Tau physics at Belle II

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Precise measurements of the τ lepton properties can serve as a unique probe of Standard Model (SM) as well as New Physics (NP) phenomena. The Belle II experiment at the SuperKEKB asymmetric energy collider provides a well-suited environment for τ lepton studies and high precision measurements. In this summary, the current status of Belle II experiment is overviewed and three ongoing τ physics analyses are presented.

1 Introduction

The τ lepton is a 3rd generation particle and with the mass of 1.777 GeV it is the heaviest known lepton of the SM. It is a highly unstable particle with lifetime of ~ 260 fs and thanks to its mass the τ lepton can decay via various channels into not only lighter leptons but also light hadrons such as π or K mesons. Measuring τ lepton properties and branching ratios (BRs) can possibly serve as physics probes of CPT (charge parity (C), spacial parity (P), and time reversal (T) symmetry) conservation, lepton universality or CKM unitarity.

Some NP scenarios predict enhanced τ lepton coupling to NP which makes τ leptons ideal for searching for NP phenomena such as lepton flavour and lepton number violation or new sources of CP violation.

The crucial step towards addressing these topic with τ leptons are high precision measurements of τ properties and B-factories such as Belle II provide a great environment for these measurements.

B-factories are electron-positron colliders with asymmetric beam energies. In this setup the collision products are boosted in the direction of the beam with higher energy and thus the created particles live longer. The collision energy of B-factories is close to the mass of the $\Upsilon(4S)$ resonance, where the production cross-section of a $B\bar{B}$ pair is 1.05 nb. At the same energy the production cross-section of a pair of τ leptons $\tau^+\tau^-$ is 0.92 nb so B-factories are τ-factories as well.

One of the most prominent experimental advantages of B-factories is a well-defined kinematics of the initial state, and with high vertex resolution, excellent calorimetry and sophisticated particle identification algorithms B-factories allow for accurate and efficient particle decays reconstructions.

Previous B-factory experiments collected large data samples. At the Belle experiment it was 711 fb^{-1} and the BaBar experiment collected 424 fb^{-1}.

Analysis of the B-factory data contributed with variety of interesting results in the last two decades. The wide physics program at B-factories includes precision SM measurements, measurements of CP asymmetry parameters and searches for rare particle decays which can possibly indicate NP processes.

1.1 Belle II experiment

Belle II is a nest-generation B-factory experiment at the SuperKEKB particle collider [1] located in Tsukuba, Japan. SuperKEKB collides 7.0 GeV electrons with 4.0 GeV positrons and compared to its predecessor KEKB it operates with higher beam currents and employs nano-beam focusing at the interaction point. Thanks to these improvements the design luminosity of SuperKEKB is $6 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$.

At this luminosity the detector needs to cope with increased background and higher trigger rates. The Belle II detector [2] is a major upgrade of the Belle [3] detector. Its trigger system has been improved to a great extent which allows for the selection of signals that were not possible to trigger at Belle. Belle II has also an excellent tracking efficiency and improved vertex resolution which enables for new measurement methods and approaches.

Belle II has been collecting data since 2018 and in the past year SuperKEKB managed to set new peak luminosity records, in particular 1.96 fb^{-1}/day, 12 fb^{-1}/week and 40 fb^{-1}/month [4]. This instantaneous luminosity rises above the levels reached at previous B-factories and also the Large Hadron Collider (LHC), with a product of beam currents 3.5 times lower than what was used at KEKB. The data taking milestones are to collect 500 fb^{-1} by summer 2022, $\mathcal{O}(10\ \text{ab}^{-1})$ by the upgrade of the IR at 2026, and 50 ab^{-1} by 2030 after further upgrade.

2 The τ Physics Studies

A great variety of physics topics is studied at Belle II, including τ lepton analyses. This review introduces the τ mass measurement, τ lifetime measurement and the study of Lepton Flavour Universality (LFU) with τ decays.

2.1 The τ Mass

Lepton masses are one of the fundamental parameters of the SM. With

$$\begin{aligned} m_e &= (0.5109989461 \pm 0.0000000031)\text{MeV} \ , \\ m_\mu &= (105.6583745 \pm 0.0000024)\text{MeV} \ , \\ m_\tau &= (1776.86 \pm 0.12)\text{MeV} \end{aligned}$$

it is clear that the τ mass is know with much smaller precision than the electron and muon masses, which impacts greatly for example LFU test.

The τ mass measurement at Belle II uses the pseudomass technique which was developed by the ARGUS collaboration [5]. The method uses $\tau \to 3\pi\nu$ decay channel, where the τ mass can be estimated using the masses and momenta of the the 3-pion system and the neutrino as

$$\begin{aligned} m_\tau^2 &= (P_h + P_\nu)^2 \\ &= 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p_h}|(E_\tau - E_h)\cos(\vec{p_h}, \vec{p_\nu}) \ . \end{aligned}$$

Since the direction of the neutrino is unknown, $\cos(\vec{p_h}, \vec{p_\nu}) = 1$ is taken and M_{min} is defined as

$$M_{min}^2 = 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p_h}|(E_\tau - E_h) < m_\tau^2 \ .$$

The M_{min} distribution is then fitted to an empirical edge function, and the position of the cutoff indicates the value of the τ mass. The main challenge of this measurement is to find the most accurate empirical function and to properly evaluate the estimator bias.

The goal of the Belle II measurement is to achieve the best precision among pseudomass measurements. The currently best measurement using pseudomass technique comes from by Belle [6] and the world-leading result by BES III [7] was achieved in a measurement in the production threshold.

The preliminary Belle II measurement from 2020 [8] is statistically dominated and is in agreement with the world average. The statistical precision of Belle/BaBar will be reached at Belle II with already 300 fb^{-1}. The systematic uncertainty is at the level of Belle, and significant reduction in the main systematic uncertainties and further improvements of reconstruction efficiency is expected in the ongoing Belle II analysis [9].

2.2 The τ Lifetime

The τ lifetime is another important SM parameter and its precision affects among other the LFU or $\alpha_s(m_\tau)$ measurements. The world-leading measurement was performed by Belle [10] where the 3x3 topology was used, with both tau leptons decaying to $3\pi\nu$. The measured lifetime is

$$\tau_\tau = (290.17 \pm 0.53(\mathrm{stat}) \pm 0.33(\mathrm{syst}))\ \mathrm{fs}.$$

The Belle II analysis introduces a new approach to the τ lifetime measurement [11]. In the first step the vertex for only one 3-prong τ decay is reconstructed which increases the statistics. In the next step the τ momentum is estimated assuming hadronic decays on both sides. The final and most challenging step consists of finding the production vertex as the intersection of the τ momentum with the Interaction Point (IP) y-plane. This is possible exclusively at Belle II thanks to the tiny beamspot size at the IP.

The Belle II τ lifetime measurement is currently done on simulation, yielding

$$\tau_\tau = 287.2 \pm 0.5(\mathrm{stat}))\ \mathrm{fs}.$$

The result shows that competitive statistical precision was reached already with 200 fb^{-1} compared to 711 fb^{-1} used at Belle. The simulation studies also showed that the resolution at Belle II is nearly two times narrower than at Belle.

The measured lifetime presents $\simeq$ 3 fs bias with respect to the generated value which was 290.57 fs. This is caused by the Initial State Radiation (ISR) and Final State Radiation (FSR) losses which lead to the underestimation of the proper time, and it is an intrinsic bias in the measurement.

Further studies to estimate systematics are ongoing to test dependence on the resolution function in the fit, on the beam-spot position, ISR/FSR simulation and on vertex detector alignment which was the dominant systematic uncertainty at Belle.

2.3 Lepton Flavour Universality

In the SM, the three lepton generations — e, μ, τ — differ by masses and separately conserved lepton numbers, but the coupling of leptons to W bosons is flavour-independent, $g_e = g_\mu = g_\tau$. This is the SM picture of leptons, however various experimental results presented in the past years potentially hint at LFU violation. The most prominent hints have been observed in the quark sector anomalies, for example the anomaly in $R(D) - R(D^*)$ plane [12] (3.1σ), $R(K)$ [13] (3.1σ) or P_5' in $B \to K^*\mu^+\mu^-$ [14] (3.4σ). Significant tensions have been measured also in the lepton sector, in particular in the anomalous magnetic moment of μ (4.5σ) and e (2.5σ).

LFU can be tested also with τ decays. The $e - \mu$ universality can be probed by measuring the ratio of leptonic τ decays,

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto \frac{BR(\tau^- \to \mu^-\bar{\nu_\mu}\nu_\tau)}{BR(\tau^- \to e^-\bar{\nu_e}\nu_\tau)}\ ,$$

and the $\tau - \mu$ universality can be tested in ratio

$$\left(\frac{g_\tau}{g_\mu}\right)_h^2 \propto \frac{BR(\tau \to h\nu_\tau)}{BR(h \to \mu\nu_\tau)} .$$

The most precise measurements were delivered by BaBar [15],

$$\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$$

is in agreement with the SM,

$$\left(\frac{g_\tau}{g_\mu}\right)_h = 0.9850 \pm 0.0054$$

shows a 2.8 σ tension with respect to the SM prediction.

The analysis at Belle II aims to use both 3x1-prong and 1x1-prong τ-pair events [17]. The selection of 3x1-prong events at Belle II has four times higher efficiency and with better purity compared to the BaBar measurement. The 1x1-prong event were not used at BaBar but are possible to select at Belle II thanks to the trigger performance. The performance of the 1x1-prong event selection at Belle II is better in the $e - \mu$ channel and very close for the $\mu - \mu$ channel compared to an analysis done by CLEO [16].

One of the main challenges of this analysis is the selection of the signal events with the highest possible purity. To achieve the best results multivariate analysis techniques such as neural networks and Boosted Decision Trees (BDTs) are employed in the signal selection, and different Lepton Identification (LID) approaches using BDT- and likelihood-based algorithms are being tested. Another great challenge will be to reduce the LID systematic uncertainty which was the main systematics source at BaBar.

3 Summary

This review introduced briefly the B-factory particle experiments and highlighted their suitability for τ lepton precision measurements. The Belle II experiment at SuperKEKB collider is a B-factory of the next generation, in 2021 SuperKEKB has set a new record in peak luminosity at $L_{\text{peak}} = 3.81 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and by summer Belle II is expected to collect data of the order of the BaBar data set.

Several τ lepton measurements are ongoing at at Belle II. The τ mass studies with the early data using the pseudomass technique are expected to improve the measurement from 2020. The lifetime measurements exploit the potential of the nano-beam scheme and upgraded vertex detection system. Probing of the LFU with τ decays using 3x1 and 1x1 τ-pair events aims for the world-leading measurement of $\left(\frac{g_\mu}{g_e}\right)_\tau$ and $\left(\frac{g_\tau}{g_\mu}\right)_h$. Apart from the τ mass, τ lifetime and LFU tests there are also ongoing studies on the V_{us} determination, τ electric and magnetic dipole moments measurement and searches for lepton flavour and number violating τ lepton decays. All these studies are expected to yield exciting results and thus present Belle II as the major player in the τ physics in the near future.

References

[1] K. Akai *et al.* (SuperKEKB), *SuperKEKB Collider*, Nucl. Instrum. Meth. A907 (2018) 188–199.

[2] T. Abe *et al.* (Belle II Collaboration), *Belle II Technical Design Report*, arXiv:1011.0352.

[3] A. Abashian *et al.* (Belle Collaboraion), *The Belle Detector*, Nucl. Instrum. Meth. A479 (2002) 117–232.

[4] CERN Courier, *SuperKEKB raises the bar*, article.

[5] H. Albrecht *et al.* (ARGUS Collaboration), *A measurement of the tau mass*, Phys. Lett. B 292,. (1992), 221.

[6] K. Belous, M. Shapkin, A. Sokolov *et al.* (Belle Collaboration), *Measurement of the τ lepton mass and an upper limit on the mass difference between τ^+ and τ^-*, arXiv:hep-ex/0608046.

[7] M. Ablikim *et al.* (BESIII Collaboration), *Precision measurement of the mass of the τ lepton*, Phys. Rev. D 90, 012001 (2014).

[8] F. Abudinén *et al.* (Belle II Collaboration), *τ lepton mass measurement at Belle II*, arXiv:2008.04665.

[9] Navid K. Rad, *Tau lepton mass measurement at Belle II*, TAU2021 conference poster.

[10] K. Belous, M. Shapkin, A. Sokolov *et al.* (Belle Collaboration), *Measurement of the τ-lepton lifetime at Belle*, arXiv:1310.8503.

[11] Stefano Moneta, *τ-lepton lifetime measurement at Belle II*, TAU2021 conference poster.

[12] G. Caria *et al.* (Belle Collaboration), *Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a Semileptonic Tagging Method*, Phys. Rev. Lett. 124 (2020) 16, 161803.

[13] R. Aaij *et al.* (LHCb Collaboration), *Test of lepton universality in beauty-quark decays*, arXiv:2103.11769.

[14] R. Aaij *et al.* (LHCb Collaboration), *Angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity*, arXiv:1512.04442.

[15] B. Aubert *et al.* (BaBar Collaboration), *Measurements of Charged Current Lepton Universality and $|V_{us}|$ using Tau Lepton Decays to $e^-\bar{\nu}_e\nu_\tau, \mu^-\bar{\nu}_\mu\nu_\tau, \pi^-\nu_\tau$, and $K^-\nu_\tau$*, arXiv:0912.0242.

[16] A. Anastassov *et al.* (CLEO Collaboration), *Experimental tests of lepton universality in τ decay*, Phys. Rev. D 55, 2559 (1997); Erratum Phys. Rev. D 58, 119903 (1998).

[17] F. Abudinén *et al.* (Belle II Collaboration), *Search for lepton flavor universality violation in leptonic τ decays with 1x1 and 3x1 topologies*, note.