Measurement of tau parameters and mu-tau universality tests

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The report reviews the measurements of the tau lepton parameters. The tau mass measurements at the KEDR detector as well as at the B-factories are considered in more details. The present limitations on the lepton universality tests are discussed.

I. INTRODUCTION

According to the Standard Model (SM) the coupling of W-boson with leptons is family-independent: \( g_e = g_\mu = g_\tau \) (lepton universality). Thus, all lepton decays induced by the charged currents are governed by the same weak constant:

\[
G_F = \frac{g^2}{4\sqrt{2}M_W^2}, \quad g = g_e = g_\mu = g_\tau,
\]

where \( G_F \) is Fermi constant.

According to the present knowledge \( g_e = g_\mu \) within at least 0.2% while an upper limit on the difference \( (g_\mu - g_\tau) \) is 2% [1]. The natural idea is to check the lepton universality using ratios of the tau branching fractions. Tests of the \( g_l \) equality were performed in the W decays (ALEPH, DELPHY, L3 and OPAL), \( \tau \) decays (ALEPH, DELPHY, L3, OPAL and CLEO), kaon decays (KLOE) and pion decays (TRIUMPH and PSI).

This report describes the status of the measurements of the tau parameters relevant to the lepton universality check and the status of these tests.

II. TAU MASS MEASUREMENT AT THE VEPP-4M COLLIDER WITH THE KEDR DETECTOR

To test the \( g_\tau / g_\mu \) ratio the precise value of \( \tau \) mass is important. Recently, new measurements of this parameter were made by the KEDR, Belle and BaBar experiments.

In the KEDR experiment [2], which operates at the VEPP-4M collider at BINP, the \( \tau \)-lepton mass was derived from the measurements of \( e^+e^- \rightarrow \tau^+\tau^- \) cross section near threshold [3]. The key problem for this approach is the precise energy determination. Two independent methods were used in this experiment. One of them was resonant depolarization method which provided the accuracy of the energy determination of about 10 keV. The other one used Compton backscattering of the laser photons by the beam in the collider and determined the energy with the accuracy 50-70 keV.

A schematic view of the KEDR detector is shown in Fig. 1. The KEDR detector comprises a vertex detector, a drift chamber, a time-of-flight system of scintillation counters, a particle identification system based on aerogel Cherenkov counters, a calorimeter with the longitudinal segmentation (liquid krypton in the barrel part and CsI crystals in the end caps) and a muon tube system inside the magnet yoke. An axial magnetic field of 0.6 Tesla is produced by the superconducting solenoid.

To diminish systematic uncertainties the event selection criteria were chosen as loose as possible while a background was kept to be negligible. The two-prong events with up to three photons due to \( e^+e^- \rightarrow (\tau \rightarrow e\nu\nu)(\tau \rightarrow e\nu\nu,\nu\nu,\pi\nu,K\nu,\rho\nu)^+ + c.c. \) were selected. At least one track must be identified as an electron using the signal in the calorimeter and the momentum measurement. The \( \mu/\pi/K \) identification was not
applied as it does not reduce the systematic uncertainty of the mass. No photons with $E_\gamma > 30$ MeV were allowed. The other cuts were $E < 2200$ MeV, $p_T > 200$ MeV, $p_T/(W - E) > 0.06$, where $p_T$ is the total transverse momentum, $E$ is total energy of the detected particles and $W = 2E\text{ beam}$ . With these cuts the residual background (mainly two-photon) is expected to be uniform in the energy region of the experiment.

An integrated luminosity of $L = 14.3\text{ pb}^{-1}$ provided 26 events at the threshold range. Measured $\tau^+\tau^-$ cross section is shown in the Fig. 2. A fit of the data produced in the following result:

$$M_\tau = 1776.96^{+0.17}_{-0.19} \pm 0.15\text{ MeV},$$

where the first error is statistical and the second one is systematic.

Conservative estimations of the systematic uncertainties are presented in the Table I.

### III. Tau Mass Measurement at Belle and Babar

During last ten years a lot of physics results came from two B-factories - Belle [4] and BaBar [5]. Both detectors are forward/backward asymmetric detectors with high vertex resolution, magnetic spectrometry, excellent calorimetry and sophisticated particle identification ability. Integrated luminosity collected by both detectors exceeded $1500\text{ fb}^{-1}$.

In the Belle and BaBar experiments the $\tau$ mass values were determined by the fit of the pseudomass distribution of the hadronic decays. The pseudomass is defined by the formulae:

$$M_\tau^2 = (E_h + E_\nu)^2 - (\vec{p}_h + \vec{p}_\nu)^2 = M_h^2 + 2(E_\tau - E_h)(E_h - p_h \cos(\theta)) \geq M_p^2 = M_h^2 + 2(E_\tau - E_h)(E_h - p_h).$$

Typical pseudomass spectrum obtained in [4] is shown in the Fig. 3. The results of the BaBar and Belle experiments, based on 389 and 370 million $\tau^+\tau^-$ pairs respectively [6, 7] are presented in the Table II.

### TABLE I: Systematic uncertainties.

| Source of Uncertainty                                    | Error |
|----------------------------------------------------------|-------|
| Beam energy determination                                | 35 keV|
| Detection efficiency variations                          | 120 keV|
| Energy spread determination accuracy                     | 20 keV |
| Background dependence on the beam energy                 | 20 keV |
| Luminosity measurement instability                       | 80 keV |
| Beam energy spread variation                             | 10 keV |
| Cross section calculation (t.c., 0 interference)         | 30 keV |
| Sum in quadrature                                        | 150 keV|

The progress of $M_\tau$ measurements can be seen in the Fig. 4. The quoted results should be compared with the PDG average [8]: $M_\tau = (1776.82 \pm 3$.
FIG. 3: Pseudomass distribution, Belle experiment. The black and empty circles correspond to the negative and positive tau leptons.

0.16) MeV.

FIG. 4: Measurements of τ-lepton mass.

The pseudomass method provides a separate results for the masses of the positive and negative leptons. The difference between these masses tests CPT theorem. The results are presented in the Table III.

After all efforts on tau mass measurement, its contribution to the lepton universality check became very small and now the accuracies of other tau parameters dominate. The ratio \( r = g_\tau / g_\mu \) is expressed as:

\[
\begin{align*}
\tau = \left( \frac{g_\tau}{g_\mu} \right)^2 \left( \frac{m_\mu}{m_\tau} \right)^5 \left( \frac{\tau_\mu}{\tau_\tau} \right) F_{\text{cor}}(m_\mu, m_\tau) F_{\text{cor}}(m_\tau, m_\mu),
\end{align*}
\]

where a function \( F_{\text{cor}}(m_1, m_2) \) takes into account the electroweak corrections. These corrections are small and are calculated with high accuracy. Contributions of the uncertainties of the relevant parameters to the final precision of this ratio can be seen in the Table IV.

| Experiment | OPAL, 2000 | Belle, 2007 | BaBar, 2008 |
|------------|------------|------------|-------------|
| \( N_{e+e-} \times 10^6 \) | 0.16 | 380 | 388 |
| \( \Delta m/m_\tau \times 10^{-4} \) | 0.0 ± 18.0 | 0.3 ± 1.5 | -3.4 ± 1.3 |
| \( \Delta m/m_\tau \times 10^{-4}, 90\% \text{ CL} \) | < 30.0 | < 2.8 | < 5.6 |

### IV. MEASUREMENTS OF TAU LIFETIME

The most precise published results on the tau lepton lifetime were obtained by the CLEO (1996), OPAL (1996), ALEPH (1997), L3 (2000) and DELPHI (2004). The typical total (statistical plus systematics) precisions were (2-4) fs. However, averaged by PDG value has much better accuracy: \( \tau_\tau = 290.6 ± 1.0 \text{ fs} \).

The Belle and the BaBar collected a huge statistics of the tau lepton decays. However, the tau lepton energy in these experiments is much lower than that was at LEP, which implies much shorter decay length and, as a result, much more complicated analysis. The BaBar collaboration released a preliminary result several years ago \( \tau_\tau = 289.40 ± 0.91(\text{stat.}) ± 0.90(\text{syst.}) \text{ fs} \), but final results are not published yet.

The tau lifetime analysis at the Belle is in progress \[10\]. The result, even preliminary, is not released yet, however, the achieved accuracy referred as \((±0.37(\text{stat})±0.33(\text{syst})) \text{ fs}\). Analysis of systematics is in progress.

Since the lifetime of the positive and negative tau leptons are measured separately, the difference between them can be derived. The Belle experiment measured this difference using the decays \( e^+e^- \rightarrow \tau^+\tau^- \rightarrow (3\pi\nu)(3\pi\nu) \): \( \Delta(\tau\tau) = c\tau^+ - ct^- = 0.16 ± 0.22 \mu\text{m} \) that corresponds to \( |\tau^+ - \tau^-|/\tau_{\tau\tau} < 6 \times 10^{-3} \) @ 90% CL.
The BaBar result on this difference is [9]: $$\frac{(\tau^+ - \tau^-)}{(\tau^+ + \tau^-)} = (0.12 \pm 0.32)\%,$$

V. LEPTON UNIVERSALITY AND BRANCHING FRACTIONS

Lepton branching fractions of the tau lepton are very important for the lepton universality check. The values provided by PDG [8], $B_{\mu\nu\nu} = 17.36 \pm 0.05\%$ and $B_{e\nu\nu} = 17.85 \pm 0.05\%$, already have high accuracy and improvement of the precision is a quite difficult task. However, the ratio of the branching fractions can be measured with better accuracy using the large statistics collected at the B-factories. Recently the BaBar collaboration measured several ratios [11] used 467 fb$^{-1}$ of the integrated luminosity:

$$\frac{B(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)} = (0.9796 \pm 0.0016 \pm 0.0036),$$

$$\frac{B(\tau^- \rightarrow \pi^- \bar{\nu}_\pi \nu_\tau)}{B(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)} = (0.5945 \pm 0.0014 \pm 0.0061),$$

$$\frac{B(\tau^- \rightarrow K^- \bar{\nu}_K \nu_\tau)}{B(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)} = (0.03882 \pm 0.00032 \pm 0.00057),$$

where the uncertainties are statistical and systematic, respectively.

The first measured ratio provides a check of muon/electron universality: $$(g_{\mu}/g_e) = 1.0036 \pm 0.0020$$ which does not contradict to SM and improves slightly the averaged PDG value. Two latter ratios can be used for $(g_\tau/g_\mu)$ check taking into account branching fractions $\pi \rightarrow \mu \nu_\mu$ and $K \rightarrow e \nu_e$. The BaBar presented the following combined result: $$(g_\tau/g_\mu) = 0.9850 \pm 0.0057$$ that is 2.8 standard deviation lower than SM prediction.

VI. PROJECT OF TAU MASS MEASUREMENT AT BEPC II

Few years ago the modified collider, BEPC-II with the new detector, BES-III, came to the operation at the IHEP in Beijing [12]. Main parameters of the collider are presented in the Table

| TABLE V: Main parameters of the BEPC collider |
|-----------------------------------------------|
| Beam energy | 1.0-2.3 GeV |
| Luminosity  | $10^{33}$ cm$^{-2}$s$^{-1}$ |
| Optimum energy | 1.89 GeV |
| Energy spread | $5.16 \times 10^{-4}$ |
| No. of bunches | 93 |
| Bunch length | 1.5 cm |
| Total current | 0.91 A |

One of the important studies planning at BES-III is tau lepton mass measurement with the accuracy better than 100 keV [13]. The beam energy measurement system based on the Compton backscattering of the laser photons by the beam has been created for this experiment. First test measurements were performed in the $J/\Psi$ energy range. The backscattered photon energy distribution at the end of the Compton spectrum is shown in the Fig. 5. The position of the Compton edge can be precisely determined.

The $J/\Psi$ curve measured using the energy measurement system is presented in Fig. 6. The obtained systematic uncertainty of the beam energy is
\[ \delta E/E \approx 2 \times 10^{-5}. \]

VII. RESULTS FROM LHC EXPERIMENTS

Recently started experiments at LHC have already collected large number of events with \( W \) bosons production. In general, a measurement of the leptonic decays of the \( W \) bosons provides a direct check of the lepton universality. This year the ATLAS collaboration presented the measurement of the \( W \) boson production cross section followed with the leptonic decay \[ W \to \tau \nu. \]

Obtained cross section value with the decay \( W \to \tau \nu \) is:

\[ \sigma_{W \to \tau \nu}^{\text{tot}} = (11.1 \pm 0.3(\text{stat}) \pm 1.7(\text{syst}) \pm 0.4(\text{lumi})) \text{ nb}, \]

where the first error is statistical, second is systematic and the third one is induced by the uncertainty of the luminosity determination. The CMS collaboration also observed such decays \[ 16 \] but the values are not released yet.

The results from ATLAS are presented in Fig. 7 taken from \[ 15 \]. As seen from the figure, accuracy of the measurements does not allow yet to improve the check of the lepton universality. However, we can hope on the improvement of the precision in future.

VIII. CONCLUSION

- In the last decade a lot of efforts were applied to measure tau mass with high accuracy. At present the most crucial parameters for the lepton universality check are branching fractions and tau lifetime.
- To improve accuracy in the \( (g_\tau/g_e) \) and \( (g_\tau/g_\mu) \) ratios, first of all, more precise measurements of the tau leptonic branching fractions are needed. Huge data samples of the tau decays \( (10^9 \) events) is available at B-factories. However, to make use from high statistics a decrease of the systematic uncertainties is necessary, which is a very difficult task.

- A considerable progress in the tau mass measurement is anticipated in near future from a new experiment prepared at the BEPC-II/BES-III. We can hope for the further progress in the measurements of the tau lepton parameters in the LHC experiments as well as future super B- and C-factories.

\footnotesize

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