PROCEEDINGS OF SCIENCE

First Results and Prospects for τ Lepton Physics at Belle II

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Belle II has a comprehensive τ physics program, particularly in precision measurements of τ lepton properties and in searches for lepton flavour and lepton number violations. Belle II profits from the relatively large τ-pair production rate in the low background environment of e^+e^- -collisions at 10.58 GeV. Up to mid-2021, Belle II collected a sample corresponding to 214 fb^{-1} of data. We present a first measurement of the τ mass, prospects for the τ-lifetime measurement, and we review the overall τ lepton physics program of Belle II.

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1. Introduction

SuperKEKB [1] is an energy-asymmetric e^+e^--collider located in Tsukuba, Japan. It operates at the $\Upsilon(4S)$ resonance, corresponding to a centre-of-mass energy of 10.58 GeV. It uses the nano-beam scheme [1] to reach an expected instantaneous luminosity of about 6×10^{35} cm^{2}s^{-1}. Although SuperKEKB is optimised for B-meson physics, it also provides an ideal environment for τ-lepton physics. The cross-section for τ-pair production is almost as high as the cross-section for B-meson production. SuperKEKB is expected to deliver an integrated luminosity of 50 ab^{-1}, corresponding to forty-five billion τ-pair events. It offers a low background environment and a well-known initial state that constrains the τ kinematic properties.

The Belle II detector surrounds the interaction point of SuperKEKB [1]. It has the same general layout as its predecessor Belle, but with upgraded sub-detectors. Belle II can cope with higher occupancies and data rates and with the increased beam background rate due to the higher instantaneous luminosity of SuperKEKB compared to its predecessor KEKB. In the following, we discuss the expected increase in precision in τ-property measurements and the potential to probe the mass scale, or coupling strength, for beyond the Standard Model physics. The quality of early Belle II data is illustrated by a first preliminary measurement of the τ-mass.

2. Measurements of τ Properties

The precise measurement of τ-properties is important for Standard Model predictions and beyond-the-Standard-Model physics searches. Belle II has the potential to constrain Standard Model deviations further, and for the first non-zero measurement of the anomalous magnetic moment, $a_\tau = (g-2)/2$.

2.1 τ-Mass Measurement

Belle II follows the approach of ARGUS [2] to measure the τ mass, m_τ. Here, the pseudomass of the decay channel $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ is used

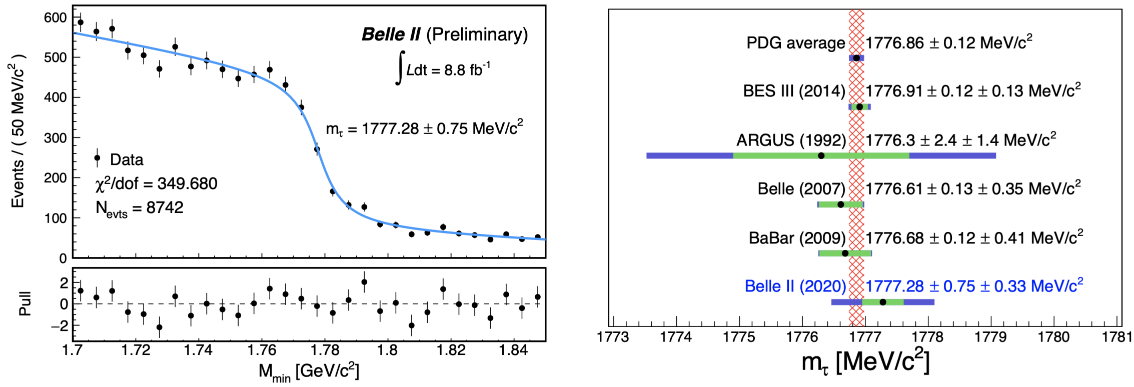
$$M_{\min} = \sqrt{m_{3\pi}^2 + 2(\frac{\sqrt{s}}{2} - E_{3\pi})(E_{3\pi} - p_{3\pi})}, \quad (1)$$

where $m_{3\pi}$ is the mass of the 3π-system, $\sqrt{s}$ is the centre of mass energy, $E_{3\pi}$ is the energy of the 3π-system, and $p_{3\pi}$ is the four-momentum of the 3π-system. The speed of light in a vacuum is set to one in natural units for all equations. The measured τ mass,

$$m_\tau = (1777.28 \pm 0.75 \pm 0.33)\,\mathrm{MeV/c^2},$$

is given by the endpoint of the distribution, which is determined by fitting Belle II data corresponding to 8.8 fb^{-1} using an empiric fit function, such as a modified arctangent shown in Figure 1a.

The result is consistent with the average value reported by the Particle Data Group [3] and has a similar systematic uncertainty as the measurements by Belle and BaBar. Belle II is expected to reduce the systematic uncertainties further, thanks to an improved understanding of the detector performance. The precision is expected to surpass that of the B-factories with the currently available data set of more than 200 fb^{-1}.



(a) **(b)**

Figure 1: τ-mass measurement of Belle II using the pseudo mass technique from ARGUS. The left figure shows the pseudo mass distribution of Belle II data, corresponding to 8.8 fb^{-1}, with fit projection overlaid [3]. The right figure compares τ-mass measurements. Green indicates systematic uncertainties, blue is the total uncertainty of the measurement.

2.2 τ-Lifetime Measurement

The τ lifetime is determined from the decay time, $t_\tau = m_\tau \frac{\ell_\tau}{p_\tau}$, which is calculated from the observed decay length ℓ_τ, corresponding to the distance between the nominal interaction point and 3-prong decay vertex, and the τ momentum, approximated by $p_\tau = \sqrt{\left(\frac{\sqrt{s}}{2}\right)^2 - m_\tau^2}$, neglecting initial state and final state radiation. Thanks to the small beam spot size and excellent vertex resolution, Belle II can include the abundant 3x1 prong decay topology in the measurement.

The currently most precise τ lifetime measurement was obtained by Belle, with an integrated luminosity of 711 fb^{-1}, $\tau_\tau = 290.17 \pm 0.53 \pm 0.33$ fs. Thanks to the improvements of Belle II, statistical competitive results are expected with the currently available data set of more than 200 fb^{-1}, already.

2.3 Further Standard Model Measurements

In addition to the mass and lifetime, Belle II currently works on measurements of two notable quantities of the τ, the electric dipole moment, d_τ, and the anomalous magnetic moment, $a_\tau = (g-2)/2$. The recent muon $g-2$ result [4] increased interest in these parameters. The most precise measurement for d_τ, to date, was published by Belle with about 30 fb^{-1} of data [5]. An update, using 833 fb^{-1}, was recently submitted for publication [6]. This improves the result to $-1.85 \times 10^{-17} < \Re(d_\tau) < 0.61 \times 10^{-17}$ and $-1.03 \times 10^{-17} < \Im(d_\tau) < 0.23 \times 10^{-17}$.

To date, the most precise measurement was performed with the process $e^+e^- \to e^+e^-\tau^+\tau^-$ by the DELPHI collaboration, $a_\tau = 0.018 \pm 0.017$ [7]. The result is one order of magnitude larger than the Standard Model prediction of $\frac{g-2}{2} \equiv a_\tau^{\text{SM}} = (1.17721 \pm 0.00005) \times 10^{-3}$ [8]. In the long-term, the complete Belle II data set may enable reaching the precision necessary to probe the Standard Model prediction [9].

3. Lepton Flavour Violation

In recent years, lepton-universality violation and lepton-flavour violation gained more and more interest. The Standard Model predicts only highly suppressed lepton flavour violating processes if neutrino oscillations are induced [9]. Belle II is expected to improve the sensitivity for all lepton flavour violating processes in the τ sector by one order of magnitude or more with the complete Belle II data set.

3.1 Early Results for $\tau \to \mu\mu\mu$

The search for the lepton-flavour-violating process $\tau \to \mu\mu\mu$ has a highly suppressed background because a misidentification of three muons is very unlikely. We expect a peak in the two-dimensional distribution at zero for the missing energy of the τ, $\Delta E_\tau = E_{\mu\mu\mu} - \sqrt{s}/2$, and at m_τ for $M_{\mu\mu\mu}$.

Because the background in this search is suppressed, the uncertainties approximately scale with sample size. Belle set a limit at $Br(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$ [10]. With improved selection criteria and overall improved analysis, Belle II is expected to achieve competitive results in the near future.

3.2 Early Results for $\tau \to \ell\alpha$

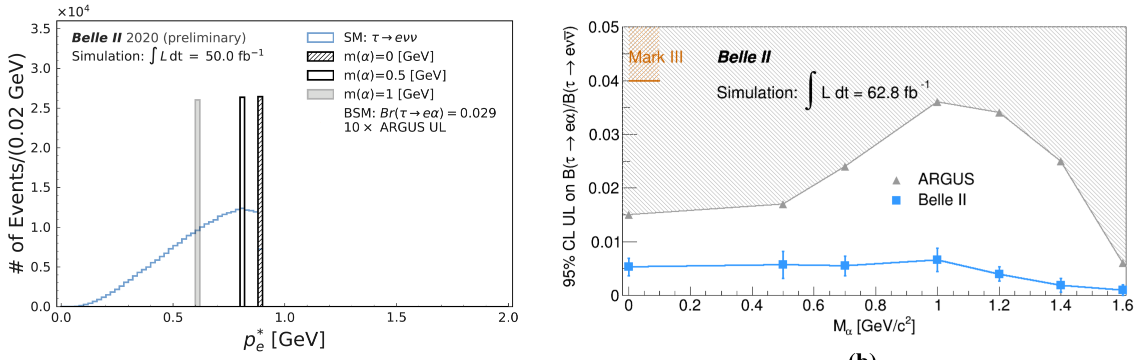
Belle II pursues a generic search for a beyond the Standard Model invisible particle α using the lepton flavour violating decay $\tau \to \ell\alpha$. Several theories propose $\tau \to \ell\alpha$ including Z' [11] and axion-like particle models [12]. The $\tau \to \ell\alpha$ process is especially sensitive to probe Z' models. In the case of the axion-like particles, $\tau \to \ell\alpha$ has a unique parameter space above the μ mass.

The strategy is to look for a signal peak on top of the $\tau \to \ell\nu\nu$ momentum distribution in the rest-frame of the τ. Figure 2a shows the expected monochromatic ℓ-momentum distribution for several mass hypotheses of $\tau \to \ell\alpha$ in the rest-frame of the τ, compared to the Standard Model background. The rest-frame estimate relies on the tag-τ, which is used to identify the event. To estimate the tau direction Belle II uses the momentum direction of the 3π-system and approximates the τ energy with $E_\tau \approx \sqrt{s}/2$ [13].

Belle II uses a limit-setting procedure based on the CLs method. The upper limit expected for an integrated luminosity of 62.8 fb^{-1}, with dominant systematic uncertainties included, is shown in Figure 2b.

4. Conclusion

Belle II is currently working on measuring τ Standard Model parameters such as the τ mass and τ lifetime. In the mid- to long-term, Belle II has the potential to measure the magnetic and electric dipole moments of the τ and to improve the sensitivity to lepton flavour violating processes in many decay channels, with early competitive results expected in $\tau \to \mu\mu\mu$. Potential for increased sensitivity is already evident for early Belle II data in the lepton flavour violating sector for the $\tau \to \ell\alpha$ decay. Belle II will lead the study of the τ physics sector for at least the next decade.



(a) **(b)**

Figure 2: Expected electron momentum distribution for $\tau \to e\alpha$ compared to the Standard Model prediction in the τ rest-frame (left). Upper limit estimate as a function of the invisible mass for a simulation study with dominant systematic uncertainties taken into account (right).

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