PROCEEDINGS OF SCIENCE

Searches for lepton-flavor violation in τ decays at Belle and Belle II

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Lepton-flavor violation (LFV) in charged-lepton decays is negligibly small in the Standard Model (SM), arising only through neutrino-mass suppressed loops with rates proportional to the ratio $(m_\nu^2/M_W^2)^2 \lesssim 10^{-50}$, and thus well beyond experimental reach. Any observation of a τ LFV decay would be an unambiguous sign of physics beyond the SM. The Belle II experiment at the SuperKEKB asymmetric-energy e^+e^- collider, together with the Belle legacy sample, provides a uniquely clean environment and large data sets of approximately 1.3 billion $e^-e^+ \to \tau^-\tau^+$ events for LFV searches. This contribution reports: the world-leading Belle II search for $\tau^- \to \mu^-\mu^+\mu^-$ using an inclusive "untagged" strategy; the first Belle+Belle II combined search for $\tau^- \to \ell^- K_S^0$; Belle II searches for $\tau^- \to e^\pm\ell^\mp\ell^-$; and searches for invisible pseudoscalar bosons produced in $\tau \to \ell\alpha$ decays at Belle and Belle II.

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1. Introduction and motivation

Tau leptons, copiously produced in e^+e^- collisions at the $\Upsilon(4S)$ energy, are a unique laboratory both for precision tests of the SM and for direct searches for rare and forbidden processes. In particular, LFV decays such as $\tau \to \ell\ell\ell$ or $\tau \to \ell P^0$, with $\ell = \mu, e; P^0$ = neutral pseudoscalar particle, are forbidden in the SM at tree level, with branching fractions $\lesssim 10^{-50}$. Therefore, any observation would be a clear indication of new interactions (e.g. Z', leptoquarks, charged-Higgs bosons) that couple non-universally to lepton flavors. Belle II's clean environment, hermetic detector, and excellent lepton and K^0_S identification make it ideal for such searches. In $e^+e^- \to \tau^+\tau^-$, the two τ's are produced nearly back-to-back in the center-of-mass (c.m.) system, allowing the event to be partitioned into two hemispheres by the plane perpendicular to the thrust axis, which best approximates the tau direction of flight, and enabling powerful background suppression using topology and missing-energy constraints.

At $\sqrt{s} \simeq 10.58$ GeV, the $\sigma(e^+e^- \to \tau^+\tau^-)$ is of order 1 nb, comparable to $b\bar{b}$ production. Belle accumulated 980 fb^{-1}; Belle II has entered since 2024 Run 2 and surpassed 0.6 ab^{-1} with dedicated low-multiplicity triggers, aiming at 50 ab^{-1} total. These samples enable world-leading sensitivities to LFV branching fractions at the 10^{-9}–10^{-8} scale and to invisible final states.

2. Experimental environment and common strategy

We analyze data recorded at or near the $\Upsilon(4S)$. 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

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

where $\mathbf{p}_i$ is the momentum of the final state particle i, including both charged and neutral particles. Candidate events are selected depending on their topologies and number of charged tracks in each hemisphere (*one or three prong* decays). Signal-side reconstruction targets a fully visible, neutrino-less τ decay (for LFV modes) or a two-body $\tau \to \ell\alpha$ decay with a mono-energetic lepton in the τ rest frame (for invisible-scalar searches). The rest of the event (ROE) is used for vetoes and multivariate-based suppression of $e^+e^- \to \ell^+\ell^-(\gamma)$, four-lepton, and continuum $q\bar{q}$ backgrounds. To discriminate signal from background, two variables that encode the lack of neutrinos in tau LFV decays are used: (i) the reconstructed invariant mass M_τ peaking at the nominal τ mass; and (ii) the difference of the reconstructed energy and half the c.m. energy $\Delta E_\tau = E_\tau - \sqrt{s}/2$ consistent with zero. The signal extraction proceeds via Poisson counting in an elliptical signal region in the $(\Delta E_\tau, M_\tau)$ plane; or unbinned/binned likelihood fits to discriminating spectra (e.g. invariant masses, lepton momentum).

3. Search for $\tau^- \to \mu^-\mu^+\mu^-$ at Belle II

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 suppressing the higher background. We perform the first LFV τ search with an *inclusive untagged* approach, reconstructing only the signal side as three charged tracks identified as muons and with total charge equal ± 1 and treating all remaining activity as ROE. A boosted decision tree (BDT) classifier trained on signal and ROE observables suppresses continuum background; radiative di-lepton and four-lepton backgrounds are rejected with data-driven selections, achieving a final signal efficiency above 20%. 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. 1, where signal candidates are expected to peak at the nominal tau mass and at an energy difference consistent with zero. 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. We set a 90% CL upper limit with the CL$_s$

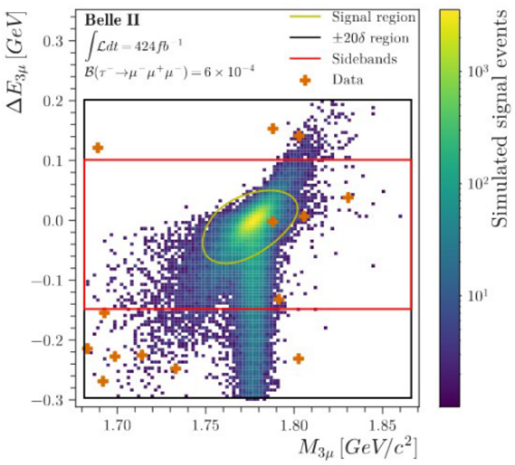

Figure 1: Scatter plot of selected events in the $(M_{3\mu}, \Delta E_{3\mu})$ plane for data (orange crosses) and simulated signal (color-filled area). The sideband region is shown as the red rectangle. The yellow ellipse represents the signal region.

method at $\mathcal{B}(\tau \to \mu\mu\mu) < 1.9 \times 10^{-8}$, currently the world's best constraint [1].

4. Search for LFV $\tau^- \to e^\pm \ell^\mp \ell^-$ ($\ell = e, \mu$) decays at Belle II

We generalize the inclusive strategy to five trilepton final states separated by lepton-ID categories. The primary backgrounds due to radiative $e^+e^- \to \ell^+\ell^-(\gamma)$ and $e^+e^- \to \ell^+\ell^-\ell'^+\ell'^-$ processes are known to be mis-modeled in simulation. After some pre-selections to improve data and simulation agreement, we therefore devise a *data-driven BDT* trained in regions away from signal. The output of the BDT classifier on sideband data outside the signal elliptical region is shown comparing data (black dots) and simulation (solid stacked histrograms)in Figure 2, together with the resulting invariant mass $M_{e\ell\ell}$ distribution for the final selected events in data, for the mode $\tau^\pm \to \mu^\pm e^\mp \mu^\pm$.

Signal yields are extracted from unbinned maximum-likelihood fits to $M_{e\ell\ell}$ distributions, using sidebands to constrain background. No excess is seen in 428 fb^{-1}; the observed 90% CL upper limits span $(1.3\text{–}2.5) \times 10^{-8}$ with four modes achieving the most stringent limits to date [2], reported in Figure 3.

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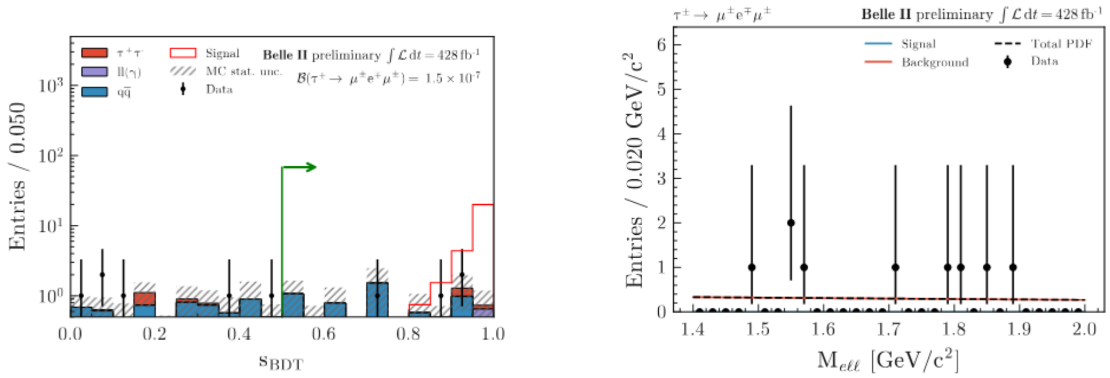


Figure 2: The BDT score distribution in the sideband region after the preselection (left) and the invariant mass $M_{\ell\ell}$ distributions for final selected events in data for the mode $\tau^{\pm} \to \mu^{\pm} e^{\mp} \mu^{\pm}$ (right). In the left plot, the green arrow indicates the selection criteria applied to the BDT score. The various simulated background processes are shown as a stack of color-filled histograms, with statistical uncertainties displayed as hatched areas. The signal in the full fitting region is shown as a red histogram with branching fraction values given on the plots. In the right plot, signal (solid blue line) and background (solid red line) components of the total fit (black dashed line) are superimposed on the data.

	N_{exp}	N_{obs}	C_{bg}	$\mathcal{B}$ (10^{-8})	$\mathcal{B}^{UL}_{\text{exp}}$ (10^{-8})	$\mathcal{B}^{UL}_{\text{obs}}$ (10^{-8})
$e^-e^+e^-$	$6.1^{+4.3}_{-2.9}$	5	$0.52^{+2.64}_{-2.60}$	0	2.7	2.5
$e^-e^+\mu^-$	$12.1^{+5.7}_{-4.3}$	12	$-0.40^{+1.67}_{-1.68}$	0	2.1	1.6
$e^-\mu^+e^-$	$10.5^{+5.3}_{-4.3}$	17	$-2.90^{+1.48}_{-1.54}$	0	1.7	1.6
$\mu^-\mu^+e^-$	$20.7^{+6.6}_{-5.5}$	18	$-2.50^{+1.45}_{-1.52}$	$0.48^{+0.90}_{-0.48}$	1.6	2.4
$\mu^-e^+\mu^-$	$7.5^{+4.5}_{-3.2}$	9	$-0.34^{+1.93}_{-1.94}$	0	1.4	1.3

Figure 3: Number of expected and observed events, fitted value of C_{bg} and branching fractions, and expected and observed upper limits at 90% C.L. The subscript exp refers to expected values obtained from the fit to sidebands only. For the mode $\tau^- \to e^-\mu^+e^-$ the limit is consistent with the previous one at Belle [3], and the other modes provide the most stringent limits to date.

5. Combined Belle + Belle II search for $\tau^- \to \ell^- K^0_S$

The LFV decays $\tau \to \ell K^0_S$ can probe new phsysics scenarios involving leptoquark operators [4]. We perform the *first combined analysis* of Belle (980 fb^{-1}) and Belle II (428 fb^{-1}) datasets, totaling 1408 fb^{-1}. Events are reconstructed in a one-prong tag approach, while in the signal hemisphere $K^0_S \to \pi^+\pi^-$ candidates are built from displaced two-track vertices, and combined with a charge track identified as muon(electron) to reconstruct the tau signal canidate in the LFV decay $\tau \to \mu(e)K^0_S$. After data-driven preselections to reject radiative di-lepton and four lepton contamination, a BDT classifier using tag-side, event-level, and K^0_S variables suppresses the remaining background from $q\bar{q}$continuum processes. The expected background in the $(M_{\ell K_S}, \Delta E)$ signal ellipse is extrapolated from sidebands with exponential fits. Applying a Poisson counting technique to extract the signal yield for each cahnnle/experiement, with no significant excess observed, we set world-leading 90%

CL limits on both modes:

$$\mathcal{B}(\tau \to eK_S^0) < 0.8 \times 10^{-8}, \qquad \mathcal{B}(\tau \to \mu K_S^0) < 1.2 \times 10^{-8}. \tag{2}$$

These improve on earlier Belle results [5] by factors of ≈ 3.2 (e channel) and ≈ 1.9 (μ channel), driven by both statistics and better particle identification.

6. Invisible scalar boson in $\tau \to \ell\alpha$

Light, invisibly decaying bosons (e.g. axion-like particles) can be produced in two-body $\tau \to \ell\alpha$ decays, yielding a monochromatic lepton in the τ rest frame. Belle II's first search (63 fb^{-1} [6]) used the *ARGUS* pseudo-rest-frame approximation; Belle ($\sim$ 800 fb^{-1} [7]) extends the reach by including more tag-side (*one-prong*) modes and by improving the estimate of the τ direction using the angle between the signal τ and the hadronic system ($\theta_{\tau h}$). Selections are independent of the assumed m_α, with final signal efficiencies range from 0.3–1.5%, validated on control samples. The signal and background yields are extracted from binned maximum likelihood fits to the transverse component of signal lepton momentum p_ℓ^T distributions in the tau rest frame, looking for bumps over the smooth irreducible $\tau \to \ell\bar{\nu}_\ell\nu_\tau$ background.

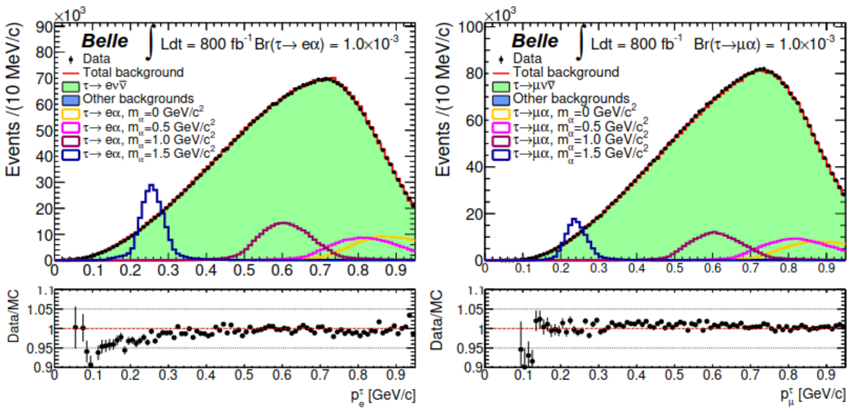
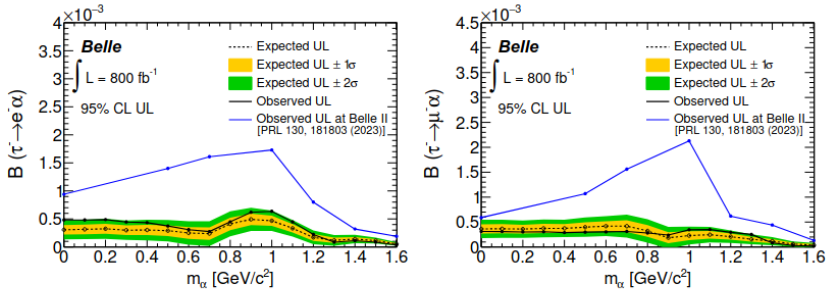


Figure 4: Distributions of p_ℓ^T for events satisfying all selection criteria are shown, on the left (right) for the $\tau \to e\alpha(\tau \to \mu\alpha)$ search. The simulated background samples are normalized to the SM expectation. The simulated signal distributions are shown for an arbitrary branching fraction $\mathcal{B}(\tau \to \ell\alpha) = 10^{-3}$. The bottom figure shows the ratio of the data and the sum of backgrounds.

The final selected spectra are shown in Figure 4. No excess is observed in 7.36×10^8 τ pairs; Belle sets the most stringent 95% CL limits to date $\mathcal{B}(\tau \to e\alpha)$, $\mathcal{B}(\tau \to \mu\alpha) \lesssim (0.2\text{–}6.4) \times 10^{-4}$ depending on the channel and m_α, reported in Figure 5. A new Belle II method exploiting 1×1 topologies and optimized kinematics (motivated by dedicated theory work [8]) promises better discriminating power and improved sensitivity.

7. Outlook and conclusions

Belle II has inaugurated new *untagged* and *data-driven* strategies that substantially raise LFV signal efficiencies while keeping backgrounds under control. The $\tau \to \mu^-\mu^+\mu^-$ limit reaches



(a) $\tau^- \to e^-\alpha$ (b) $\tau^- \to \mu^-\alpha$

Figure 5: Upper limit at the 95% CL on the branching fraction of $\mathcal{B}(\tau \to e\alpha)$ (a) and $\mathcal{B}(\tau \to \mu\alpha)$ (b) as a function of the α mass. The dashed (solid) lines are expected (observed) upper limits. The blue line shows the observed upper limits at Belle II [6]

1.9×10^{-8} with 424 fb^{-1}, and $\tau \to e^\pm\ell^\mp\ell^-$ limits are competitive across five modes. The first Belle+Belle II combination in $\tau \to \ell K_S^0$ sets world-best bounds below 1.2×10^{-8}. Invisible-scalar searches at Belle and Belle II now provide leading constraints on $\mathcal{B}(\tau \to \ell\alpha)$ over a broad mass range. With increasing luminosity, further gains are expected from improved particle identification, enhanced low-multiplicity triggers, and multivariate analyses. Pushing sensitivities toward the 10^{-9} level across many modes is within reach, offering discovery potential for LFV τ decays and decisive tests of new-physics scenarios.

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