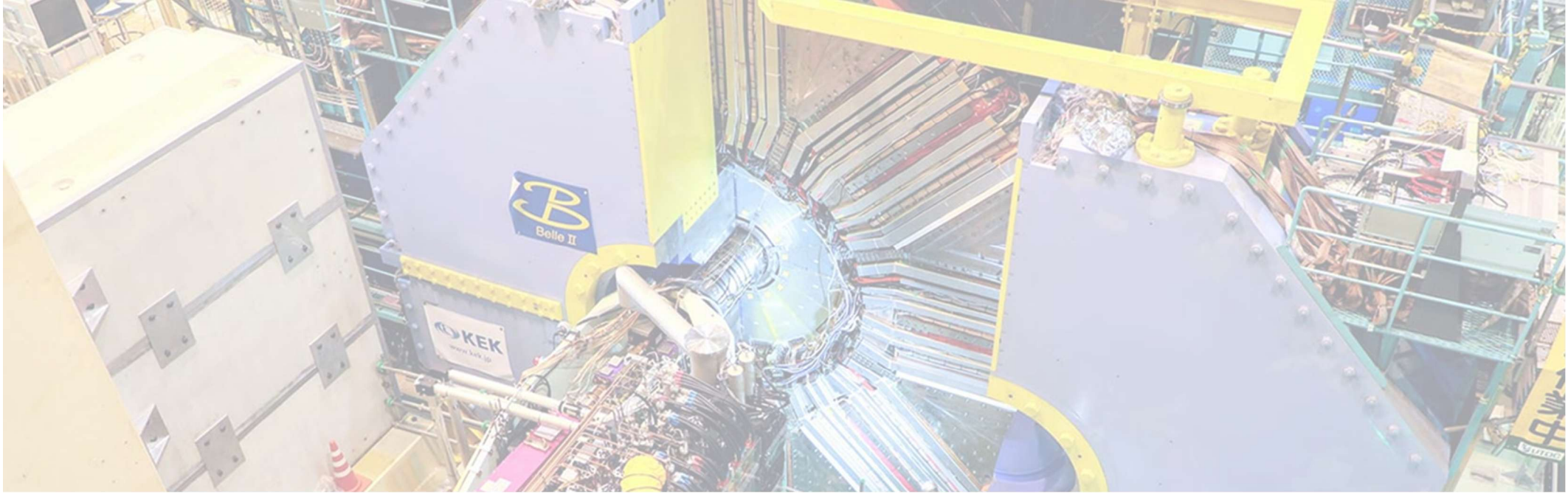
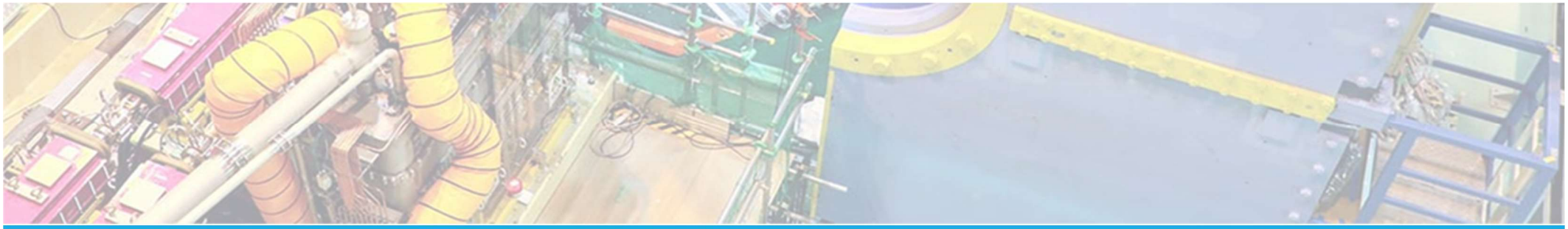


Results from Belle and Belle II for Dark Sector searches

WIFAI, November 11-14th 2025, Bari
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

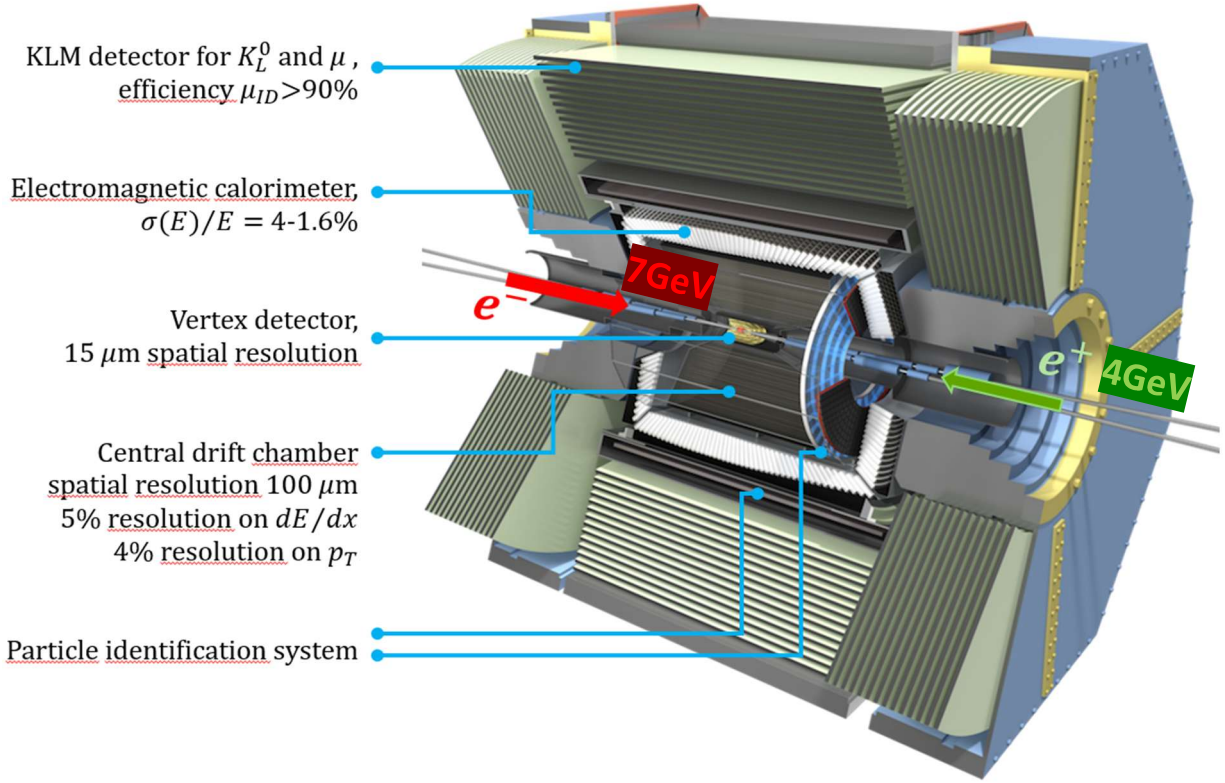
Belle II @ SuperKEKB – run 1 (2018 -2022), run 2 (feb 2024 -): second generation, collected 0.6 ab^{-1}

- **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**



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

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

vector portal:

$$\frac{\epsilon}{2} B^{\nu\mu} A'_{\nu\mu}$$

scalar portal:

$$H^\dagger H(As + \lambda S^2)$$

pseudoscalar portal:

$$\frac{a}{f_a}(c_G \tilde{G}G + c_W \tilde{W}W + c_B \tilde{B}B)$$

neutrino portal:

$$Y_N^{ij} \bar{L}_i H N_j$$

Dark sector and Dark Matter at B-factories

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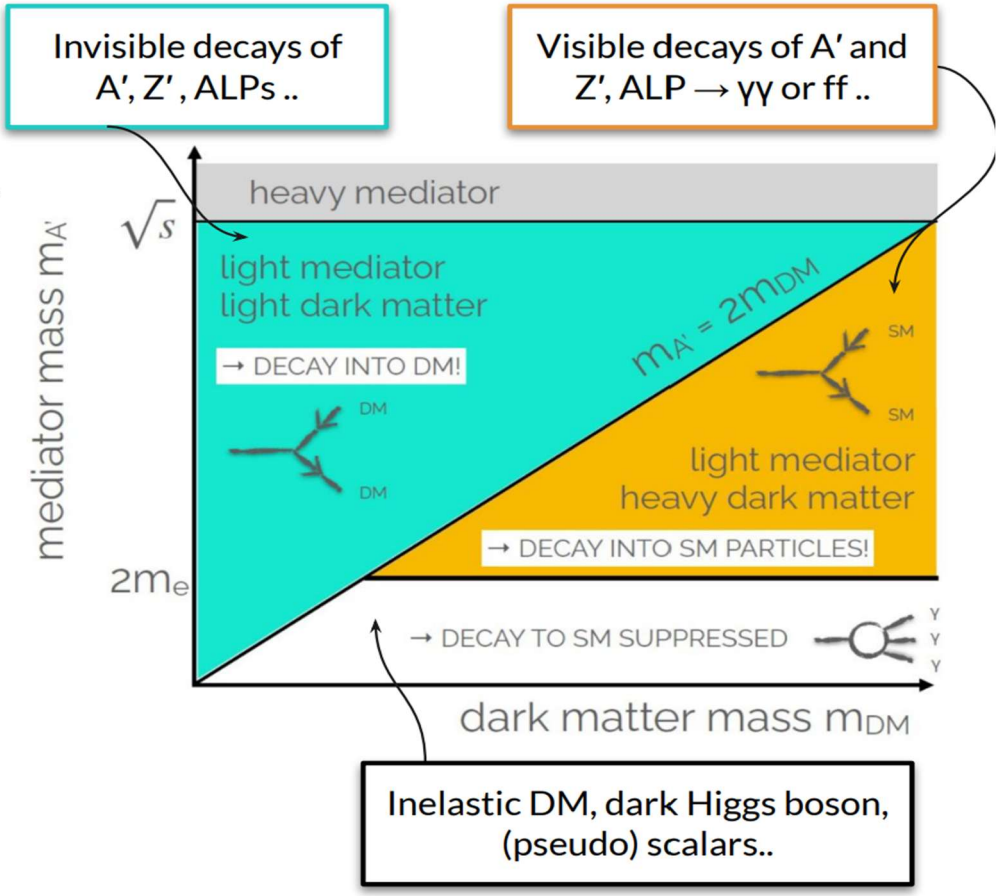
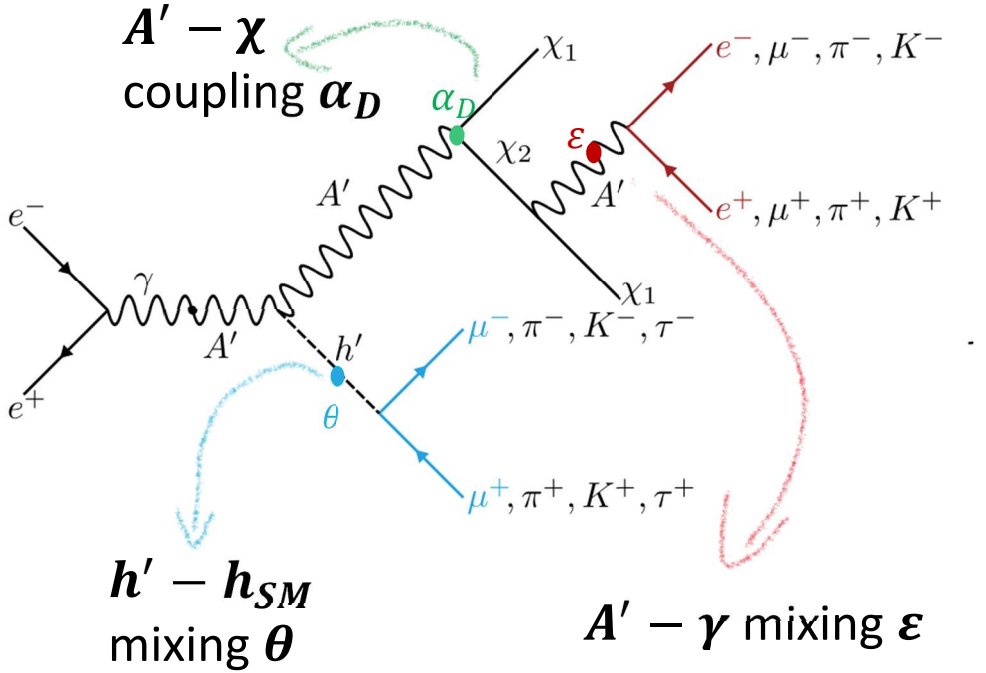


Inelastic dark matter with a dark Higgs

Phys. Rev. Lett. **135**, 131801

- 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:

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

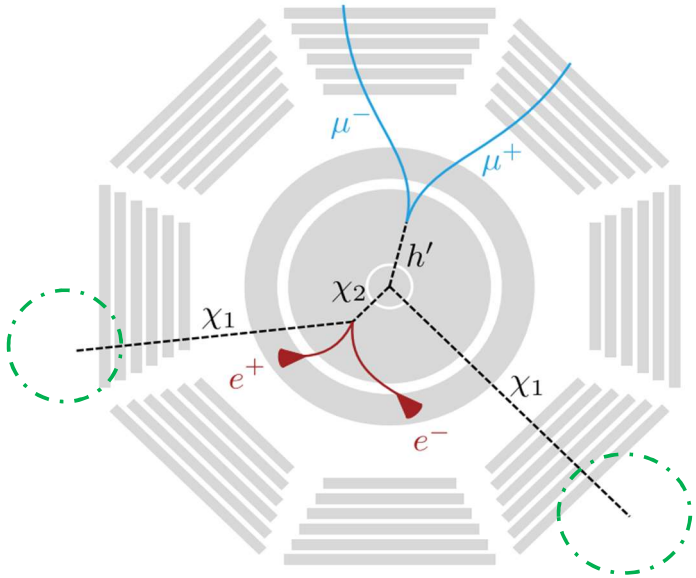
- e^+e^- final state chosen because of better trigger performance (ECL)

Inelastic dark matter with a dark Higgs

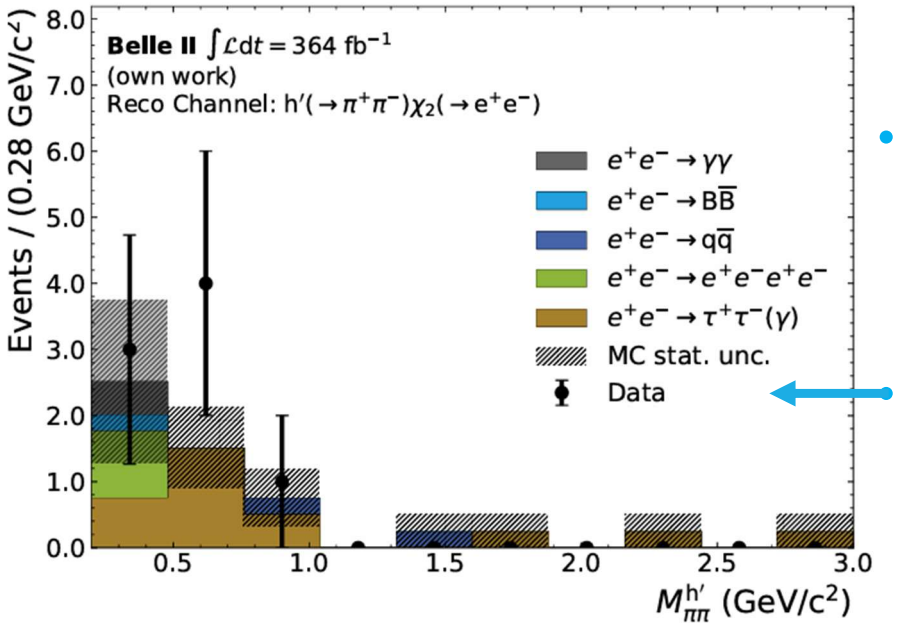
Phys. Rev. Lett. 135, 131801

Events reconstruction require :

- Up to 2 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



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
  - 0 events found in μ-channel, 1 in K-channel
- Background estimated from sideband regions

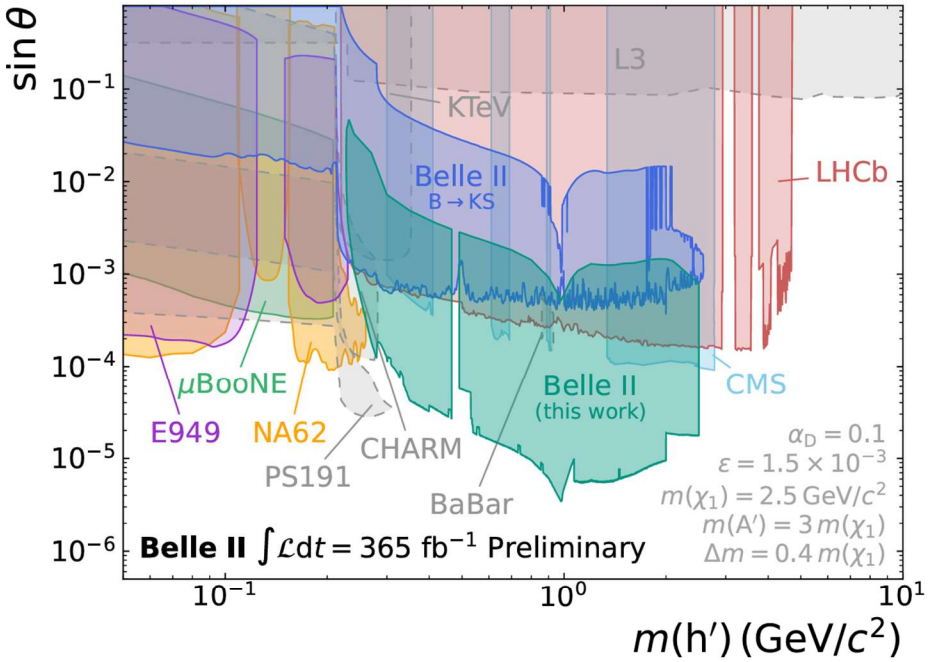
Inelastic dark matter with a dark Higgs

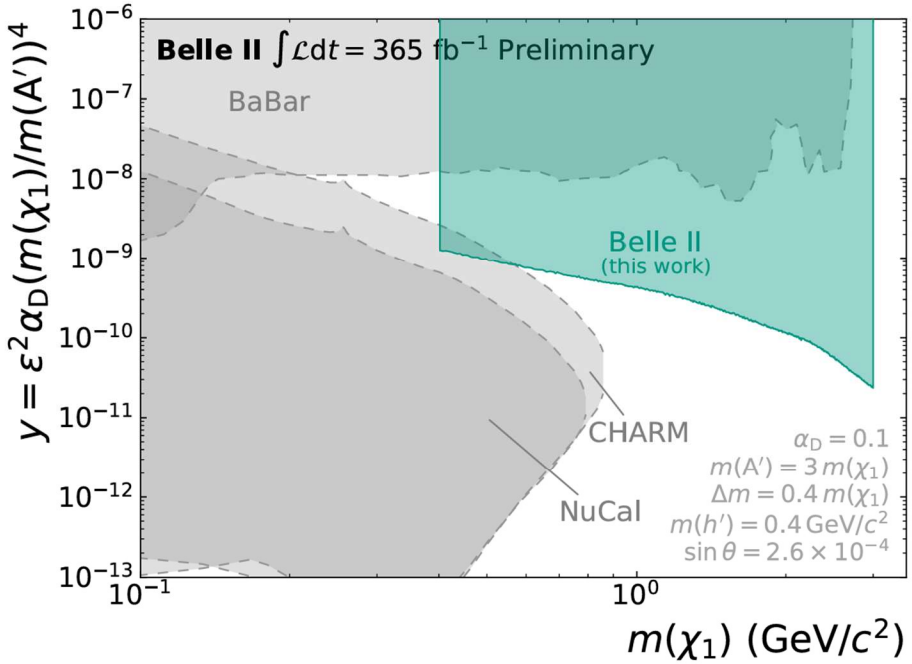
Phys. Rev. Lett. 135, 131801

No significant excess found in data

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

~30 plots produced for different parameter configurations

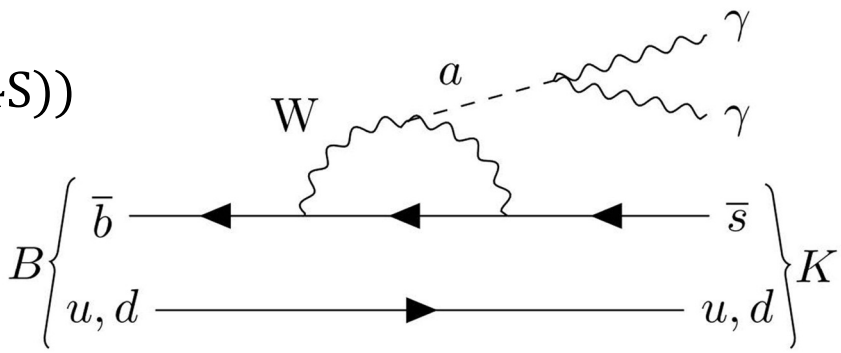




Search: $B \rightarrow K^{(*)} a(\rightarrow \gamma\gamma)$

New!
arxiv.2507.01249

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

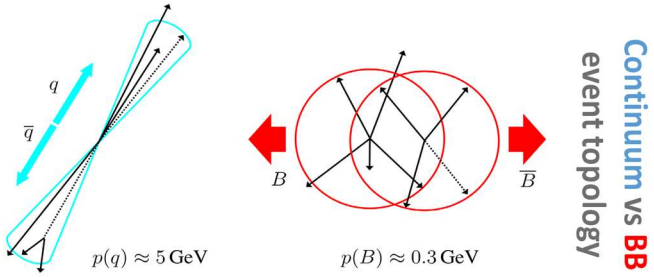
New!
arxiv.2507.01249

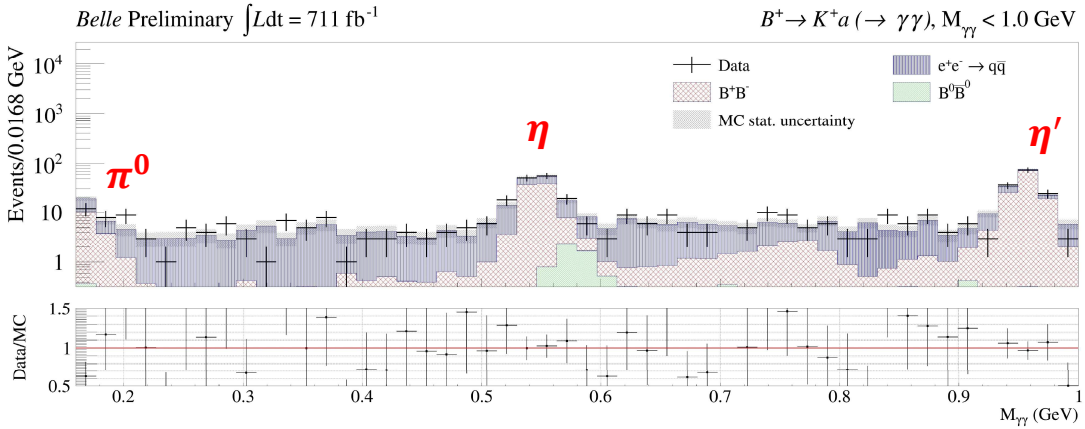
Background contributions:

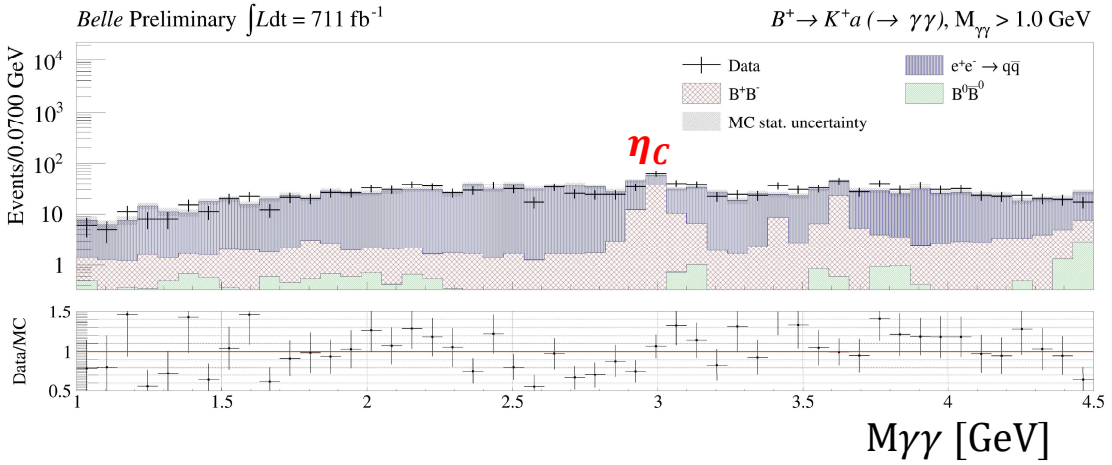
- Mainly from $e^+e^- \rightarrow q\bar{q}$ (continuum)
- Rejected with a Boosted Decision Tree (BDT) based on kinematics and topology variables
- Use of BDTs also to check whether the γ associated to the ALP do not originate from a π^0

Signal extraction:

- **Fit the di-photon invariant mass** and extract signal yield
- Signal peak parameters fixed from MC
- Peaking background (π, η, η') mass regions are excluded from signal extraction
  - Use them to validate signal extraction method







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

New!
arxiv.2507.01249

Simultaneous fit on all four channels show no significant excess

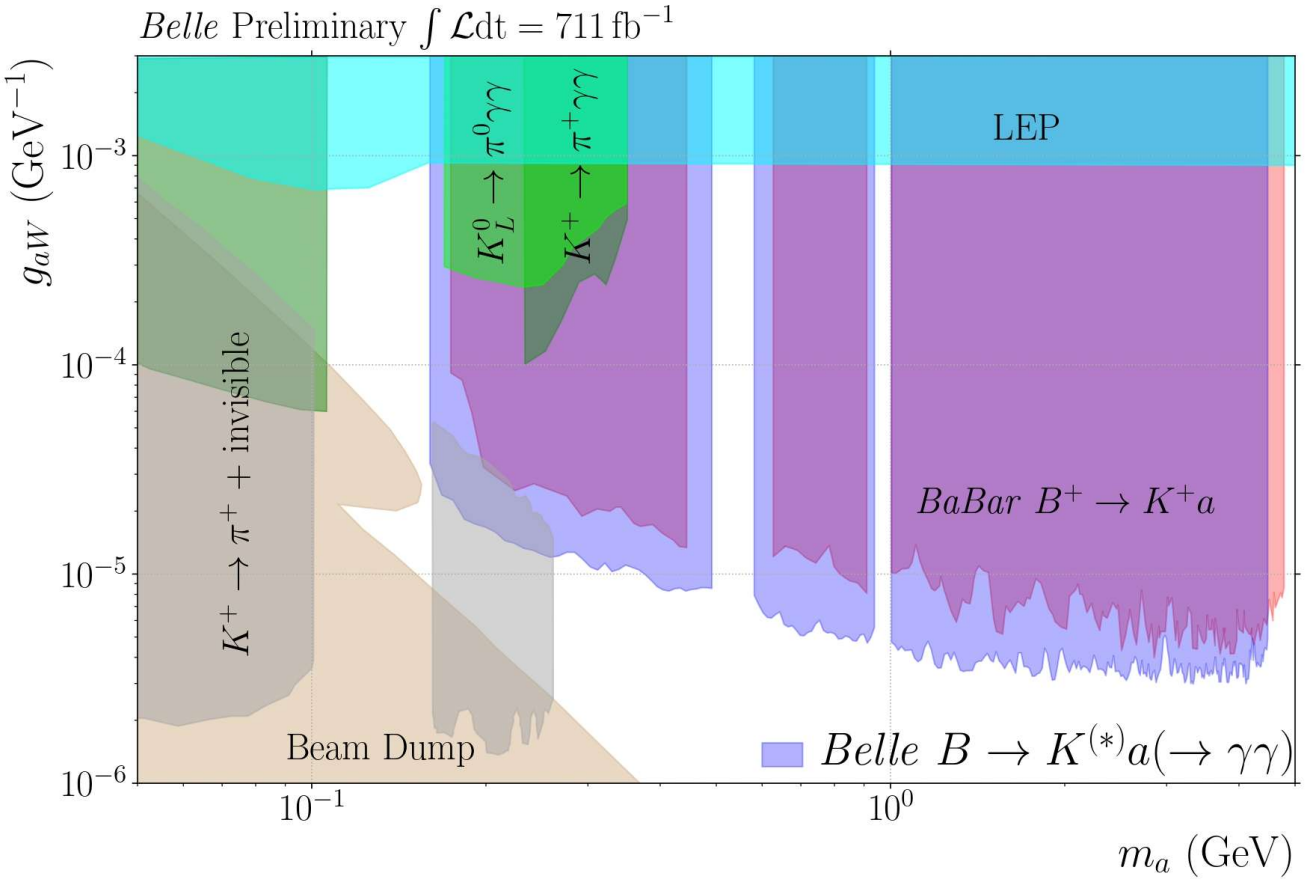
World leading 90% CL upper limits on coupling g_{aW}

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



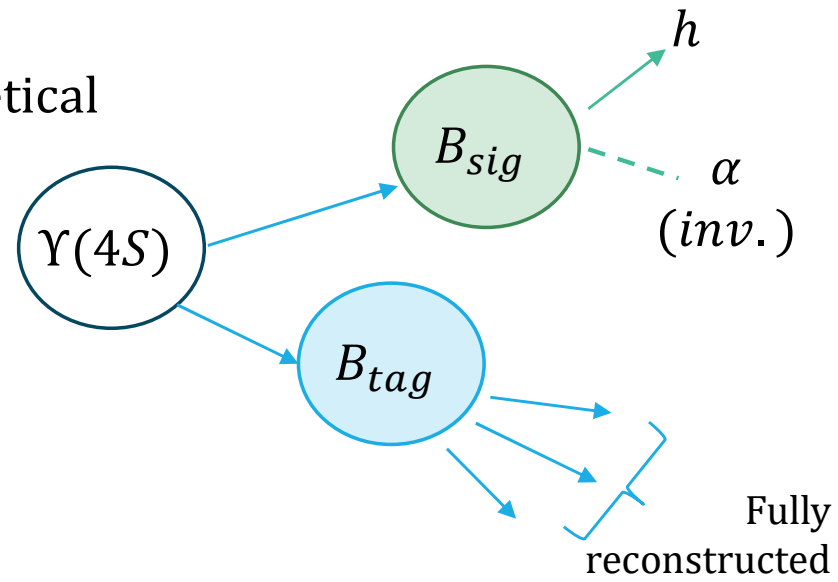
Feebly interacting particles as missing energy in B decays at Belle

Preliminary study

Many particles in BSM theories are FIP candidates.

- ALPs (as in prev. slides) are greatly motivated
- Scalars S as dark mediators
- Dark baryons

→ this search is broadly interpretable across theoretical scenarios



Channels chosen :

- $B_{sig} \to h\,\alpha$, with $h \in (\pi^{\pm}, K^{\pm}, p^{\pm}, D_s^{\pm}, \overline{D^0})$
- Range for m_α : from 1 MeV up to max 5 GeV depending on the channel (due to kinematics)
- Use **Belle full dataset** 711 fb^{-1} ($772 \cdot 10^6$ of $\Upsilon(4S)$)

Strategy

- **Reconstruct the full event** with B_{sig} and B_{tag} in order to **quantify the missing energy**
- **Exploit 2-body decay kinematics:** the hadron momentum $\overrightarrow{p_h}$ in the B_{sig} c.m.s. uniquely determines the mass of the invisible particle
- Search for a narrow bump in the hadron momentum through a scan

Feebly interacting particles as missing energy in B decays at Belle

Preliminary study

Event reconstruction and main selections common to all channels:

- Reconstruct $\boldsymbol{B_{tag}}$ with **Full Event Interpretation** (FEI): uses all final states particle to reconstruct the decay chain. Select particles offering best candidate
  - Require $\Delta E_{tag} = 0$
- **signal** $\boldsymbol{B_{sig}}$ partially reconstructed using only the hadron track, not used in FEI
  - Specific PID requirements for each channel
- Reconstruct Rest Of Event with all particles in the final state which are **not associated** to B_{tag} or B_{sig}
  - Require no additional tracks
  - Require energy deposits in ECL<1.5GeV

Background:

- Generic $B\bar{B}$ and continuum $q\bar{q}$ both rejected with a **BDT**
- **Peaking background** are treated differently
  - Narrow resonances are vetoed, e.g. **K mass region, $\boldsymbol{D^*}$ mass region vetoed**
  - Rare decays are modeled with same signal PDF

Feebly interacting particles as missing energy in B decays at Belle

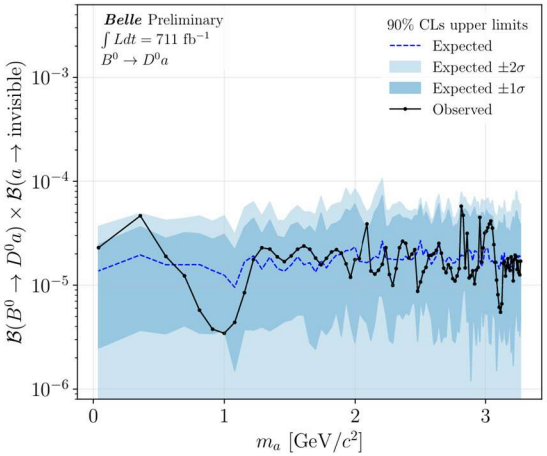
Preliminary study

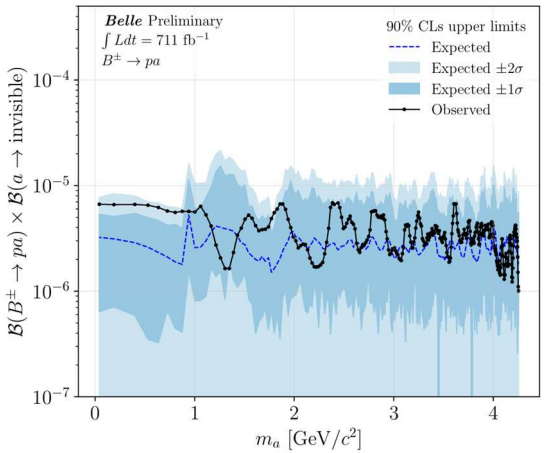
- Perform a fit on $\overrightarrow{p_h}$ in sliding window. The signal PDF parametrized as function of $\overrightarrow{p_h}$
- No excess is found, we **evaluate the 90%CL upper limits on the branching ratio**
- Compared to previous studies, these are the **most stringent**

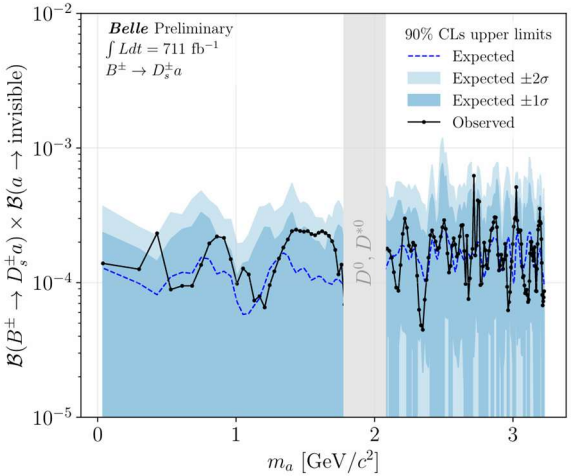
Decay measured in this work	Previous study	Decay measured in previous study
$B^\pm \to \pi^\pm$ inv.	Belle [11]	$B^\pm \to \pi^\pm \nu\bar{\nu}$
$B^\pm \to K^\pm$ inv.	Belle [11]	$B^\pm \to K^\pm \nu\bar{\nu}$
$B^\pm \to p^\pm$ inv.	BABAR [15]	$B^\pm \to p^\pm$ inv.
$B^\pm \to D_s^\pm$ inv.	N/A	N/A
$B^0 \to \overline{D}^0$ inv.	N/A	N/A

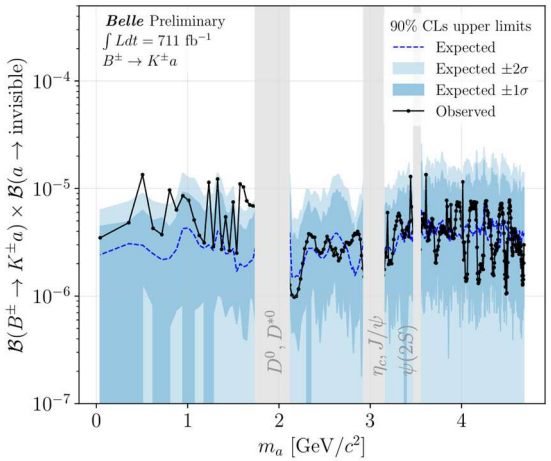
Previous world best	This work
1.4×10^{-5}	$\sim 10^{-6}$
1.6×10^{-5}	$\sim 10^{-6}$
$10^{-5} - 10^{-6}$	$\sim 10^{-6}$
N/A	$\sim 10^{-4}$
N/A	$\sim 10^{-5}$

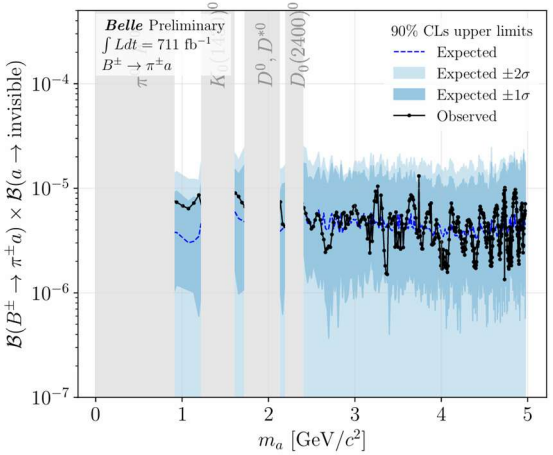
[11] P. R.D **96**, 091101
[15]P.R.L. 131, 20, 201801









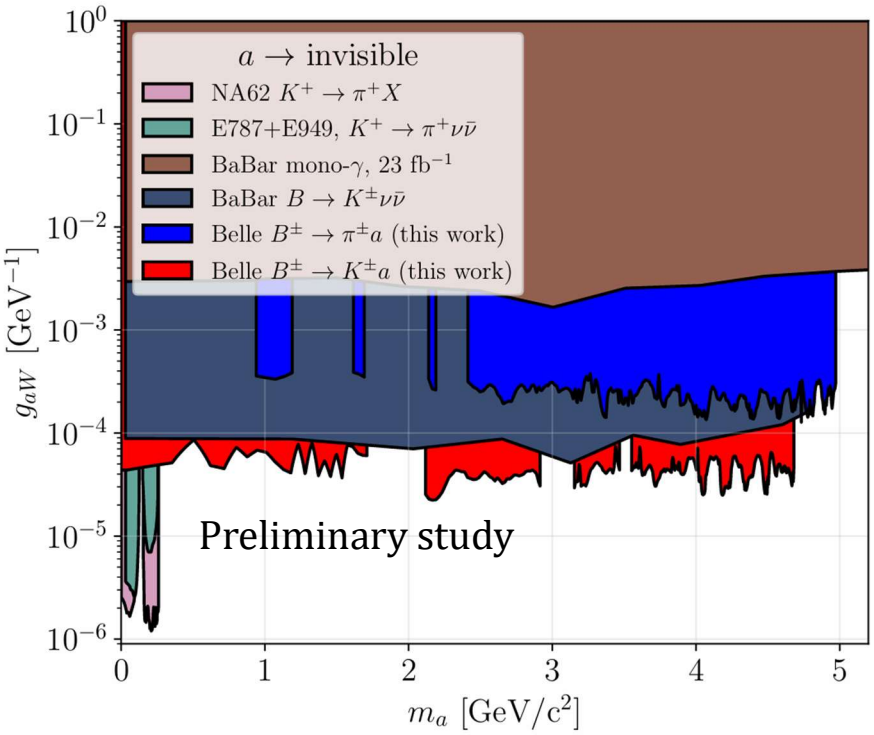


Feebly interacting particles as missing energy in B decays at Belle

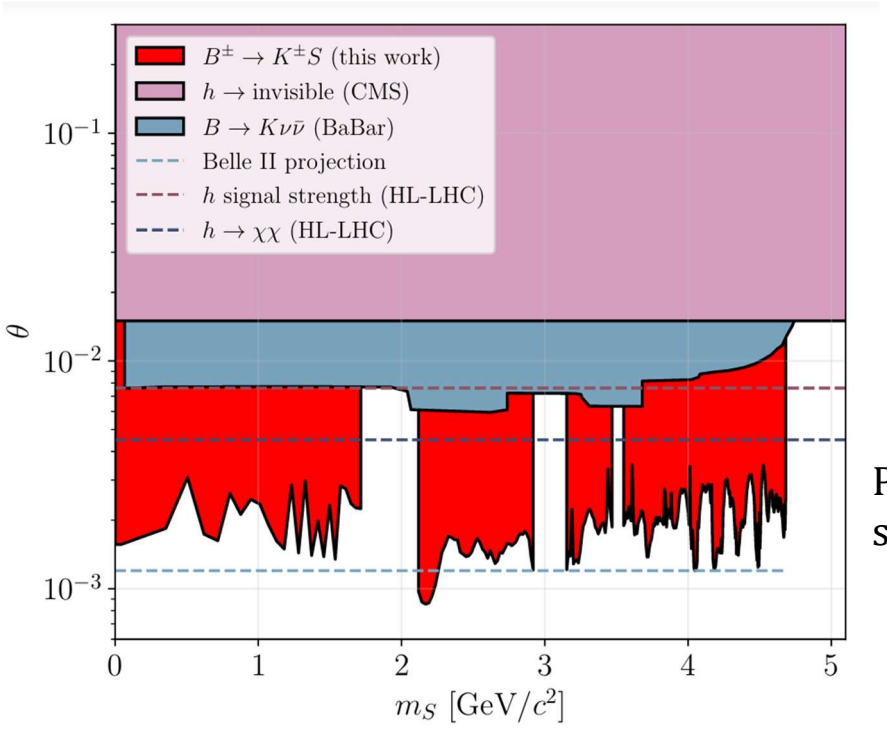
Preliminary study

Results reformulated for two different interpretations of the feebly interacting particle. Only the channels with most stringent limits are shown

Limits on the ALP-W coupling g_{aW} for an invisible ALP arising in FCNC from B decays



Limits on the θ_{mix} between a dark sector scalar S and SM particles, produced in rare B decays



Preliminary study

Summary

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

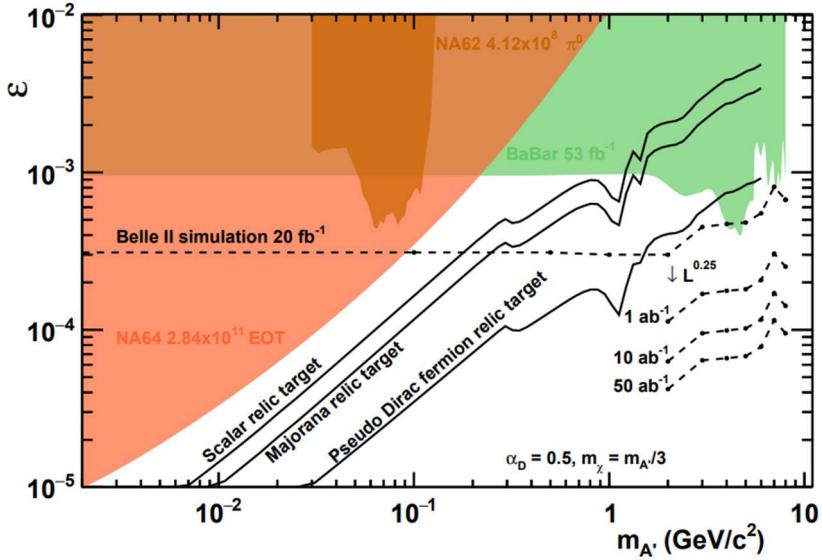
Here briefly presented the latest analyses:

- **Inelastic dark matter and dark higgs , published in PRL** (Belle II)
- **Search for ALPs in B meson decays, submitted to JHEP** (Belle)
- **Search for feebly interacting particles as missing energy** (Belle)

Outlook

- We expect to be **even more competitive**, see details in our Snowmass report:
  - Increase dataset size, for which we have already reliable limit projections
  - Second run ongoing!

- Analyses ongoin (non exhaustive):
  - Dark photon in visible final state
  - **Dark photon in invisibile final state**
  - IDM without Higgs boson
  - Simultaneous search for dark Higgs and dark photon
    - Both for visibile and invisible dark Higgs



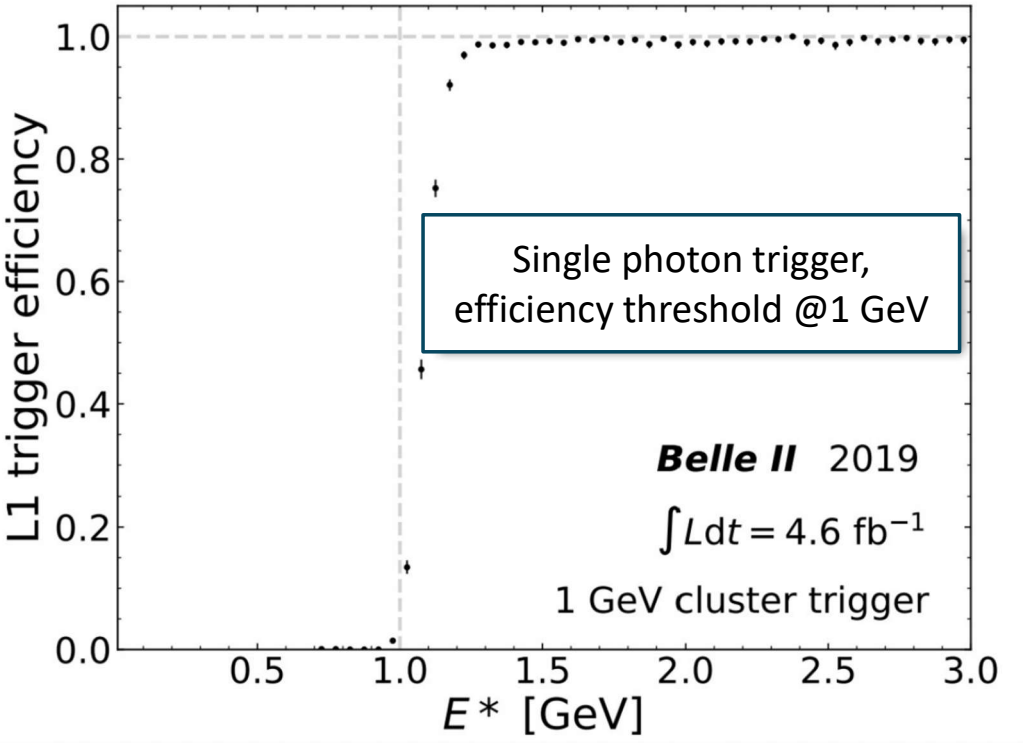
- Challenges:
  - Keep under control the higher background due to higher luminosity
  - Keep **single-object triggers** (track, photon, muon) at best condition
  - Implement displaced vertex trigger and tracking

Stay tuned!

Backup

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

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)