

# IMPORTANCE OF PRECISION MEASUREMENTS IN THE TAU SECTOR\*

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**Abstract.**  $\tau$  decays provide a powerful tool to test the structure of the weak currents and the universality of their couplings to the  $W$  boson. The constraints implied by present data and the possible improvements at the  $\tau$ cF are analyzed.

## INTRODUCTION

The light quarks and leptons are by far the best known ones. Many experiments have analyzed in the past the properties of  $e$ ,  $\mu$ ,  $\nu_e$ ,  $\nu_\mu$ ,  $\pi$ ,  $K$ ,  $\dots$ . However, one naïvely expects the heavier fermions to be much more sensitive to New Physics, since they may couple more strongly to whatever dynamics is responsible for the fermion-mass generation. Obviously, new heavy-flavour facilities, such as the  $B$  and Tau-Charm Factories ( $\tau$ cF), are needed to match (at least) the precision attained for the light flavours.

Similarly to the bottom quark, the tau lepton is a third generation fermion, with a wide variety of decay channels into particles belonging to the first and second fermionic families. Therefore, one can expect that  $\tau$  and  $b$  physics will provide some clues to the puzzle of the recurring generations of leptons and quarks. While the decays of the  $b$ -quark are ideally suited to look for quark mixing and CP-violating phenomena, the pure leptonic or semileptonic character of  $\tau$  decays provides a much cleaner laboratory to test the structure of the weak currents and the universality of their couplings to the gauge bosons. Moreover, the tau is the only known lepton massive enough to decay into hadrons; its semileptonic decays are then an ideal tool for studying strong interaction effects in very clean conditions.

The last five years have witnessed a substantial change on our knowledge of the  $\tau$  properties. The large (and clean) data samples collected by the most recent experiments have improved considerably the statistical accuracy and, moreover, have brought a new level of systematic understanding. The qualitative change of the  $\tau$  data can be appreciated in Table 1, which compares the status of several  $\tau$  measurements in 1990 [1, 2] with the most recent world averages [3, 4]. All experimental results obtained so far confirm the Standard Model (SM) scenario in which the  $\tau$  is a sequential lepton, with its own quantum number and associated neutrino.

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Table 1: Recent improvements in  $\tau$  physics and expected precision at the  $\tau$ cF.

Parameter	1990 [1, 2]	1995 [3, 4]	$\tau$ cF sensitivity
$m_\tau$ (MeV)	$1784.1^{+2.7}_{-3.6}$	$1777.0 \pm 0.3$	0.1
$m_{\nu_\tau}$ (MeV)	$< 35$ (a)	$< 24$ (a)	1–2
$\tau_\tau$ (fs)	$303 \pm 8$	$291.6 \pm 1.6$	–
$B_e$ (%)	$17.7 \pm 0.4$	$17.79 \pm 0.09$	0.02
$B_\mu$ (%)	$17.8 \pm 0.4$	$17.33 \pm 0.09$	0.02
$B(\pi^- \nu_\tau)$ (%)	$11.0 \pm 0.5$	$11.09 \pm 0.15$	0.01
$B(K^- \nu_\tau)$ (%)	$0.68 \pm 0.19$	$0.68 \pm 0.04$	0.003
$B(\pi^- \eta \nu_\tau)$	$< 9 \times 10^{-3}$ (a)	$< 3.4 \times 10^{-4}$ (a)	$10^{-6}$
$B(l^- G)$	$< 10^{-2}$	$< 2.7 \times 10^{-3}$ (a)	$10^{-5}$
$B(\mu^- \gamma)$	$< 5.5 \times 10^{-4}$ (b)	$< 4.2 \times 10^{-6}$ (b)	$10^{-7}$
$B(e^- e^+ e^-)$	$< 3.8 \times 10^{-5}$ (b)	$< 3.3 \times 10^{-6}$ (b)	$10^{-7}$
$\rho_{\tau \rightarrow \mu}$	$0.84 \pm 0.11$	$0.738 \pm 0.038$	0.002
$\eta_{\tau \rightarrow \mu}$	–	$-0.14 \pm 0.23$	0.003
$\xi_{\tau \rightarrow \mu}$	–	$1.23 \pm 0.24$	0.02
$(\xi\delta)_{\tau \rightarrow \mu}$	–	$0.71 \pm 0.15$	0.02
$\xi'_{\tau \rightarrow \mu}$	–	–	0.15
$h_{\nu_\tau}$	–	$-1.014 \pm 0.027$	0.003
$a_\tau^\gamma$	$< 0.1$ (b)	$< 0.01$ (a)	0.001
$d_\tau^\gamma$ (e cm)	$< 6 \times 10^{-16}$ (b)	$< 5 \times 10^{-17}$ (a)	$10^{-17}$

(a) 95% CL ; (b) 90% CL

The present experiments are soon going to reach their systematic limits. Further improvements in  $\tau$  physics require then new high-precision facilities, to push the significance of the  $\tau$  tests beyond the present few per cent level. The last column in Table 1 shows the sensitivities that could be achieved at the  $\tau$ cF. In some cases, a much better accuracy could be obtained with polarized beams or monochromatic optics.

In the following, I discuss several precision tests of the SM, using the present  $\tau$ -decay data, and the expected improvements at the  $\tau$ cF. I will concentrate on the universality and Lorentz-structure of the charged leptonic currents. A discussion of other important topics in  $\tau$  physics can be found in refs. [2, 5–8].

## CHARGED-CURRENT UNIVERSALITY

The leptonic decays  $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau, \mu^- \bar{\nu}_\mu \nu_\tau$  are theoretically understood at the level of the electroweak radiative corrections [9]. Within the SM,

$$\Gamma_{\tau \rightarrow l} \equiv \Gamma(\tau^- \rightarrow \nu_\tau l^- \bar{\nu}_l) = \frac{G_F^2 m_\tau^5}{192\pi^3} f(m_l^2/m_\tau^2) r_{EW}, \quad (1)$$

where  $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$ . The factor  $r_{EW} = 0.9960$  takes into account radiative corrections not included in the Fermi coupling constant  $G_F$ , and the non-local structure of the  $W$  propagator [9].

Using the value of  $G_F$  measured in  $\mu$  decay, Eq. (1) provides a relation [2] between the  $\tau$  lifetime and the leptonic branching ratios  $B_l \equiv B(\tau^- \rightarrow \nu_\tau l^- \bar{\nu}_l)$ :

$$B_e = \frac{B_\mu}{0.972564 \pm 0.000010} = \frac{\tau_\tau}{(1.6321 \pm 0.0014) \times 10^{-12} \text{ s}}. \quad (2)$$

The errors reflect the present uncertainty of 0.3 MeV in the value of  $m_\tau$ .

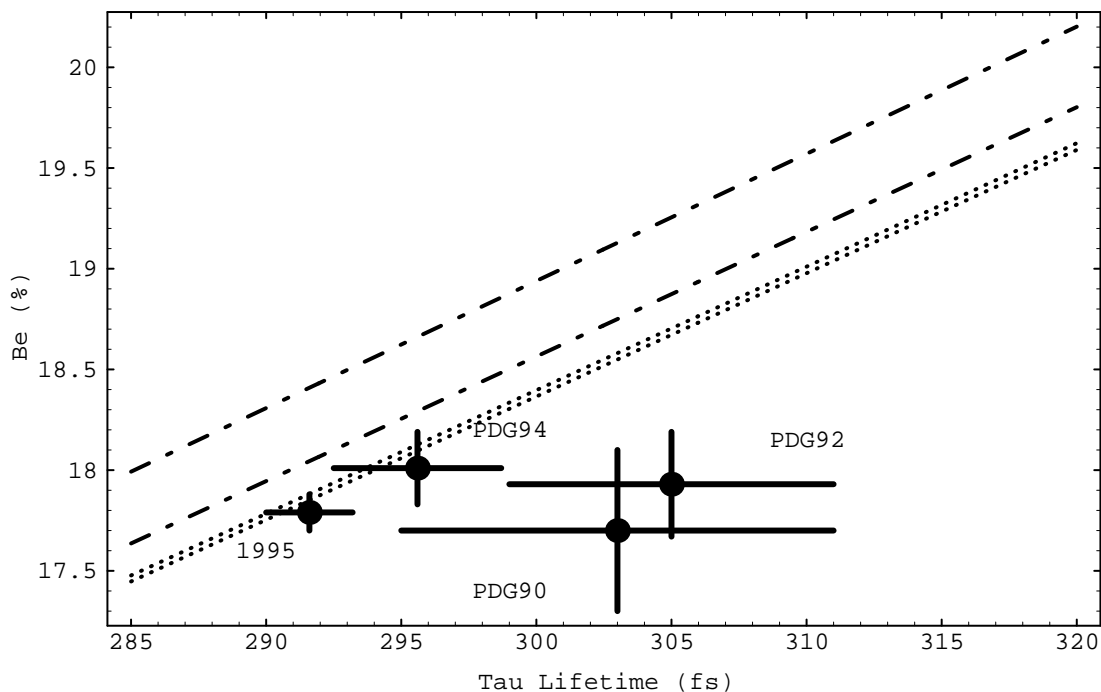


Figure 1: Relation between  $B_e$  and  $\tau_\tau$ . The narrow dotted band corresponds to the prediction in Eq. (2). The larger region between the two dot-dashed lines indicates the relation obtained with the old [10] value of  $m_\tau$ . The experimental points show the present world averages [4], together with the values quoted by the Particle Data Group [1, 3, 10] since 1990.

Table 2: Present constraints on  $|g_\mu/g_e|$ .

	$B_\mu/B_e$ [4]	$R_{\pi\rightarrow e/\mu}$ [12]	$\sigma \cdot B_{W\rightarrow\mu/e}$ [13]
$ g_\mu/g_e $	$1.0008 \pm 0.0036$	$1.0017 \pm 0.0015$	$1.01 \pm 0.04$

Table 3: Present constraints on  $|g_\tau/g_\mu|$ .

	$B_e\tau_\mu/\tau_\tau$ [4]	$R_{\tau/\pi}$ [4]	$R_{\tau/K}$ [4]	$\sigma \cdot B_{W\rightarrow\tau/\mu}$ [13]
$ g_\tau/g_\mu $	$0.9979 \pm 0.0037$	$1.006 \pm 0.008$	$0.972 \pm 0.029$	$0.99 \pm 0.05$

The predicted  $B_\mu/B_e$  ratio is in perfect agreement with the measured value  $B_\mu/B_e = 0.974 \pm 0.007$  [4]. As shown in Fig. 1, the relation between  $B_e$  and  $\tau_\tau$  is also well satisfied by the present data. Notice, that this relation is very sensitive to the value of the  $\tau$  mass [ $\Gamma_{\tau\rightarrow l} \propto m_\tau^5$ ]. The most recent measurements of  $\tau_\tau$ ,  $B_e$  and  $m_\tau$  have consistently moved the world averages in the correct direction, eliminating the previous ( $\sim 2\sigma$ ) disagreement. The experimental precision (0.5%) is already approaching the level where a possible non-zero  $\nu_\tau$  mass could become relevant; the present bound [11]  $m_{\nu_\tau} < 24$  MeV (95% CL) only guarantees that such effect is below 0.14%.

These measurements can be used to test the universality of the  $W$  couplings to the leptonic charged currents. The  $B_\mu/B_e$  ratio constraints  $|g_\mu/g_e|$ , while the  $B_e/\tau_\tau$  relation provides information on  $|g_\tau/g_\mu|$ . The present results are shown in Tables 2 and 3, together with the values obtained from the ratio [12]  $R_{\pi\rightarrow e/\mu} \equiv \Gamma(\pi^- \rightarrow e^- \bar{\nu}_e)/\Gamma(\pi^- \rightarrow \mu^- \bar{\nu}_\mu)$ , and from the comparison of the  $\sigma \cdot B$  partial production cross-sections for the various  $W^- \rightarrow l^- \bar{\nu}_l$  decay modes at the  $p\bar{p}$  colliders [13].

The decay modes  $\tau^- \rightarrow \nu_\tau \pi^-$  and  $\tau^- \rightarrow \nu_\tau K^-$  can also be used to test universality through the ratios

$$R_{\tau/\pi} \equiv \frac{\Gamma(\tau^- \rightarrow \nu_\tau \pi^-)}{\Gamma(\pi^- \rightarrow \mu^- \bar{\nu}_\mu)} = \left| \frac{g_\tau}{g_\mu} \right|^2 \frac{m_\tau^3}{2m_\pi m_\mu^2} \frac{(1 - m_\pi^2/m_\tau^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} (1 + \delta R_{\tau/\pi}), \quad (3)$$

$$R_{\tau/K} \equiv \frac{\Gamma(\tau^- \rightarrow \nu_\tau K^-)}{\Gamma(K^- \rightarrow \mu^- \bar{\nu}_\mu)} = \left| \frac{g_\tau}{g_\mu} \right|^2 \frac{m_\tau^3}{2m_K m_\mu^2} \frac{(1 - m_K^2/m_\tau^2)^2}{(1 - m_\mu^2/m_K^2)^2} (1 + \delta R_{\tau/K}), \quad (4)$$

where the dependence on the hadronic matrix elements (the so-called decay constants  $f_{\pi,K}$ ) factors out. Owing to the different energy scales involved, the radiative corrections to the  $\tau^- \rightarrow \nu_\tau \pi^-/K^-$  amplitudes are however not the same than the corresponding effects in  $\pi^-/K^- \rightarrow \mu^- \bar{\nu}_\mu$ . The size of the relative correction was first estimated by Marciano and Sirlin [14] to be  $\delta R_{\tau/\pi} = (0.67 \pm 1.)\%$ , where the 1% error amounts for the missing long-distance contributions to the tau decay rate. A recent evaluation of those long-distance

corrections [15] quotes the more precise values:

$$\delta R_{\tau/\pi} = (0.16 \pm 0.14)\% , \quad \delta R_{\tau/K} = (0.90 \pm 0.22)\% . \quad (5)$$

Using these numbers, the measured [4]  $\tau^- \rightarrow \pi^- \nu_\tau$  and  $\tau^- \rightarrow K^- \nu_\tau$  decay rates imply the  $|g_\tau/g_\mu|$  ratios given in Table 3. The inclusive sum of both decay modes, i.e.  $\Gamma[\tau^- \rightarrow h^- \nu_\tau]$  with  $h = \pi, K$ , provides a slightly more accurate determination:  $|g_\tau/g_\mu| = 1.004 \pm 0.007$ .

The present data verifies the universality of the leptonic charged-current couplings to the 0.15% ( $e/\mu$ ) and 0.37% ( $\tau/\mu$ ) level. The precision of the most recent  $\tau$ -decay measurements is becoming competitive with the more accurate  $\pi$ -decay determination. It is important to realize the complementarity of the different universality tests. The pure leptonic decay modes probe the charged-current couplings of a transverse  $W$ . In contrast, the decays  $\pi/K \rightarrow l\bar{\nu}$  and  $\tau \rightarrow \nu_\tau \pi/K$  are only sensitive to the spin-0 piece of the charged current; thus, they could unveil the presence of possible scalar-exchange contributions with Yukawa-like couplings proportional to some power of the charged-lepton mass. One can easily imagine new-physics scenarios which would modify differently the two types of leptonic couplings [16]. For instance, in the usual two-Higgs doublet model, charged-scalar exchange generates a correction to the ratio  $B_\mu/B_e$ , but  $R_{\pi \rightarrow e/\mu}$  remains unaffected. Similarly, lepton mixing between the  $\nu_\tau$  and an hypothetical heavy neutrino would not modify the ratios  $B_\mu/B_e$  and  $R_{\pi \rightarrow e/\mu}$ , but would certainly correct the relation between  $B_l$  and the  $\tau$  lifetime.

At the  $\tau$ cF, the accurate measurement of the  $B_\mu/B_e$  ratio would allow to test  $|g_\mu/g_e|$  to the 0.05% level, compared to the present 0.36% precision (0.15% from  $R_{\pi \rightarrow e/\mu}$ ). The final accuracy of the  $|g_\tau/g_\mu|$  universality test will be limited by the knowledge of the  $\tau$  lifetime. Assuming that the  $\tau_\tau$  measurement will be improved (at LEP or at the  $B$  Factory) by a factor of 2, i.e.  $\delta\tau_\tau/\tau_\tau \sim 0.3\%$ ,  $|g_\tau/g_\mu|$  would be tested with a 0.16% precision.

## LORENTZ STRUCTURE OF THE CHARGED CURRENT

Let us consider the leptonic decays  $l^- \rightarrow \nu_l l' \bar{\nu}_{l'}$ , where the lepton pair  $(l, l')$  may be  $(\mu, e)$ ,  $(\tau, e)$ , or  $(\tau, \mu)$ . The most general, local, derivative-free, lepton-number conserving, four-lepton interaction Hamiltonian, consistent with locality and Lorentz invariance [17–23],

$$\mathcal{H} = 4 \frac{G_{ll'}}{\sqrt{2}} \sum_{\epsilon, \omega = R, L}^{n=S, V, T} g_{ll'}^n \left[ \bar{l}'_\epsilon \Gamma^n (\nu_{l'})_\sigma \right] \left[ (\nu_l)_\lambda \Gamma_n l_\omega \right] , \quad (6)$$

contains ten complex coupling constants or, since a common phase is arbitrary, nineteen independent real parameters.  $\epsilon, \omega, \sigma, \lambda$  are the chiralities (left-handed,

right-handed) of the corresponding fermions, and  $n$  labels the type of interaction: scalar ( $I$ ), vector ( $\gamma^\mu$ ), tensor ( $\sigma^{\mu\nu}/\sqrt{2}$ ). For given  $n, \epsilon, \omega$ , the neutrino chiralities  $\sigma$  and  $\lambda$  are uniquely determined. Taking out a common factor  $G_{\nu l}$ , which is determined by the total decay rate, the coupling constants  $g_{\nu\epsilon\omega}^n$  are normalized to [21]

$$1 = \frac{1}{4} \left( |g_{RR}^S|^2 + |g_{RL}^S|^2 + |g_{LR}^S|^2 + |g_{LL}^S|^2 \right) + 3 \left( |g_{RL}^T|^2 + |g_{LR}^T|^2 \right) + \left( |g_{RR}^V|^2 + |g_{RL}^V|^2 + |g_{LR}^V|^2 + |g_{LL}^V|^2 \right). \quad (7)$$

In the SM,  $g_{LL}^V = 1$  and all other  $g_{\nu\epsilon\omega}^n = 0$ .

For an initial lepton-polarization  $\mathcal{P}_l$ , the final charged lepton distribution in the decaying lepton rest frame is usually parametrized in the form [18, 19]

$$\frac{d^2\Gamma}{dx d\cos\theta} = \frac{m_l\omega^4}{2\pi^3} G_{\nu l}^2 \sqrt{x^2 - x_0^2} \left\{ x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x) - \frac{1}{3}\mathcal{P}_l \xi \sqrt{x^2 - x_0^2} \cos\theta \left[ 1 - x + \frac{2}{3}\delta(4x - 4 + \sqrt{1 - x_0^2}) \right] \right\}, \quad (8)$$

where  $\theta$  is the angle between the  $l^-$  spin and the final charged-lepton momentum,  $\omega \equiv (m_l^2 + m_{\nu'}^2)/2m_l$  is the maximum  $l^-$  energy for massless neutrinos,  $x \equiv E_{\nu'}/\omega$  is the reduced energy and  $x_0 \equiv m_{\nu'}/\omega$ . For unpolarized  $l^-$ 's, the distribution is characterized by the so-called Michel [17] parameter  $\rho$  and the low-energy parameter  $\eta$ . Two more parameters,  $\xi$  and  $\delta$  can be determined when the initial lepton polarization is known. If the polarization of the final charged lepton is also measured, 5 additional independent parameters [3] ( $\xi', \xi'', \eta'', \alpha', \beta'$ ) appear.

The total decay rate is given by (neutrinos are assumed to be massless)

$$\Gamma = \frac{m_l^5 G_{\nu l}^2}{192\pi^3} \left\{ f\left(\frac{m_{\nu'}^2}{m_l^2}\right) + 4\eta \frac{m_{\nu'}}{m_l} g\left(\frac{m_{\nu'}^2}{m_l^2}\right) \right\} r_{\text{EW}}, \quad (9)$$

where  $g(z) = 1 + 9z - 9z^2 - z^3 + 6z(1+z)\ln z$ , and the SM radiative corrections  $r_{\text{EW}}$  have been included<sup>1</sup>.

Thus, the normalization  $G_{e\mu}$  corresponds to the Fermi coupling  $G_F$ , measured in  $\mu$  decay. The  $B_\mu/B_e$  and  $B_e\tau_\mu/\tau_\tau$  universality tests, discussed in the previous section, actually prove the ratios  $|\hat{G}_{\mu\tau}/\hat{G}_{e\tau}|$  and  $|\hat{G}_{e\tau}/\hat{G}_{e\mu}|$ , respectively, where

$$\hat{G}_{\nu l} \equiv G_{\nu l} \sqrt{1 + 4\eta_{l\nu'} \frac{m_{\nu'}}{m_l} \frac{g(m_{\nu'}^2/m_l^2)}{f(m_{\nu'}^2/m_l^2)}}. \quad (10)$$

<sup>1</sup> Since we assume that the SM provides the dominant contribution to the decay rate, any additional higher-order correction beyond the effective four-fermion Hamiltonian (6) would be a subleading effect.

An important point, emphatically stressed by Fetscher and Gerber [22], concerns the extraction of  $G_{e\mu}$ , whose uncertainty is dominated by the uncertainty in  $\eta_{\mu \rightarrow e}$ .

In terms of the  $g_{e\omega}^n$  couplings, the shape parameters in Eq. (8) are:

$$\begin{aligned}
\rho - \frac{3}{4} &= -\frac{3}{4} \left[ |g_{LR}^V|^2 + |g_{RL}^V|^2 + 2|g_{LR}^T|^2 + 2|g_{RL}^T|^2 + \text{Re}(g_{LR}^S g_{LR}^{T*} + g_{RL}^S g_{RL}^{T*}) \right], \\
\eta &= \frac{1}{2} \text{Re} \left[ g_{LL}^V g_{RR}^{S*} + g_{RR}^V g_{LL}^{S*} + g_{LR}^V (g_{RL}^{S*} + 6g_{RL}^{T*}) + g_{RL}^V (g_{LR}^{S*} + 6g_{LR}^{T*}) \right], \\
\xi - 1 &= -\frac{1}{2} \left[ |g_{LR}^S|^2 + |g_{RR}^S|^2 + 4(-|g_{LR}^V|^2 + 2|g_{RL}^V|^2 + |g_{RR}^V|^2) \right. \\
&\quad \left. - 4|g_{LR}^T|^2 + 16|g_{RL}^T|^2 - 8\text{Re}(g_{LR}^S g_{LR}^{T*} - g_{RL}^S g_{RL}^{T*}) \right], \quad (11) \\
(\xi\delta) - \frac{3}{4} &= -\frac{3}{4} \left[ \frac{1}{2}(|g_{LR}^S|^2 + |g_{RR}^S|^2) + (|g_{LR}^V|^2 + |g_{RL}^V|^2 + 2|g_{RR}^V|^2) \right. \\
&\quad \left. + 2(2|g_{LR}^T|^2 + |g_{RL}^T|^2) - \text{Re}(g_{LR}^S g_{LR}^{T*} - g_{RL}^S g_{RL}^{T*}) \right].
\end{aligned}$$

In the SM,  $\rho = \delta = 3/4$ ,  $\eta = \eta'' = \alpha' = \beta' = 0$  and  $\xi = \xi' = \xi'' = 1$ .

It is convenient to introduce [21] the probabilities  $Q_{e\omega}$  for the decay of a  $\omega$ -handed  $l^-$  into an  $\epsilon$ -handed daughter lepton,

$$\begin{aligned}
Q_{LL} &= \frac{1}{4} |g_{LL}^S|^2 + |g_{LL}^V|^2 &= \frac{1}{4} \left( -3 + \frac{16}{3}\rho - \frac{1}{3}\xi + \frac{16}{9}\xi\delta + \xi' + \xi'' \right), \\
Q_{RR} &= \frac{1}{4} |g_{RR}^S|^2 + |g_{RR}^V|^2 &= \frac{1}{4} \left( -3 + \frac{16}{3}\rho + \frac{1}{3}\xi - \frac{16}{9}\xi\delta - \xi' + \xi'' \right), \\
Q_{LR} &= \frac{1}{4} |g_{LR}^S|^2 + |g_{LR}^V|^2 + 3|g_{LR}^T|^2 &= \frac{1}{4} \left( 5 - \frac{16}{3}\rho + \frac{1}{3}\xi - \frac{16}{9}\xi\delta + \xi' - \xi'' \right), \quad (12) \\
Q_{RL} &= \frac{1}{4} |g_{RL}^S|^2 + |g_{RL}^V|^2 + 3|g_{RL}^T|^2 &= \frac{1}{4} \left( 5 - \frac{16}{3}\rho - \frac{1}{3}\xi + \frac{16}{9}\xi\delta - \xi' - \xi'' \right).
\end{aligned}$$

Upper bounds on any of these (positive-semidefinite) probabilities translate into corresponding limits for all couplings with the given chiralities.

For  $\mu$ -decay, where precise measurements of the polarizations of both  $\mu$  and  $e$  have been performed, there exist [21] upper bounds on  $Q_{RR}$ ,  $Q_{LR}$  and  $Q_{RL}$ , and a lower bound on  $Q_{LL}$ . They imply corresponding upper bounds on the 8 couplings  $|g_{RR}^n|$ ,  $|g_{LR}^n|$  and  $|g_{RL}^n|$ . The measurements of the  $\mu^-$  and the  $e^-$  do not allow us to determine  $|g_{LL}^S|$  and  $|g_{LL}^V|$  separately [21, 24]. Nevertheless, since the helicity of the  $\nu_\mu$  in pion decay is experimentally known [25] to be  $-1$ , a lower limit on  $|g_{LL}^V|$  is obtained [21] from the inverse muon decay  $\nu_\mu e^- \rightarrow \mu^- \nu_e$ . The present (90% CL) bounds [3, 26] on the  $\mu$ -decay couplings are given in Table 4. These limits show nicely that the bulk of the  $\mu$ -decay transition amplitude is indeed of the predicted V–A type.

The experimental analysis of the  $\tau$ -decay parameters is necessarily different from the one applied to the muon, because of the much shorter  $\tau$  lifetime. The

Table 4: 90% CL experimental limits [3, 26] for the  $\mu$ -decay  $g_{e\epsilon\mu\omega}^n$  couplings.

$ g_{e_L\mu_L}^S  < 0.55$	$ g_{e_L\mu_L}^V  > 0.96$	–
$ g_{e_R\mu_R}^S  < 0.066$	$ g_{e_R\mu_R}^V  < 0.033$	–
$ g_{e_L\mu_R}^S  < 0.125$	$ g_{e_L\mu_R}^V  < 0.060$	$ g_{e_L\mu_R}^T  < 0.036$
$ g_{e_R\mu_L}^S  < 0.424$	$ g_{e_R\mu_L}^V  < 0.110$	$ g_{e_R\mu_L}^T  < 0.122$

Table 5: Experimental averages [3, 35–37] of the Michel parameters. The last column ( $\tau \rightarrow l$ ) assumes identical couplings for  $l = e, \mu$  (the quoted value for  $\eta_{\tau \rightarrow l}$  is that obtained directly from measurements of the energy distribution).  $\xi_{\mu \rightarrow e}$  refers to the product  $\xi_{\mu \rightarrow e} \mathcal{P}_\mu$ , where  $\mathcal{P}_\mu \approx 1$  is the longitudinal polarization of the muon from pion decay.

	$\mu \rightarrow e$	$\tau \rightarrow \mu$	$\tau \rightarrow e$	$\tau \rightarrow l$
$\rho$	$0.7518 \pm 0.0026$	$0.738 \pm 0.038$	$0.736 \pm 0.028$	$0.733 \pm 0.022$
$\eta$	$-0.007 \pm 0.013$	$-0.14 \pm 0.23$	–	$-0.01 \pm 0.14$
$\xi$	$1.0027 \pm 0.0085$	$1.23 \pm 0.24$	$1.03 \pm 0.25$	$1.06 \pm 0.11$
$\xi\delta$	$0.7506 \pm 0.0074$	$0.71 \pm 0.15$	$1.11 \pm 0.18$	$0.76 \pm 0.09$

measurement of the  $\tau$  polarization and the parameters  $\xi$  and  $\delta$  is still possible due to the fact that the spins of the  $\tau^+\tau^-$  pair produced in  $e^+e^-$  annihilation are strongly correlated [27–34]. However, the polarization of the charged lepton emitted in the  $\tau$  decay has never been measured. In principle, this could be done for the decay  $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$  by stopping the muons and detecting their decay products [31]. The measurement of the inverse decay  $\nu_\tau l^- \rightarrow \tau^- \nu_l$  looks far out of reach.

The present experimental status on the  $\tau$ -decay Michel parameters is shown in Table 5 [23], which gives the world-averages of all published [3, 35–37] measurements. For comparison, the values measured in  $\mu$ -decay [3] are also given. The improved accuracy of the most recent experimental analyses has brought an enhanced sensitivity to the different shape parameters, allowing the first measurements of  $\eta_{\tau \rightarrow \mu}$  [35, 36],  $\xi_{\tau \rightarrow e}$ ,  $\xi_{\tau \rightarrow \mu}$ ,  $(\xi\delta)_{\tau \rightarrow e}$  and  $(\xi\delta)_{\tau \rightarrow \mu}$  [35]. (The ARGUS measurement [37] of  $\xi_{\tau \rightarrow l}$  and  $(\xi\delta)_{\tau \rightarrow l}$  assumes identical couplings for  $l = e, \mu$ . A measurement of  $\sqrt{\xi_{\tau \rightarrow e} \xi_{\tau \rightarrow \mu}}$  was published previously [38]).

The determination of the  $\tau$ -polarization parameters [35, 37] allows us to bound the total probability for the decay of a right-handed  $\tau$  [31],

$$Q_{\tau_R} \equiv Q_{l'_R \tau_R} + Q_{l'_L \tau_R} = \frac{1}{2} \left[ 1 + \frac{\xi}{3} - \frac{16}{9}(\xi\delta) \right]. \quad (13)$$



Table 6: 90% CL limits [23] for the  $\tau_R$ -decay  $g_{l_e\tau_R}^n$  couplings. The numbers with an asterisk use the measured value of  $(\xi\delta)_e$ .

$\tau \rightarrow \mu$	$\tau \rightarrow e$	$\tau \rightarrow l$
$ g_{\mu_R\tau_R}^S  < 1.05$	$ g_{e_R\tau_R}^S  < 0.75^*$	$ g_{l_R\tau_R}^S  < 0.74$
$ g_{\mu_L\tau_R}^S  < 1.05$	$ g_{e_L\tau_R}^S  < 0.75^*$	$ g_{l_L\tau_R}^S  < 0.74$
$ g_{\mu_R\tau_R}^V  < 0.53$	$ g_{e_R\tau_R}^V  < 0.38^*$	$ g_{l_R\tau_R}^V  < 0.37$
$ g_{\mu_L\tau_R}^V  < 0.53$	$ g_{e_L\tau_R}^V  < 0.38^*$	$ g_{l_L\tau_R}^V  < 0.37$
$ g_{\mu_L\tau_R}^T  < 0.30$	$ g_{e_L\tau_R}^T  < 0.22^*$	$ g_{l_L\tau_R}^T  < 0.21$

One finds (ignoring possible correlations among the measurements) [23]:

$$\begin{aligned}
Q_{\tau_R}^{\tau \rightarrow \mu} &= 0.07 \pm 0.14 < 0.28 \quad (90\% \text{ CL}), \\
Q_{\tau_R}^{\tau \rightarrow e} &= -0.32 \pm 0.17 < 0.14 \quad (90\% \text{ CL}), \\
Q_{\tau_R}^{\tau \rightarrow l} &= 0.00 \pm 0.08 < 0.14 \quad (90\% \text{ CL}),
\end{aligned} \tag{14}$$

where the last value refers to the  $\tau$ -decay into either  $l = e$  or  $\mu$ , assuming universal leptonic couplings. Since these probabilities are positive semidefinite quantities, they imply corresponding limits on all  $|g_{l_R\tau_R}^n|$  and  $|g_{l_L\tau_R}^n|$  couplings. The quoted 90% CL have been obtained adopting a Bayesian approach for one-sided limits [3]. Table 6 gives the implied bounds on the  $\tau$ -decay couplings.

The central value of  $Q_{\tau_R}^{\tau \rightarrow e}$  turns out to be negative at the  $2\sigma$  level; i.e., there is only a 3% probability to have a positive value of  $Q_{\tau_R}^{\tau \rightarrow e}$ . Therefore, the limits on  $|g_{e_R\tau_R}^n|$  and  $|g_{e_L\tau_R}^n|$  should be taken with some caution, since the meaning of the assigned confidence level is not at all clear. The problem clearly comes from the measured value of  $(\xi\delta)_e$ . In order to get a positive probability  $Q_{\tau_R}$ , one needs  $(\xi - 1) > \frac{16}{3}[(\xi\delta) - \frac{3}{4}]$ . Thus,  $(\xi\delta)$  can only be made larger than  $3/4$  at the expense of making  $\xi$  correspondingly much larger than one [23].

If lepton universality is assumed (i.e.  $G_{l\tau} = G_F$ ,  $g_{l_e\tau}^n = g_{e\tau}^n$ ), the leptonic decay ratios  $B_\mu/B_e$  and  $B_e\tau_\mu/\tau_\tau$  provide limits on the low-energy parameter  $\eta$ . The best sensitivity [39] comes from  $\hat{G}_{\mu\tau}$ , where the term proportional to  $\eta$  is not suppressed by the small  $m_e/m_l$  factor. The measured  $B_\mu/B_e$  ratio implies then [23]:

$$\eta_{\tau \rightarrow l} = 0.007 \pm 0.033 . \tag{15}$$

This determination is more accurate than the one in Table 5, obtained from the shape of the energy distribution, and is comparable to the value measured in  $\mu$ -decay:  $\eta_{\mu \rightarrow e} = -0.007 \pm 0.013$  [40].

A non-zero value of  $\eta$  would show that there are at least two different couplings with opposite chiralities for the charged leptons. Since, we assume the

V–A coupling  $g_{LL}^V$  to be dominant, the second coupling would be [31] a Higgs-type coupling  $g_{RR}^S$  [ $\eta \approx \text{Re}(g_{RR}^S)/2$ , to first-order in new-physics contributions]. Thus, Eq. (15) puts the (90% CL) bound:  $-0.09 < \text{Re}(g_{RR}^S) < 0.12$ .

### Model-Dependent Constraints

The general bounds in Table 6 look rather weak. The sensitivity of present experiments is not good enough to get interesting constraints from a completely general analysis of the four-fermion Hamiltonian. Nevertheless, stronger limits can be obtained within particular models, as shown in Tables 7, 8 and 9.

Table 7 assumes that there are no tensor couplings, i.e.  $g_{e\omega}^T = 0$ . This condition is satisfied in any model where the interactions are mediated by vector bosons and/or charged scalars [23]. In this case, the quantities  $(1 - \frac{4}{3}\rho)$ ,  $(1 - \frac{4}{3}\xi\delta)$  and  $(1 - \frac{4}{3}\rho) + \frac{1}{2}(1 - \xi)$  reduce to sums of  $|g_{l'e'l\omega}^n|^2$ , which are positive semidefinite; i.e. , in the absence of tensor couplings,  $\rho \leq \frac{3}{4}$ ,  $\xi\delta \leq \frac{3}{4}$  and  $(1 - \xi) > 2(\frac{4}{3}\rho - 1)$ . This allows us to extract direct bounds on several couplings.

Table 7: 90% CL limits for the couplings  $g_{e\omega}^n$ , assuming that there are no tensor couplings [23]. The numbers with an asterisk use the measured value of  $(\xi\delta)_e$ .

	$\mu \rightarrow e$	$\tau \rightarrow \mu$	$\tau \rightarrow e$	$\tau \rightarrow l$
$ g_{LL}^S $	$< 0.55$	$\leq 2$	$\leq 2$	$\leq 2$
$ g_{RR}^S $	$< 0.066$	$< 0.80$	$< 0.63^*$	$< 0.62$
$ g_{LR}^S $	$< 0.125$	$< 0.80$	$< 0.63^*$	$< 0.62$
$ g_{RL}^S $	$< 0.424$	$\leq 2$	$\leq 2$	$\leq 2$
$ g_{LL}^V $	$> 0.96$	$\leq 1$	$\leq 1$	$\leq 1$
$ g_{RR}^V $	$< 0.033$	$< 0.40$	$< 0.32^*$	$< 0.31$
$ g_{LR}^V $	$< 0.060$	$< 0.31$	$< 0.27$	$< 0.25$
$ g_{RL}^V $	$< 0.047$	$< 0.23$	$< 0.27$	$< 0.18$

If one only considers  $W$ -mediated interactions, but admitting the possibility that the  $W$  couples non-universally to leptons of any chirality, the stronger limits in Table 8 are obtained [23]. In this case, the  $g_{l'e'l\omega}^V$  constants factorize into the product of two leptonic  $W$  couplings, implying [41] additional relations among the couplings, such as  $g_{LR}^V g_{RL}^V = g_{LL}^V g_{RR}^V$ , which hold within any of the three channels,  $(\mu, e)$ ,  $(\tau, e)$ , and  $(\tau, \mu)$ . Moreover, there are additional equations relating different processes, such as [23]  $g_{\mu L \tau L}^V g_{e L \tau R}^V = g_{\mu L \tau R}^V g_{e L \tau L}^V$ . The normalization condition (7) provides lower bounds on the  $g_{LL}^V$  couplings.

For  $W$ -mediated interactions, the hadronic  $\tau$ -decay modes can also be used to test the structure of the  $\tau\nu_\tau W$  vertex, if one assumes that the  $W$  coupling to

Table 8: 90% CL limits on the  $g_{e\omega}^V$  couplings, assuming that (non-standard)  $W$ -exchange is the only relevant interaction [23].

	$\mu \rightarrow e$	$\tau \rightarrow \mu$	$\tau \rightarrow e$
$ g_{LL}^V $	$> 0.997$	$> 0.95$	$> 0.96$
$ g_{RR}^V $	$< 0.0028$	$< 0.019$	$< 0.013$
$ g_{LR}^V $	$< 0.060$	$< 0.31$	$< 0.27$
$ g_{RL}^V $	$< 0.047$	$< 0.060$	$< 0.047$

the light quarks is the SM one. The  $\mathcal{P}_\tau$  dependent part of the decay amplitude is then proportional to the mean  $\nu_\tau$  helicity

$$h_{\nu_\tau} \equiv \frac{|g_R|^2 - |g_L|^2}{|g_R|^2 + |g_L|^2}, \quad (16)$$

which plays a role analogous to the leptonic-decay parameter  $\xi$ . The analysis of  $\tau^+\tau^-$  decay correlations in leptonic-hadronic and hadronic-hadronic decay modes, using the  $\pi$ ,  $\rho$  and  $a_1$  hadronic final states, gives  $h_{\nu_\tau} = -1.014 \pm 0.027$  [35,37,42]; this implies  $|g_R/g_L|^2 = -0.007 \pm 0.013 < 0.018$  (90% CL). The sign of the  $\nu_\tau$  helicity can be determined [43] to be negative with the decay  $\tau^- \nu_\tau a_1^-$ , because there are two different amplitudes [corresponding to two different ways of forming the rho in  $a_1^- \rightarrow (\rho\pi)^-$ ] and their interference contains information on the sign.<sup>2</sup>

Table 9: 90% CL limits for the  $g_{e\omega}^n$  couplings, taking  $g_{RR}^n = 0$ ,  $g_{LL}^S = 0$ ,  $g_{LR}^V = g_{LR}^S = 2g_{LR}^T$  and  $g_{RL}^V = g_{RL}^S = 2g_{RL}^T$  [23].

	$\mu \rightarrow e$	$\tau \rightarrow \mu$	$\tau \rightarrow e$	$\tau \rightarrow l$
$ g_{LL}^V $	$> 0.998$	$> 0.95$	$> 0.96$	$> 0.97$
$ g_{LR}^V $	$< 0.047$	$< 0.22$	$< 0.19$	$< 0.18$
$ g_{RL}^V $	$< 0.033$	$< 0.16$	$< 0.19$	$< 0.13$

Table 9 shows the constraints obtained under the assumption that the interaction is mediated by the SM  $W$  plus an additional neutral scalar [23]. The scalar contributions vanish for the LL and RR couplings and satisfy the relations  $g_{LR}^V = g_{LR}^S = 2g_{LR}^T$ ,  $g_{RL}^V = g_{RL}^S = 2g_{RL}^T$ . This allows to express everything in terms of the vector couplings. The quantities  $(1 - \frac{4}{3}\rho)$ ,  $(1 - \frac{4}{3}\xi\delta)$

<sup>2</sup> Once the  $h_{\nu_\tau}$  sign is fixed, the measurement of leptonic-hadronic correlations determines the signs of  $\xi_{\tau \rightarrow e}$  and  $\xi_{\tau \rightarrow \mu}$  to be positive. At the  $Z$  peak, the signs of  $\xi_{\tau \rightarrow l}$  and  $h_{\nu_\tau}$  can be directly determined [44] from the sign of  $\mathcal{P}_\tau$ , which is fixed by combining the measurements of the polarization and left-right asymmetries.

and  $(1 - \frac{4}{3}\rho) + \frac{1}{2}(1 - \xi)$  are also positive semidefinite in this case. Moreover,  $(1 - \frac{4}{3}\rho) = (1 - \frac{4}{3}\xi\delta)$ .

### Expected Signals in Minimal New-Physics Scenarios

All experimental results obtained so far are consistent with the SM. Clearly, the SM provides the dominant contributions to the  $\tau$ -decay amplitudes. Future high-precision measurements of allowed  $\tau$ -decay modes should then look for small deviations of the SM predictions and find out the possible source of any detected discrepancy.

In a first analysis, it seems natural to assume [23] that new-physics effects would be dominated by the exchange of a single intermediate boson, coupling to two leptonic currents. The new contribution could be originated by non-standard couplings of the usual  $W$  boson, or by the exchange of a new scalar or vector particle (intermediate tensor particles hardly appear in any reasonable model beyond the SM).

Table 10 [23] summarizes the expected effects of different new-physics scenarios on the measurable shape parameters. The four general cases studied correspond to adding a single intermediate boson-exchange,  $V^+$ ,  $S^+$ ,  $V^0$ ,  $S^0$  (charged/neutral, vector/scalar), to the SM contribution (a non-standard  $W$  would be a particular case of the SM +  $V^+$  scenario). AS indicates that any sign is allowed.

Table 10: Theoretical constraints on the Michel parameters [23]

	SM + $V^+$	SM + $S^+$	SM + $V^0$	SM + $S^0$
$\rho - 3/4$	$< 0$	0	0	$< 0$
$\xi - 1$	AS	$< 0$	$< 0$	AS
$(\delta\xi) - 3/4$	$< 0$	$< 0$	$< 0$	$< 0$
$\eta$	0	AS	AS	AS

It is immediately apparent that  $\rho \leq 3/4$  and  $(\delta\xi) < 3/4$  in all cases studied. Thus one can have new physics and still  $\rho$  be equal to the SM value. In fact, any interaction consisting of an arbitrary combination of  $g_{e\omega}^S$ 's and  $g_{\gamma\gamma}^V$ 's yields this result [31]. On the other hand,  $(\delta\xi)$  will be different from  $3/4$  in any of the cases above providing, in principle, a better opportunity for the detection of Physics Beyond the SM.

The above features are easy to understand by looking back at Eqs. (11) and recalling that the tensor couplings can only be generated by neutral scalar interactions (violating individual lepton flavours), in which case they are proportional to the scalar couplings. It is easy to see that having two such neutral scalars will not alter the situation. Indeed, to obtain  $\rho > 3/4$  or

$(\delta\xi) > 3/4$  one would need to get contributions from charged and neutral scalars simultaneously[23]. Moreover,  $(\delta\xi) > 3/4$  can only happen through  $RL$  couplings and must be accompanied by  $\xi > 1$ .

The  $\tau cF$  offers an ideal experimental environment to perform this kind of analyses. The expected sensitivities to the different shape parameters, quoted in Table 1, would allow to prove the effective four-fermion Hamiltonian to a level where very interesting constraints on new-physics scenarios could be obtained. The numbers given in Table 1 are somehow conservative, since they only take into account the information obtained from correlated  $\tau^+\tau^-$  events where both  $\tau$ 's decay into leptons [5, 45]. Better precisions may be reached including the correlations of the leptonic decays with the hadronic ones [5, 45].

## DISCUSSION

The flavour structure of the SM is one of the main pending questions in our understanding of weak interactions. Although we do not know the reason of the observed family replication, we have learn experimentally that the number of SM fermion generations is just three (and no more). Therefore, we must study as precisely as possible the few existing flavours, to get some hints on the dynamics responsible for their observed structure. The construction of high-precision flavour factories is clearly needed.

Without any doubt, the  $\tau cF$  is the best available tool to explore the  $\tau$  and  $\nu_\tau$  leptons and the charm quark. This facility combines the three ingredients required for making an accurate and exhaustive investigation of these particles: high statistics, low backgrounds and good control of systematic errors. The threshold region provides a series of unique features (low and measurable backgrounds free from heavy flavour contaminations, monochromatic particles from two-body decays, small radiative corrections, single tagging, high-rate calibration sources, ...) that create an ideal experimental environment for this physics.

Two basic properties make the  $\tau$  particle an ideal laboratory for testing the SM: the  $\tau$  is a lepton, which means clean physics, and moreover, it is heavy enough to produce a large variety of decay modes. In the previous sections I have discussed two particular topics, charged-current universality and Lorentz structure of the weak currents, which would greatly benefit from a high-precision experimental study of the  $\tau$  lepton. There are, in addition, many other interesting subjects to be investigated.

The  $\tau cF$  could carry out a precise and exhaustive study of all exclusive  $\tau$  decay channels, looking for signs of discrepancies with the theoretical expectations. The accurate measurement of the  $q^2$  distribution of the final hadrons would allow a detailed analysis of the vector and axial-vector spectral functions and, therefore, a significant improvement of our knowledge of QCD.

Rare and forbidden  $\tau$  decays could be looked for, with a sensitivity better than  $10^{-7}$  in some channels. The bound on the  $\nu_\tau$  mass could be pushed down to the 1–2 MeV level. The present knowledge of the  $\tau$  electromagnetic moments could be improved by more than one order of magnitude. Last but not least, CP-violation in the lepton sector at the milli-weak ( $10^{-3}$ ) level could be investigated (with longitudinal beam polarization).

In addition to the large improvement in our knowledge of the  $\tau$  lepton, the  $\tau cF$  would also provide precious information on the  $c$  quark, through the detailed study of the  $D$  mesons and the  $J/\Psi$  and other charmonium states. A comprehensive set of precision measurements for  $\tau$ , charm and light-hadron spectroscopy would be obtained, proving the SM to a much deeper level of sensitivity and exploring the frontiers of its possible extensions.

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