SciPost Phys. Proc. 16, 015 (2025)

Status and prospects for τ property measurements at Belle II

Michel Hernández Villanueva, on behalf of the Belle II collaboration

Deutsches Elektronen-Synchrotron (DESY)

michel.hernandez.villanueva@desy.de

16th International Workshop on Tau Lepton Physics (TAU2021)
Online, September 27 - October 1, 2021
doi:10.21468/SciPostPhysProc.16

Abstract

Belle II is a major upgrade of the Belle detector, operating at the SuperKEKB asymmetric-energy e^+e^- collider with a design luminosity of 8×10^{35} cm^{-2}s^{-1}. To date, the detector has recorded over 200 fb^{-1} of data and aims to collect 50 ab^{-1}, a factor of 50 more than its predecessor. Belle II has a broad τ physics program, from high-precision measurements of Standard Model parameters to searches of new non-Standard-Model interactions. In this work, we review the status of the Belle II experiment and the prospects for the measurement of the τ lepton mass and lifetime, which are fundamental inputs in tests of LFU violation.

Received 2021-12-10
Accepted 2024-12-23
Published 2025-07-14
Check for updates
doi:10.21468/SciPostPhysProc.16.015

1 Introduction

The Belle II experiment is a detector installed on the asymmetric electron-positron collider SuperKEKB, located at the KEK laboratory in Tsukuba, Japan. Working at the center-of-mass energy of 10.58 GeV, SuperKEKB is designed to reach an instantaneous luminosity of 8×10^{35} cm^{-2}s^{-1}. Belle II is an upgrade of its predecessor Belle, with major modifications in each of the subsystems aiming to reconstruct collision products in a high-luminosity environment and collect 50 ab^{-1} by the end of the operation. A complete description of the Belle II detector can be found in Ref [1]. In 2021, SuperKEKB has set a new world record reaching a peak luminosity of $L_{\text{peak}} = 3.1\times10^{34}$ cm^{-2} s^{-1}. To date, 213 fb^{-1} of collision data have been recorded by Belle II.

At SuperKEKB collision energy, the cross-section of the process $e^+e^- \to \tau^+\tau^-$ (0.92 nb) is similar to the cross-section for the production of B-meson pairs (1.10 nb). The well-defined initial-state kinematics, along with low backgrounds and large signal yields, enable a world-leading τ physics program in the next decade [2], with 45 billions of τ lepton pairs expected in the data set recorded by the end of the operations.

One important step for precision measurements and searches of non-Standard Model physics is the measurement of the τ lepton properties with the highest precision, since the uncertainty in quantities such as the mass or the lifetime has important consequences in searches like lepton flavor universality violation induced by non-Standard Model interactions.

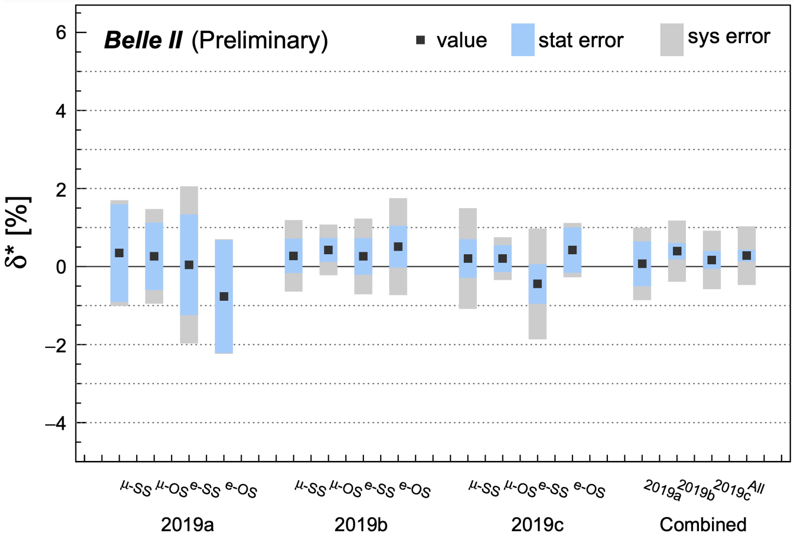

Figure 1: Overall data vs MC discrepancy for tracking efficency, shown for individual τ pairs with one of them decaying into an electron or a muon, and with the two tagging tracks in the 3-prong side of same-sign (SS) or opposite-sign (OS), as well as for different data taking periods [4]. Statistical and systematic uncertainties are shown in grey and blue, respectively.

2 Performance studies with τ leptons

The production of τ lepton pairs in Belle II is not only useful for the understanding of the physics involved in the decays but also a powerful tool for detector-performance studies. Unique features of τ leptons allow the study of the efficiency in the charged-particle reconstruction and their identification.

2.1 Tracking efficiency

The tracking efficiency is determined using unbiased tracks following Ref [3], using $e^+e^- \to \tau^+\tau^-$ events where one of the τ leptons decay leptonically into either an electron or a muon, while the other τ lepton decays as $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu_\tau + \geq 0\pi^0$. Such τ decays are labeled as 1-prong and 3-prong respectively, depending on the number of the charged tracks in the channel. Three good quality tracks with total charge ± 1 are used to tag events, while the presence of a probe track ensured charge conservation.

Precision analyses require to measure the tracking efficiency in data to assign a systematic uncertainty due to mismodeling in the Monte Carlo simulation (MC). The data-MC discrepancy is defined as

$$\delta^* = 1 - \frac{\epsilon_{\text{data}}}{\epsilon_{\text{MC}}}, \tag{1}$$

where ϵ_{data} and ϵ_{MC} are the tracking efficiencies measured in data and simulation. Figure 1 shows the overall discrepancy between data and MC, as a function of channel and data-taking time, as well as the combined result, yielding

$$\delta^*_{\text{overall}} = 0.13 \pm 0.16(\text{stat}) \pm 0.89(\text{syst})\%\,. \tag{2}$$

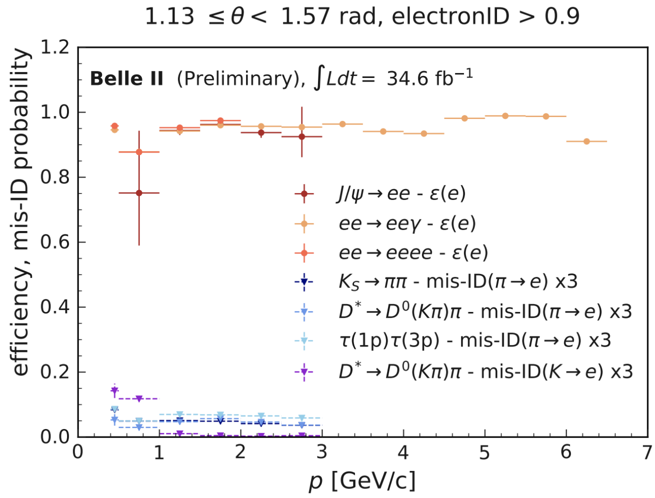

Figure 2: Electron identification efficiency and misidentification probability as a function of momentum for electron candidates restricted in a polar range of 1.13 – 1.57 rad, and with electron-identification-variable greater than 0.9 [5]. The mis-identification rates have been inflated by a factor of 3 for illustration. $\pi \to e$ mis-identification obtained from τ lepton decays is shown in cyan.

2.2 Particle identification performance

With a similar approach to that of section 2.1, unbiased tracks from τ pair events are used, selecting pions from one of the τ leptons decaying to a 3-prong channel $\tau^\pm \to h^\pm h^\mp h^\pm \nu_\tau$. Tagging two same-charged tracks as pions provides a pure sample of pions in the remaining opposite-charge track, since the modes with kaons that would pass the tag selection, such as $\tau^- \to \pi^- K^+ \pi^- \nu_\tau$, are highly suppressed.

The unbiased track is used to calculate particle identification (ID) efficiency for pions and $\pi^\pm \to \ell^\pm$ misidentification rates, as functions of momentum and polar angle. Figure 2 shows the example of a bin for electron ID, where the $\pi \to e$ misidentification obtained from τ lepton decays is compared with other methods.

3 Measurements of τ lepton properties

3.1 τ lepton mass

Lepton masses are fundamental parameters of the Standard Model. While the mass of the electron and the muon are known with very high precision, the short lifetime of the τ lepton complicates the measurement of its mass, m_τ. The two methods available for the determination of m_τ are the scan of the production threshold, used by the BESIII collaboration to provide the most precise measurement of m_τ [6], and the pseudomass method developed originally by the ARGUS collaboration [7], with recent updates by Belle and BaBar [8,9].

Belle II has performed a preliminary measurement of the τ lepton mass with the data recorded during 2019 – 2020, corresponding to an integrated luminosity of 8.8 fb^{-1}. Using $e^+e^- \to \tau^+\tau^-$ events at the center-of-mass energy of 10.58 GeV, with one of the τ leptons decaying in a 3-prong mode $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu_\tau$, and the other in a 1-prong channel $\tau^\pm \to \ell^\pm \bar{\nu}_\ell \nu_\tau$ or $\tau^\pm \to \pi^\pm \nu_\tau$. Since in Belle II the collisions happen far from the production threshold, the pseudomass technique is used to measure the mass of the τ lepton. To construct the pseudomass, the kinematic properties of a semileptonic decay $\tau^{\pm} \to h^{\pm} + \nu_{\tau}$ are used,

$$m_{\tau}^2 = (p_h + p_{\nu})^2 = 2E_h(E_{\tau} - E_h) + m_h^2 - 2|\vec{p}_h|(E_{\tau} - E_h)\ \cos(\vec{p}_h, \vec{p}_{\nu})\,, \tag{3}$$

where E_i, p_i and m_i are the energy, four-momentum and invariant mass for the i-particle, h is the hadronic system coming from the τ lepton, and $m_{\nu} = 0$ is assumed. As the neutrinos in the event escape from detection and $\vec{p}_{\nu}$ is not known, the approximation $\cos(\vec{p}_{\nu}, \vec{p}_h) = 1$ is taken, resulting in

$$M_{\text{min}}^2 = 2E_h(E_{\tau} - E_h) + m_h^2 - 2|\vec{p}_h|(E_{\tau} - E_h)\ < m_{\tau}^2\,, \tag{4}$$

with M_{min} being called the pseudomass. The position of the cutoff in M_{min} estimates the value of the mass, while the distribution is smeared by the resolution in the detectors and initial-state radiation / final-state radiation effects.

Figure 3 shows the distribution of M_{min} for the τ decaying to the 3-prong mode in both data and MC, and a magnification into the region of interest $1.7 < M_{\text{min}} < 1.85$ GeV/c^2 where the cutoff is observed. An empirical probability density function (p.d.f.) is built to determine the mass of the τ lepton,

$$F(M_{\text{min}}, \vec{P}) = (P_3 + P_4 \cdot M_{\text{min}}) \cdot \tan^{-1}[(M_{\text{min}} - P_1)/P_2] + P_5 M_{\text{min}} + 1\,, \tag{5}$$

where P_1 is an estimator of m_{τ}. Figure 4 shows the result of a maximum likelihood fit performed with (5), yielding after correction factors $m_{\tau} = 1777.28 \pm 0.75(\text{stat})$ MeV/c^2.

Main sources of systematic uncertanties are the momentum shift due to imperfections on the magnetic field map (0.29 MeV/c^2), the determination of the bias in the estimator P_1 (0.12 MeV/c^2), the choice of the p.d.f. versus alternative functions (0.08 MeV/c^2), the choice of the fit window (0.04 MeV/c^2) and the energy beam determination from the beam-energy-constrained mass of fully reconstructed neutral and charged B decays (0.03 MeV/c^2) [10]. Therefore, the mass of the τ lepton measured is

$$m_{\tau} = 1777.28 \pm 0.75(\text{stat}) \pm 0.33(\text{syst})\ \text{MeV}/c^2\,. \tag{6}$$

The systematic uncertainty of m_{τ} in the Belle II measurement is compatible with the systematic uncertainty reported by Belle [8]. The analysis is being updated to use the most recent data, where an improved understanding of the detector could reduce the current systematic uncertainty.

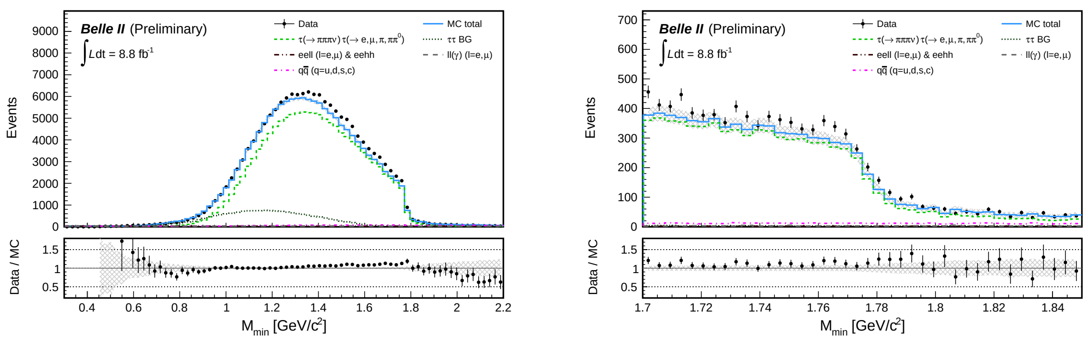

Figure 3: Distribution of the pseudomass for the $\tau^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau}$ mode in both data and MC, and the magnification into the region of interest 1.7 to 1.85 GeV/c^2 where the cutoff is observed [10].

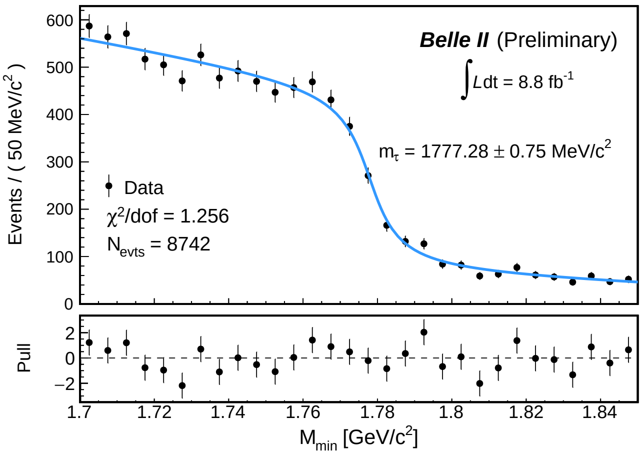

Figure 4: Distribution of the pseudomass for the $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu_\tau$ mode in the region of interest 1.7 to 1.85 GeV/c^2 [10]. The blue solid line represents the p.d.f. described in the text, with parameters determined by a maximum likelihood fit.

3.2 τ lepton lifetime

Since the τ lepton discovery, a large variety of methods have been applied to determine its lifetime. The most precise measurement has been provided by the Belle collaboration [11] with $\tau^+\tau^-$ events where both τ-leptons decay to three charged pions and a neutrino. The technique proposed at Belle II exploits the small beam spot size at the interaction region, obtained through the nano-beam scheme of SuperKEKB, where the vertical size of the beam is $\sigma_y < 1\mu$m and the primary vertex position $\vec{\text{IP}}$ on the transverse plane is treated as known. The advantage with respect to the method used by Belle is that only one of the pair-produced τ leptons is required to decay to three charged particles, while the other can be reconstructed in a 1-prong final state exploiting the larger branching fraction.

In the center-of-mass frame, the momentum $\vec{p}_\tau^{\,CM}$ of a τ lepton produced from a e^+e^- collision can be determined by the intersection of two cones when both leptons decay semileptonically, up to a two-fold ambiguity. Using the average of the two possible solutions for $\vec{p}_\tau^{\,CM}$, the lifetime of the τ lepton is determined from the distribution of the proper time t, obtained from the reconstructed decay length ℓ_τ and the estimated $\vec{p}_\tau^{\,CM}$ boosted to the laboratory frame,

$$t = \ell_\tau \frac{m_\tau}{|\vec{p}_\tau| c} \,. \tag{7}$$

The decay length ℓ_τ is obtained from the relation

$$\vec{\text{IP}} + \ell_\tau \hat{n}_\tau - \vec{v} = 0 \,, \tag{8}$$

where IP_y is fixed, and $\hat{n}_\tau = \vec{p}_\tau/|\vec{p}_\tau|$ is the direction of the τ lepton in the laboratory frame. The decay vertex position $\vec{v}$ of a 3-prong τ decay is determined by the intersection of the tracks coming from the τ.

A sensitivity study for the determination of the τ lifetime has been performed in Belle II, with a simulated data set corresponding to 200 fb^{-1} at the $\Upsilon(4S)$ collision energy. τ pair events are selected with one decaying in a 3-prong mode $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu_\tau$, and the other to a 1-prong mode $\tau^\pm \to (\rho^\pm \to \pi^\pm\pi^0)\nu_\tau$. Figure 5 shows the distribution of the reconstructed proper time in MC events. The resulting lifetime from the fit is $\tau_\tau = 287.2 \pm 0.5(\text{stat.})$ fs. Using an integrated luminosity 3.5 lower, the statistical uncertainty is compatible with the most precise measurement performed by Belle. However, the central value is 3.0 fs lower than

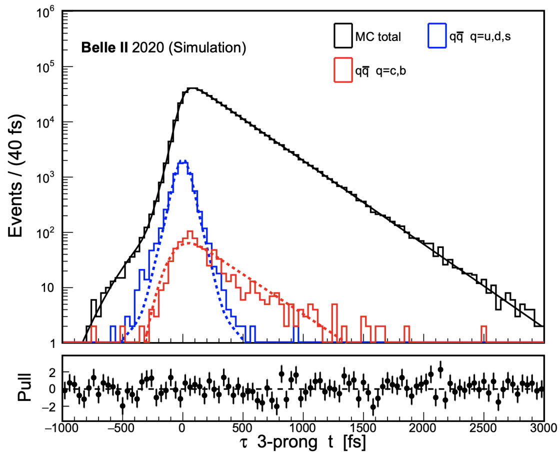

Figure 5: Distribution of reconstructed proper time for simulated τ decays into 3-prong modes with fit projection overlaid. Background contribution from $q\bar{q}, q = u, d, s$ events is substracted with a fit to a linear combination of three Gaussians, while $q\bar{q}, q = c, b$ is fitted with a convolution of a Gaussian and an exponential function.

the lifetime set in the generator (290.2 fs). The bias is explained by an overestimation of $|\vec{p}_\tau|$ coming from initial-state and final-state radiation losses, resulting in an underestimation of the proper time. Evaluation of systematic uncertainties is in progress.

4 Conclusion

Precision measurements of fundamental τ lepton parameters are an important part of the world-leading Belle II physics program towards the searches of non-standard-model physics. τ lepton mass studies performed with the early data show a good performance of the detector, with perspectives to reduced systematic uncertainties in the update for the measurement of m_τ using the pseudomass technique. The lifetime measurements at Belle II show the potential of the nano-beam scheme with an upgraded vertex detection system. First studies are promising, with an update in the measurement feasible in the coming months.

References

[1] T. Abe et al., *Belle II technical design report*, (arXiv preprint) doi:10.48550/arXiv.1011.0352.

[2] E. Kou et al., *The Belle II physics book*, Prog. Theor. Exp. Phys. 123C01 (2019), doi:10.1093/ptep/ptz106.

[3] T. Allmendinger et al., *Track finding efficiency in BaBar*, Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip. **704**, 44 (2013), doi:10.1016/j.nima.2012.11.184.

[4] Belle II collaboration: F. Abudinén et al., *Measurement of the tracking efficiency and fake rate with $e^+e^- \to \tau^+\tau^-$ events*, BELLE2-NOTE-PL-2020-014, Tsukuba, Japan (2020).

[5] Belle II collaboration: F. Abudinén et al., *Muon and electron identification efficiencies and hadron-lepton mis-identification probabilities*, BELLE2-NOTE-PL-2020-027, Tsukuba, Japan (2020).

[6] M. Ablikim et al., *Precision measurement of the mass of the τ lepton*, Phys. Rev. D **90**, 012001 (2014), doi:10.1103/PhysRevD.90.012001.

[7] H. Albrecht et al., *A measurement of the tau mass*, Phys. Lett. B **292**, 221 (1992), doi:10.1016/0370-2693(92)90634-G.

[8] K. Belous et al., *Measurement of the τ lepton mass and an upper limit on the mass difference between τ^+ and τ^-*, Phys. Rev. Lett. **99**, 011801 (2007), doi:10.1103/PhysRevLett.99.011801.

[9] B. Aubert et al., *Measurements of the τ mass and the mass difference of the τ^+ and τ^- at BABAR*, Phys. Rev. D **80**, 092005 (2009), doi:10.1103/PhysRevD.80.092005.

[10] Belle II collaboration: F. Abudinén et al., *τ lepton mass measurement at Belle II*, (arXiv preprint) doi:10.48550/arXiv.2008.04665.

[11] Belle II collaboration: F. Abudinén et al., *Measurement of the τ-lepton lifetime at Belle*, Phys. Rev. Lett. **112**, 031801 (2014), doi:10.1103/PhysRevLett.112.031801.