Measurements of τ decays at Belle and Belle II

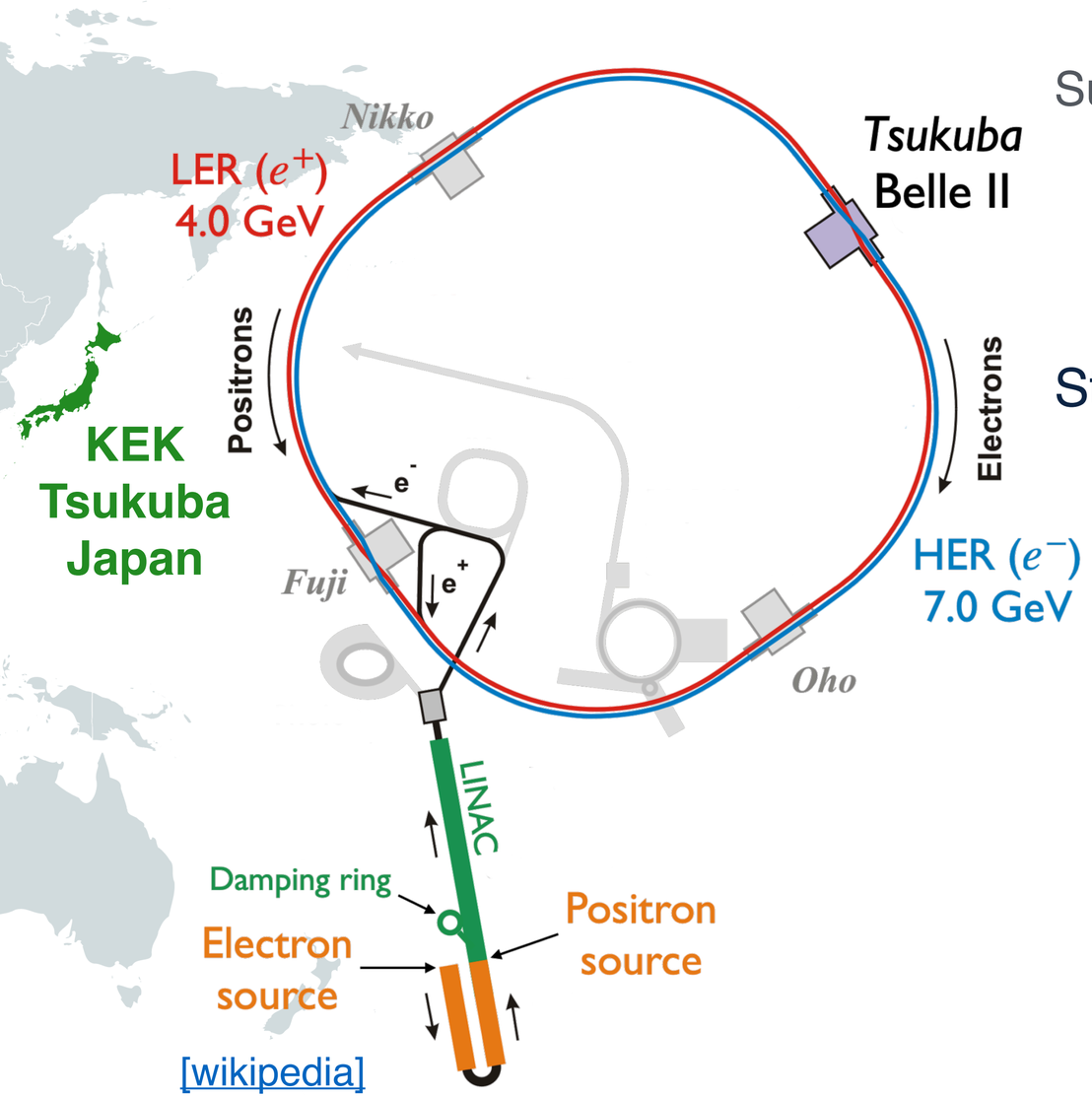
Lake Louise Winter Institute 2025

Wednesday 5th March, 2025

Robin Leboucher, on behalf of the Belle and Belle II collaborations

THE UNIVERSITY OF BRITISH COLUMBIA

SuperKEKB/Belle II for τ^- physics



KEKB (1999-2010) e^-e^+ collider at 10.58 GeV:

- Recorded luminosity $\approx 1\ ab^{-1}$

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

- World Record instantaneous luminosity = $5.1 \times 10^{34}\ cm^{-2}s^{-1}$
- Recorded luminosity = $575\ fb^{-1}$
- Run 1 = $424\ fb^{-1}$ ($363\ @\ \Upsilon(4S)\ +\ 61$ off-resonance)

Strengths for τ^- physics:

- High cross-section:

$$\left.\begin{aligned}\sigma(e^-e^+ \to \Upsilon(4S)) &= 1.05\ nb \\ \sigma(e^-e^+ \to c\bar{c}) &= 1.3\ nb \\ \sigma(e^-e^+ \to \tau^-\tau^+) &= 0.92\ nb\end{aligned}\right\} B,\ c \text{ and } \tau\text{-factory}$$

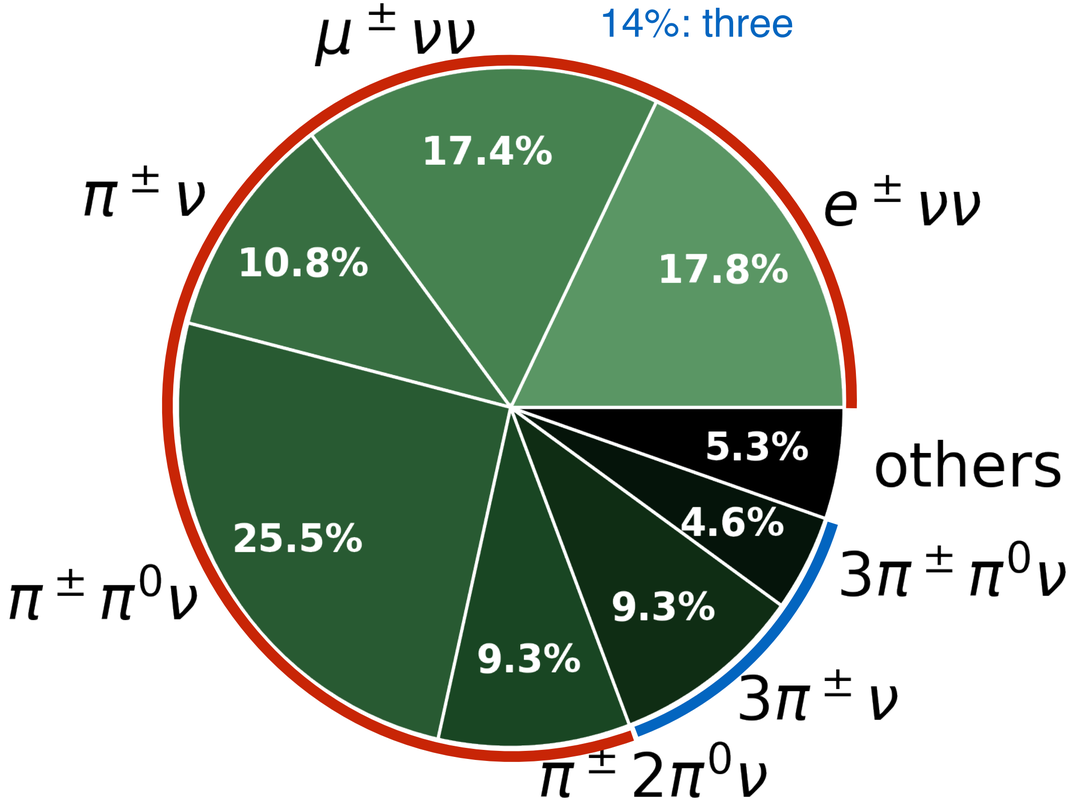
- Good missing energy reconstruction:
  - Clean collision environment
  - Hermetic detector (90% solid angle coverage)
- Excellent vertexing and track reconstruction
- Good particle identification (leptonID, π/K separation)

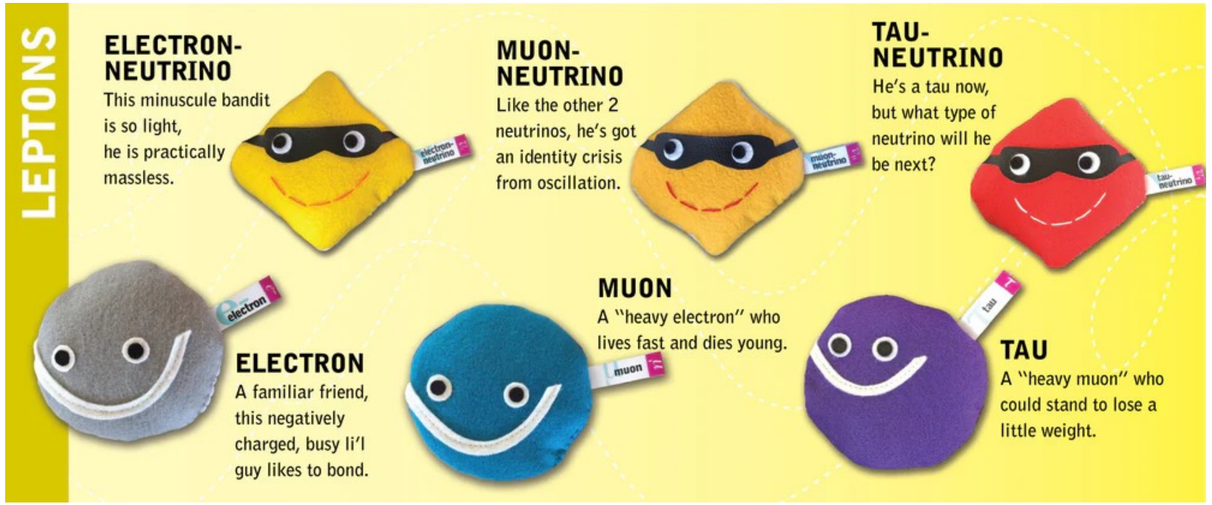
Belle II τ^- Physics

The τ^- is the heaviest lepton in the SM:

- Decays into leptons and hadrons
- Decays into one or three final-state particles
- Sensitive to more new physics models (large mass)

81%: one charged particle final state
14%: three





[particlezoo]

Tests of the standard model (SM):

- τ^- mass
- τ^- lifetime
- Electric/Magnetic DM
- V_{us} measurement
- Lepton flavour universality
- Michel parameters
- CP violation

Direct new physics searches:

- Lepton flavour violation (LFV)
- Baryon number violation (BNV)
- Heavy neutrinos

...

*In this talk

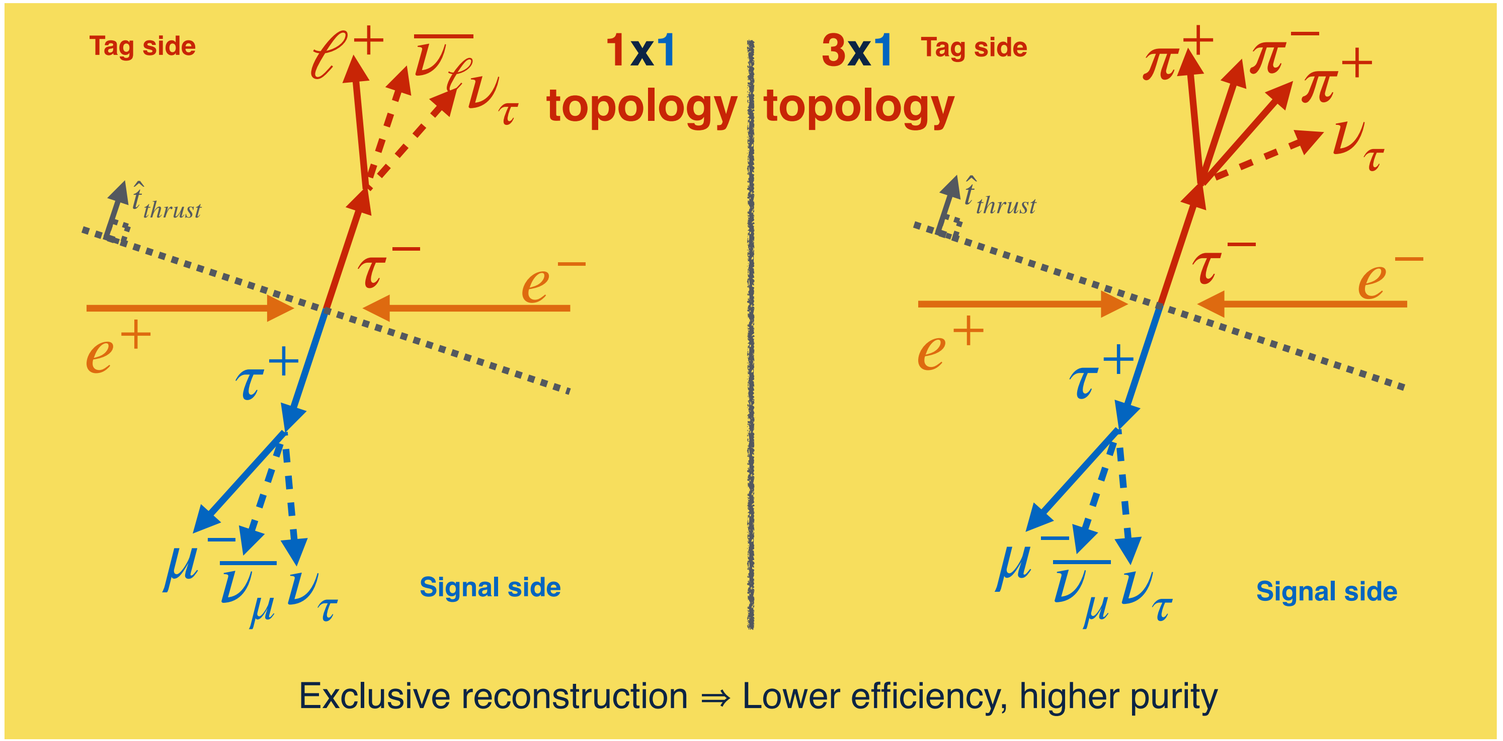
Working with τ^- at Belle (II)

In e^-e^+, τ^- pairs are produced **back to back and boosted**
⇒ We can exploit the τ^- pairs geometry by defining **two hemispheres** wrt to a plane perpendicular

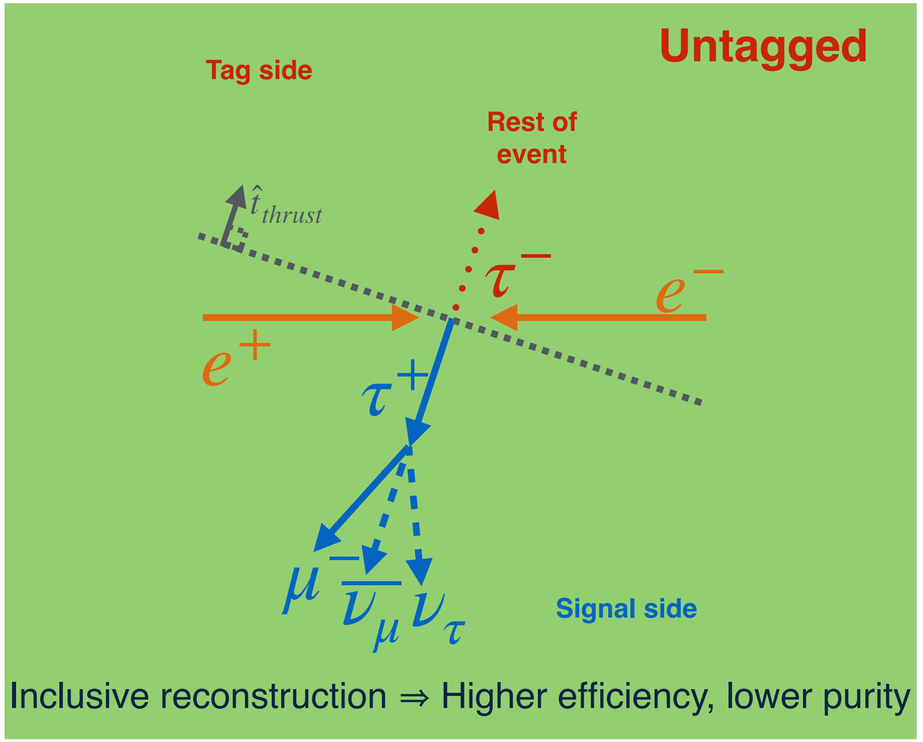
to the thrust axis $\hat{t}_{thrust}$ maximising

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

Reconstruct three kinds of topologies:



Exclusive reconstruction ⇒ Lower efficiency, higher purity



Inclusive reconstruction ⇒ Higher efficiency, lower purity

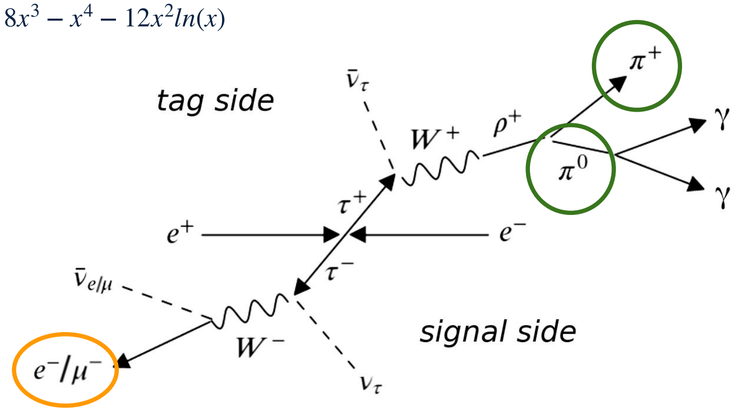
Belle II - Lepton Flavour Universality Measurement

Test if the W gauge bosons have the same couplings g as the three generations of leptons $g_e = g_\mu = g_\tau$ as predicted in the SM:

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau = R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \overset{\text{SM}}{=} 1$$

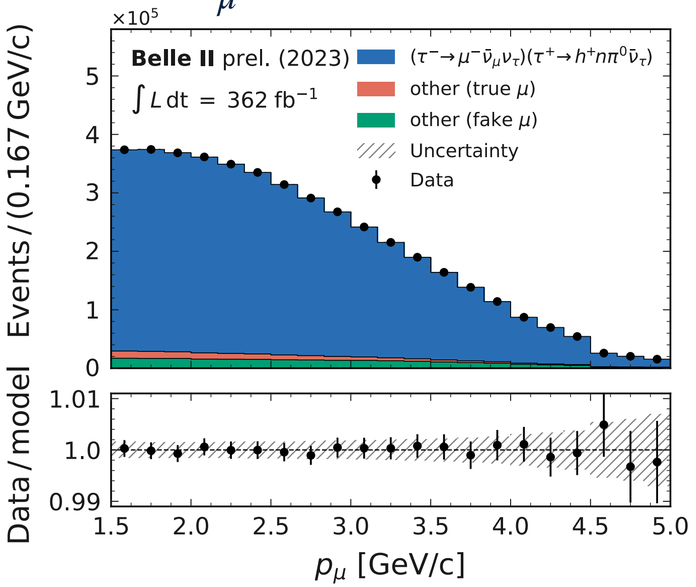
$$R_\mu \equiv \frac{\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu_\mu})}{\mathcal{B}(\tau^- \to \nu_\tau e^- \overline{\nu_e})} \overset{\text{SM}}{=} 0.9726$$

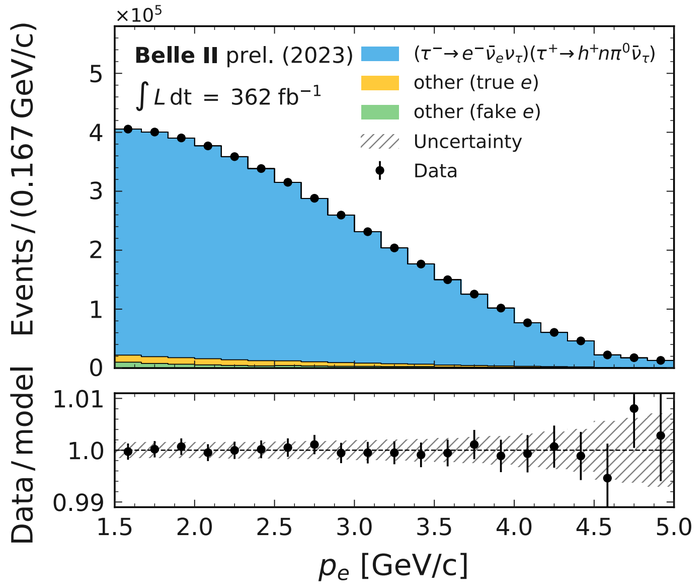
$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 ln(x)$

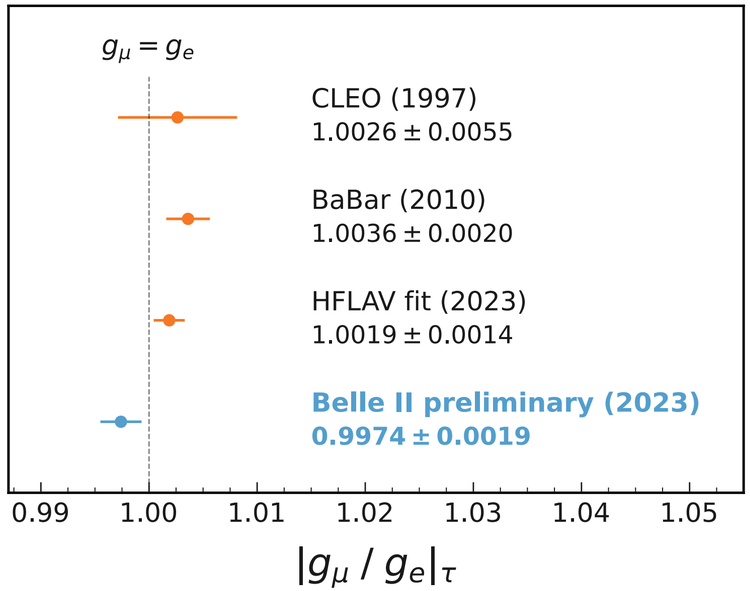


- Event selection is performed with **rectangular cuts** and a **neural network**
- 94% purity with 9.6% signal efficiency for the combined sample
- Main systematics are from **PID** (0.32%) and **trigger** (0.1%)

R_μ is extracted with a **binned maximum likelihood fit**







- **No deviation from the SM**
- **World's most precise R_μ and g_μ/g_e in τ^- decays from a single measurement**

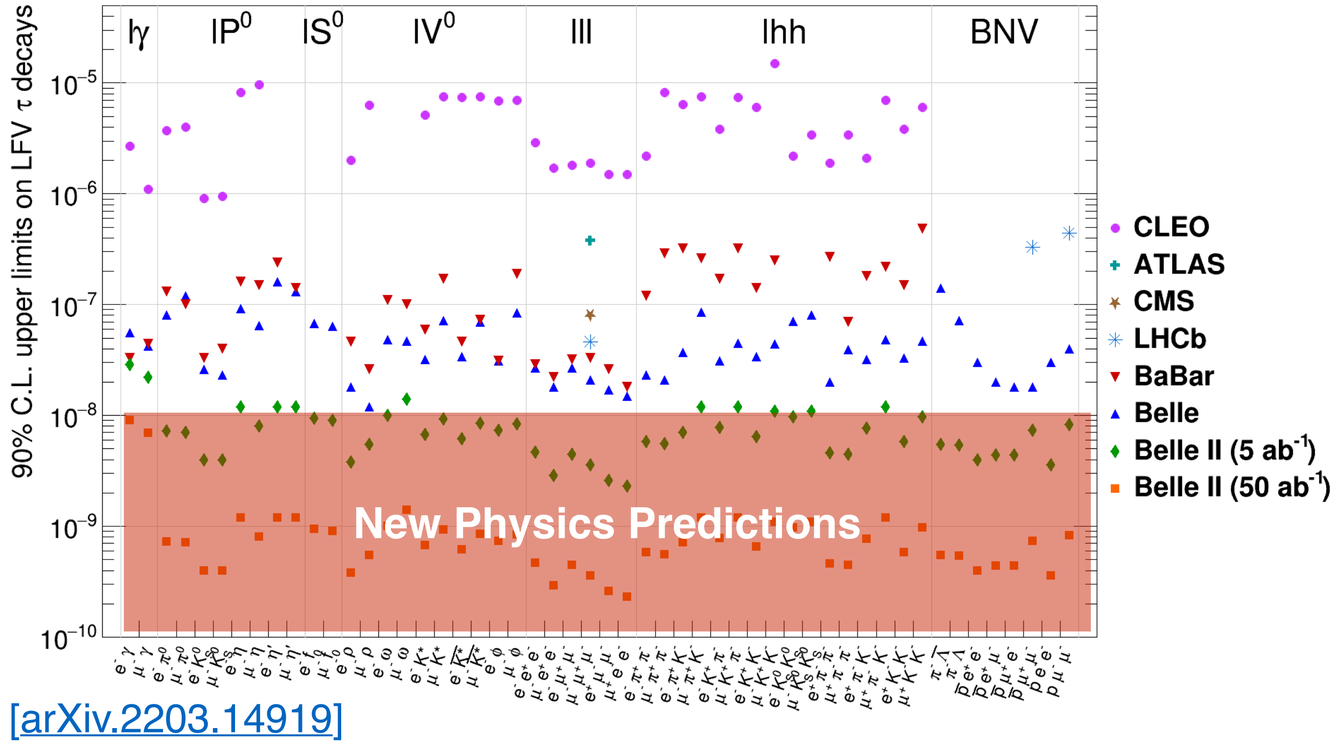
$R_\mu = 0.9675 \pm 0.0007_{\text{stat.}} \pm 0.0036_{\text{sys.}}$

[JHEP08(2024)205]

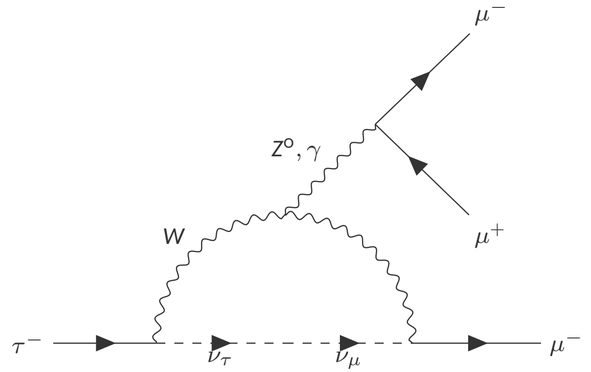
New Physics Direct Searches

- In SM, the Charged Lepton Flavour Violation is allowed through weak charged current and neutrino oscillation
  - Order $\mathcal{O}(10^{-55})$ ⇒ **no Flavour Violation in current experiments**

- Various **New Physics predict Lepton Flavour Violation** at observable rates $\mathcal{O}(10^{-8} - 10^{-10})$
  - e.g leptoquarks for $\tau^- \to \ell^- V^0$ related $b \to c\tau\nu$ anomalies



[arXiv.2203.14919]



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}

[PhysRevD.77.073010]

A lot of interesting decays at e^-e^+ colliders with 50 modes:

- $\tau^- \to \mu^-\mu^+\mu^-$ most accessible
- $\tau^- \to \ell^-\phi$ linked to $b \to c\tau\nu$ within the Leptoquarks models
- $\tau^- \to \Lambda(\overline{\Lambda})\pi^-$ violated the Baryon number ⇒ condition for matter/antimatter asymmetry
- $\tau^- \to \ell^-\alpha$ new boson candidate for dark matter

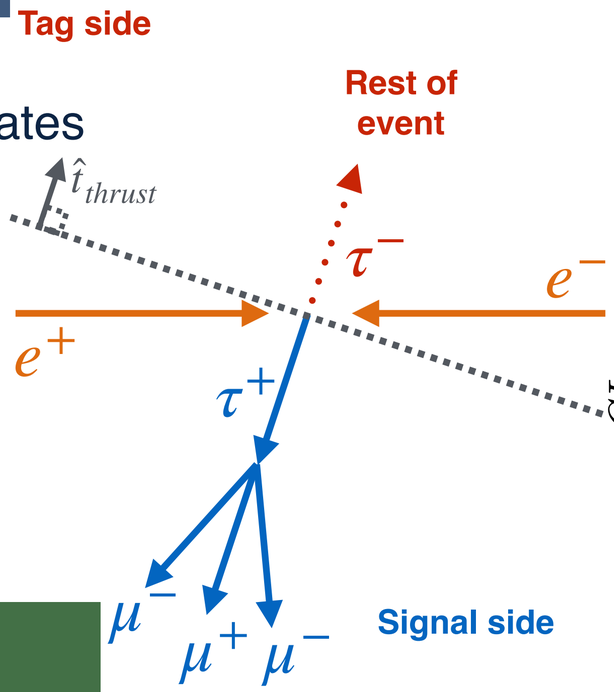
Belle II - $\tau^- \to \mu^-\mu^+\mu^-$ Lepton Flavour Violation

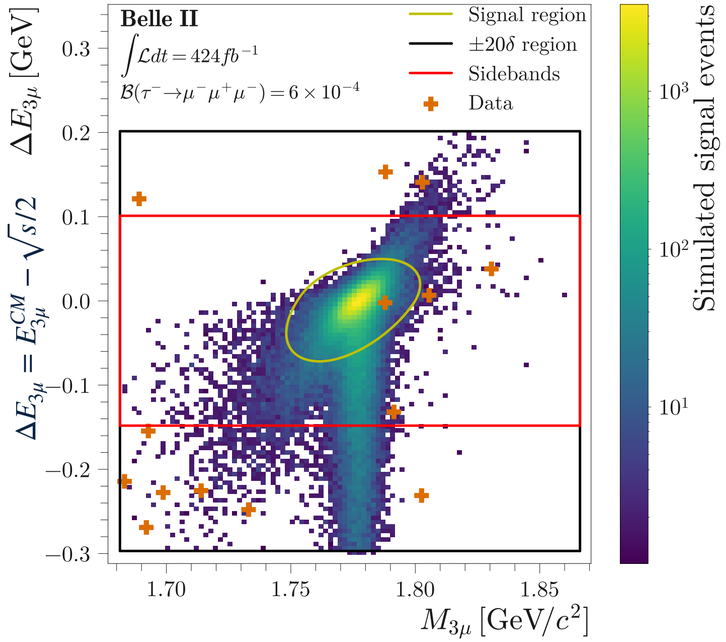
- Almost **free from SM background**
- Excellent resolution on energy and momentum
- Also probed by LHC experiments

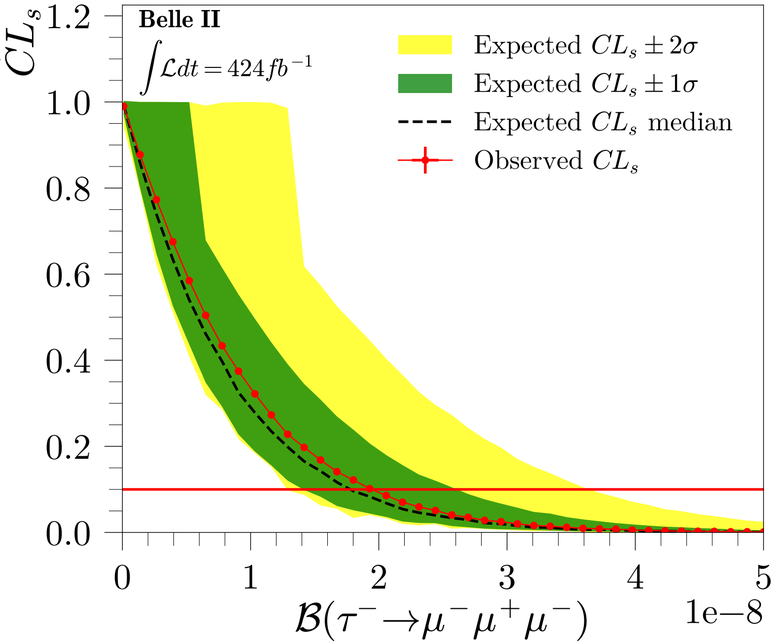
Existing measurements: 2.1×10^{-8} by Belle
2.9×10^{-8} by CMS

Signal efficiency challenge:

- **Untagged τ reconstruction** to cover more final states
- **BDT classifier**: reject main backgrounds $e^-e^+ \to q\bar{q}$ using signal, rest of event and kinematic variables
- $\varepsilon_{sig} \simeq 20.41\,\%$, 3 times Belle efficiency
- Extract expected backgrounds $0.7^{+0.6}_{-0.5} \pm 0.01$ by rescaling yields from sidebands data in signal region (ABCD)







- **Observed 1 event in $424 fb^{-1}$**
- **Set 90% CL upper limit on the branching fraction**

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

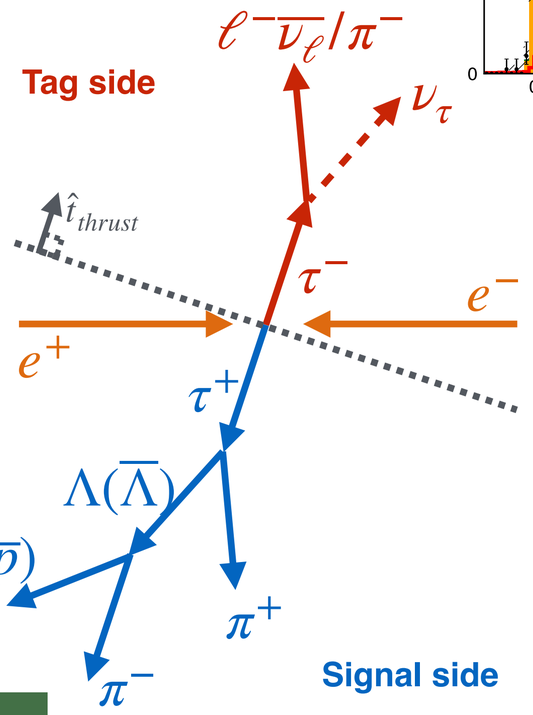
- **World's best limit**
- Results confirmed by a conventional 3 by 1 tag method

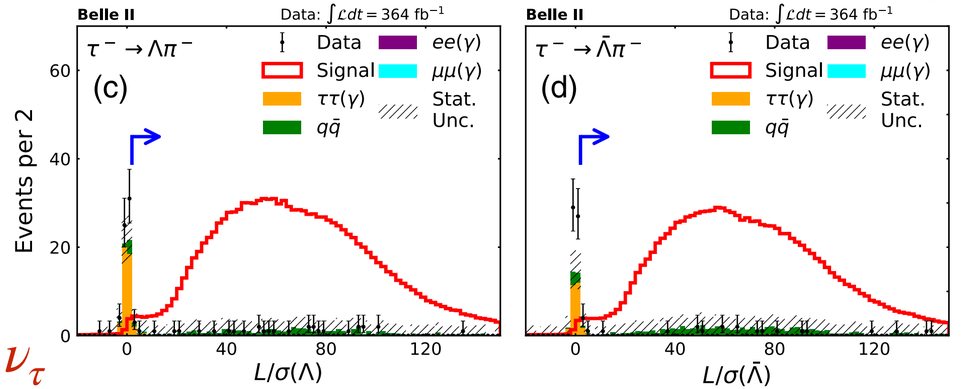
[JHEP09(2024)062]

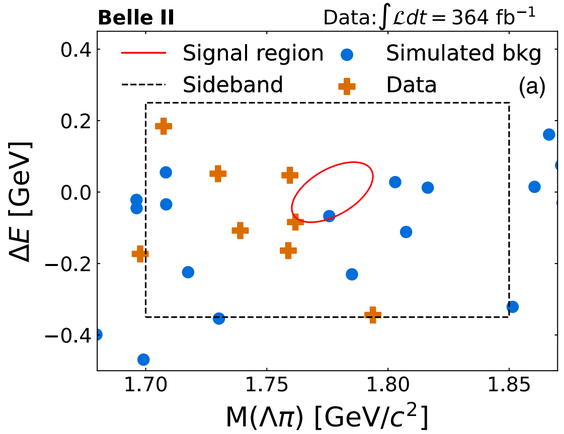
Belle II - $\tau^- \to \Lambda\pi^-/\tau^- \to \overline{\Lambda}\pi^-$ Baryon Number Violation

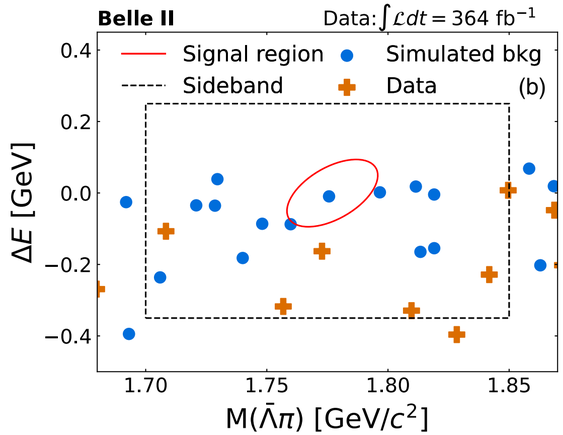
- **BNV is a key ingredient to explain asymmetry of matter**
- Plenty of BSM scenari allow it
- Belle result: $7.2(14) \times 10^{-8}$ with $154 fb^{-1}$

- Reconstruct 4 charged particles (0 net charge) in **1x3 topology**
- $\Lambda(\overline{\Lambda})$ reconstructed from $p(\overline{p})$ and π^-
- Background suppression: **loose preselection** (flight significance most discriminant) + **gradient BDT**
- $\varepsilon_{sig} \simeq 9.5(9.9)\,\%$ for $\tau^- \to \Lambda(\overline{\Lambda})\pi^-$
- Extract expected backgrounds $1.0^{+1.3}_{-1.1}(0.5 \pm 0.6)$ by rescaling yields from sidebands data in signal region









- **No observed event** in $364 fb^{-1}$
- **Set 90% CL upper limit on the branching fraction**

$$\mathcal{B}(\tau^- \to \Lambda(\overline{\Lambda})\pi^-) < 4.7(4.3) \times 10^{-8}$$

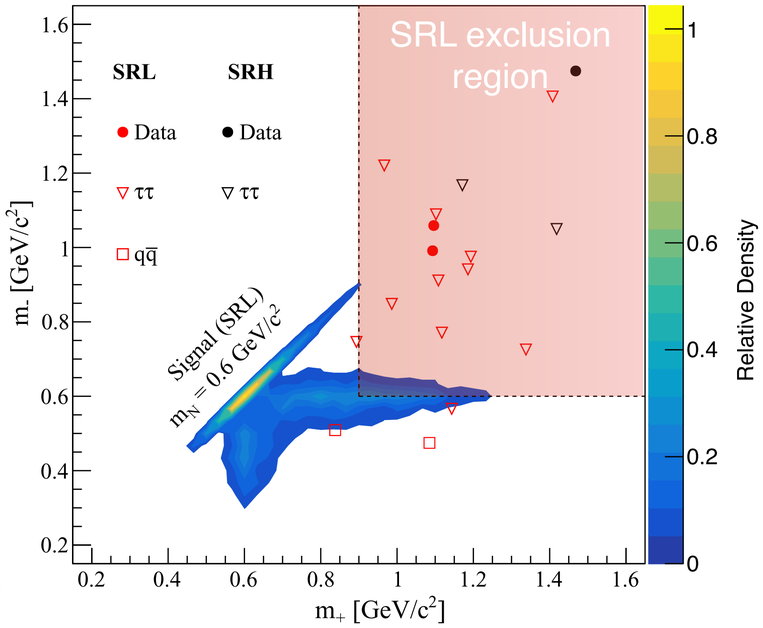
- **New, most stringent limit**

[PhysRevD.110.112003]

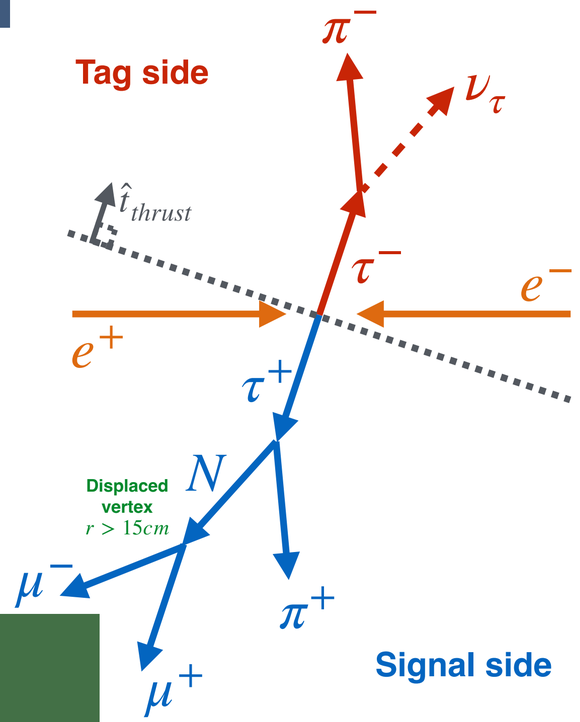
Belle - Search for Heavy Neutral Lepton

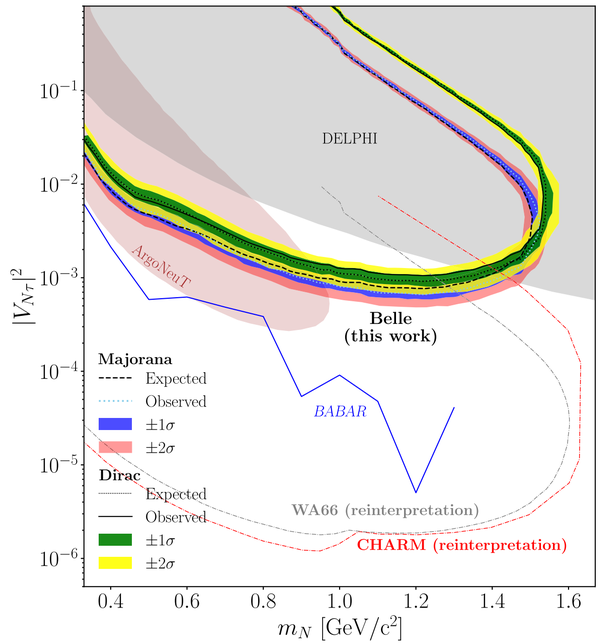
- Can interact with ν_{SM} via $N \leftrightarrow \nu_{SM}$ mixing
- Long lifetime→ Displaced vertex
- Probe $m_N < m_\tau$ in $\tau^- \to N\pi^-$ decay

SRH: $m_{DV} > 520$ MeV/c^2
SRL: $m_{DV} < 420$ MeV/c^2
Excluded 100 MeV/c^2 window to reject K^0_S contamination



- Reconstruction in 1x1 topology:
  - Tag $\tau^+ \to \pi^+\nu_\tau$
  - Signal $\tau^- \to N(\to \mu^-\mu^+)\pi^-$:
    - Fit the $\mu^-\mu^+$ displaced vertex
- Use the **displaced vertex** properties to extract m_N and suppress background to unit level





- **First-time $N \to \mu^-\mu^+$ displaced vertex method**
- **Observation in agreement with background expectations** with $915 fb^{-1}$
- **Set limit on the mixing coefficient** $|V_{N\nu_\tau}|^2$ between $300 < m_N < 1600$ MeV/c^2

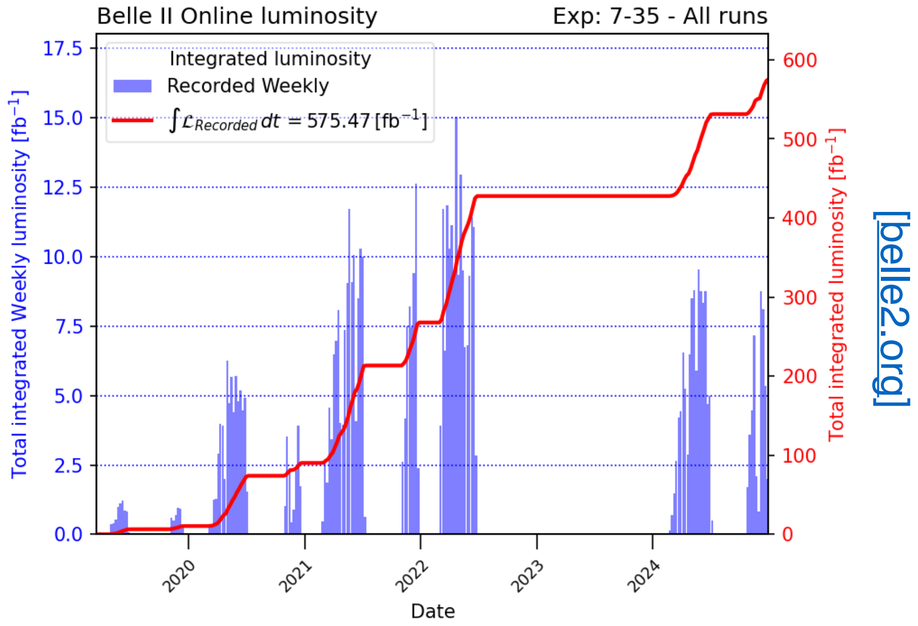
[PhysRevD.109.L111102]

Summary

- **Belle and Belle II are leading the τ^- physics research on several key areas:**
  - Various studies related to Standard Model parameters
  - Searches for phenomena beyond the Standard Model

- **There are many opportunities for improvement in these areas:**
  - Increasing the size of the data sample
  - Enhancing analysis techniques and reducing systematic uncertainties
  - Developing more accurate physics models

- **Many more results to come:**
  This is only the beginning for precision and rare decay searches with τ^- at Belle II



Thank you!

Backups

Belle II - $\tau^- \to e^\pm \ell^\mp \ell^-$ Lepton Flavour Violation

- Extend $\tau^- \to \mu^-\mu^+\mu^-$ study to 5 modes:
  $e^-e^+e^-$, $e^-e^+\mu^-$, $e^-\mu^+e^-$, $\mu^-\mu^+e^-$, $\mu^-e^+\mu^-$
- Higher background contamination from $\ell^-\ell^+(\gamma)$ and $\ell^-\ell^+\ell^-\ell^+$

Existing measurements: $1.5 - 2.7 \times 10^{-8}$ by Belle

Preliminary

Signal efficiency challenge:

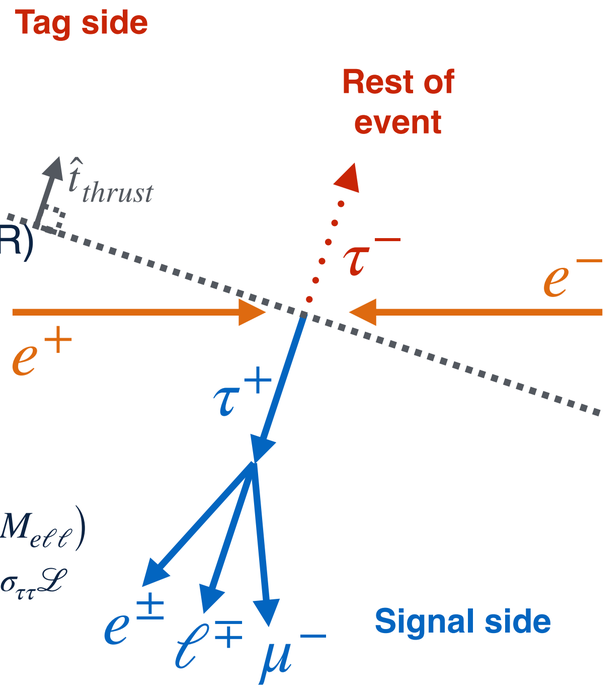
- **Untagged τ reconstruction** to cover more final states
- Preselection rectangular cuts
- **Data (blind) driven BDT classifier**:
  - reject main backgrounds $\ell^-\ell^+\ell^-\ell^+$ (mismodeled ISR/FSR)
  - training sample away from the fitted region
  - rely on signal, ROE and kinematic variables
- Resulting final $\varepsilon_{sig} \simeq 15 - 24\,\%$
- **Extract expected by fitting $M_{e\ell\ell}$**:

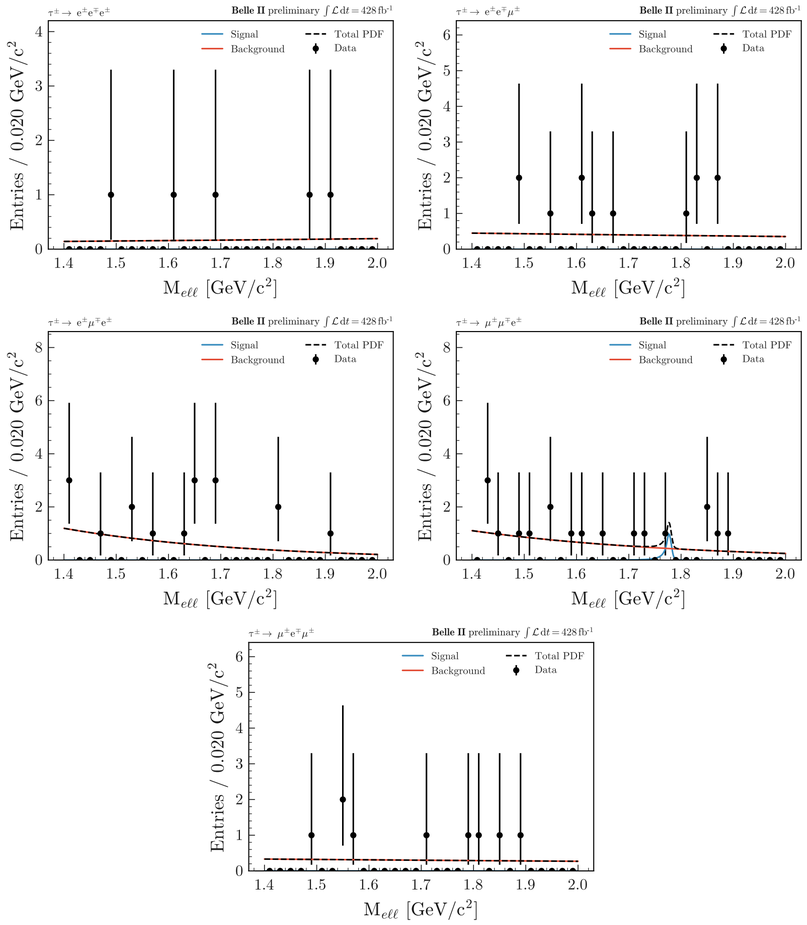
$$PDF_{tot}\left(M_{e\ell\ell}\right) = \mathcal{B}\left(\tau^- \to e^\mp \ell^\pm \ell^-\right) \cdot \mu \cdot PDF_{\text{sig}}\left(M_{e\ell\ell}\right) + N_{bg} \cdot PDF_{bg}\left(M_{e\ell\ell}\right)$$

PDF_{sig} is a double-sided Crystal Ball

PDF_{bg} is an exponential

$\mu = 2\varepsilon_{sig}\sigma_{\tau\tau}\mathcal{L}$





- **No significant signal was observed** in $424 fb^{-1}$
- **Set 90% CL upper limit on the branching fraction**
- **The most stringent upper limit on all modes**

	$\mathcal{B}^{UL}_{exp} \times 10^{-8}$	$\mathcal{B}^{UL}_{obs} \times 10^{-8}$
$e^-e^+e^-$	2.50	2.18
$e^-e^+\mu^-$	2.00	1.38
$e^-\mu^+e^-$	1.54	1.36
$\mu^-\mu^+e^-$	1.80	2.36
$\mu^-e^+\mu^-$	1.54	1.46

Belle and Belle II - $\tau^- \to \ell^- K_S^0$ Lepton Flavour Violation

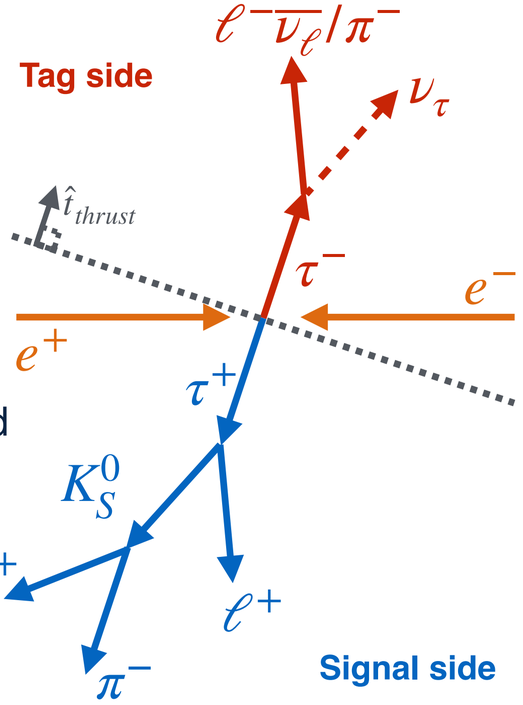
- In EFT, it can constrain different types of operators (e.g two-lepton and two-quark-operators in leptoquark models)
Existing measurements: $2.3(2.6) \times 10^{-8}$ by Belle for $e^-(\mu^-)$ mode

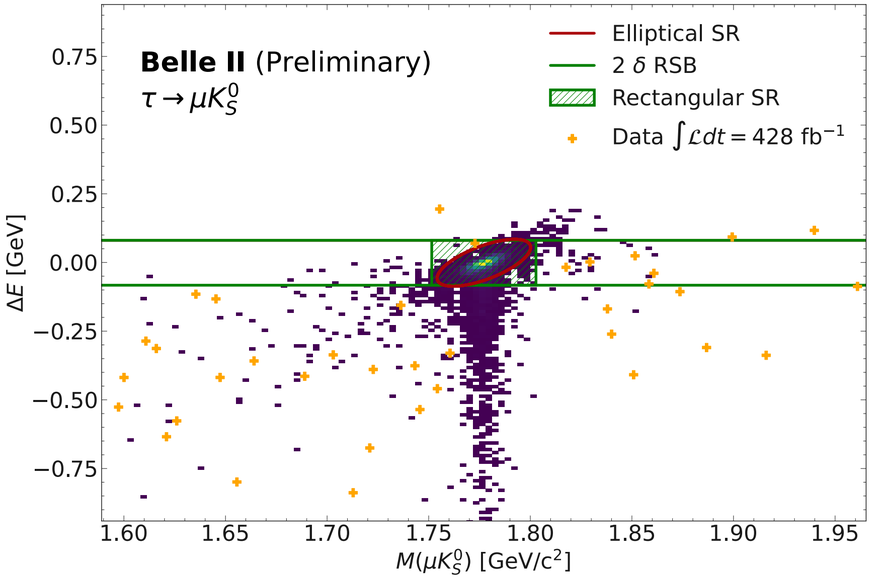
Preliminary

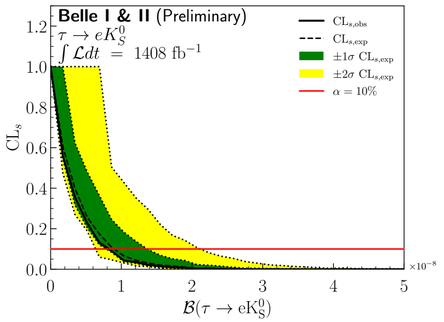
Signal efficiency challenge:

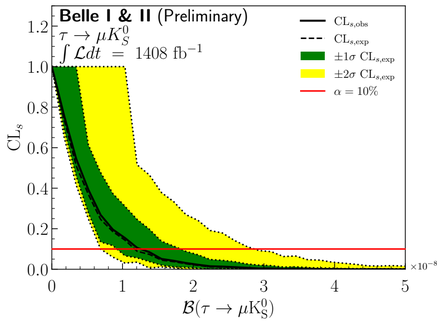
- Reconstruct 4 charged particles (0 net charge) in **1x3 topology**
- K_S^0 reconstructed from $\pi^-\pi^+$
- Preselection rectangular cuts
- **BDT classifier**:
  - different training on each Belle and Belle II samples
  - use signal (tag) τ^-, K_S^0 and track kinematics, event shape and neutrals variables
- Resulting final $\varepsilon_{sig} \simeq 10\,\%$
- **Extract expected background by fitting $M_{\ell K_S^0}$:**

PDF_{bg} is an exponential









- **No significant signal was observed** in $424 fb^{-1}$ Belle II and $980 fb^{-1}$ Belle
- **Set a combined 90% CL upper limit on the branching fraction**

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

- **Most stringent limit on all modes**