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Status and prospects for τ property measurements at Belle II

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Abstract

The Belle II experiment is a major upgrade of the Belle detector, operating at the SuperKEKB energy-asymmetric 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 x50 more than its predecessor. Belle II has a broad τ physics program, from high-precision measurements of SM parameters to searches of new physics via experimental probe of BSM processes. 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, fundamental inputs in tests of LFU violation.

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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 $3.1x10^{34}$ $cm^{-2}s^{-1}$. Belle II represents 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 $L_{peak} = 3.1x10^{34}$ cm^{-2} s^{-1}. To date, 213 fb^{-1} of collision data have been recorded by Belle II.

At the energy operation of Belle II, 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 kinematics in the events with a low-background environment, added to the enormous amount of collisons recorded by Belle II, enables a world-leading τ physics program in the next decade [2], with 45 billons 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 beyond Standard Model interactions.

2 Performance studies with τ leptons

The production of τ pair leptons in Belle II is not only useful for the understanding of the physics involved in the decays but also a powerful tool for performance studies. Unique features of τ lepton allow the study of the efficiency in the detection of tracks, as well as testing the charged-particle identification performances.

2.1 Tracking efficiency

The tracking efficiency is determined with a tag-and-probe method 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 $\tau^\pm \to \pi^\pm\pi^\pm\pi^\pm\nu_\tau + \geq 0\pi^0$. Such τ decays are labeled as 1-prong and 3-prong respectively, depending on the number of the detectable charged particles in the channel. Three good quality tracks with total charge ±1 are used to tag events, with the existence of a probe track ensured by charge conservation.

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

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

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, subdivided by channel and by run period, as well as the combined result, yielding

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

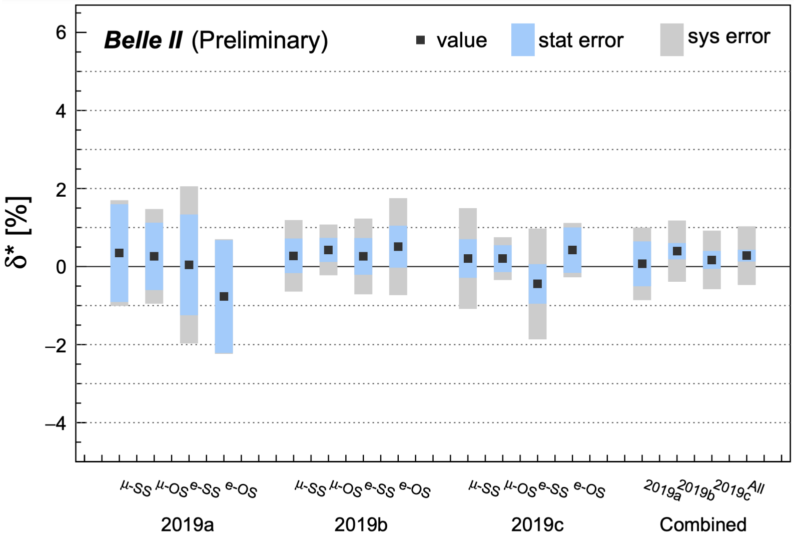

Figure 1: Overall data vs MC discrepancy for tracking efficency, shown for individual τ pairs with one of them decaying into an electron or a muon, and with the two tagging tracks in the 3-prong side of same-sign (SS) or opossite-sign (OS), as well as for different data taking periods [4]. Statistical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

2.2 Particle identification performance

Using a similar approach to that of section 2.1, a tag-and -probe method is used with τ pair events, selecting pions from one of the τ leptons decaying to a 3-prong channel $\tau^{\pm} \to h^{\pm}h^{\pm}h^{\pm}\nu_{\tau}$. Tagging two same-charged tracks as pions provide a pure sample of pions in the remaining opposite-charged track, since the mode with kaons that would pass the tag selection, such as $\tau^{-} \to \pi^{-}K^{+}\pi^{-}\nu_{\tau}$, are highly suppressed.

The probing track is used to calculate particle identification (ID) efficiency for pions and $\pi^{\pm} \to \ell^{\pm}$ mis-identification rates, in bins of momentum and polar angle. Figure 2 shows the example of a bin for electron ID, where the $\pi \to e$ mis-identification 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. 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 performing the measurement of m_{τ} at the center-of-mass energy of the $\Upsilon(4S)$ resonance [8, 9].

Belle II has performed a 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 $\tau^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_{\tau}$, 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

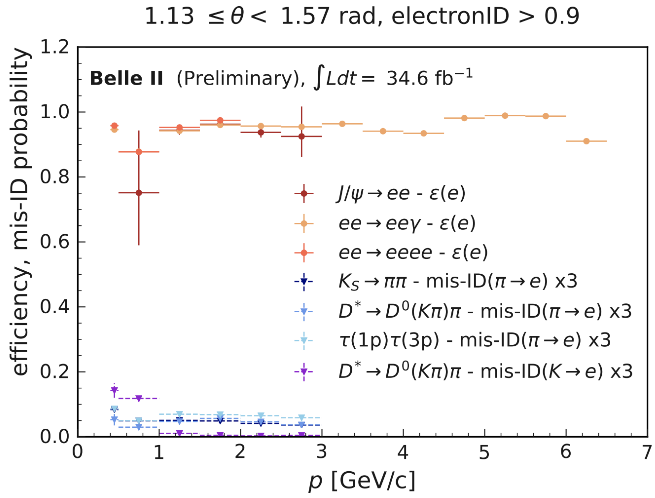

Figure 2: Example of a bin of the polar angle θ for electron ID with efficiencies and hadron-lepton mis-identification rates from all measurements [5]. The mis-identification rates have been inflated by a factor of 3 for illustration. $\pi \to e$ mis-identification obtained from τ lepton decays is shown in cyan.

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, 4-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 (ISR) / final-state radiation (FSR) 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). Details about the estimation for each source can be found in [10]. Therefore, the mass of the τ lepton measured is

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

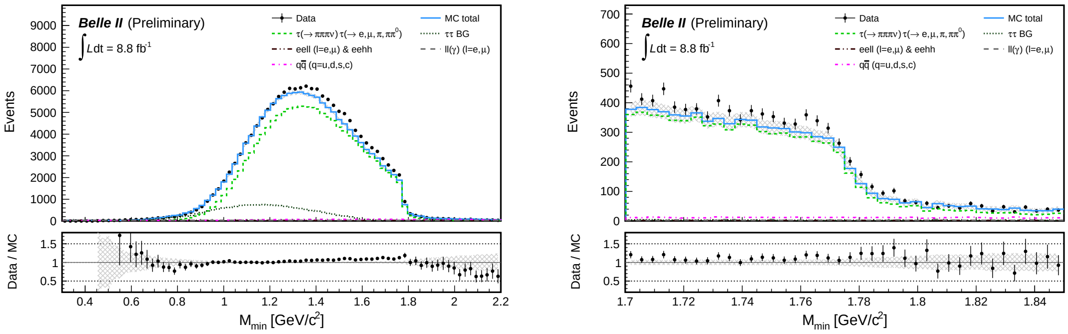

Figure 3: Distribution of the pseudomass for the $\tau^\pm \to \pi^\pm\pi^\pm\pi^\pm\nu_\tau$ mode in both data and MC, and the magnification into the region of interest 1.7 to 1.85 GeV/c^2 where the cutoff is observed [10].

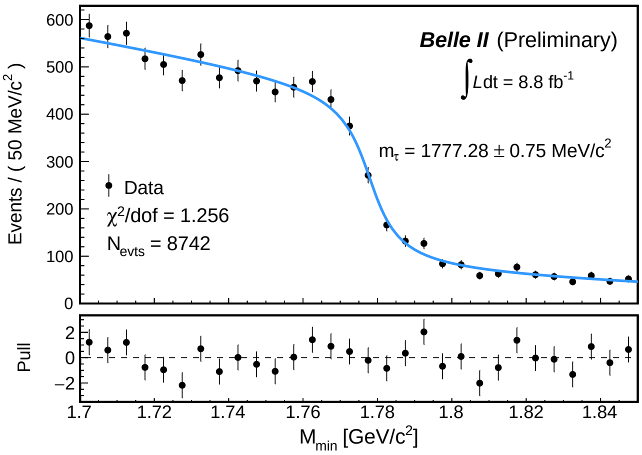

Figure 4: Distribution of the pseudomass for the $\tau^\pm \to \pi^\pm\pi^\pm\pi^\pm\nu_\tau$ mode in the region of interest 1.7 to 1.85 GeV/c^2 [10]. The blue solid line represents the p.d.f. described in the text, with parameters determined by a maximum likelihood fit.

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 collected, where an improved understanding of the detector could reduce the current systematic uncertainty.

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 leptons in the τ pair produced from the collision requires to decay to three charged particles, while the other can be reconstructed via 1-prong channels with highest branching ratios.

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

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

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 $\tau^\pm \to \pi^\pm\pi^\pm\pi^\pm\nu_\tau$, 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 extracted 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.

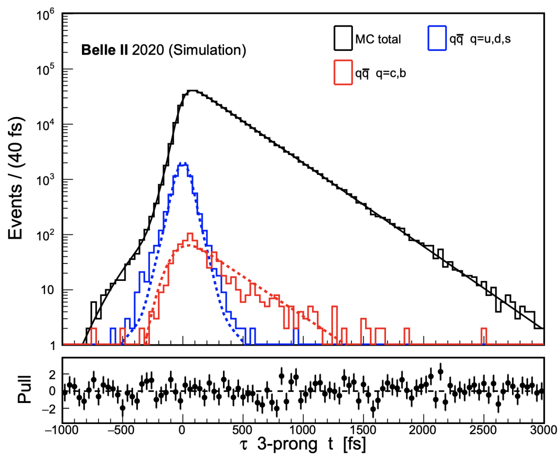

Figure 5: Fit on the distribution of the reconstructed proper time for events with a 3-prong τ lepton selection. Background contribution from $q\bar{q}, q = u, d, s$ events is substracted with a fit to a linear combination of three Gaussians, while $q\bar{q}, q = c, b$ is fitted with a convolution of a Gaussian and an exponential function.

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 peformance 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.

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