Physics of τ lepton at Belle II

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Summary. —
The Belle II experiment at SuperKEKB e^+e^- collider provides a unique environment for τ physics, thanks to the large sample of τ-pair events collected and the clean experimental conditions. We present recent results on: searches for lepton flavor violating (LFV) τ decays into three leptons final state and one lepton and one meson final state; tests of lepton flavor universality (LFU) in leptonic τ decays; and a precise measurement of the τ lepton mass m_τ.

1. – Introduction

1˙1. *Motivation*. – The τ lepton is a powerful probe for testing the Standard Model (SM) and exploring possible new physics scenarios, due to its well-understood electroweak production and decay mechanisms.

In the SM, electroweak interactions are the same for all three leptons — a principle known as Lepton Flavor Universality (LFU). This can be translated to a mixing matrix describing the electroweak transition for charged leptons which is diagonal and with equal elements. It thus implies that, up to mass effects, the coupling of each charged lepton to the W boson is identical. Deviations from LFU would be a clear sign of new physics, potentially pointing to new mediators such as leptoquarks, *W'*, *Z'*, or charged Higgs bosons [1]. Tests of LFU can be performed using semileptonic or leptonic τ decays, as well as through precision measurements of the τ mass m_τ.

On the other hand, the presence of non-zero off-diagonal elements in the charged lepton mixing matrix would imply lepton flavor violating (LFV) processes. Lepton flavor is only an accidental symmetry in the SM, and is known to be violated in the neutrino sector through oscillations. However, LFV in charged lepton decays is highly suppressed, with expected branching fractions on the order of 10^{-50} due to the factor $(m_\nu/m_W)^2$ [2]. Observation of any LFV signal in charged lepton decays would therefore be an unambiguous indication of physics beyond the Standard Model.

1˙2. *Experiment*. – Belle II [3] is a high-intensity frontier experiment operating at the SuperKEKB e^+e^- asymmetric-energy collider, working mainly at a center-of-mass energy of $\sqrt{s} = 10.58$ GeV [4]. During its first data-taking period (2019–2022), Belle II collected an integrated luminosity of 424 fb^{-1}.

Thanks to the large production cross section for τ pairs at this energy, $\sigma_{\tau\tau} \sim 0.9$ nb, Belle II has already collected billions of τ-pair events, making it effectively a τ-factory. The experimental conditions are ideal for τ physics: well-defined initial state, relatively low multiplicities events, dedicated triggers for low-multiplicity final states, and a hermetic detector enable excellent reconstruction of events with few tracks and missing energy.

1˙3. *Methodology.* – In e^+e^- collisions, τ pairs are produced back-to-back in the center-of-mass frame (CMS), a feature widely exploited in Belle II τ analyses. The exact flight direction of each τ lepton cannot be fully reconstructed due to the presence of undetected neutrinos in the final state. As an approximation, the Thrust axis $\vec{T}$ is used to estimate the event topology [5]. Once the flight direction is approximated, the event can be divided into two hemispheres using the plane perpendicular to $\vec{T}$, allowing the definition of a *signal side* (where the decay of interest occurs) and a *tag side* (used to identify the event and suppress background). Each τ decay is categorized by its topology, most commonly as one-prong or three-prong, referring to the number of charged particles in the final state. These classifications help reduce background by exploiting the kinematic and topological properties of τ decays.

In LFV searches, the absence of neutrinos in the signal final state can be exploited through two key observables: the invariant mass M_{inv} of the final state particles, and the energy difference $\Delta E = E^*_{\text{inv}} - \sqrt{s}/2$, where E^*_{inv} is the reconstructed energy in the CMS. Signal events are expected to cluster around $M_{\text{inv}} \sim m_\tau$ and $\Delta E \sim 0$, while backgrounds are broadly distributed.

2. – Recent results in LFV processes

2˙1. *Search for* $\tau^- \to e^\pm l^\mp l^-$. – We use 428 fb^{-1} of e^+e^- collected at the $\Upsilon(4S)$ to search for $\tau^- \to e^\mp l^\pm l^-$ where l is either an electron or muon. We consider five final states: $e^+e^-\mu^+$, $e^+e^-e^-$ and $e^+\mu^+\mu^-$ for single lepton number violation; $e^+\mu^-\mu^-$ and $e^-e^-\mu^+$ for double lepton number violation. The analysis strategy exploits the un-tagged reconstruction approach, already devised for previous LFV analysis [6] to enhance signal efficiency, while the signal side requires the combination of an electron and two leptons with net charge ± 1 and belonging to the same hemisphere. Background contributions come from $ee \to q\bar{q}$, $ee \to b\bar{b}$, $ee \to ll(\gamma)$ and $ee \to 4l$. The suppression is a two-level strategy. The first one targets the easier components to reject using a cut-based selection, while the second one is designed to remove any remaining background components ($2l$ and $4l$) using a *Boosted Decision Tree* (BDT) classifier (one for each mode). Since some background contributions are either missing or mis-modeled in the simulations, all background suppression is performed on data, and the BDT classifiers are trained on data events. A blind region is defined in the two dimensional plane given by M_{ell} and ΔE_{ell} in order not to bias the selection, as well as a fitting region as shown in Fig. 1. The signal branching ratio is extracted by the fit on the M_{ell} distribution. In all channels, the branching ratio is compatible with zero, thus we compute upper limits using the CL method. The upper limits on $\mathcal{B}(t \to ell)$ range from 1.3×10^{-8} to 2.5×10^{-8} in the five different final state. For all channels, except the $e^-e^-\mu^+$ one, these represent the lowest upper limits, updating the previous ones from Belle [7]

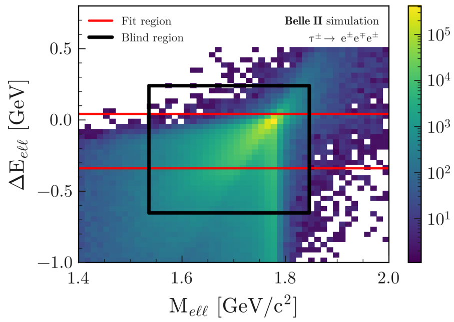

Fig. 1. – Phase space given by the invariant mass and missing energy of the final state M_{ell} and ΔE_{ell}. The distribution is the Belle II signal simulation. The blind region is indicated by the black box and the fit band from the red lines. BDT is based on data not included in these regions.

2·2. *Search for* $\tau^\pm \to l^\pm K^0_s$. – We present a combined search for charged-lepton-flavor-violating decays $\tau^- \to e^- K^0_S$ and $\tau^- \to \mu^- K^0_S$ using 428 fb^{-1} collected by Belle II and 980 fb^{-1} from Belle, corresponding to a total of approximately 1.3×10^9 $\tau^+\tau^-$ events [8].

The signal side is reconstructed by identifying a $K^0_S \to \pi^+\pi^-$ decay plus an electron or a muon, while the other τ is tagged in a one-prong mode. Background, mainly coming from $ee \to q\bar{q}$ is suppressed with the use of pre-selections and a BDT based on signal- and tag-side τ kinematics, K^0_S and track kinematics and event shape properties.

Signal region is defined as an elliptical window in the $(M_{lK^0}, \Delta E_{lK^0})$ plane, optimized using MC to contain 90% of signal. Backgrounds are estimated from the sidebands in this plane and are found to be extremely low (< 1 event expected). A simple cut-and-count method is thus employed. After unblinding, the signal yields are found to be consistent with background-only expectations: zero events for the eK^0_S mode, and one event for the μK^0_S mode. Observed upper limits at 90% confidence level are shown in Fig. 2. They result in: $\mathcal{B}(\tau^- \to e^- K^0_S) < 0.8 \times 10^{-8}$, and $\mathcal{B}(\tau^- \to \mu^- K^0_S) < 1.2 \times 10^{-8}$. These results represent the most stringent limits to date for these modes, improving on previous Belle-only limits by roughly a factor of two [9]. This result further constrains new-physics models that predict LFV in τ decays, such as leptoquarks, Higgs-mediated interactions, or Z' scenarios.

2·3. *Search for* $\tau \to \mu\mu\mu$. – We perform a search for $\tau^- \to \mu^-\mu^+\mu^-$ using 424 fb^{-1} of Belle II data [6]. Events are selected by reconstructing three muons from one τ decay, while the other τ is inclusively tagged. The dominant backgrounds originate from generic $\tau^+\tau^-$ events with misidentified hadrons, and from QED processes such as Bhabha and dimuon events. A BDT is trained to discriminate signal from backgrounds. Signal and background is studied in the $(M_{3\mu}, \Delta E_{3\mu})$ plane, and background levels in the signal region are estimated from sidebands and validated in data control samples. One event is observed, compatible with the expected background. A 90% CL upper limit is set: $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 1.9 \times 10^{-8}$ (see Fig. 3) currently the most stringent limit worldwide for this channel (previous ones [10], [7], [11], [12]).

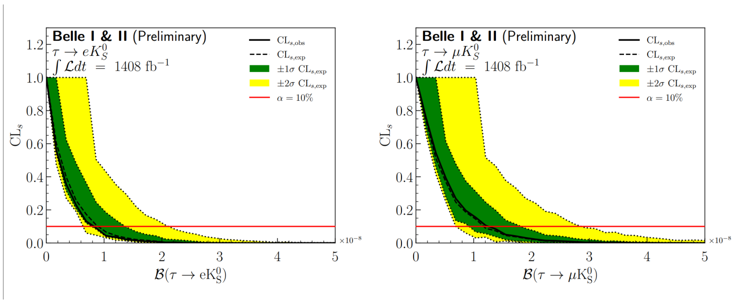

Fig. 2. – Resulting 90% CL upper limits on the $\tau \to eK^0$ channel (left) and $\tau \to \mu K^0$ channel (right).

3. – Recent results in precise measurements

3·1. *Lepton flavor universality test with* $\tau^\pm \to l^\pm \bar{\nu}_l \nu_\tau$. – Measuring the ratio of decay rates (R) involving different lepton species is a very precise probe for LFU because it partially cancels out theoretical uncertainties and experimental uncertainties. For instance, the branching-fraction ratio $R = \frac{\mathcal{B}(\tau \to \mu \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau \to e \bar{\nu}_e \nu_\tau)}$ is a sensitive probe for the universality of the third generation. We perform the measurement of the ratio R which can be converted as a measure of the ratio between the coupling constants for muon and electron g_μ, g_e. The analysis uses $\tau \to l \bar{\nu}_l \nu_\tau$ with $l = e, \mu$ as signal side, and τ decaying in a charged hadron and at least one π^0 as tag side. The main background processes, $e^+e^- \to \tau^+\tau^-$, with τ decaying into different final states with respect to the signal side decay, and $e^+e^- \to e^+e^-\tau^+\tau^-$, are suppressed with the use of a neural network, obtaining 94% of signal purity and 9.6% signal efficiency. The value of the ratio is extracted through a maximum-likelihood fit based on template distributions of the signal lepton momentum. The ratio value obtained using on 362 fb^{-1} of data is $R = 0.9675 \pm 0.0007$stat± 0.0036syst. This gives a measure of the ratio $(g_\mu/g_e)_\tau = 0.9974 \pm 0.0019$, compatible with the SM prediction at 1.4σ (as shown in Fig.4), and is the most precise test of the $e - \mu$ LFU produced by a single experiment.

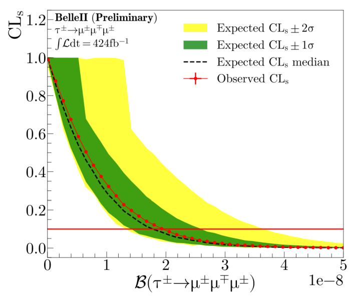

Fig. 3. – Observed 90% CL upper limits on the $\tau \to \mu\mu\mu$ channel

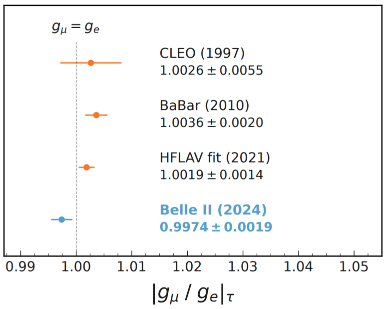

Fig. 4. – Results of the R_μ measurement given by Belle II, in comparison with the PDG value (solid line) and the results from CLEO [13], BaBar [14] and the average computed by the Heavy Flavor Averaging Group [15]

3$\cdot$2. *Measurement of m_τ*. – We perform a high-precision measurement of the τ lepton mass using a data sample of 190 fb^{-1} collected at $\sqrt{s} = 10.58$ GeV [16]. This analysis exploits the kinematic endpoint of the pseudomass distribution in $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ decays. The pseudomass m_{min} is defined under the assumption that the τ direction is collinear with its visible decay products, providing a sharp endpoint at m_τ. Events are selected with three charged pions on the signal side and a one-prong decay on the tag side. We correct the pseudomass spectrum for detector resolution and fitted with an empirical function that models the endpoint behavior. Systematic uncertainties are dominated by tracking, momentum scale calibration, and fit model dependence. The measured value is: $m_\tau = 1777.09 \pm 0.08_{\text{stat}} \pm 0.11_{\text{syst}}$ MeV$/c^2$ which is the most precise single measurement to date from an individual experiment, show in Fig.5. This result provides a competitive test of lepton universality and input to precision electroweak fits.

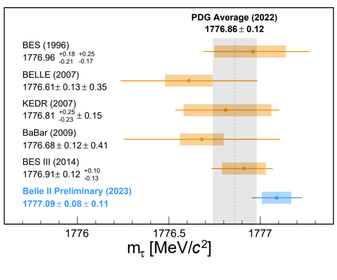

Fig. 5. – Results of the $m\tau$ measurement given by Belle II, in comparison with the results from BES [17], KEDR [18], BESIII [19], Belle [20] and Babar [21]. The gray band indicates the average value of previous measurement [22]

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