



LFV and Dark Sector Searches at Belle and Belle II

60th Rencontres de Moriond 2026 – EW Interactions & Unified Theories

Devender Kumar

Institute of Nuclear Physics - Polish Academy of Sciences (IFJ PAN)
(On behalf of the Belle and Belle II Collaboration)

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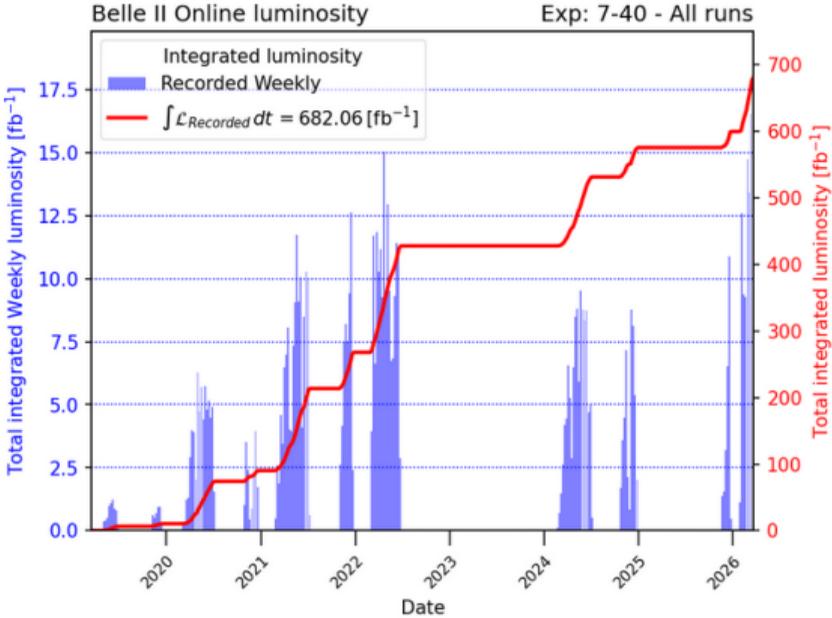
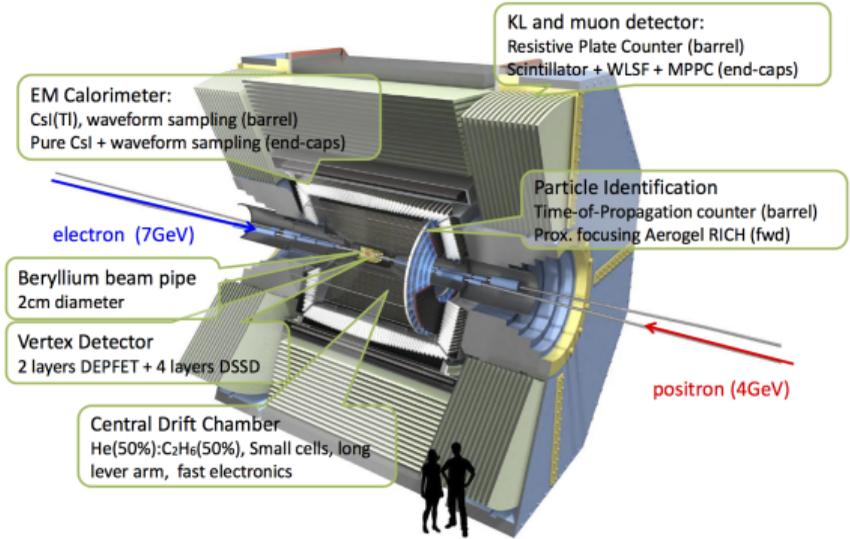


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Belle II Detector

Belle II Detector

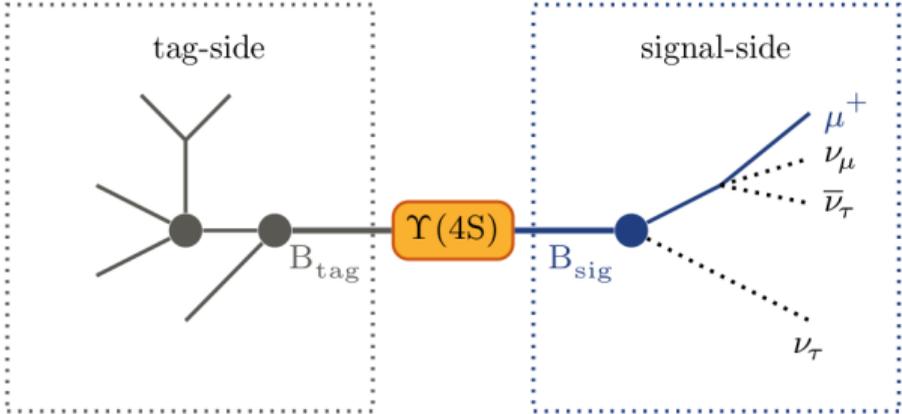
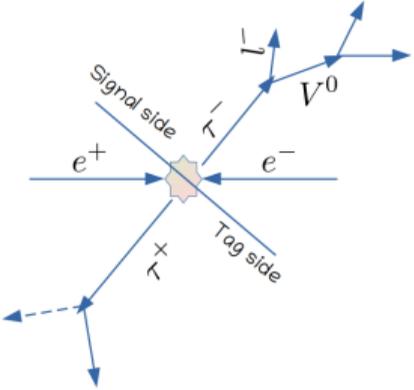
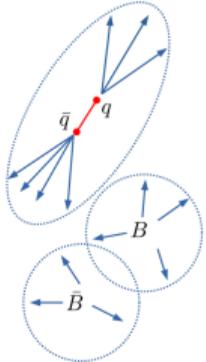


■ e^+ and e^- beams are collided with energies at $\Upsilon(4S)$ resonance producing $B\bar{B}$ & $\tau^+\tau^-$ pairs copiously. SuperKEKB recorded a world's best instantaneous luminosity of $5.1 \times 10^{34} cm^{-2}s^{-1}$.

Event Topology and the Tagging of Accompanying Partner

- B_{tag} is reconstructed using Full Event Interpretation (FEI) machine learning algorithm [CSBS(2019)3,6].
- Reconstructing the B_{tag} with hadronic tagging allows to determine the B_{sig} kinematics, an important tool in the missing particle decays. Good B selection: $M_{bc} = \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$ & $\Delta E = E_B^* - E_{\text{beam}}^*$ and FEI probability.

Center of Mass frame



Event topology

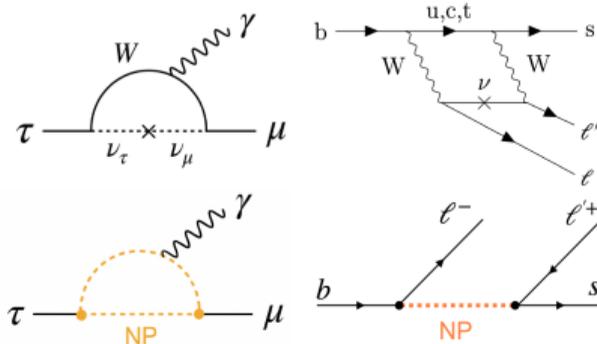
τ -tagging

B -tagging

Lepton Flavour Violation

- Lepton flavour violation (LFV) is forbidden at the tree level within the Standard Model (SM) of particle physics.
- The branching fraction of the lepton flavor violating (LFV) $l_1 \rightarrow l_2 \gamma$ decay

$$\mathcal{B}(l_1 \rightarrow l_2 \gamma) \propto \left(\frac{\delta m_\nu^2}{m_W^2} \right)^2 \sim \mathcal{O}(10^{-50})$$



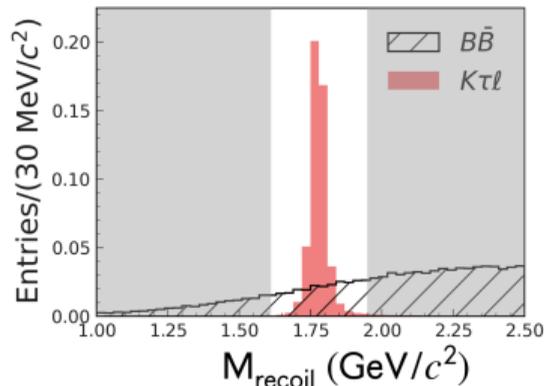
- In B decays, if the observed anomalies in the $R(D)$ & $R(D^*)$ averages [2411.18639] and in the measurement of $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$ [PRD 109, 112006 (2024)] are confirmed, several extensions of the SM allow LFV to describe the deviations [EPJC 76, 134 (2016), PRD, 075004 (2024), EPJST 233, 2105 (2024), PRD 109, 112006 (2024), PLB 848, 138411 (2024)].
- In the framework of SM effective field theory, the deviation in the measurement of $\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$ can be accounted by turning on the off-diagonal coupling between lepton flavors. Consequently, $\mathcal{B}(B \rightarrow K \tau \mu)$ is predicted to be around $[2, 3] \times 10^{-6}$ [PLB 848, 138411 (2024)].

Search for the $B^0 \rightarrow K^{(*)0} \tau \ell$ Decay

- Analyses $B^0 \rightarrow K_s^0 [\rightarrow \pi^+ \pi^-] \tau \ell$ and $B^0 \rightarrow K^{*0} [\rightarrow K^+ \pi^-] \tau \ell$ search for the LFV decays using the Belle (711 fb^{-1}) & (365 fb^{-1}) Belle II data.
- B_{tag} : using hadronic FEI with requirements on M_{bc} & ΔE .
- Decay $B^0 \rightarrow K^{*0} \tau \ell$ is reconstructed with a **missing τ** hypothesis.
- $\tau \rightarrow e \nu \bar{\nu}, \mu \nu \bar{\nu}, \pi \nu, \pi \pi^0 \nu$ for the channel $B^0 \rightarrow K_s^0 \tau \ell$.

$$M_{\tau}^2 = m_B^2 + m_{K^{(*)0} \ell}^2 - 2 \left(\frac{E_{\text{beam}}^* E_{K^{(*)0} \ell}^*}{c^4} + \frac{p_{B_{\text{tag}}}^* p_{K^{(*)0} \ell}^* \cos \theta}{c^2} \right)$$

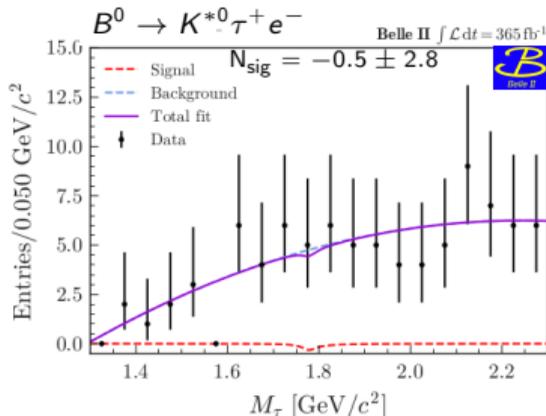
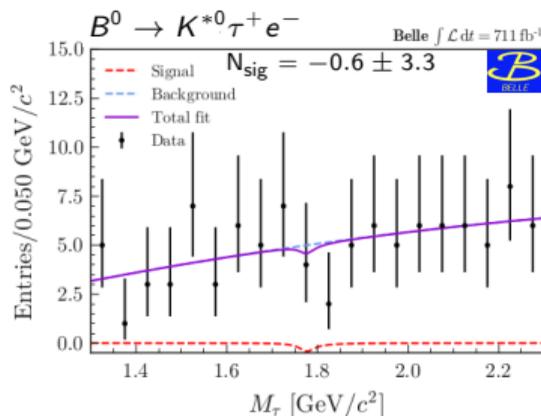
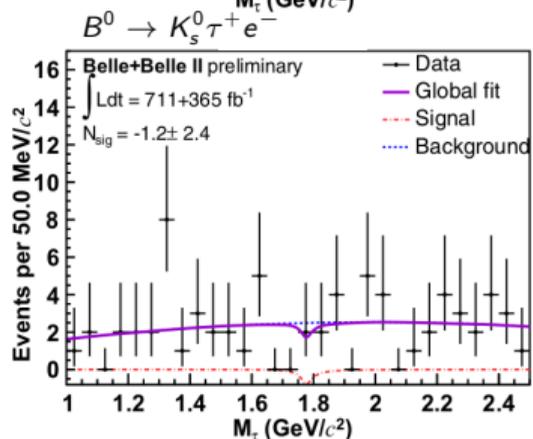
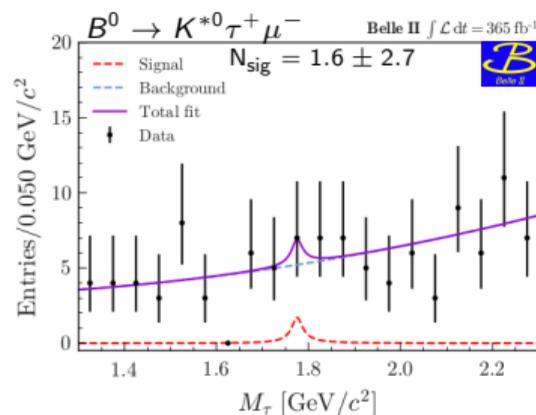
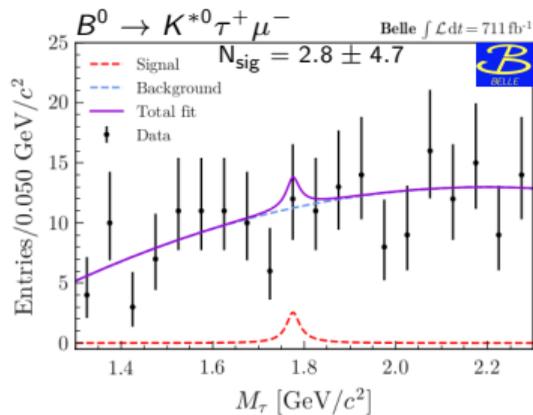
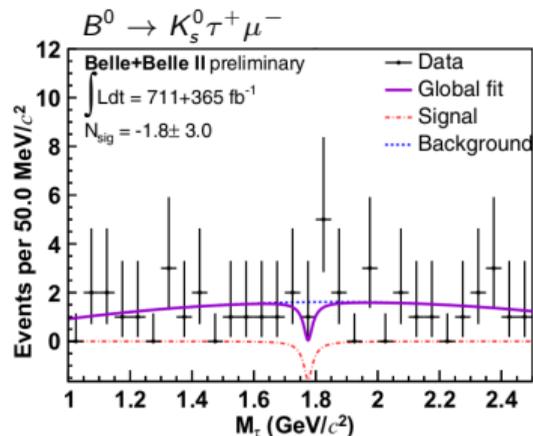
- The background is suppressed using preselection + BDT.
- Signals are extracted by fitting the recoil mass using extended unbinned maximum likelihood fit method.



$B^0 \rightarrow K_s^0 \tau \ell$ using Belle + Belle II dataset [[PRL 135, 041801 \(2025\)](#)]

$B^0 \rightarrow K^{*0} \tau \ell$ using Belle + Belle II dataset [[JHEP08\(2025\)184](#)]

LFV $B^0 \rightarrow K^{(*)0} \tau \ell$ Search: Fit Results



Search for $\tau \rightarrow \mu\gamma$ at Belle II

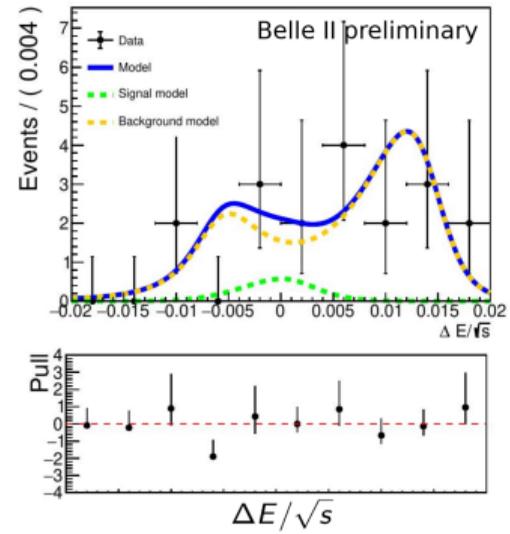
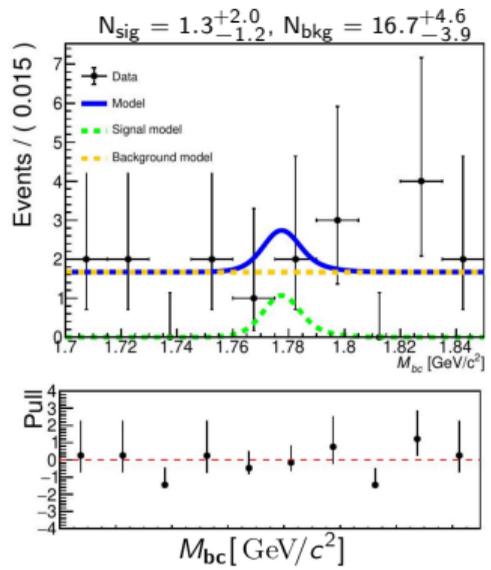
- Signal side: A good μ and high energy ECL cluster. Observables:

- $M_{bc} = \sqrt{E_{beam}^{*2} - p_{\mu\gamma}^{*2}}$
- $\Delta E = E_{\mu\gamma}^* - E_{beam}^*$

- Tag: 1-prong with μ veto.
- Main backgrounds: $e^+e^- \rightarrow \tau^+\tau^-$ & $\mu^+\mu^-$.
- Belle II dataset: 428 fb^{-1} .

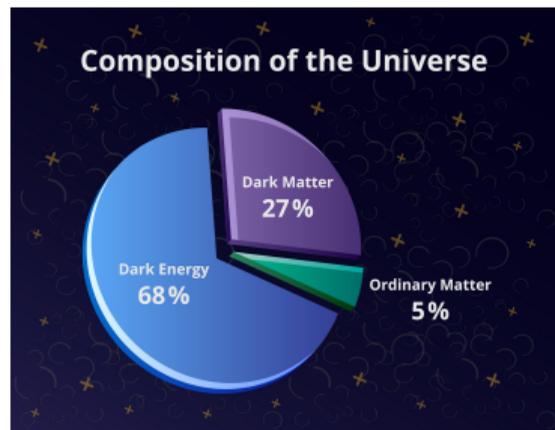
Preliminary results:

- Within the same signal enhanced region, this work achieves better signal efficiency of 5.2% with 1.1 ± 0.2 background events as compared to previous Belle values of 3.7% and 5.8 ± 0.04 events.
- Upper limit on $\mathcal{B}(\tau \rightarrow \mu\gamma) < 9.5 \times 10^{-8}$ at 90% CL using modified frequentist methodology.



Dark Sector

- There are several models in literature proposing new particles and their interactions from a scale of ultralight to massive in TeV .
- Belle II experiment provides an excellent platform for probing the DM particles in the range of few MeV to the electroweak scale, where the heavy particles can appear in the loop-level rare processes. In this presentation, we focus on the following searches:
- **Feebly interacting particles (FIPs)**: Hypothetical particles that interact with SM particles extremely weakly.
 - $B \rightarrow hX_{inv}$ [[arXiv.2601.07104](#)] **New results!**
- **Axion like particles (ALPs)**: Hypothetical light pseudoscalar particles originally proposed from the Peccei–Quinn mechanism to solve the strong CP violation problem in Quantum Chromodynamics.
 - $e^+e^- \rightarrow a\gamma$ **New results!**
 - $\tau \rightarrow a\ell$ [[JHEP08\(2025\)155](#)].

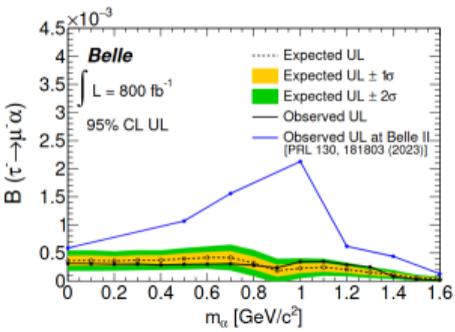
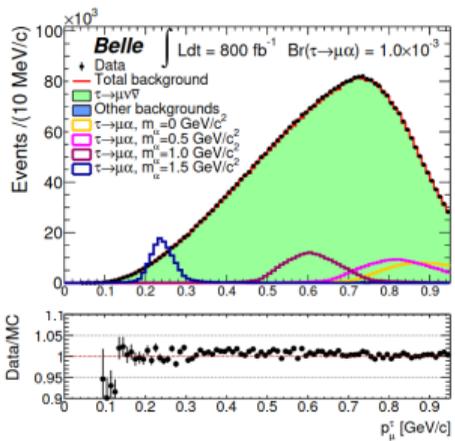


Search for the LFV Invisible Decay of τ at Belle: $\tau^\pm \rightarrow \ell^\pm \alpha$

- Studying the LFV $\tau^\pm \rightarrow \ell^\pm \alpha$ decay is a good hunt for the axion like particles, where α is a spin-0 boson.
- τ_{tag} : $\tau \rightarrow (h, 2h, 3h)\nu_\tau$ decays.
- The momentum resolution of the p_ℓ^T is improved by requiring a tight condition on opening angle between τ_{tag} and 3-momentum of tag-side hadronic system in the CM frame.
- $\mathcal{B}(\tau^- \rightarrow \ell^- \alpha)$ for a range of $m_\alpha \in (0.0 - 1.6) \text{ GeV}/c^2$ are:

Coll.	Data	ℓ	$\mathcal{B}_{\text{UL}}^{95\% \text{CL}} (10^{-4})$	References
Belle	800 fb^{-1}	μ	0.2 – 3.5	JHEP08(2025)155
		e	0.4 – 6.4	

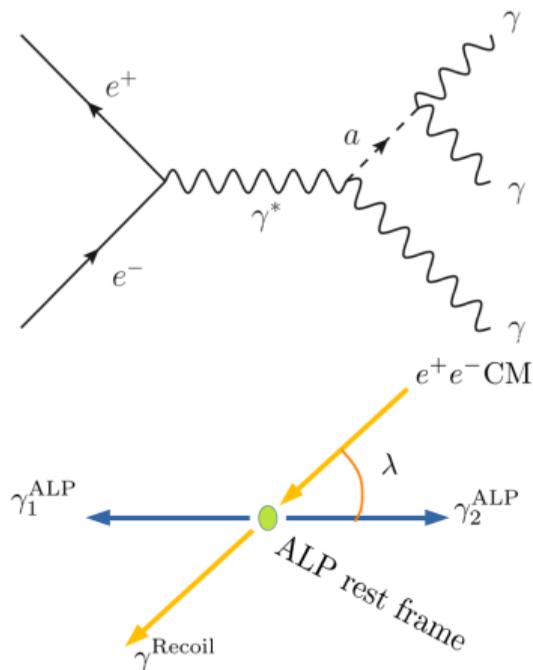
- These results supersede the previous result by Belle II using 62.8 fb^{-1} of data [[PRL 130, 18, 181803](#)].



See [Michele Mantovano's](#) talk for additional results on LFV in τ decays.

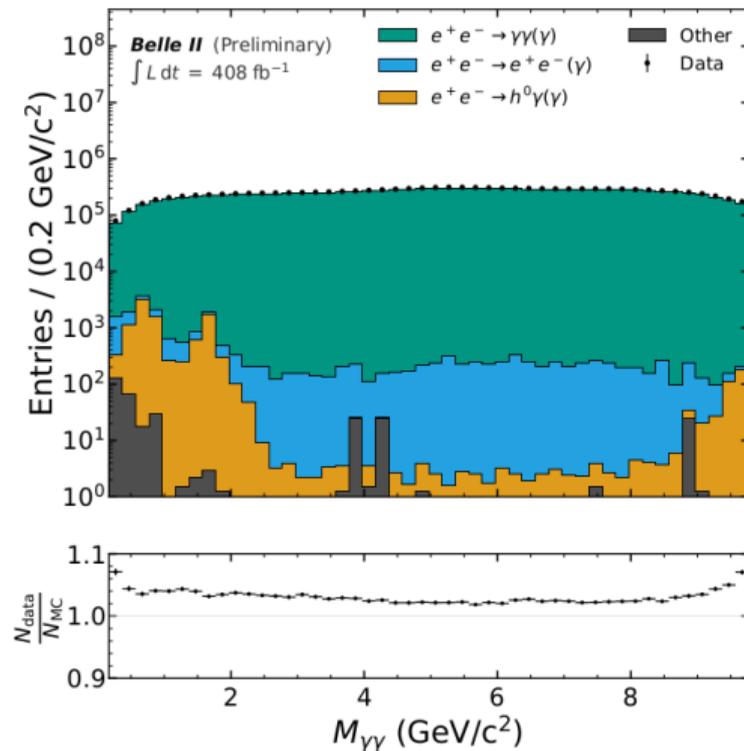
Search for ALPs in $e^+e^- \rightarrow a\gamma$ at Belle II

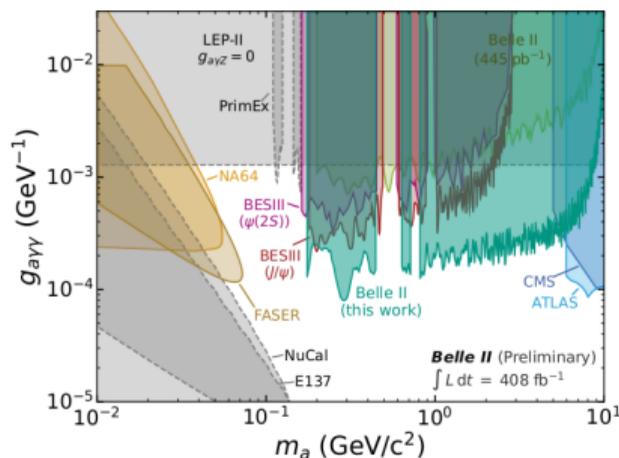
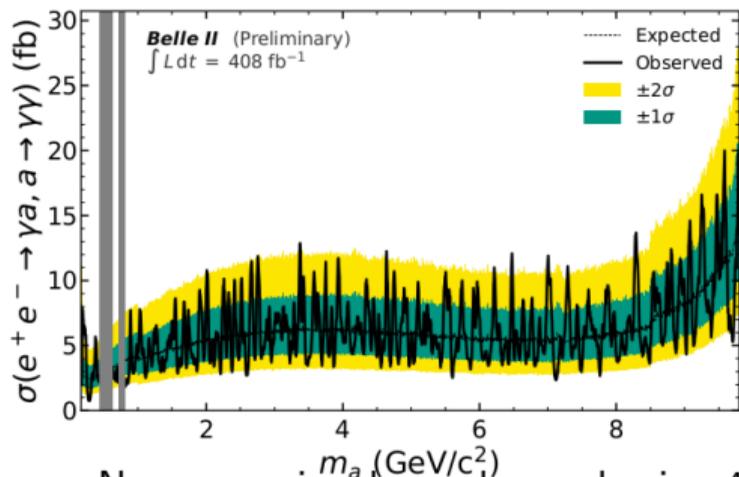
- a : An ALP having $m_a \in (0.17, 9.80) \text{ GeV}/c^2$ and coupling strength $g_{a\gamma\gamma}$ at the vertex $a \rightarrow \gamma\gamma$.
- Only three high energy photons are allowed in an event.
- N_{tracks} originating from the IP < 2 .
- Helicity angle $\cos \lambda$:
 - Two body decay: Uniform distribution.
 - $e^+e^- \rightarrow \gamma\gamma(\gamma)$: $|\cos \lambda| \rightarrow 1$.
- Feed-forward neural network to separate the signal from $e^+e^- \rightarrow \gamma\gamma(\gamma)$ events [Nature 323, 533 (1986)].



To be submitted to PRL.

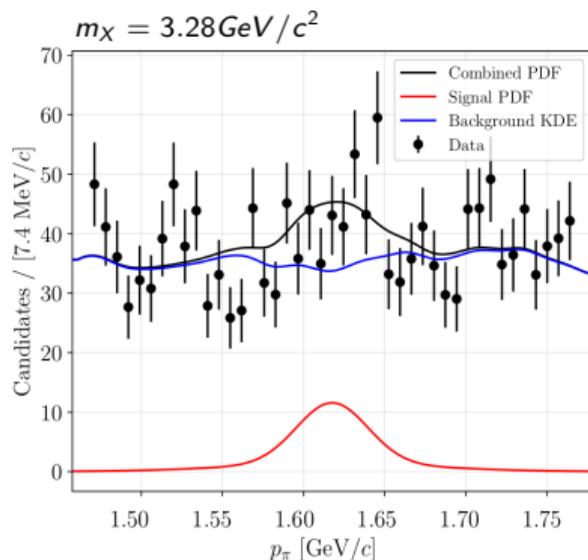
- No peaking component for the total background.
- Overall good agreement between the data and MC simulation except that the background in the actual data is over-estimated by around 4%.
- Signal extraction: Unbinned maximum-likelihood fits to $M_{\gamma\gamma}$ distributions.





- No excess signal are observed using 408 fb^{-1} of Belle II dataset. Local significance for $m_a = 0.22 \text{ GeV}/c^2$: 3.3σ , Global significance considering the look-elsewhere effect: 1.4σ .
- Upper limit at 95% CL on the $\sigma(e^+e^- \rightarrow a\gamma, a \rightarrow \gamma\gamma)$ is estimated as a function of m_a .
- Most restrictive upper limits at 95% CL on $g_{a\gamma\gamma}$ over $m_a \in (0.17, 5.00) \text{ GeV}/c^2$, except near $m_a = 0.22 \text{ GeV}/c^2$. An improvement by a factor of 9 with respect to the previous Belle II report.

- Analysis¹ searches for the FIPs in $B^0 \rightarrow \bar{D}^0 X_{\text{inv}}$ & $B^+ \rightarrow h X_{\text{inv}}$ decays where $h = \pi^+, K^+, D_s^+, \rho$ & X_{inv} is an invisible particle.
- D reconstruction: $D_s^+ \rightarrow K^+ K^- \pi^+$ & $D^0 \rightarrow K^- \pi^+, K^- \pi^+ \pi^0, K^- \pi^+ \pi^- \pi^+$.
- B_{tag} : Hadronic FEI with conditions on M_{bc} & ΔE .
- Peaking background from process like $B^+ \rightarrow K^+ \bar{D}^0$ are particularly vetoed.
- $e^+ e^- \rightarrow q \bar{q}$ events are suppressed using BDTs trained on event topology variables.
- Mass of the invisible particle X , m_X is varied from 1 MeV/c^2 to the allowed region of $m_B - m_h \implies p_h$ distribution are parameterised accordingly.

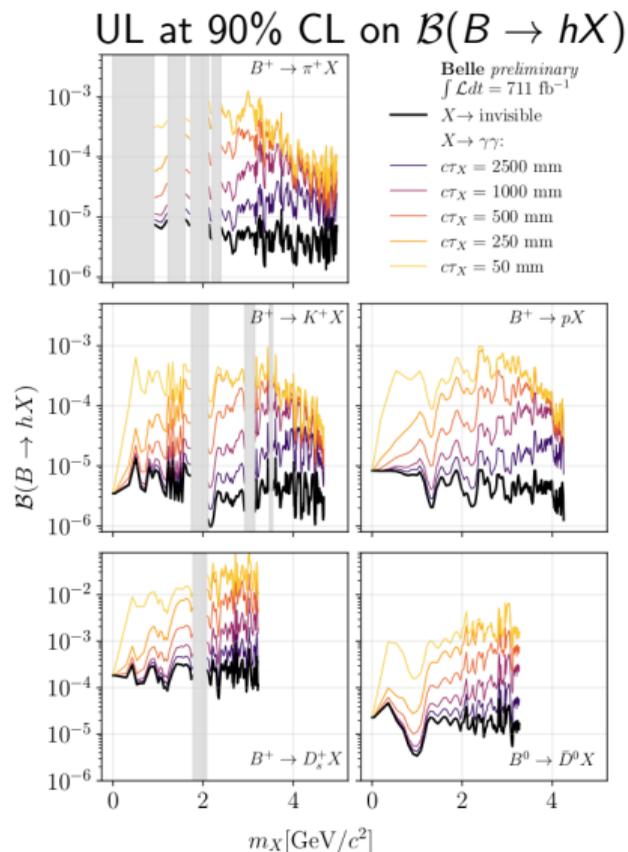


- No significant global excess using look elsewhere effect.

¹Physics letter has been submitted to PRL [[2601.07104](https://arxiv.org/abs/2601.07104)].

Search for the FIPs in B decays at Belle

- No significant excess over background is observed using the 711fb^{-1} of Belle dataset.
- The upper limits at 90% CL are set on the $\mathcal{B}(B \rightarrow hX_{\text{inv}})$ ranging from $10^{-6} - 10^{-4}$ as a function of m_X .
- Corresponding upper limits for $\mathcal{B}(B \rightarrow hX) \times \mathcal{B}(X \rightarrow \gamma\gamma)$ are also reported for a range lifetime allowing X to decay within and outside the detector.
- This work is a **first search for $B^+ \rightarrow \pi^+ X_{\text{inv}}$, $B^+ \rightarrow D_s^+ X_{\text{inv}}$, & $B^0 \rightarrow \bar{D}^0 X_{\text{inv}}$ decays and all the reported limits are most stringent ones.**



Summary

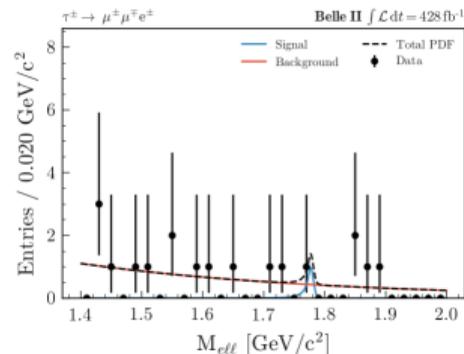
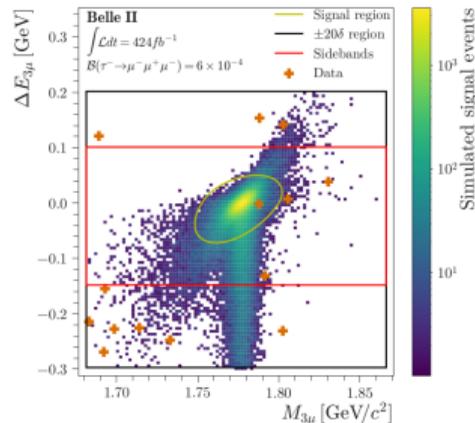
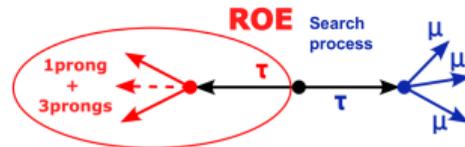
- We have produced one of the most stringent limits on LFV decays.
- Belle and Belle II experiments are searching extensively for the dark matter particles hypotheses; Some of the searches are the first ever.
- Belle II can provide even stringent bounds on the LFV and dark sector in the upcoming years.

Thank you for your kind attention!!!

Back up slides

LFV $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ & $e^\mp l^\pm l'^-$ decays

- Signal side: 3 good lepton tracks.
- Novel inclusive-tagging approach.
- Low background for the 3μ selection¹.
- Background due to low multiplicity events in $\tau^- \rightarrow e^\mp l^\pm l'^-$; BDT suppression².



	$\mathcal{B}_{\text{Belle II}}^{90\% \text{UL}} (10^{-8})$	$\mathcal{B}_{\text{Belle}}^{90\% \text{UL}} (10^{-8})$	$\epsilon_{\text{Belle II}} \%$	$\epsilon_{\text{Belle}} \%$
$\mu^- \mu^+ \mu^-$	1.9 ¹	2.1 ³	20.0	7.6
$e^- e^+ e^-$	2.5 ²	2.7 ³	15.0	6.0
$e^- e^+ \mu^-$	1.6 ²	1.8 ³	20.4	9.3
$e^- \mu^+ e^-$	1.6 ²	1.5 ³	23.5	11.5
$\mu^- \mu^+ e^-$	2.4 ²	2.7 ³	20.1	6.1
$\mu^- e^+ \mu^-$	1.3 ²	1.5 ³	24.1	10.1

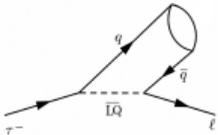
¹ [JHEP09\(2024\)062](#)

² [JHEP12\(2025\)169](#)

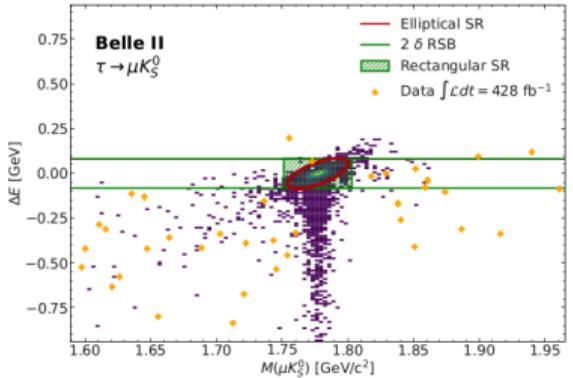
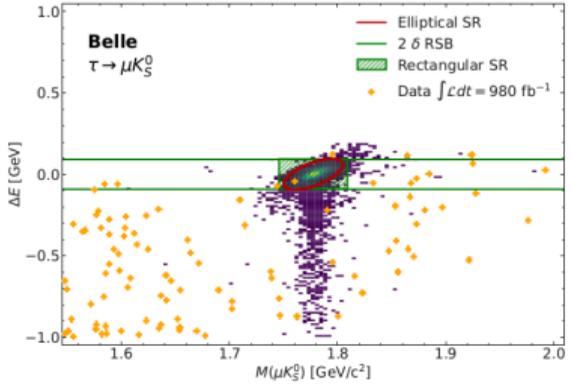
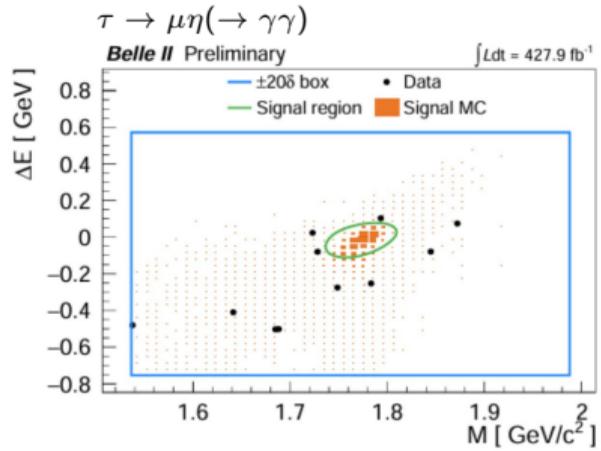
³ [PLB 687 \(2010\) 139](#)

$\tau \rightarrow \ell K_S^0$ & $\ell \eta$ decay

- Searches for semileptonic $\tau \rightarrow \ell K_S^0$ ¹ $\tau \rightarrow \ell \eta$ ²
- Sensitive to new physics scenarios, such as leptoquark.
- Background suppression: Cut based + BDT for $q\bar{q}$ events.
- Counting in elliptical signal region.



	$B^{90\%UL}(10^{-8})$
$\tau \rightarrow eK_S^0$	0.8
$\tau \rightarrow \mu K_S^0$	1.2
$\tau \rightarrow e\eta$	9.2
$\tau \rightarrow \mu\eta$	4.2

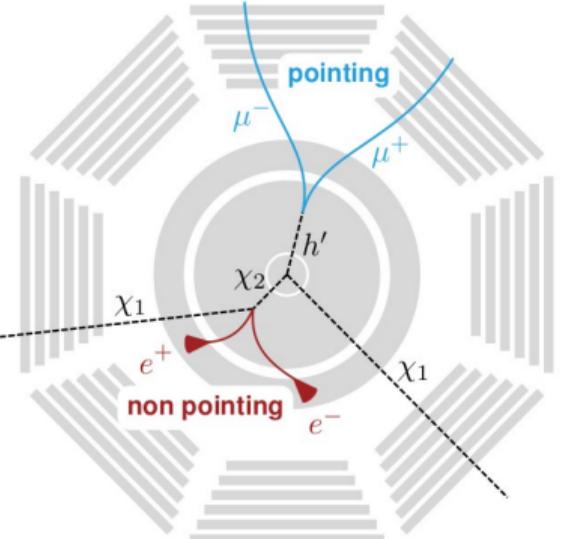
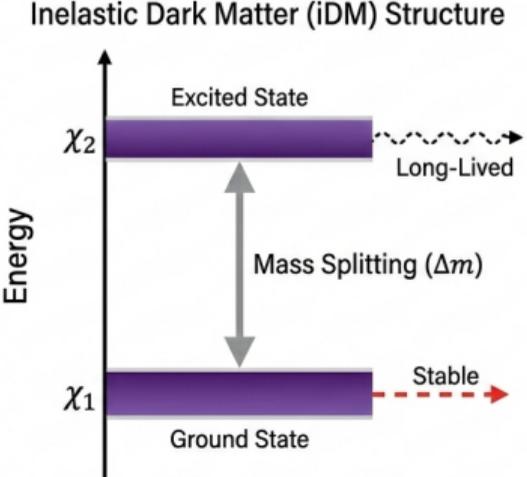
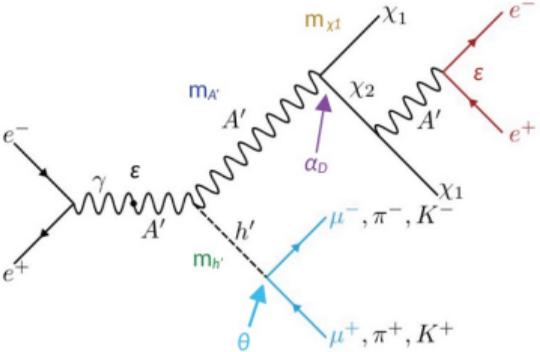


¹ [JHEP08\(2025\)092](#). Uses Belle + Belle II data = $980 \text{ fb}^{-1} + 428 \text{ fb}^{-1}$

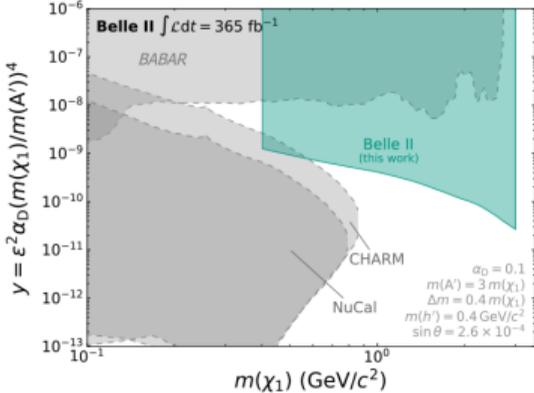
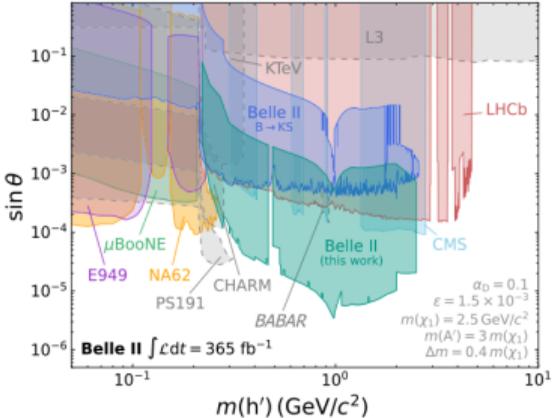
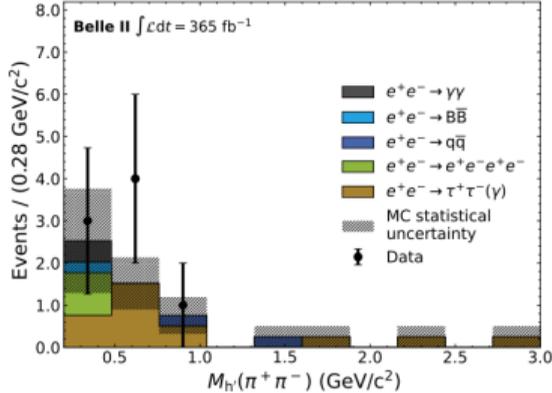
² Upcoming new result from Belle II.

Dark Higgs Boson along with iDM

- A nonminimal class of models introduces inelastic DM (iDM), where DM couples inelastically to SM states, depending on the mass difference $\Delta m = m(\chi_1) - m(\chi_2)$.
- Dark photon A' and higgs h' mixes with the SM photon and higgs field via the mixing parameters ϵ (kinetically) [PRD93,063523(2016), PRD96,055007(2017), JHEP04(2021)146] and θ [PRD75,037701(2007), JPG47,010501(2020)].



Dark Higgs Boson along with iDM : Results

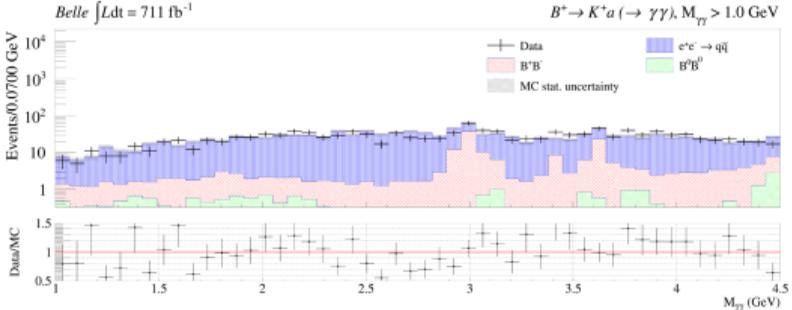
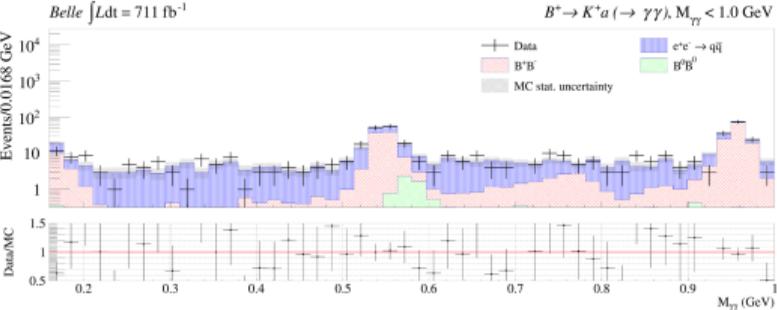
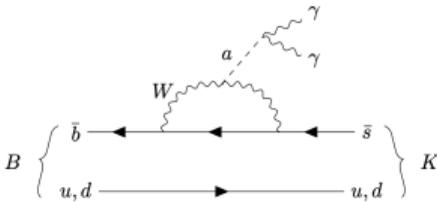


- No significant excess over expected is observed using 365 fb^{-1} of Belle II dataset ¹.
- 95% CL upper limits are set on the $\mathcal{B}(e^+e^- \rightarrow \chi_1\chi_2 h') \times \mathcal{B}(\chi_2 \rightarrow \chi_1 e^+e^-) \times \mathcal{B}(h' \rightarrow x^+x^-)$ as a function of h' mass and lifetime at the level of 10^{-1} fb . Other model-dependent ULs are:
 - Dark Higgs mixing angle θ at the level of 10^{-5} &
 - Dark photon kinetic mixing parameter ϵ at the level of 10^{-3} .

¹Phys. Rev. Lett. 135, 131801

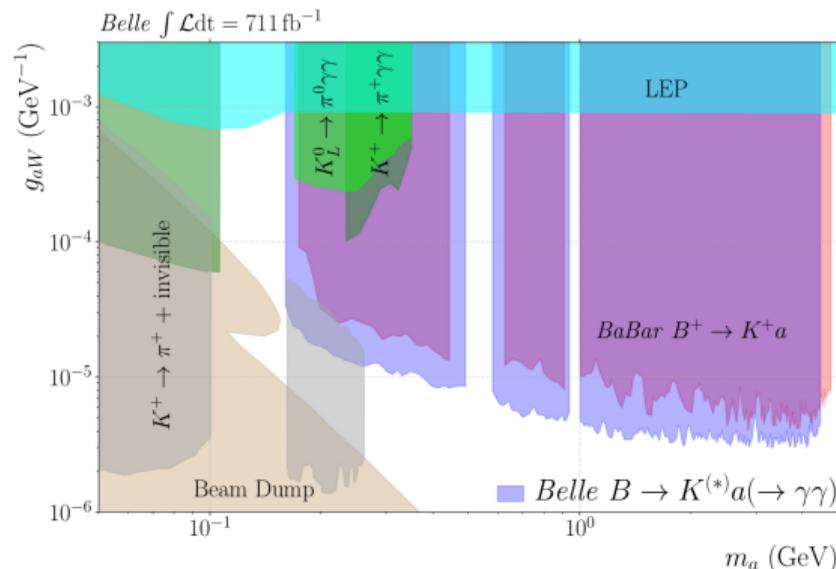
Axion-like-particle in $B \rightarrow K^* a (\rightarrow \gamma\gamma)$ at Belle

- a : Dark matter particle coupling with W boson with a strength g_{aW} through axion portal [PRD 79(2009)075008].
- Analysis¹ assumes the $\mathcal{B}(a \rightarrow \gamma\gamma)$ to be 100%.
- Signal channel considers K^+ , K^{*+} , K_s^0 , and K_s^{*0} modes.
- Good $B \rightarrow Ka$ are selected with tight conditions M_{bc} & ΔE .
- The ALP mass is scanned from 0.16 GeV/c^2 to 4.50 (4.20) GeV/c^2 for the K (K^*) modes.
- Continuum suppression for the $e^+e^- \rightarrow q\bar{q}$ events.



$B \rightarrow K^* a(\rightarrow \gamma\gamma)$ Results

- In the absence of any observed signals, an upper limit on the coupling strength g_{aW} is estimated as a function of the m_a hypothesis using Belle luminosity of 711fb^{-1} .
- For a range of m_a from lowest to $m_a > 2\text{ GeV}/c^2$, UL increases from $3.0 \times 10^{-5} \rightarrow 3.0 \times 10^{-6}$ at 90% CL.



- The constraints on the coupling of the axion-like particle to electroweak gauge bosons g_{aW} are improved by a factor of two compared to the most stringent previous experimental results by BABAR Collaboration [PRL 128 (2022) 131802].