Abstract

The main highlights discussed at TAU2012 are briefly summarized. Besides the standard topics on lepton physics covered also at previous conferences (universality, QCD tests, $V_{us}$ determination from $\tau$ decay, $g - 2$, $\nu$ oscillations, lepton-flavour violation), the $\tau$ lepton is playing now a very important role in searches for new physics phenomena.

1. Leptonic decays

In the Standard Model (SM) all lepton doublets have identical couplings to the $W$ boson. Comparing the measured decay widths of leptonic or semileptonic decays which only differ in the lepton flavour, one can test experimentally that the $W$ interaction is indeed the same, i.e. that $g_e = g_\mu = g_\tau \equiv g$. As shown in Table [1], the present data verify the universality of the leptonic charged-current couplings at the 0.2\% level.

The $\tau$ leptonic branching fractions and the $\tau$ lifetime are known with a precision of 0.3\% [1], far away from the impressive $10^{-6}$ accuracy recently achieved for the muon lifetime [2]. The preliminary Belle measurement $\tau_\tau = 290.18 \pm 0.54 \pm 0.33$ [2] shows that improvements are underway. The universality tests require also a good determination of the $\tau$ mass, which is only known at the $10^{-3}$ level. Uncertainties comparable to the $m_\tau$ world average are being reached by BES-III, which aims to an accuracy better than 0.1 MeV [3].

Table [1] shows also the contraints obtained from pion and kaon decays [5]. The accuracy achieved with $K_{2\pi}$ and $K_{3\pi}$ data is already competitive with the one obtained from $\tau$ or $\pi_2$ decays.

Owing to the limited statistics available, the leptonic decays of the $W$ boson only test universality at the 1\% level. At present, $\text{Br}(W \to \nu_\tau \tau)$ is $2.1 \sigma/2.7 \sigma$ larger than $\text{Br}(W \to \nu_e e/\nu_\mu \mu)$ [1]. This discrepancy cannot be easily explained, given the stringent limits on $|g_\tau/g_e|$ from $W$-mediated decays [5].

2. Hadronic decays

The $\tau$ is the only known lepton massive enough to decay into hadrons. Its semileptonic decays are ideally suited to investigate the hadronic weak currents and perform low-energy tests of the strong interaction.

2.1. The inclusive hadronic width

The inclusive character of the total $\tau$ hadronic width renders possible [7] an accurate calculation of the ra-
tio \( R_\tau \equiv \Gamma[\tau^- \to \nu_\tau \text{hadrons}] / \Gamma[\tau^- \to \nu_\tau e^-\bar{\nu}_e] \). Its Cabibbo-allowed component can be written as [8]

\[
R_{\tau,\nu+A} = N_C |V_{ud}|^2 S_{EW} (1 + \delta_\tau + \delta_{NP}) ,
\]

where \( N_C = 3 \) is the number of quark colours and \( S_{EW} = 1.0201 \pm 0.0003 \) contains the electroweak radiative corrections. The non-perturbative contributions are suppressed by six powers of the \( \alpha_S \) mass, can be theoretically estimated through a careful QCD analysis [17,19]. Taking the conservative value \( \delta_\tau = 0.239 \pm 0.030 \) [20], \( R_{\tau,S} = 0.1612 \pm 0.0028 \) [14] and \( |V_{ud}| = 0.97425 \pm 0.00022 \) [11], one obtains

\[
|V_{us}| = \left( \frac{R_{\tau,S}}{|V_{ud}|} \right)^{1/2} \frac{R_{\tau,\nu+A} - \delta R_{\nu,\text{th}}}{R_{\tau,\nu+A}} \\
= 0.2173 \pm 0.0020 \exp \pm 0.0010_{\text{th}} .
\]

This result is lower than the most recent determination from \( K_{\Omega} \) decays, \( |V_{us}| = 0.2238 \pm 0.0011 \) [21,22]. The branching ratios measured by BaBar and Belle are smaller than previous world averages, which translates into smaller results for \( R_{\tau,S} \) and \( |V_{us}| \). Slightly larger central values, \( R_{\tau,S} = 0.1653 \) and \( |V_{us}| = 0.2201 \), are obtained using the \( \tau \to \nu_\tau K(\pi) \) branching ratios estimated from \( K \to (\pi)\mu^+\mu^- \) [23], or combining the measured Cabibbo-suppressed \( \tau \) distribution with electroproduction data [19]. Contrary to \( K_{\Omega} \), the final error of the \( V_{us} \) determination from \( \tau \) decay is dominated by the experimental uncertainties and, therefore, sizeable improvements can be expected. Progress on the theoretical side requires a better understanding of the perturbative QCD corrections included in \( \delta_\tau \).

\[ |V_{us}| \] can also be obtained from exclusive modes, either from the ratio \( \Gamma(\tau \to \nu_\tau K) / \Gamma(\tau \to \nu_\tau \pi) \) or from \( \Gamma(\tau \to \nu_\tau K\pi) \), using the appropriate hadronic inputs from lattice calculations \( (f_k/f_\tau, f_\tau(0)) \). This gives values closer to the \( K_{\Omega} \) result, but with larger errors [14].

\[ 2.3. \quad \text{Exclusive decays} \]

A big effort is underway to fully understand the rich pattern of hadronic decay modes of the \( \tau \) [11,14,24,25]. The huge data samples accumulated at the B factories allow for a sizeable reduction of the statistical errors, so systematic uncertainties dominate in most cases. The decrease of many experimental branching ratios is worrisome. As pointed out by the PDG [11], 18 of the 20 branching fractions measured at the B factories are smaller than the previous non-B-factory values. The average normalized difference between the two sets of measurements is \( -1.30 \sigma \). Moreover, the BaBar and Belle results differ significantly for the 6 decay modes measured by both experiments. New measurements and refined analyses are clearly needed.

Recent progress includes the measurement of many high-multiplicity 3- and 5-prong decays [26], modes with \( K_S \) \( [\pi^- K_S(\rho^0), \pi^- K_S K_S(\rho^0), K^- K_S(\rho^0)] \) [27,29].
and analyses of hadronic distributions [29, 30]. Refined theoretical studies allow for a better understanding of hadronic form factors [31, 32], including the second-class-current decay $\tau \to \nu \nu \pi^\pm$ [32]. Forthcoming B-factory analyses and LHC searches will benefit from improved Monte Carlo tools [33] and the incorporation into the TAUOLA library [34] of the Resonance Chiral Theory constraints [35].

3. Anomalous magnetic moments

The most stringent QED test comes from the high-precision measurements of the $e$ [36] and $\mu$ [37] anomalous magnetic moments $a_i \equiv (g_i^\text{em} - 2)/2$:

$$a_e = (1159.625 \pm 0.028) \cdot 10^{-12},$$

$$a_\mu = (11.659.209.89 \pm 6.3) \cdot 10^{-10}. \quad (4)$$

The $O(\alpha^5)$ calculation has been completed in both cases [38], with an impressive agreement with the measured $a_e$ value. The dominant QED uncertainty is the input value of $\alpha$, therefore $a_e$ provides the most accurate determination of the fine structure constant ($0.25$ ppm),

$$\alpha^{-1} = 137.035 \cdot 999 \cdot 174 \pm 0.000 \cdot 000 \cdot 035, \quad (5)$$

in agreement with the recent (0.66 ppm) measurement from the atomic $h/m_Rb$ ratio in $^{87}$Rb [39]. The heavier muon mass makes $a_\mu$ sensitive to electroweak corrections from virtual heavier states, $\delta a_\mu^{\text{exp}} = 15.4(0.2) \cdot 10^{-10}$ [40], and QCD effects which are present the main source of uncertainty [41]. There is still a significant difference between the hadronic vacuum polarization (hvp) corrections extracted [42] from $e^+e^-$, $\delta a_{\mu}^{\text{hvp}}$ = 692.4$(4.1) \cdot 10^{-10}$, and $\tau$ data, $\delta a_{\mu}^{\text{hvp}}$ = 701.5$(4.7) \cdot 10^{-10}$, and discrepancies among different $e^+e^-$ experiments remain after the most recent BaBar, Belle, CMD-3, KLOE and SND analyses [43, 44]. Including the so-called light-by-light corrections, $\delta a_{\mu}^{\text{LL}} = 10.5(2.6) \cdot 10^{-10}$ [45], and NLO hvp corrections, $\delta a_{\mu}^{\text{NLO}}$ = $-9.8(0.1) \cdot 10^{-10}$ [46], the final SM prediction $\delta a_{\mu}^{\text{SM}} = \left\{ \begin{array}{l} (11659 \cdot 180.4 \pm 4.9) \cdot 10^{-10} \ (e^+e^-) \\ (11659 \cdot 189.5 \pm 5.4) \cdot 10^{-10} \ (\tau) \end{array} \right.$

differs from the experimental value by $3.6 \sigma$ ($e^+e^-$) or $2.3 \sigma$ ($\tau$). New precise $e^+e^-$ and $\tau$ data sets are needed to settle the true value of $\delta a_{\mu}^{\text{SM}}$. Improved predictions are needed to match the aimed $10^{-10}$ accuracy of the proposed muon experiments at Fermilab and J-PARC [47].

With a predicted value $\delta a_{\mu} = 117.721(5) \cdot 10^{-8}$ [48], the $\tau$ anomalous magnetic moment has an enhanced sensitivity to new physics because of the large tau mass. However, it is essentially unknown experimentally: $a_{\tau}^{\text{exp}} \approx -0.018 \pm 0.017$ [49].

4. CP violation

A variety of CP-violating observables (rate, angular and polarization asymmetries, triple products, Dalitz distributions, etc.) can be exploited to search for violations of the CP symmetry in $\tau$ decay and/or production [50]. While the SM predictions are very small, new-physics signals could show up in the $\tau$ data.

The $\tau^+ \to \pi^+K^0\bar{\nu}_\tau (\geq 0\theta)$ rate asymmetry recently measured by BaBar [28, 51].

$$\mathcal{A}_\tau \equiv \frac{\Gamma_{\tau^+ \to \pi^+K^0\bar{\nu}_\tau}}{\Gamma_{\tau^+ \to \pi^+\pi^+\pi^-}} = (0.36 \pm 0.23 \pm 0.11)\% , \quad (7)$$

differs by 2.8σ from the expected value due to $K^0$-$\bar{K}^0$ mixing, $\mathcal{A}_\tau = (0.36 \pm 0.01)\%$ [52, 53]. Belle has also searched for a CP signal in this decay mode through a difference in the $\tau^+$ angular distributions, finding a null result at the 0.2–0.3% level [54].

5. Tau production in B decays

An excess of events in two $b \to c \tau^-\bar{\nu}_\tau$ transitions has been reported by BaBar [55]. Including the previous Belle measurements [56] ($\ell = e, \mu$),

$$R(D) \equiv \frac{\text{Br}(B \to D\tau^-\bar{\nu}_\tau)}{\text{Br}(B \to D\ell^-\bar{\nu}_\ell)} = 0.438 \pm 0.056, \quad \text{(8)}$$

$$R(D^+) \equiv \frac{\text{Br}(B \to D^+\tau^-\bar{\nu}_\tau)}{\text{Br}(B \to D^+\ell^-\bar{\nu}_\ell)} = 0.354 \pm 0.026.$$  

The SM expectations, $R(D) = 0.296 \pm 0.016$ and $R(D^+) = 0.252 \pm 0.003$ [57, 58], are significantly lower. If confirmed, this could signal new-physics contributions violating lepton-flavour universality.

A sizable deviation from the SM was previously observed in $B^0 \to \tau^-\bar{\nu}_\tau$. However, Belle [59] finds now a much lower value in agreement with the SM; combined with the BaBar result [60], gives the average Br($B^0 \to \tau^-\bar{\nu}_\tau$) = (1.15 ± 0.23)$ \cdot 10^{-4}$, to be compared with the SM expectation (0.733$ \pm 0.012$)$ \cdot 10^{-4}$ [61].

These results are intriguing enough to trigger the theoretical interest. The enhancement of $\tau$ production could be generated by new physics contributions with couplings proportional to fermion masses. In particular, it could be associated with the exchange of a charged scalar within two-Higgs-doublet models. Although the Babar data rules out the usually adopted “Type II” scenario [55, 57], these measurements can be accommodated [62] by the more general framework of the “Aligned Two-Higgs-Doublet Model” (A2HDM) [63], albeit creating a tension with charm data.
6. Lepton-flavour violation

We have clear experimental evidence that neutrinos are massive particles and there is mixing in the lepton sector. The solar, atmospheric, accelerator and reactor neutrino data, lead to a consistent pattern of oscillation parameters [1]. The main recent advance is the establishment of a sizeable non-zero value of $\theta_{13}$, both in accelerator (T2K, Minos) and reactor experiments (Double-Chooz, Daya Bay, Reno) [64], with a statistical significance which reaches the 7.7 $\sigma$ at Daya Bay [65].

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005 .$$  \hspace{1cm} (9)

This increases the interest for a next-generation of long-baseline $\nu$ experiments to measure the CP-violating phase $\delta$ and resolve the neutrino mass hierarchy [66].

Other neutrino highlights presented at this conference include the second $\nu_e \to \nu_x$ candidate reported by OPERA [67], and the IceCube search for ultra-high energy $\nu_x$, finding three events which are statistically consistent with background fluctuations [68].

The smallness of neutrino masses implies a strong suppression of lepton-flavour-violation (LFV) in charged lepton decays, which can be avoided in models with sources of LFV not related to $m_{\nu}$. LFV processes have the potential to probe physics at scales much higher than the TeV. The LFV scale can be constrained imposing the requirement of a viable leptogenesis. Recent studies within different new-physics scenarios find interesting correlations between $\mu$ and $\tau$ LFV decays, with $\mu \to e\gamma$ often expected to be close to the present exclusion limit [69].

The B Factories are pushing the experimental limits on neutrinoless LFV $\tau$ decays to the $10^{-9}$ level [70], increasing in a drastic way the sensitivity to new physics scales. A rather competitive upper bound on $\tau \to 3\mu$ has been also obtained at LHCb [71]. Future experiments could improve further some limits to the $10^{-9}$ level [72], allowing to explore interesting and totally unknown phenomena.

Complementary information is the MEG experiment, which has already set a limit on $\mu^+ \to e^+\gamma$ five times tighter than previous experiments and aims to reach a sensitivity of $10^{-13}$ [73, 74]. A possible $10^4$ improvement in $\mu \to 3e$, reaching a sensitivity of $10^{-16}$, is also under study at PSI [75], and ongoing projects at J-PARC [76] and FNAL [75] aim to study $\mu \to e$ conversions in muonic atoms, at the $10^{-16}$ level.

Lepton-number violation has also been tested in $\tau$ ($\tau^+ \to (e/\mu)^{+}h^{\pm}h^{\mp}$, $\Lambda^{\tau}$, $\beta\gamma$ [1], $\tau^+ \to p\mu^+\mu^-\mu^-$ [71]) and meson ($M \to hh^{+}$ [77]) decays with sensitivities approaching in some cases the $10^{-8}$ level. These bounds constrain models of new physics involving Majorana neutrinos with masses in the GeV range [78].

7. Tau physics at the LHC

Owing to their high momenta, tightly collimated decay products and low multiplicity, $\tau$ leptons provide excellent signatures to probe new physics at high-energy colliders [79]. Moreover, the distribution of the $\tau$ decay products contains precious polarization information. The $\tau$ signal has been already exploited successfully at the LHC to measure $W$, $Z$ and top production cross sections ($W^+ \to \tau^+\bar{\nu}_\tau$, $Z \to \tau^+\tau^-$, $t \to b\tau^+\nu_\tau$) [80, 81], and ATLAS has reported the first $\tau$ polarization measurement ever made at hadron colliders, using the $\tau \to 2\nu_\tau\nu_\tau$ decay in $W^+ \to \tau^+\bar{\nu}_\tau$ [81].

The $\tau$ is the heaviest lepton coupling to the Higgs; with $m_H = 126$ GeV, the decay $H \to \tau^+\tau^-$ has the fourth largest Higgs branching ratio. No significant $H \to \tau^+\tau^-$ signal has been found up to now. The experimental analyses are quantified in terms of the signal-strength parameter, measuring the product of Higgs production cross section and branching ratio, normalized to the SM prediction. In the $H \to \tau^+\tau^-$ mode ATLAS quotes $\mu_H = 0.8 \pm 0.7$ [82], while CMS finds $\mu_H = 0.7 \pm 0.5$ [83]. These values are consistent with either the SM or the absence of a $H\tau^+\tau^-$ coupling.

Present searches for new phenomena, taking advantage of the $\tau$ signal, include bounds on $Z'$ bosons ($Z' \to \tau^+\tau^-$), supersymmetric neutral ($H \to \tau^+\tau^-$) and charged ($t \to H^+b \to \tau^+\nu_\tau b$) Higgses [84], and the BaBar constraints on a light CP-odd neutral scalar ($t' \to gA^0 \to \gamma\tau^+\tau^-$) [24, 85]. Significant improvements are to be expected with the increasing LHC luminosity and the use of more refined tools, such as charge asymmetries [86], to disentangle different new-physics scenarios.

8. Outlook

While the $\tau$ lepton continues being an increasingly precise laboratory to perform relevant tests of QCD and the electroweak theory, this conference has witnessed the opening of a new era with this heavy lepton becoming now a superb tool in searches for new phenomena. The ongoing LHC programme will be complemented with refined low-energy measurements at Belle-II [72], Bes-III [44] and, perhaps, a future Super Tau-Charm Factory [44], and muon experiments [47, 74, 76]. There is an exciting future ahead of us and unexpected surprises may arise, probably establishing the existence of new physics beyond the SM and offering clues to the
problems of mass generation, fermion mixing and family replications.

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References

[1] Particle Data Group, Phys. Rev. D 86 (2012) 010001.
[2] McLan Collaboration, Phys. Rev. Lett. 106 (2011) 041803, 079901.
[3] A. Sokolov, these proceedings.
[4] X.H. Mo, these proceedings.
[5] A. Pich, PoS HQL 2012 (2012) 019.
[6] A. Filipuzzi, J. Portolés and M. González-Alonso, Phys. Rev. D 85 (2012) 116010.
[7] E. Braaten, S. Narison and A. Pich, Nucl. Phys. B 373 (1992) 581. E. Braaten, Phys. Rev. Lett. 60 (1988) 1606; Phys. Rev. D 39 (1989) 1458. S. Narison and A. Pich, Phys. Lett. B 211 (1988) 183.
[8] A. Pich, arXiv:1107.1123 [hep-ph].
[9] F. Le Diberder and A. Pich, Phys. Lett. B 256 (1992) 147, 289 (1992) 165.
[10] M. Davier et al., Rev. Mod. Phys. 78 (2006) 1043; Eur. Phys. J. C 56 (2008) 305.
[11] P.A. Baikov, K.G. Chetyrkin and J.H. Kühn, Phys. Rev. Lett. 101 (2008) 012002.
[12] M. Beneke and M. Jamin, JHEP 0809 (2008) 044.
[13] I. Caprini and J. Fischer, Eur. Phys. J. C 64 (2009) 35.
[14] Heavy Flavor Averaging Group, arXiv:1207.1158 [hep-ex]; http://www.slac.stanford.edu/xorg/hfag/.
[15] M. Golterman and P. Roig, these proceedings.
[16] D. Boito et al., Phys. Rev. D 85 (2012) 093015.
[17] E. Gámiz et al., Phys. Rev. Lett. 94 (2005) 011803; JHEP 0301 (2003) 060; PoS KAO4 (2008) 005; hep-ph/0610246.
[18] A. Pich and J. Prades, JHEP 9910 (1999) 004, 9806 (1998) 013.
[19] M. Talmant, these proceedings.
[20] E. Gámiz, arXiv:1301.2206.
[21] A. Bazavov et al., arXiv:1212.4093 [hep-lat].
[22] V. Cirigliano et al., Rev. Mod. Phys. 84 (2012) 399.
[23] E. Passenmar, these proceedings.
[24] S. Banerjee, these proceedings.
[25] A. Lusiani, these proceedings.
[26] BaBar Collaboration, Phys. Rev. D 86 (2012) 092010.
[27] BaBar Collaboration, Phys. Rev. D 86 (2012) 092013.
[28] R. Sobue, these proceedings.
[29] S. Ryu, these proceedings.
[30] I.M. Nugent, these proceedings.
[31] D. Gómez-Dumm and P. Roig, these proceedings.
[32] B. Moussallam, these proceedings.
[33] P. Ilten, these proceedings.
[34] O. Shekhovtsova and Z. Was, these proceedings.
[35] G. Ecker et al., Nucl. Phys. B 321 (1989) 311; Phys. Lett. B 223 (1989) 425. V. Cirigliano et al., Nucl. Phys. B 753 (2006) 139.
[36] D. Hanneke, S. Fogwell and G. Gabrielse, Phys. Rev. Lett. 100 (2008) 120801.
[37] G.W. Bennett et al., Phys. Rev. D 73 (2006) 072003.