Tau and Dark Sector Physics at Belle and Belle II

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Belle & Belle II

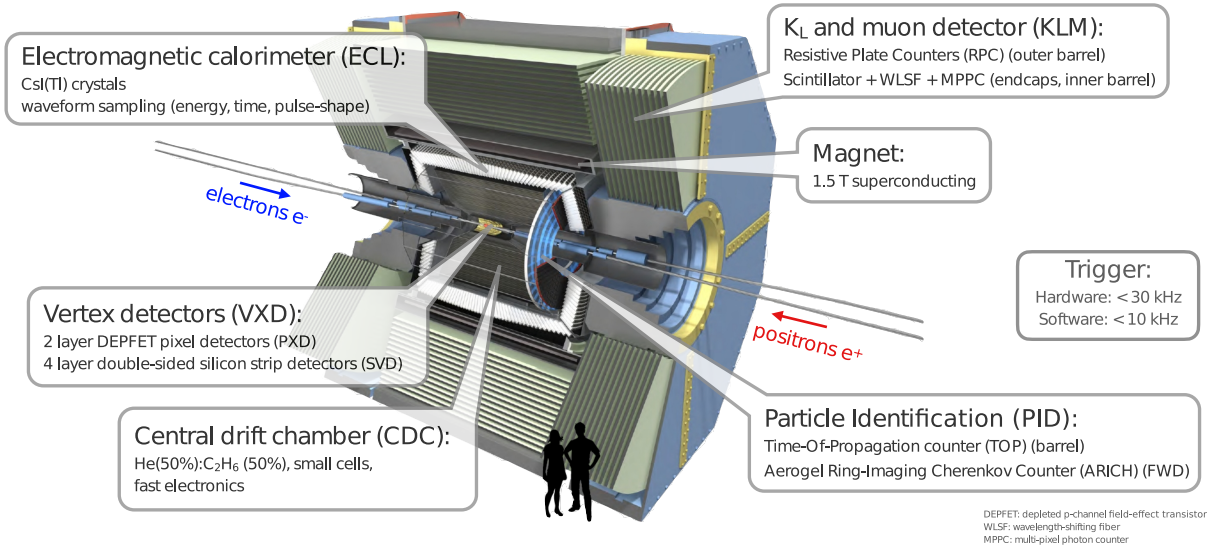
More than just B-factories

Key Features

- Mostly operating at the $\Upsilon(4S)$ resonance $\sqrt{s} = 10.58\,\mathrm{GeV}$
- Clean experimental environment
- Well-known initial state kinematics $\Rightarrow$ **Strong in searches with missing energy**
- Collected $1\,\mathrm{ab}^{-1}$ @ Belle and $0.6\,\mathrm{ab}^{-1}$ @ Belle II (so far)
- **World record instantaneous luminosity** of $5.1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Tau Physics

- Large cross section for $e^+e^- \to \tau^+\tau^-$
- **Test the SM** (lepton flavour universality, V_{us}, ...)
- **Search for new physics** (lepton flavour violation, heavy neutrinos, ...)

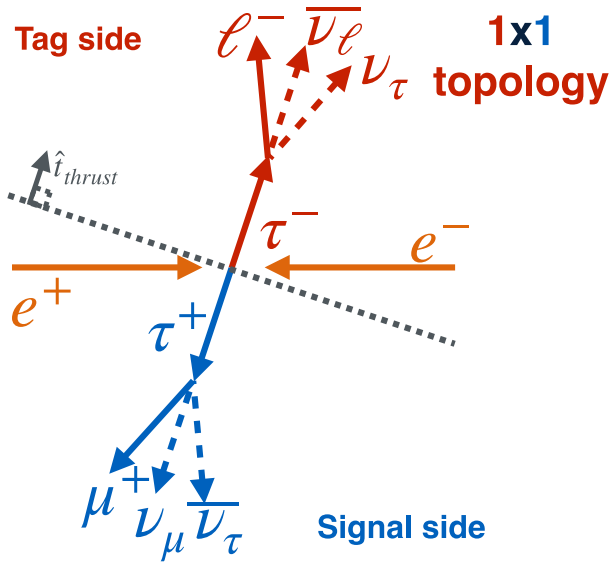


Dark Sector Physics

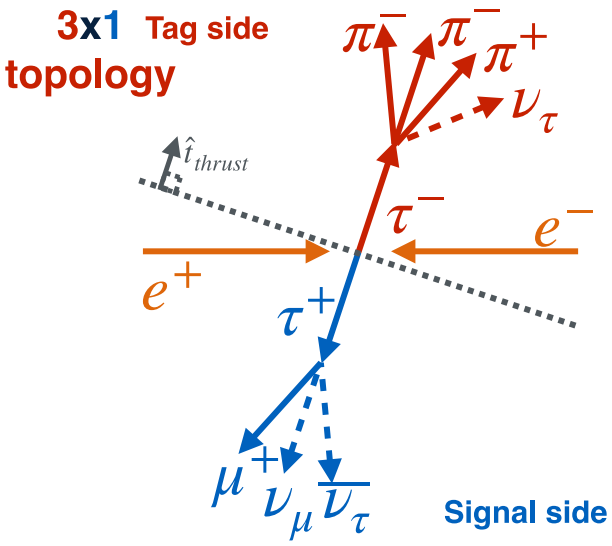
- Unveil the nature of dark matter
- **Search for dark mediators in visible and invisible decays in the MeV to 10 GeV range**
- Searches for long-lived particles

Tau Physics

General overview



$$T = \max_{\hat{t}} \left(\frac{\sum_i |p_i^{\mathrm{CMS}} \cdot \hat{t}|}{\sum_i |p_i^{\mathrm{CMS}}|} \right)$$

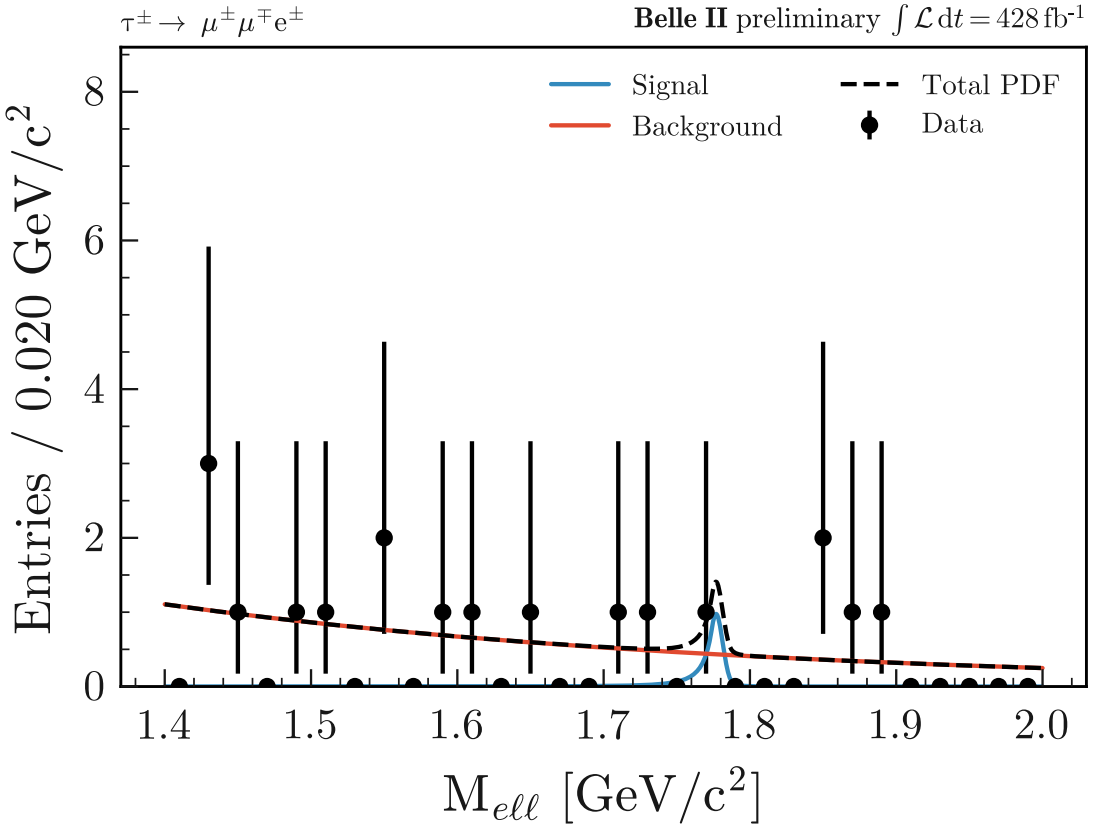


- τ pairs are produced **back-to-back** and boosted in the CM frame
- **Identification** via topology requirements
- Separation into **two opposite hemispheres** via the **thrust axis** $\hat{t}$ (maximizes thrust T)
- Can **reconstruct** τ either via **one charged track (1-prong)** or via **three charged tracks (3-prong)**
- Use one τ to **tag the event** and **reconstruct the signal on the other side**
- Also exploit **untagged analyses** to **boost the signal efficiency**
- Can perform either **precision measurements** (LFU JHEP08(2024)205, ...) or **searches for new physics**

$\tau^- \to e^\pm \ell^\mp \ell^-$ @ Belle II

New result

- **LFV is expected in the SM** due to neutrino masses (and oscillations) at **rates** $\sim$ **10^{-50}**, beyond any current and future sensitivity
  - Observation would be **unambiguous sign of NP**
  - **Several models** (new Z', charged Higgs boson..) could **enhance rates up to $10^{-10} - 10^{-8}$**
- Search for the **charged-lepton-flavour violating** process $\tau^- \to e^\pm \ell^\mp \ell^-$ using 428 fb^{-1} of Belle II data
- Untagged measurement
- Data-driven BDT classifier trained on sideband data
- **Factor 2 to 3.3 higher signal efficiency** compared to previous Belle analysis [Phys. Lett. B 687, 139–143 (2010)]
- Signal extraction via fit of $M(e\ell\ell)$



- **No significant signal observed** $\to$ Derived **most stringent 90% CL upper limits** on $\mathcal{B}(\tau^- \to e^\pm \ell^\mp \ell^-)$ in all considered modes
- $\mathcal{B}$'s in the range between 1.4 and 2.4 $\times$ 10^{-8}

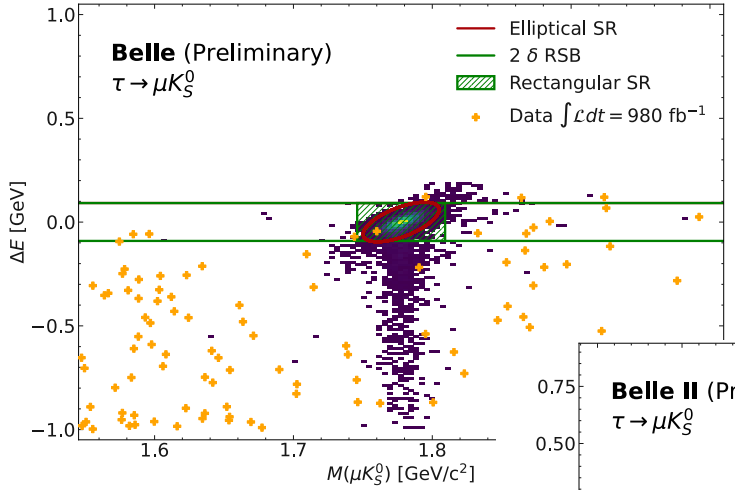
$\tau^- \to \ell^- K_S^0$ @ Belle + Belle II

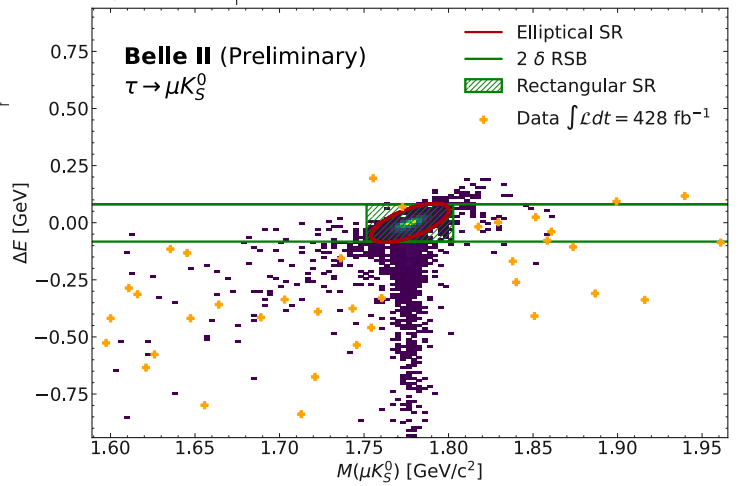
New result

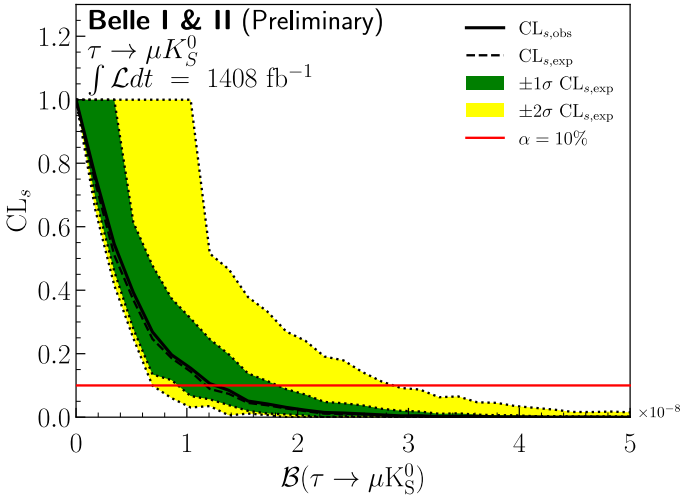
- **New leptoquark mediators could enhance rate** and simultaneously **accommodate for the** $b \to c\ell\nu$ **anomalies** [Eur. Phys. J. C 70, 1071–1090 (2010)]
- Search for the **LFV** process $\tau^- \to \ell^- K_S^0$ using a combined dataset from Belle and Belle II of $1.41\,\mathrm{ab}^{-1}$
- Measured using **1x3-prong topology** with $\tau^- \to \ell^- \overline{\nu_\ell}/\pi^- \nu_\tau$ on the tag side
- Rectangular selections and BDT classifier
- Signal extraction in 2D plane: $M(\tau^- \to \ell^- K_S^0)$ **vs.** $\Delta E = E_\tau - E_{\mathrm{beam}}$

- **No significant signal observed** $\to$ Derived **most stringent 90% CL upper limits** on $\mathcal{B}(\tau^- \to \ell^- K_S^0)$

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



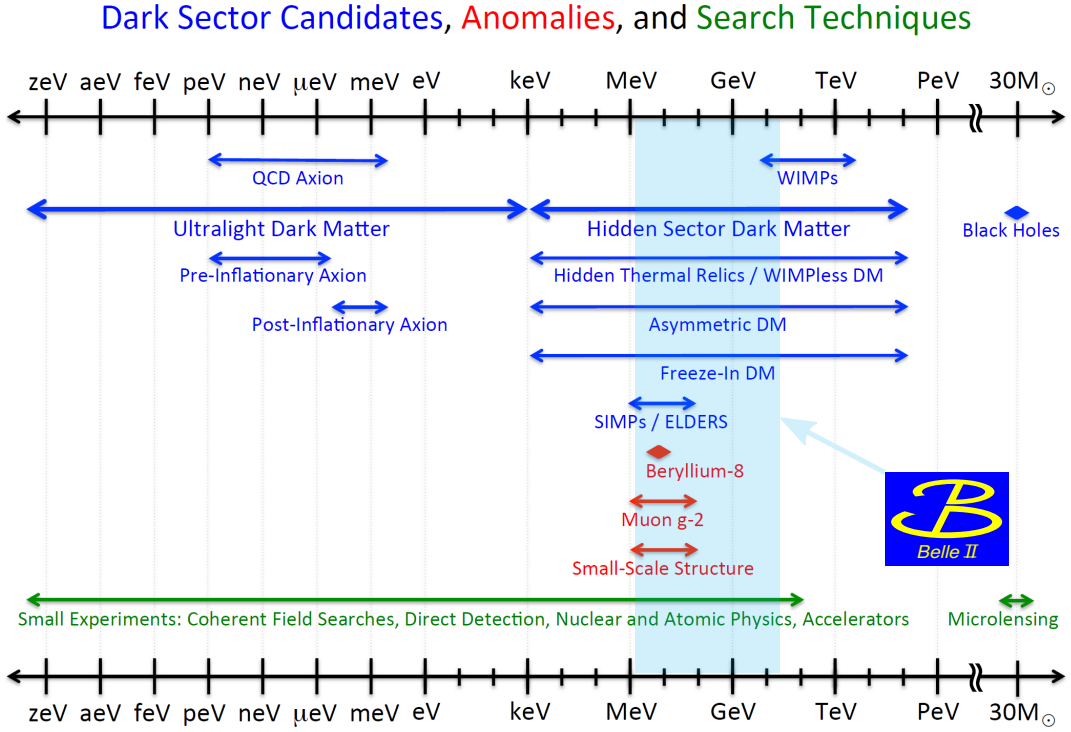




Dark Sector Physics

General Overview

- **Interactions of dark matter (DM) with the SM still a big mystery**
- Many potential DM candidates and portals between DM and SM are available:
  - **Vector portals: Dark photon A', Z', ...**
  - **Scalar portals: Dark Higgs, scalars, ...**
  - **Pseudoscalar portals: Axions, axion-like particles (ALPs), ...**
  - **Neutrino portal: Sterile neutrinos**
- **Belle (II) is an ideal playground** to investigate mediators in the **MeV – 10 GeV range**

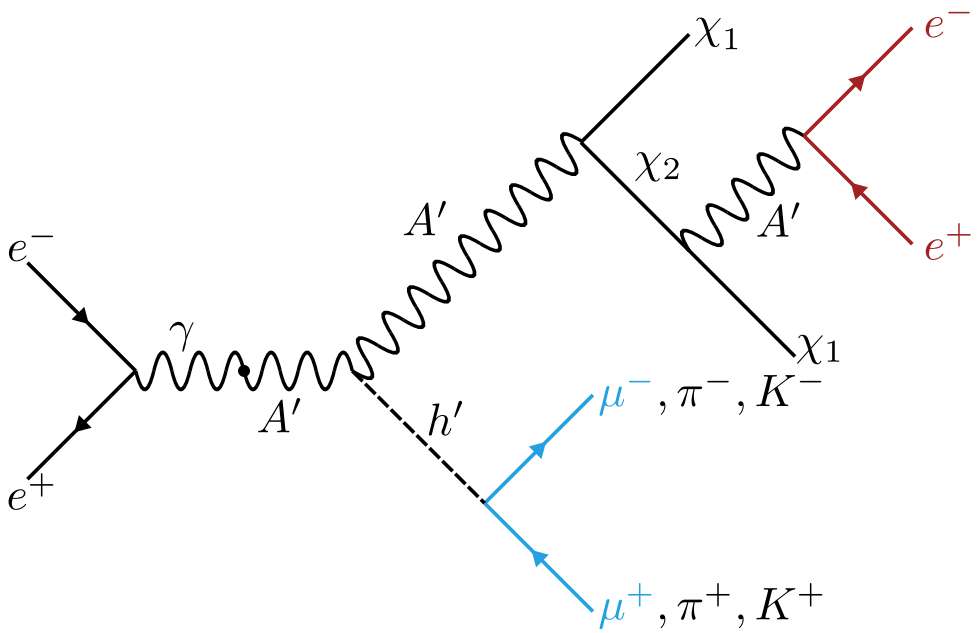


Strengths of Belle (II)

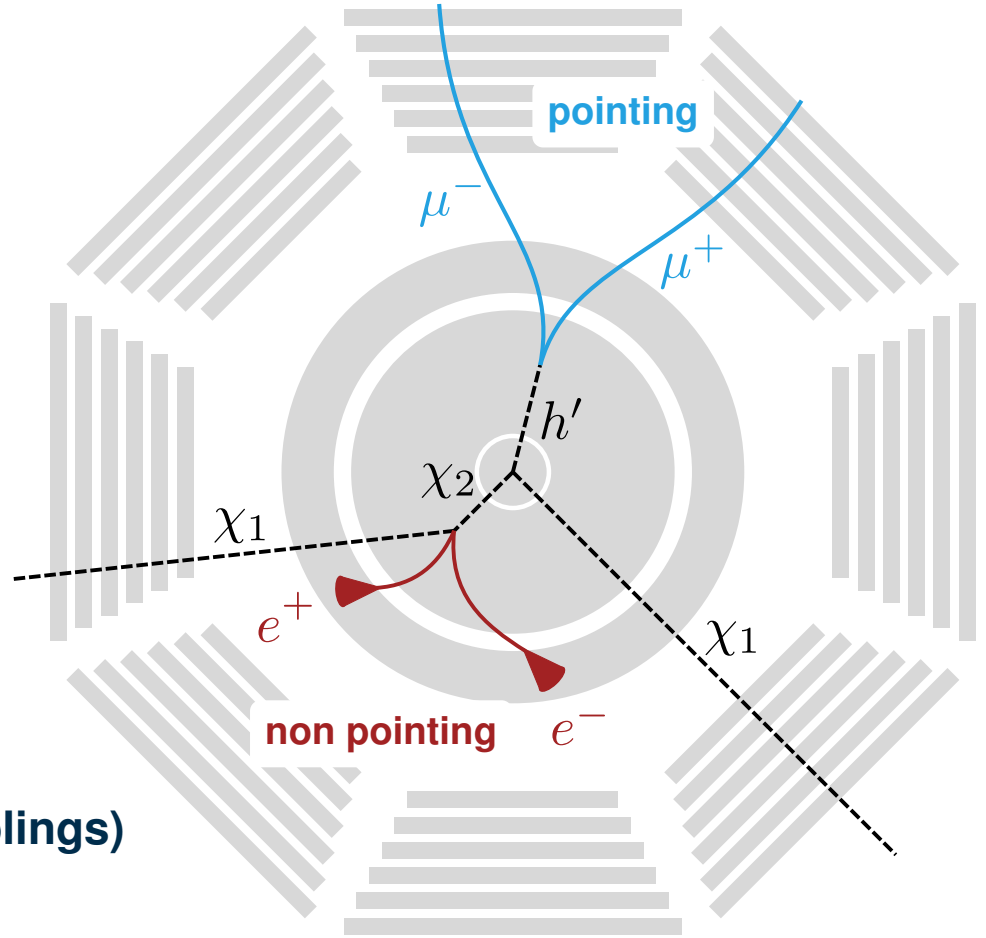
- **Missing energy** channels
- **Low multiplicity** signatures
- Searches for **long-lived particles**
- Signatures containing **invisible particles**

Dark Higgs + Inelastic Dark Matter @ Belle II

Overview



Signature based analysis!



- **Model can reproduce the relic DM density**
- 4 new dark sector particles: χ_1, χ_2, h', A'
- **7 free model parameters (3 masses, 2 mixings, 2 couplings)**
- **up to two displaced vertices + missing energy**
- Covering three final states: $x = \mu, \pi, K$

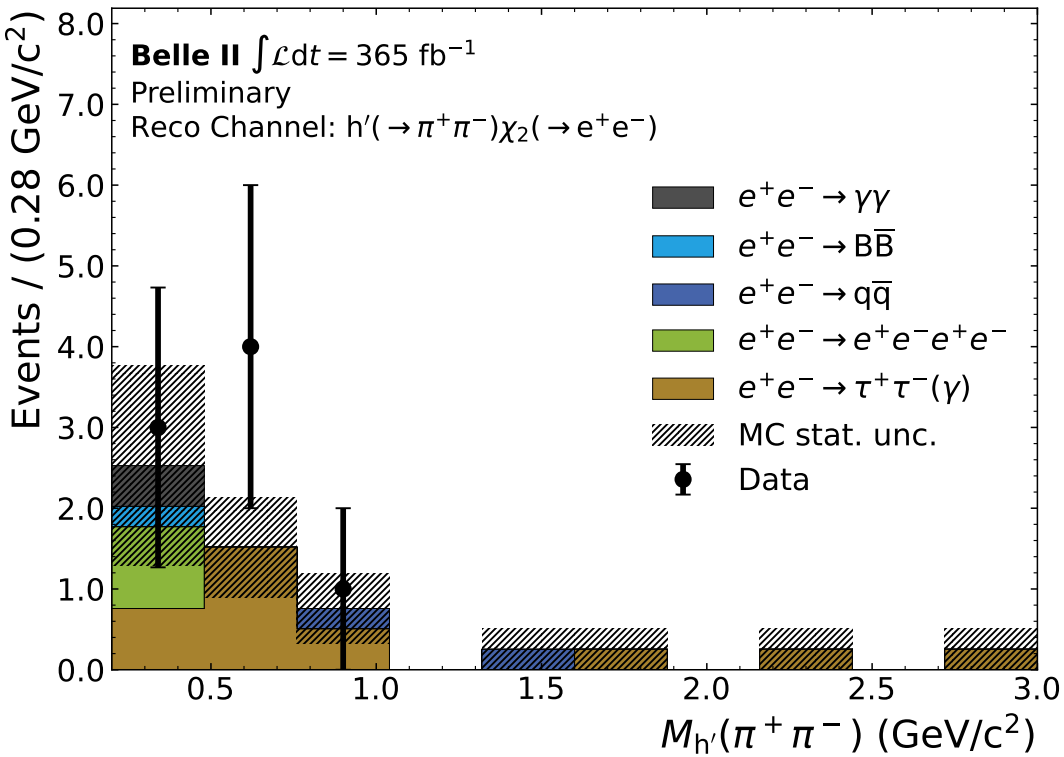
[Duerr, Ferber, Garcia-Cely, Hearty, Schmidt-Hoberg(JHEP 04 (2021), 2012.08595)]

Dark Higgs + Inelastic Dark Matter @ Belle II

Results

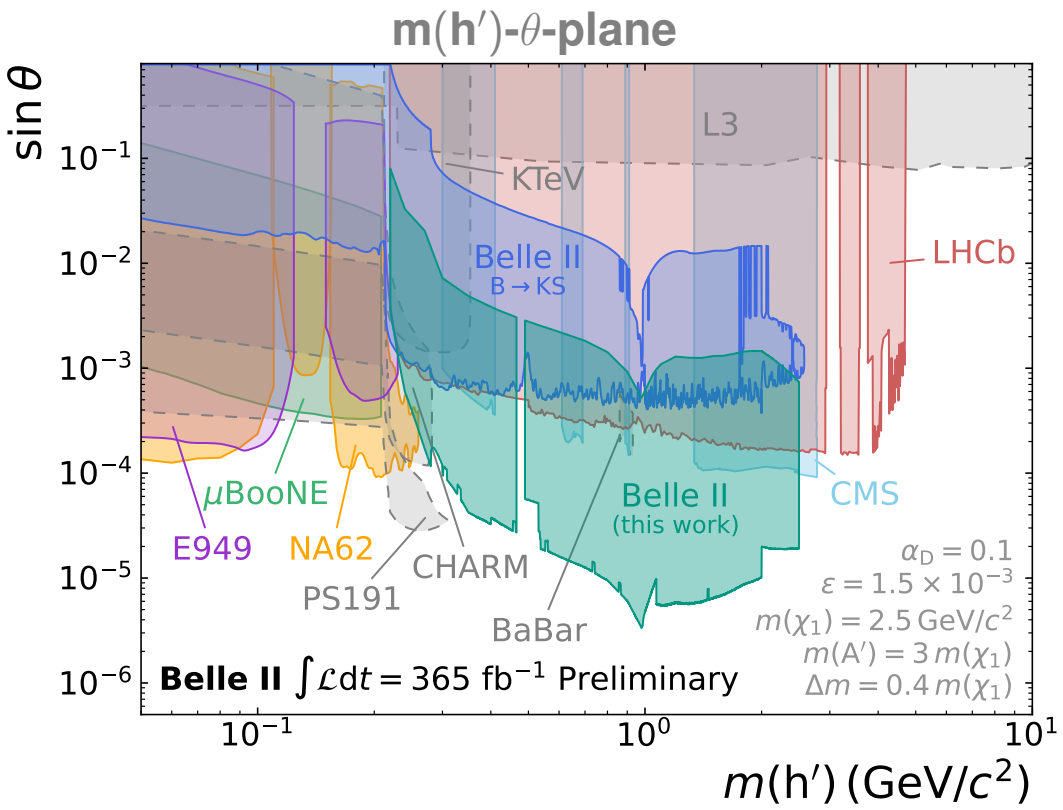
- Search performed using 365 fb^{-1} of Belle II data
- Challenging due to **displaced vertices** and the **trigger**
- Achieve a **nearly background free** scenario
- **Counting experiment** in $M_{h'}(x^+x^-)$ with background estimated from sidebands in data

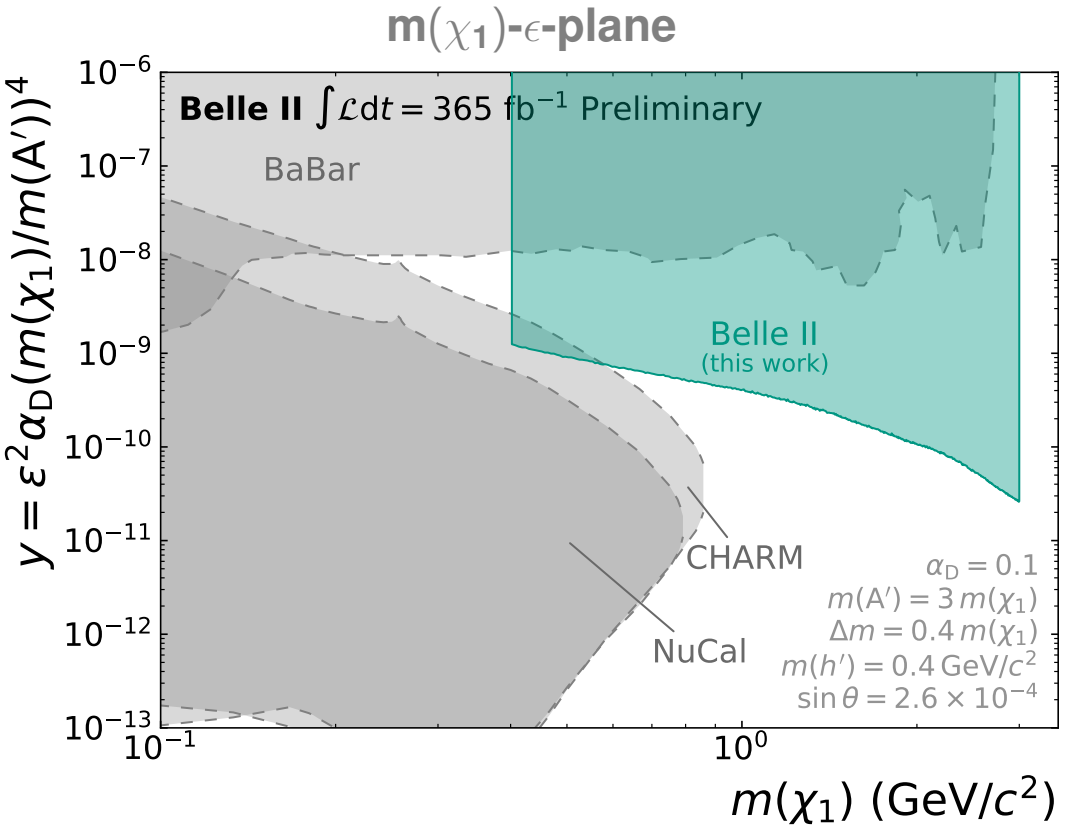
- **No significant excess observed** in the individual final states nor the combination
- Set upper limits on $\sigma(e^+e^- \to \chi_1\chi_2 h') \times \mathcal{B}(\chi_2 \to \chi_1 e^+e^-)\,[\times\mathcal{B}(h' \to x^+x^-)]$
- Analysis statistically limited



Dark Higgs + Inelastic Dark Matter @ Belle II

Upper limits + interpretations

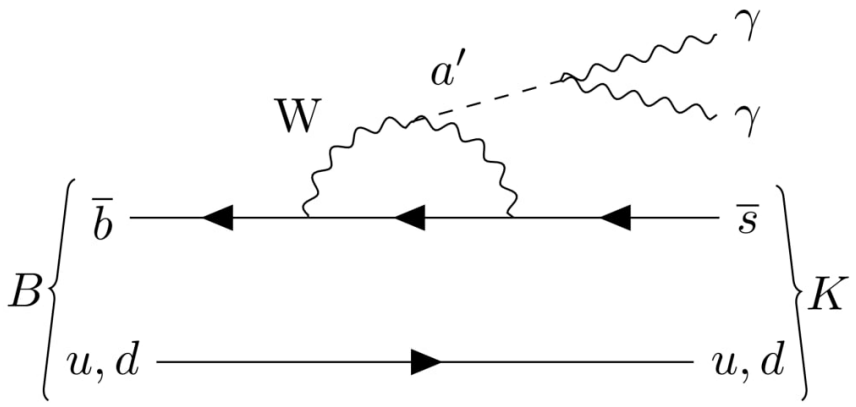




World leading limits, but dependent on the choice of the remaining parameters
→ **Provide interpretations for around 30 model parameter configurations**

$B \to K^{(*)} a'(\to \gamma\gamma)$ @ Belle

Overview



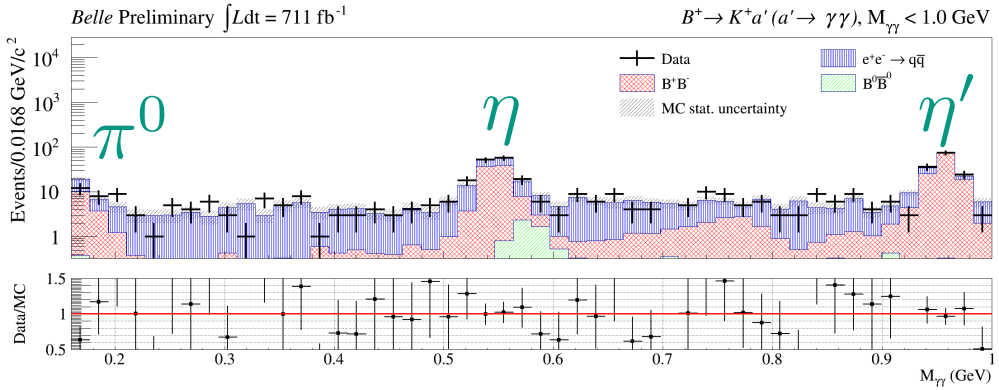
- **Search for ALPs in flavour changing neutral currents**
  $\to$ Heavily suppressed in the SM
- For $m(a') \ll m(W^{\pm})$ the final state $a' \to \gamma\gamma$ is the dominant contribution ($\sim 100\%$)
- Analysis based on the **full Belle** $\Upsilon(4S)$ **dataset** of $711\,\mathrm{fb}^{-1}$
- Cover the mass region from 0.16 to 4.50 $\mathrm{GeV/c^2}$ using **four kaon modes**: K_S^0, K^+, K^{*0}, and K^{*+}
- Search **includes long-lived ALPs**
- Dominant background arises from $e^+e^- \to q\bar{q} \Rightarrow$ Suppressed by two layers of BDTs using event shape variables
- Two additional layers of BDTs to suppress photons arising from π^0 and one additional BDT to suppress rare B decays

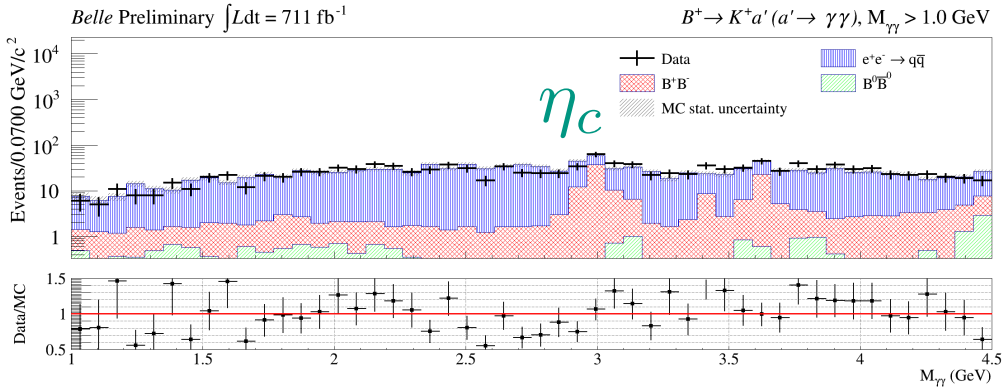
$B \to K^{(*)} a'(\to \gamma\gamma)$ @ Belle

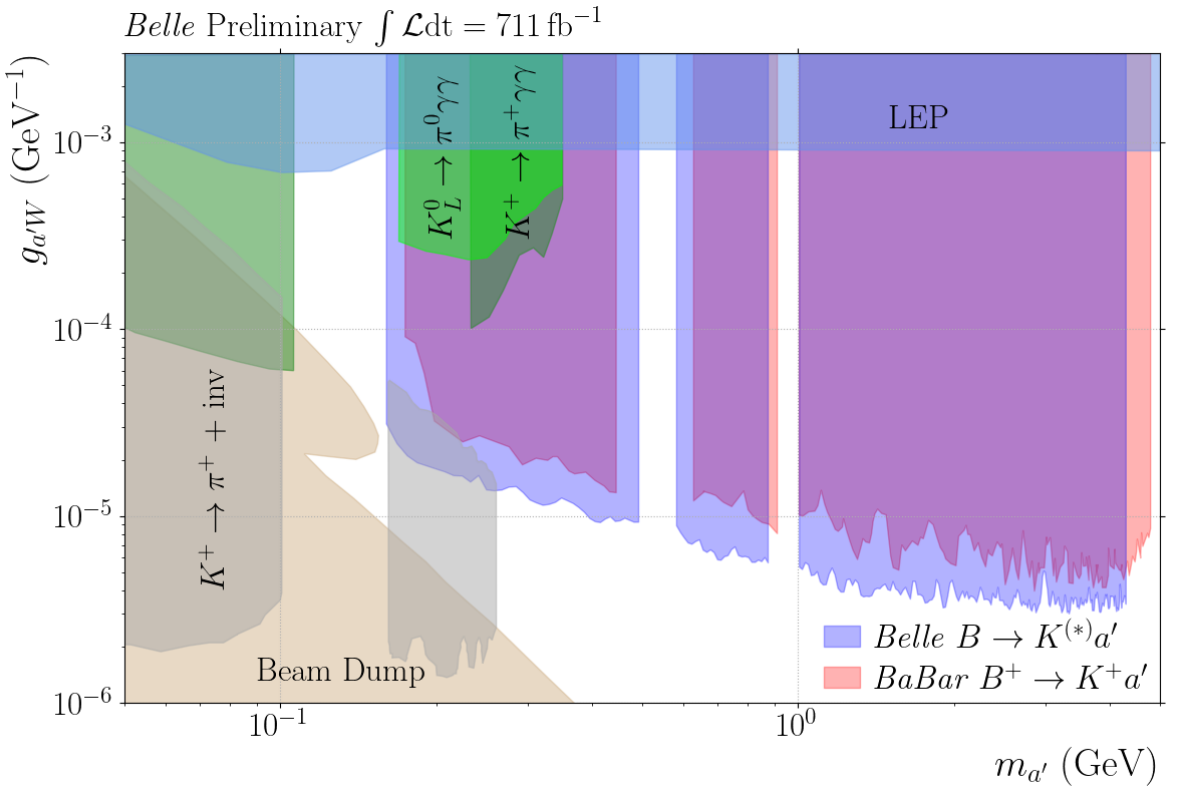
Results

- Extract signal with a **scan over M($\gamma\gamma$)**
- **Combined fit in all four modes**
- Veto peaking backgrounds

- **No significant excess observed → Set upper limits on the coupling $g_{a'W}$**
- **World leading upper limits!**



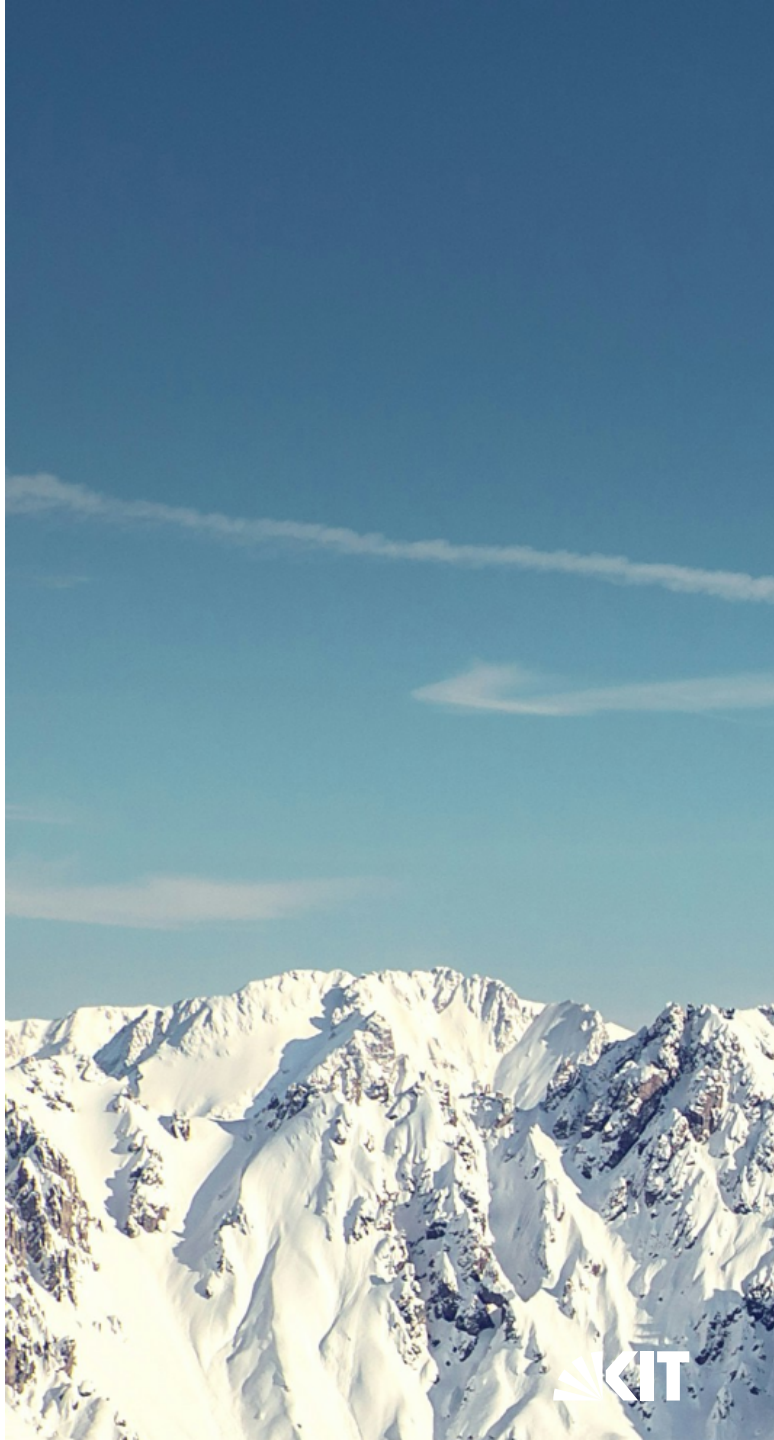




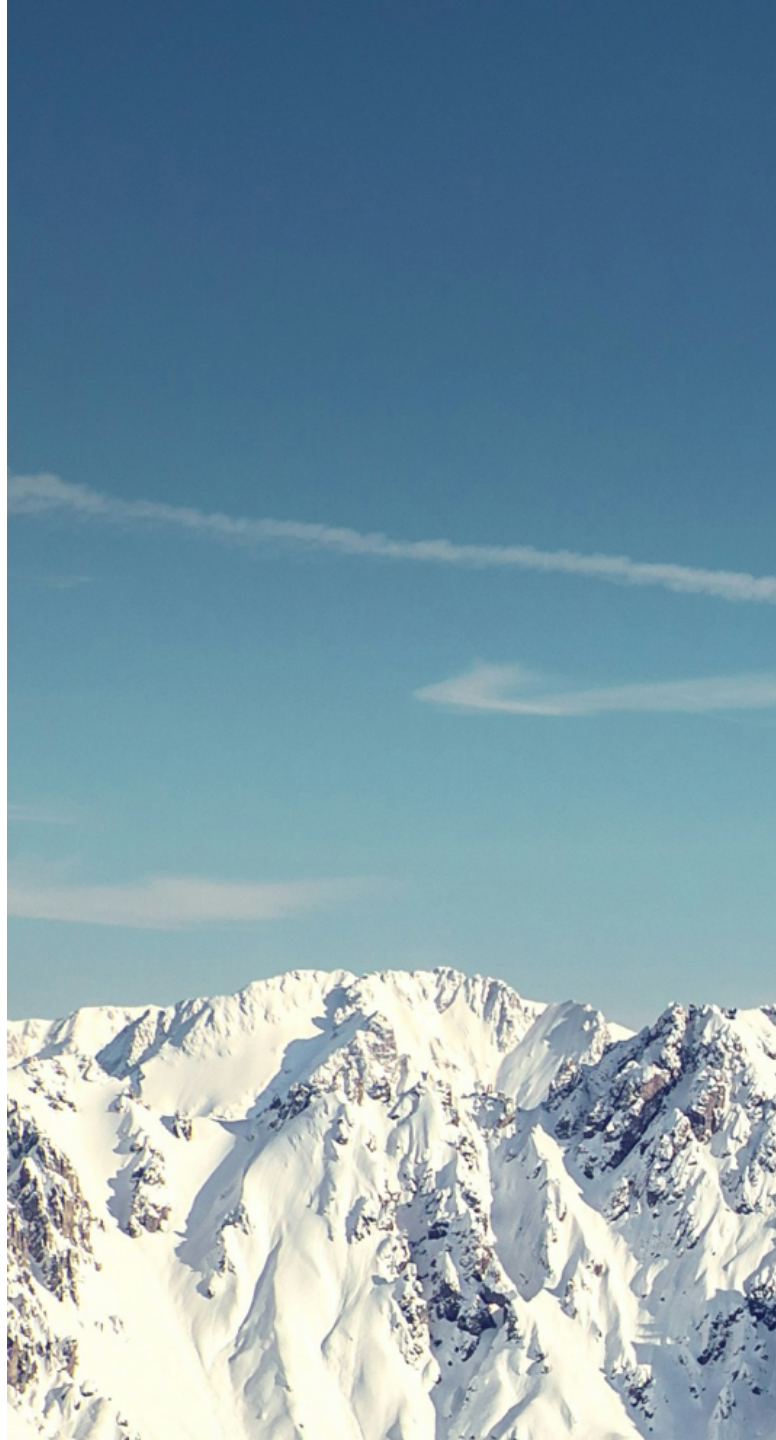
Conclusion

Belle & Belle II provide an excellent environment for studies in the τ and the dark sector

- New world leading results in LFU and LFV searches
- First search for dark Higgs bosons produced in association with inelastic dark matter
- World leading limits on ALP coupling $g_{a'W}$



Backup



Lepton Flavour Universality Measurement @ Belle II

JHEP08(2024)205

- Test the **coupling strength of the electron and muon to the** W using τ decays

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

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

- Measured using **1x1-prong topology** with $\tau^+ \to h^+ n\pi^0 \overline{\nu_\tau}$ on the tag side
- 94% purity and 9.6% efficiency obtained using rectangular selections and a neural network
- Dominant systematics from PID (0.32%) and trigger (0.10%)

- **Most precise determination** of R_μ and g_μ/g_e in τ decays from a single measurement
- **In agreement with the SM prediction** at the level of $1.4\,\sigma$