Dark Sector Searches at Belle and Belle II

on behalf of the Belle and Belle II collaborations

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Outline

- Introduction to dark matter
- *B*-factories
- Belle and Belle II experiment
- Dark sector searches at Belle and Belle II Experiment

  1. Inelastic dark matter with a dark Higgs

  - Axion-like-particle (ALP) searches

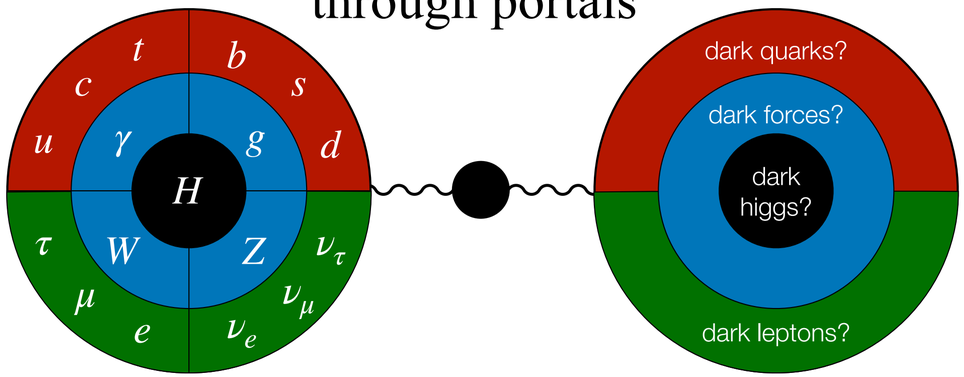
    2. $B \to Ka(\to x^+x^-)$ i.e. Long Lived ALP in B decays
    3. $B \to K^{(*)}a(\to \gamma\gamma)$

- Summary and Conclusion

Dark Sector - Introduction

- The particles in the hidden/dark sectors (DS) do not interact with the Standard Model (SM) particles directly, but there can be "portals" acting as indirect interactions. [arXiv:1311.0029]

Dark Sectors could communicate to SM through portals



$$\mathscr{L}_{\text{portal}} = \sum \mathcal{O}_{\text{SM}} \times \mathcal{O}_{\text{DS}}$$

Portals	Mediators	Field symbol
Vector	Dark photon, Z' boson	A'
Scalar	Dark scalar/Dark Higgs	ϕ
Pseudoscalar	Axion/ALP	a
Fermion	Sterile Neutrino	N

- The SM needs to be at least a little coupled to the dark sector

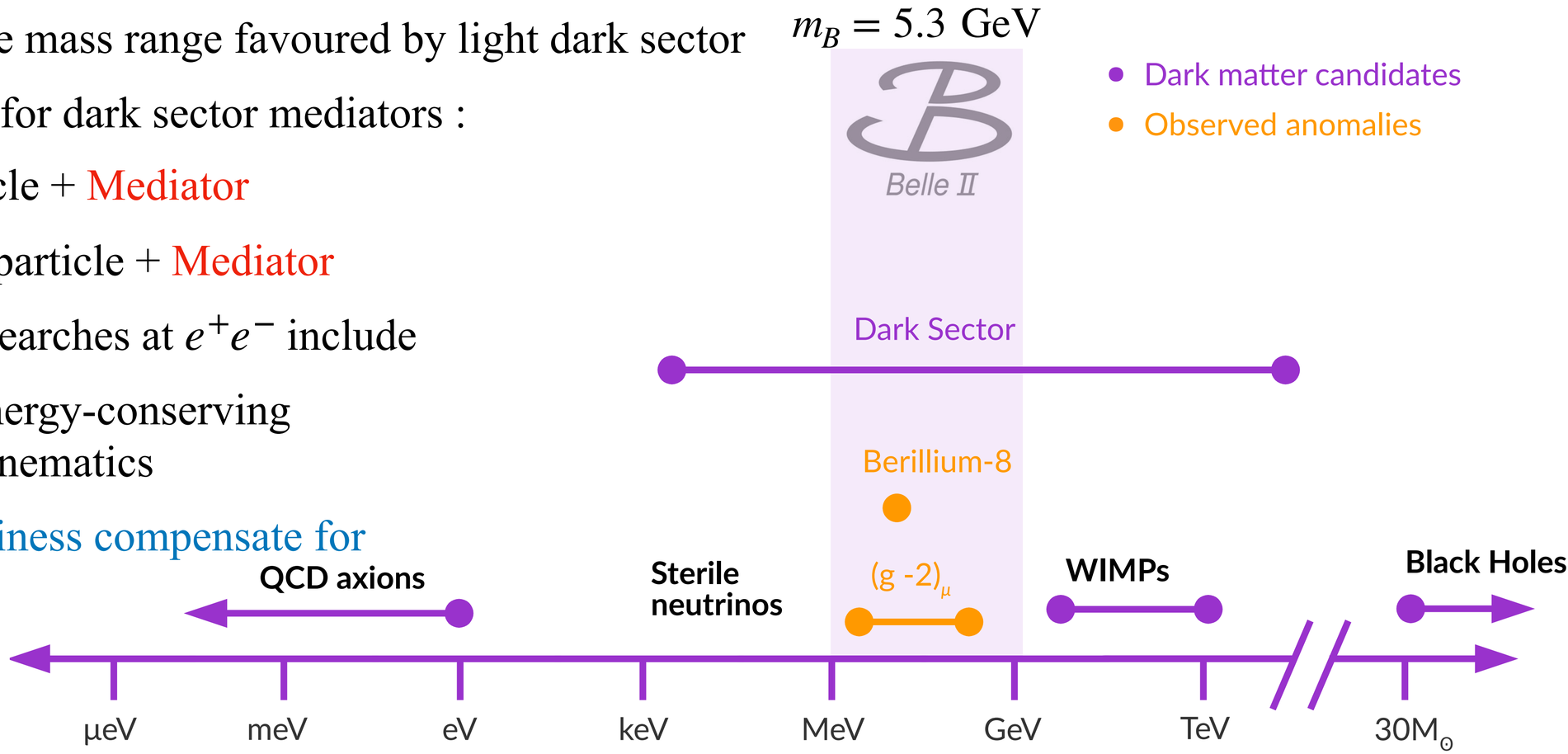
Many opportunities for accelerator experiments for both high energy and high intensity

Dark sector covered by e^+e^- colliders

- The dark matter (DM) scale is unknown; completely different search strategies depending on the mass of dark matter
- DM weakly couples to SM particle annihilation at accelerators
- e^+e^- collider can access the mass range favoured by light dark sector
- Typical process for to look for dark sector mediators :

  $e^- + e^+ \rightarrow$ SM-particle + Mediator

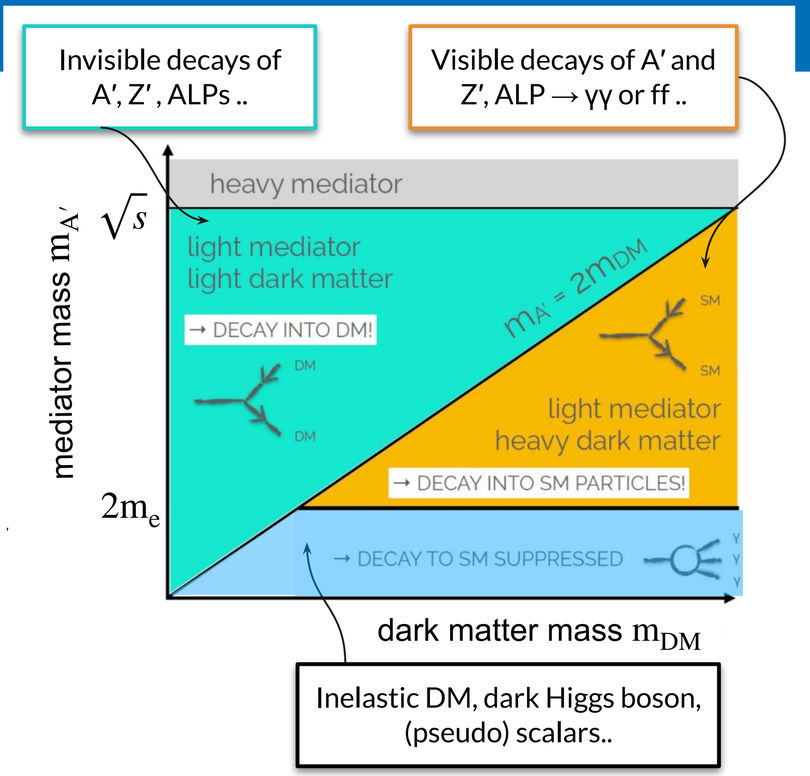
  B(or other hadron)$\rightarrow$ SM-particle + Mediator
- Important features for DS searches at e^+e^- include
- Clean, low-background, energy-conserving environment with closed kinematics
- High luminosity and cleanliness compensate for small cross sections

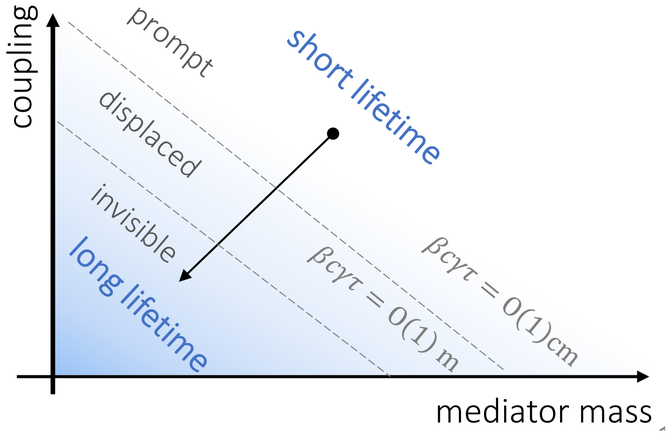


Dark Sector and Dark Matter at *B*- factories

- Different scenario arise, depending on the dark sector mediator and dark matter mass hypothesis
  - Negligible interaction probability of DM with the detector
- Visible decay to SM particles: allow to search for dark sector mediators
- Invisible decay to dark matter candidates: allow us to search for DM or dark sector mediators in final states with missing energy
- Displaced vertices: weaker couplings lead to long lifetime and therefore long decay length

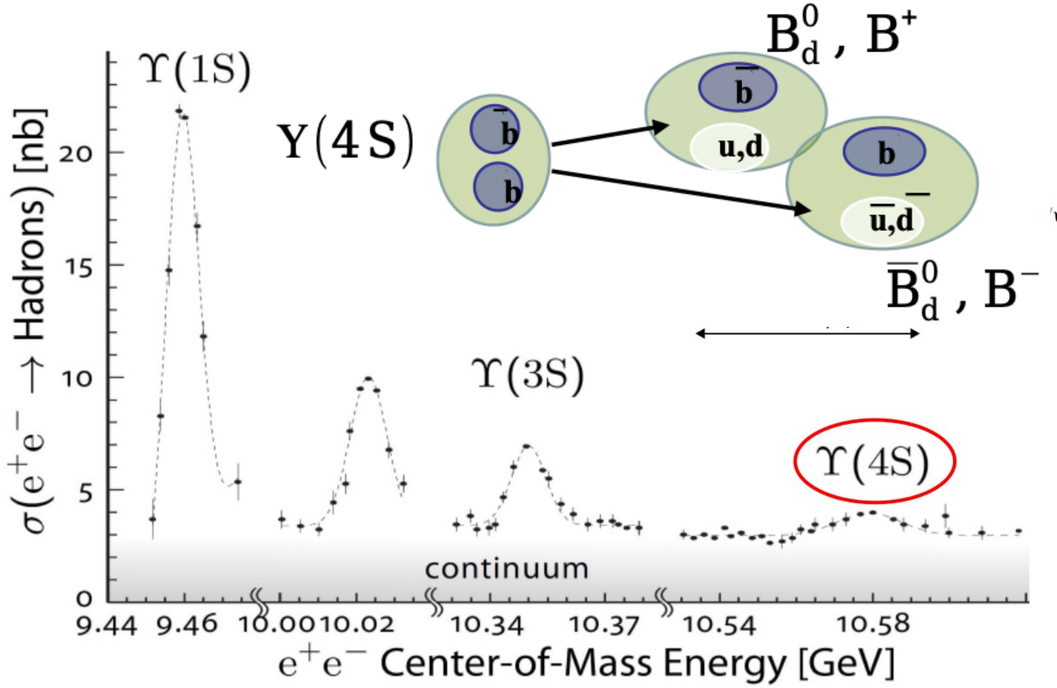
  - **Lifetime** is an additional player: proportional to some inverse power of the coupling and of the mediator mass
    - decay-length $< \mathcal{O}(1)$ m: displaced decay vertices
    - decay-length $> \mathcal{O}(1)$ m: decay outside the detector (invisible)





B-factories

- Asymmetric e^+e^- energy beam colliders optimized for the production of *B* meson pairs
- Collisions occur at $\Upsilon(nS)$ resonances (bound $b\bar{b}$ states), mainly at $\sqrt{s} = 10.58$ GeV
- Experiments operating at *B*-Factories:
- First generation:
  - BaBar@PEP-II, US (1999-2008)→ Collected 0.5 ab^{-1}
  - Belle@KEKB, Japan (1999-2010) → Collected 1 ab^{-1}
- Second generation:
  - Belle II@SuperKEKB, Japan (2018-Now)

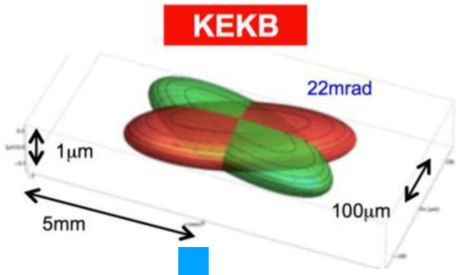


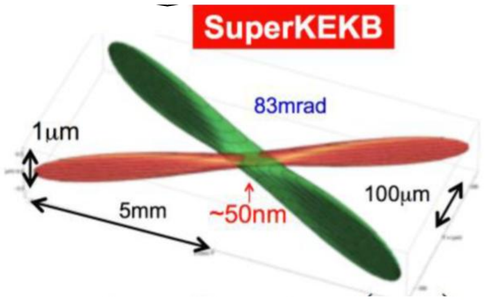
Highest peak luminosity achieved by first generation *B* factory $L > 10^{34}\text{cm}^{-2}\text{s}^{-1}$

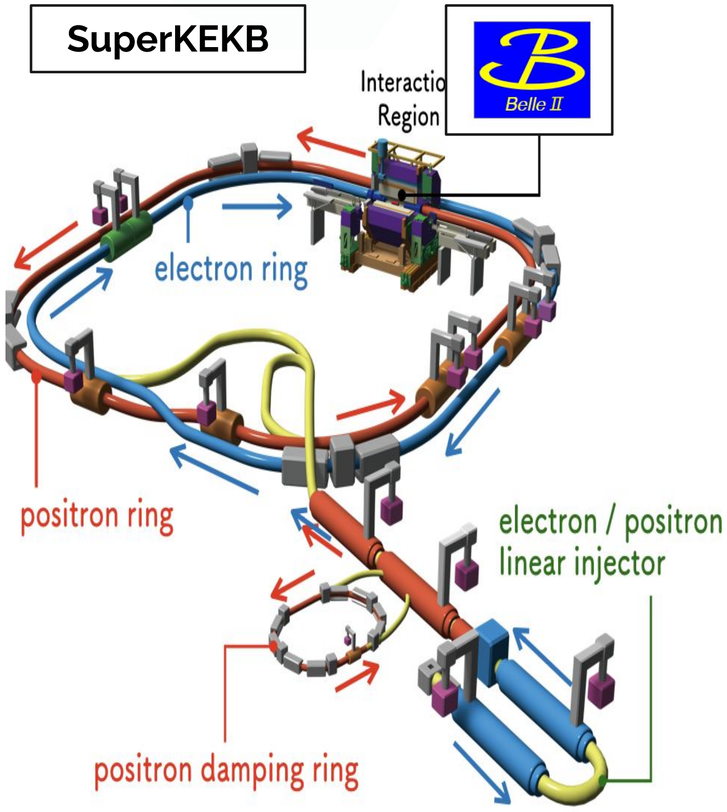
SuperKEKB

- SuperKEKB is a 2nd generation asymmetric e^+e^-collider at the $\Upsilon(4S)$ energy located at Tsukuba (Japan).
- SuperKEKB is major upgrade of KEKB
- Target is to achieve highest instantaneous luminosity ($\times$ 30 KEKB)
- SuperKEKB has been designed as a *B*-factory but ideal environments to study *D* mesons, τ leptons and **dark sector physics**

Nano-Beam scheme
beam size ↓ 20 times
currents ↑ 1.5 times







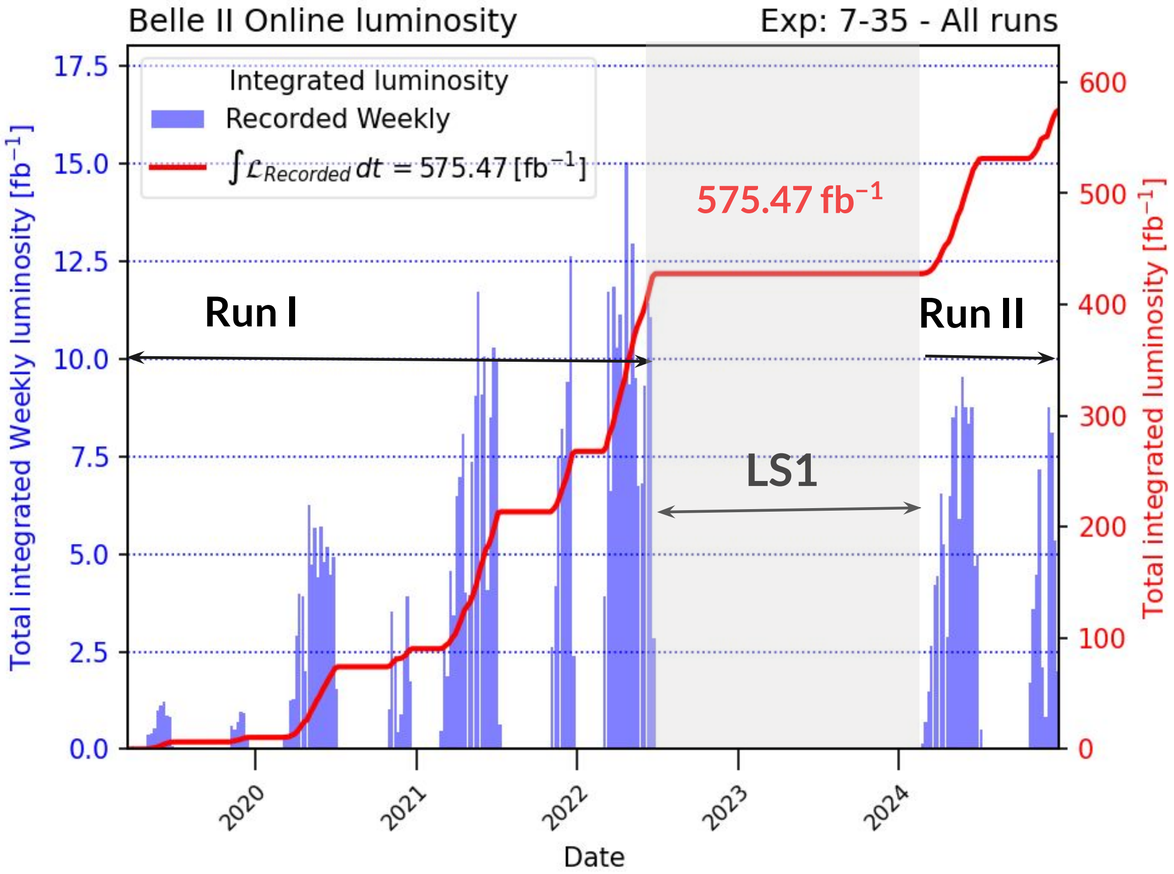
B-factory: $\sim 1.1 \times 10^9 B\bar{B}$ pairs per ab^{-1}

charm factory: $\sim 1.3 \times 10^9 c\bar{c}$ pairs per ab^{-1}

τ factory: $\sim 0.9 \times 10^9 \tau^+\tau^-$ pairs per ab^{-1}

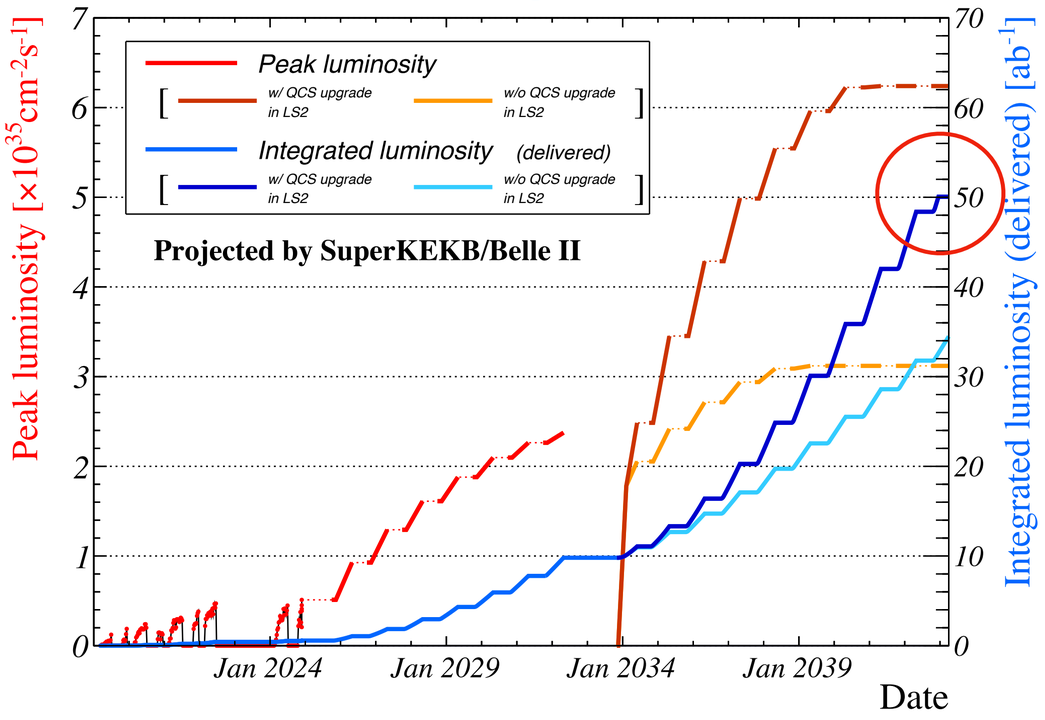
Luminosity status and projection

Collected luminosity up to now: 2019 - 2024



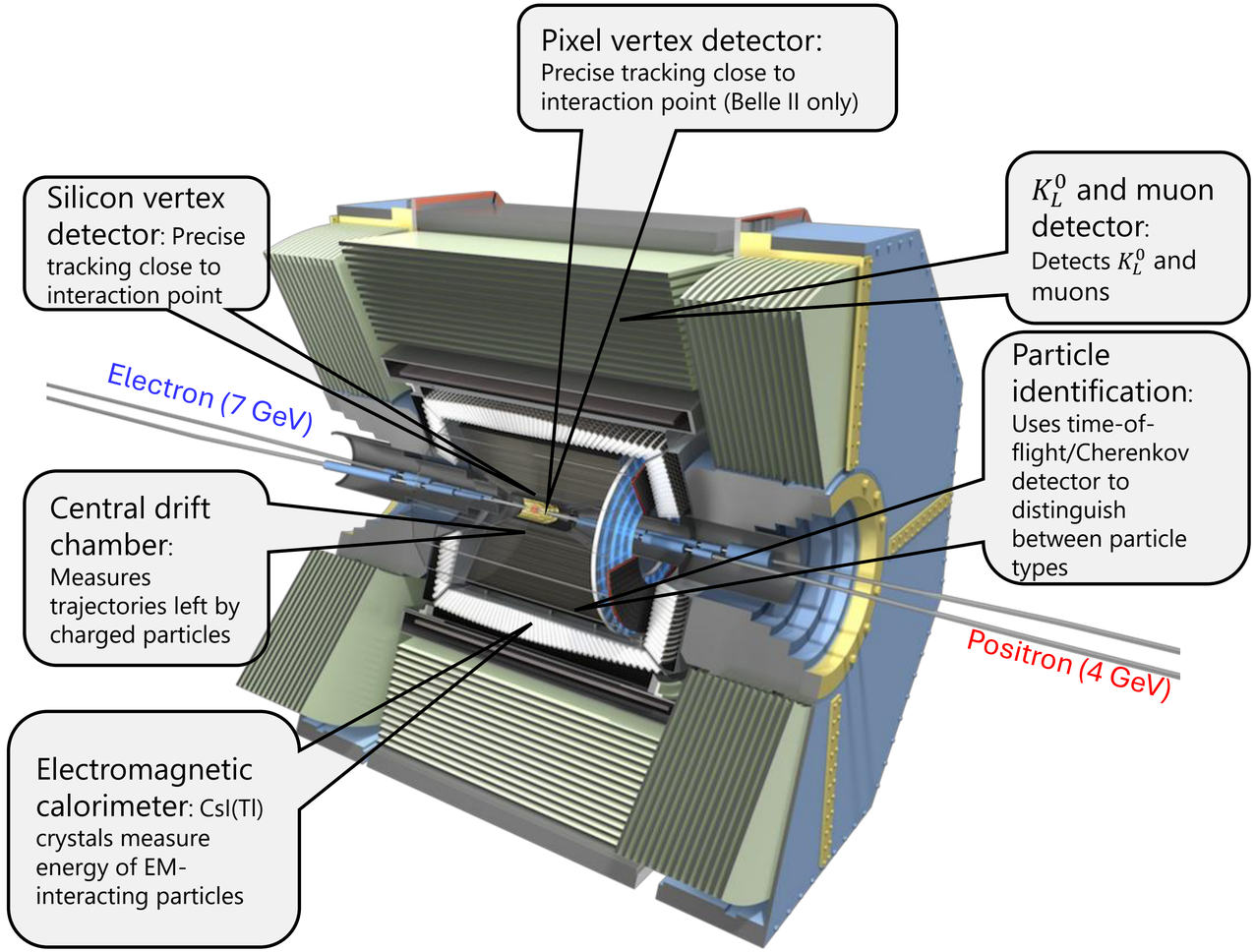
Long-shutdown (LS1) Several accelerator and detector maintenance and improvements

- So far $L_{\text{int}} = 575\ \text{fb}^{-1}$($\sim$ 1/2 Belle)
- Goal: $L_{\text{int}} = 50\ \text{ab}^{-1}$($50 \times$ Belle)
- World record: $L_{\text{peak}} = 5.1 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$
- Target: $L_{\text{peak}} = 6 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$
  - Restart data taking in Fall 2025



Belle II detector

- Belle II upgrade of Belle → Hermetic detector
- Belle II key features:
  - Known initial state kinematics
  - Very clean environment
  - Excellent charged particles identification (kaon, pions, protons, electrons, muons)
  - Good neutrals reconstruction
    - γ down to 50 MeV
  - **Dedicated triggers for low-multiplicity final states**
    - Only Belle II has single-photon or single-track and single muon triggers
- Possible to probe all the possible dark sector portals



Belle and Belle II have excellent sensitivity for dark sector searches in the MeV – GeV range

Inelastic dark matter with a dark Higgs

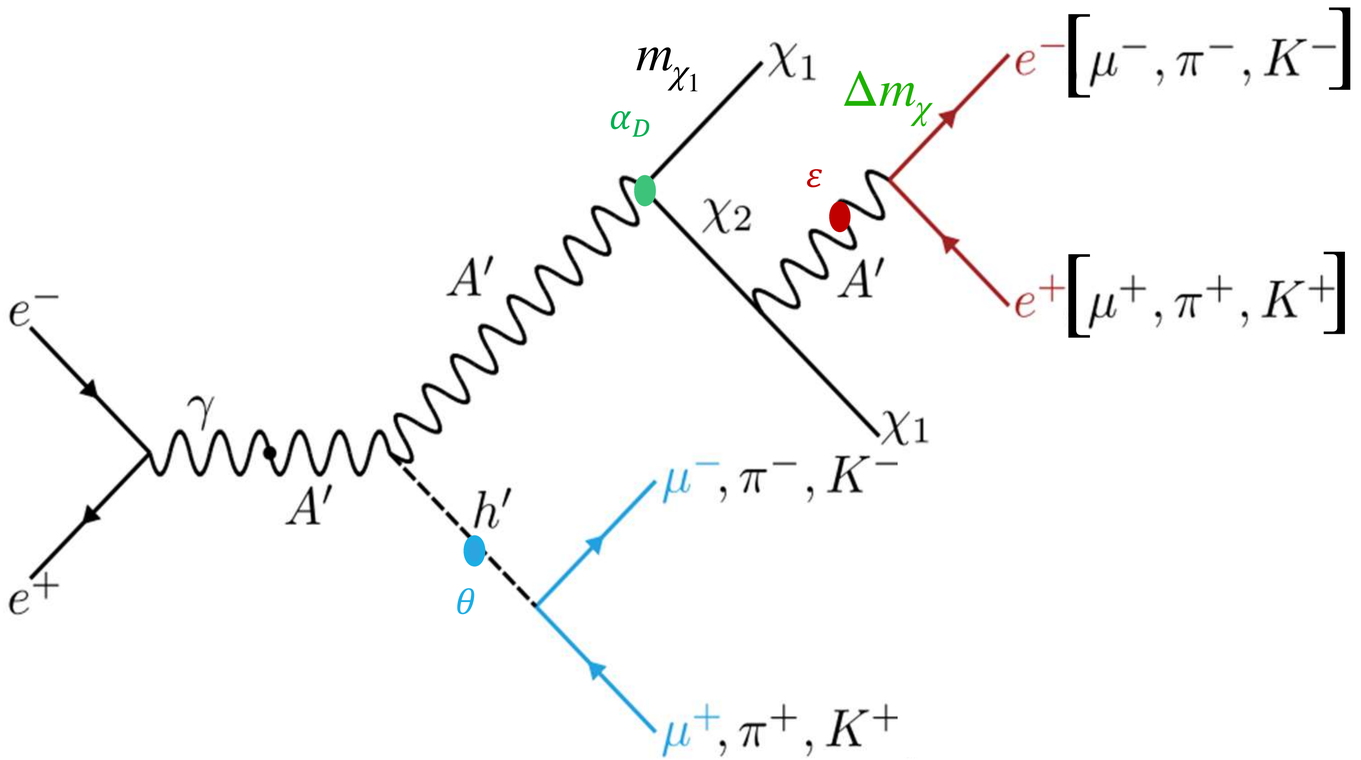
Belle II
[arXiv:2505.09705 (2025)]
Submitted to PRL

- Inelastic dark matter (iDM) models can avoid cosmological constraints on dark matter [PRD 64, 043502 (2001)]
- Model with inelastic coupling between DM and SM particles could explain lack of signal in direct detection
- One such non-minimal dark sector consists of:
  - Two dark matter states (χ_1, a stable, light particle (relic DM) and χ_2, a long-lived particle can decay to DM
  - A' massive dark photon
  - h' dark Higgs boson
- h' mixes with SM Higgs through mixing angle θ
- A' mixes with SM photon with strength ϵ
- Coupling between DM and A' is α_D.

7 free parameters; 4 masses + α_D , ϵ and θ

Signal processes

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



χ_2 is search for in electrons-only final state to exploit the ECL triggers to have better trigger performance.

Inelastic dark matter with a dark Higgs

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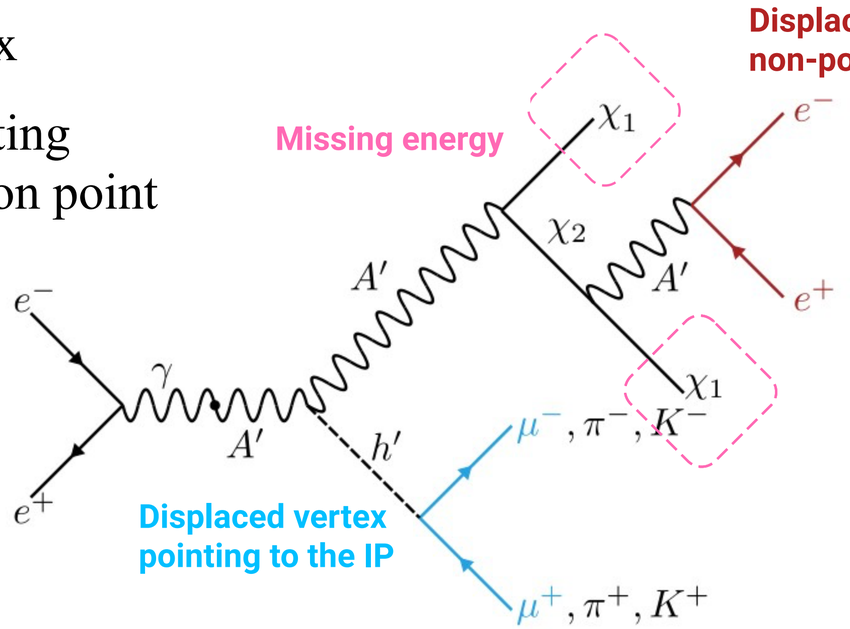
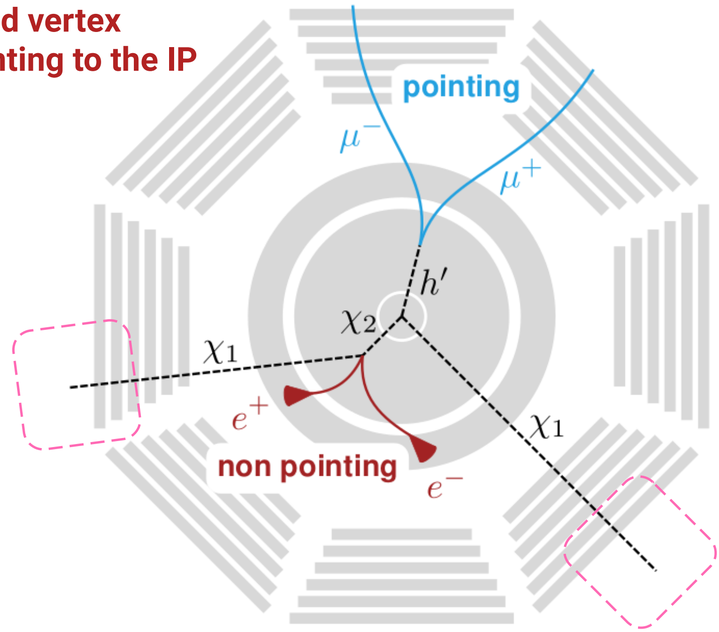
[arXiv:2505.09705 (2025)]
Submitted to PRL

Event reconstruction require:

- Require missing energy ($\chi_1\chi_2$) plus four tracks in the final state
- Two displaced vertices
  - $h' \to x^+x^-$ pointing displaced vertex
  - $\chi_2 \to \chi_1 e^+e^-$ non-pointing displaced vertex
- **Signal selection** using requirements on pointing angles and vertex distance from the interaction point
  - very low SM background
- Search for a bump in the h' invariant $M_{h'}$
- Cut-and-count strategy for extracting signal yields
- Events rejected with h' candidates with $0.467 < M(\pi^+\pi^-) < 0.529$ GeV/c² to reduce background from K^0_S decays;
- **Expected background** estimated in data from sidebands to not rely on simulation

Experimentally challenging for tracking and trigger due to presence of displaced vertices





Inelastic dark matter with a dark Higgs

Belle II
[arXiv:2505.09705 (2025)]
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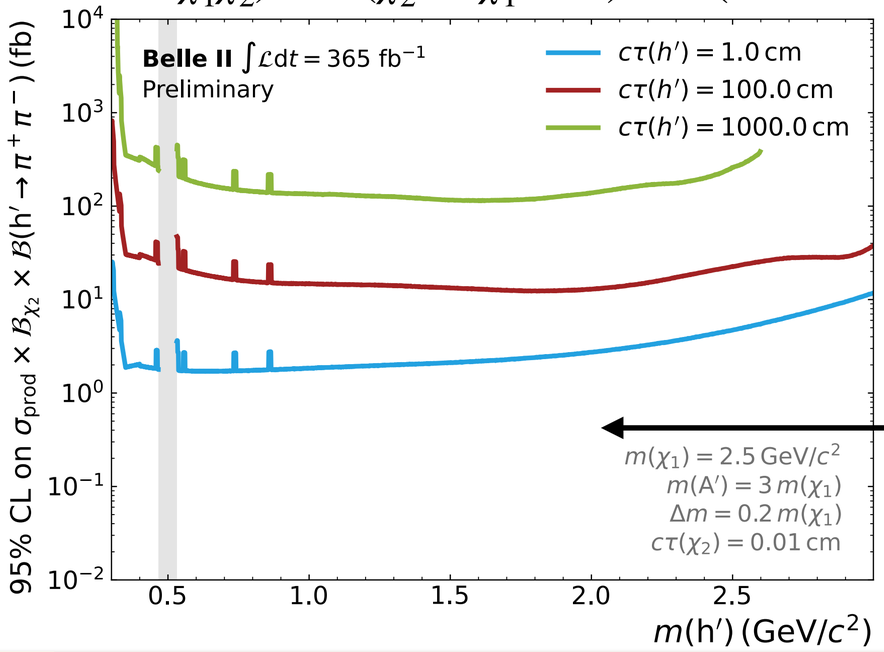
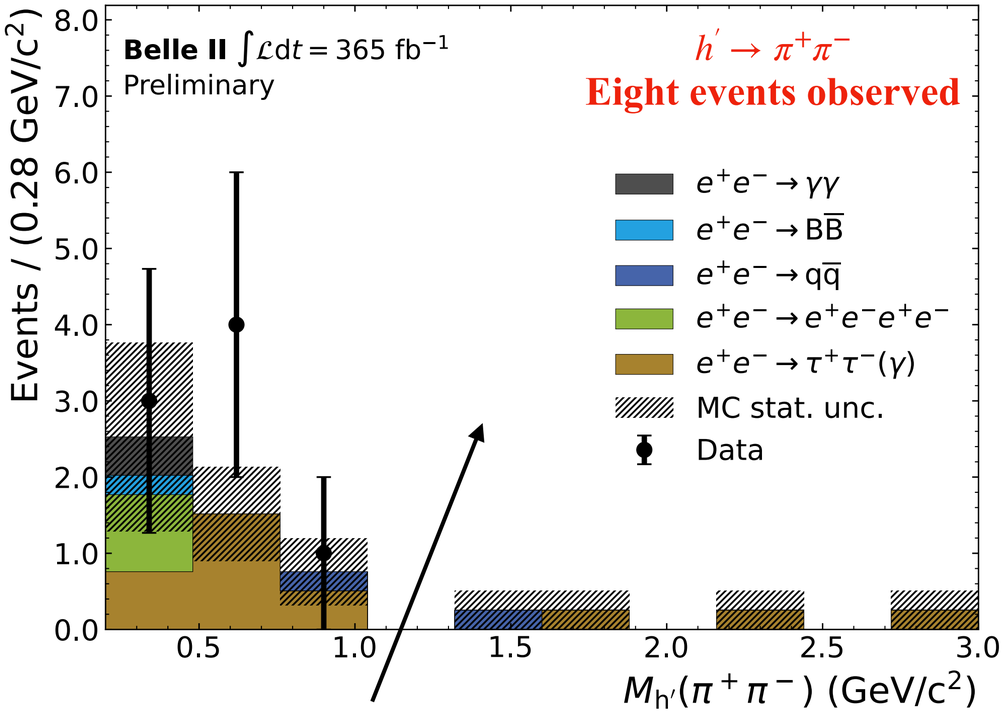
- Dataset: 365 fb^{-1} from Belle II
- **No significant excess found** in the individual final states or the combination $m_{h'}$ channels:
  - 9 events observed, (8 of 9 in $\pi^+\pi^-$) consistent with expected background
- **95% CL upper limit set on**

$$\sigma(e^+e^- \to h'\chi_1\chi_2) \times \mathcal{B}(\chi_2 \to \chi_1 e^+e^-) \times \mathcal{B}(h' \to x^+x^-) \quad [x^\pm = \mu^\pm, \pi^\pm, K^\pm]$$





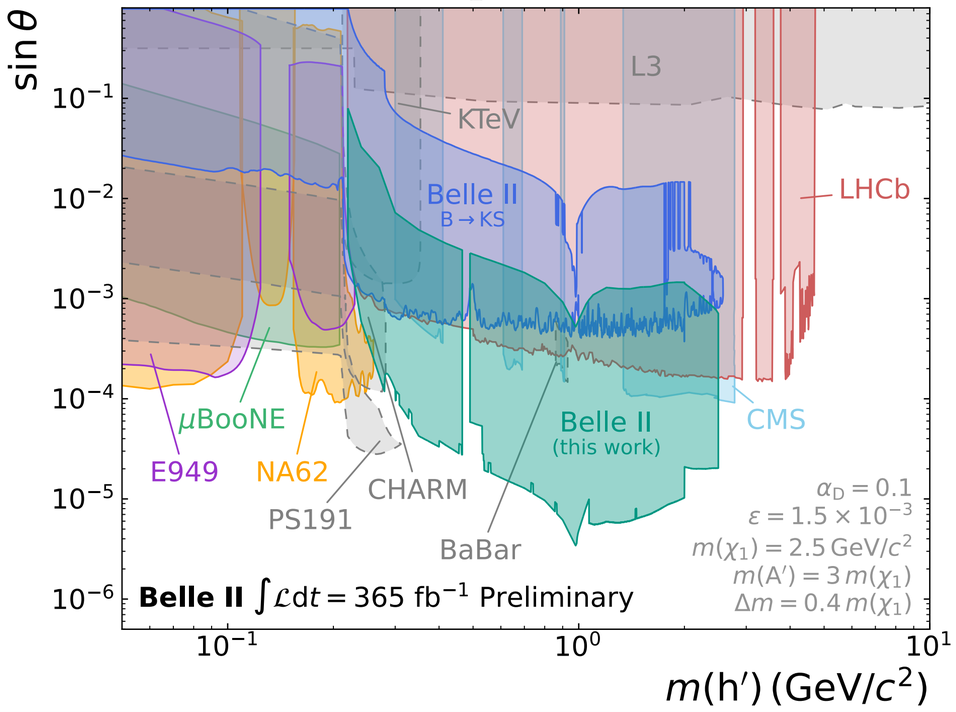
- Reconstructed h' mass distributions for $h' \to \pi^+\pi^-$
- The product of the production cross section $\sigma(e^+e^- \to h'\chi_1\chi_2)$, and the product of B.F $\mathcal{B}(\chi_2 \to \chi_1 e^+e^-) \times \mathcal{B}(h' \to x^+x^-) \quad [x^\pm = \pi^\pm]$ as a function of dark Higgs mass. The region corresponding to the fully-vetoed K^0_S mass region is marked in grey.

Inelastic dark matter with a dark Higgs

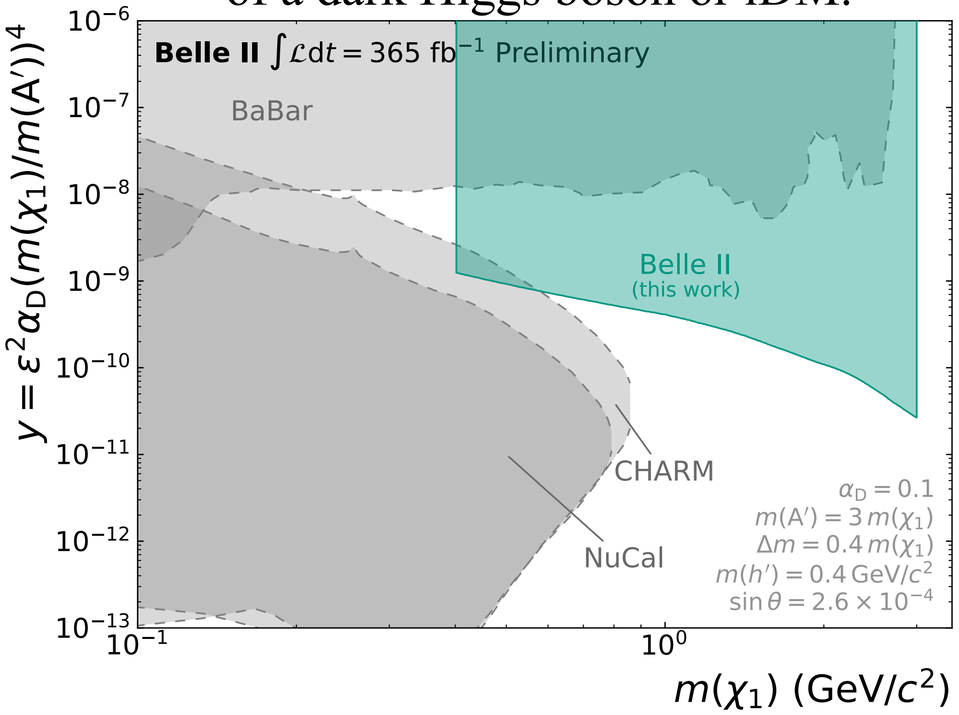
Belle II
[arXiv:2505.09705 (2025)]
Submitted to PRL

- **Strong limits** on $\epsilon \times \alpha_D$ and θ **(**dependence on other parameters**)**
- **World-leading (model dependent)** constraints on the $(\sin\theta - mh')$ parameter space
- Exclusion regions at 95 % CL from this work (teal)

All constraints except for the one from this work do not require the presence of a dark photon or iDM.



All constraints except for the one from this work do not require the presence of a dark Higgs boson or iDM.



Many more parameter configurations in paper

Axion-like-particles (ALPs)

- **Axions** were originally motivated by the strong CP problem → One of the unknown of SM
- Beyond-SM theories in which a global UV symmetry is spontaneously broken predict pseudo-Goldstone bosons known as Axion-like particles (ALPs):
- **ALPs** is generic pseudoscalar particles with arbitrary mass and couplings, at ~GeV scale
- Many possible couplings for ALPs: $g_{a\gamma\gamma}$, g_{aW}, g_q and more
- The $B \to Ka$ searches are:
  - *visible* – ALP decays to SM particles inside detector [$a \to \gamma\gamma$ decays]
  - *invisible* – ALP decays outside of detector, or to dark matter

CP phase in strong sector

$$\frac{\alpha_s \bar{\theta}}{8\pi} G^{a\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\downarrow$$

$$\frac{\alpha_s}{8\pi}\frac{a}{f_a} G^{a\mu\nu}\tilde{G}^{a\mu\nu}$$

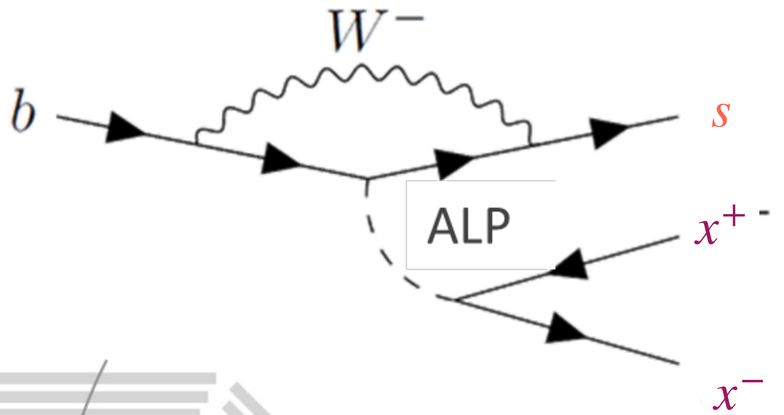
Peccei, Quinn, [PRL 38, 1440 (1977)] [PRD 16, 1791 (1977)]

ALPs proposed as a mediators between the dark sector and ordinary matter and they could be cold dark matter candidates themselves.

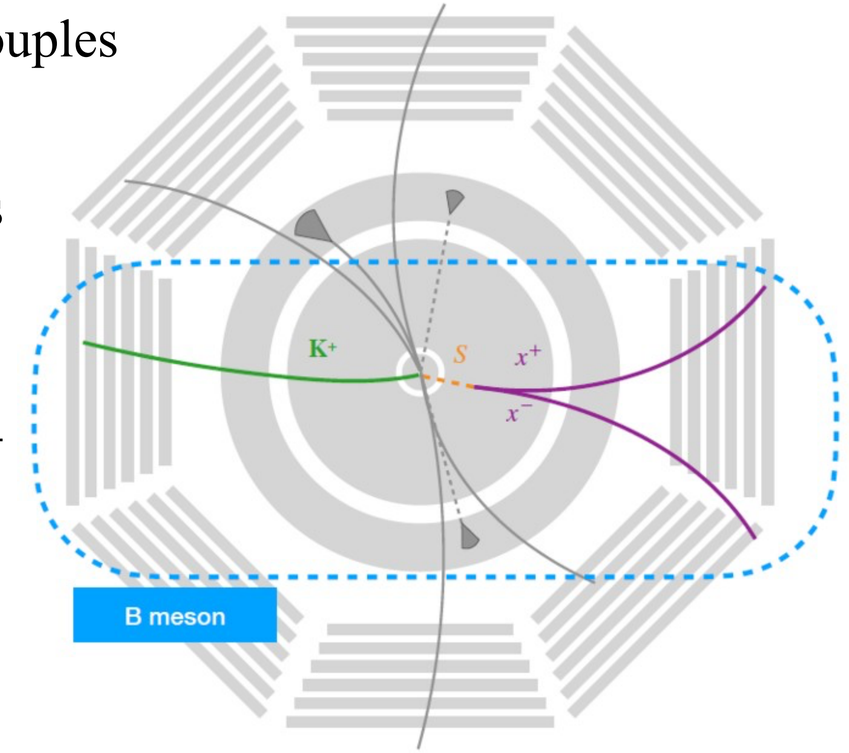
Long Lived ALP in B decays

Belle II
[PRD 108, L111104 (2023)]

- Cases for long lived particle (LLP) can be from scalar mediator (S) or a pseudo-scalar ALP (a).
  - S can mix with SM Higgs boson with mixing angle θ_s
- For couplings much weaker than the electroweak interaction, the scalar S is long-lived.
- Another possible extension of the SM introduces an ALP that couples to photons, fermions, or gluons



- Search for long-lived S that decays visibly into charged particles $B^+ \to K^+ S(S \to x^+ x^-)$ $[x = e, \mu, \pi, K]$
- High performance in LLP vertex reconstruction are necessary
- **First Belle II long-lived particle (LLP) search** with $B^+ \to K^+$ LLP and $B^0 \to K^{*0}[K^+\pi^0]$ LLP using 189 fb^{-1}
- Displaced vertex distance from interaction region > 0.05 cm
  - displaced vertex → low backgrounds;

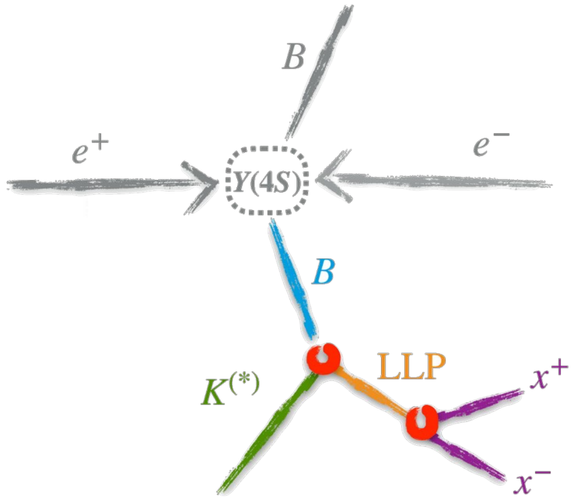


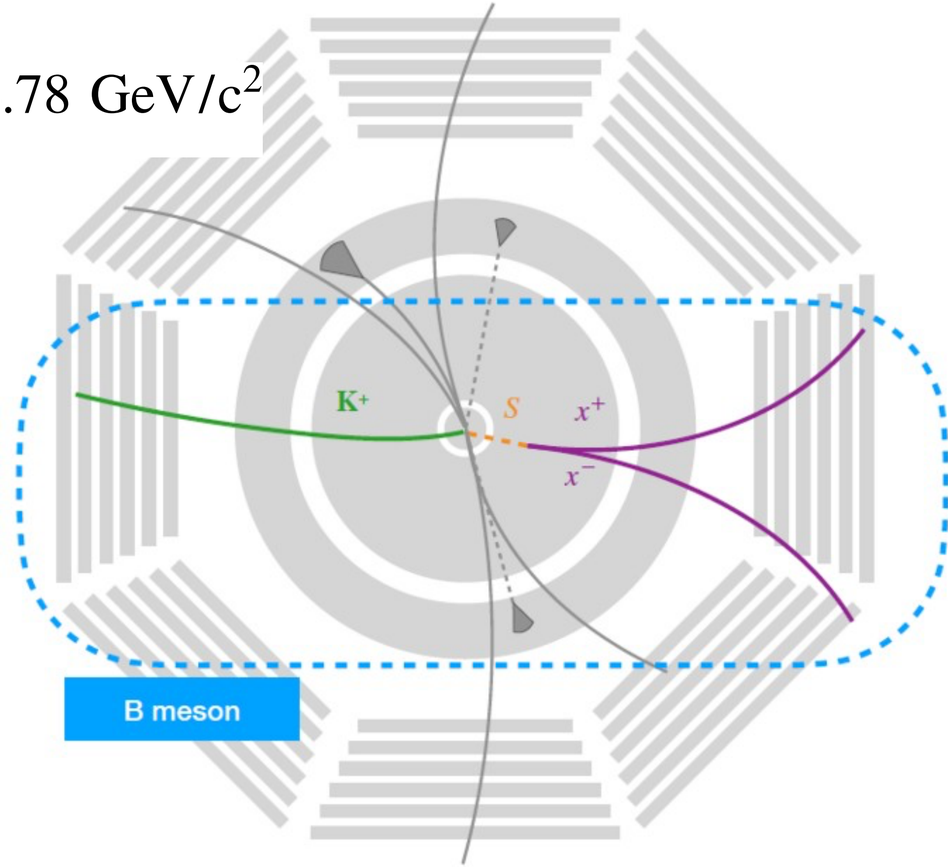
Long Lived ALP in B decays

Belle II
[PRD 108, L111104 (2023)]

Event Reconstruction:

- Signal B-meson fully reconstructed by prompt K or K^* decay + two oppositely charged tracks that make a displaced vertex
  - Signal events are simulated for various scalar masses $0.025 < m_S < 4.78$ GeV/c^2
- Search for a bump in invariant mass *mLLP* distribution
  - Separately for $x = e, \mu, \pi, K$
  - Separately for different lifetimes ($0.001 < c\tau < 400$ cm)



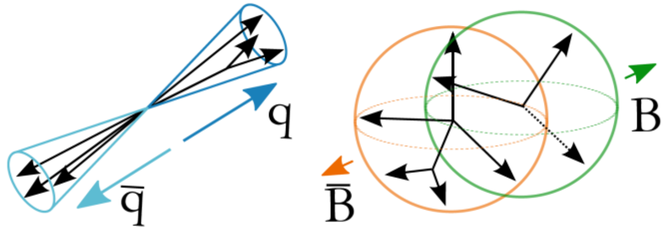


Long Lived ALP in B decays

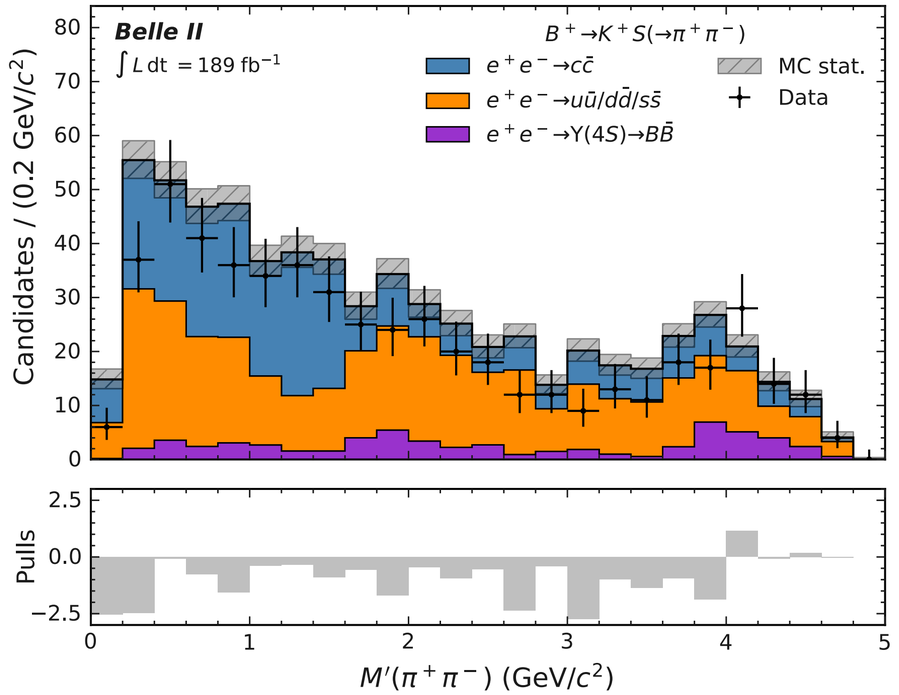
Belle II
[PRD 108, L111104 (2023)]

Background rejection:

- For continuum and $B\bar{B}$ background
  - constrains on $M_{\mathrm{bc}} = \sqrt{s/4 - |\overrightarrow{p_B^*}|^2} > 5.27\ \mathrm{GeV/c^2}$ and $\Delta E = |E_B^* - \sqrt{s}/2| < 0.05\ \mathrm{GeV}$
  - event shape variable $R_2 < 0.45$
  - SM long-lived K_S^0 mass region vetoed and used to evaluate LLP-performance (efficiencies, shapes, particle identification);
- Further peaking backgrounds (ϕ, J/ψ) suppressed by tighter displacement selection;
- Background determined directly in data (robust against un-modelled non-peaking background)



Continuum vs. $B\bar{B}$ event shapes

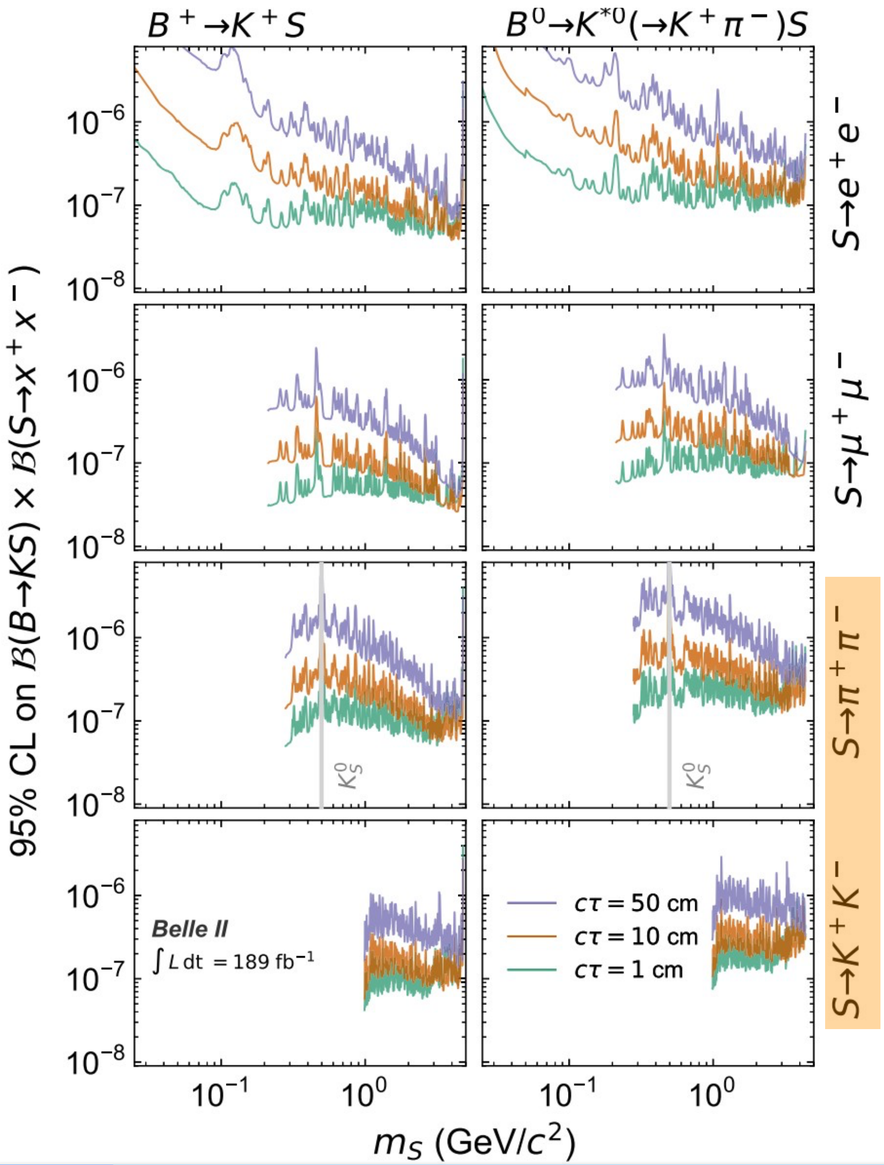


Signal extraction:

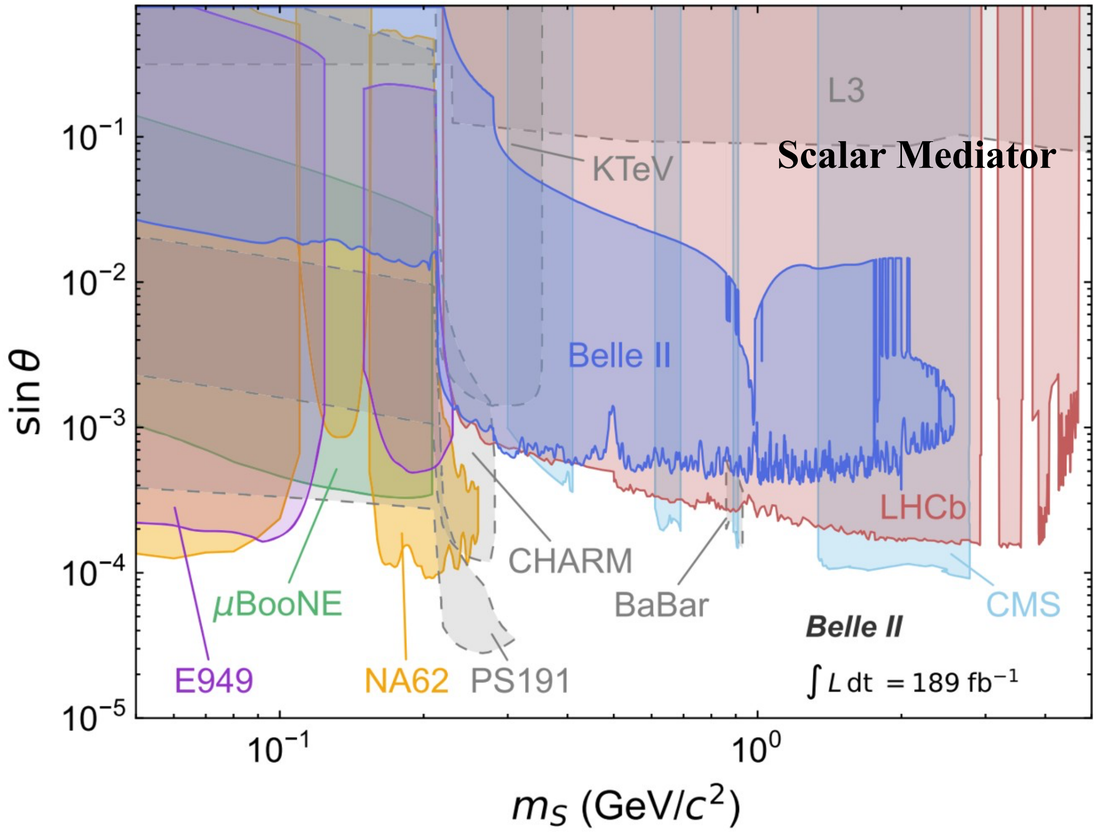
- Search for a bump by performing fit to LLP modified mass $\longrightarrow$ $M'(x^+x^-) = \sqrt{M^2_{a\to x^+x^-} - 4m_x^2}$
  - Scan in step of half resolution (2 to 10 MeV)

Long Lived Scalar in B decays

Belle II
[PRD 108, L111104 (2023)]



- **No excess found**
- First model independent limits for exclusive $B \to K^{(*)}S$; $S \to$ hadrons
- Most stringent limits for direct search in $K^{(*)}e^+e^-$
- Interpretation as dark scalar Higgs with mixing angle θ with SM Higgs

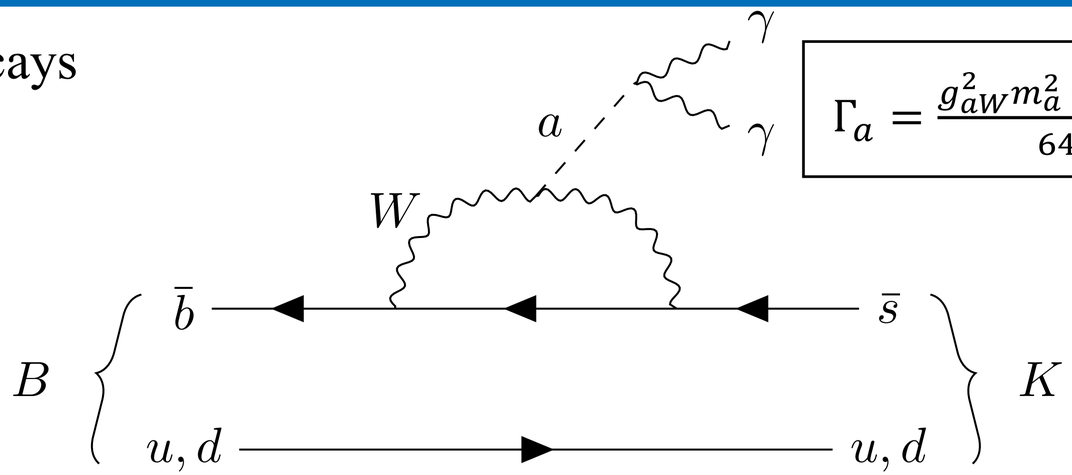


Search for $B \to K^{(*)}a(\to \gamma\gamma)$

Belle
[arXiv:2507.01249 (2025)]
Submitted to JHEP

- Search for an ALP in flavour-changing neutral current B decays
  - Highly suppressed in SM
  - New physics could appear at the same order of the SM processes
- ALP production from $W^{\pm}$ boson in $B \to K^{(*)}a$ decays
  - $B(a \to \gamma\gamma) \simeq 100\,\%$ for $m_a < m_W$
  - g_{aW} is coupling strength of a to W boson.
  - 4 kaon modes: K^0_S, K^+, K^{*0} and K^{*+}
  - Mass range: $0.16 - 4.50\ (4.20)\ \mathrm{GeV/c^2}$ for $K^{(*)}$
- Previous limits from BaBar, which used only $B^+ \to K^+a$ and smaller dataset [PRL.1.28.131802]

Belle analysis with $711\ \mathrm{fb}^{-1}$ **corresponding to 772 M** $B\bar{B}$ **pairs**



$$\Gamma_a = \frac{g_{aW}^2 m_a^2 \sin^4\theta_W}{64\pi}$$

- **Event reconstruction**
  - Signal B candidates reconstructed by combining a pair of photons and a K candidate
  - vertex fit to the selected B candidates, constraining photon and kaon candidates to originate from IP
  - Constrain mass and energy exploiting no missing energy in final state
  - $\mathrm{M_{bc}} = \sqrt{\mathrm{E^2_{beam}} - \mathrm{p^2_B}} > 5.27\ \mathrm{GeV}$
  - $\Delta\mathrm{E} = \mathrm{E_B} - \mathrm{E_{beam}}$ between -0.2 to 0.1 GeV

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

Belle
[arXiv:2507.01249 (2025)]
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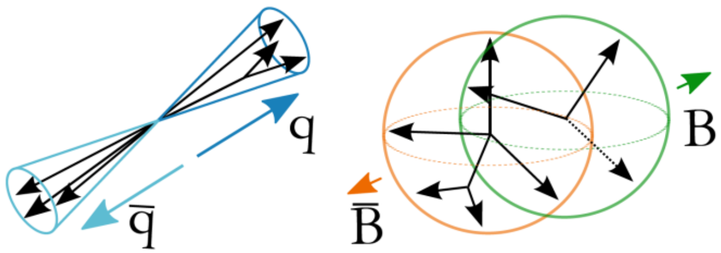
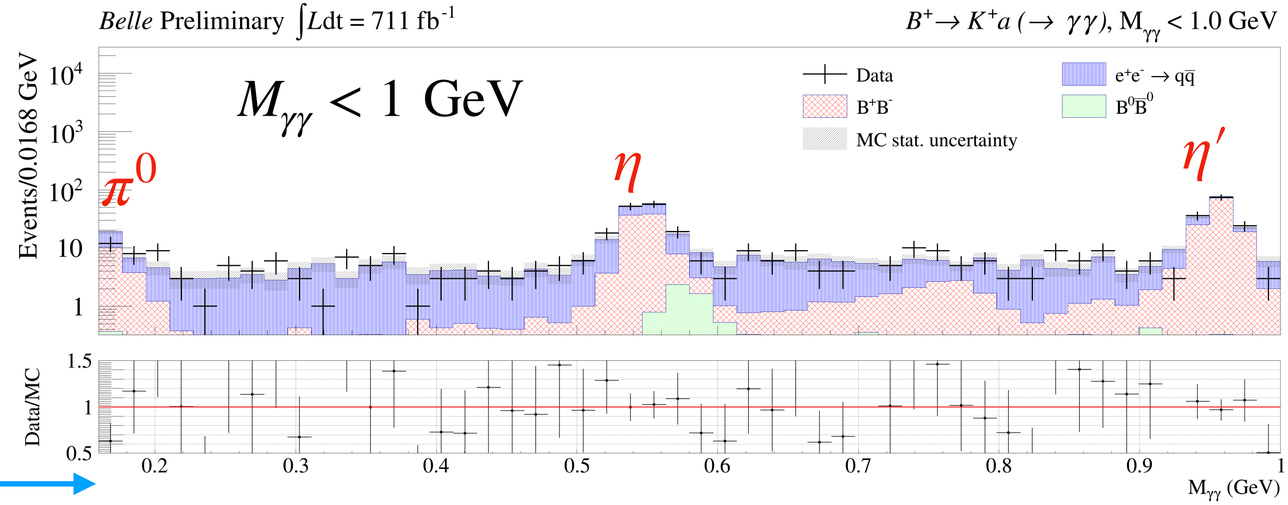
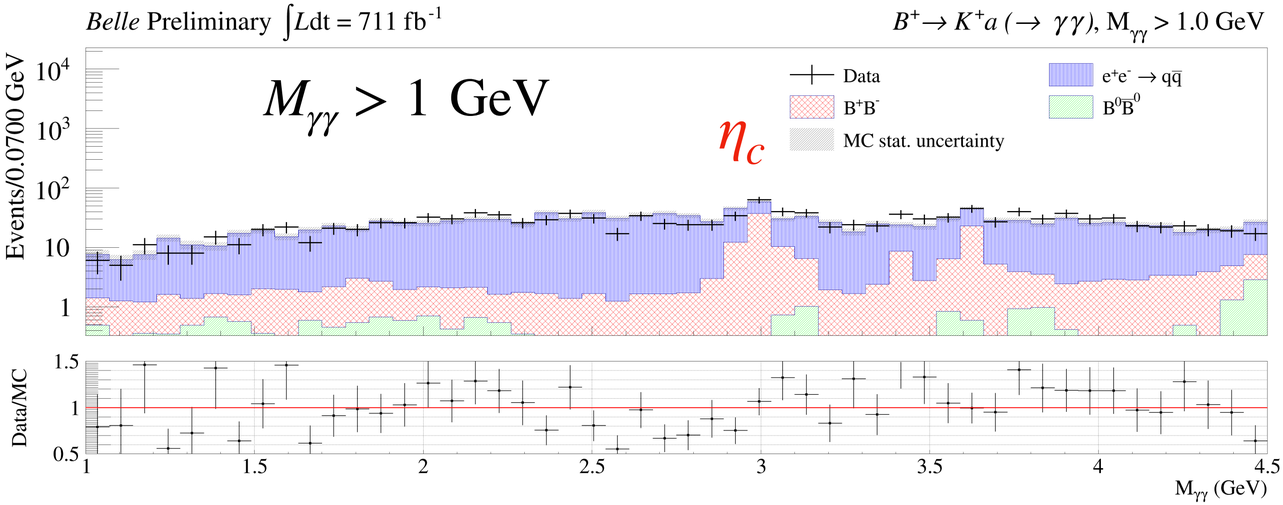
Background contributions:

- From $e^+e^- \to q\bar{q}$ (continuum)
- B decays ($e^+e^- \to \Upsilon(4S) \to B\bar{B}$)
- Boosted decision trees (BDT) used to reject background
  - Event shape discrimination for $B\bar{B}$ vs. continuum
- $\pi^0 \to \gamma\gamma$ rejected with , additional BDT trained by calorimeter cluster variables
- Peaking background regions (π^0, η, η') in **di-photon invariant mass** $M_{\gamma\gamma}$ are vetoed.



Continuum vs. BB event shapes





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

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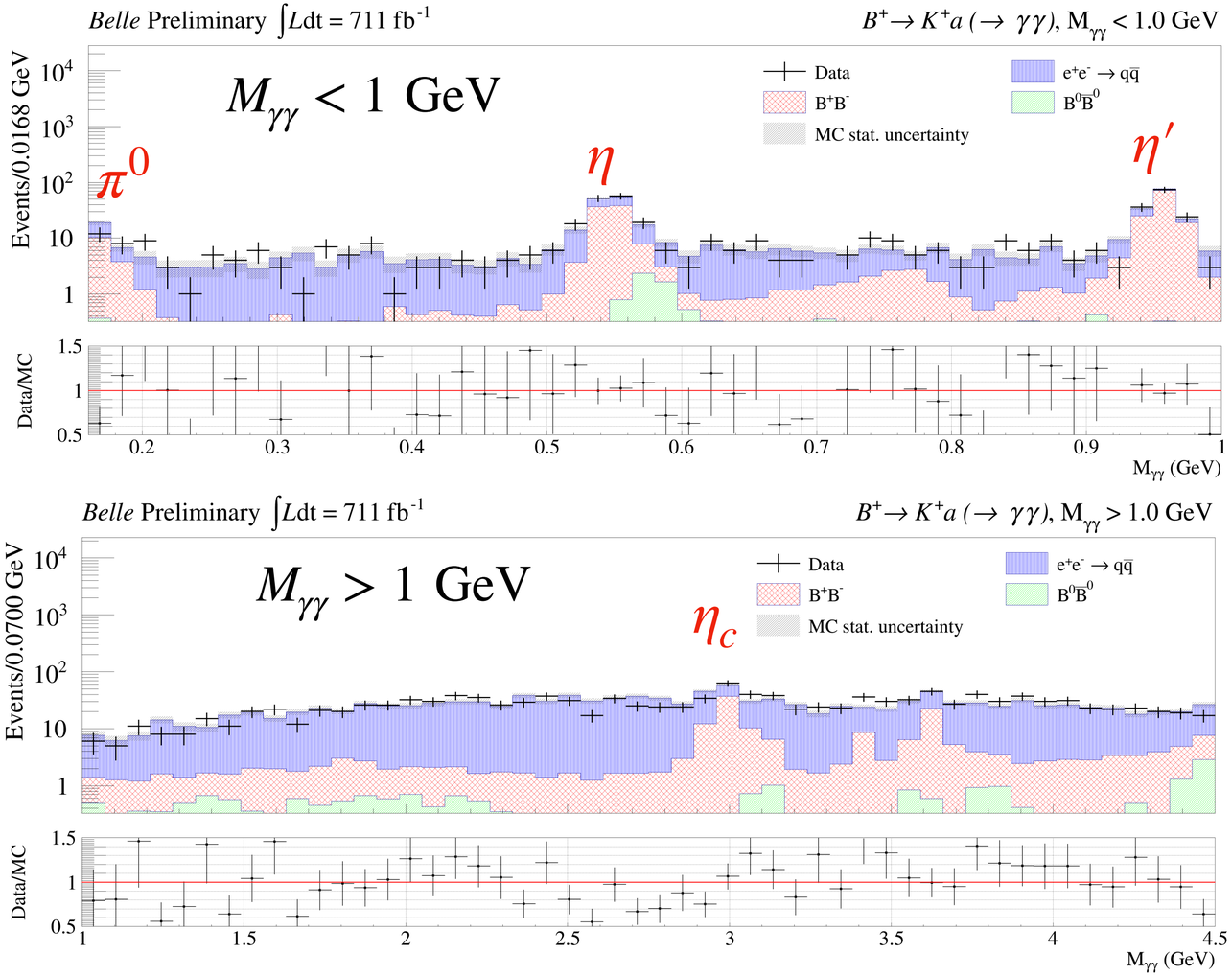
Signal extraction

- Signal extracted with a scan over $M_{\gamma\gamma}$
- Steps of signal mass resolution (~8 - 18 MeV)
- Use $B \to Kh(\to \gamma\gamma)$ $(h \to \eta, \eta', \pi^0)$ to validate signal extraction method
- Simultaneous fit on all 4 kaon modes: K^0_S, K^+, K^{*0} and K^{*+}



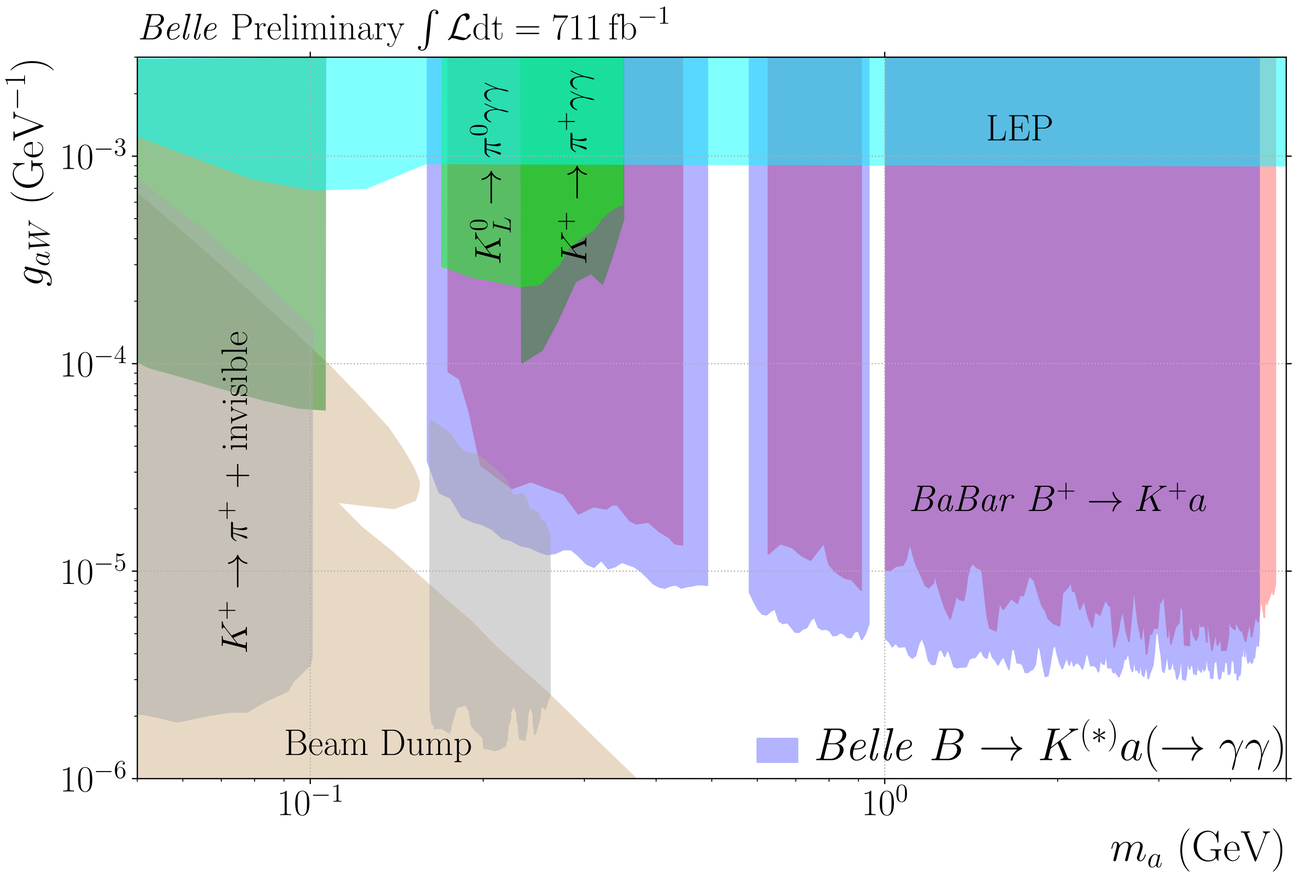
Search for $B \to K^{(*)}a(\to \gamma\gamma)$

Belle
[arXiv:2507.01249 (2025)]
Submitted to JHEP

- **No significant excess observed**
- upper limits evaluated from simultaneous fit to four kaon modes as a function of the ALP mass, compared with existing constraints
- ALP lifetimes
  - At low masses, ALP can have long decay length
  - Signal efficiency goes down as light ALPs escape the detector (long lived ALP is taken into account)
  - This is accounted for

$$\Gamma_a = \frac{g_{aW}^2 m_a^2 \sin^4 \theta_W}{64\pi}$$

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



Summary

- World leading or competitive results from Belle data and even with a subset of the Belle II available data
- Belle and Belle II have set world-leading constraints on a number of models and published several additional dark sector analyses (list in the backup)
- Results covered in this talk:
  - Belle II analysis: Search for inelastic dark matter with a dark Higgs [arXiv:2505.09705 (2025)], submitted to PRL
  - Search for ALPs in B meson decays
    - Belle II analysis: $B \to KS(\to e^+e^-/\mu^+\mu^-/\pi^+\pi^-/K^+K^-)$ [PRD 108, L111104 (2023)]
    - Belle analysis: $B \to K^{(*)}a(\to \gamma\gamma)$ [arXiv:2507.01249 (2025)], submitted to JHEP
- So far Belle II recorded ~575 fb^{-1} ; more results with higher statistics and improved analyses are in the pipeline, with reliable sensitivity projections at future luminosity.

Snowmass White Paper:
[arXiv:2207.06307 (2022)]

BACKUP

Belle and Belle II analyses

Belle II

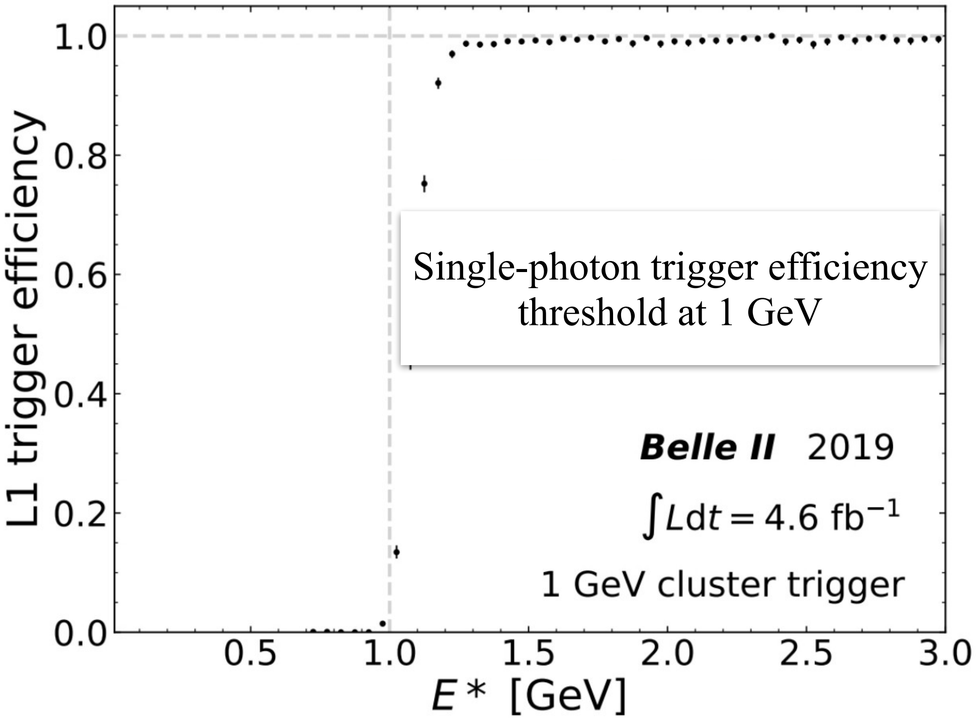
- Search for a $\mu^+\mu^-$ resonance in $ee \to \mu\mu\mu\mu$ events Phys. Rev. D 109, 112015 (2024)
- Search for a Dark Photon and an invisible Dark Higgs in $\mu^+\mu^-$ Phys. Rev. Lett. 130, 071804 (2023)
- Search for a resonance decaying to $\tau^+\tau^-$ in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events Phys. Rev. Lett. 131, 121802 (2023)
- Search for the LFV$\tau \to l\alpha$ (invisible) decay Phys. Rev. Lett. 130, 181803 (2023)
- Search for an invisible Z' in $ee \to \mu\mu Z'$ Phys. Rev. Lett. 130, 231801 (2023)
- Search for an invisibly decaying Z' in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ plus missing energy final states Phys. Rev. Lett. 124, 141801 (2020)
- Search for ALPs produced in e^+e^- collisions Phys. Rev. Lett. 125, 161806 (2020)

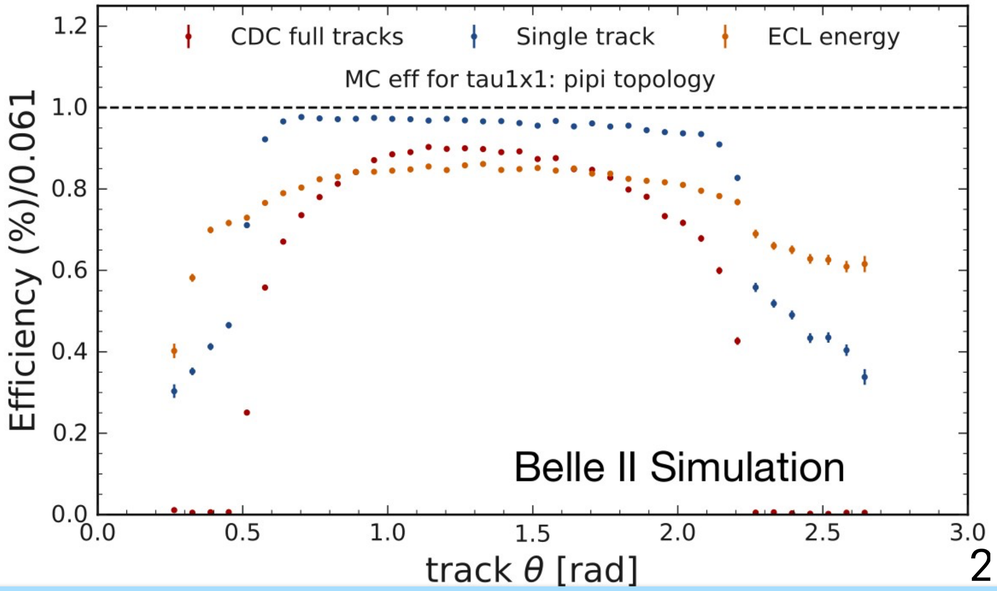
Belle

- Search for lepton-flavour-violating tau decays to ℓa arXiv: 2503.22195 (2025) accepted by JHEP
- Search for a dark leptophilic scalar Phys. Rev. D 109, 032002 (2024)
- Search for a heavy neutral lepton Phys. Rev. D 109, L111102 (2024)
- Search for $Z' \to \mu^+\mu^-$ in the $L_\mu - L_\tau$ gauge-symmetric model Phys. Rev. D 106, 012003 (2022)
- Search for the Dark Photon and the Dark Higgs Phys. Rev. Lett. 114, 211801 (2015)

Low Multiplicity Triggers

- Two-level trigger
  - Hardware-based Level 1 Trigger (L1): < 30 kHz
  - Software-based High Level Trigger (HLT): < 10 kHz
- Devised specific low-multiplicity trigger lines
  - Suppress high-cross-section QED processes without “killing” the signal
  - Precise knowledge of acceptance and efficiencies of the detector required
- **Examples**
  - Single-photon trigger
  - Single-muon trigger
  - Single-track trigger

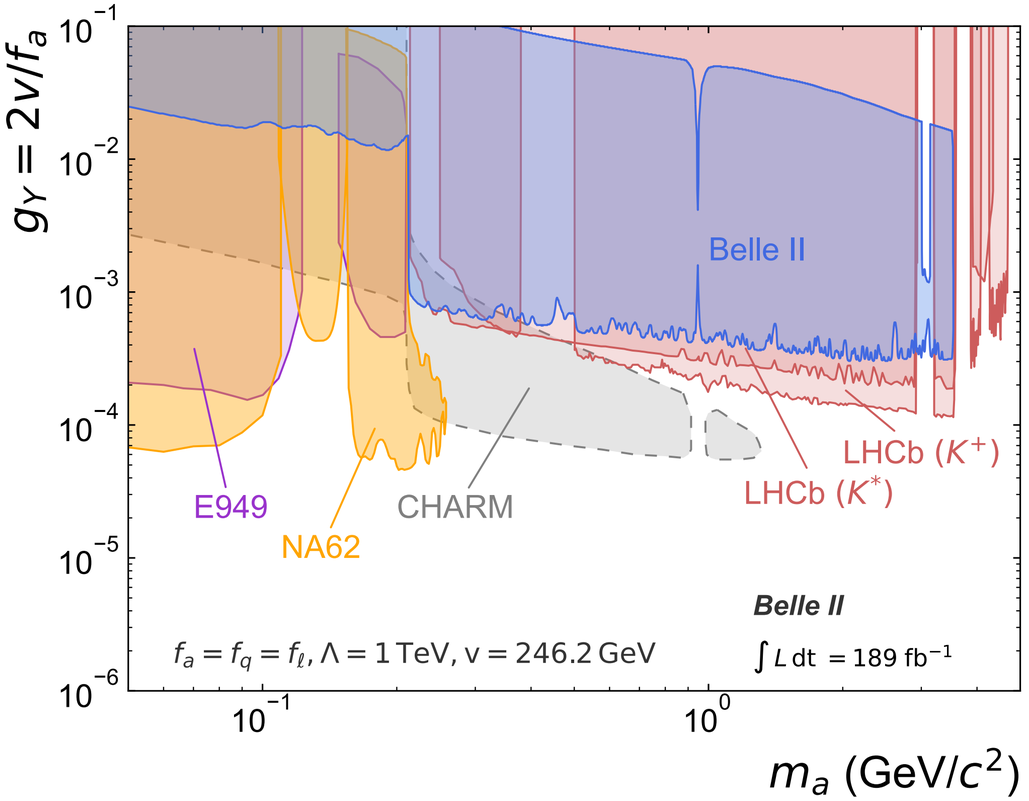




[PRD 108, L111104 (2023)]

Long Lived Scalar in B decays

- Interpretation as Pseudo-scalar ALP: For the model-dependent search for ALP with coupling to fermions, combined fit is performed in all relevant and kinematically accessible analysis channels, separately for various lifetimes.



- Exclusion regions in the plane of the coupling $g_Y = 2v/f_a$ with the vacuum expectation value v and the ALP mass m_a from this work (blue).
- The constraint colored in gray with dashed outline is a reinterpretation not performed by the experimental collaboration and without access to raw data.

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

Belle
[arXiv:2507.01249 (2025)]
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- 90% CL upper limits on the coupling g_{aW} as a function of the ALP mass obtained with the CLs method with simultaneous fit to the four kaon modes. The green and yellow bands are the ± 1 and ± 2 standard deviation ranges, respectively, for the expected upper limits in the background only model.