Dark Sector Searches at Belle and Belle II

The 27th International Conference From the Planck Scale to the Electroweak Scale

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Dark Sector Searches with Belle and Belle II

- Luminosity frontier e^+e^- colliders operating at or near $\Upsilon(4S)$ ($\sqrt{s}$ ~ 10.6 GeV)

$$e^+e^- \to B\bar{B} \sim 1.1 \text{ nb} \qquad e^+e^- \to c\bar{c} \sim 1.3 \text{ nb}$$

$$e^+e^- \to \tau^+\tau^- \sim 0.9 \text{ nb}$$

Variety of methods to access production of MeV to GeV scale dark mediators

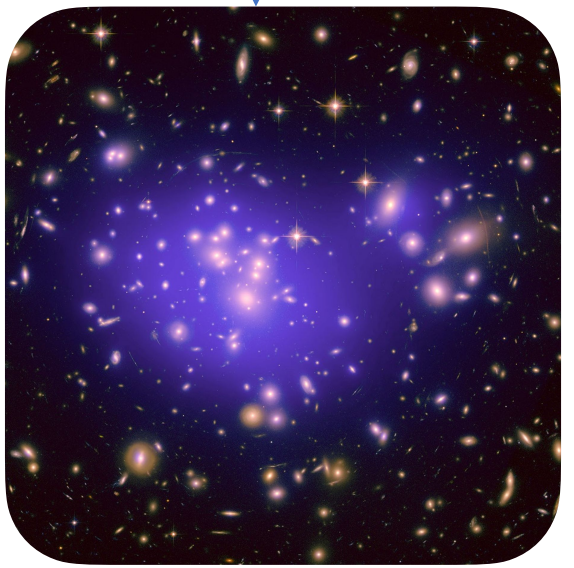
$$e^+e^- \to X_{Dark}X_{SM} \qquad B/D/\tau \to X_{Dark}X_{SM}$$

- Belle (1999 - 2010) collected 1040 fb^{-1}
- Belle II at SuperKEKB (2019 - present)
  - Major detector and accelerator upgrade from Belle and KEKB
  - SuperKEKB holds word record luminosity of $4.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  - Total dataset to-date is 570 fb^{-1} (target 50 ab^{-1})

Standard Model

Dark Mediator "Portals"

- Dark Photon
- Z'
- Heavy Neutral Lepton
- Axion-Like Particle
- Dark Higgs



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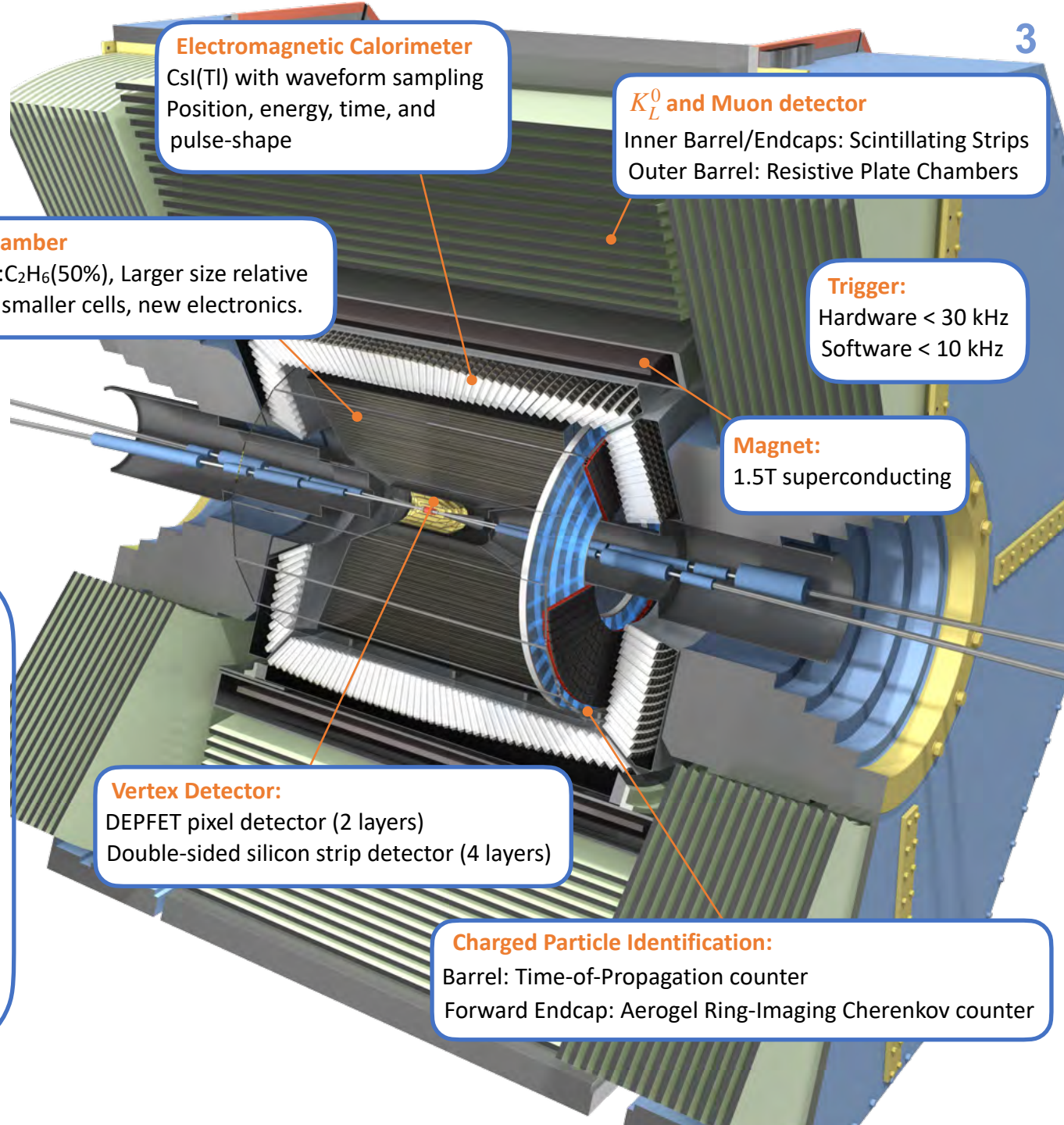
https://science.nasa.gov/asset/hubble/dark-matter-map-in-galaxy-cluster-abell-1689/

Belle II Detector

- Precise determination of missing energy/ momentum:
  - ✓ Minimal collision pile-up
  - ✓ Well-known initial collision energy and momentum
  - ✓ Hermetic detectors with high detection efficiency for charged and neutral particles

New at Belle II: Low multiplicity triggers targeting dark sector signatures

- ➡ Single photon trigger operational for entire dataset
- ➡ Single muon trigger
- ➡ Single Track Trigger with 3D track reconstruction at L1 using neural networks
- ➡ Displaced vertex trigger in development



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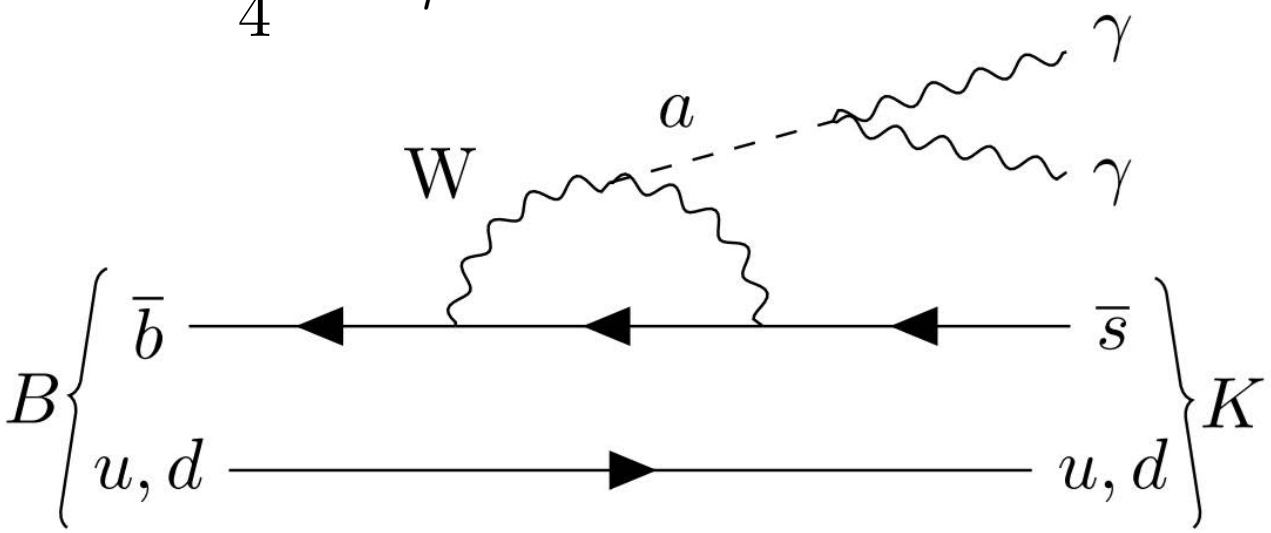
Search for an axion-like particle in B meson decays at Belle

- Search for Axion-Like Particle (ALP, a): Has same quantum numbers as axion that solves the strong CP problem, but uncorrelated mass and coupling
- GeV-scale ALPs can mediate interactions between standard model and dark matter
- Belle search for ALPs production in decay:

Y. Nomura and J. Thaler Phys. Rev. D 79 (2009) 075008

$$B \to K^{(*)} a(\to \gamma\gamma) \text{ with } K^0_S, K^+, K^{*0}, K^{*+}$$

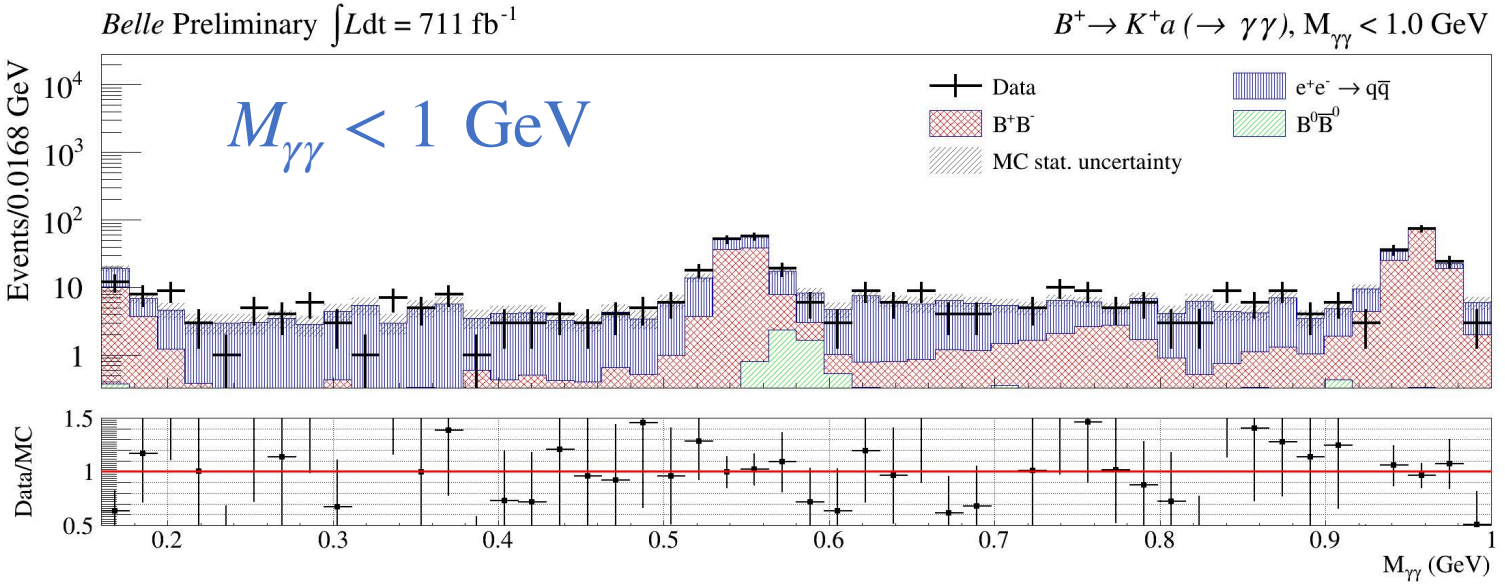
$$\mathcal{L} = -\frac{g_{aW}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

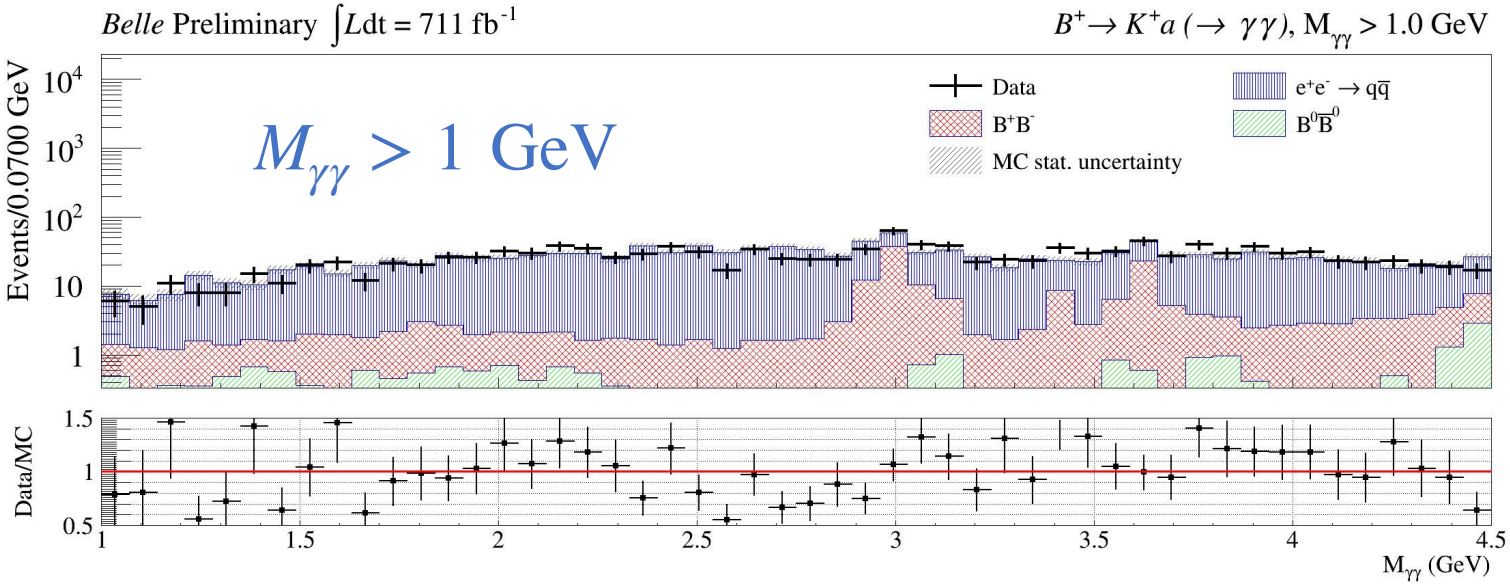


- ALP is reconstructed from pairs of photons in calorimeter
- ALP can decay promptly or be long-lived particle
- Combined with $K^{(*)}$ to fully reconstruct the B decay

Search for an axion-like particle in B meson decays at Belle

- Main backgrounds:
  - $e^+e^- \to q\bar{q}, \quad q = u, d, s, c$
  - $B \to X_s\gamma$
  - Events with π^0 mesons
- Background suppression using multiple Boosted Decision Trees trained on event level ($q\bar{q}$ vs $b\bar{b}$) and calorimeter information
- Search for localized peak in $M_{\gamma\gamma}$ distribution with simultaneous fit to all kaon modes





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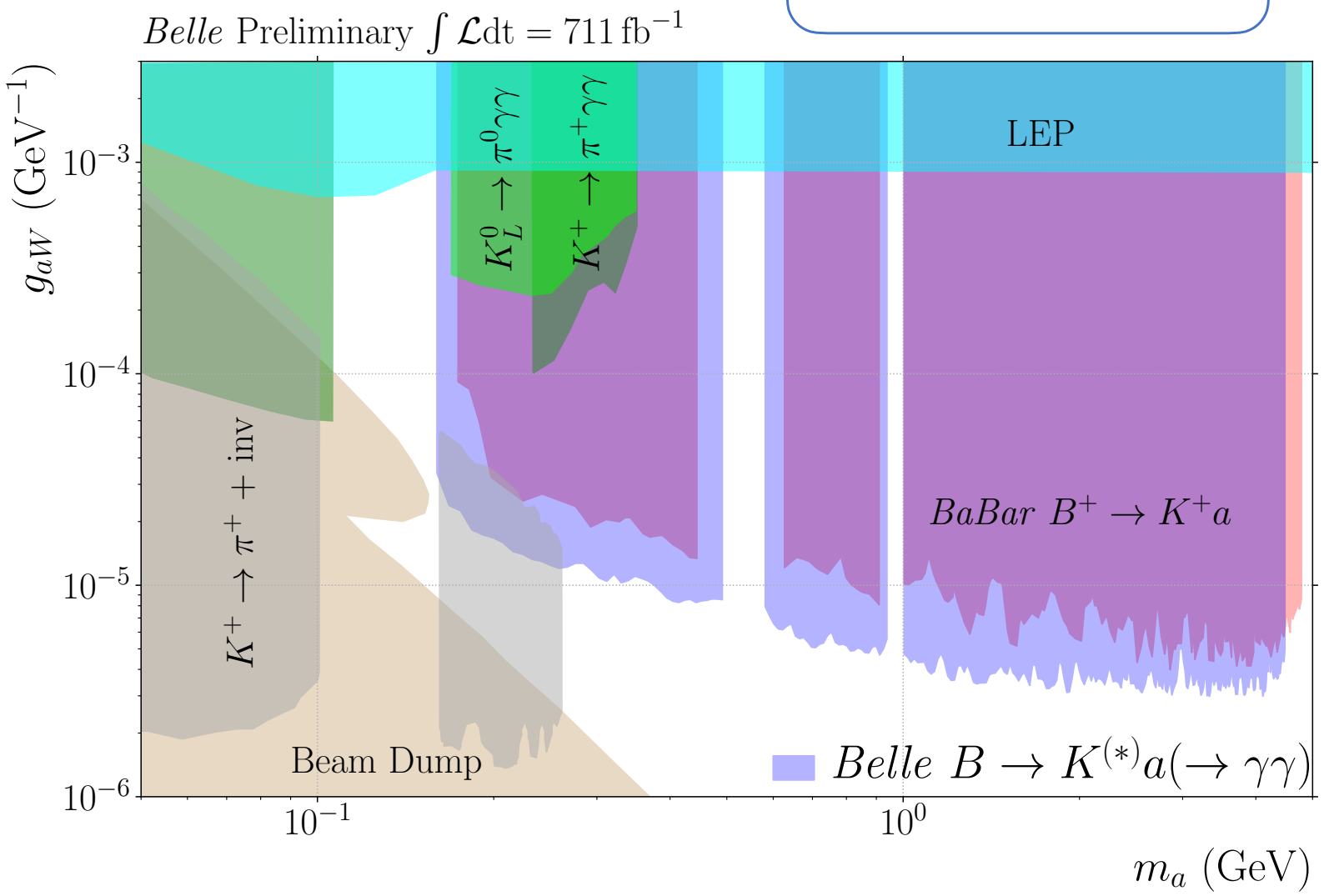
Search for an axion-like particle in B meson decays at Belle

- No significant signal is observed in all channels
- Limits are set on the g_{aW} coupling as a function of ALP mass

$$\mathcal{L} = -\frac{g_{aW}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

- Limits improve on previous BaBar result by a factor of two
- Improvement driven by larger dataset and inclusion of additional kaon modes

To be submitted to JHEP



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Search for a dark Higgs boson produced in association with inelastic dark matter at the Belle II experiment

- Non-minimal dark sector where relic dark matter couples inelastically to standard model

  χ_1 = relic dark matter

  χ_2 = excited dark matter state; Decays $\chi_2 \rightarrow \chi_1 A' \rightarrow \chi_1 e^+ e^-$

  χ_2 is a long lived particle for small χ_1/χ_2mass splitting

- Dark mediators:

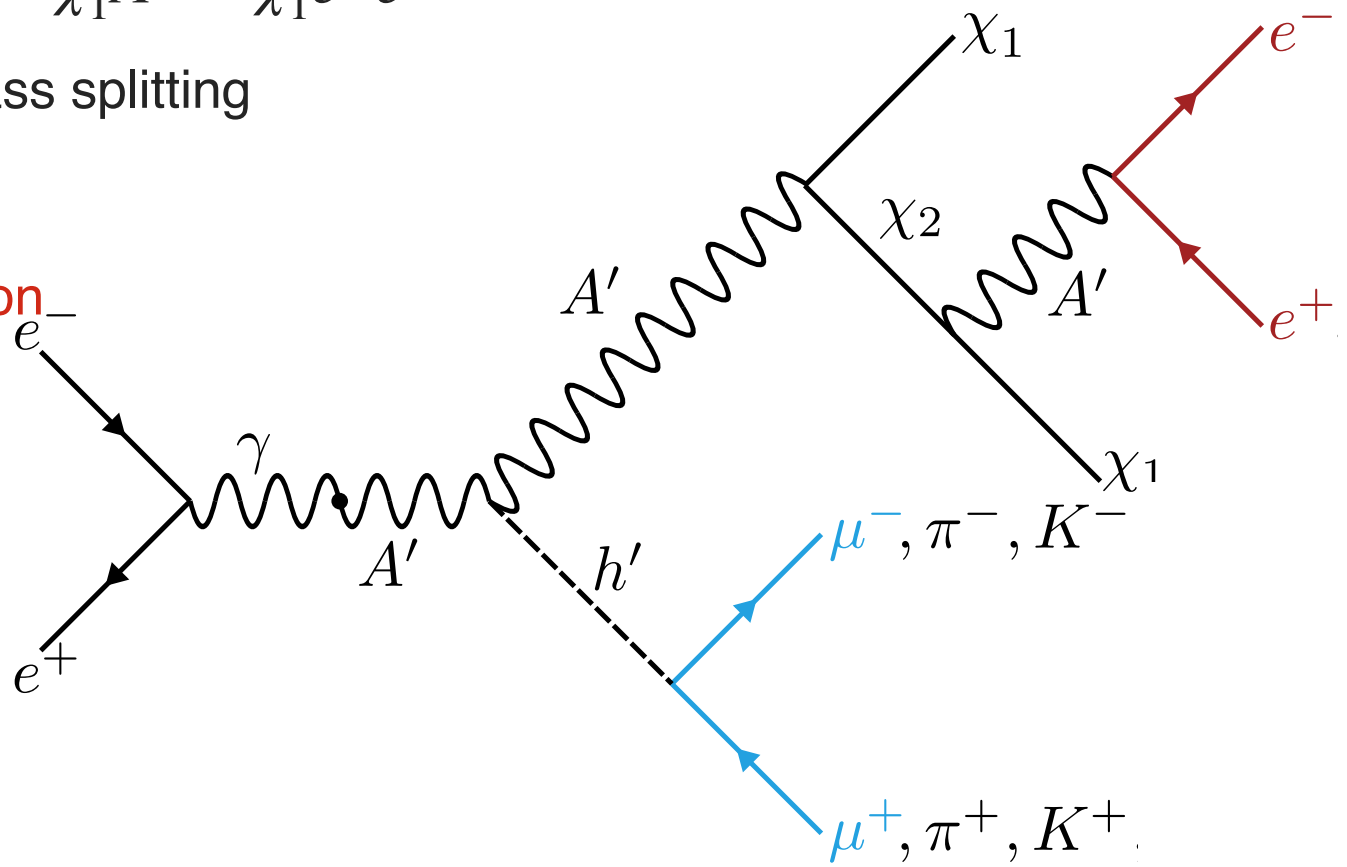
  A' = dark photon that mixes with SM photon

  h' = dark Higgs that mixes with SM Higgs

In region of parameter spaced considered, both the χ_2 and h' can be long lived particles

M. Duerr, et al. J. High Energ. Phys. 2021, 146 (2021)

D. Smith and N. Weiner PhysRevD.64.043502 (2001)



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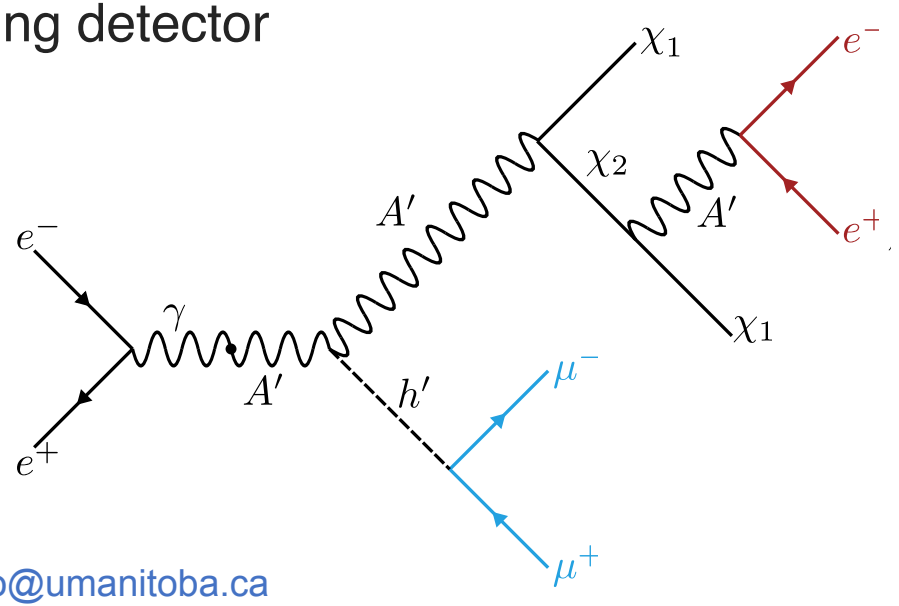
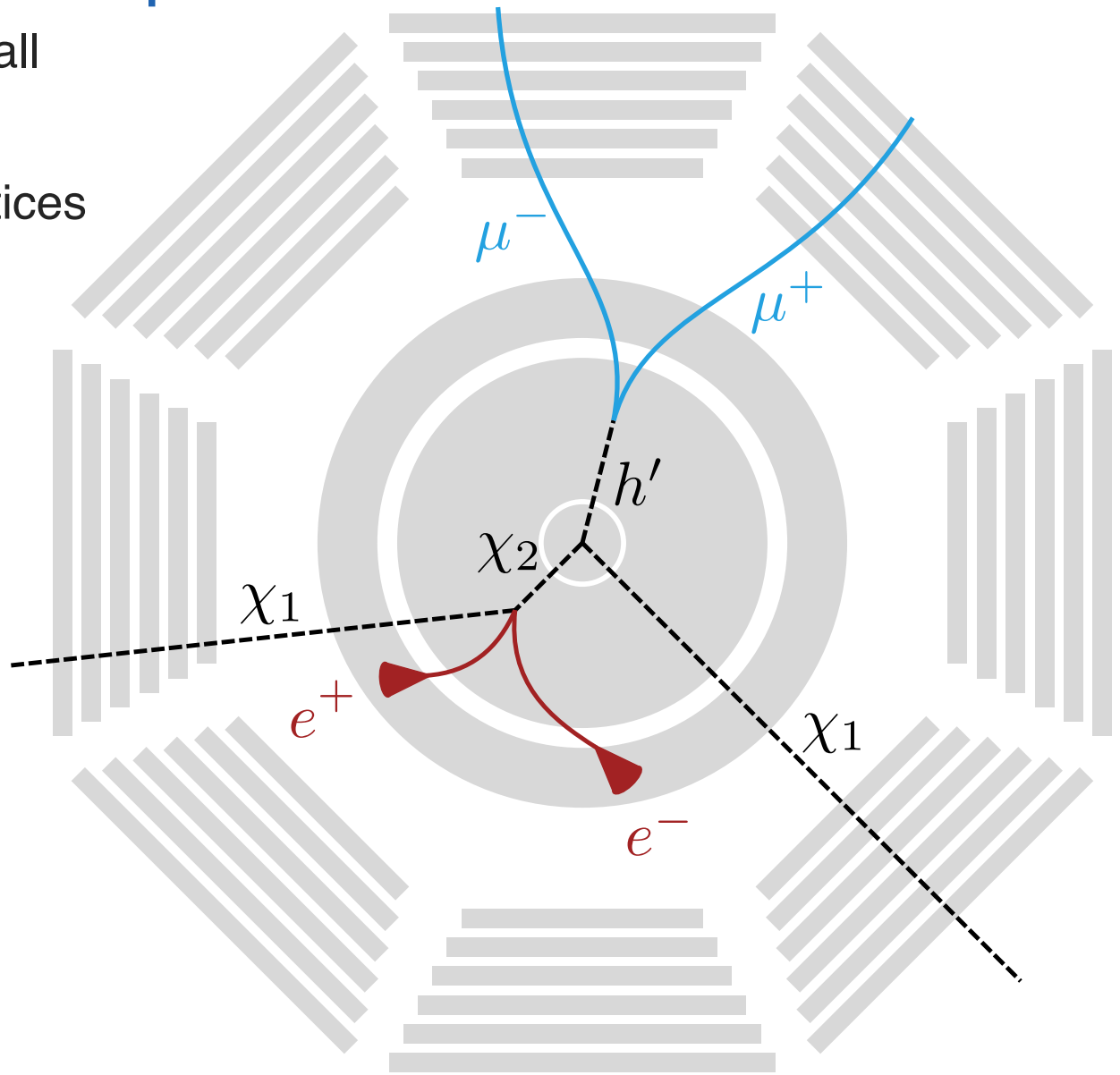
Search for a dark Higgs boson produced in association with inelastic dark matter at the Belle II experiment

- χ_2 and dark Higgs are Long Lived Particles for small coupling/mixing
- Decays of h' and χ_2 result in separate 2-track vertices displaced from collision point
- Missing energy from χ_2 decay produces displaced vertex that does not point back to collision point
- Event has large missing energy from multiple χ_1 escaping detector





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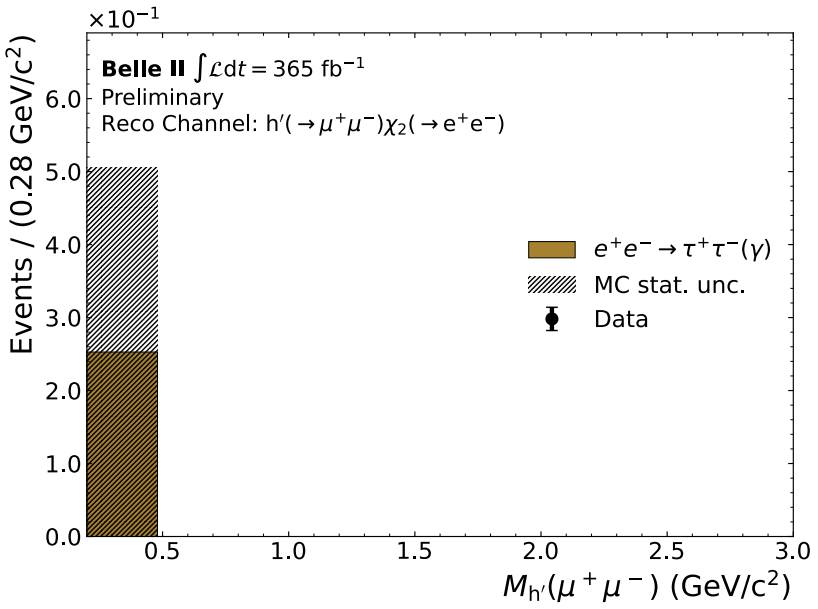
Search for a dark Higgs boson produced in association with inelastic dark matter at the Belle II experiment

- Signal will result in localized excess in $M_{x^+x^-}$ distribution
- Presence of two displaced vertices and missing energy significantly suppresses backgrounds; search is nearly background-free

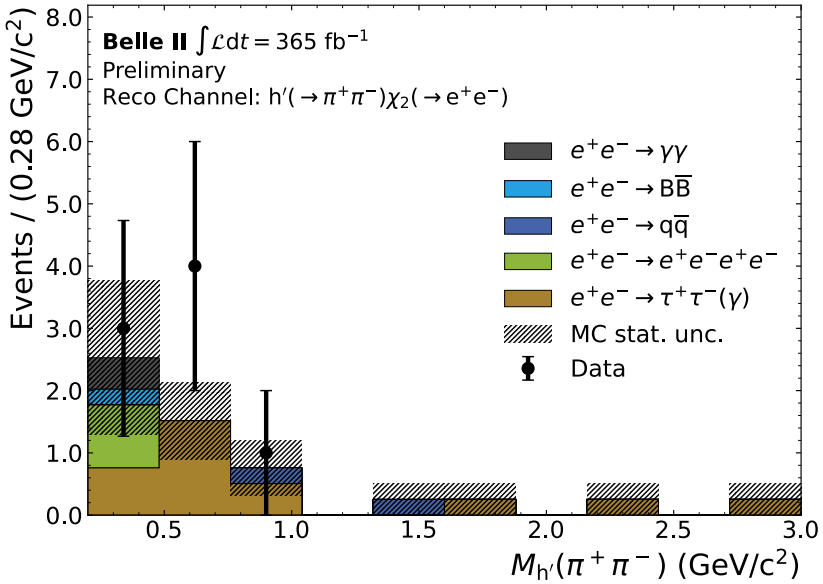
$h' \to \mu^+\mu^-$

Zero events observed



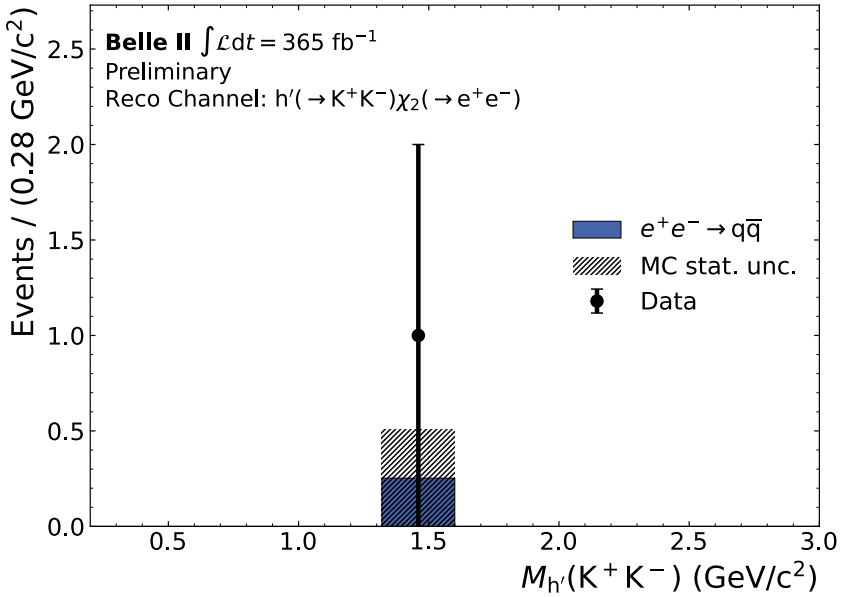
$h' \to \pi^+\pi^-$

Eight events observed



$h' \to K^+K^-$

One event observed



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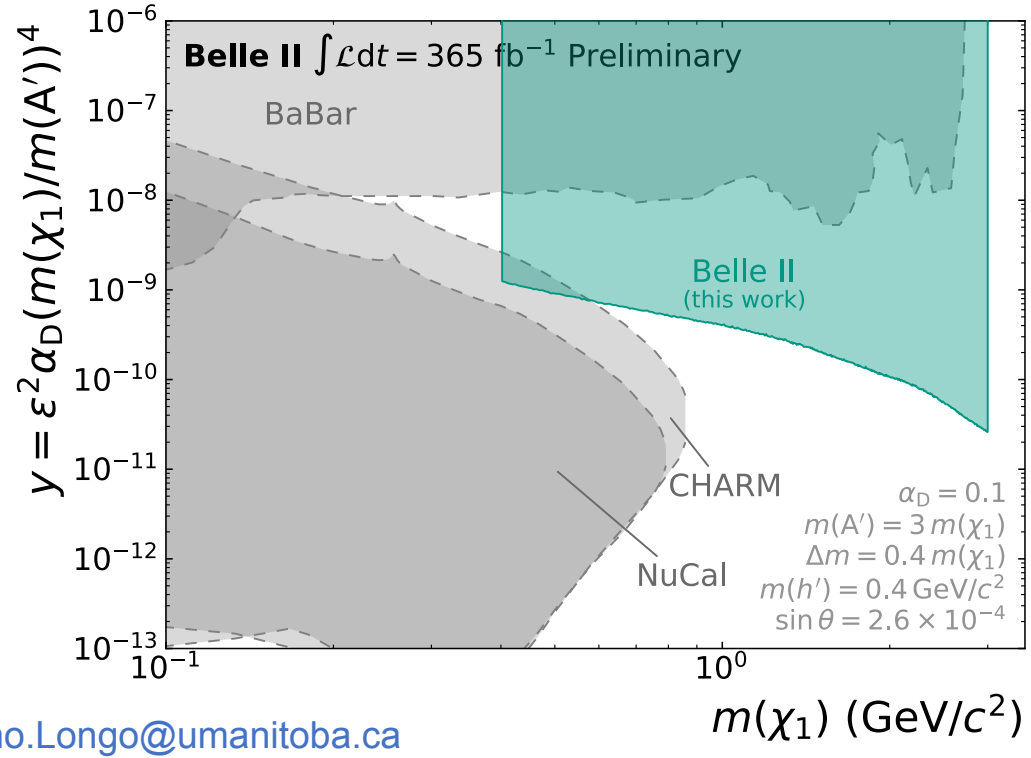
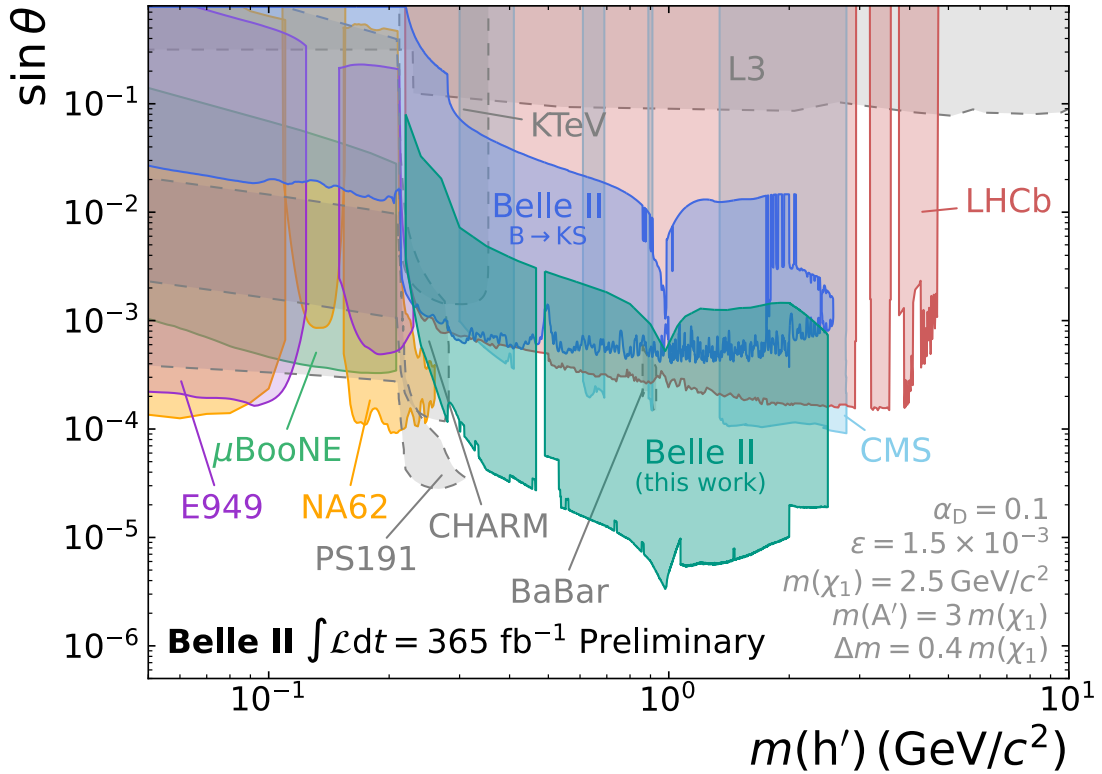
Search for a dark Higgs boson produced in association with inelastic dark matter at the Belle II experiment

- No significant excess is observed
- Upper limits are set on: $\sigma(e^+e^- \to h'\chi_1\chi_2) \times \mathcal{B}(\chi_2 \to \chi_1 e^+e^-) \times \mathcal{B}(h' \to x^+x^-)$
- Exclusions set for A' and h' for large range of parameter space
- Note limits by other experiments do not require A'/h' or inelastic dark matter

Submitted to PRL
arxiv:2505.09705





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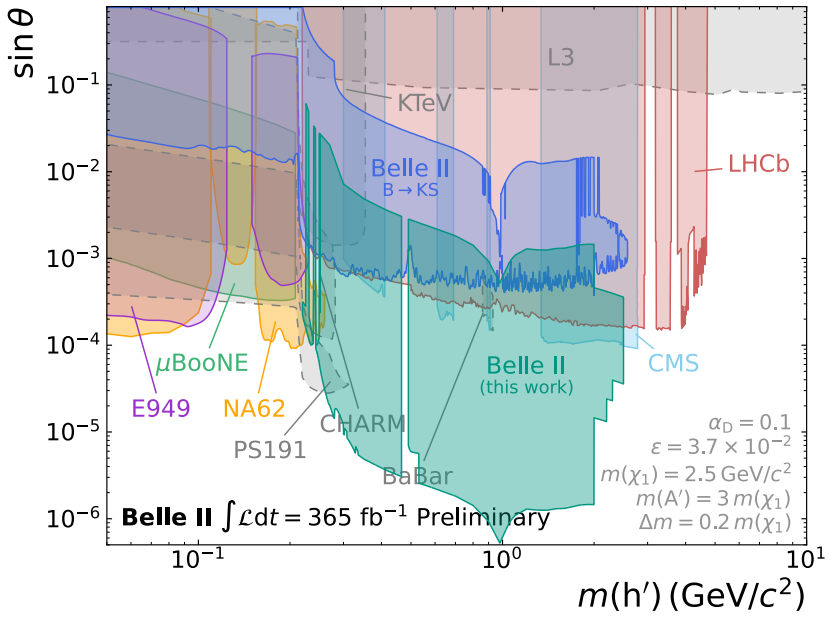
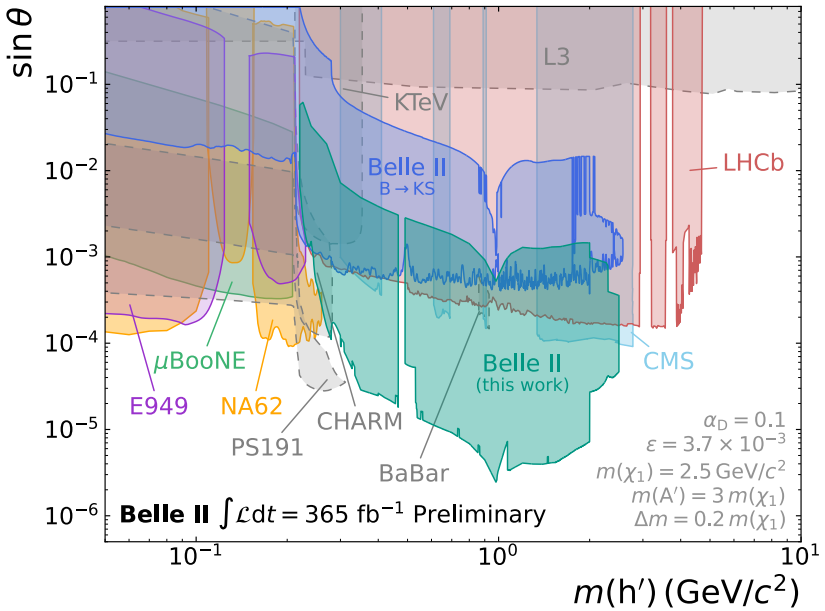
Search for a dark Higgs boson produced in association with inelastic dark matter at the Belle II experiment

- Limits improve over existing searches by up to two orders of magnitude depending on combination of model parameters
- $\Delta m = 0.2 m_{\chi_1}$ in plots below

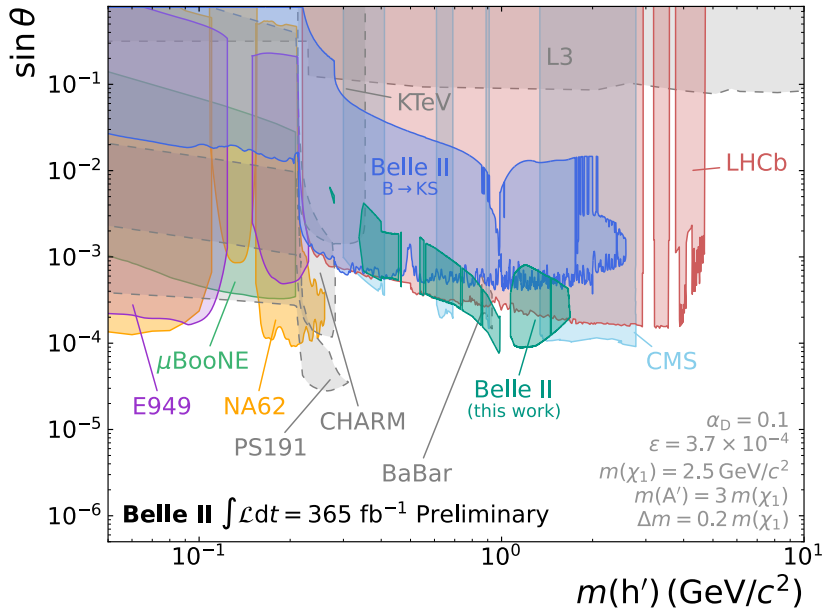
$\epsilon = 3.7 \times 10^{-2}$
$c\tau(\chi_2) = 0.01$ cm



$\epsilon = 3.7 \times 10^{-3}$
$c\tau(\chi_2) = 1$ cm



$\epsilon = 3.7 \times 10^{-4}$
$c\tau(\chi_2) = 100$ cm



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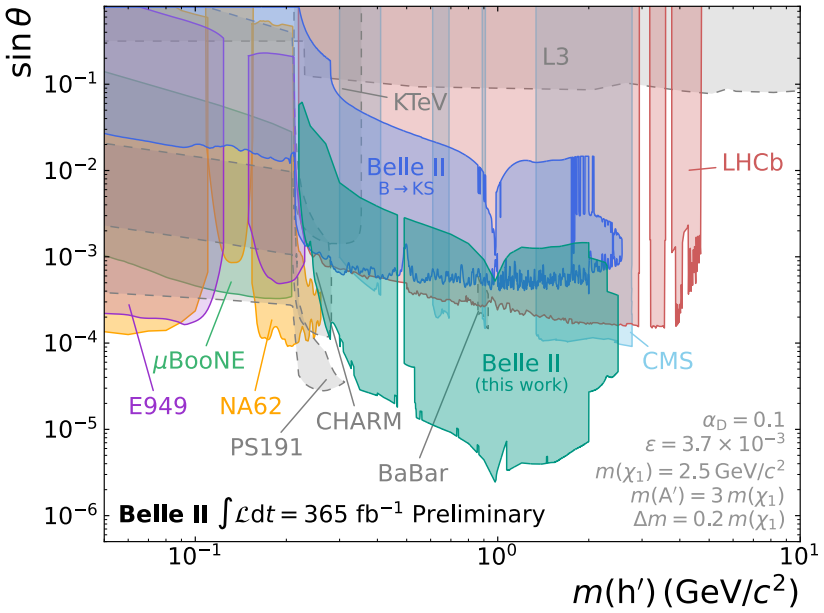
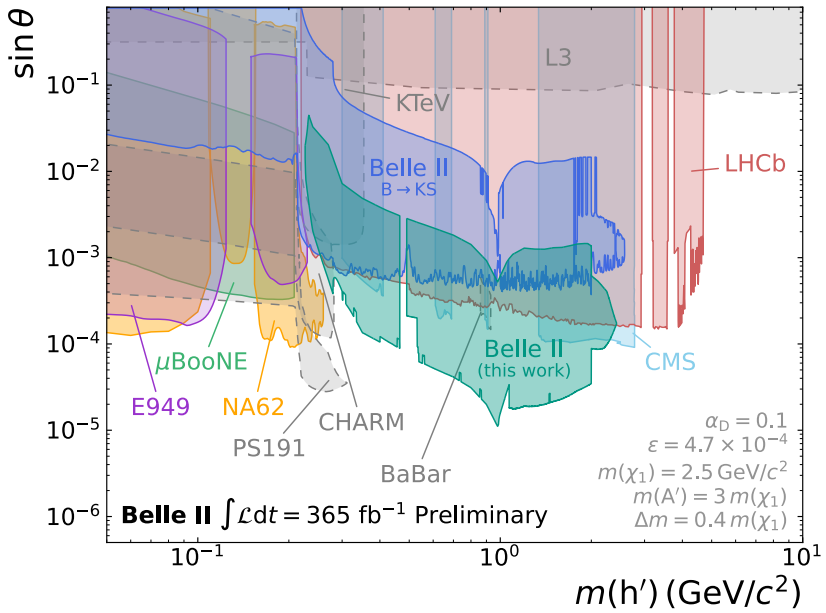
Search for a dark Higgs boson produced in association with inelastic dark matter at the Belle II experiment

- Limits improve over existing searches by up to two orders of magnitude depending on combination of model parameters
- $c\tau(\chi_2) = 1$ cm in plots below

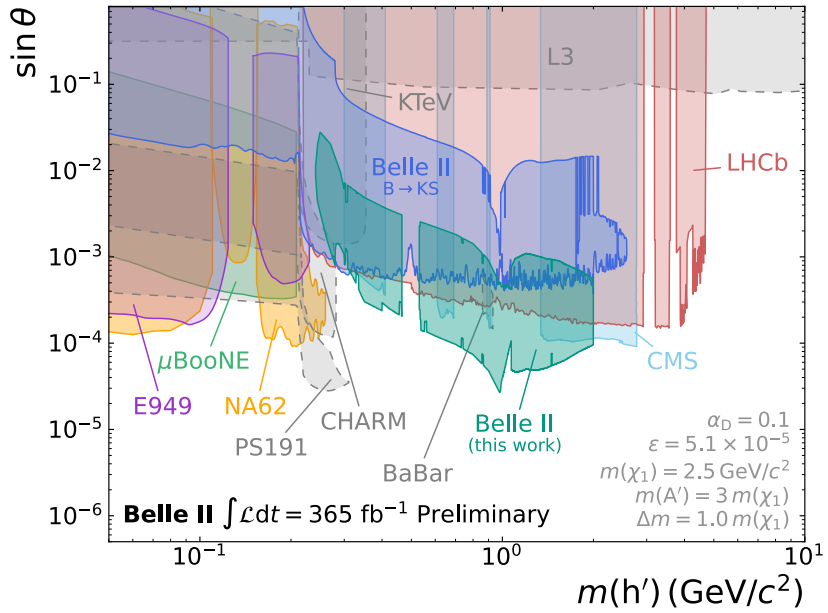
$\epsilon = 3.7 \times 10^{-3}$
$\Delta m = 0.2 m_{\chi_1}$



$\epsilon = 4.7 \times 10^{-4}$
$\Delta m = 0.4 m_{\chi_1}$



$\epsilon = 5.1 \times 10^{-5}$
$\Delta m = 1 m_{\chi_1}$



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Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II

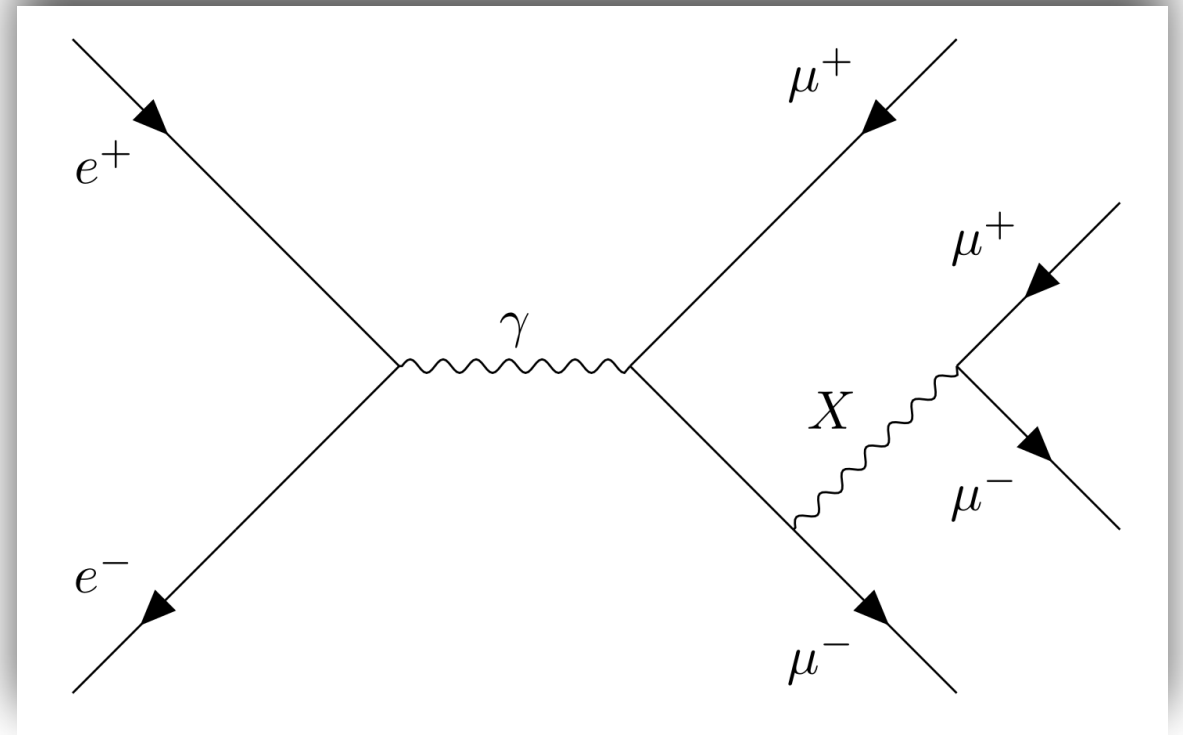
- Search for a dark mediator (X) decaying to $\mu^+\mu^-$
- Multiple interpretations:
  - $Z' \to \mu^+\mu^-$ from $L_\mu - L_\tau$ extensions of standard model
  - Muonphilic scalar $S \to \mu^+\mu^-$ proposed to resolve $(g-2)_\mu$ anomaly

P. Harris, P. Schuster, and J. Zupan (2022), arXiv:2207.08990

N. Tran, et al., PRD 107, 116026 (2023)

- Belle II production channel:

$$e^+e^- \to \mu^+\mu^- X, \quad X \to \mu^+\mu^-$$



- Select events with four tracks identified as muons
- Require the four tracks to have total centre-of-mass energy consistent with collision $\sqrt{s}$

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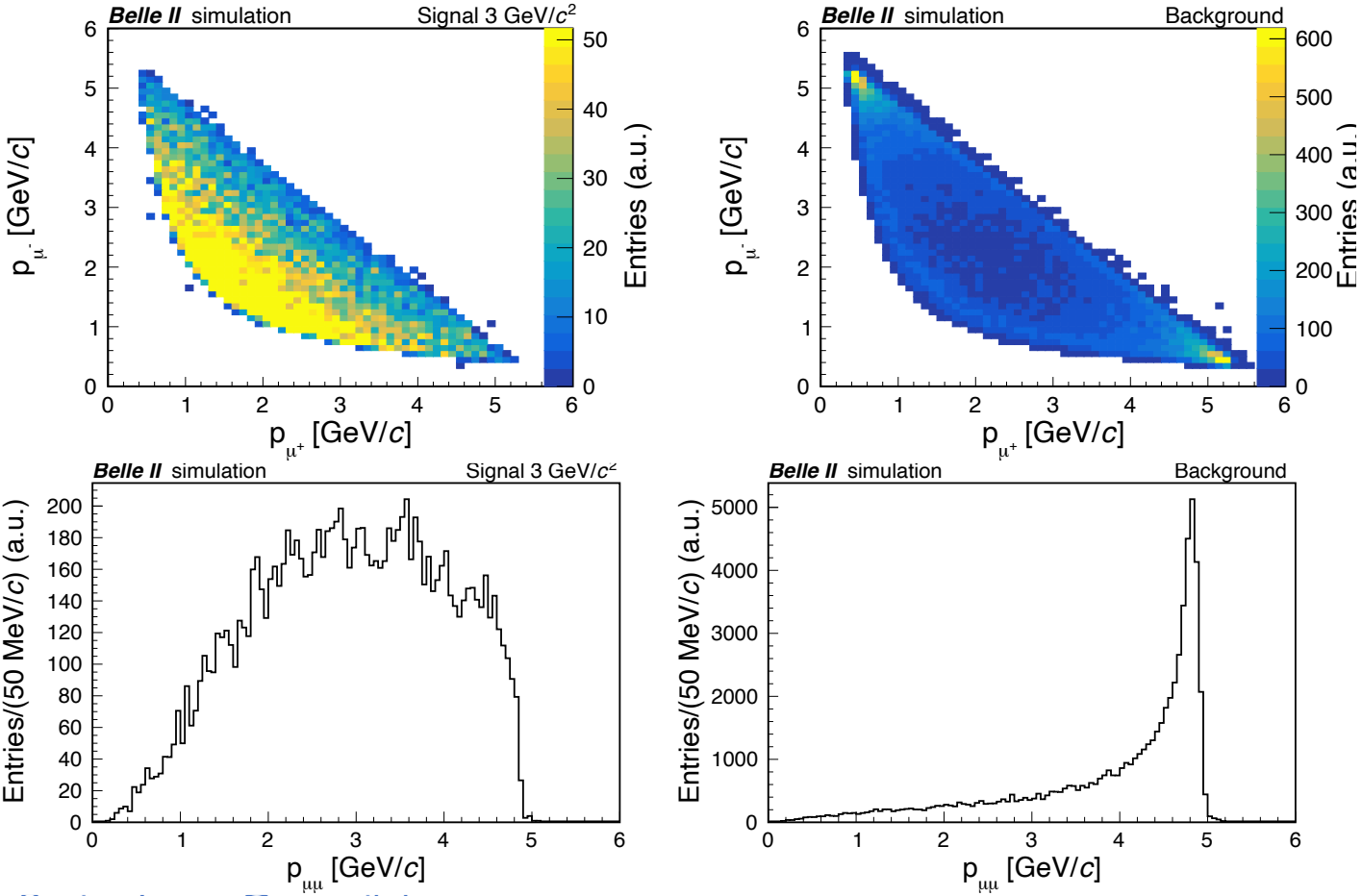
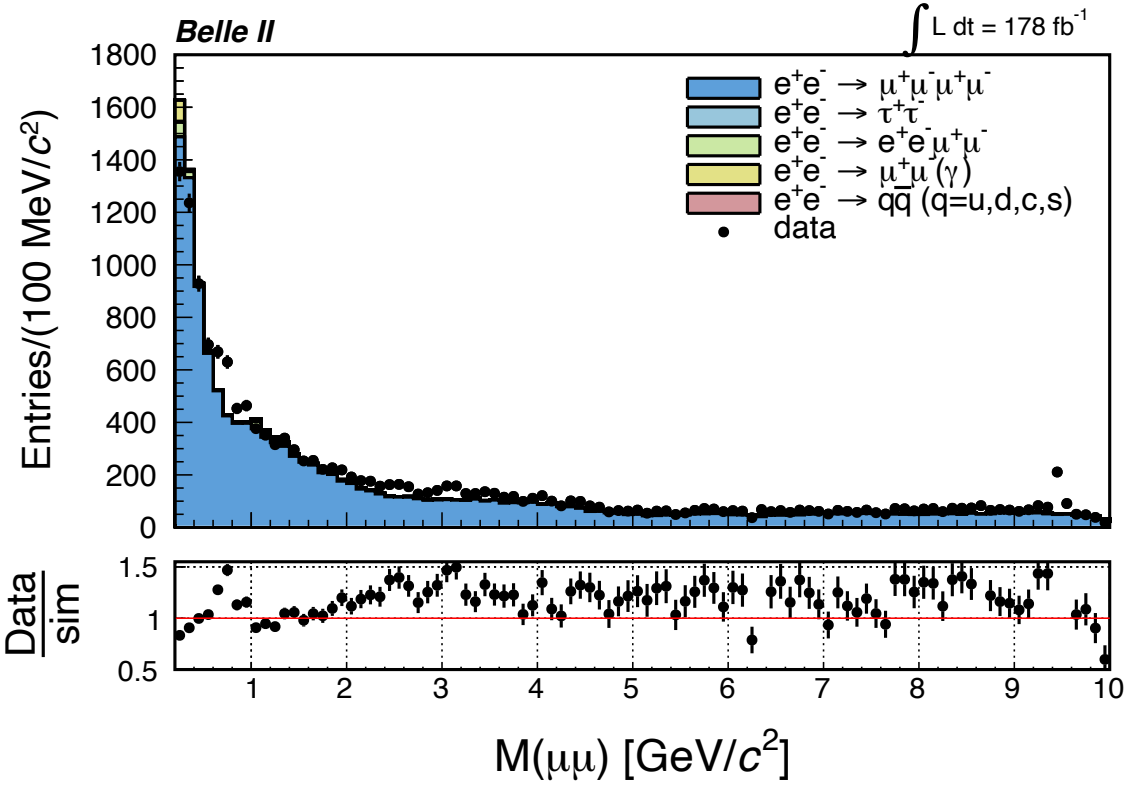
Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II

- Main background from $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
  - Suppressed with neural network trained on kinematic quantities
- Search for localized excess in M($\mu\mu$) distribution





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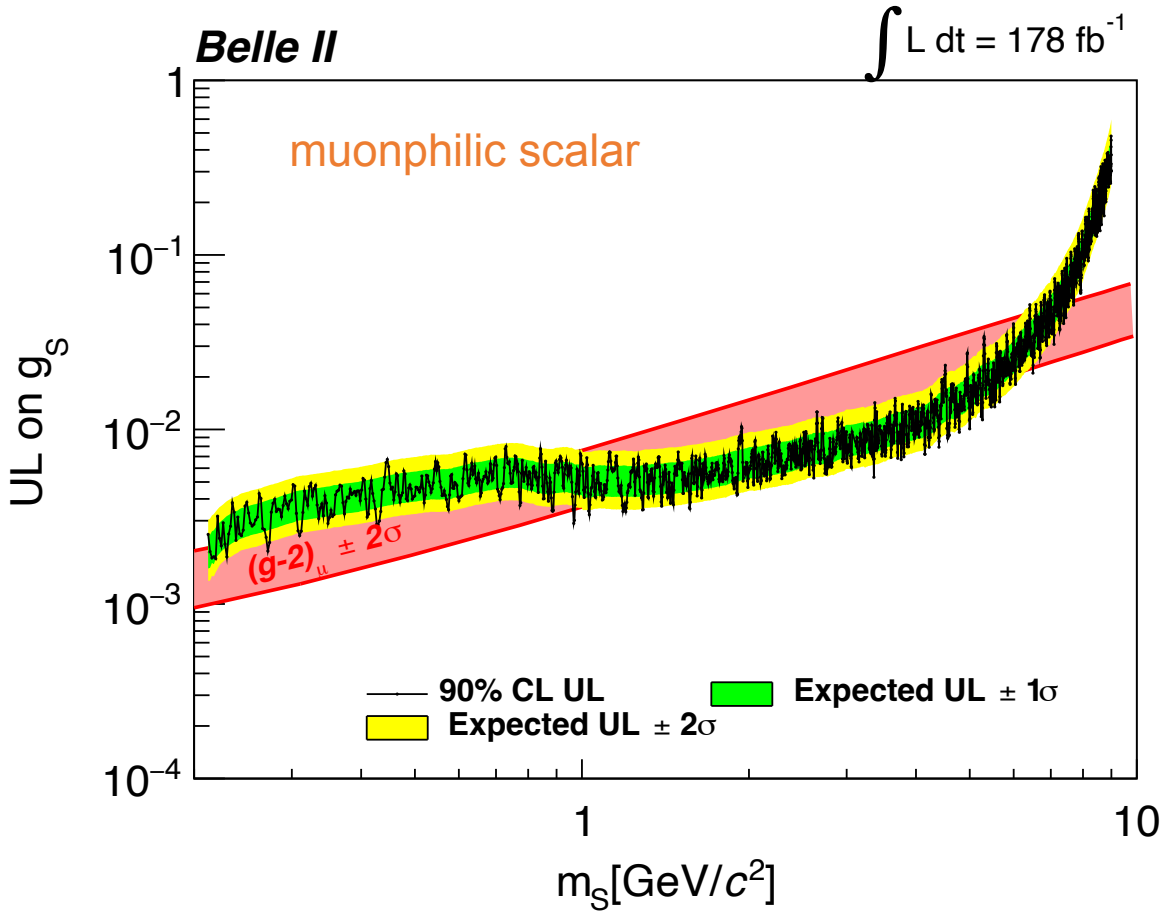
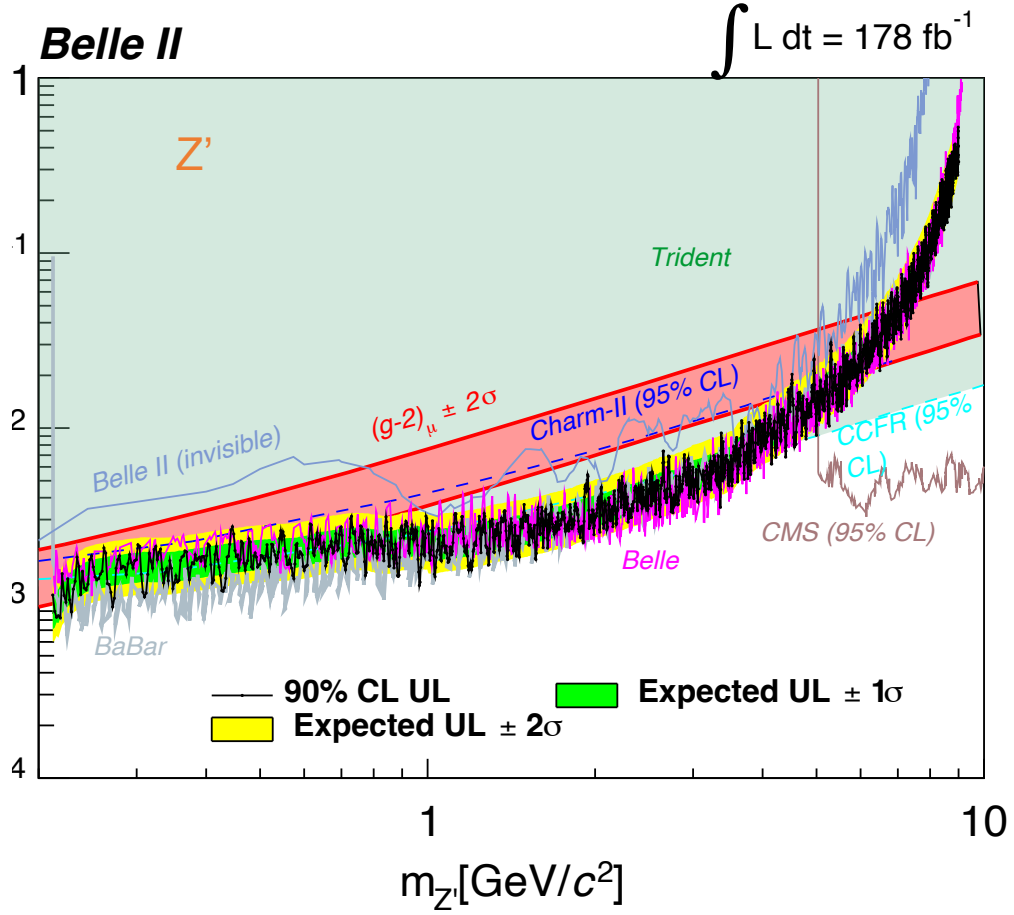
Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II

- No significant excess observed in 178 fb^{-1}
- Limits set on Z' and muonphilic scalar interpretations
- First experiment to set limits on muonphilic scalar. Constrains explanation for muon g-2 anomaly

Phys. Rev. D 109, 112015 (2024)
arXiv:2403.02841





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Conclusions

- Variety of methods to search for production of MeV-to-GeV scale dark mediators at Belle and Belle II
- New triggers introduced at Belle II for low multiplicity final states open additional dark sector search opportunities
- Recent dark sector searches by Belle and Belle II were reported

➡Belle Collaboration, Search for an axion-like particle in B meson decays To be submitted to JHEP

➡Belle II Collaboration, Search for a dark Higgs boson produced in association with inelastic dark matter at the Belle II experiment Submitted to PRL arxiv:2505.09705

➡Belle II Collaboration, Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II Phys. Rev. D 109, 112015 (2024) arXiv:2403.02841

- Additional dark sector searches in progress and future results will benefit from full Belle II dataset (575 fb^{-1})
- Belle II Run 2 will resume in Fall 2025

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