



Der Wissenschaftsfonds.

# Dark Sector Searches at Belle II

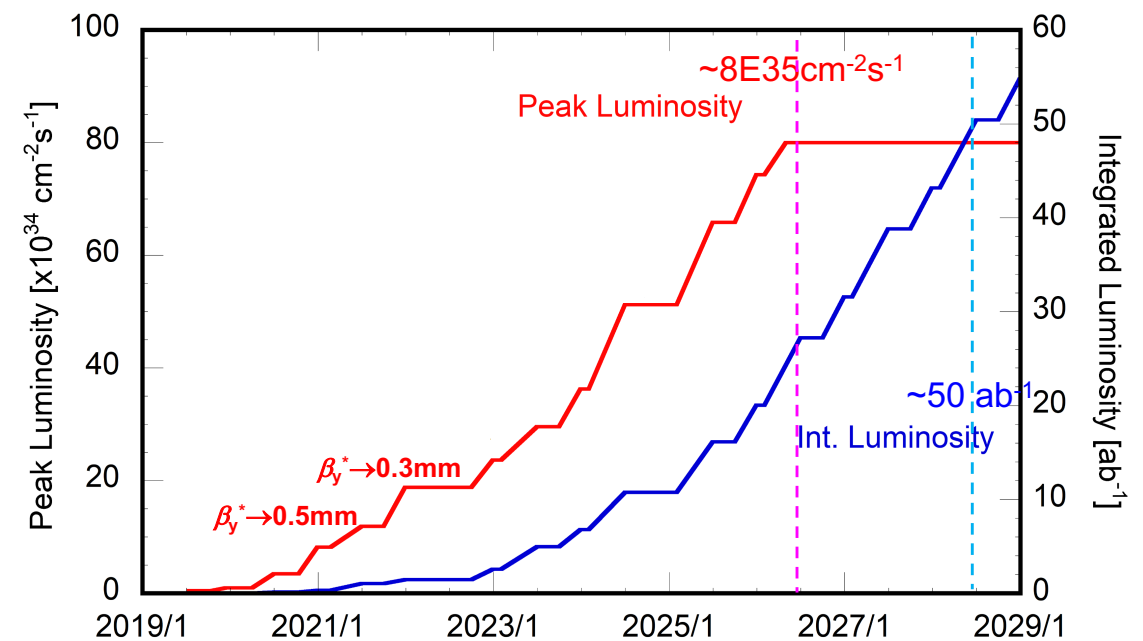
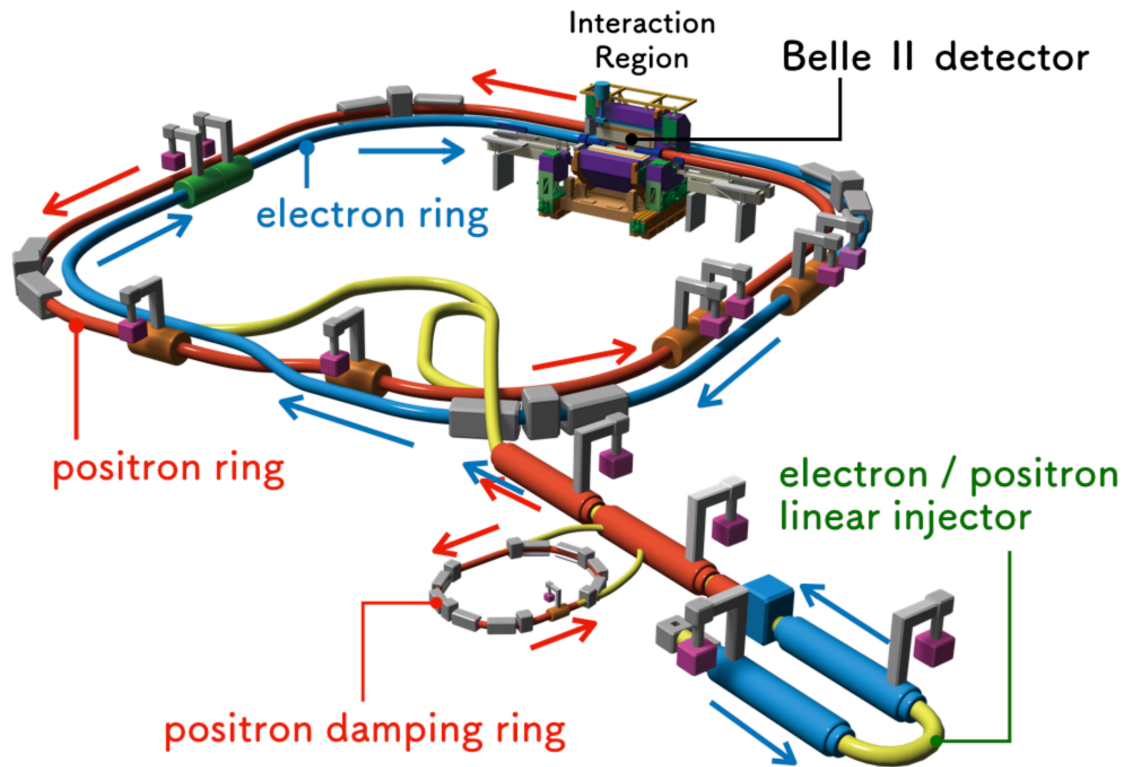
Michel Bertemes, HEPHY Vienna  
World Summit on Exploring the Dark Side of the Universe  
12/03/2020



# Belle II and SuperKEKB



# SuperKEKB



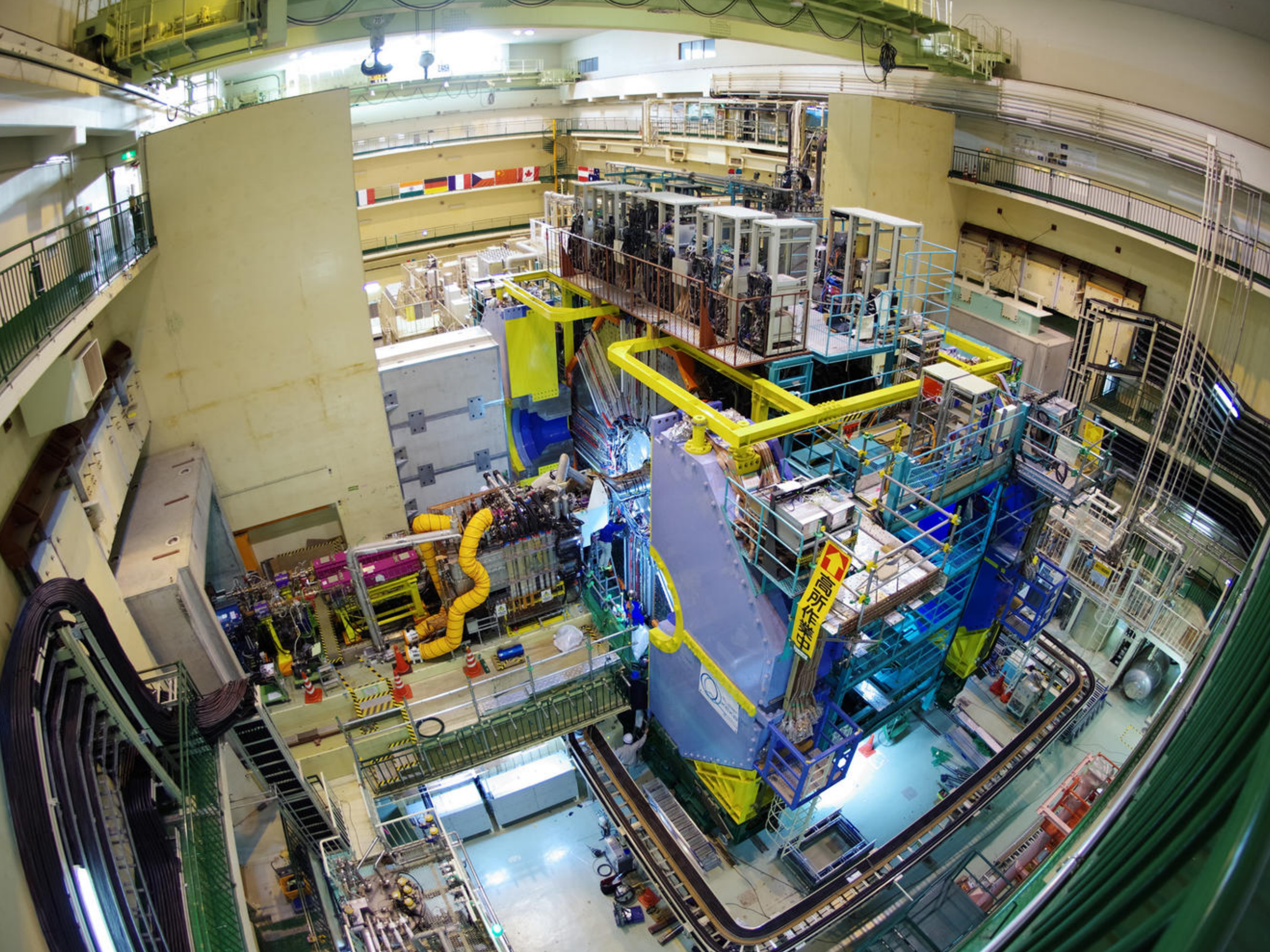
**→ 40 times higher luminosity**

**2x higher beam currents  
20x smaller beam spot**

- super  $B$ -factory, located in Tsukuba, Japan
- asymmetric  $e^+e^-$  collider ( $e^-$  at 7 GeV,  $e^+$  at 4 GeV,  $\langle\beta_y\rangle \approx 0.284$ )
- commissioning run from Feb to Jul 2018
- regular operations started in Mar 2019
- operated around 10.58 GeV ( $=m_{\Upsilon(4S)}$ )
- design luminosity  $8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$



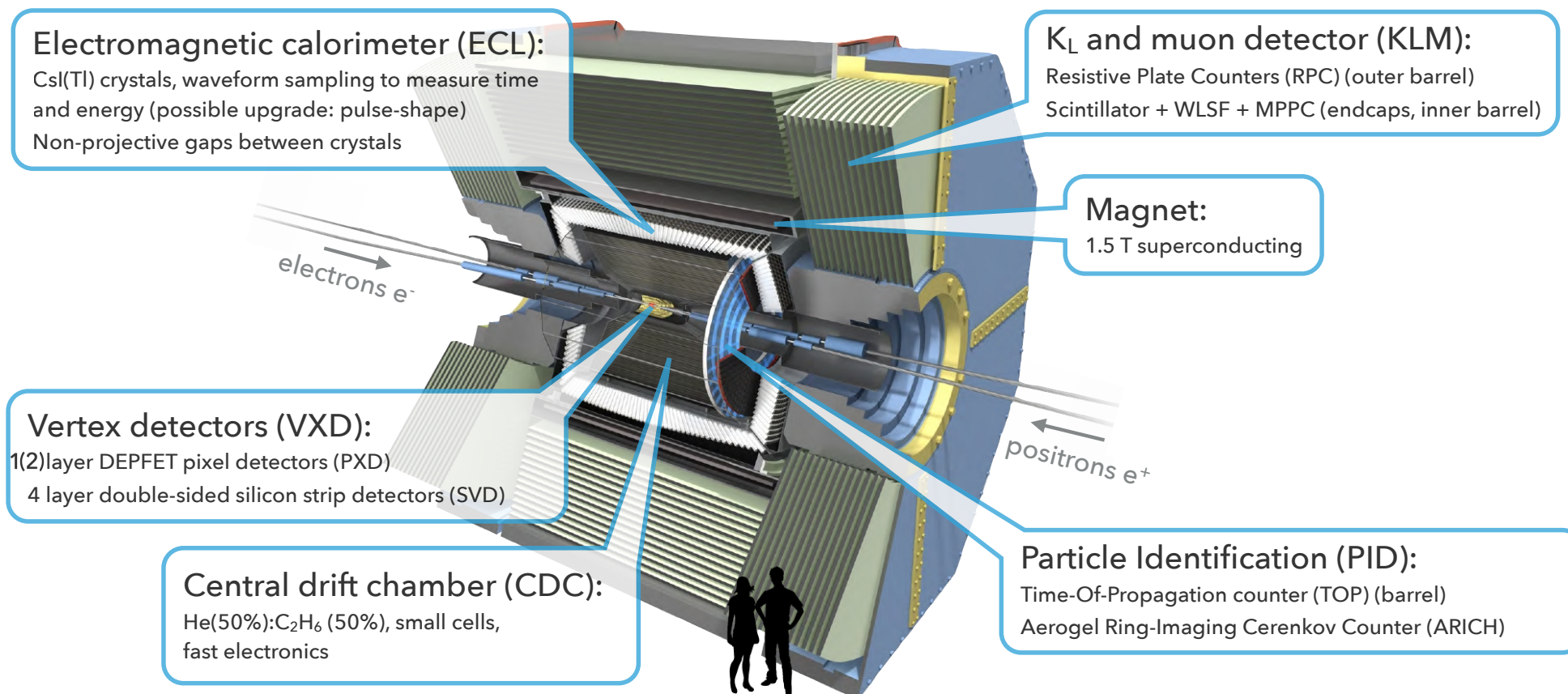
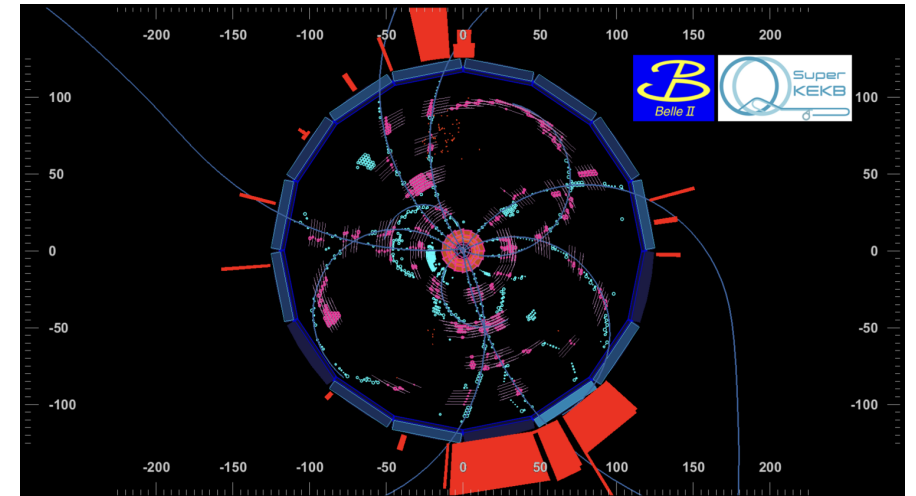






# Belle II

- $0.5 \text{ fb}^{-1}$  collected during commissioning run in 2018
- $10.5 \text{ fb}^{-1}$  collected in 2019
- plan to collect 50 times more data than Belle
- rich physics program:  $B$  and  $D$  physics, quarkonium,  $\tau$ , low mass dark sector, ...





→ first physics paper!

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## High Energy Physics - Experiment

# Search for an invisibly decaying $Z'$ boson at Belle II in $e^+e^- \rightarrow \mu^+\mu^-(e^\pm\mu^\mp)$ plus missing energy final states

Belle II Collaboration: I. Adachi, P. Ahlburg, H. Aihara, N. Akopov, A. Aloisio, N. Anh Ky, D. M. Asner, H. Atmacan, T. Aushev, V. Aushev, T. Aziz, V. Babu, S. Baehr, P. Bambade, Sw. Banerjee, V. Bansal, M. Barrett, J. Baudot, J. Becker, P. K. Behera, J. V. Bennett, E. Bernieri, F. U. Bernlochner, M. Bertemes, M. Bessner, S. Bettarini, F. Bianchi, D. Biswas, A. Bozek, M. Bračko, P. Branchini, R. A. Briere, T. E. Browder, A. Budano, L. Burmistrov, S. Bussino, M. Campajola, L. Cao, G. Casarosa, C. Cecchi, D. Červenkov, M.-C. Chang, R. Cheaib, V. Chekelian, Y. Q. Chen, Y.-T. Chen, B. G. Cheon, K. Chilikin, K. Cho, S. Cho, S.-K. Choi, S. Choudhury, D. Cinabro, L. Corona, L. M. Cremaldi, S. Cunliffe, T. Czank, F. Dattola, E. De La Cruz-Burelo, G. De Nardo, M. De Nuccio, G. De Pietro, R. de Sangro, M. Destefanis, S. Dey, A. De Yta-Hernandez, F. Di Capua, Z. Doležal, I. Domínguez Jiménez, T. V. Dong, K. Dort, D. Dossett, S. Dubey, S. Duell, G. Dujany, S. Eidelman, M. Eliachevitch, J. E. Fast, T. Ferber, D. Ferlewicz, G. Finocchiaro, S. Fiore, A. Fodor, F. Forti, B. G. Fulsom, E. Ganiev, M. Garcia-Hernandez, R. Garg, V. Gaur, A. Gaz, A. Gellrich, J. Gemmler, T. Geßler, R. Giordano, A. Giri, B. Gobbo, R. Godang, P. Goldenzweig, B. Golob et al. (261 additional authors not shown)

(Submitted on 24 Dec 2019 (v1), last revised 25 Feb 2020 (this version, v2))

Theories beyond the standard model often predict the existence of an additional neutral boson, the  $Z'$ . Using data collected by the Belle II experiment during 2018 at the SuperKEKB collider, we perform the first searches for the invisible decay of a  $Z'$  in the process  $e^+e^- \rightarrow \mu^+\mu^-Z'$  and of a lepton-flavor-violating  $Z'$  in  $e^+e^- \rightarrow e^\pm\mu^\mp Z'$ . We do not find any excess of events and set 90% credibility level upper limits on the cross sections of these processes. We translate the former, in the framework of an  $L_\mu - L_\tau$  theory, into upper limits on the  $Z'$  coupling constant at the level of  $5 \times 10^{-2} - 1 M_{Z'} \leq 6 \text{ GeV}/c^2$ .

Comments: 9 pages, 5 figures + supplemental materials. Accepted for publication in Physical Review Letters  
Subjects: High Energy Physics - Experiment (hep-ex)  
Report number: Belle II Preprint 2019-002, KEK Preprint 2019-55,  
Cite as: arXiv:1912.11276 [hep-ex]  
(or arXiv:1912.11276v2 [hep-ex] for this version)



# Invisible Z'





# Invisible $Z'$

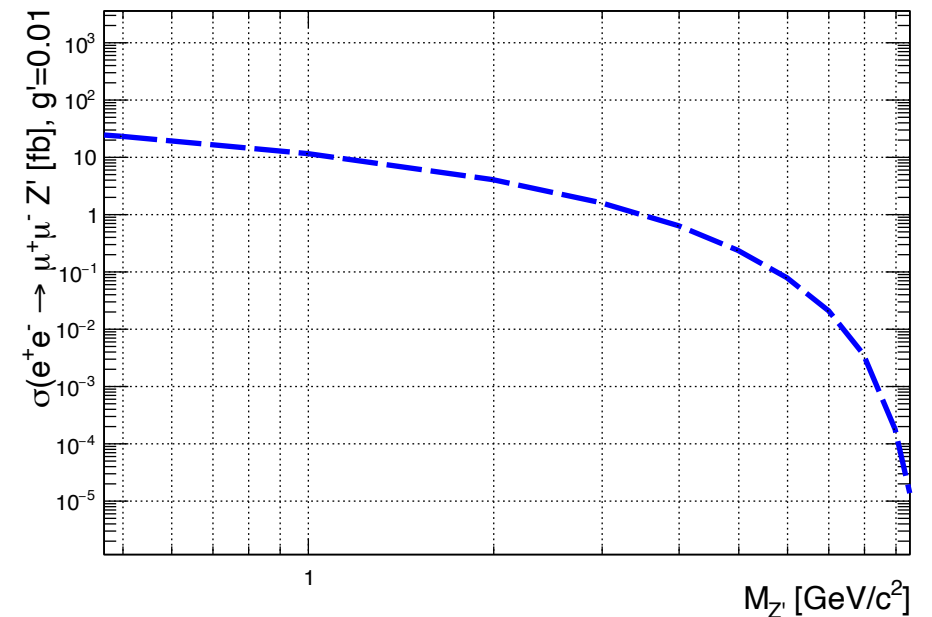
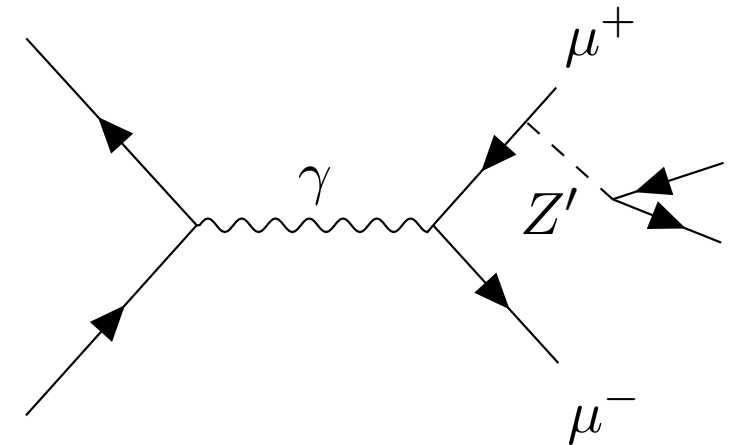
- extend SM by adding a  $U(1)'$  group
- new massive gauge boson  $Z'$  couples only to leptons of 2<sup>nd</sup> and 3<sup>rd</sup> generation
- $Z'$  coupled to  $L_\mu - L_\tau$  via  $g'$
- focus on invisible  $Z'$  decay produced with a pair of muons
- invisible decay channel explored for the first time

**arXiv:1609.04026**  
**arXiv:1403.2727**

$$\begin{aligned}
 M_{Z'} < 2M_\mu &\implies BF[Z' \rightarrow \text{invisible}] = 1, \\
 2M_\mu < M_{Z'} < 2M_\tau &\implies BF[Z' \rightarrow \text{invisible}] \simeq 1/2, \\
 M_{Z'} > 2M_\tau &\implies BF[Z' \rightarrow \text{invisible}] \simeq 1/3.
 \end{aligned}$$

$$\begin{aligned}
 &\text{if } M_{Z'} > 2M_\chi \\
 &BF(Z' \rightarrow \chi\bar{\chi}) = 1
 \end{aligned}$$

$$\mathcal{L} = \sum_\ell \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell$$



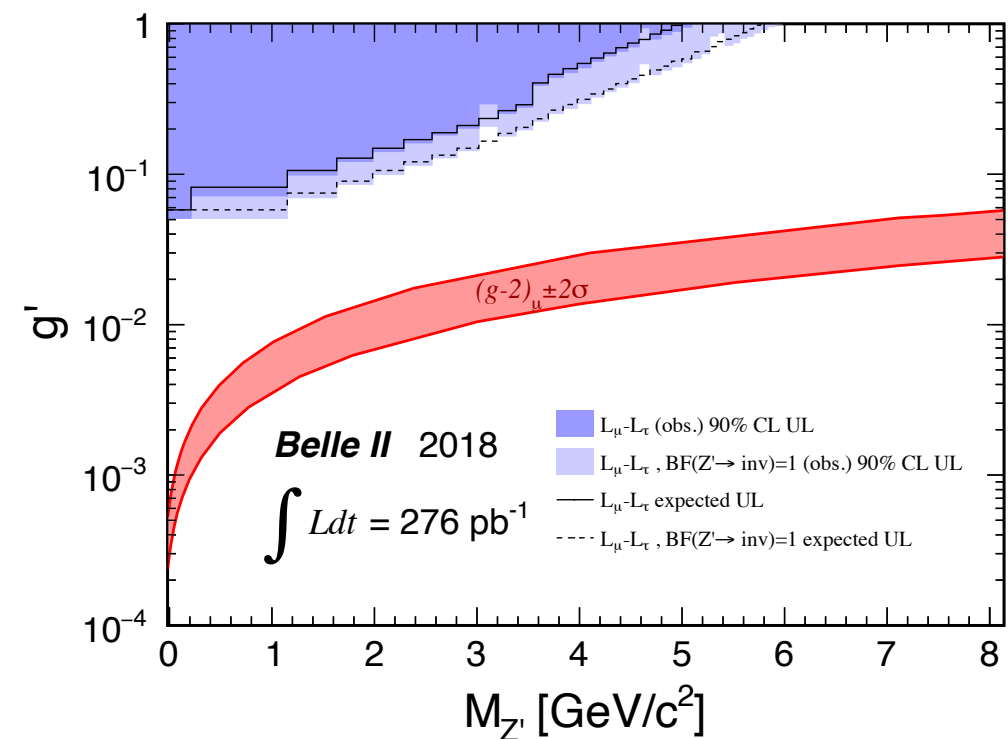
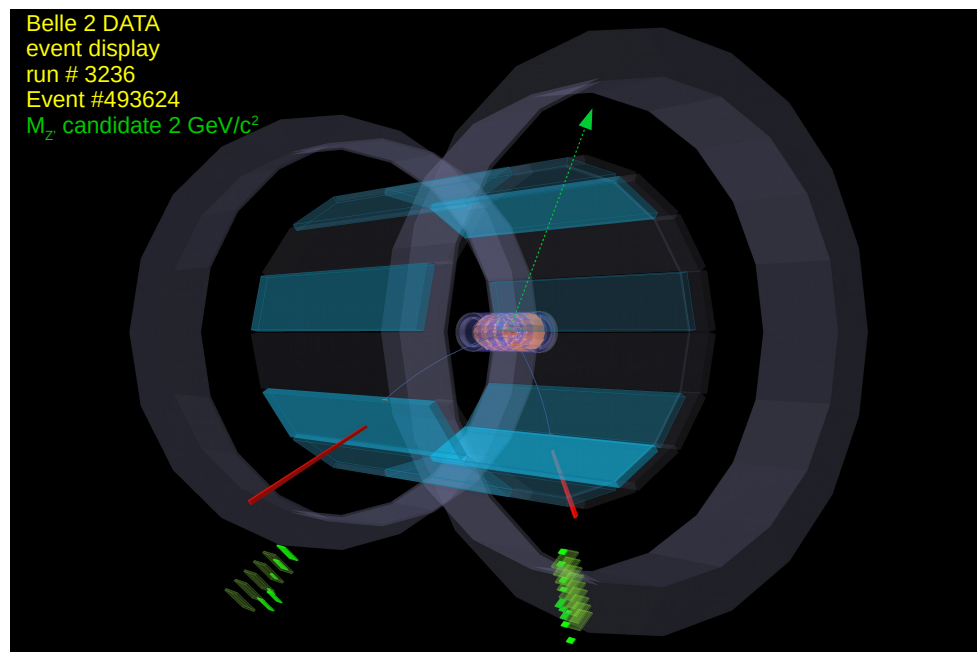
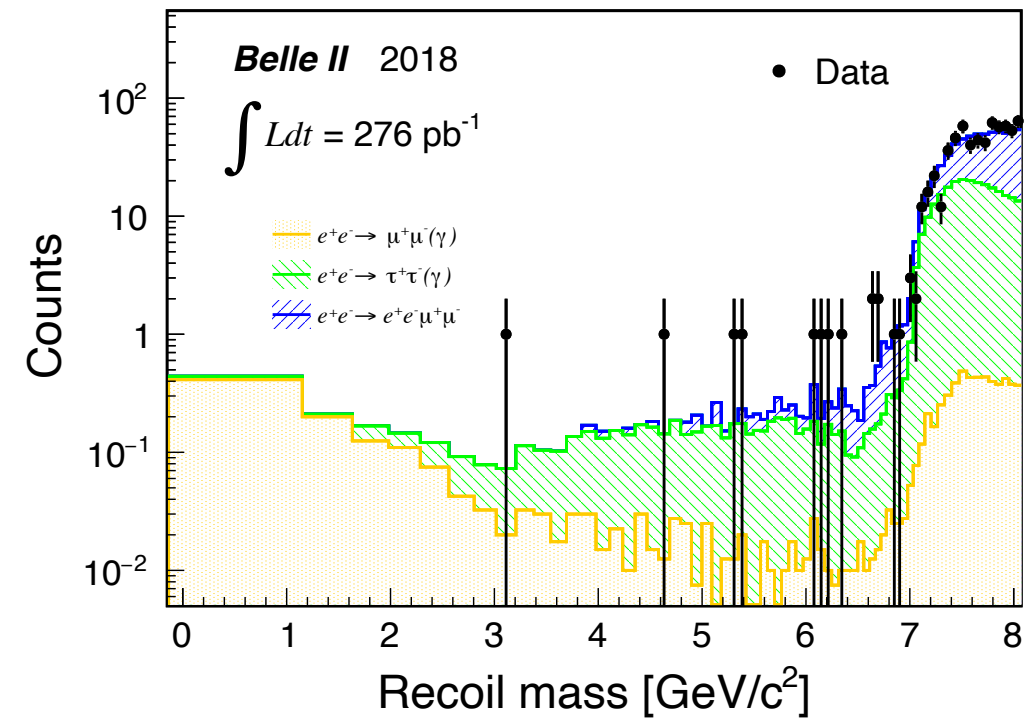
- ★ may serve as mediator between SM and DS
- ★ may explain  $(g-2)_\mu$
- ★ may address anomalies in  $b \rightarrow s\mu^+\mu^-$





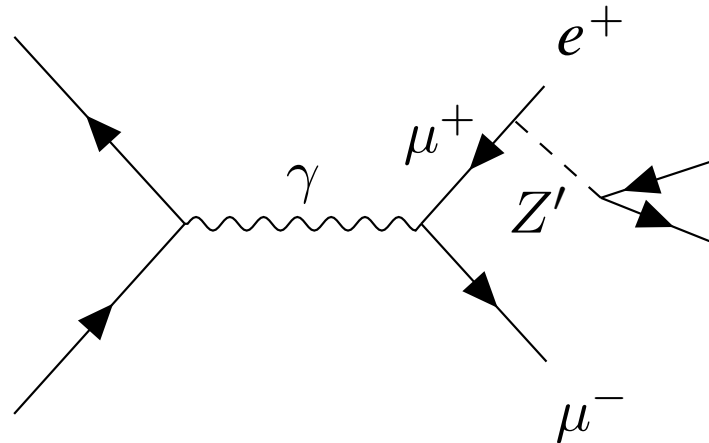
# Invisible $Z'$

- reconstruct recoiling mass against  $\mu\mu$ -pair, require nothing else to be in rest of event
- look for a peak in recoil mass distribution
- main bkg arise from QED processes:
  - $\mu^+\mu^-(\gamma)$
  - $\tau^+\tau^-(\gamma), \tau \rightarrow \mu\nu$
  - $\mu^+\mu^-e^+e^-$

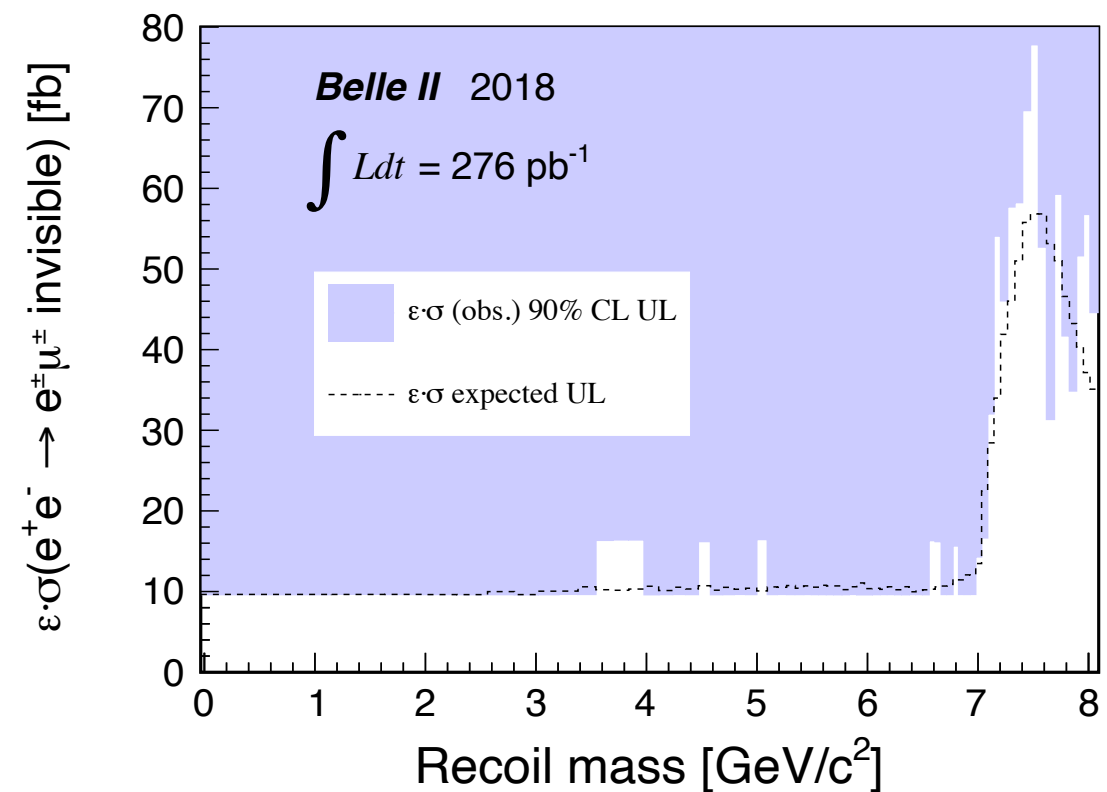
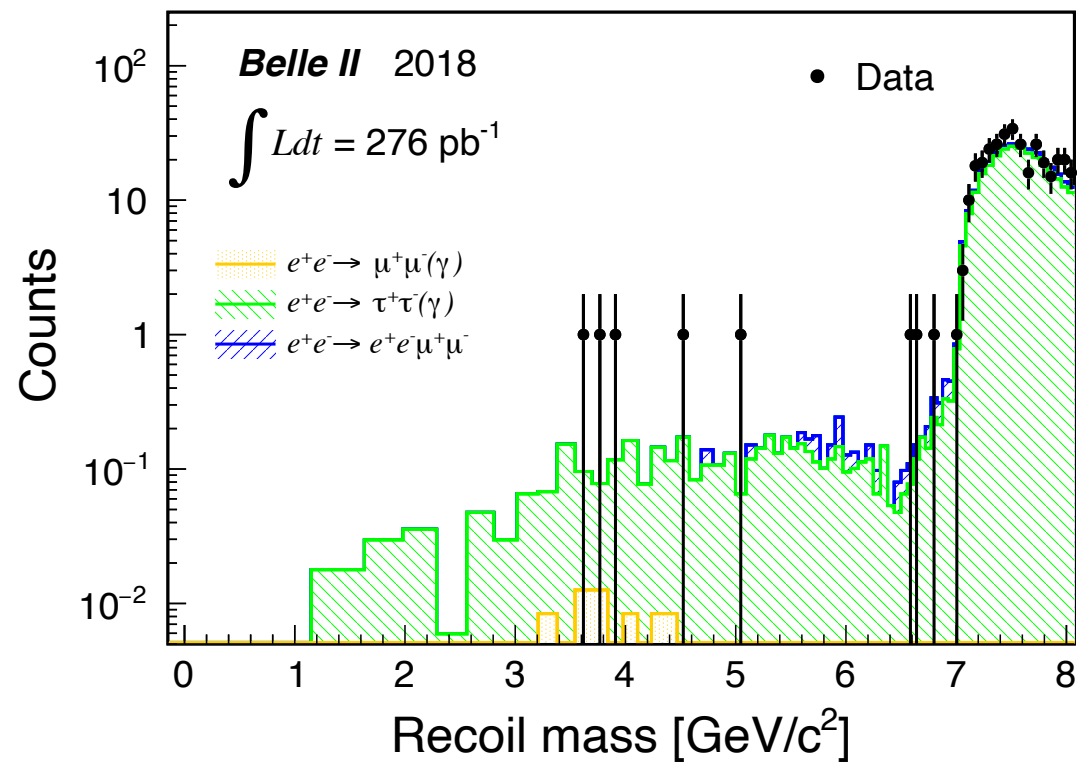




# Invisible $Z'$ - LFV

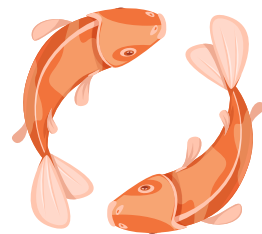


- look for LFV  $Z'$  that couples to  $e\mu$
- model-independent search with same selection criteria
- included in same publication





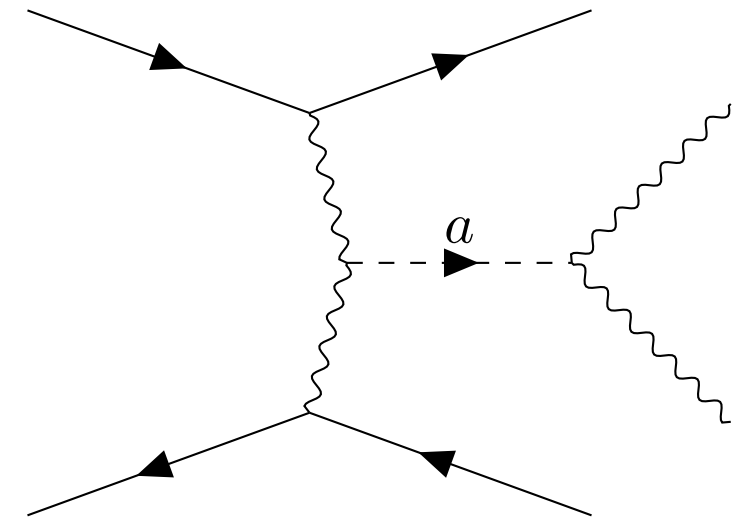
# ALPs





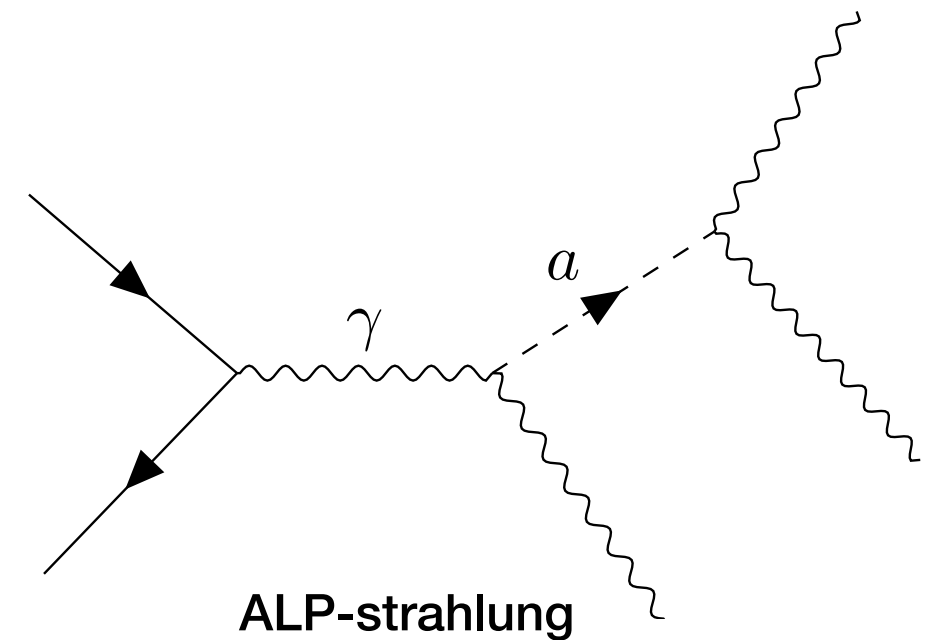
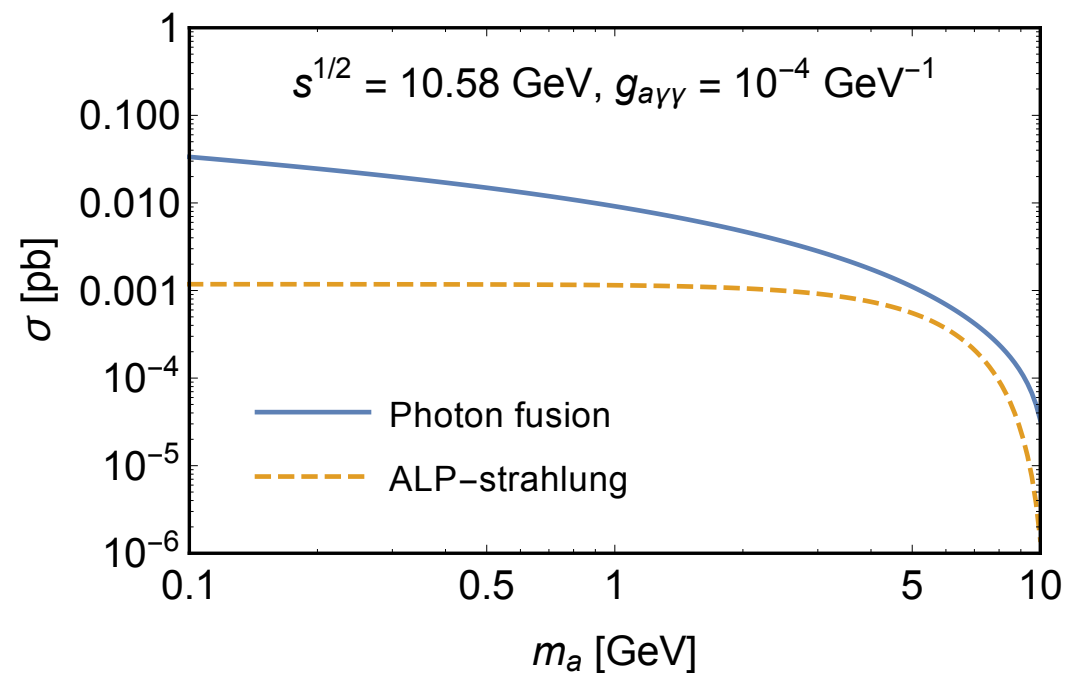
# ALPs

- axion-like particles are pseudoscalar particles that couple to bosons and appear in different extensions to the SM
- coupling and mass of ALPs are taken to be independent
- simplest approach at Belle II is via two photon coupling
  - photon-fusion, high QED background
  - ALP-strahlung, most promising channel



Photon fusion

[arXiv:1709.00009](https://arxiv.org/abs/1709.00009)



ALP-strahlung

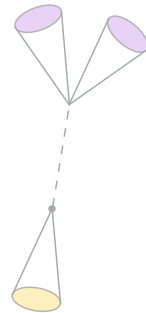




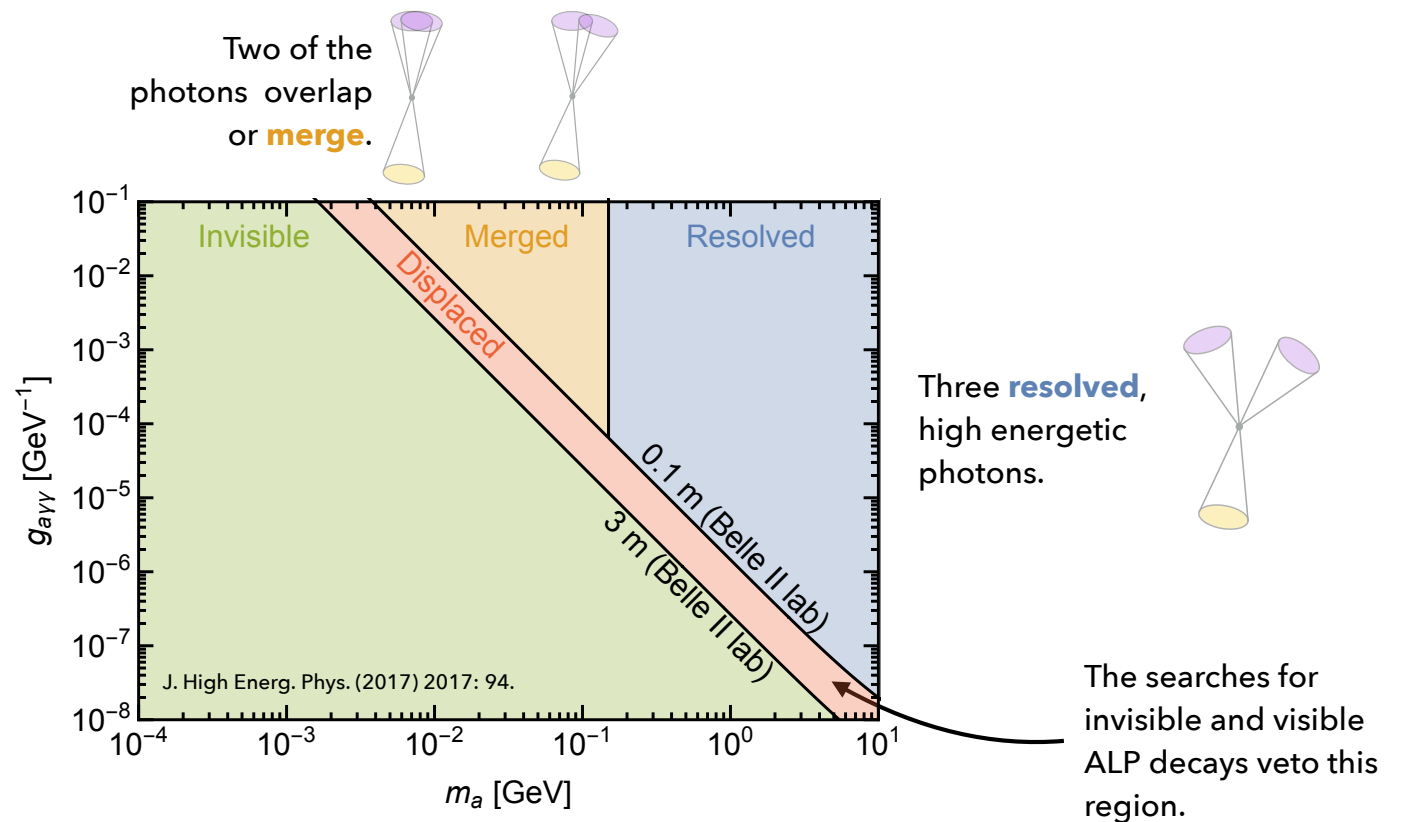
# ALPs

- different topologies according to ALP mass and coupling
- search for 3 photons with energies summing up to beam energy and no tracks in event
- look for peak in di-photon and recoil mass
- bkg:

- $\gamma(\gamma)$
- $e^+e^-(\gamma)$
- $P\gamma, P=\pi^0/\eta/\eta', P\rightarrow\gamma\gamma$

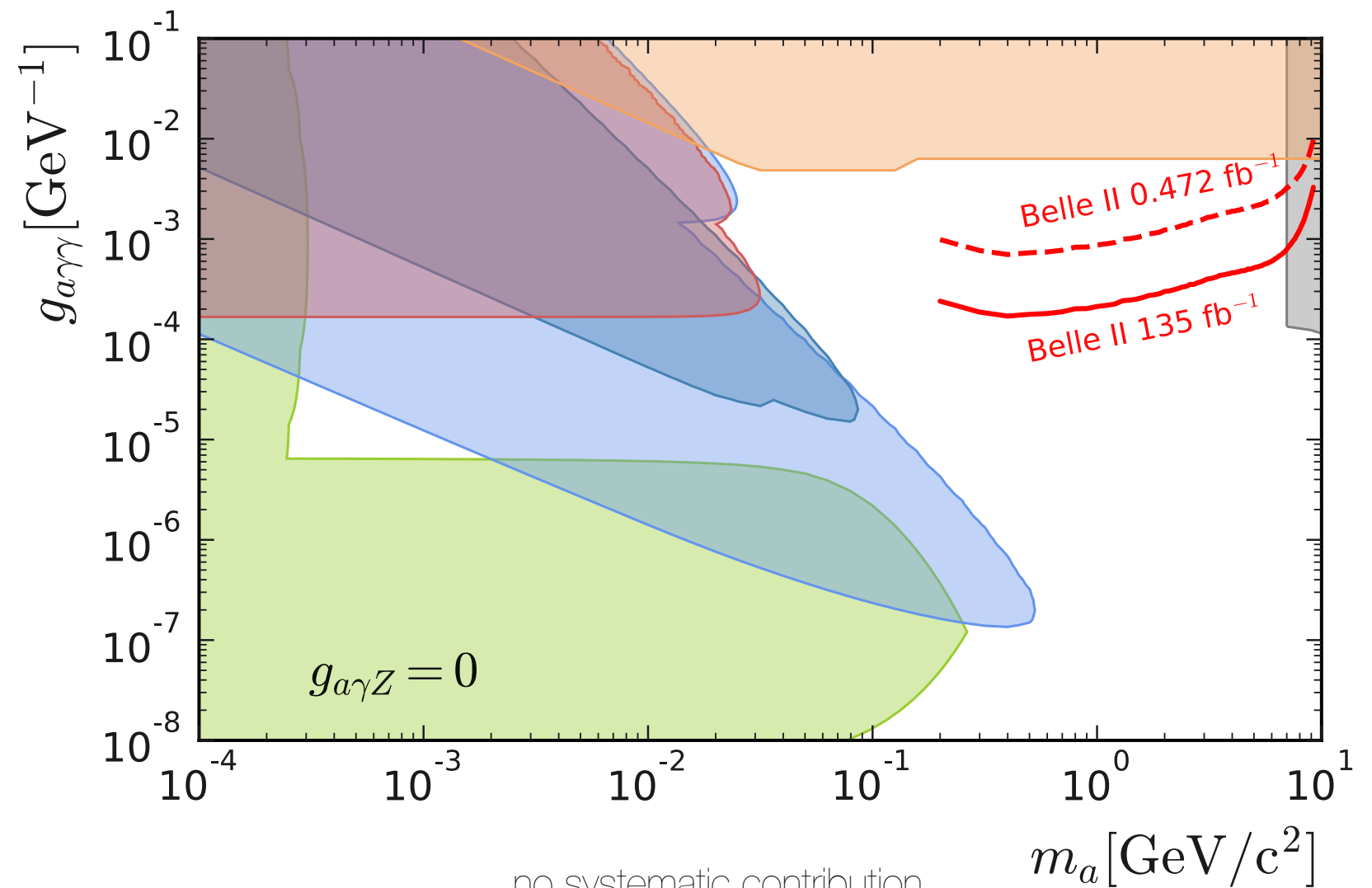


ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.



# ALPs

- Belle II can be competitive with Phase 2 dataset
- results expected (very) soon



no systematic contribution  
only dominant  $\gamma\gamma(\gamma)$  bkg  
assumption of no  $\gamma\gamma$  trigger veto in barrel for  
135fb<sup>-1</sup> projection



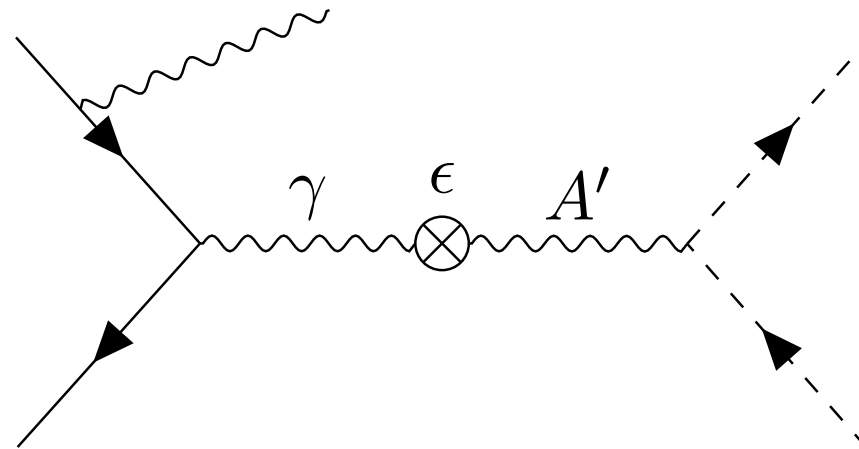


# Dark Photon



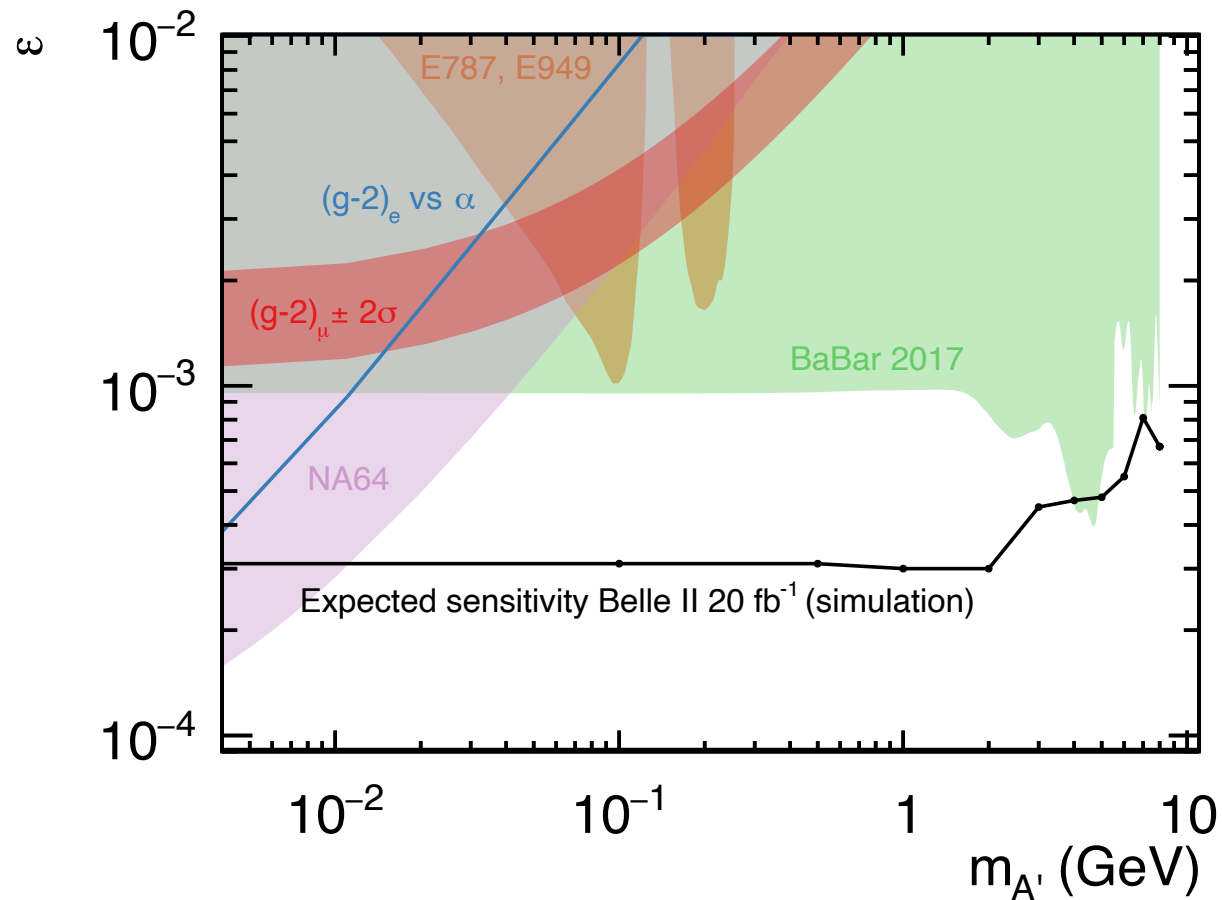
# Dark Photon

- dark photon can couple to SM photon via kinetic mixing parameter  $\epsilon$
- consider on-shell  $A'$  decays, different experimental signatures according to  $m_{A'}$ 
  - if  $A'$  is the lightest DS particle, decay into SM, peak in invariant mass of decay products
  - if  $A'$  is not the lightest DS particle, decay into DM, mono-chromatic ISR photon
- explore invisible decay first,  $A' \rightarrow \chi_1 \chi_2$



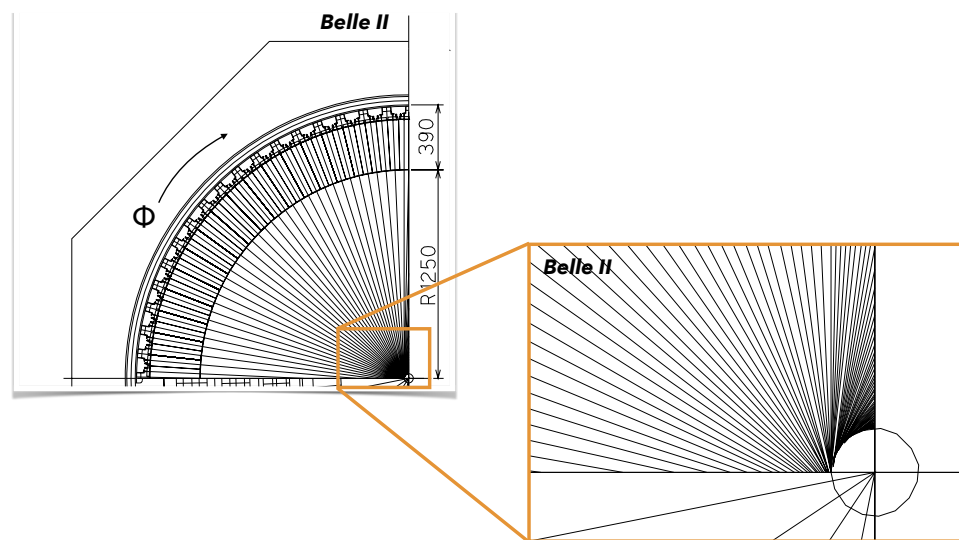


# Dark Photon



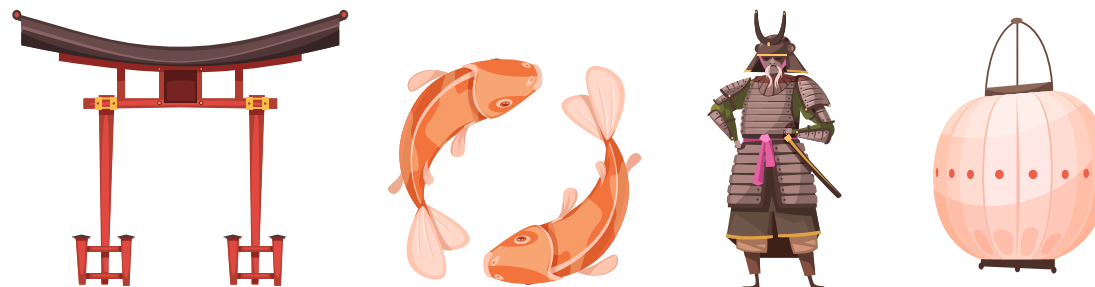
$$E_\gamma = \frac{s - m_{A'}^2}{2\sqrt{s}}$$

- require one ISR photon and nothing else in the event
- needs a single photon trigger (not available in Belle, 10% of data in BaBar)
- bkg:
  - $\Upsilon(\gamma)$
  - $e+e-\gamma(\gamma)$
  - cosmoics
- advantages over BaBar
  - no projective cracks in ECL
  - smaller boost and larger calorimeter
  - KLM veto



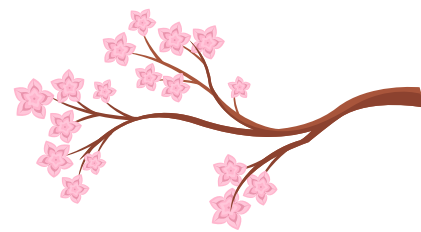
# Conclusion

- broad and active program of DS physics at Belle II
- available phase-space is probed with many different models
- further analysis include Higgsstrahlung, LLP, ... (some target ICHEP)
- first results published
- much more to come





# Backup



# What about a Dark Higgs?

arXiv:1501.06795

- extend SM by adding a  $U(1)$  group
- new minimal model includes dark photon ( $A'$  boson), coupled to SM  $\mathbf{y}$  via kinetic mixing parameter  $\epsilon$
- introduce in analogy to SM a spontaneous symmetry breaking mechanism of  $U(1)$  with new particle, dark Higgs  $h'$
- $e^+e^- \rightarrow A'h'$  (Higgsstrahlung), distinguish different signatures according to mass hypothesis
  - $m_{h'} > 2m_{A'}$ ,  $h'$  decays to  $A'$  pair, six charged particle final state, investigated by BaBar and Belle
  - $m_{h'} < m_{A'}$ ,  $h'$  has large lifetime to escape detection, 2 charged particle final state plus missing energy, only investigated by KLOE

