The Dark Sector Physics at the Belle II Experiment

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on behalf of the Belle II Collaboration

6th symposium on

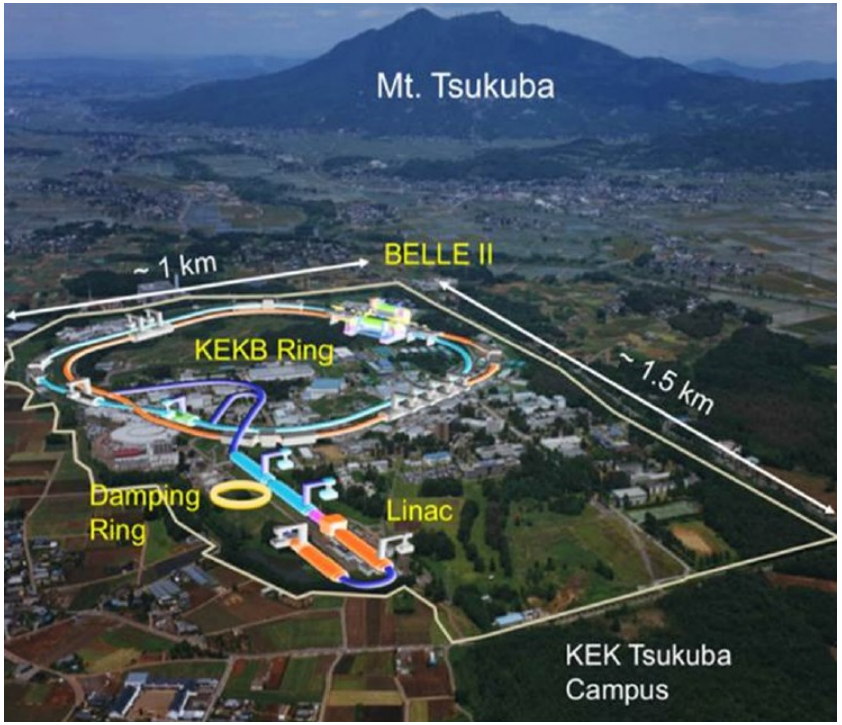
Neutrinos and Dark matter in Nuclear physics 2018

Content

- The Belle II experiment
  - SuperKEKB accelerator
  - Belle II detector
- Dark sector searches at Belle II
  - Dark photon searches
  - Axion-like particles searches
  - Muonic dark force searches

Belle II experiment

- An electron positron collider experiment in Japan.
  - Upgrade of the Belle experiment. (1999-2010)
  - Goal: Collect 50 times more data with a better detector



[1]

Belle experiment

- Intensity frontier experiment.
- Provided evidence for *CP* violation in B meson sector.
- Experimental foundation for 2008 Nobel Prize in physics.
- Discovery of X(3872) particle

SuperKEKB accelerator

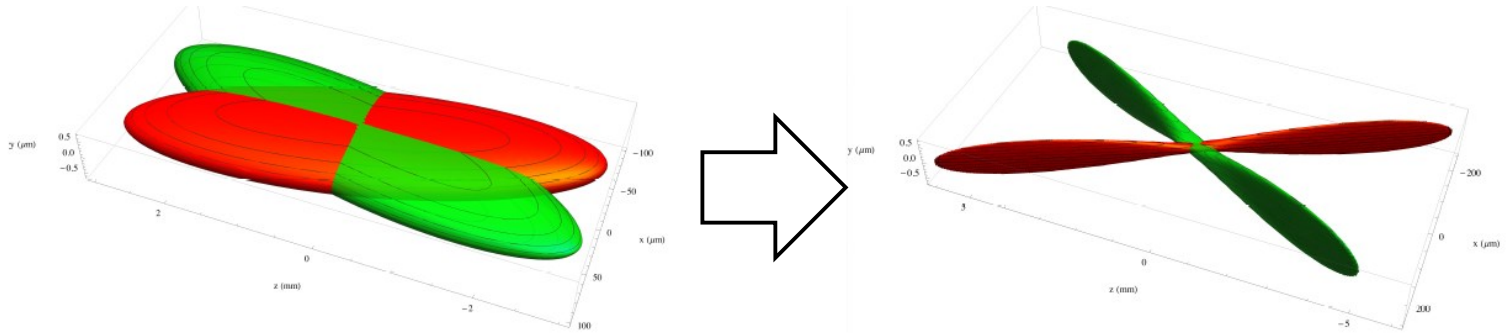
- Collides 7 GeV electrons with 4 GeV positrons.
  - Center-of-momentum energy: 10.58 GeV ($b\bar{b}$ resonance)
- Luminosity is designed to be 40 times higher.
  - Increase current and “squeeze” beam.

[2]

$$L \propto \frac{I_{e^\pm}}{\beta^*_{y\,e^\pm}}$$

Current: 2 times increased

Vertical beta function: 1/20 smaller



[3]

SuperKEKB accelerator

Physics processes

e^+e^-

Two-photon

$u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$

$\gamma\gamma$

$\Upsilon(4S)$

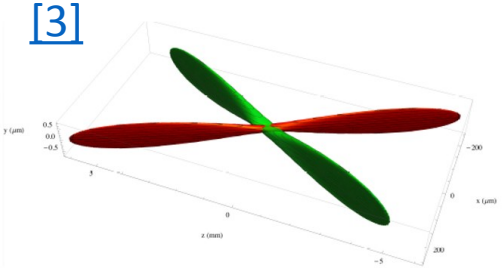
$\mu^+\mu^-$

$\tau^+\tau^-$

Dark sector physics

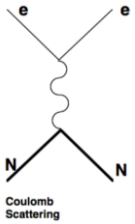
$\sqrt{s}$ = 10.58 GeV

[3]



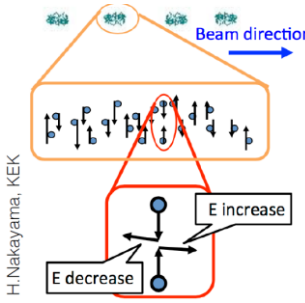
Beam background

Beam-gas interaction



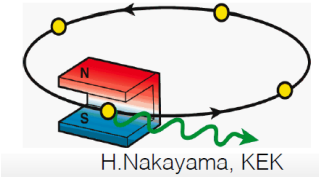
[4]

Touscheck scattering



[4]

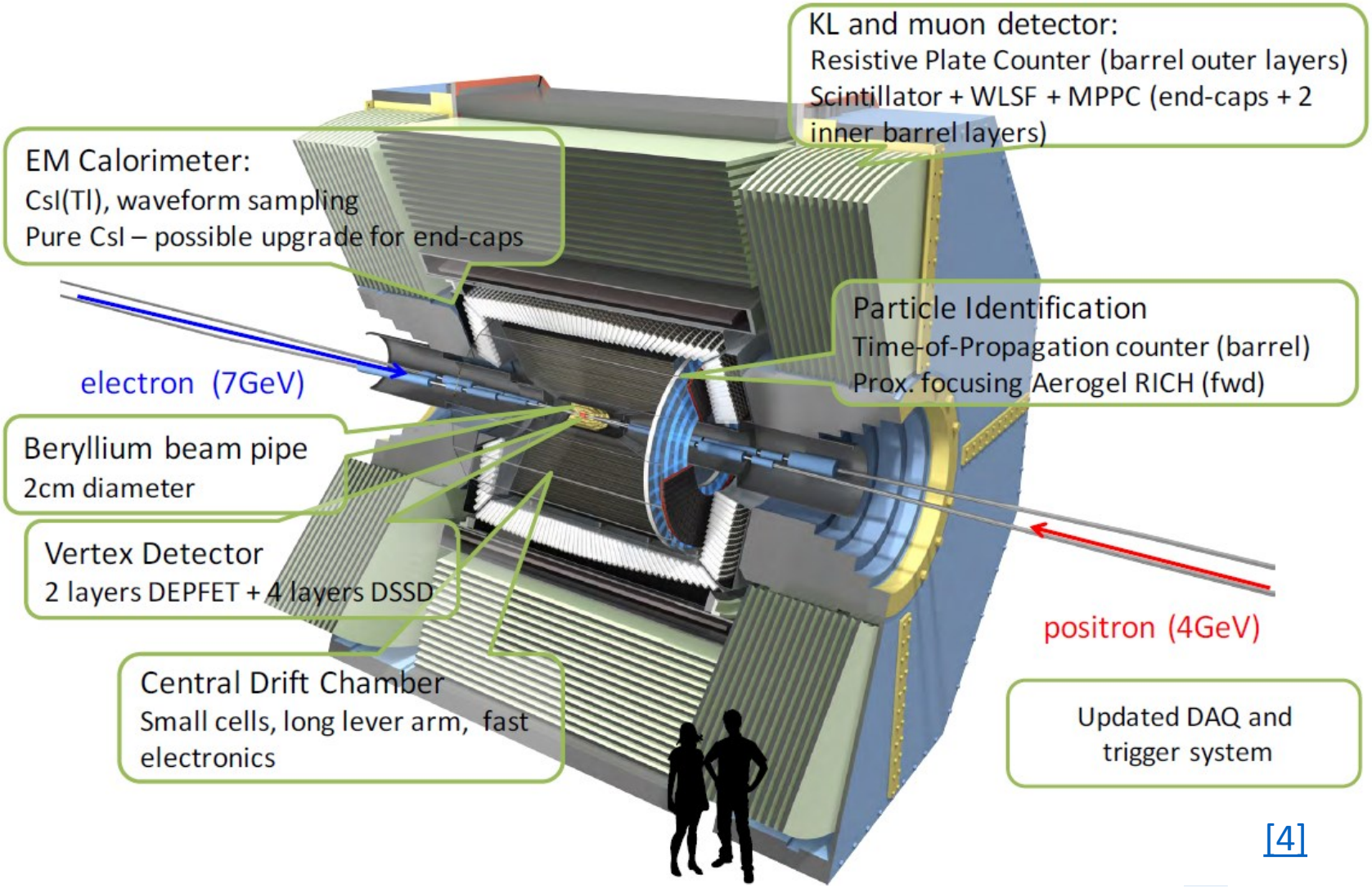
Synchrotron radiation



[4]

Injection background

Belle II Detector

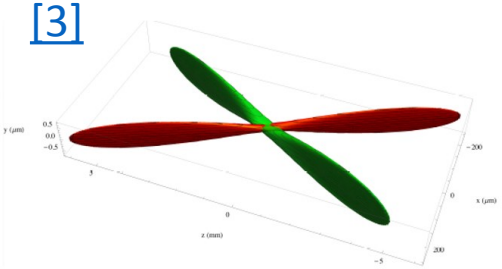


[4]

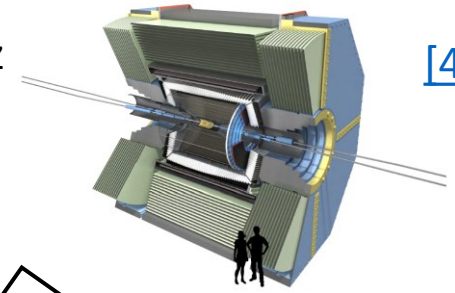
Trigger/DAQ

- Have hardware triggers and software trigger.
  - Reconfigurable hardware trigger (FPGA)
  - Full reconstruction software trigger

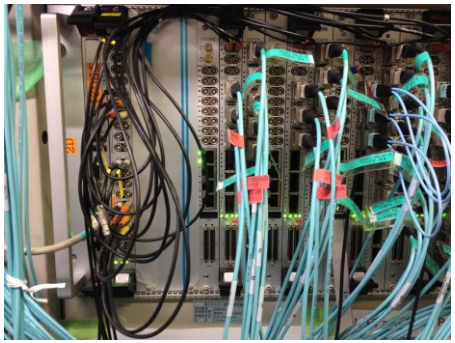
[3]



254 MHz



[4]



Hardware trigger

Max.
30 kHz

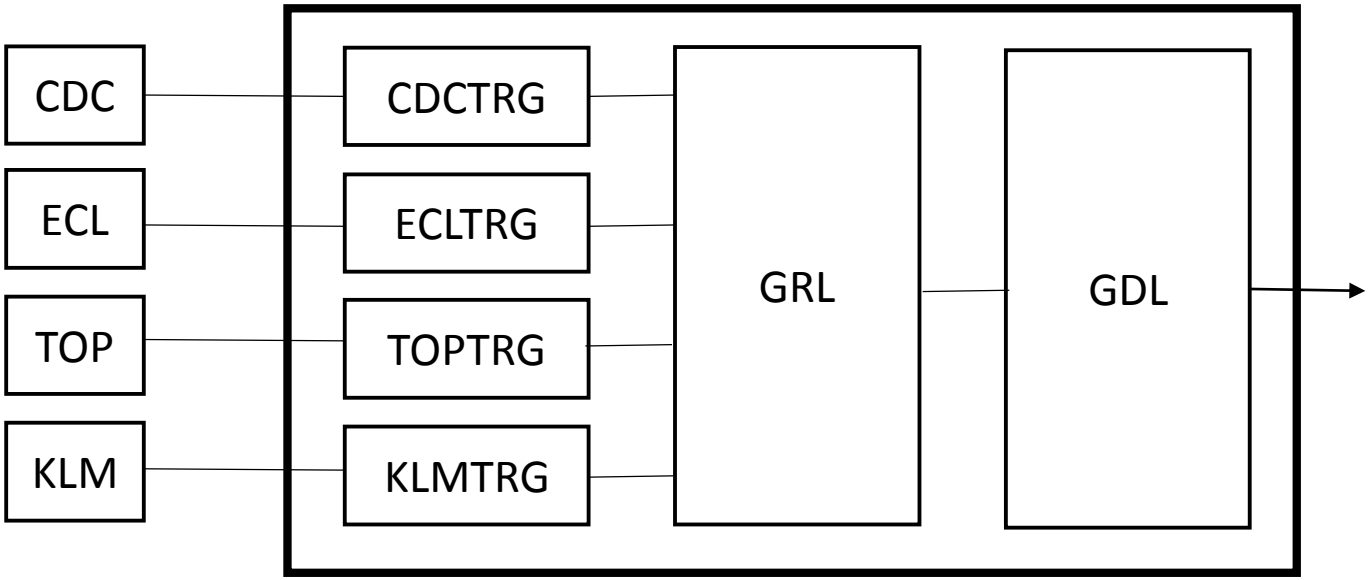
Software trigger (HLT)

Max.
10 kHz

[7]

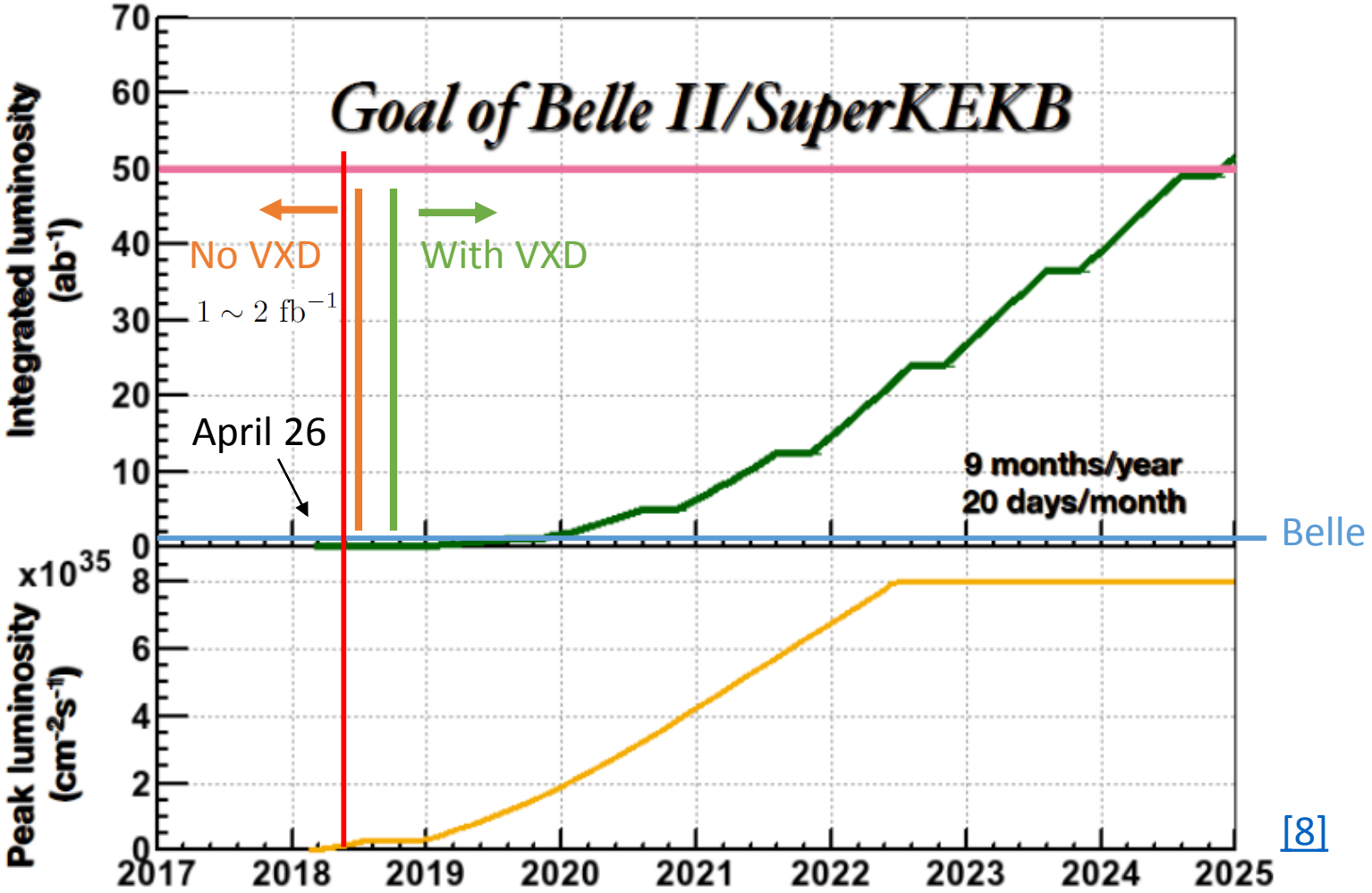
Data storage

Hardware trigger



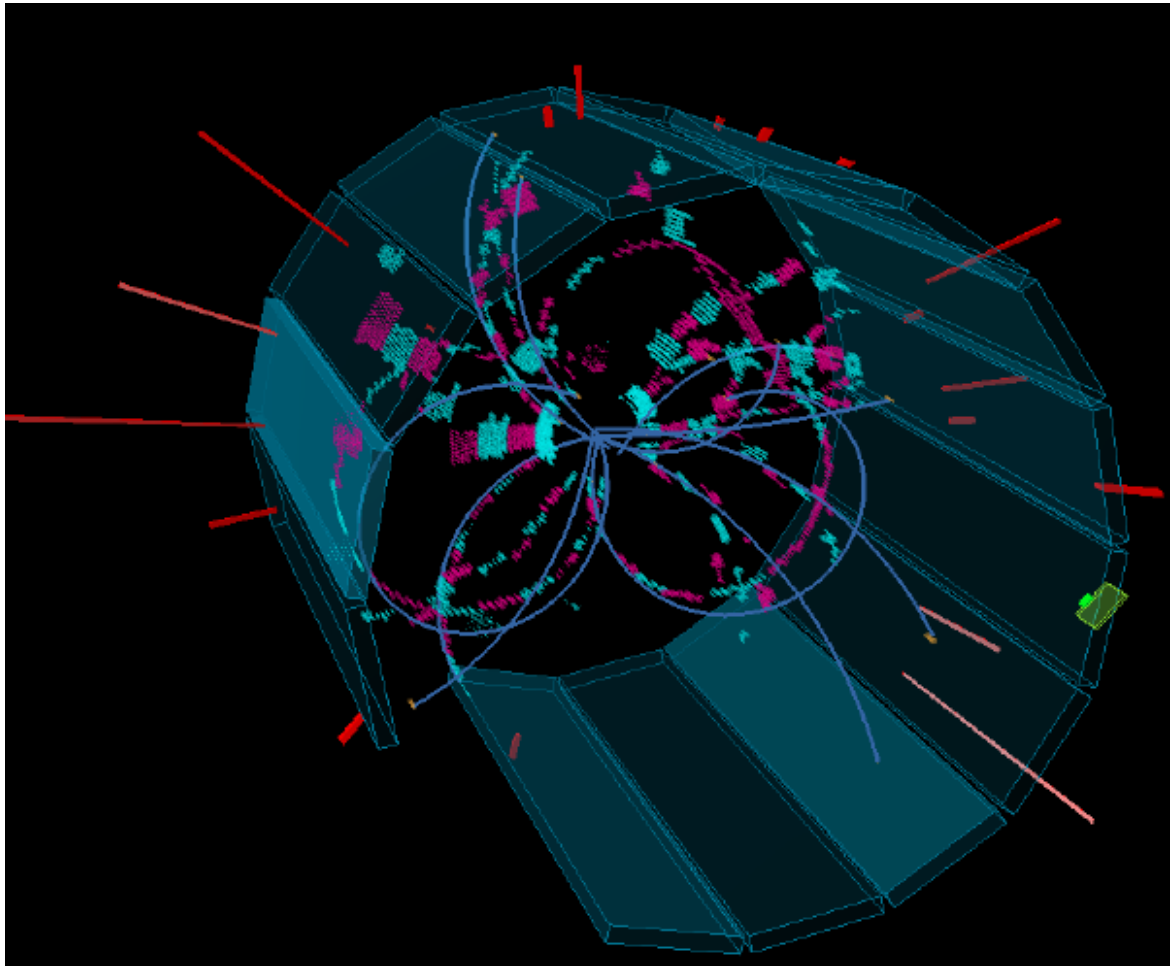
- Trigger information used for dark sector searches
  - E^*_γ : Energy of photon in ECL at CM
  - Number of clusters at ECL
  - Number of charged tracks at CDC

Timeline


Goal of Belle II/SuperKEKB
No VXD
$1 \sim 2$ fb^{-1}
With VXD
April 26
9 months/year
20 days/month
Belle
Integrated luminosity (ab^{-1})
Peak luminosity (cm^{-2}s^{-1})
x10^{35}
0
10
20
30
40
50
60
70
0
2
4
6
8
2017
2018
2019
2020
2021
2022
2023
2024
2025

[8]

First hadron event



[9]

2018. April 26 0:38

Light Dark Sector

- Dark sector (DS) at or below the GeV scale.
- Motivation [10]
  - Can explain anomaly in cosmic ray positron spectrum.
  - Can explain the relic abundance of dark matter.
- Possible interactions between SM sector and DS

(Standard Model)

Portal	Particles	Operator(s)
"Vector"	Dark photons	$-\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}$
"Axion"	Pseudoscalars	$\frac{a}{f_a} F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
"Higgs"	Dark scalars	$(\mu S + \lambda S^2) H^\dagger H$
"Neutrino"	Sterile neutrinos	$y_N L H N$

[11]

Light Dark Sector at Belle II

- Dark photon searches
  - Decays to dark matter (DM)
  - Decays to dark Higgs
  - Decays to leptons
- Axion-like particles (ALP) searches
  - Decays to 2 photons
  - Decays to DM
- Muonic dark force (MDF) searches
  - Decays to invisible
  - Decays to leptons
- And more…

Light Dark Sector at Belle II

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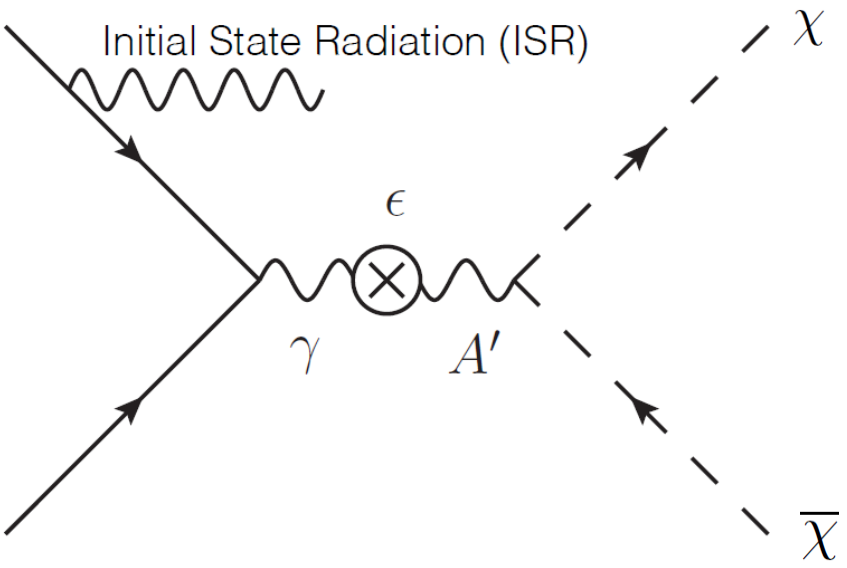
- And more…

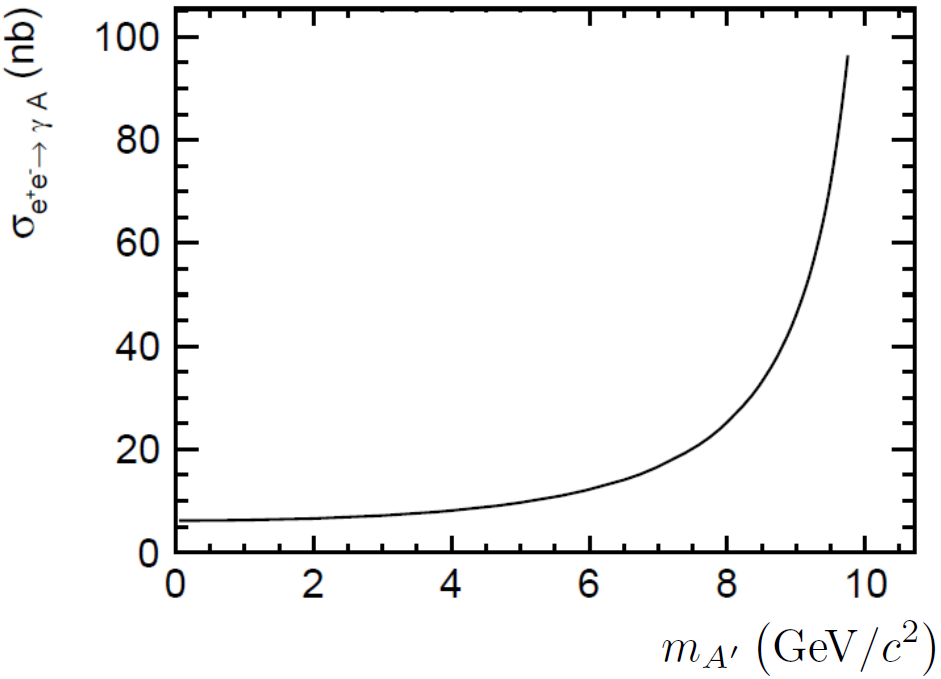
Dark photon to DM (at Belle II)

- A dark photon (A') can mix kinetically with SM. [12]
- The dark photon can decay to DM (χ).



[13]

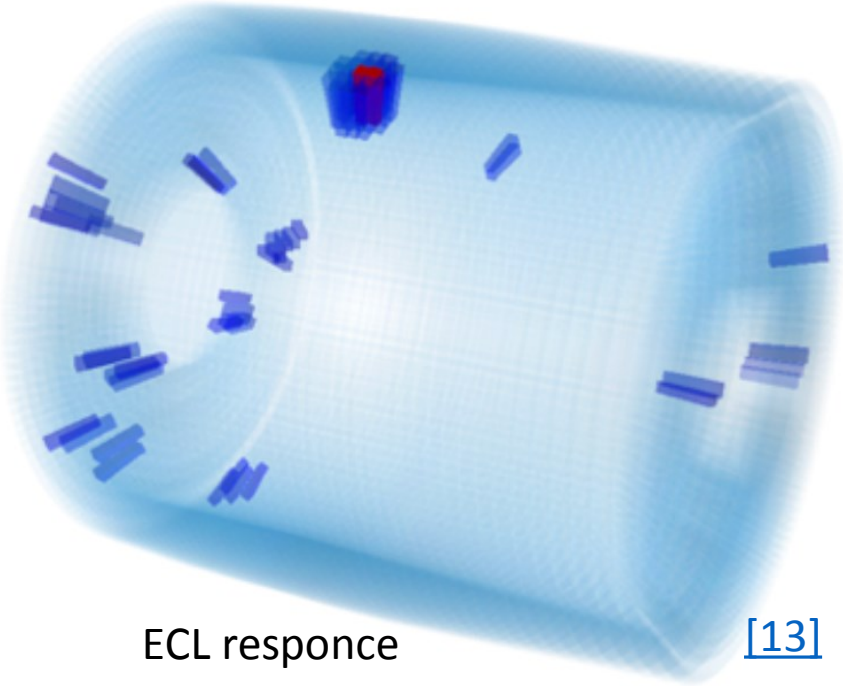
Cross section using MadGraph [10]



Dark photon to DM (Signal)

- Trigger events that have a single photon. [10]
  - $E^*_\gamma > 2$ GeV and $e^+e^- \to e^+e^-$ veto and $e^+e^- \to \gamma\gamma$ veto
  - $E^*_\gamma > 1$ GeV and other photons smaller than 0.2 GeV

Simulated event: $e^+e^- \to \gamma A',\ A' \to \chi\overline{\chi}$

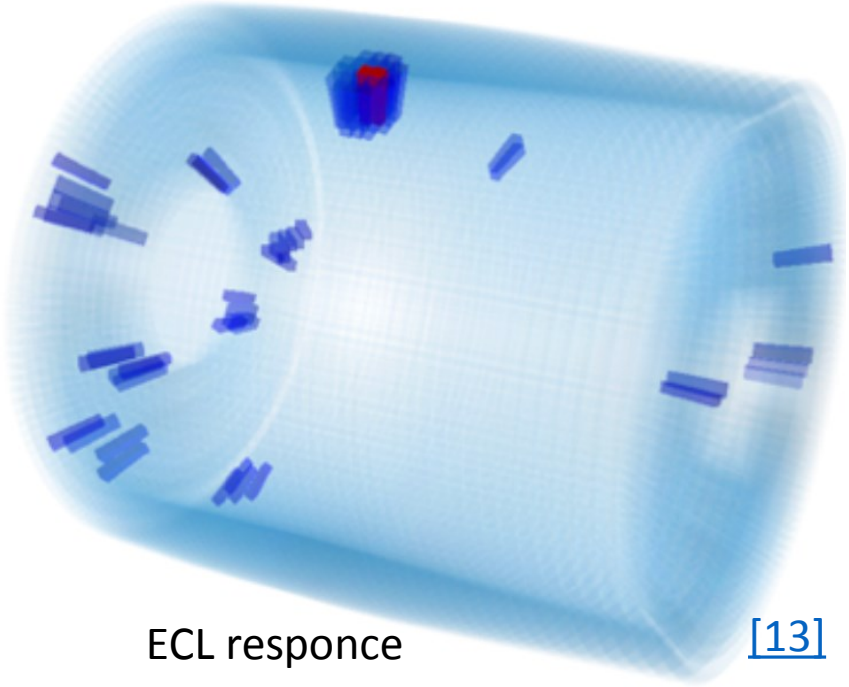


ECL responce [13]

Dark photon to DM (Signal)

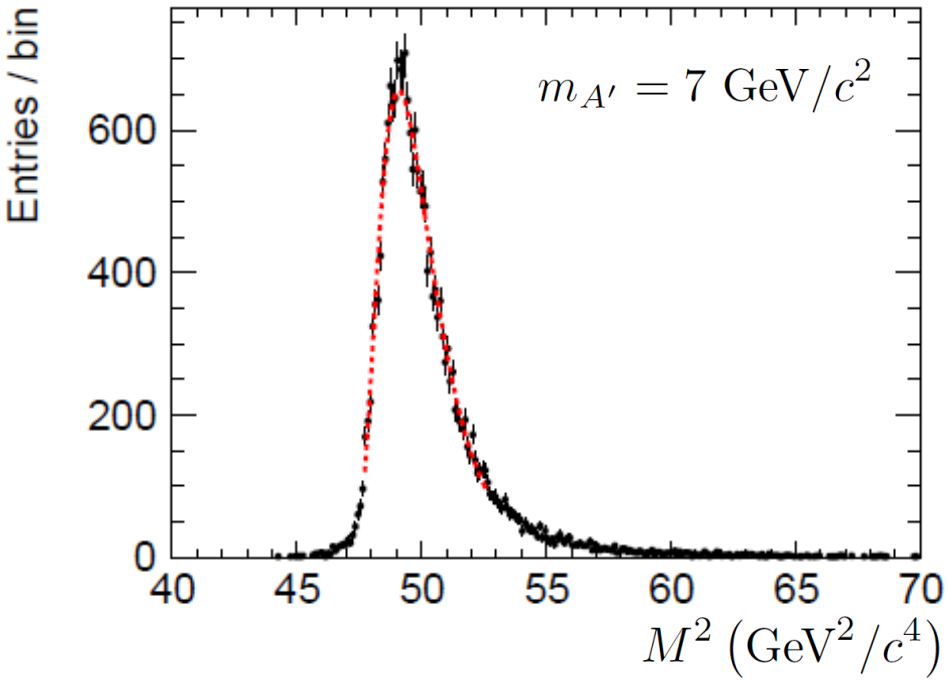
- Trigger events that have a single photon. [10]
- Observable: Recoiled mass. $M_{\mathrm{recoil}} = \sqrt{s - 2\sqrt{s}E^*_\gamma}$

Simulated event: $e^+e^- \to \gamma A',\ A' \to \chi\overline{\chi}$



ECL responce [13]

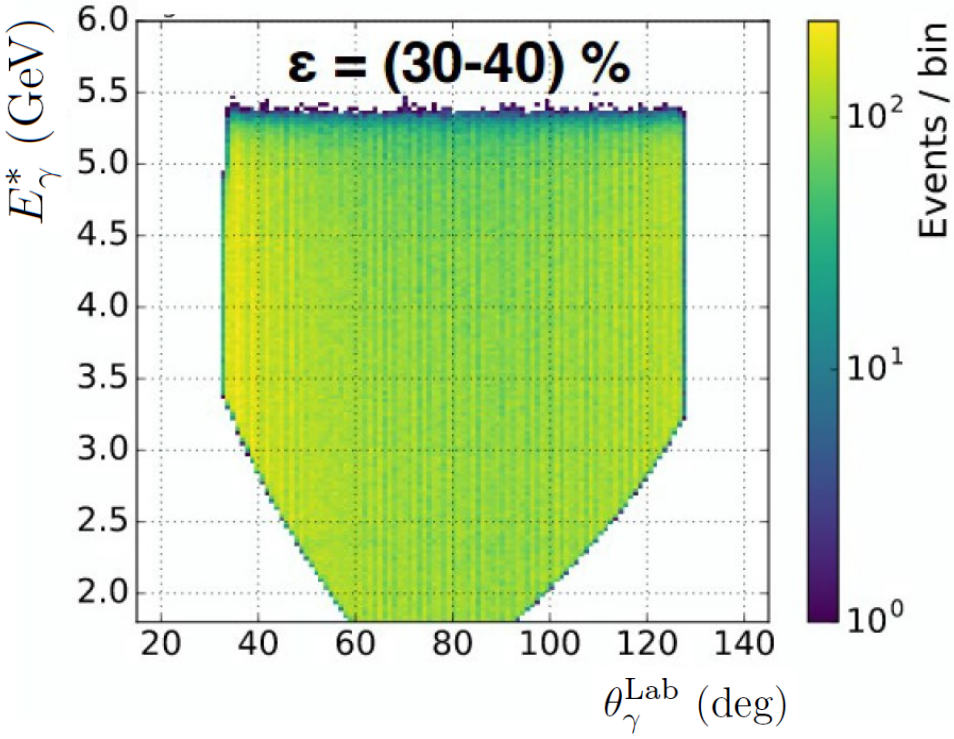
Monte Carlo (MC) signal example [10]



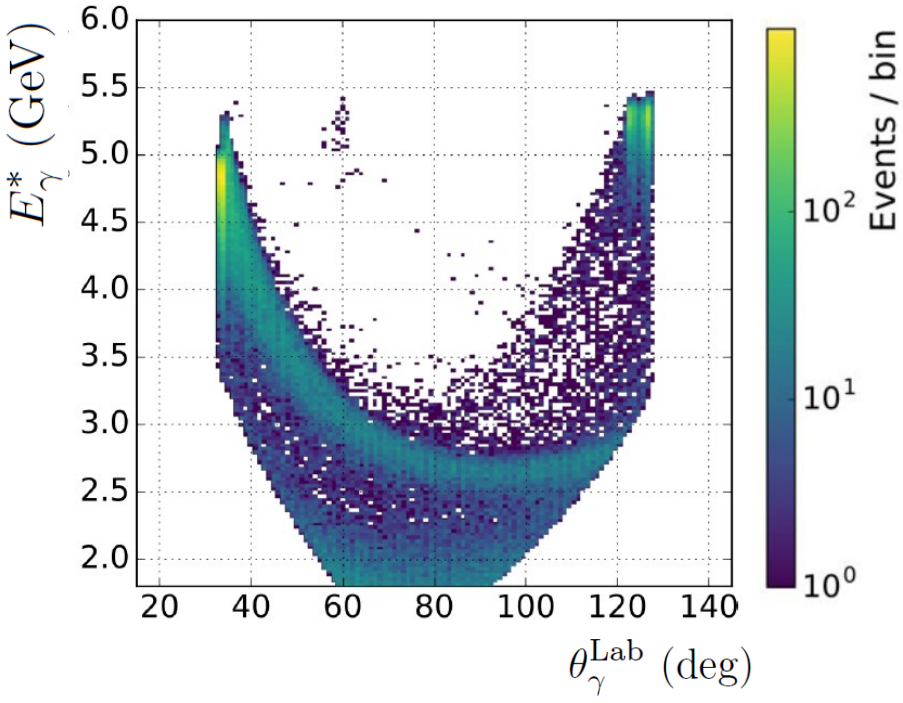
Dark photon to DM (Selection)

- Selection criteria: E^*_γ vs $\theta^{\mathrm{Lab}}_\gamma$ [13]

MC signal [14]



MC background [15]

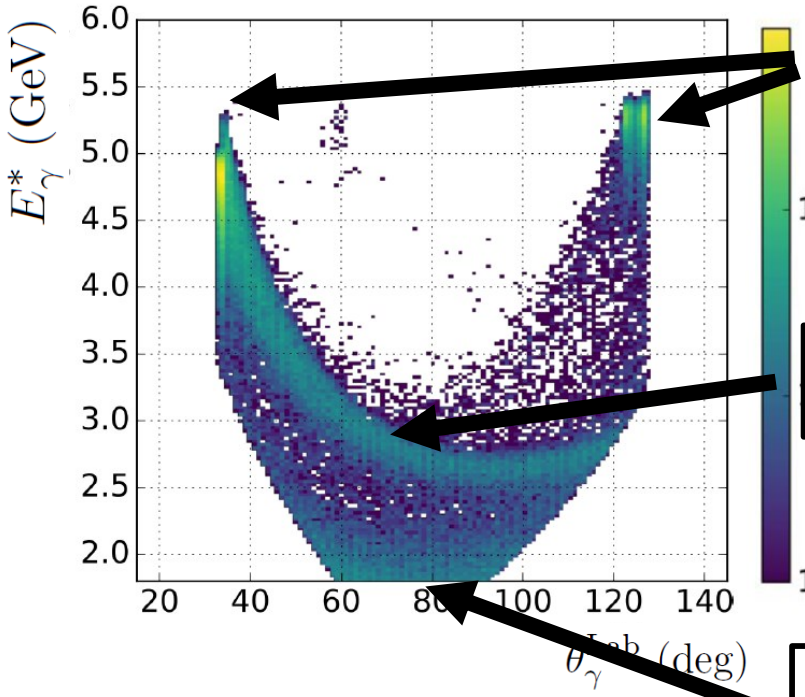


Dark photon to DM (Selection)

- Selection criteria: E^*_γ vs $\theta^{\mathrm{Lab}}_\gamma$ [13]

Due to the ECL gap

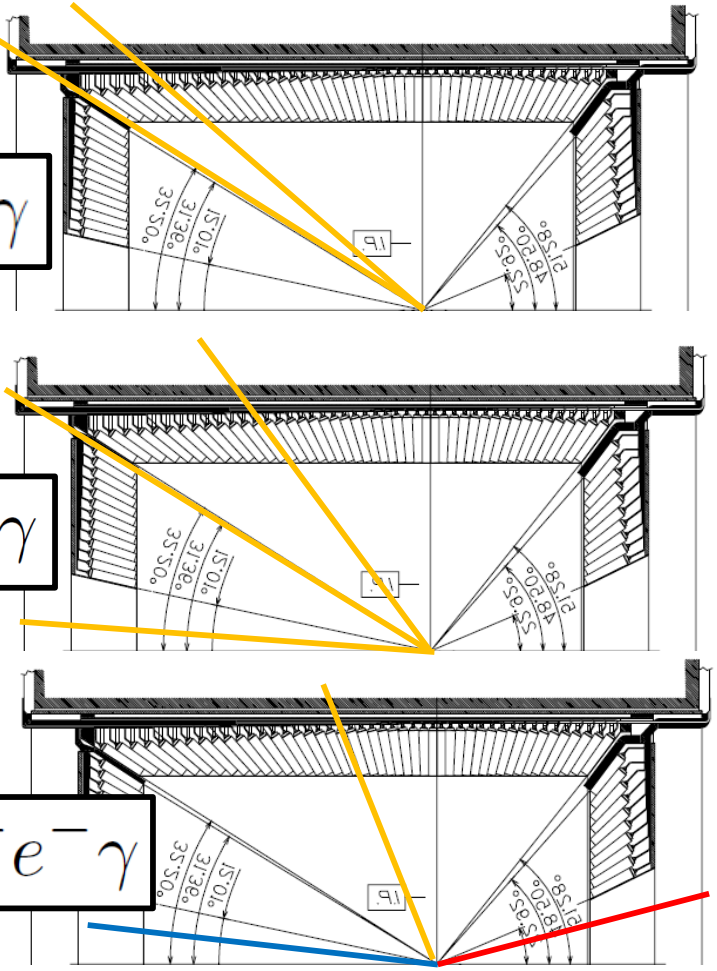
MC background [15]



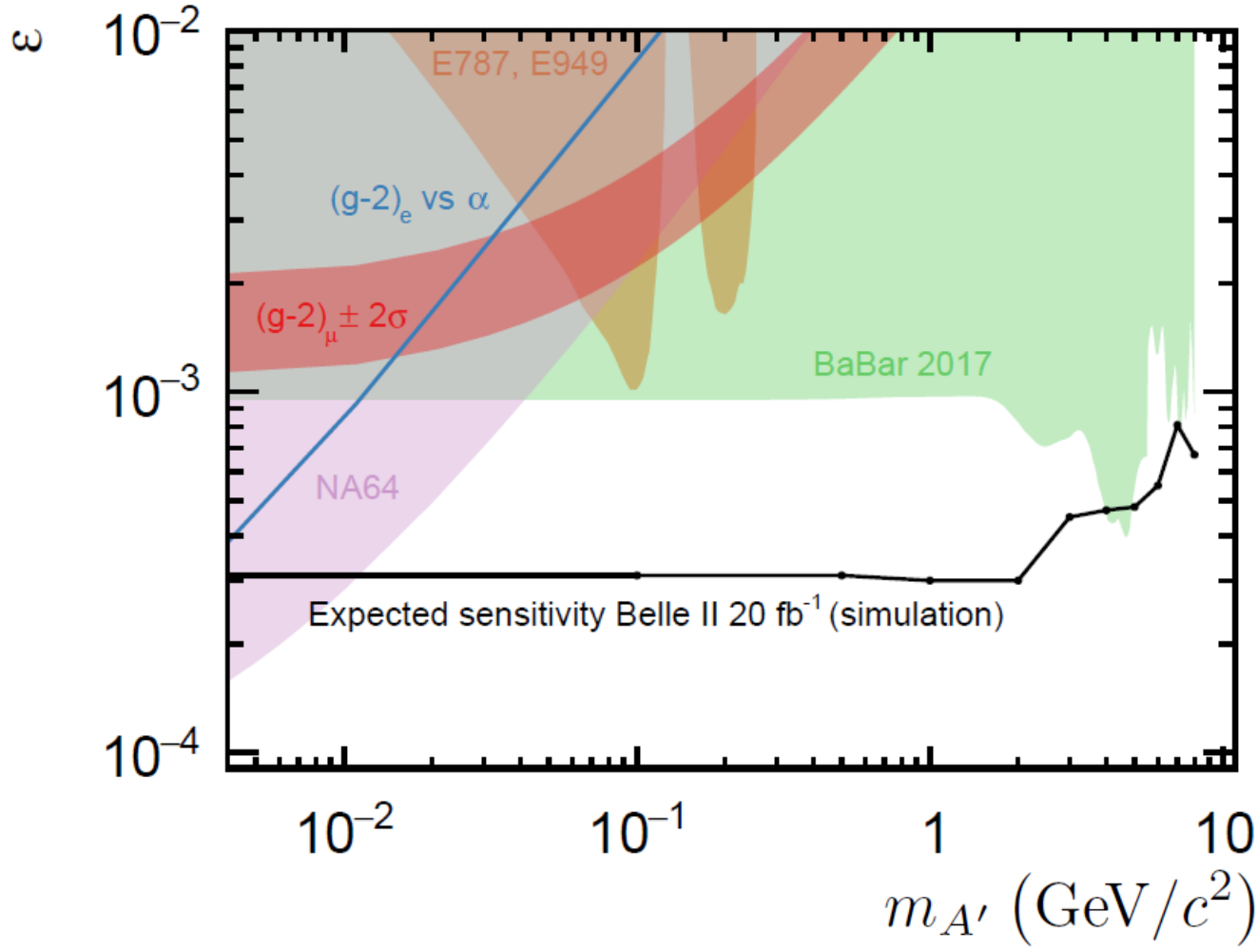
$e^+e^- \to \gamma\gamma$

$e^+e^- \to \gamma\gamma\gamma$

$e^+e^- \to e^+e^-\gamma$



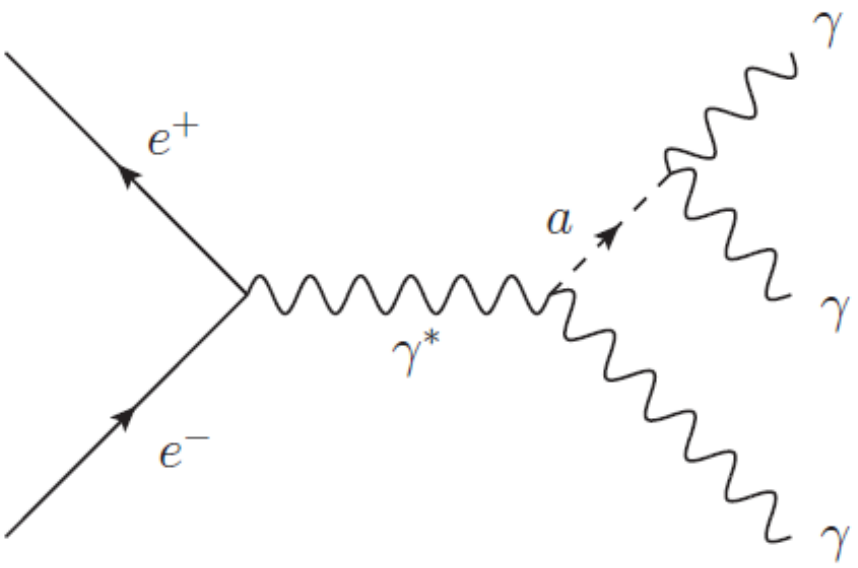
Dark photon to DM (Sensitivity)



[10]

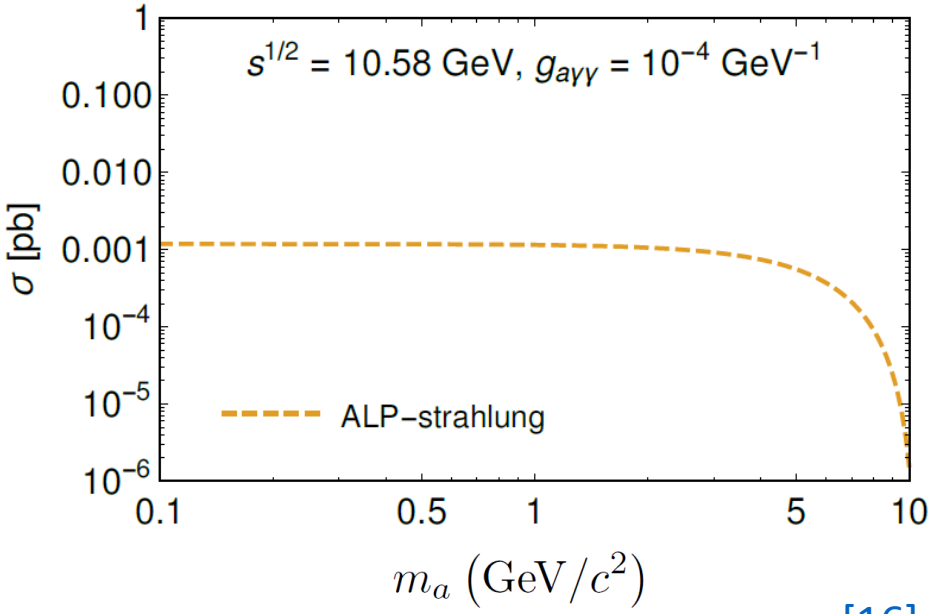
ALP to 2 photons (at Belle II)

- ALP are pseudo-scalars that couple with bosons. [16]
- ALP (a) can decay into two photons.



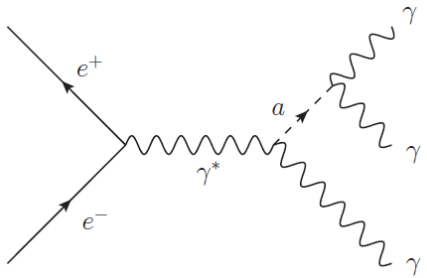
[16]

Cross section using MadGraph

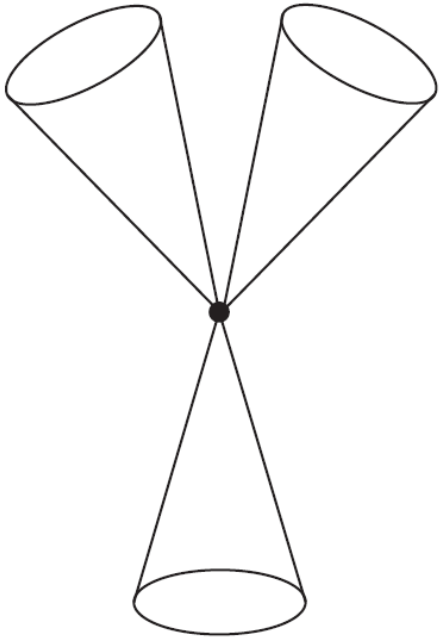


[16]

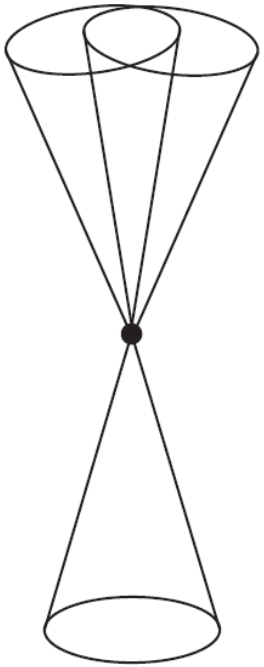
ALP to 2 photons (Signal)



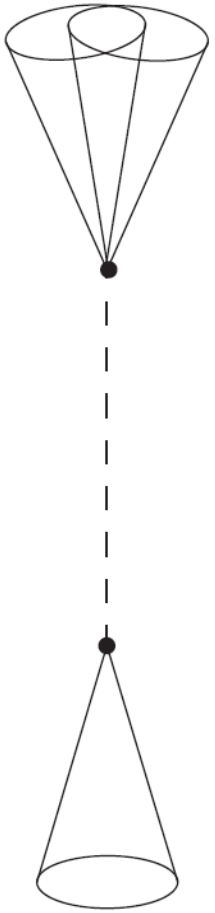
[16]



[13] mass is GeV scale

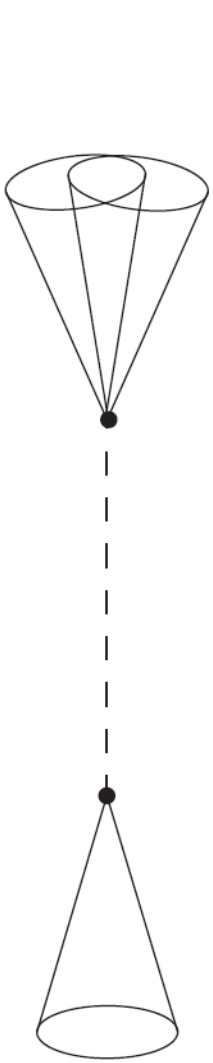


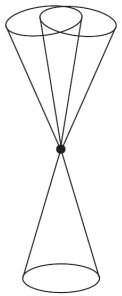
mass is light
coupling is large

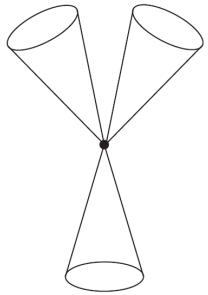


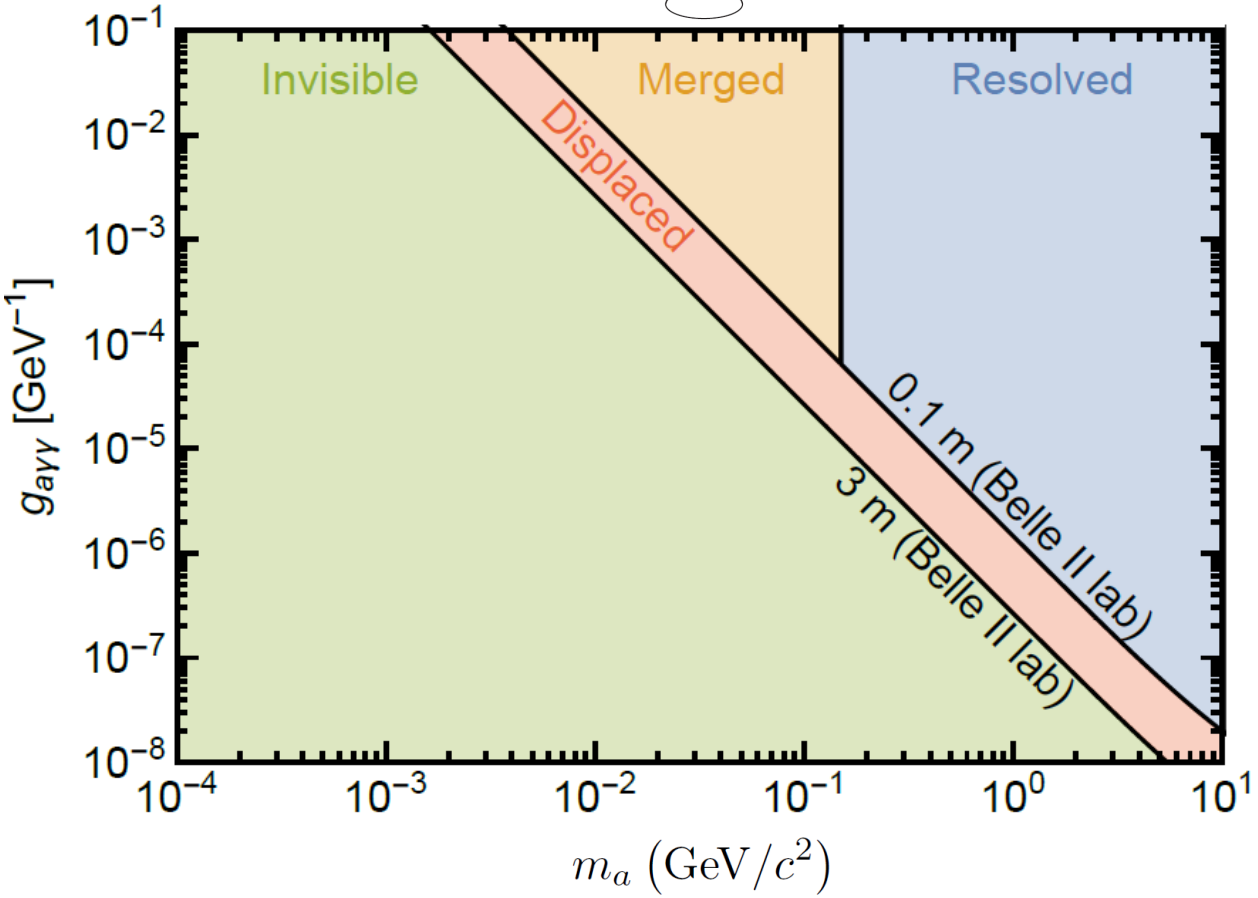
mass is light
coupling is small

ALP to 2 photons (Signal)









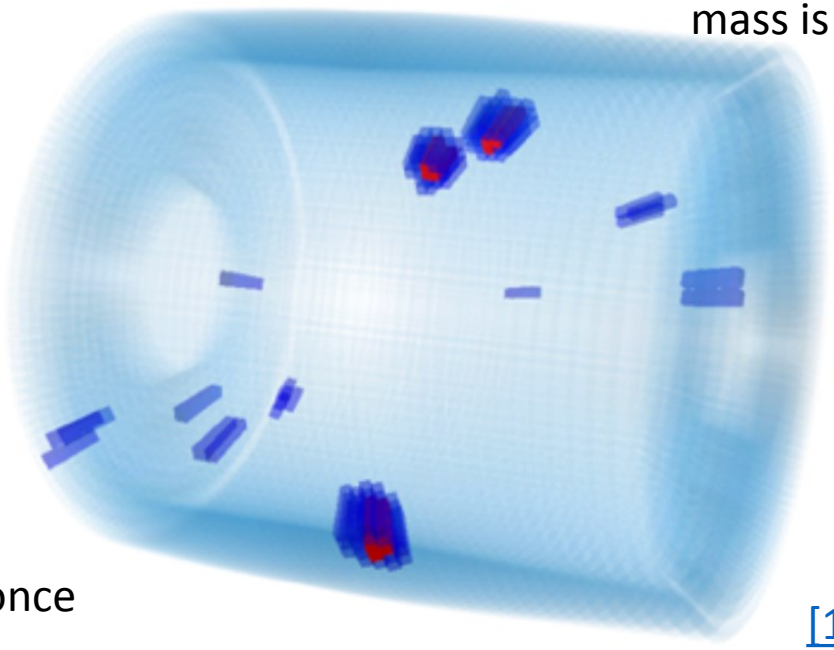
[13]

ALP to 2 photons (Signal)

- Trigger events that have multiple photons.
  - Scale multiple photon events at HLT.
- Observable: Invariant mass of 2 photons.

Simulated event: $e^+e^- \to \gamma a,\ a \to \gamma\gamma$

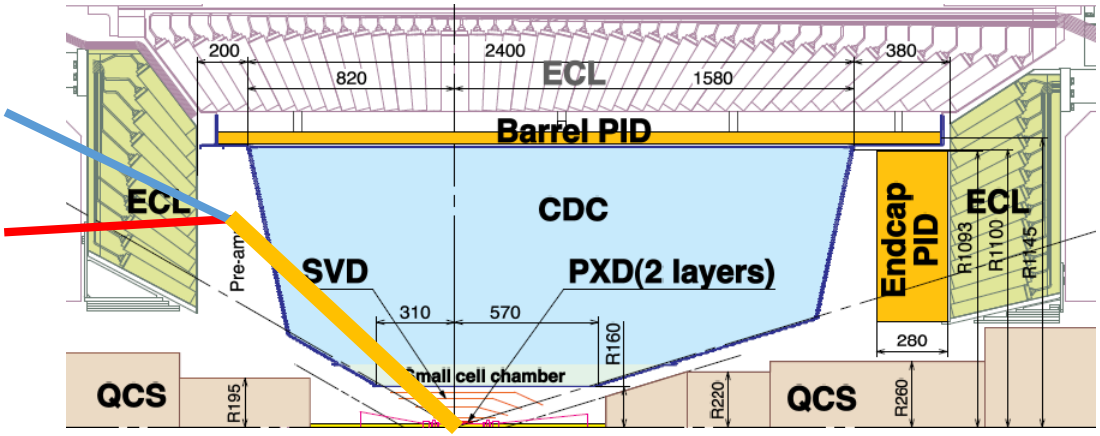
mass is GeV



ECL responce

[13]

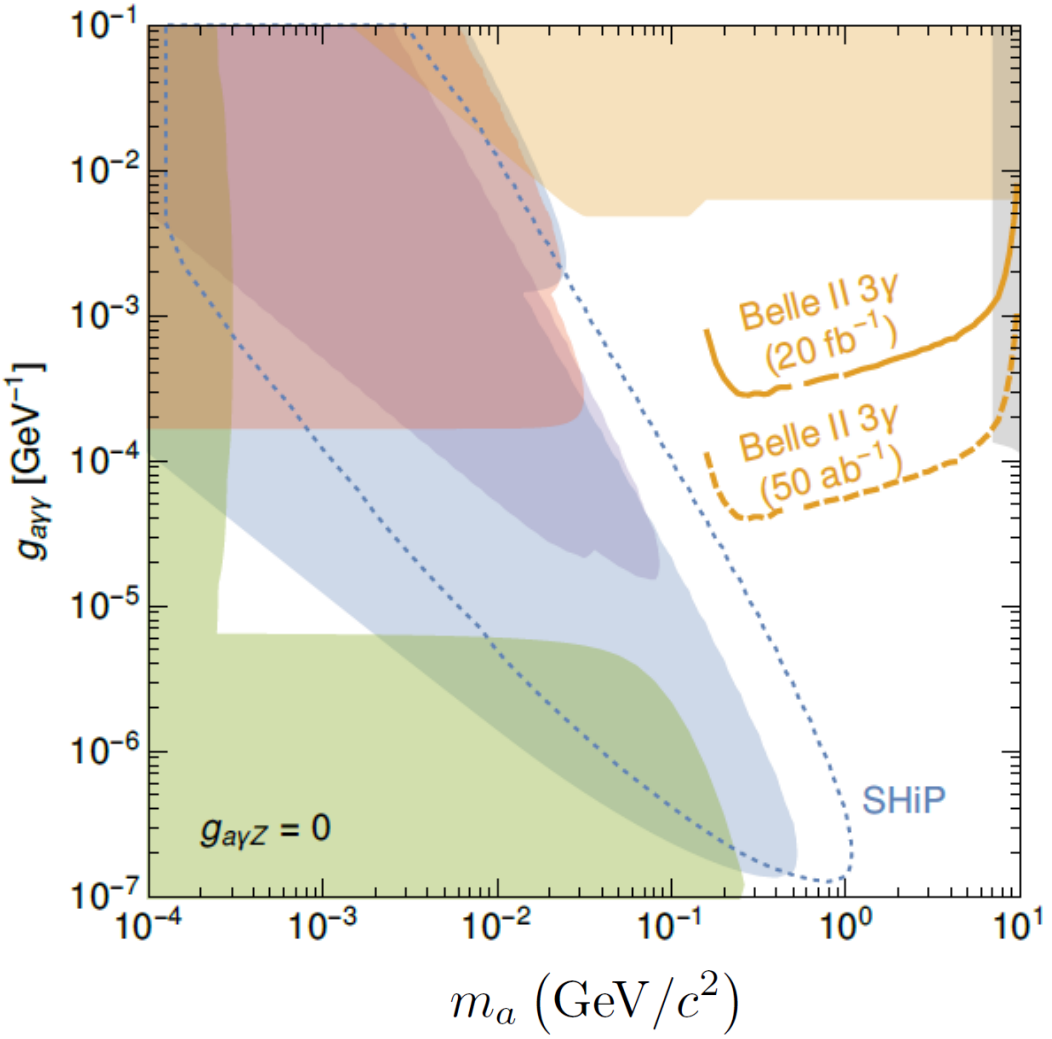
ALP to 2 photons (Selection)



[17]

- Backgrounds [16]
  - $e^+e^- \to \gamma\gamma\gamma$
    - Reduce with helicity selection
  - $e^+e^- \to \gamma\gamma$ + beam background γ
    - Reduce with hit time selection
  - $e^+e^- \to \gamma\gamma,\ \gamma \to e^+e^-$ (outside of tracking volume)
    - Reduce with angle between hits selection
  - $e^+e^- \to \pi^0\gamma, \eta\gamma, \eta'\gamma$
    - Reduce with mass selection

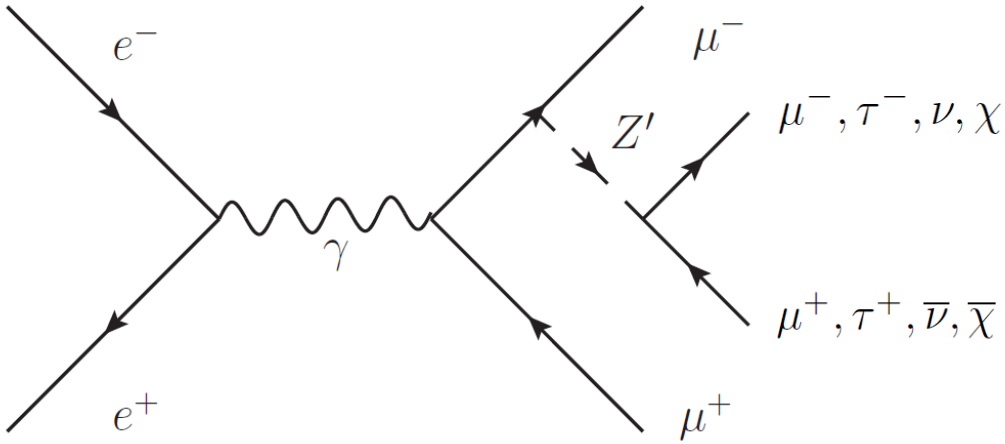
ALP to 2 photons (Sensitivity)



[14]

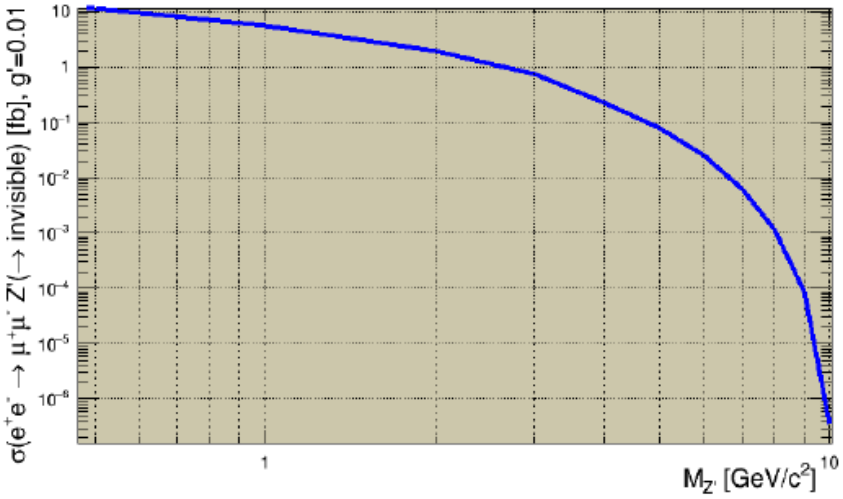
MDF to invisible (at Belle II)

- A gauge boson (Z') that can couple only to 2nd and 3rd lepton generation. [18]
- Z' can decay into invisible particles.



[14]

Cross section using MadGraph

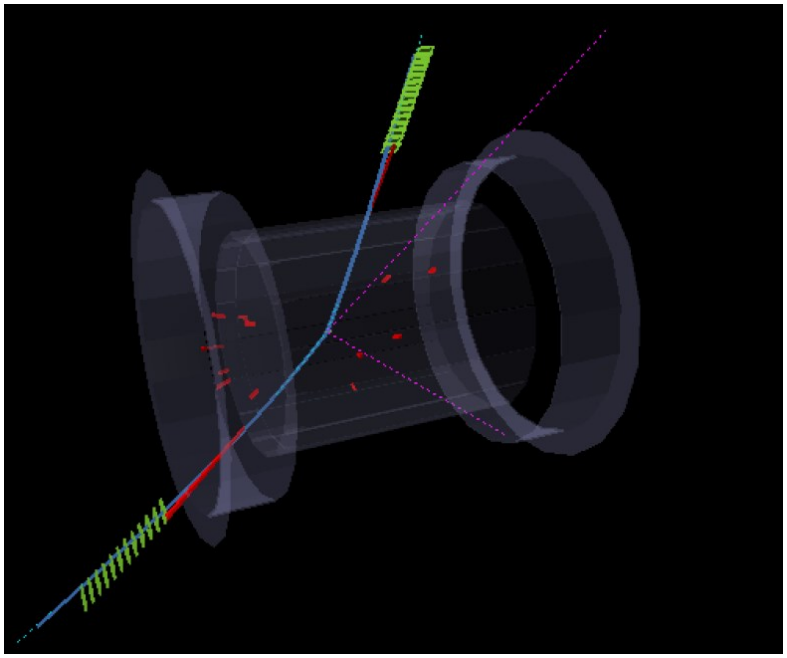


[14]

MDF to invisible (Signal)

- Trigger events that have muons.
  - Two charged tracks + $e^+e^- \to e^+e^-$ veto
  - One charged track + ECL hit

Simulated event: $e^+e^- \to \mu^+\mu^- Z'$

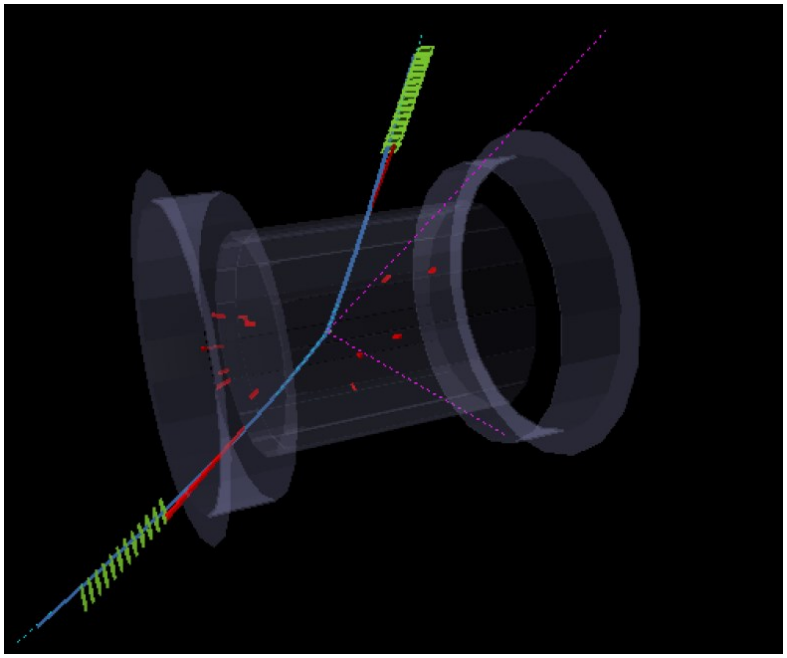


Belle II responce [19]

MDF to invisible (Signal)

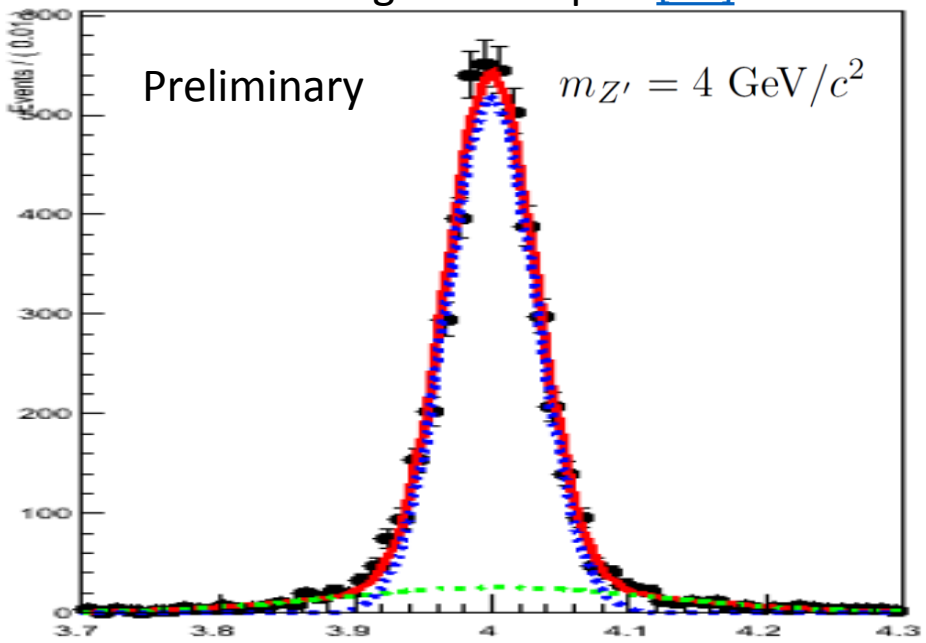
- Trigger events that have muons.
- Observable: Recoiled mass. $M_{\mathrm{recoil}} = \sqrt{s + M^2_{\mu^+\mu^-} - 2\sqrt{s}\left(E^*_{\mu^+} + E^*_{\mu^-}\right)}$

Simulated event: $e^+e^- \to \mu^+\mu^- Z'$



Belle II responce [19]

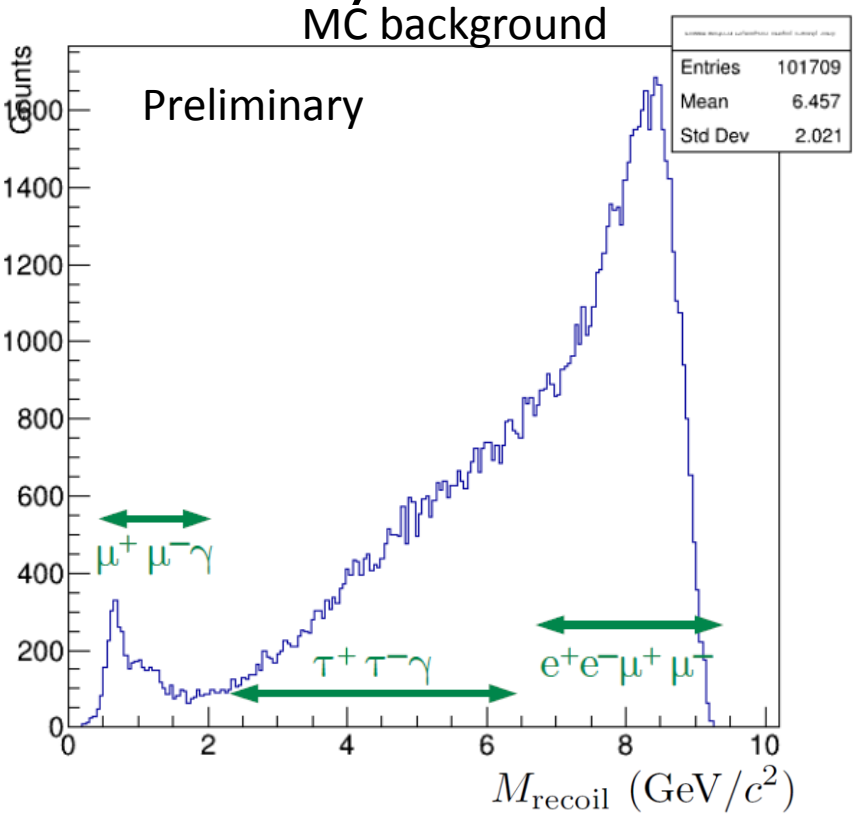
MC signal example [19]



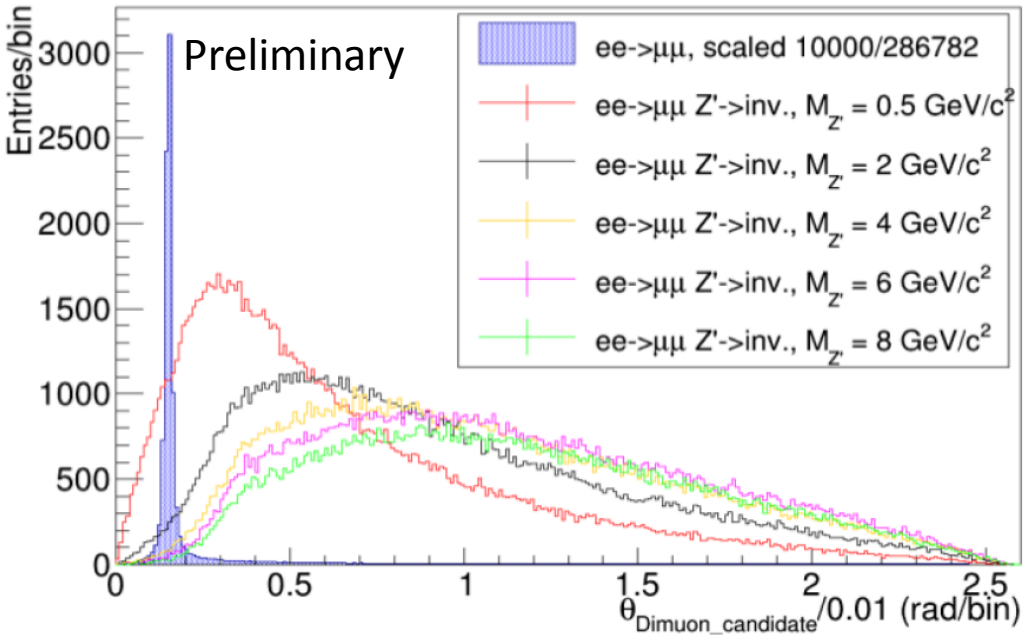
MDF to invisible (Selection)

- Backgrounds
  - $e^+e^- \to \mu^+\mu^-(\gamma)$
  - $e^+e^- \to \tau^+\tau^-(\gamma)$
  - $e^+ e^- \to e^+ e^- \mu^+ \mu^-$
- Selection criteria

MC background



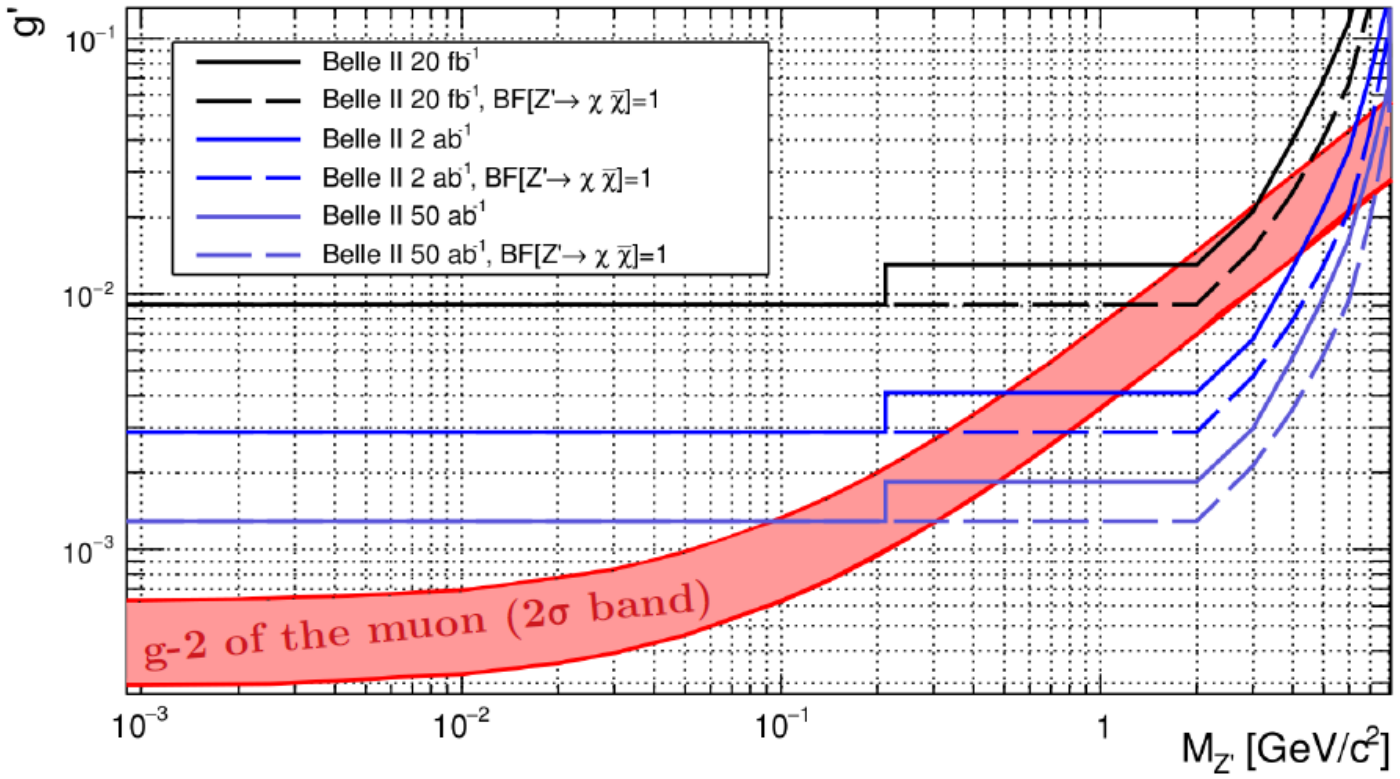
[20]



[20]

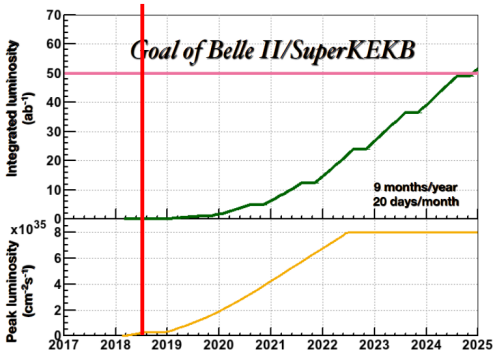
MDF to invisible (Sensitivity)

Preliminary



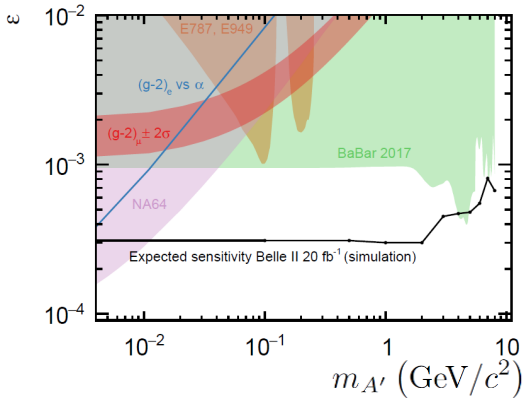
[21]

Summary

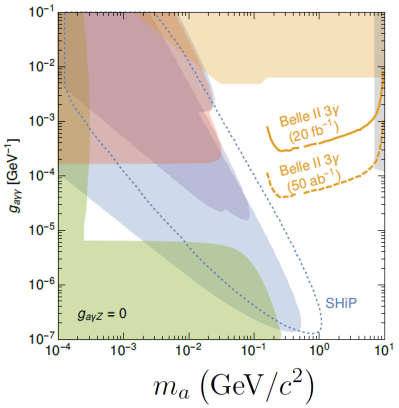


[9]

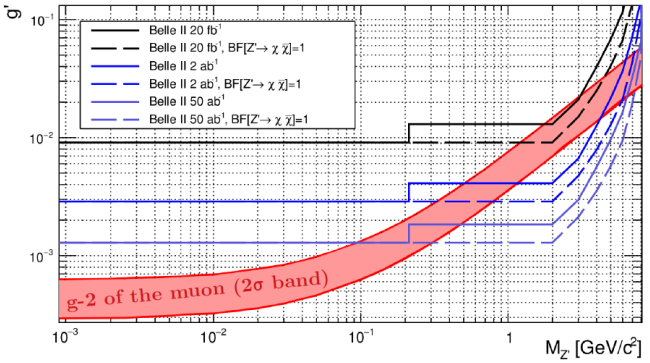
- Belle II has just started recording data.
- Belle II can increase sensitivity in LDS searches
  - Dark photon searches
  - Axion-like particles (ALP) searches
  - Muonic dark force searches
  - And more.



[10]



[14]



[21]