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Lepton Universality and Lepton Flavour Violation tests at the *B*-factories

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Abstract. We review the experimental status of the lepton universality tests and lepton flavour violation searches after the completion of the data-taking and most of the data analysis of the ***B***-factories BABAR and Belle. The universality of the Standard Model charged weak couplings has been confirmed and moderately improved in precision by the ***B***-factories results. Lepton Flavour violation in the τ lepton decays has been searched in several decay modes and no evidence has been found. We set 90% confidence level upper limits on the Lepton Flavour violating branching ratios in the 10^{-7}–10^{-8} range, greatly extending the previous limits set mainly by CLEO in the 10^{-6} range.

1 Introduction

In the Standard Model (SM) the lepton couplings are the same for each lepton generation. The universality of the charged weak coupling for charged leptons can be tested by combining the measurements of decay widths with leptons in the initial and/or final state, which can be obtained by measuring the relevant branching fractions, the lepton masses and the leptons lifetimes.

In the SM with zero neutrino masses, the lepton flavour is exactly (accidentally) conserved. When we take into account the experimentally measured neutrino mass squared differences and neutrino mixing, lepton-flavour-violating (LFV) branching fractions, such as for instance $\tau \to \mu\gamma$, $\mu \to e\gamma$, $\tau \to 3\mu$, are predicted to be non-zero but suppressed by a factor of order $(m_\nu/m_W)^4$ to values several orders of magnitude smaller than the current experimental reach.

Models beyond the SM like Supersymmetry, Grand Unification or Extra Dimensions typically include additional lepton-flavour-violating processes, which can produce observable LFV τ lepton decay rates, even when the model parameters are constrained with the available experimental data [1–9].

Since about year 2000, the *B*-factories BABAR and Belle have collected unprecedented samples of clean e^+e^- collisions at and around the $\Upsilon(4S)$ peak, which have improved the experimental test of the SM lepton universality. The *B*-factories have ceased data-taking in 2008 (BABAR) and 2010 (Belle) and have now completed and published most of the data-analyses, increasing the experimental knowledge on lepton universality and lepton flavour violation.

Before the *B*-factories BABAR and Belle, experimental measurements have permitted testing the lepton universality to a precision around 0.2%. The most important contributions have been the τ lifetime measurements by the LEP experiments, the τ leptonic branching fraction measurements by the LEP experiments and in particular ALEPH, and the BES τ mass measurement. We report in the following the present status after the *B*-factories results.

BABAR and Belle have provided effective conditions to search for LFV τ lepton decay branching fractions with clean and unambiguous experimental signatures [10], like a final state with invariant mass matching the τ mass and with total energy matching half the event energy in the center-of-mass frame. We report in the following significant advancements that have been obtained with respect to the pre-existing limits set mainly by CLEO around 10^{-6}.

2 Lepton Universality Tests

In the Standard Model, the partial width of a heavier lepton λ decaying to a lighter lepton ρ are, neglecting neutrino masses and including radiative corrections [11],

$$\Gamma[\lambda \to \nu_\lambda \rho \bar{\nu}_\rho(\gamma)] = \frac{G_\lambda G_\rho m_\lambda^5}{192\pi^3} f\left(\frac{m_\rho^2}{m_\lambda^2}\right) r_W^\lambda r_\gamma^\lambda ,$$

where

$$G_\rho = \frac{g_\rho^2}{4\sqrt{2}M_W^2} \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

$$r_W^\lambda = 1 + \frac{3}{5}\frac{m_\lambda^2}{M_W^2} \qquad r_\gamma^\lambda = 1 + \frac{\alpha(m_\lambda)}{2\pi}\left(\frac{25}{4} - \pi^2\right) .$$

Computing the proper ratios of the above partial widths using the HFAG 2014 τ world averages [12], the Review of Particle Physics (PDG) 2014 [13] and CODATA 2010 [14]

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results we obtain the following charged weak current coupling ratios:

$$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{B_{\tau e}}{B_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} r_W^\mu r_\gamma^\mu}{\tau_\tau m_\tau^5 f_{\tau e} r_W^\tau r_\gamma^\tau}} = 1.0011 \pm 0.0015$$

$$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{B_{\tau\mu}}{B_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} r_W^\mu r_\gamma^\mu}{\tau_\tau m_\tau^5 f_{\tau\mu} r_W^\tau r_\gamma^\tau}} = 1.0029 \pm 0.0015$$

$$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{B_{\tau\mu}}{B_{\tau e}} \frac{f_{\tau e}}{f_{\tau\mu}}} = 1.0018 \pm 0.0014$$

The data are consistent with lepton universality, and the precision of the tests improved from 0.20−0.23% before the B-Factories to 0.14−0.15%, thanks primarily to the Belle tau lifetime measurement [15]. The BABAR measurement of the ratio between the muon and electron branching fraction [16] and the BABAR and Belle τ mass measurements [17, 18] provide negligible contributions. The precision of the tests is now mainly limited by the uncertainties on the τ lifetime (0.09%) and on the τ leptonic branching fractions (0.11−0.12%). The overall consistency of the data with the SM is summarized in figure 1, which reports the experimental measurements of the τ lifetime and of the "universality improved" $\tau^- \to e^-\overline{\nu}_e\nu_\tau$ branching fraction [19], together with the constraint on them from the SM, which relies on the measurements of the τ lifetime and the muon mass and lifetime.

Partial widths of τ decays to hadrons compared to the same hadron decay to muons measure the tau-muon universality of charged weak couplings as follows:

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{B(\tau \to h\nu_\tau)}{B(h \to \mu\overline{\nu}_\mu)} \frac{2 m_h m_\mu^2 \tau_h}{(1+\delta_h) m_\tau^3 \tau_\tau} \left(\frac{1 - m_\mu^2/m_h^2}{1 - m_h^2/m_\tau^2}\right)^2 ,$$

where $h = \pi$ or K and the radiative corrections are $\delta_\pi = (0.16 \pm 0.14)\%$ and $\delta_K = (0.90 \pm 0.22)\%$ [20], we measure:

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9963 \pm 0.0027 , \quad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9858 \pm 0.0071 .$$

The BABAR measurement of the ratio between the kaon and electron branching fractions [16] improved these tests. Similar tests could be performed with decays to electrons, however they are less precise because the hadron two body decays to electrons are helicity-suppressed. Averaging the three g_τ/g_μ ratios we obtain

$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 1.0001 \pm 0.0014 ,$$

accounting for statistical correlations.

Additional electron-muon universality tests can be obtained comparing pion and kaon leptonic branching fractions. The B-factories did not improve these tests.

3 Searches for Lepton Flavour Violation

The B-factories have searched for an extensive range of LFV τ decay modes: no evidence has been found and 90% confidence level (CL) upper limits have been set. The most recent published result are the searches for $\tau \to$ 3 charged leptons [21, 22], $\tau \to \ell K_S^0$ and $\tau \to \ell K_S^0 K_S^0$ [23], $\tau \to \ell V^0$ [24], $\tau \to \ell h h'$ [25]. Recently, the LHCb collaboration has published the result of the search for $\tau \to \mu\mu\mu$ [26].

The most recent published result by the B-factories Belle and BABAR and by LHCb are the searches for $\tau \to$ 3 leptons by Belle [21],

$B(\tau \to e^-e^+e^-) < 2.7 \cdot 10^{-8}$,
$B(\tau \to \mu^-e^+e^-) < 1.8 \cdot 10^{-8}$,
$B(\tau \to e^-\mu^+\mu^-) < 2.7 \cdot 10^{-8}$,
$B(\tau \to \mu^-\mu^+\mu^-) < 2.1 \cdot 10^{-8}$,
$B(\tau \to e^-\mu^+e^{)} < 1.5 \cdot 10^{-8}$,
$B(\tau \to \mu^-e^+\mu^-) < 1.7 \cdot 10^{-8}$,

by BABAR [22]

$B(\tau \to e^-e^+e^-) < 2.9 \cdot 10^{-8}$,
$B(\tau \to \mu^-e^+e^-) < 2.2 \cdot 10^{-8}$,
$B(\tau \to e^-\mu^+\mu^-) < 3.2 \cdot 10^{-8}$,
$B(\tau \to \mu^-\mu^+\mu^-) < 3.3 \cdot 10^{-8}$,
$B(\tau \to e^-\mu^+e^{)} < 1.8 \cdot 10^{-8}$,
$B(\tau \to \mu^-e^+\mu^-) < 2.6 \cdot 10^{-8}$,

and by LHCb [26]

$B(\tau \to \mu^-\mu^+\mu^-) < 4.6 \cdot 10^{-8}$,

the searches for $\tau \to \ell K_S^0$ and $\tau \to \ell K_S^0 K_S^0$ by Belle [23]

$B(\tau \to e^-K_S^0) < 2.6 \cdot 10^{-8}$,
$B(\tau \to \mu^-K_S^0) < 2.3 \cdot 10^{-8}$,
$B(\tau \to e^-K_S^0K_S^0) < 7.1 \cdot 10^{-8}$,
$B(\tau \to \mu^-K_S^0K_S^0) < 8.1 \cdot 10^{-8}$,

the searches for $\tau \to \ell V^0$ by Belle [24]

$B(\tau \to e^-\rho^0) < 1.8 \cdot 10^{-8}$,
$B(\tau \to \mu^-\rho^0) < 1.2 \cdot 10^{-8}$,
$B(\tau \to e^-K^*(892)^0) < 3.2 \cdot 10^{-8}$,
$B(\tau \to \mu^-K^*(892)^0) < 7.2 \cdot 10^{-8}$,
$B(\tau \to e^-\overline{K}^*(892)^0) < 3.4 \cdot 10^{-8}$,
$B(\tau \to \mu^-\overline{K}^*(892)^0) < 7.0 \cdot 10^{-8}$,
$B(\tau \to e^-\phi) < 3.1 \cdot 10^{-8}$,
$B(\tau \to \mu^-\phi) < 8.4 \cdot 10^{-8}$,
$B(\tau \to e^-\omega) < 4.8 \cdot 10^{-8}$,
$B(\tau \to \mu^-\omega) < 4.7 \cdot 10^{-8}$,

and the searches for $\tau \to \ell h h'$ by Belle [25]

$B(\tau \to e^-\pi^+\pi^-) < 2.3 \cdot 10^{-8}$,
$B(\tau \to \mu^-\pi^+\pi^-) < 2.1 \cdot 10^{-8}$,
$B(\tau \to e^-\pi^+K^-) < 3.7 \cdot 10^{-8}$,
$B(\tau \to \mu^-\pi^+K^-) < 8.6 \cdot 10^{-8}$,
$B(\tau \to e^-K^+\pi^-) < 3.1 \cdot 10^{-8}$,
$B(\tau \to \mu^-K^+\pi^-) < 4.5 \cdot 10^{-8}$,
$B(\tau \to e^-K^+K^-) < 4.4 \cdot 10^{-8}$,
$B(\tau \to \mu^-K^+K^-) < 7.1 \cdot 10^{-8}$,

The Heavy Flavour Averaging Group has collected all the upper limits on the LFV τ branching fractions [12] and we report here just the summary plot in figure 2. In addition, we report in figure 3 the upper limits combinations computed in the HFAG 2014 report. The significant progress made with the B-factories results is evident.

4 Conclusions and prospects

The B-factories helped improving the precision of the lepton universality tests, which continue to confirm the

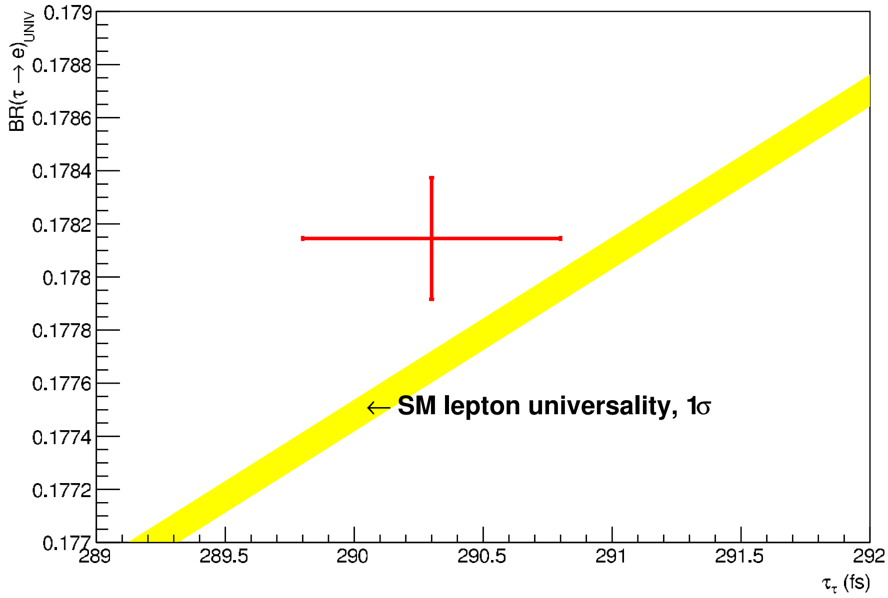

Figure 1. Experimental measurements of the τ lifetime and of the "universality improved" $\tau \to e$ branching fraction compared with the Standard Model prediction (yellow band). The width of the band is dominated by the uncertainty on the τ lifetime.

SM predictions with a precision that increased from 0.20–0.23% to 0.14–0.15%. The relevant experimental measurements are systematically limited, and there are only modest prospects of further improvements at the planned future high luminosity B-factory Belle-II. A high luminosity LEP-like e^+e^- collider at the Z^0 peak would most probably provide better conditions for precision measurements of the τ branching fractions.

The B-factories have experimentally probed the LFV τ branching fractions from the CLEO limits around 10^{-6} up to 10^{-7}–10^{-8} without finding any evidence of a signal. Future high luminosity B-factories like Belle II offer good prospects to advance the experimental reach close to 10^{-7} for decay modes such as $\tau \to \mu\gamma$ and close to 10^{-8} for the cleanest decay modes such as $\tau \to 3$ charged leptons.

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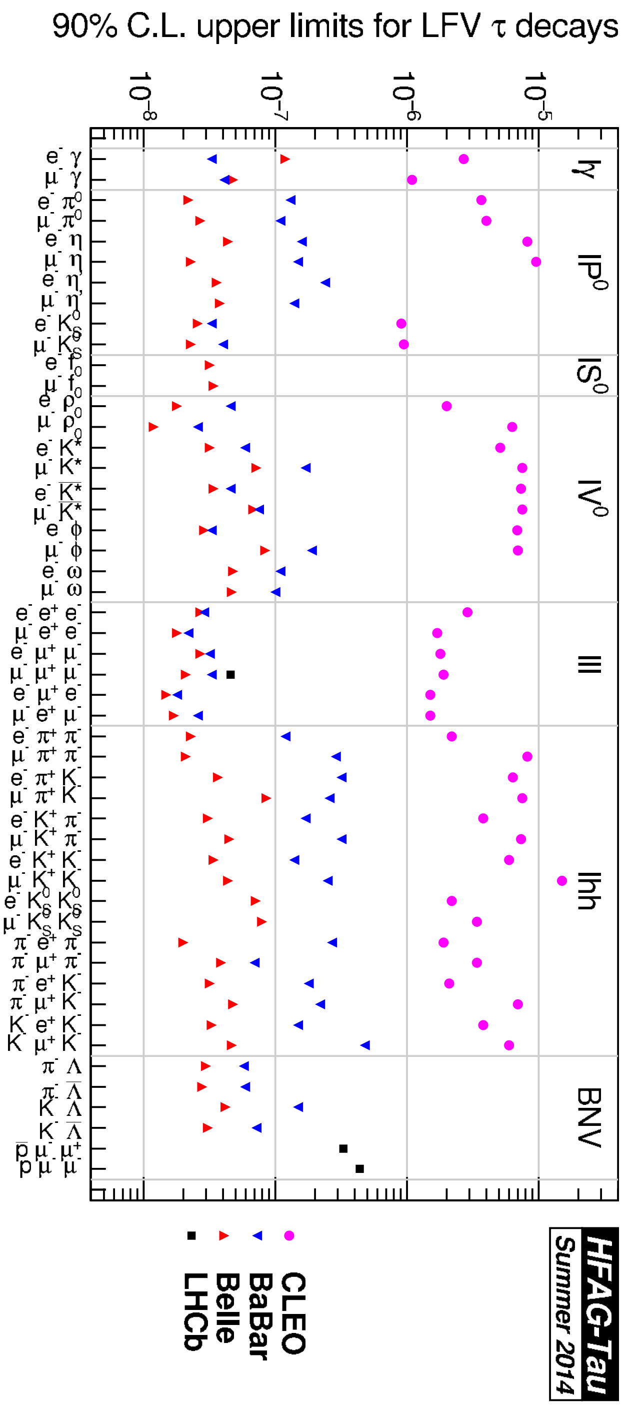

Figure 2. τ lepton-flavour-violating branching fraction upper limits summary plot from the HFAG 2014 report.

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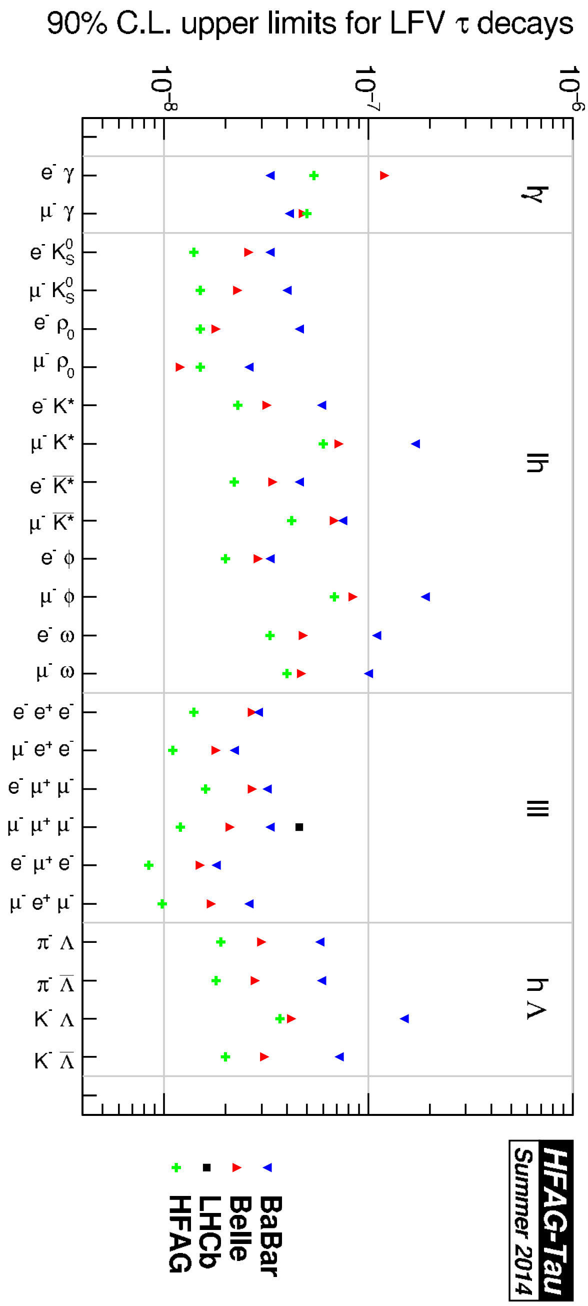

Figure 3. Combinations of the upper limits published by *BABAR*, Belle and LHCb on a list of searches for τ LFV branching fractions, from the HFAG 2014 report.