selection criteria for particle identification and the event selection in the  $M_{3\ell}$  sideband region, which is defined as the box inside the horizontal lines but excluding the signal region, as shown by the horizontal lines in Fig. 2. For example, we obtain 5 events in the sideband region for  $\tau^- \to \mu^- \mu^+ \mu^-$ , when a less stringent PID criterion,  $\mathcal{P}(\mu) > 0.6$ , is applied. Assuming that the background distribution is uniform in the sideband region, the number of

Table 2 Results with nominal selection criteria: the signal efficiency  $(\varepsilon)$ , the number of expected background events  $(N_{\rm BG})$  estimated from the sideband data, the total systematic uncertainty  $(\sigma_{\rm syst})$ , the number of observed events in the signal region  $(N_{\rm obs})$  and 90% C.L. upper limit on the branching fraction  $(\mathcal{B})$  for each individual mode.

Mode	ε (%)	$N_{ m BG}$	$\sigma_{\rm syst}$ (%)	$N_{ m obs}$	$\mathcal{B}(\times 10^{-8})$
$\tau^- \to e^- e^+ e^-$	6.0	$0.21 \pm 0.15$	9.8	0	< 2.7
$\tau^- \to \mu^- \mu^+ \mu^-$	7.6	$0.13 \pm 0.06$	7.4	0	< 2.1
$\tau^- \to e^- \mu^+ \mu^-$	6.1	$0.10 \pm 0.04$	9.5	0	< 2.7
$\tau^- \to \mu^- e^+ e^-$	9.3	$0.04 \pm 0.04$	7.8	0	<1.8
$\tau^- \to e^+ \mu^- \mu^-$	10.1	$0.02 \pm 0.02$	7.6	0	< 1.7
$\tau^- \to \mu^+ e^- e^-$	11.5	$0.01 \pm 0.01$	7.7	0	<1.5

background events in the signal box is estimated by interpolating the number of observed events in the sideband region into the signal region. The signal efficiency and the number of expected background events for each mode are summarized in Table 2.

We estimate the systematic uncertainties due to lepton identification, charged track finding, MC statistics, and the integrated luminosity. The uncertainty due to the trigger efficiency is negligible compared with the other uncertainties. The uncertainties due to lepton identification are 2.2% per electron and 2.0% per muon. The uncertainty due to charged track finding is estimated to be 1.0% per charged track. The uncertainty due to the electron veto on the tag side applied for the  $\tau^- \to e^- e^+ e^-$  and  $\tau^- \to e^- \mu^+ \mu^-$  modes is estimated to be the same as the uncertainty due to the electron identification. For other modes, we use the same systematic uncertainty for leptonic and hadronic decays on the tag side, because we do not apply any lepton/hadron identification requirements for any charged track on the tag side. The uncertainties due to MC statistics and luminosity are estimated to be (0.5 - 0.9)% and 1.4%, respectively. We do not include an uncertainty due to the signal MC model. All these uncertainties are added in quadrature, and the total systematic uncertainty for each mode is listed in Table 2.

# 4 Upper Limits on the branching fractions

Finally, we examine the signal region and find no events for all considered modes. Therefore, we set upper limits on the branching fractions of  $\tau^- \to \ell^- \ell^+ \ell^-$  based on the Feldman-Cousins method. The 90% C.L. upper limit on the number of signal events including the systematic uncertainty  $(s_{90})$  is

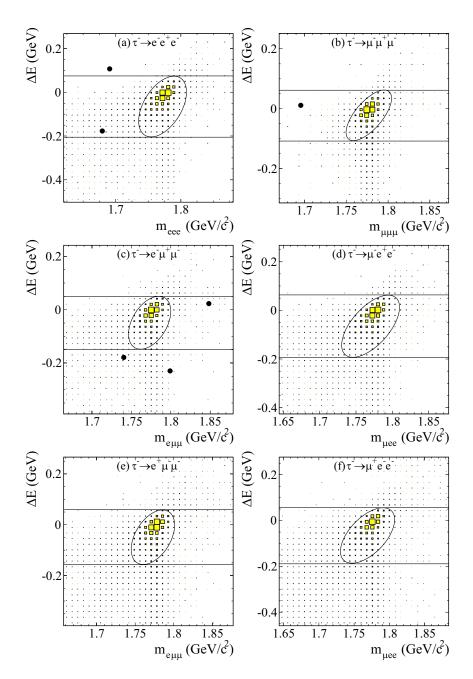


Fig. 2. Scatter-plots in the  $M_{3\ell}$  –  $\Delta E$  plane, showing the  $\pm 20\sigma$  area for (a)  $\tau^- \to e^- e^+ e^-$ , (b)  $\tau^- \to \mu^- \mu^+ \mu^-$ , (c)  $\tau^- \to e^- \mu^+ \mu^-$ , (d)  $\tau^- \to \mu^- e^+ e^-$ , (e)  $\tau^- \to e^+ \mu^- \mu^-$  and (f)  $\tau^- \to \mu^+ e^- e^-$ . The data are indicated by the solid circles. The filled boxes show the MC signal distribution with arbitrary normalization. The elliptical signal regions shown by the solid curves are used for evaluating the signal yield. The region between the horizontal solid lines excluding the signal region is used to estimate the background expected in the elliptical region.

obtained by the POLE program without conditioning [29] with the number of expected background events, the number of observed events and the systematic

uncertainty. The upper limit on the branching fraction  $(\mathcal{B})$  is then given by

$$\mathcal{B}(\tau^- \to \ell^- \ell^+ \ell^-) < \frac{s_{90}}{2N_{\tau\tau}\varepsilon},\tag{1}$$

where the number of  $\tau$  pairs,  $N_{\tau\tau}=719\times10^6$ , is obtained from the integrated luminosity of 782 fb<sup>-1</sup> and the cross section of  $\tau$  pair production, which is calculated in the updated version of KKMC [31] to be  $\sigma_{\tau\tau}=(0.919\pm0.003)$  nb. The 90% C.L. upper limits on the branching fractions  $\mathcal{B}(\tau^-\to\ell^-\ell^+\ell^-)$  are in the range between  $1.5\times10^{-8}$  and  $2.7\times10^{-8}$  and are summarized in Table 2.

# 5 Summary

We report results of a search for lepton-flavor-violating  $\tau$  decays into three leptons using 782 fb<sup>-1</sup> of data. No events are observed and we set 90% C.L. upper limits on the branching fractions:  $\mathcal{B}(\tau^- \to e^- e^+ e^-) < 2.7 \times 10^{-8}$ ,  $\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-) < 2.1 \times 10^{-8}$ ,  $\mathcal{B}(\tau^- \to e^- \mu^+ \mu^-) < 2.7 \times 10^{-8}$ ,  $\mathcal{B}(\tau^- \to \mu^- e^+ e^-) < 1.8 \times 10^{-8}$ ,  $\mathcal{B}(\tau^- \to e^+ \mu^- \mu^-) < 1.7 \times 10^{-8}$  and  $\mathcal{B}(\tau^- \to \mu^+ e^- e^-) < 1.5 \times 10^{-8}$ . These results improve the best previously published upper limits by factors from 1.3 to 1.6, and are the most stringent upper limits of all  $\tau$  decays. These upper limits can be used to constrain the space of parameters in various models beyond the SM.

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### References

- [1] J.R. Ellis *et al.*, Phys. Rev. D **66**, 115013 (2002).
- [2] J.P. Saha and A. Kundu, Phys. Rev. D 66, 054021 (2002).
- [3] A. Brignole *et al.*, Phys. Lett. B **566**, 217 (2003).
- [4] A. Brignole and A. Rossi, Nucl. Phys. B **701**, 3 (2004).
- [5] R. Barbier et al., Phys. Rep. B **420**, 1 (2005).
- [6] P. Paradisi, JHEP **10**, 006 (2005).
- [7] E. Arganda and M.J. Herrero, Phys. Rev. D 73, 055003 (2006).
- [8] A. Ilakovac and A. Pilaftsis, Phys. Rev. D 80, 091902 (2009).
- [9] M. Blanke et al., JHEP 5, 013 (2007).
- [10] C.-X. Yue and Sh. Zhao, Eur. Phys. J. C **50**, 897 (2007).
- [11] A. G. Akeroyd *et al.*, Phys. Rev. D **76**, 013004 (2007).
- [12] A. Ilakovac, Phys. Rev. D **62**, 036010 (2000).
- [13] A. Cordero-Cid et al., Phys. Rev. D 72, 117701 (2005).
- [14] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667**, 1 (2008) and the 2009 web update.
- [15] K.G. Hayes et al., Phys. Rev. D 25, 2869 (1982).
- [16] Y. Miyazaki *et al.* (Belle Collaboration), Phys. Lett. B **660**, 154 (2008).
- [17] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 99, 251803 (2007).
- [18] S. Kurokawa and E. Kikutani, Nucl. Instr. and Meth. A **499**, 1 (2003), and other papers included in this Volume.
- [19] A. Abashian et al. (Belle Collaboration), Nucl. Instr. and Meth. A 479, 117 (2002).

- [20] K. Hanagaki et al., Nucl. Instr. and Meth. A 485, 490 (2002).
- [21] A. Abashian et al., Nucl. Instr. and Meth. A 491, 69 (2002).
- [22] S. Jadach et al., Comp. Phys. Commun. 130, 260 (2000).
- [23] For the most general expressions for the distributions in the LFV  $\tau$  decays to three leptons see the model-independent analysis of B.M. Dassinger *et al.*, JHEP **0710**, 039 (2007).
- [24] D. J. Lange, Nucl. Instr. and Meth. A 462, 152 (2001).
- [25] S. Jadach et al., Comp. Phys. Commun. 70, 305 (1992).
- [26] F. A. Berends et al., Comp. Phys. Commun. 40, 285 (1986).
- [27] S. Brandt et al., Phys. Lett. 12, 57 (1964); E. Farhi, Phys. Rev. Lett. 39, 1587 (1977).
- [28] K. Hayasaka et al. (Belle Collaboration), Phys. Lett. B 613, 20 (2005).
- [29] See http://www3.tsl.uu.se/~conrad/pole.html, J. Conrad *et al.*, Phys. Rev. D **67**, 012002 (2003).
- [30] G. J. Feldman and R. D. Cousins, Phys. Rev. D 57, 3873 (1998).
- [31] S. Banerjee et al., Phys. Rev. D 77, 054012 (2008).