PROCEEDINGS OF SCIENCE

Lepton flavour at Belle II

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Leptons are powerful tools to probe physics beyond the Standard Model. The Belle II experiment installed at the SuperKEKB asymmetric energy electron-positron collider has collected a 428 fb^{-1}sample of collisions during Run 1 (2019-2022). This data set, thanks to the excellent lepton identification capability and initial kinematics constraints, can be used to study lepton flavour universality in semileptonic decays of the B meson and τ decays. We present measurements of branching-fraction ratios that test the universality of τ and light leptons, using both exclusive and inclusive B semileptonic decays and τ decays into lighter leptons. We also report the world's best limit for the search for lepton flavour violating decays such as $\tau^- \to \mu^- \mu^+ \mu^-$.

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1. Introduction

The Belle II experiment, operating at the SuperKEKB collider, collects data from e^+e^- collisions mainly at the $\Upsilon(4S)$ resonance, which can be used for precision studies of B meson and τ decays. The Standard Model (SM) predicts that the electroweak interactions of leptons are identical up to mass effects, a principle known as Lepton Flavour Universality (LFU). This can be translated to a mixing matrix describing the electroweak transition for charged leptons which is diagonal and with equal diagonal elements. Deviations from this could indicate new physics, such as the presence of new mediators like leptoquarks or W', Z', and charged Higgs bosons [1]. Semileptonic decays of the B meson and decays of τ lepton into muon or electron offer sensitive tests of LFU. 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 (e.g. form factors) and experimental uncertainties (e.g. absolute normalization and reconstruction efficiencies). For instance, the branching-fraction ratio $R(H\tau/\ell) = \frac{B(B\to H\tau\nu_\tau)}{B(B\to H\ell\nu_\ell)}$, where ℓ is either an electron or a muon and H is a hadron, is a sensitive probe for the universality of the third generation. Here, the final state hadron H can be $D(^*), \pi$, or other hadrons from exclusive modes, or it can be an inclusive hadronic system X. This paper presents Belle II's latest results on the exclusive $R(D^*)$ and inclusive $R(X)$ measurements, and the most precise test of light lepton universality with τ decays.

Additionally, non-null out-of-diagonal couplings in the charged leptons mixing would imply electroweak transitions violating Lepton flavour (LFV). Lepton flavour is only an accidental symmetry, known to be broken by neutrino masses, which induce oscillations. All LFV amplitudes are suppressed by the squared ratio of the neutrino mass to the W-boson mass $(m_\nu/m_W)^2$. Consequently, predicted branching fractions are of the order of 10^{-50} [2–4], well below the sensitivities of current experiments. The detection of charged LFV decays would unambiguously indicate physics beyond the SM. We report here the most stringent limit on the search for the LFV decay $\tau^- \to \mu^-\mu^+\mu^-$.

2. Measurement of $R(D^*)$ using hadronic B-Tagging at Belle II

The ratio $R(D^*) = \frac{B(B\to D^*\tau\nu_\tau)}{B(B\to D^*\ell\nu_\ell)}$, where $\ell = e, \mu$, is a sensitive probe of LFU in charged-current interactions. The world averages of existing measurements, $R(D^*) = 0.287 \pm 0.012$, exceed the SM expectation [5] by 2.5σ. The novelty in the experimental method for this measurement at Belle II is the Full Event Interpretation (FEI) technique [6] to exclusively reconstruct the tagged B meson decaying into hadrons (hadronic tag): one B meson is fully reconstructed in hadronic decay modes, and the signal B meson is reconstructed in its semileptonic decay. The main challenge is to control the large background due to fake D^* from poorly known $B \to D^{**}\ell\nu$ modes, which is estimated by using sideband regions (requiring at least one additional π^0) in data. The analysis exploits a two-dimensional fit in the missing mass squared (M^2_{miss}) and residual calorimeter energy (E_{ECL}) not associated to any reconstructed particle, to distinguish between signal and background. The missing mass squared is given by $M^2_{miss} = (E^*_{\text{beam}} - E^*_{D^*} - E^*_\ell)^2 - (-\vec{p}^*_{B_{\text{tag}}} - \vec{p}^*_{D^*} - \vec{p}^*_\ell)^2$, where $E^*_{\text{beam}} = \sqrt{(s)}/2, E^*_{D^*}, E^*_\ell$ represent the beam energy, the D^* and ℓ energy, whereas $\vec{p}^*_{D^*}, \vec{p}^*_{B_{\text{tag}}}, \vec{p}^*_\ell$ are the momentum vectors of the D^*, ℓ, and B_{tag}. All quantities are calculated in the centre-of-mass (c.m.) frame. Distributions of final selected events for the two discriminant variables are given in Figure 1. The preliminary Belle II result $R(D^*) = 0.262^{+0.041}_{-0.039}(\text{stat})^{+0.035}_{-0.032}(\text{syst})$ [7] has already

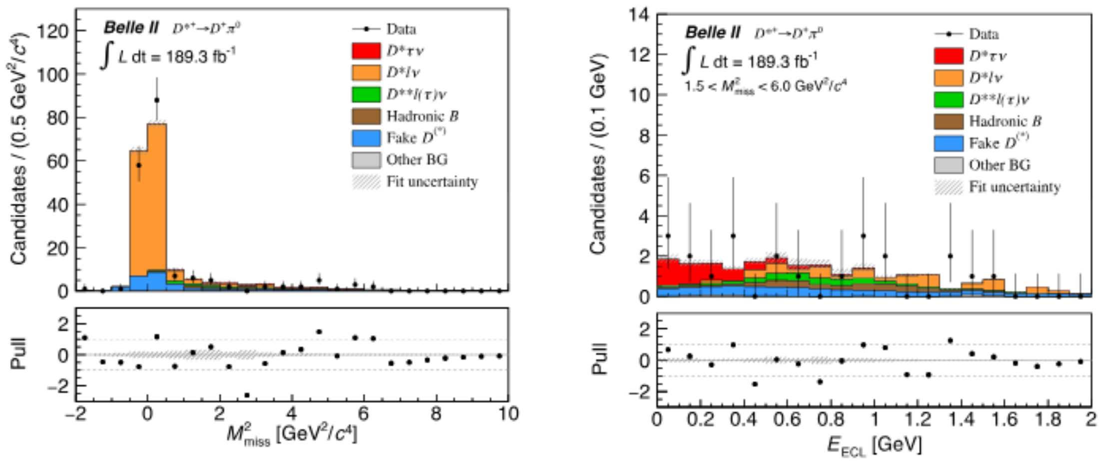

Figure 1: On the left, the distribution of the missing mass squared for the $D^{*+} \to D^+\pi^0$ mode, with fit projections overlaid. The bottom panel presents pull values from fit results. On the right, the residual calorimeter energy E_{ECL} distribution for the same mode in the signal-enhanced region $1.5 < M^2_{miss} < 6\ \text{GeV}^2/c^2$.

reached the same precision as the previous determination at Belle on 711 fb^{-1}data [8], with a data set of only 189 fb^{-1}. It is consistent with the SM expectation and contributes to the global fit of $R(D^*)$ measurements [5].

3. Inclusive measurement of $R(X)$

A complementary test of LFU in semileptonic B decays is provided by the inclusive ratio $R(X) = \frac{\mathcal{B}(B\to X\tau\nu_\tau)}{\mathcal{B}(B\to X\ell\nu_\ell)}$, where X represents all final states containing a charm hadron. The measurement includes a variety of hadronic final states. After reconstructing the candidate with the hadronic B-tagging technique, a two-dimensional fit in signal lepton momentum p^B_ℓ and missing mass squared is used to extract the signal yield. The primary experimental challenge is the background characterization and modeling. For this purpose, we use signal free control samples to estimate the normalization of the contributing background processes, coming from mis-recontructed $B\bar{B}$ pairs and continuum events $e^+e^- \to q\bar{q}$, the latter rate estimated from the off-resonance data. The final result is systematically limited already with 189 fb^{-1}, where the largest contribution to the total uncertainty comes from the size of the control samples defined in the high-momentum signal lepton tail ($p^B_\ell > 1.4\text{GeV}/c^2$) sideband regions, used to rewieght the missing mass square distribution in the $B \to X\ell\nu$ modeling. The measured value $R(X) = 0.228 \pm 0.016_{(\text{stat})} \pm 0.036_{(\text{syst})}$ [9] is consistent with the SM prediction of $R(X) = 0.223 \pm 0.005$ [10] and provides an independent test of the $b \to c\ell\nu$ anomaly, complementary to the $R(D^*)$ results from the exclusive measurement.

4. LFU and LFV tests in τ decays

The Belle II data set collected during Run 1 of 428 fb^{-1}, corresponding to approximately 3.9×10^8 produced τ-pair events, is well-suited for both tests of the SM via precision measurements and direct searches for LFV final states exploiting τ decays.

4.1 Typical τ signatures in e^-e^+ collisions

In $e^-e^+ \to \tau^-\tau^+$ processes, τ candidates are produced back-to-back in c.m. system. Their decay products are well separated into two opposite hemispheres, defined by the plane perpendicular to the thrust axis $\hat{\mathbf{t}}$, which is the vector maximizing the quantity

$$T = \max_{\hat{\mathbf{t}}} \left(\frac{\sum_i |\mathbf{p}_i \cdot \hat{\mathbf{t}}|}{\sum_i |\mathbf{p}_i|} \right), \quad (1)$$

where $\mathbf{p}_i$ is the momentum of the final state particle i, including both charged and neutral particles. According to the number of charged particles in each hemisphere, consistently with charge conservation in τ decays, two main topologies can be selected: the 3×1-prong decays, with three charged particles on one side and only one in the opposite hemisphere; or the 1×1-prong decays.

Requiring the reconstructed tracks to match one of these topology classes is a powerful way to suppress the main background from continuum $q\bar{q}$ processes and enhance signal purity when reconstructing $e^-e^+ \to \tau^-\tau^+$ events. In the next Section 5, results based on these selections are reported.

5. Measurement of the R_μ ratio at Belle II

Testing LFU in τ decays is possible by measuring the ratio of branching fractions of τ decays to muons and electrons $R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$. In the ratio, most experimental and theoretical systematic uncertainties in common between numerator and denominator cancel out, and it is possible to precisely constrain the quantity $|g_\mu/g_e|_\tau = \sqrt{R_\mu \cdot f(m_e^2/m_\tau^2)/f(m_\mu^2/m_\tau^2)}$, where g_μ, g_e are the muon and electron coupling constants to the $W^\pm$ bosons, respectively; m_e, m_μ, m_τ are the masses of the corresponding leptons. The function $f(x) = 1 - 8x + 8x^2 - x^4 - 12x^2 ln(x)$ accounts for different phase space dependences, assuming negligible neutrino masses.

In the SM, $|g_\mu/g_e|_\tau$ is expected to equal one and deviations from unity could indicate new physics beyond the SM [11].

5.1 The analysis strategy

Events classified as 1x1-prong topologies, where one τ decays leptonically (signal side) and the other decays into a hadronic final state $\tau^- \to \rho^-(\pi^- n\pi^0)\nu$ (tag side) with a single charged track and at least one neutral pion, are selected. The hadronic decay serves as a tag to identify the event with a very high online selection (trigger) efficiency due to the π^0 decaying into two photons that are detected by the calorimeter, while the leptonic decay is analyzed to measure the branching fractions and relies on lepton identification (LID) variables to select the signal mode (muon or electron). A neural network, fed with the magnitude and polar angle of the thrust vector $\hat{t}$, the visible energy in the c.m. frame, the missing momentum information, and kinematic variables sensitive to the hadronic tag-side system, is used to suppress background contaminations from radiative di-lepton processes and mis-reconstructed τ decays. It achieves a signal purity of 94%, with a final signal efficiency of 9.6%.

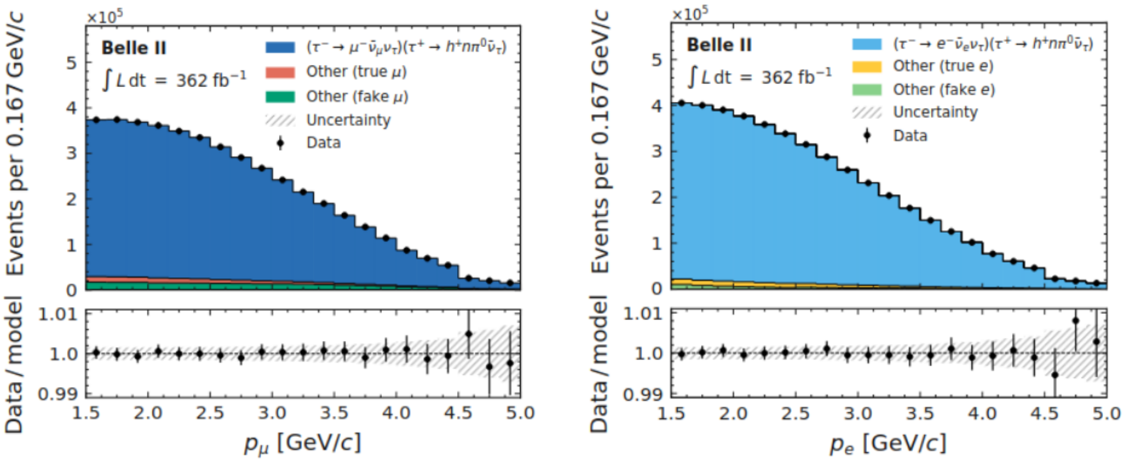

Figure 2: On the left, the distribution of the signal lepton momentum for the muon channel, after the template fit, showing data (black dots) superimposed on the simulated samples (stack filled histograms). In the lower panel, the ratio between data and fit results are reported. The hatched area indicates the possible variation of the fitted yields due to systematic effects. On the right, the same is shown for the electron channel.

The R_μ value is extracted from template fits to the signal lepton momentum distributions, which are reported in Fig. 2. The main experimental challenge in this precision measurement is to control the instability of the extracted R_μ value in function of lepton identification selections, which depend on the polar angular region of the detector and the momentum range. Thanks to a precise calibration of the LID efficiencies comparing data and simulation on control samples, the total systematic contribution due to the LID selections is reduced to be 0.32%.

5.2 Results

The current Belle II result provides the most stringent test for light lepton universality from a single measurement in τ decays and show no significant deviation from SM predictions, reinforcing the validity of LFU in tau decays. The measured $R_\mu = 0.9675 \pm 0.0007_{\rm (stat)} \pm 0.0036_{\rm (syst)}$ value is shown in the left plot of Fig. 3, together with the measurements from kaons and the world averages, and it's translated into the constraint on $|g_\mu/g_e|_\tau = 0.9974 \pm 0.0019$, consistent with the SM expectation within 1.4σ.

6. Search for the lepton-flavour-violating decay $\tau^- \to \mu^-\mu^+\mu^-$

Belle II's large data sample of τ pair events and clean experimental environment make it ideal for searching for LFV τ decays. These channels are experimentally favoured because of the absence of neutrinos, so the τ mass and the energy can be precisely determined, and the SM background sources are suppressed. The decay we searched for in this analysis is $\tau^- \to \mu^-\mu^+\mu^-$. The previous best limit on this search is from Belle [12], which performed the study using 782 $\text{fb}^{-1}$and set an upper limit of 2.1×10^{-8} at 90% confidence level. The Belle II study is competitive with 428 fb^{-1}due to the novel method for reconstructing τ pair topologies, deploying an inclusive tagging technique that boosts the signal efficiency, and the multivariate analysis method devised for

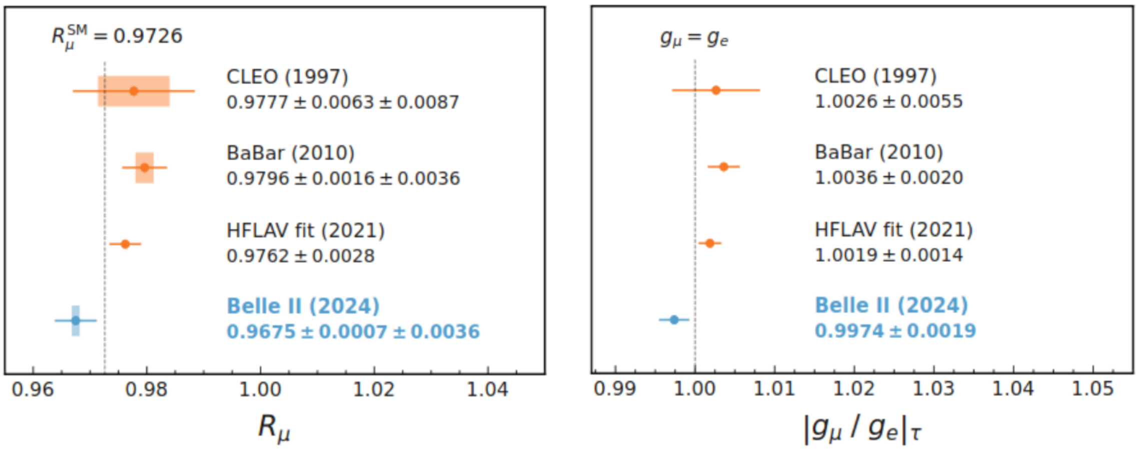

Figure 3: Determinations of R_μ (left) and $|g_\mu/g_e|_\tau$ (right) from previous individual measurements and the fit from the Heavy flavour Averaging Group [5], compared with Belle II result.

suppressing the higher background. In the signal side, three charged tracks identified as muons are required, while all remaining charged and neutral particles in the event are associated to the Rest Of Event (ROE). Contamination from four-lepton and radiative di-lepton events are rejected with data-driven selections. The remaining background comes mainly from continuum $q\bar{q}$ processes, and it's suppressed with a BDT classifier, exploiting signal kinematics features and ROE kinematics properties and particle multiplicities, with a final signal efficiency above 20%. Final selected signal candidates are expected to have an invariant mass $M_{3\mu}$ close to the τ mass and the difference of the reconstructed energy and half the c.m. energy $\Delta E_{3\mu} = E_{3\mu} - \sqrt{s}/2$ consistent with zero. The signal extraction is performed with a Poisson counting experiment technique in the elliptical signal region in the $(M_{3\mu}, \Delta E_{3\mu})$ plane, which is shown in Fig. 4. In data, we observe one event in the signal region, which is compatible with the background expectation of 0.5 event from a data-driven estimation performed in sideband regions.

6.1 Results

No significant excess over the expected background is observed and we compute the upper limit at 90% confidence level on the branching fraction with the CLs method, including systematic uncertainties, to be $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 1.9 \times 10^{-8}$ [13]. This work set the world's best limit on the LFV rate for $\tau^- \to \mu^-\mu^+\mu^-$ decays.

7. Conclusion

LFU precision measurements are compelling tests of the SM and can constrain new physics. Similarly, LFV processes are predicted by many new models and it is compelling to search for them. The Belle II experiment has provided precise tests of LFU measuring $R(D^*)$, $R(X)$, and the R_μ ratio in τ decays, the latter providing the most stringent constrain on $\mu - e$ universality from a single measurement. All these results are consistent with the SM predictions and set stringent limits on potential new physics effects. We also report about LFV searches in τ decays, which provide

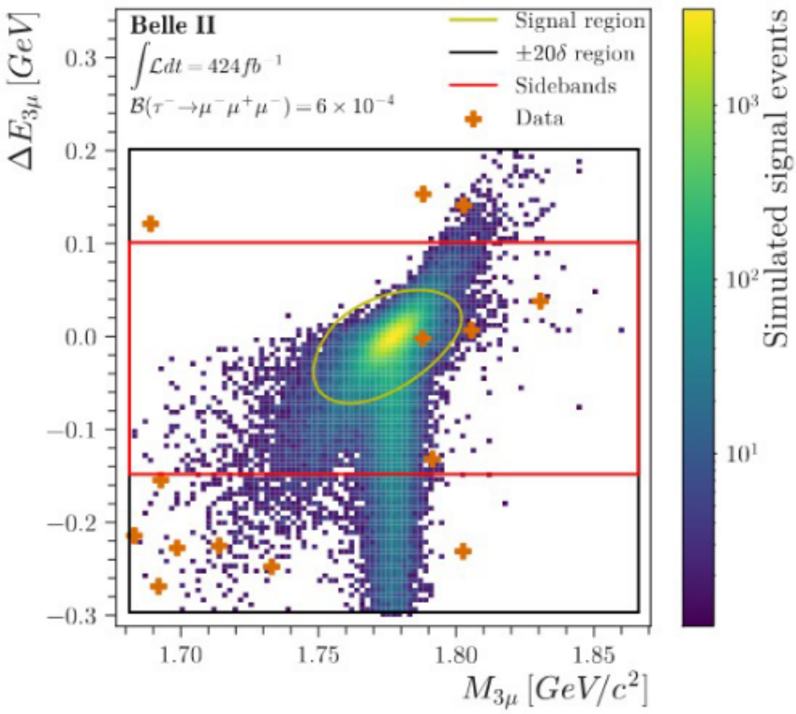

Figure 4: Scatter plot of selected events in the $(M_{3\mu}, \Delta E_{3\mu})$ plane for data (orange crosses) and simulated signal (color-filled area). The sideband region is shown as the red rectangle. The yellow ellipse represents the signal region.

the world's best limit on $\tau^- \to \mu^-\mu^+\mu^-$ decays. As Belle II continues to accumulate data, further improvements in sensitivity are expected, providing deeper insights into lepton flavour physics.

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