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

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on behalf of the Belle & Belle II collaborations

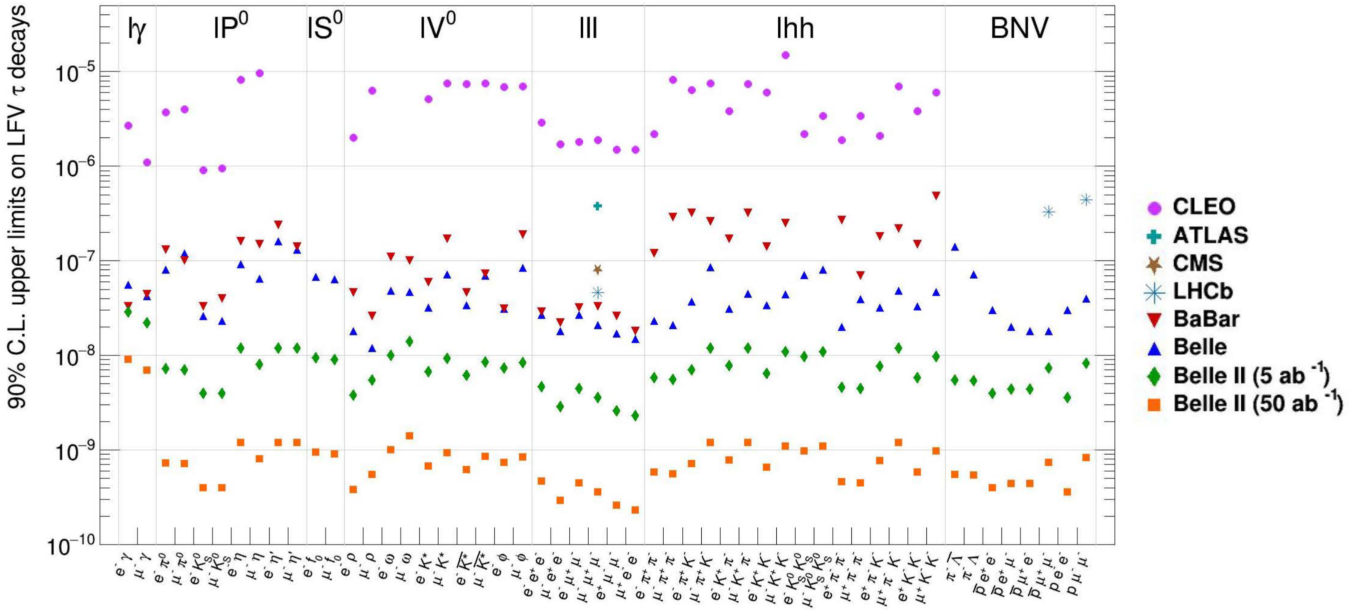
ICHEP 2024 conference - 18 July 2024

LFV τ Decays at Belle & Belle II

- **Lepton Flavor Violation (LFV)**
  - LFV has long been recognized as unambiguous signature of New Physics;
  - LFV is allowed in various extensions of the Standard Model (SM) but it has never been observed.

- **Search for LFV in 52 benchmark τ decays:**
  - Radiative decays: $\tau \to \ell\gamma$;
  - leptonic decays: $\tau \to \ell\ell\ell$;
  - semi-leptonic decays: $\tau \to \ell + \text{hadron(s)}$;
  - BNV decays: $\tau \to p(\bar{p})\ell\ell$、$\tau \to \Lambda(\bar{\Lambda})\pi$.

Existing and expected limits on LFV τ decays [1]



[1] Snowmass 2021: cLFV in τ sector - arXiv:2203.14919

B(τ)-factories: Belle & Belle II

- **Clean environment** at asymmetric energy e^+e^- collider ~ **hermetic detector:**
  - at $\sqrt{s} = 10.58$ GeV: $\sigma_{bb} \cong 1.1$ nb ~ $\sigma_{\tau\tau} \cong 0.9$ nb, **B & τ factory**;
  - known **initial state** + efficient reconstruction of **neutrals** (π^0, η), **recoiling system** and **missing energy**;
  - specific **low-multiplicity triggers (at Belle II)**.

- **Advantages of Belle and Belle II in τ LFV searches:**
  - the increase of the luminosity;
  - the increase of the signal detection efficiency and background suppression:
    - ✓ on clean environment,
    - ✓ high trigger efficiency,
    - ✓ zero background searches

Belle: $\int \mathcal{L}dt \approx 1000\ \mathrm{fb}^{-1}$

Belle II: $\int \mathcal{L}dt \approx 427\ \mathrm{fb}^{-1}$ in Run1 (2018 - 2022)
: $\int \mathcal{L}dt \approx 103\ \mathrm{fb}^{-1}$ in Run2 (2024 -)

τ LFV channels

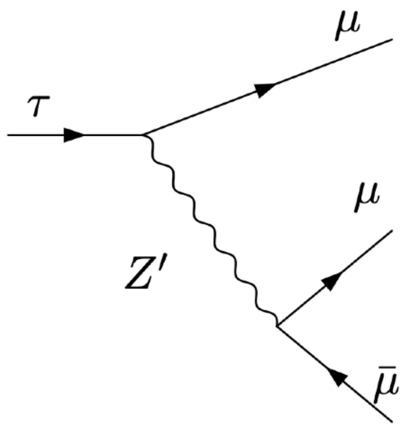
- **Search for various decay models:**
  - $\tau \to \ell\ell\ell$
  - $\tau \to \ell K_S, \Lambda\pi$
  - $\tau \to \ell V^0(\to hh')$
  - $\tau \to \ell P^0(\to \gamma\gamma)$
  - $\tau \to \ell hh'$
  - $\tau \to \ell\gamma$

higher background

Simple: good determination of m_τ and E_τ, few SM background sources

Golden channel: $\tau \to \mu\mu\mu$

experimentally the most accessible



- **Motivation:** the decay channels forbidden in the SM but allowed in several new physics scenarios
  - LFV decay $\tau \to \ell V^0$
    - ✓ The $\tau \to \mu\phi$ mode is a sensitive probe for leptoquark models
  - BNV decay $\tau \to \Lambda(\bar{\Lambda})\pi$
    - ✓ BNV is one of the necessary conditions to explain the asymmetry of matter
    - ✓ Beyond SM scenarios allow for BNV and LNV
  - LFV decay $\tau \to \mu\mu\mu$ **(Golden channel)**

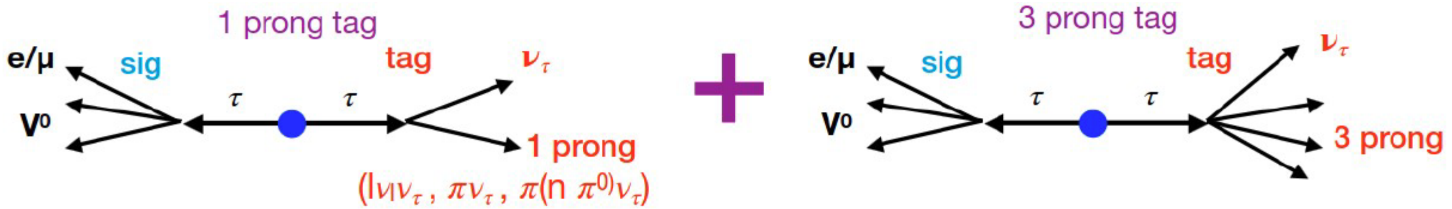
Physics Models	$\mathcal{B}(\tau \to \mu\mu\mu)$
SM	10^{-53}~10^{-55}
SM + seesaw	10^{-10}
SUSY + Higgs	10^{-8}
SUSY + SO(10)	10^{-10}
Non-universal Z'	10^{-8}

Search for LFV decay $\tau \to \ell V^0$ at Belle

- **Previous search at Belle on 854 fb^{-1} exploiting 1-prong tag [1]:**
  - ➢ $V^0 = \rho, \omega, \phi, K^{*0}$, and $\bar{K}^{*0}$;
  - ➢ set 90% C.L. upper limits on the branching fractions in the range of $(1.2{\sim}8.4) \times 10^{-8}$.
- **Latest results [2]:**

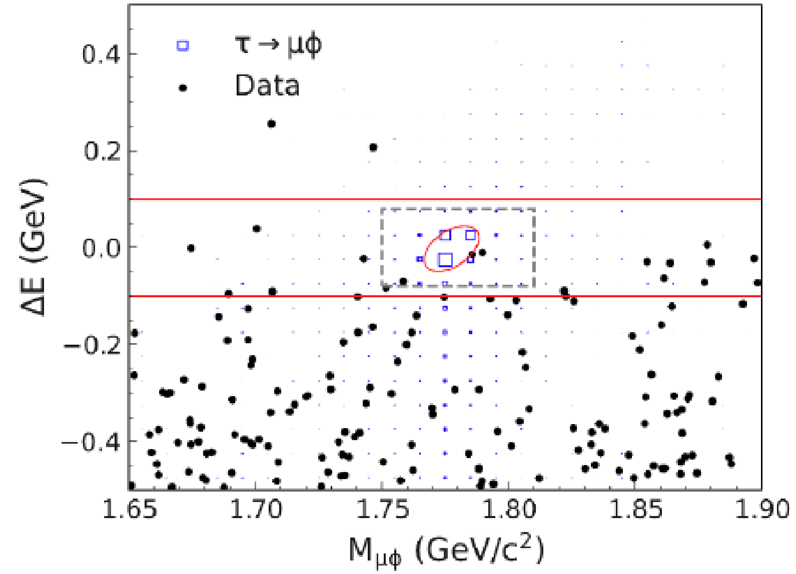
JHEP06(2023)118

  - ➢ full data set of 980 fb^{-1} ;
  - ➢ more decay modes in the tag side;

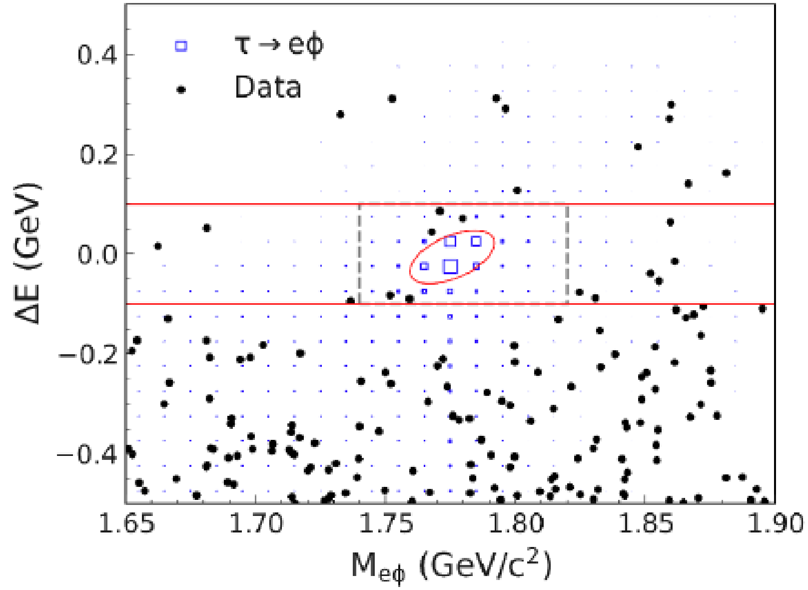


  - ➢ further suppress $\tau \to 3\pi\nu$ and $ee \to q\bar{q}$ with BDT;
  - ➢ Estimate expected background in SR from sideband interpolation.

$$M_{\ell V^0} = \sqrt{E^2_{\ell V^0} - P^2_{\ell V^0}}$$



$$\Delta E = E^{CM}_{\ell V^0} - \sqrt{s}/2$$



[1] Y. Miyazaki, *et.al*, (Belle collaboration) Phys. Lett. B 699, 251 (2011).

[2] N. Tsuzuki, *et, al*, (Belle collaboration) JHEP 2023, 118, (2023).

Search for LFV decay $\tau \to \ell V^0$ at Belle

JHEP06(2023)118

- **No significant access in all modes → set ULs at 90% C.L.**
- **30% improvement over previous measurements:**
  - increased statistics (124 fb^{-1});
  - higher signal efficiency (9%) .

$\mathcal{B}(\tau \to eV^0) < (1.7\sim2.4) \times 10^{-8}$

$\mathcal{B}(\tau \to \mu V^0) < (1.7\sim4.3) \times 10^{-8}$

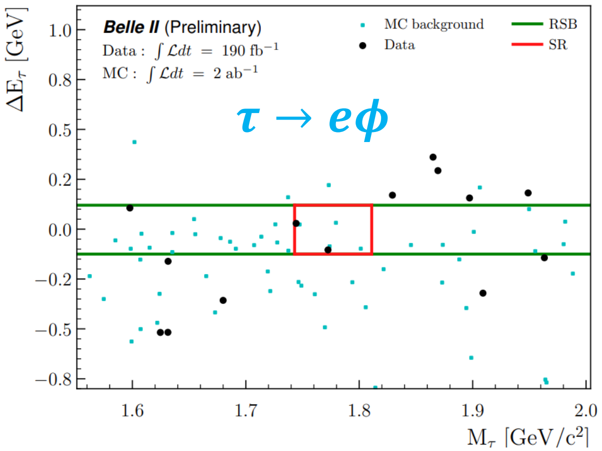
Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	$\mathcal{B}_{\rm obs}$ ($\times 10^{-8}$)
$\tau^\pm \to \mu^\pm \rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	$<$ 1.7
$\tau^\pm \to e^\pm \rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	$<$ 2.2
$\tau^\pm \to \mu^\pm \phi$	5.59	0.47±0.15(stat.) ±0.05(syst.)	4.8	0	$<$ 2.3
$\tau^\pm \to e^\pm \phi$	6.45	0.38±0.21(stat.) ±0.00(syst.)	4.5	0	$<$ 2.0
$\tau^\pm \to \mu^\pm \omega$	3.27	0.32±0.23(stat.) ±0.19(syst.)	4.8	0	$<$ 3.9
$\tau^\pm \to e^\pm \omega$	5.41	0.74±0.43(stat.) ±0.06(syst.)	4.5	0	$<$ 2.4
$\tau^\pm \to \mu^\pm K^{*0}$	4.52	0.84±0.25(stat.) ±0.31(syst.)	4.3	0	$<$ 2.9
$\tau^\pm \to e^\pm K^{*0}$	6.94	0.54±0.21(stat.) ±0.16(syst.)	4.1	0	$<$ 1.9
$\tau^\pm \to \mu^\pm \overline{K}^{*0}$	4.58	0.58±0.17(stat.) ±0.12(syst.)	4.3	1	$<$ 4.3
$\tau^\pm \to e^\pm \overline{K}^{*0}$	7.45	0.25±0.11(stat.) ±0.02(syst.)	4.1	0	$<$ 1.7

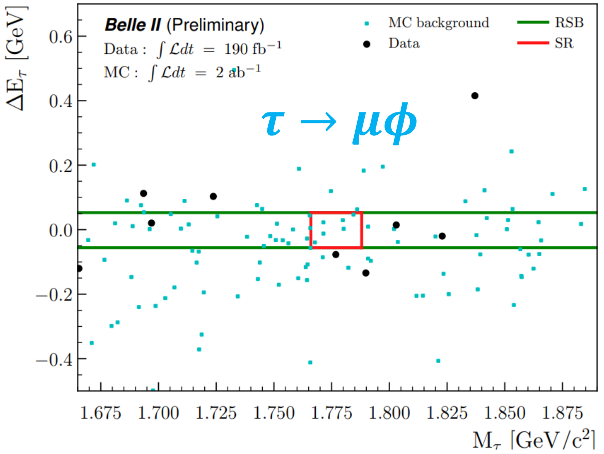
World leading results

Search for LFV decay $\tau \to \ell\phi$ at Belle II

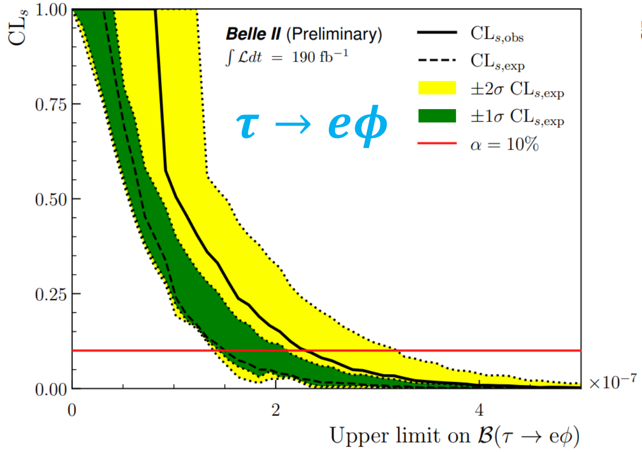
- **Untagged inclusive reconstruction, reconstruct signal side as phi meson + lepton candidate, assign everything else (neutral clusters, tracks) to the rest of event (ROE):**
  - higher signal efficiency (~16% improvement), more background;
  - backgrounds reduced with pre selections and a BDT trained against $q\bar{q}$ events.

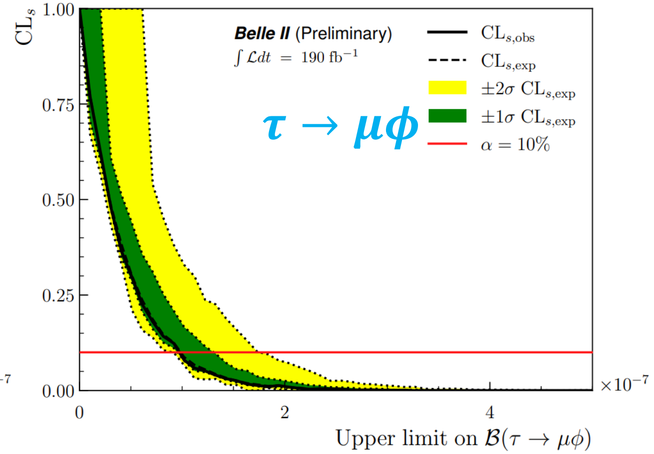
arXiv:2305.04759





Experiment	Lum (fb^{-1})	$\mathcal{B}^{90}_{UL}(e\phi)$ ($\times 10^{-8}$) exp. / obs.	$\mathcal{B}^{90}_{UL}(\mu\phi)$ ($\times 10^{-8}$) exp. / obs.
BaBar [1]	451	5.0 / 3.1	8.2 / 19
Belle	854	4.3 / 3.1	4.9 / 8.4
Belle II	190	15 / 23	9.9 / 9.7





Results not competitive yet (Small data set);

↓

First, successfully untagged strategy approach for tau physics at Belle II;

↓

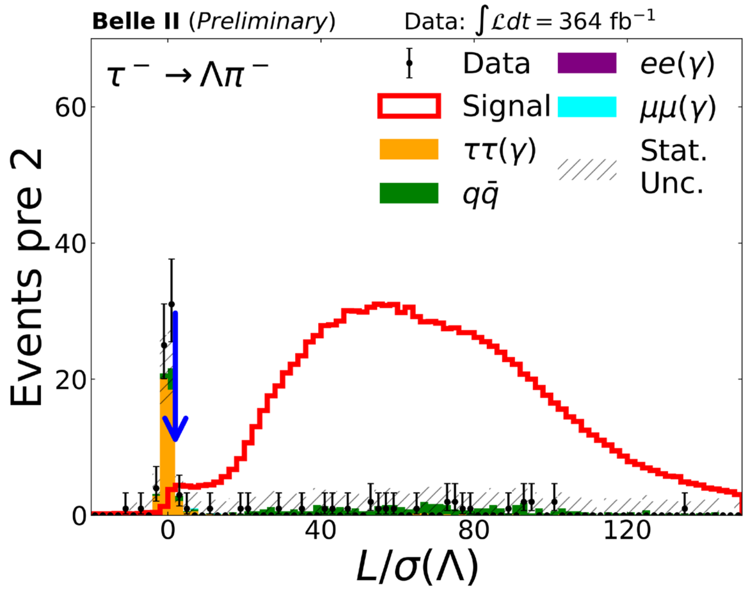
exploited for other measurements;

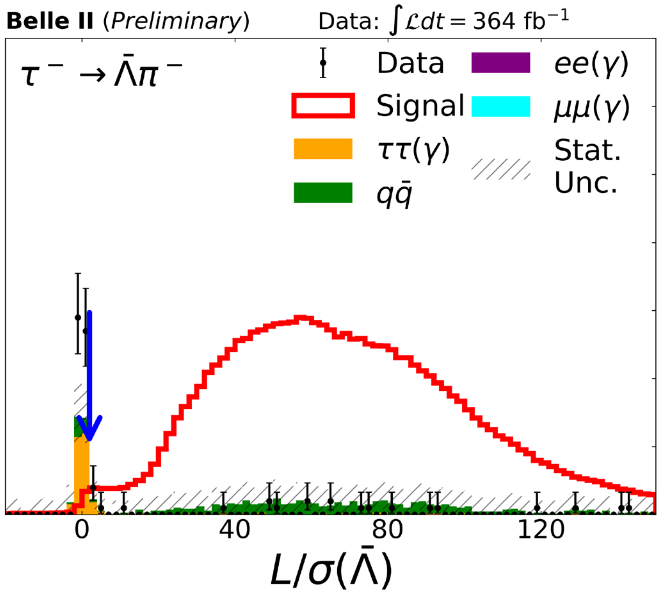
[1] B. Aubert, *et al.*, (BaBar Collaboration), Phys. Rev. Lett. 103, 021801 (2009).

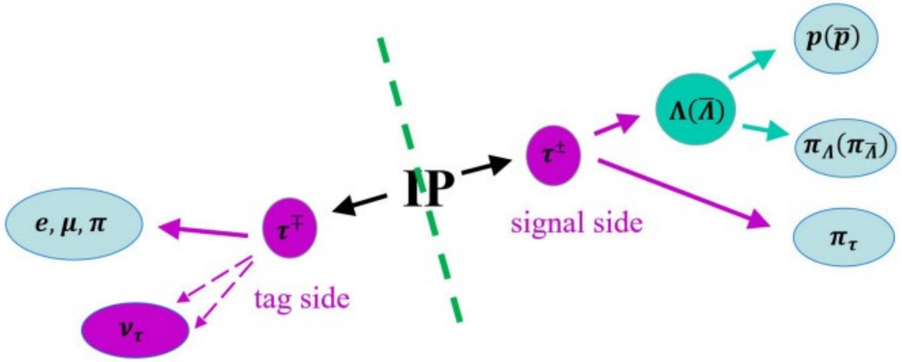
Search for BNV decay $\tau \to \Lambda(\bar{\Lambda})\pi$ at Belle II

- **A baryon number violation decay that is also an LFV decay.**
- **Previous search on 154 fb^{-1} at Belle [1] set limits at 90% C.L. of $0.72(1.4) \times 10^{-7}$ for $\mathcal{B}(\tau \to \Lambda(\bar{\Lambda})\pi)$.**
- **At Belle II:**
  - Reconstruct exactly 4 charged tracks (total null charge) in one-prong tag approach;
  - $\Lambda(\bar{\Lambda})$ is reconstructed from proton (anti-proton) and pion;
  - Signal selection and background suppression using loose pre-selection, followed by Gradient-BDT;
    - ✓ The flight significance (L/σ) of Λ and $\bar{\Lambda}$ candidates is one of the most discriminant variables.

arXiv:2407.05117





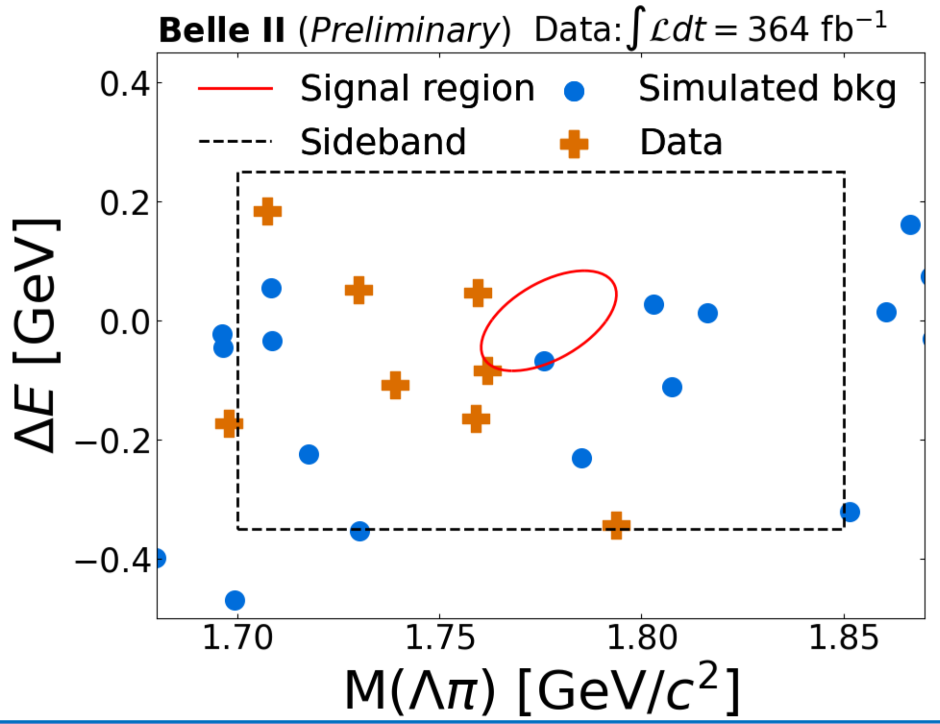


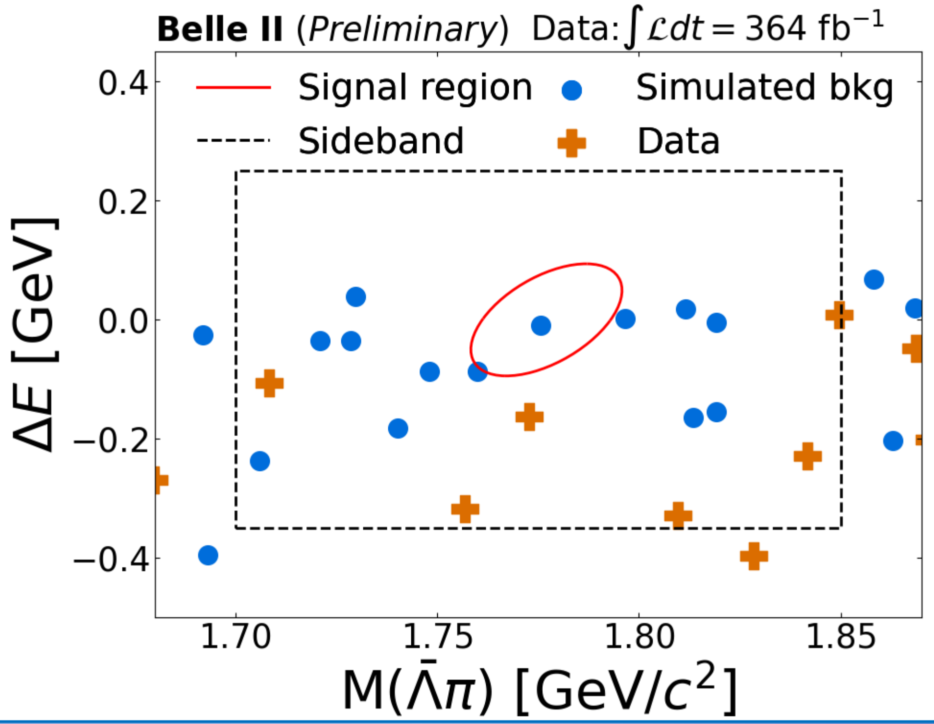
[1] Y. Miyazaki, *et al.*, (Belle Collaboration), Phys. Lett. B **632**, 51 (2006).

Search for BNV decay $\tau \to \Lambda(\bar{\Lambda})\pi$ at Belle II

arXiv:2407.05117

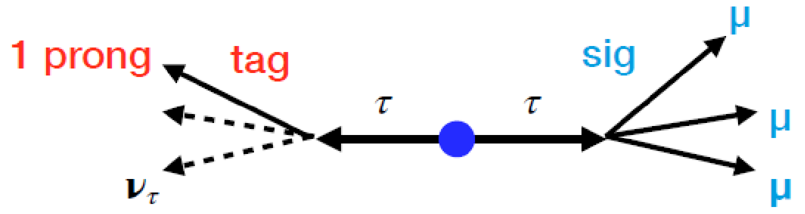
- Signal efficiencies are 9.5% and 9.9% for $\tau \to \Lambda\pi$ and $\tau \to \bar{\Lambda}\pi$;
- Poisson counting experiment technique in signal region in the $M(\Lambda\pi) = \sqrt{E_{\Lambda\pi}^2 - P_{\Lambda\pi}^2}$ and $\Delta E = E_{\Lambda\pi}^{CM} - \sqrt{s}/2$ plane;
- Expected events are 1 and 0.5 for $\tau \to \Lambda\pi$ and $\tau \to \bar{\Lambda}\pi$;
- No observed events;
- World's best upper limits at 90% C.L. of 4.7×10^{-8} for $\mathcal{B}(\tau \to \Lambda\pi)$ and 4.3×10^{-8} for $\mathcal{B}(\tau \to \bar{\Lambda}\pi)$;



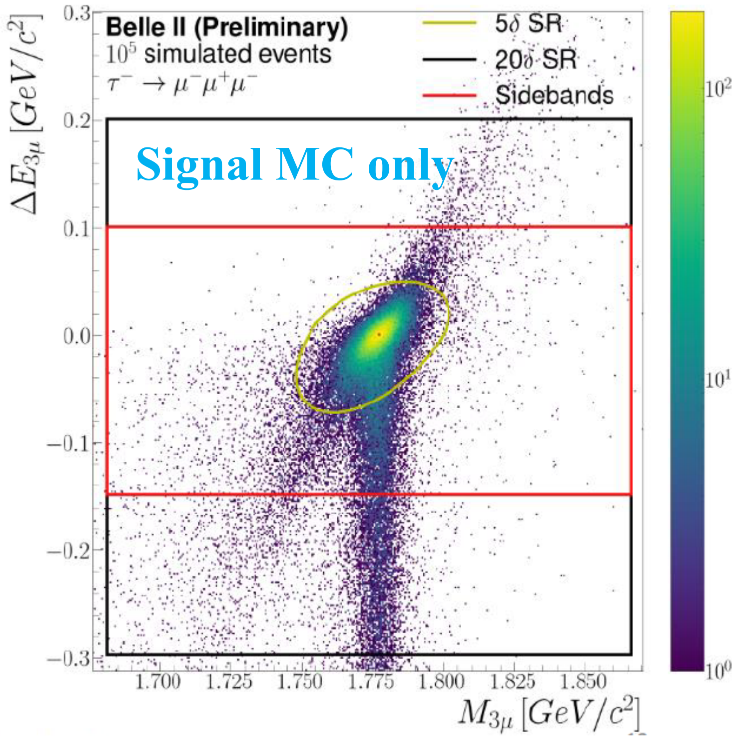


Search for LFV decay $\tau \to \mu\mu\mu$ at Belle II

- **Previous results from Belle: 2.1×10^{-8} at 90% C.L. with 782 fb^{-1} [1].**
  - Signal side: three muons;
  - Tag side: 1-track τ decay (events with 4 tracks) ;



- **Belle II with 424 fb^{-1}**



arXiv:2405.07386

- Extract signal yield from 2D plane ($M_{3\mu}$, $\Delta E_{3\mu}$):

$$M_{3\mu} = \sqrt{E_{3\mu}^2 - P_{3\mu}^2}$$

$$\Delta E_{3\mu} = E_{3\mu}^{CM} - E_{\text{beam}}^{CM}$$

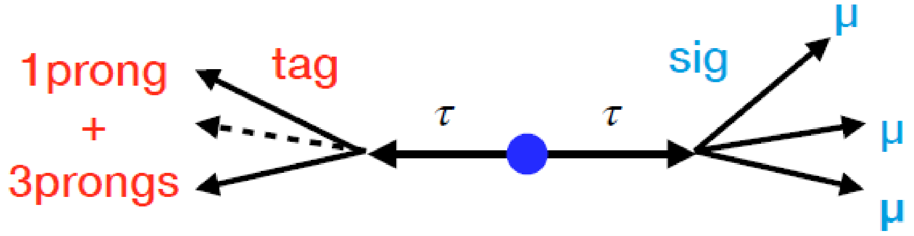
- For signal:
  - ✓ $\Delta E_{3\mu}$ close to 0 and $M_{3\mu}$ close to τ mass;
  - ✓ Tails due to initial and final state radiation.

[1] K. Hayasaka, *et al.*, (Belle Collaboration) Phys. Lett. B 687, 139 (2010).

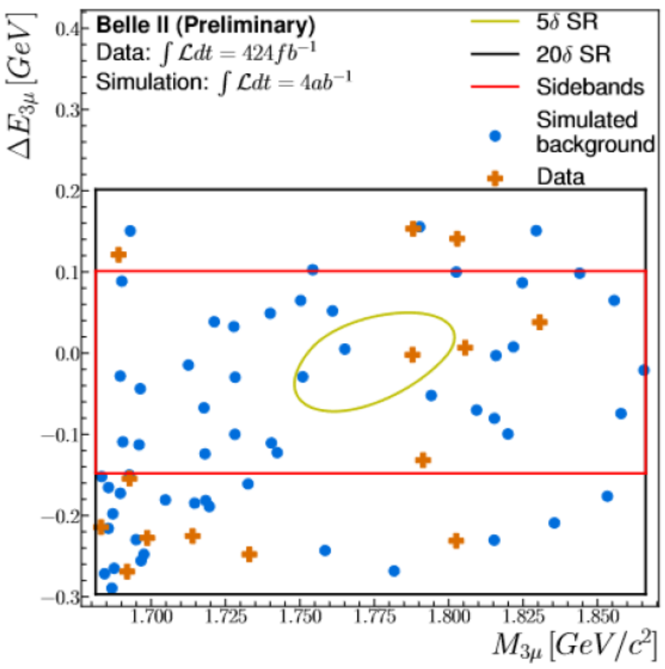
Search for LFV decay $\tau \to \mu\mu\mu$ at Belle II

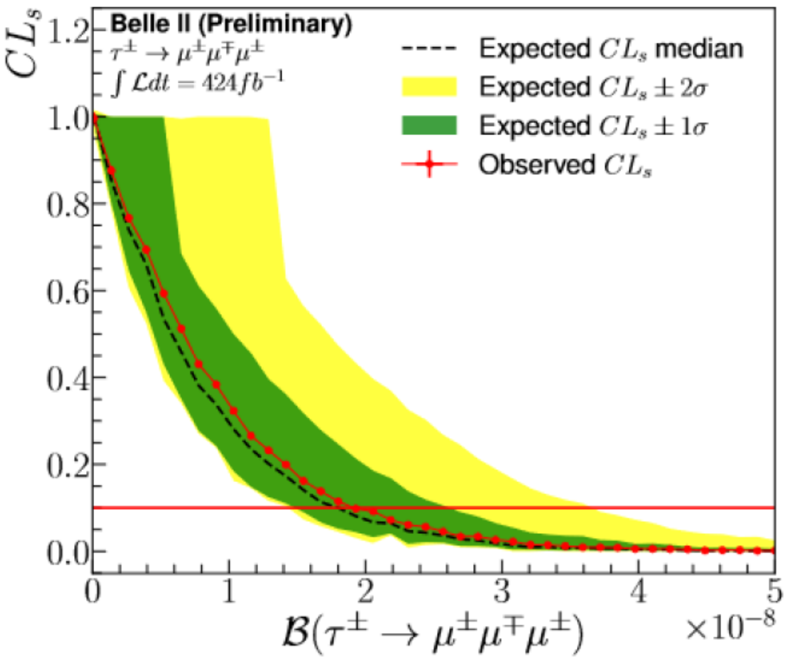
arXiv:2405.07386

- Main analysis approach:
  - ✓ Inclusion of 3×1 and 3×3 toplogies;
  - ✓ Selection and background rejection using BDT;



- Signal: efficiency: 20.4% (2.7 × Belle efficiency);
- Number of expected BG: 0.5;
- 1 event observed inside the SR;
- $\mathcal{B}(\tau \to 3\mu) < 1.9 \times 10^{-8}$ at 90% C.L.;





Most stringent limit to date

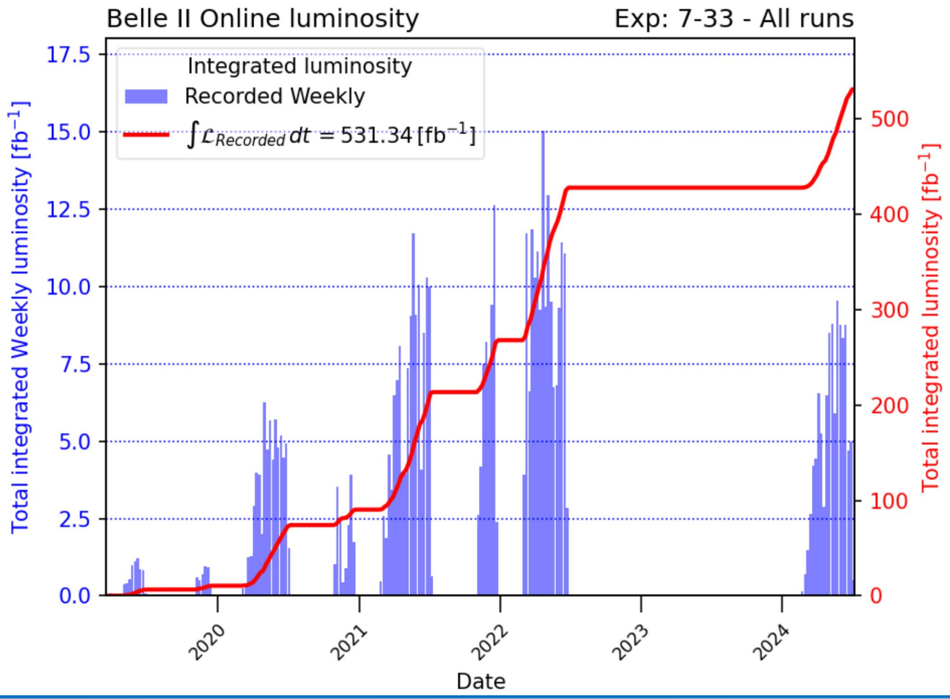
	UL at 90% C.L. on $\mathcal{B}(\tau \to 3\mu)$
ATLAS	3.8×10^{-7} ($\mathcal{L} = 20.3$ fb^{-1})
LHCb	4.6×10^{-8} ($\mathcal{L} = 3.0$ fb^{-1})
CMS	2.9×10^{-8} ($\mathcal{L} = 131$ fb^{-1})
Belle	2.1×10^{-8} ($\mathcal{L} = 782$ fb^{-1})
BaBar	3.3×10^{-8} ($\mathcal{L} = 486$ fb^{-1})
Belle II	1.9×10^{-8} ($\mathcal{L} = 424$ fb^{-1})

Summary

- **New high profile searches:**
  - LFV decay $\tau \to \ell V^0$ at Belle;
  - LFV decay $\tau \to \mu\mu\mu$ and BNV decay $\tau \to \Lambda(\bar{\Lambda})\pi$ at Belle II.

World leading results

- **More results are on the way.**



Backup

Estimate N_{BG}:

$$F(M_{\ell V^0}, \Delta E) = f(M_{\ell V^0}) \times \frac{1}{1+\exp[a_y(\Delta E - y_0)]} + c_0^{\text{flat}}, \tag{4.2}$$

$$f(x) = \begin{cases} \int_{x-5\sigma}^{x+5\sigma} g(x') \times \frac{1}{\sqrt{2\pi}\sigma}\exp\left[\frac{-(x-x')^2}{2\sigma^2}\right] \mathrm{d}x' \quad (V^0 = \rho^0, \omega) \\ c_1(x-x_0)^2 + c_0 \quad (V^0 = K^{*0}, \overline{K}^{*0}) \\ c_0 \quad (V^0 = \phi) \end{cases} \tag{4.3}$$

$$g(x) = \begin{cases} c_1[(x-x_0)^2 + k(x-x_0)] + c_0 \quad (x < x_0, V^0 = \rho^0) \\ c_1(x-x_0) + c_0 \quad (x < x_0, V^0 = \omega) \\ c_0 \quad (x \geq x_0) \end{cases}$$

where $f(x)$ represents the background distribution as a function of $M_{\ell V^0}$; c_1, c_0, x_0, and k are parameters that define the shape of the function; a_y represents sharpness of the sigmoid function along the ΔE axis; y_0 is the center of the sigmoid function; and c_0^{flat} is a term of flat background events in the $M_{\ell V^0}$–ΔE plane. We define $f(x)$ for each V^0 in eq. (4.3) and the functions for the $\ell\rho^0$ ($\ell\omega$) modes are smeared by a Gaussian with standard deviation (σ) of 6.6 (9.6) MeV/c^2. This σ corresponds to the mass resolution that affects the edge of the $M_{\ell V^0}$ distribution close to the τ mass for the $\tau^+\tau^-$ background. The edge is broad for the other modes owing to wrong mass assignment of fake kaons. The $\tau^+\tau^-$ background events for the $\ell\phi$ modes are included in c_0 because they are flat along the $M_{\ell V^0}$ axis in $1.65\,\text{GeV}/c^2 < M_{\ell V^0} < 1.9\,\text{GeV}/c^2$.

Search for LFV devay $\tau \to \ell V^0$ at Belle

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}_{obs}$ ($\times 10^{-8}$)
$\tau^\pm \to \mu^\pm \rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	< 1.7
$\tau^\pm \to e^\pm \rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	< 2.2
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World leading results

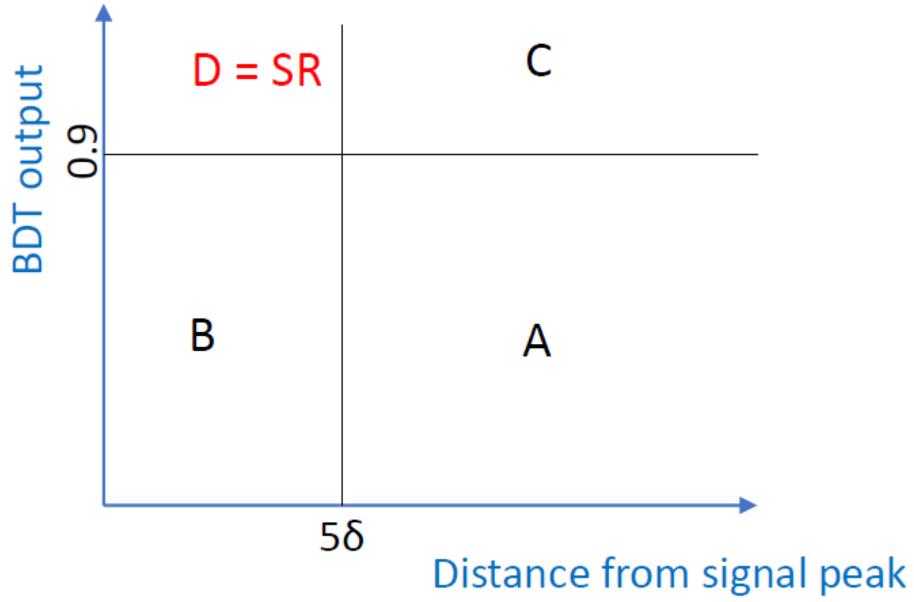
- **Reasons why $\tau^\pm \to \ell^\pm \rho^0$ did not get world leading results:**
  - $\tau^\pm \to \mu^\pm \rho^0$: use the Bayesian limits instead of the Frequentist limits, which are negatively proportional to N_{BG} when N_{obs} is fixed.
  - $\tau^\pm \to e^\pm \rho^0$: after unblinding, one event is observed in the signal region and the N_{BG} is greater than previously expected.

Expected background in SR and BR measurement

Use a data-driven method 'ABCD' based on 2 uncorrelated variables : BDT output and distance to the signal peak

$ND = NB \times NC / NA = 0.5^{+1.4}_{-0.5}$

Method validated with simulation



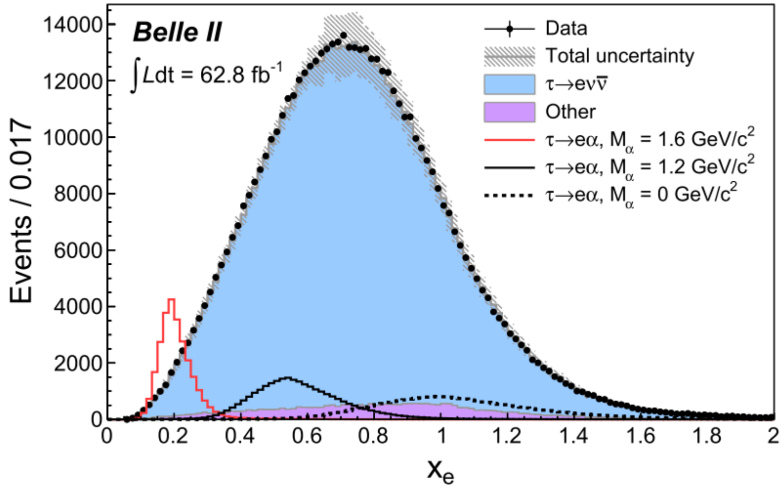
Search of $\tau \to \ell\alpha$ at Belle II

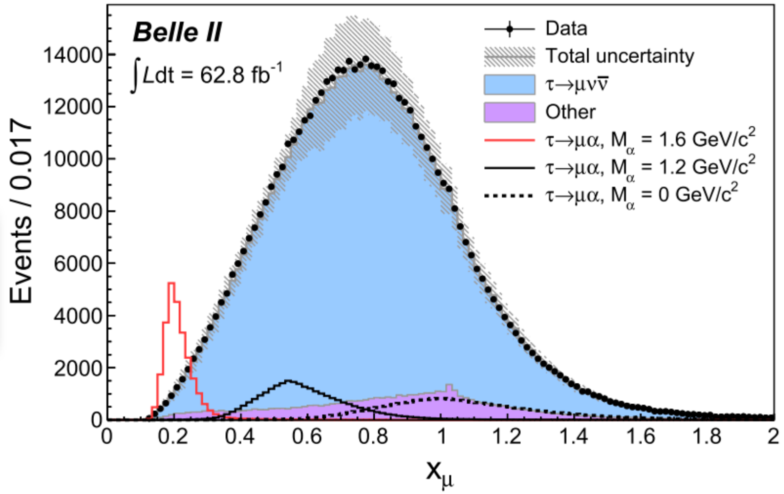
PRL 130 (2023) 181803

- **α is invisible spin-0 boson.**
  - Predicted by many models trying to incorporate neutrino-oscillation, muon magnetic moment anomaly or indirect evidence of dark matter in SM.
- **This direct search probes BSM theories with high sensitivity.**
- **Previous limits from ARGUS [1]: (Result from 1995)**
  - 10^{-2} to 10^{-3}; 0.5 fb^{-1} of data;
- **Tag tau is reconstructed via $\tau^+ \to h^+h^-h^+\bar{\nu}_\tau$ ($h = \pi, K$).**
- **Tau momentum is unknown.**
  - Pseudo rest frame is used ($\vec{p}_\tau \approx -\vec{p}_{3h}/|\vec{p}_{3h}|$);
  - Look for an excess above $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ background;

$$x_\ell \equiv \frac{E_\ell^*}{m_\tau c^2/2}$$

where E_ℓ^* is the energy of the charged lepton in the τ pseudo rest frame.





[1] H. Albrecht, et.al, (ARGUS Collaboration), Z.Phys.C 68, 25 (1995).

Search of $\tau \to \ell\alpha$ at Belle II

- **Simulation derived templates fit for different α mass hypotheses.**
- **ULs are 2 to 14 times more stringent than ARGUS.**
- **Measure $\mathcal{B}_{\ell\alpha}/\mathcal{B}_{\ell\bar{\nu}\nu} \equiv \mathcal{B}(\tau^- \to \ell^-\alpha)/\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$ with $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ as normalization channel.**
- **$\int \mathcal{L}\,dt = 62.8\ \mathrm{fb}^{-1} \sim 58$ Million $ee \to \tau\tau$.**

M_α [GeV/c^2]	$\mathcal{B}_{e\alpha}/\mathcal{B}_{e\bar{\nu}\nu}$ ($\times10^{-3}$)	UL at 95% C.L. ($\times10^{-3}$)	UL at 90% C.L. ($\times10^{-3}$)
0.0	-8.1 ± 3.9	5.3(0.94)	4.3(0.76)
0.5	-0.9 ± 4.3	7.8(1.40)	6.5(1.15)
0.7	1.7 ± 4.0	9.0(1.61)	7.6(1.36)
1.0	1.7 ± 4.2	9.7(1.73)	8.2(1.47)
1.2	-1.1 ± 2.6	4.5(0.80)	3.7(0.66)
1.4	-0.3 ± 1.0	1.8(0.32)	1.5(0.26)
1.6	0.2 ± 0.5	1.1(0.19)	0.9(0.16)

M_α [GeV/c^2]	$\mathcal{B}_{\mu\alpha}/\mathcal{B}_{\mu\bar{\nu}\nu}$ ($\times10^{-3}$)	UL at 95% C.L. ($\times10^{-3}$)	UL at 90% C.L. ($\times10^{-3}$)
0.0	-9.4 ± 3.7	3.4(0.59)	2.7(0.47)
0.5	-3.2 ± 3.9	6.2(1.07)	5.1(0.88)
0.7	2.7 ± 3.4	9.0(1.56)	7.8(1.35)
1.0	1.7 ± 5.4	12.2(2.13)	10.3(1.80)
1.2	-0.2 ± 2.4	3.6(0.62)	2.9(0.51)
1.4	0.9 ± 0.9	2.5(0.44)	2.2(0.38)
1.6	-0.3 ± 0.5	0.7(0.13)	0.6(0.10)