La Thuile 2025

Les Rencontres de Physique de la Vallée d'Aoste
March 12, 2025

Tau and dark sector physics at Belle and Belle II

Marcello Campajola

on behalf of the Belle and Belle II collaborations

Marcello Campajola
Università di Napoli ‘Federico II’ and INFN Napoli
marcello.campajola@na.infn.it

Belle and Belle II experiments

B-factory concept

Experiments at symmetric e^+e^- colliders running mostly at the Y(4S) energy (=10.58 GeV), located at Tsukuba (JP).

- **KEKB (1990-2010)**
- **Super KEKB: major upgrade of KEKB (2019-ongoing)**
  - Target word highest instantaneous luminosity:
    - $6x10^{35}$ $cm^{-2}s^{-1}$ (x30 KEKB)
    - So far, world instantaneous luminosity of $5.1x10^{34} cm^{-2}s^{-1}$

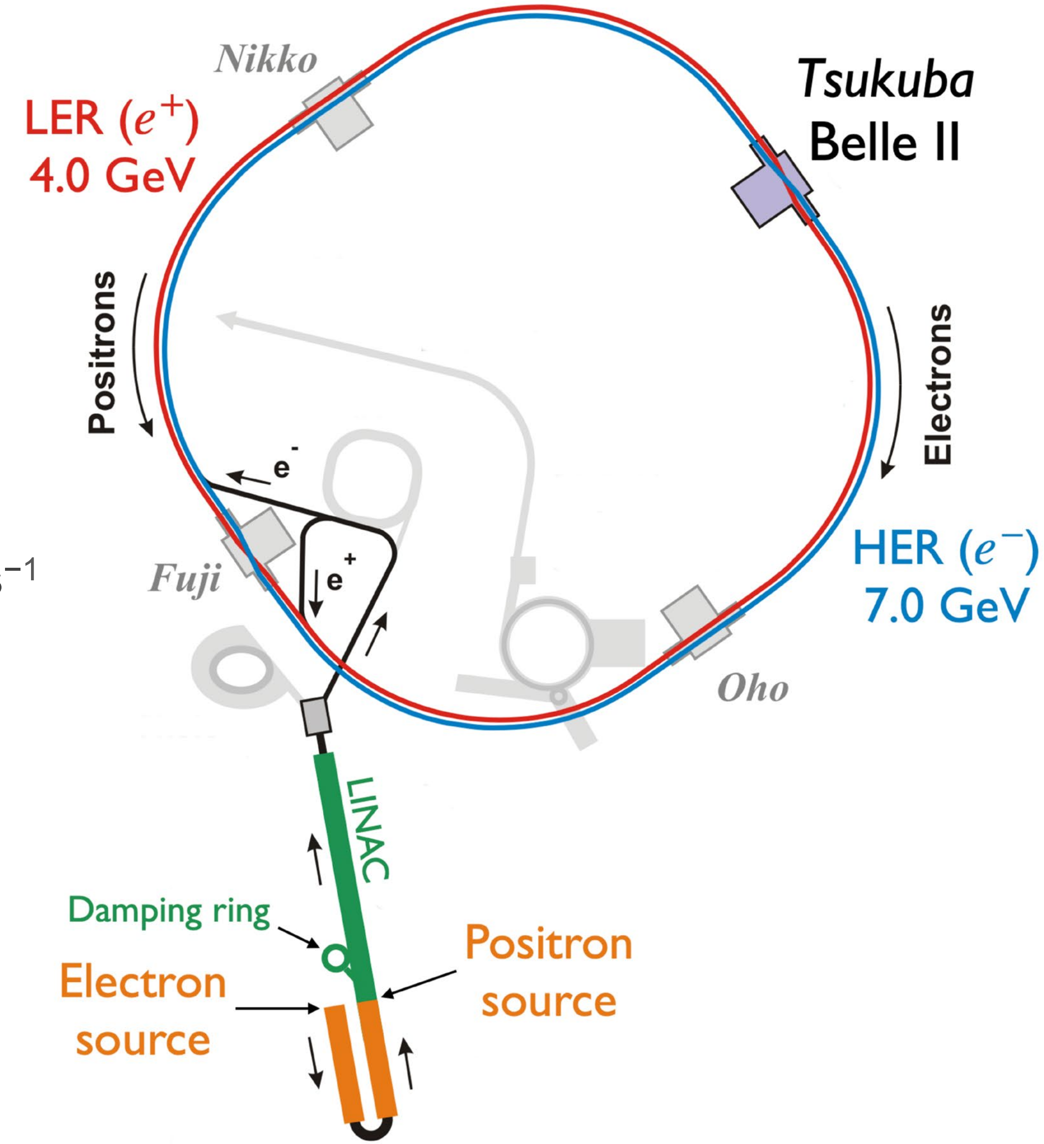
✓ **Available datasets: 1 ab^{-1} @Belle, 0.6 ab^{-1} @Belle II**

✓ **Rich physics program:**

- **beauty, charm, τ and dark sector**

see
M. Veronesi talk

covered in this talk



Belle and Belle II experiments

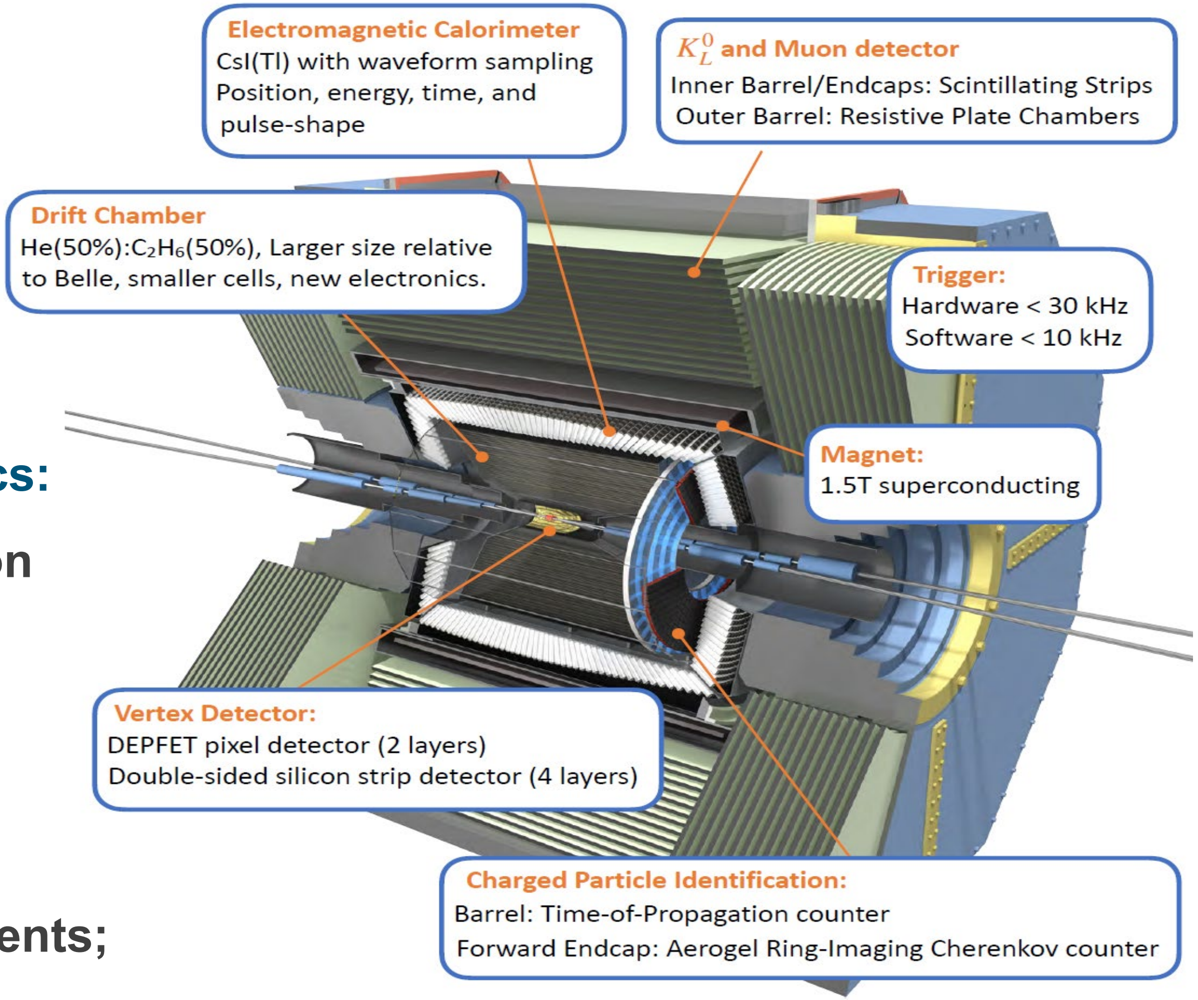
Detector overview

General purpose detectors

- Belle II is the major upgrade of Belle detector.
  - Better resolution, particle identification and capability to cope with higher background;

✓ **Excellent capabilities for tau and dark sector physics:**

- **Good missing energy and neutral reconstruction**
  - Well defined initial state;
  - Hermetic detector coverage (almost 4π);
  - Clean environment
- **Good particle identification**;
- **Excellent vertexing and tracking**;
- Special **triggers dedicated to low-multiplicity events;**



Prog. Theo. Exp. Phys. 12 (2019)

Tau searches

Tau physics at Belle and Belle II

Overview

B-factories are also τ factories

- τ pairs cross-section equivalent to BB procces

$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.92\, nb$$
$$\sigma(e^+e^- \to B\bar{B}) = 1.05\, nb$$

Testbed for:

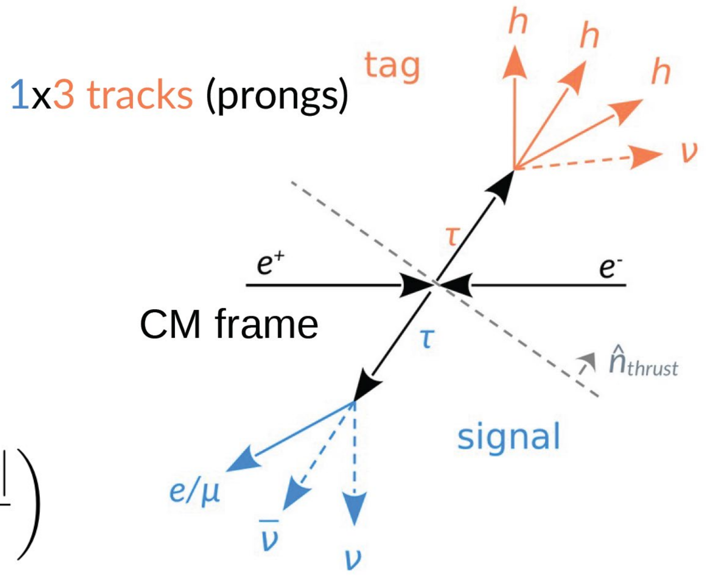
✓ **precision SM measurements**
- τ lifetime, mass, coupling (universality)

✓ **searches for rare or forbidden processes**
- Mostly lepton flavor violating τ decays

Produced in pairs: $e^+e^- \to \tau^+\tau^-$

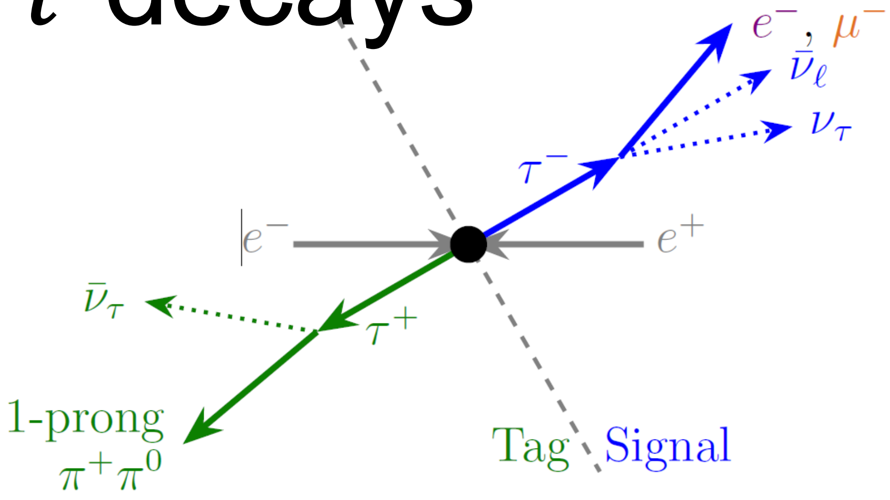
- **Back to back and boosted in the center-of-mass frame**
- Identify events by reconstructing the thrust axis n_T (maximizes thrust T)
- Separate them in two opposite hemispheres
- Typically use one side to tag the event by reconstructing decays with 1 charged track (1-prong) or 3 charged tracks (3-prong)
  - Reconstruct signal on other hemisphere

$$T = \max_{\hat{n}_T}\left(\frac{\sum_i |p_i \cdot \hat{n}_T|}{\sum_i |p_i|}\right)$$



Lepton Flavor Universality in τ decays

Overview



Test of ***μ*-e universality** in the τ decays

$$R_\mu = \frac{B(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{B(\tau^- \to e^-\bar{\nu}_e\nu_\tau)} \overset{\text{SM}}{=} 0.9726 \qquad \left(\frac{g_\mu}{g_e}\right)^2_\tau \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \overset{\text{SM}}{=} 1$$

R_μ measured in **1x1 prong topology** with $\pi^- + n\pi^0$ tag by Belle II with 365 fb^{-1}

Rectangular cuts and a neural network selection

- **94% purity with 9.6% signal efficiency**

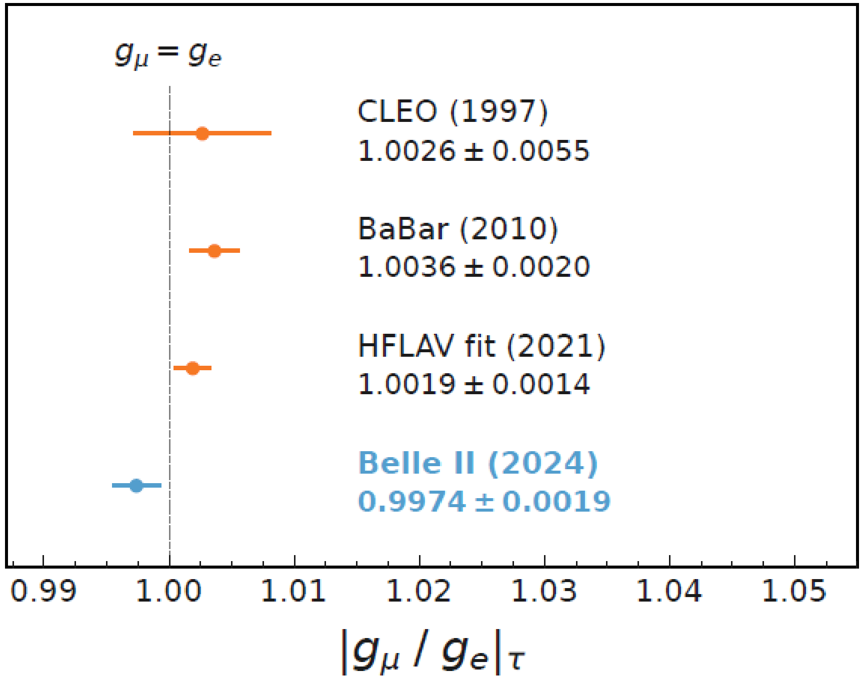
Main systematics are from PID (0.32%) and trigger (0.1%)

***R_μ* = 0.9675 ± 0.0007 (stat.) ± 0.0036 (sys.)**

✓ **Most precise test of *e*-*μ* universality in *τ* decays from a single measurement**

✓ Consistent with SM expectation at the level of 1.4σ

JHEP08(2024)205



Lepton Flavor Violation searches

Motivations

Lepton Flavor Violation (LVF) is negligibly small in SM

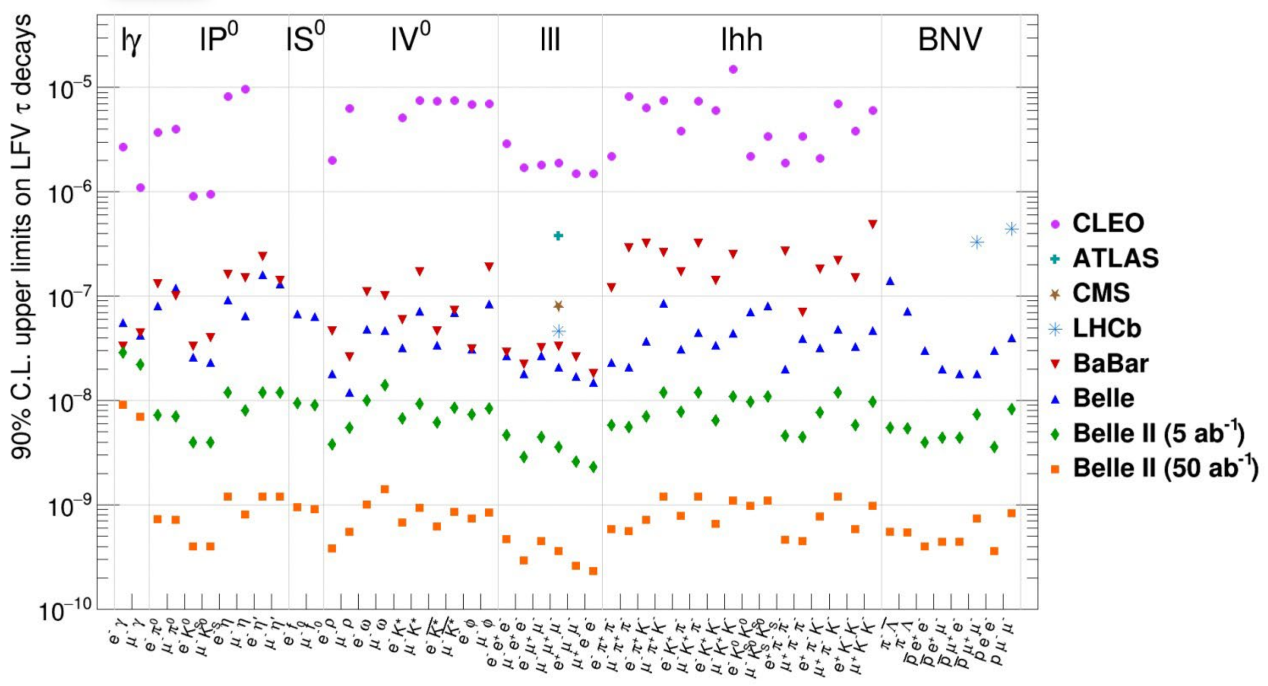
- Only allowed by neutrino oscillations $O(10^{-55})$

Various new-physics models predict branching fractions in the range 10^{-7} – 10^{-10}

- Observation of LFV decays would be a clear signature of New Physics

[arXiv.2203.14919]

Existing and expected limits on LFV $\tau\tau$ decays

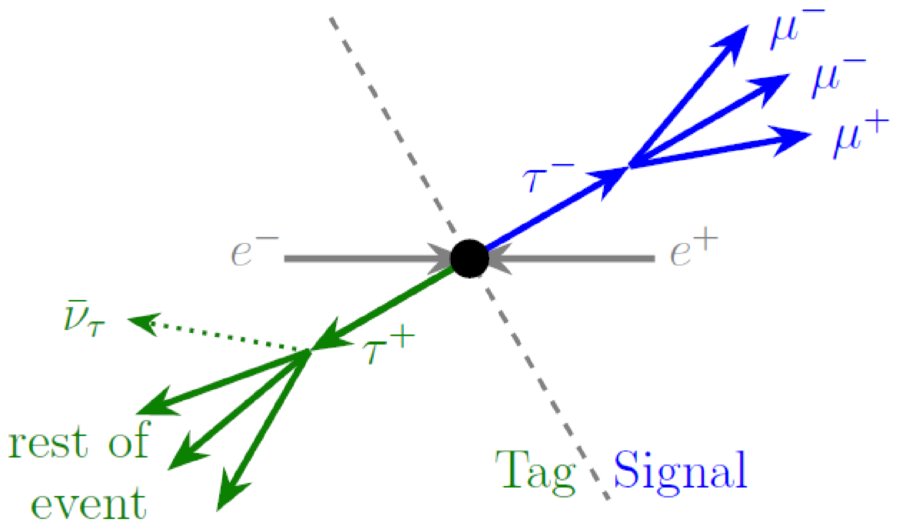


projections

Neutrinoless 2-body or 3-body decays to **52 final states.**

$\tau \rightarrow 3\mu$

Results



Belle II search for the clean channel: $\tau \rightarrow 3\mu$

- Good reconstruction of τ mass end energy
- Low SM background

Already probed by Belle and LHC experiments

Use untagged reconstruction

Require 3 tracks identified as muons (signal side) and use BDT classifier exploiting kinematic variables to reject the main $e^+e^- \rightarrow qq$ backgrounds

- x3 efficiency compared to Belle

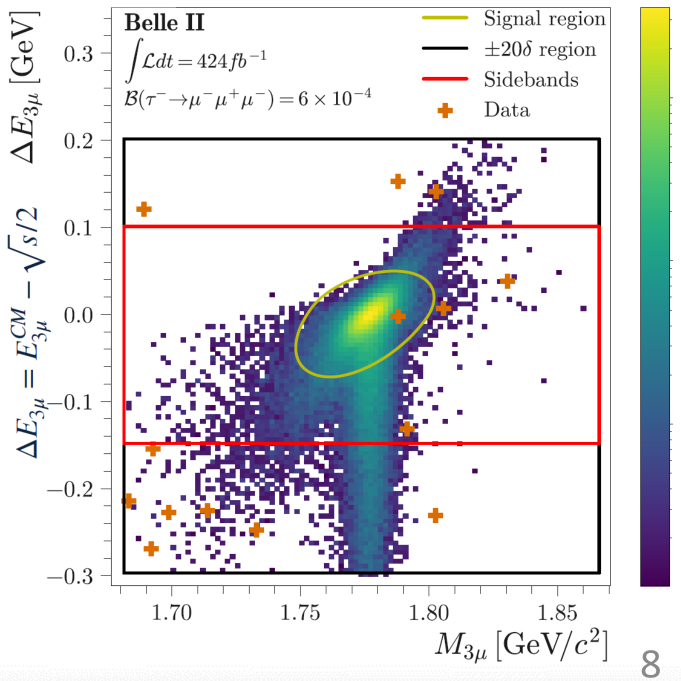
Extract signal yield from 2D plane (M_{3u}, $\Delta E_{3\mu} = E_\tau - E_{beam}$)

- 1 event in the signal region in 424 fb^{-1} consistent with data-driven background prediction (0.5 events)

Set 90% CL upper limits on the BF

✓ **New most stringent results**

[JHEP09(2024)062]



Most stringent limit to date

	UL at 90% C.L. on $\mathcal{B}(\tau \rightarrow 3\mu)$
ATLAS	3.8×10^{-7} ($\mathcal{L}$ = 20.3 fb^{-1})
LHCb	4.6×10^{-8} ($\mathcal{L}$ = 3.0 fb^{-1})
CMS	2.9×10^{-8} ($\mathcal{L}$ = 131 fb^{-1})
Belle	2.1×10^{-8} ($\mathcal{L}$ = 782 fb^{-1})
BaBar	3.3×10^{-8} ($\mathcal{L}$ = 486 fb^{-1})
Belle II	1.9×10^{-8} ($\mathcal{L}$ = 424 fb^{-1})

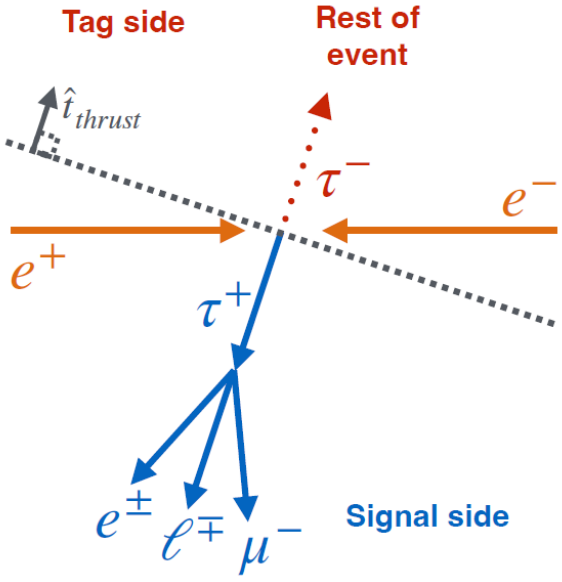
$\tau \to e2\ell$

new result

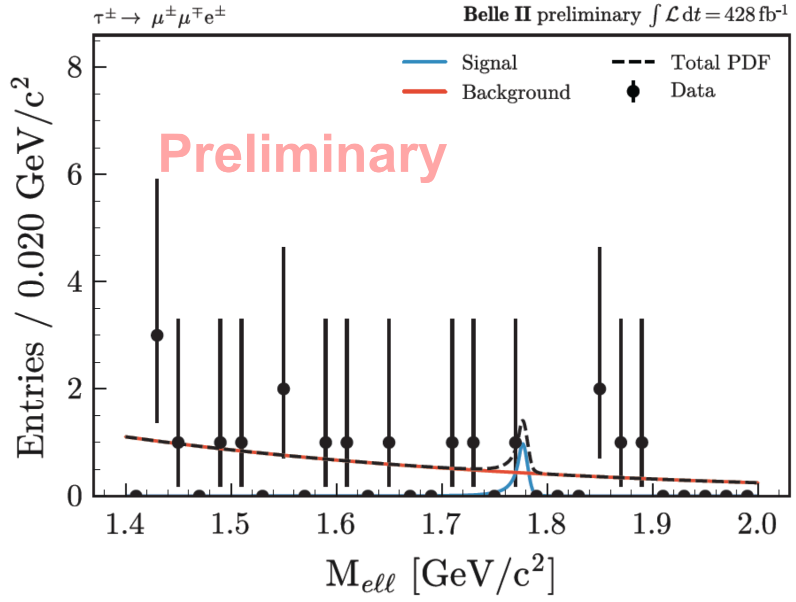
Results

Extend previous study to 5 more modes: with at least one electron in the final state

- ○ $e^-e^+e^-$, $e^-e^+\mu^-$, $e^-\mu^+e^-$, $\mu^-\mu^+e^-$, $\mu^-e^+\mu^-$
  - ➢ **Higher background contamination**



Use **untagged reconstruction**



Data driven BDT classifier trained on sideband in data

- Rely on rest of event and kinematic variables
- Reject the main four leptons backgrounds

Signal extracted by fitting M_{ell}

No significant excess was observed in 424 fb^{-1}

- **Set 90% CL upper limit on the branching fraction**

✓ **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

Preliminary

$\tau^- \to \ell^- K_S^0$ new result

Results

Belle + Belle II search for $\tau^- \to \ell^- K_S^0$ (ℓ=e, μ)

Reconstruct 4 charged particles (0 net charge) in **1x3 topology**

- K_S^0 reconstructed from $\pi^+\pi^-$

Preselection rectangular cuts and BDT classifier

- Use track kinematics, event shape and neutral variables
- Resulting efficiency: 10%

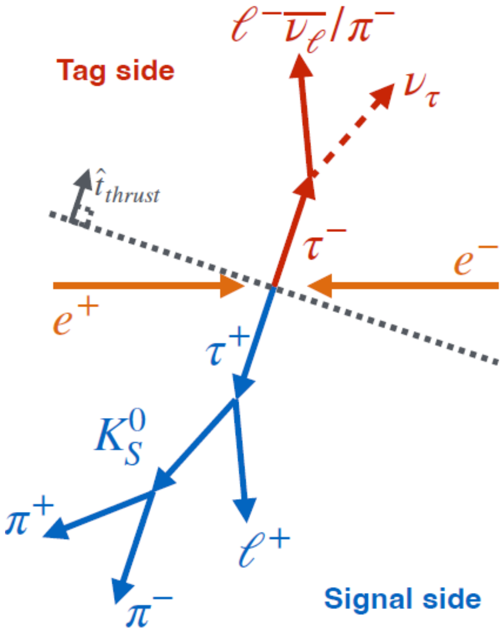
Extract signal yield from 2D plane $(\mathrm{M}_\tau,\ \Delta E = \mathrm{E}_\tau - \mathrm{E}_{\mathrm{beam}})$

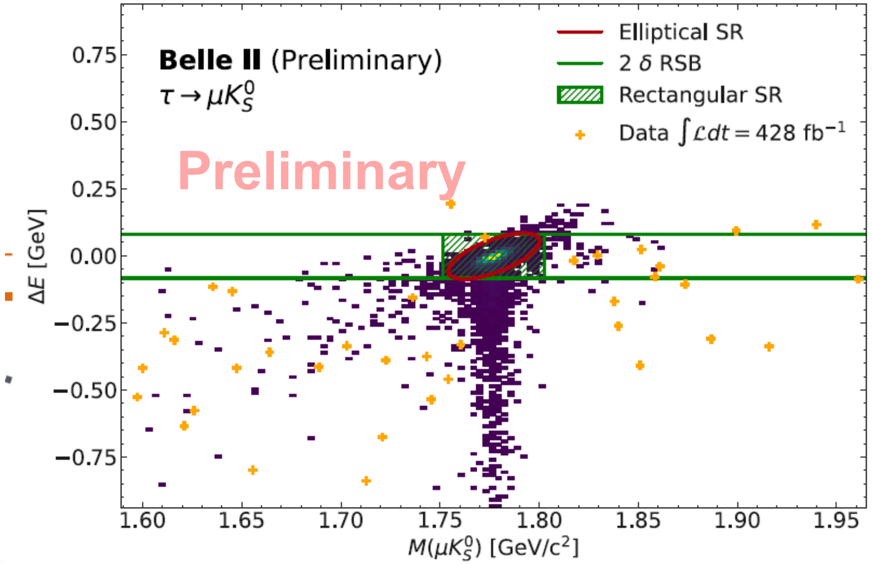
No significant signal was observed in 424 fb^{-1} + 980 fb^{-1} (Belle + Belle II)

Set a combined 90% CL upper limit on the BR

$$B(\tau \to K_S^0 e) < 0.8\times10^{-8}$$
$$B(\tau \to K_S^0 \mu) < 1.2\times10^{-8}$$

✓ **World most stringent upper limit on all modes**





dark sector searches

Dark sector at Belle (II)

Motivations

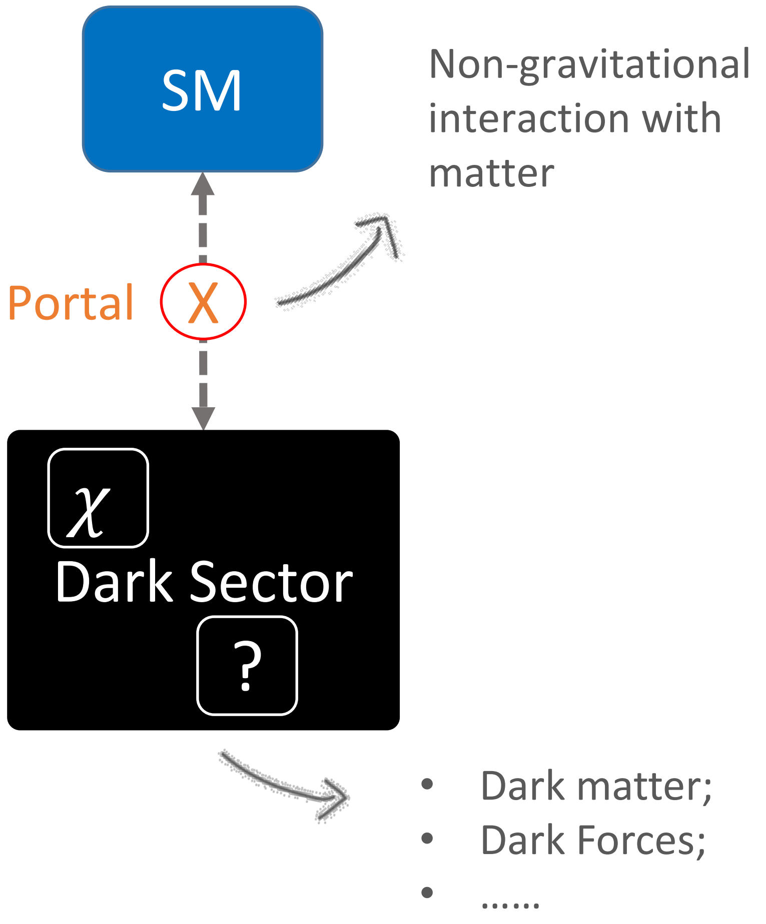
The particle nature of dark matter is still a compelling question

- No evidence of DM at electro-weak scale in experiments motivates a considerable focus on **“dark sector” models** [1]:
  - Light dark matter particles;
  - New dark force carriers with feeble interactions with the SM (portals).

B-factories can access the mass range favored by light dark sectors

Able to explore on-shell mediators in the MeV – 10 GeV range in

- **visible** and **invisible decays**
- **displaced decay topologies**: up to o(1) m decay-lengths



[1] Essig et al., arXiv:1311.0029 (2013)

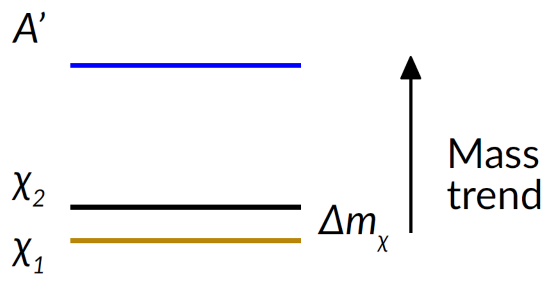
Inelastic dark matter with a dark Higgs

Overview

Non minimal dark sector with a dark photon A’, a dark higgs h’ and two **dark matter states with a small mass splitting [1]:**

- χ_1 is stable (relic DM candidate)
- χ_2 is long-lived;

Can explain the lack of a signal in direct detection.

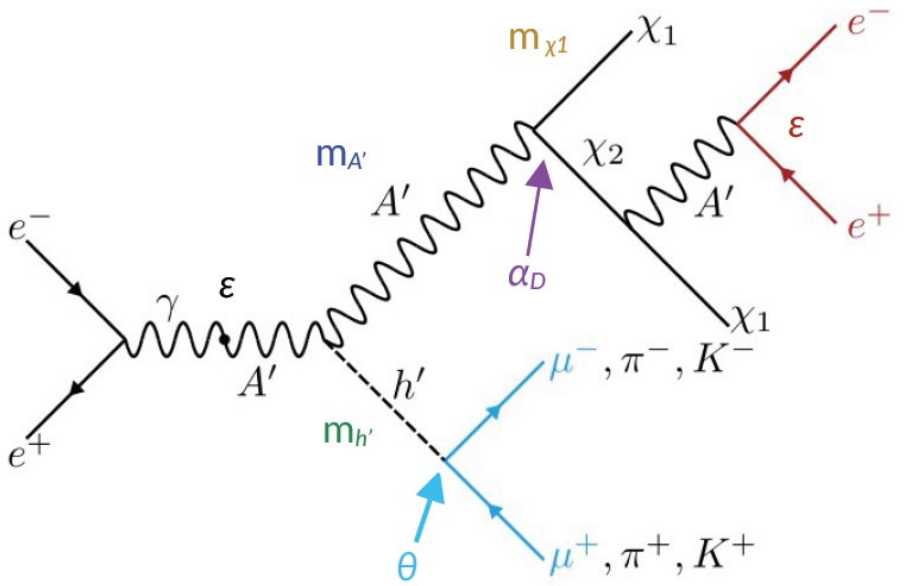


[1] PRD 64, 043502 (2001)

Here looking for A’ and h’ simultaneous production:

$e^+e^- \rightarrow h'(\rightarrow x^+x^-)A'(\rightarrow \chi_1\chi_2(\rightarrow \chi_1 e^+e^-)$, $x = \mu, \pi, K$

- *h’* mixes with SM Higgs with strength θ
- A’ mixes with SM photon with strength ϵ
- focus on $m_{A'} > m_{\chi_1} + m_{\chi_2}$
    - the decay $A' \rightarrow \chi_1\,\chi_2$ is favored



Dataset: 365 fb^{-1} from Belle II

4 dark sector particles: $A', h', \chi_1\, \chi_2$
7 parameters: $m_{A'}, m_{h'}, m_{\chi_1}, m_{\chi_2}, \theta, \epsilon, \alpha_D$

Inelastic dark matter with a dark Higgs

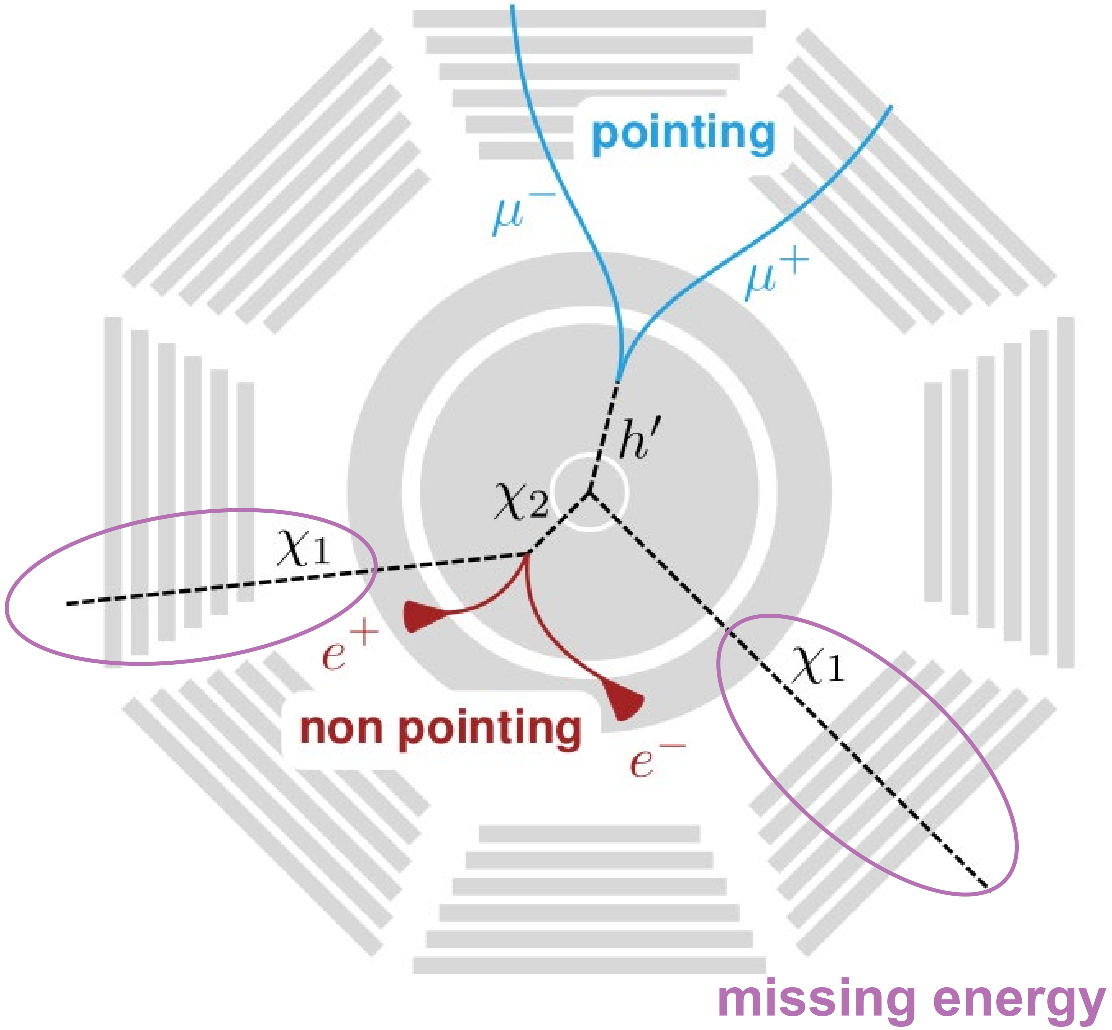
Strategy

Challenging analysis for tracking (and trigger)

- χ_2 is long lived (small mass splitting considered)
- *h'* long lived for small mixing angle θ

Require four tracks in the final state:

- 2 forming a **pointing displaced vertex**
- 2 forming a **non-pointing displaced vertex**
- **Missing energy** $(\chi_1\ \chi_2)$
  - **3 channel explored:** ***h'*(→ *x*⁺*x*⁻), *x* = *μ*, *π*, *K***



Inelastic dark matter with a dark Higgs

Results

Signal selection using ponting angles and vertex distance from the interaction point

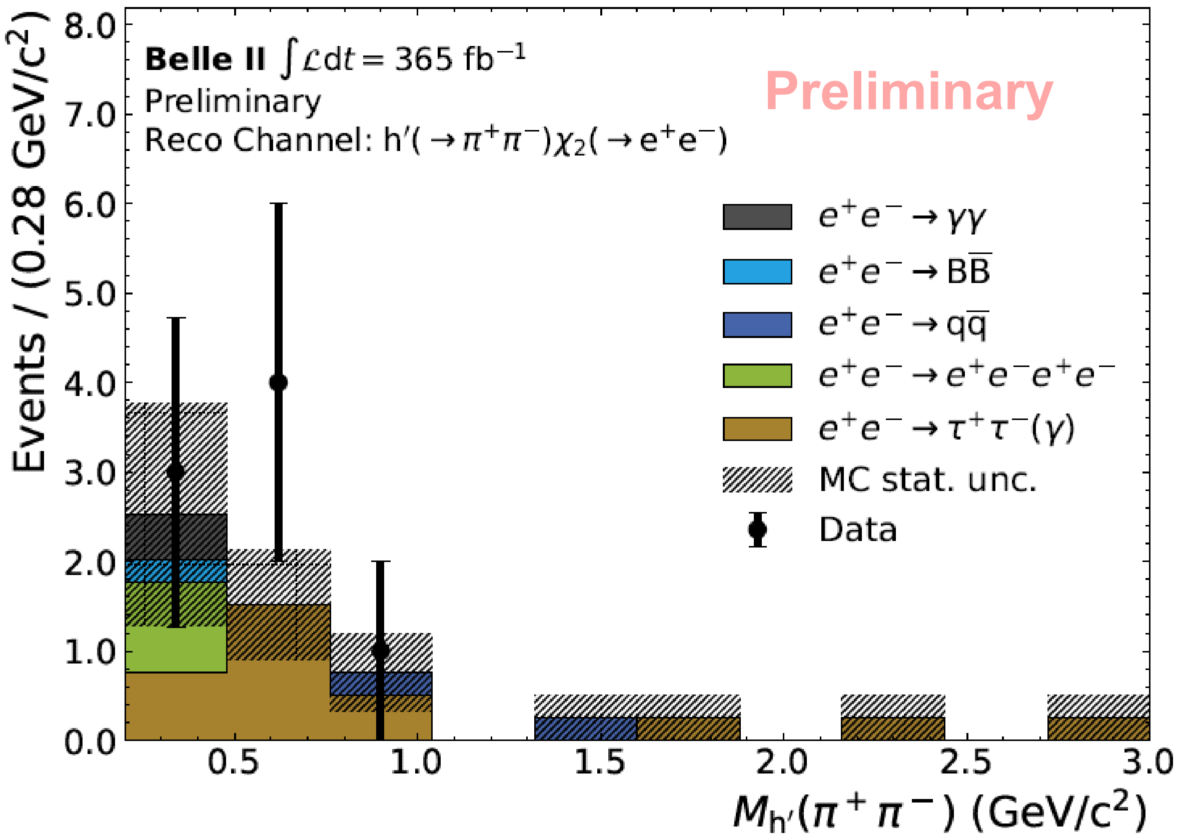
- **very low SM background**

Expected background estimated in data from sidebands to not rely on MC

Counting strategy to extract signal yields

No significant excess found in the individual final states or the combination:

- 9 events observed (8 of 9 are $\pi^+\pi^-$) consistent with expected background.

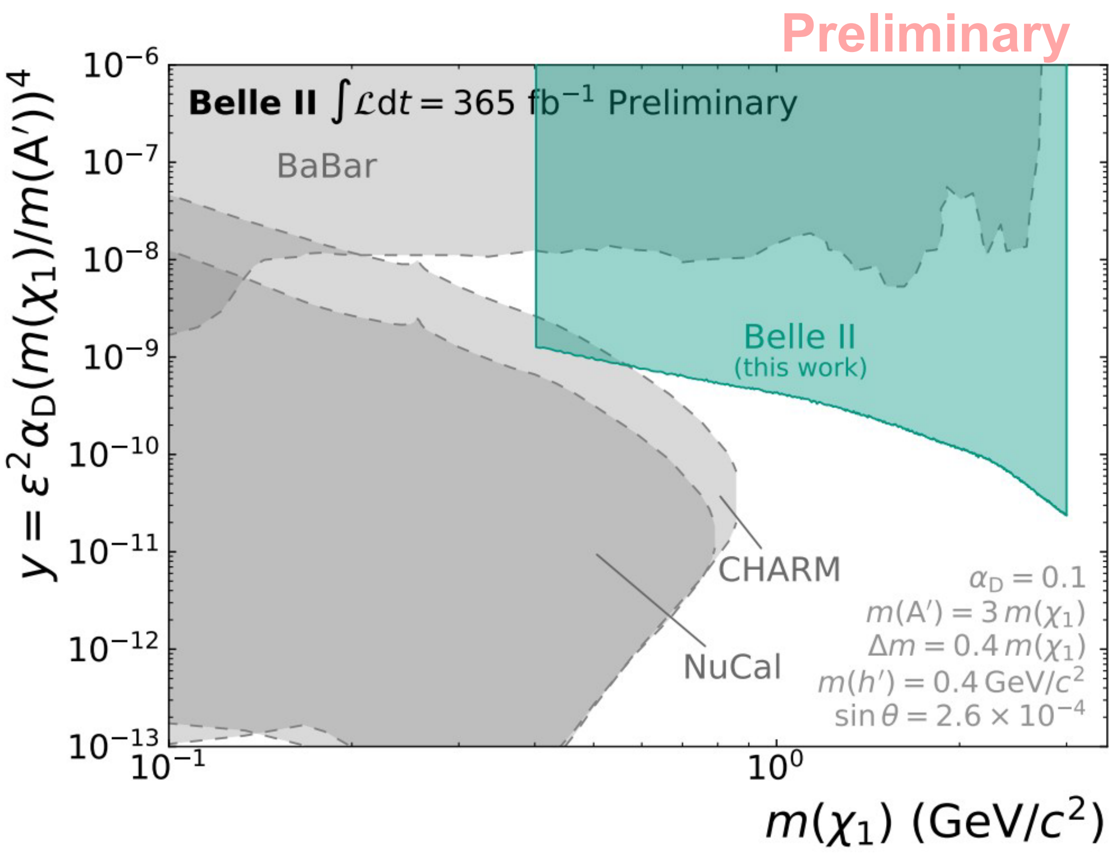


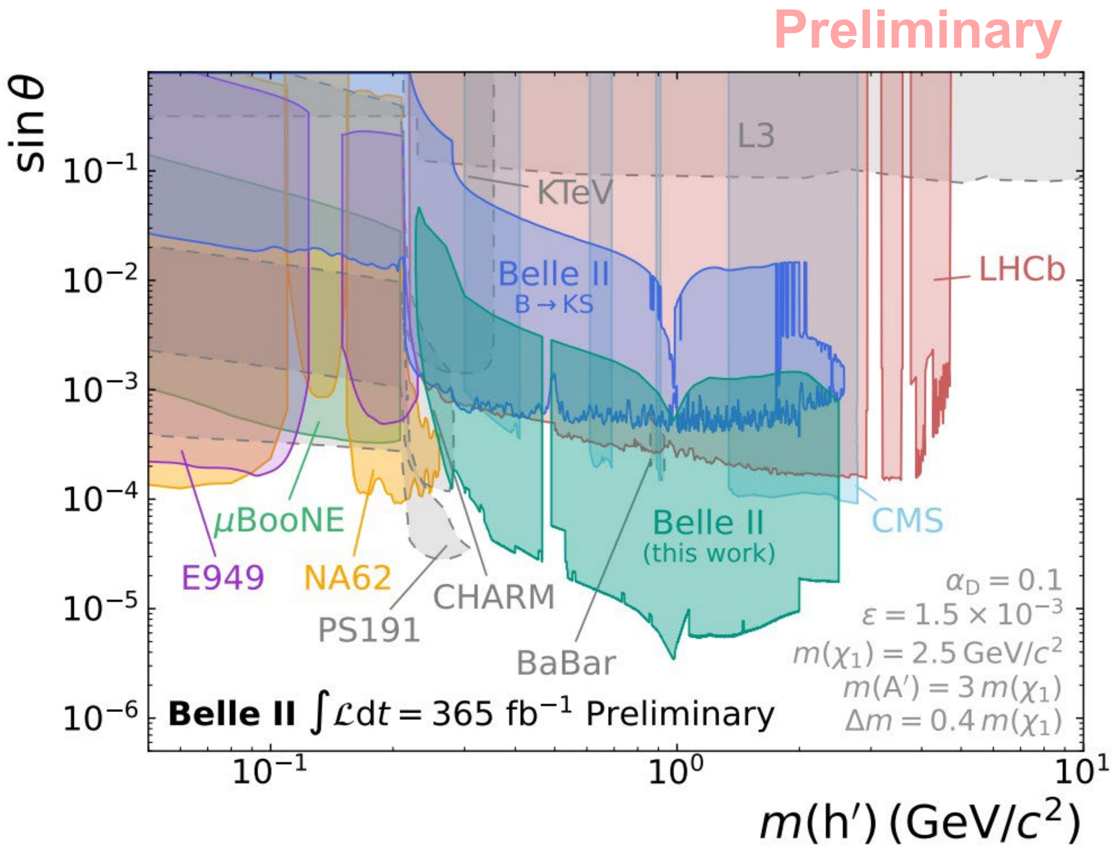
Inelastic dark matter with a dark Higgs

Results

✓ **Strong limits on θ and $\epsilon \times \alpha_D$, but dependence on 5 other parameters.**

- Many more (~30) plots for different parameter configurations





$B \rightarrow K^{(*)} a(\rightarrow \gamma\gamma)$ new result

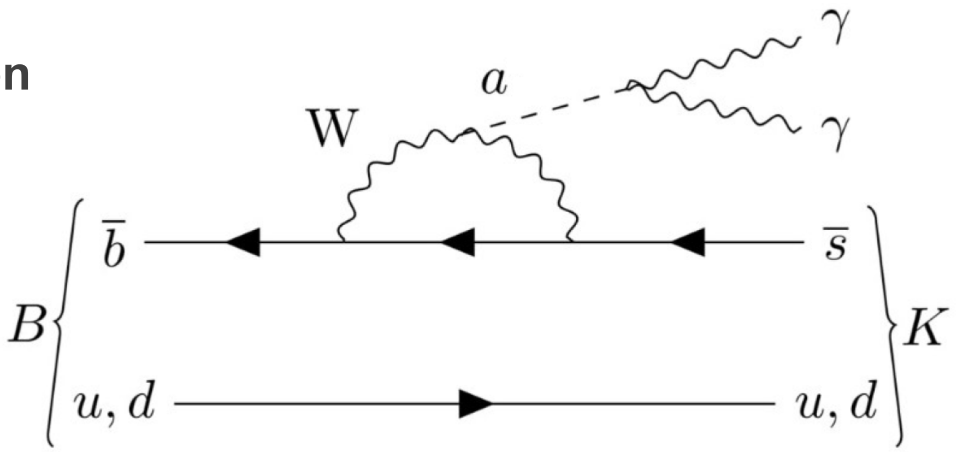
Overview

Flavor changing neutral current B decays are perfect testbed to search for new physics

- Extremely suppressed in SM
- New physics could appear at the same order of the SM processes

Here searching for an Axion-Like particle emission by $W^{\pm}$ boson in $B \rightarrow K(*)$ a decays

- $BR(a \rightarrow \gamma\gamma) \simeq 100\%$ for $m_a \ll m_{W^\pm}$
- Mass region investigated 0.16 – 4.50 (4.20) GeV/c^2



Existing constraints from BaBar (424 fb^{-1})

This analysis:

- **full Belle dataset (711 fb^{-1})**
- **exploiting multiple kaon modes: K^0_S , K^+, K^{*0}, and K^{*+}**

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

Overview

Signal B reconstructed combining a pair of photons with a track identified as a kaon

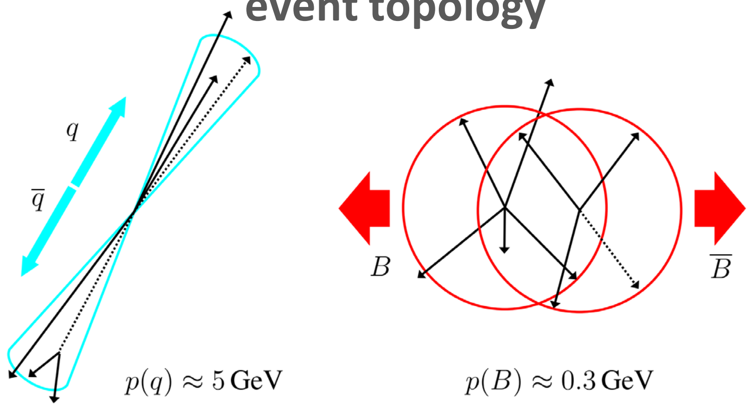
Main background from continuum, while *BB* subdominant. Smooth backgrounds, but near SM pseudoscalars masses.

- **Rejected using few BDTs exploiting:**
  - Differences from B nominal kinematics and event-topology variables to separate signal from the continuum
  - Calorimeter cluster variables to suppress π^0 backgrounds

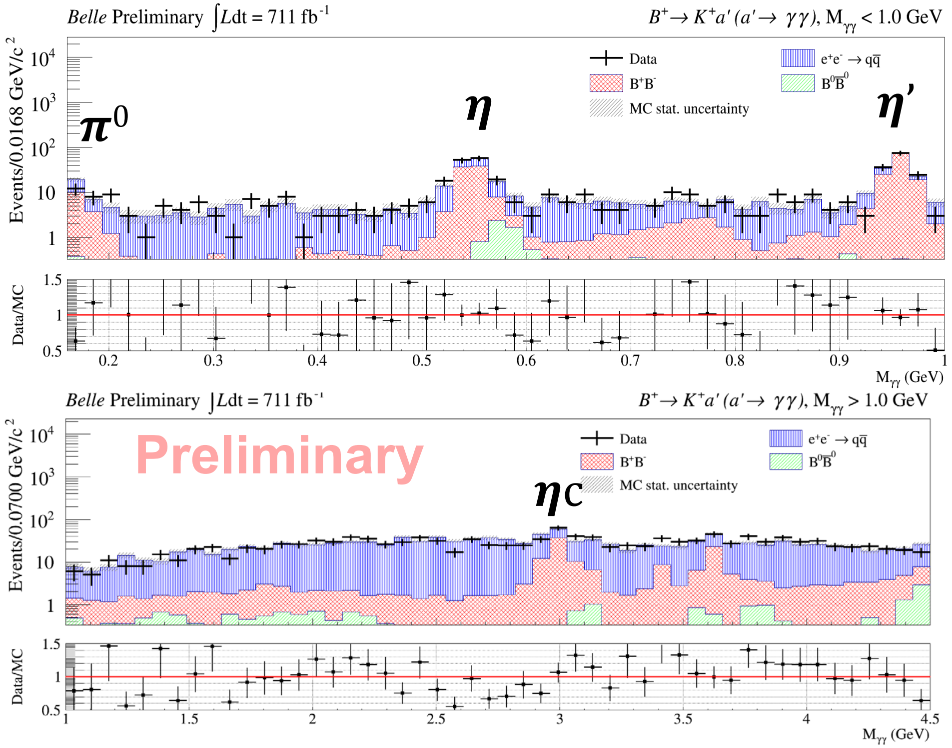
Signal extracted with a scan over $M_{\gamma\gamma}$

- Steps of signal mass resolution (~ 8 – 18 MeV);
- Peaking background regions vetoed

Continuum vs BB event topology



$M_{\gamma\gamma}$ for the K^+ mode



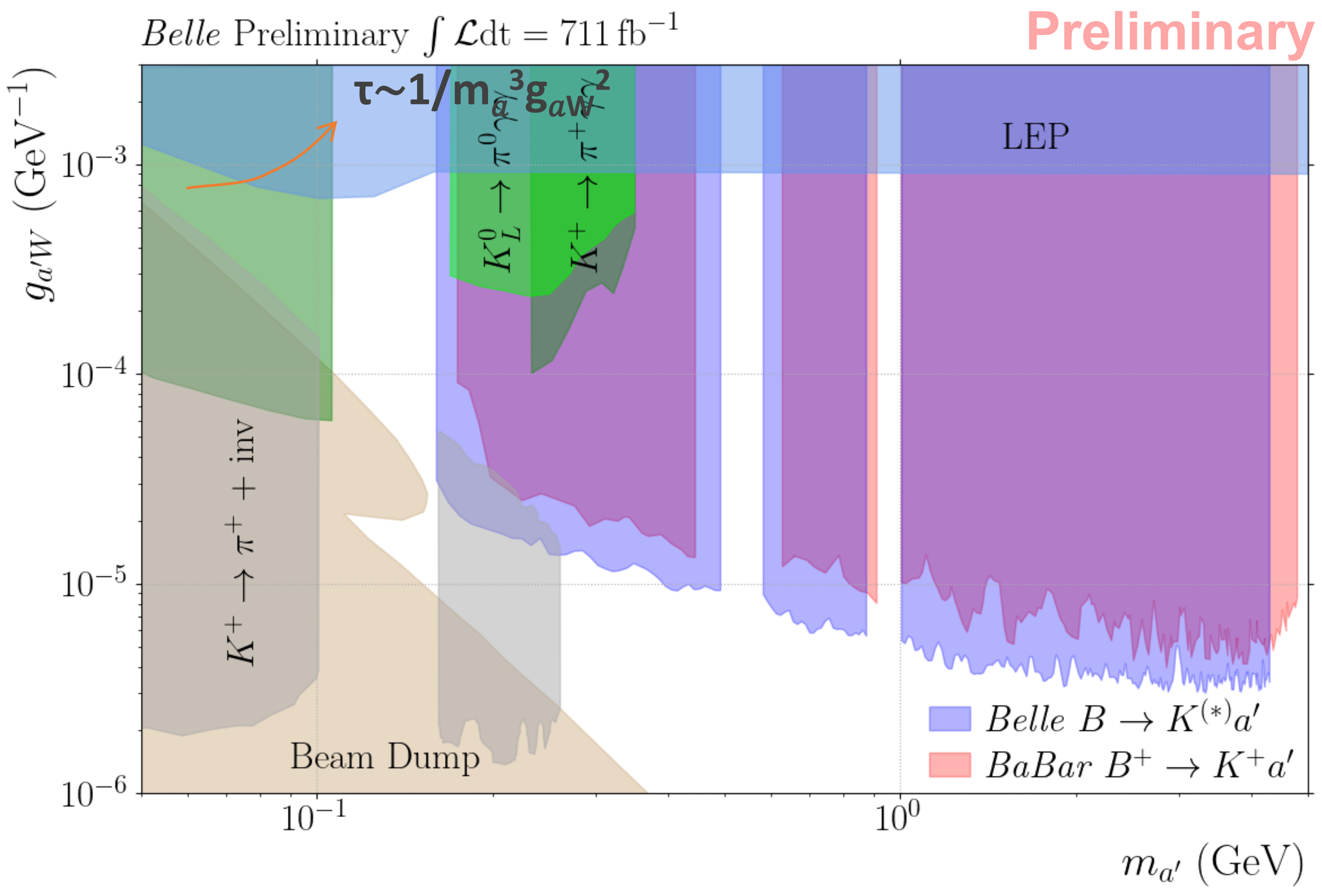
B → $K^{(*)} a(\to \gamma\gamma)$

Overview

No significant excess observed in 711 fb^{-1}

- **Simultaneous fit on 4 kaon modes**

✓ **World leading 90% CL upper limits to g_{aW}**



❖ ALP lifetime becomes important at low masses and couplings ($\tau \sim 1/m_a^3 g_{aW}^2$)

❖ Signal efficiency drop due to long-lived ALP is taken into account in results

Conclusion

Belle and Belle II: unique facilities with many exciting dark sector and tau physics opportunities

- **Several new world best limit on high-profile τ LFU / LFV searches**
  - Proving that Belle and Belle II are also τ-factories

- **Unique sensitivity for light dark sectors searches**
  - Excellent performance with displaced vertices and missing energy allows the world's leading results complementary to other experiments

Still many frontiers of improvements:

- Increase data sample size;
- Improved analysis techniques, and reduced systematic uncertainties

➢ **Luminosity and physics output expected to continue to ramp up with next data-taking period**

Stay tuned….