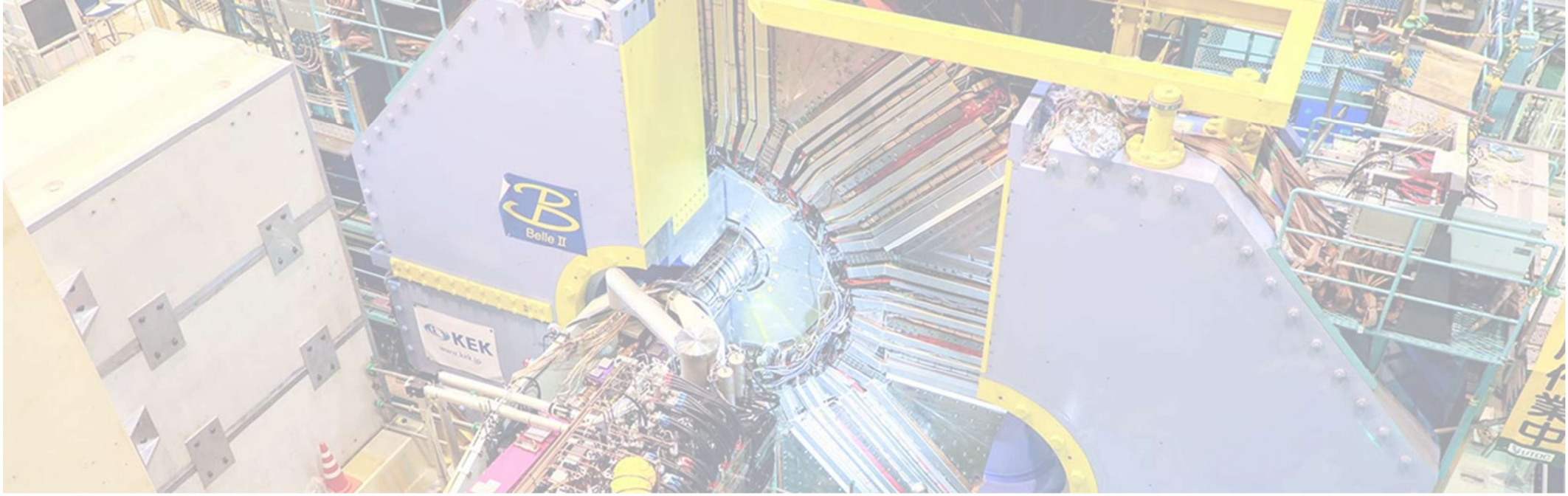
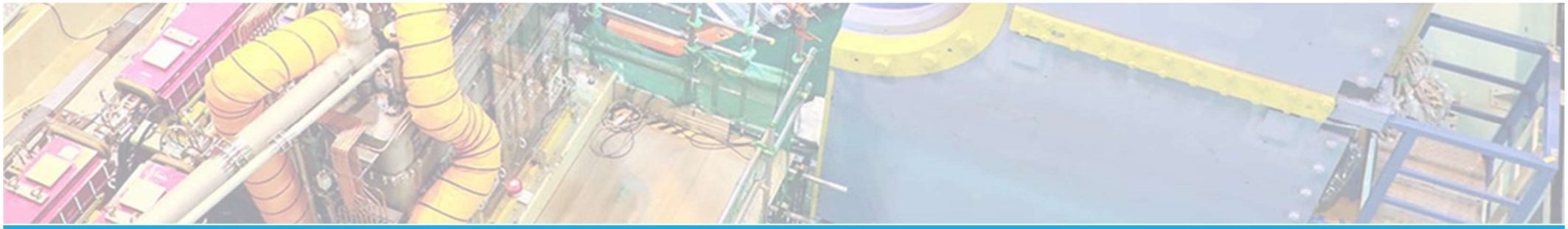


Searches for dark sector particles at Belle and Belle II

EPS-HEP, July 7 – 11 2025, Marseille

Laura Salutari – INFN Roma 3, on behalf of the Belle II collaboration
laura.salutari@roma3.infn.it



B-factories experiments

Experiments at asymmetric e^+e^- colliders, running mainly at $\Upsilon(4S)$:
$\sqrt{s} = 10.58$ GeV

Belle @ KEKB (1998-2010): belongs to first generation of B-factories, collected 1 ab^{-1} of data

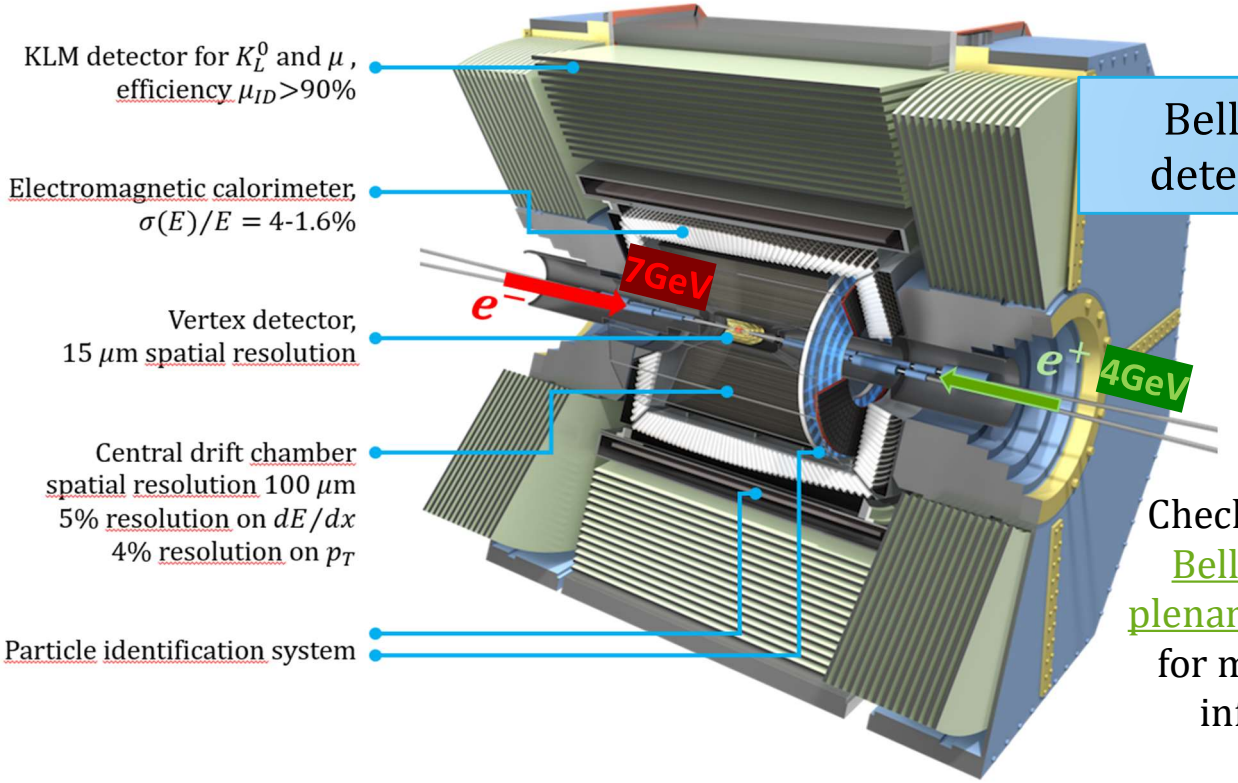
Belle II @ SuperKEKB – run 1 (2018 -2022), run 2 (feb 2024 -): second generation, collected 0.6 ab^{-1}

- World record $\mathcal{L}$: 5.1 x 10^{34} $cm^{-2}s^{-1}$
- Target $\mathcal{L}$: 6 x 10^{35} $cm^{-2}s^{-1}$
- Target $\int \mathcal{L} = 50$ ab^{-1}

Ideal for dark matter search!

Key features:

- Well **know collision conditions**
- Clean environment with low multiplicity events
- **Hermetic detector**
- **Trigger lines specific** for low multiplicity events
- Overall **excellent reconstruction of events even with missing energy & low multiplicity**

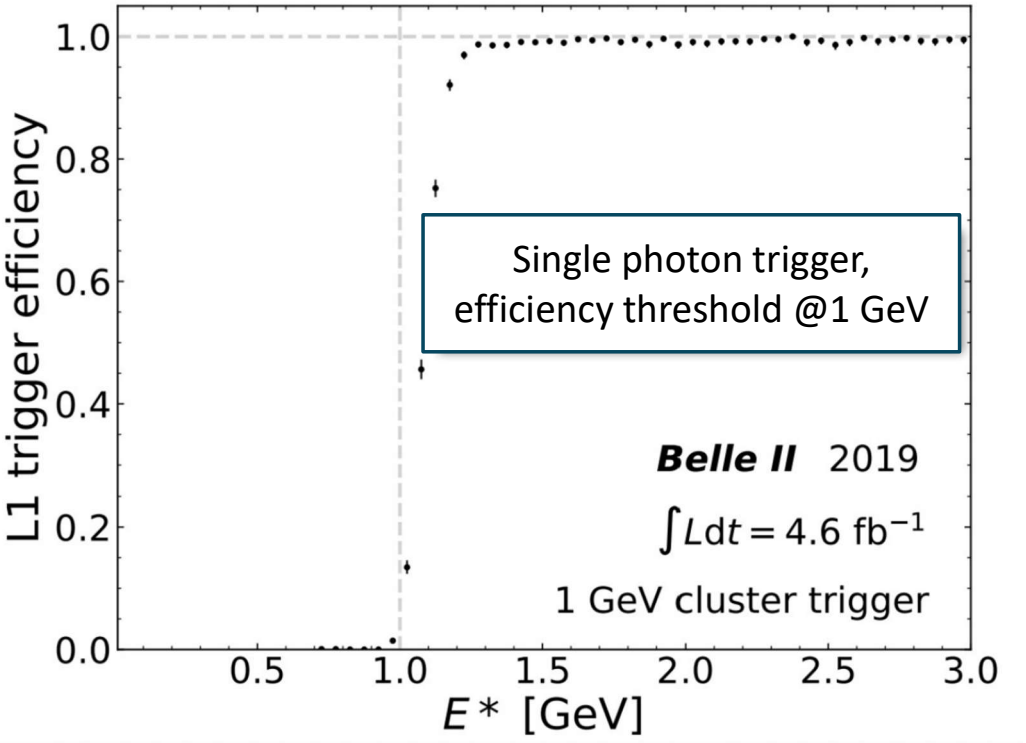


Belle II detector

Check the Belle II plenary talk for more info

Belle II trigger system

- Trigger must suppress high-cross-section QED processes O(1-300 nb), without «killing» the signal cross section <O(fb)
- **Need precise knowledge of acceptance & efficiencies of detector**



Trigger based on:

- calorimeter clusters (ECL) for electrons and neutral particles
- Central Drift Chamber (CDC) for charged particles tracks
- KLM for μ, K particles

Example of **low multiplicity lines** available at Belle II :

- Single-photon trigger (ECL)
- Single-track trigger (CDC)
- Single-muon trigger (KLM)

Makes Belle II dataset world-unique

Dark sector and Dark Matter at B-factories

Dark Matter (DM) nature still unknown, and it could be part of a **Dark Sector (DS)**

→ Light dark matter candidates

→ Dark force with feeble SM interactions a.k.a. portals

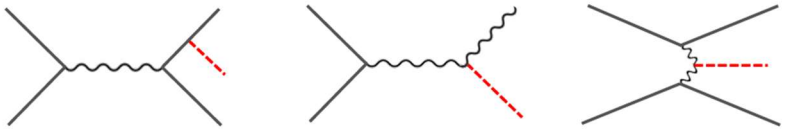
$$\mathcal{L}_{\text{portals}} = -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \cdots$$

Vector portal | Higgs portal | Neutrino portal

Low energy e^+e^- colliders, such as B-factories, can access the mass range favored by light dark sectors and explore on-shell mediators in the MeV – 10 GeV range

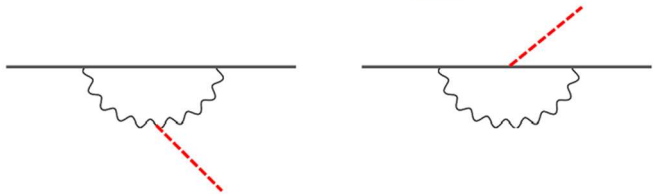
Direct production from collision

$e^+e^- \to X_{Dark} X_{SM}$

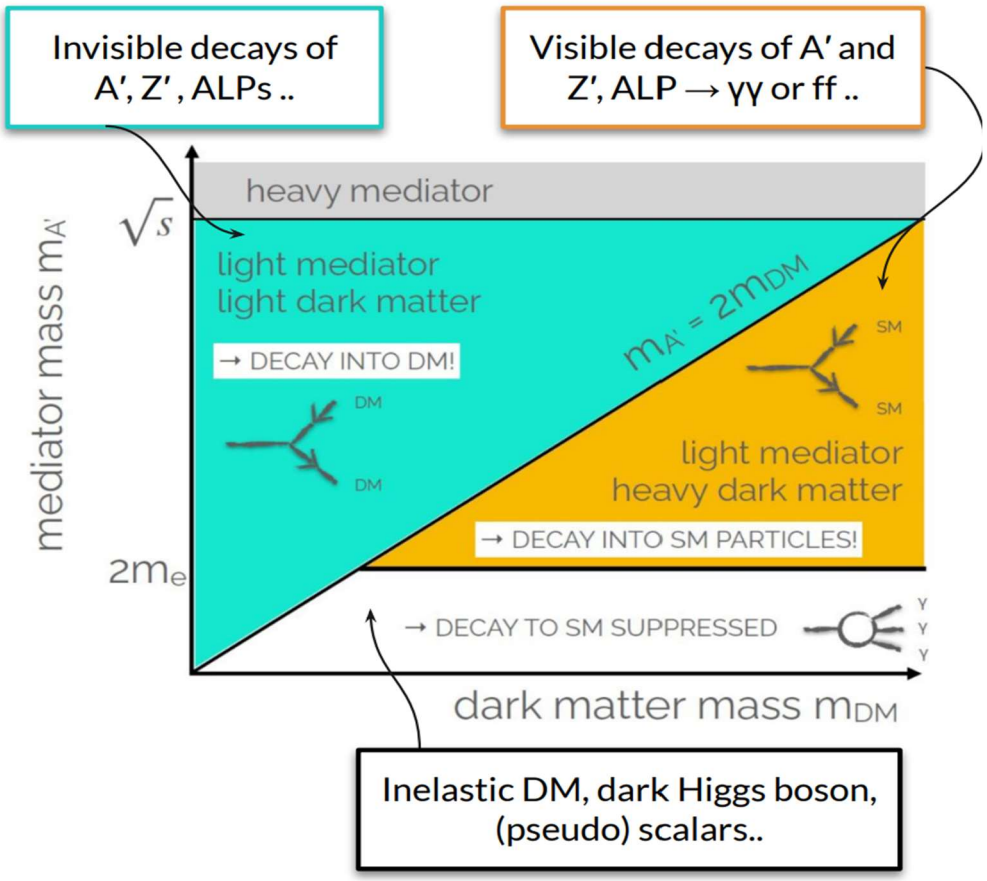


Production in SM particle decays

$B/D/\tau/\ldots \to X_{Dark} X_{SM}$



Dark sector and Dark Matter at B-factories



Different scenarios arise, depending on the dark sector mediator and DM mass hypothesis:

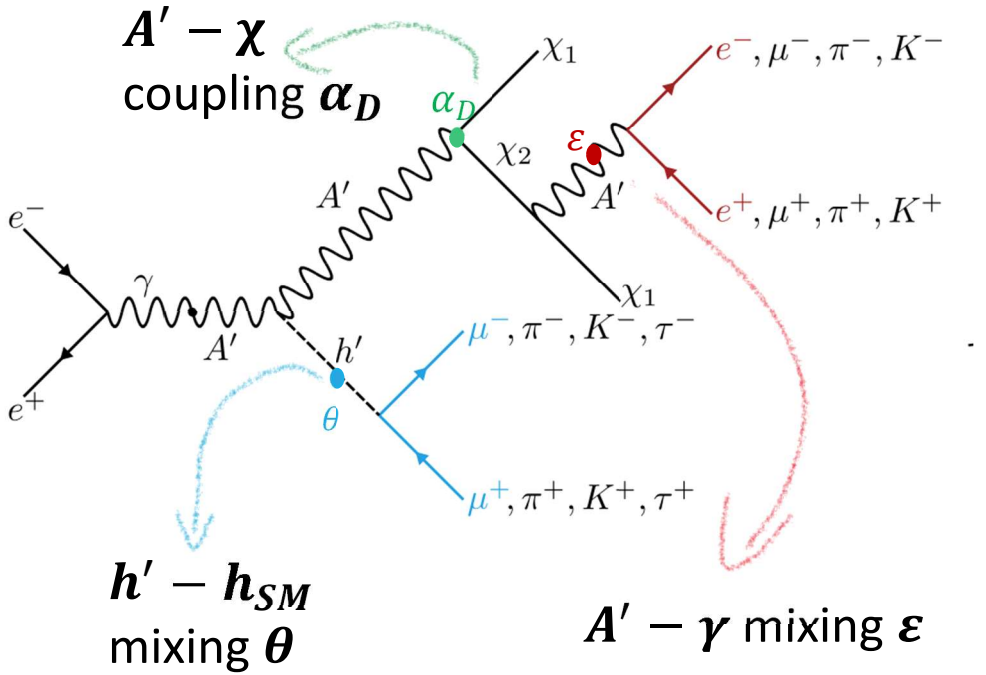
- Visible decay to SM particles: allow to search for DS mediators
- Invisible decay to DM candidates or DS mediators in final states with missing energy
- Suppressed decays to SM lead to long-lived mediators

Inelastic dark matter with a dark Higgs

arXiv: 2505.09705 (2025)

- Model with inelastic coupling between DM and SM [PRD 64, 043502 (2001)]
- Four dark sector particles
  - Dark photon A'
  - Dark higgs boson h'
  - Two dark matter states χ_1 , χ_2 with mass splitting Δm_χ $(\chi_2 > \chi_1)$

- **χ_2 is long lived** and can decay into DM, while χ_1 is a stable (relic DM candidate)
- **h' is long lived**



Analysis with 365 fb^{-1} in the channel:

$e^+ e^- \to h'(\to x^+x^-)\text{A}'\left(\chi_1\chi_2 \to (\to \chi_1 e^+e^-)\right)$ where $x \in (\mu, \pi, K)$

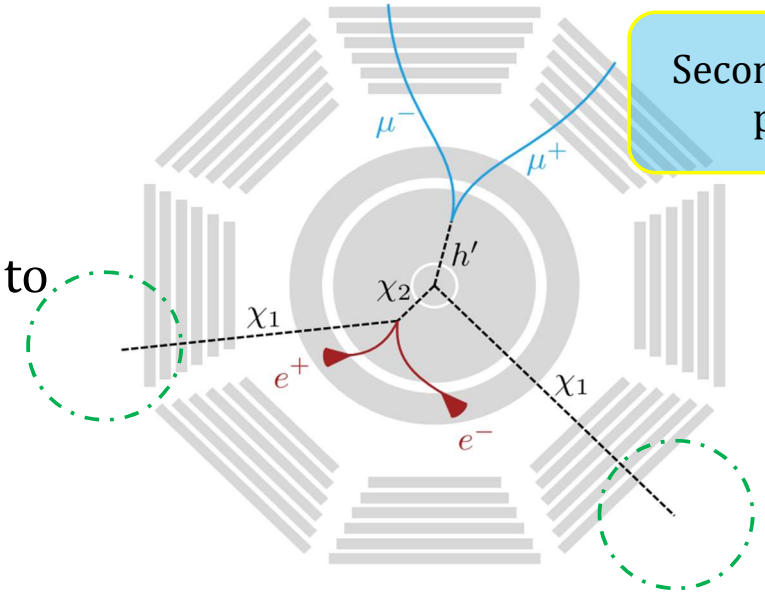
- e^+e^- final state chosen because of better trigger performance (ECL)

Inelastic dark matter with a dark Higgs

arXiv: 2505.09705 (2025)

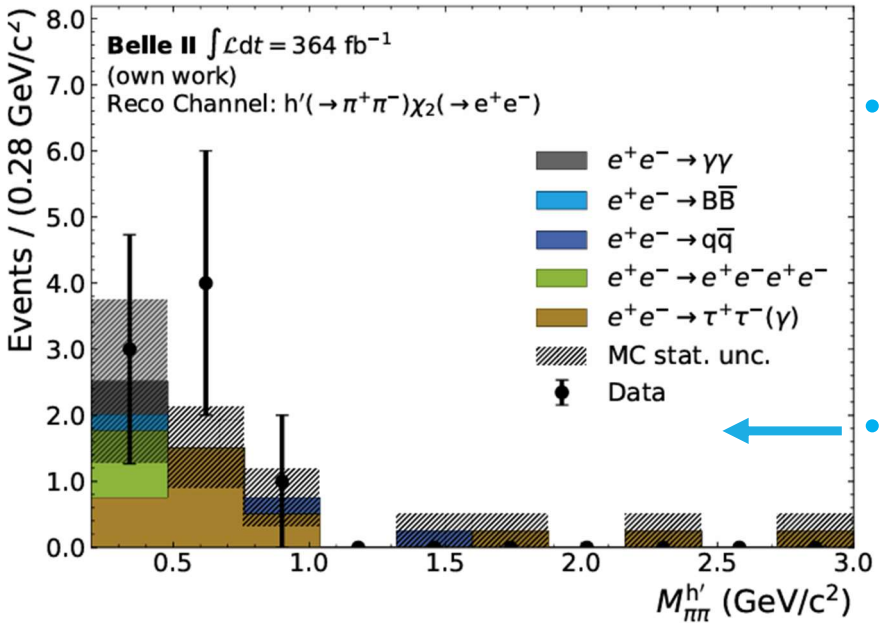
Events reconstruction require :

- Two displaced vertices
  - $h'(\rightarrow x^+x^-)$ pointing back to IP
  - $\chi_2 \rightarrow \chi_1 e^+e^-$ non-pointing back to IP displaced vertex
- Missing energy due to χ_1



Second search for long lived particles at Belle II

Experimentally challenging for trigger due to presence of displaced vertices!



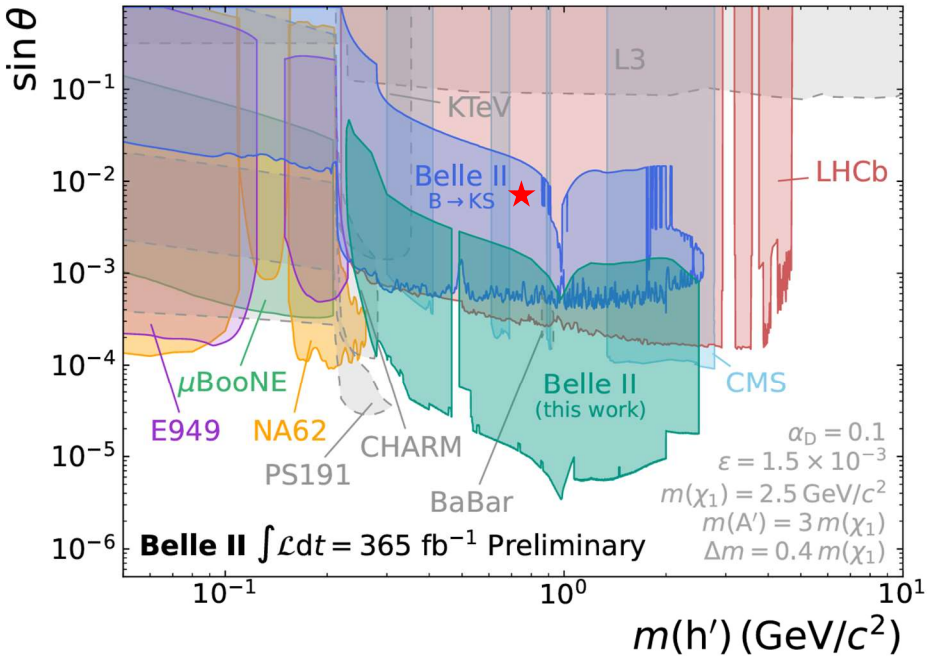
- Exploiting the characteristic of h' **pointing back to IP**
  - Almost **zero background**
  - Veto the K_S^0 mass region
- **Search for a bump in the h' invariant mass $M_{h'}$**
  - cut and count method
  - Background estimated from sideband regions

Inelastic dark matter with a dark Higgs

arXiv: 2505.09705 (2025)

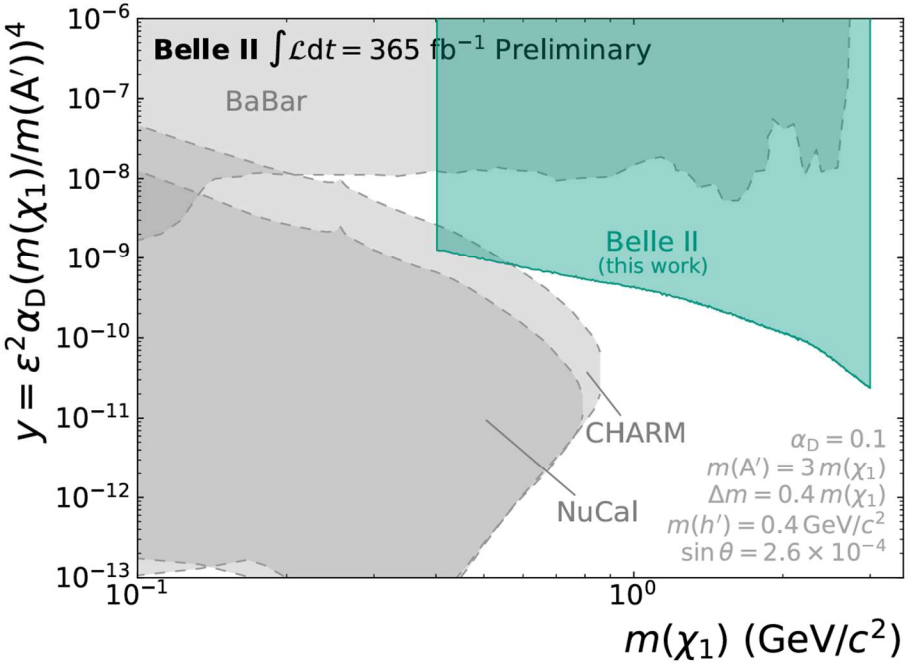
No significant excess found in data

- set 95% CL upper limits model independent on the cross section
- set 95% CL upper limits model dependent on θ and $\varepsilon^2 \times \alpha_D$, **which are the most stringent limits**



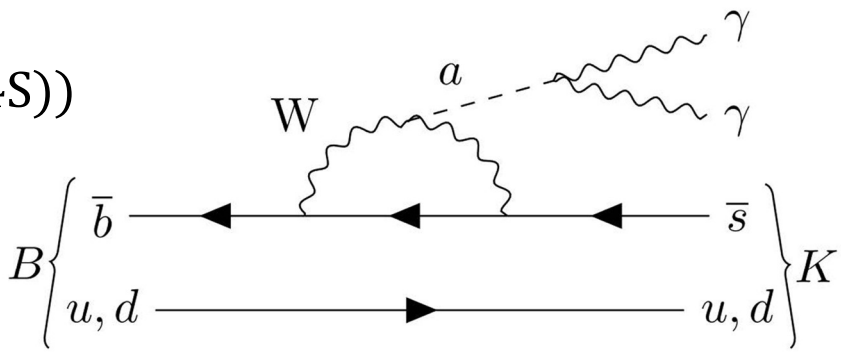
★ Firs search for long lived particles at Belle II

~30 plots produced for different parameter configurations



Search for $B \rightarrow K^{(*)} a(\rightarrow \gamma\gamma)$

Belle analysis with 711 fb^{-1} ($772 \cdot 10^6$ of $\Upsilon(4S)$)



Search targeting Axion-Like Particles (ALPs) in the **MeV-GeV** mass range and their coupling with W boson g_{aW}

- Four kaon modes included: $K_S^0, K^+, K^{*+}, K^{*0}$
- $\mathcal{B}(a \rightarrow \gamma\gamma) \sim 100\%$ when $m_a \ll m_{W^\pm}$
- m_a investigated between **0.16 – 4.50 (4.20) GeV** for K (K^*) modes

Previous limits from BaBar, which used only $B^+ \rightarrow K^+ a$ and smaller dataset [PRL.128.131802]

Signal B candidates reconstructed by combining two photons and one candidate K

- Constrain mass and energy exploiting **no missing energy** in final state:
- $M_{bc} = \sqrt{E_{beam}^2 - p_B^2} > 5.27 GeV$
- $\Delta E = E_B - E_{beam}$ between -0.2 and 0.1 GeV

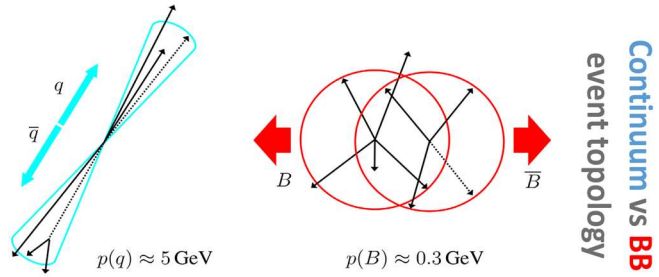
Search for $B \rightarrow K^{(*)}a(\rightarrow \gamma\gamma)$

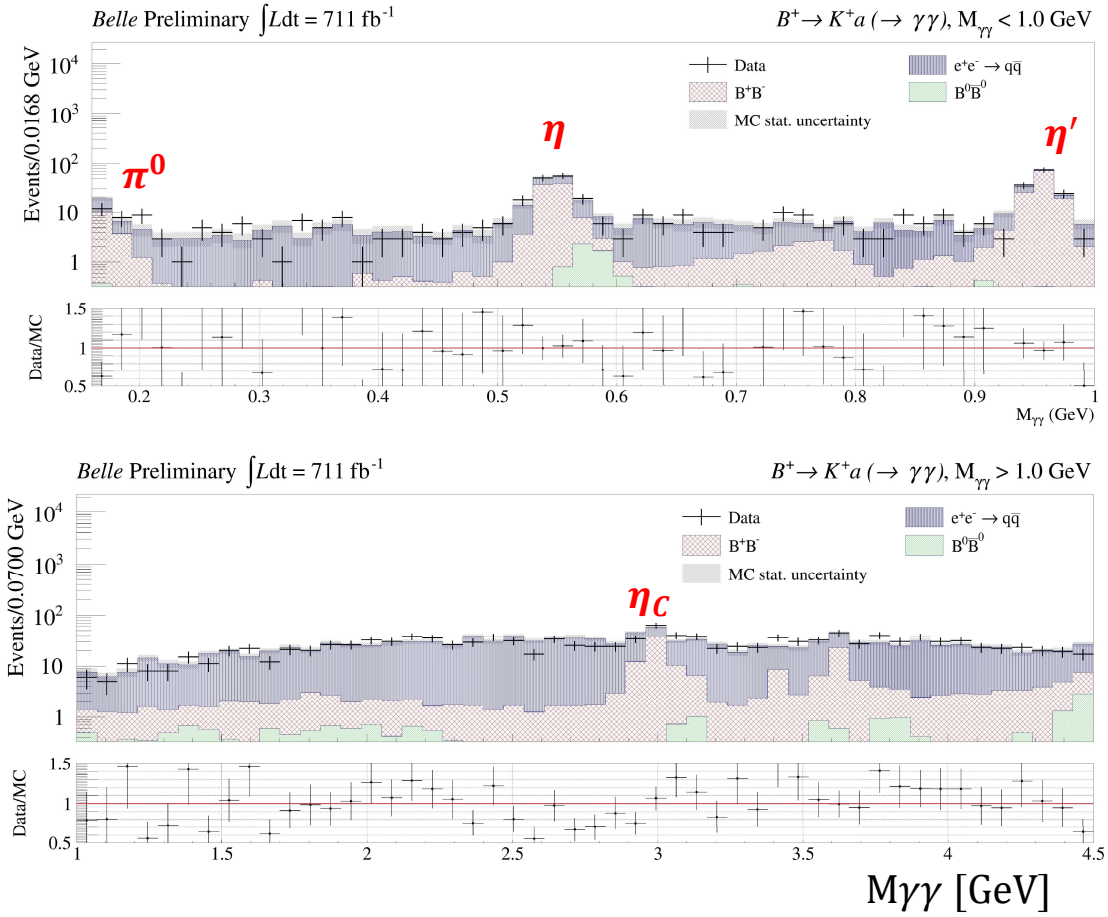
Background contributions:

- Mainly from $e^+e^- \rightarrow q\bar{q}$ (continuum)
- Rejected with a Boosted Decision Tree (BDT) based on kinematics and topology variables
- $\pi^0 \rightarrow \gamma\gamma$ rejected with calorimeter cluster requirements

Signal extraction:

- **Fit the di-photon invariant mass** and extract signal yield
- Peaking background regions are vetoed (π, η, η')
- Use B $\rightarrow Kh(\rightarrow \gamma\gamma)$ to validate signal extraction method





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

Simultaneous fit on all four K modes show no significant excess

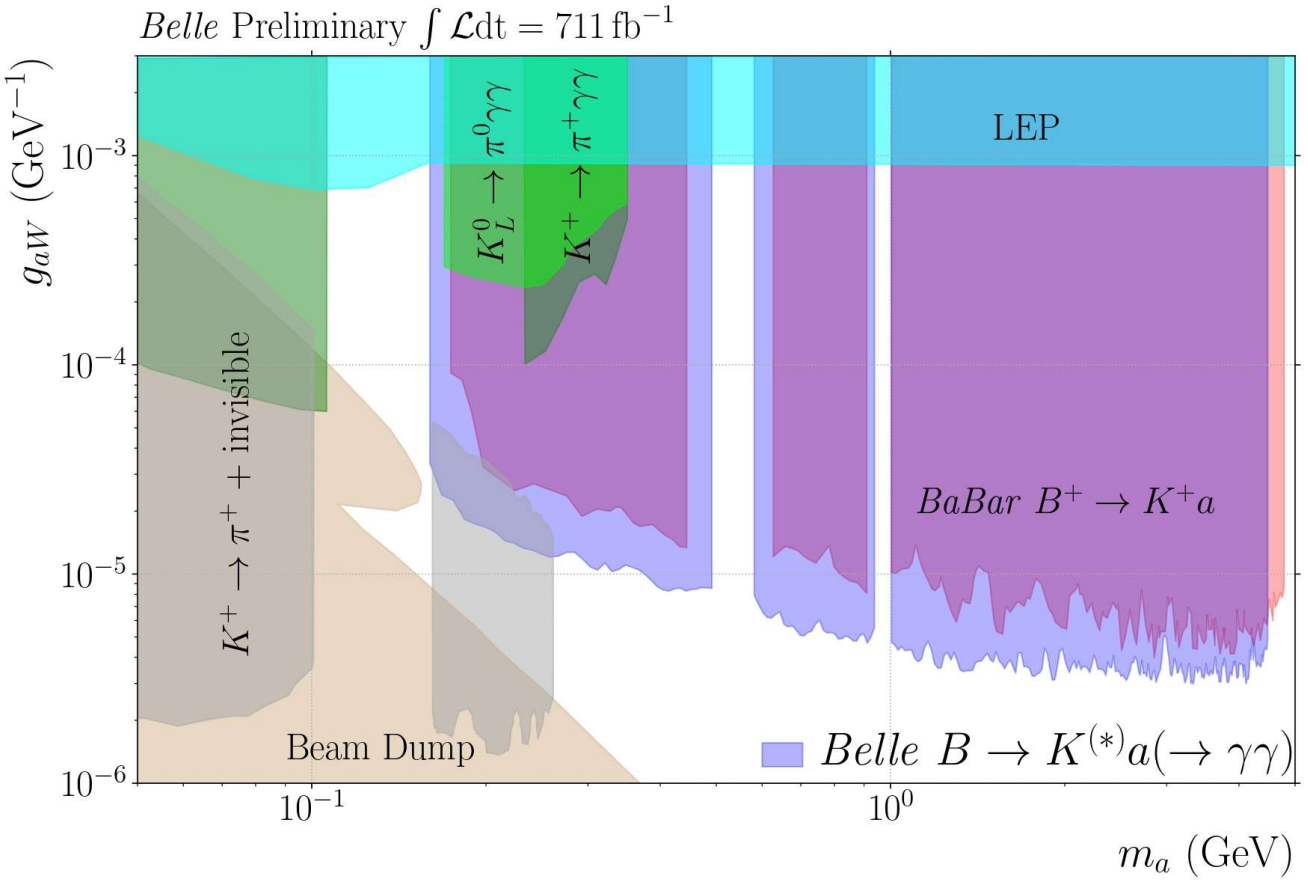
World leading 90% CL upper limits on coupling g_{aW}

improved at least by factor 2 from BaBar

ALP lifetime (100mm – 500mm) has an impact especially in the low mass and low coupling region

- Drop in the signal efficiency taken into account

Submitted to JHEP



Summary and Outlook

- Belle and Belle II have a unique sensitivity to dark matter particles in the MeV-GeV mass region
  - Provide world leading limits in many searches
  - Full list of publications targeting dark sector in backup

Here briefly presented the latest analyses:
- **Inelastic dark matter and dark higgs , submitted to PRL** (Belle II)
- **Search for ALPs in B meson decays , submitted to JHEP** (Belle)

- We expect to be **even more competitive**, see details in our Snowmass report: arXiv: 2207.06307
  - Increase dataset size, for which we have already reliable limit projections
  - Improved analysis techniques
  - Better understanding of the detector
  - Many more analyses ongoing

Stay tuned!

Backup

Belle and Belle II dark sector searches

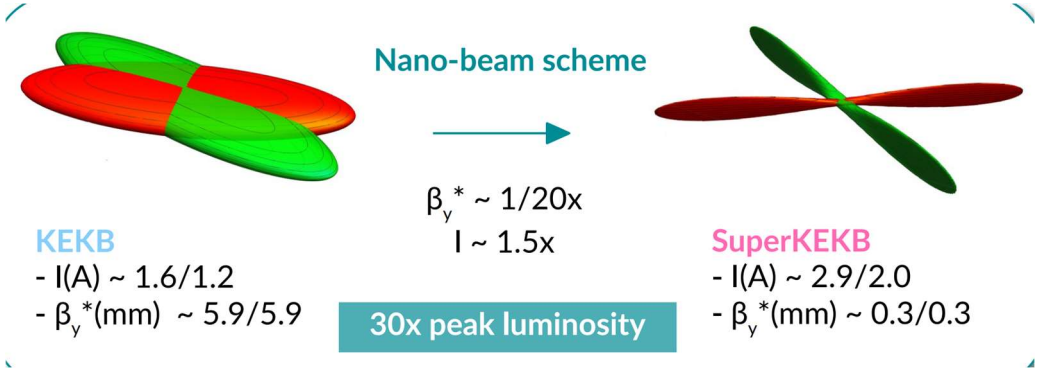
Belle

- $e^+e^- \to h'(\to A'A')A'(\to x^+x^-)$ with $x = e, \mu, \pi$ ..... [PRL 114.211801] (2015)
- $e^+e^- \to Z'(\to \mu^+\mu^-)\mu^+\mu^-$ .....[PRD 106.012003] (2022)
- Dark leptophilic scalar ϕ_L in $e^+e^- \to \tau^+\tau^-\phi_L(\to \ell^+\ell^-)$ .....[PRD 109.032002] (2024)
- Heavy neutral lepton N in $\tau^- \to \pi^- N(\to \mu^+\mu^-\nu_\tau)$.....[PRD 109.L111102] (2024)
- $\tau \to \ell\alpha$ .....[arXiv 2503.22195] (2025)

Belle II

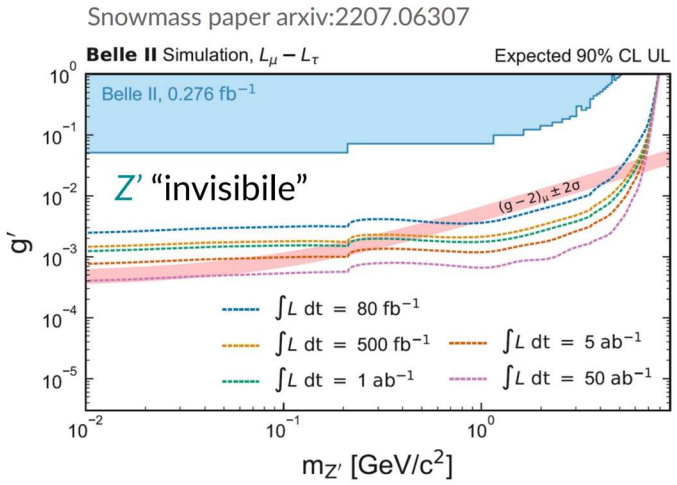
- $e^+e^- \to \gamma a(\to \gamma\gamma)$ .....[PRL 125.161806] (2020)
- $e^+e^- \to \mu^+\mu^- Z'$ and $e^+e^- \to e^{\mp}\mu^{\pm}Z'$ .....[PRL 124.141801] (2020)
- $\tau \to \ell\alpha$ .....[PRL 130.181803] (2023)
- $e^+e^- \to A'(\to \mu^+\mu^-)h'$ .....[PRL 130.071804] (2023)
- $e^+e^- \to \mu^+\mu^- Z'$ .....[PRL 130.231801] (2023)
- Non SM resonance in $\mu^+\mu^-\tau^+\tau^-$ final state .....[PRL 131.121802] (2023)
- Long lived spin 0 mediator in $b \to s$ transitions..... [PRD 108.L111104] (2023)
- Non SM resonance in 4 muon final state..... [PRD 109.112015] (2024)

Second generation B-factory



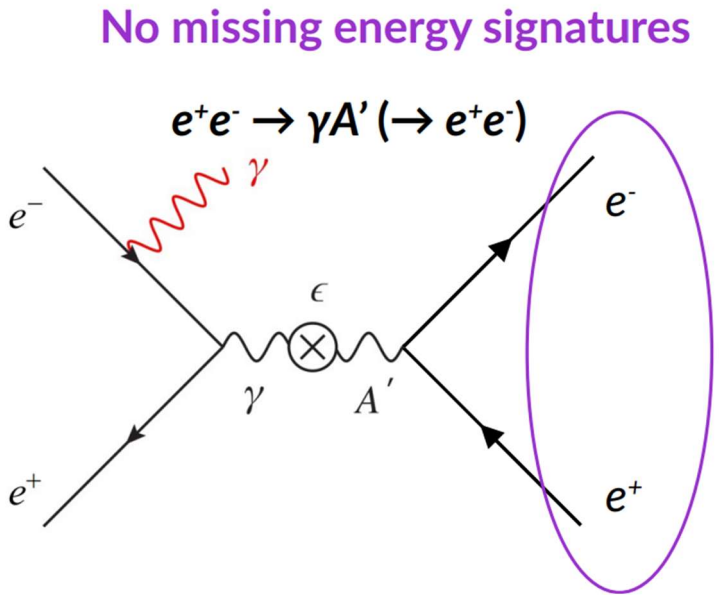
- Collision scheme difference between KEKB (first generation) and SuperKEKB (secondo generation)
- SuperKEKB designed to reach peak world luminosity

- Belle II@SuperKEKB luminosity projection
- Many world-leading results limited by statistics → expected major improvements



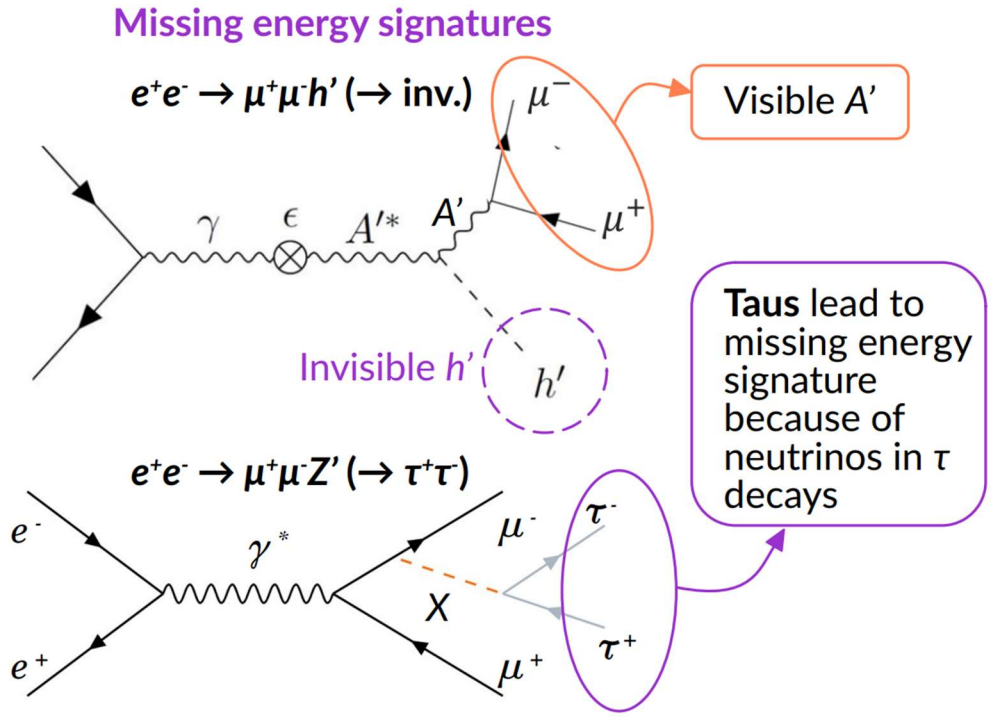
Visible & invisible final state

Visible decay



Visible: DM mass as invariant mass of final state particles → better resolution

Invisible decay



Invisible: DM mass as recoil mass against final state particles

Search for $B \to K\,S$

PRD 108 (2023) L111104

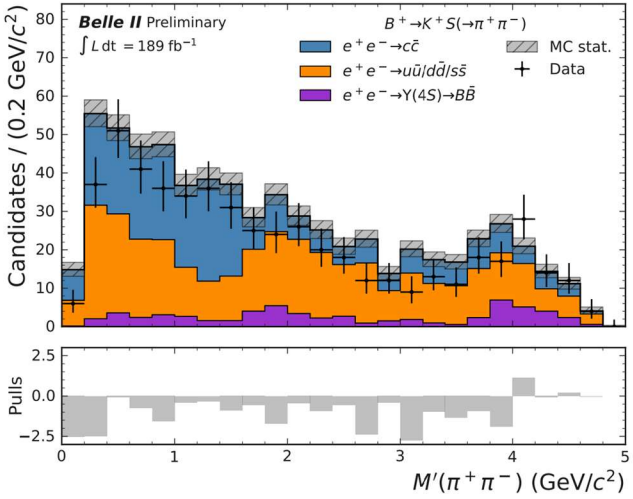
- Dark sector scalar particle S
  - *Higgs-like,* couples with Higgs SM via angular parameter θ
  - ALP type scalar
- For $m_s < m_B$ search in SM decay
- **First** search for a **long lived** scalar at Belle II!

Analysis at Belle II with $\mathbf{189 fb^{-1}}$: PRD 108 (2023) L111104

- Channels: $\boldsymbol{B^+ \to K^+(S \to x^- x^+)}$ e $\boldsymbol{B^0 \to (K^{*0} \to K^+\pi^-)\,(S \to x^- x^+)}$
  - $x^- x^+ = [e^- e^+, \mu^- \mu^+, \pi^- \pi^+, K^- K^+]$
- Many lifetime hypothesis : $\boldsymbol{0.001 < c\tau_S < 400\ cm}$
- B fully reconstructed, constraint on mass $M_{bc} = \sqrt{s/4 - |\overrightarrow{p_B^*}|}$

S reconstructed from two identical particles with vertex fit and on invariant mass $M'(x^- x^+) = \sqrt{M^2(x^- x^+) - 4m_x^2}$

- Search for peak in the $M'(x^- x^+)$ distribution + fit
- Background: $e^- e^+ \to B\bar{B}$, $e^- e^+ \to q\bar{q}(\gamma)$, $e^- e^+ \to \tau\bar{\tau}(\gamma)$, flat in the interesting variable
- Control sample K_S^0

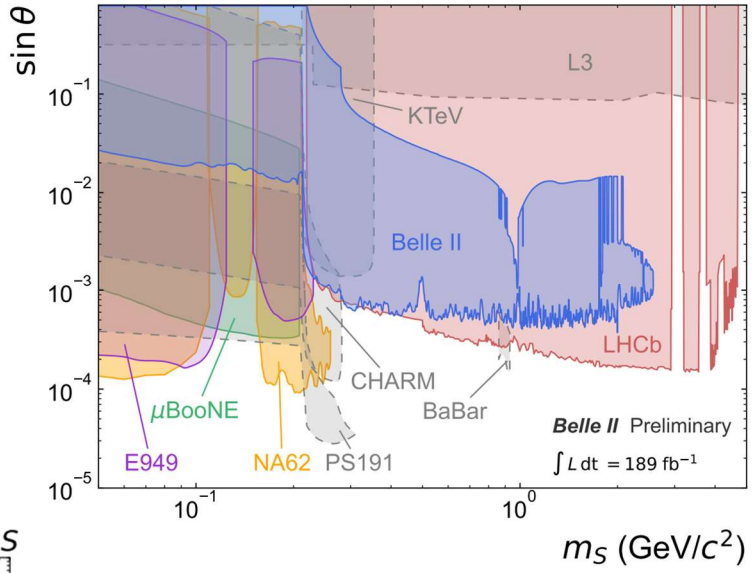


Search for $B \to K\,S$

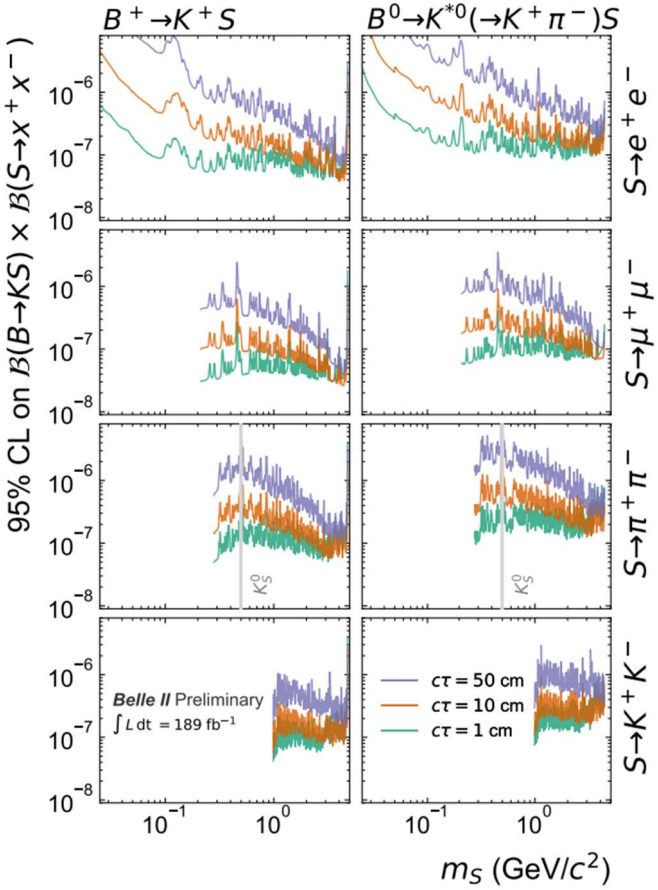
PRD 108 (2023) L111104

- Dark sector scalar particle S
  - *Higgs-like,* couples with Higgs SM via angular parameter θ
  - ALP type scalar
- For $m_s < m_B$ search in SM decay
- **First** search for a **long lived** scalar at Belle II!

- **No excess found**



Limits on ***Br***



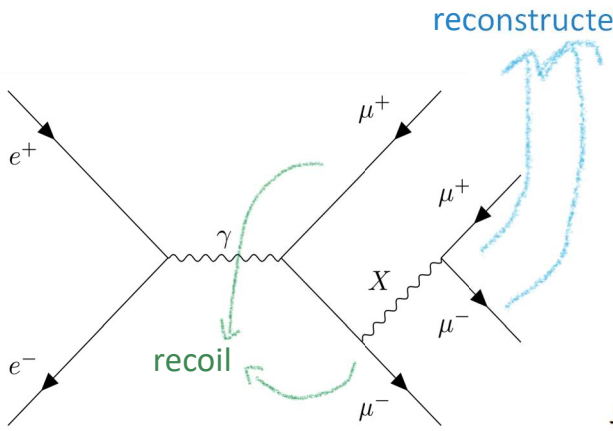
- **First limits for S in hadrons**
- **Most stringent limits** for direct search in $K^{(*)}e^-e^+$

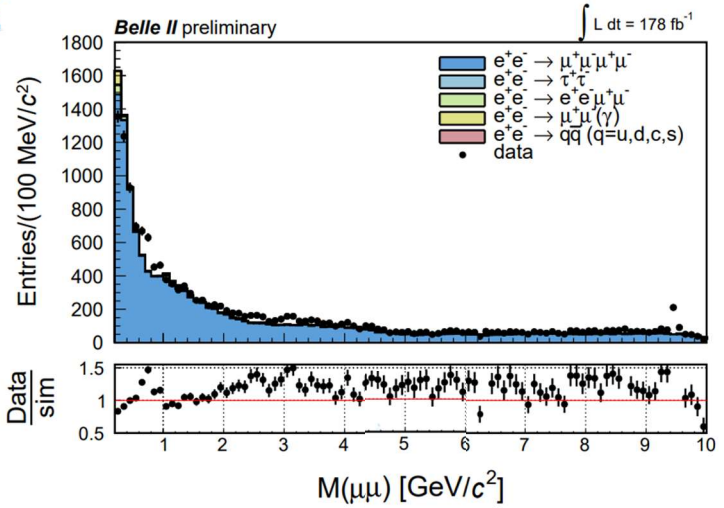
Search for $X \rightarrow \mu\mu$

- Part of a broad BSM search as a solution of $(g-2)_\mu$ and other SM discrepancies
- X as Z$'$ of a LFUV $L_\mu - L_\tau$ model, where it couples onyl to 2° and 3° lepton family
  - Search for Z' already made by Babar, Belle, Cleo and Belle II
- X as scalar S with Yukawa coupling only to μ

Belle II analysis with $\mathbf{178\ fb^{-1}}$: arxiv:2403.02841

- Channel with 4 charged tracks of which at least 3 identified as muons; and a fit on the total invariant mass
- Two reconstructed muons, two muons as recoil
- search for a peak in the invariant mass $M_{\mu\mu}$ of the two reconstructed μ





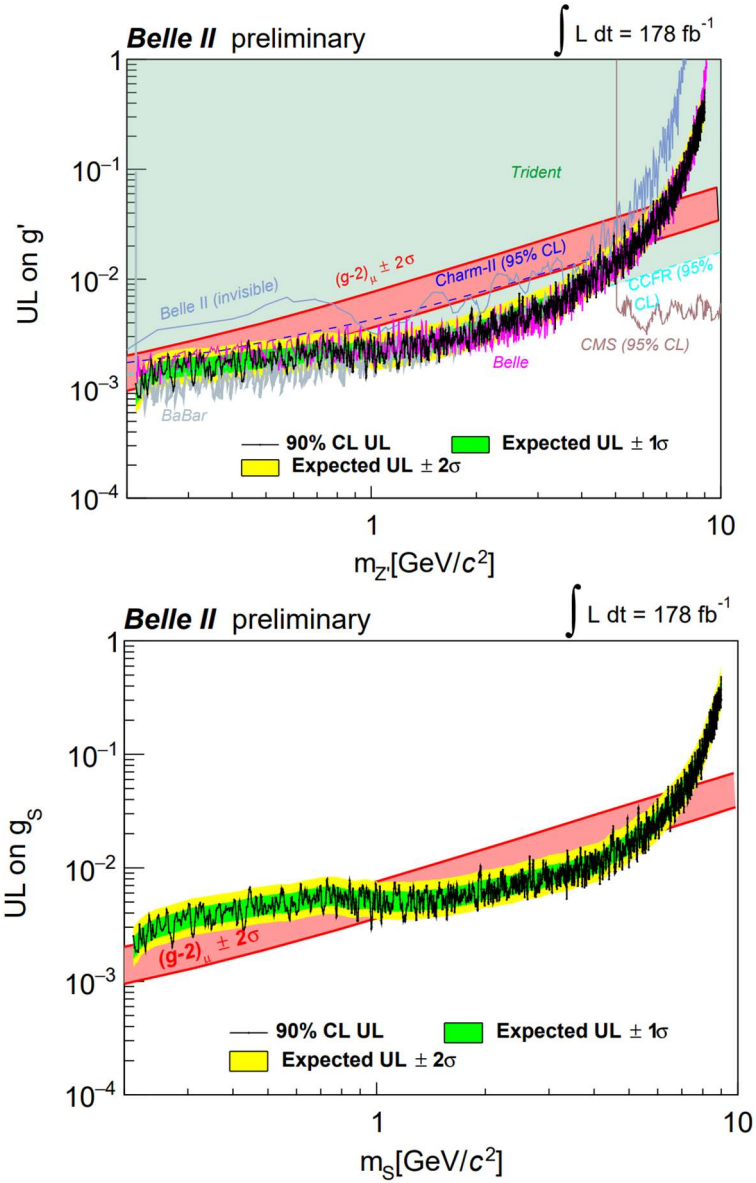
- Main background: $e^-e^+ \rightarrow \mu^-\ \mu^+\ \mu^-\ \mu^+$
- Background suppressed witha classifier based on kinematic distributions (helicity angle, momentum distributions, ecc)

Search for $X \rightarrow \mu\mu$

- Part of a broad BSM search as a solution of $(g-2)_\mu$ and other SM discrepancies
- X as Z$'$ of a LFUV $L_\mu - L_\tau$ model, where it couples onyl to 2° and 3° lepton family
  - Search for Z' already made by Babar, Belle, Cleo and Belle II
- X as scalar S with Yukawa coupling only to μ

No significant excess found

- 90% CL upper limits on coupling parameters in the two models



- **Competitive limits** with Belle and BaBar ones, but lower luminosity
- **First limits** on muonphilic scalar