τ lepton decays*

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Abstract We discuss recent results on τ lepton physics obtained at the BABAR, Belle and KEDR detectors. They include tests of lepton universality using new measurements of τ lepton mass and some branching fractions. Also described are selected results on τ lepton hadronic decays coming from BABAR and Belle.

Key words lepton universality, lepton mass measurements, hadronic branching fractions

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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 (τ decays are characteristic of low multiplicity: 85.36% of events are one-prong only, 14.56% have three prongs and only $\sim 10^{-3}$ are five-prong). 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 $0.9\cdot 10^6$ $\tau^+\tau^-$ 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 at LEP and CLEO or can be expected at the c−τ factory in Beijing and at the Super B factory, see Table 1.

Table 1. Statistics of τ leptons at various machines.

Group	$\int L\ \mathrm{d}t$, 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

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 of processes. E. g., $\tau-\mu$ universality can be checked using decays of μ and τ into electron and corresponding pairs of neutrinos. The relation between the coupling constants is given by

$$r = \left(\frac{G_\tau}{G_\mu}\right)^2 = \left(\frac{M_\mu}{M_\tau}\right)^5\left(\frac{t_\mu}{t_\tau}\right)\mathcal{B}(\tau\to e\nu_\tau\bar{\nu}_e)\frac{F_{\mathrm{cor}}(M_\mu,M_e)}{F_{\mathrm{cor}}(M_\tau,M_e)}, \quad (1)$$

where $M_{e(\mu,\tau)}$ are lepton masses, $t_{\mu(\tau)}$ are their lifetimes and a factor F_{cor} including various phase space and radiative corrections is numerically very close to unity. Since τ lepton mass enters Eq. (1) in the fifth power, precise M_τ measurements are mandatory. When the BES group published results of its precise mass determination in 1996 [2], the value they obtained was 7 MeV lower than previously and order of

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magnitude more accurate. BES used a so called near-threshold measurement in which the energy dependence of $\sigma(e^+e^- \to \tau^+\tau^-)$ near threshold predicted by QED includes a single unknown parameter –τ lepton mass. A unique feature of this method is that near threshold the cross section is falling rapidly and 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 a corresponding systematic uncertainty [3]. Fig. 1 illustrates this measurement where with 6.7 pb^{-1} and only 81 events selected KEDR obtains

$$M_\tau = (1776.81^{+0.25}_{-0.23} \pm 0.15)\ \text{MeV}/c^2,$$

i.e., already a precision of BES, and hopes to improve the uncertainty to reach 0.15 MeV in total [4].

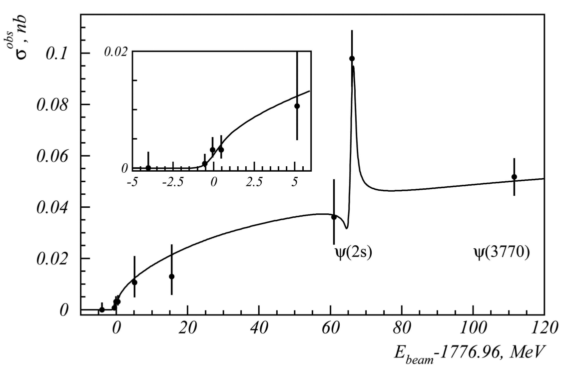

Fig. 1. τ mass measurement at KEDR.

Two other M_τ measurements have recently been performed at Belle [5] and BABAR [6]. In this case a pseudomass method developed by the ARGUS Collaboration [7] 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 BABAR measurement in Fig. 2. Both Belle and BABAR use τ decay into three charged pions, which has a fairly large ($\sim 9\%$) branching fraction.

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 2. It can be seen that all three new measurements agree with the BES value thus confirming the "low" value of τ mass measured by BES. $\tau - \mu$ universality as in Eq. 1 holds and further progress of such a test is limited by the current accuracy of the τ lepton lifetime and its leptonic branching fraction.

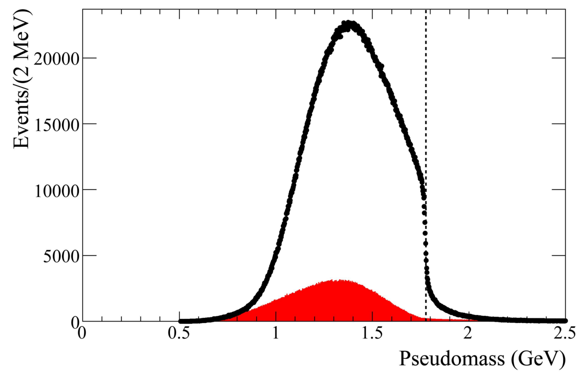

Fig. 2. Invariant mass of hadrons in $\tau^- \to 2\pi^-\pi^+\nu_\tau$ decay at BABAR.

Table 2. 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	$1776.81^{+0.25}_{-0.23} \pm 0.15$
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 3. New limits are by one order of magnitude more stringent that those of OPAL [8].

Table 3. Comparison of τ^+ and τ^- masses.

Group	OPAL, 2000	Belle, 2007	BABAR, 2009
$N_{\tau^+\tau^-}, 10^6$	0.16	380	388
ΔM, MeV	0.0 ± 3.2	0.05 ± 0.27	-0.61 ± 0.24
$\Delta M/M_\tau, 10^{-4}$	0.0 ± 18.0	0.3 ± 1.5	-3.4 ± 1.4
	< 30.0	< 2.8	< 5.5

From MC studies BABAR finds, assuming no CPT violation, that there is a 1.2% chance of obtaining a result as different from zero as that of BABAR.

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 [9]. Recently BABAR measured three basic branching fractions using a data sample of 467 fb^{-1} (about $429 \cdot 10^6$ $\tau^+\tau^-$ pairs produced) [10]. They present their results as the ratios of the partial widths of a specific mode studied to that of electron decay, $\Gamma(\tau^- \to e^-\nu_\tau\bar{\nu}_e)$, see Table 4.

Table 4. BABAR results on three basic branching fractions.

Decay mode	BABAR (PDG-08)
$\mu^-\bar{\nu}_\mu\nu_\tau$	$0.9796\pm0.0016\pm0.0035$ (0.9725 ± 0.0039)
$\pi^-\nu_\tau$	$0.5945\pm0.0014\pm0.0061$ (0.6076 ± 0.0061)
$K^-\nu_\tau$	$0.03882\pm0.00032\pm0.00056$ (0.0384 ± 0.0013)

From these measurements a few interesting tests of lepton universality can be performed. A test of $\mu-e$ universality can be expressed as.

$$\left(\frac{G_\mu}{G_e}\right)^2=\frac{\mathcal{B}(\tau^-\to\mu^-\bar{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^-\to e^-\bar{\nu}_e\nu_\tau)}\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}, \quad (2)$$

where $f(x)=1-8x+8x^3-x^4-12x^2\log x$ and it is assumed that the neutrino masses are negligible [11]. This relation yields $|G_\mu/G_e|=1.0036\pm0.0020$, consistent with the SM expectation as well as with other determinations giving 1.000 ± 0.002 [9].

Two other decays help to test $\tau-\mu$ universality using the relation

$$\left(\frac{G_\tau}{G_\mu}\right)^2=\frac{\mathcal{B}(\tau^-\to h^-\nu_\tau)}{\mathcal{B}(h^-\to\mu^-\bar{\nu}_\mu)}\frac{2m_h m_\mu^2\tau_h}{(1+\delta_h)m_\tau^3\tau_\tau}\times$$

$$\left(\frac{1-m_\mu^2/m_h^2}{1-m_h^2/m_\tau^2}\right)^2, \quad (3)$$

where $h=\pi$ or K and the higher-order corrections are $\delta_\pi=(0.16\pm0.14)\%$ and $\delta_K=(0.90\pm0.22)\%$ [12]. Using the world average values for all parameters entering Eq. (3), one obtains $|G_\tau/G_\mu|=0.9859\pm0.0057\,(0.9836\pm0.0087)$ with pions (kaons) compared to $0.996\pm0.005\,(0.979\pm0.017)$ from other measurements [9].

Comparison of the results above with those obtained in previous tests of lepton universality collected in Ref. [9] shows that tests involving τ leptons are among the most sensitive and can hopefully provide stringent limitations on various theoretical models [13].

3 Hadronic decays

3.1 τ^- decays with η mesons

Before making a search for the second-class currents [14] in τ^- decays to the $\eta\pi^-\nu_\tau$ and $\eta'\pi^-\nu_\tau$ final states, Belle performed a detailed analysis of various τ decays involving η mesons [15]. Some of these decays were previously studied by ALEPH [16] and CLEO [17, 18]. One should remember that these relatively rare but not suppressed in SM decays have branching fractions $\sim10^{-3}-10^{-4}$ and are two orders of magnitude more probable than those proceeding via second-class currents (for theoretical predictions see Ref. [19] and references therein). Therefore, they are a potential source of large background and should be well studied (both various spectra and branching fractions). Results of Belle analysis based on 490 fb^{-1} (about $450\cdot10^6$ $\tau^+\tau^-$ pairs) are shown in Table 5, which compares branching fractions measured by Belle with those from CLEO.

Table 5. Comparison of branching fractions of τ decays with η's.

Mode	Group	$\mathcal{B}_{\text{exp}}$
$\pi^-\pi^0\eta\nu_\tau$	Belle, 2008	$(1.35\pm0.03\pm0.08)\cdot10^{-3}$
	CLEO, 1992	$(1.7\pm0.2\pm0.2)\cdot10^{-3}$
$K^-\eta\nu_\tau$	Belle, 2008	$(1.58\pm0.05\pm0.09)\cdot10^{-4}$
	CLEO, 1996	$(2.6\pm0.5\pm0.4)\cdot10^{-4}$
$K^-\pi^0\eta\nu_\tau$	Belle, 2008	$(4.6\pm1.1\pm0.4)\cdot10^{-5}$
	CLEO, 1999	$(17.7\pm5.6\pm7.1)\cdot10^{-5}$
$K^{*-}\eta\nu_\tau$	Belle, 2008	$(1.30\pm0.13\pm0.11)\cdot10^{-4}$
	CLEO, 1999	$(2.90\pm0.80\pm0.42)\cdot10^{-4}$
$K_S\pi^-\eta\nu_\tau$	Belle,2008	$(4.4\pm0.7\pm0.2)\cdot10^{-4}$
	CLEO, 1999	$(1.00\pm0.35\pm0.11)\cdot10^{-3}$

Progress in accuracy is obvious. All branching fractions measured by Belle are consistent within errors with the best previous results coming from CLEO and much more precise. It is interesting to note that in all cases the values of Belle are lower than those of CLEO.

3.2 τ^- decays with kaons

Rich physics is expected from decays with kaons in the final state. Decays with one or three kaons are Cabibbo-suppressed, the corresponding branching fraction $\mathcal{B}(\tau^-\to S=-1)=(2.8-2.9)\%$ [20]. Measuring hadronic spectra in such decays one can determine strange spectral functions from which m_s and $|V_{us}|$ can be extracted [21]. By studying $Kn\pi$ decays one can learn a lot about spectroscopy of various K^* resonances.

Cabibbo-favored decays with two final-state kaons have a branching fraction $\mathcal{B}(\tau^-\to(K\bar{K}X)^-\nu_\tau)\sim0.7\%$. They are interesting to study Wess-Zumino anomaly [22, 23] by determining the fraction of the vector and axial-vector part in $\tau^- \to (K\bar{K}\pi)^-\nu_\tau$ decays, for CVC tests [11, 24, 25] and determination of hadronic form factors and intermediate mechanisms ($K^*\bar{K}n\pi$, $V(\rho,\phi)n\pi$) in the final $K\bar{K}n\pi$ state.

Recently BABAR and Belle performed high-statistics studies of $\tau \to K\pi\nu_\tau$ decays. The BABAR group studied both $K^-\pi^0$ [26] and $K_S\pi^-$ [27] hadronic states, and Belle studied in detail the latter [28]. General information about these decays and the obtained branching fractions are summarized in Table 6.

Table 6. Summary of $\tau \to K\pi\nu_\tau$ measurements at BABAR and Belle.

Mode	Group	$\int Ldt$, fb^{-1}	$N_{\tau\tau}$, 10^6	$N_{\rm ev}$, 10^3	$\mathcal{B}$,%
$K^-\pi^0\nu_\tau$	BABAR	230	212	78.1	$0.416\pm0.003\pm0.018$
$K^0_S\pi^-\nu_\tau$	BABAR	385	353	83.7	$0.420\pm0.002\pm0.012$
$K^0_S\pi^-\nu_\tau$	Belle	351	313	53.1	$0.404\pm0.002\pm0.013$

In Fig. 3 BABAR and Belle results on the branching fraction of $\tau^- \to \bar{K}^0\pi^-\nu_\tau$ decay (twice the measured $\mathcal{B}(K^0_S\pi^-\nu_\tau)$ to take into account $\mathcal{B}(K^0_L\pi^-\nu_\tau)$) are compared to other measurements. It can be seen that the central values of $\mathcal{B}$ from BABAR and Belle agree with each other and with previous measurements and are much more precise. For another decay mode BABAR gives $\mathcal{B}(K^-\pi^0\nu_\tau) = (0.416\pm0.003\pm0.018)\%$, consistent with and more precise than the world average of $(0.454\pm0.030)\%$. Note that in all cases the new branchings are lower than previously measured.

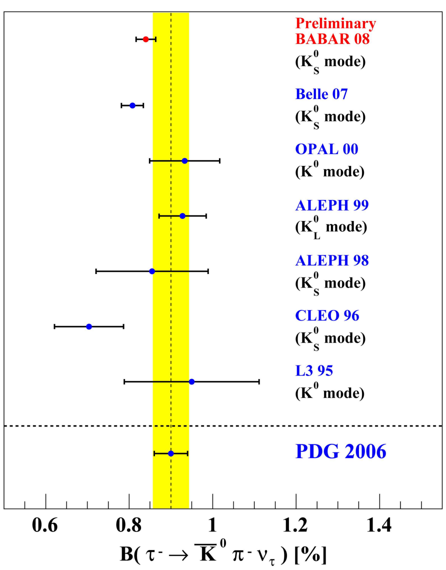

Fig. 3. Comparison of BABAR and Belle results on $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$ with other measurements.

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, see Fig. 4.

The values of the $K^*(892)^-$ mass and width that Belle obtains are more precise than any of the existing measurements of these quantities listed in Ref. [1] and shown in Fig. 5. While their value of the width is compatible with most of the previous measurements within experimental errors, the mass value of Belle is systematically higher than those before and is in fact consistent with the world average value of the neutral

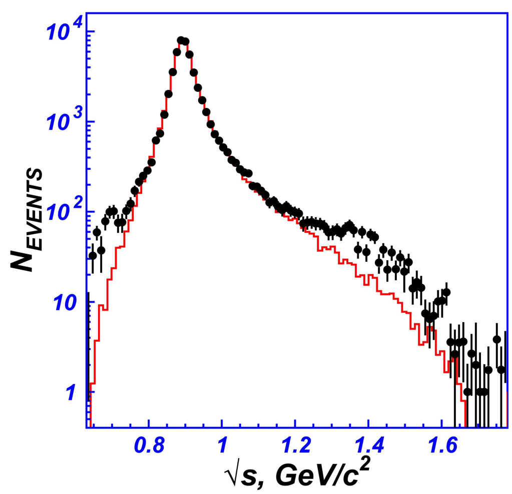

Fig. 4. Spectrum of $M_{K\pi}$ in $\tau^- \to K^0_S\pi^-\nu_\tau$ decay from Belle.

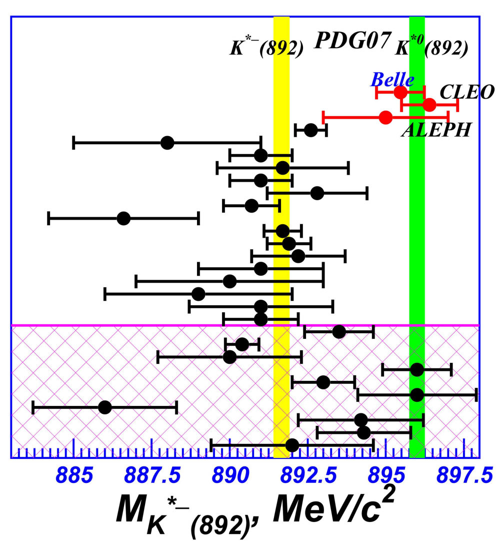

Fig. 5. K^* mass measurements.

$K^*(892)^0$ mass, which is (896.00 ± 0.25) MeV/c^2 [1]. Note that all earlier mass measurements listed in Ref. [1] come from analysis of hadronic reactions and include the effects of final state interaction while Belle presents a measurement based on τ^- decays, where the decay products of the $K^*(892)^-$ are the only hadrons involved. It is also noteworthy that none of the previous measurements in Ref. [1], all of which were performed more than 20 years ago, present systematic uncertainties for their measurements. Unfortunately, previous studies of the $K^*(892)^-$ in τ^- lepton decays usually do not determine its parameters. The only published result is that of ALEPH [20], which is consistent with that of Belle. Its accuracy, however, is much worse and no systematic errors are presented, which precludes any detailed comparisons. A similar $K^*(892)^-$ mass shift of $(+4.7 \pm 0.9)$ MeV/c^2 was reported by CLEO [29], but no dedicated study of this effect was published.

BABAR [30] and Belle [31] 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, see Table 7. For all modes with kaons the precision achieved at BABAR and Belle is higher than that of the world average values [32]. However, comparison of the central values shows striking differences in all channels other than $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$. For the $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ mode, the result of Belle is 1.4 σ lower than that of BABAR and 2.2 σ lower than the previous world average value, while for all other modes, the branching fractions obtained at Belle are higher by 3.0 σ, 3.0 σ and 5.4 σ than those of BABAR for the $\tau^- \to K^-\pi^+\pi^-\nu_\tau$, $\tau^- \to K^-K^+\pi^-\nu_\tau$, and $\tau^- \to K^-K^+K^-\nu_\tau$ modes, respectively. In the $\tau^- \to K^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to K^-K^+\pi^-\nu_\tau$ cases, the Belle values of the branching fractions are much closer to the world average values than those of BABAR.

Table 7. Branching fractions of τ decay into three hadrons

Mode	BABAR, 342 fb^{-1}	Belle, 666 fb^{-1}	PDG2006
$\mathcal{B}(\pi^-\pi^+\pi^-\nu_\tau), 10^{-2}$	$8.83 \pm 0.01 \pm 0.13$	$8.42 \pm 0.01 \pm 0.26$	9.02 ± 0.08
$\mathcal{B}(K^-\pi^+\pi^-\nu_\tau), 10^{-3}$	$2.73 \pm 0.02 \pm 0.09$	$3.30 \pm 0.01 \pm 0.17$	3.33 ± 0.35
$\mathcal{B}(K^-K^+\pi^-\nu_\tau), 10^{-3}$	$1.346 \pm 0.010 \pm 0.036$	$1.55 \pm 0.01 \pm 0.06$	1.53 ± 0.10
$\mathcal{B}(K^-K^+K^-\nu_\tau), 10^{-5}$	$1.58 \pm 0.13 \pm 0.12$	$3.29 \pm 0.17 \pm 0.20$	$< 3.7 \times 10^{-5}$

4 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) [33–35], which use was extremely fruitful for experiments at LEP, CLEO, BABAR and Belle. It should also be a very important instrument in the future at LHC.

High-statistics experiments at Belle and BABAR require more precise description of hadronic form factors, which are now based on a series of papers of J. Kühn with coauthors [36]. There were some recent attempts of their improvement like, e.g., use of Novosibirsk e^+e^- data for hadronic currents in $\tau \to 4\pi\nu_\tau$ [37] or application of theoretical considerations for $\tau \to 5\pi\nu_\tau$ in [38].

5 Conclusions

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 large 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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