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

Laura Zani

on behalf of the Belle II collaboration

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI ROMA TRE

Belle II

laura.zani@roma3.infn.it

Outline

- Motivation
- Experimental method
- Searching for Lepton Flavor Violation in τ decays
  - $\tau \to \ell\ell\ell$ at Belle II
  - $\tau \to \ell K^0_S$ at Belle + Belle II
  - $\tau \to \ell\alpha$ at Belle II and Belle
- Outlook and conclusion

Why τ decays?

$M_\tau = 1777.09$ MeV/c^2

Lifetime: 290.17 fs

τ pairs produced in the e^+e^- collisions are a unique laboratory to **test the Standard Model (SM)** through **precision** measurements and **search** for **non-SM physics**!

- **High precision** measurements of SM properties: study of the hadronization, light lepton flavor universality [1], determination of mass [2], lifetime

  → **systematically limited**, understanding of the experiment performance and background description necessary to control of systematic sources

  < fractions of ‰ level

- **World's leading sensitivities** for direct searches, target rare or forbidden processes ($\tau^+ \to \mu^+\mu^-\mu^+$, $\tau^+ \to \ell^+ V^0$, etc.)

  → **statistically limited**, largest data sets + new techniques to increase signal efficiencies and reduce backgrounds

  < 10^{-8} level

[1] JHEP08(2024)205 [2] PRD 108 032006

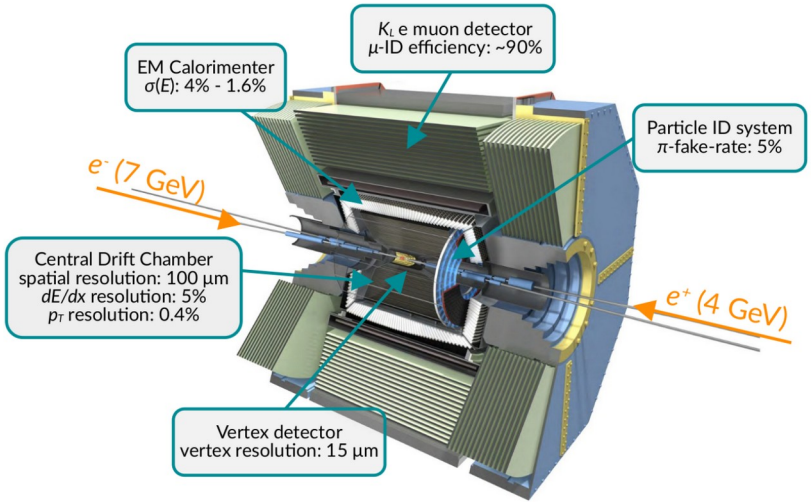
Working at ~~B~~ tau factories

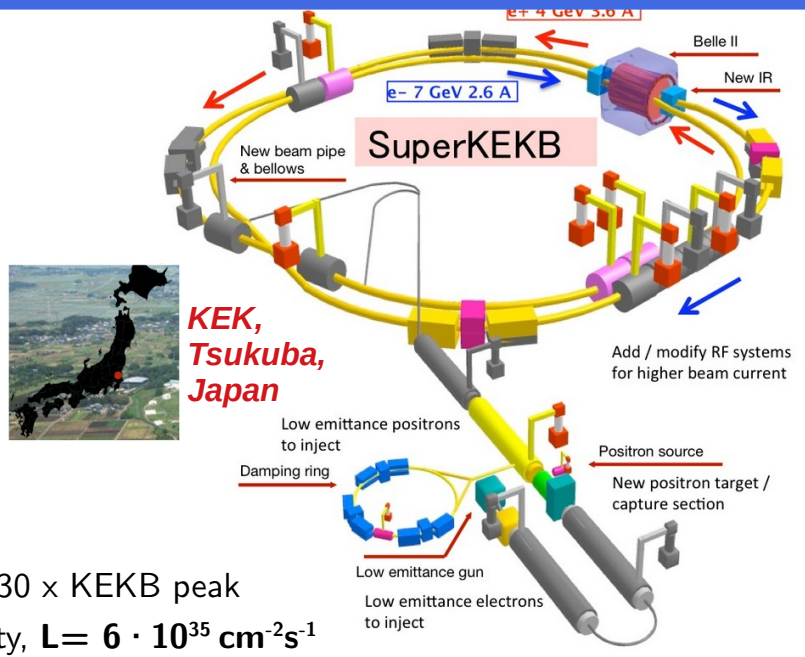
- **Clean environment** at asymmetric energy e^+e^- collider and **hermetic detector:**

  → at $\sqrt{s} = 10.58$ GeV: $\sigma_{b\bar{b}} \sim \sigma_{\tau\tau} \sim 1$ nb, B & **τ factory**

  → known initial state + efficient reconstruction of **neutrals** (π^0, η), **recoiling system** and **missing energy**

  → specific **low-multiplicity triggers** (previously not available at Belle)





- **GOAL:** 30 x KEKB peak luminosity, **$L = 6 \cdot 10^{35}$ cm^{-2}s^{-1}** *(nano-beam scheme*)*
- Collect 50 x Belle → 50 ab^{-1}

1.3 billion τ pairs

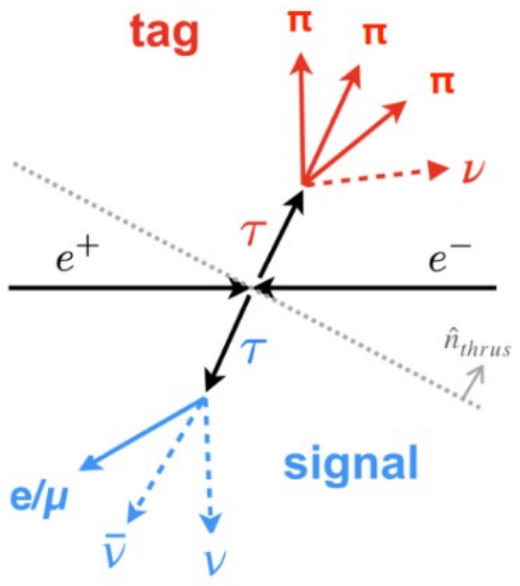
BELLE (1999-2010): 1 ab^{-1}, arXiv:1212.5342

BELLE II: Run 1 (2109-2022) + Run 2 (2024 – present) accumulated 0.6 ab^{-1} and unique energy scan samples

Tau topologies and signatures

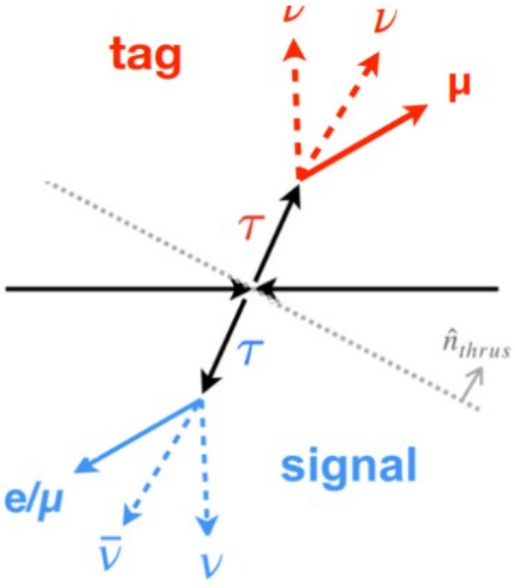
- Tau pairs in $e^+e^- \to \tau^+\tau^-$ events produced back-to-back in CM system
- Possible to separate them in **two opposite hemispheres** defined by the plane perpendicular to the **thrust axis** n_τ

$$T = \max_{\hat{\mathbf{n}}_T} \left(\frac{\sum_i |\mathbf{p}_i \cdot \hat{\mathbf{n}}_T|}{\sum_i |\mathbf{p}_i|} \right)$$

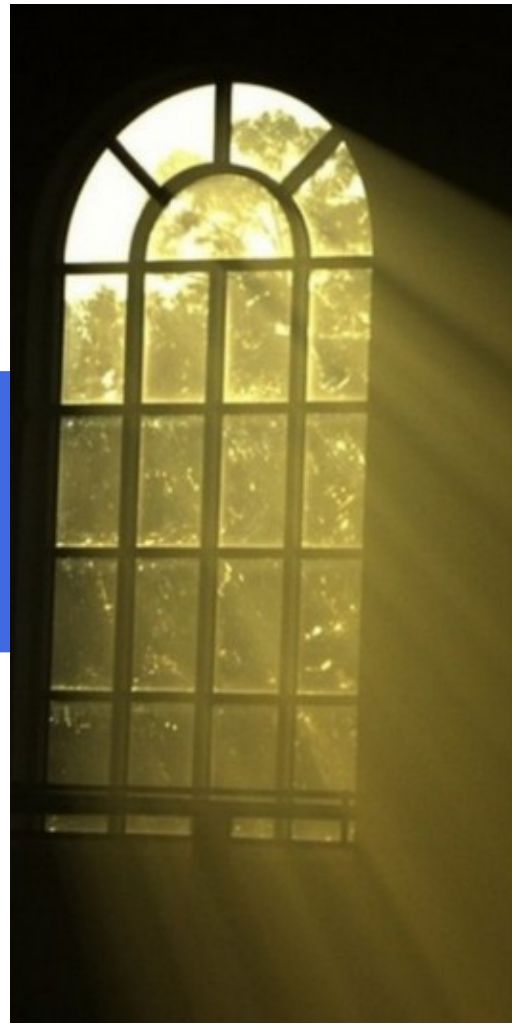


(1x3)-prong Vs (1x1)-prong

Reconstruct a **specific topology** to suppress background, mainly from $e^+e^- \to q\bar{q}$



Beyond SM searches



Lepton flavor violation

- ***Lepton Flavor Violation (LFV)*** in charged lepton decays is allowed via weak charged currents and neutrino oscillation, but immeasurably small

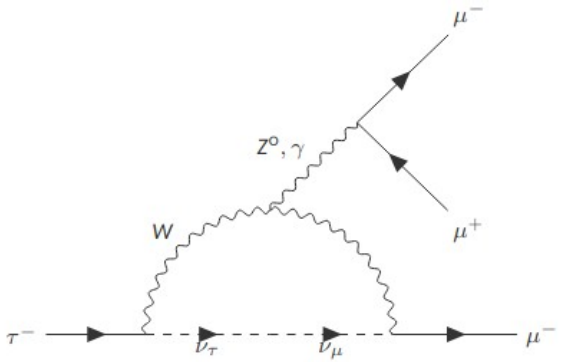
$$BR(\ell_1 \to \ell_2\gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2}\right)^2 \sim 10^{-54}\text{-}10^{-49}$$

→ **observation of LFV decays would be *per se* a proof of non-SM physics!**

- Hints of lepton-flavor universality violation and deviation from SM predictions in rare B decays (B anomalies in $b \to c l \nu$, **τ** Vs light leptons)
- Various new physics models predict LFV at observable rates

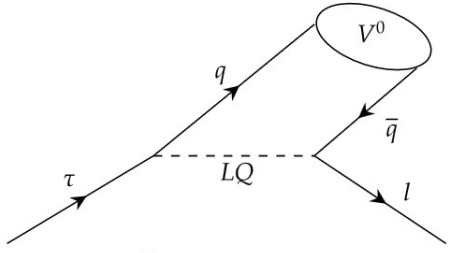
PRD.77.073010

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



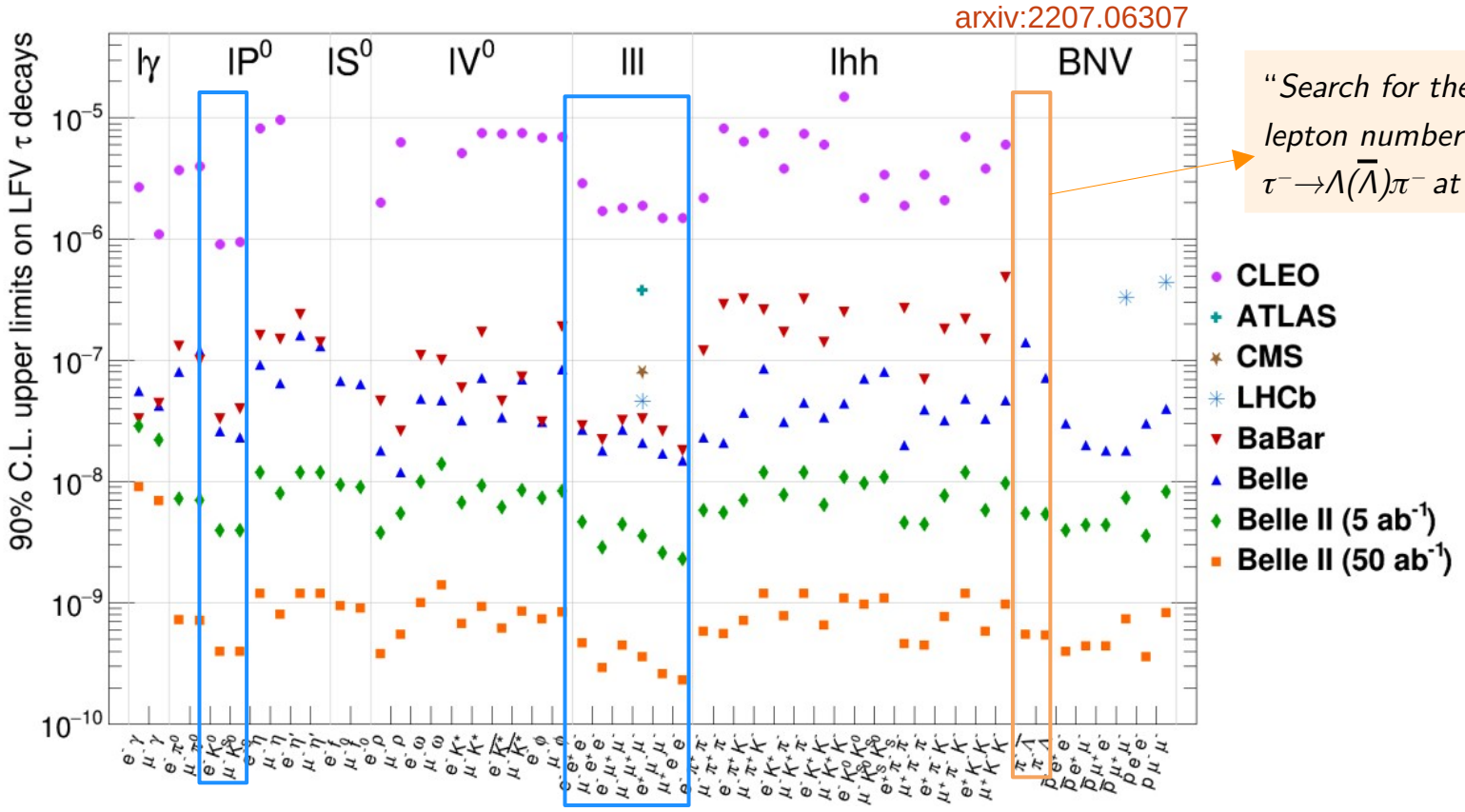
New interaction that violates flavor (Z' boson, leptoquark)

→ ***Special role of the third family***



$\tau \to l\, V^0$ *via leptoquark interaction*

LFV sensitivities



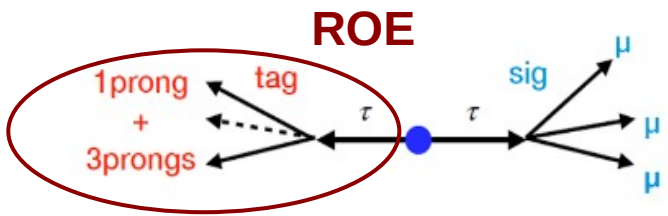
"*Search for the baryon number and lepton number violating decays* $\tau^- \to \Lambda(\bar{\Lambda})\pi^-$ *at Belle II*", *PRD110, 112003*

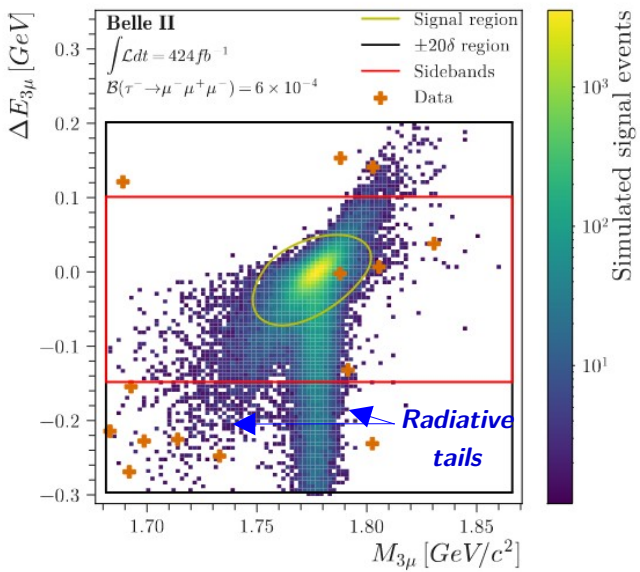
- Belle II expected to provide world's leading limits on many channels

Search for $\tau^+ \to \mu^+\mu^-\mu^+$

JHEP09(2024)062

- Motivated by new Z', charged Higgs models [1]
- Reconstruct signal in inclusive untagged approach → new at Belle II [2]
- Reject $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ processes with data driven selections + Boosted Decision Tree (BDT) classifier to suppress $q\bar{q}$ background exploiting signal and Rest Of Event (ROE) properties → final signal **efficiency above 20% (~3 x Belle)**
- Extract signal by Poisson counting in **elliptical signal region** in $\Delta E_{3\mu} = E_{3\mu} - \sqrt{(s)}/2$ and $M_{3\mu}$ plane





$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \frac{N_{obs} - N_{exp}}{\mathcal{L} \times 2\sigma_{\tau\tau} \times \varepsilon_{3\mu}}$$

- **One event observed in 424 fb^{-1}** (expected 0.5 from data-driven estimate)
- Compute 90% CL upper limit with CLs method:

$$B^{UL}(\tau \to \mu\mu\mu) = 1.9 \times 10^{-8}$$

World's best

Experiment (Luminosity [fb^{-1}])	$\mathcal{B}_{90}^{UL}(\tau \to \mu\mu\mu)$ [x 10^{-8}]
Belle (782) [a]	2.1
CMS (131) [b]	2.9
LHCb (3) [c]	4.6
Belle II (424)	1.9

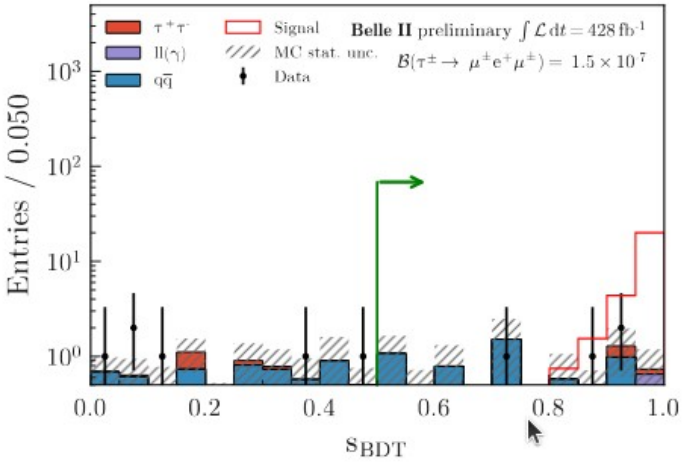
[1] PRD.77.073010 [2] ArXiv: 2305.04759

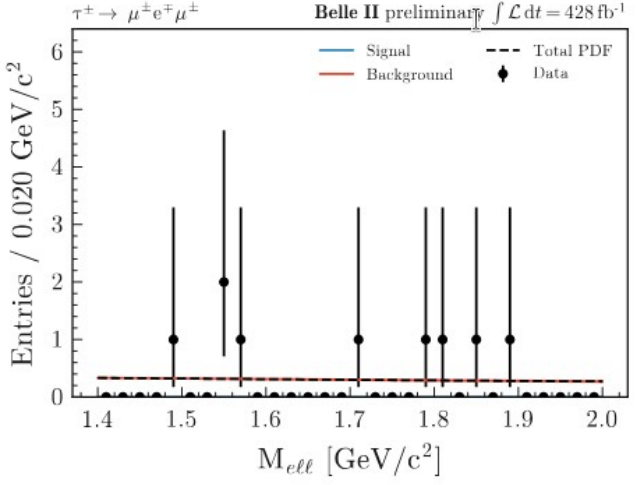
[a] Phys. Lett. B 687 (2010) 139 , [b] arXiv:2312.02371, [c] JHEP02(2015)121

Extending the search to $\tau^- \to e^{\pm}\ell^{\mp}\ell'^-$

Preliminary

- Inclusive tagging applied, **add 5 modes** differentiating via lepton ID selectors
- Higher background contamination from $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ processes known to be mismodeled in simulation $\to$ **data-driven BDT classifier**
  - background training sample selected away from the signal region and rely on signal kinematics from simulation $\to$ $\boldsymbol{\varepsilon_{sig} \simeq 15 - 24\ \%}$
- Improve sensitivity extracting the signal from unbinned max likelihood fits to $M_{e\ell}$ distributions $\to$ use sidebands to extrapolate expected background yields
- No significant excess in 428 fb^{-1} $\to$ observed upper limits computed with CLs method are between 1.3-2.5 x 10^{-8}





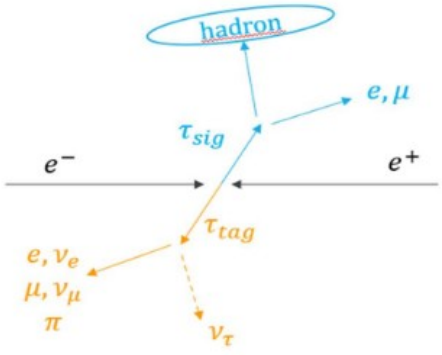
Most stringent to date for four modes ★

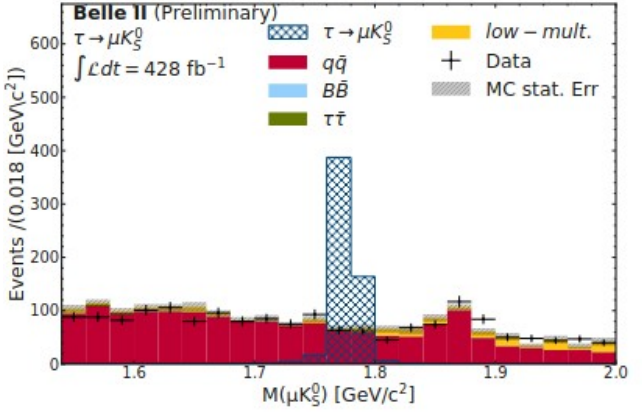
	N_{exp}	N_{obs}	C_{bg}	$\mathcal{B} \times 10^{-8}$	$\mathcal{B}^{UL}_{exp} \times 10^{-8}$	$\mathcal{B}^{UL}_{obs} \times 10^{-8}$	
$e^-e^+e^-$	$6.1^{+4.3}_{-2.9}$	5	$0.52^{+2.64}_{-2.60}$	0	2.7	2.5	★
$e^-e^+\mu^-$	$12.1^{+5.7}_{-4.3}$	12	$-0.40^{+1.67}_{-1.68}$	0	2.1	1.6	★
$e^-\mu^+e^-$	$10.5^{+5.3}_{-4.3}$	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	★

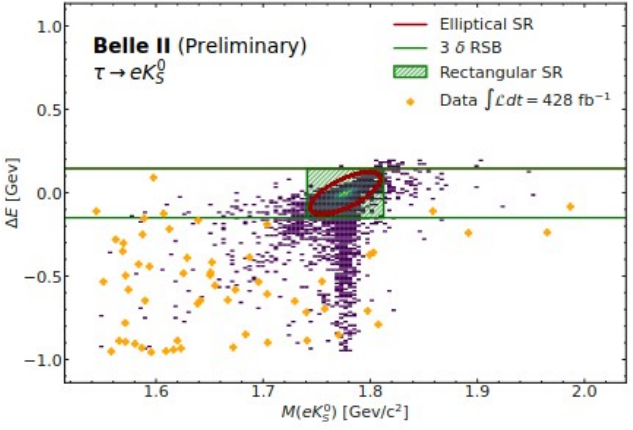
Search for $\tau^- \to \ell^- K_S^0$ (ℓ = e, μ)

arxiv:2504.15745
Accepted for publication in JHEP

- It can constrain new physics models with leptoquark operators [1]
- First LFV search on the combined data set **Belle (980 fb^{-1}) + Belle II (428 fb^{-1}) → 1408 fb^{-1}**
- Reconstruct in **one-prong tag** approach, use lepton ID to distinguish **signal** channels and tag sides, K_S candidate from two charged pions
- Data-driven selections against $\ell^+\ell^-(\gamma)$ and $\ell^+\ell^-\ell^+\ell^-$ processes + BDT trained on input features from tag-side, event and signal K_S^0 properties to suppress $ee \to q\bar{q}$ → $\varepsilon_{sig} > 10\%$
- Signal yield from Poisson counting in **elliptical signal region (SR)** in M_{IKS}, $\Delta E = (E_{IKS} - E_{beam})$
- Expected background extrapolated in SR from exponential fits to **M_{IKs} sideband**







Better performance in the electron channel due better particle ID

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

$$BF^{UL}(\tau \to e(\mu) K^0_S) < 0.8\,(1.2) \times 10^{-8}$$

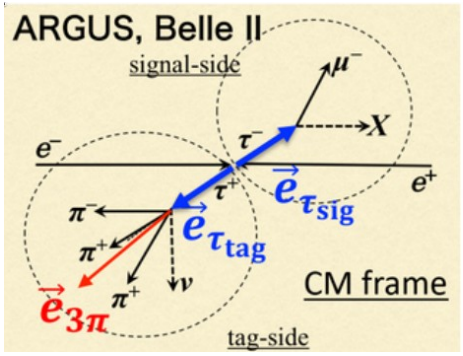
Between 3.2(1.9) times more stringent than Belle [2], 671 fb^{-1}

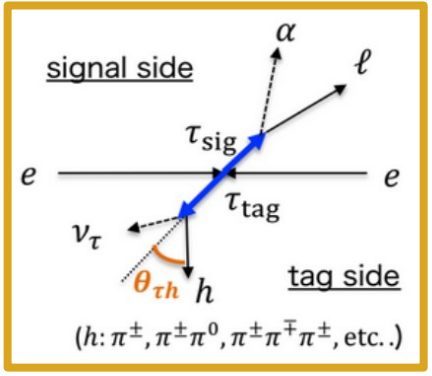
[1] EPJ.C.10052-010-1482-4 [2] Phys.Lett.B, Vol. 692, 1 (2010)

Invisible scalar boson in τ decays

- τ decays to **new LFV bosons** (e.g., ALPs) predicted in many models [1]
- Search for the process $e^+e^- \to \tau_{sig}(\to l\alpha)\,\tau_{tag}(\to n\pi\nu)$, with l=e or l=μ
- Approximate τ_{sig} pseudo-rest frame (ARGUS method [2]) as $E_{sig} \sim \sqrt{s}/2$ and $\hat{p}_{sig} \approx -\vec{p}_{\tau_{tag}}/|\vec{p}_{\tau_{tag}}|$
- Two-body decay: search a bump in the lepton momentum spectrum over irreducible background from $\tau_{SM} \to l\nu\nu$

Belle II (63 fb $^{-1}$): PRL 130 (2023) 181803
New at Belle: arxiv:2503.22195v2





- **NEW** at Belle (800 fb $^{-1}$): enhance efficiency adding one-prong decays on the tag-side
- Improve estimate of τ_{sig} direction by reconstructing opening angle between τ_{sig} and the hadronic system, $\theta_{\tau h}$

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

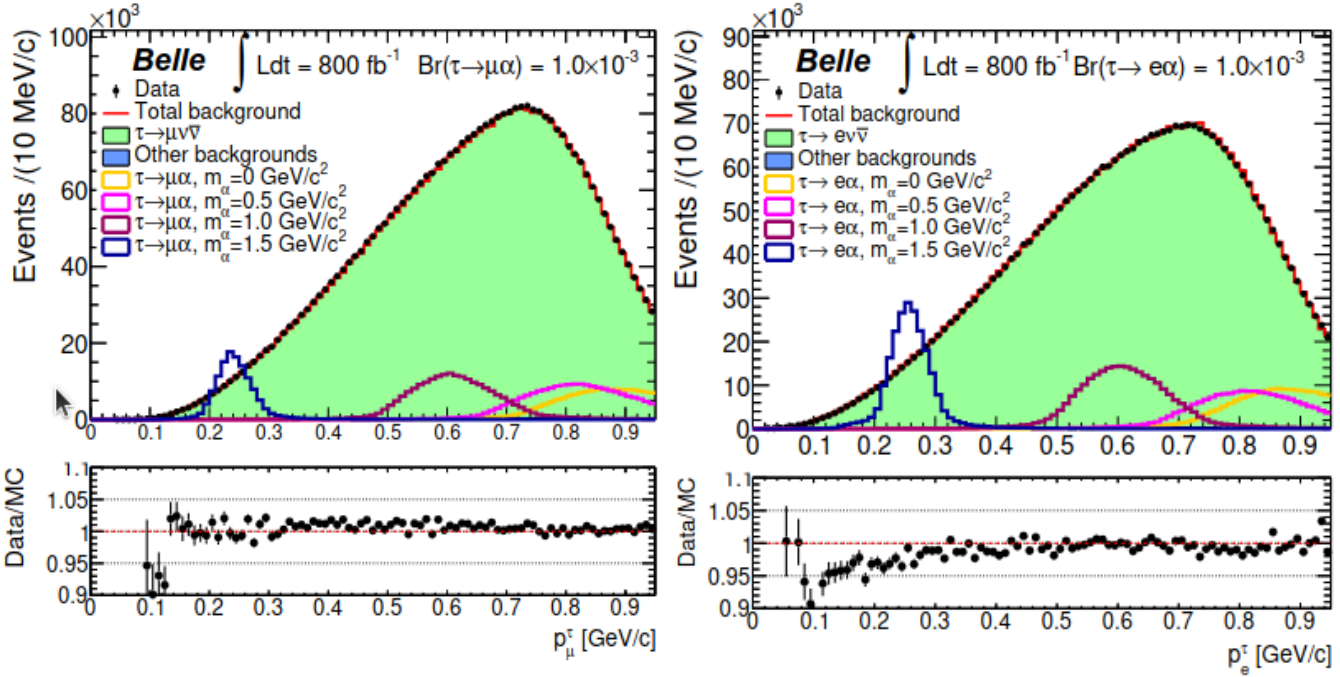
[1] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020), [2] ARGUS Collaboration, Z. Phys. C 68, 25 (1995)

Invisible boson in τ decays at Belle

arxiv:2503.22195v2

NEW!

- Require the τ_{sig} aligned with the hadronic system ($|\theta_{\tau h}| < 4$) improves the signal lepton momentum p_ℓ resolutions → **better sensitivity** in the final fits
- Selections independent from the α mass: ε_{sig} ranges in [0.3 -1.5]%
  - validated on control samples in data and simulation using $\tau \to \pi \pi^0 \nu$ events

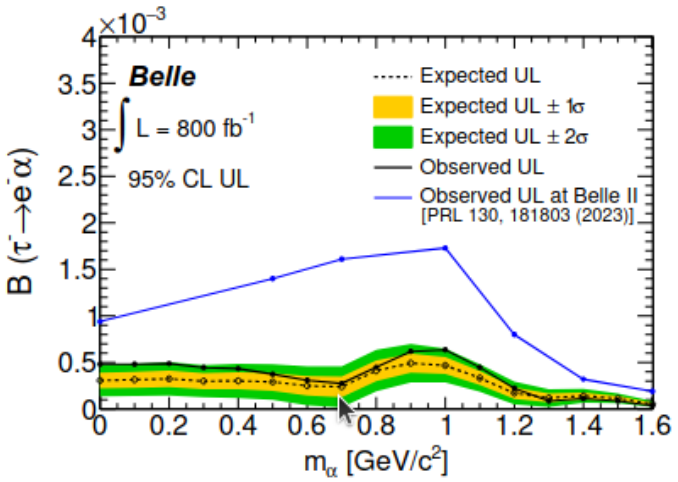


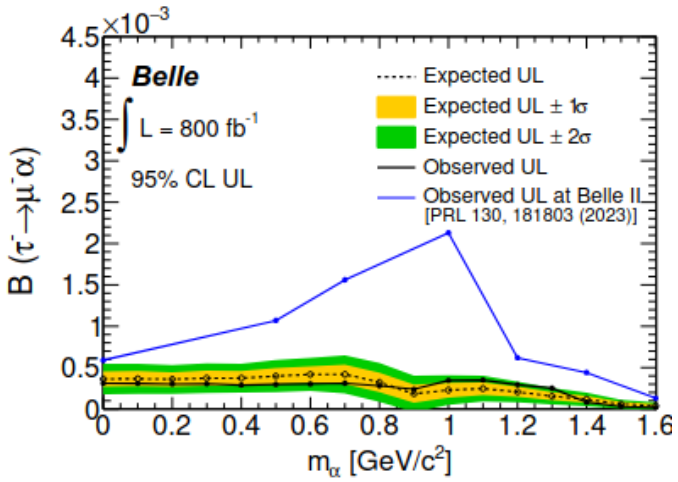
Invisible boson at Belle: results

arxiv:2503.22195v2

NEW!

- No significant excess found in 736 x 10^6 τ pairs $\rightarrow$ set 95% CL upper limits on BF($\tau_{sig} \rightarrow l\alpha$)





Between 0.4-6.4 (0.2-3.5) x 10^{-4} for electron(muon) channels

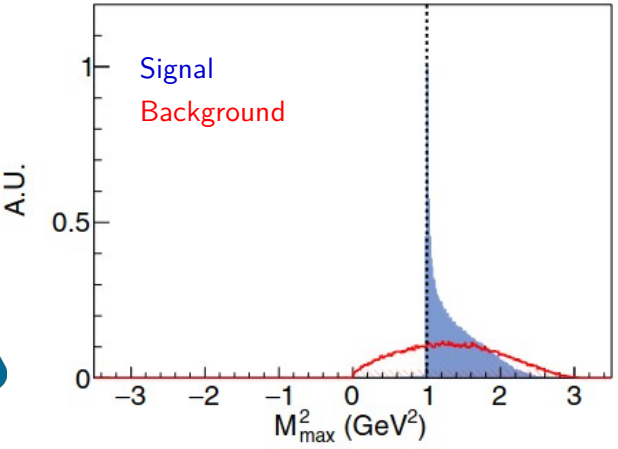
$\rightarrow$ most stringent to date

TEASER: new method at Belle II, exploiting 1x1 τ pairs topology and new kinematic variables [1]

$\rightarrow$ sensitive to the α mass at the lower/upper bounds of the distributions, improves signal/background discrimination

WORK IN PROGRESS

[1] PRD.102.115001



Summary and outlook

- Study of LFV in τ decays ongoing at Belle II $\rightarrow$ Run 2 started, with more data possible to improve almost all LFV channels
- New strategies to boost signal efficiency keeping the background under control applied to $\tau \rightarrow \mu\mu\mu$ and $\tau^- \rightarrow e^{\pm}\ell^{\mp}\ell'^-$, JHEP09(2024)062
- Increase the available statistics by combining Belle and Belle II data set, first combined analysis for $\tau \rightarrow \ell K_S^0$, arxiv:2504.15745
- Plans to enhance analysis performance exploiting improved particle identification and multivariate techniques

$\rightarrow$ **Expected world's best sensitivities!**

Thanks for your attention!

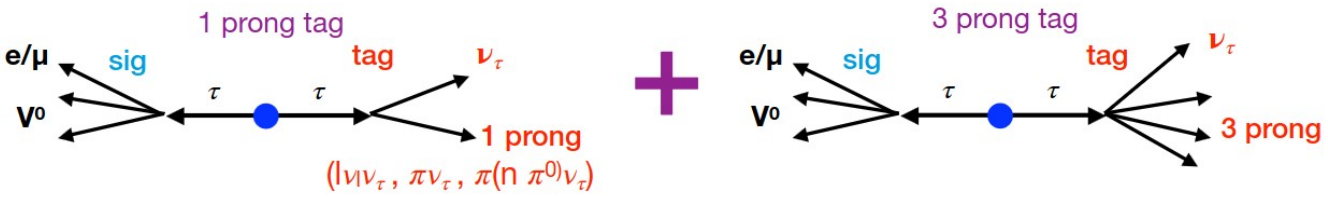
backup

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

JHEP06(2023)118

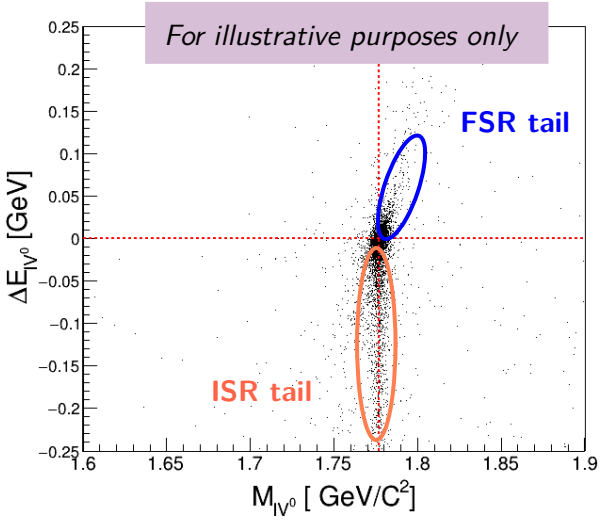
strategy

- Previous search at Belle on 854 fb^{-1} exploiting one-prong tag [1]



Full Belle data set of 980 fb^{-1}
$\to$ 9.05 x 10^8 tau pairs

- **Signal side**: reconstruct lepton and $V^0 \in [\rho, \phi, \omega, K^*]$ from invariant mass windows around M_{V0}
  - Use particle identification (PID) variables, likelihood ratios to identify(veto) leptons and hadrons
- **Tag side**: reconstruct 1 or 3-prong decays
- Exploit kinematics of the signal as *neutrinoless* decays
  - M_{lV0} expected to peak at known tau mass
  - $\Delta E_{lV0} = E^*_{sig} - \sqrt{s}/2$ peaks at 0 $\to$ up to initial/final state radiation (ISR, FSR) effects
- Count in elliptical signal region (SR) in ΔE_{lV0} and M_{lV0} plane



[1] Phys. Lett. B 699 (2011) 251

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

background suppression and yields extraction

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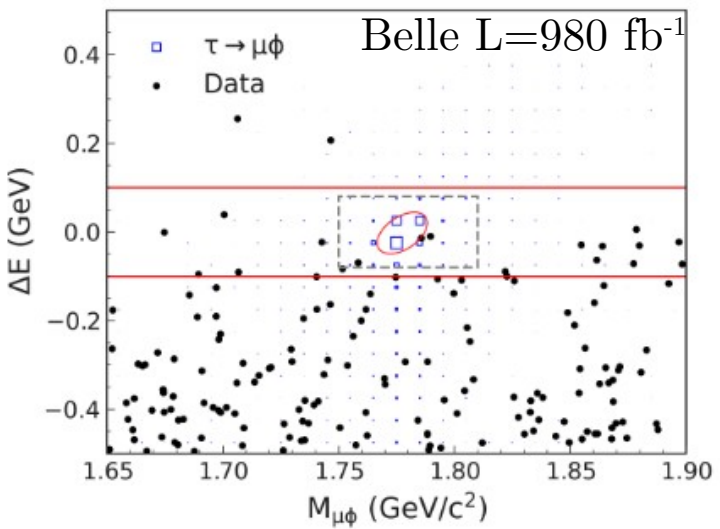
- Backgrounds mimic the presence of neutrinos in the tag side (detector inefficiencies), wrong PID in the signal side → exploit topology and tag kinematics to reject low-multiplicity: $e^+e^- \to e^+e^-(\gamma)$, $e^+e^- \to \mu\mu(\gamma)$, $e^+e^- \to e^+e^-ll$
- Further suppress $\tau \to 3\pi\nu$ and $ee \to q\bar{q}$ with BDT
  - use **missing momentum** and **V^0** properties, and **event tag** categorical variables
- Estimate expected background in SR from **sideband interpolation**
  - Model the shape from hadron enhanced data samples scaled to sideband
  - Integrate over the elliptical SR area

→ Count number of observed events in data inside SR

- Dominant systematic uncertainties from tracking and PID (negligible impact compared to the **statistical** one)



(b) $\tau \to \mu\phi$

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

JHEP06(2023)118

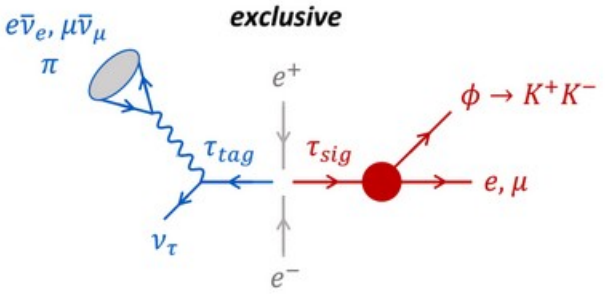
results

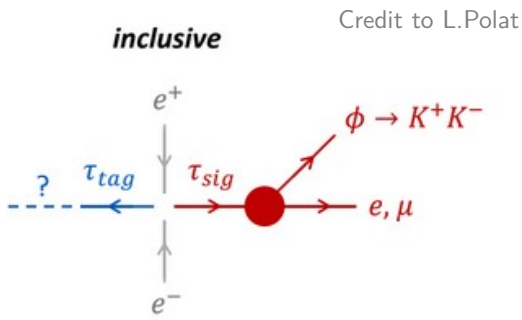
- No significant excess observed → set ULs at 90% CL

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

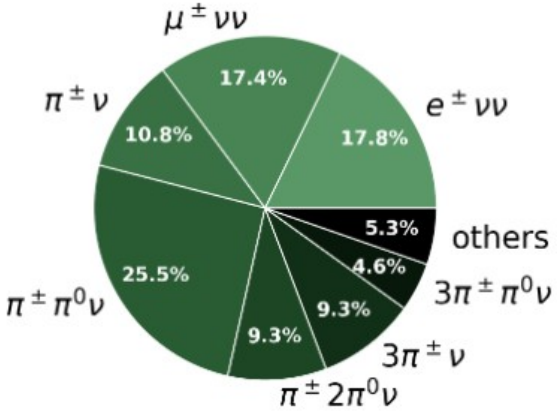
Average 30% improvement from both increased statistics (+ 124 fb^{-1}) and improved analysis (+ 9% efficiency)

New untagged approach for LFV decays





Credit to L.Polat



- First application for $\tau \to l\Phi$
- Untagged reconstruction + BDT classifier: ε_{sig} = **6.5%** for muon mode, ~ **2 x Belle (tagged approach, [1])**

→ **Increase signal efficiency:** reconstruct **signal side**, no requirement on the **tag side** (**untagged reconstruction**)

– Exploit signal and event features in **BDT classifiers** to suppress background

[1]arxiv: 2301.03768

R_μ measurement strategy

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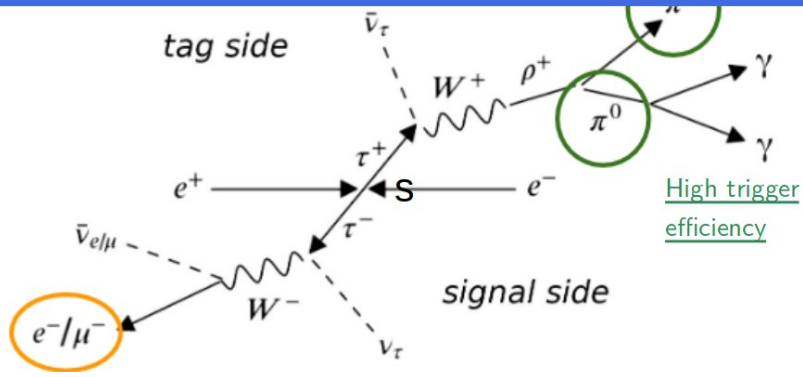
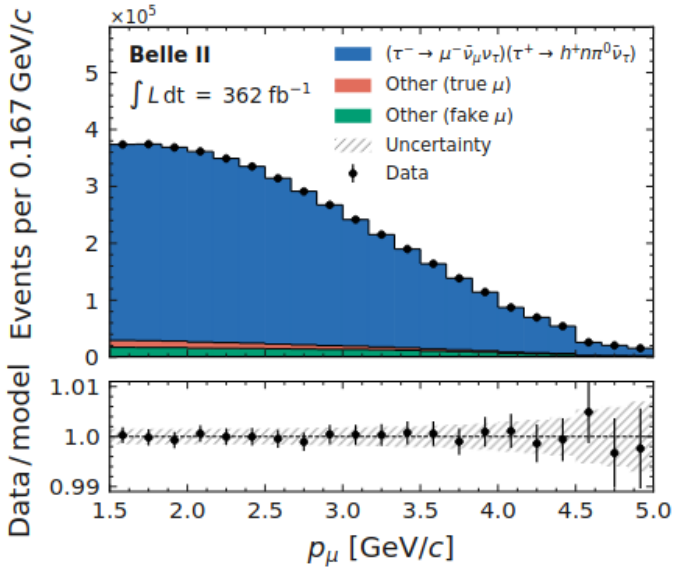
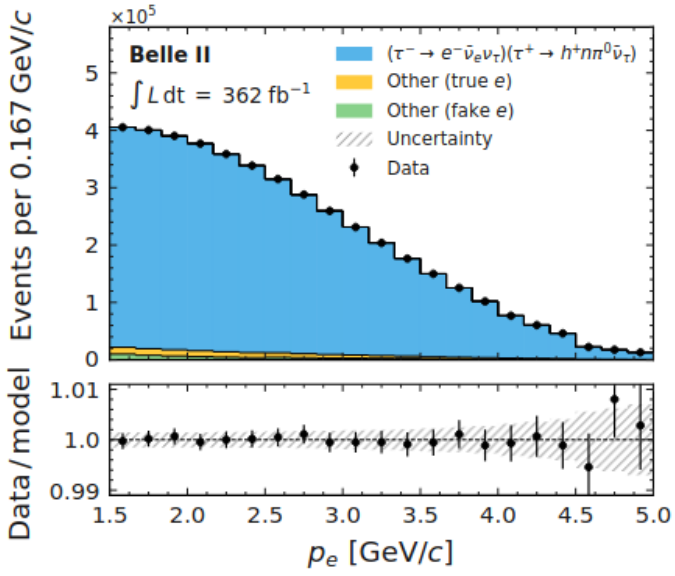
- Select 1x1-prong decays, with one charged hadron + nπ^0 on the tag side
- Rely on lepton ID to select signal side (muon or electron)
- Use neural network to isolate signal (94% purity, 9.6% efficiency)
- Extract R_μ with **template** fit to the lepton momentum distributions







Experimental challenge: instability of R_μ in function of lepton ID selection and polar angle

R_μ results at Belle II

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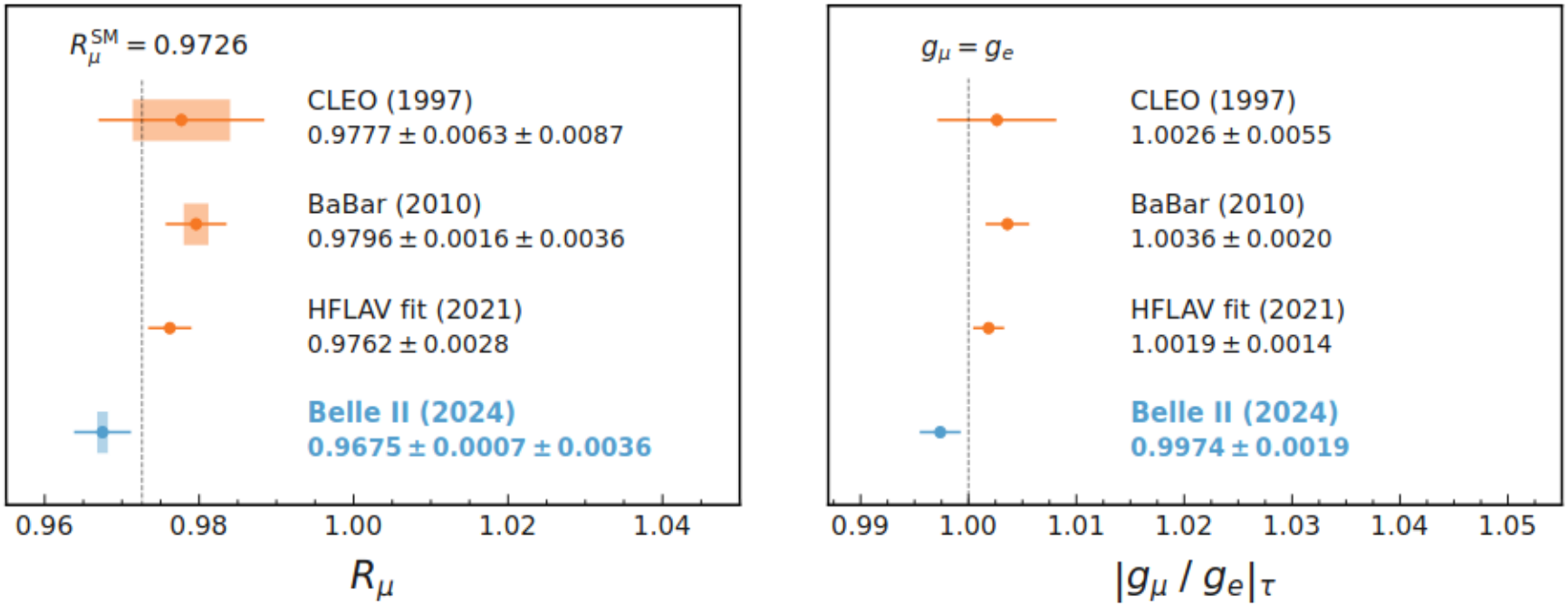
- Most precise test of μ-e universality in τ decays from a single measurement, systematically limited by lepton ID (0.32%)



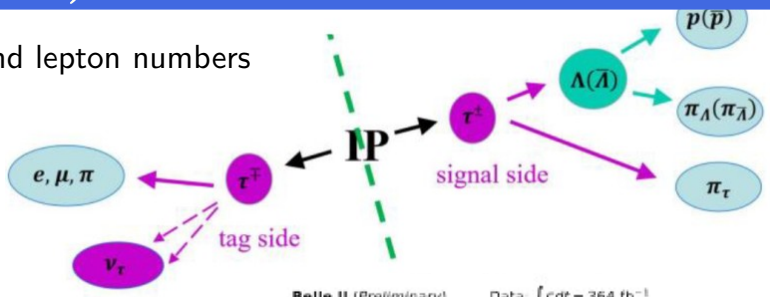
→ consistent with SM expectation at 1.4σ

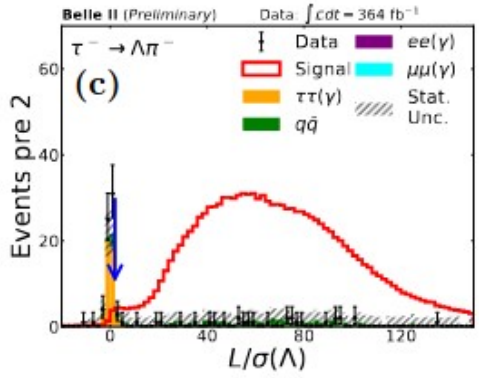
[1] Phys.Rev.Lett. 61 (1988) 1815

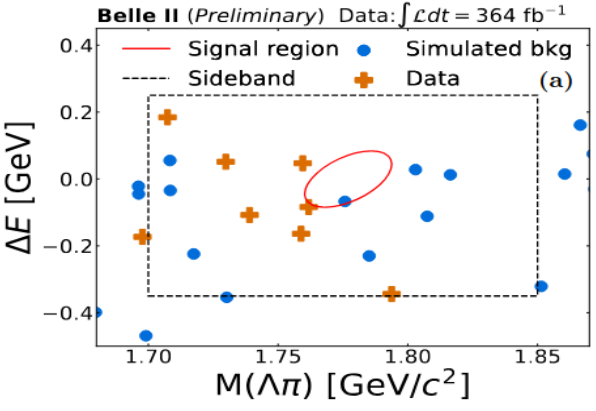
Search for $\tau^- \to \Lambda\,(\overline{\Lambda})\,\pi^-$

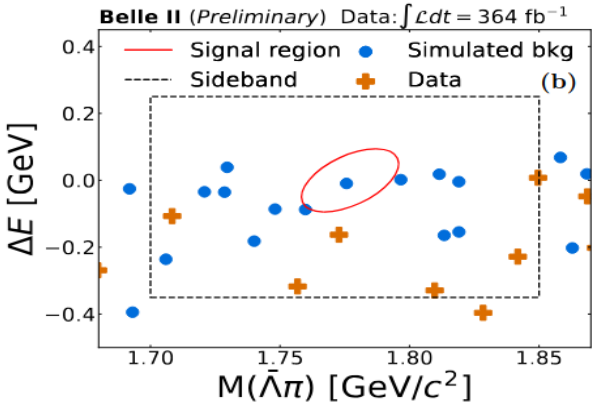
PRD110, 112003

- Baryon number violation required for explaining matter-antimatter asymmetry. Baryon and lepton numbers conserved in the SM, might be violated in beyond SM scenarios.
- Previous limits 90% CL of order 10^{-7} at Belle (154 fb^{-1}) [1]
- Reconstruct events with four tracks and total null charge: use Λ flight significance (L/σ) and gradient BDT selector to reject $e^+e^- \to \tau^+\tau^-$ background and continuum $q\bar{q}$
- Poisson counting experiment technique in elliptical signal regions in $M_{\Lambda\pi}$ and $\Delta E = E^*_{sig} - \sqrt{s}/2$ plane
- Final signal efficiencies of **9.5% (9,9%)** for $\tau^- \to \Lambda(\bar{\Lambda})\pi^-$ with **1 (0.5) expected events**









- No event observed in 364 fb^{-1}, set **world's best upper limits at 90% CL:**

$$\mathcal{B}(\tau \to \Lambda\pi) < 4.7\text{x}10^{-8}$$

$$\mathcal{B}(\tau \to \bar{\Lambda}\pi) < 4.3\text{x}10^{-8}$$

[1] Physics Letters B,Volume 632, 1 (2006)