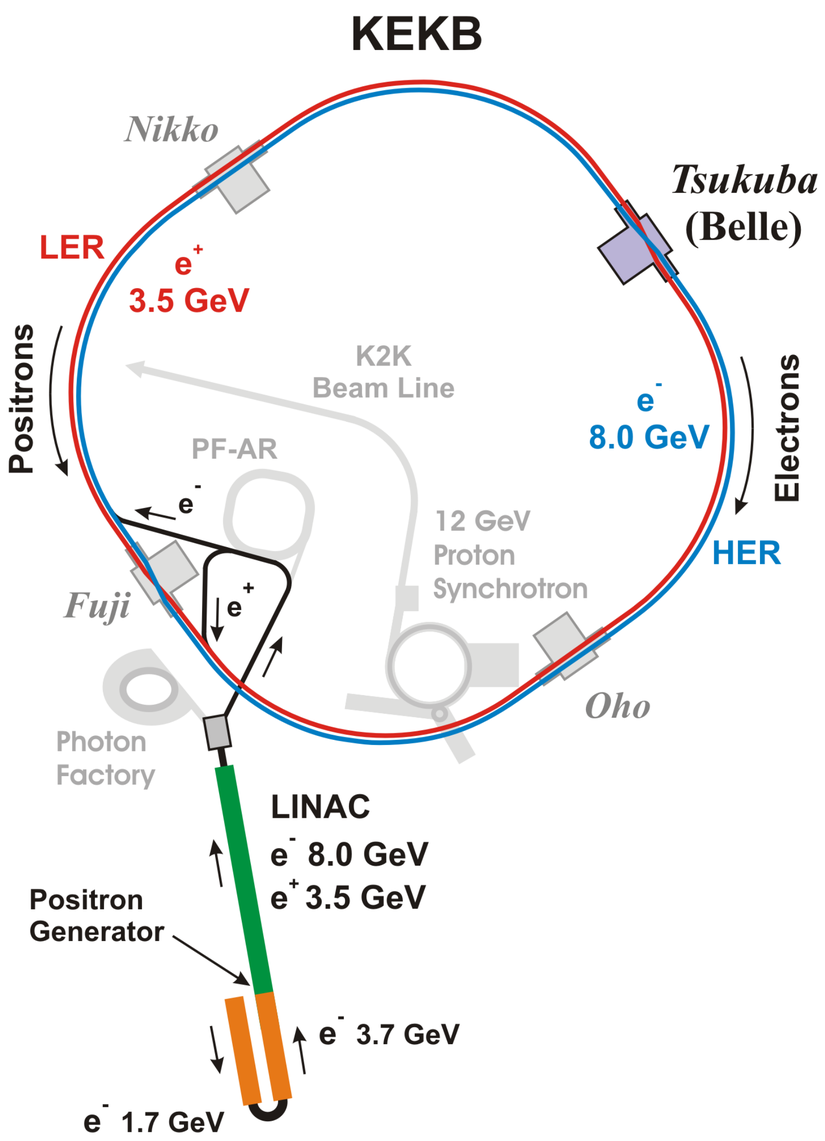
Searches for dark sector particles at Belle and Belle II

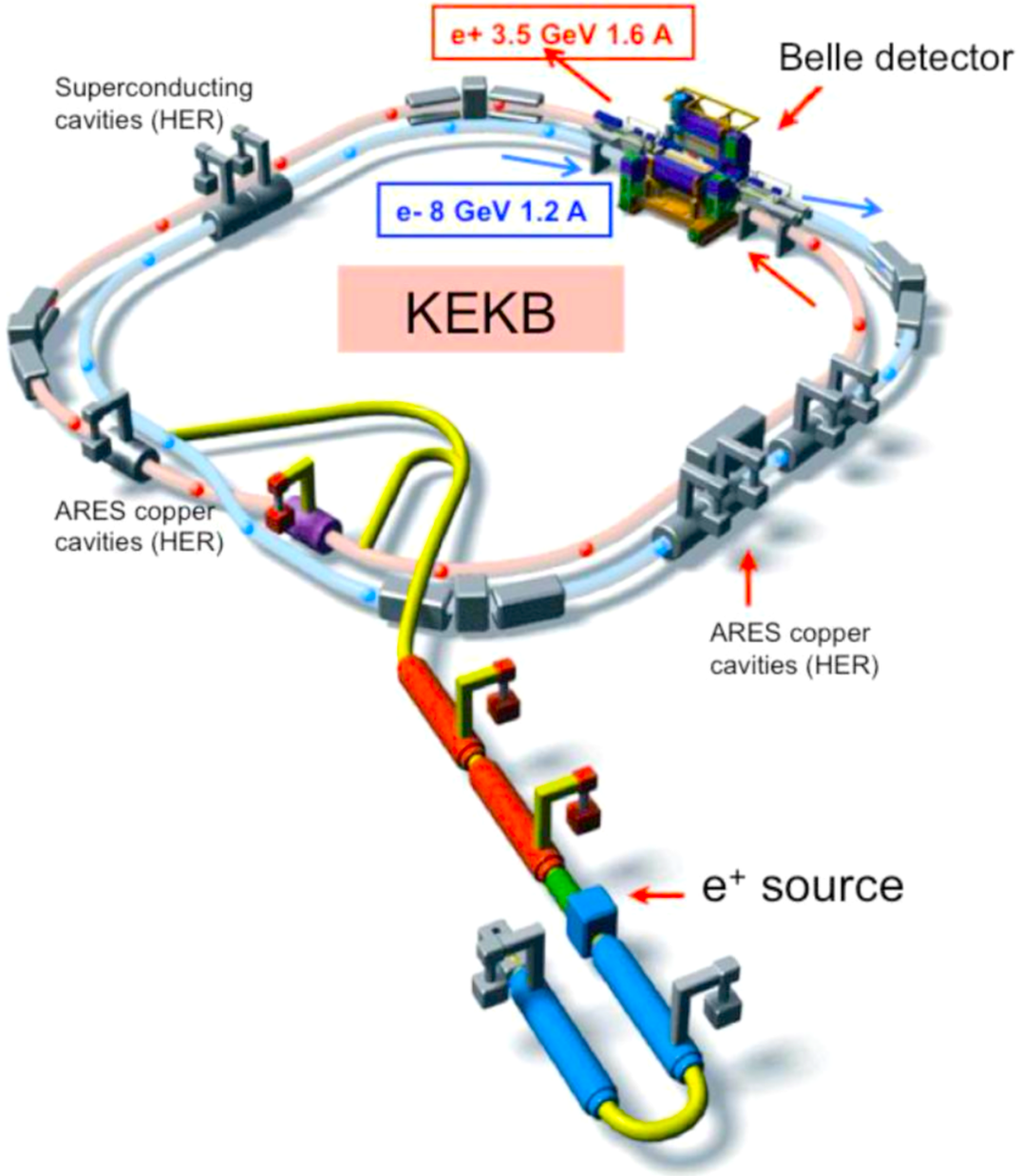
Sourav Dey

Dark matter and black holes 2025, Kavli IPMU, The University of Tokyo, Japan, Dec 1 -5 2025

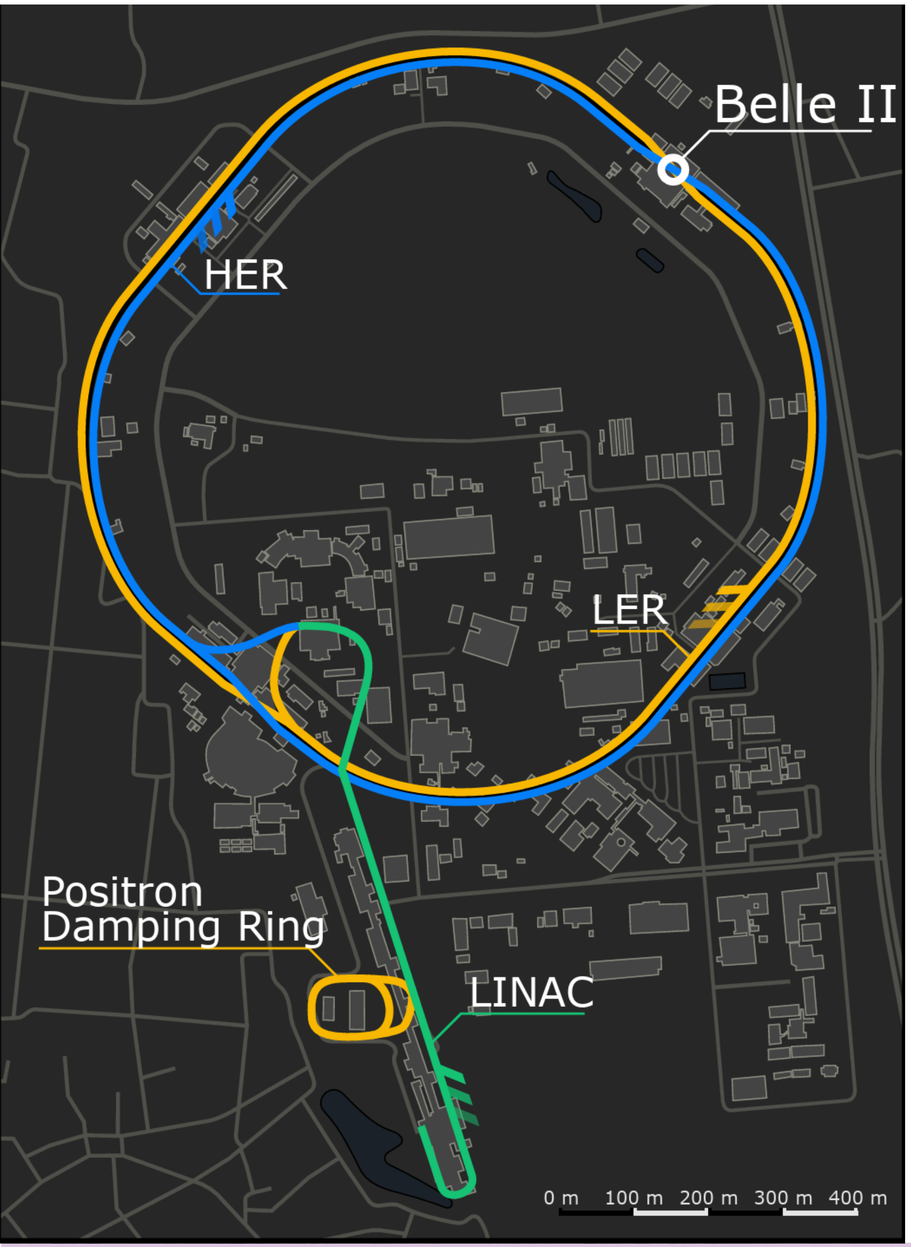
The Facility

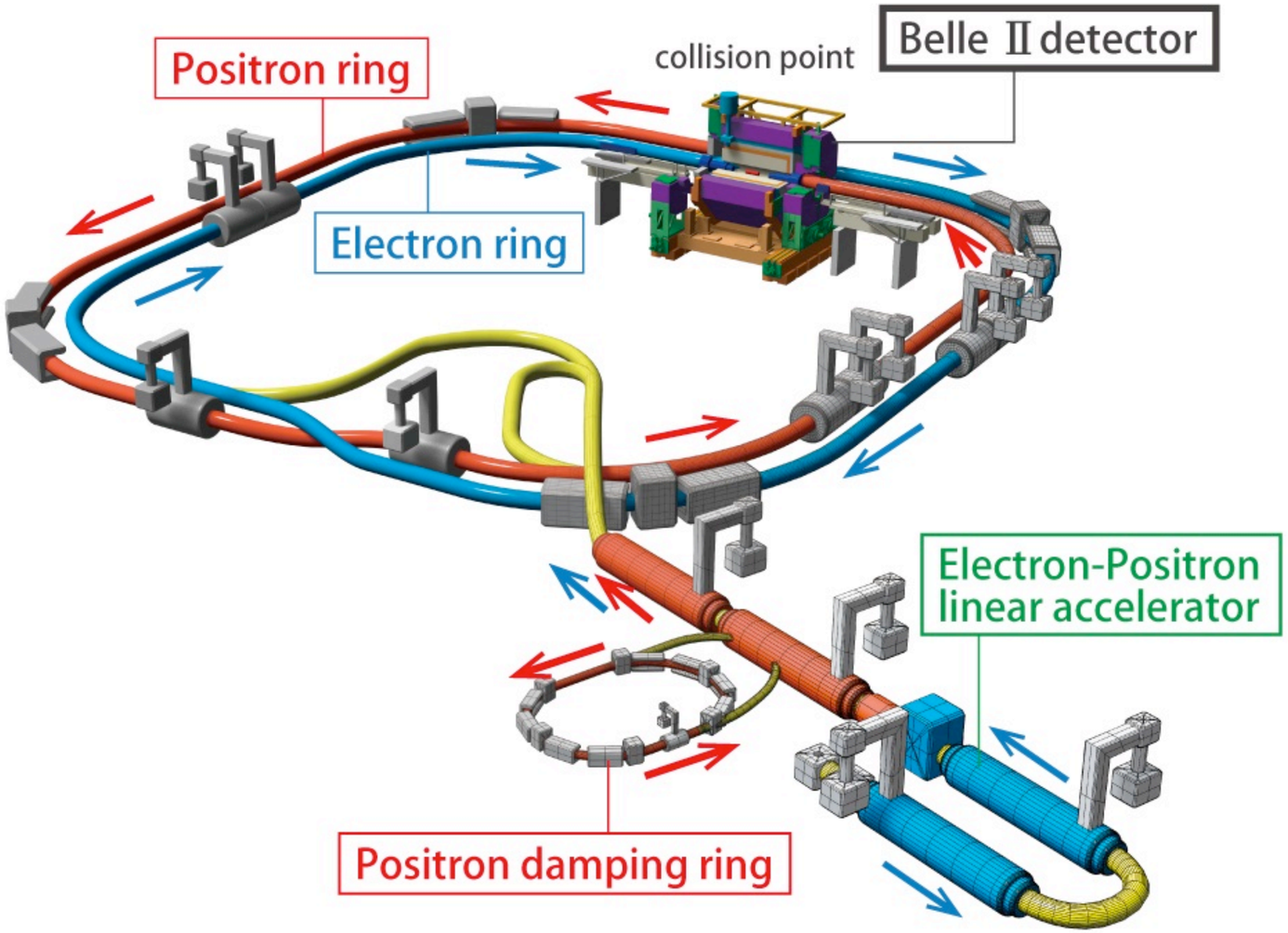
The KEKB


KEKB
Nikko
Tsukuba
(Belle)
LER
e+
3.5 GeV
Positrons
K2K
Beam Line
e-
8.0 GeV
Electrons
PF-AR
e-
12 GeV
Proton
Synchrotron
HER
Fuji
e+
Oho
Photon
Factory
LINAC
e- 8.0 GeV
e+ 3.5 GeV
Positron
Generator
e- 3.7 GeV
e- 1.7 GeV

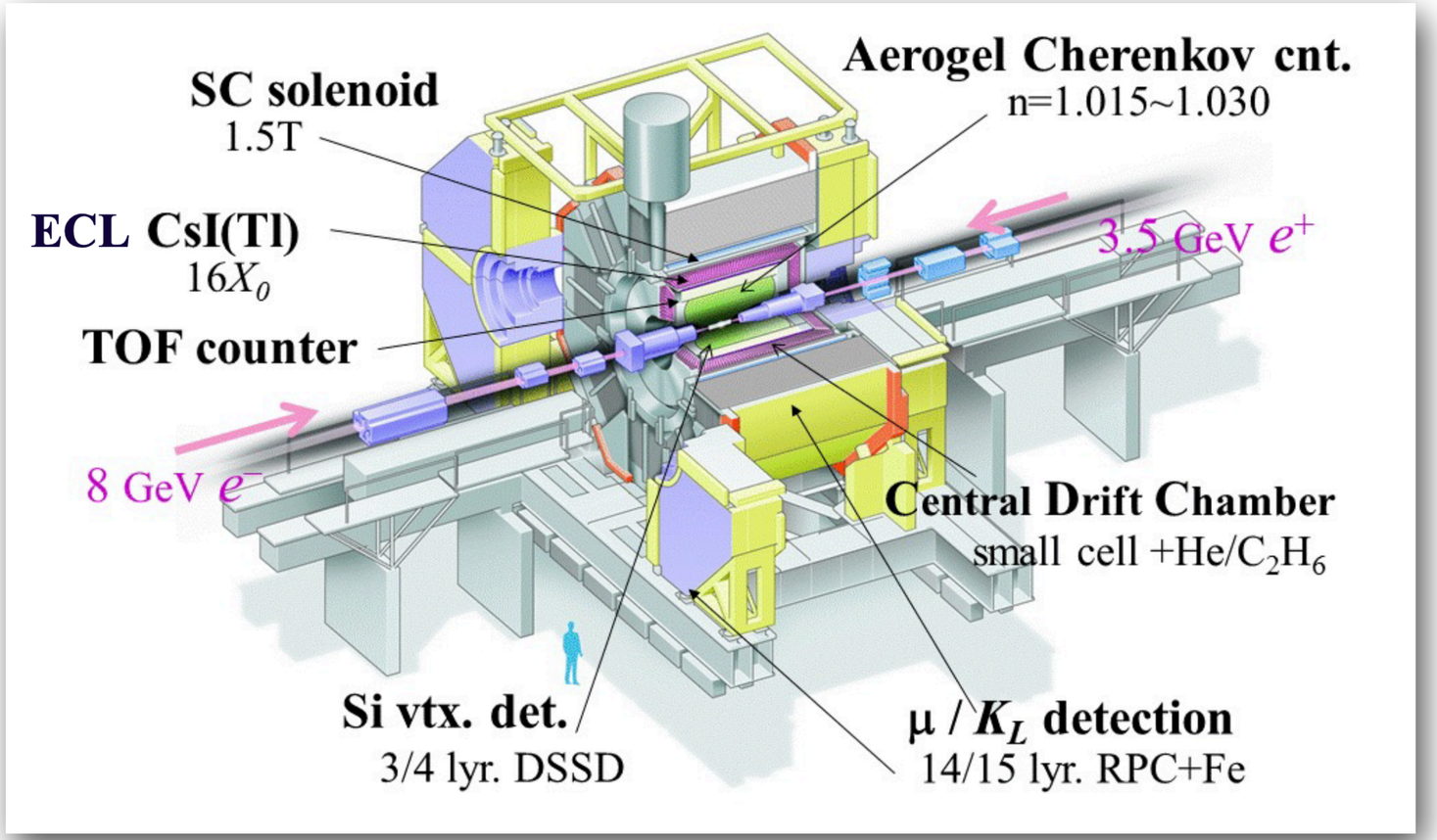

e+ 3.5 GeV 1.6 A
Belle detector
Superconducting
cavities (HER)
e- 8 GeV 1.2 A
KEKB
ARES copper
cavities (HER)
ARES copper
cavities (HER)
e+ source

The SuperKEKB





The Belle, and the Belle II Detector



- $\sqrt{s} = 10.58$ GeV : mass of $\Upsilon(4S)$
- asymmetric detector
- a vast region of particle physics (Precision studies of B, charm, and tau physics, QCD and exotic hadrons, searches for BSM particles etc.)

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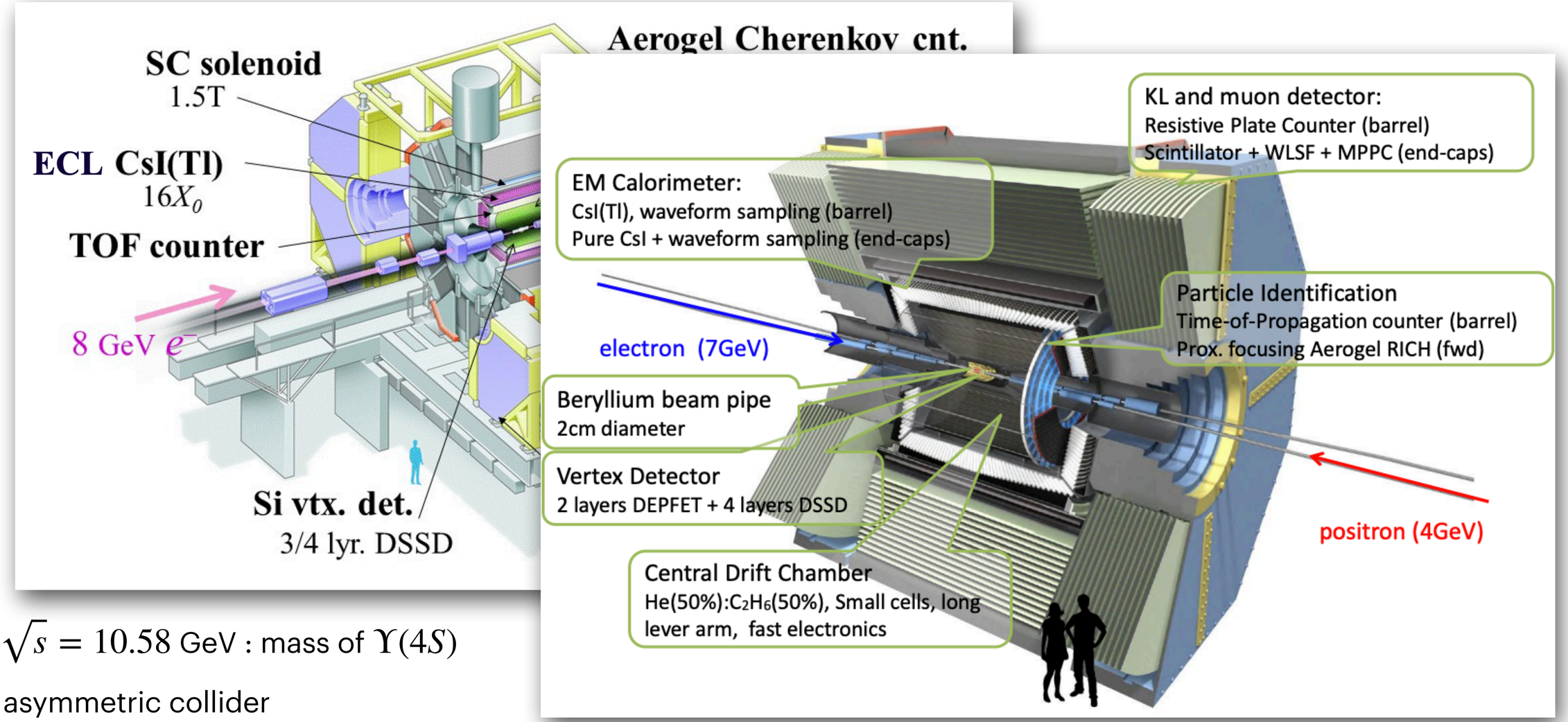
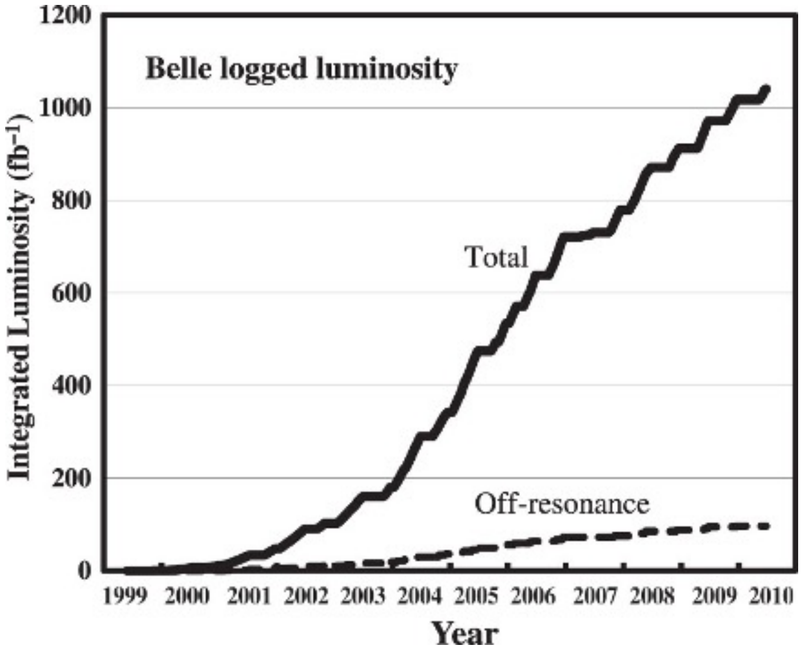
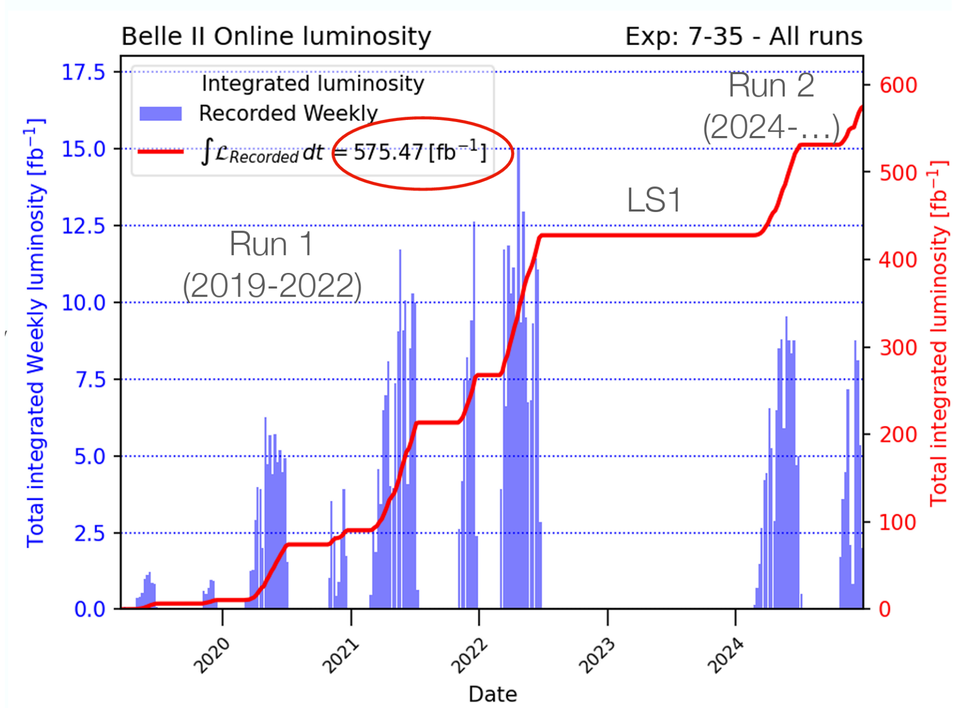


- $\sqrt{s} = 10.58$ GeV : mass of $\Upsilon(4S)$
- asymmetric collider
- a vast region of particle physics (Precision studies of B, charm, and tau physics, QCD and exotic hadrons, searches for BSM particles etc.)

The Data

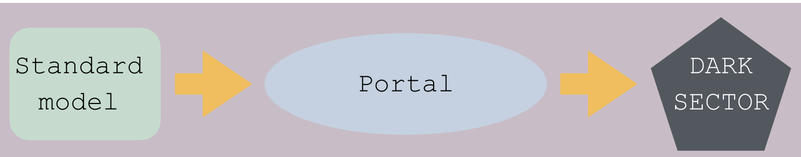
- Belle : 1999-2010 : 1040 fb^{-1}, Belle II : since 2019 : ~0.6 ab-1
- $\sigma(e^+e^- \to b\bar{b}) = 1.05\ nb$
- $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92\ nb$: B factories are also τ factories
- $\sigma(e^+e^- \to c\bar{c}) = 1.3\ nb$
- $\Upsilon(nS)\epsilon[n = 1,..,5]$, use of off resonance data





Dark Sector

Dark sector: A Hidden sector, with Dark matter, that talks to us through a Portal



- Dark Matter existence established in astrophysics, e.g. rotation curves of spiral galaxies, bullet clusters, …
- No dark matter candidate in the Standard Model (SM)
  - One of the most convincing indications of new physics
- Sub-GeV Light Mediator portals:
  - Vector portal Dark Photons, Z' bosons
  - Pseudo-scalar portal Axion Like Particles (ALPs)
  - Scalar portal Dark Higgs / Scalars
  - Neutrino portal Sterile neutrinos

Dark Sector Candidates, Anomalies, and Search Techniques

Dark Sector searches in Belle and Belle II

Vector portal Dark Photons, Z' bosons

- $e^+e^- \to \mu^+\mu^- Z', Z' \to$ invisible (Invisible: neutrino , dark matter)(Belle II : PRL 130.231801)
- $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$(Belle II : arXiv 2306.12294)
- $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$(Belle II : arXiv 2403.02841)

Pseudo-scalar portal Axion Like Particles (ALPs)

- $e^+e^- \to \gamma a, a \to \gamma\gamma$(Belle II : PRL 125.161806)
- $\tau \to l\alpha, \alpha$ invisible(Belle II : PRL 130.181803)

Scalar portal Dark Higgs / Scalars

- $e^+e^- \to \tau^+\tau^- l^+l^-$(Belle : PRD 109.032002)
- $e^+e^- \to \mu^+\mu^-$ + invisible h'(Belle II : PRL 130.071804)

Neutrino portal Sterile neutrinos

- $\tau \to \pi N(\to \mu^+\mu^-\nu_\tau)$(Belle : 10.1103/PhysRevD.109.L111102)

Dark-Sector at Belle II

- **Clean e^+e^- environment** : excellent vertexing & hermeticity → ideal for rare, low-mass, and weakly coupled new-physics searches
  - Closed kinematics, 3D momentum conservation
  - Full Event Interpretation
- **Dark sector**: World-leading sensitivity to light new particles
  - Probes sub-GeV–few-GeV mass range inaccessible to many other experiments
  - Strong reach in missing energy, displaced vertices, and low-visible-energy final states
- Capabilities for the following signatures
  - Low multiplicity signatures
  - Fully neutral final states
  - Missing energy signatures
  - Dark sector signatures in B, D, τ, ϕ, J/ψ and ϒ decays

In this presentation...

- $\tau \to \ell + \alpha$
- $B \to K^{(*)} a(\to \gamma\gamma)$
- *Dark Higgs (h') + Inelastic Dark Matter (iDM)*

$\tau \to \ell + \alpha$

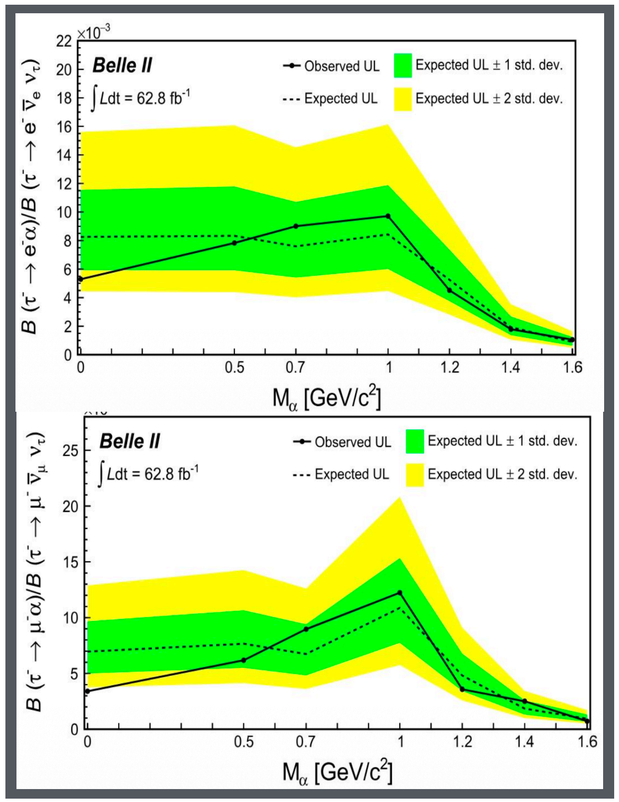
Motivation, Past Strategies

- α : BSM unobservable particle, which could be an **Axion-Like Particle (ALP)**, often the pseudo-Nambu-Goldstone Boson of a spontaneously broken global symmetry
- ALPs represent a standard "portal" to the dark sector
- An invisible ALP is particularly interesting as Belle II can probe a wide mass range
- This BSM particle could potentially **explain the nature of neutrino masses**, the strong CP problem, or be a **Dark Matter (DM) candidate**

PhysRevLett.130.181803, 2023

Belle and Initial Belle II Strategies

Initial Belle II Picture (3x1 prong)	$62.8\,fb^{-1}$	Used a signal side (1 lepton + invisible) and a tag side (3-tracks + invisible). Required a **pseudo-rest frame approximation** due to neutrinos
Recent Belle Strategy	$800\,fb^{-1}$	Required tag-side decays like $\tau \to 3\pi\nu$, $\pi\nu$, or $\pi\pi^0\nu$. Enhanced discrimination using a θ_{Th} **cut** to select events. This method yielded the most restrictive limits to date.
Signal Extraction (Belle)	$800\,fb^{-1}$	Extended maximum likelihood fit used template PDFs constructed via Monte Carlo (MC) simulations. Upper Limits (UL) were determined using Toy MC generation (Frequentist approach)



$\tau \to \ell + \alpha$

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JHEP08(2025)155

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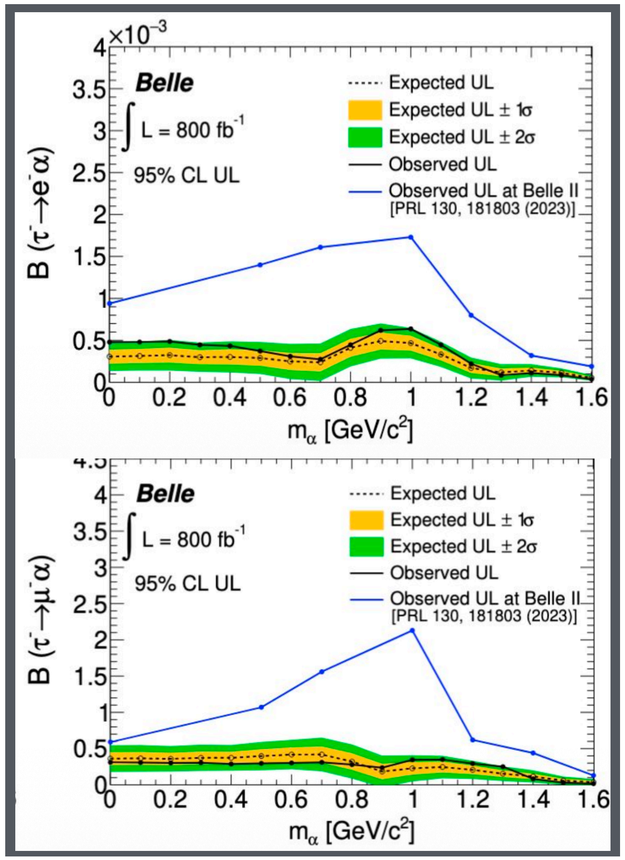
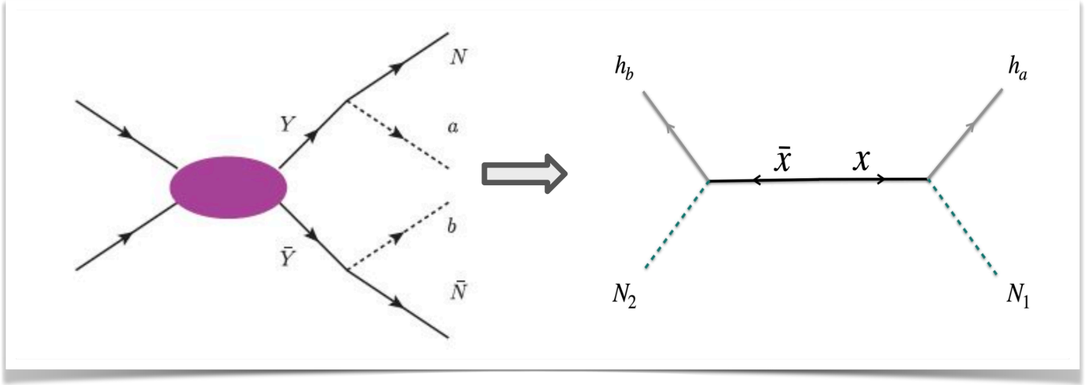


$\tau \to \ell + \alpha$

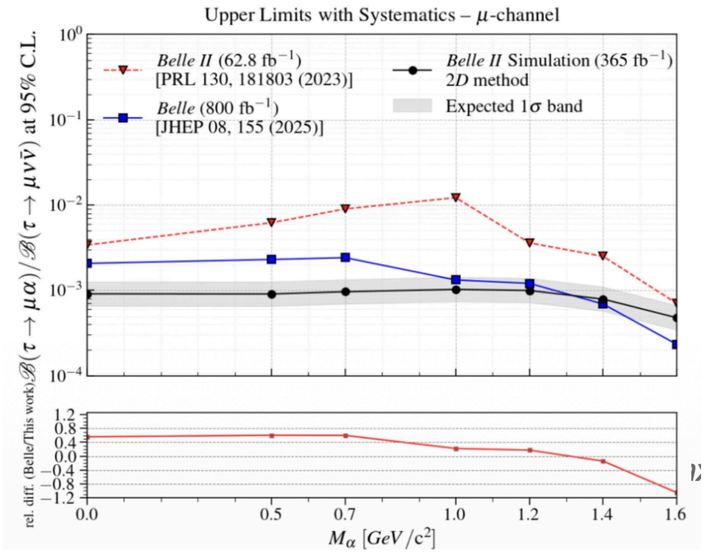
New Belle II Strategy and Sensitivity using 1x1 Decays

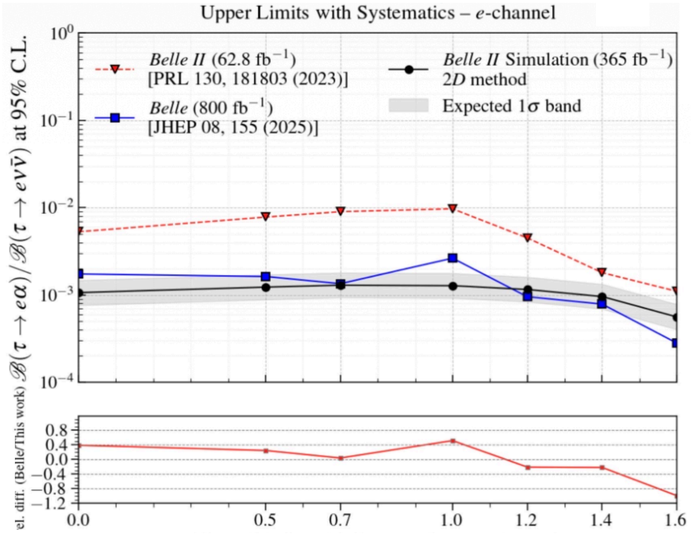


- Suitable for leptonic collider
- h_a, h_b could be a bunch of detectable particles
- N_1, N_2 : couple of particles that evade the detector
- This allows studying τ pair decays where one side exhibits a BSM process ($\tau \to \ell\alpha$) and the complementary side exhibits an SM process with missing particles

$$X\overline{X} \to (h_a + N_1)(h_b + \overline{N}_2)$$

- This new 2D fitting method shows strong potential, especially at low m_a.
- This is the first application of this 2D method in a Belle II physics analysis
- The hadronic 1-prong mode ($\tau \to \pi\nu$) is enabled and offers competitive performance





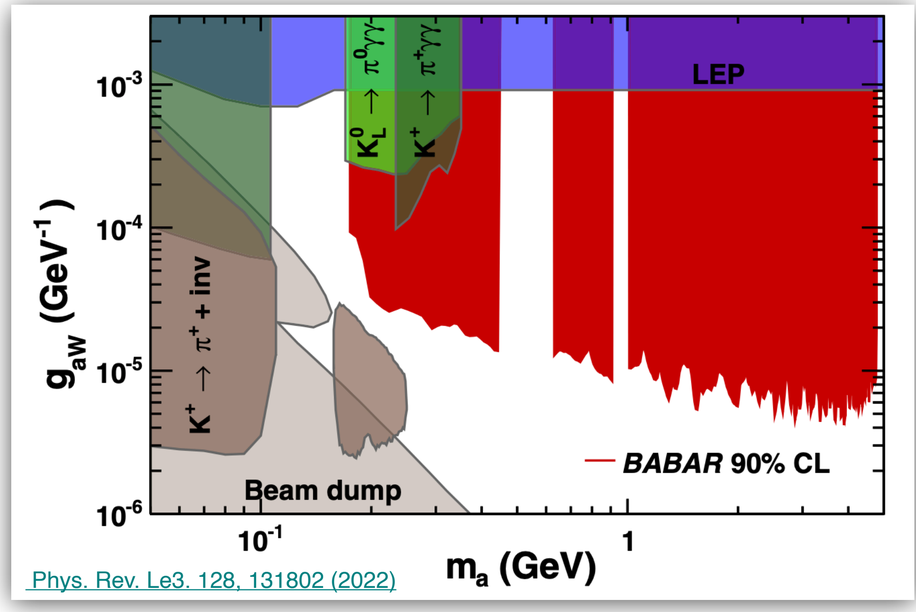
UL on the ratio
$\mathcal{B}(\tau \to \ell\alpha)/\mathcal{B}(\tau \to \ell\nu\nu)$

Reference: Phys. Rev. D 102, 115001

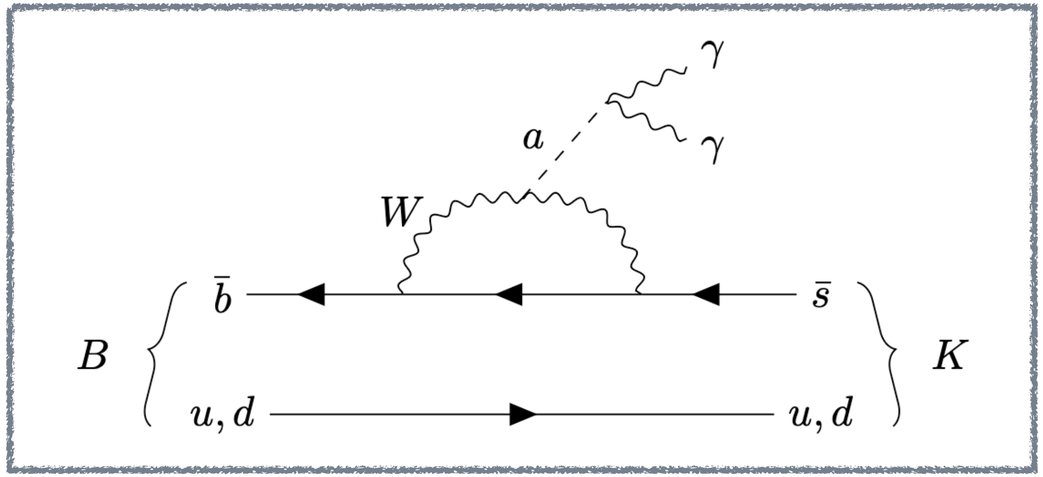
$B \to K^{(*)} a(\to \gamma\gamma)$

Motivation and Theoretical Framework

- Pseudo-scalar portal: Axion-Like Particles (ALPs, denoted as a) -> non-Standard Model (SM) extensions and potential dark matter mediators between dark sector and SM
- The analysis assumes the ALP decays almost 100% into a pair of photons (a→γγ) in the analyzed mass range
- Existing results from BaBar with 424 fb^{-1} ($B^+ \to K^+ a(\to \gamma\gamma)$)
- Uses 711 fb^{-1} data sample collected by the **Belle detector** at the $\Upsilon(4S)$ resonance
- Four kaon modes are investigated simultaneously: $K^+, K^{*+}, K^{*0}, K_S^0$
- The ALP mass is scanned from 0.16 GeV/c² up to 4.50 GeV/c² (K modes) or 4.20 GeV/c (K* modes)



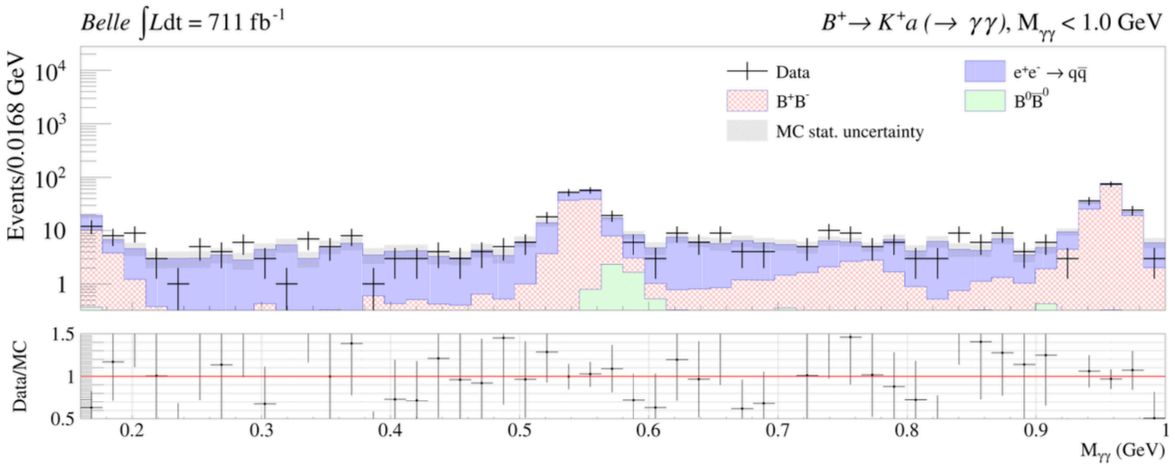
Phys. Rev. Le3. 128, 131802 (2022)

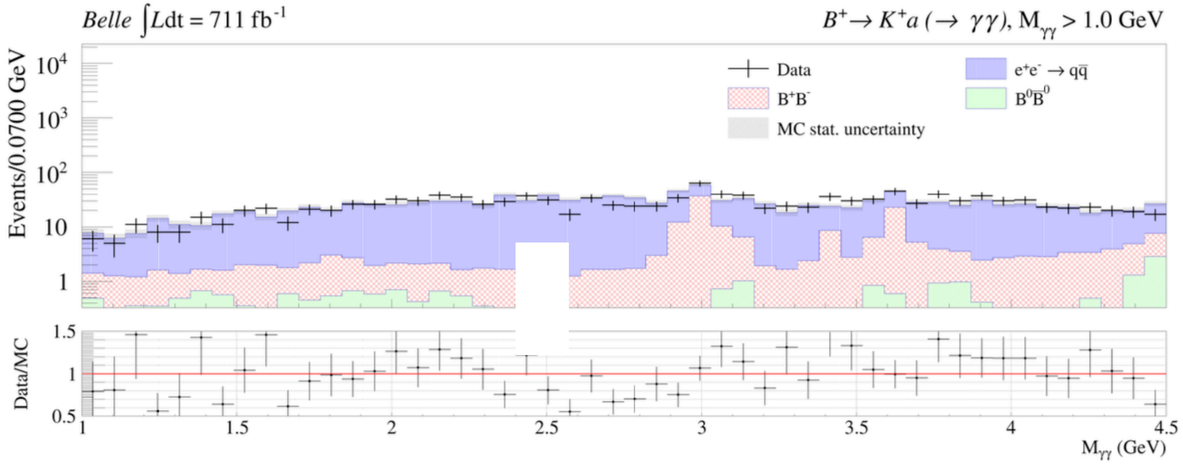


$B \to K^{(*)} a(\to \gamma\gamma)$

Analysis Methodology Highlights

- **Signal Identification**: The presence of an ALP is sought as a narrow peak in the two-photon invariant mass ($M_{\gamma\gamma}$) distribution
- **Background Suppression:** Dominant background from continuum processes ($e^+e^- \to q\bar{q}$) is suppressed using two Boosted Decision Tree (BDT) classifiers
  - BDT training is optimized separately for low ($M_{\gamma\gamma}$ < 1 GeV) and high ($M_{\gamma\gamma}$ > 1 GeV) mass regions
- **SM Peaking Veto:** Mass regions corresponding to π^0, η and η' decays are explicitly excluded (vetoed) from the ALP mass scan
- **Lifetime Correction:** The possibility of a **long-lived ALP** (which has a greater impact at lower mass) is accounted for, as displaced vertices reduce signal efficiency due to assumptions that photons originate from the interaction point (IP).
- **Uncertainty:** The total systematic uncertainty for the signal extraction is estimated to be 22.3%



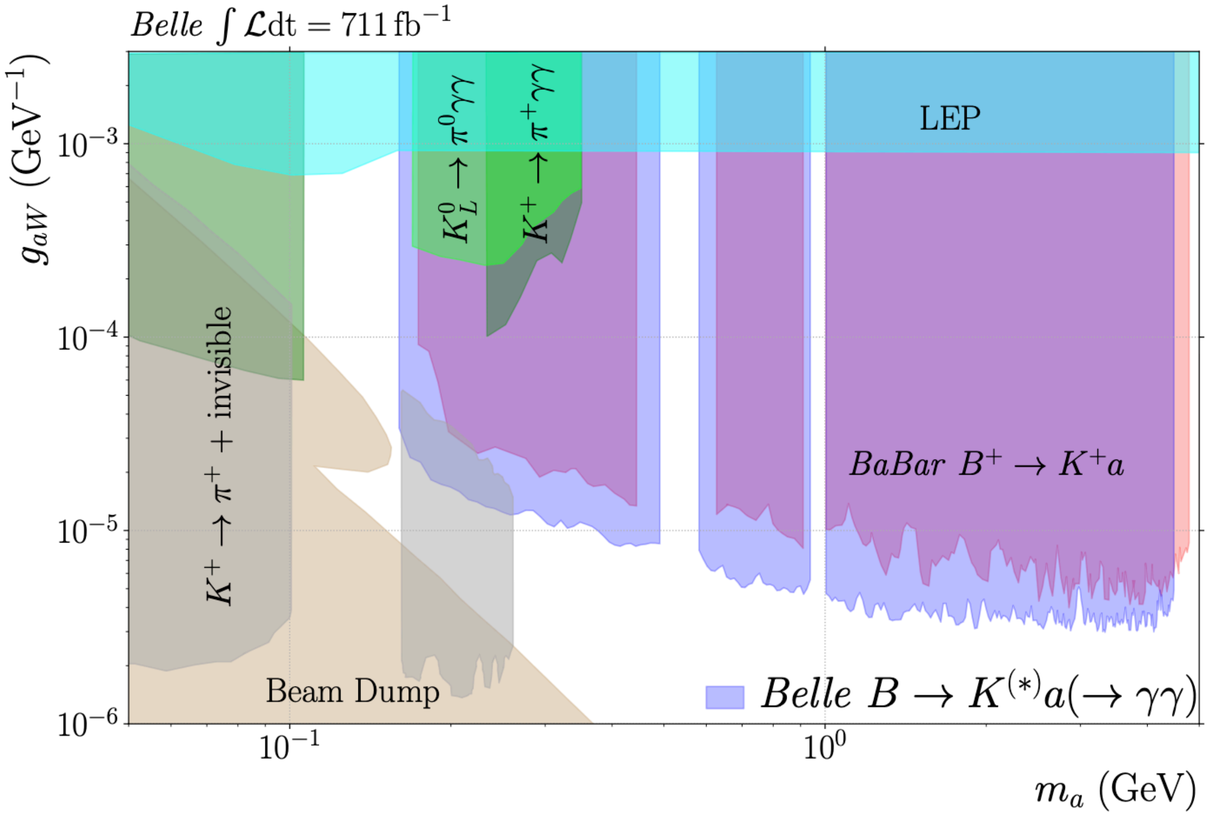


$B \to K^{(*)} a(\to \gamma\gamma)$

Results

- World-Leading Constraints on g_{aW}
- No significant signal excess observed in any of the four kaon decay modes
- The largest local significance observed was 2.74σ corresponding to a global significance of 1.89σ

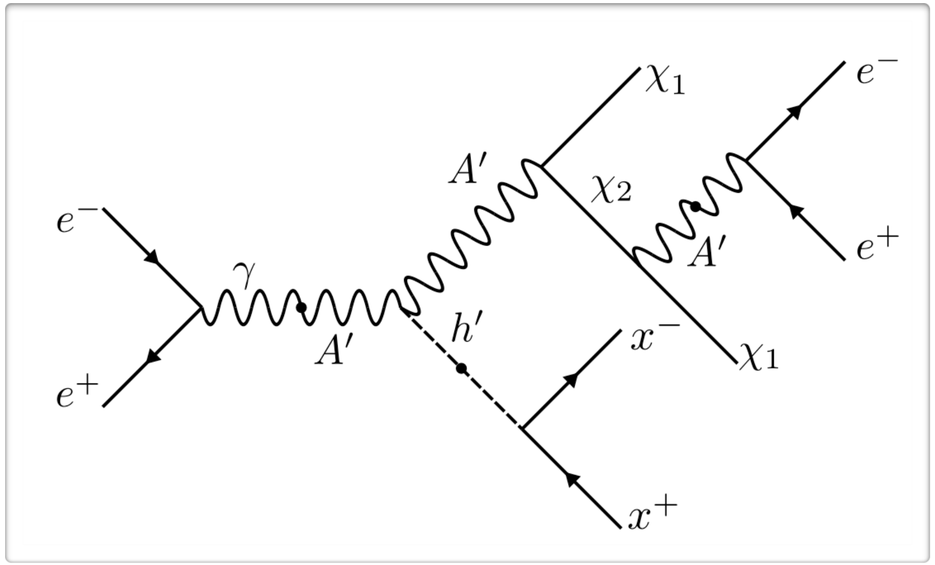
- **90%** Confidence Level (CL) upper limits are established on the coupling strength g_{aW} as a function of m_a through a simultaneous fit to all four channels
- Impact: These new constraints improve the limits on g_{aW} by a factor of two over the most stringent previous experimental results (e.g., BABAR)



arXiv:2507.01249 [hep-ex] (2025) : Submitted to JHEP

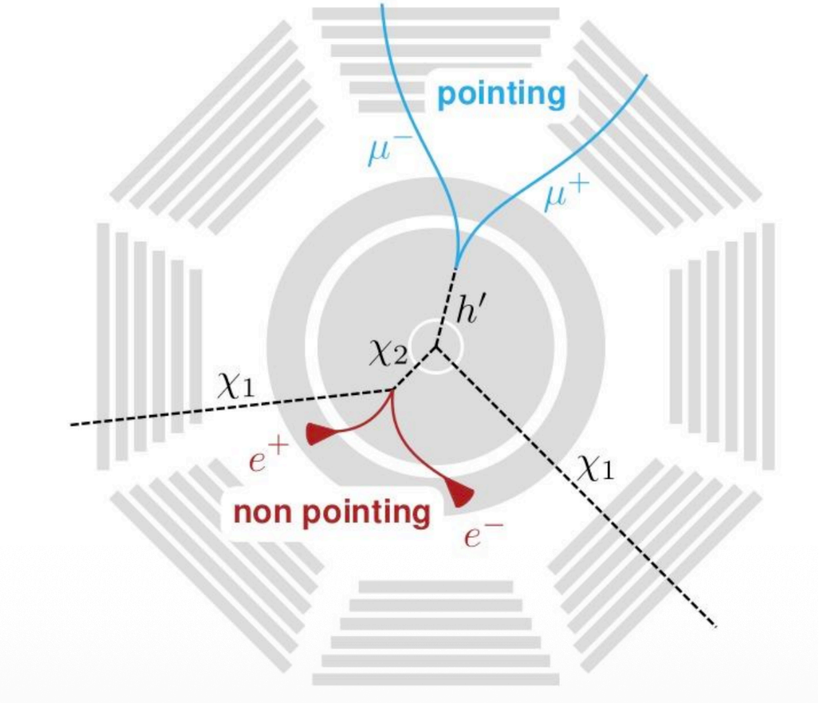
Physics Motivation

- Inelastic Dark Matter (iDM) models, where dark matter particles ($\chi 1, \chi 2$) have a mass splitting (Δm) generated by a Dark Higgs field and its corresponding boson, h'
- **Dark Higgs Role:** The h' mixes with the Standard Model Higgs boson via a mixing angle θ.
- **Search Channel:** $e^+e^- \to h'\chi 1\chi 2$
- **Observed Decay Path:** The signal sought is $e^+e^- \to h'(\to x^+x^-)A'[\to \chi 1\chi 2(\to \chi 1 e^+e^-)]$.
  - x^+x^- indicates $\mu^+\mu^-, \pi^+\pi^-$ or K^+K^-
- **Novelty:** This represents the first search for dark Higgs bosons in association with inelastic dark matter



Experiment and Signature

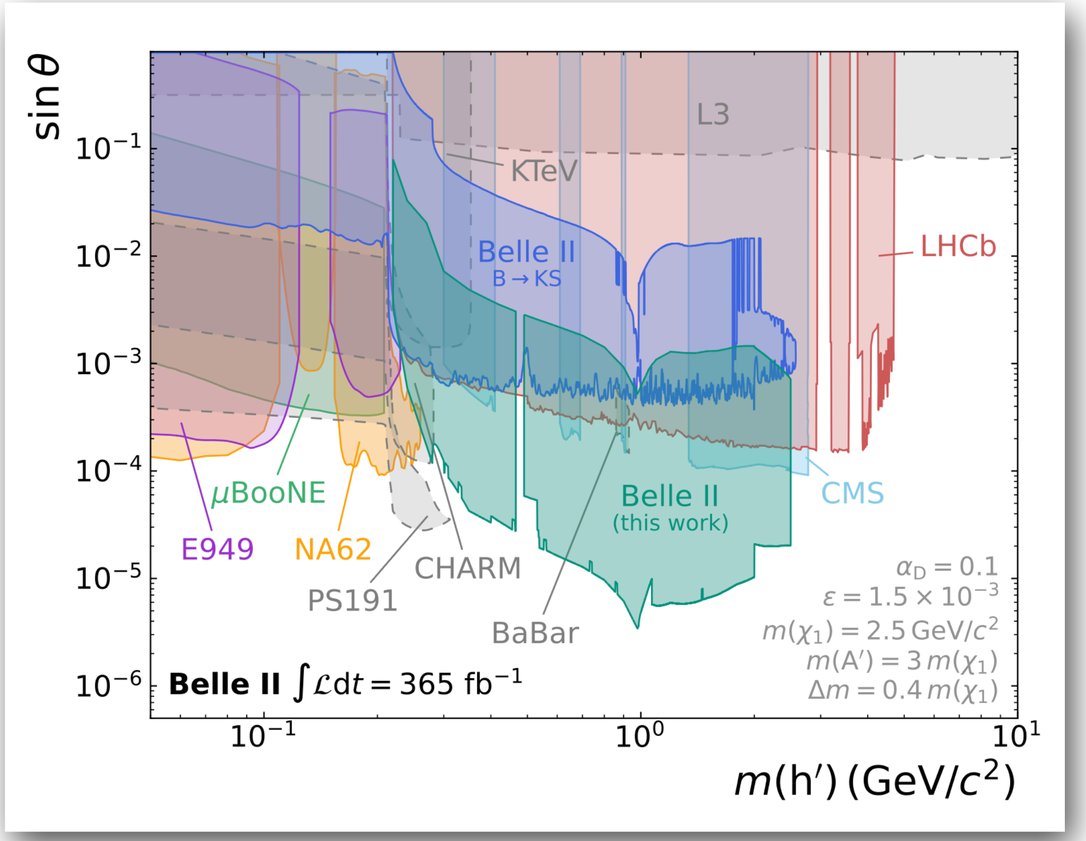
- **Data Sample:** 365 fb^{-1} data sample used, collected at $\sqrt{s} = 10.58$ GeV at Belle II
- **Signal Signature:** The search targets events with **missing energy** (due to the stable $\chi 1$ particle escaping detection) and **up to two vertices**
- **Displaced Vertices:** At least one reconstructed vertex must be displaced from the interaction region (IP) by a transverse distance (d_v) of at least **0.2** cm to suppress promptly decaying Standard Model backgrounds. This requirement targets long-lived h' and $\chi 2$ particles
- **Signal Extraction:** The signal yield is extracted via a mass scan of the invariant mass of the decay products $M(x^+x^-)$, seeking a narrow enhancement



Dark Higgs (h') + Inelastic Dark Matter (iDM)

Results

- **No Significant Signal:** No significant excess above the expected background is observed.
- The largest positive local significance found was **2.9**σ (global significance **1.1**σ) in the $\pi^+\pi^-$ final state near $m(h')$=0.531 GeV/c^2.
- **Model-Independent Limits:** 95% Bayesian credibility level upper limits are set on the product of cross section and branching fractions (σ_{sig}) at the level of **10**$^{-1}$ fb.
- **Model-Dependent Limits:** Stringent upper limits are set on key parameters of the iDM model:
- The dark Higgs mixing angle, sinθ, is constrained at the level of **10**$^{-5}$
- The dark photon kinetic mixing parameter is constrained at the level of **10**$^{-3}$
- **Impact:** The constraints set by this search improve upon existing searches by up to **two orders of magnitude**, depending on the model parameters chosen



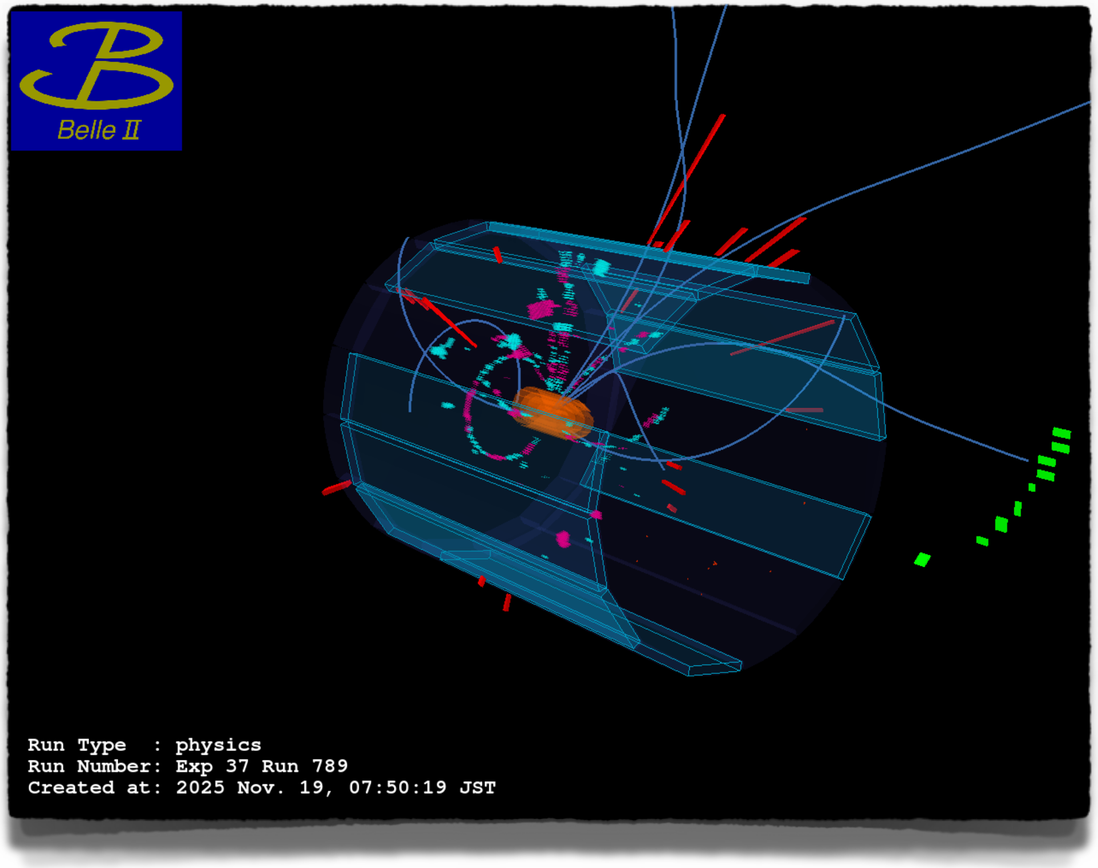
Accepted by PRL : arXiv:2505.09705

Recent publications on dark sector

$B \to K^* a (\to \gamma\gamma)$	2025	arXiv:2507.01249	Belle
$\tau \to \ell\, a$	2025	arXiv:2503.22195	Belle
$\tau^- \to \pi^- N \to \mu^+\mu^- \tau\, \nu$ (HNL)	2024	PhysRevD.109.L111102	Belle
$e^+e^- \to \tau^+\tau^- \phi_l \to \ell^+\ell^-$	2024	PhysRevD.109.032002	Belle
Heavy neutrino in τ decays	2023	PhysRevLett.131.211802	Belle
$e^+e^- \to Z' \to \mu^+\mu^- \mu^+\mu^-$	2022	PhysRevD.106.012003	Belle
Inelastic dark matter with a dark Higgs	2025	arXiv:2505.09705	Belle II
$e^+e^- \to \mu^+\mu^-(\mu^+\mu^-)$ (non-SM resonance)	2024	PhysRevD.109.112015	Belle II
Long-lived spin-0 mediator in b→s	2023	PhysRevD.108.L111104	Belle II
$e^+e^- \to \mu^+\mu^- X(\tau^+\tau^-)$ (Z', S, ALP)	2023	PhysRevLett.131.121802	Belle II
$e^+e^- \to \mu^+\mu^- Z'$	2023	PhysRevLett.130.231801	Belle II
$e^+e^- \to A'(\to \tau^+\tau^-)\, h'$	2023	PhysRevLett.130.071804	Belle II
$\tau \to \ell\, a$	2023	PhysRevLett.130.181803	Belle II
$e^+e^- \to \gamma\, a (\to \gamma\gamma)$	2020	PhysRevLett.125.161806	Belle II
$e^+e^- \to \ell\pm\, \mu\mp\, Z'$	2020	PhysRevLett.124.141801	Belle II

To conclude…

- No significant excess observed
- Strong limits set in most analyses; **Belle and Belle II** maintain world-leading sensitivity in many dark-sector searches
- Physics data taking resumed from 18th November after a long shutdown, with major hardware issues resolved and the detector now more robust
- Higher luminosity will also mean higher background levels
- Analysis techniques continue to improve, strengthening future reach
- Exciting opportunities ahead as Belle II enters the next phase of data taking



THANK YOU FOR YOUR ATTENTION