



# Searches for Dark Sector Particles at Belle and Belle II

14th International Workshop on  $e^+e^-$  collisions from Phi to Psi 2026

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University of Manitoba*

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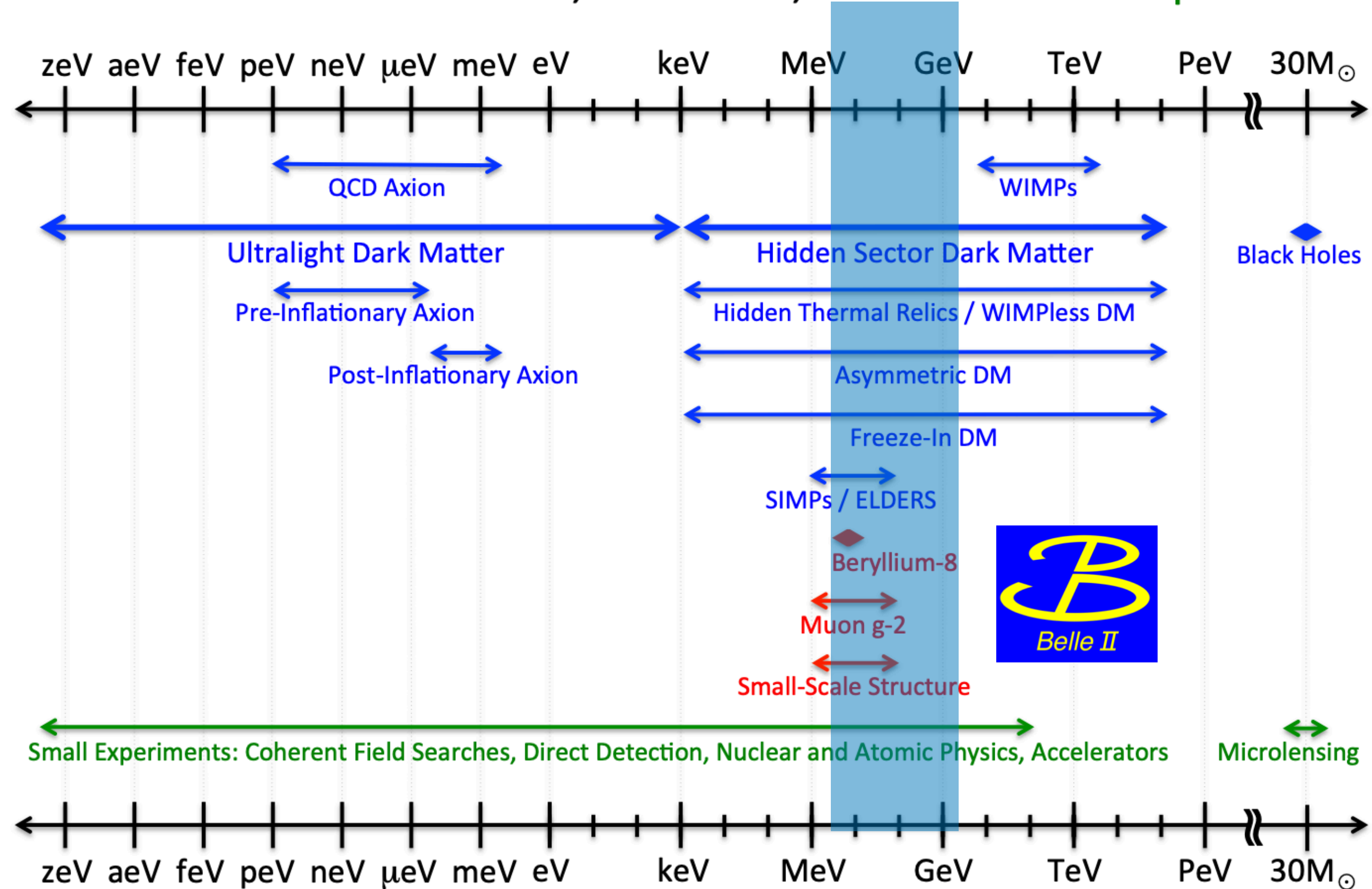
- Dark particle searches at B factories
- Dark particle searches at Belle II
- Recent dark particle results at Belle and Belle II
  - Dark Matter With Dark Higgs *PRL 135, 131801 (2025)*
  - $B \rightarrow K^{(*)}\gamma\gamma$  for ALP search *JHEP 12 (2025) 109*
  - $e^+e^- \rightarrow \gamma a(\rightarrow \gamma\gamma)$  for ALP search *Submitted to PRL (2026)*
  - Feebly Interacting Particles(FIP) searches at  $B \rightarrow hX_{Inv}$  *Accepted by PRL (2026)*

# Dark particle searches at B factories

arXiv:1707.04591

- Access to sub-GeV models where Dark Matter feebly interacts with the Standard Model through a light mediator
- Vector portal
  - Dark Photons, bosons
- Pseudo-scalar portal
  - Axion Like Particles (ALPs)
- Scalar portal
  - Dark Higgs / Scalars
- Neutrino portal
  - Sterile neutrinos

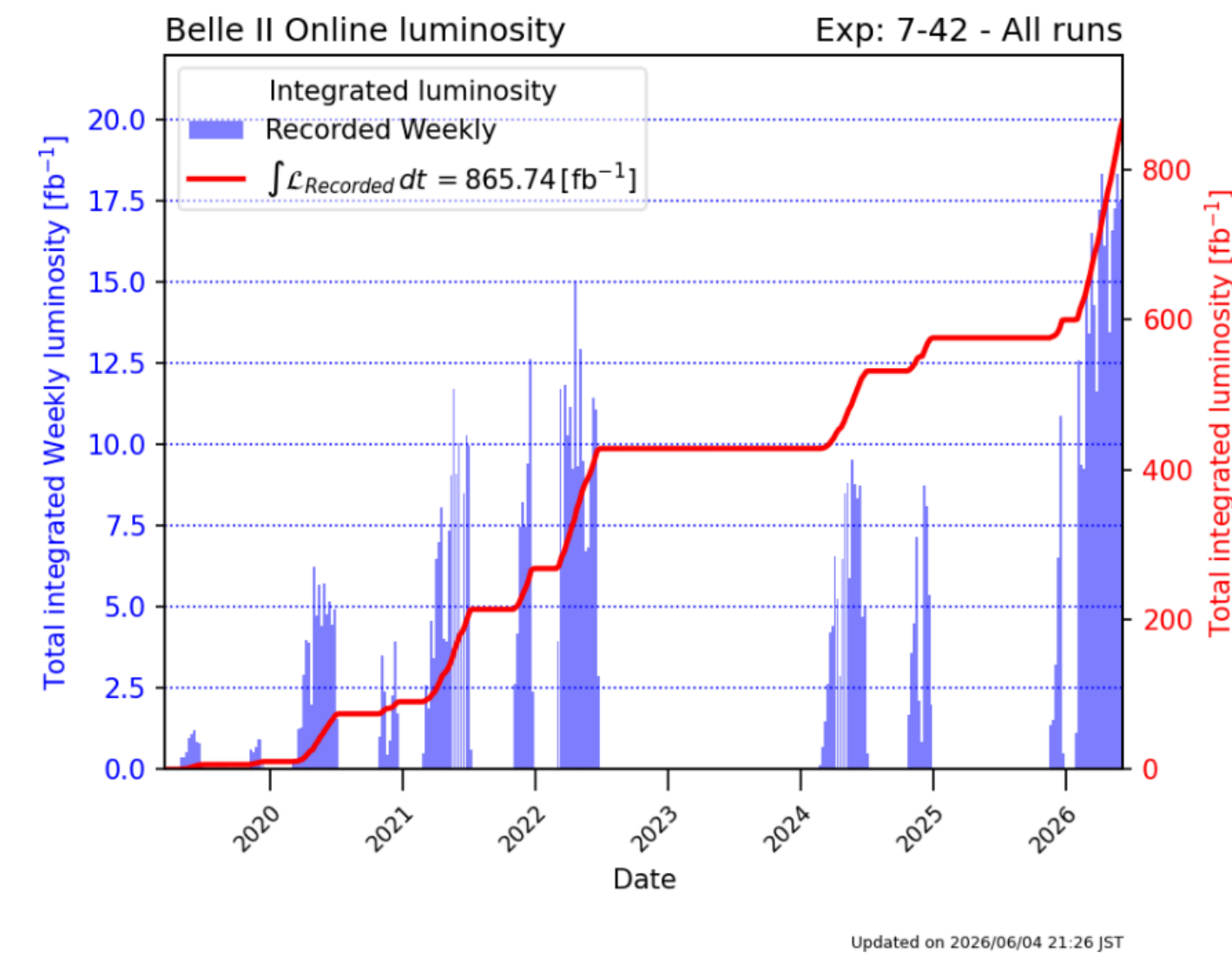
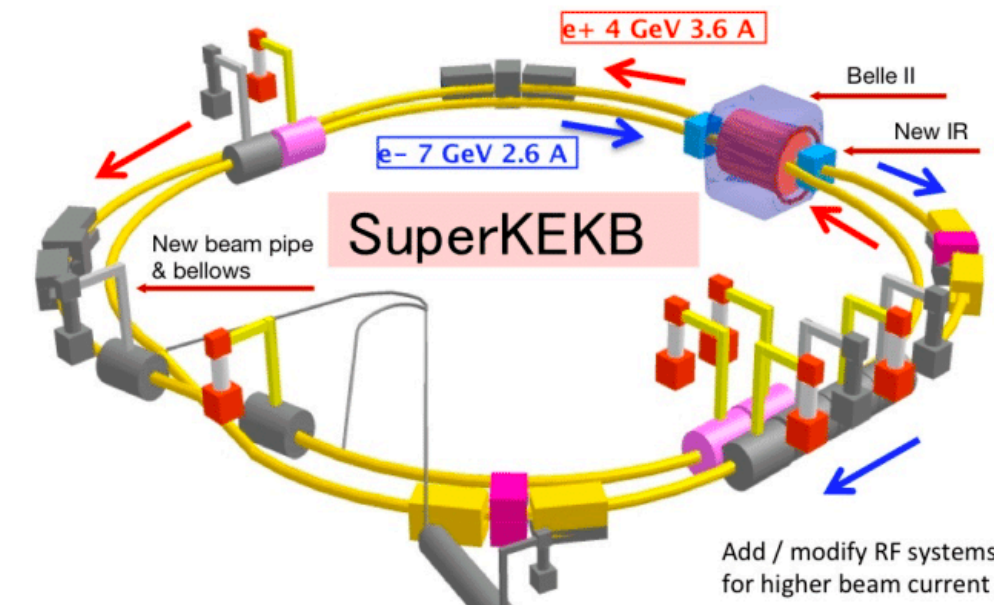
## Dark Sector Candidates, Anomalies, and Search Techniques



# Dark particle searches at Belle II

## SuperKEKB

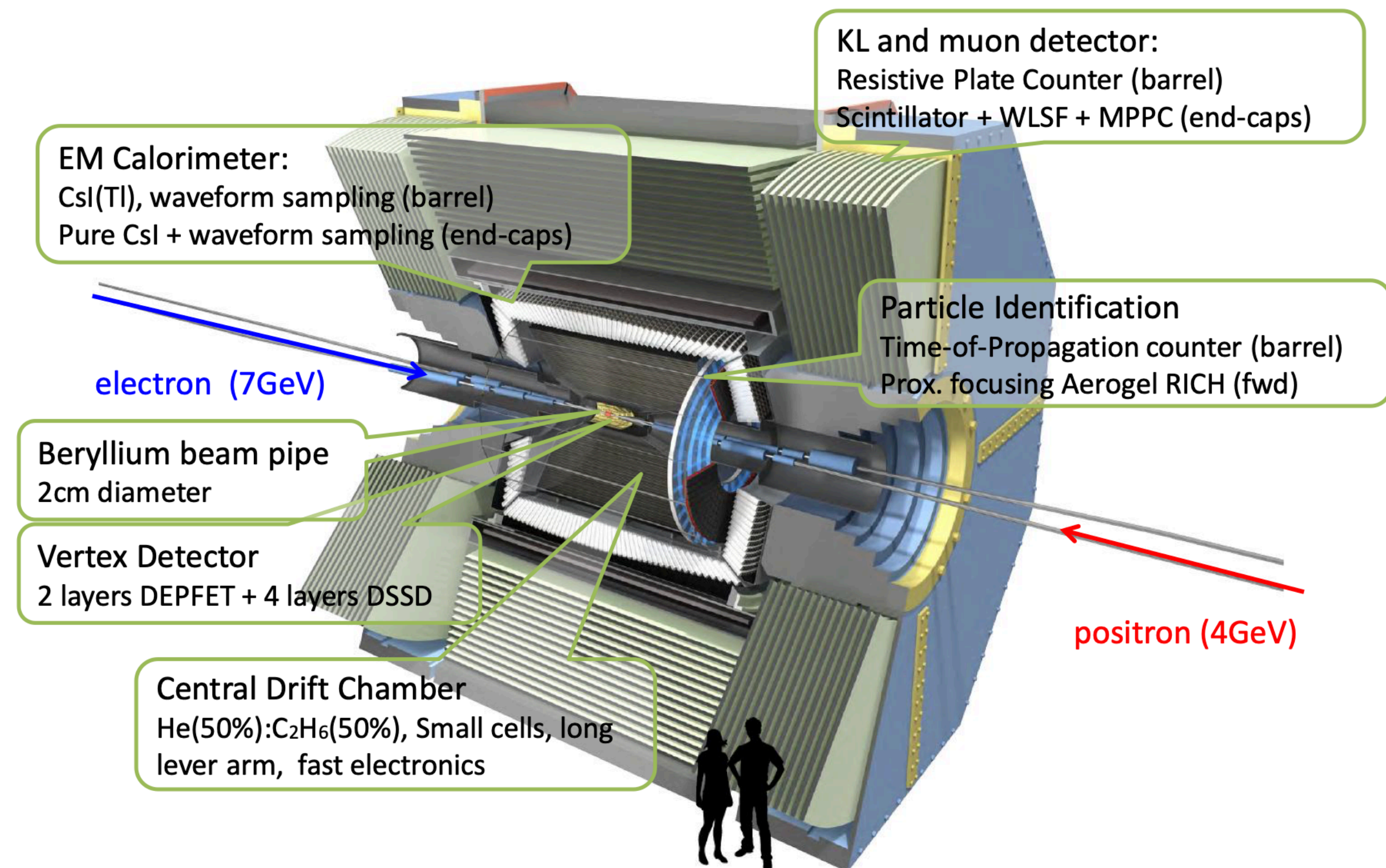
- 2nd generation asymmetric  $e^+e^-$  collider at 10.58GeV energy
- World's highest instantaneous luminosity  $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$
- Integrated luminosity  $\sim 866/\text{fb}$



## Belle II

- Clean initial state  $e^+e^-$  with excellent hermeticity
- Improved vertexing resolution and tracking performance, specialized triggers for dark sector signatures
- Full event interpretation

*Advantages for low multiplicity events, missing energy events and full neutral final states*



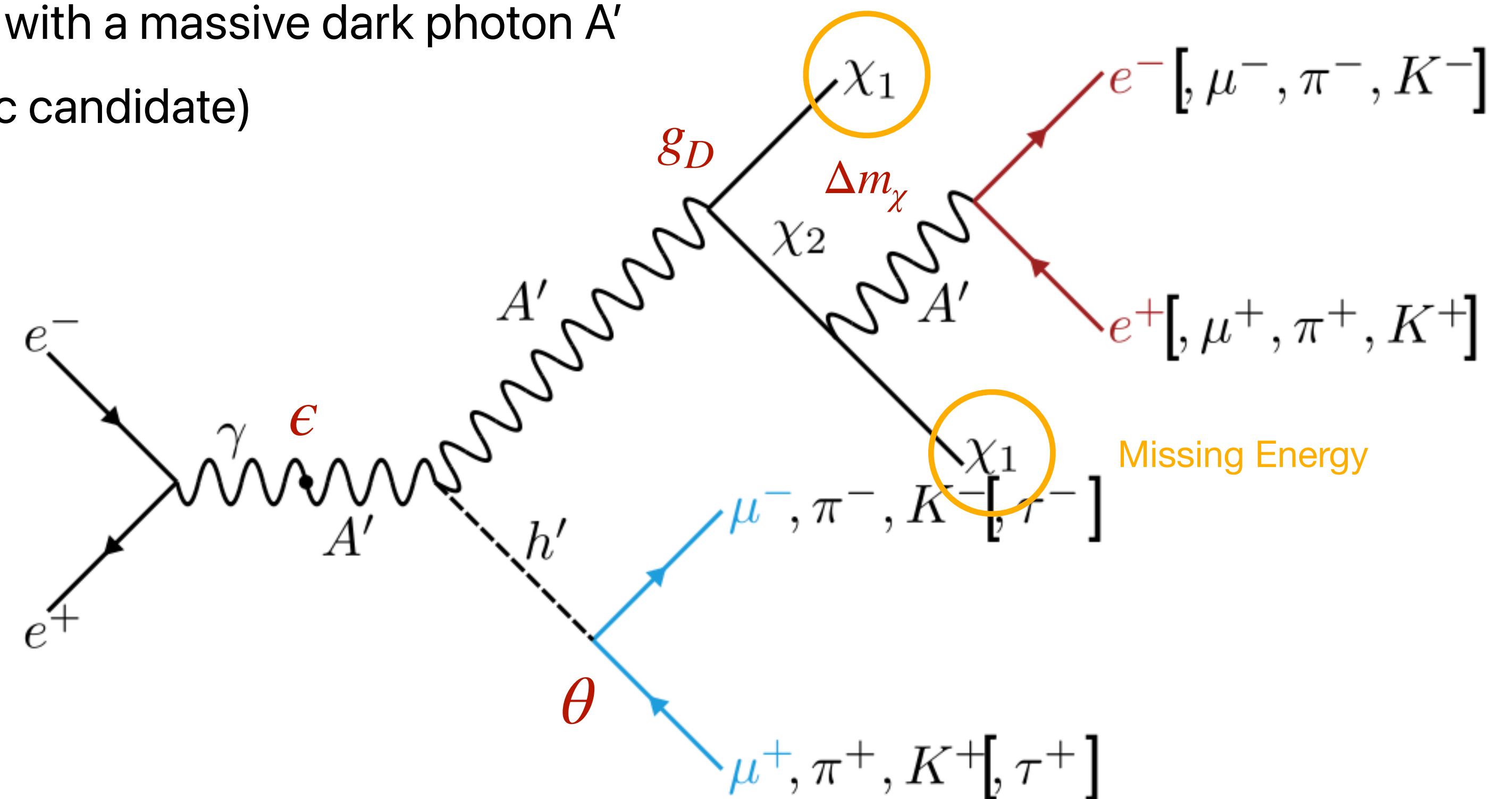
# Recent Dark Sector Studies

# Inelastic Dark Matter With Dark Higgs

## Introduction

- First search for dark Higgs bosons in association with inelastic dark matter
- Signal process:  $e^+e^- \rightarrow h'(\rightarrow x^+x^-)A'(\rightarrow \chi_1\chi_2(\rightarrow \chi_1e^+e^-))$ ,  $x = \mu, \pi, K$
- Two states  $\chi_1$  and  $\chi_2$  with mass splitting coupled with a massive dark photon  $A'$ 
  - $\chi_1$  Dark matter, stable (lightest, stable relic candidate)
  - $\chi_2$  Dark matter, long lived
  - $h'$  dark Higgs
  - $A'$  dark photon

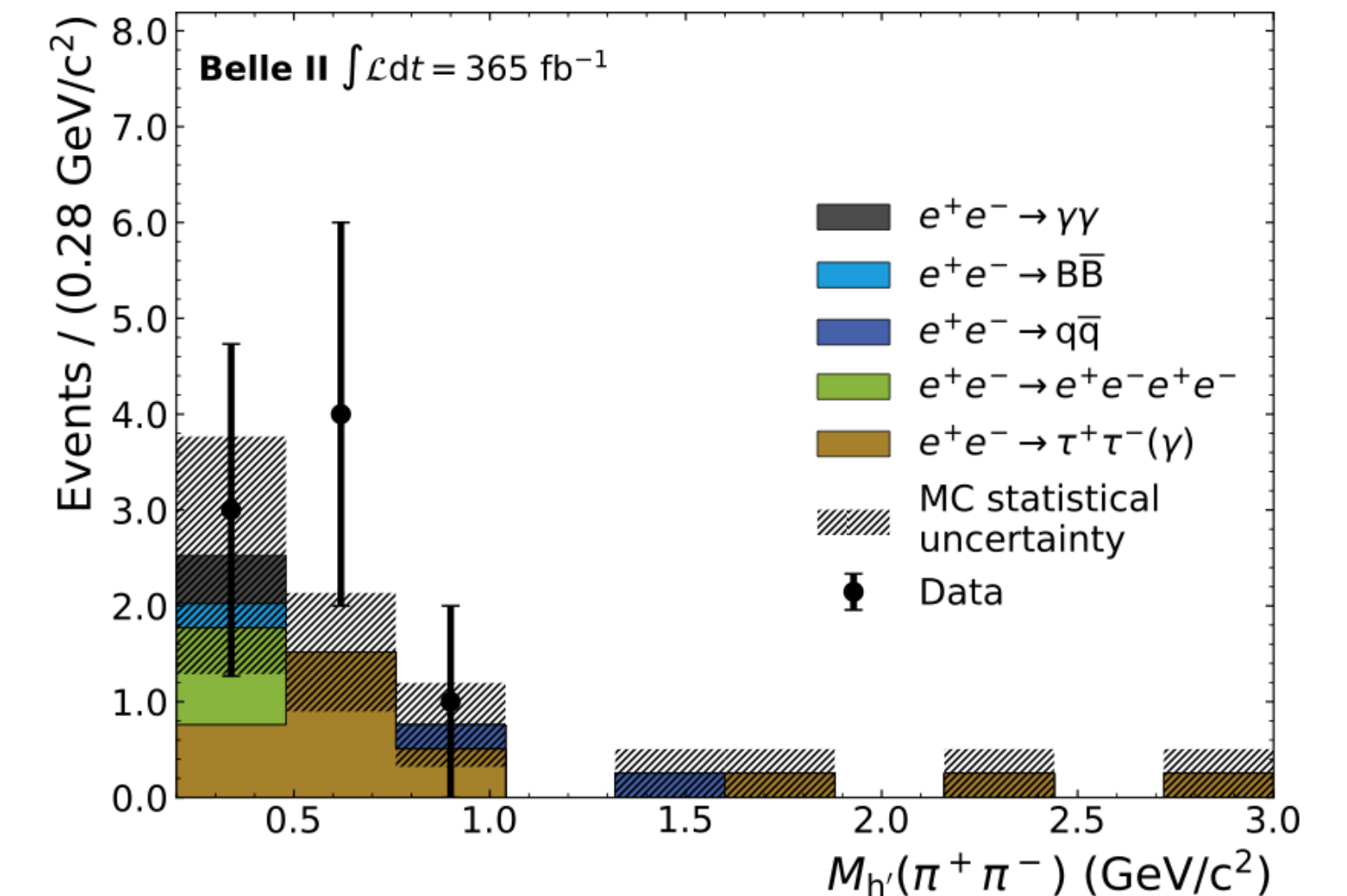
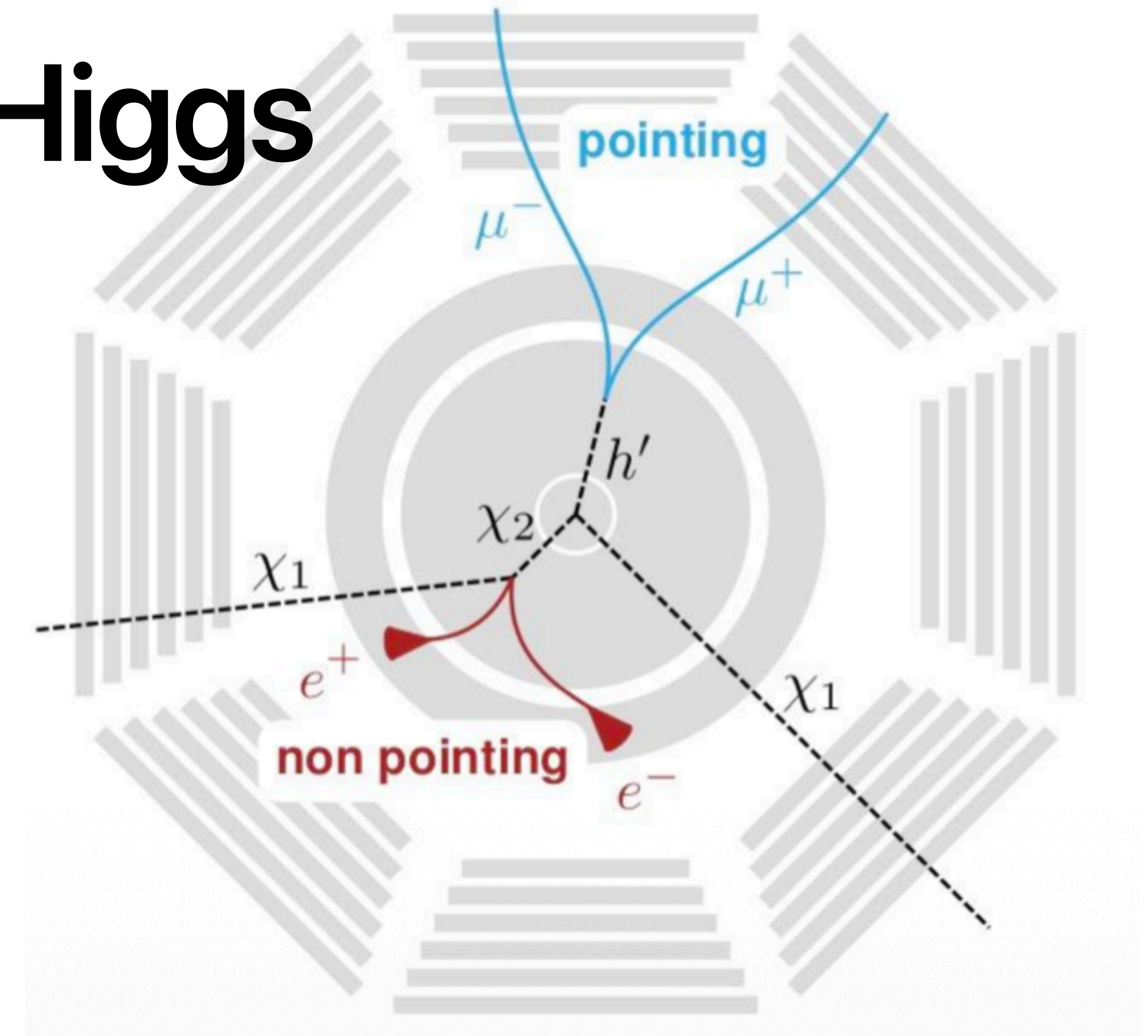
- Set model-independent upper limit on cross section and branching fraction



# Inelastic Dark Matter With Dark Higgs

## Signal Signature

- 365 fb<sup>-1</sup> Belle II data used
- Up to two displaced vertices with missing energy due to undetected  $\chi_1$ 
  - $h'(\rightarrow x^+x^-), x = \mu, \pi, K$  pointing to interaction point
  - $\chi_2 \rightarrow \chi_1 A'(\rightarrow e^+e^-)$  non-pointing, missing energy
- Search for excess in invariant mass distribution  $M_{x^+x^-}$  of  $h'$  decay
- Very small background but challenging due to displaced vertex

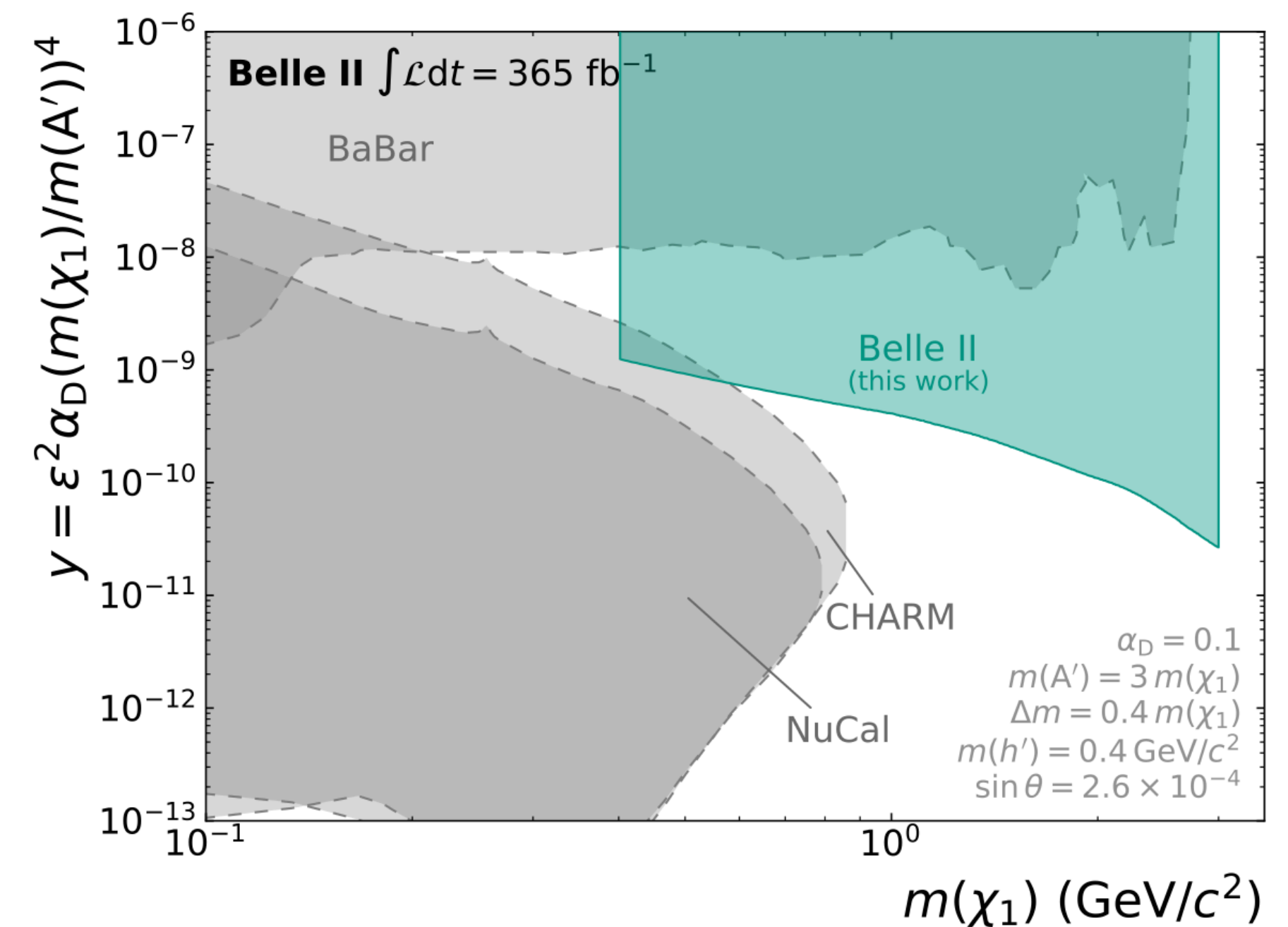
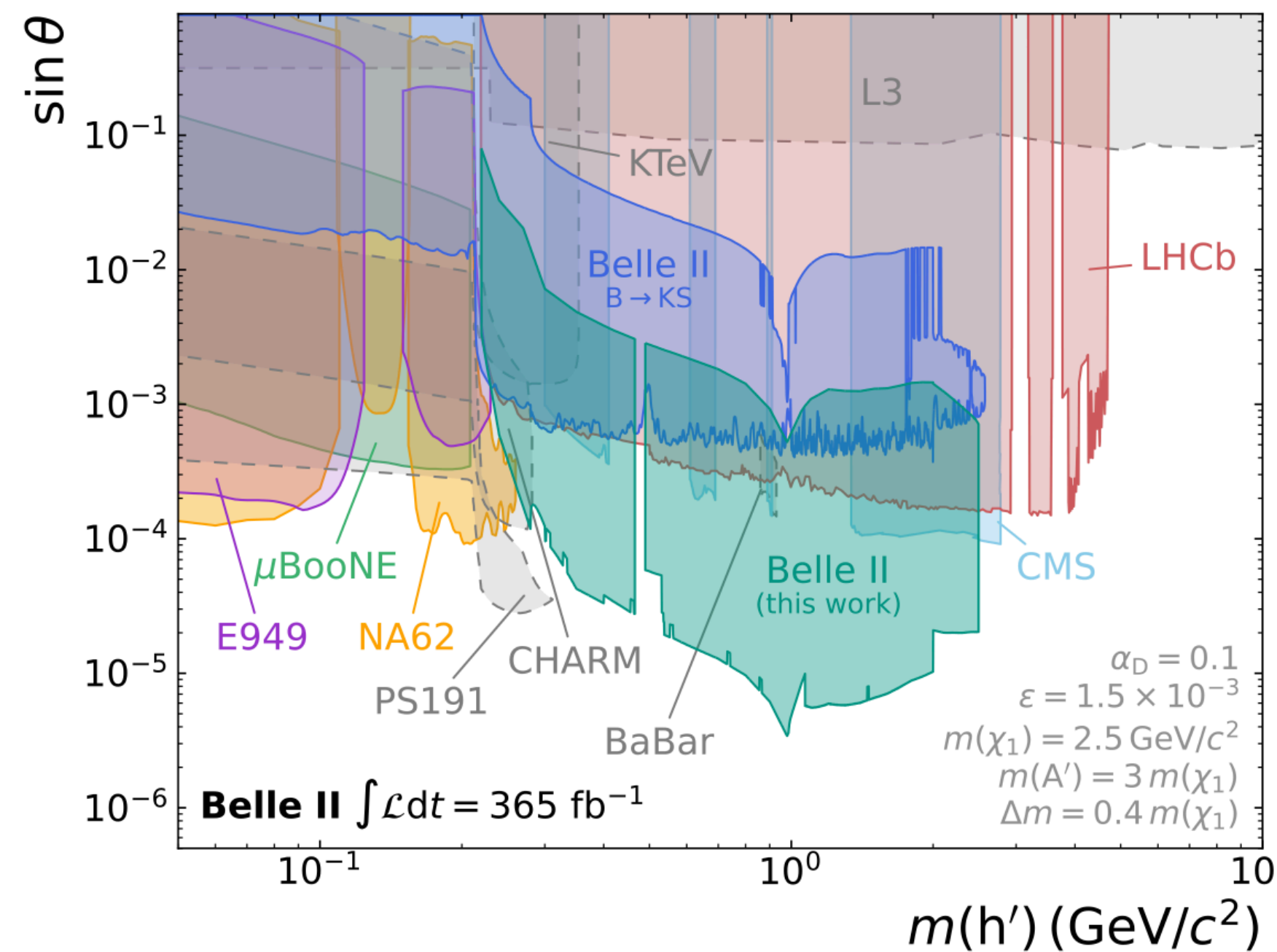


# Inelastic Dark Matter With Dark Higgs

## Results

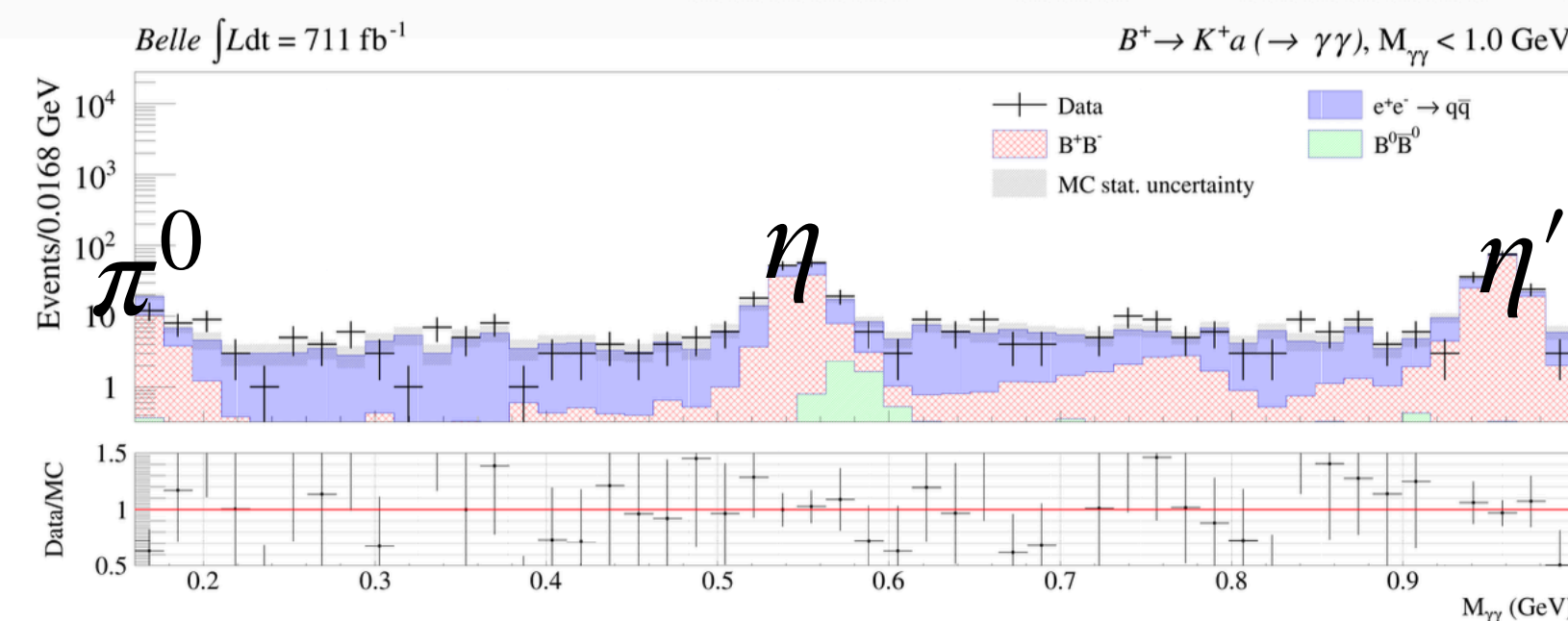
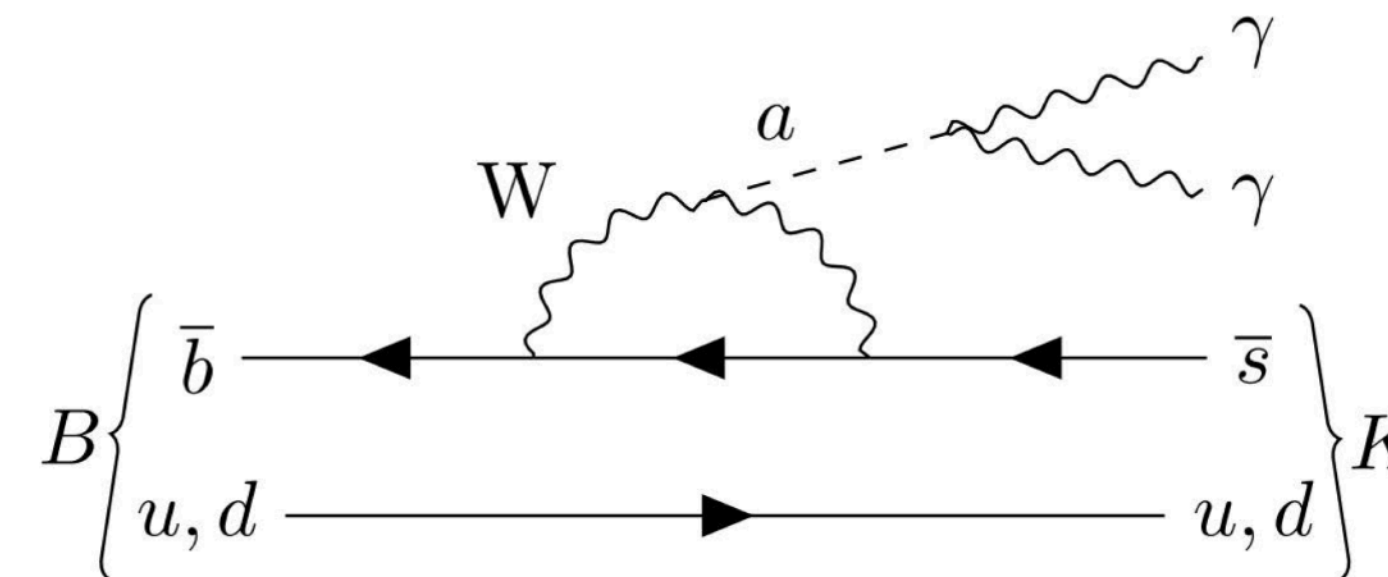
- No significant signal observed
- Set 95% upper limits on production cross section x branching fractions  

$$\sigma_{sig} = \sigma(e^+e^- \rightarrow h'A'(\rightarrow \chi_1\chi_2)) \times \beta(h' \rightarrow x^+x^-) \times \beta(\chi_2 \rightarrow \chi_1 e^+e^-)$$
- Model-dependent upper limit also provided; dark Higgs mixing angle and mixing strength

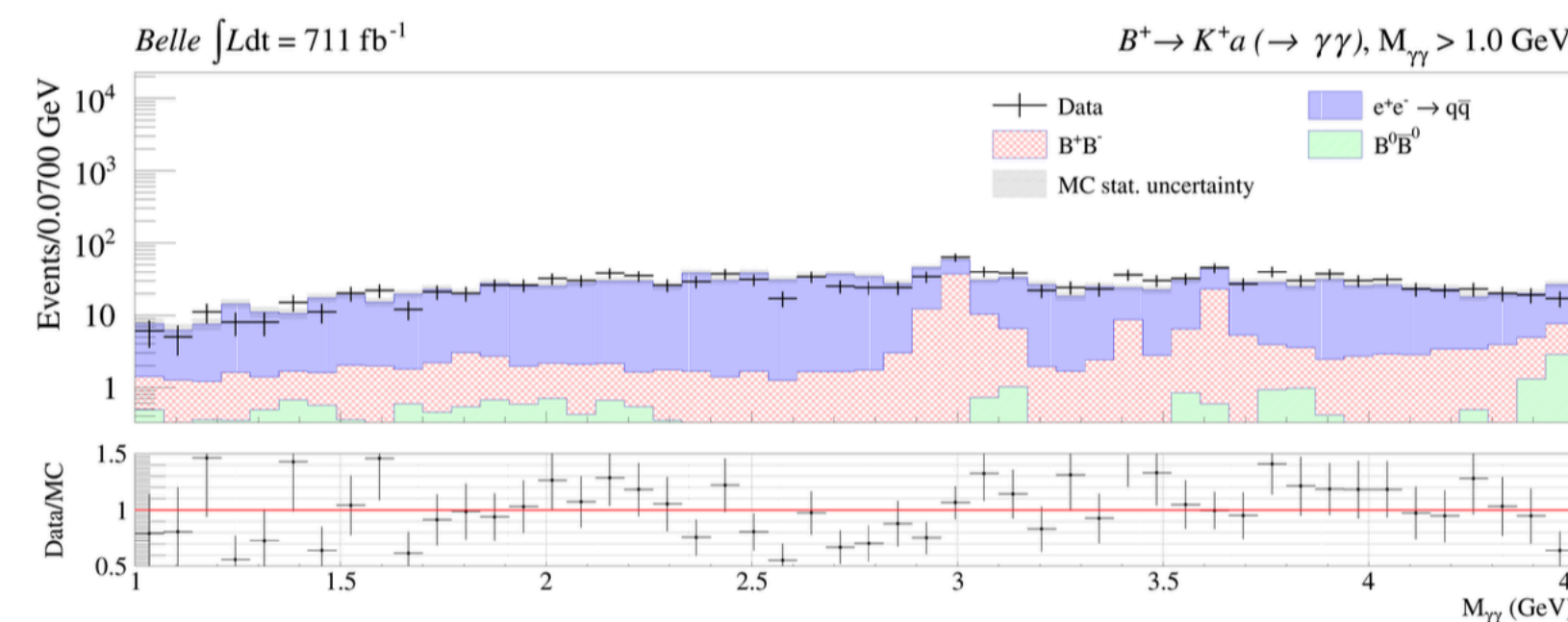


# ALP search from $B \rightarrow K^{(*)}a(a \rightarrow \gamma\gamma)$ at Belle

- 711 fb<sup>-1</sup> Belle data samples
- Search for  $B \rightarrow K^{(*)}a(a \rightarrow \gamma\gamma)$  reaction in four kaon modes  $K_S^0, K^+, K^{*+}, K^{*0}$  where  $a$  decays into two photons promptly
- Signal : narrow excess in  $M_{\gamma\gamma}$  distribution
- Mass range  $0.16 < m_a < 4.20(4.50)$  GeV,
  - 4.2GeV for  $K^*$  mode, 4.5GeV for  $K$  modes
  - $\pi^0, \eta, \eta'$  windows vetoed
- Major backgrounds from continuum is suppressed by BDT



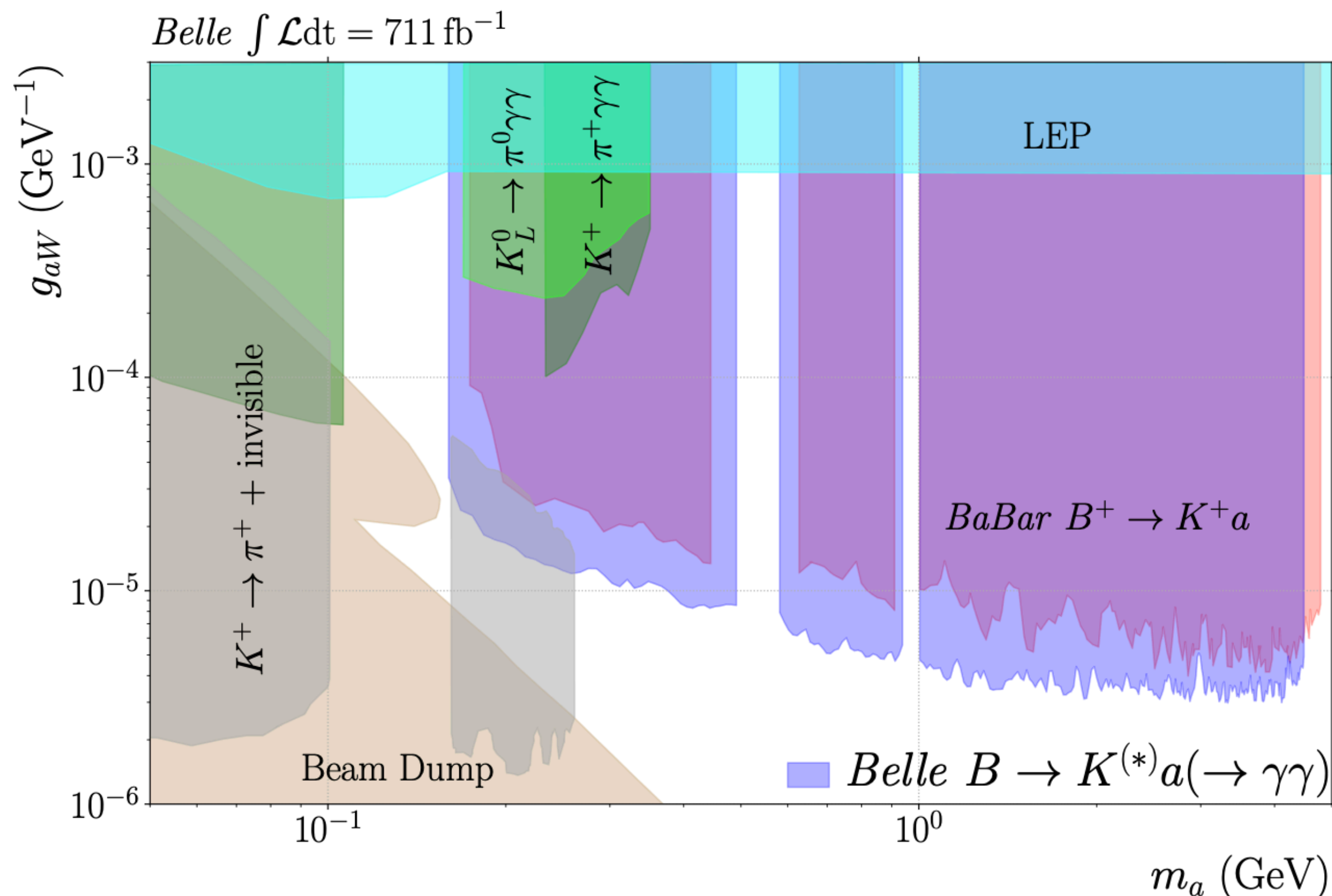
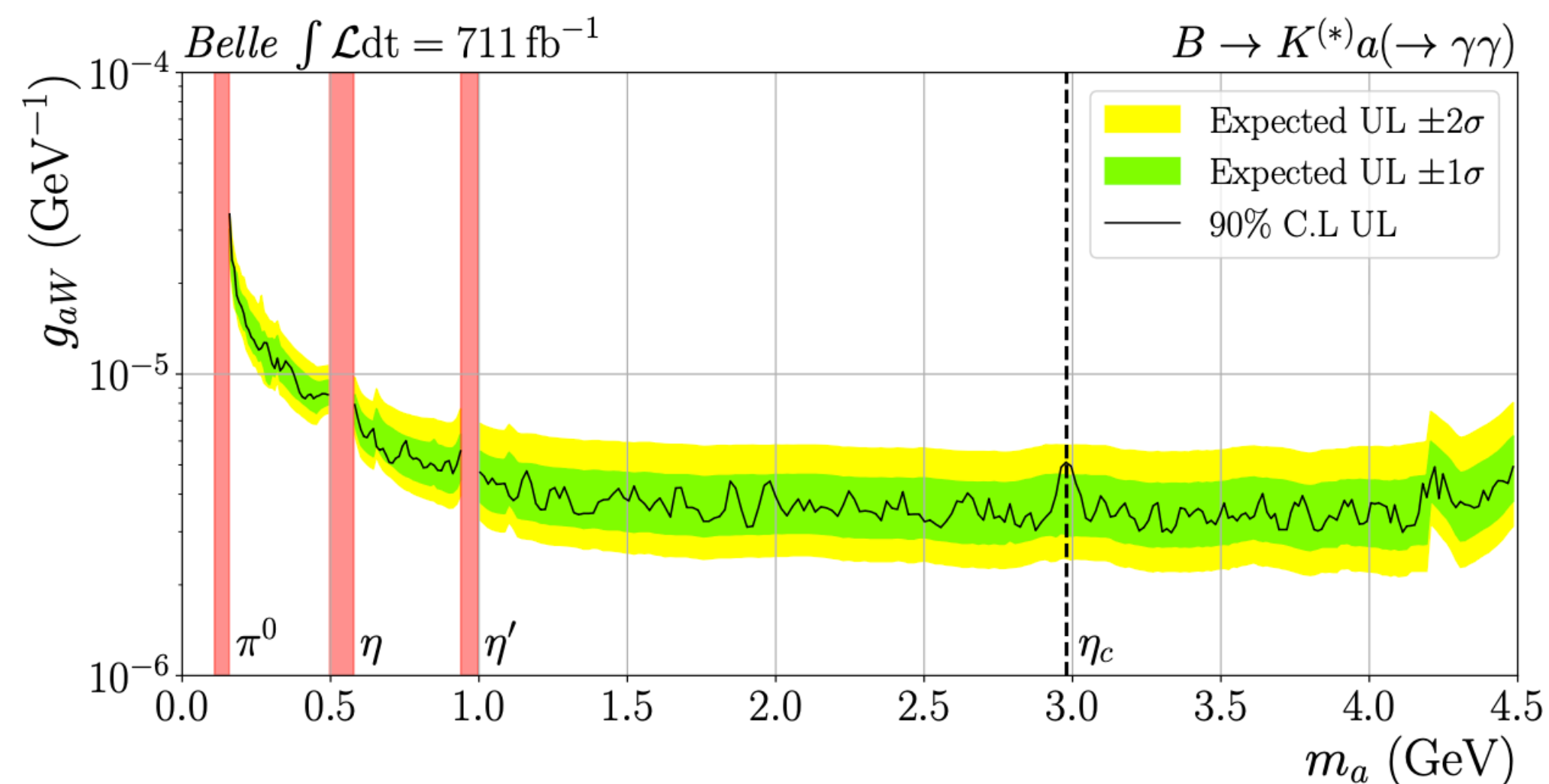
(a)



# ALP search from $B \rightarrow K^{(*)}a(a \rightarrow \gamma\gamma)$ at Belle

## Results

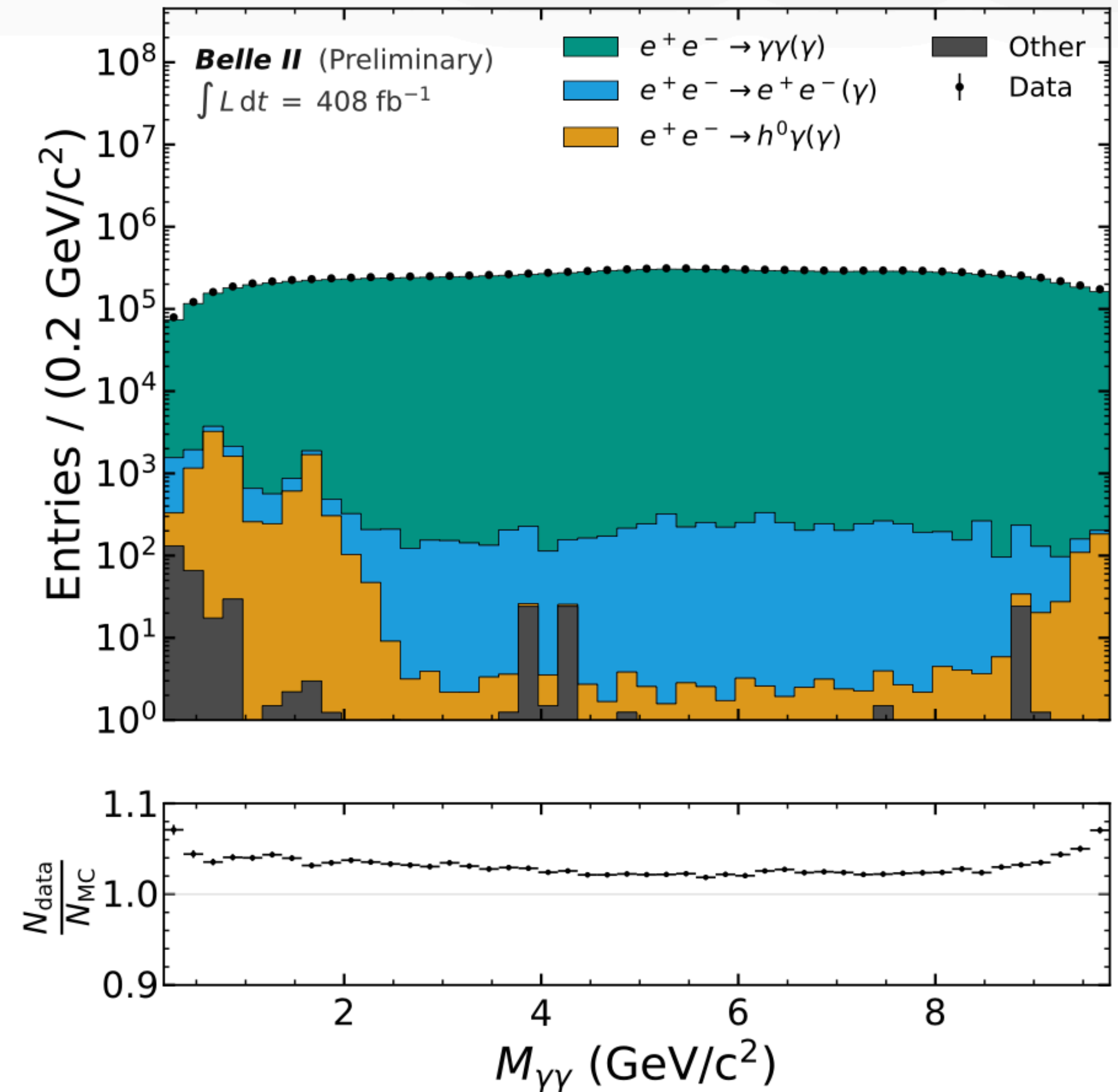
- No signal observed from four kaon decay modes
- World-best limit on ALP-W coupling ( $g_{aW}$ )
- Improved previous upper limit by factor of two



# ALP search from $e^+e^- \rightarrow \gamma a (a \rightarrow \gamma\gamma)$ at Belle II

## Method

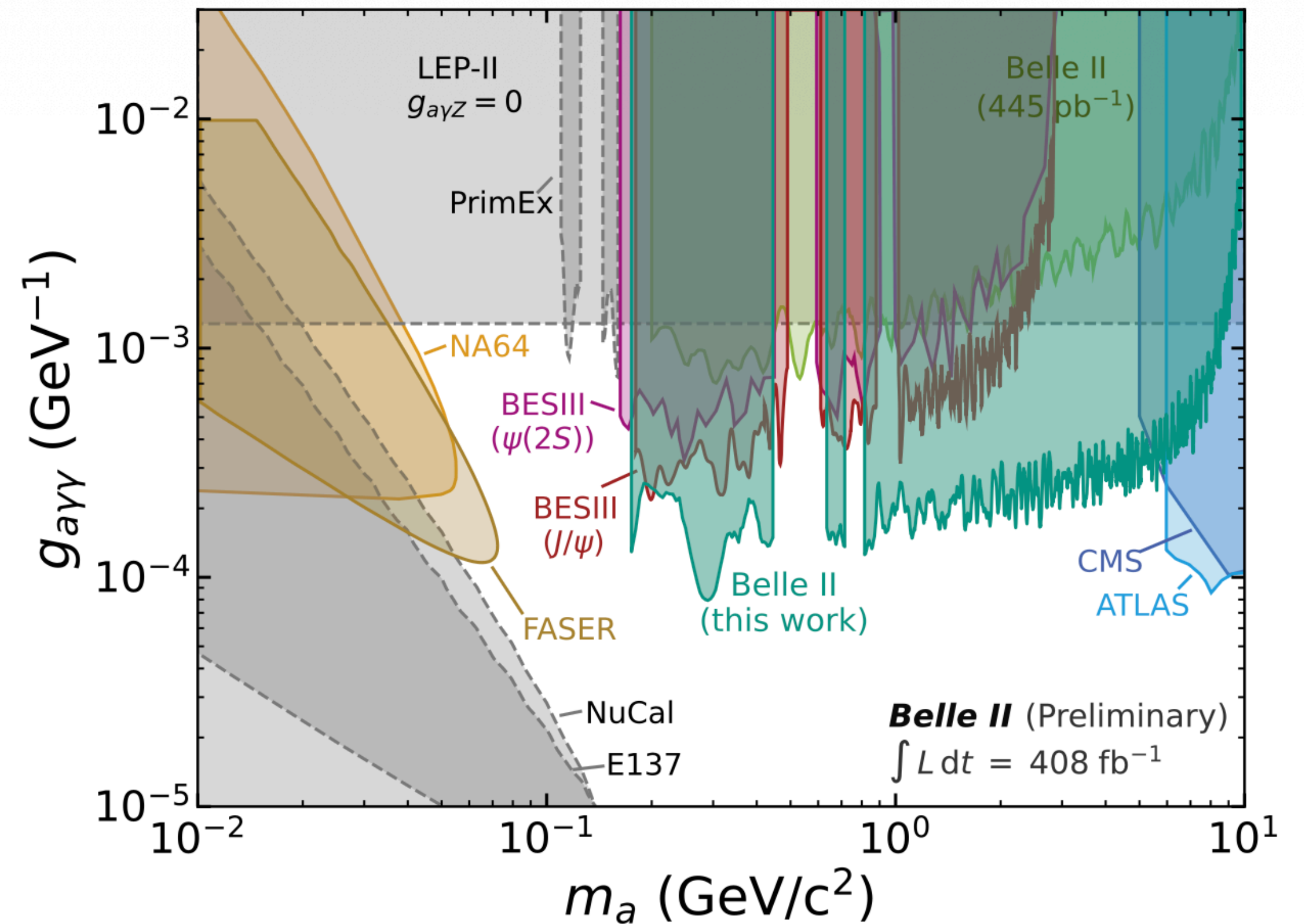
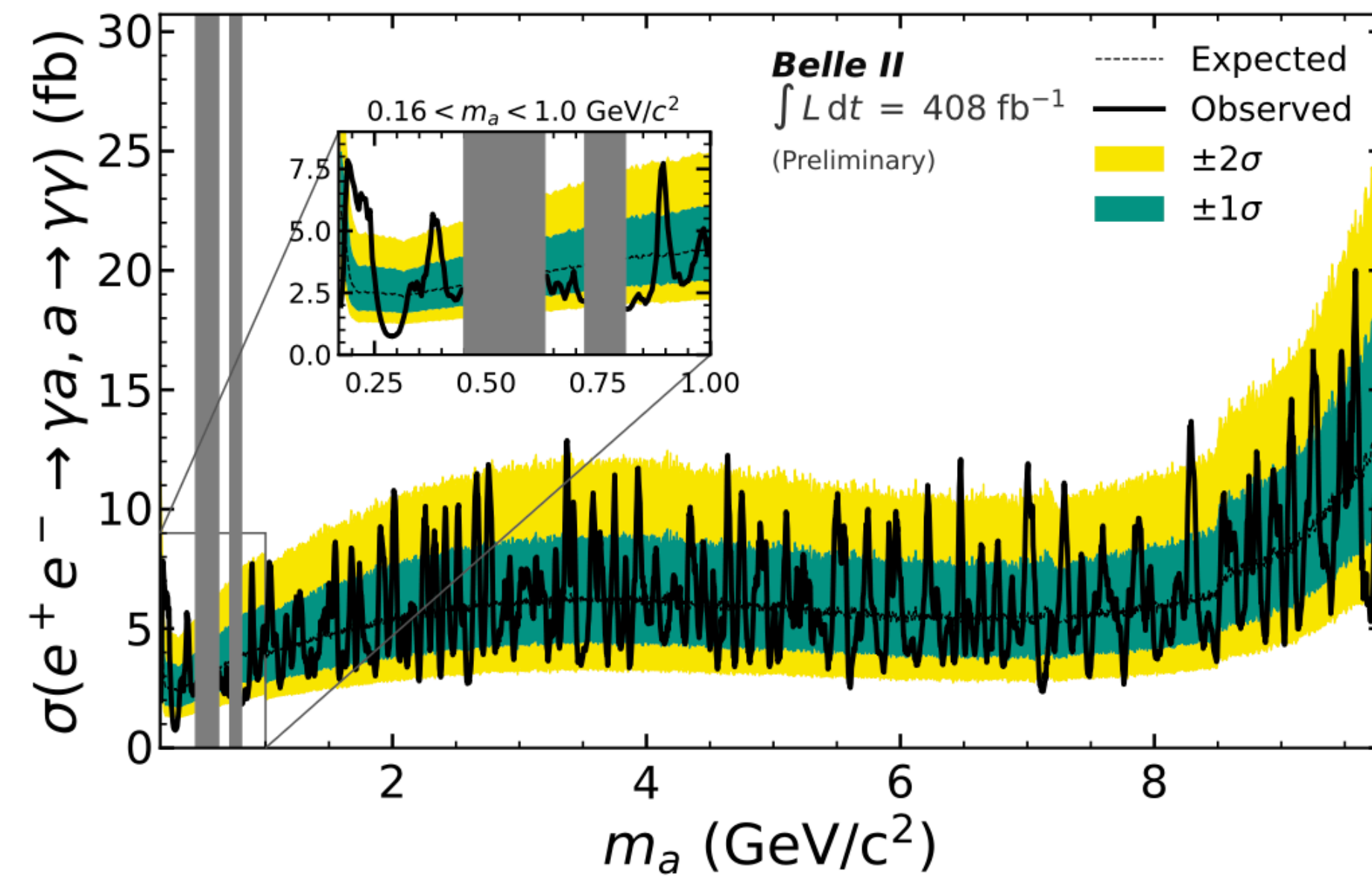
- 408 fb<sup>-1</sup> Belle II data samples
- ALP search in  $e^+e^- \rightarrow \gamma a$  where  $a$  decays into photon pair
- Signal : resonance in  $M_{\gamma\gamma}$  distribution
- Mass range  $0.17 < m_a < 9.80$  GeV
  - Veto  $\eta \rightarrow \gamma\gamma$  and  $\omega \rightarrow \pi^0\gamma$
- Major backgrounds from  $e^+e^- \rightarrow \gamma\gamma(\gamma)$
- Background rejection by Neural Network



# ALP search from $e^+e^- \rightarrow \gamma a (a \rightarrow \gamma\gamma)$ at Belle II

## Results

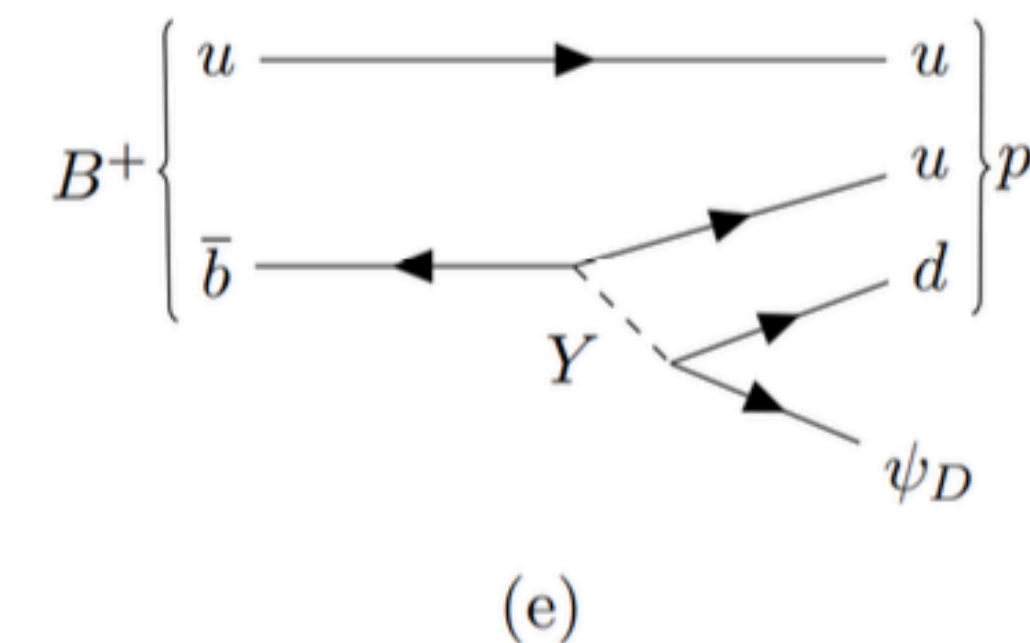
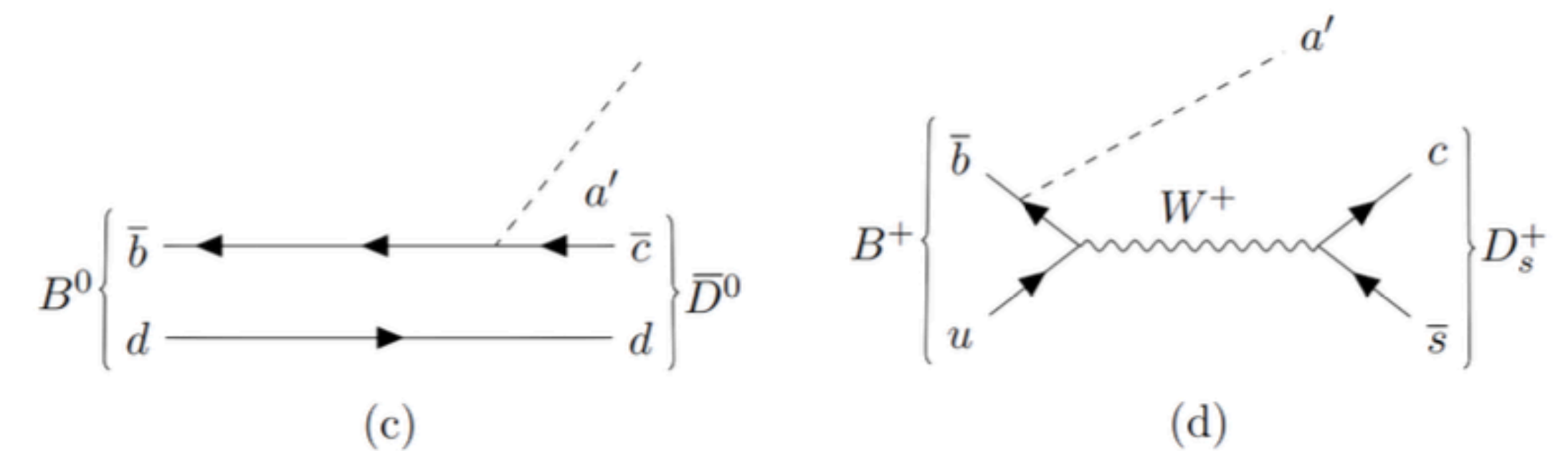
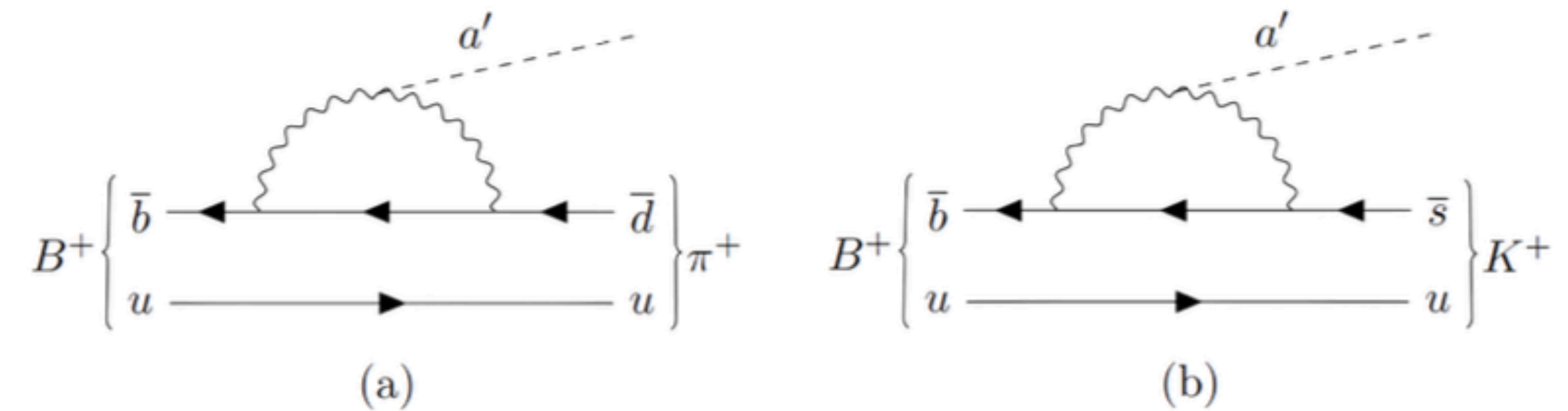
- Set 95% upper limit on  $g_{a\gamma\gamma}$  and  $m_a$  space
- Most restrictive upper limits



# FIP searches at Belle from $B \rightarrow hX_{Inv}$

## Motivation

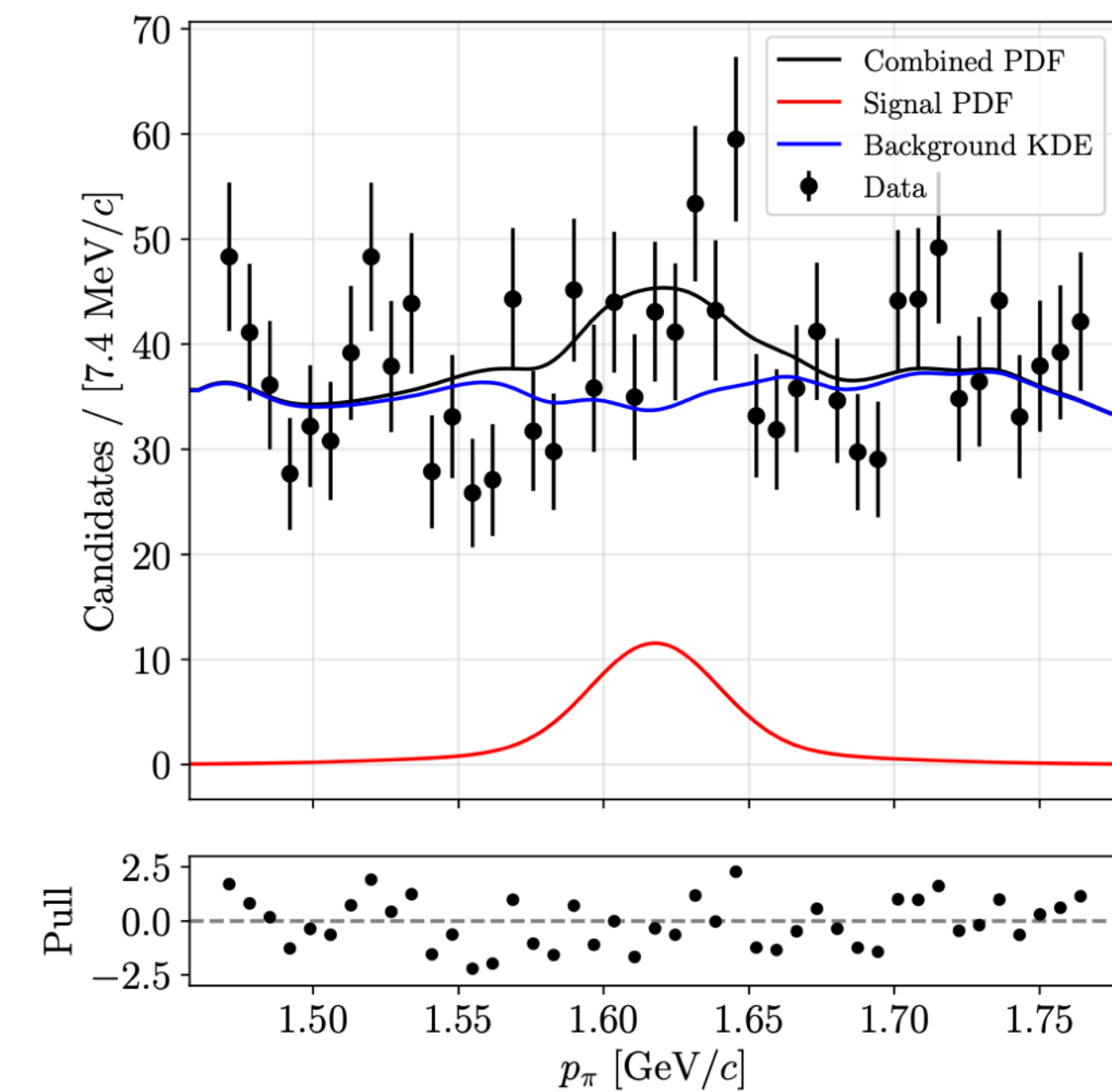
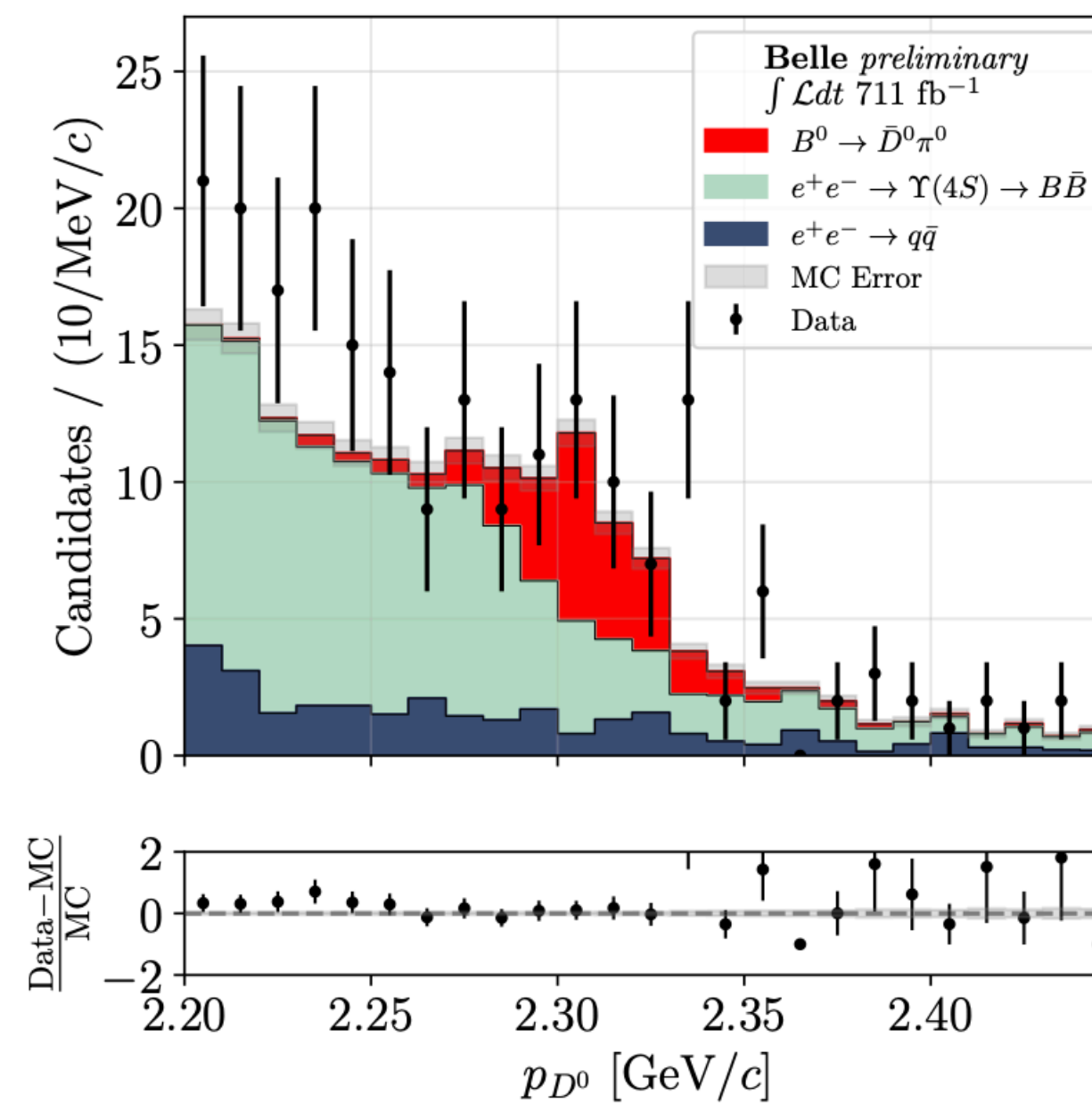
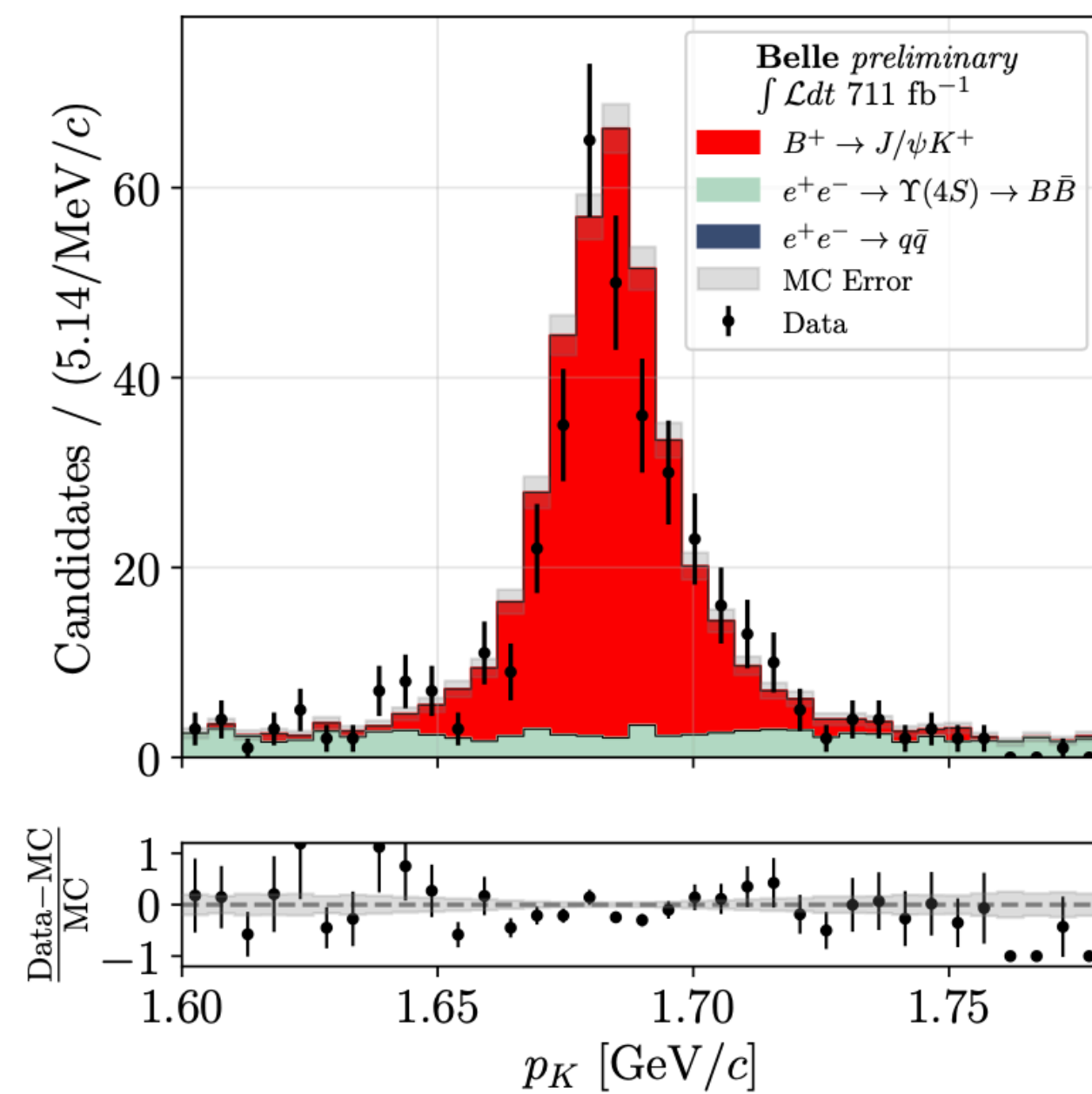
- Belle  $711 \text{ fb}^{-1}$  data
- Search for invisible Feebly Interacting Particle (FIP)  $X_{inv}$
- Channels:
  - $B^+ \rightarrow hX_{inv}, B^0 \rightarrow \overline{D}^0 X_{inv} h = \pi^+, K^+, D_s^+, p$
- Model-agnostic search to explore
  - dark scalar
  - dark pseudo scalar
  - B-mesogenesis
- B factories can reach mediator masses up to couple GeV



# FIP searches at Belle from $B^+ \rightarrow hX$

## Methods

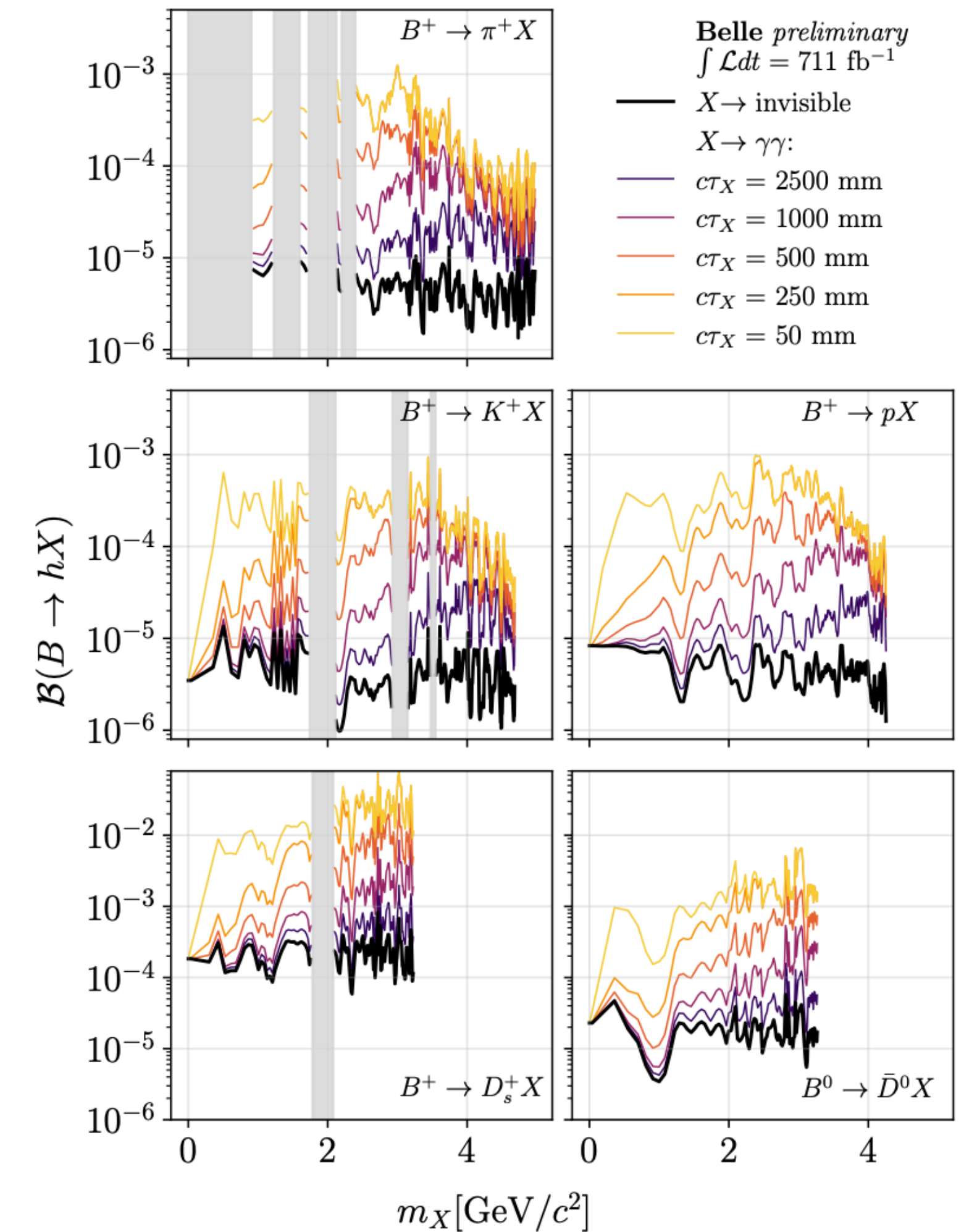
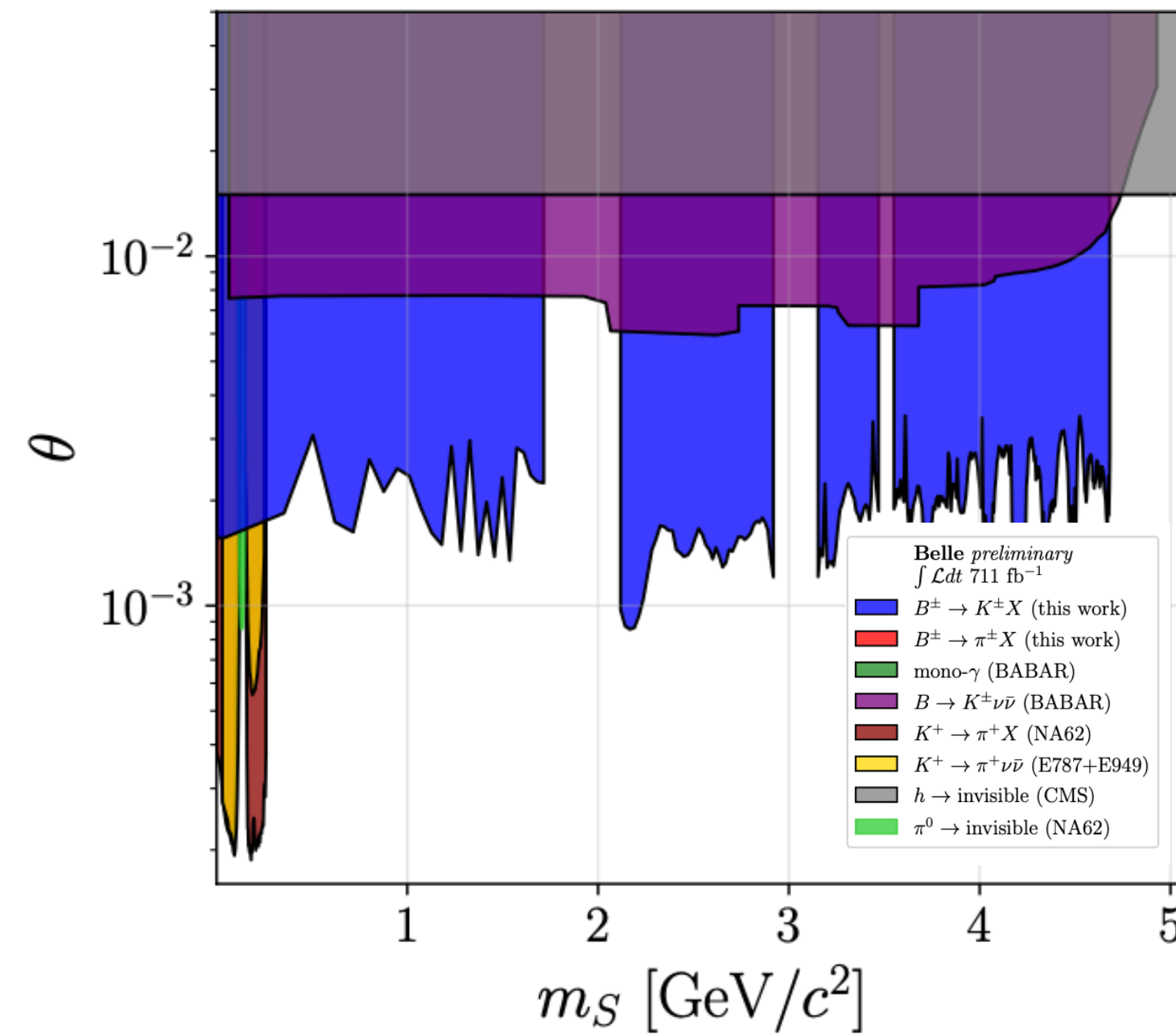
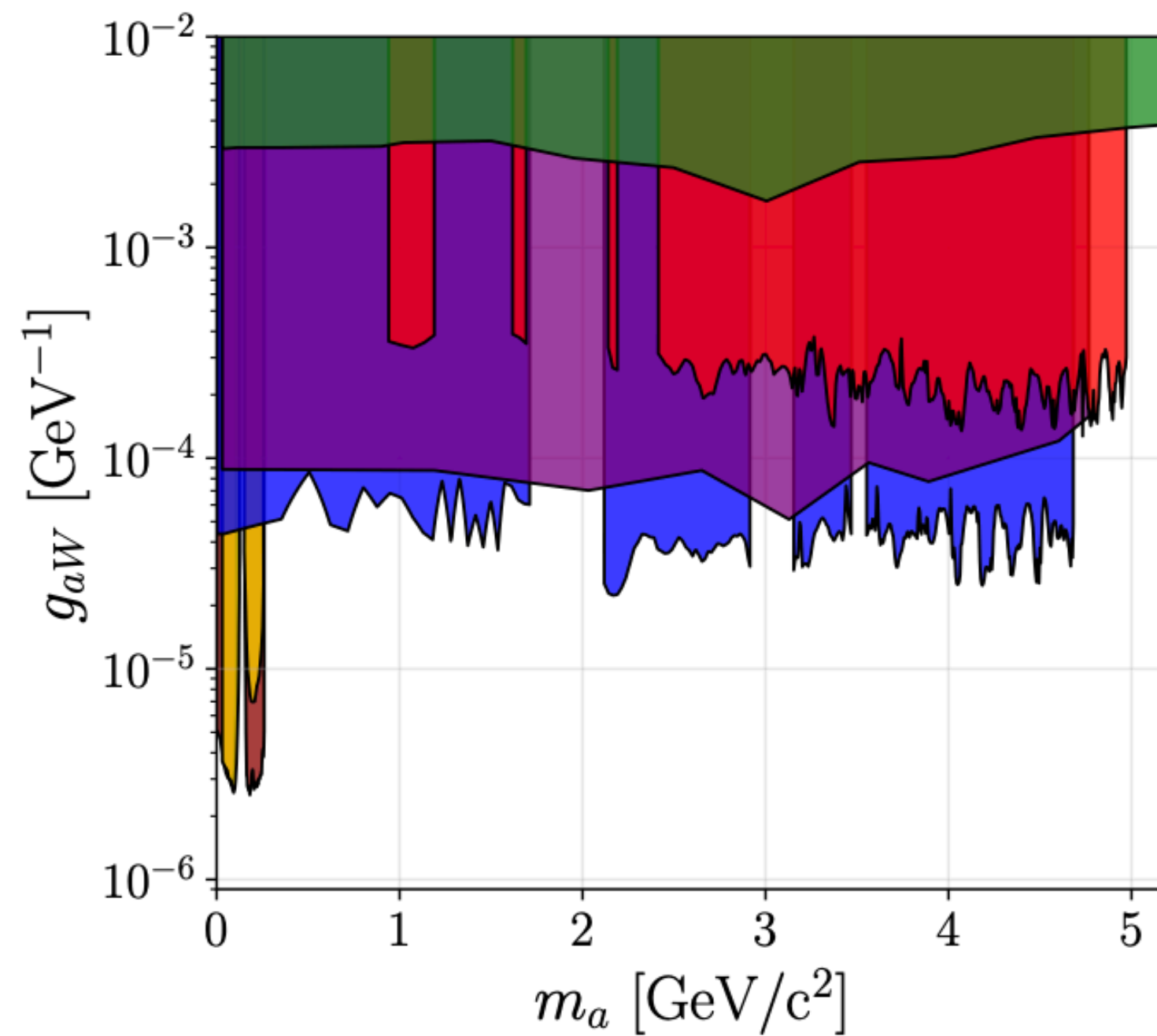
- Scan the p of recoiling hadron, search for narrow peaks above the background
- Tag side B reconstructed with the Full Event Interpretation (FEI)
- Two-stage background suppression for continuum rejection



# FIP searches at Belle from $B^+ \rightarrow hX$

## Motivations

- No significant signal observed
- 90% CL upper limits ( $CL_s$ ) on  $Br(B \rightarrow hX_{inv})$  or all channels



# Conclusion

- Belle II has advantages to search for dark sector particles in MeV~GeV range
- Three recent results presented with world-leading limits
  - Dark Matter With Dark Higgs at Belle II *PRL 135, 131801 (2025)*
  - ALP search from  $B \rightarrow K^{(*)}\gamma\gamma$  at Belle *JHEP 12 (2025) 109*
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Thank you !