Tau LFV/LFU measurements

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On behalf of the Belle II collaboration
17th International Conference on Heavy Quarks and Leptons
Beijing, 15.09.2025

Outline

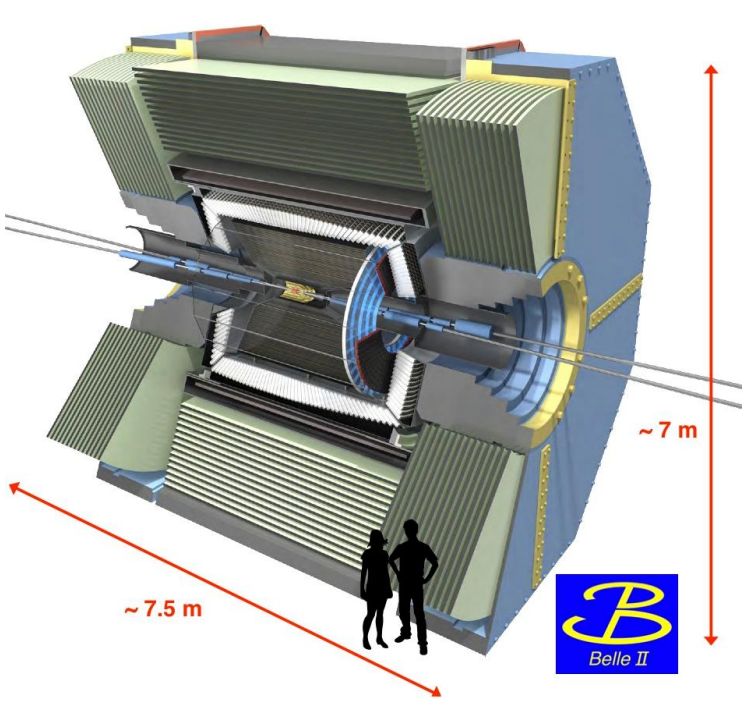
- Motivation
- Experimental Method
- Testing Lepton Flavor Universality (**LFU**) in τ decays
- Searching for Lepton Flavor Violation (**LFV**) in τ decays
- Outlook and conclusion

Why τ decays?

- τ pairs produced by e^+e^- collisions provide a unique laboratory
  → Test the Standard Model (**SM**) through precision measurements
  → Search for non-SM physics
- High-precision measurements of SM properties: Study of hadronization, light LFU, determination of mass and lifetime
  → Mostly limited by systematics
  → Requires understanding of detector performance and background modeling to control systematic uncertainties
- World-leading sensitivities for direct searches, target rare or forbidden processes ($\tau \to \mu\mu\mu, \tau \to \ell V^0$, etc.)
  → Statistically limited
  → Larger data sets, new techniques to increase signal efficiency and reduce backgrounds, new detectors

Working at B(τ) - factories

- Clean environment at e^+e^-colliders
- Ongoing experiment: Belle II
  → At $\sqrt{s} = 10.58$ GeV: $\sigma(b\bar{b}) \approx \sigma(\tau\tau) \approx 1$ nb → B & τ-factory
  → Known initial states + efficient reconstruction of neutrals (π^0 and η), recoiling system, and missing energy
  → Specific low-multiplicity triggers (not available at Belle)

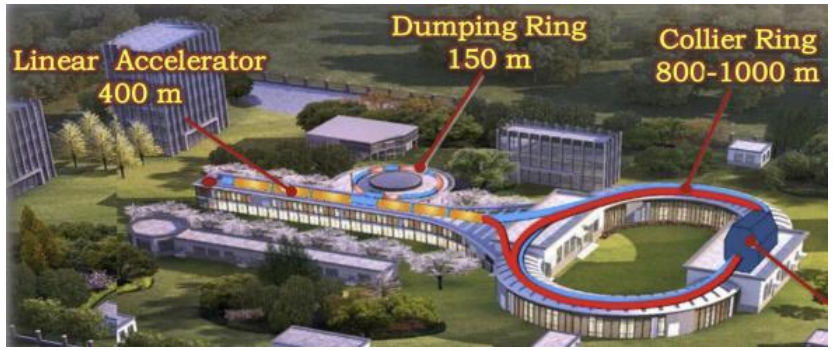


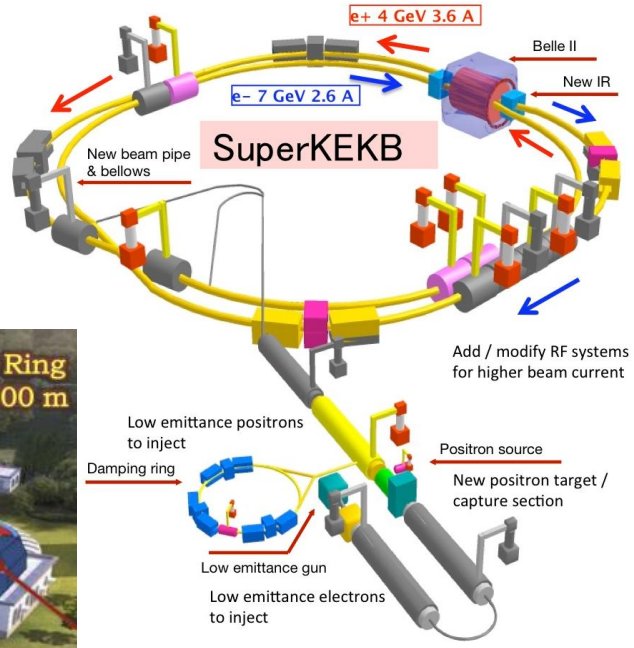
Current datasets:

- BaBar (1999-2008): 0.5 ab^{-1}
- Belle (1999-2010): 1 ab^{-1}
- Belle II: Run1 (2019-2022) + Run2 (2024-present) 0.6 ab^{-1}

Future dataset:

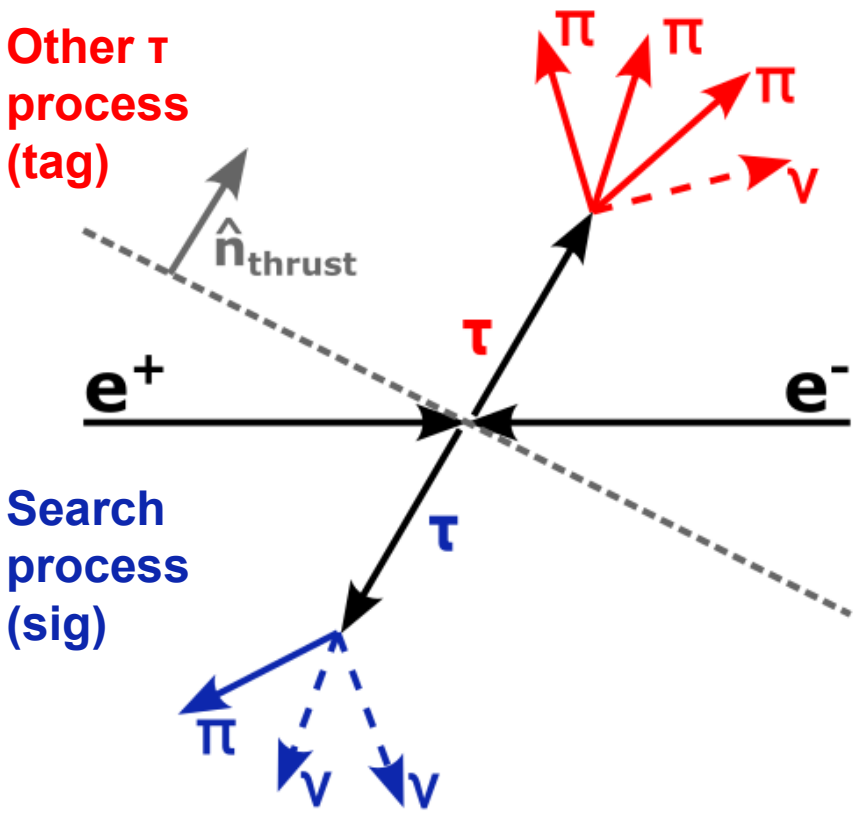
- Belle II:
  30 × KEKB peak luminosity → $6 \times 10^{35} cm^{-2} s^{-1}$
  50 × BELLE integrated luminosity → 50 ab^{-1}
  → 4.6×10^{10} τ pairs
- Future super τ-charm factory (STCF)
  1 ab^{-1}/per year at 4-5 GeV (3.5×10^9 τ pairs pairs)





τ topologies and signatures

- τ pairs in $e^+e^- \to \tau\tau$ events are produced back-to-back in center-of-mass system
- Separation into two hemispheres defined by the plane perpendicular to the thrust axis $\hat{n}_{thrust}$



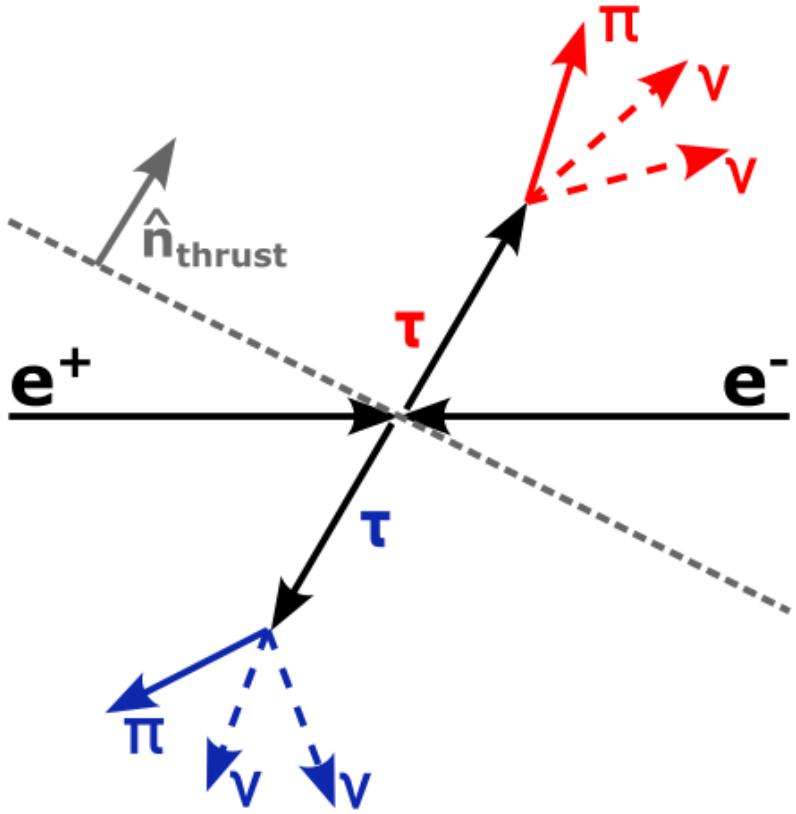
Use different topologies:

(1x3) vs (1x1)

Define best topologies for each analysis, e.g., to suppress background

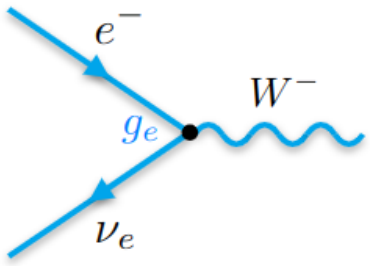
$$T = \max_{\hat{n}_{thrust}} \left(\frac{\sum_i |p_i \cdot \hat{n}_{thrust}|}{\sum_i |p_i|} \right)$$

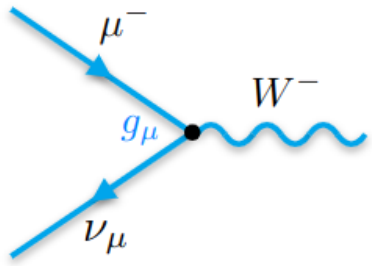
$\hat{n}_{thrust}$, the best approximation of the τ flight direction

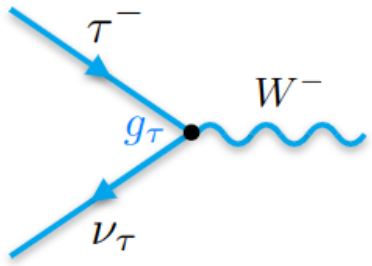


Lepton Flavor Universality

The W boson of the SM couples equally to all charged leptons (LFU): $g_e = g_\mu = g_\tau$







- Experimentally often tested via branching ratio ratios to cancel systematic uncertainties e.g.:

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

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

- A deviation from 1 would directly hint to physics beyond the SM

τ properties at B factories

LFU test with lepton – properties

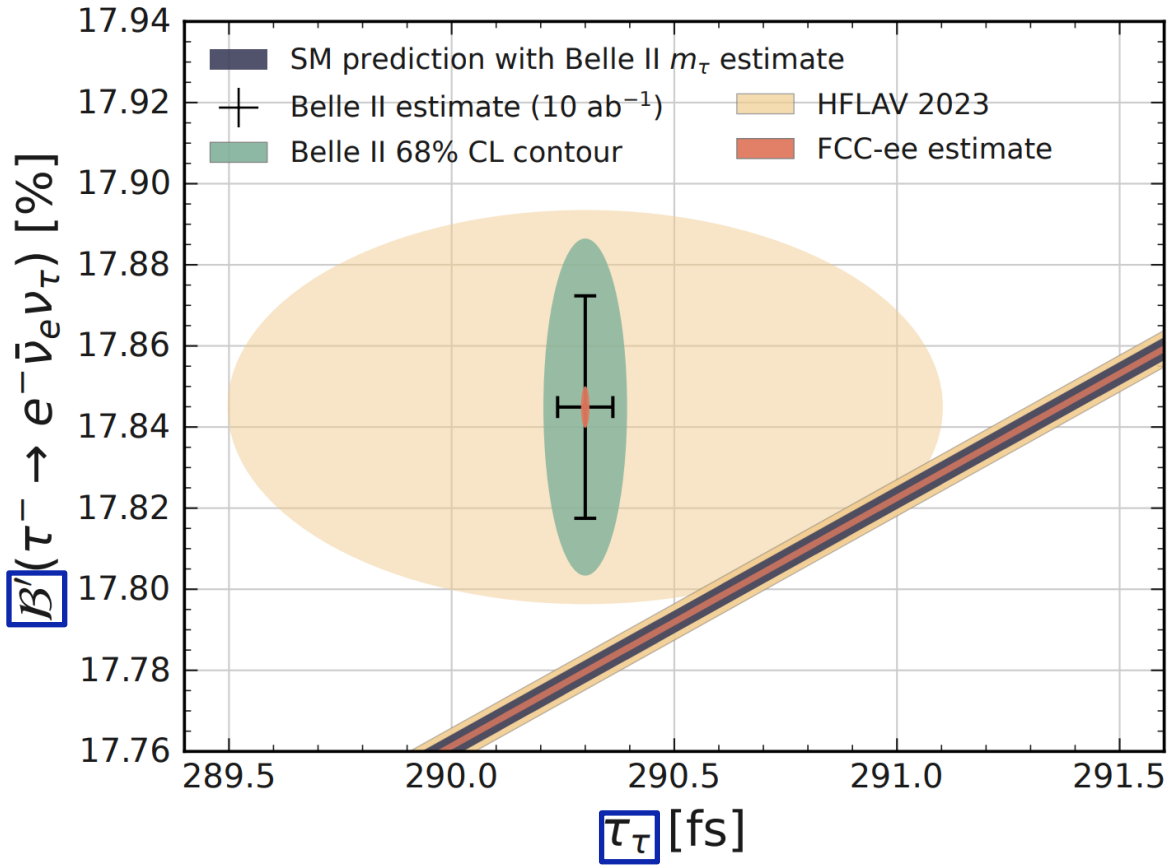
https://agenda.infn.it/event/44943/contributions/266592/attachments/137404/206425/TAU_ESPP_Venice.pdf

τ mass (MeV/c^2):

Experiment	Value	Stat.	Syst.	Reference
Belle II	1777.09	± 0.08	± 0.11	PRD 108, 032006 (2023)
BES3	1776.91	± 0.12	± 0.12	PRD 90, 012001 (2014)
KEDR	1776.81	± 0.18	± 0.15	PPN 54, 185 (2023)
Belle	1776.61	± 0.13	± 0.35	PRL 99, 011801 (2007)
BaBar	1776.68	± 0.12	± 0.41	PRD 80, 092005 (2009)

τ lifetime (fs):

Experiment	Value	Stat.	Syst.	Reference
Belle	290.17	± 0.53	± 0.33	PRL 112, 031801 (2014)
BaBar	289.40	± 0.91	± 0.90	Nucl. Phys. B 144, 105 (2005)



BR τ lepton:

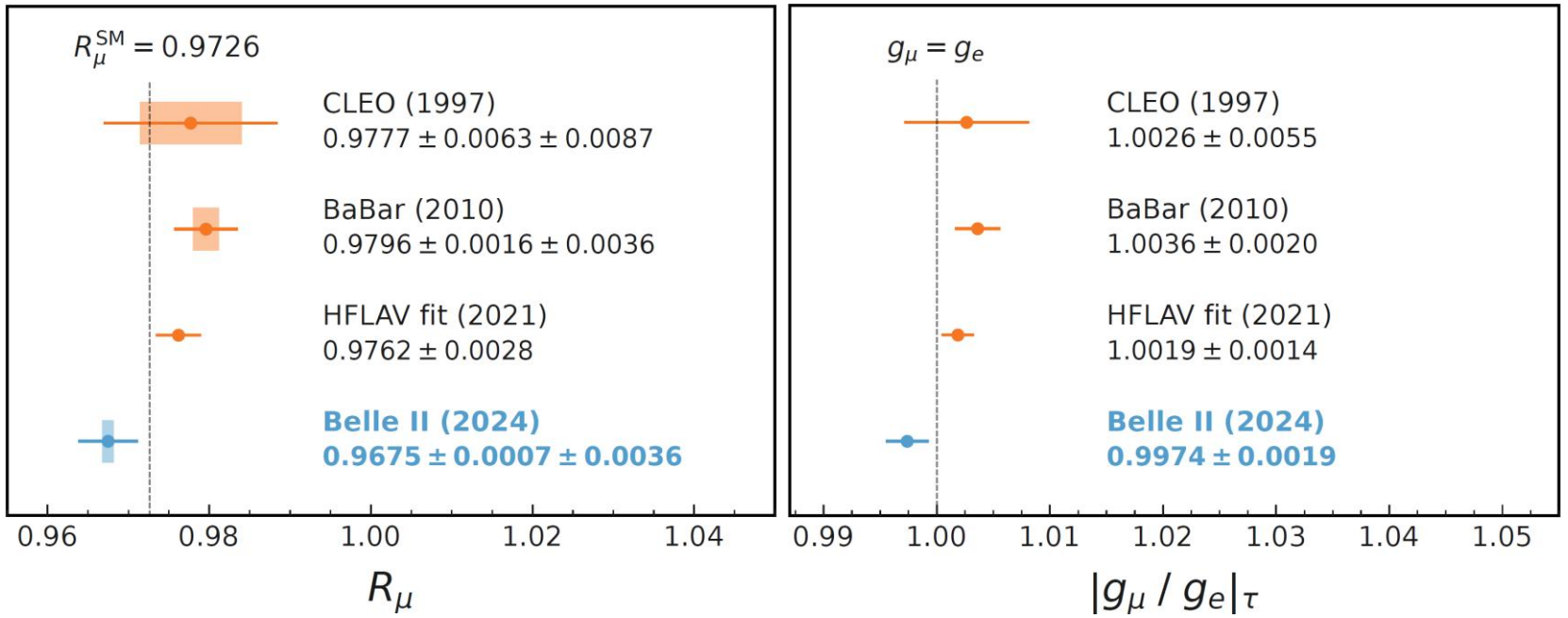
- Currently, τ lepton list contains 252 entries, 148 experimentally measured, 94 with upper limits
- Current PDG table is based on a fit using 170 measurements
- Last measurement of $\tau \to \ell$ by ALEPH (complex) → No direct measurements at B-factories
- Belle II: $\mathcal{B}(\tau \to \mu)/\mathcal{B}(\tau \to e) = 0.9675 \pm 0.0007\ (\text{stat}) \pm 0.0036\ (\text{syst})$; JHEP 08, 205 (2024)

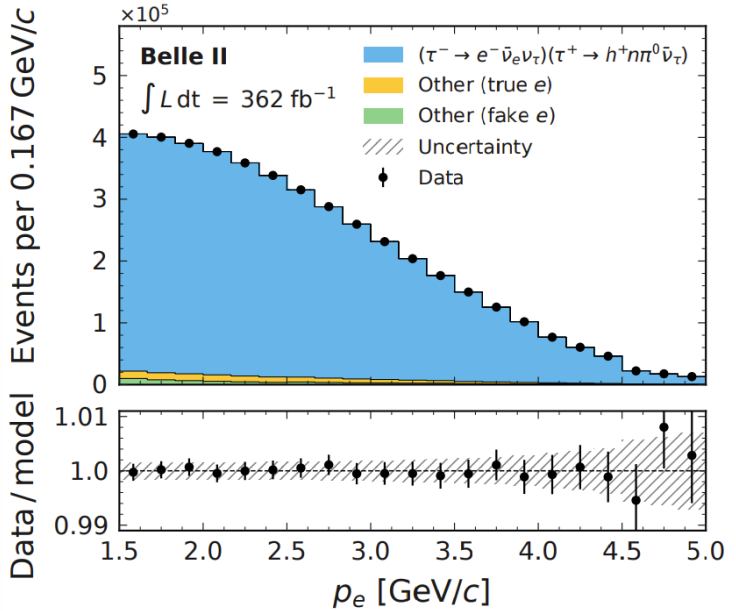
$$\mathcal{B}_{\tau e} \propto \mathcal{B}_{\mu e} \frac{\tau_\tau}{\tau_e} \frac{m_\tau^5}{m_\mu^5}$$

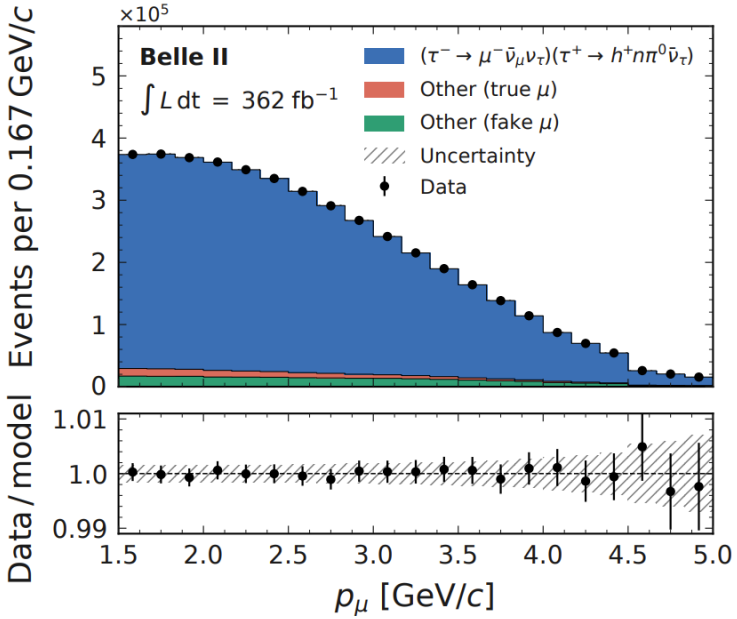
Belle II is working on updated τ-lepton inputs!

Test of LFU at Belle II [JHEP 08, 205 (2024)]

- Data sample: 362 fb^{-1} with 3×10^8 τ pairs
- Both leptonic decay modes studied as signal processes
- Use 1-prong tag with one or two π^0
- Neural network classifier used to improve signal purity
  → Signal purity of 96% (electron) and 92% (muon) samples
- Binned likelihood fit of momentum distribution used to extract R_μ

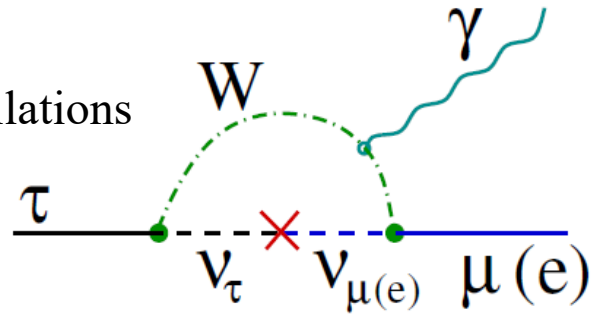






Lepton Flavor Violation

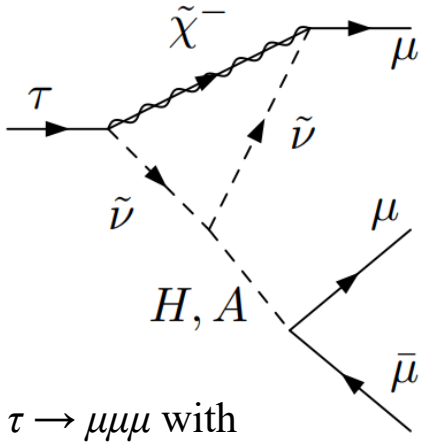
- SM allows LFV in charged lepton decays via weak charged currents and neutrino oscillations
  → But immeasurably small: $\mathcal{B} \approx 10^{-54} - 10^{-49}$
  → Observation of LFV decays would be a direct evidence of non-SM physics!



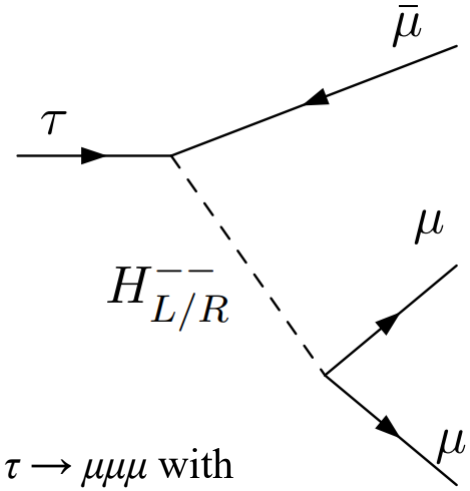
- Hints of LFV and deviation from SM predications in rare B decays (B anomalies in $b \to c/u$, τ vs. light leptons)
- Various new physics models predict LFV at observable rates

Physics Model	BR ($\tau \to \mu\mu\mu$)
SM	10^{-55}
SM + Seesaw	10^{-10}
SUSY + Higgs	10^{-8}
SUSY + SO(10)	10^{-10}
Non-universal Z'	10^{-8}

PRD 77, 073010

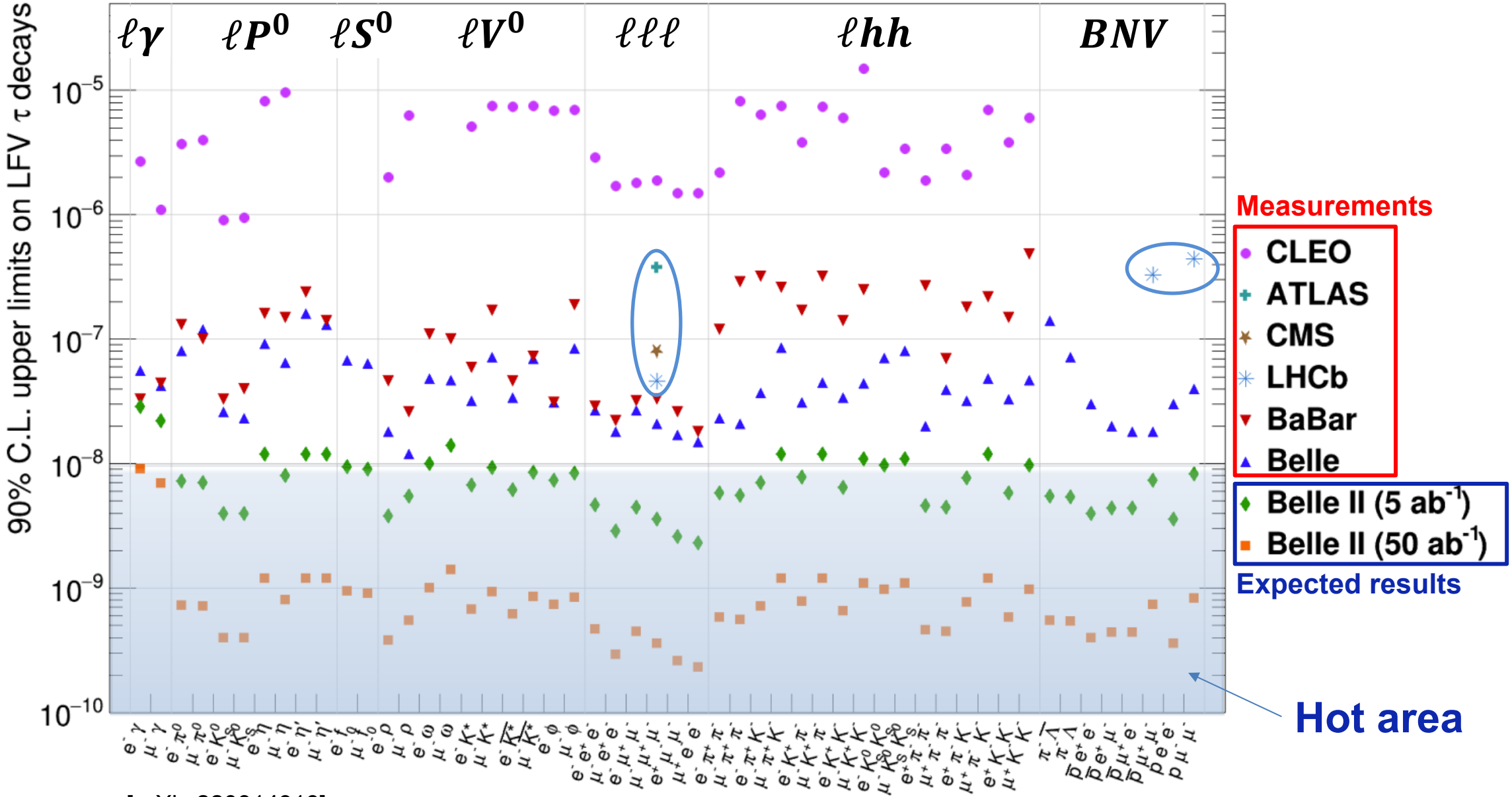


$\tau \to \mu\mu\mu$ with
seesaw MSSM (large tan β)



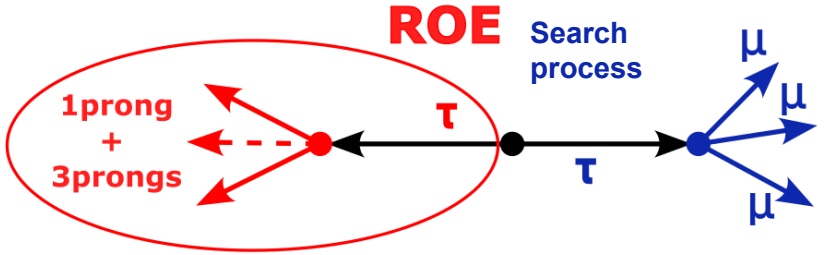
$\tau \to \mu\mu\mu$ with
doubly-charged Higgs bosons

LFV sensitivities

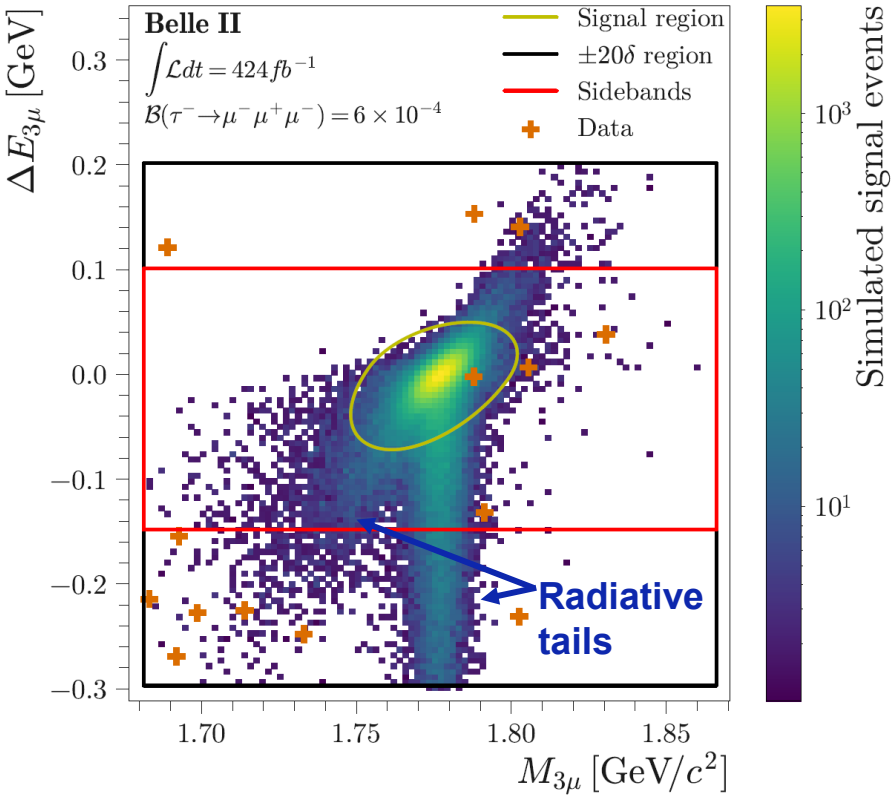


[arXiv.220314919]

Search for τ→μμμ at Belle II [JHEP 09, 062 (2024)]



- Motivated by new Z', charged Higgs models
- Reconstruct signal in an inclusive, untagged approach → new at Belle II
- Reject $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ processes using data-driven selections + Boosted Decision Tree (**BDT**) classifier to suppress $q\bar{q}$ background (signal and Rest Of Event (**ROE**) properties) → Signal efficiency $\varepsilon_{\text{sig}} > 20\%$ (~3× Belle)
- Extract signal by Poisson counting in an elliptical signal region (**SR**) in the $\Delta E_{3\mu} = E_{3\mu} - \sqrt{s}/2$ and $M_{3\mu}$ plane



$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \frac{N_{\text{obs}} - N_{\text{exp}}}{\mathcal{L} \times 2\sigma_{\tau\tau} \times \varepsilon_{3\mu}} = \left(2.1^{+5.1}_{-2.4} \pm 0.4\right) \times 10^{-9}$$

Experiment	Luminosity [fb^{-1}]	$\mathcal{B}^{UL}_{90CL}(\tau \to \mu\mu\mu)$ [10^{-8}]	Reference
Belle	782	2.1	Phys. Lett. B 687,139 (2010)
CMS	131	2.9	Phys. Lett. B 853,138633 (2024)
LHCb	3	4.6	JHEP 02,121 (2015)
Belle II	424	1.9	JHEP 09, 062 (2024)

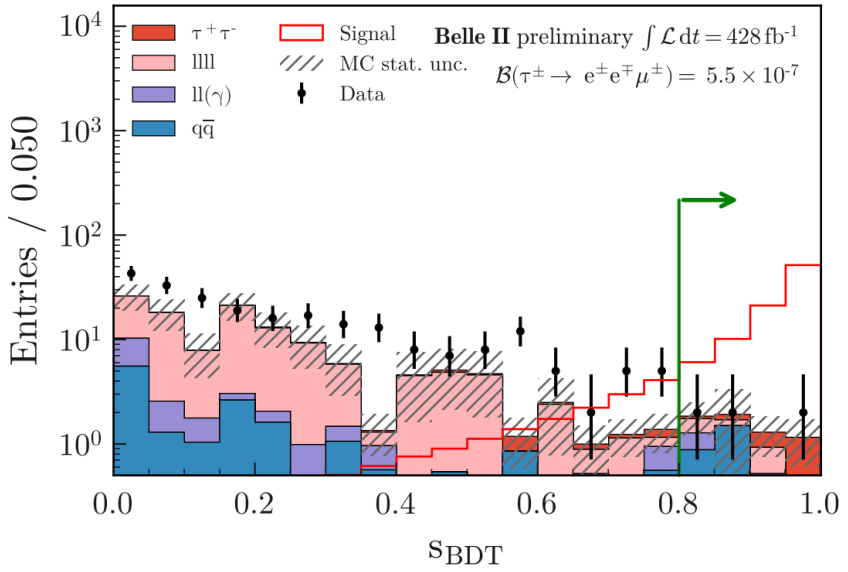
World's best result

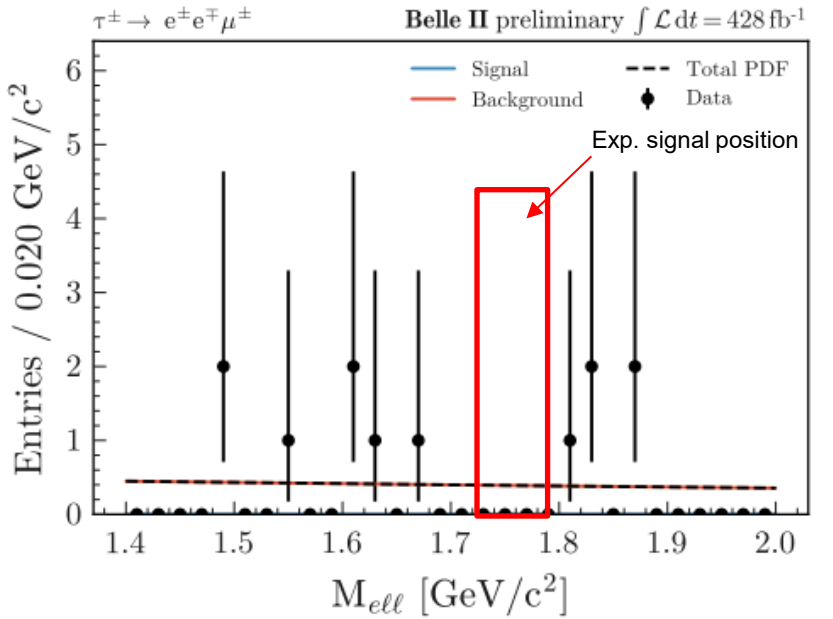
Extending the search to $\tau \to e^{\pm}\ell^{\mp}\ell'^{-}$ at Belle II [arXiv:2507.18236 (JHEP)]

- Inclusive tagging applied → 5 modes differentiated via lepton ID selectors
- Higher contamination from $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ processes (known to be mismodeled in simulation)
  → Use data-driven BDT classifier
  → Background samples selected away from the SR; rely on signal kinematics from simulation
  → $\varepsilon_{sig} \approx 15 - 24\%$
- Improve sensitivity by extracting the signal from unbinned maximum-likelihood fits to M_{ell} distributions → Use sidebands to extrapolate expected background yields
- No significant excess in 428 fb^{-1} observed → upper limits computed with CLs approach are between $1.3 - 2.5 \times 10^{-8}$

	N_{exp}	N_{obs}	C_{bg}	$\mathcal{B}$ (10^{-8})	$\mathcal{B}^{UL}_{exp}$ (10^{-8})	$\mathcal{B}^{UL}_{obs}$ (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★

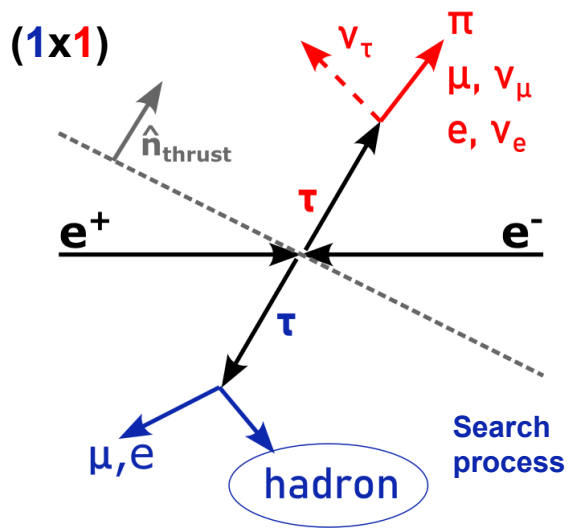
★World's best results

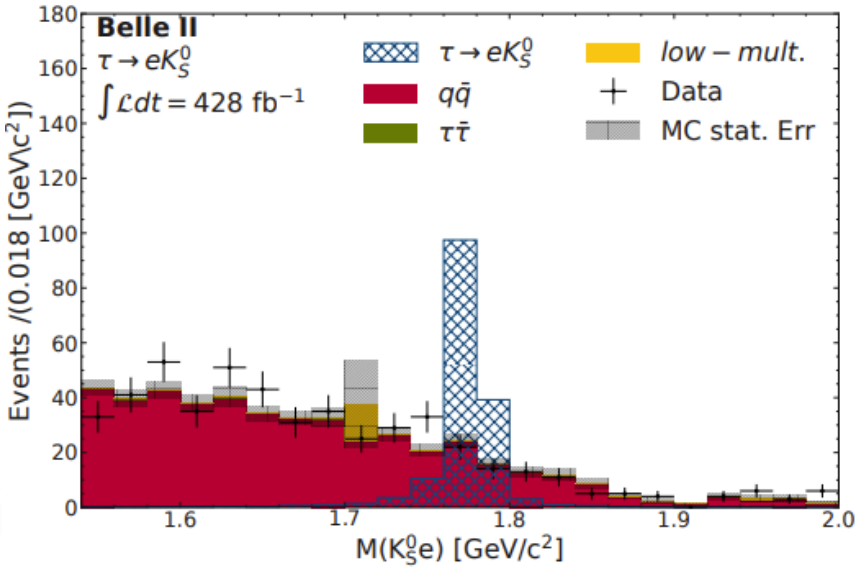


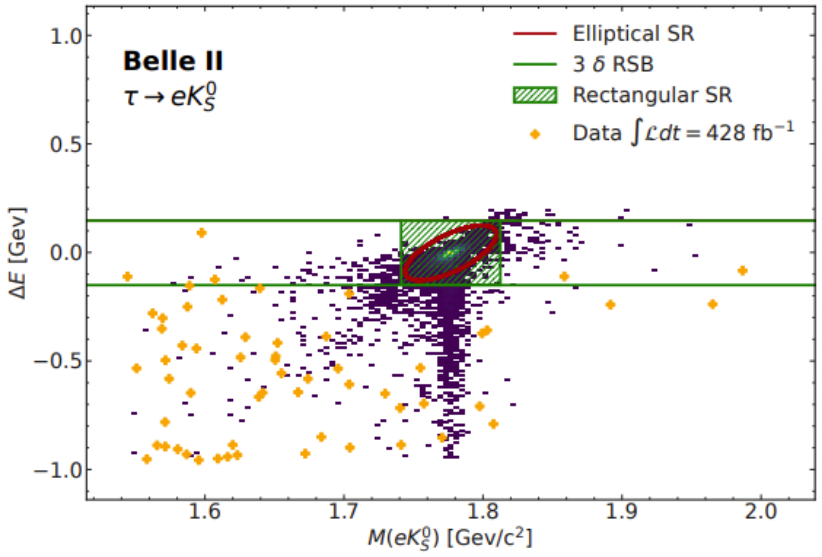


Search for $\tau \to \ell K_S^0$ ($\ell = e, \mu$) at Belle + Belle II [JHEP 08, 092 (2025)]

- Constrains new physics models with leptoquark operators
- First LFV search using the combined data set Belle + Belle II → 1408 fb^{-1}
- 1-prong tag approach; use lepton ID to distinguish signal channels and tag sides
- K_S^0 candidate reconstructed from two πs
- Data-driven selection against $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ processes + BDT to suppress $q\bar{q}$ background (input features from tag-side, event and signal K_S^0 properties) → $\varepsilon_{sig} > 10\%$
- Signal yield extracted by Poisson counting in an elliptical SR in $\Delta E_{\ell K_S^0}$ and $M_{\ell K_S^0}$ plane
- Expected background extrapolated into SR from exponential fits to $M_{\ell K_S^0}$ sideband







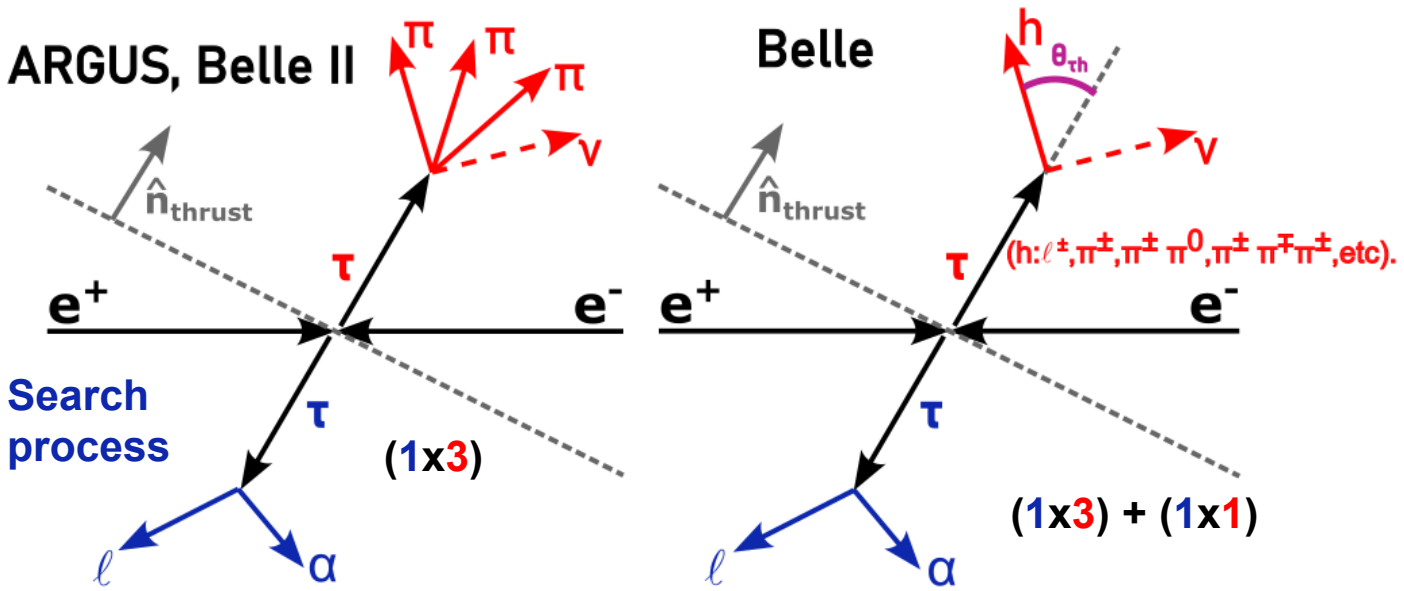
- No significant event found → Set 90% CL **world's best** upper limits:

$$\mathcal{B}^{UL}(\tau \to e(\mu)K_S^0) < 0.8(1.2) \times 10^{-8}$$

- 3.2 (1.9) times more stringent than Belle with 671 fb^{-1}
- Better performance in the electron channel due to superior particle ID

Invisible scalar boson in τ-decays at Belle [arXiv:2503.22195v3 (2025)]

- τ decays to new long-lived bosons (e.g. ALPs) predicted in many models
- Search for the process: $e^+e^- \rightarrow \tau_{sig}(\rightarrow \ell\alpha)\,\tau_{tag}(\rightarrow \mathrm{n}\pi\upsilon)$, with $\ell = e, \mu$
- Approximate τ_{sig} pseudo-rest frame (ARGUS method) as $E_{sig} \approx \sqrt{s}/2$ and $\vec{p}_{sig} \approx -\vec{p}_{tag}/|\vec{p}_{tag}|$
- Two-body decay: Search a bump in the lepton momentum spectrum over irreducible background from $\tau_{SM} \rightarrow \ell\upsilon\upsilon$



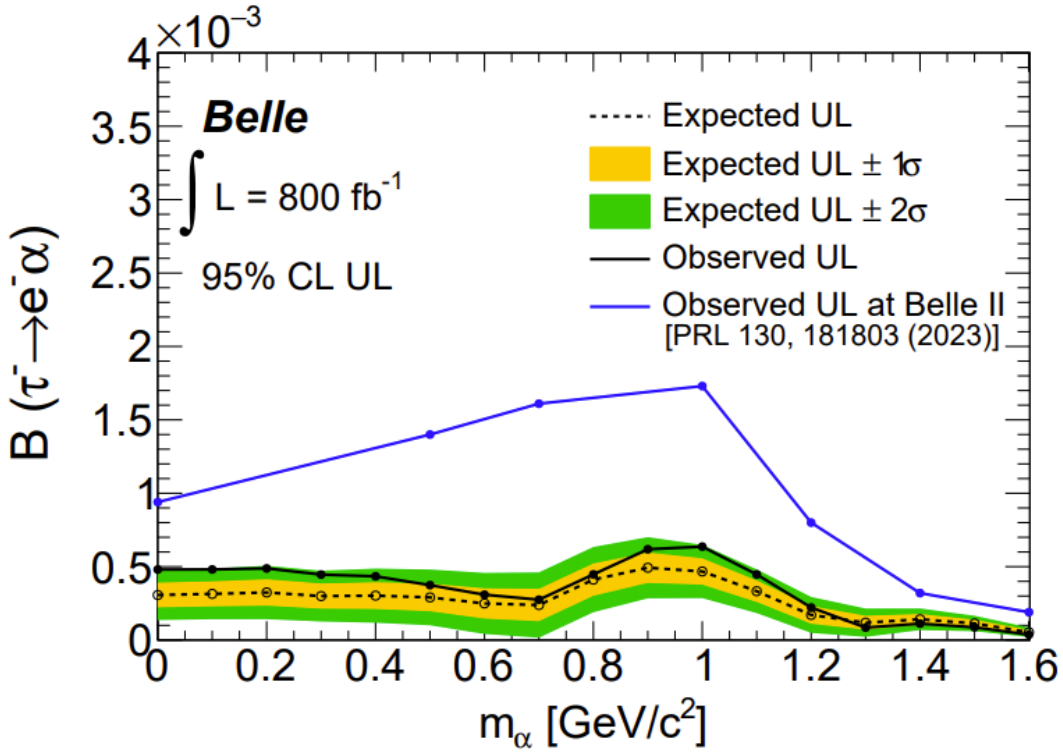
$$\theta_{\tau h} = \cos^{-1}\left(\frac{\left|\vec{p}^{\,c.m.}_{\tau_{tag}}\right|^2 + \left|\vec{p}^{\,c.m.}_{h_{tag}}\right|^2 - \left(\sqrt{s}/2 - E^{c.m.}_{h_{tag}}\right)^2}{2\left|\vec{p}^{\,c.m.}_{\tau_{tag}}\right|\left|\vec{p}^{\,c.m.}_{h_{tag}}\right|}\right)$$

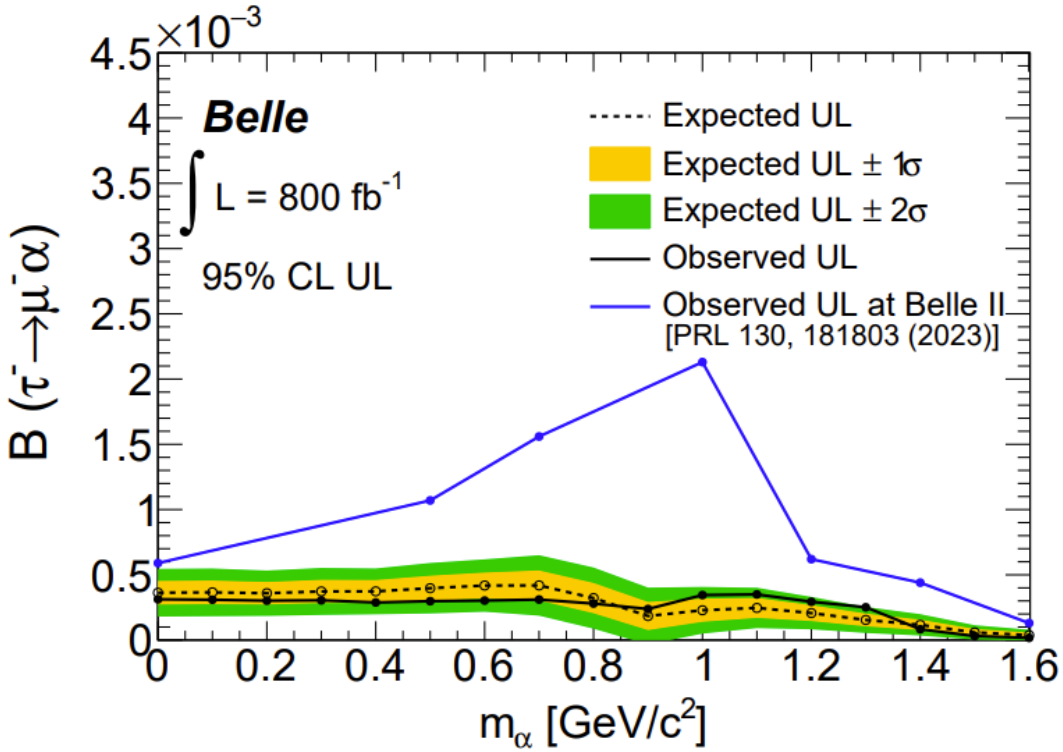
New at Belle (800 fb^{-1}): Adding 1-prong tag
→ ε_{sig} ranges in [0.3-1.5]%

Improve estimate of τ_{sig} direction by reconstructing opening angle between τ_{sig} and the hadronic system

Invisible scalar boson in τ-decays at Belle [arXiv:2503.22195v3 (2025)]

- No significant excess found in 736×10^6 τ pairs → set 95% CL upper limits on $\mathcal{B}(\tau_{sig} \to \ell\alpha)$
- Between $0.4-6.4$ $(0.2-3.5) \times 10^{-4}$ for electron (muon) channels
  → Most stringent limits to date

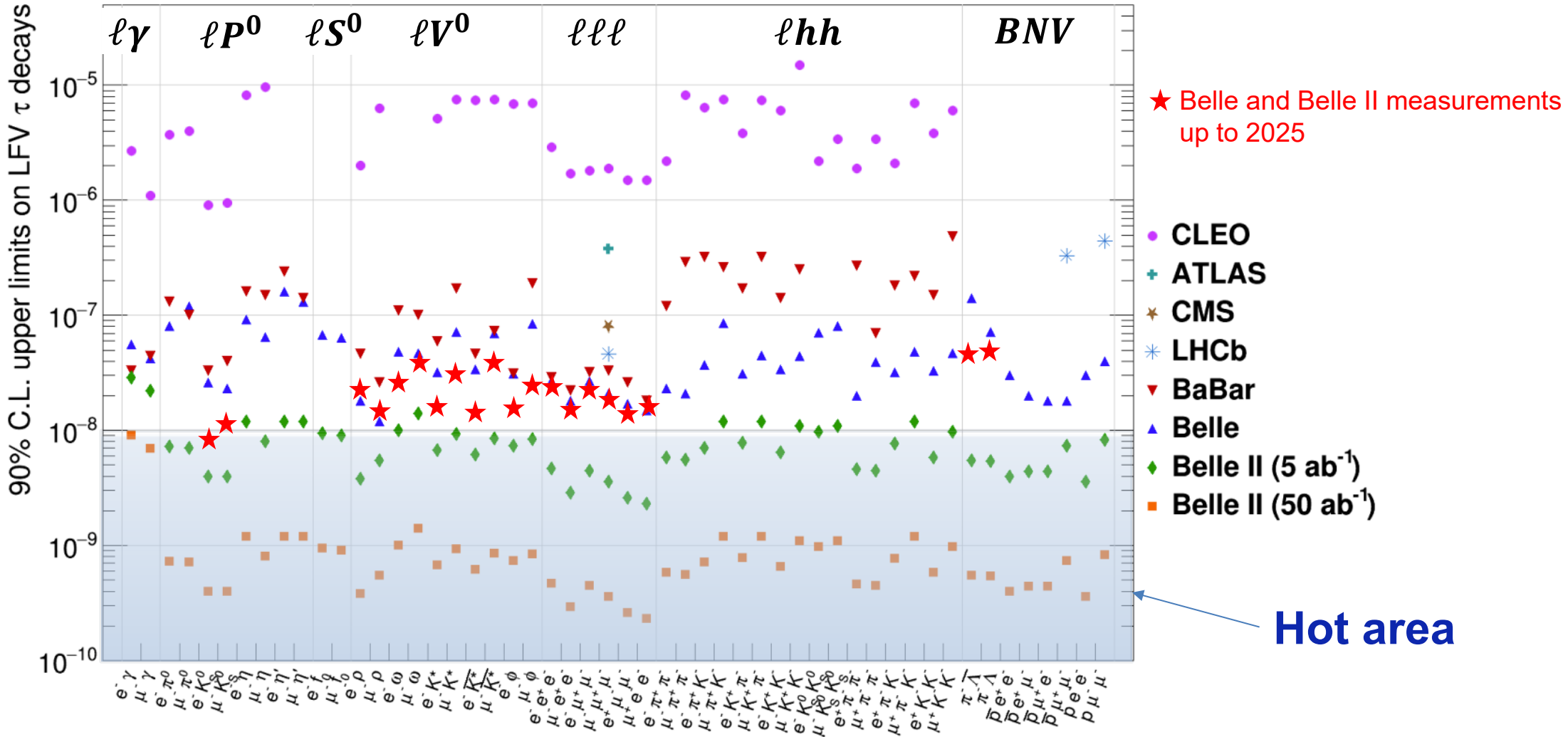




- Update of Belle II analysis [PhysRevLett.130.18180] in internal review!
- Novel technique used based on [PhysRevD.102.115001] → Stay tuned

LFV sensitivities

- Many other publication from Belle and Belle II up to 2025, with several ongoing analysis
- In many decays, we are reaching the “hot area”!



[arXiv.220314919]

Summary

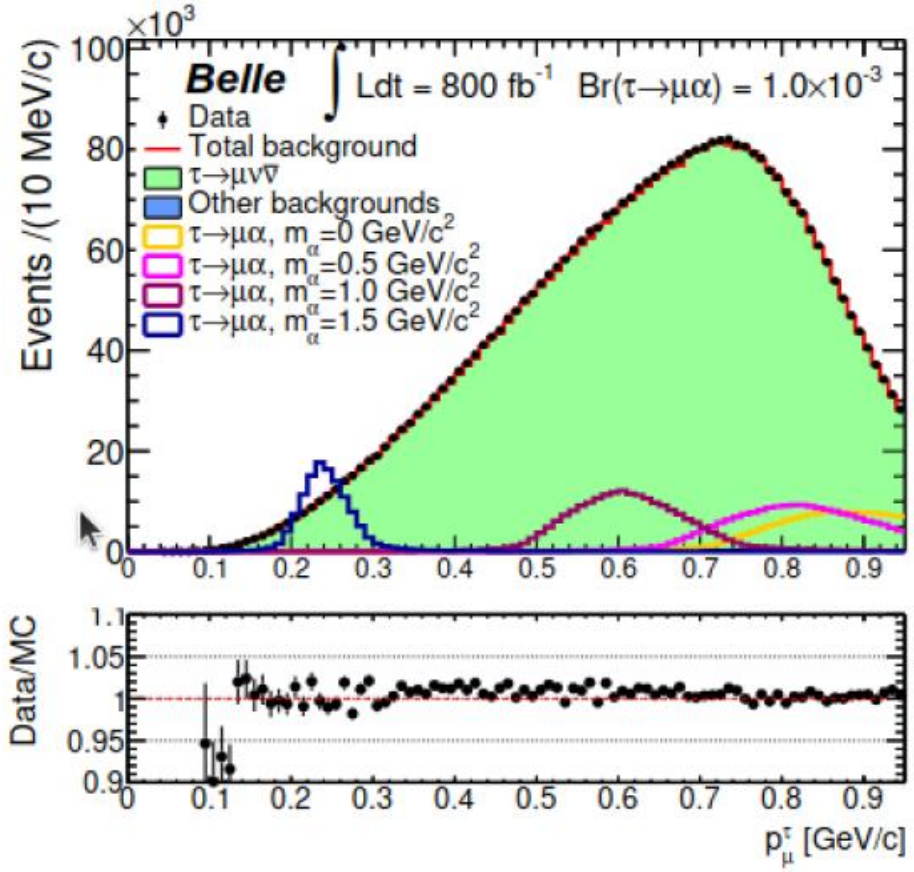
- Studies of LFU and LFV in τ decays are an exciting field dominated by e^+e^- colliders
- Ongoing LFV studies at Belle II → Run 2 has started
  → New data will allow improvements in almost all LFV channels
- Ongoing work at Belle II to improves precision measurements of τ properties
  → Input for LFU test
- Direct LFU tests ongoing at Belle II with the latest result in JHEP 08, 205 (2024)
  → World's best result for $|g_\mu/g_e|_\tau$
- New strategies to boost signal efficiency while controlling the background applied to $\tau \to \mu\mu\mu$ and $\tau \to e^\pm \ell^\mp \ell'^-$
- Statistics can be increased by combining Belle and Belle II datasets
  → First combined analysis for $\tau \to \ell K_S^0$
- Plans to enhance analysis performance by exploiting improved particle identification and multivariate techniques

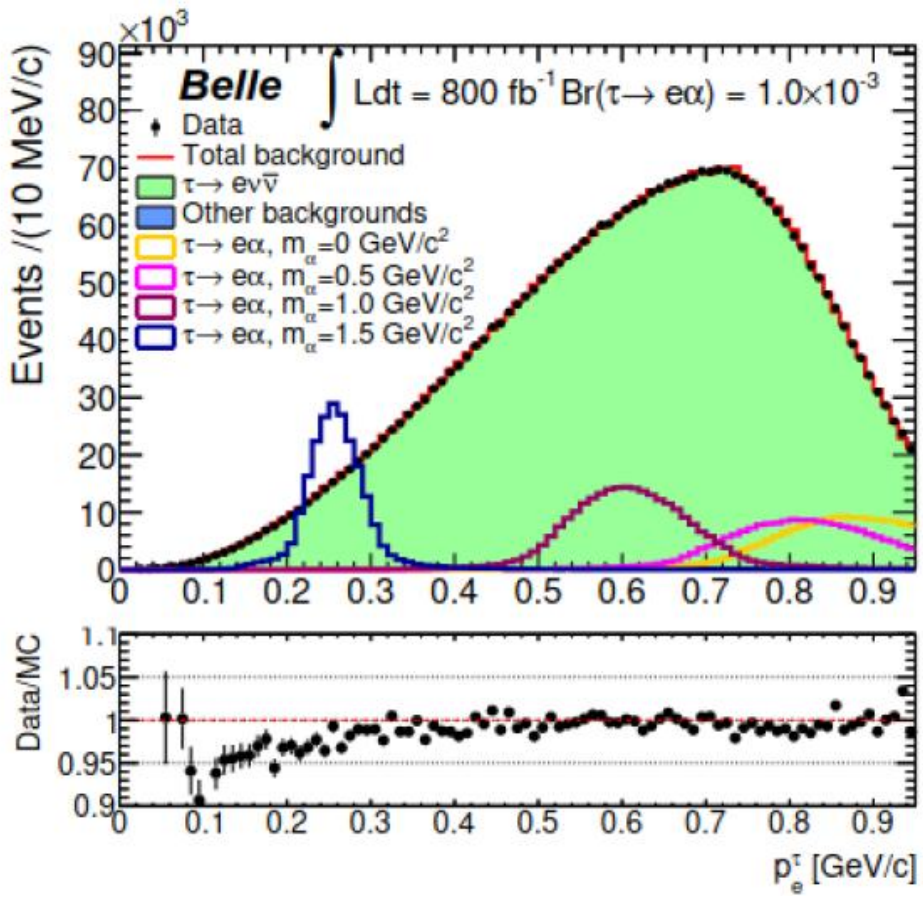
→ Expected world's best sensitivities!

Backup

Invisible scalar boson in τ-decays at Belle [arXiv:2503.22195v3]

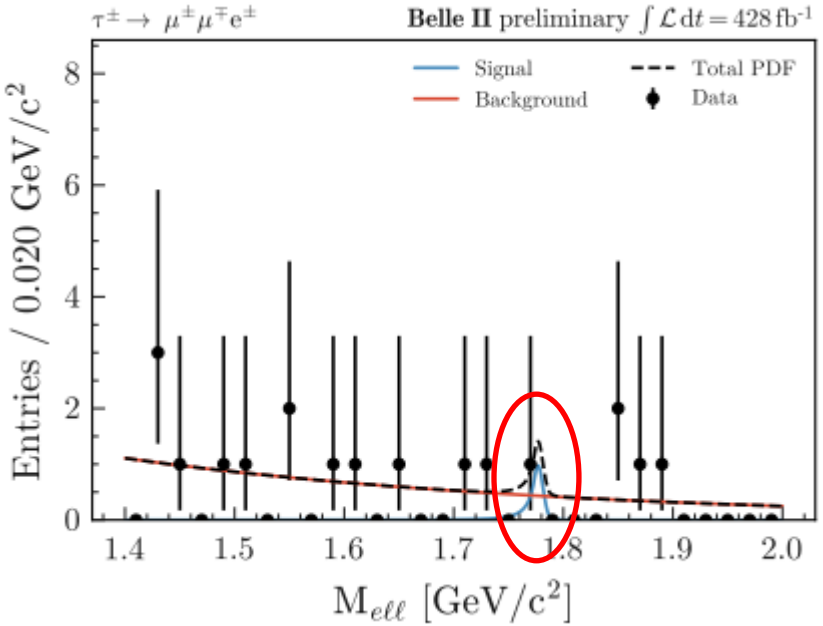
- Require τ_{sig} aligned with the hadronic system ($|\theta_{\tau h}| < 4$) improves the signal lepton momentum resolutions → Better sensitivity
- Selections are independent of α mass: ε_{sig} ranges in [0.3-1.5]%
- Signal and background yields extracted from binned maximum-likelihood fits to the signal lepton momenta
  → Shape modeling from simulation





Extending the search to $\tau \to e^{\pm}\ell\ \ell'^{-}$ at Belle II [arXiv:2507.18236 (JHEP)]

- On data event exactly at signal position
- Probably unlucky statistical fluctuation of a background event



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$e^-e^+e^-$	$6.1^{+4.3}_{-2.9}$	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