Dark sector searches at Belle II

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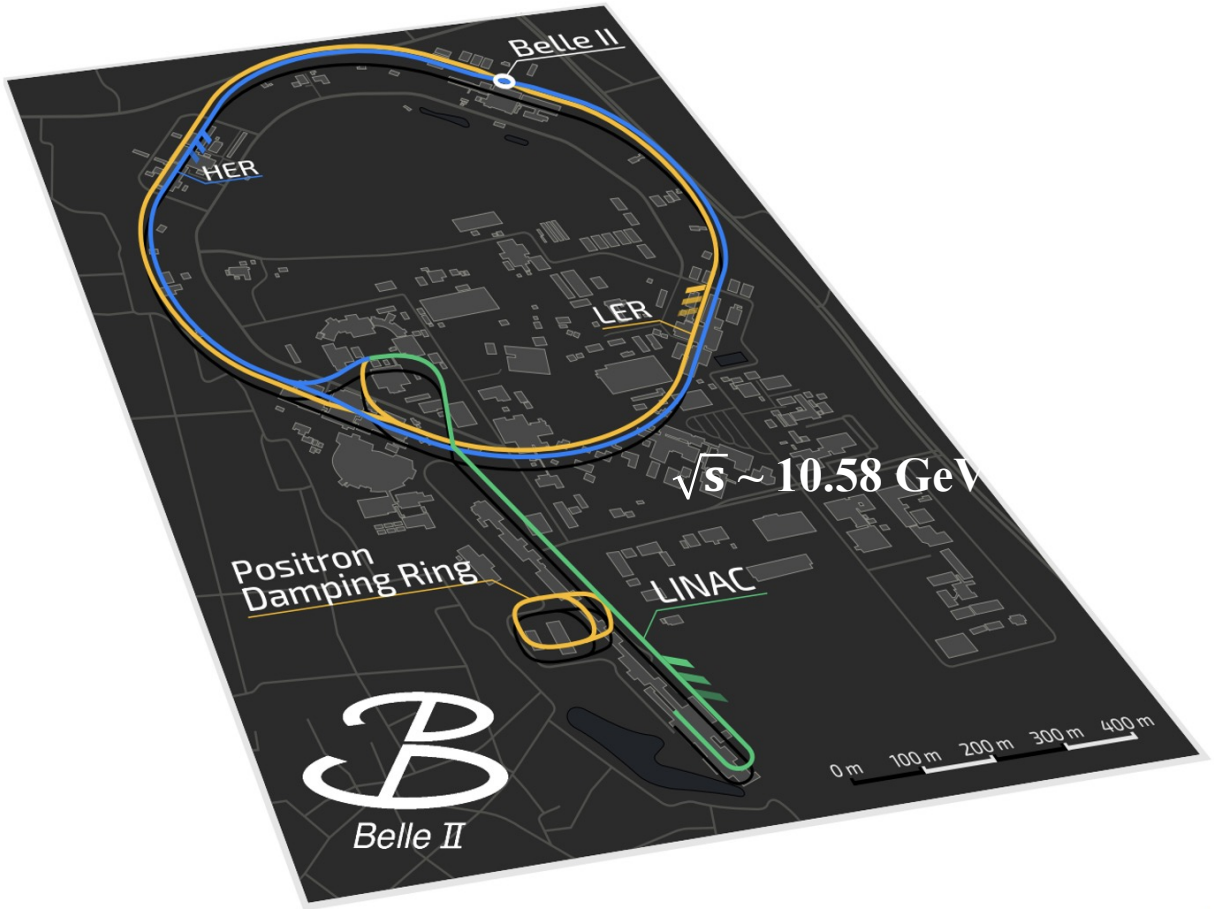
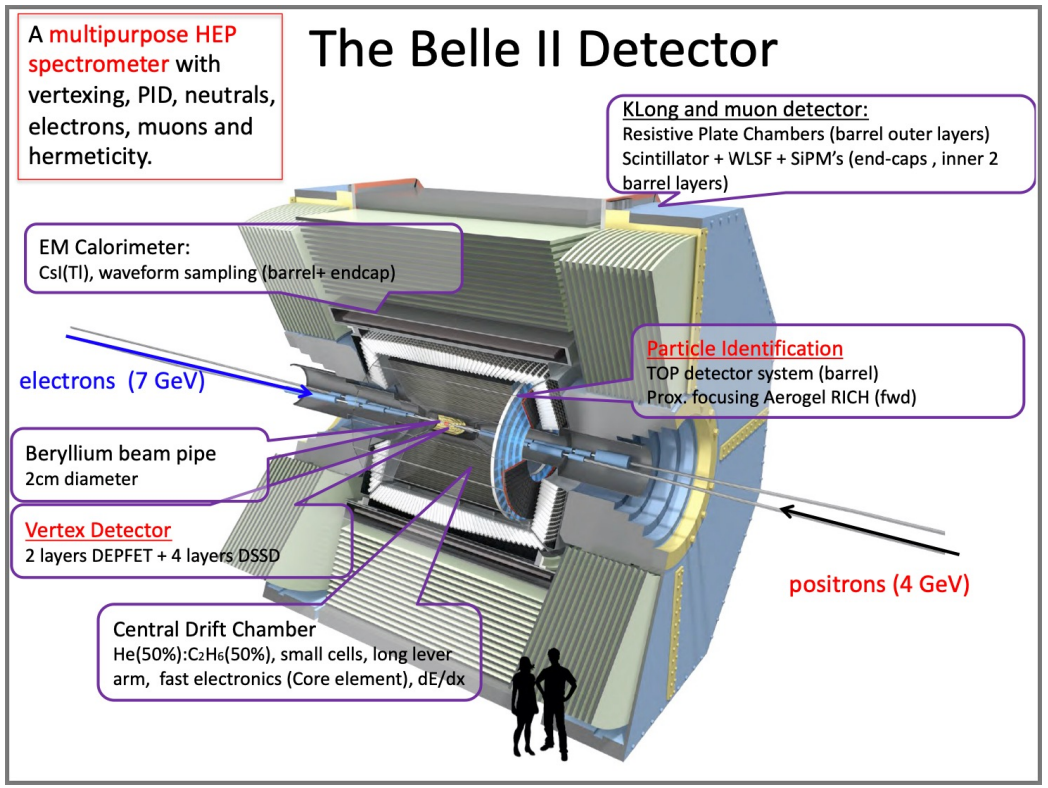
on behalf of the Belle II Collaboration

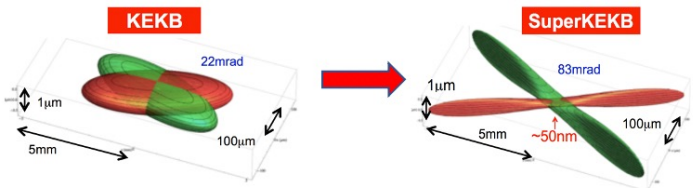
Workshop on Physics Beyond SM
November 21-23, 2025, Nanjing

SuperKEKB and Belle II





Nano-beam design:



Nano-beam design:
Beam squeezing: ×20 smaller;
Beam current: ×2 larger
Target peak luminosity: KEKB×30

- **Trigger:**

L1: < 30 kHz; HLT: < 10 kHz
Dedicated lines for dark physics: Single muon, single track, and single photon

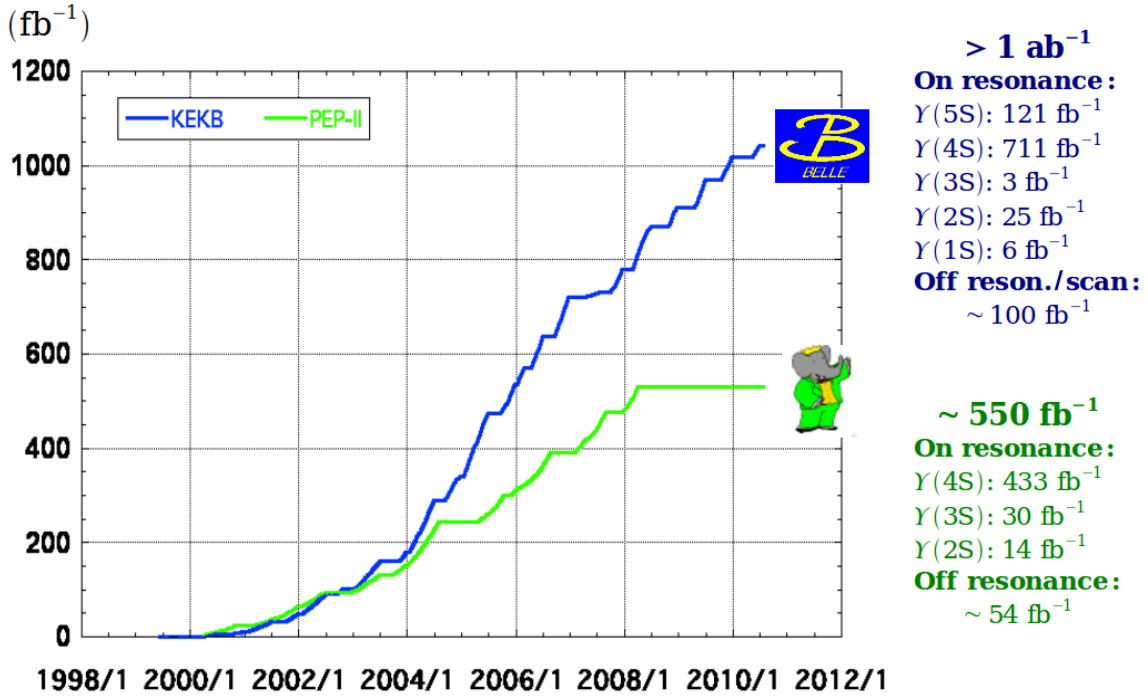
- **New PXD detector:**

Improve vertex performance for identification of long-lived particles (LLP)

Belle and Belle II Datasets

- **Belle (1999 - 2010)**
- **Belle II RUN-I (2019 - 2023)**
- **Belle II RUN-II (2024 - 2025)**

Integrated luminosity of B factories

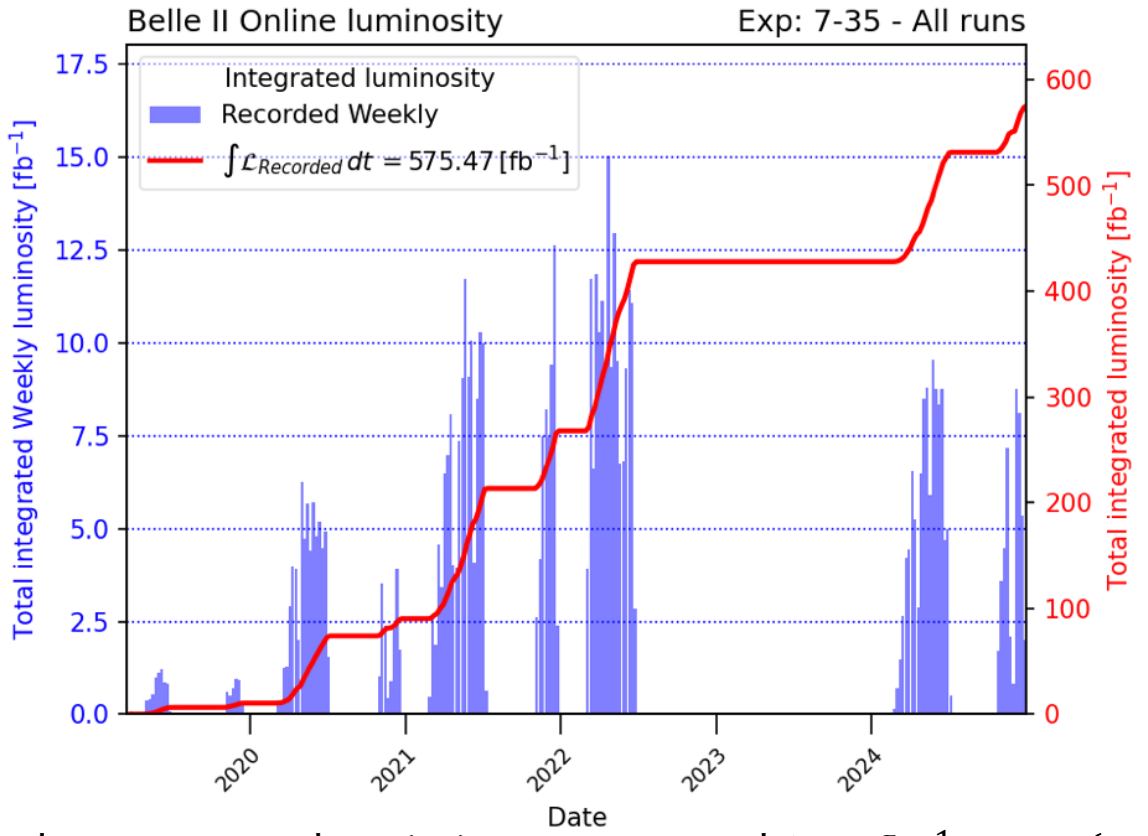


> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

In December 2024

WORLD RECORD: 5.1×10^{34} cm^{-2}s^{-1}



Most data at or near the $\Upsilon(4S)$ resonance, and 19.6 fb^{-1} near $\Upsilon(10753)$

The Belle II experiment began collecting data on 18 November.

Features of dark sector searches at B-factory

- Clean, low background, ``energy conserving" environment, closed kinematics
- Production modes: B-decays, τ-decays, direct production, . . .
- Decay modes: leptonic, semi-leptonic, hadronic, . . .
- Some fully neutral final states accessibility

$e^+e^- \to$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3

Luminosity	$B\bar{B}$ pair	$\tau^+\tau^-$ pair
1.5 ab^{-1} (current)	1.7×10^9	1.4×10^9
40 ab^{-1} (future)	4.4×10^{10}	3.7×10^{10}

Cons:

- Not as many B's as at the LHC
- Can't test high-mass LLP directly

Selected topic

$L_\mu - L_\tau$ model

$Z' \to$ invisible

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

$Z' \to \tau^+\tau^-$

Axion like particles (ALP)

$a \to \tau^+\tau^-$

$B \to K\, a,\ a \to \gamma\gamma$

$\tau \to \ell\, \alpha$

$B \to h\, X,\ X \to$ invisible

long-lived particles (LLP)

$B \to h\, X,\ X \to$ invisible

$B \to K\, S,\ S \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$

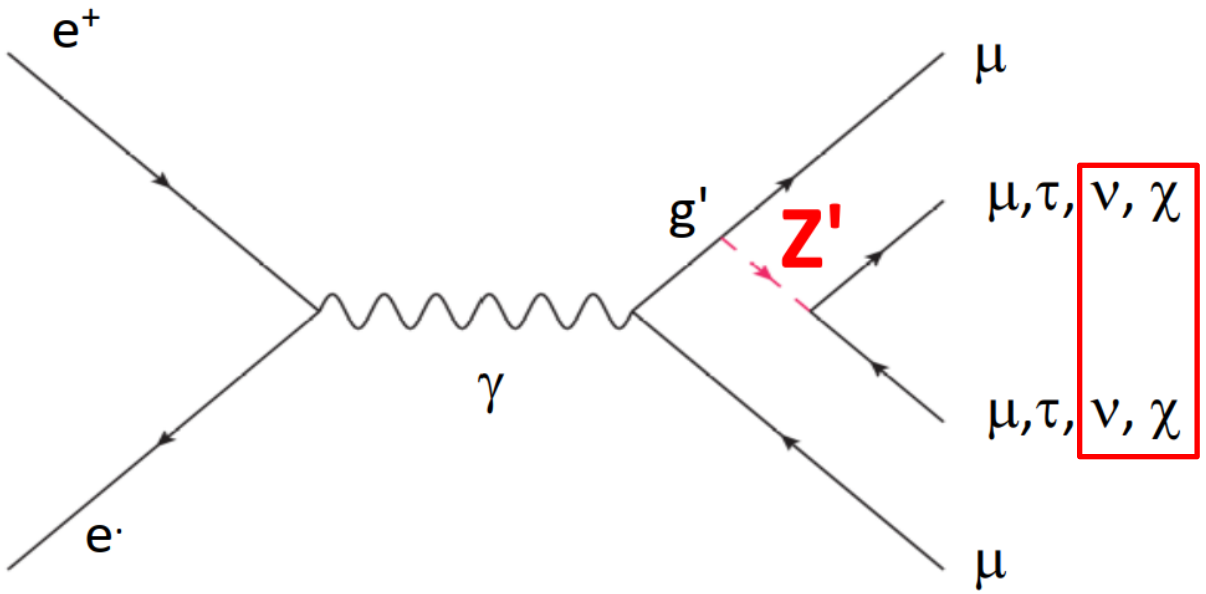
Dark Higgs boson with inelastic dark matter

$A'h'$: $A' \to \chi_1\chi_2,\ h' \to \mu^+\mu^-,\ \mu^+\mu^-,\ K^+K^-$

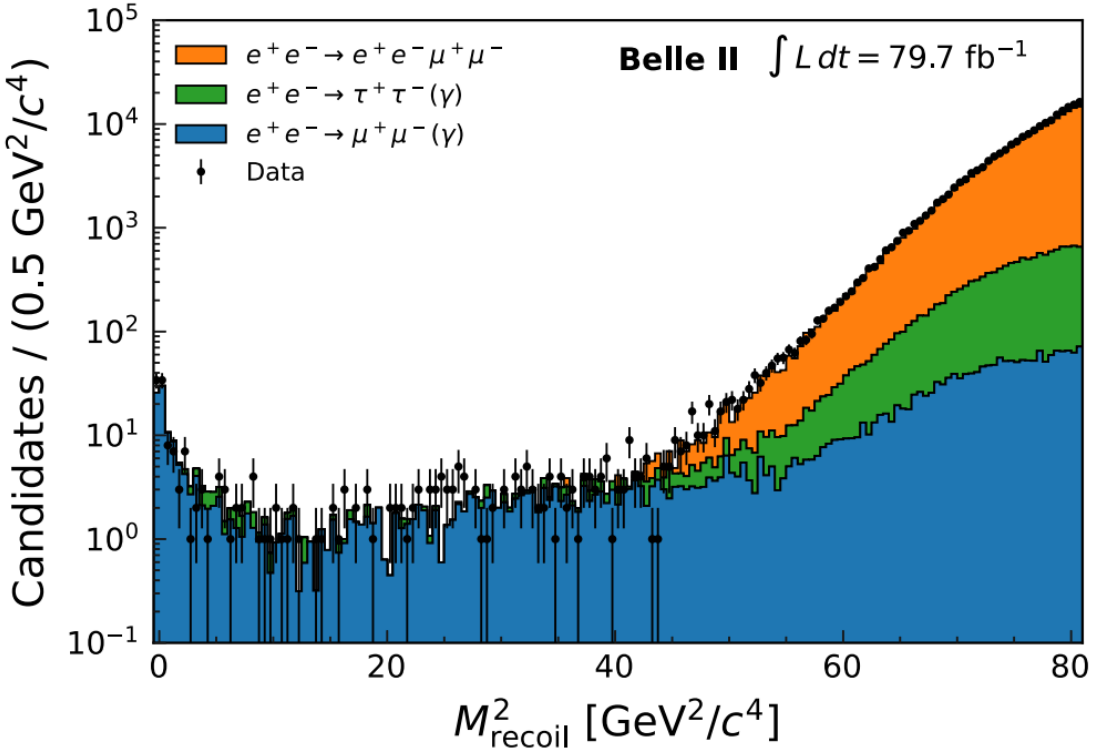
$L_\mu - L_\tau$ model, $Z' \rightarrow$ invisible

PRL 130, 231801 (2023)

- **The $L_\mu - L_\tau$ extension of the SM** could explain the muon anomalous magnetic moment and the existence of dark matter [PRD 43, R22 (1991), PRD 89, 113004 (2014), JHEP 12 (2016) 106].
- This model gauges the difference of the muon and tau lepton numbers, giving rise to a massive, neutral, vector boson, **the Z′**.
- This particle would couple to the SM only through μ, τ, ν_μ, and ν_τ with **coupling g′**.



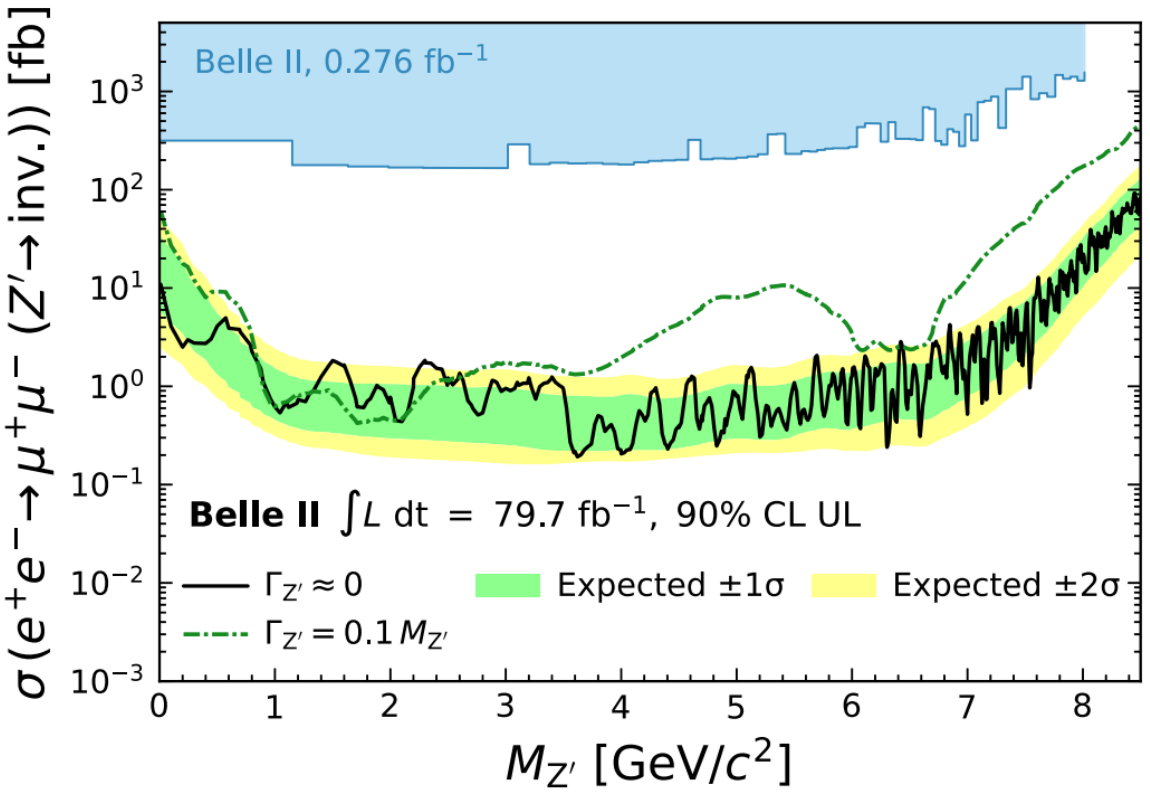
$e^+e^- \rightarrow \mu^+\mu^-$ + missing energy
Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

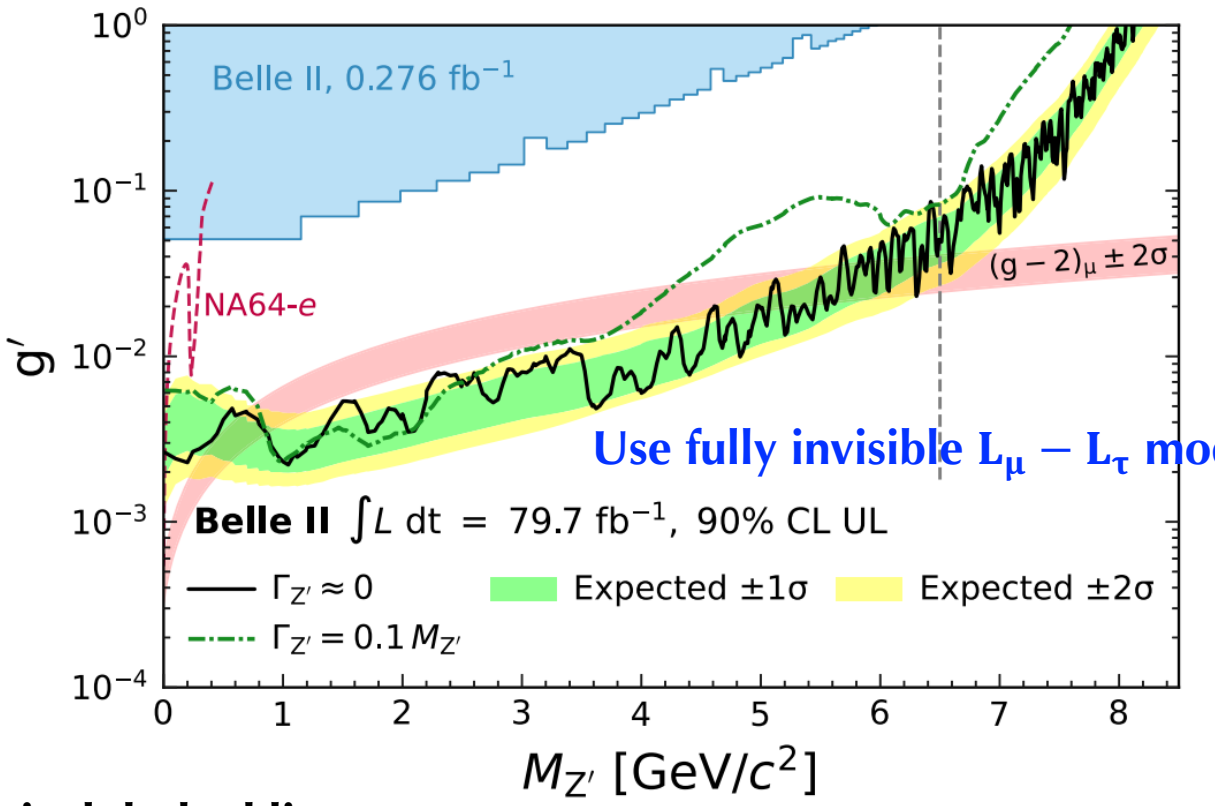


$L_\mu - L_\tau$ model, $Z' \to$ invisible

PRL 130, 231801 (2023)

- No excesses were found.
- Set 90% C.L. limits on cross section and coupling g′.
- The world-leading direct-search results for Z′ masses above 11.5 MeV/c^2 in the fully invisible $L_\mu - L_\tau$ model

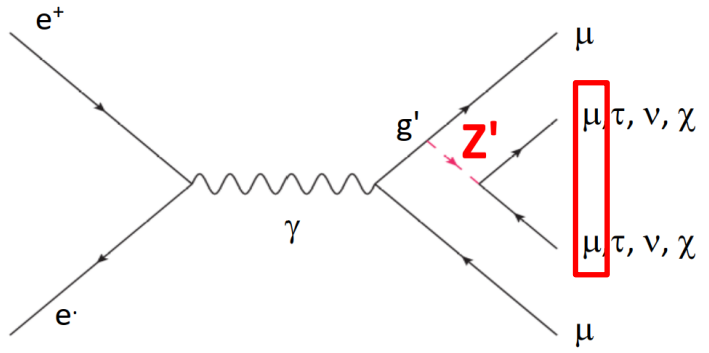




The vertical dashed line:
Above this mass, hypothesis $\mathcal{B}(Z' \to \chi\bar{\chi}) \approx 1$ is not respected.

$L_\mu - L_\tau$ model, $Z' \to \mu^+\mu^-$

$e^+e^- \to \mu^+\mu^-\mu^+\mu^-$



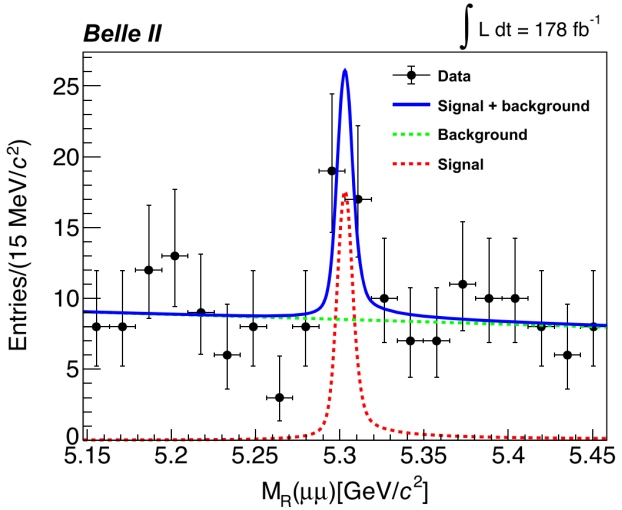
- **Exactly four charged particles in one event. Four-momentum of $\mu^+\mu^-\mu^+\mu^-$ is constrained to match the initial e^+e^- C.M. system**

- **Main background: SM $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$**
- **Aggressive background suppression through multilayer perceptron (MLP) artificial neural networks (NN) based on kinematic and helicity angle features**

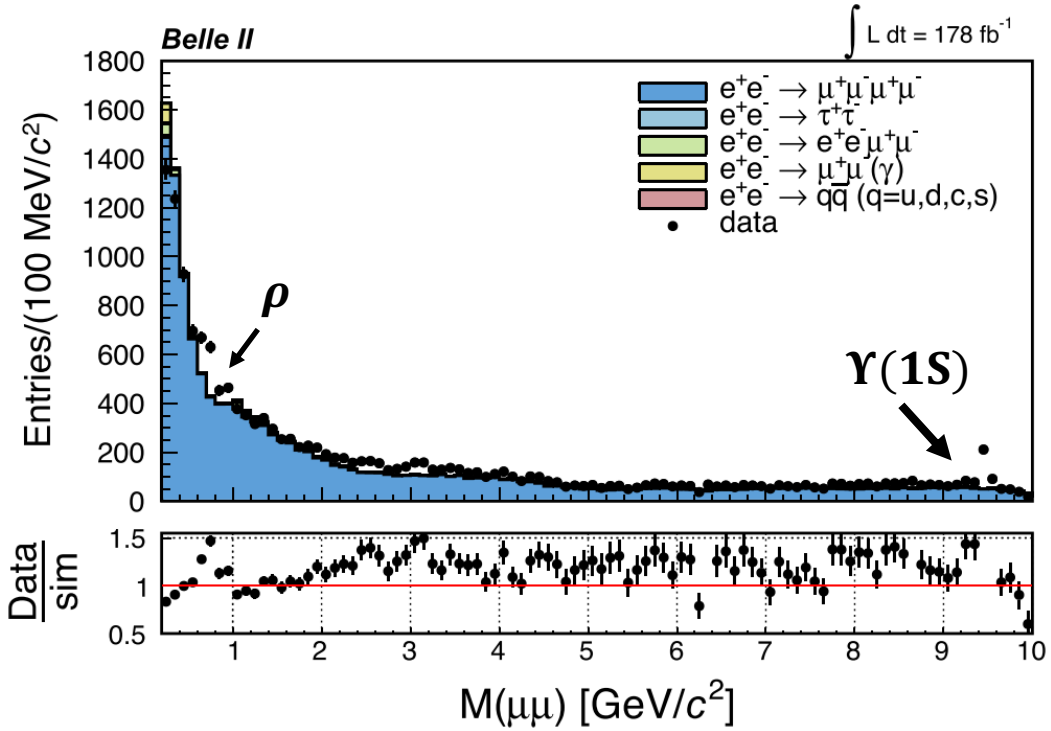
- **Signal extraction using the reduced dimuon mass**

$$M_R \equiv \sqrt{M^2(\mu\mu) - 4m_\mu^2}$$

The largest significance is 3.4σ at $M(\mu^+\mu^-) = 5.307$ GeV/c^2, correspoding a 1.6σ significance after taking into account the look-else effect.



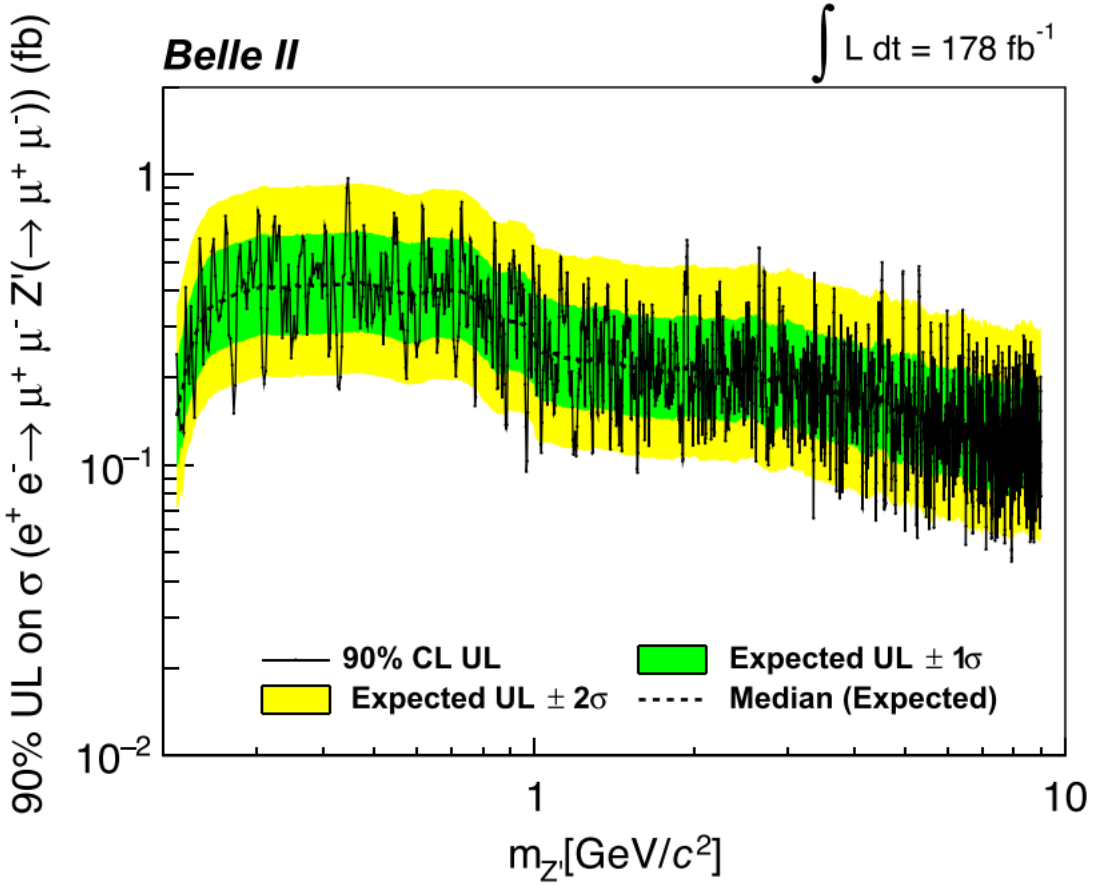
PRD 109, 112015 (2024)

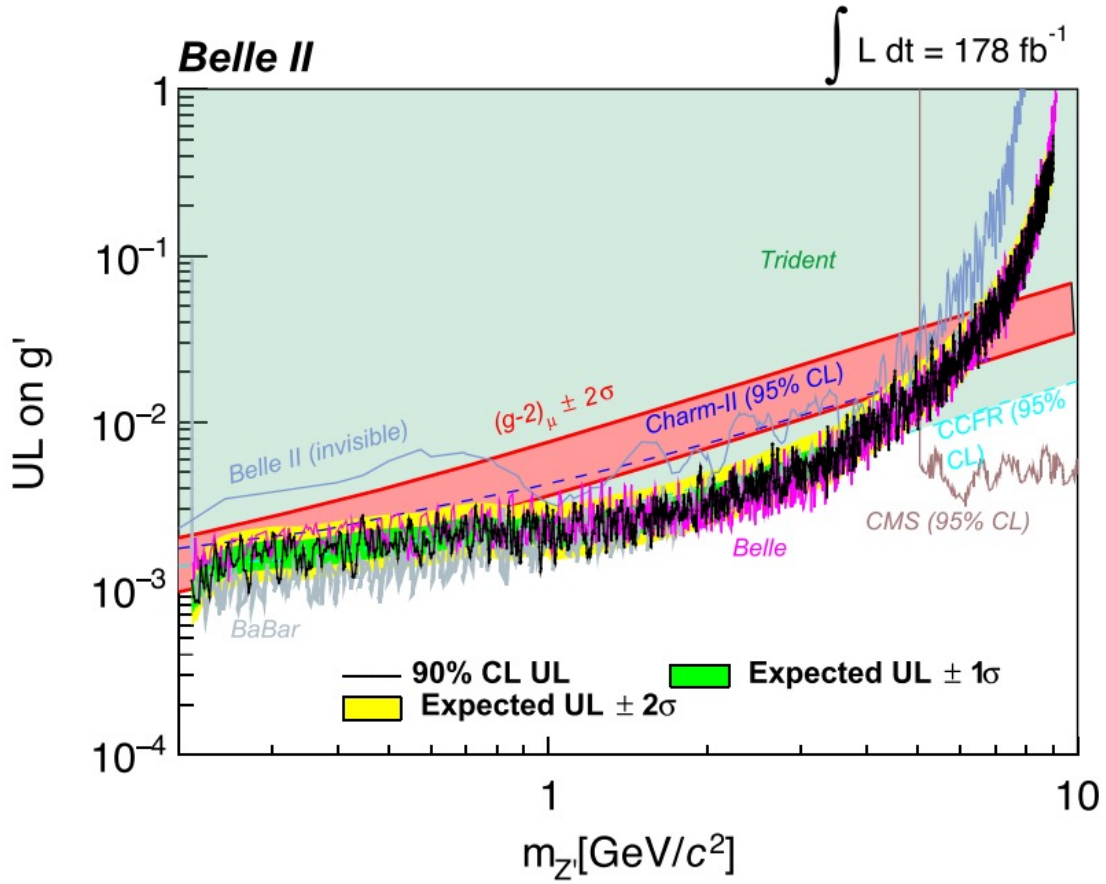


$L_\mu - L_\tau$ model, $Z' \to \mu^+\mu^-$

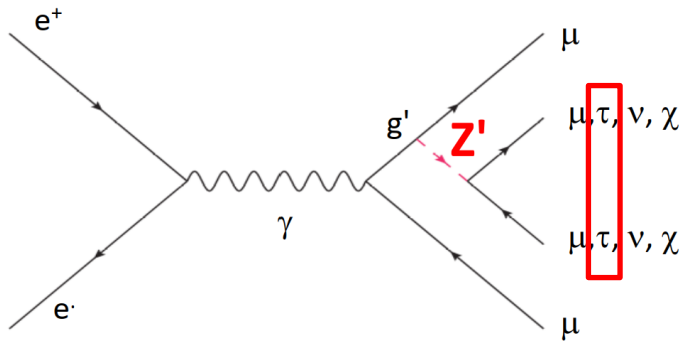
PRD 109, 112015 (2024)

- No excesses were found.
- Set 90% C.L. limits on cross section and coupling g′.
- Limits on Z′ similar to BaBar (514 fb^{-1}) and Belle (643 fb^{-1}) with lower luminosity.





$L_\mu - L_\tau$ model, $Z' \to \tau^+\tau^-$



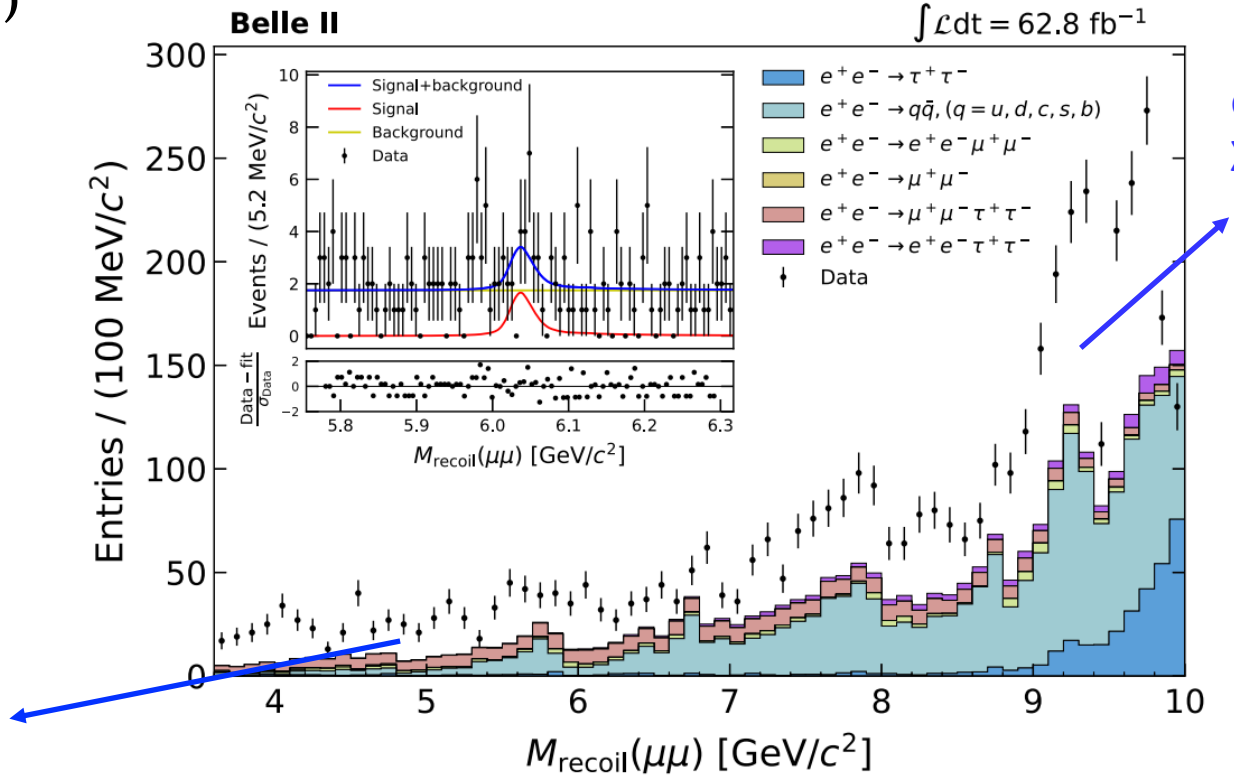
$e^+e^- \to \mu^+\mu^-\tau^+\tau^-$

- Exactly four charged particles in one event. 1+1 prong for $\tau^+\tau^-$

PRL 131, 121802 (2023)

- Aggressive background suppression through multilayer perceptron (MLP) artificial neural networks (NN)
  - resonance
  - FSR production
  - $\tau^+\tau^-$ system

- Signal extraction in recoil mass against a $\mu^+\mu^-$ pair



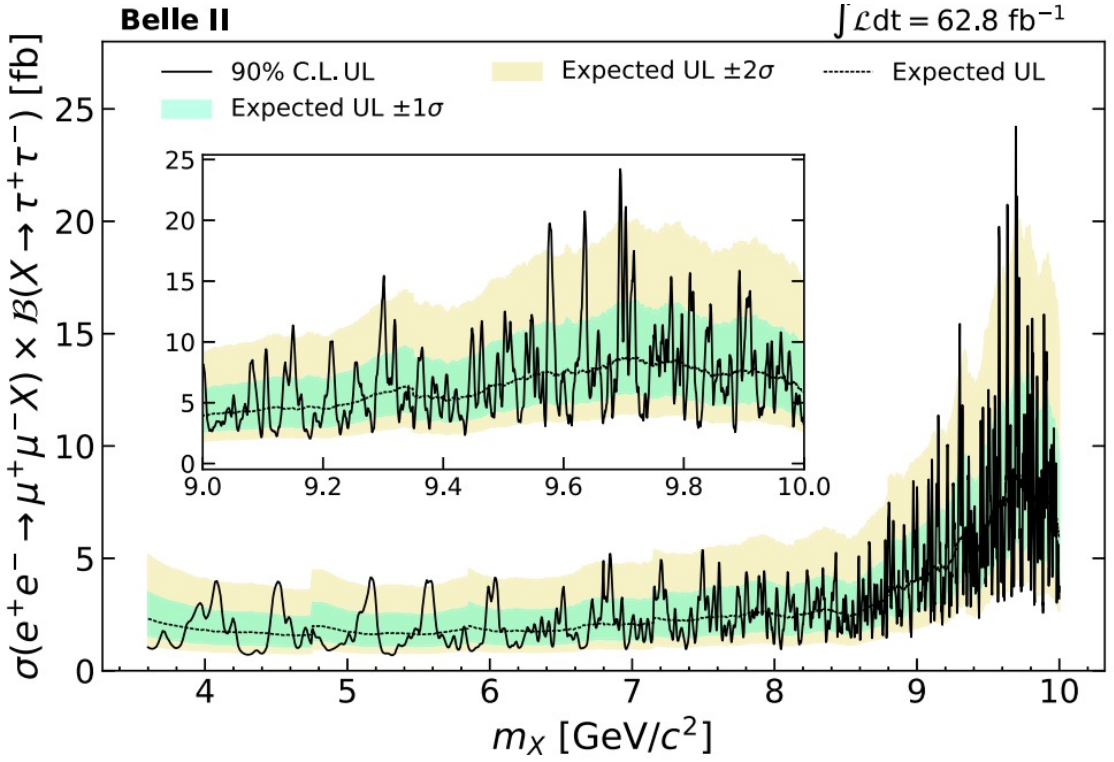
$e^+e^- \to e^+e^- + X_{hadron}$

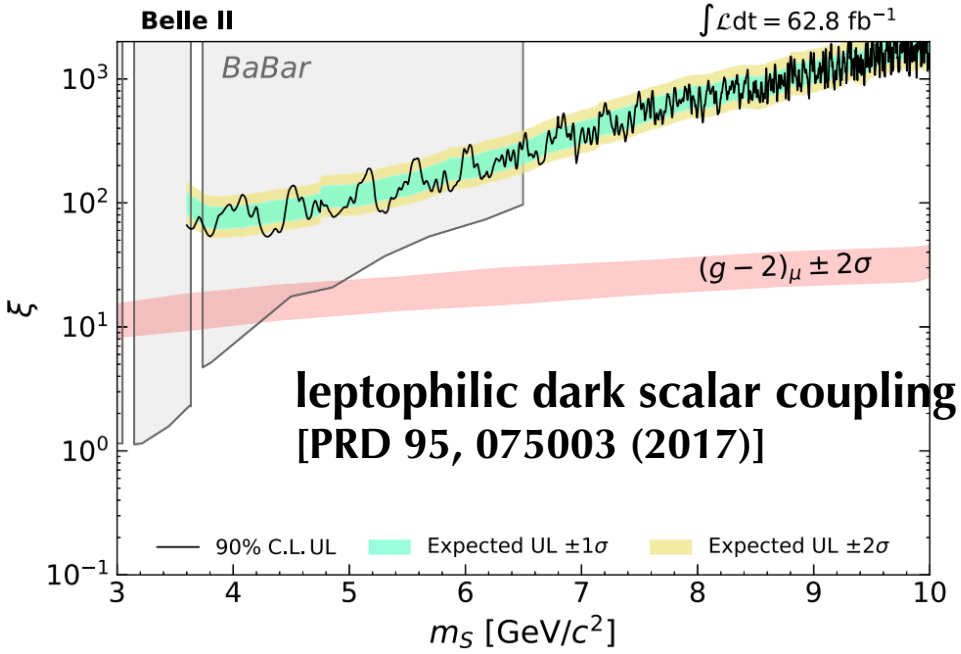
The discrepancies between data and simulation are due to $e^+e^- \to 4\ell$ + ISR.

$L_\mu - L_\tau$ model, $Z' \to \tau^+\tau^-$

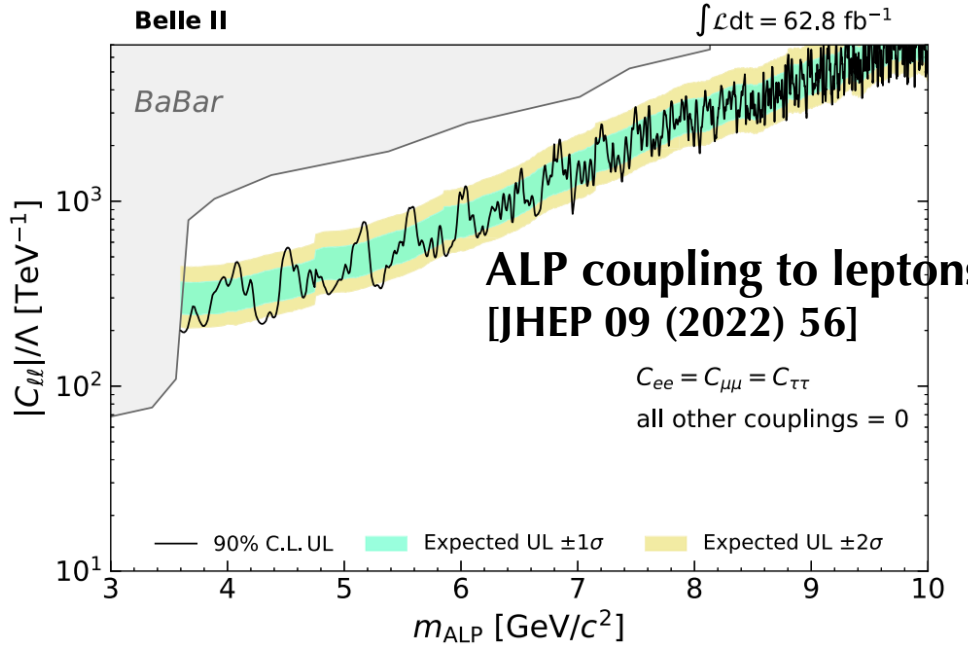
PRL 131, 121802 (2023)

- No excesses were found.
- Set 90% C.L. limits on cross section and couplings ξ and $|C_{\ell\ell}|/\Lambda$
- World-leading constraints on the ξ for $m_S > 6.5$ GeV/c² and on the $|C_{\ell\ell}|/\Lambda$ for $m_{ALP} > 3.6$ GeV/c²





leptophilic dark scalar coupling ξ
[PRD 95, 075003 (2017)]



ALP coupling to leptons $|C_{\ell\ell}|/\Lambda$
[JHEP 09 (2022) 56]

$C_{ee} = C_{\mu\mu} = C_{\tau\tau}$
all other couplings = 0

$B \to K\, a,\ a \to \gamma\gamma$

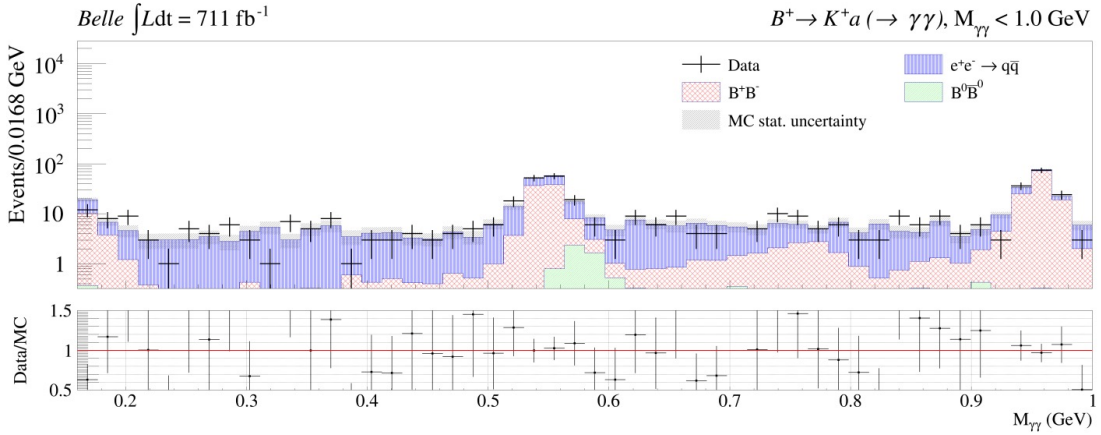
arXiv:2507.01249

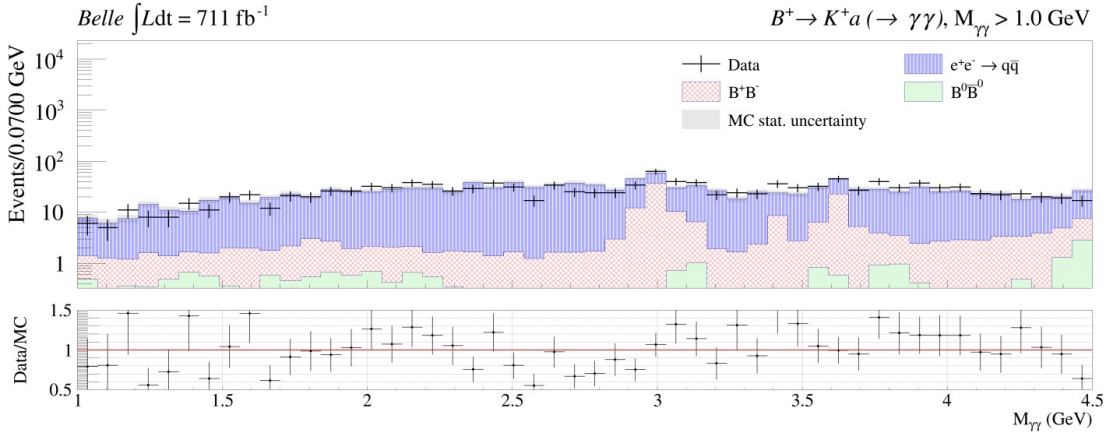
Axion-like particles in B decays

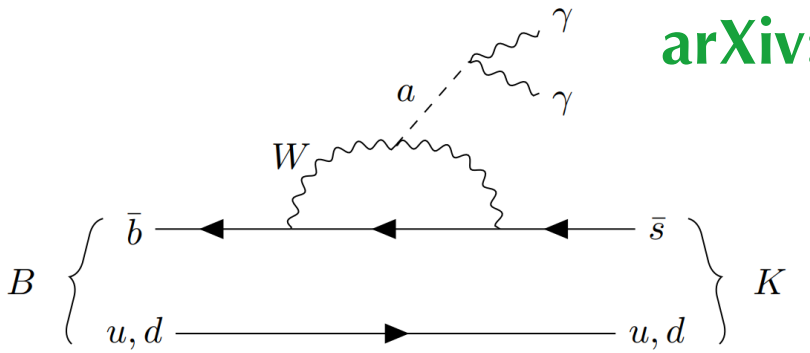
Dominant backgrounds:

1. The γ is from π^0 decay

2. $B \to X_s\gamma$ (X_s is hadronic state that contains an s quark)



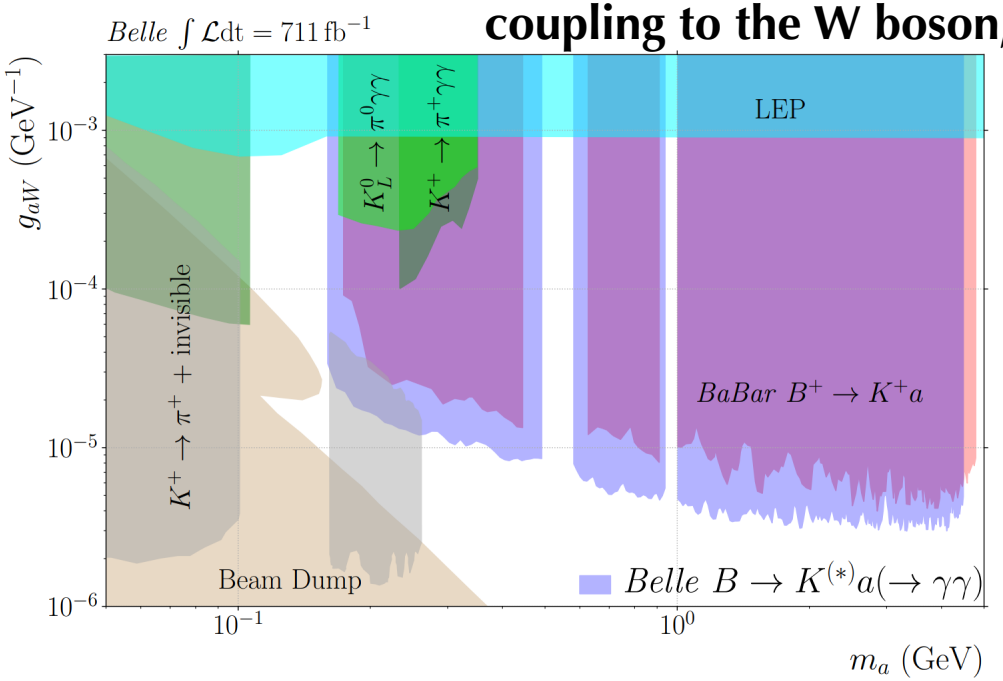




K includes $K^{(*)\pm}$, K^0_s, and K^{*0}

- **No excesses were found.**
- **Improve the current constraints on g_{aW} by a factor of two over the most stringent previous experimental results.**

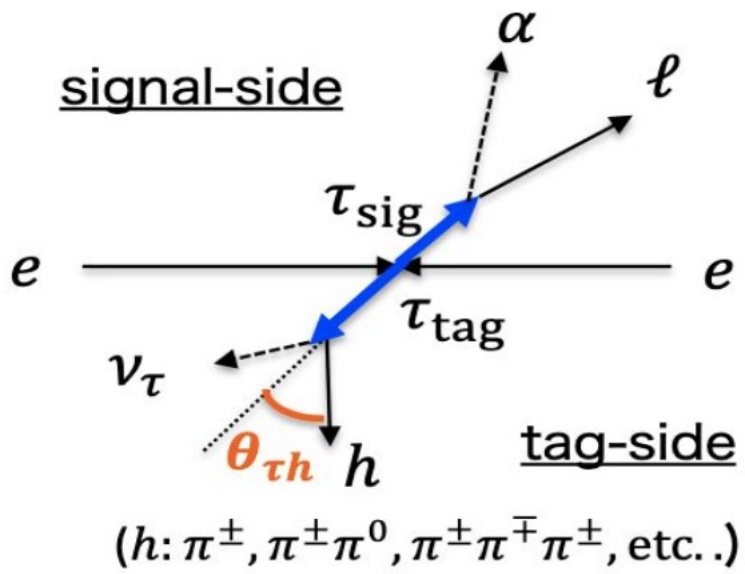
coupling to the W boson, g_{aW}

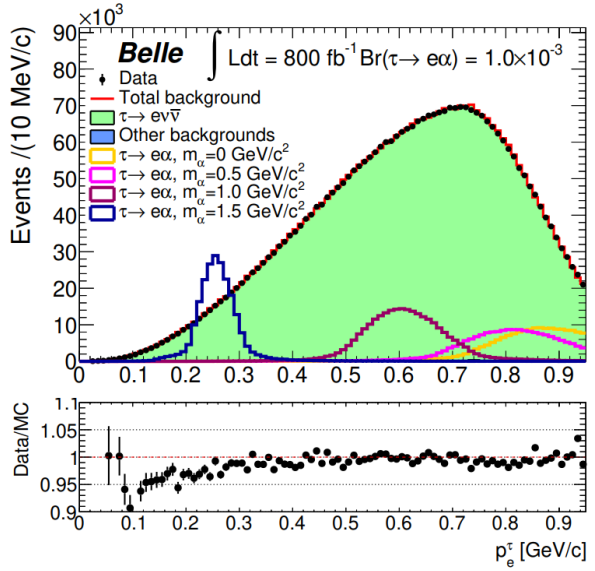


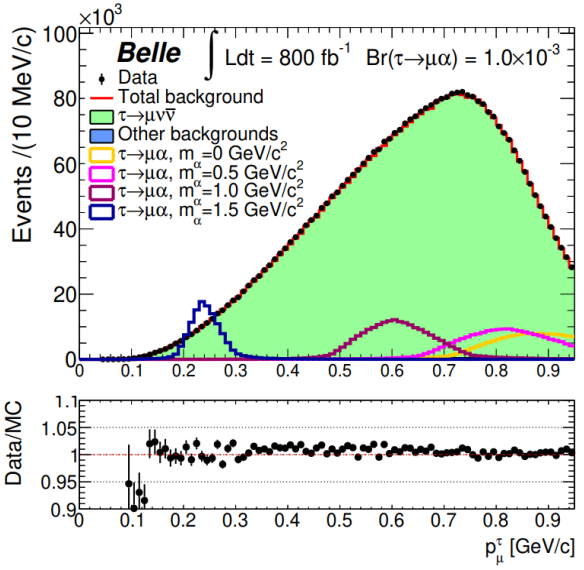
Invisible α in τ decays

JHEP 08 (2025) 155

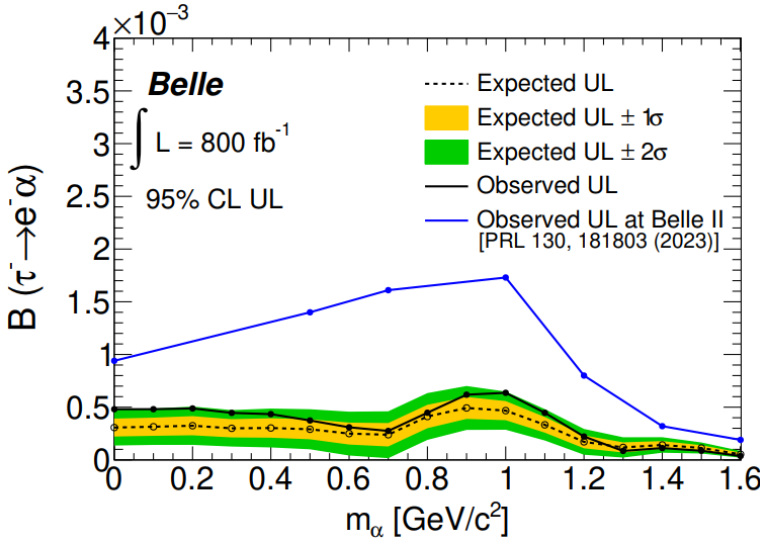
An invisible spin-0 boson (α) in τ decays predicted in axionlike particle models

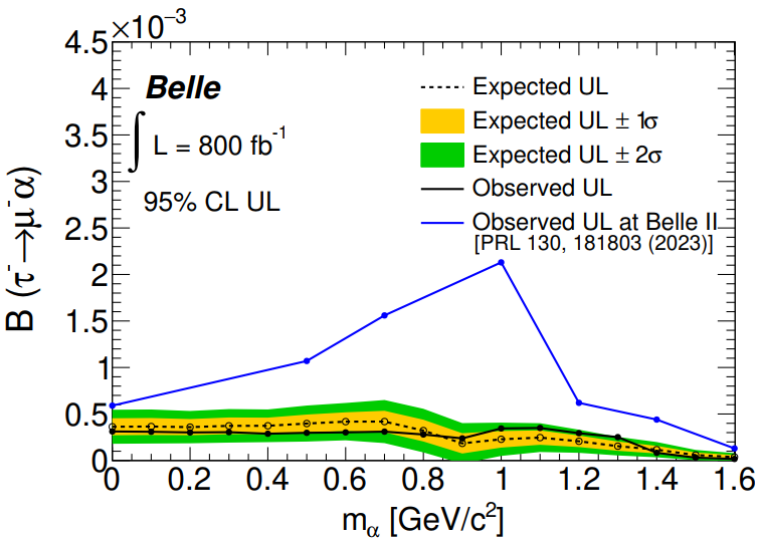






- We find no evidence of signal.
- We obtain the most stringent upper limits on the branching fractions at 95% confidence level.





$B \to h X$, $X \to$ invisible

Belle II preliminary

Feebly-interacting invisible particles in B decays

Motivations:

1. ALP → invisible
2. LLP → invisible
3. Excess in $B^+ \to K^+ \nu\nu$ by Belle II

Both B mesons are reconstructed, B_{tag} and B_{sig}

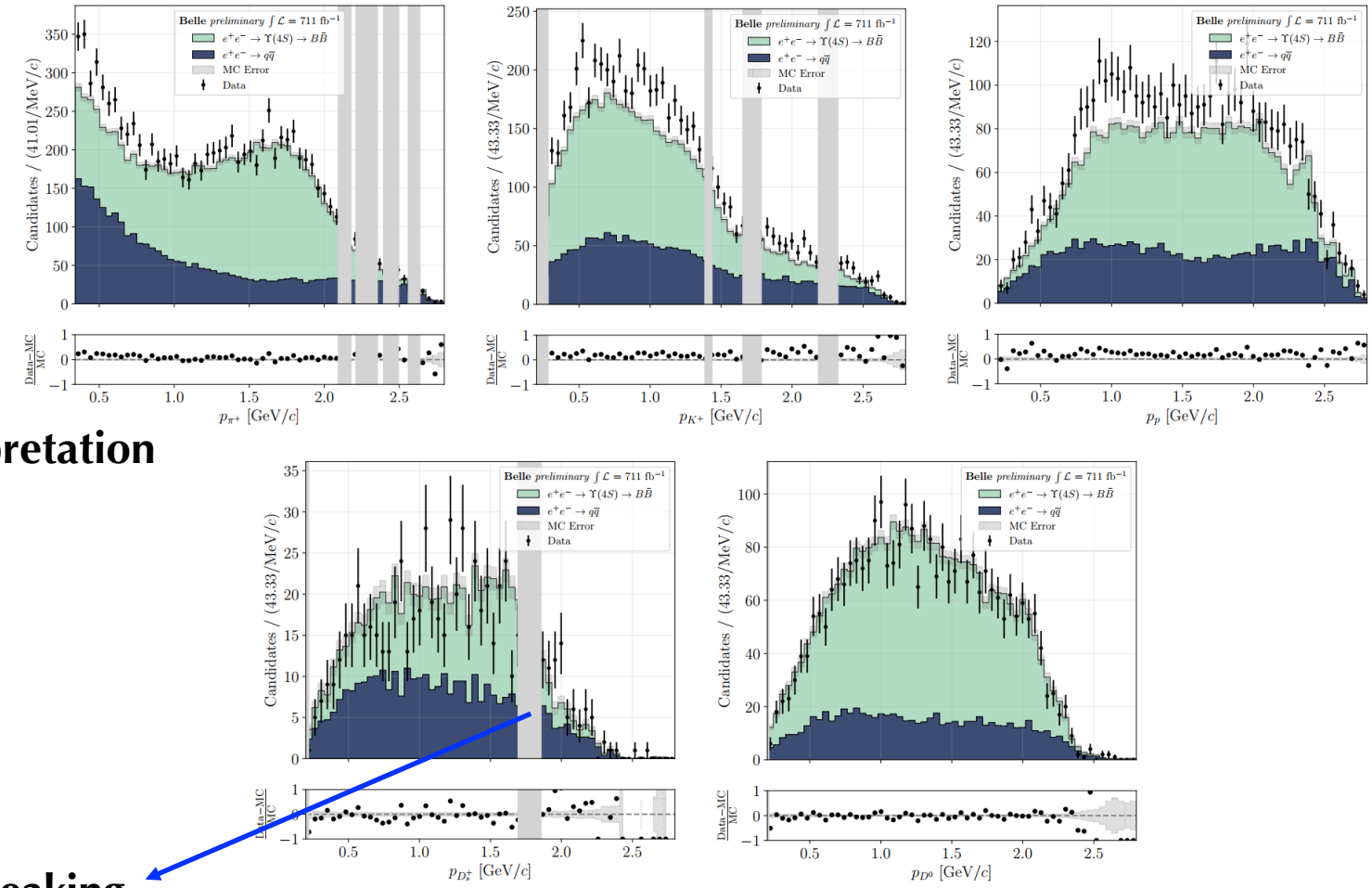
B_{tag} is reconstructed using our Full Event Interpretation algorithm.

B_{sig} is shown below.

$$B^+ \to h^+ X \quad h^+ = \pi^+, K^+, p, D_s^+$$
$$B^0 \to \bar{D}^0 X$$

Main backgrounds: ee→q$\bar{q}$, ee →B$\bar{B}$, and SM peaking backgrounds.

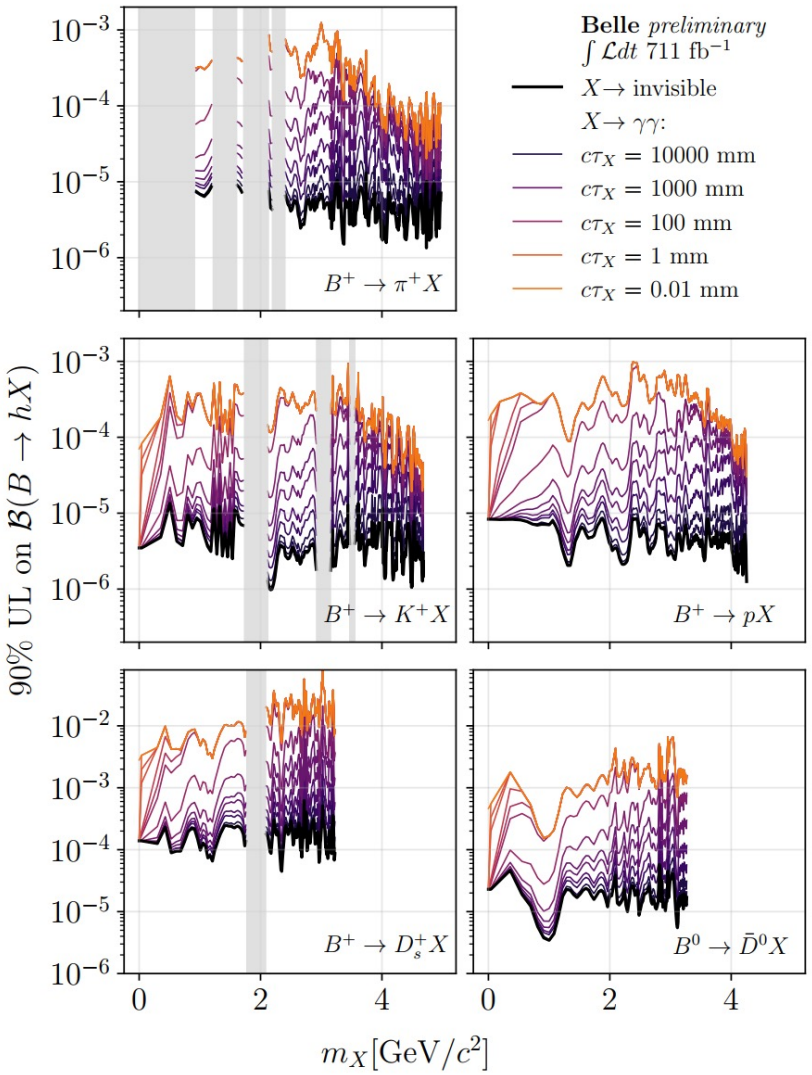
Signal extracted from momentum p_h in the B_{sig} rest frame:



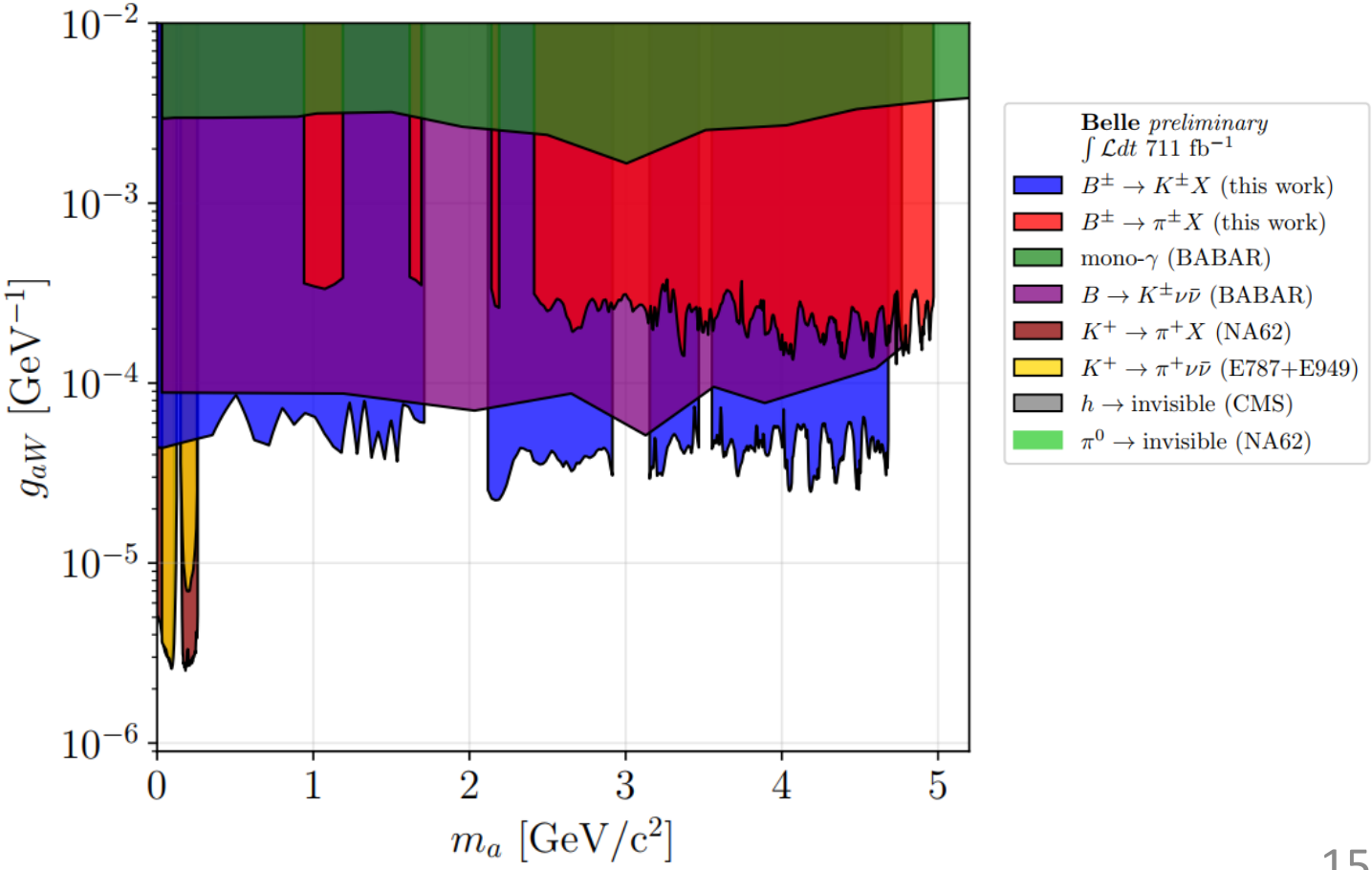
B → h X, X → invisible

Belle II preliminary

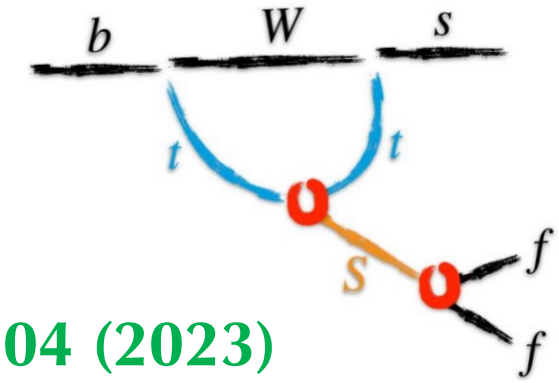
- No excesses were found.
- The most stringent exclusion limits to date on the branching fractions for all search channels.



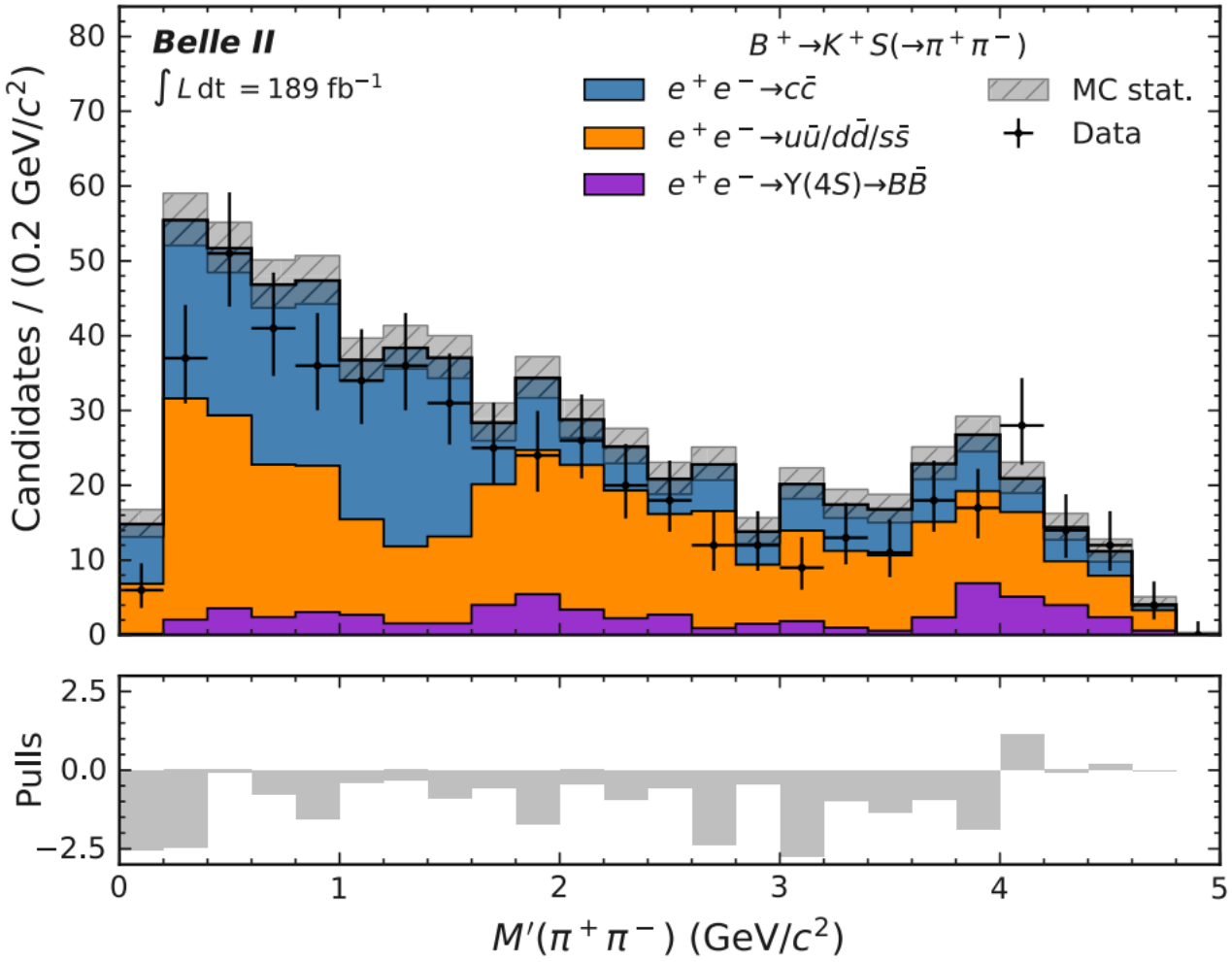
The coupling g_{aW} in the invisible ALP scenario from Ref. [PRL 118, 111802 (2017)]



$B \to K S, S \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$



long-lived spin-0 particles S in B-meson decays mediated by a b → s transition



PRD 108, L111104 (2023)

- $B^+ \to K^+S$, $B^0 \to K^{*0}[\to K^+\pi^-]S$
- Signal search: fits to the LLP reduced mass

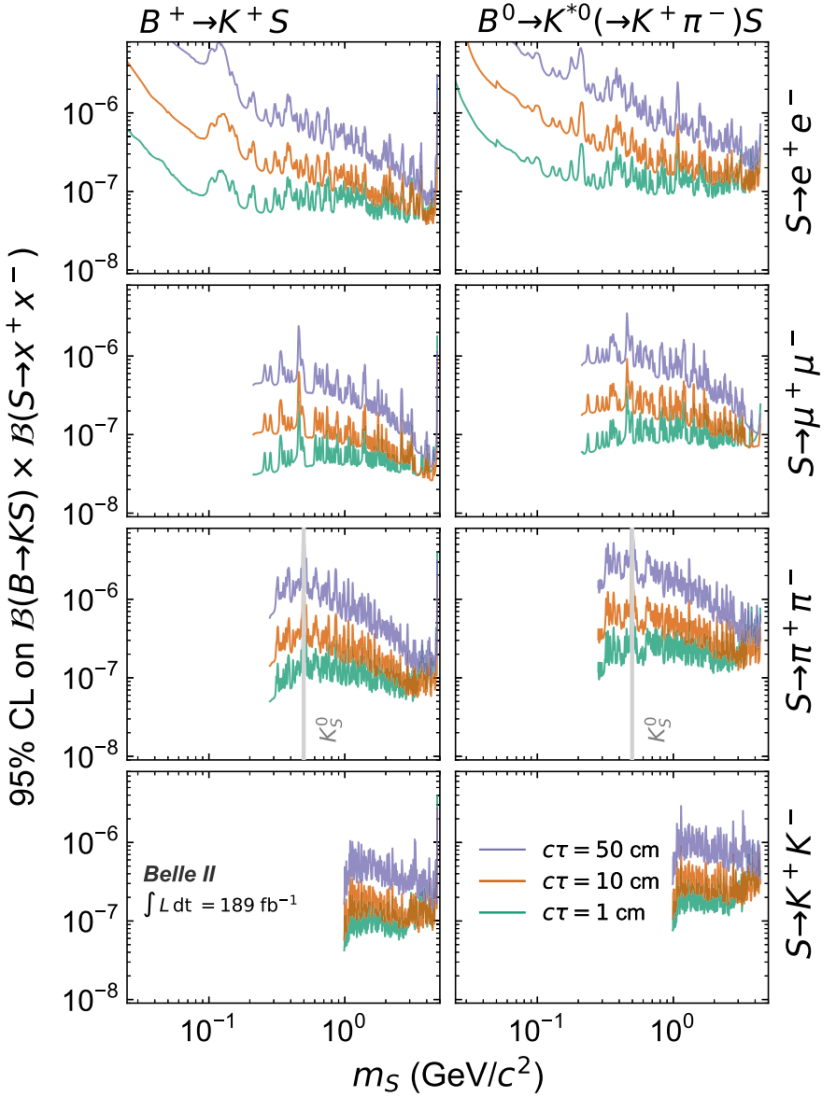
$$M'(x^+x^-) = \sqrt{M^2(x^+x^-) - 4m_x^2}$$

- Main backgrounds: ee→q$\bar{q}$ and ee →B$\bar{B}$

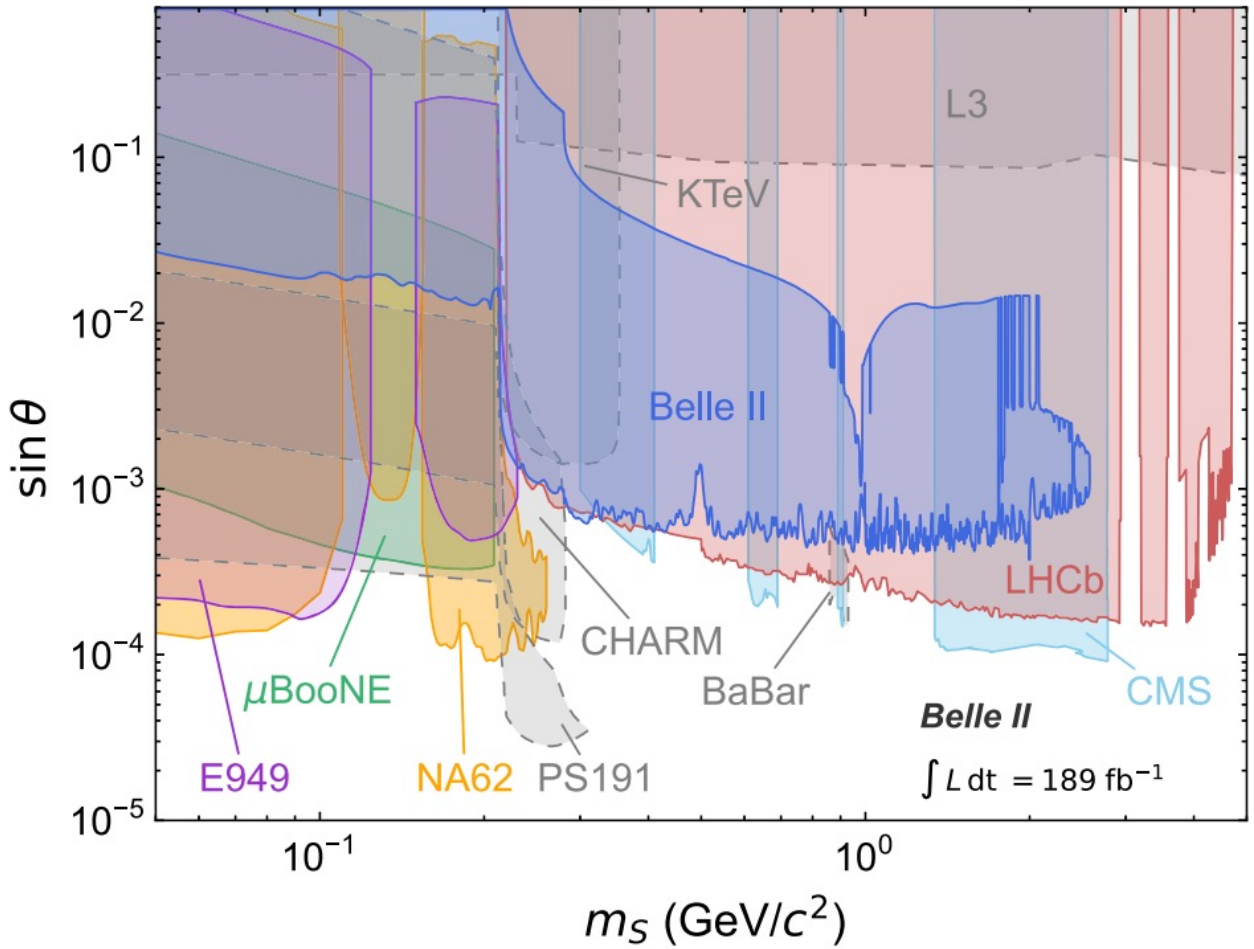
$B \to K S, S \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$

- No excesses were found.
- Set 95% CL upper limits on the product of branching fractions

PRD 108, L111104 (2023)



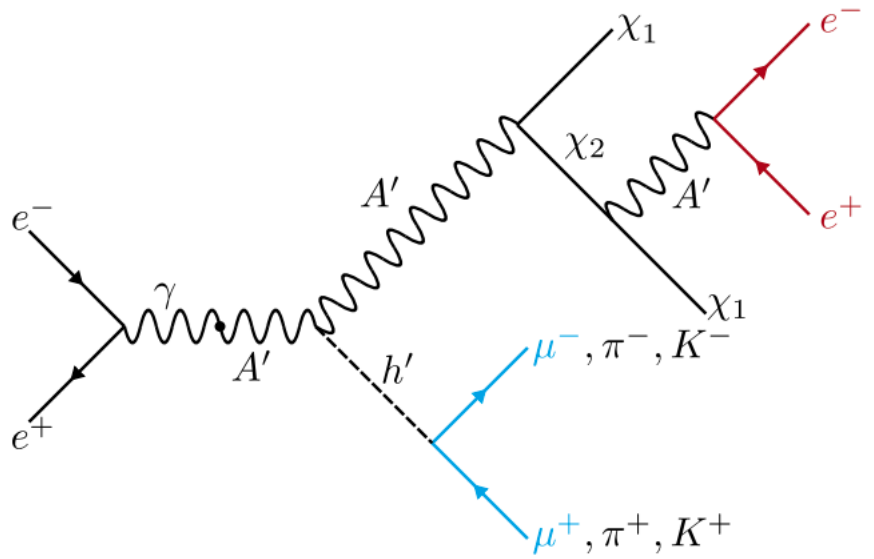
Convert to mixing angle θ and compare to other results:



A dark Higgs boson with inelastic dark matter

PRL 135, 131801 (2025)

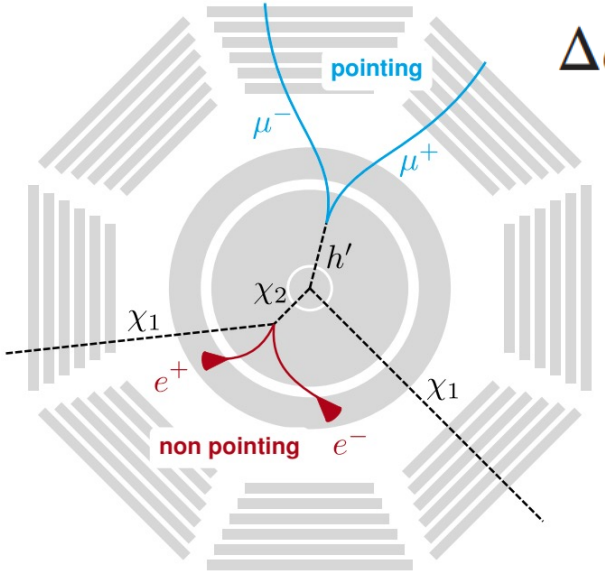
- Dark photon A′
- Dark Higgs h′ is generally long-lived and mixes with SM H_0
- Dark matter χ_1 is stable
- Dark matter χ_2 is generally long-lived



$$e^+e^- \to h'(\to x^+x^-)A'[\to \chi_1\chi_2(\to \chi_1 e^+e^-)]$$

Looking for simultaneous production of A′ and h′

- 4 tracks in the final states
- $\chi_2 \to \chi_1 A'$ non-pointing + missing energy
- $h' \to x^+x^-$ pointing

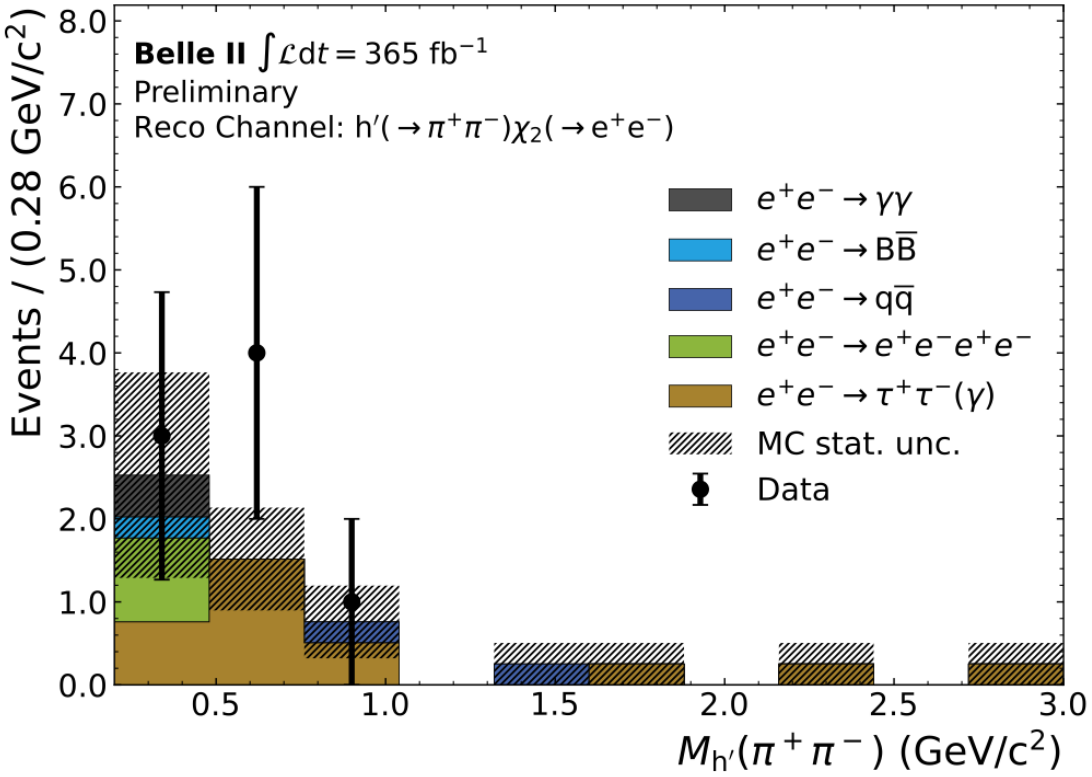


$$\Delta\alpha_{\vec{x},\vec{p}} < 3.1°$$

A dark Higgs boson with inelastic dark matter

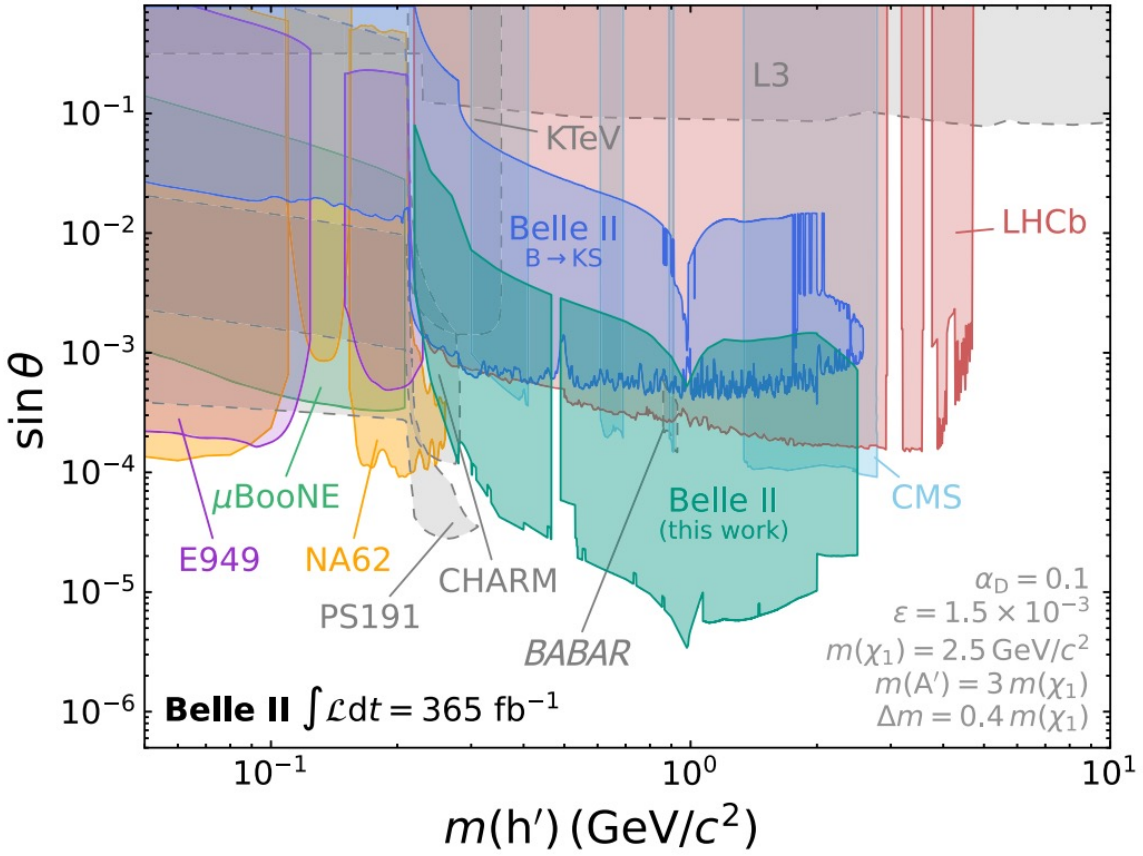
PRL 135, 131801 (2025)

- Cut-and-count strategy in $M_{h'}(x^+x^-)$ distributions
- No signicant excess found
- Convert UL at 90% C.L. of $\sigma(e^+e^- \to \chi_1\chi_2 h') \times \mathcal{B}(\chi_2 \to \chi_1 e^+e^-) \times \mathcal{B}(h' \to x^+x^-)$ to mixing angle θ



- 8 events observed consistent with expected background

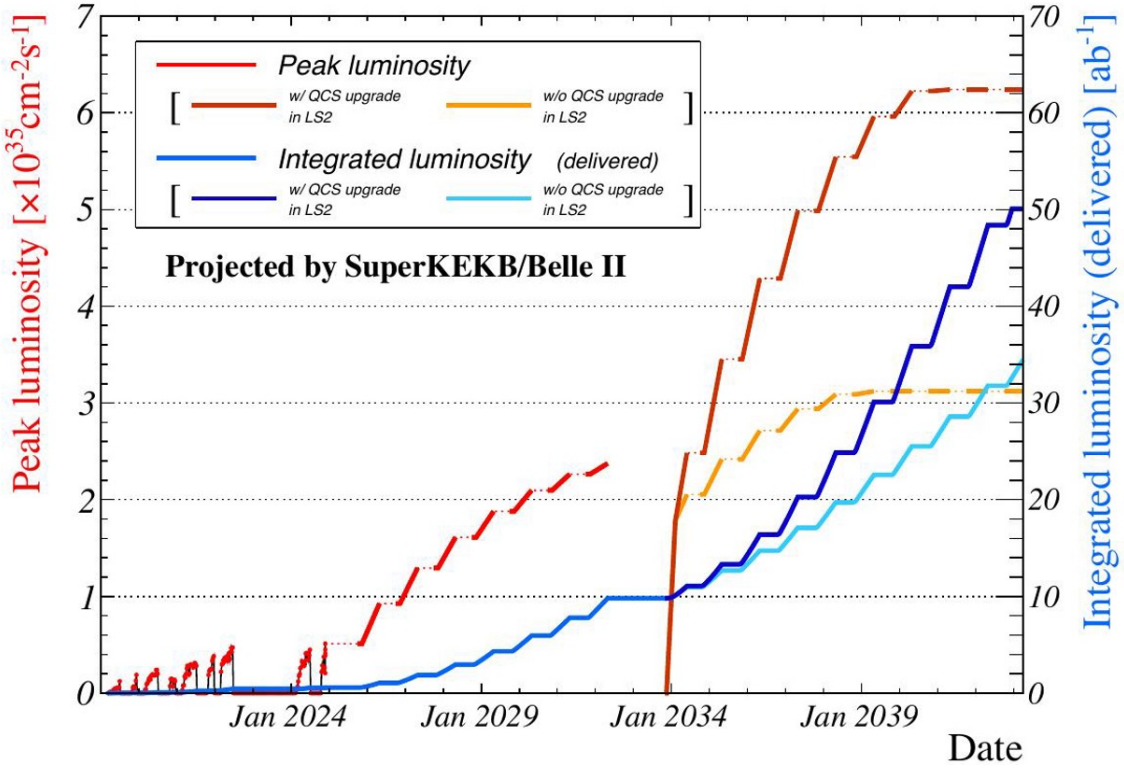
- The first search for dark Higgs bosons in association with inelastic dark matter.
- The limits improve over existing searches by up to 2 orders of magnitude.



Summary

- Searches for dark-sector particles in B-decays, τ-decays, and direct production are now a reality at Belle and Belle II.
- Enter the dark photon business: both visible and (especially) invisible
- Belle II gives the world best sensitivity in some light dark sector searches
- LLP searches will have a considerable weight in the next years (especially with a new displaced-vtx trigger&tracking)

Data-taking plan at Belle II



- Until 2026, about 1 ab^{-1} data, comparable to Belle
- Until 2029, about 4 ab^{-1} data.

Thanks for your attention!