

# Recent results from Belle II on dark sector searches

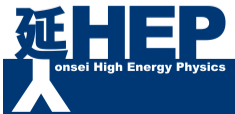
Sungjin Cho (sjcho93@yonsei.ac.kr)

On behalf of Belle and Belle II collaboration

Dec 9-13th, 2024

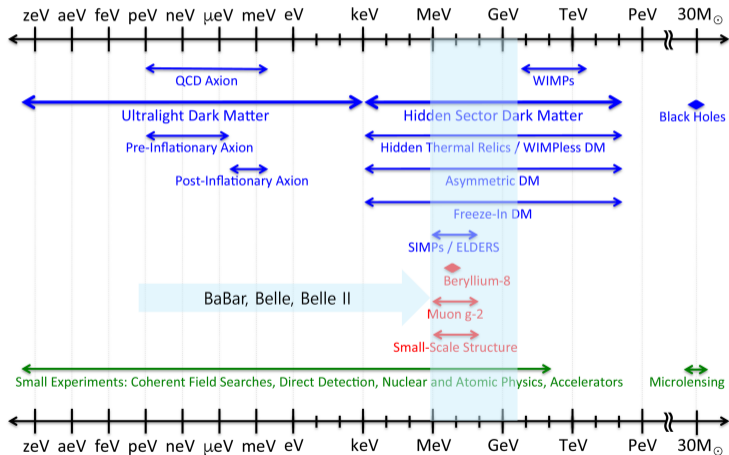
BCVSPIN Conference

Kathmandu, Nepal



# Dark Sector Covered by $e^+e^-$ B-Factories

## Dark Sector Candidates, Anomalies, and Search Techniques



US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

## Dark matter mediators

- Vector portal
  - ▶ Dark photon,  $Z'$
- Pseudoscalar portal
  - ▶ Axions or ALPs
- Scalar portal
  - ▶ Dark Higgs, scalars
- Neutrino portal
  - ▶ Sterile neutrino

# Dark Sector searches in Belle and Belle II

Vector portal Dark Photons,  $Z'$  bosons

- $e^+e^- \rightarrow \mu^+\mu^-Z', Z' \rightarrow \text{invisible}$   
(Belle II : PRL 130, 231801)
- $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$   
(Belle II : PRL 131, 121802)
- $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$   
(Belle II : PRD 019, 112015)

Pseudo-scalar portal Axion Like Particles (ALPs)

- $e^+e^- \rightarrow \gamma a, a \rightarrow \gamma\gamma$   
(Belle II : PRL 125,161806)
- $\tau \rightarrow l\alpha, \alpha \text{ invisible}$   
(Belle II : PRL 130,181803)
- $B^{+ / 0} \rightarrow K^{+ / * 0} S, S \rightarrow x^+ x^-, x = e, \mu, \pi, K$   
(Belle II : PRD 108.L111104)

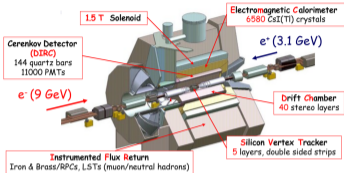
Scalar portal Dark Higgs / Scalars

- $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$   
(Belle : PRD 109, 032002)
- $e^+e^- \rightarrow \mu^+\mu^- + \text{invisible } h'$   
(Belle II : PRL 130, 071804)

Neutrino portal Sterile neutrinos

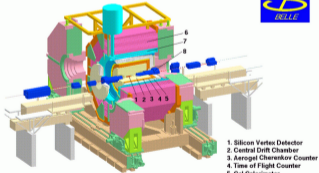
- $\tau \rightarrow \pi N (\rightarrow \mu^+\mu^-\nu\tau)$   
(Belle : PRD 109,L111102)

# Asymmetric $e^+e^-$ B Factories: Concept



BaBar / PEP II

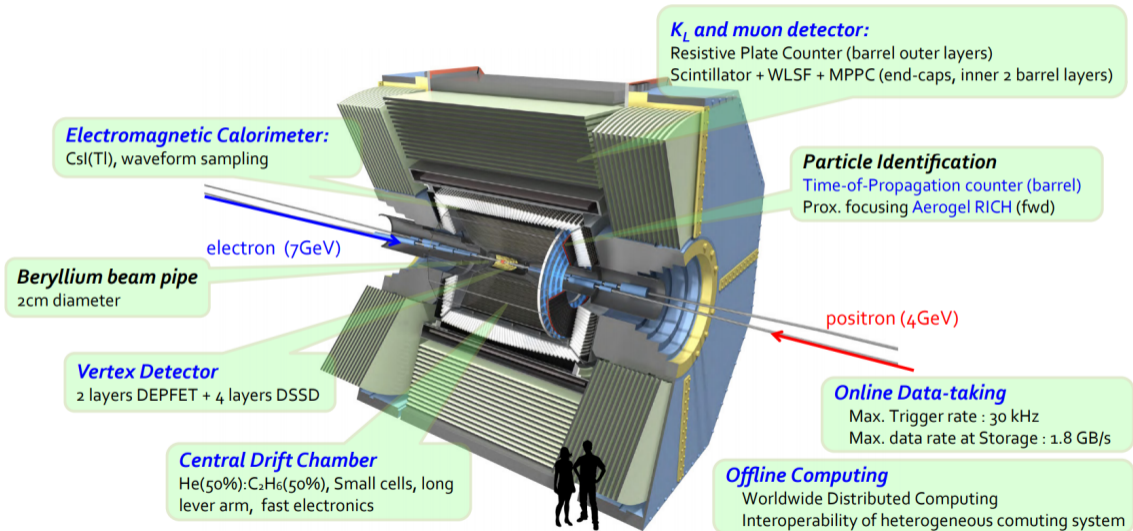
BELLE Detector



Belle / KEKB

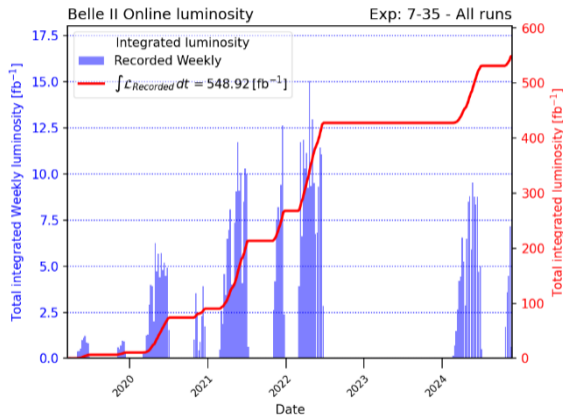
- Mass of B meson is around 5.28 GeV.
  - ▶ B pairs can be generated plentifully using 10.58 GeV  $\Upsilon(4S)$  colliders
- Relatively lower energy  $\rightarrow$  intensity up easily  $\rightarrow$  intensity frontier
- First generation B factory
  - ▶ ARGUS/DORIS II at DESY 1982 - 1992
  - ▶ CLEO/CESR at Cornell 1979 - 2008 (including Cleo-c)
- Next, asymmetric B factory: one side flavor tag, the other side signal
  - ▶ BaBar/PEP-II at SLAC 1999 - 2008
  - ▶ Belle/KEKB at KEK 1999 - 2010
- 2nd generation asymm. B factory: Belle II/SuperKEKB at KEK 2019 -
- Detectors at B-Factories have versatile particle identification and reconstruction abilities.
  - ▶ Dark sector search is one of core projects at B-Factories.

# The Belle II Experiments



# SuperKEKB Luminosity: Current Status

- After SuperKEKB commissioning phases, Physics runs started spring 2019.
- Run 1 ended June 2022.
  - ▶ Peak luminosity at  $L_{peak} = 4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , the world record set on June 22nd, 2022.
  - ▶ Run 1 integrated luminosity at  $\int L_{recorded} dt = 424 \text{ fb}^{-1}$ . (~ Babar, ~ 1/2 Belle sample size)
- Long shutdown 1 (LS1) 2022 – 2023.
- Run 2 started February 2024.
- Integrated luminosity at  $549 \text{ fb}^{-1}$  now.

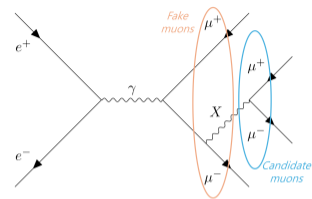


# Merits of Dark Search at $e^+e^-$ B-Factories

- B-Factories are competitive in the light dark matter search from 1 MeV to  $\sim 10$  GeV.
- Background is lower compared to hadron colliders.
- Closed detectors means the coverage is almost  $4\pi$ .
  - ▶ Missing momentum and energy can be a signature of invisible particle(s).
  - ▶ Full event interpretation is possible.
- Neutral particle findings have high efficiencies.
- Dedicated trigger for low-multiplicity is introduced for Belle II.
  - ▶ Low multiplicity signature observation is possible.
  - ▶ Dark particle signatures in B and  $\tau$  decays are available ( $\sigma(b\bar{b}), \sigma(c\bar{c}), \sigma(\tau\bar{\tau}) \sim 1\text{nb}$ ).
  - ▶ Clean environment can compensate for lower production cross-section than LHCb.

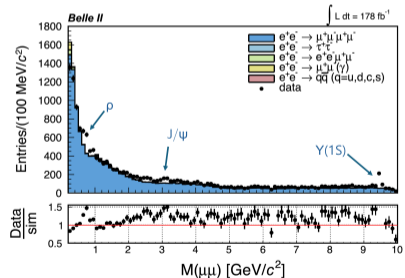
# $\mu^+ \mu^-$ resonance in $e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ @ Belle II $178 \text{ fb}^{-1}$

- Search for process  $e^+ e^- \rightarrow \mu^+ \mu^- X, X \rightarrow \mu^+ \mu^-$ .
- Probing two different models :
  - ▶  $L_\mu - L_\tau$  vector mediator ( $Z$ ) [ $\mathcal{L} = \sum_l \theta g^l \bar{l} \gamma^\mu Z'_\mu$ ] [1]
  - ▶ Muonphilic scalar ( $S$ ) [ $\mathcal{L} \subset g_s S \bar{\mu} \mu$ ] (first time search) [2]
- Targeted luminosity is  $178 \text{ fb}^{-1}$ , which is  $\sim 2\text{-}3$  times less data used by Babar and Belle experiments for the  $Z'$  search.



## Event Selections :

- At least three muons are identified.
- Total charge is zero and  $M(4 \text{ tracks}) \sim \text{beam energy}$ .  
No extra energy is allowed.
- Multi-layer Perceptron (MLP) is applied to suppress background peaks.



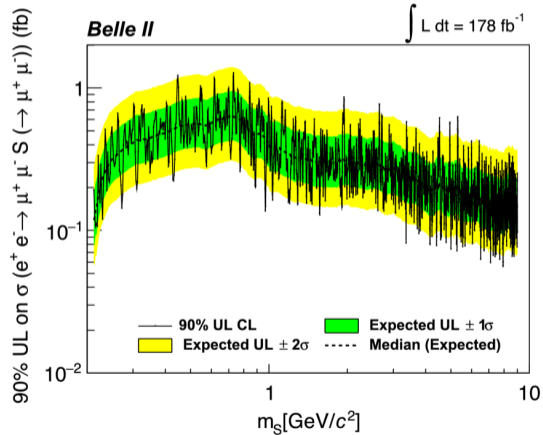
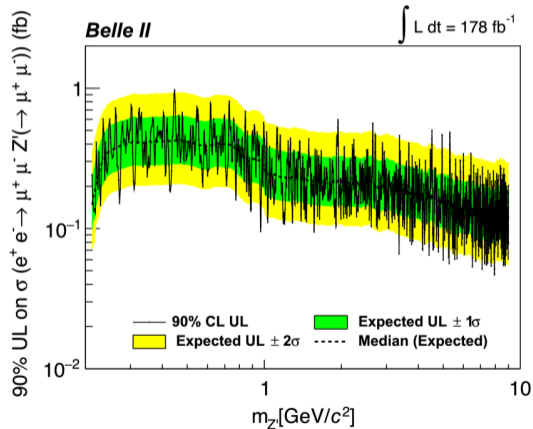
Data MC disagreement mainly due to missing ISR of the used generator

[1] J. High Energ. Phys. 2016, 106 (2016)  
 [2] J. High Energ. Phys. 2022, 129 (2022)



# $\mu^+ \mu^-$ resonance in $e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ @ Belle II $178 \text{ fb}^{-1}$

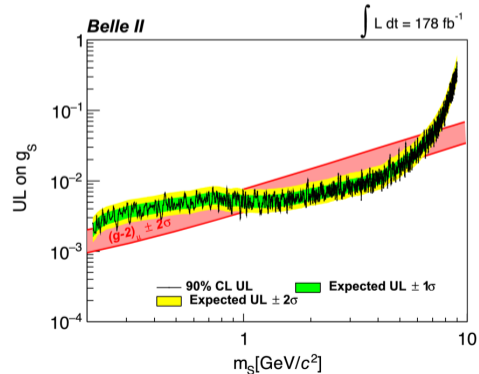
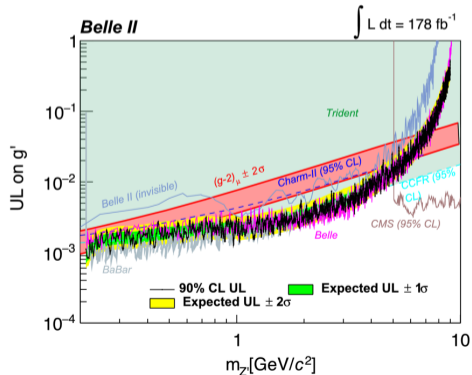
- No significant excess are found in  $178 \text{ fb}^{-1}$
- 90% CL upper limits on the process cross-section are obtained.



Phys. Rev. D. 019, 112015 (2024)

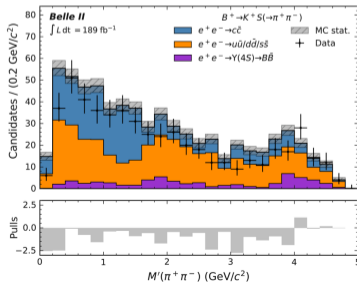
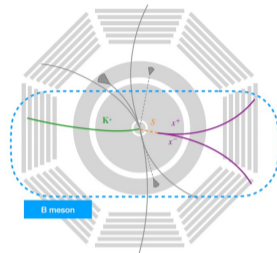
# $\mu^+ \mu^-$ resonance in $e^+ e^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ @ Belle II $178 \text{ fb}^{-1}$

- Cross-section limits are translated into upper limits on the coupling constant for respective hypotheses,
  - ▶  $g'$  for the  $L_\mu - L_\tau$  model and  $g_s$  for the muon-philic dark scalar  $S$  model.
- Almost similar result of BaBar ( $\sim 500 \text{ fb}^{-1}$ ) and Belle ( $\sim 600 \text{ fb}^{-1}$ ) with  $178 \text{ fb}^{-1}$ .
- First 90% CL upper limits for the muonphilic dark scalar (S) model.

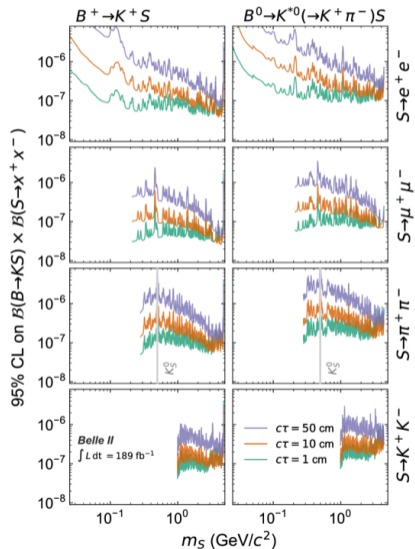


# Long-lived scalar ( $S$ ) in B decays @ Belle II $189 \text{ fb}^{-1}$

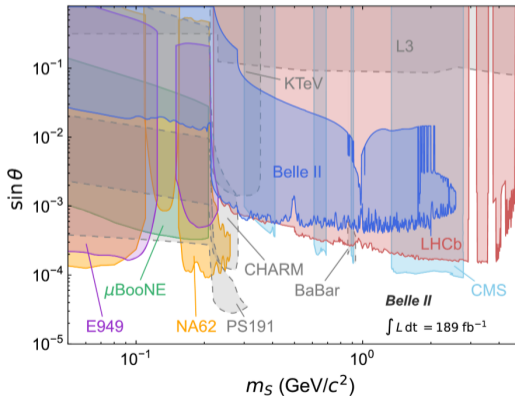
- Search parameters are mass of dark scalar  $S$  and mixing angle  $\theta$  between the SM Higgs and  $S$ .
- search for long lived spin-0 mediator  $S$  in B decays.
  - ▶  $(e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B})$ .
  - ▶ First Belle II long-lived spin-0 ( $S$ ) particle search.
- Channels studied :  $B^+ \rightarrow K^+ S, B^0 \rightarrow K^{*0} S$ .
- $S$  is assumed to decay to a pair of charged tracks.
  - ▶  $S \rightarrow x^+ x^-, x = e, \mu, \pi, K$ .
- $S$  is assumed to live long:  $S$  decay vertex is far from the beam interaction point.



# Long-lived scalar ( $S$ ) in B decays @ Belle II $189 \text{ fb}^{-1}$

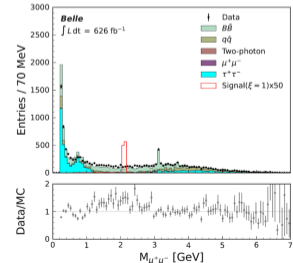
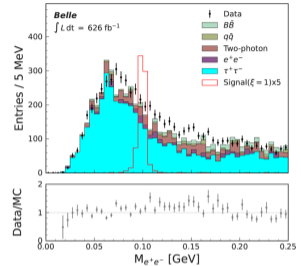
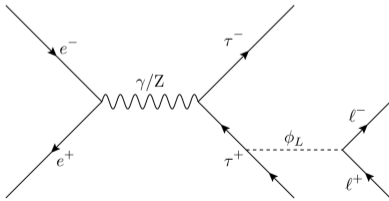


- No observed excess.
- 95% CL exclusion region is obtained.
- Limits on branching fractions and mixing angle  $\sin\theta$ .
- First measurements for exclusive hadronic states.

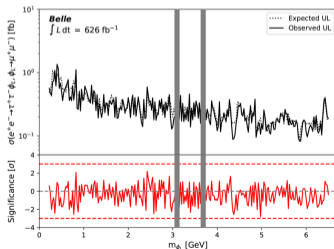
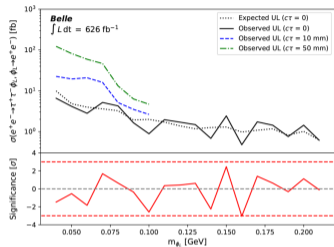


# Leptophilic scalar ( $\phi_L$ ) in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ @ Belle 626 fb<sup>-1</sup>

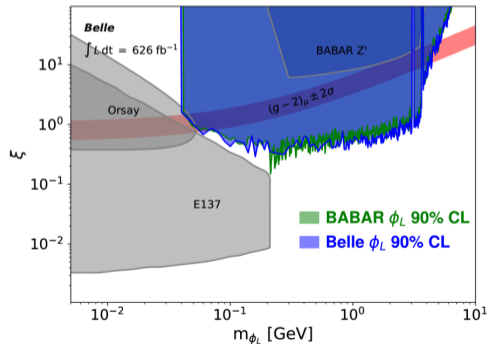
- Belle on 626 fb<sup>-1</sup>: search for leptophilic dark scalar ( $\phi_L$ ) in 2 tau (1-prong decay) + 2 lepton ( $e$  or  $\mu$ ) events.
- 1-prong: one charged track + neutrals.
- This mode can affect  $(g-2)_\mu$  results.
- A major background is  $e^+e^- \rightarrow \tau^+\tau^-$ .
- Radiative Bhabha (photon decaying to two muons) are removed by cuts on missing energy and its angle.
- Boosted Decision Tree (GradientBoostingClassifier,scikit) is used to suppress backgrounds.



# Leptophilic scalar ( $\phi_L$ ) in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ @ Belle 626 fb $^{-1}$

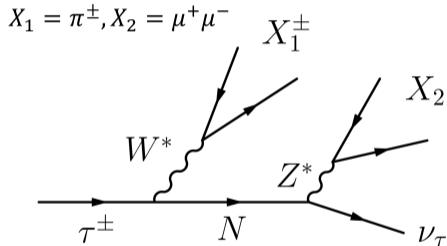


- No significant excess found in 626 fb $^{-1}$ .
- 90% CL upper limits on  $\sigma(e^+e^- \rightarrow \tau^+\tau^-\phi_L(\rightarrow l^+l^-))$  and flavor-independent coupling to leptons  $\xi$ .
- Limits are on average 19% more constraining than BaBar.
- More searches on the full Belle sample is continuing.



# Heavy Neutral Leptons (HNL) in $\tau$ decays at Belle 915 fb $^{-1}$

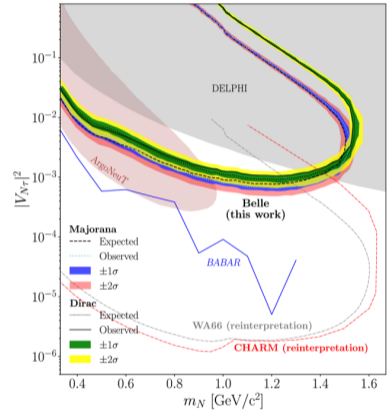
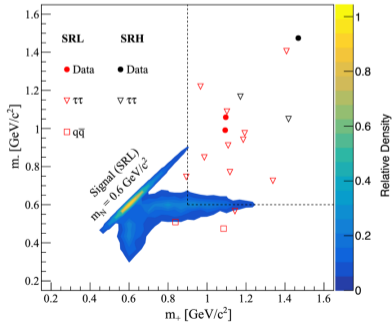
- Heavy sterile neutrinos  $N$  appears in many extensions of the SM
  - ▶  $N$  mixes with  $\nu_{SM}$
  - ▶  $N$  long-lived for small values of  $N$ - $\nu_{SM}$  coupling
- Limits on  $|V_{N\tau}|^2$  are much weaker than limits on  $|V_{Ne}|^2, |V_{N\mu}|^2$
- Process:  $e^+e^- \rightarrow \tau^+\tau^-$ 
  - ▶ Signal side:  $\tau^- \rightarrow \pi^- N; N \rightarrow \mu^+\mu^-\nu_\tau$
  - ▶  $N \rightarrow \mu^+\mu^-\nu_\tau$  forms a displaced vertex (DV)  $> 15$  cm from the beam axis.
  - ▶ Tag side:  $\tau^+ \rightarrow \pi^+\bar{\nu}_\tau / \pi^+\pi^0\bar{\nu}_\tau / l^+\nu_l\bar{\nu}_\tau$
- Main background from  $K^0 \rightarrow \pi^+\pi^-$  vetoed
- Signal region divided in
  - ▶ Low-mass region (SLR):  $m_{DV} < 0.42$  GeV
  - ▶ High-mass region (SHR):  $m_{DV} > 0.52$  GeV



Phys. Rev. D 109, L111102 (2024)

# Heavy Neutral Leptons (HNL) in $\tau$ decays at Belle 915 fb $^{-1}$

- Despite the neutrino in the final state, the constraints of the signal decay allows reconstruction of full kinematics with a two-fold ambiguity on  $m_N$  ( $m_+$  and  $m_-$ )
- SRL and SRH have only 0 and 1 events respectively.
- Since no significant excess is observed for 915 fb $^{-1}$  (4S + 5S combined), 95% CL upper limits on  $|V_{N\tau}|^2$  are set





# Summary

- $e^+e^-$  B factories provide unique opportunities to study dark sector.
  - ▶ Belle and Belle II are actively producing search results in the field.
  - ▶ No significant signal observed yet,  
but we set various exclusion region on dark sector candidates.
- SuperKEKB has achieved  $L_{peak} = 4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ,  
the world record at the end of Run 1 on June 22nd, 2022.
  - ▶ The SuperKEKB and Belle II are in the full mode for physics data taking.
- Belle II started Run 2 this year (2024).
  - ▶ There will be new search results beyond the Standard Model with the upcoming data,  
especially in the Dark Sector.