



# Dark sector searches at $e^+e^-$ colliders

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*Snowmass RF-6 kickoff meeting*

# Outline

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- Projects: Belle II, BESIII
- Mediators:
  - Vector
  - Scalar
  - Neutrino
  - Axion-like particles
- Long-lived / invisible particles
- *Not a complete survey of all possible analyses.*

# LOIs

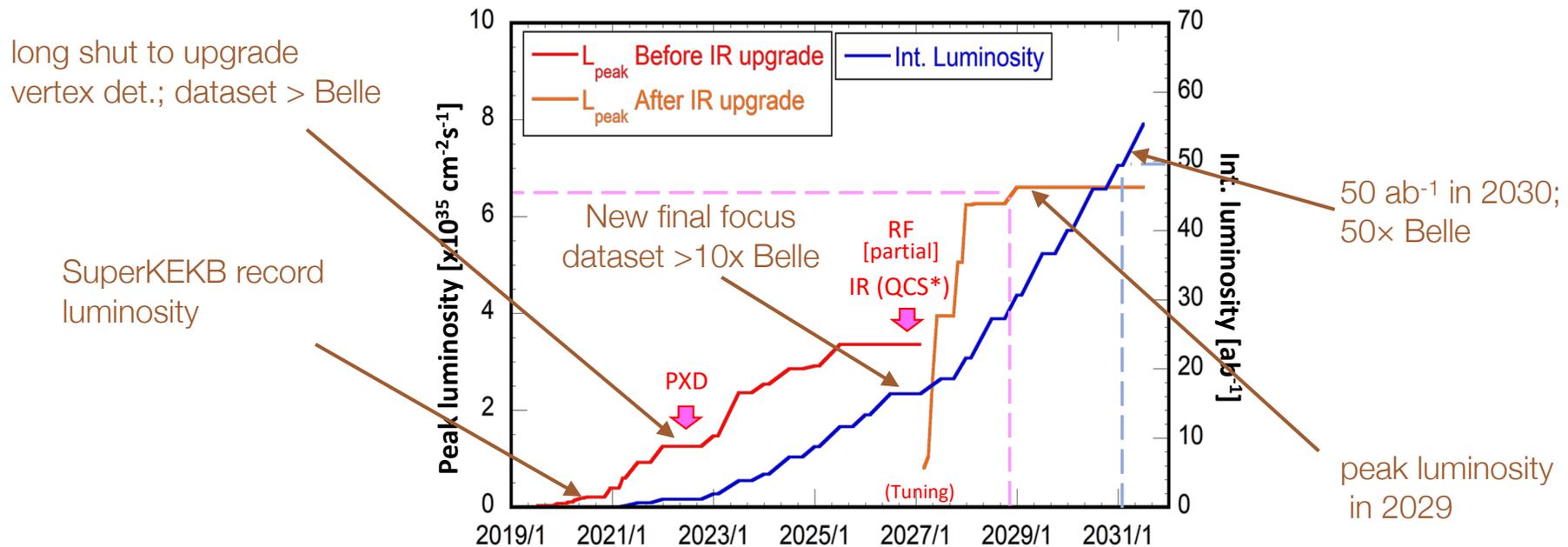
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- I know of two in preparation:
  - “Dark sector studies at Belle II”, Belle II collaboration
  - “Long lived particles at Belle II”, S. Dreyer, T. Ferber, A. Filimonova, C. Hearty, S. Longo, R. Schaefer, K. Trabelsi, S. Westhoff, and J. Zupan
- This presentation also uses material from BESIII, including “Future Physics Programme of BESIII”, Chinese Physics C Vol. 44, No. 4 (2020) 040001

# Projects

# Belle II

- Upgrade of Belle, located at the SuperKEKB  $e^+e^-$  collider at KEK, Tsukuba, Japan. Will search for deviations from the Standard Model in a wide range of final states.
  - asymmetries (CP violation), rare decays, forbidden decays, direct production of new particles.



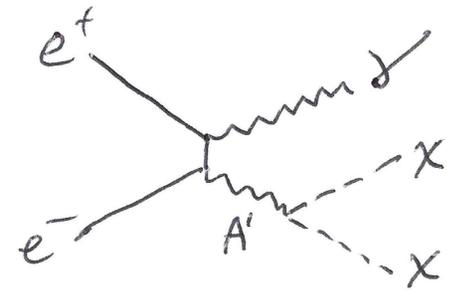
# BESIII

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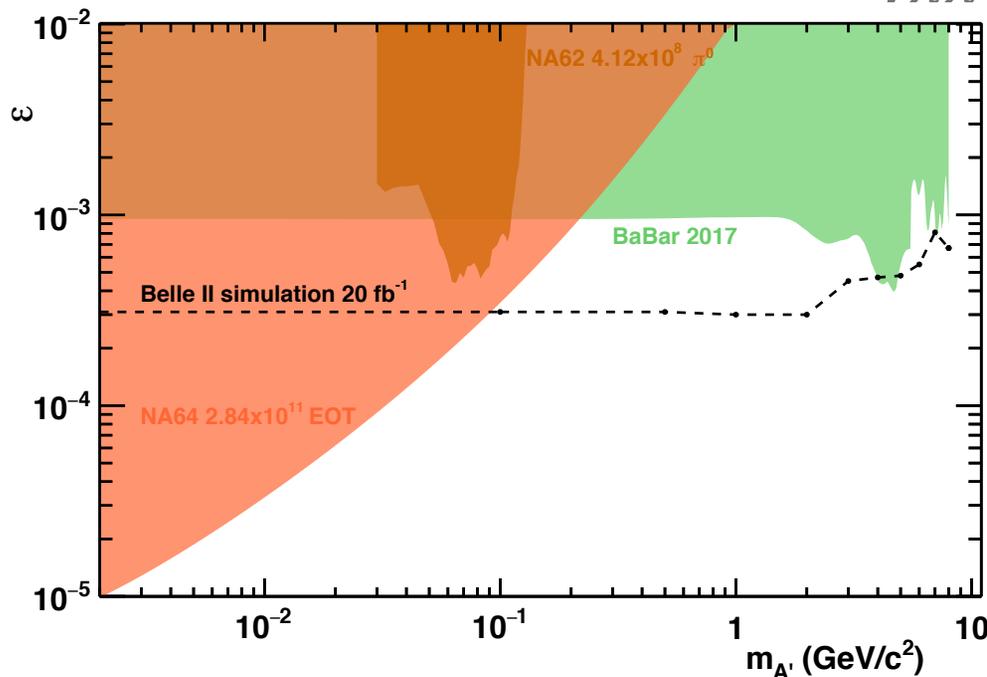
- BESIII has recorded  $30 \text{ fb}^{-1}$  of data at the BECP-II  $e^+e^-$  collider since 2009. Includes  $10^{10} \text{ J}/\psi$ .
- Main physics focus is hadronic physics, including charm, charmonium, and XYZ states.
- Plan is to collect  $56 \text{ fb}^{-1}$  more data over the next 10 years, with some detector upgrades. In particular:
  - $\psi(3686)$   $0.67 \text{ fb}^{-1}$  (0.45 billion)  $\rightarrow$   $4.5 \text{ fb}^{-1}$  (3.0 billion)
  - $\psi(3770)$   $2.9 \text{ fb}^{-1}$   $\rightarrow$   $20 \text{ fb}^{-1}$

# Vector mediator

# Invisible decays of the dark photon $A'$ : “single photon” analysis



- Monoenergetic photon, if  $A'$  is on shell.  
- offshell case  $e^+e^- \rightarrow \gamma\chi\chi$  is difficult.

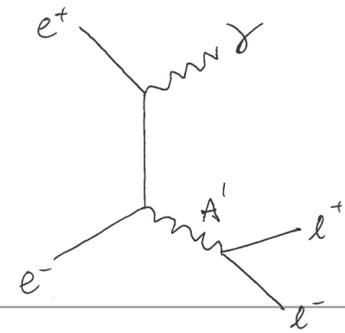


BaBar collab, PRL 119, 131804 (2017)

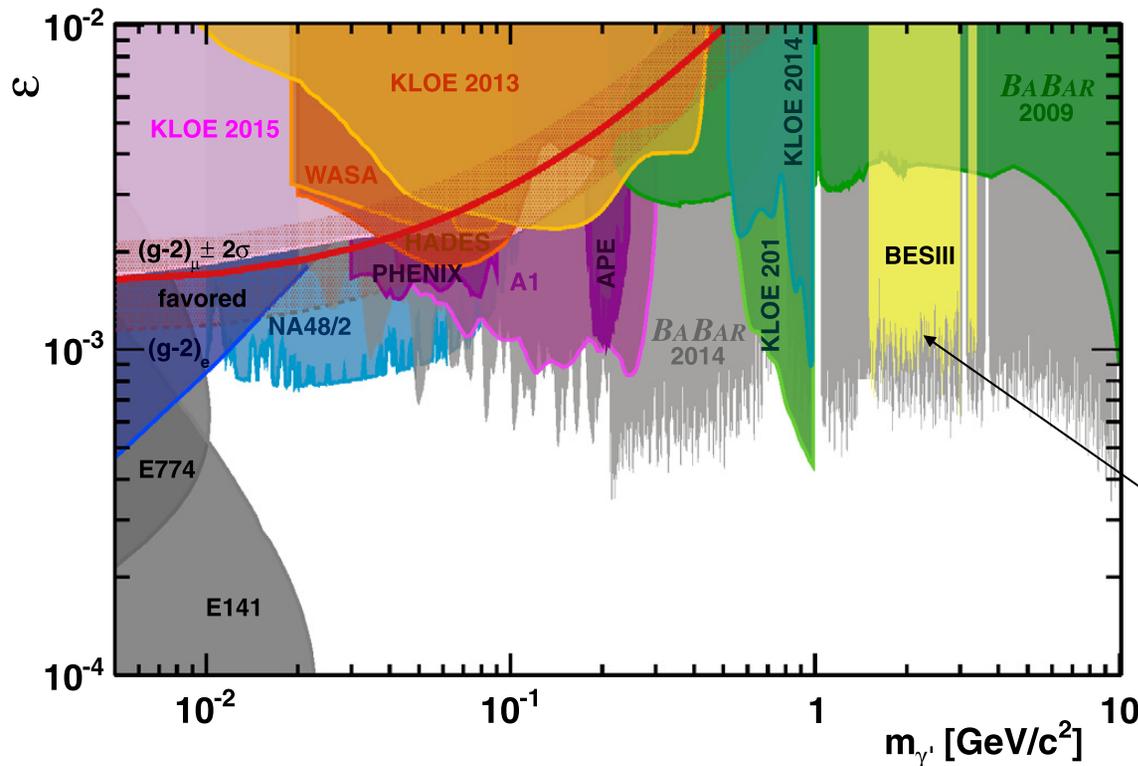
Belle II projection from PTEP 2019, 123C01 (2019)

- BESIII will add single  $\gamma$  trigger for  $20 \text{ fb}^{-1} \psi(3770)$  run, next 2 years. Cross section is higher than Belle II by  $8 \times$  (1/s).

# Visible decays of the dark photon



- If dark photon can't decay to dark matter, it will decay to SM particles. Depending on mass, most useful final states are  $e^+e^-$ ,  $\mu^+\mu^-$ , or  $\pi^+\pi^-$ .



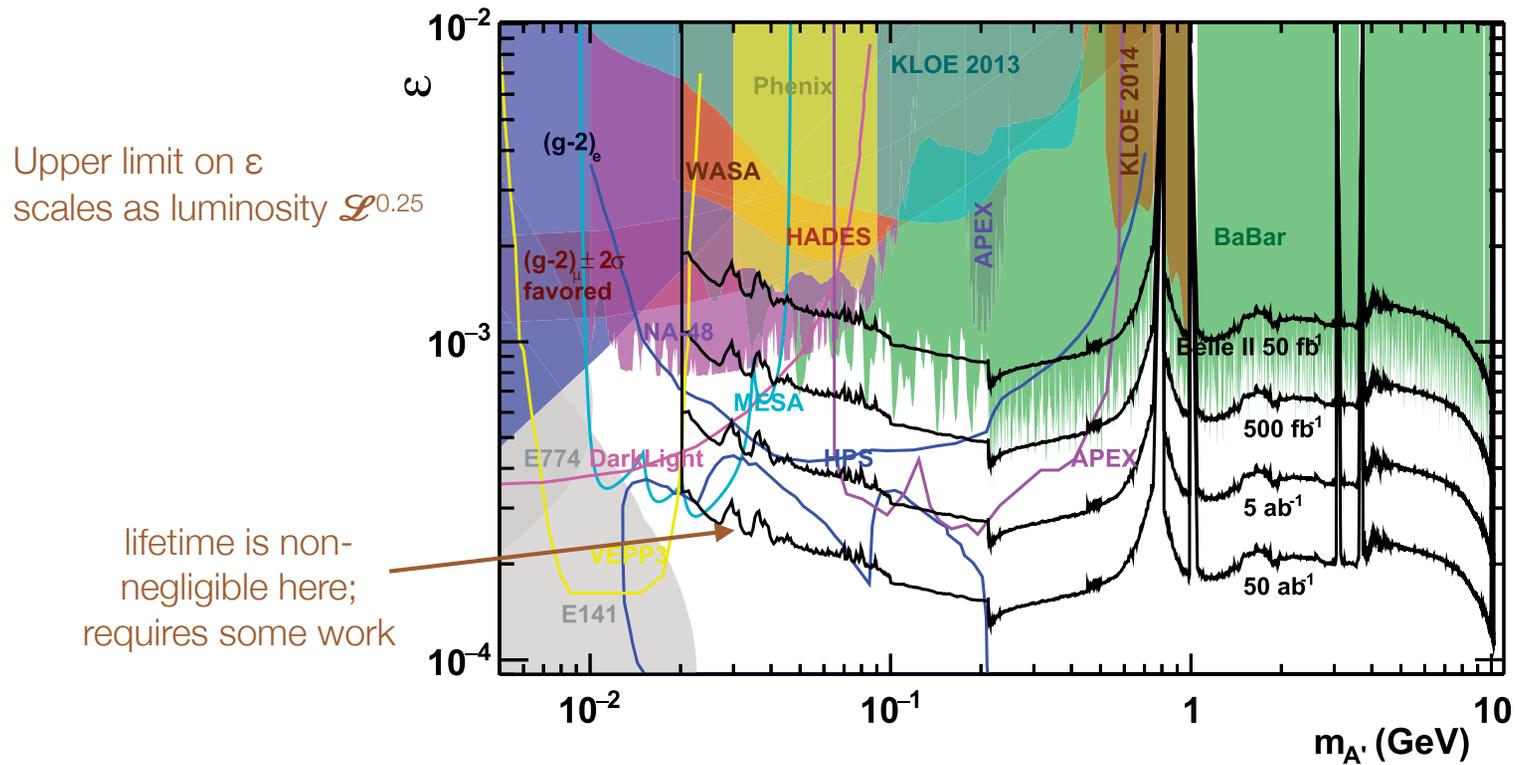
KLOE-2 collab, PLB 757, 356 (2016)

BaBar collab, PRL 113, 201801 (2014)

Missing from this plot:  
LHCb PRL 124, 041801 (2020)

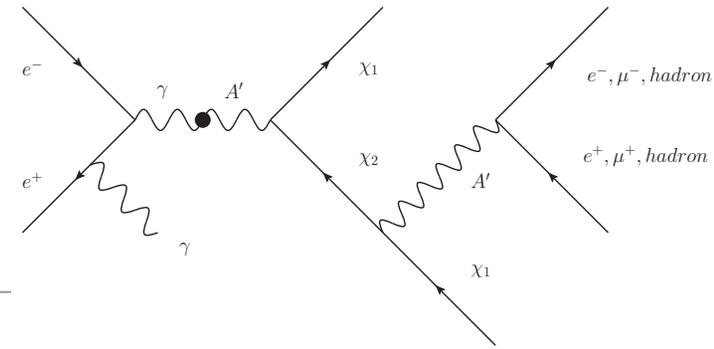
BESIII collab, PLB 774, 252 (2017)  
With full  $\psi(3770)$  dataset, BESIII limits  
using  $\mu^+\mu^-$  will exceed BaBar

- Belle II projection is derived from BaBar results.

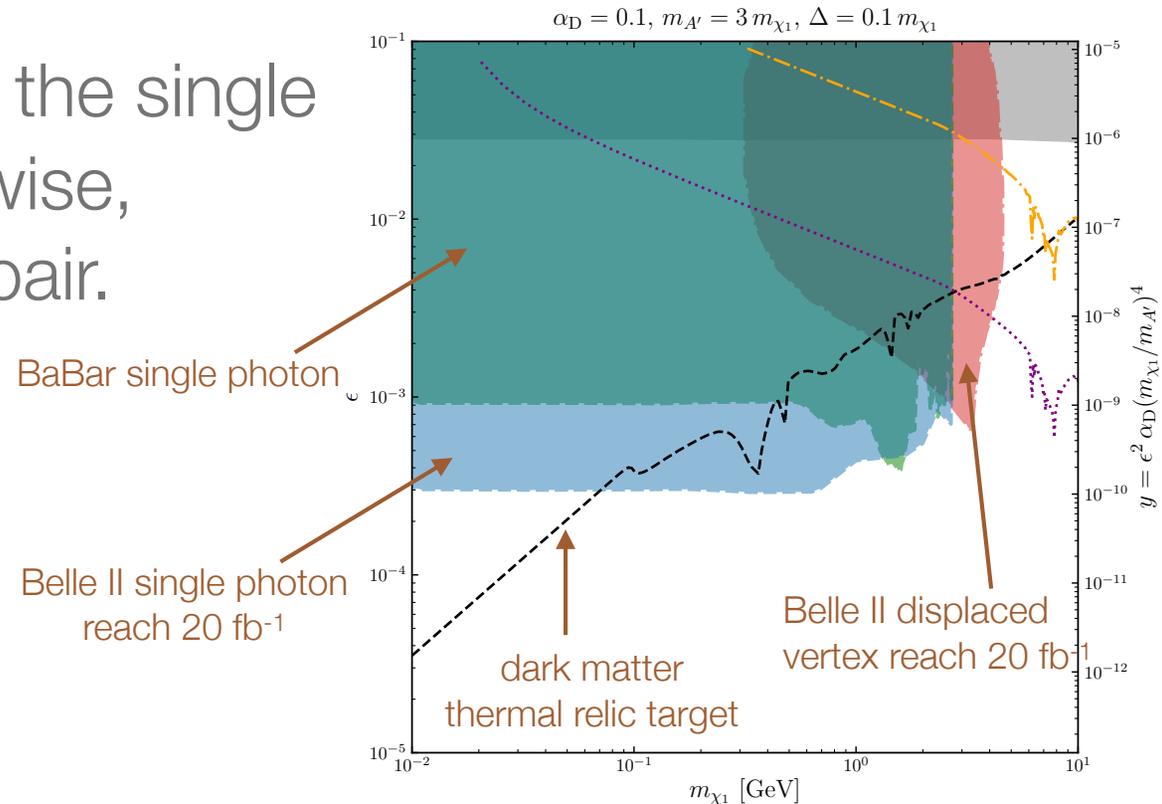
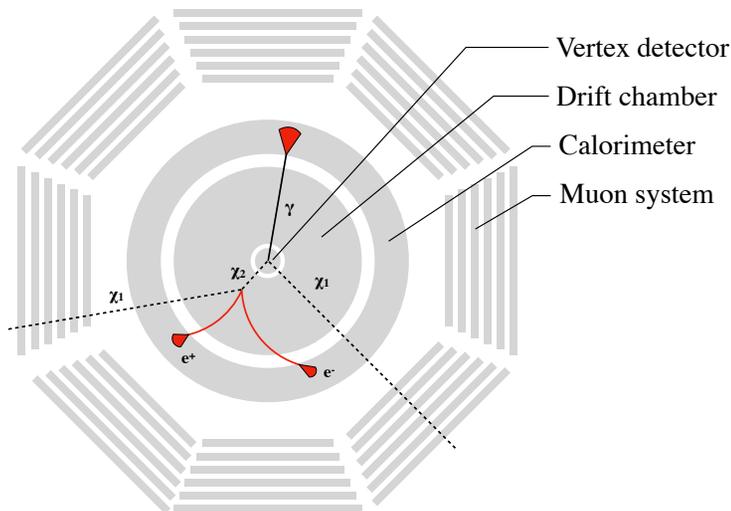


Belle II projection from PTEP 2019, 123C01 (2019)

# Indirect dark matter iDM

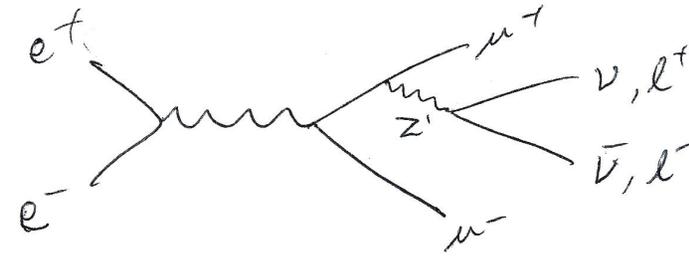


- The dark photon couples to two dark matter states. The heavier  $\chi_2$  decays to  $\chi_1$  plus SM particles.
- If  $\chi_2$  is long-lived, this is the single photon analysis. Otherwise, photon plus displaced pair.

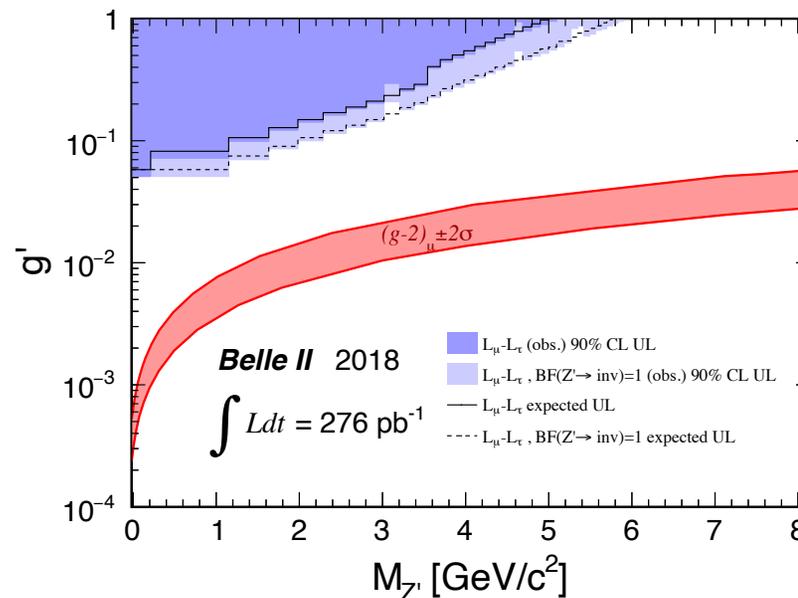


M. Duerr et al, JHEP 02, 039 (2020)

# $Z'$ , invisible or visible decays



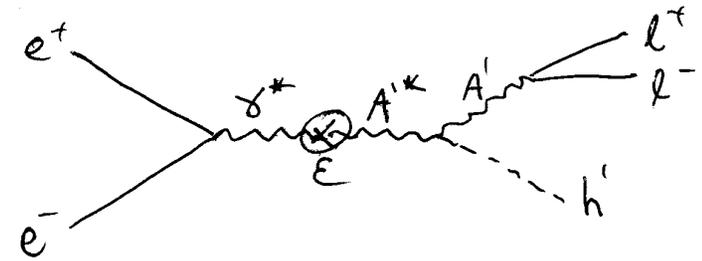
- $L_\mu - L_\tau$ ; direct coupling to SM leptons, 2<sup>nd</sup> and 3<sup>rd</sup> generations only.
- First Belle II physics paper: search for invisible decays. BaBar has published 4 muon search.



Belle II collab, PRL 124, 141801 (2020)

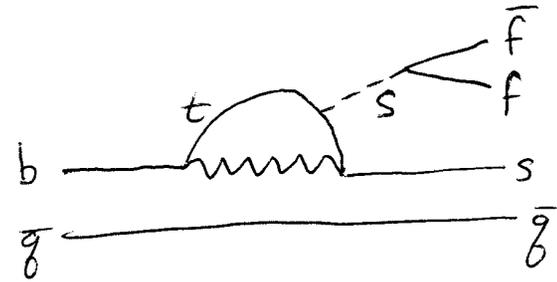
# Scalar mediator

# Dark Higgsstrahlung

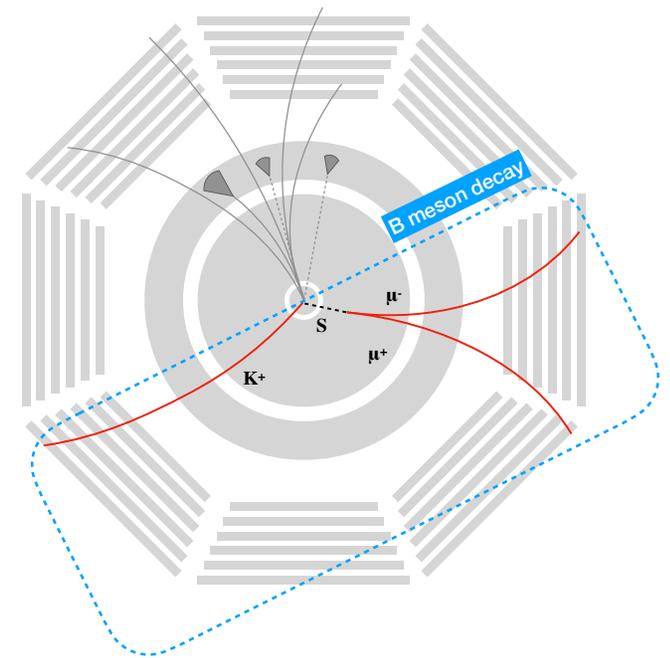


- Dark Higgs  $h'$  produced in association with a dark photon  $A'$ .
- If dark Higgs is long-lived, search for dark photon (only) decaying to two tracks.
  - search previously done by KLOE
- If dark Higgs decays to two dark photons, 6 track final state.
  - searches done by Belle, BaBar

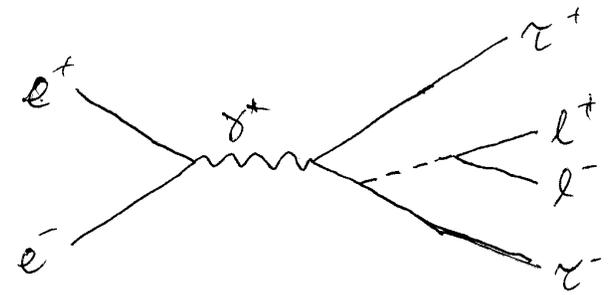
# Dark scalar S



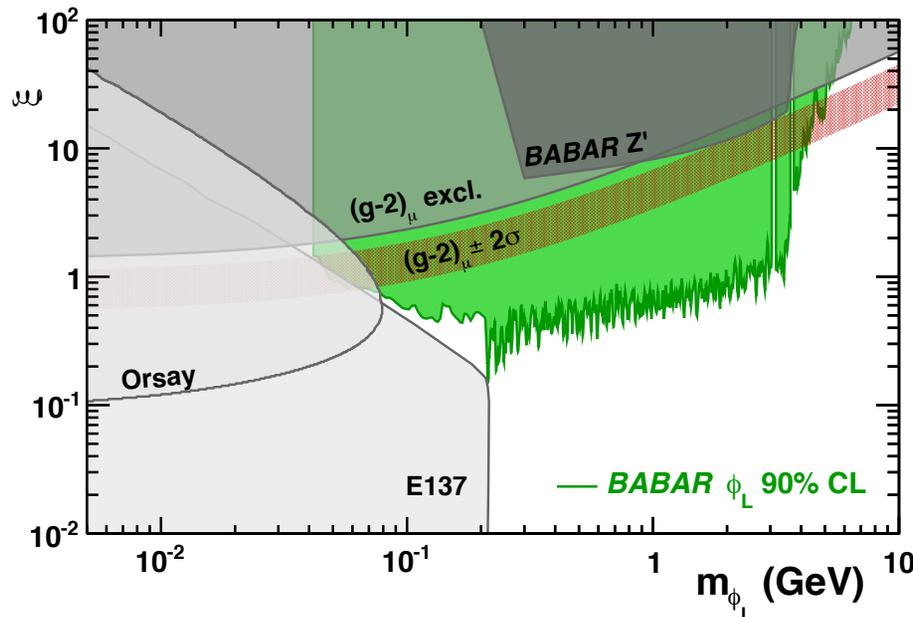
- Mixes with Higgs; inherits mass-dependent couplings.
- Produce through coupling to virtual top in  $B \rightarrow K^{(*)}S$ .
- Could be displaced, or live long enough to be invisible.
- Belle II can reconstruct B decays that include invisible particles by fully reconstructing the other B in the event: “full event interpretation”.



# Leptophilic scalar



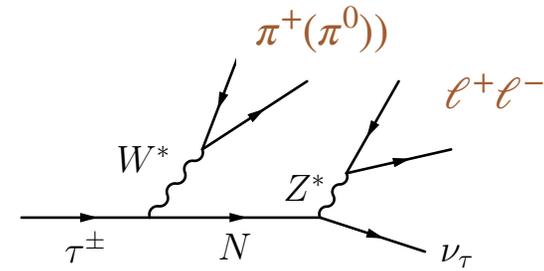
- If coupling to quarks is suppressed, the scalar would be produced in association with a  $\tau^+\tau^-$  pair.
- Decay would be to kinematically available lepton pairs
  - at low masses, lifetime may be non-negligible.



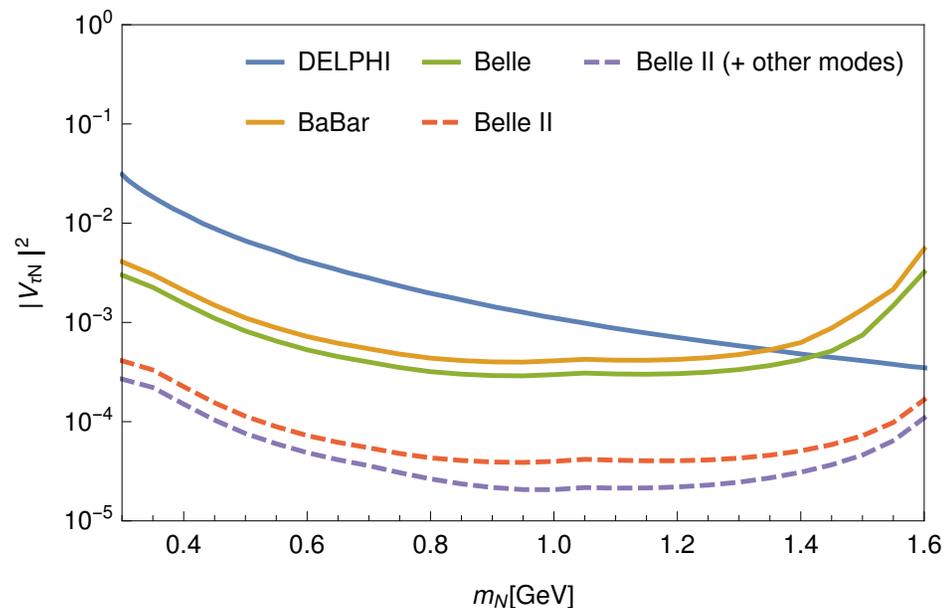
BaBar collab., arXiv:2005.01885

Neutrino mediator

# Sterile neutrino in tau decay



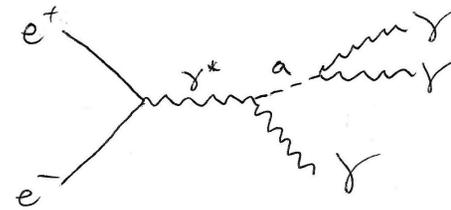
- Use the large tau-pair sample available to Belle II to search for sterile neutrino  $N$  with mass  $<$  tau mass.
- Lifetime produces displaced vertex. Sufficient kinematic constraints to obtain sterile neutrino mass.



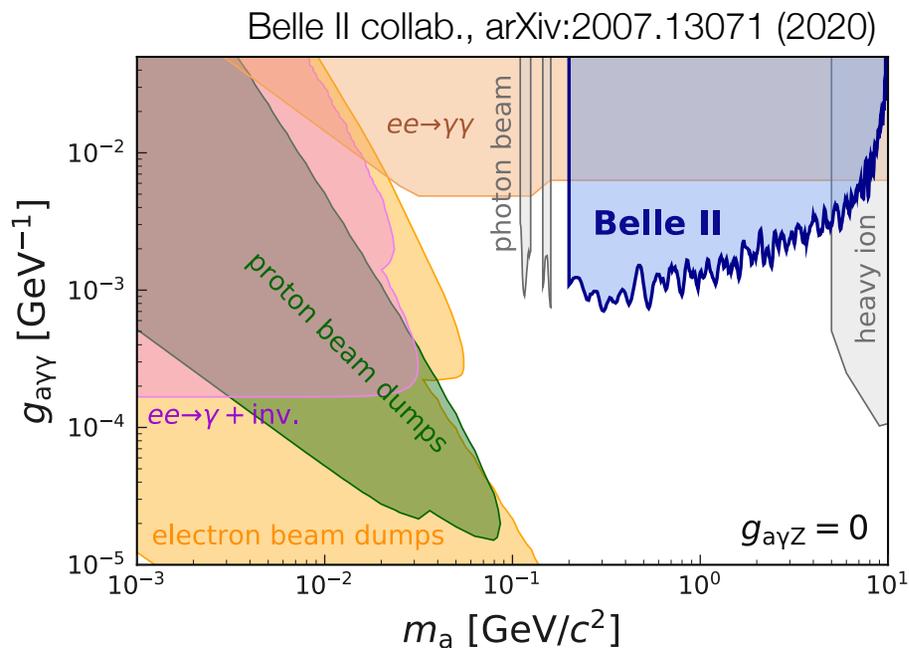
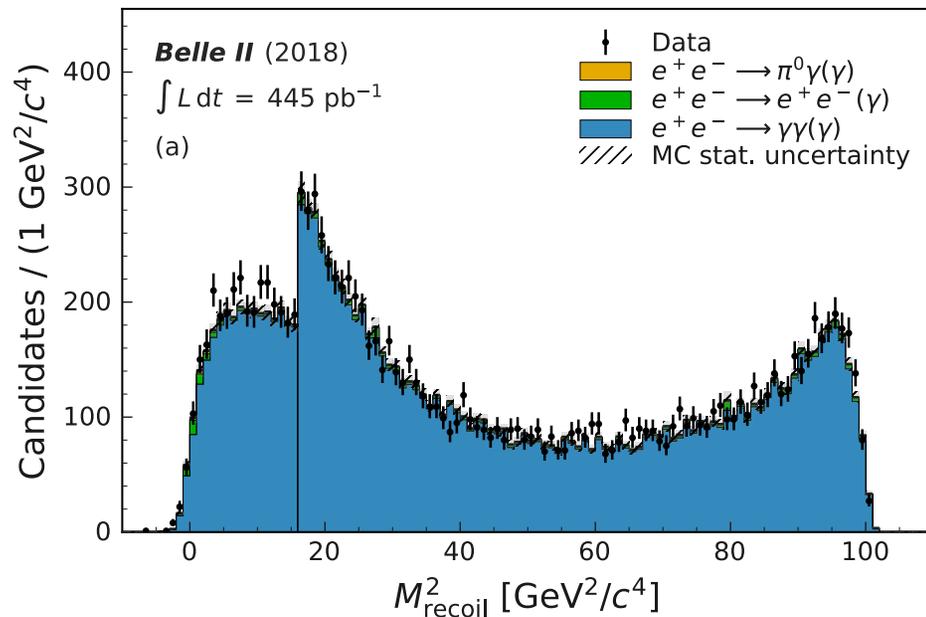
C O Dib et al, PRD 101, 093003 (2020)

# Axion-like particles

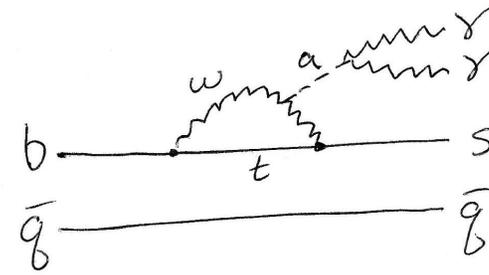
# Direct ALP ( $a$ ) production



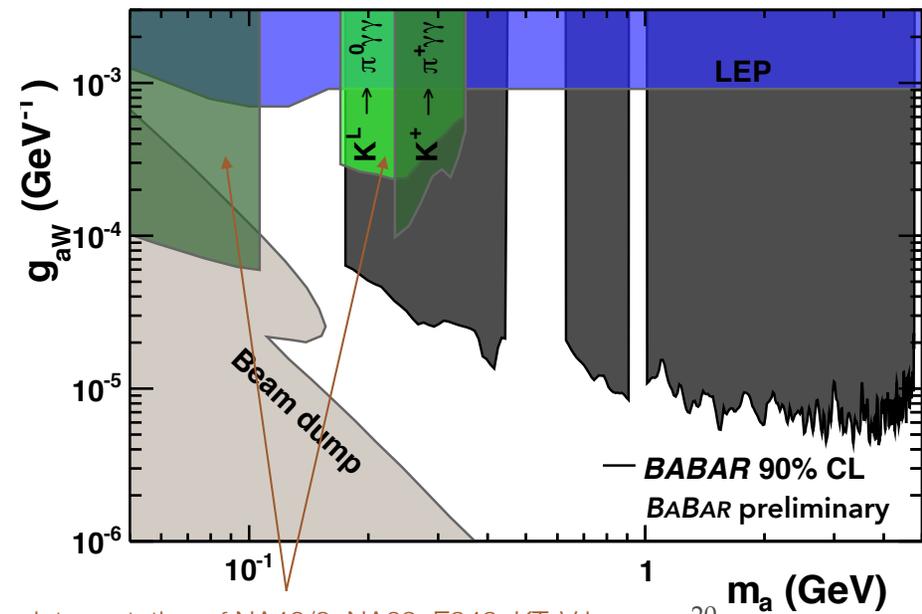
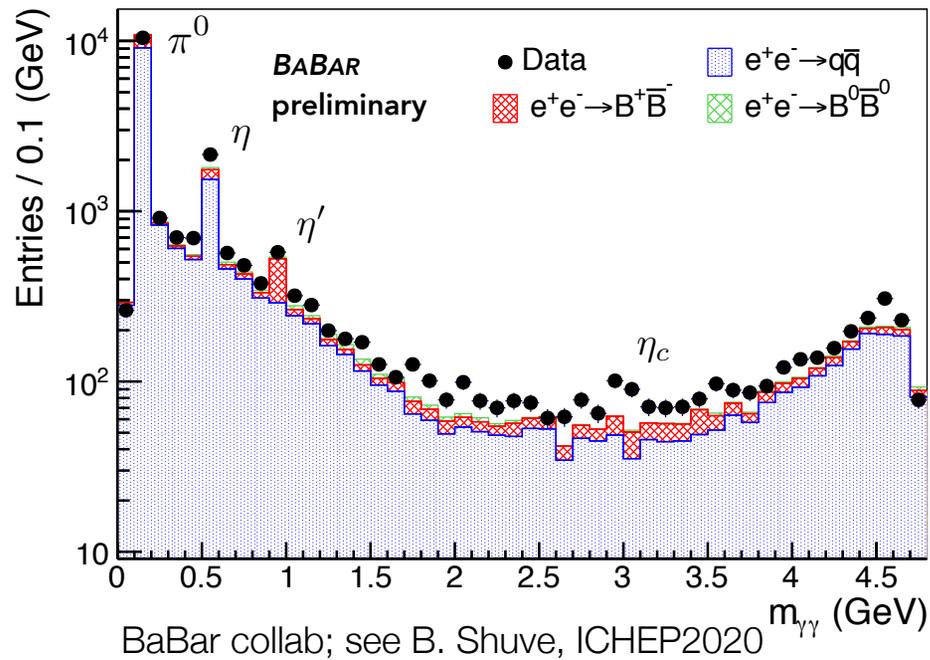
- Relies only on coupling to  $\gamma$
- Recent Belle II paper requires three distinct photons; other topologies are possible (long lived, merged).



# ALP production in B decay



- Can also be produced through its coupling to the virtual  $W$  in the decay  $B \rightarrow K^{(*)}a$ , followed by  $a \rightarrow \gamma\gamma$ .
  - ALP can be long lived

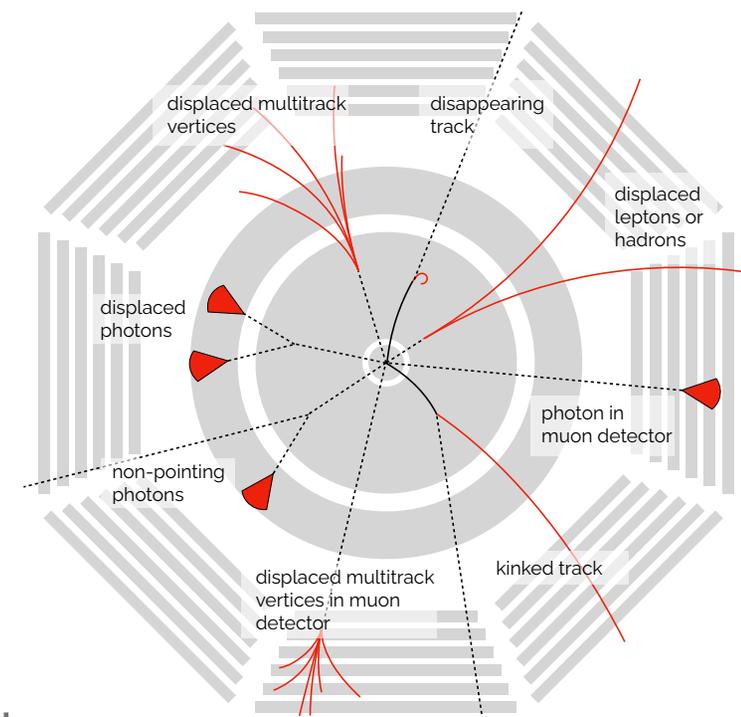


reinterpretation of NA48/2, NA62, E949, KTeV in PRL 118, 111802 (2017);  $\pi^0$  mass excluded

# Long-lived particles / invisible decays

# Searches for long-lived particles at Belle II

- Long-lived particles can arise in any of the three portals, giving a variety of signatures:
  - displaced charged particles (e.g.  $A' \rightarrow e^+e^-$ )
  - displaced neutral (e.g.  $a \rightarrow \gamma\gamma$ )
  - kinked, “disappearing” tracks.
- Belle II triggering and reconstruction capabilities in some of these areas will need to be quantified / optimized.



# Invisible decays

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- Long-lived particles can also produce “invisible” decays.
- Clean  $e^+e^-$  environment enables such searches.
- Belle and BaBar: invisible decays of the  $B^0$  and  $Y(1S)$ .
- BESIII:  $J/\psi$ ,  $D^0$ ,  $\eta$ ,  $\eta'$

# Dedicated long-lived particle detector: GAZELLE

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- Proposal is to investigate the physics case for a dedicated detector located near Belle II.
  - directly detect LLPs that in Belle II will be missing / invisible.
- Readout synchronized with Belle II. Also Belle II trigger?
- With appropriate shielding, backgrounds should be small compared to LHC and beam dump experiments.

# Summary

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- $e^+e^-$  colliders can study a wide range of dark sector models.
- Existing experiments have published a number of results. Belle II will accumulate a significantly larger dataset over the next decade. BESIII will increase by 7–8 $\times$ .
- Long-lived new particles may be particularly interesting.