τ LEPTON PHYSICS AT B FACTORIES*

Simon Eidelman

Budker Institute of Nuclear Physics
Lavrentyev Ave. 11, Novosibirsk 630090, Russia

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Recent results on τ lepton physics predominantly coming from the BaBar and Belle detectors are discussed.

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1. Introduction

τ lepton is one of the six fundamental leptons. As the heaviest lepton, it may decay into both leptons and hadrons: PDG lists more than 200 different τ decays [1]. Using them we can study all interactions allowed in the Standard Model (SM) and search for effects of New Physics. It is a very clean laboratory with no hadrons in the initial and only a few in the final state. It is also worth mentioning that τ leptons will be an important tool at LHC.

Recently the high energy physics community started realizing that B factories are also τ factories. Indeed, at the $\Upsilon(4S)$ energy 0.9×10^6 $\tau^+\tau^-$ pairs are produced per each fb^{-1} of collected integrated luminosity. By now, BaBar (~ 557 fb^{-1}) and Belle (~ 946 fb^{-1}) collected together about 1.5 ab^{-1} that corresponds to almost three billions of τ leptons produced and decayed. This amount can be compared to what was achieved previously or can be expected at the c–τ factory in Beijing or at the Super$B$ factory, see Table I.

2. Lepton universality

Lepton universality in the charged lepton sector is one of the crucial points of the Standard Model stating that W-mediated processes are flavor-independent. In other words, the coupling constant G is equal for all types of leptons: $G = G_e = G_\mu = G_\tau$. This relation can be tested in various types

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TABLE I

Statistics of τ leptons at various machines.

Group	$\int L\,dt$, fb^{-1}	$N_{\tau\tau}$, 10^6
LEP (Z-peak)	0.34	0.33
CLEO (10.6 GeV)	13.8	12.6
c–τ (4.2 GeV)	10	32
Super$B$	50k	45k

of processes. *E.g.*, $\tau - \mu$ universality can be checked using purely leptonic decays of μ and τ. Since τ lepton mass enters the relation in the fifth power, precise M_τ measurements are mandatory. For many years the only precise determination was that of the BES group [2] using the energy dependence of $\sigma(e^+e^- \to \tau^+\tau^-)$ near threshold. A unique feature of this method is that even with a few dozens of events a high precision mass determination is possible. Recently such a measurement has also been performed at the KEDR detector in Novosibirsk, which additionally used high precision of the absolute energy determination to decrease corresponding systematic uncertainty [3]. KEDR has already reached a precision of BES and hopes to improve the uncertainty to reach 0.15 MeV [4]. Two other M_τ measurements have recently been performed at Belle [5] and BaBar [6]. In this case a pseudomass method is applied, which uses the spectrum of the invariant mass of hadrons observed and determines its endpoint, see, *e.g.*, the corresponding illustration from the Belle measurement in Fig. 1.

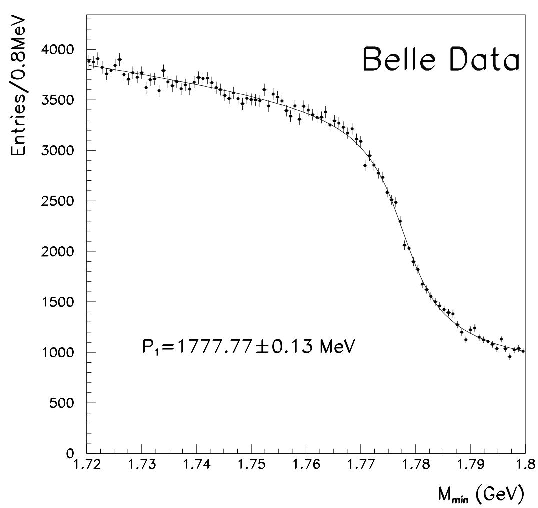

Fig. 1. Invariant mass of hadrons at Belle.

Both groups obtain consistent results, which despite huge statistics available at the B factories, have somewhat larger total error compared to the threshold measurements because of larger systematic effects. The results are summarized in Table II. τ–μ universality is OK and further progress of such tests is limited by the current accuracy of the τ lepton lifetime and its leptonic branching fraction.

TABLE II

Summary of M_τ measurements.

Group	M_τ, MeV
BES, 1996	$1776.96^{+0.18+0.25}_{-0.21-0.17}$
PDG, 2006	$1776.99^{+0.29}_{-0.26}$
KEDR, 2007	$1776.81^{+0.25}_{-0.23} \pm 0.15$
Belle, 2007	$1776.61 \pm 0.13 \pm 0.35$
PDG, 2008	1776.83 ± 0.18
KEDR, 2008	$1776.69^{+0.17}_{-0.19} \pm 0.15$
BaBar, 2008	$1776.68 \pm 0.12 \pm 0.41$

The pseudomass method has an additional advantage of measuring masses of τ^+ and τ^- separately providing an opportunity to test CPT. Results of such comparison are given in Table III. New limits are by one order of magnitude more stringent that those of OPAL [7].

TABLE III

$\Delta M = M_{\tau^+} - M_{\tau^-}$.

Group	OPAL, 2000	Belle, 2007	BaBar, 2008
$N_{\tau^+\tau^-}$, 10^6	0.16	370	389
$\Delta M/M_\tau$, 10^{-4}	0.0 ± 18.0	0.3 ± 1.5	-3.5 ± 1.3
$\Delta M/M_\tau$, 10^{-4} 90% C.L.	< 30.0	$< 2.8 \times 10^{-4}$	$-5.6 < \ldots < -1.4$

Lepton universality can be also checked in hadronic decays of the τ as well as in decays of the π, K mesons and W bosons [8]. Comparison of different methods shows that those involving τ leptons are among the most sensitive and can provide stringent limitations on various theoretical models [9].

3. CVC and $\tau^- \to \nu_\tau \pi^- \pi^0$

Conservation of vector current (CVC) relates cross-sections of $e^+e^- \to X^0$ to the branching fractions and invariant mass spectra in $\tau^- \to \nu_\tau X^-$, where X is a vector, isovector state [10, 11]. Thus, the allowed quantum numbers are $I^{\rm G}J^{\rm P}=1^+1^-$, so, *e.g.*, $X^-=\pi^-\pi^0$, $(4\pi)^-$, $\omega\pi^-$, $K^-K^0,\ldots$. Its early tests showed that it works well within the accuracy of (5–10)% [12]. After fruitful studies of the τ lepton decays at LEP and CLEO it was suggested to use rather precise τ data for an independent calculation of the corresponding e^+e^- cross-sections with their subsequent application to $a_\mu^{\rm had,LO}$, the hadronic contribution to the muon anomalous magnetic moment [13]. The very first usage of the τ data improved the accuracy of $a_\mu^{\rm had,LO}$ by a factor of 1.5. However, further increase of accuracy in both τ and e^+e^- sectors revealed some problems. Consistent application of the isospin-breaking corrections in [14, 15] showed that the spectral functions for two- and four-pion production are notably higher in τ decays.

Recently a high-statistics study of the $\tau^-\to\pi^-\pi^0\nu_\tau$ was performed at Belle [16]. From 64 M $\tau^+\tau^-$ pairs they selected 5.4 million $\tau^-\to h^-\pi^0\nu_\tau$ events. They clearly observe the $\rho(770)$ and its excitations, Fig. 2.

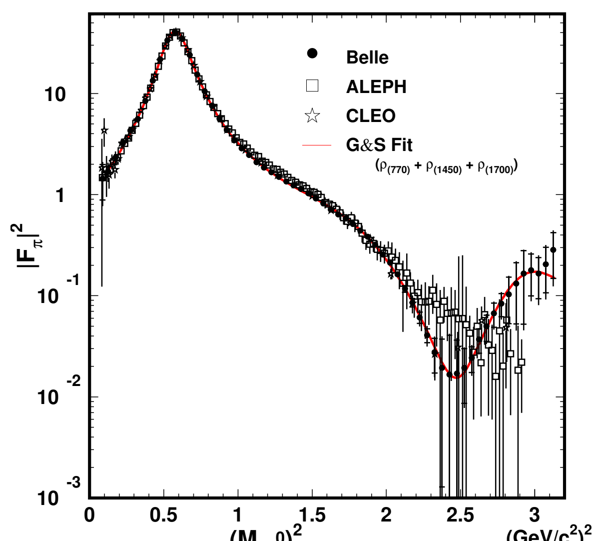

Fig. 2. The invariant mass distribution of two pions at Belle.

The obtained value of the branching fraction $(25.24\pm0.01\pm0.39)$% is in a good agreement with the most precise measurement at ALEPH $(25.471\pm0.097\pm0.085)$% [17]. Comparison of the mass spectra with other measurements clearly shows that above 0.9 GeV the spectrum of ALEPH is significantly higher than that of Belle and CLEO, Fig. 3.

However, the contributions to $a_\mu^{\rm had}$ are compatible due to compensation at tails. In particular, the contribution of the $\pi\pi$ channel, $a_\mu^{\pi\pi}$, is for Belle $(519.4\pm1.5({\rm exp.})\pm2.7({\rm Br.})\pm2.5({\rm isospin}))\times10^{-10}$ and consistent with

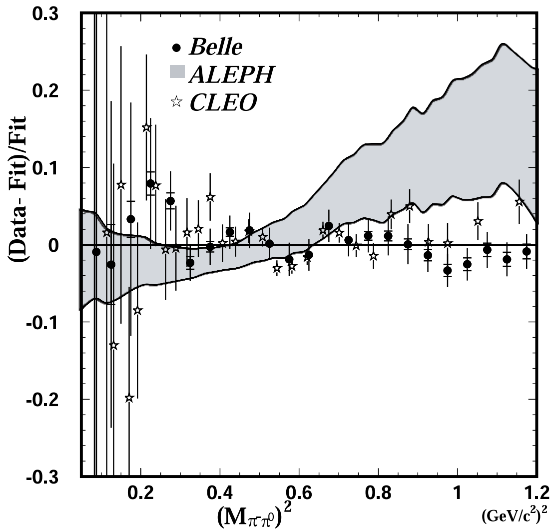

Fig. 3. Comparison of the Belle mass spectrum with others.

the estimate based on the other τ results $(520.1 \pm 2.4(\mathrm{exp.}) \pm 2.7(\mathrm{Br.}) \pm 2.5(\mathrm{isospin})) \times 10^{-10}$, both significantly higher than the e^+e^- based value $(504.6 \pm 3.1(\mathrm{exp.}) \pm 0.9(\mathrm{rad.})) \times 10^{-10}$.

On the other hand, a recent comprehensive analysis of the e^+e^- data below 1 GeV and those on the 2π decay of the τ lepton performed in Ref. [18] shows that two data sets can be reconciled if mixing between the ρ, ω, ϕ mesons is taken into account in a consistent way. A recent reevaluation of isospin-breaking effects in [19] reconsidered SU(2) breaking corrections, mainly long-distance radiative corrections as well as M, Γ splittings and somewhat decreases the discrepancy.

4. τ^- decays with kaons

Rich physics is expected from the decays with kaons in the final states. Decays with 1 or 3 kaons are Cabibbo-suppressed, the corresponding branching fraction $\mathcal{B}(\tau^- \to \mathrm{S} = -1) = (2.8\text{–}2.9)\%$ [20]. From strange spectral functions one can determine m_s and $|V_{us}|$. By measuring $Kn\pi$ decays one can study various K^* resonances.

Cabibbo-favored decays with two final-state kaons have a branching fraction $\mathcal{B}(\tau^- \to (K\bar{K}X)^-\nu_\tau) \sim 0.7\%$. They are interesting to study Wess–Zumino anomaly by determining the fraction of the vector and axial-vector part in $\tau^- \to (K\bar{K}\pi)^-\nu_\tau$ decays, for CVC tests and determine hadronic form factors and intermediate mechanisms $(K^*\bar{K}n\pi,\ V(\rho,\phi)n\pi)$.

A high-statistics study of $\tau^- \to K_S\pi^-\nu_\tau$ was performed at Belle [21]. They analysed 351 fb^{-1} or 313×10^6 $\tau^+\tau^-$ pairs and selected 53110 lepton tagged events. Their result for the branching fraction $(0.808 \pm 0.004 \pm 0.026)\%$ agrees with the world average of $(0.90 \pm 0.04)\%$ and is more precise. BaBar measured $\mathcal{B}(\tau^- \to K^-\pi^0\nu_\tau)$ using 342 fb^{-1} [22]. Their result $(0.832 \pm 0.006 \pm 0.036)\%$ agrees with that of Belle, both are a bit lower than the corresponding world average $(0.90 \pm 0.04)\%$.

Belle has also studied the $K_S\pi$ mass spectrum and concludes that it is well described by the combination of the $K^*(892)$, $K^*(800)$ (κ) and $K_0^*(1430)$ (or $K^*(1410)$) resonances. They also perform a precise $K^*(892)^0$ mass and width measurement and unexpectedly obtain that the mass of the charged $K^*(892)$ is in excellent agreement with that of the neutral one. This is in conflict with the usual belief that it is about 4.3 MeV lighter.

BaBar [23] and Belle [24] have also measured with high precision the branching fractions of the τ decay into three charged pions or kaons. All four possible combinations were studied. Comparison shows that the branching fraction of Belle and BaBar are not very consistent (with the exception of the decay into three charged pions). Belle data are also closer to the world average values [25].

Although BaBar and Belle have not yet measured all relevant decays with the odd number of final kaons, some branching fractions are already known with much better accuracy than before. Banerjee at KAON 07 combined the recent data from BaBar and Belle on the $K\pi\nu_\tau$ with older data for the other modes and estimated $|V_{us}|$ [26]. The result 0.2171 ± 0.0030 is significantly lower than the one based on unitarity (0.2275 ± 0.0012) that might be due to theoretical problems, see Fig. 4.

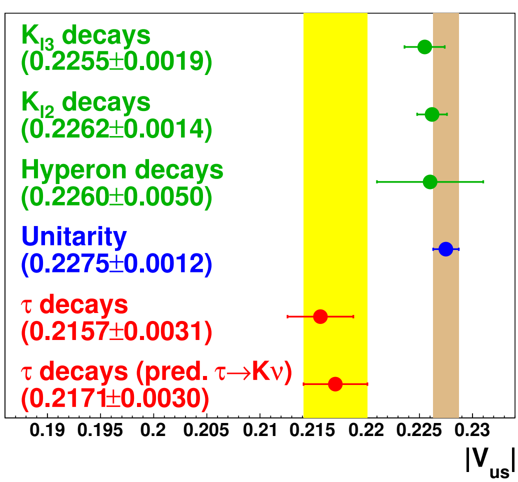

Fig. 4. Comparison of $|V_{us}|$ from τ decays with others.

5. Second class currents

Second class currents (SCC) were suggested 50 years ago by Weinberg [27]. In SM they are suppressed since their amplitude $\propto m_u - m_d$. As a result, the decay $\tau^- \to \eta\pi^-\nu_\tau$ with $J^{\rm PG} = 0^{+-}$ has a very small branching fraction: theory prediction is $\mathcal{B}(\tau^- \to \eta\pi^-\nu_\tau) \sim 10^{-6} - 10^{-5}$, see [28] and references therein. Its experimental observation is complicated because of large background from a non-suppressed decay $\tau^- \to \eta\pi^-\pi^0\nu_\tau$ with a much larger branching fraction $\mathcal{B} = (1.77 \pm 0.24) \times 10^{-3}$. In addition, CLEO [29] and ALEPH [30] observed one more potential background from $\tau^- \to \eta K^-\nu_\tau$ decay with $\mathcal{B}_{\rm exp} = (2.7 \pm 0.6) \times 10^{-4}$ *vs* $\mathcal{B}_{\rm th} \sim 1.2 \times 10^{-4}$. The best limit for the discussed SCC decay comes from CLEO: $\mathcal{B}(\tau^- \to \eta\pi^-\nu_\tau),\ < 1.4 \times 10^{-4}$ [29]. For a similar decay $\tau^- \to \eta'\pi^-\nu_\tau$ the best limit also came from CLEO: $\mathcal{B} < 7.4 \times 10^{-4}$ [31].

Recent progress is quite impressive. Belle studied all possible decays with η mesons and significantly improved our knowledge of the corresponding branching fractions [32]. Belle placed the most stringent limit of $\mathcal{B} < 7.3 \times 10^{-5}$ at 90% C.L. (they observe $\mathcal{B}(\tau^- \to \eta\pi^-\nu_\tau) = (4.4 \pm 1.6 \pm 0.8) \times 10^{-5}$ or a $2.4\,\sigma$ signal) [33].

Belle and BaBar also set the most stringent 90% C.L. upper limits for $\mathcal{B}(\tau^- \to \eta'\pi^-\nu_\tau) < 4.4 \times 10^{-6}$ [33] and $\mathcal{B}(\tau^- \to \eta'\pi^-\nu_\tau) < 7.2 \times 10^{-6}$ [34], respectively. These limits can be confronted to the theoretical prediction of $< 1.4 \times 10^{-6}$ in Ref. [35].

6. Monte Carlo simulation

It is worth reminding that for many years Monte Carlo simulation of τ lepton production and decays was based on TAUOLA, KORALB(Z) [36–38], which use was extremely fruitful for experiments at LEP, CLEO, BaBar and Belle. It should also be a very important tool in the future at LHC.

High-statistics experiments at Belle and BaBar require more precise description of hadronic form factors, which are now using a series of papers of Kühn with coauthors [39]. There were some recent attempts of improving like, *e.g.*, using Novosibirsk e^+e^- data for hadronic currents in $\tau \to 4\pi\nu_\tau$ [40] or based on theoretical consideration for $\tau \to 5\pi\nu_\tau$ in [41].

7. Searches for New Physics in the leptonic sector

Searches for New Physics in the leptonic sector, in particular by looking for lepton-flavor-violating (LFV) or lepton-number-violating processes have been performed for already more than 20 years [1]. Until recently focus was on the μ–e LFV processes with rather stringent limits on the branching fractions $\mathcal{B}(\mu^- \to e^-e^+e^-) < 1.0 \times 10^{-12}$ [42], $\mathcal{B}(\mu^- \to e^-\gamma) < 1.2 \times 10^{-11}$ [43] or μ–e conversion probability $< 7 \times 10^{-13}$ [44].

Discovery of neutrino oscillations, in particular $\nu_\mu \to \nu_\tau$ oscillations with a big mixing angle [45] motivated extensive searches for large $\mu - \tau$ LFV, *e.g.*, $\tau^- \to \mu^-\gamma$. In schemes with inverted hierarchy τ–e is also possible, *e.g.*, $\tau^- \to e^-\gamma$. Many theoretical models consider extensions of the Standard Model with enhanced LFV [46]. Particularly popular are SUSY models, *e.g.*, MSSM extension of SM, also discussed are SUGRA, GUT, Higgs, little Higgs *etc.* Predicted $\mathcal{B}(\tau^- \to \mu^-\gamma)$ reaches $10^{-8} - 10^{-7}$. More than 40 different modes of the τ lepton have been studied. For $\mathcal{B}(\tau^- \to \mu^-\gamma)$ the upper limit was improved from $< 5.5 \times 10^{-4}$ in 1982 [47] to $< 4.4 \times 10^{-8}$ in 2009 [48] The most stringent limit is $\mathcal{B}(\tau^- \to \mu^+e^-e^-) < 1.5 \times 10^{-8}$. The sensitivity of such searches is limited by background suppression/statistics. At Super$B$ factories one can hope to improve these limits by more than one order of magnitude reaching a $\sim 10^{-9}$ sensitivity. In conclusion, Belle and Babar reached very impressive results due to their huge statistics and added important information to what we knew after CLEO and LEP. Progress is particularly big while studying invariant mass spectra and intermediate mechanisms and in a search for rare decay modes. In some cases, *e.g.*, in the lifetime and leptonic branching fraction measurements there are still limitations because of systematic effects. One of the new puzzles is why most of the new measured branching fractions are smaller than those obtained before. It is clear that B factories with ~ 1.5 ab^{-1} are also unique τ factories with high potential for New Physics and precision studies in SM, even more can be expected from the future Super$B$ factories.

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