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ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

Tau physics at Belle II

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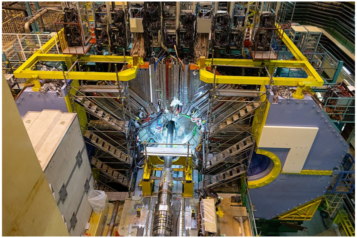
Outline:

1. Introduction
2. Measurement of τ mass at Belle II
3. Test of LFU in τ decays at Belle II
4. Search for LFV τ decays at Belle/Belle II
5. Summary

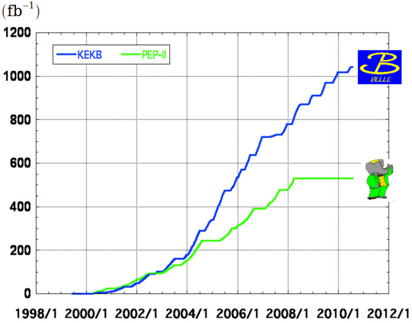


Introduction: τ physics

- In the Standard Model (SM) τ decays due to the charged weak interaction described by the exchange of $W^{\pm}$ with a pure vector coupling to only left-handed fermions. There are two main classes of tau decays:
  - Decays with leptons, like: $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$, $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau \gamma$, $\tau^- \to \ell^- \ell'^+ \ell'^- \bar{\nu}_\ell \nu_\tau$; $\ell, \ell' = e, \mu$. They provide very clean laboratory to probe electroweak couplings, which is complementary/competitive to precision studies with muon (in experiments with muon beam). Plenty of New Physics models can be tested/constrained in the precision studies of the dynamics of decays with leptons.
  - Hadronic decays of τ offer unique tools for the precision study of low energy QCD.
- The world largest statistics of τ leptons collected by e^+e^- B factories (Belle II, Belle and *BABAR*) opens new era in the precision tests of the SM.
- **Belle II is the ongoing and very promising experiment in this area.**

Introduction: Belle and *BABAR*

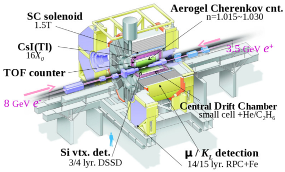
Integrated luminosity of B factories



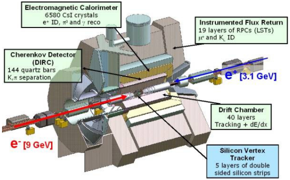
> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
$\sim$100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
$\sim$ 54 fb^{-1}

Belle Detector



BABAR detector

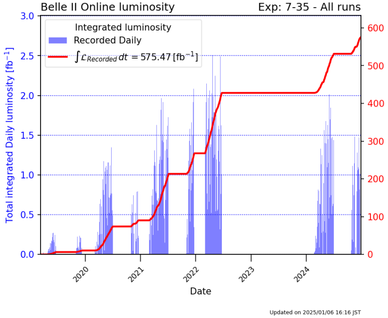


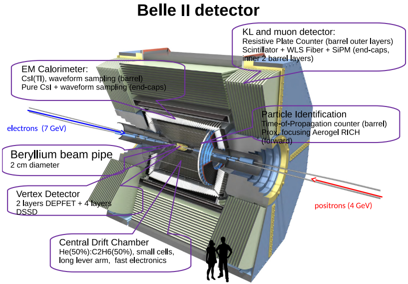
$$\sigma(b\bar{b}) = 1.05 \text{ nb } N_{b\bar{b}} = 1.2 \times 10^9$$
$$\sigma(c\bar{c}) = 1.30 \text{ nb } N_{c\bar{c}} = 2.0 \times 10^9$$
$$\sigma(\tau\tau) = 0.92 \text{ nb } N_{\tau\tau} = 1.4 \times 10^9$$

B-factories are also charm- and τ-factories !

Introduction: Belle II

Next generation e^+e^- B-factory at the HEP intensity frontier

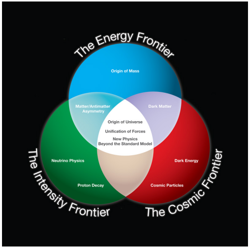




SuperKEKB luminosity record (December 2024):
5.1×10^{34} cm^{-2}s^{-1}

The project SuperKEKB luminosity: 6×10^{35} cm^{-2}s^{-1}
Planned integrated luminosity is 50 ab^{-1}

$\sigma(b\bar{b}) = 1.05$ **nb** $\quad N_{b\bar{b}} = 53 \times 10^9$
$\sigma(c\bar{c}) = 1.30$ **nb** $\quad N_{c\bar{c}} = 65 \times 10^9$
$\boldsymbol{\sigma(\tau\tau) = 0.92}$ **nb** $\quad \boldsymbol{N_{\tau\tau} = 46 \times 10^9}$



Introduction: τ properties at B factories

- **Tau mass:**

  Belle II: $m_\tau = (1777.09 \pm 0.08(\mathrm{stat}) \pm 0.11(\mathrm{syst}))$ MeV/c^2; PRD 108, 032006 (2023)

  BES3: $m_\tau = (1776.91 \pm 0.12(\mathrm{stat}) \pm {}^{0.10}_{0.13}(\mathrm{syst}))$ MeV/c^2; PRD 90, 012001 (2014)

  KEDR: $m_\tau = (1776.81 \pm {}^{0.17}_{0.19}(\mathrm{stat}) \pm 0.15(\mathrm{syst}))$ MeV/c^2; PPN 54, 185 (2023)

  Belle: $m_\tau = (1776.61 \pm 0.13(\mathrm{stat}) \pm 0.35(\mathrm{syst}))$ MeV/c^2; PRL 99, 011801 (2007)

  BABAR: $m_\tau = (1776.68 \pm 0.12(\mathrm{stat}) \pm 0.41(\mathrm{syst}))$ MeV/c^2; PRD 80, 092005 (2009)

- **Tau lifetime:**

  Belle: $\tau_\tau = (290.17 \pm 0.53(\mathrm{stat}) \pm 0.33(\mathrm{syst}))$ fs; PRL 112, 031801 (2014)

  BABAR: $\tau_\tau = (289.40 \pm 0.91(\mathrm{stat}) \pm 0.90(\mathrm{syst}))$ fs; Nucl. Phys. B 144, 105 (2005)

- **Lepton universality with $\tau \to \ell\nu\nu$ and $\tau \to h\nu$ (h=π,K):**

  Belle II $\left(\frac{g_\mu}{g_e}\right)_\tau = 0.9974 \pm 0.0019$; JHEP 08 2024, 205 (2024)

  BABAR **:** $\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$, $\left(\frac{g_\tau}{g_\mu}\right)_\mathrm{h} = 0.9850 \pm 0.0054$; PRL 105, 051602 (2010)

- **Tau electric dipole moment (EDM):**

  Belle: $-1.85 \times 10^{-17} < \mathrm{Re}(d_\tau) < 0.61 \times 10^{-17}$ e·cm (CL=95%),
  $-1.03 \times 10^{-17} < \mathrm{Im}(d_\tau) < 0.23 \times 10^{-17}$ e·cm (CL=95%);

  JHEP 04 2022, 110 (2022)

Measurement of τ mass at Belle II (I)

I. Adachi *et al.* Phys. Rev. D **108**, no.3, 032006 (2023).

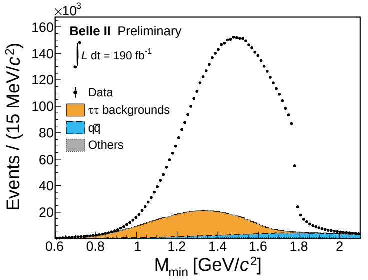
Use the data sample of $\int Ldt = 190$ fb^{-1} with $N_{\tau\tau} = 175 \times 10^6$
m_τ is measured in the decay $\tau^\mp \to \pi^\mp\pi^+\pi^-\nu$ using the pseudomass edge method

Method

$$m_\tau = \sqrt{M^2_{3\pi} + 2(E^{\rm CMS}_\tau - E^{\rm CMS}_{3\pi})(E^{\rm CMS}_{3\pi} - p^{\rm CMS}_{3\pi}\cos\alpha^{\rm CMS})}$$

$\alpha^{\rm CMS}$ is the angle between the momenta of the 3π system and the τ-neutrino,
$E^{\rm CMS}_\tau = E_{\rm beam} = \sqrt{s}/2$. The pseudomass is defined by $\alpha^{\rm CMS} = 0$:

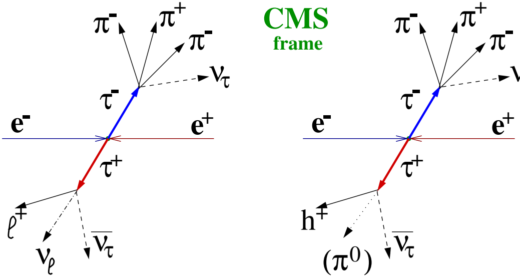
$$M_{\rm min} = \sqrt{M^2_{3\pi} + 2(\sqrt{s}/2 - E^{\rm CMS}_{3\pi})(E^{\rm CMS}_{3\pi} - p^{\rm CMS}_{3\pi})} \le m_\tau$$



In the tests of lepton universality m^5_τ appears, so m_τ accuracy is crucial

Measurement of τ mass at Belle II (II)

In the analysis the central value of the m_τ was blinded until the method was validated and statistical and systematic uncertainties were estimated.



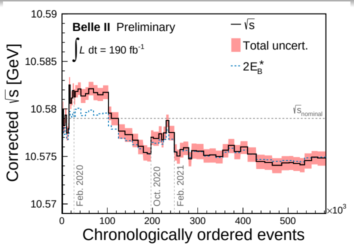
Selections

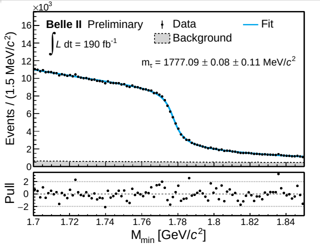
- **4-track events with zero net charge**;
- $0.87 <$thrust< 0.97, signal hemisphere: $\tau \to 3\pi\nu$, tag hemisphere: $\tau \to \ell\nu\nu,\ h\nu,\ h\pi^0\nu$;
- $E_\gamma > (60 \div 600)$ *MeV*, $115 < m_{\gamma\gamma}(\pi^0) < 152\,\text{MeV}/c^2$;
- $2.5 < E_{\text{vis}}^{\text{CMS}} < 9.0\,\text{GeV}$, $0.05 < p_{\text{miss}}^{\text{CMS}} < 3.5\,\text{GeV}/c$, $0.5 < \theta_{\text{miss}}^{\text{CMS}} < 2.7\,\text{rad}$, $0 < M_{\text{miss}}^2 < 54\,\text{GeV}^2/c^4$.

In the analyzed pseudomass range $\mathbf{1.70 < M_{min} < 1.85\,GeV/c^2}$: **purity** of the sample is **90%**, with the dominant **background** from $e^+e^- \to q\bar{q}$ (**6.4%**) and non-3π τ decays (**2.0%**).

$$\varepsilon_{\text{trig}} = 92\%,\ \varepsilon_{\text{sig}} = 2.3\%,\ N_{\text{sel}} = 583192$$

Measurement of τ mass at Belle II (III)





- Beam energy $\sqrt{s}$ was calibrated using fully reconstructed neutral and charged B-meson decays from $e^+e^- \to B\bar{B}$. The most probable $E_B^{\mathrm{CMS}} = \sqrt{m_B^2 + (p_B^{\mathrm{CMS}})^2}$ B-meson energy was corrected for the effects of the $e^+e^- \to B\bar{B}$ cross section shape and ISR to get $\sqrt{s}$.
- The momenta of charged particles are scaled depending on the charge and $\cos\theta$ to correct for imperfect magnetic-field description, misalignment of the detector, material mismodeling. The correction factors are evaluated by measuring the mass-peak position of high-yield samples of $D^0 \to K^-\pi^+$ decays reconstructed in data and comparing them to the PDG value.

m_τ is extracted from the maximum-likelihood fit of the M_{min} with:

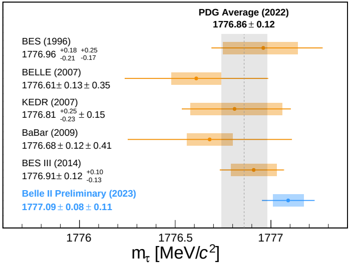
$$F = 1 - P_3 \cdot \arctan\left(\frac{M_{\mathrm{min}} - P_1}{P_2}\right) + P_4(M_{\mathrm{min}} - P_1) + P_5(M_{\mathrm{min}} - P_1)^2$$

$P_1 = 1777.49 \pm 0.08\,\mathrm{MeV}/c^2$ (estimator of m_τ) overestimates m_τ by a constant bias $0.40 \pm 0.03\,\mathrm{MeV}/c^2$ determined from MC, as result:

$$\boldsymbol{m_\tau = 1777.09 \pm 0.08\,\mathrm{MeV}/c^2}$$

Measurement of τ mass at Belle II (IV)

Source	Δm_τ, MeV/c^2
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Reconstruction of charged particles:	
Momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Imperfections of the simulation:	
Detector material density	0.03
ISR, FSR and τ decay	0.02
Total	**0.11**



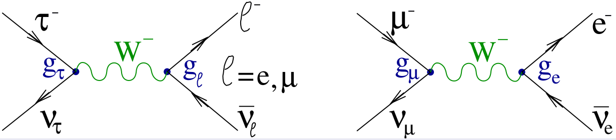
Consistency checks

- Stability of the result throughout various data-taking periods was confirmed.
- m_τ values for the data in sub-regions of various kinematic variables are consistent with each other.
- The dependence of the m_τ on the dynamics of $\tau \to \pi\pi\pi\nu$ decay is negligibly small.

$$m_\tau = 1777.09 \pm 0.08 \pm 0.11 \ \mathrm{MeV}/c^2$$

Test of LFU in τ decays at Belle II (I)

In the Standard Model: $\boldsymbol{g_e = g_\mu = g_\tau}$



$$\Gamma(L^- \to \ell^- \bar{\nu}_\ell \nu_L(\gamma)) = \frac{\mathcal{B}(L^- \to \ell^- \bar{\nu}_\ell \nu_L(\gamma))}{\tau_L} = \frac{g_L^2 g_\ell^2}{32 M_W^4} \frac{m_L^5}{192\pi^3} F_{\rm corr}(m_L, m_\ell)$$

$$F_{\rm corr}(m_L, m_\ell) = f(x)\left(1 + \frac{3}{5}\frac{m_L^2}{M_W^2}\right)\left(1 + \frac{\alpha(m_L)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right)$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x, \;\; x = m_\ell / m_L$$

$$\mathcal{B}(\mu^- \to e^- \bar{\nu}_e \nu_\mu(\gamma)) = \mathcal{B}(\mu^- \to e^- \bar{\nu}_e \nu_\mu) + \mathcal{B}(\mu^- \to e^- \bar{\nu}_e \nu_\mu \gamma) + \ldots = 1$$

$$\frac{g_\tau}{g_e} = \sqrt{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\rm corr}(m_\mu, m_e)}{F_{\rm corr}(m_\tau, m_\mu)}}, \;\; \frac{\mathbf{g}_\tau}{\mathbf{g_e}} = \mathbf{1.0027 \pm 0.0014} \text{ (HFLAV2022)}$$

$$\frac{g_\tau}{g_\mu} = \sqrt{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\rm corr}(m_\mu, m_e)}{F_{\rm corr}(m_\tau, m_e)}}, \;\; \frac{\mathbf{g}_\tau}{\mathbf{g}_\mu} = \mathbf{1.0009 \pm 0.0014} \text{ (HFLAV2022)}$$

$$\frac{g_\mu}{g_e} = \sqrt{\frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau(\gamma))}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau(\gamma))} \frac{F_{\rm corr}(m_\tau, m_e)}{F_{\rm corr}(m_\tau, m_\mu)}}, \;\; \frac{\mathbf{g}_\mu}{\mathbf{g_e}} = \mathbf{1.0019 \pm 0.0014} \text{ (HFLAV2022)}$$

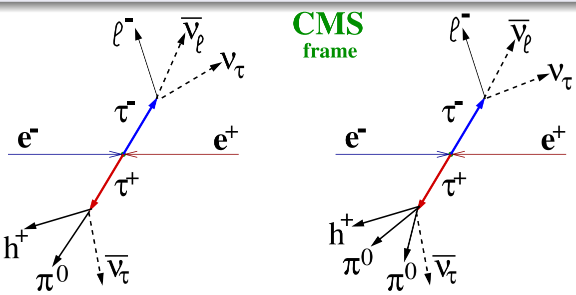
Test of LFU in τ decays at Belle II (II)

I. Adachi *et al.* JHEP **08**, 205 (2024).

Use the data sample of $\int Ldt = 362$ fb^{-1} with $N_{\tau\tau} = 333 \times 10^6$
Both τ leptonic decay modes $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ and $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ are studied

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}, \quad \left|\frac{g_\mu}{g_e}\right|_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

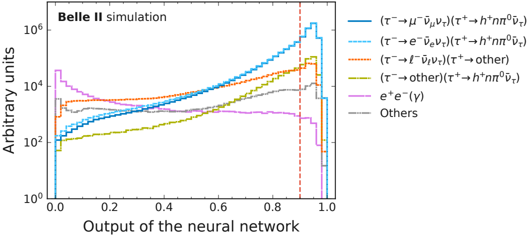


The plane perpendicular to the thrust axis divides event into two hemispheres: one charge particle in the signal hemisphere and one charge particle with one or two π^0 candidates in the tag hemisphere.

Test of LFU in τ decays at Belle II (III)

Selections

- **2-track events with zero net charge**;
- thrust$>$ 0.85, $M^2_{\rm miss} < 20 + 40 * p^{\rm CMS}_{T,\rm miss}$ MeV/c^2;
- $E_\gamma > (30 \div 80)$ MeV, $120 < m_{\gamma\gamma} < 145$ MeV/c^2, $\psi_{\gamma\gamma} < 1.4$ rad, $|\Delta\varphi_\gamma| <$ 1.5 rad, $\varepsilon_{\pi^0 \rm ID} \approx 30\%$;
- signal side: $\mathcal{P}_e > 0.5$, $\mathcal{P}_\mu > 0.9$, $1.5 < p_\ell < 5$ GeV/c, $0.82 < \theta_\ell < 2.13$ rad; $\varepsilon_{eID} = 99.7\%$, $\varepsilon_{\mu ID} = 93.9\%$;
- tag side: $E_{\rm ECL}/pc < 0.8$, 1 or 2 π^0 candidates;
- signal and background MC events were used to train neural network classifier (NNC) including 7 variables: thrust, $\theta_{\rm thrust}$, $E^{\rm CMS}_{\rm vis}$, $\theta^{\rm CMS}_{\rm miss}$, $p^{\rm CMS}_{hn\pi^0}$, $\theta^{\rm CMS}_{hn\pi^0}$, $m^{\rm CMS}_{hn\pi^0}$. NNC>0.9



e-sample:
$\varepsilon_{\rm trig} = 99.8\%$, $\varepsilon_{\rm det} = 9.60\%$
4358376 selected events
the purity is 96%

μ-sample:
$\varepsilon_{\rm trig} = 96.6\%$, $\varepsilon_{\rm det} = 9.55\%$
4371737 selected events
the purity is 92%

The dominant background comes from the other τ decays.

Method

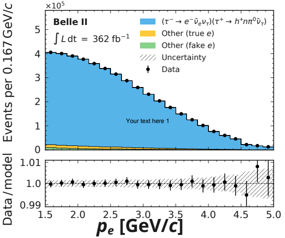
Binned likelihood fit of the momentum distributions in 21 bins was used to extract $\boldsymbol{R_\mu}$. The templates for the signal and background distributions are derived from MC.

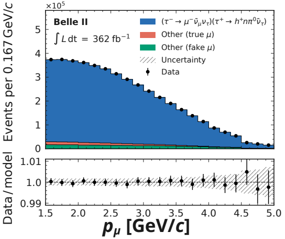
$$L(R_\mu, \vec{\chi}) = \prod_{b\in\text{bins}} \mathcal{P}(n_b^e \mid \nu_b^e(\vec{\chi})) \prod_{b\in\text{bins}} \mathcal{P}(n_b^\mu \mid \nu_b^\mu(\boldsymbol{R_\mu}, \vec{\chi})) \prod_{\chi\in\vec{\chi}} c_\chi(a_\chi \mid \chi)$$

$$\nu_b^e(\vec{\chi}) = \kappa_e \nu_b^{e\text{-sig}}(\vec{\chi}) + \nu_b^{e\text{-bkg(true)}}(\vec{\chi}) + \nu_b^{e\text{-bkg(fake)}}(\vec{\chi}),$$

$$\nu_b^\mu(R_\mu, \vec{\chi}) = \boldsymbol{R_\mu} \kappa_{e/\mu}^{\text{gen}} \kappa_e \nu_b^{\mu\text{-sig}}(\vec{\chi}) + \nu_b^{\mu\text{-bkg(true)}}(\vec{\chi}) + \nu_b^{\mu\text{-bkg(fake)}}(\vec{\chi}),$$

n_b^e, n_b^μ - numbers of observed events in bin b. ν_b^e, ν_b^μ - numbers of expected MC events in bin b. Systematic uncertainties are included as a set of nuisance parameters $\vec{\chi}$.
$\nu_b^{e\text{-sig}}, \nu_b^{\mu\text{-sig}}$ - signal yields. $\nu_b^{e\text{-bkg(true)}}, \nu_b^{\mu\text{-bkg(true)}}, \nu_b^{e\text{-bkg(fake)}}, \nu_b^{\mu\text{-bkg(fake)}}$ - background yields.
κ_e - free normalization parameter. $\kappa_{e/\mu}^{\text{gen}} = \mathcal{B}_e^{\text{gen}}/\mathcal{B}_\mu^{\text{gen}}$.

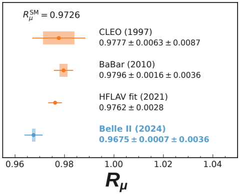


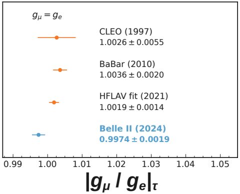


The method was validated with MC. To estimate uncertainties using data the central value of the $\boldsymbol{R_\mu}$ was blinded with help of the random $\kappa_{e/\mu}^{\text{gen}}$.

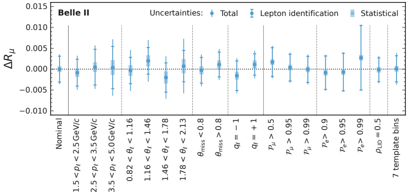
Test of LFU in τ decays at Belle II (V)

Source	Uncertainty [%]	
Charged-particle identification:	0.32	
Electron identification		0.22
Muon misidentification		0.19
Electron misidentification		0.12
Muon identification		0.05
Imperfections of the simulation:	0.14	
Modelling of FSR		0.08
Normalisation of individual processes		0.07
Modelling of the momentum distribution		0.06
Tag side modelling		0.05
π^0 efficiency		0.02
Particle decay-in-flight		0.02
Trigger	0.10	
Size of the simulated samples	0.06	
Luminosity	0.01	
Total	0.37	





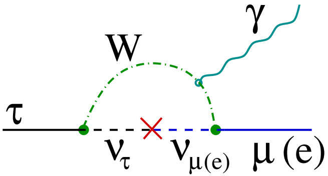
Consistency check



$$R_\mu = 0.9675 \pm 0.0007 \pm 0.0036$$

$$\left|\frac{g_\mu}{g_e}\right|_\tau = 0.9974 \pm 0.0019$$

Lepton-flavor-violating (LFV) τ decays

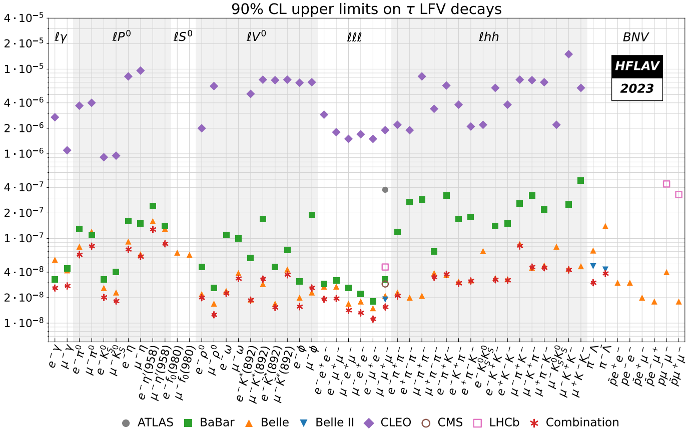


Model	$\mathcal{B}(\tau \to \mu\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
mSUGRA+seesaw	10^{-8}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-8}

- Probabililty of LFV decays of charged leptons is extremely small in the Standard Model, $\mathcal{B}(\tau \to \ell\nu) \sim \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$
- Many models beyond the SM predict LFV decays with the branching fractions up to $\lesssim 10^{-8}$. As a result observation of LFV is a clear signature of New Physics (NP).
- τ lepton is an excellent laboratory to search for the LFV decays due to the enhanced couplings to the new particles as well as large number of LFV decay modes.
- Study of the different τ LFV decay modes allows us to test various NP models.

Results on LFV decays of τ

52 different LFV modes were studied mostly at B factories



Recent Belle II (+ Belle) results:

$\mathcal{B}(\tau^- \to \mu^-\mu^-\mu^+) < 1.9 \times 10^{-8}$ (CL=90%) JHEP **09**, 062 (2024)

$\mathcal{B}(\tau^- \to \Lambda\pi^-(\bar{\Lambda}\pi^-)) < 4.7(4.3) \times 10^{-8}$ (CL=90%) PRD **110**, no.11, 112003 (2024)

$\mathcal{B}(\tau \to e\ell\ell) < (1.3 \div 2.5) \times 10^{-8}$ (CL=90%) arXiv:2507.18236 [hep-ex]

$\mathcal{B}(\tau^- \to e^- K^0_S(\mu^- K^0_S)) < 0.8(1.2) \times 10^{-8}$ (CL=90%) arXiv:2504.15745 [hep-ex]

Search for LFV $\tau \to \ell\alpha$ at Belle (I)

K. Uno *et al.* [Belle], arXiv:2503.22195 [hep-ex].

Use Belle data sample of $\int Ldt = 800$ fb^{-1} with $N_{\tau\tau} = 736 \times 10^6$

The idea is to search for a peak in the distribution of the signal lepton momentum p_ℓ^τ in the τ rest frame. The peak position depends on the mass of the invisible 0-spin α-particle.

Selections

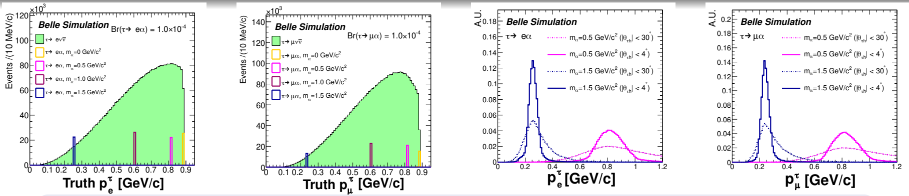
The plane perpendicular to the thrust axis divides event into two hemispheres: one charge particle in the signal hemisphere and 1- or 3-prong τ decay in the tag hemisphere.

- **2-track or 4-track events with zero net charge**;
- **criteria are optimized to maximize** $\mathrm{FOM} = \varepsilon_{\mathrm{sig}}/\sqrt{N_{\mathrm{bkg}}}$;
- $2 < E_{\mathrm{vis}}^{\mathrm{CMS}} < 10$ GeV; photons: $E_\gamma > 0.1$ GeV, $-0.625 < \cos\theta_\gamma < 0.846$; π^0 candidates: $120 < m_{\gamma\gamma} < 135$ MeV/c^2; no photons and π^0s on the signal side, $N_\gamma < 4$ for 1-prong and $N_\gamma < 2$ for 3-prong events on the tag side.
- **signal side:** $\mathcal{P}_e > 0.9$, $\varepsilon_{e\mathrm{ID}} = (80 \div 91)\%$; $\mathcal{P}_\mu > 0.95$, $\varepsilon_{\mu\mathrm{ID}} = (80 \div 88)\%$;
- $e\alpha(\mu\alpha)$: thrust$> 0.85(0.87)$; for 1-prong tag $-0.88 < \cos\theta_{\mathrm{miss}} < 0.95$ $(-0.87 < \cos\theta_{\mathrm{miss}} < 0.97)$; for 3-prong tag $-0.90 < \cos\theta_{\mathrm{miss}} < 0.99$ $(-0.98 < \cos\theta_{\mathrm{miss}} < 0.99)$; $\sum \vec{p}_T > 0.1(0.4)$ GeV/c; for 1-prong tag $\sum \vec{p}_{T,\mathrm{sig}} > 0.2$ GeV/c and $\sum \vec{p}_{T,\mathrm{tag}} > 0.2$ GeV/c, $p_\ell^{\mathrm{CMS}} < 5.0$ GeV/c ($p_\ell^{\mathrm{CMS}} < 4.8$ GeV/c);
- **to validate the procedure the control channel $\tau^- \to \pi^-\pi^0\nu_\tau$ is used.**

The dominant background comes from ordinary leptonic τ decays.

$$N_{\mathrm{sel}}(\tau \to e\alpha) = 3390311,\ \varepsilon_{\mathrm{det}}(\tau \to e\alpha) = (0.9 \div 1.4)\%$$
$$N_{\mathrm{sel}}(\tau \to \mu\alpha) = 3757311,\ \varepsilon_{\mathrm{det}}(\tau \to \mu\alpha) = (0.3 \div 1.5)\%$$

Search for LFV $\tau \to \ell\alpha$ at Belle (II)

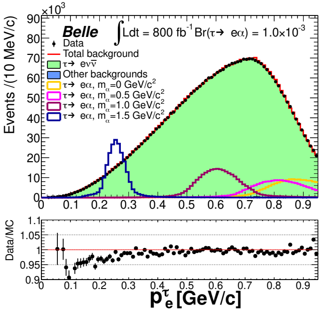


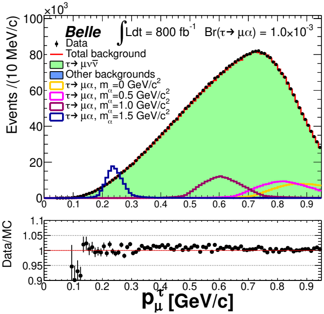
- Signal τ flight direction is taken as $\vec{n}_{\tau_{\rm sig}} = -\vec{p}_{h_{\rm tag}}/|\vec{p}_{h_{\rm tag}}|$, where $\vec{p}_{h_{\rm tag}}$ is the total momentum of the detected particles ($h_{\rm tag}$) on the tag side. To improve the p_ℓ^τ resolution, $|\theta_{\tau h}| < 4^\circ$ is applied, where:

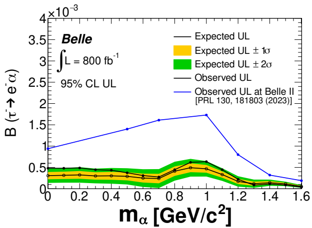
$$\theta_{\tau h} = \arccos\left(\frac{2E_\tau^{\rm CMS}E_{h_{\rm tag}}^{\rm CMS} - m_\tau^2 - m_{h_{\rm tag}}^2}{2p_\tau^{\rm CMS}p_{h_{\rm tag}}^{\rm CMS}}\right),\ E_\tau^{\rm CMS} = E_{\rm beam}^{\rm CMS},\ p_\tau^{\rm CMS} = \sqrt{(E_\tau^{\rm CMS})^2 - m_\tau^2}.$$

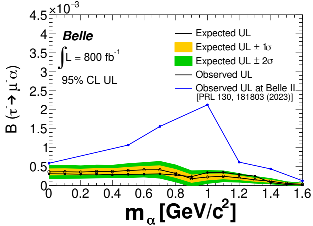
- **The p_ℓ^τ experimental distribution is blinded before the whole analysis procedure is established and validated.**
- Binned extended maximum-likelihood fit of the p_ℓ^τ distribution is performed in 17 α-mass points for both types of the final state in the range $0 < p_\ell^\tau < 0.95\,{\rm GeV}/c$. Signal and background PDFs are taken from MC. The signal ($n_{\rm sig}$) and total background yields are free parameters in the fit.
- No significant excess of the signal events is observed in the data, upper limit on the $\mathcal{B}(\tau^- \to \ell^-\alpha)$ at 95% CL is set following frequentist approach ($\varepsilon_{\rm det}$-detection efficiency for a given α mass): $UL(\mathcal{B}(\tau^- \to \ell^-\alpha)) = \frac{n_{\rm sig}^{0.95}}{2\varepsilon_{\rm det}N_{\tau\tau}}$.
- $1/(2\varepsilon_{\rm det}N_{\tau\tau})$ systematic uncertainty ((5.1 ÷ 6.0)% for $e\alpha$ and (4.7 ÷ 6.2)% for $\mu\alpha$) as well as systematic uncertainties in the PDF modeling are taken into account.

Search for LFV $\tau \to \ell\alpha$ at Belle (III)









$\mathcal{B}(\tau^- \to e^-\alpha) < (0.4 \div 6.4) \times 10^{-4}$, $\mathcal{B}(\tau^- \to \mu^-\alpha) < (0.2 \div 3.5) \times 10^{-4}$ **95% CL**

Summary

- **The world largest statistics of τ leptons collected by Belle and Belle II allows us to perform precision tests of the Standard Model and search for the effects of New Physics.**
- With the statistics of 190 fb^{-1} τ mass has been measured at Belle II:
$$m_\tau = 1777.09 \pm 0.08 \pm 0.11\ \mathrm{MeV}/c^2$$
Belle II result has the best accuracy and improved the accuracy of the world average τ mass by a factor of 1.3.
- Using data sample of 362 fb^{-1} Belle II tested lepton flavor universality measuring the ratio $R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$:
$$R_\mu = 0.9675 \pm 0.0007 \pm 0.0036$$
$$\left|\frac{g_\mu}{g_e}\right|_\tau = 0.9974 \pm 0.0019$$
Belle II result has the best accuracy and improved the accuracy of the $\left|\frac{g_\mu}{g_e}\right|_\tau$ ratio by a factor of 1.3.
- Recently Belle II performed a search for a number of LFV τ decays, and improved upper limits on the branching ratios:
$$\mathcal{B}(\tau^- \to \mu^-\mu^-\mu^+) < 1.9 \times 10^{-8}\ \text{(CL=90\%)}$$
$$\mathcal{B}(\tau^- \to \Lambda\pi^-(\bar{\Lambda}\pi^-)) < 4.7(4.3) \times 10^{-8}\ \text{(CL=90\%)}$$
$$\mathcal{B}(\tau \to e\ell\ell) < (1.3 \div 2.5) \times 10^{-8}\ \text{(CL=90\%)}$$
- Combined Belle+Belle II data sample of 1.4 ab^{-1} was used to measure the upper limit on the $\mathcal{B}(\tau^- \to \ell^- K^0_S)$ for the first time:
$$\mathcal{B}(\tau^- \to e^- K^0_S(\mu^- K^0_S)) < 0.8(1.2) \times 10^{-8}\ \text{(CL=90\%)}$$
- With the statistics of 800 fb^{-1} Belle performed a search for LFV $\tau^- \to \ell^-\alpha$ decay (α is neutral 0-spin invisible particle) and got the best upper limit on the $\mathcal{B}(\tau^- \to \ell^-\alpha)$:
$$\mathcal{B}(\tau^- \to e^-\alpha) < (0.4 \div 6.4) \times 10^{-4},\ \mathcal{B}(\tau^- \to \mu^-\alpha) < (0.2 \div 3.5) \times 10^{-4}\ 95\%\,\text{CL}$$
- **More interesting results on τ from Belle and Belle II will come soon, stay tuned !**

Backup slides

LFU test status

HFLAV-Tau report (arXiv:2411.18639) after Belle II results on m_τ and R_μ