

Status and perspectives of LFV & LFU searches at Belle II

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INFN Roma3

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The Belle II experiment

Lepton flavour

1) LFU measurements

- $b \rightarrow c \tau \nu$
- $\tau \rightarrow \ell \nu \nu$

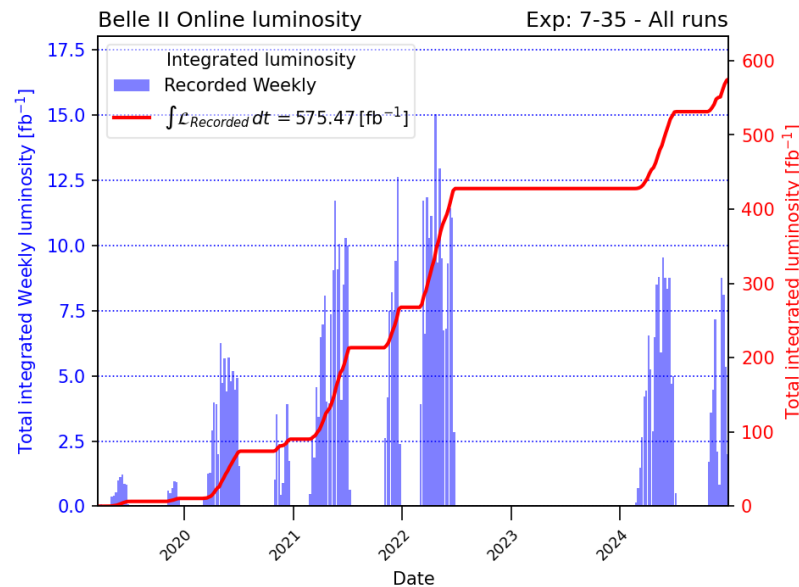
2) LFV searches

- $B \rightarrow K^{(*)} \tau \ell$
- $\tau \rightarrow \ell \alpha$
- $\tau \rightarrow \ell K_S^0$
- $\tau \rightarrow 3\ell$

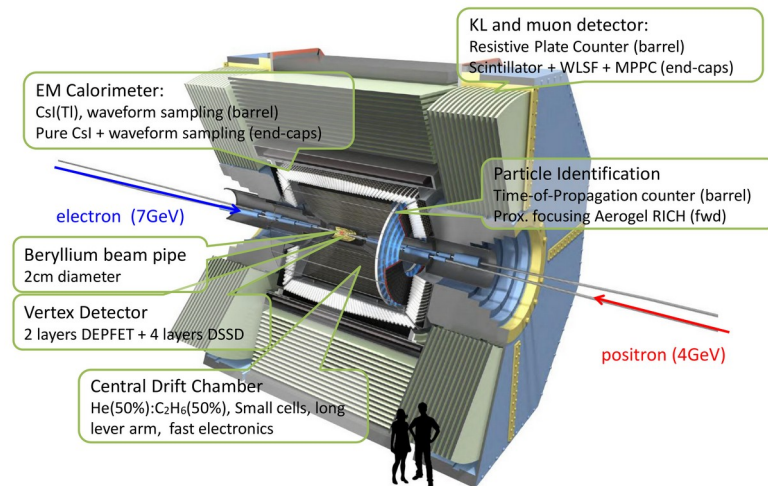
Belle II : a B & τ factory

Operating at the interaction point of **SuperKEKB**

- **Record instantaneous luminosity** $5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Currently $\sim 575 \text{ fb}^{-1}$ recorded
- Target 50 ab^{-1}



B/ τ /c -factory : Currently
 $\sim 500\,000\,000$ pairs of B and
 $\sim 500\,000\,000$ pairs of τ



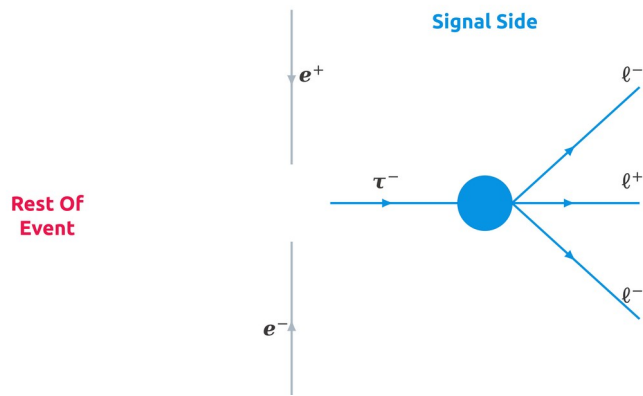
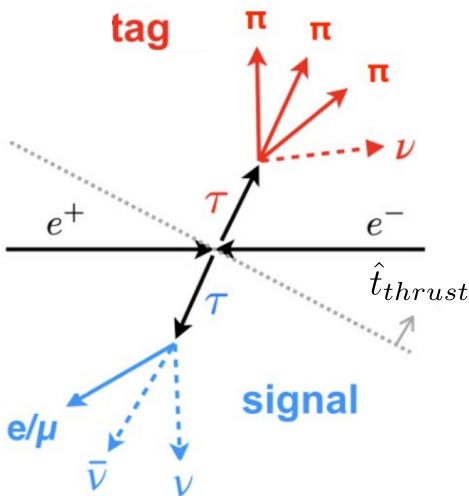
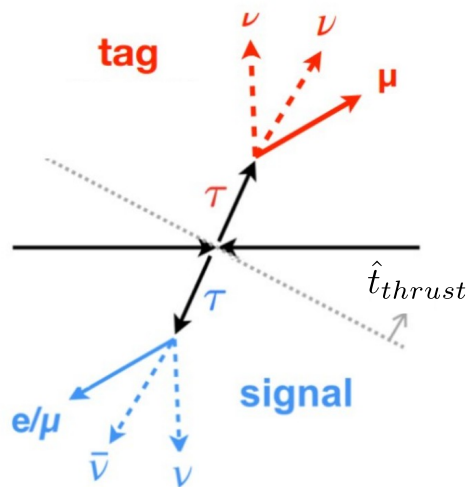
- Excellent **vertexing** and **tracking** performance
- **Clean environment** from e^+e^- collisions
- **Hermetic** and (almost) **4 π** detector : reconstruction of **missing energy** and **neutrals**
- Good particle identification (**PID**) performance : K/ π separation, lepton identification

Working with τ 's at Belle II

τ are produced in pairs in the $e^+e^- \rightarrow \tau^+\tau^-$ collisions, **back-to-back and boosted** in the c.m. !
→ We exploit this geometrical separation : define two hemispheres separated by a plane perpendicular to the thrust axis

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

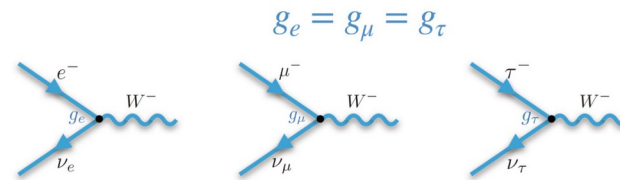
Reconstruct different topologies : **1x1**, **3x1**,
and even **untagged**!



See [Vidya's talk](#) for B-tagging

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 !



$\tau \rightarrow \ell \nu \bar{\nu}$ only through charged current

→ The only difference in the rates comes from the mass of the leptons :

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

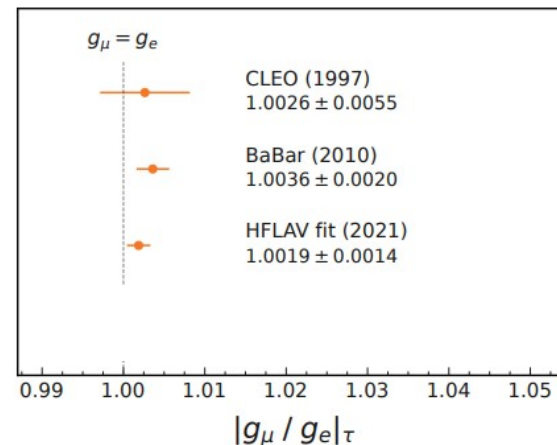
$$(R_\mu^{SM} = 0.9726)$$

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

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

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

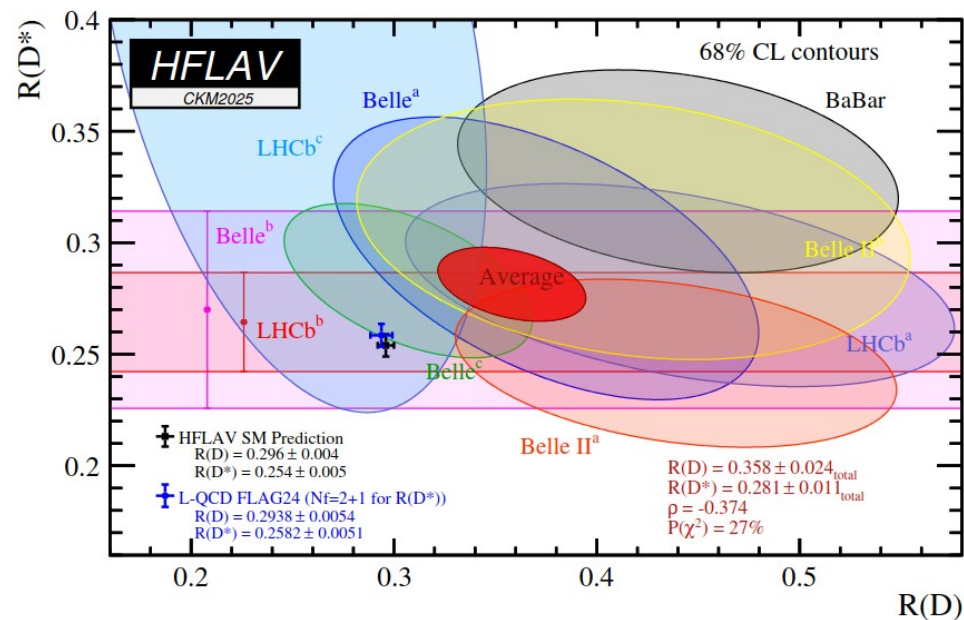
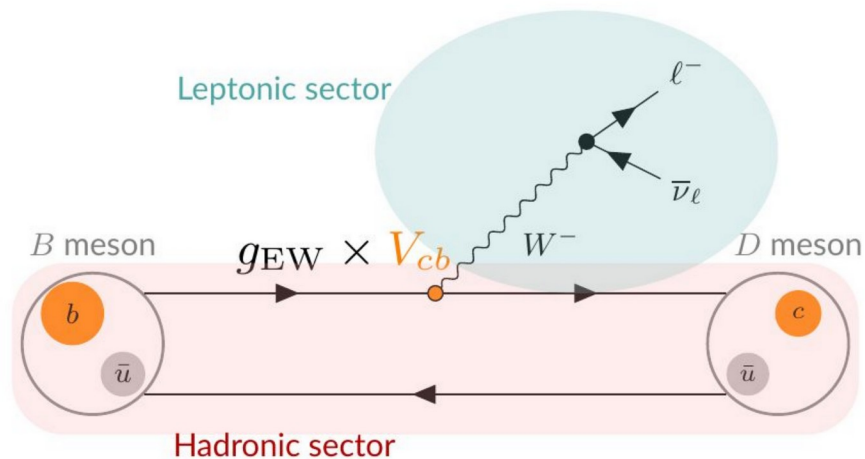
Deviation might indicate
BSM physics contribution
from new weak currents
(charged and neutral)



LFU in B decays

LFU can also be tested in B decays with $b \rightarrow c$ semileptonic transitions

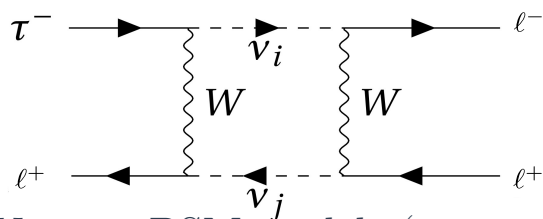
$$R(D^{(*)}) = \frac{B \rightarrow D^{(*)} \tau \nu_\tau}{B \rightarrow D^{(*)} \ell \nu_\ell}$$



3.8 σ away from SM prediction

Lepton flavour violation (LFV)

Charged lepton flavour violation
possible in the SM at loop level,
through neutrino oscillations
→ suppressed at rates $\sim 10^{-55}$

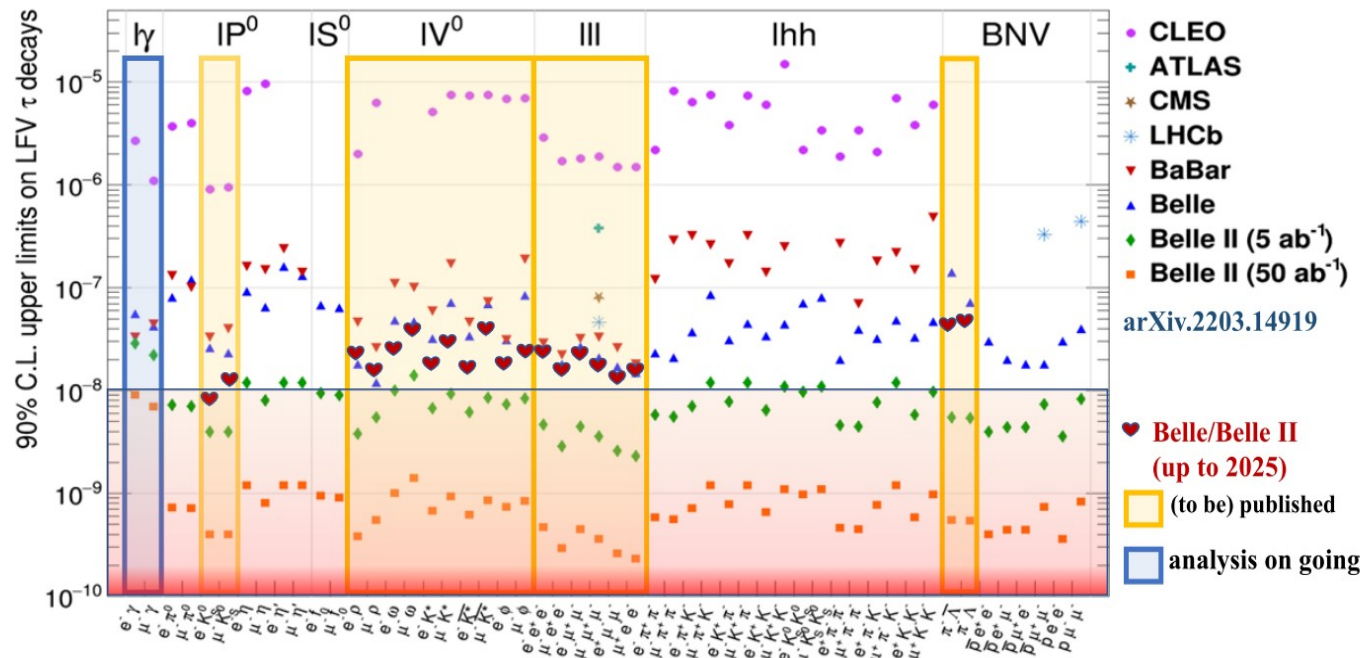


Various BSM models (neutrino mass, leptoquark, SUSY...) greatly enhance the branching fractions to **experimentally accessible** levels : $10^{-8} - 10^{-9}$

Over **50 τ decays** searched in the past decades :
 $\tau \rightarrow lll$, $\tau \rightarrow l K_S^0$, $\tau \rightarrow l V^0$, $\tau \rightarrow l \gamma$,
etc.

Best limits by Belle & Belle II

Status of LFV search in τ sector at Belle/Belle II

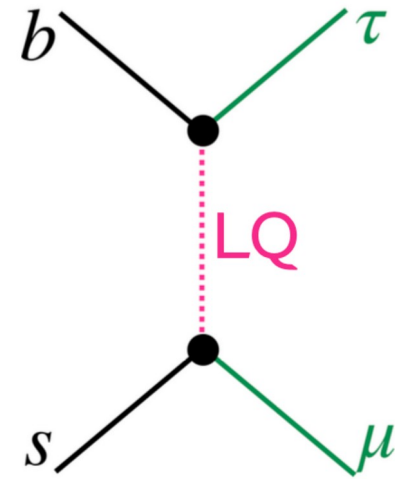
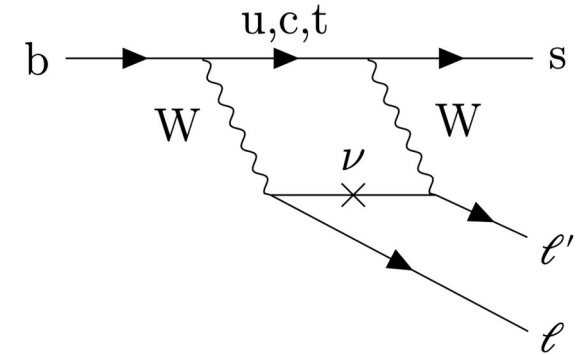
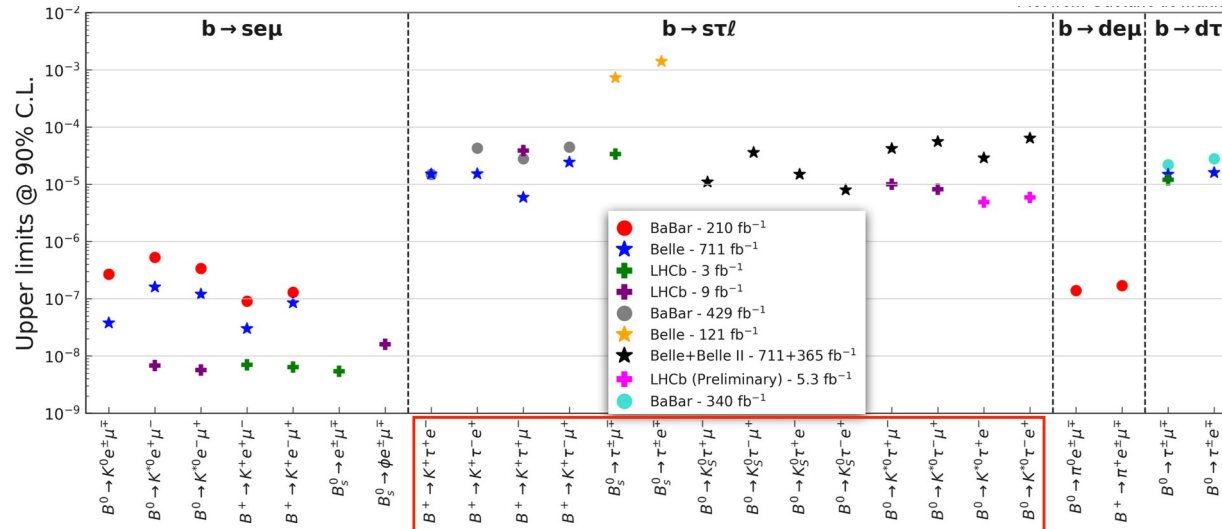


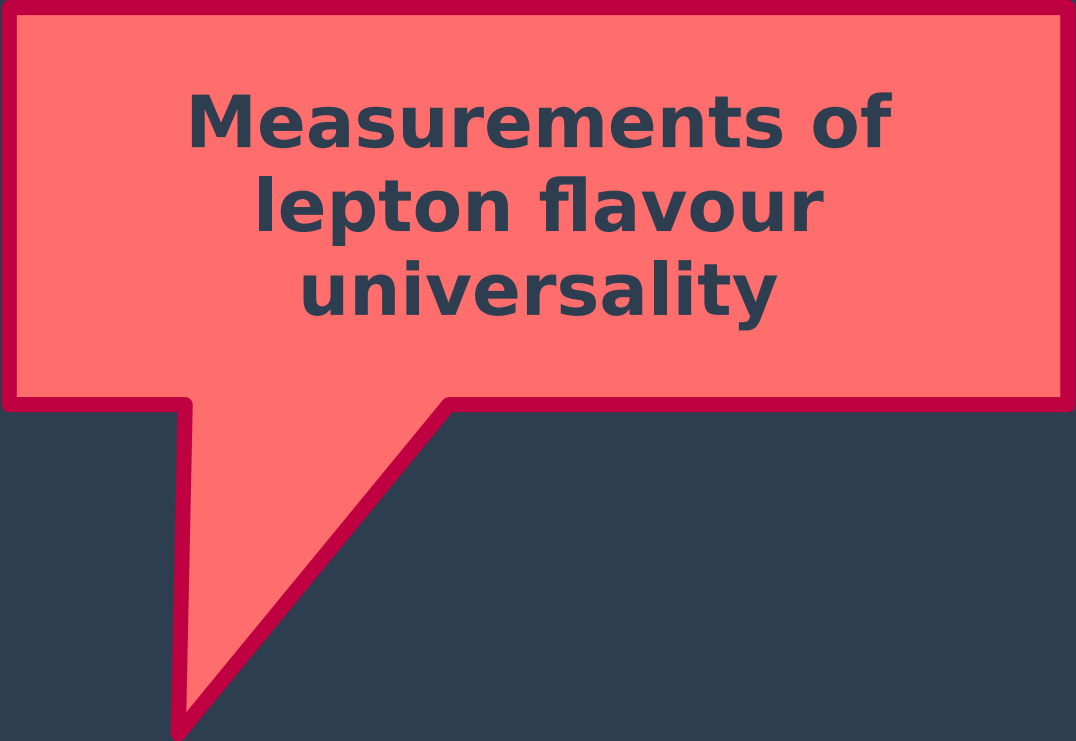
LFV in B decays

Similarly, LFV in B decays from neutrino oscillations

Existing tensions in e.g. $b \rightarrow c \tau \nu$ & $B \rightarrow K \nu \nu$

→ possible explanation can also enhance LFV rates, e.g. leptoquark models





Measurements of lepton flavour universality

LFU: measurement of $R(D^{(*)})$ with SL tag

Measurement of $R(D) - R(D^*)$ with semi-leptonic tag

$$R(D^{(*)}) = \frac{B \rightarrow D^{(*)} \tau \nu_\tau}{B \rightarrow D^{(*)} \ell \nu_\ell}$$

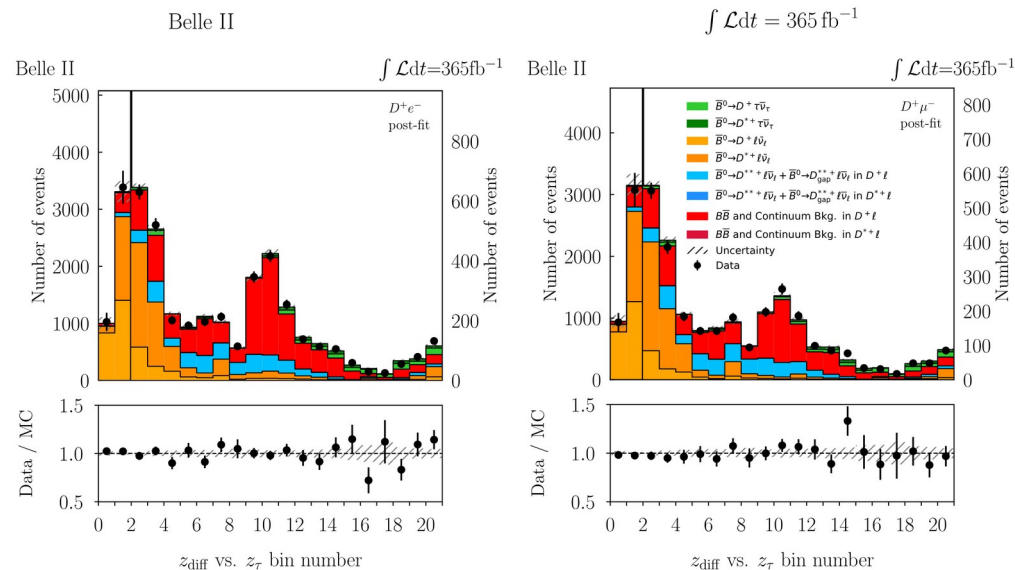
- Reconstruct B_{sig} from $D^{(*)}$ (13 final states), leptons and τ ($\rightarrow \ell \nu \nu$)
- Train a multi-class BDT, three scores: respectively z_τ , z_ℓ and z_{bkg} for semitauonic, semileptonic and background events

Signal extraction from a 2D binned fit in $(z_\tau, z_{diff} = z_\ell - z_{bkg})$

$$\mathcal{R}(D^+) = 0.418^{+0.075}_{-0.073}(\text{stat})^{+0.049}_{-0.056}(\text{syst}),$$

$$\mathcal{R}(D^{*+}) = 0.306^{+0.035}_{-0.033}(\text{stat})^{+0.016}_{-0.018}(\text{syst}),$$

Consistant with
SM within 1.7σ



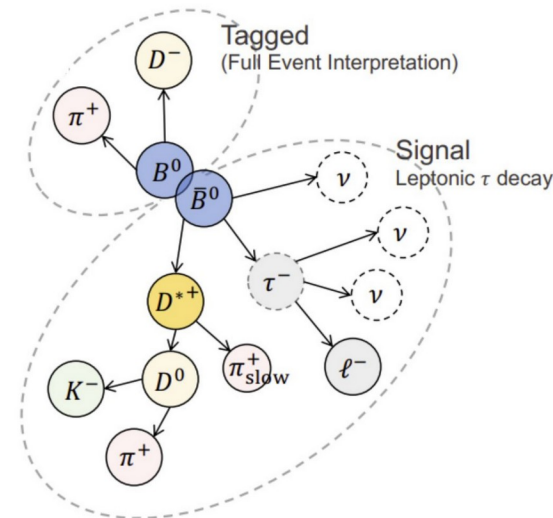
Phys. Rev. D 112

LFU: measurement of $R(D^{(*)})$ with hadronic tag

First measurement of $R(D^*)$ at Belle II was done on 189 fb⁻¹
 Phys. Rev. D 110

Recently: new measurement (see CKM talk)

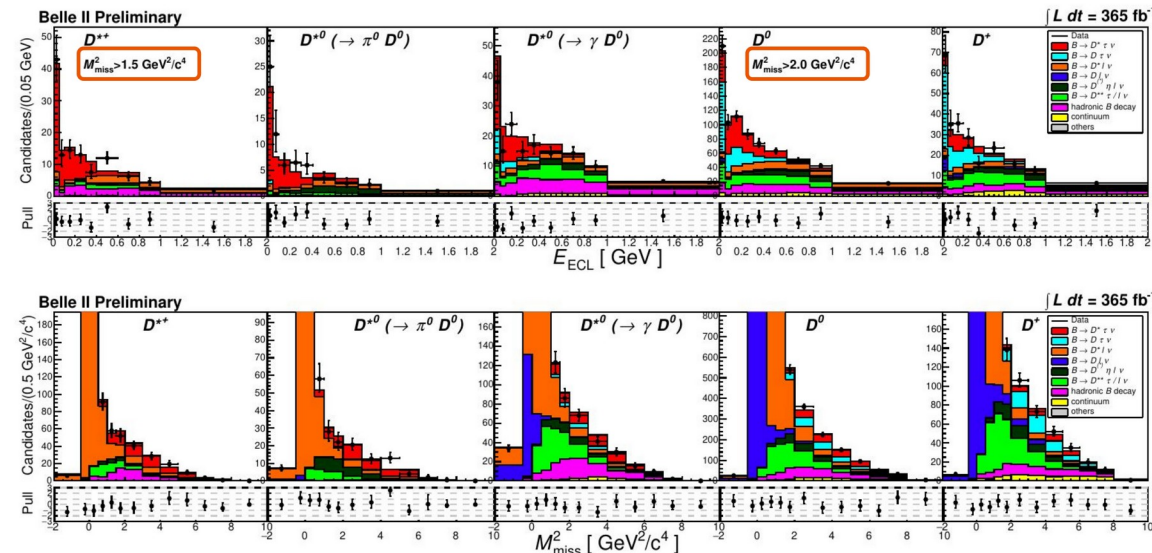
- Extend D^* and $D^{0/+}$ modes
- 2D binned fit to E_{ECL} and M_{miss}^2 (E_{ECL} = Additional energy in the calorimeter)



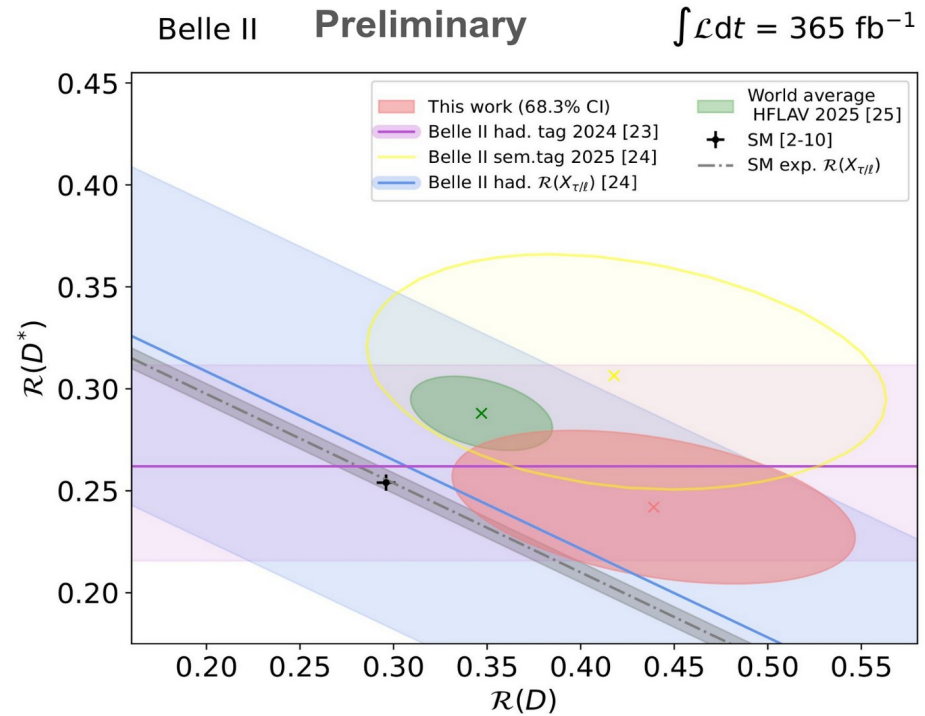
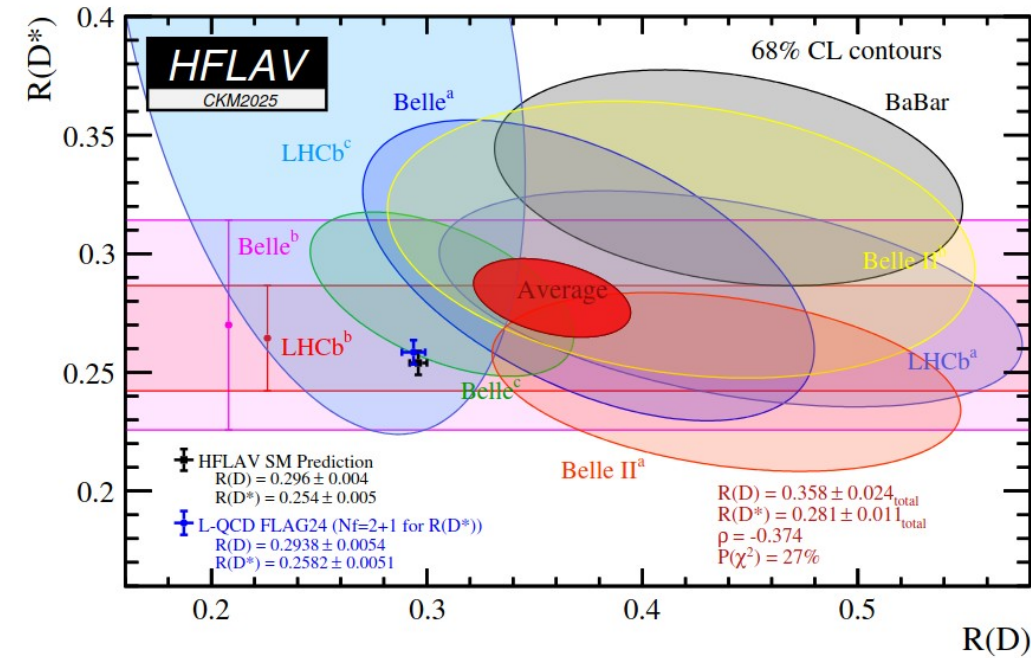
$$R(D^*) = 0.242 \pm 0.019 \text{ (stat.)} \pm 0.016 \text{ (syst.)}$$

$$R(D) = 0.439 \pm 0.055 \text{ (stat.)} \pm 0.046 \text{ (syst.)}$$

Most precise measurement using
 hadronic tag!
 1.5 σ agreement to SM



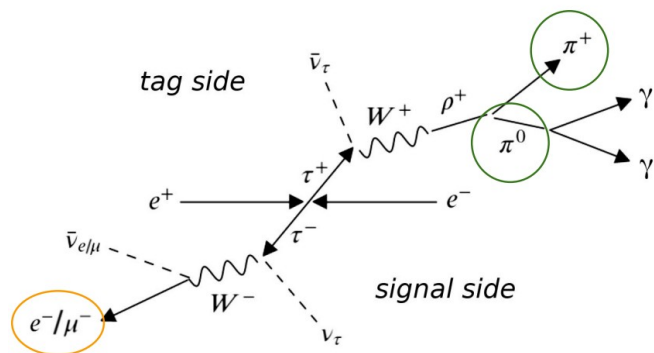
HFLAV average of $R(D) - R(D^*)$



Semileptonic tag in yellow & hadronic tag in orange

LFU test in τ decays

Event selection using the 1x1 topology :



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

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

Leptons restricted to :

- $1.5 \text{ GeV}/c < p_\ell < 5.0 \text{ GeV}/c$

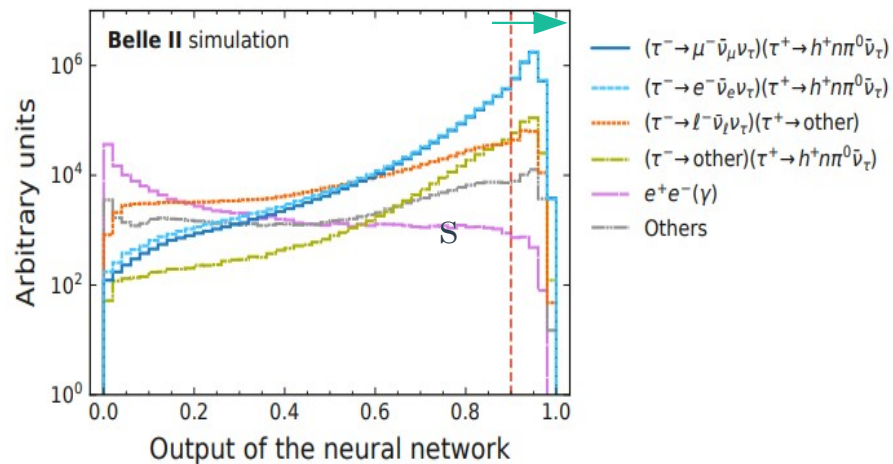
- $47^\circ < \theta_\ell < 122^\circ$ (polar angle w.r.t to the beam axis)

to reduce PID systematics

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

94 % purity and 9.6 % signal efficiency

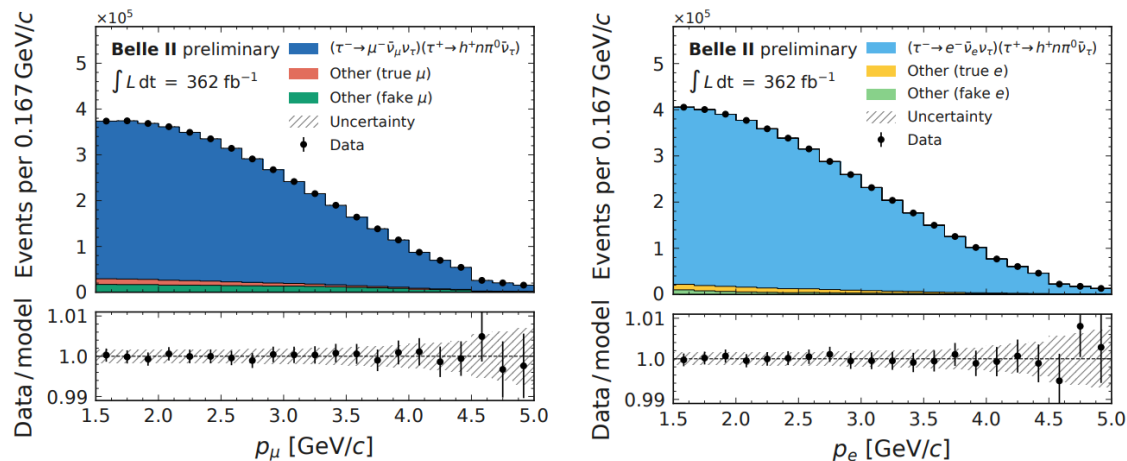
Remaining backgrounds : $e^+e^- \rightarrow \tau^+\tau^-$ with $\pi^\pm$ mis-id as $\ell^\pm$ or wrong tag



LFU : R_μ extraction and result

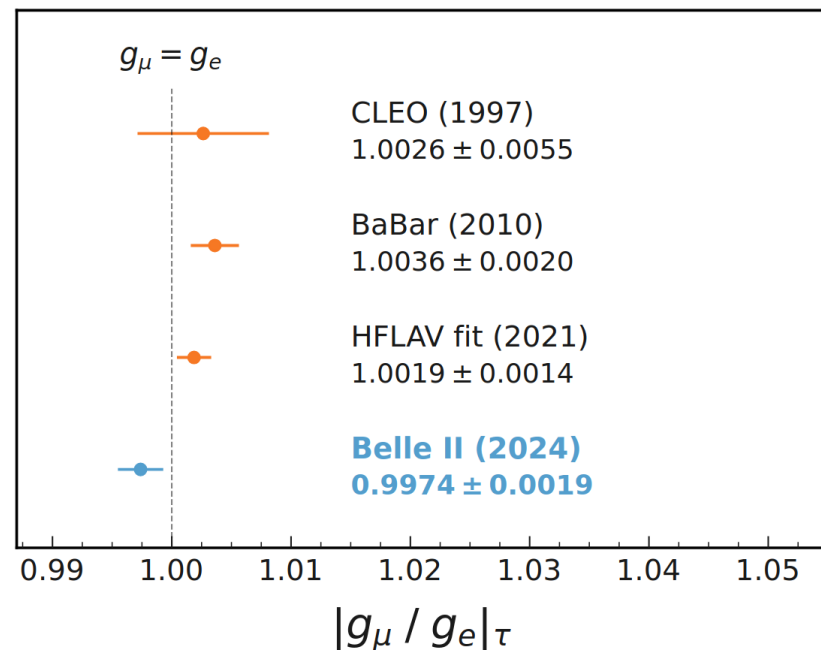
R_μ is extracted with a binned maximum likelihood fit

- 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

Published in JHEP
JHEP 08, 205 (2024)

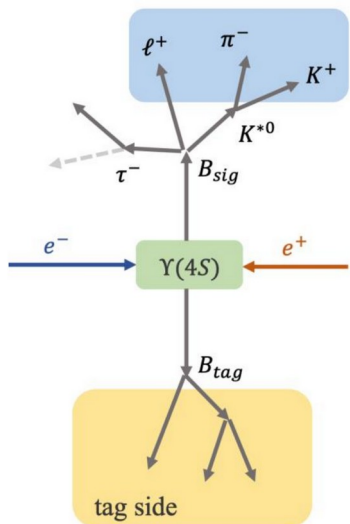


Searches for lepton flavour violation

Highlight : LFV from B decays

$$B \rightarrow K \tau \ell \quad (K_S^0, K^*)$$

- Hadronic tagging and combined dataset of Belle & Belle II
- Reconstruct the τ mass as the recoil mass
- Fit to the τ mass



Limits at 90% C.L:

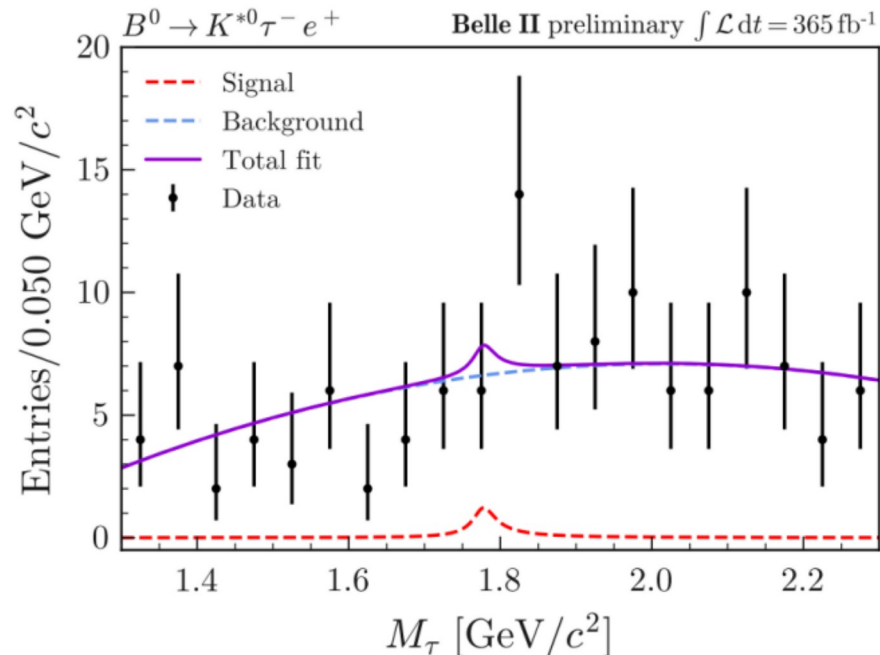
$$\mathcal{B}(B^0 \rightarrow K_S^0 \tau \ell) < [0.8, 3.6] \times 10^{-5}$$

[PRL 135, 041801 \(2025\)](#)

$$\mathcal{B}(B^0 \rightarrow K^* \tau \ell) < [2.9, 6.4] \times 10^{-5}$$

[JHEP08\(2025\)](#)

First search for the K_S^0 modes
 K^* results compatible with LHCb



Highlight : LFV from bottomium decay

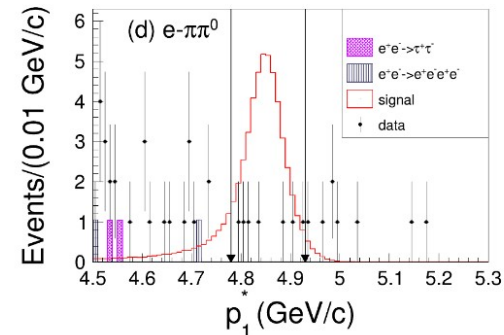
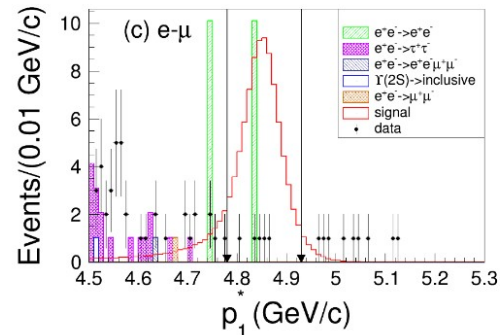
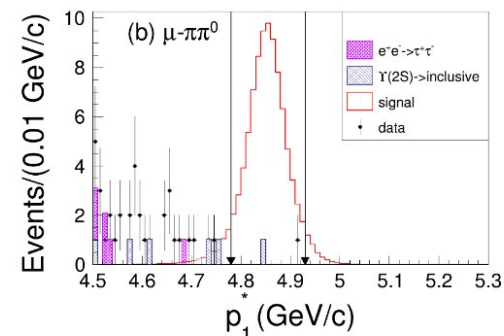
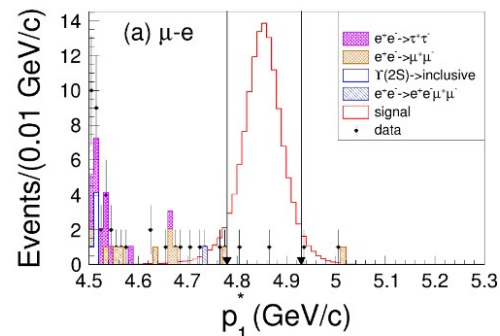
Previous search : $\Upsilon(1S) \rightarrow (\gamma)\ell\ell'$

(in $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$)

by Belle JHEP05(2022)095, $\Upsilon(2S) \rightarrow \ell\tau$ by
CLEO & BaBar

Here: extending the search to $\Upsilon(2S) \rightarrow \ell\tau$
($\ell = e, \mu$) at Belle with 25 fb^{-1}

- τ reconstructed as $\ell\nu_e\nu_\tau$ and $\pi\pi^0\nu_\tau$
- Signal region defined in the **momentum** of the **primary** lepton in the **c.m.s.**, p_1^*
- **Most stringent limits** on $B(\Upsilon(2S) \rightarrow \ell\tau)$ improving by a **factor 13 & 3** the bounds on the **μ** and **e** channels respectively



JHEP02(2024)187

LFV : search for $\tau^\pm \rightarrow \ell^\pm \alpha$ at Belle

LFV decay with invisible boson α :
forbidden in SM but allowed in BSM
models (such as ALPs)

1x1 & 3x1 topology :

Signal side : 1 lepton track

Tag side : hadronic : 1 & 3 pions

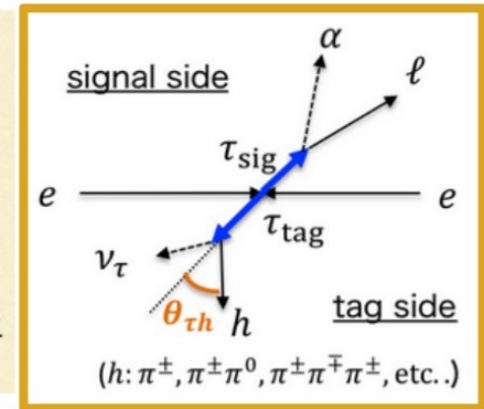
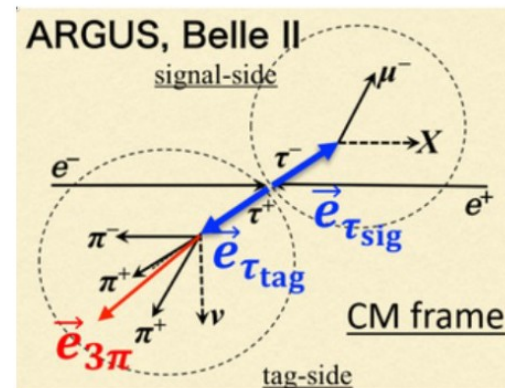
Completely irreducible background $\tau \rightarrow \ell \nu \nu$:

- Perform a boost into the τ rest frame, where the lepton momentum p_ℓ^τ must be monochromatic (2-body decay)
- τ direction is determined from the hadronic tag
- Look for a bump in the distribution

Improvements w.r.t Belle II
(62.8 fb⁻¹:[\[PRL 130, 181803 \(2023\)\]](#)):

- Efficiency enhanced by adding 1 pion tag decay
- Better estimation of the direction of τ_{sig} by reconstruction the opening angle $\theta_{\tau h}$ between τ_{sig} & the hadronic tag system

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

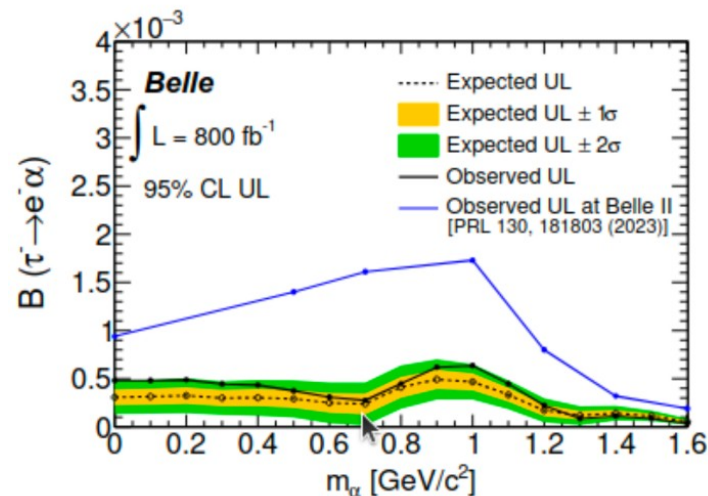
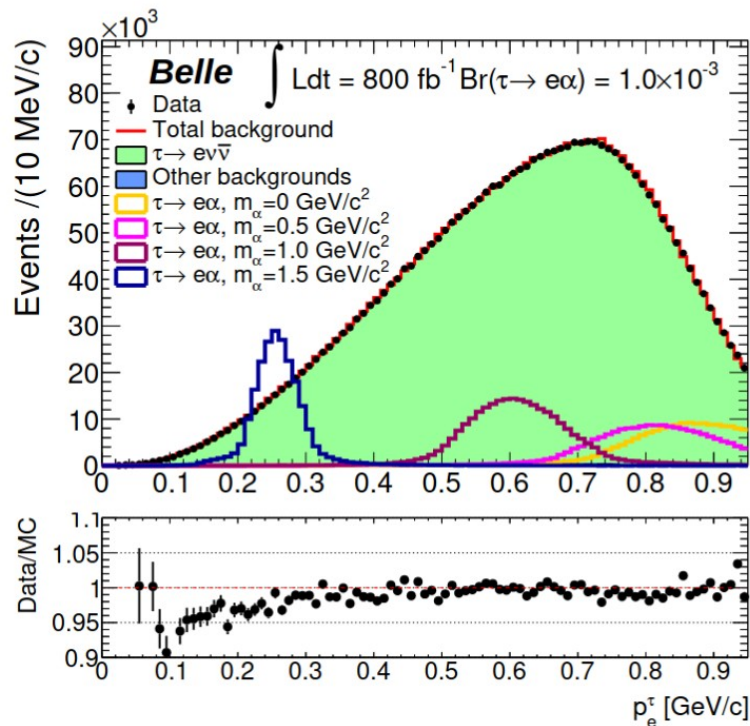


LFV : search for $\tau^\pm \rightarrow \ell^\pm \alpha$ at Belle

Signal extraction from binned fit to p_ℓ^τ for 17 mass points

No excess is observed $\rightarrow$ Limits at 95% CL :

$$\mathcal{B}(\tau \rightarrow e \alpha) < 0.4 - 6.4 \cdot 10^{-4}$$
$$\mathcal{B}(\tau \rightarrow \mu \alpha) < 0.2 - 3.5 \cdot 10^{-4}$$



Published in JHEP [JHEP 2025, 155]

- Check recent Belle II update !
(Tau 2025)

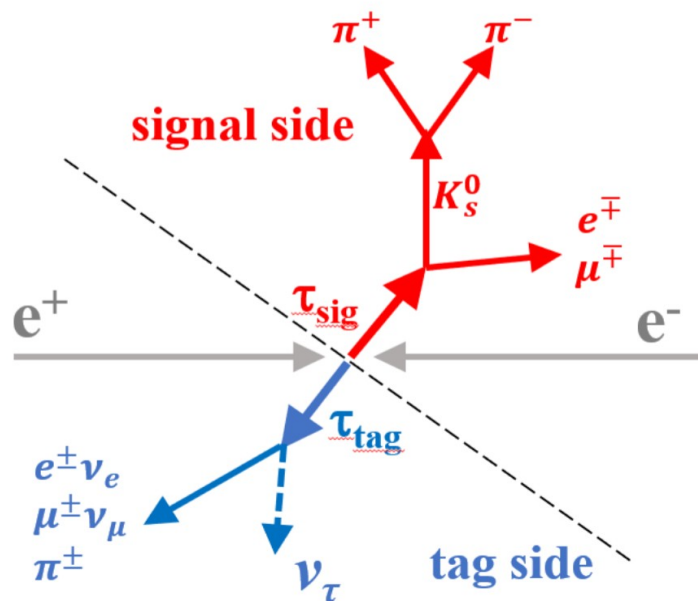
$\tau^\pm \rightarrow \ell^\pm K_s^0$ at Belle & Belle II

Reconstruct events with exactly 4 tracks
and 0 net charge

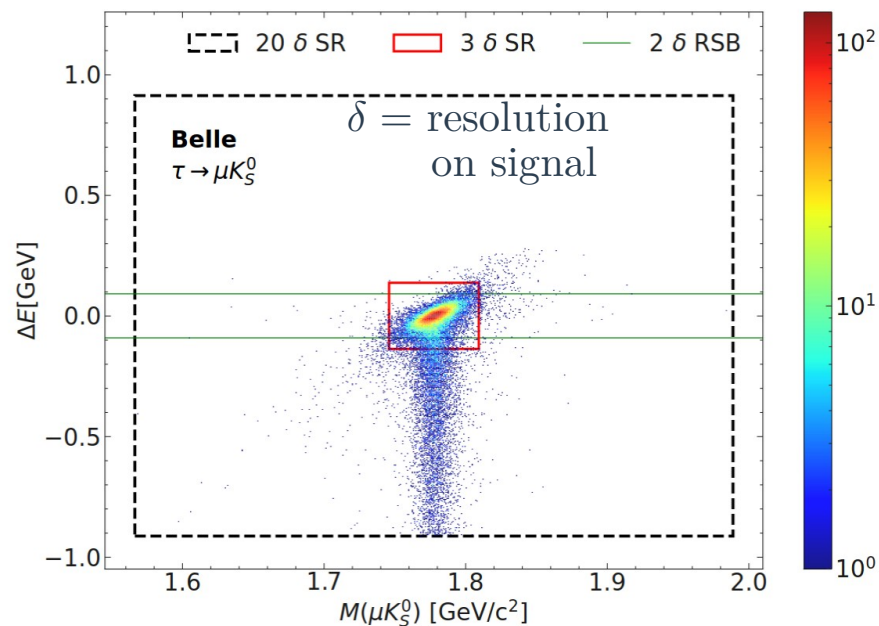
3x1 topology :

Signal side: 2 pions that form a K_s^0
and one lepton (e/μ)

Tag side : one charged particle $\rightarrow e, \pi$ or μ



- Use the $(M, \Delta E = E - E_{beam}/2)$ plane to define the search region
 $\rightarrow$ signal peaks sharply in $(m_\tau, 0)$
- 1 workflow per mode & experiment



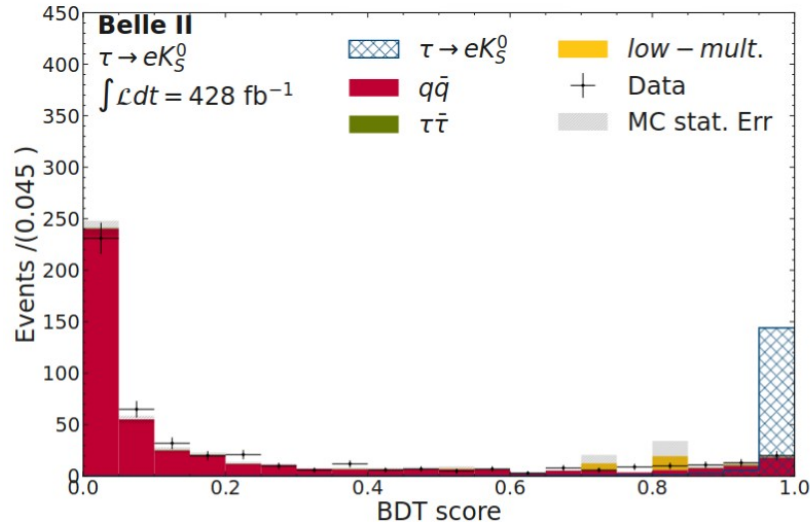
$\tau^\pm \rightarrow \ell^\pm K_S^0$ at Belle & Belle II

Background suppression :

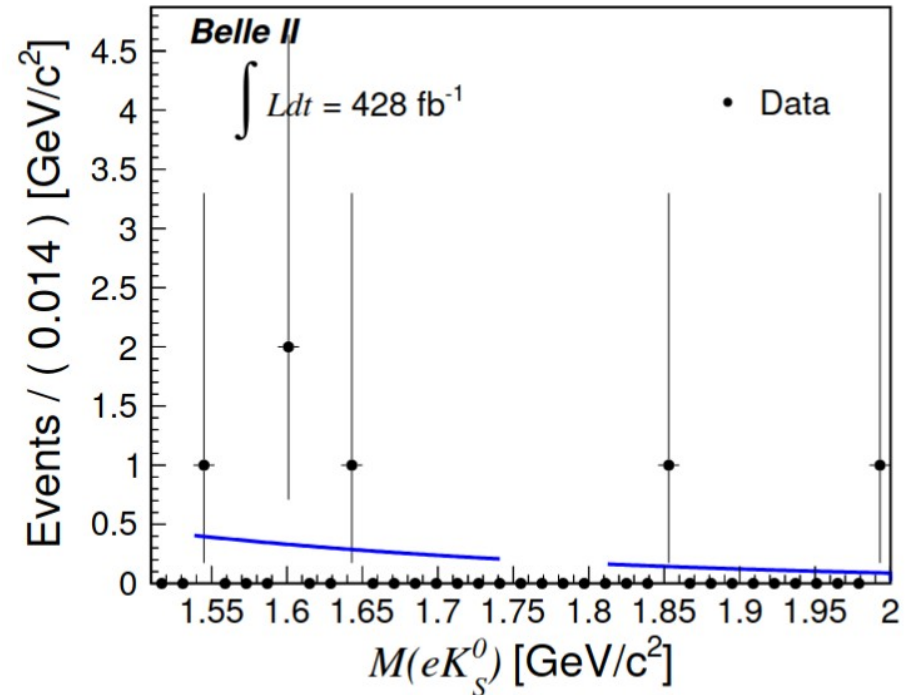
- Light quark pairs ($u\bar{d}sc$) continuum
- Low multiplicity $2\ell(\gamma), 4\ell(\gamma)$ ($\ell = e, \mu$)

Preselection + BDT to suppress background

- Optimisation of the BDT cut depends on the tag



Remaining background is **estimated** from a **fit** in **sidebands** in $M(\ell K_S^0)$ and **integrated** in the signal region



LFV : search for $\tau^\pm \rightarrow \ell^\pm K_S^0$ at Belle & Belle II

10% signal selection **efficiency** &
 ~ 0.5 **background** events **expected**

- Cut and count method
- **No excess** observed in **elliptical** signal regions

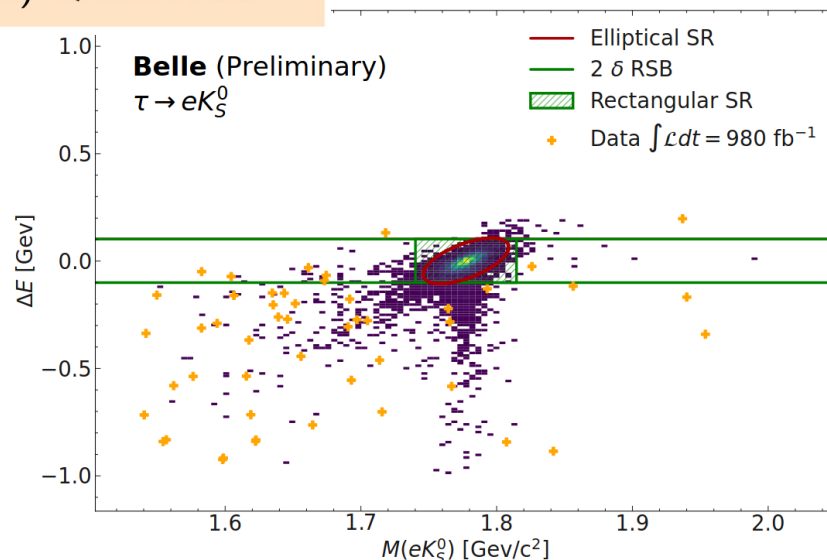
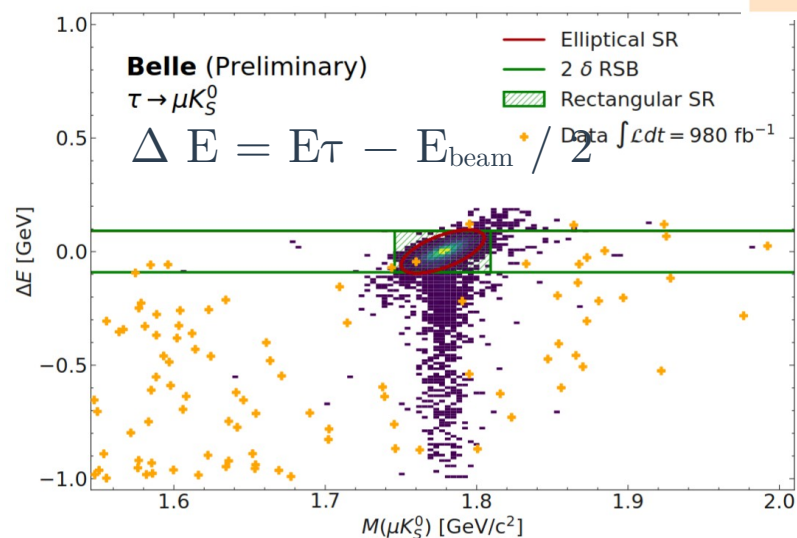
$$\mathcal{BR}(\tau \rightarrow K_S^0 e) < 0.8 \times 10^{-8}$$

$$\mathcal{BR}(\tau \rightarrow K_S^0 \mu) < 1.2 \times 10^{-8}$$

First τ LFV search with **combined** Belle & Belle II datasets ($980 + 424 \text{ fb}^{-1}$)

World most stringent limits at 90% CL:

[JHEP08(2025)092]



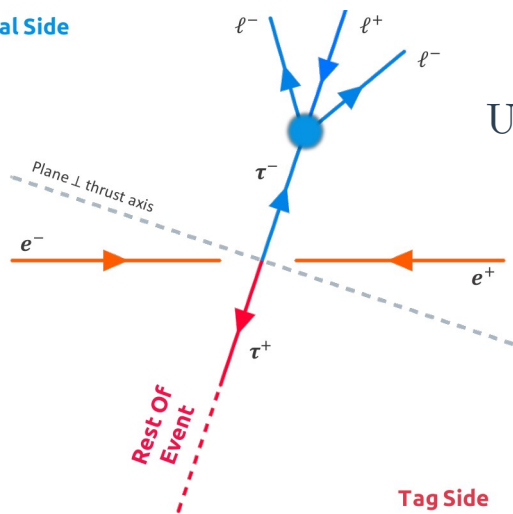
$\tau \rightarrow 3\ell$: inclusive tagging

Signal reconstructed from any combination of 3 leptons (e & μ)

Inclusive tagging: the other τ is not reconstructed & not limiting efficiency

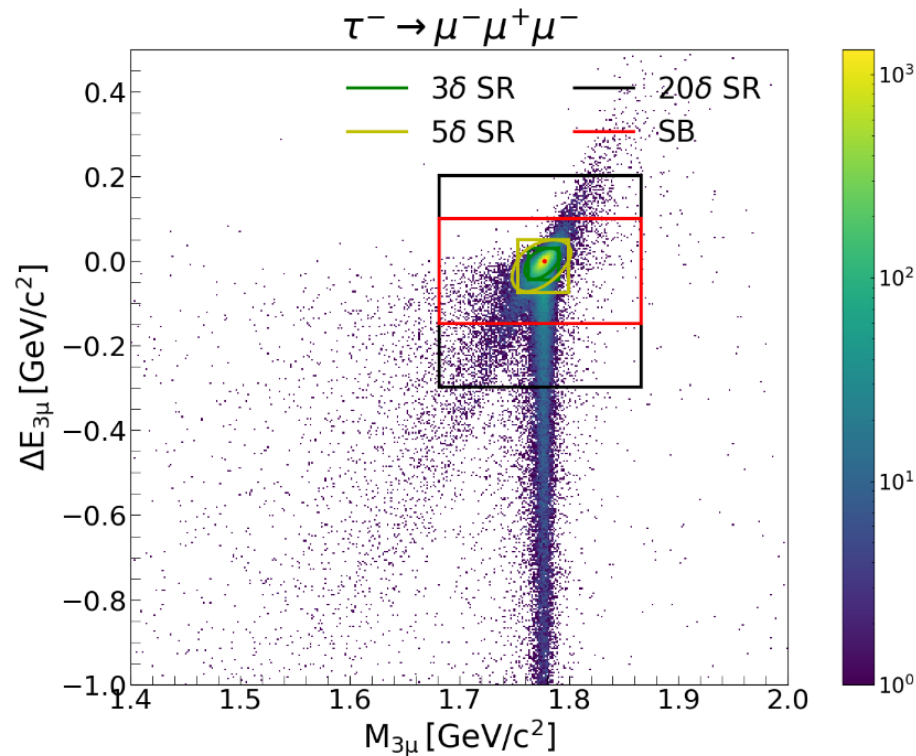
Everything not used for signal reconstruction is combined in **one single object** « Rest of Event », whose properties are used for background suppression

Signal Side



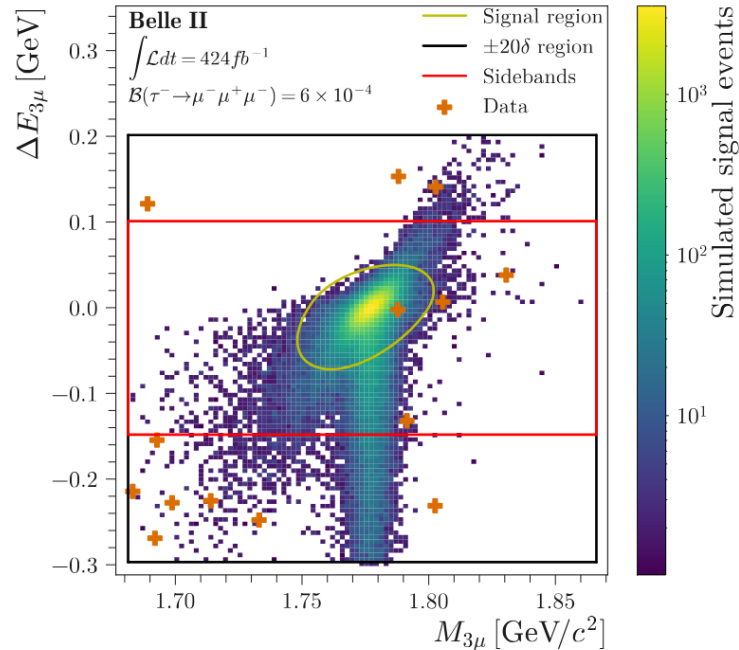
Used for the first time in
 $\tau \rightarrow \ell \phi$
[arXiv:2305.04759]

Use here also the $(M, \Delta E)_{3\ell}$ plane

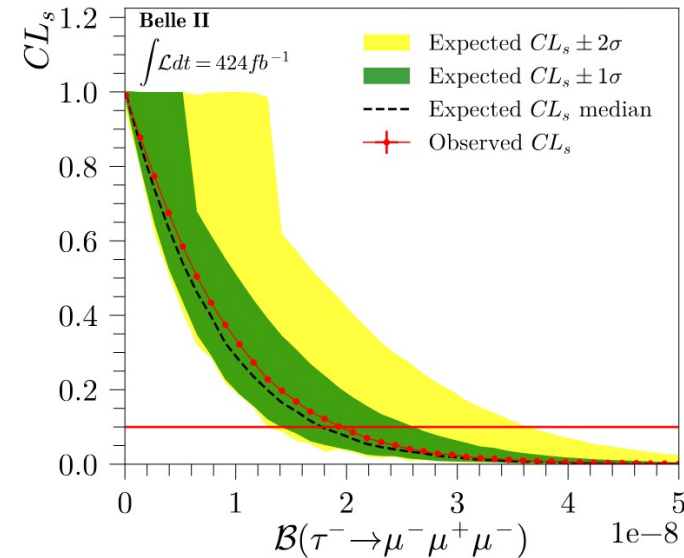


$\tau \rightarrow 3\mu$: signal extraction

- Signal selection efficiency: **20.1%**
- Background in the signal region estimated by **rescaling** the number of events in the sidebands
- **Counting** method with 0.7 expected background events



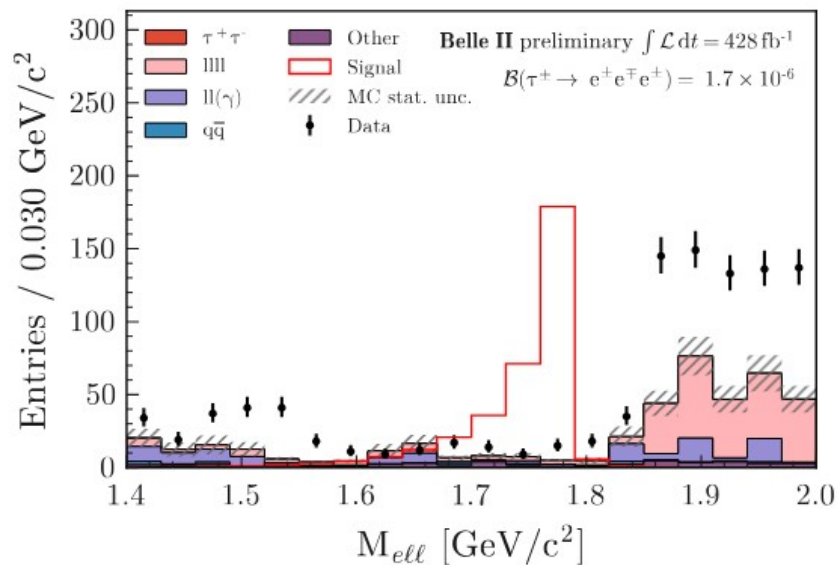
- No excess & set upper limit at 90% C.L.: **1.9×10^{-8}**
- World's best limit, improving on Belle measurement despite lower dataset
- [\[JHEP09\(2024\)062\]](#) [[JHEP 2024, 062](#)]



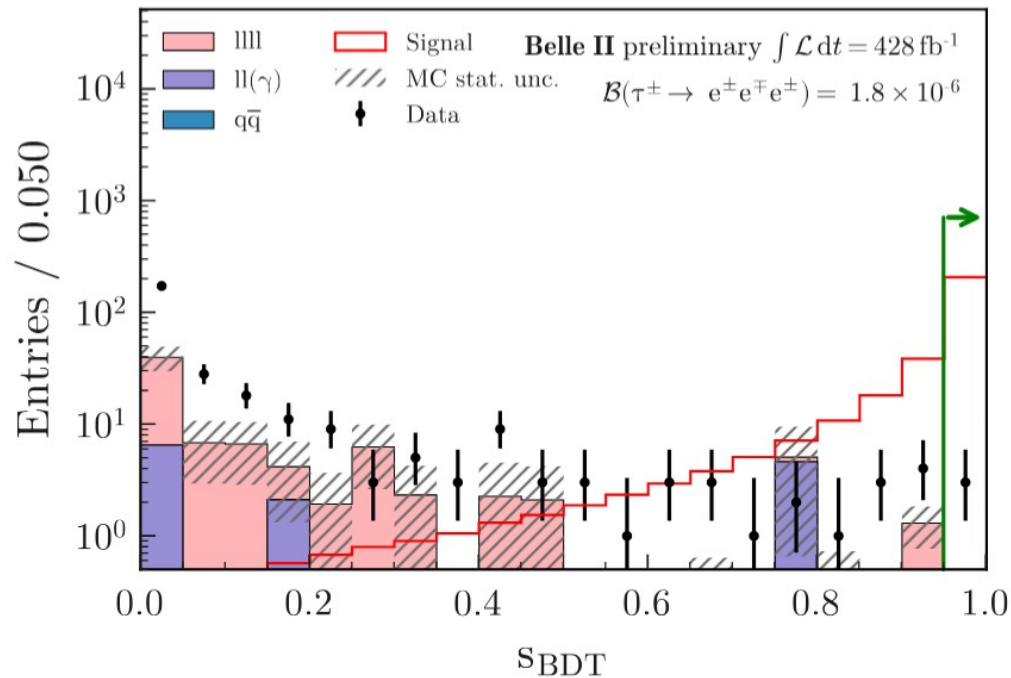
$\tau \rightarrow e \ell \ell'$ at Belle II: background 1

$\tau \rightarrow e \ell \ell'$: same **inclusive** tagging method

- Challenge: radiative dilepton and four-leptons $e^+e^- \rightarrow 2\ell(\gamma)$ & $e^+e^- \rightarrow 4\ell(\gamma)$ **much more dominant** in these modes (presence of an electron)
- Not far from the signal



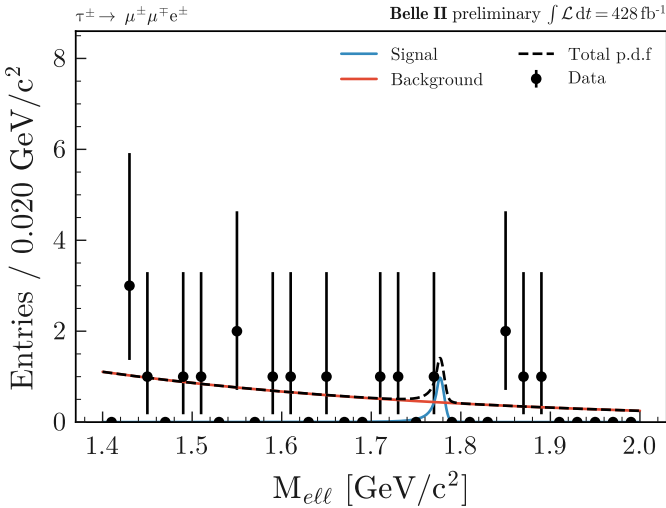
- BDT trained directly on datasidebands



$\tau \rightarrow e \ell \ell'$ at Belle II: signal extraction

- Signal extraction from unbinned fit to the mass
- No excess observed across the 5 modes $\rightarrow$ compute upper limits
- World's **leading upper limits** at 90% CL for 4 modes

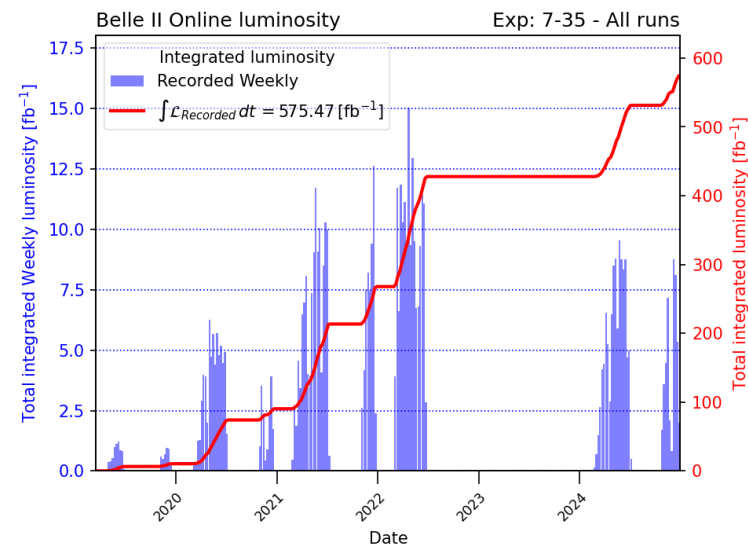
	$\mathcal{B}_{obs}^{UL} \times 10^{-8}$	$\mathcal{B}_{Belle}^{UL} \times 10^{-8}$	ϵ_{sig}	ϵ_{Belle}
$e^-e^+e^-$	★ 2.5	2.7	15.0%	6.0%
$e^-e^+\mu^-$	★ 1.6	1.8	20.4%	9.3%
$e^-\mu^+e^-$	1.6	1.5	23.5%	11.5 %
$\mu^-\mu^+e^-$	★ 2.4	2.7	20.1%	6.1%
$\mu^-e^+\mu^-$	★ 1.3	1.5	24.1%	10.1%
	@ 428 fb ⁻¹	@ 782 fb ⁻¹		

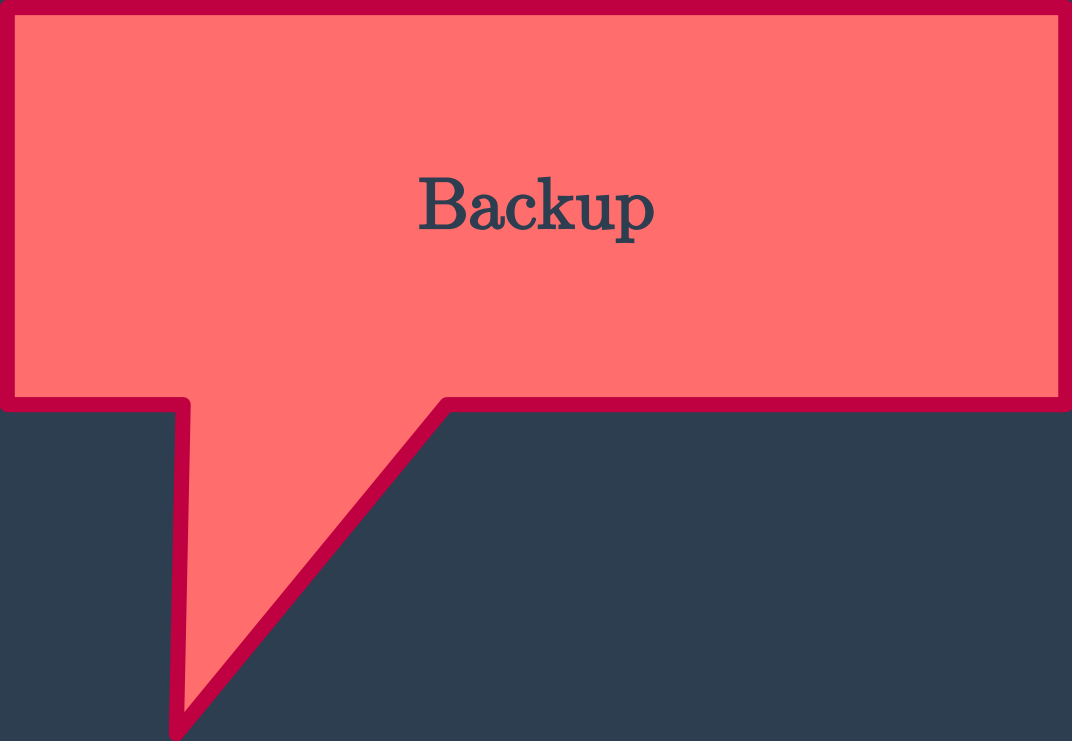


Accepted by JHEP
[arXiv:2507.18236]

Summary

- **LFU** under tension but still holds!
 - Precision is increasing
 - Complementary to LHCb measurements
- **LFV**: Belle and Belle II offer a **unique sensitivity** to new physics
 - We are setting **world's best limits**!
 - B decays close to be competitive with LHC experiments
 - τ decays: we are reaching interesting region
 - LHC exps not so far behind!
- Many more exciting results are coming:
**it's only the beginning for lepton flavour searches
& dataset keeps growing !**

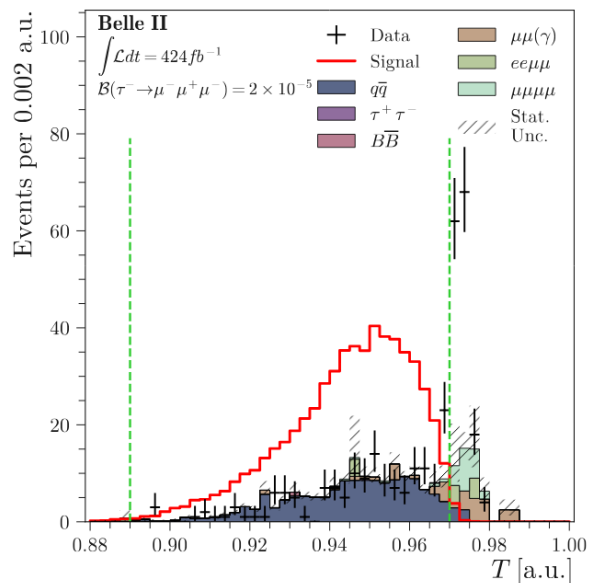
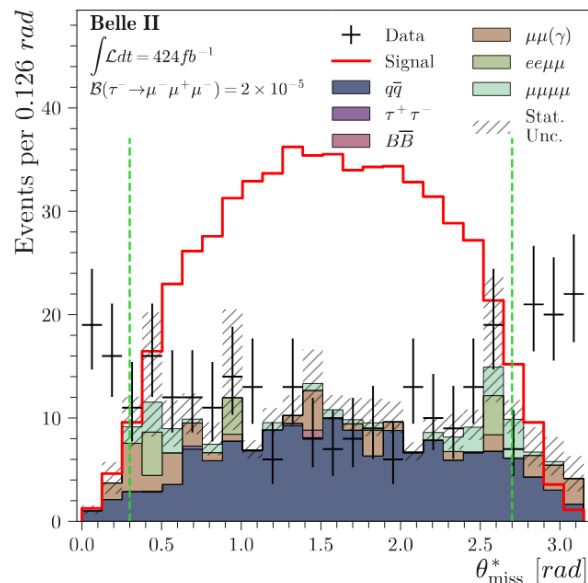




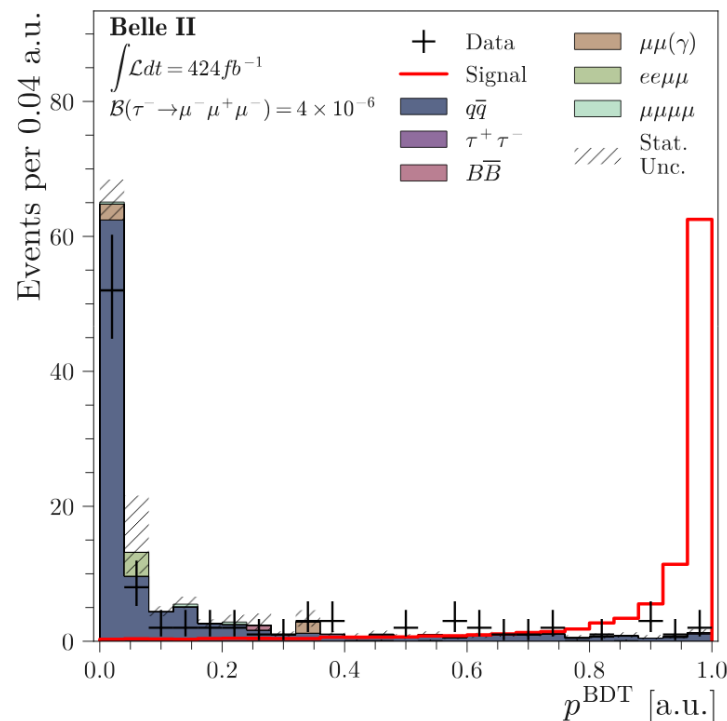
Backup

$\tau \rightarrow 3\mu$: background suppression

- Presence of low multiplicity (**radiative dilepton** and **four-lepton** final states), **missing** from the simulation
- Rejected with cut on the **angle of missing** momentum and **thrust** value



- Continuum pair of light quarks rejected with a BDT



LFU in τ decays: systematics

The measurement is systematically limited

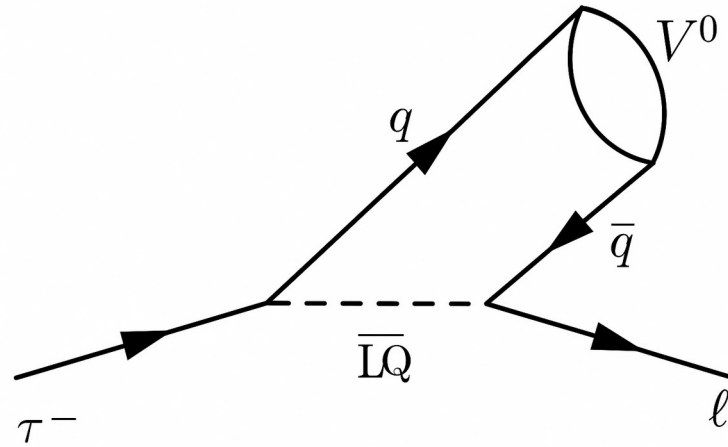
- and dominated by PID uncertainty
 - Efficiency measured with
 $J/\psi \rightarrow \ell^+ \ell^-$, $e^+ e^- \rightarrow e^+ e^- \ell^+ \ell^-$ and $e^+ e^- \rightarrow \ell^+ \ell^- (\gamma)$

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

LFV : search for $\tau^\pm \rightarrow \ell^\pm K_S^0$ at Belle & Belle II

$\tau \rightarrow \ell K_S^0$ in models such as **leptoquarks**,
related to anomalies in $b \rightarrow c \tau \nu$



Leptoquarks operators allows various LFV semi-leptonic decays

Previous searches at **Belle**:

- $\tau \rightarrow \ell V^0$ ($V^0 = \rho, \omega, \phi, K^*, \bar{K}^*$)
with 980 fb^{-1}
[\[JHEP06 \(2023\) 118\]](#)

Mode	$\mathcal{B}_{\text{obs}} (\times 10^{-8})$
$\tau^\pm \rightarrow \mu^\pm \rho^0$	< 1.7
$\tau^\pm \rightarrow e^\pm \rho^0$	< 2.2
$\tau^\pm \rightarrow \mu^\pm \phi$	< 2.3
$\tau^\pm \rightarrow e^\pm \phi$	< 2.0
$\tau^\pm \rightarrow \mu^\pm \omega$	< 3.9
$\tau^\pm \rightarrow e^\pm \omega$	< 2.4
$\tau^\pm \rightarrow \mu^\pm K^{*0}$	< 2.9
$\tau^\pm \rightarrow e^\pm K^{*0}$	< 1.9
$\tau^\pm \rightarrow \mu^\pm \bar{K}^{*0}$	< 4.3
$\tau^\pm \rightarrow e^\pm \bar{K}^{*0}$	< 1.7

- $\tau \rightarrow \ell K_S^0$
with 671 fb^{-1} :

[\[Phys. Lett. B 692 \(2010\) 4\]](#)

$$\mathcal{B}_{\text{obs}} < 2.3 - 2.6 \times 10^{-8}$$

$\tau \rightarrow 3\ell$

- Discovery potential not as high as in $\mu \rightarrow e$ transition
- But can help to **differentiate** between the different models & the LFV operators
- Previous limit on the branching fractions $\mathcal{B}(\tau \rightarrow 3\ell)$ by Belle **using 782 fb⁻¹**

[Phys. Lett. B 687 (2010) 139]

Mode	$\mathcal{B}(3\ell) >$
$e^-e^+e^-$	2.7
$e^-\mu^+\mu^-$	2.7
$e^-e^+\mu^-$	1.8
$e^+\mu^-\mu^-$	1.7
$\mu^+e^-e^-$	1.5
$\mu^-\mu^+\mu^-$	2.1

$\times 10^{-8}$

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