Tau physics at Belle II

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on behalf of the Belle II Collaboration

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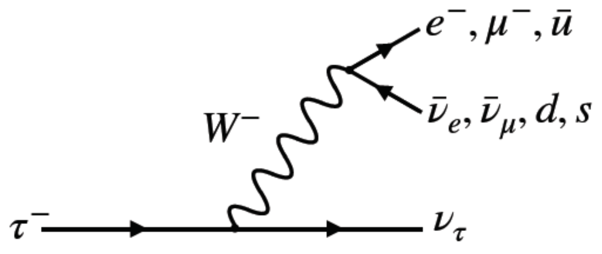
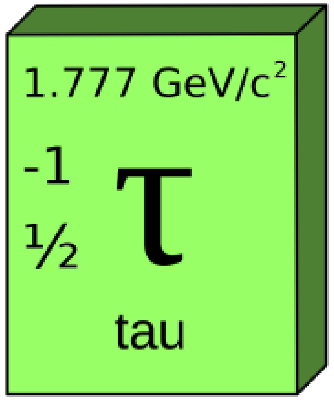
Why τ leptons?

- τ lepton is the heaviest lepton in the Standard Model (SM) with both leptonic and hadronic decay modes.
- Larger mass compared to muon makes τ lepton more sensitive to some models of New Physics (NP).



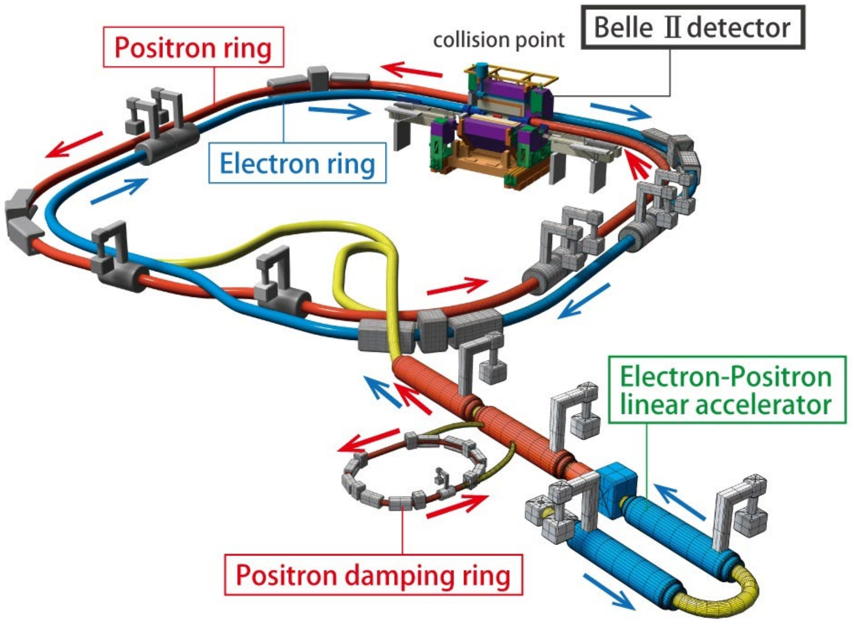
Broad range of available measurements:

- Precise measurements of properties with possibility of CPT tests:
  - Mass
  - Lifetime
  - Electric and Magnetic DM
- Study of pure leptonic decays:
  - Lepton flavour universality (LFU)
  - Michel parameters
- Study of hadronic decays:
  - QCD
  - LFU
  - CP violation (CPV)
- Direct search for New Physics:
  - Lepton flavour violation (LFV)
  - Lepton number violation (LNV)
  - Baryon number violation (BNV)
  - Invisible particles



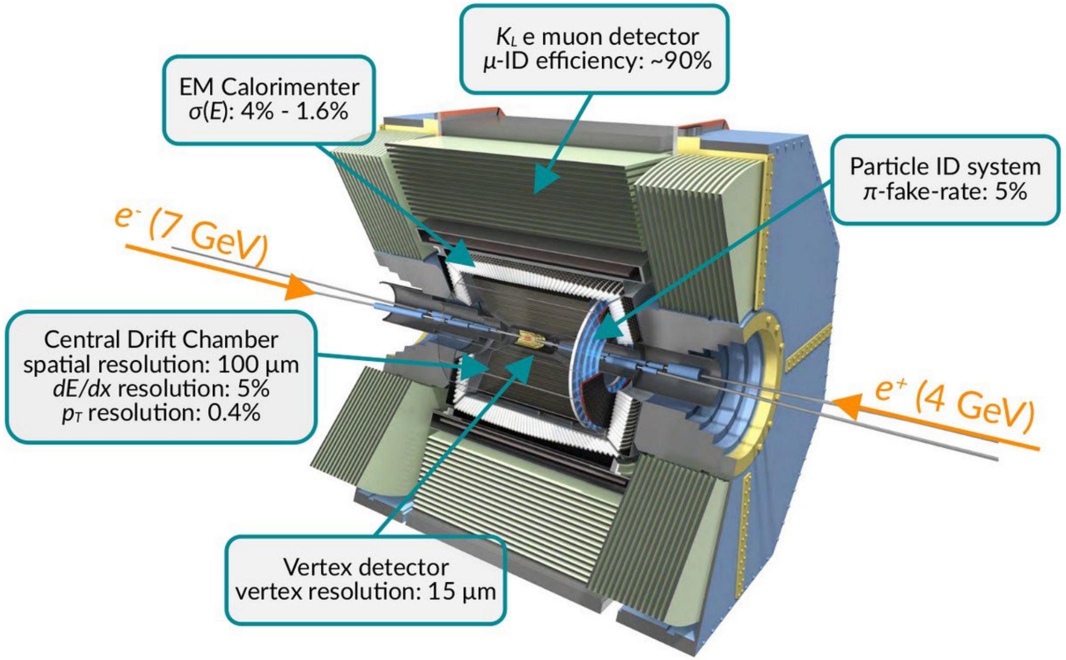
Belle II detector

- Belle II (successor of Belle)
  - 7 GeV electron and 4GeV positron beams
    - ➢ Smaller boost → new vertex detector using 2 layers of pixels and 4 layers of strips
  - 531 fb^{-1} up to now ($4.9 \times 10^8\ \tau^+\tau^-$ pair)
  - Goal: 50 fb^{-1}



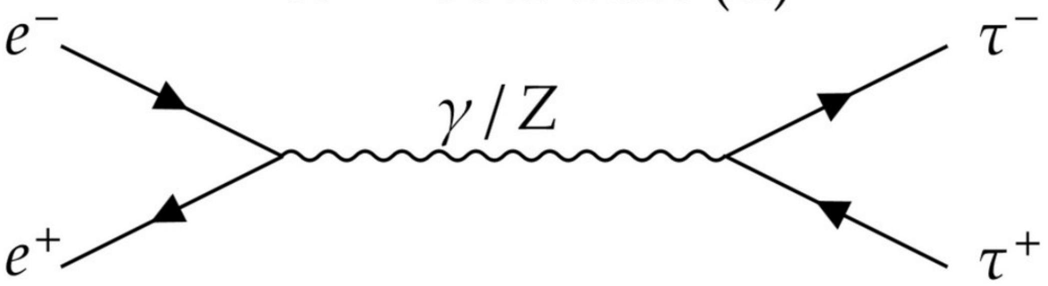
- Detection
  - Good momentum resolution & particle ID
  - Good efficiency for neutral particles
  - Missing energy reconstruction
  - Specific low-multiplicity event triggers

PTEP 2019 (2019) 12, 123C01



Why at Belle II?

- 96.2% of ee collisions do Bhabha scattering background
- Remaining 3.8 % compose Belle II physics program
  - 9.7% $\Upsilon(4S) \to BB$
  - 7.76% $\tau\tau$ production



- **Advantages:**
  - Clean physics environment, known initial state
  - Missing energy reconstruction
  - high trigger efficiency

$\sigma[e^+e^- \to e^+e^-(\gamma)] = 300\ nb$

$\sigma[e^+e^- \to \gamma\gamma(\gamma)] = 4.99\ nb$

$\sigma[e^+e^- \to u\bar{u}] = 1.61\ nb$

$\sigma[e^+e^- \to c\bar{c}] = 1.3\ nb$

$\sigma[e^+e^- \to \mu\mu] = 1.15\ nb$

$\sigma[e^+e^- \to \Upsilon(4S)] = 1.11\ nb$

$\sigma[e^+e^- \to \tau\tau] = 0.9\ nb$

$\sigma[e^+e^- \to d\bar{d}] = 0.4\ nb$

$\sigma[e^+e^- \to s\bar{s}] = 0.38\ nb$

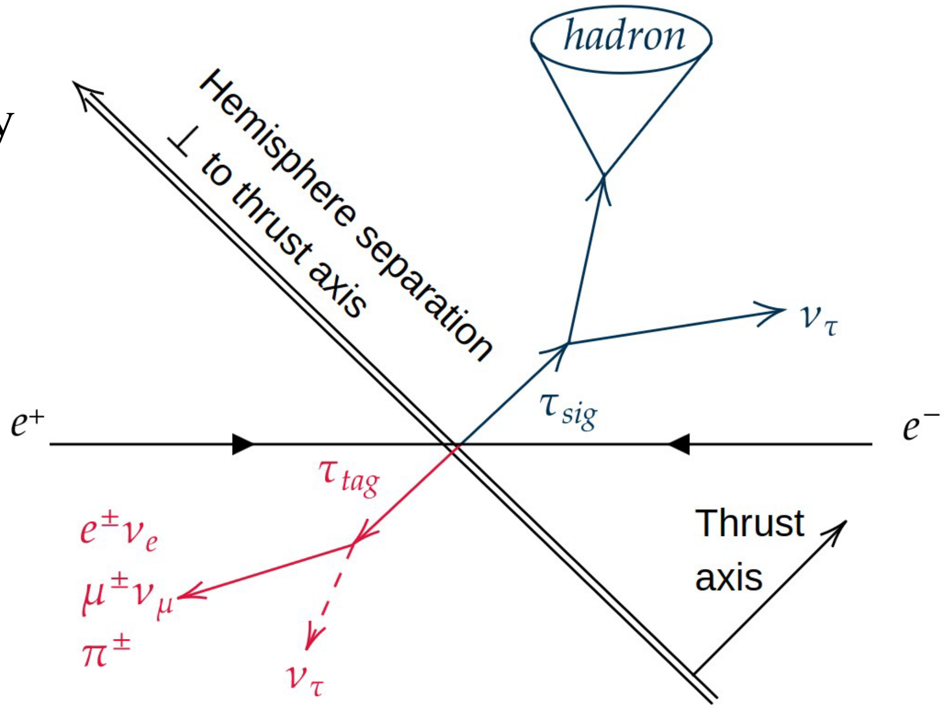
- **Possible studies**
  - High precision studies
  - Searches for rare decays

How to reconstruct τ at Belle II?

- SM τ decays are not fully reconstructable due to missing neutrino
- Identify $\tau^+\tau^-$ events using thrust axis ($\hat{t}$):
  - Maximizes projection of all final state particle momenta in event:

$$T = \max_{\hat{t}} \frac{\sum_i |\vec{p}_i^{\,CM} \cdot \hat{t}|}{\sum_i |\vec{p}_i^{\,CM}|}$$

- Define two hemispheres divided by the plane perpendicular to the thrust axis
- Reconstruct tag-side tau in standard model 1-prong or 3-prong decay
  - Exclusive → use only 1-prong or 3-prong events
    - ➢ High purity, less efficiency
  - Inclusive → do not reconstruct tag-side tau in a specific mode
    - ➢ Higher signal efficiency
    - ➢ Higher background levels



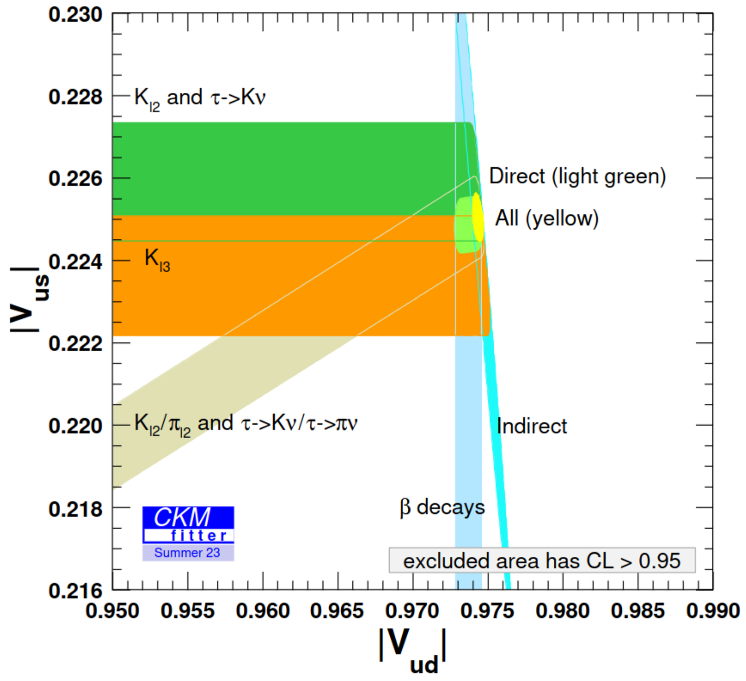
SM Measurements: Motivation

- Precision measurement of tau quantities can have significant impact
  - First row unitarity of CKM-Matrix (Cabibbo-angle-anomaly)
  - $\mathcal{B}(\tau \to K\nu)/\mathcal{B}(\tau \to \pi\nu) \sim |V_{us}|/|V_{ud}|$
  - Mass of tau is the one with worst (relative) precision among leptons

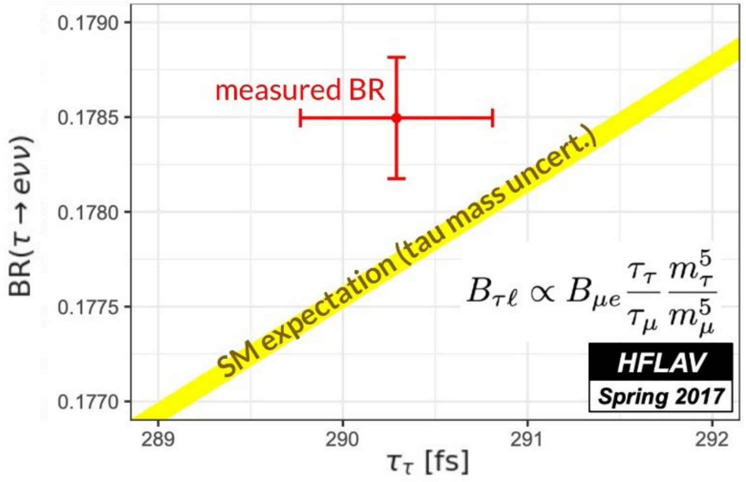
$$m_e = (0.51099895000 \pm 0.00000000015)\ \mathrm{MeV}/c^2$$

$$m_\mu = (105.6583755 \pm 0.0000023)\ \mathrm{MeV}/c^2$$

$$m_\tau = (1776.86 \pm 0.12)\ \mathrm{MeV}/c^2$$



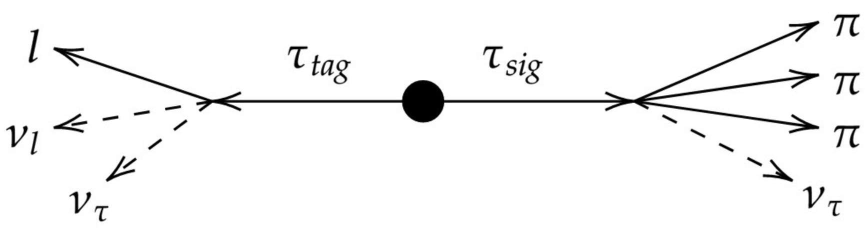
- Lepton Flavor Universality
  - All leptons are expected to have same coupling strength to W-boson in SM
    - ➢ Different observations would suggest NP contributions
  - Mass and lifetime of τ are important inputs to those calculations



Mass of the τ lepton

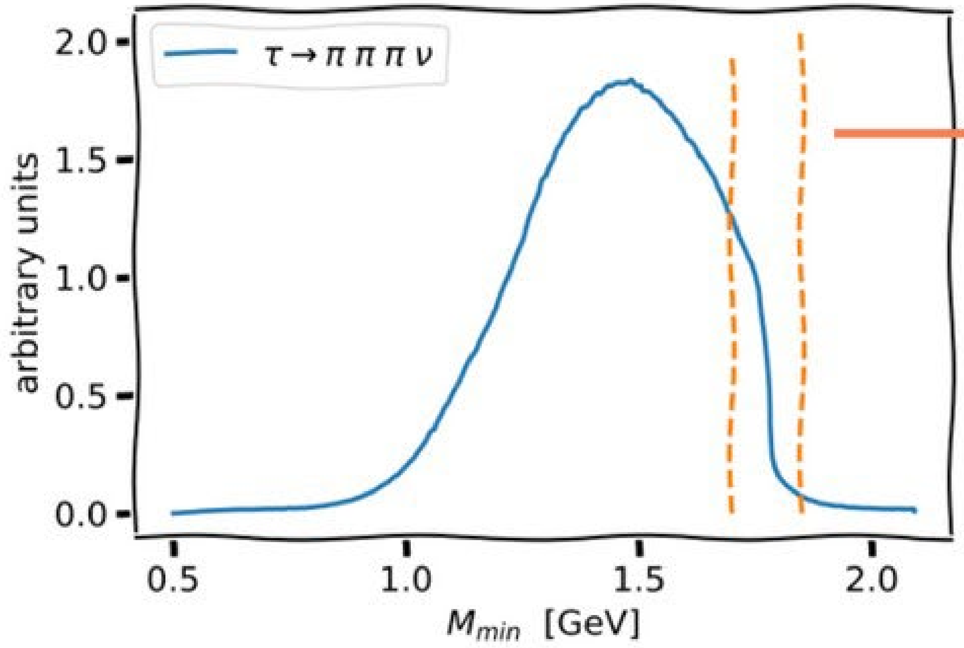
Phys.Rev.D 108 (2023) 032006

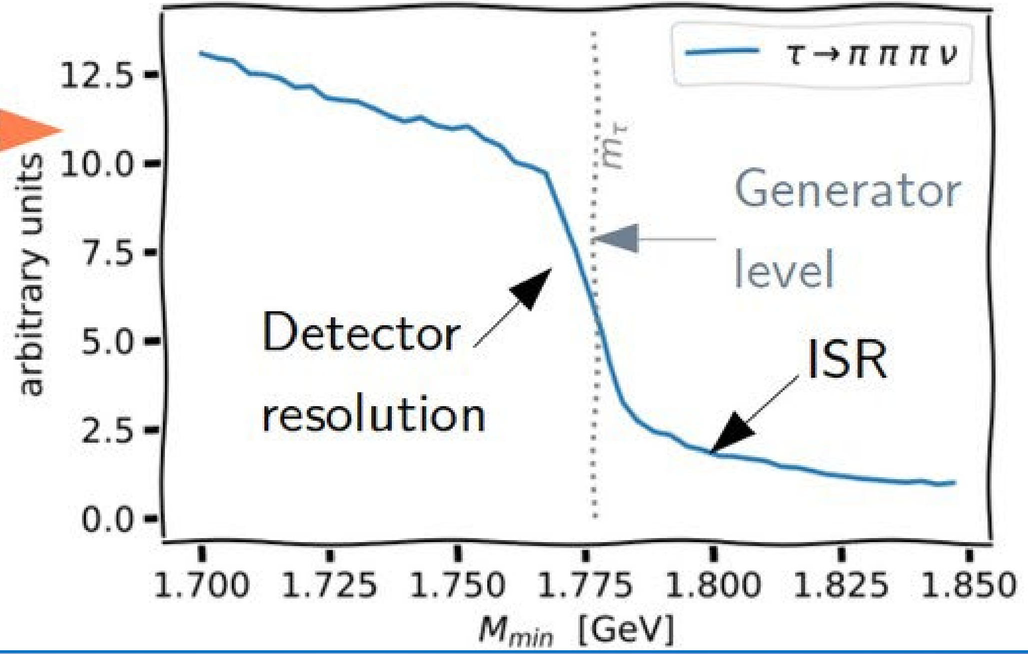
- Precision is needed for LFU and α_s (m_τ)
- Belle II in $\tau^- \to \pi^-\pi^+\pi^-\upsilon_\tau$ ($\mathcal{L} = 190\ \mathrm{fb}^{-1}$)
- Pseudomass method:
  - Fit kinematic edge of M_{min} distribution in $\tau \to 3\pi\upsilon_\tau$ decays with empirical function
  - Smeared edge due to ISR/FSR and detector resolution



$$M_{min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$

Accuracy in $\sqrt{s}$ and p is the key to precision



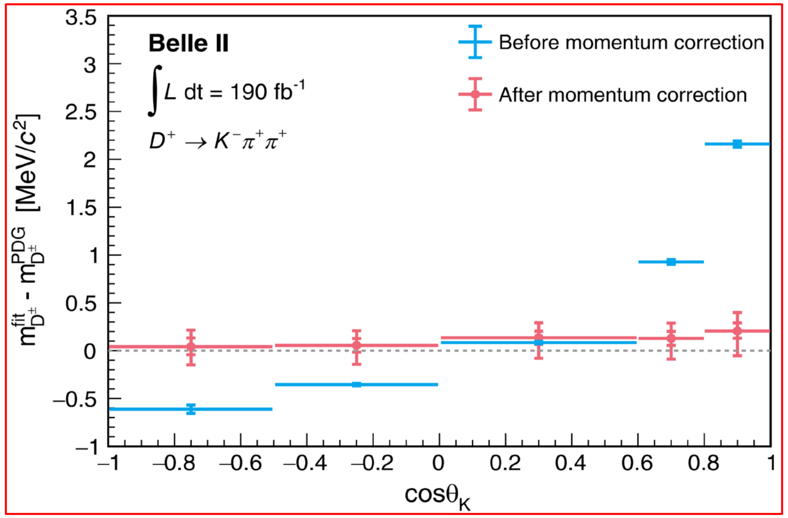


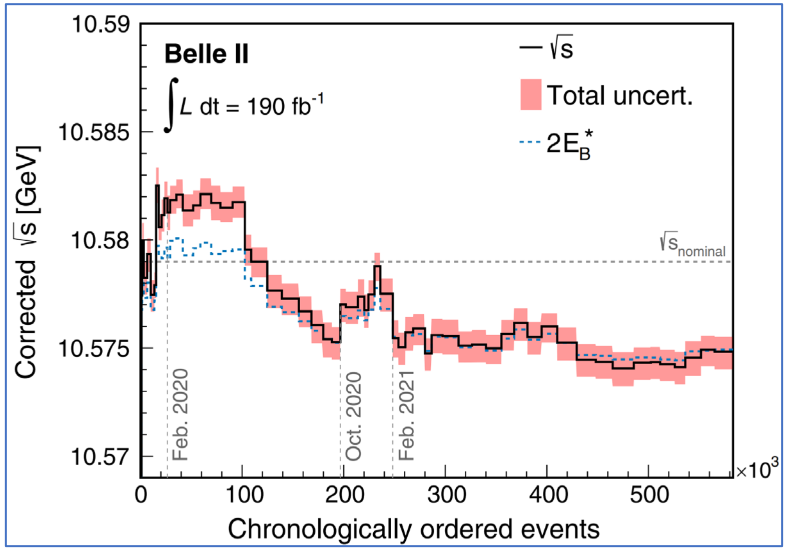
Mass of the τ lepton

Phys.Rev.D 108 (2023) 032006

- Beam energy calibration and momentum correction are crucial for this measurement

- E_{beam} corrected by hadronic B-Meson decays ~ 0.07 MeV/c^2
  - the B-meson energy relies on the knowledge of the energy dependence of the $e^+e^- \to B\bar{B}$ cross section
  - the average values of the charged (0.26 MeV/c^2) and neutral (0.20 MeV/c^2) B-meson masses
  - the measurement of B-meson energy based on simulation





$\sqrt{s}$: corrected center-of-mass energy

$2E^*_B$: center-of-mass energy of $B\bar{B}$ pair

- Charged-particle momentum correction using $D^0 \to K^-\pi^+$ sample ~ 0.06 MeV/c^2
  - some residual dependence of the scale factors on the transverse momentum (with consistency check in $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+ K^-\pi^+$, and $J/\psi \to \mu^+\mu^-$)
  - deviation from the known value of the D^0 mass-peak observed in simulation
  - modeling of the D^0 mass peak
  - the known D^0 mass
  - a bias due to differences in the cos θ distributions

Mass of the τ lepton

Phys.Rev.D 108 (2023) 032006

- Perform unbinned maximum likelihood fit to the kinematic edge of the mass distribution

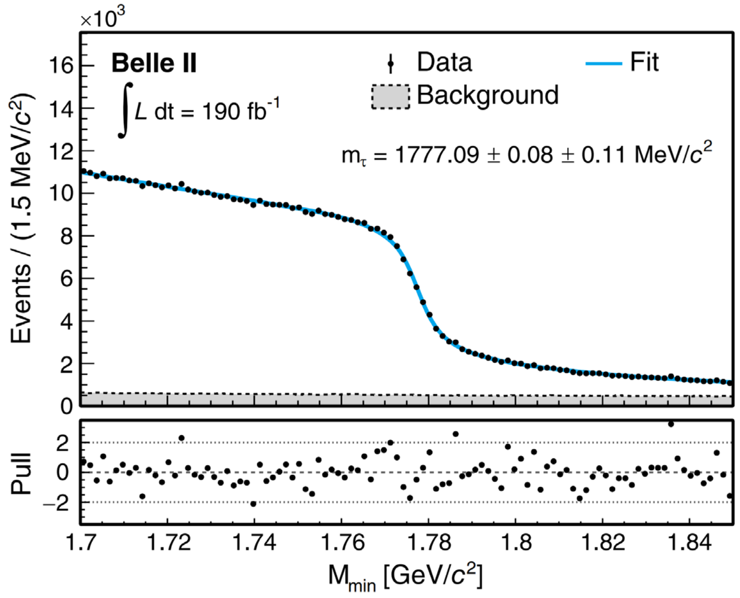
$$F(M_{min}) = 1 - P_3 \cdot \arctan\left(\frac{M_{min} - P_1}{P_2}\right) + P_4(M_{min} - P_1) + P_5(M_{min} - P_1)^2$$

P_1: an estimator of the τ mass

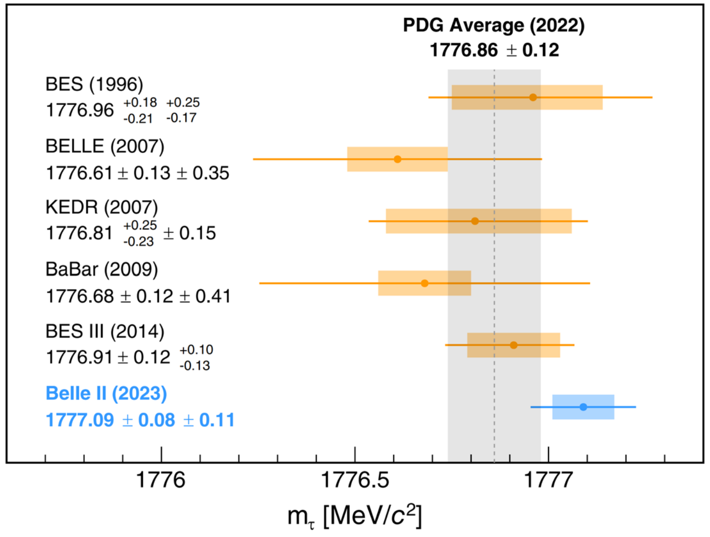
P_2: the slope of the threshold

$P_3 \sim P_5$: the shape away from the edge

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



- Belle II provides World's most precise result
  - the statistical uncertainty per unit sample size is smaller
    - ➢ improved event selection and momentum resolution
  - our result is consistent with previous measurements and is the most precise to date



Test of LFU in τ decays JHEP 08 (2024) 205

- Precise test of μ-e universality by measuring

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

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

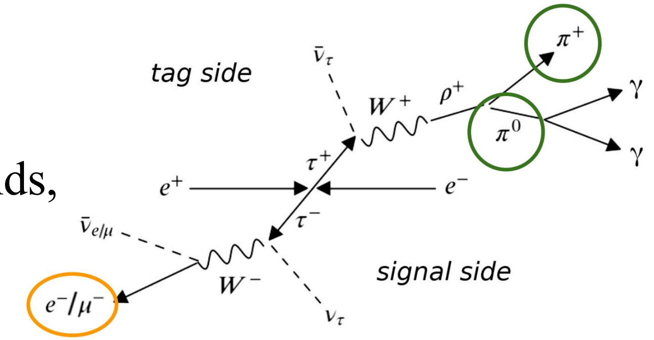
- Ratio of leptonic branching fractions

$$R_\mu \equiv \frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu(\gamma))}{\mathcal{B}(\tau^- \to \nu_\tau e^- \bar{\nu}_e(\gamma))} \stackrel{\text{SM}}{=} 0.9726$$

is sensitive to new physics if it violates
  - Lepton flavor [2]
  - Lepton universality in weak charged-currents
- Using the **362 fb^{-1}** dataset collected by Belle II

[1] Phys.Rev.Lett. 61 (1988) 1815
[2] Phys. Lett. B 762 (2016) 389-398

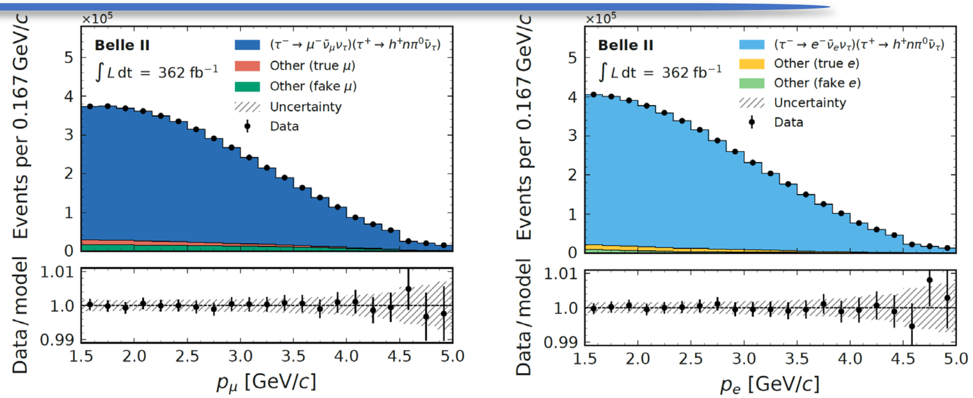
- 1 × 1-track topology decays
  - **Tag side**: one charged hadron and **at least one** π^0
  - **Signal side**: one e or μ
  - BF(~35%) , low backgrounds, high trigger efficiency

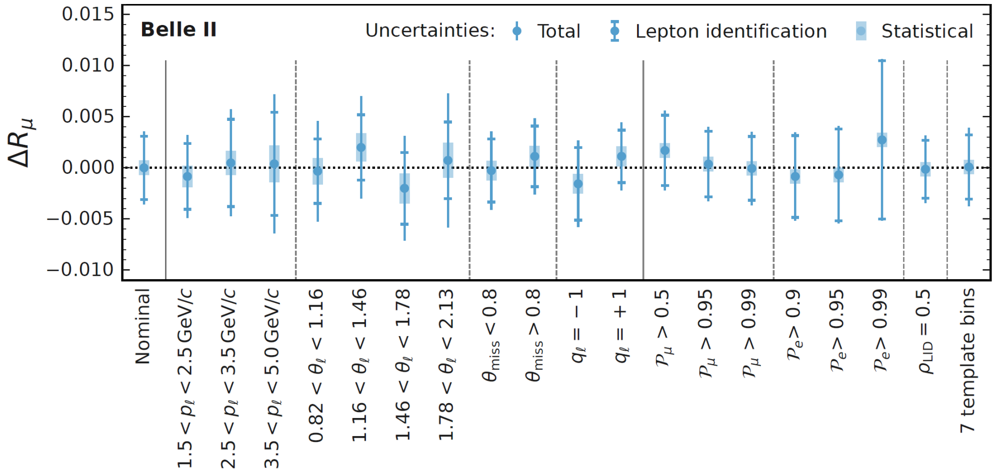


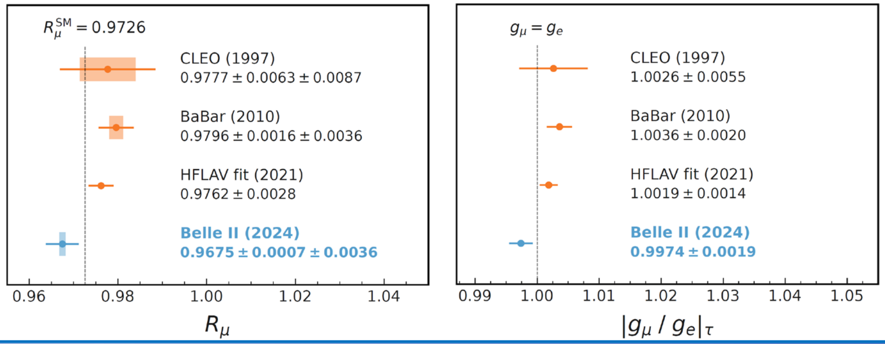
- **Background suppressed** through rectangular cuts and **neural network**
  - 94% purity at 9.6% signal efficiency for combined e/μ samples
  - Main backgrounds:
    - ➢ $e^+e^- \to \tau^+\tau^-$: $\pi^\pm$ faking $e^\pm$~1.3%, $\mu^\pm$ ~5.2%
    - ➢ $e^+e^- \to \tau^+\tau^-$: misidentified tag side~2.3%
    - ➢ $e^+e^- \to e^+e^-\tau^+\tau^-$: 0.2%

Test of LFU in τ decays JHEP 08 (2024) 205

- R_μ measured through **template binned maximum likelihood fits**
  - Cover lepton momentum bins from **1.5 to 5 GeV/c**
- **Main systematics** from **PID**~0.32%, and **triggers**~0.10%
  - Included in the fit as nuisance parameters
  - **Total systematic** uncertainty of 0.37%
- **Stability of the result**
  - **Checked for consistency of the result before unblinding**
  - Sub-regions for different kinematic variables, data periods, PID requirements
  - **Good agreement between the measured values**
- $R_\mu = 0.9675 \pm 0.0007(stat.) \pm 0.0036(sys.)$ and $\left(\frac{g_\mu}{g_e}\right)_\tau = 0.9974 \pm 0.0019$
  - **Most precise** test of μ-e universality in τ decays
  - Consistent with SM at 1.4σ
- Combination of CLEO, Babar and Belle II yields (assuming independent systematics)
  - $\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0005 \pm 0.0013$



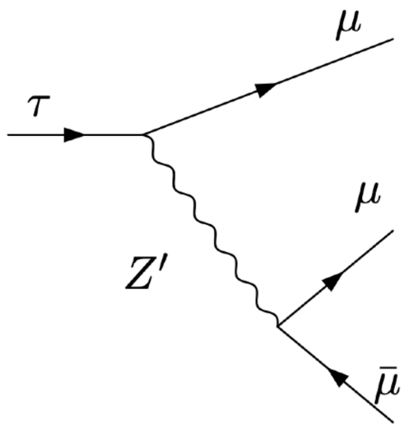




BSM Search: Motivation

- **Motivation:** the decay channels forbidden in the SM but allowed in several new physics scenarios
  - LFV decay $\tau \to \ell\phi$
    - 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:** experimentally the most accessible)

Physics Models	$\mathcal{B}(\tau \to \mu\mu\mu)$
SM	$10^{-53}\sim10^{-55}$
SM + seesaw	10^{-10}
SUSY + Higgs	10^{-8}
SUSY + SO(10)	10^{-10}
Non-universal Z'	10^{-8}

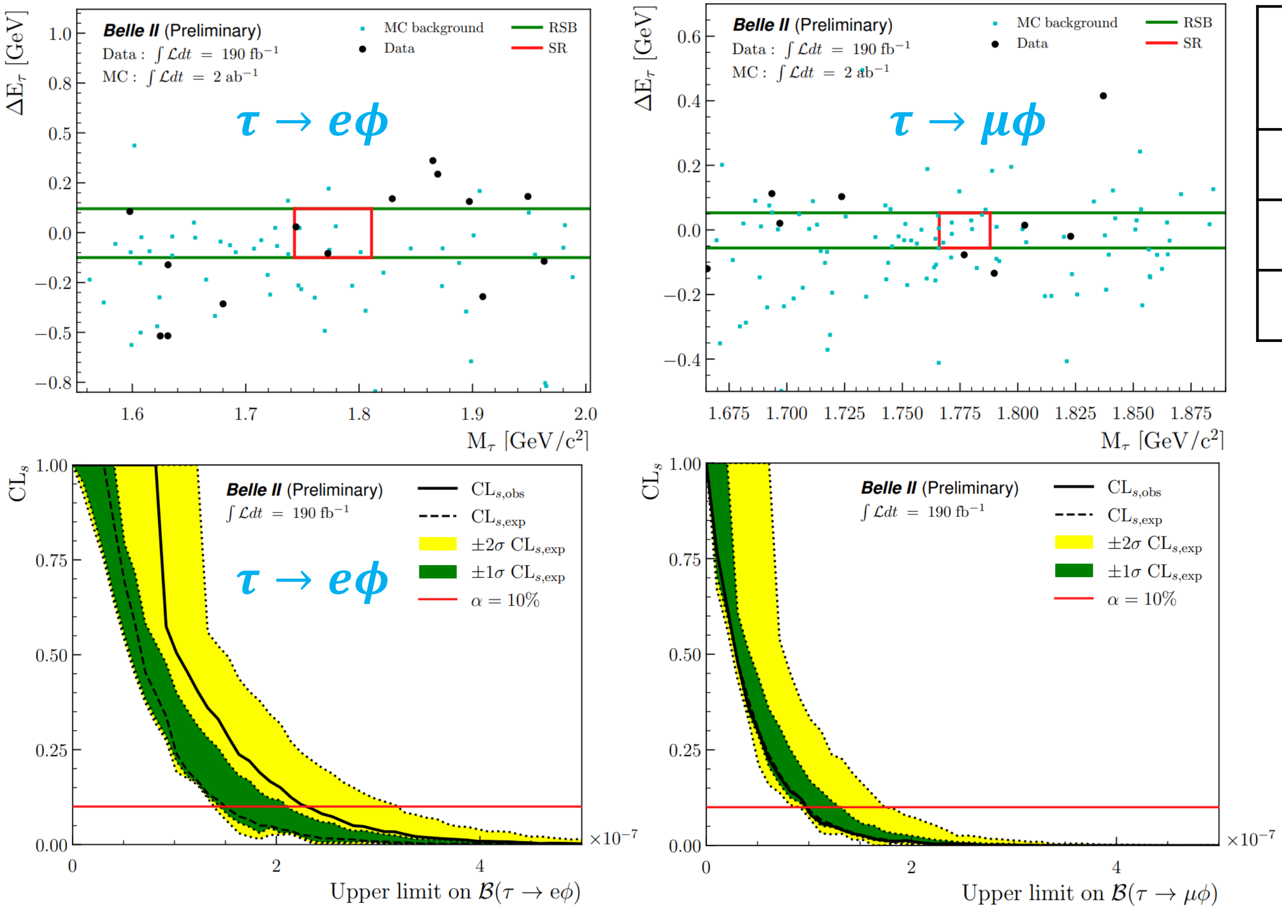


  - LFV decay $\tau \to \ell\alpha$
    - new bosons as candidates for dark matter
    - explain the anomalous magnetic moment of the muon

LFV decay $\tau \to \ell\phi$

arXiv:2305.04759

- **Untagged inclusive reconstruction, reconstruct signal side as ϕ 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.



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;

↓

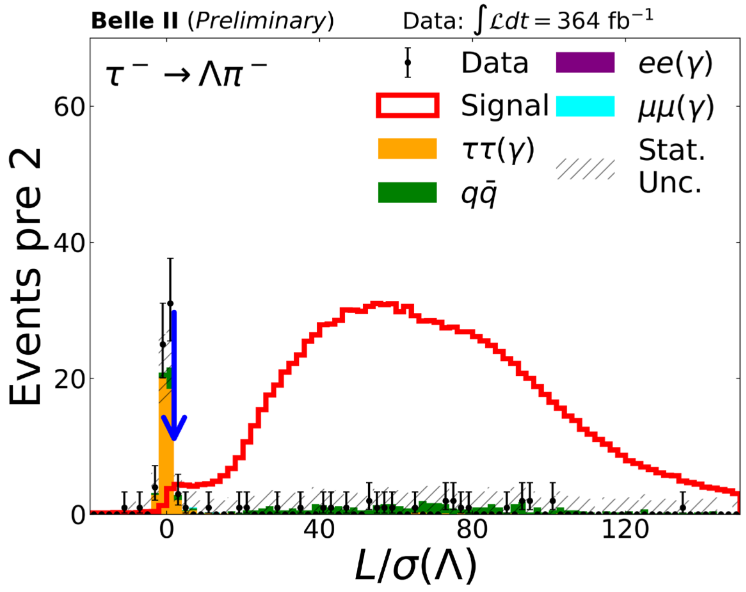
exploited for other measurements;

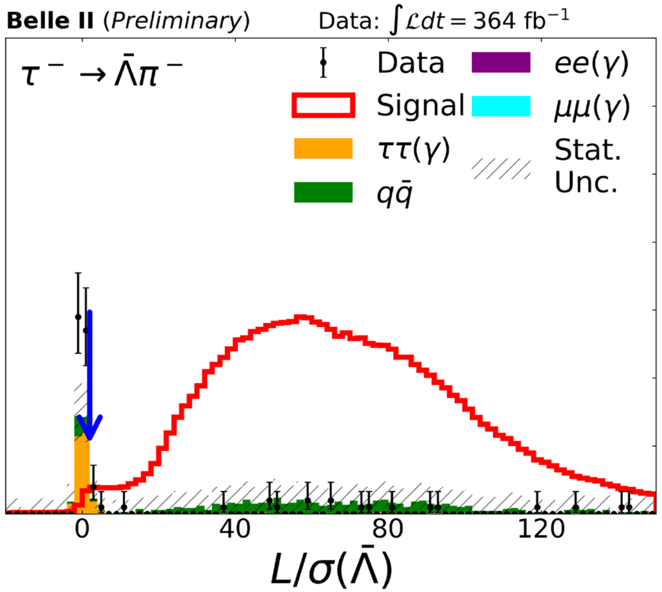
[1] B. Aubert, *et al.*, (BaBar Collaboration), Phys. Rev. Lett. 103, 021801 (2009).

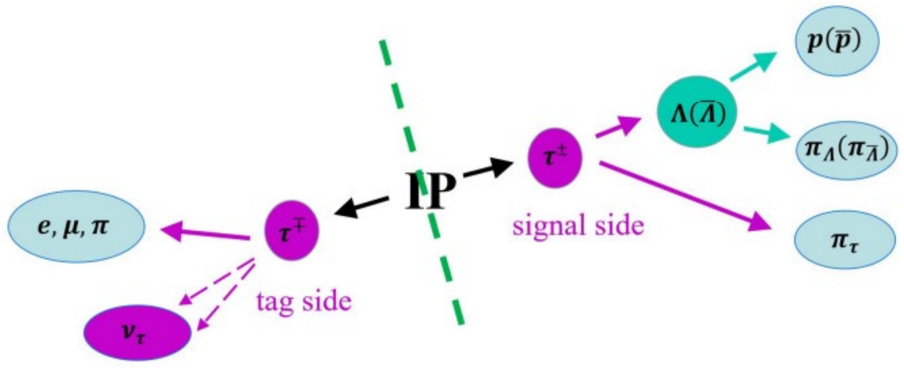
BNV decay $\tau \to \Lambda(\bar{\Lambda})\pi$

arXiv:2407.05117

- **A baryon number violation decay that is also an LFV decay.**
- **Belle II with 364 fb^{-1} :**
  - 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.



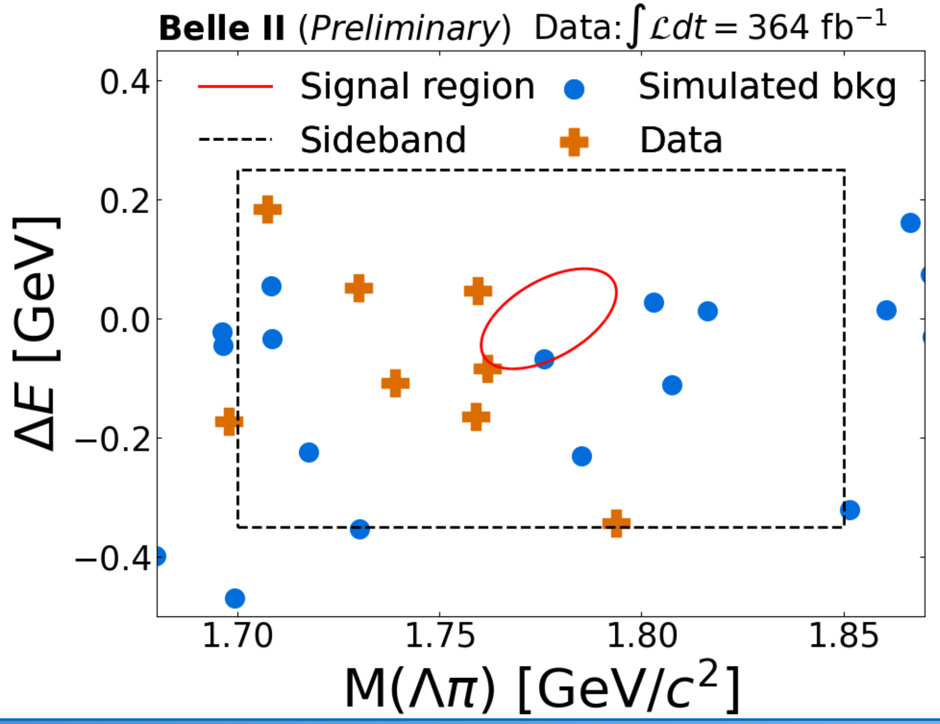


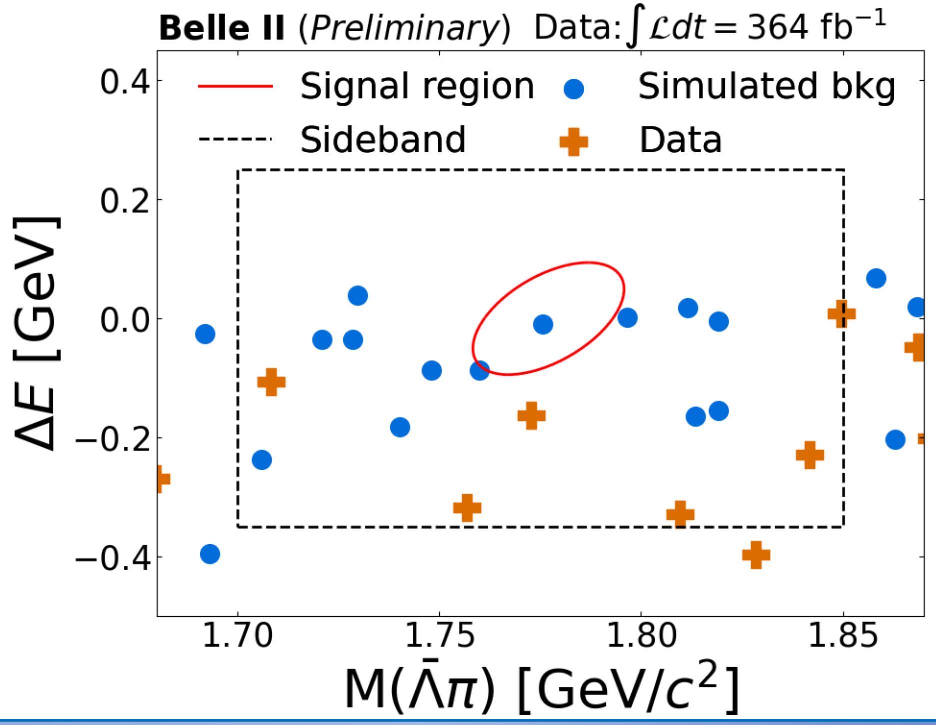


[1] Y. Miyazaki, *et al.*, (Belle Collaboration), Phys. Lett. B **632**, 51 (2006).

BNV decay $\tau \to \Lambda(\bar{\Lambda})\pi$

- 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 $M(\Lambda\pi) = \sqrt{E^2_{\Lambda\pi} - P^2_{\Lambda\pi}}$ and $\Delta E = E^{CM}_{\Lambda\pi} - \sqrt{s}/2$ plane;
- Expected events are $1^{+1.3}_{-1.1}$ and 0.5 ± 0.6 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 $\mathcal{B}(\tau \to \bar{\Lambda}\pi)$;





LFV decay $\tau \to \mu\mu\mu$

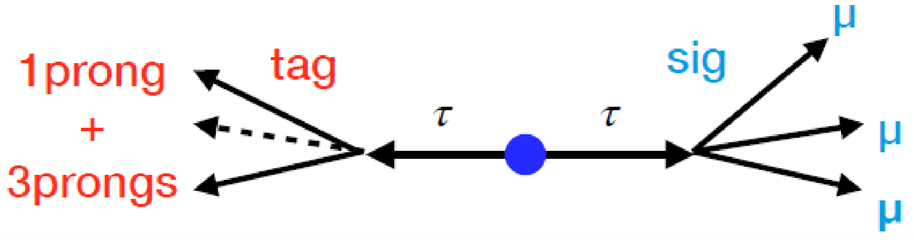
JHEP 09 (2024) 062

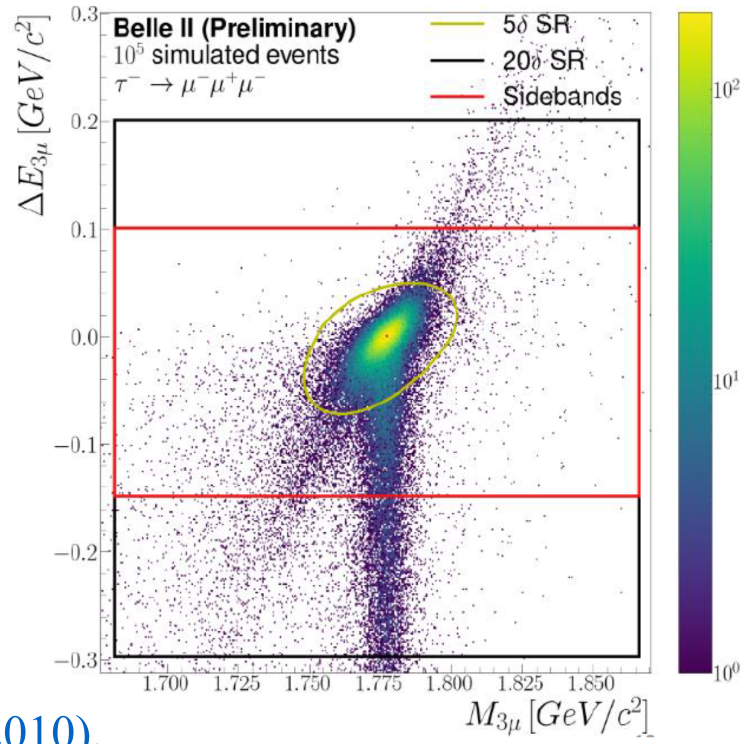
- **Belle II with 424 fb^{-1}**
- Main analysis approach:
  - Inclusion of 3×1 and 3×3 toplogies;
  - Selection and background rejection using BDT;
- Extract signal yield from 2D plane ($M_{3\mu}$, $\Delta E_{3\mu}$):

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

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

- 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).

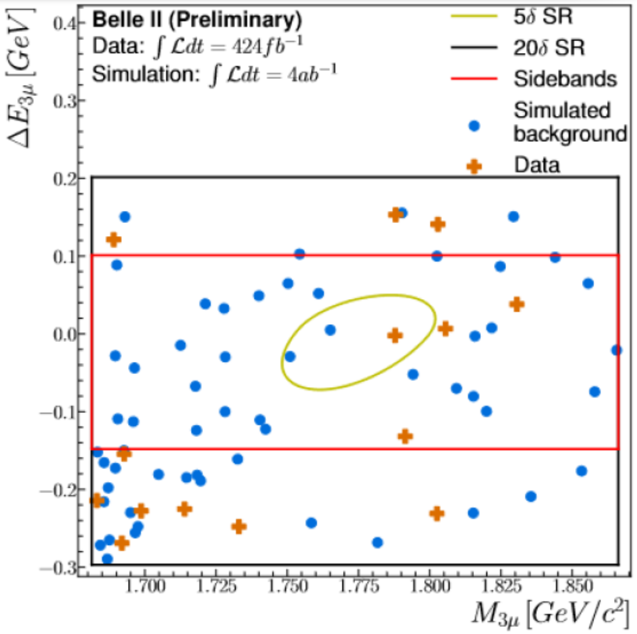
LFV decay $\tau \to \mu\mu\mu$

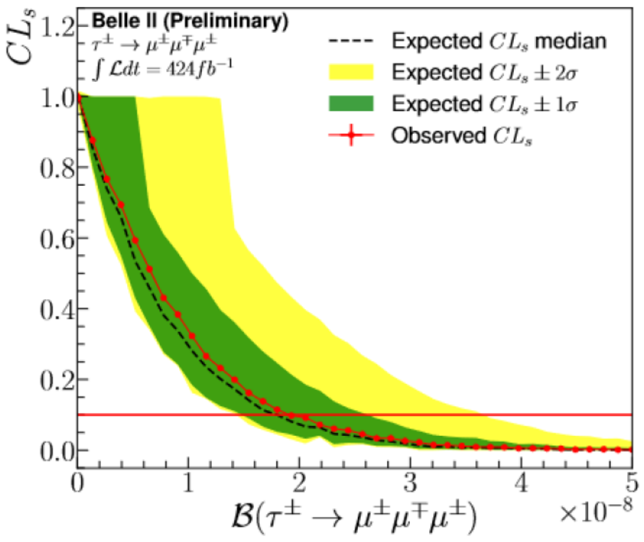
JHEP 09 (2024) 062

- 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} ($\mathcal{L} = 20.3\ \text{fb}^{-1}$)
LHCb	4.6×10^{-8} ($\mathcal{L} = 3.0\ \text{fb}^{-1}$)
CMS	2.9×10^{-8} ($\mathcal{L} = 131\ \text{fb}^{-1}$)
Belle	2.1×10^{-8} ($\mathcal{L} = 782\ \text{fb}^{-1}$)
BaBar	3.3×10^{-8} ($\mathcal{L} = 486\ \text{fb}^{-1}$)
Belle II	1.9×10^{-8} ($\mathcal{L} = 424\ \text{fb}^{-1}$)





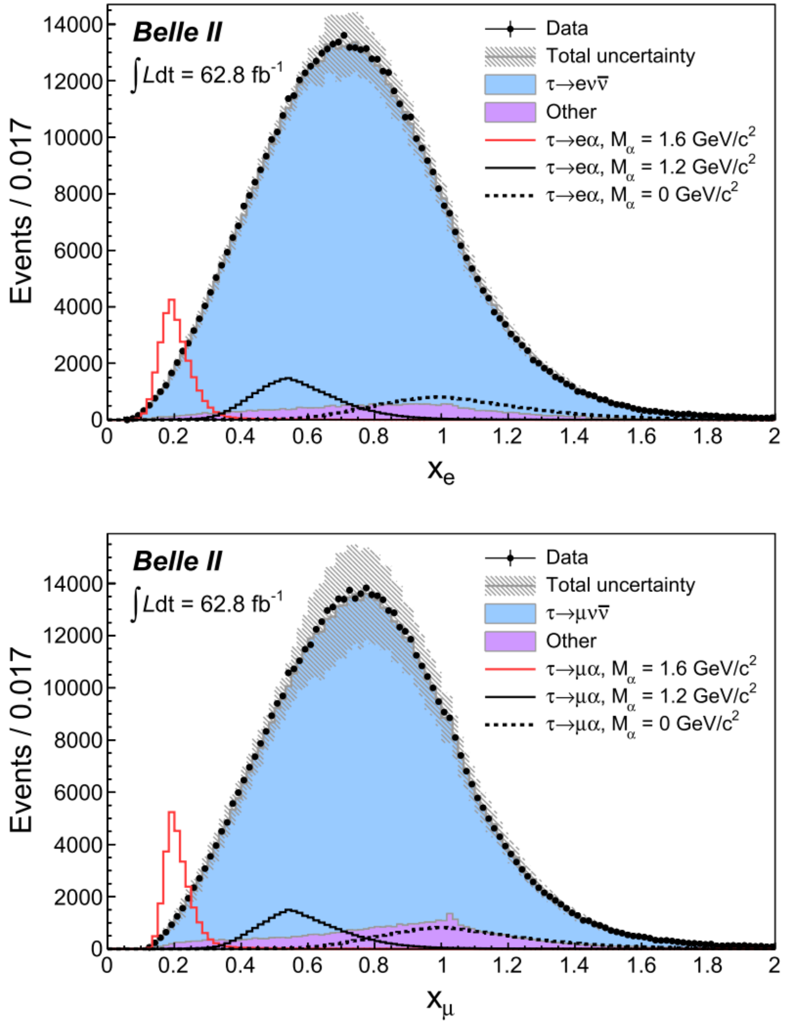
LFV invisible decay $\tau \to \ell\alpha$

PRL 130 (2023) 181803

- α **is an invisible spin-0 boson.**
- $\int \mathcal{L}\,dt = 62.8\ \mathrm{fb}^{-1} \sim$ **58 Million** $ee \to \tau\tau$.
- **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.



- **Simulation derived templates fit for different α mass hypotheses.**

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

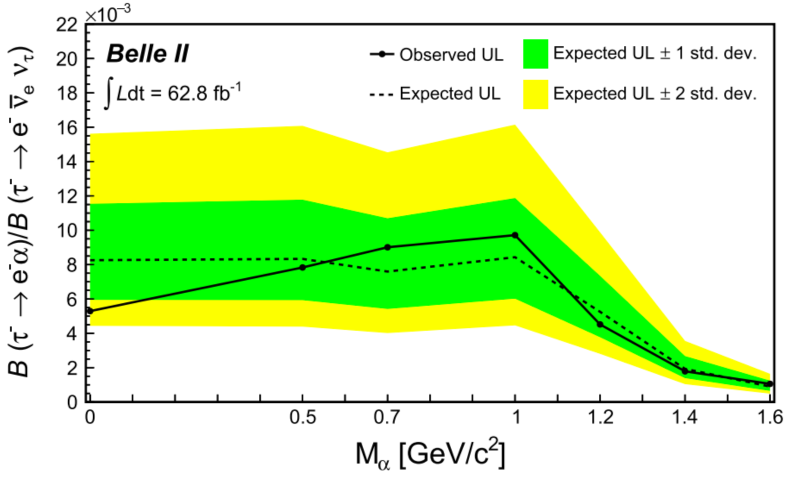
LFV invisible decay $\tau \to \ell\alpha$

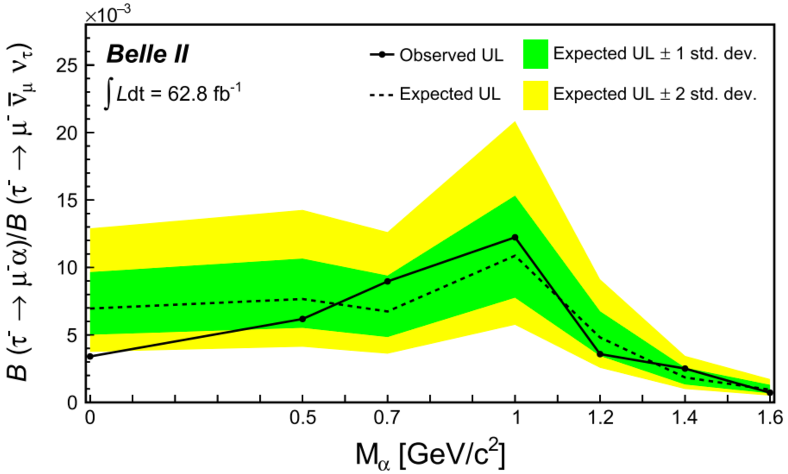
PRL 130 (2023) 181803

- **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.**

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)

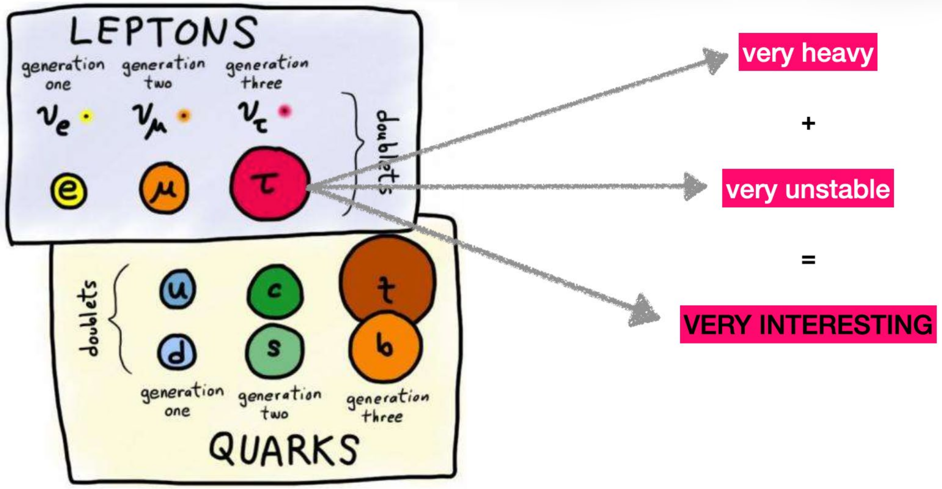
M_α [GeV/c^2]	$\mathcal{B}_{\mu\alpha}/\mathcal{B}_{\mu\bar{\nu}\nu}$ ($\times10^{-3}$)	UL at 95% C.L. ($\times10^{-3}$)	UL at 90% C.L. ($\times10^{-3}$)
0.0	-9.4 ± 3.7	3.4(0.59)	2.7(0.47)
0.5	-3.2 ± 3.9	6.2(1.07)	5.1(0.88)
0.7	2.7 ± 3.4	9.0(1.56)	7.8(1.35)
1.0	1.7 ± 5.4	12.2(2.13)	10.3(1.80)
1.2	-0.2 ± 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)

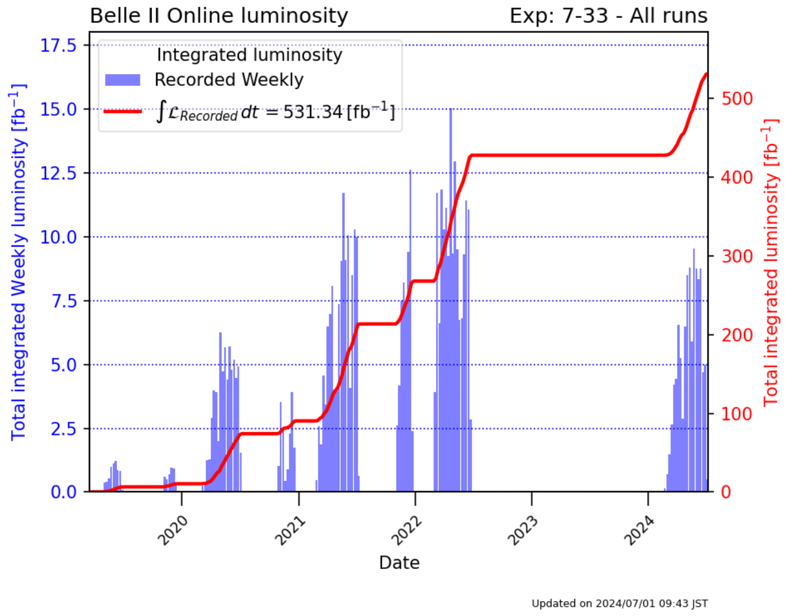




Summary

- B factories are a good environment for tau physics!
- Belle II will contribute to the understanding of tau lepton properties
  - Searches for BSM physics
  - Test of LFU
  - Precision measurements of SM parameters
- Based on the early data set, Belle II has already provided the community with competitive results and new methods applications, and more are upcoming.
- A lot more to come with more data,
  - Now 531 fb^{-1} is accumulated, next run is underway.
- Belle II provides an opportunity to update measurements done by Belle and BaBar with improved precision and to conduct new studies, not available for the previous generation.





Thank you for attention!