Precision measurement of τ lepton decays at Belle II

Arthur Thaller on behalf of Belle II
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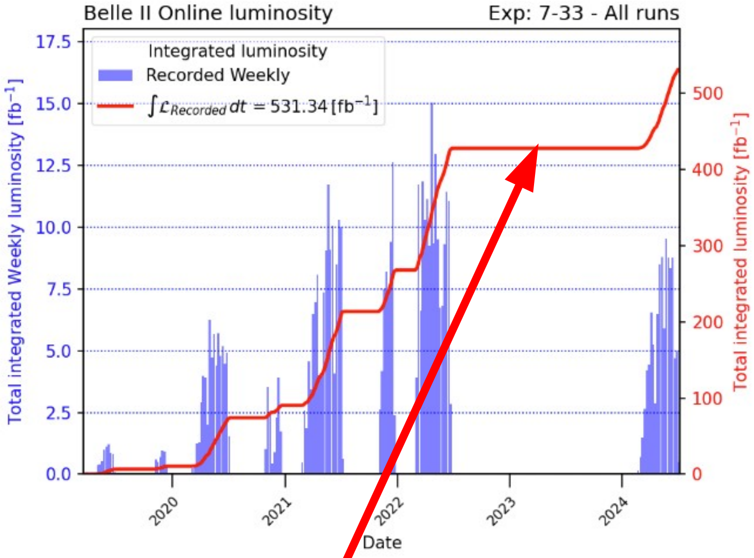
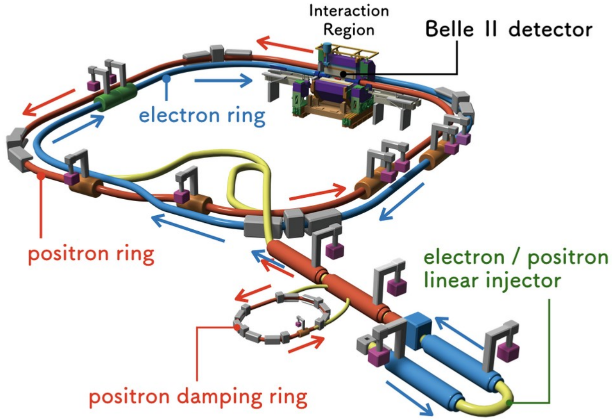
Aix Marseille Univ, CNRS/IN2P3, CPPM

The Belle II experiment : SuperKEKB accelerator

The SuperKEKB e^+e^- collider at 10.58 GeV :

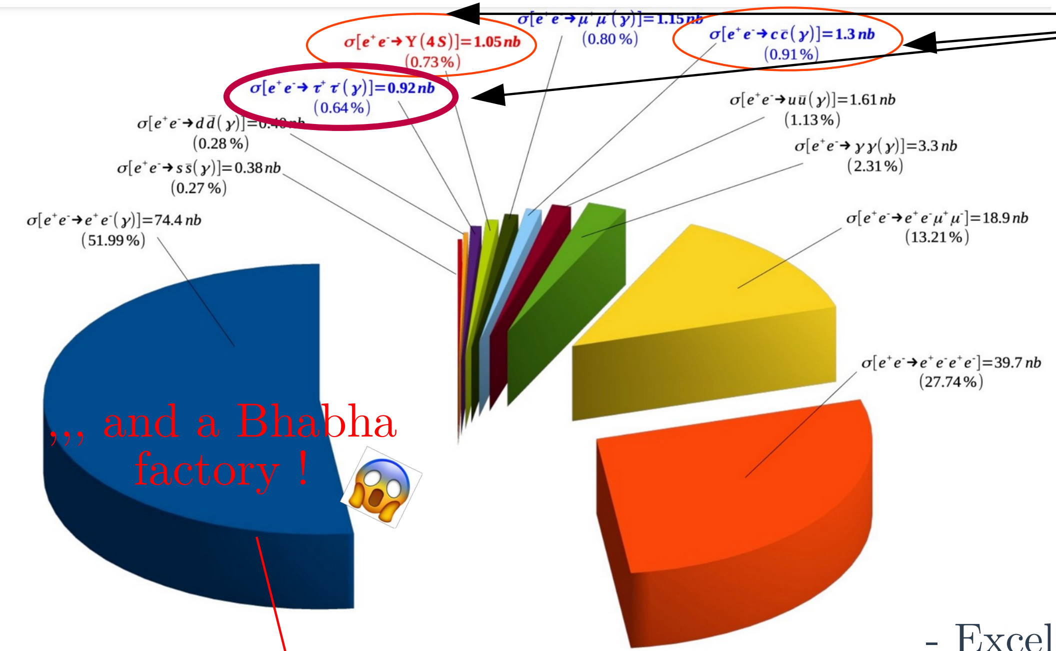
- Upgrade from KEKB, 30-fold increase in luminosity
  - Nano-beam scheme and higher currents
- Record instantaneous luminosity $4.7 \times 10^{34} cm^{-2} s^{-1}$
- Currently ~ 530 fb^{-1} recorded
  - Run 1 : 424 fb^{-1} (363 @ $\Upsilon(4S)$ + 61 off-resonnance)
- Targeting 50 ab^{-1}



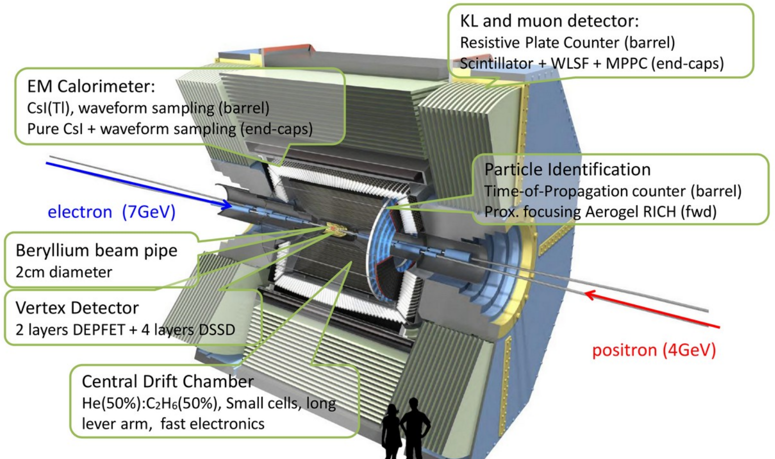


2022-2024 : LS1
Installation of the PXD (pixel detector) and accelerator upgrade

Belle II : a multi-purpose experiment



B/τ/c- factory : From Run 1,
~ 360 000 000 pairs of B and
~ <u>380 000 000 pairs of τ</u>



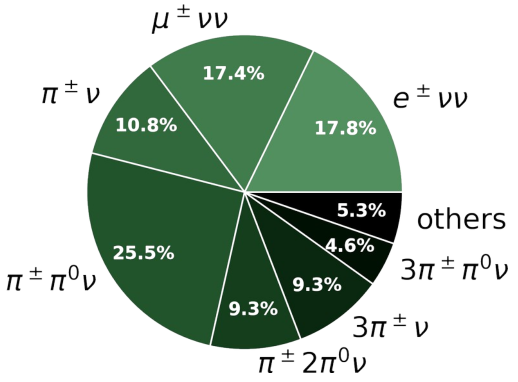
<u>Efficient triggers for τ analyses</u> (and low multiplicity) + <u>Bhabha veto</u>

- Excellent vertexing and tracking performances
- Clean environment from e^+e^- collisions
- Hermetic and (almost) 4π detector : reconstruction of missing energy and neutrals
- Good particle identification (PID) performances : K/π separation, lepton identification

Belle II τ physics program

Why τ physics ?

- Heaviest lepton $\rightarrow$ many decay modes
- Only lepton to decay into hadrons
- Tests of the Standard Model
- Search for New Physics



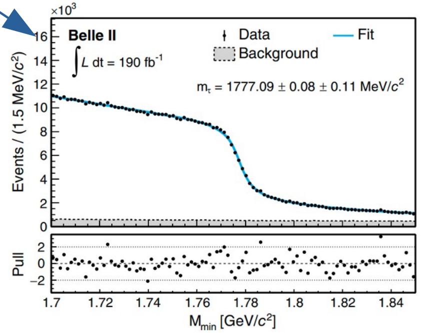
τ decay modes

Belle II τ physics program :

- τ mass measurement (PRD 108 ,032006)
- τ lifetime measurement
- V_{us} measurement
- LFU test (this talk)
- CP violation in $\tau \rightarrow K^0_S \pi \nu$

- LFV searches :
  - $\tau \rightarrow \ell \alpha$ (PRL 130, 181803)
  - $\tau \rightarrow \ell \phi$ (arXiv:2305.04759)
  - $\tau \rightarrow \Lambda\pi$ (arXiv:2407.05117)
  - $\tau \rightarrow \mu\mu\mu$ (this talk)
- *and other modes…*

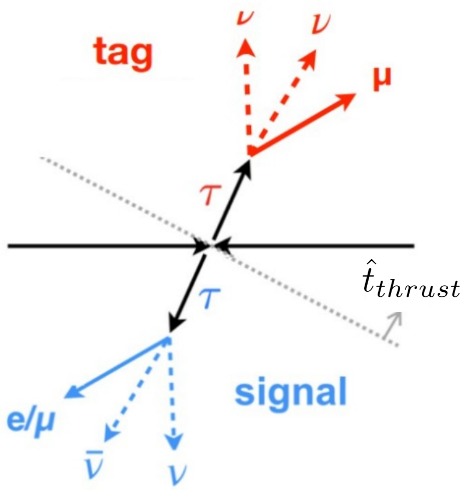
Most precise measurement of the τ mass : $1777 \pm 0.08 \pm 0.11\,\mathrm{MeV}/c^2$

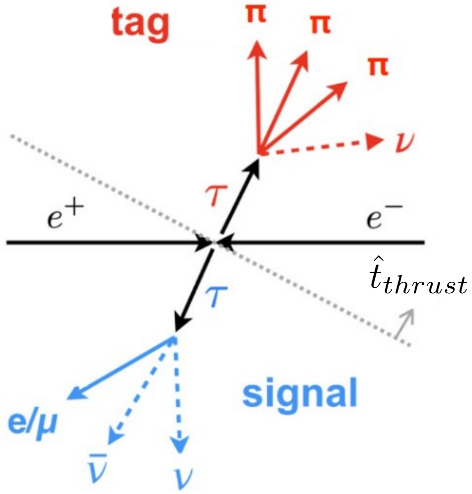


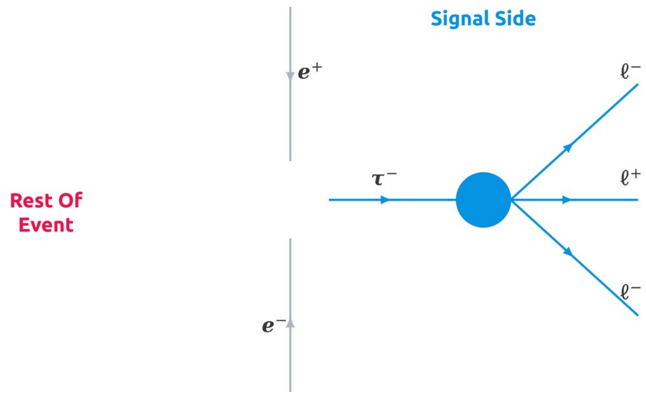
τ are produced by pairs in the e^+e^- collision, back-to-back and boosted !
$\rightarrow$ We exploit this geometrical separation : define two hemispheres with the thrust axis

$$T = \max_{\hat{\mathbf{t}}} \left(\frac{\sum_i |\mathbf{p}^*{}_i \cdot \hat{\mathbf{t}}|}{\sum_i |\mathbf{p}^*{}_i|} \right)$$

Reconstruct different topologies : 1x1, 3x1 or even untagged !

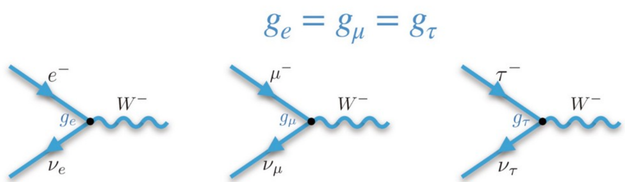






Test of Lepton Flavour Universality

Lepton Flavour Universality (LFU) is a property of the SM : the W gauge bosons are blind to the flavour of the lepton they interact with !



$\tau \to \ell\nu\nu$ only through charged current

$\to$ The only difference in the rates comes from **the mass of the leptons** :

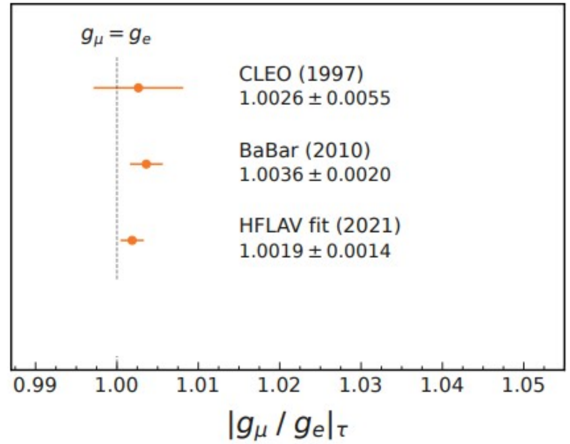
$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

$(R_\mu^{SM} = 0.9726)$

And **the ratio of the coupling is exactly 1** (in the SM) :

$$\left|\frac{g_\mu}{g_e}\right|_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

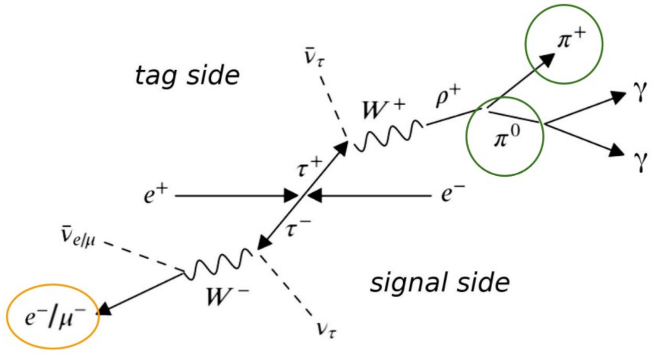
$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$

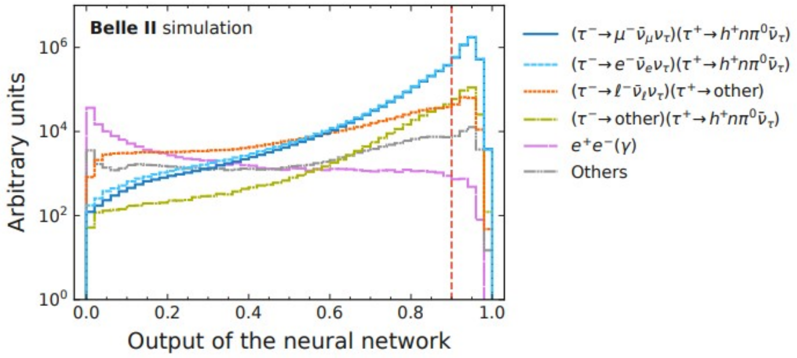


New physics potential with contribution from new weak currents (charged and neutral)

LFU test

Even selection using the 1x1 topology :





Signal side is either $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ or $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ (identified with PID variables)

Tag side is $\tau^- \to \pi^- \nu_\tau + n\pi^0$: only one charged particle ($E_{ECL}/p < 0.8$) with 1 or 2 π^0

Leptons restricted to :
- 1.5 GeV/c < p_ℓ < 5.0 GeV/c
- 47° < θ_ℓ < 122° (polar angle w.r.t to the beam axis)

to reduce PID systematics

Background rejection performed with a **set of selection** and a **neural network** : total visible energy of the event, transverse missing momentum, tag-side kinematics

94 % purity and 9.6 % signal efficiency

Remaining backgrounds : $e^+e^- \to \tau^+\tau^-$ with $\pi^\pm$ mis-id as $\ell^\pm$ or wrong tag

LFU : systematics

The error is mainly systematic

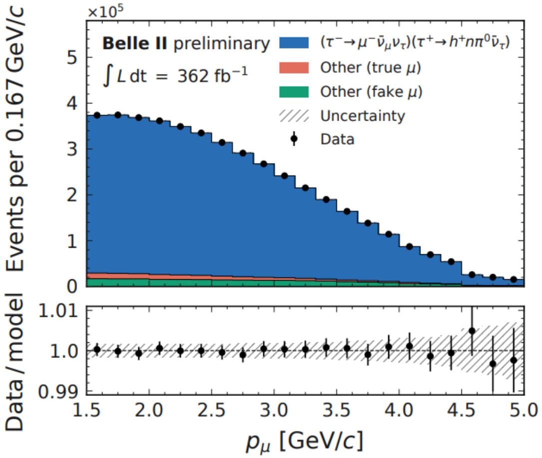
- and dominated by PID uncertainty
  - Efficiency measured with $J/\psi \to \ell^+\ell^-, e^+e^- \to e^+e^- \ell^+\ell^-$ and $e^+e^- \to \ell^+\ell^-(\gamma)$

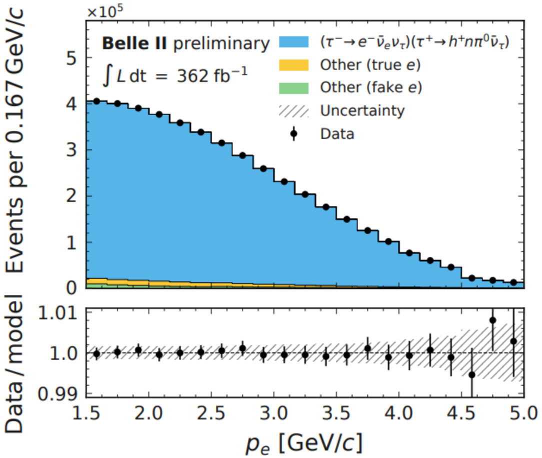
    $\to$ 99.7% and 93.9% efficiency for electrons and muons
  - Fake rate measured with $K_S^0 \to \pi^+\pi^-$ and $\tau^\pm \to \pi^\pm\pi^\mp\pi^\pm\nu_\tau$
    0.9% and 3.1% of mis-ID rate for electrons and muons
- Mis-modelling of trigger, evaluated with independant trigger selections

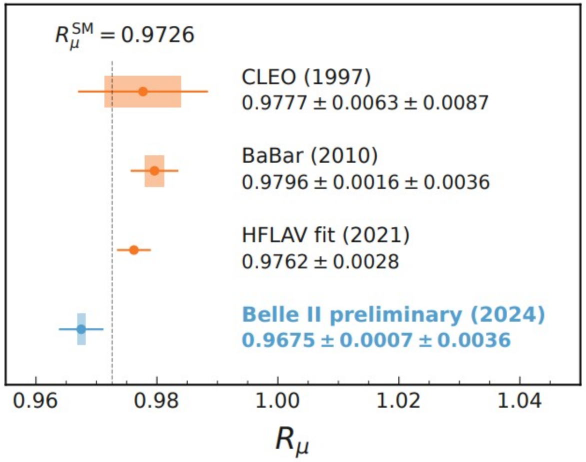
Source	Uncertainty [%]
Charged-particle identification:	0.32
Electron identification	0.22
Muon misidentification	0.19
Electron misidentification	0.12
Muon identification	0.05
Imperfections of the simulation:	0.14
Modelling of FSR	0.08
Normalisation of individual processes	0.07
Modelling of the momentum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

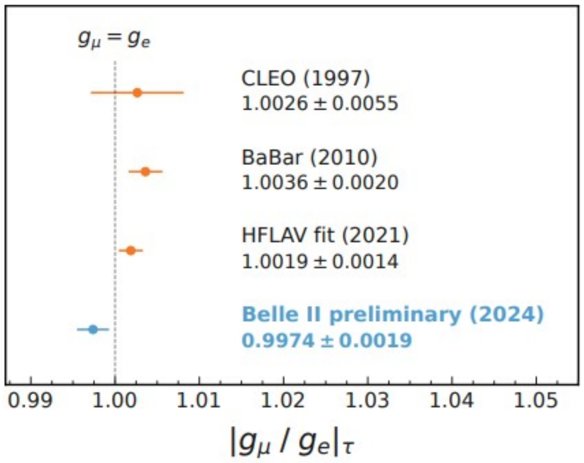
LFU : R_μ extraction and result

R_μ is extracted with a binned maximum likelihood fit
- 21 bins of lepton momentum
- 3 templates (one for the signal, two for the background)









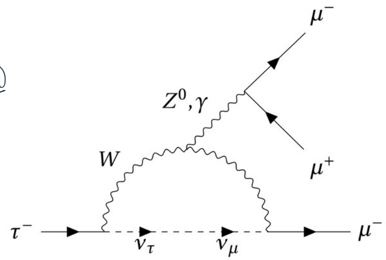
No deviation from the SM
World's most precise measurement of R_μ and g_μ/g_e

Submitted to JHEP (accepted !)
arXiv:2405.14625

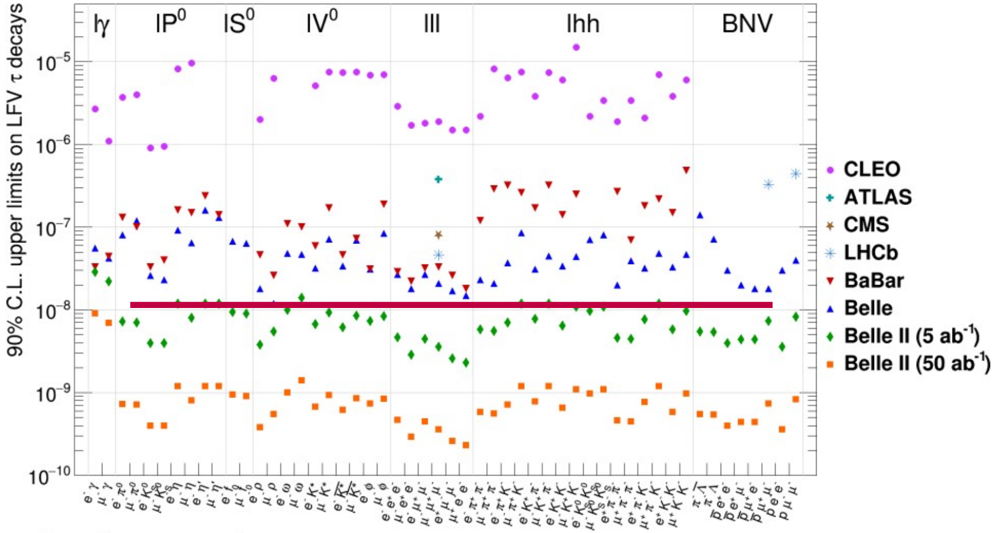
LFV : search for $\tau^{\pm} \to \mu^{\pm}\mu^{\mp}\mu^{\pm}$

- Charged Lepton Flavour Violation (cLFV) in the Standard Model **through weak charged current and neutrino oscillations** @ rates ~ 10^{-55}
  $\rightarrow$ Clear prediction : <u>**no LFV in current experiments**</u> !

- Various BSM predict LFV at much higher rates ~ $10^{-8} - 10^{-10}$ (e.g leptoquarks for $\tau \to \ell\phi$, related to anomalies in $b \to c\tau\nu$)



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}



Banerjee et al., 2022a; Kou et al., 2019a

A lot of interest in LFV decays at e^+e^- colliders, with ~ 50 modes : $\tau \to \ell\gamma, \tau \to \ell\phi, \tau \to \ell\ell\ell$, etc.

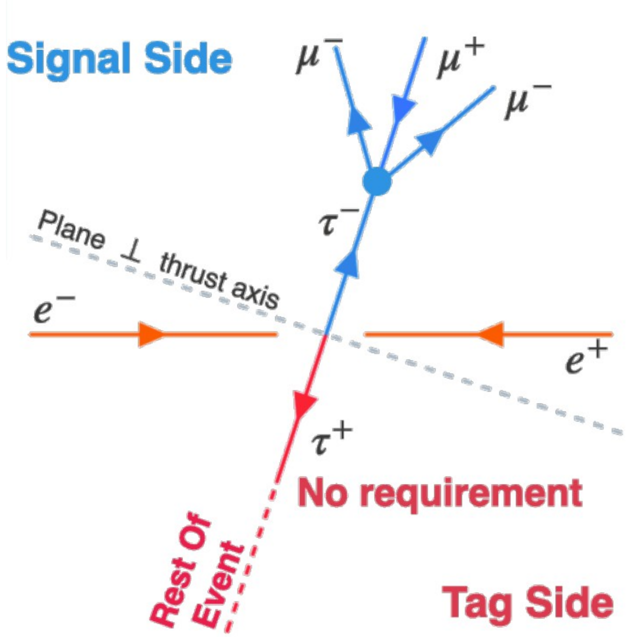
These are rare decays : it's all about **maximizing** statistics !

LFV : search for $\tau^{\pm} \to \mu^{\pm}\mu^{\mp}\mu^{\pm}$

$\tau^{\pm} \to \mu^{\pm}\mu^{\mp}\mu^{\pm}$:

- Almost free from SM background
- Very good resolution on the energy and momentum
- Can be probed by LHC experiments

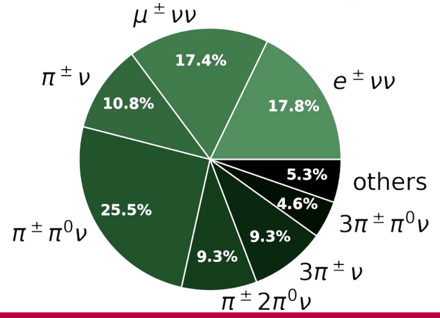
Existing measurements : 2.1×10^{-8} by Belle (Phys.Lett.B687)
2.9×10^{-8} by CMS (Phys.Lett.B853)



Untagged event selection :

- We reconstruct signal candidate by combining three muons
- **No explicit reconstruction** of the other τ : everything that is not the signal candidate is **combined in one unique object called Rest Of Event** (ROE)

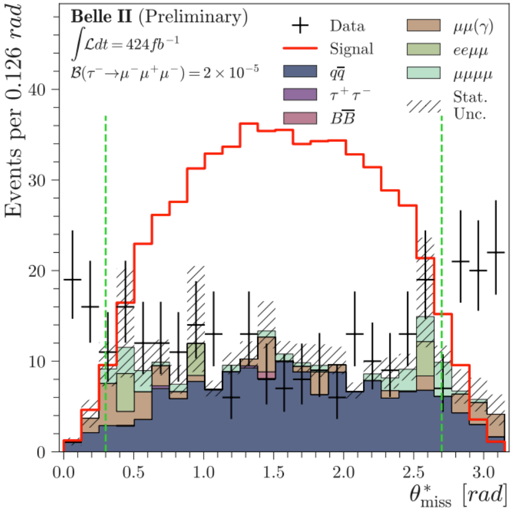
- Allows to target all the 1 and 3 prong decays of the other τ

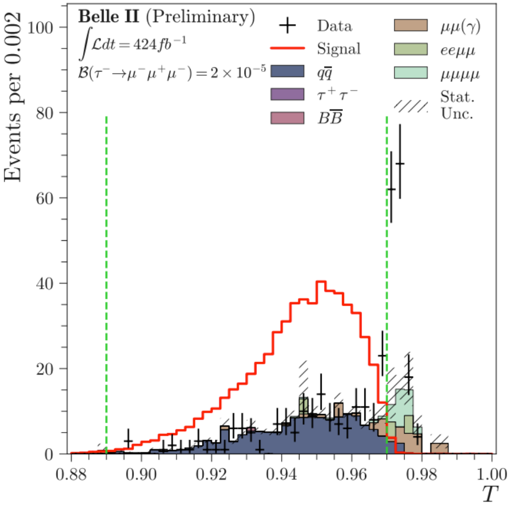


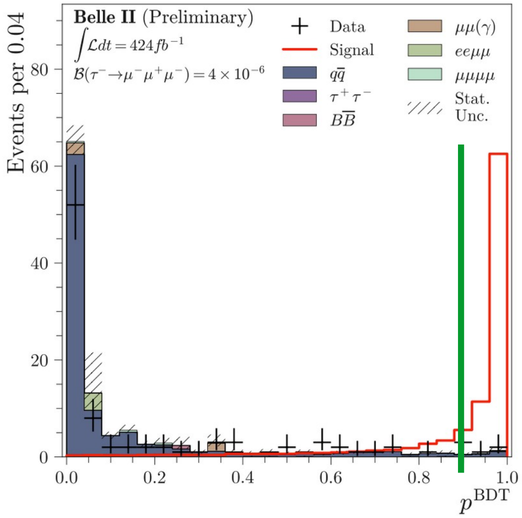
$\tau^{\pm} \to \mu^{\pm}\mu^{\mp}\mu^{\pm}$: background suppression

Background suppression
- with a set of selection to remove low multiplicity, mis-modeled background

A **BDT classifier with k-folding** to reject $e^+e^- \to q\bar{q}$
- Rest Of Event kinematics, signal candidate kinematics, missing momentum information....







Final signal efficiency : 20.4%

(3X Belle's efficiency :)

$\tau^\pm \to \mu^\pm \mu^\mp \mu^\pm$: results

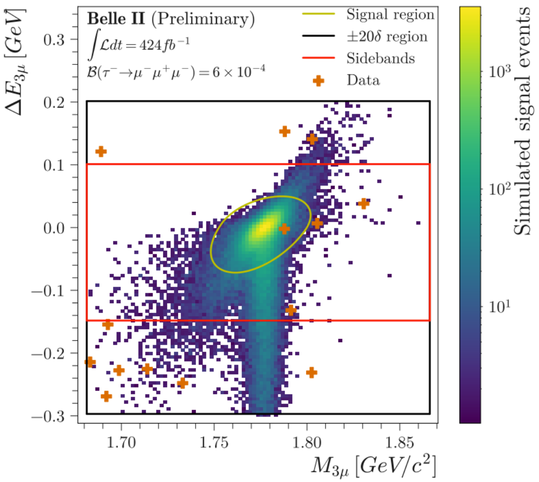
- **Poisson counting experiment**
- Signal region defined as **an ellipse** in the 2D plane $(M_{3\mu}, \Delta E_{3\mu})$ $(\Delta E_{3\mu} = E_{beam}/2 - E_{3\mu})$

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{N_{obs} - N_{exp}}{2\sigma_{\tau\bar{\tau}} \cdot \mathcal{L} \cdot \epsilon_{3\mu}}$$

Number of expected background $N_{exp} = 0.7^{+0.6}_{-0.5} \pm 0.01$ obtained by rescaling **the sidebands** in the signal region

Observed 1 event in the signal region

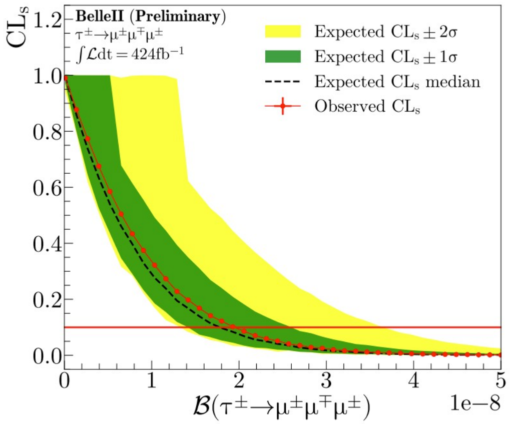
No excess is found



Summary of relative systematic uncertainties.

Quantity	Source	Uncertainty (%) Low	High
$\varepsilon_{3\mu}$	PID	2.1	2.4
	Tracking	1.0	1.0
	Trigger	0.9	0.9
	BDT	1.5	1.5
	Signal region	3.9	2.9
N_{exp}	Momentum Scale	16	16
$\mathcal{L}$		0.6	0.6
$\sigma_{\tau\tau}$		0.3	0.3

Main uncertainty is statistical !



90 % CL upper limit on the branching fraction

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

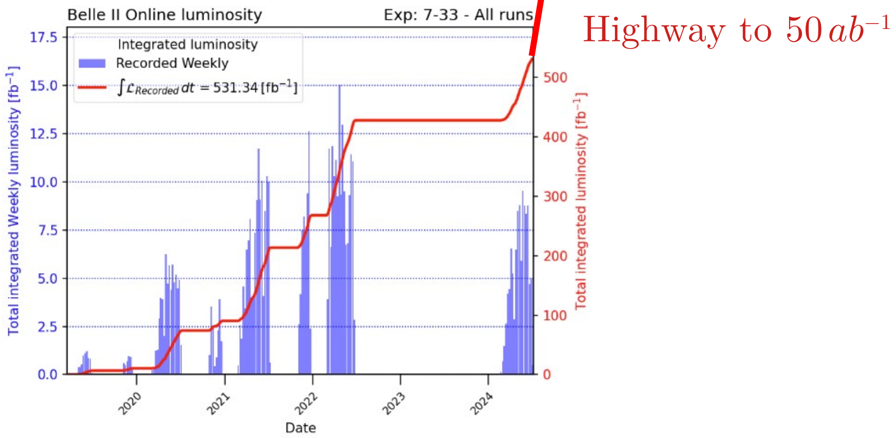
World's best limit!

Accepted by JHEP (arXiv:2405.07386)

Summary

World's leading measurements of τ decays

- LFU is safe : $R_\mu = 0.9675 \pm 0.0007_{stat} \pm 0.0036_{sys}$ $\rightarrow$ Accepted by JHEP, arXiv:2405.14625
- No LFV so far : $\mathcal{B}(\tau \rightarrow \mu\mu\mu) < 1.9 \times 10^{-8}$ $\rightarrow$ Accepted by JHEP, arXiv:2405.07386
- Many more exciting results are coming : **it's only the beginning for rare τ decay searches at Belle II**



Backup