





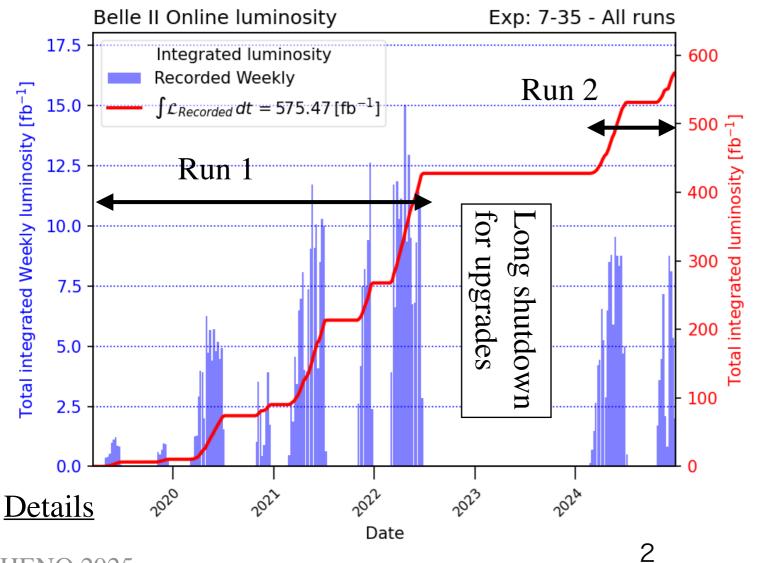
# Searches for dark sector particles at Belle and Belle II

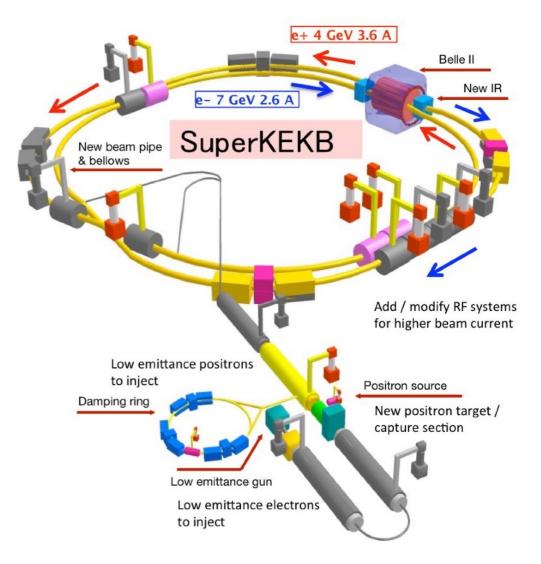
KINDO Haruki
On behalf of the Belle II collaboration

2025/5/19-21 PHENO2025

### The Belle II experiment at SuperKEKB accelerator

- Belle II is a luminosity frontier experiment looking for physics beyond the Standard Model. Continued from Belle experiment (1999-2010) that recorded about 1 ab<sup>-1</sup>.
- **SuperKEKB** is an asymmetrical  $e^+e^-$  collider operating at the  $\Upsilon(4S)$  resonance. Upgraded from **KEKB** accelerator for the **Belle** experiment.
- Run 1 finished successfully with 427 fb<sup>-1</sup> data. Run 2 started in 2024 and 575 fb<sup>-1</sup> is recorded. A new luminosity world record of  $5.1 \times 10^{-34} \, \mathrm{cm}^{-2} \, \mathrm{sec}^{-1}$  was achieved.





#### Dark sector search at Belle II

- Signature-based search in **clean environment** at lepton colliders and **hermetic detector**.
- Multipurpose detector with cylindrical symmetry that provides efficient reconstruction of neutral particles ( $\pi^0$ ,  $\eta$ ) and good particle identification for charged particles.
- Specific low-multiplicity triggers for dark sector searches; single track, muons, or photons. It was not available at Belle and BaBar experiments.

#### **Electromagnetic calorimeter (ECL):**

CsI(Tl) crystals

Waveform sampling (energy, Tim, pulse shape)

#### **Vertex Detectors (VXD):**

2 layer DEPFET pixel detectors (PXD)

4 layer double-sided silicon strip detector (SVD)

#### **Central Drift Chamber (CDC):**

He (50%): C<sub>2</sub>H<sub>6</sub> (50%), 8-15 mm pitch,

fast readout electronics

Details: Belle II Technical Design Report

#### **K**<sub>L</sub> and Muon Detector (KLM):

Resistive Plate Chamber (RPC) for outer barrel Scintillator + WLSF + MPPC for endcap and inner barrel

#### **Solenoid Magnet:**

1.5 T superconducting magnet

#### **Particle Identification detectors:**

Time-Of-Propagation Counter (TOP) for barrel Aerogel Ring-Imaging Cherenkov Counter (ARICH) for forward endcap

#### Overview of recent searches

■ 
$$\mathbf{L}_{\mu} - \mathbf{L}_{\tau}$$

▶  $Z' \rightarrow \text{invisible}$ 

▶  $Z' \rightarrow \mu\mu$ 

▶  $Z' \rightarrow \tau\tau$ 

- Axion like particles

$$\begin{array}{c} \bullet \quad a \rightarrow \tau\tau \\ \bullet \quad B \rightarrow Ka(a \rightarrow \gamma\gamma) \end{array}$$

- Dark Higgsstrahlung

$$A'h': A' \rightarrow \mu\mu, h'$$
 invisible

- LLP Dark Higgsstrahlung with IDM

$$A'h': A' \rightarrow \chi_1 \chi_2, h' \rightarrow \mu \mu, \pi \pi, KK$$

- LLP dark scalar in B decays

▶ 
$$B \rightarrow KS, S \rightarrow ee, \mu\mu, \pi\pi, KK$$

### Recent highlights

- Search for dark Higgs with inelastic dark matter Recently submitted to PRL (arXiv: 2505.09705)



- Search for Axion-like particle in  $B \to K^{(*)}a'(\to \gamma\gamma)$ Preliminary

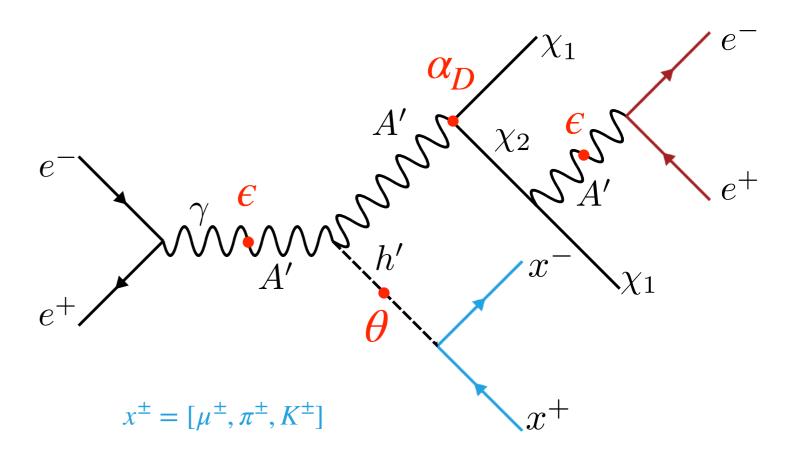


- Search for a  $\mu^+\mu^-$  resonance in four-muon final states Recently published in Phys. Rev. D. 109, 112015 (2024)



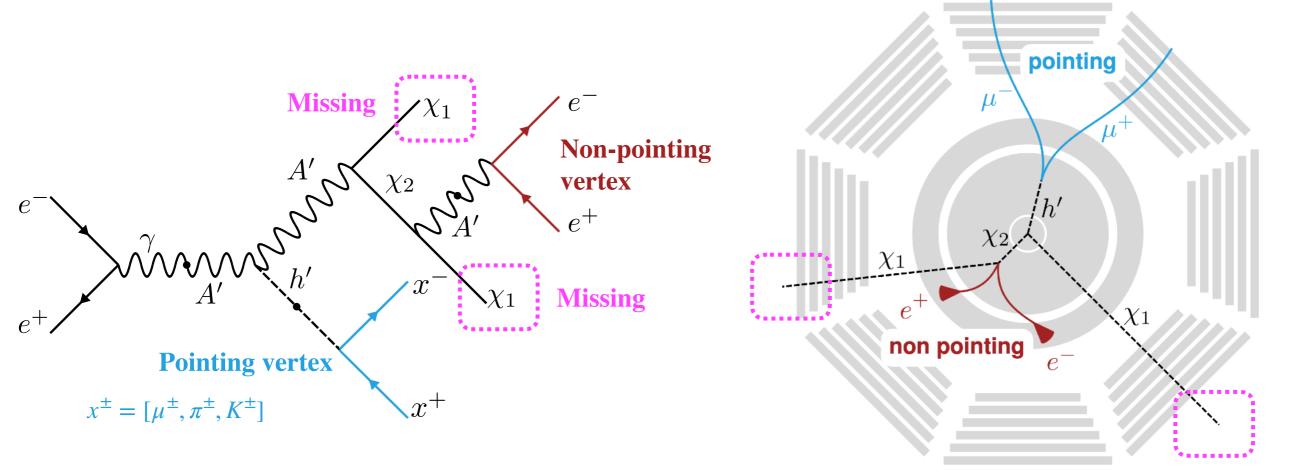


- Searching for simultaneously produced dark Higgs (h') with dark photon (A'). Use 365 fb<sup>-1</sup> of Belle II data.
- Two dark matter states  $\chi_1$  and  $\chi_2$  with small mass difference  $\Delta m = m(\chi_2) m(\chi_1)$ .
- $\chi_1$  is stable and a candidate of relic dark matter, while  $\chi_2$  is a long-lived state.
- h' is generally long-lived. It mixes SM Higgs through mixing angle  $\theta$  and decays into a pair of SM particles.
- ▶ Small  $\Delta m$  makes  $\chi_2$  long-lived.
- Assuming  $m(A') > m(\chi_1) + m(\chi_2)$ , the decay  $A' \to \chi_1 \chi_2$  is favored.
- Two displaced vertices.One is pointing to IP and the other is non-pointing.
- Missing energy.





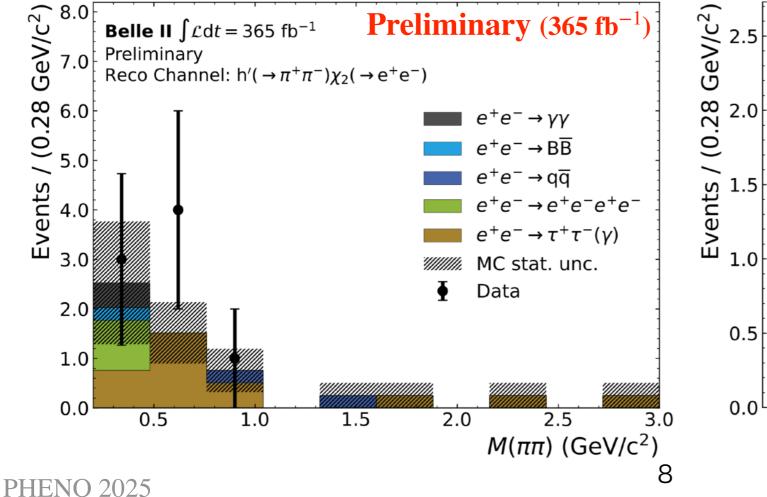
- Strategy: Search for two displaced vertices with missing energy.
- Challenges for tracking and triggering. Aiming for a zero-background analysis.
  - ▶ 4 (charged) tracks are required.
  - ▶ 2 for a pointing displaced vertex. And, 2 for a non-pointing displaced vertex.
  - Missing energies corresponding to  $\chi_1$  and  $\chi_2$ .

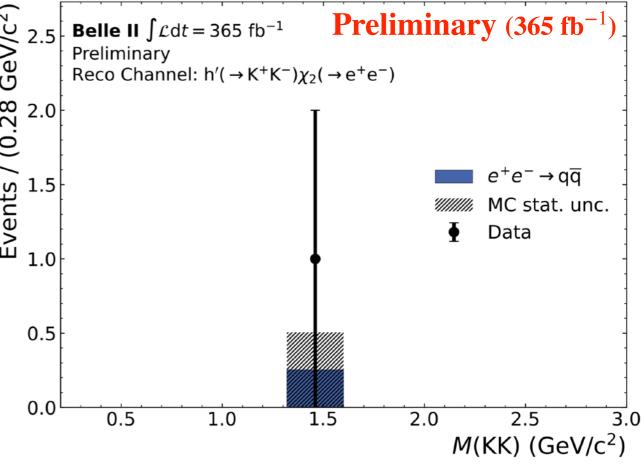




- Results: No evidence for a signal. Set upper limits on four different cross sections.

- Backgrounds are estimated in data from sidebands not to rely on MC.

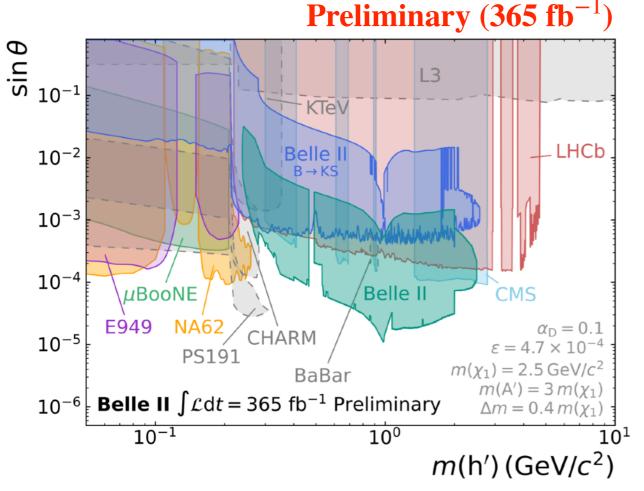


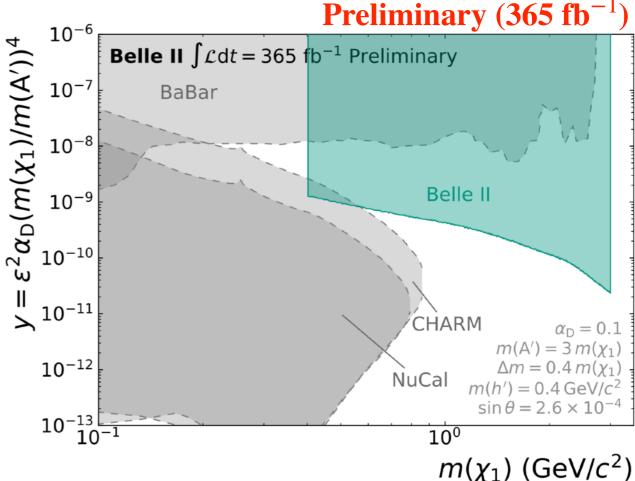




- Results: No evidence for a signal. Set upper limits on four different cross sections.

- Backgrounds are estimated in data from sidebands not to rely on MC.
- Dependent on the parameter configuration the existing limits are improved by up to two orders of magnitude.

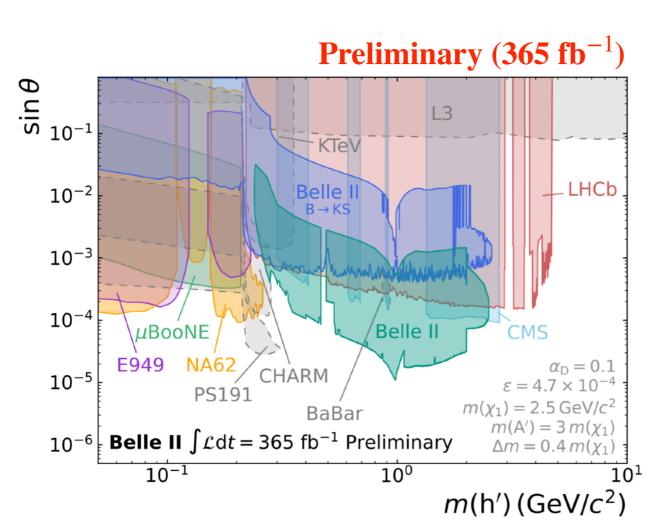


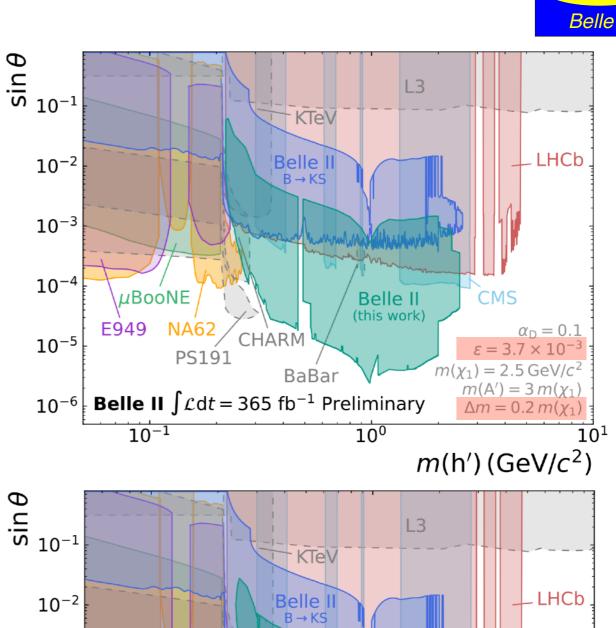


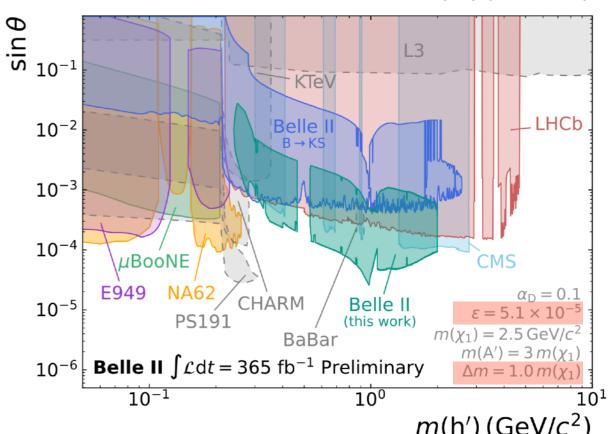
2025/5/19-21 @ U. Pittsburgh



Examples of parameter changes: Keeping the lifetime of  $\chi_2$  at  $c\tau(\chi_2)=1.0$  cm,  $\epsilon$  and  $\Delta m$  are changed.



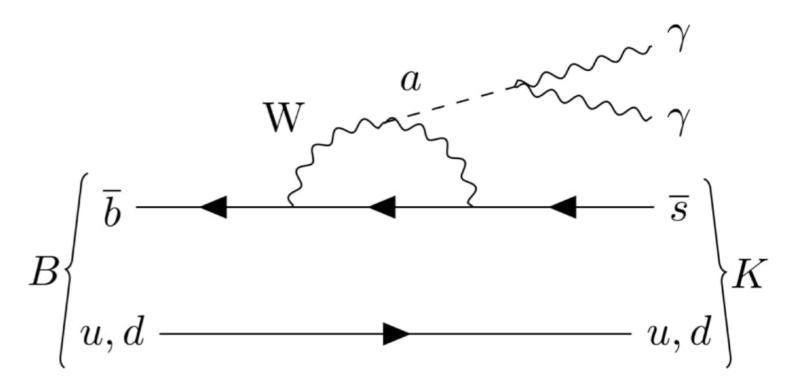




# Search for Axion-like particle in $B \to K^{(*)}a(\to \gamma\gamma)$



- Searching for axion-like particle (ALP, a) in  $B \to K^{(*)}a$  decay. Use 711 fb<sup>-1</sup> of Belle data.
- One of Flavor Changing Neutral Current (FCNC) B decays, extremely suppressed in SM.
- Searching for an ALP coupling to  $W^{\pm}$  bosons in mass region 0.16 4.50 GeV/ $c^2$ . BR( $a \rightarrow \gamma \gamma$ )  $\simeq 100 \%$  for  $m_a \ll m_{W^{\pm}}$ .
- There is a previous search by BaBar experiment using 424 fb<sup>-1</sup>. Use more integrated luminosity and additional kaon modes.

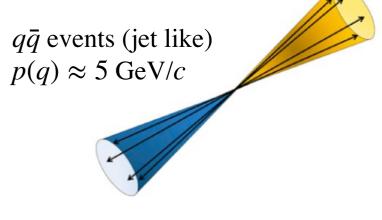


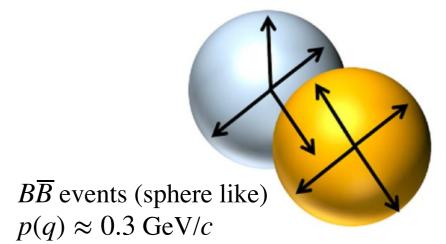
 $K = K_S^0, K^+, K^{*0}, K^{*+}$ 

# Search for Axion-like particle in $B \to K^{(*)}a(\to \gamma\gamma)$



- Strategy: Reconstruct the signal B by combining two photons and kaon.
- Challenges for suppressing background events of  $e^+e^- \rightarrow q\bar{q}$  (called continuum events).
  - ▶ Event shape parameters can suppress background events.
  - ▶ B mesons are at rest in CM frame, while  $q\bar{q}$  pair has significant momenta.
- The kinematic variables of reconstructed B meson are used for cuts.
  - In the CM frame, the beam constraint mass:  $M_{bc} = \sqrt{(E_{\rm beam}/2)^2 - (\vec{p_B})^2}$ and the energy difference:  $\Delta E = E_{\rm beam}/2 - E_B$ .
- Boosted Decision Trees (BDTs) trained by Fox-Wolfram moment 2 and cosine of thrust axes are used for signal extraction.
  - ▶ To reject  $\pi^0$  and  $B \to X_s \gamma$  backgrounds, additional BDTs are trained by calorimeter cluster variables.

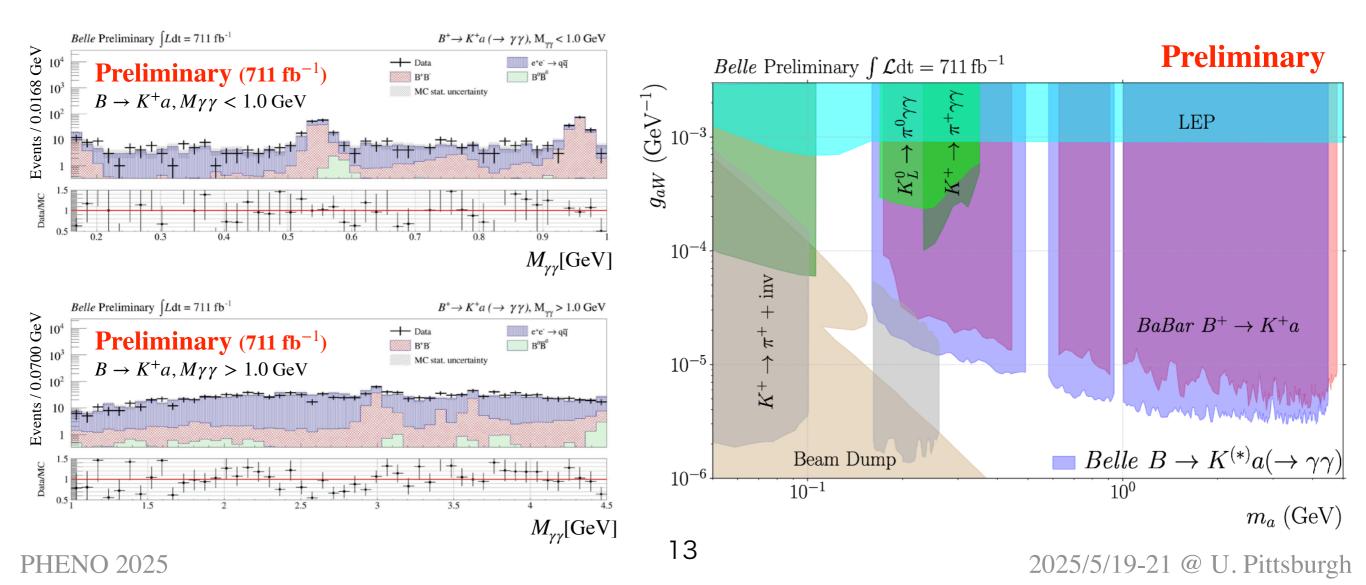




# Search for Axion-like particle in $B \to K^{(*)}a(\to \gamma\gamma)$



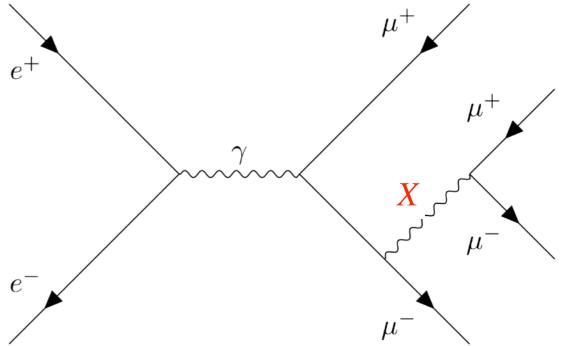
- Results: No evidence for a signal. Set upper limits on  $g_{aW}$ .
- Simultaneous fits on the four kaon modes vetoing peaking SM backgrounds.
  - ▶ Scan over  $M_{\gamma\gamma}$  with steps ~ 8 18 MeV.
  - Three peaking backgrounds corresponding  $\pi^0$ ,  $\eta$ , and  $\eta'$  are excluded.



## Search for a $\mu^+\mu^-$ resonance in four-muon final state



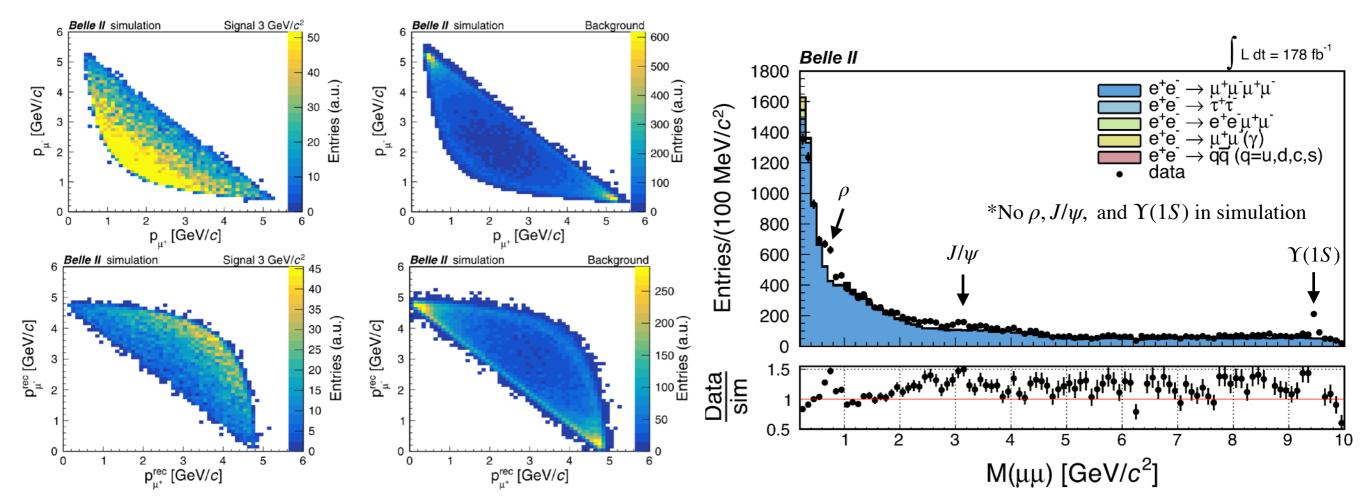
- Searching for dark **Z** boson (Z') and muonphilic scalar in  $e^+e^- \rightarrow \mu^+\mu^- X$  decay. Use 178 fb<sup>-1</sup> of Belle II data.
- The  $L_{\mu}$   $L_{\tau}$  extension of SM gives rise to a new massive and neutral vector boson, Z'.
  - ▶ The Z' couples only to  $\mu$ ,  $\tau$ ,  $\nu_{\mu}$ , and  $\nu_{\tau}$ .
  - It also can be a mediator between SM and dark matter.
- The muonphilic scalar S couples exclusively to muons through a Yukawa-like interaction.
  - ▶ It is primarily proposed as a solution of  $(g-2)_{\mu}$  anomaly.
  - ▶ The interaction is not gauge-invariant under the SM gauge symmetry and requires a high-energy completion.



## Search for a $\mu^+\mu^-$ resonance in four-muon final state



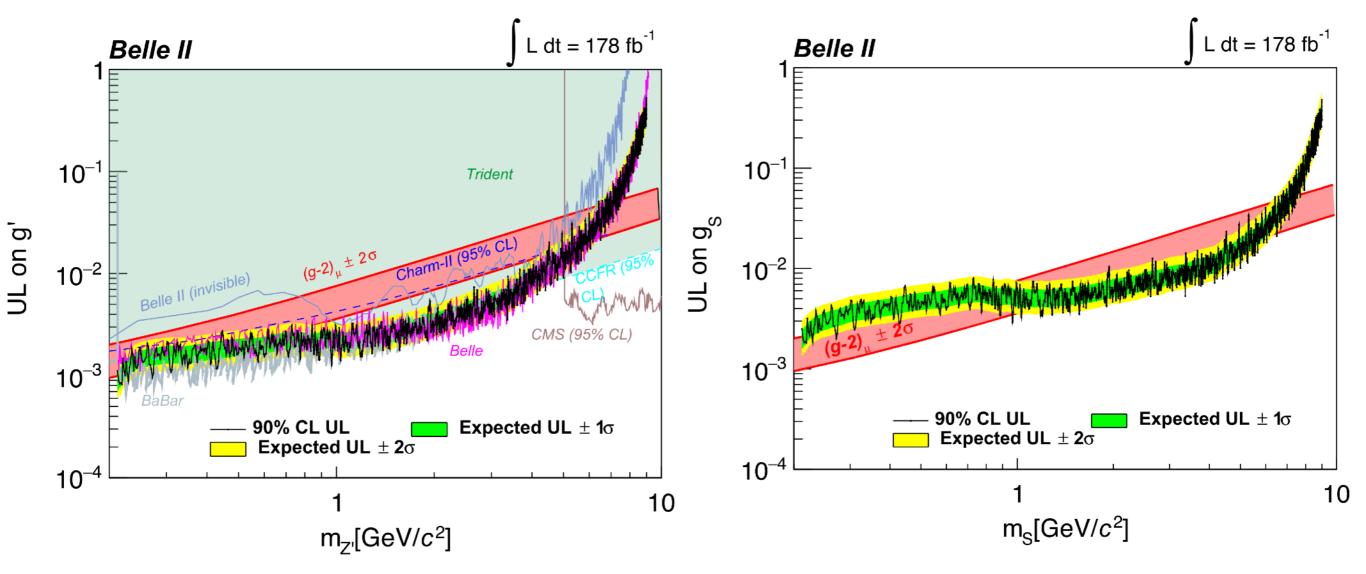
- **Strategy:** Search for 4 tracks combination at a mass  $\sim \sqrt{s}$
- Challenge for reducing the SM background  $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ .
  - ▶ The other background can be rejected by particle identification.
  - Only in low mass region,  $e^+e^- \to \mu^+\mu^-\gamma(\to e^+e^-)$  can be a problem.
- Multilayer Perceptron (MLP) NN for background suppression based on kinematics variables.
  - ▶ Each muon momentum of signal pair, momenta of the signal pair and the "recoil" pair etc... in total, 16 variables.



## Search for a $\mu^+\mu^-$ resonance in four-muon final state



- Results: No evidence for a signal. Set upper limits on the cross sections and branching fractions.
- Limits on g' similar to Belle and BaBar experiments with much lower statistics.
  - ▶ Scan over  $M_{\mu\mu}$  with steps ~ 2 5 MeV.
  - The largest local significance is 3.4  $\sigma$  at  $M_{\mu\mu} = 5.307$  GeV.



### Summary

- Belle II experiment has a unique sensitivity to MeV-GeV dark matter.
  - ▶ Clean environment in a hermetic detector with specific trigger system.
  - ▶ Complimentary to higher energy experiments and beam dump experiments.
  - ▶ World leading results are published with partial Run 1 dataset.
- Many frontiers of improvements.
  - ▶ Run 1 and 2 datasets are being processed.
  - ▶ Optimize and improve the analysis techniques.
  - ▶ Reduce systematic uncertainties.
- And more...
  - ▶ The next run will start this Autumn and more data will be delivered.
  - ▶ Along with more integrated luminosity, more results are expected; Axions (incl. ALPs), dark photons, IDMs, and dark scalars...
  - ▶ Find more details in the Snowmass White paper: <u>arXiv:2207.06307</u>