Dark sector @ Phase 2: dark photon et al.

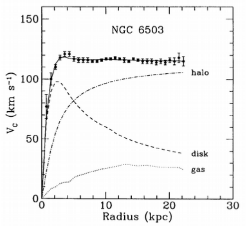
Giacomo De Pietro

Università di Roma Tre *INFN Roma Tre*

9th Belle II Italian Meeting @ Torino

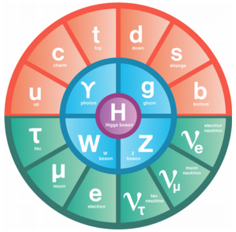
23-24 May 2018

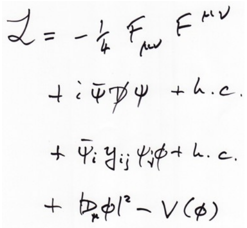
Dark Matter coupling to SM



Dark Matter

X





Standard Model

Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

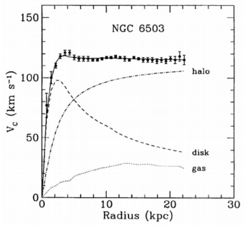
Vector portal → Dark Photon

Scalar portal → Dark Higgs/Scalars

Pseudoscalar portal → Axion-Like Particles

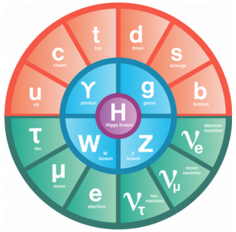
Neutrino portal → Sterile Neutrinos

Dark Matter coupling to SM



Dark Matter

X



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

Standard Model

Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

Vector portal → Dark Photon

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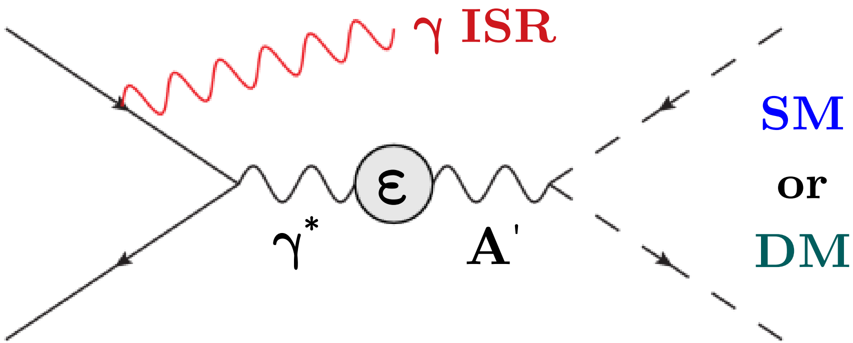
Competitive studies with Phase 2 data!

Dark Photon

A massive Dark Photon **A'** can mix with SM with coupling strength ε:

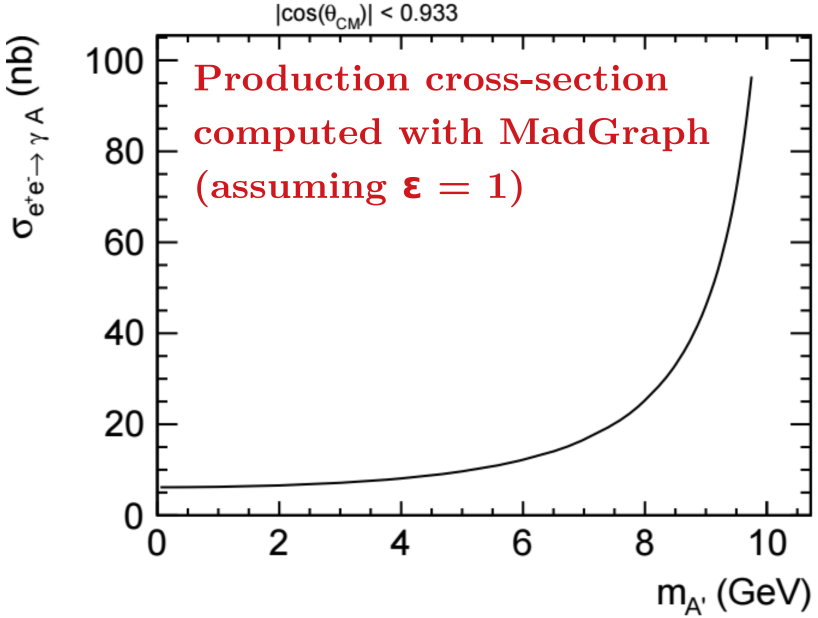
$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$



Depending on DM mass, a dark photon decays to:

DM (if $m_{DM} < \frac{1}{2} m_{A'}$) → **invisible decay**

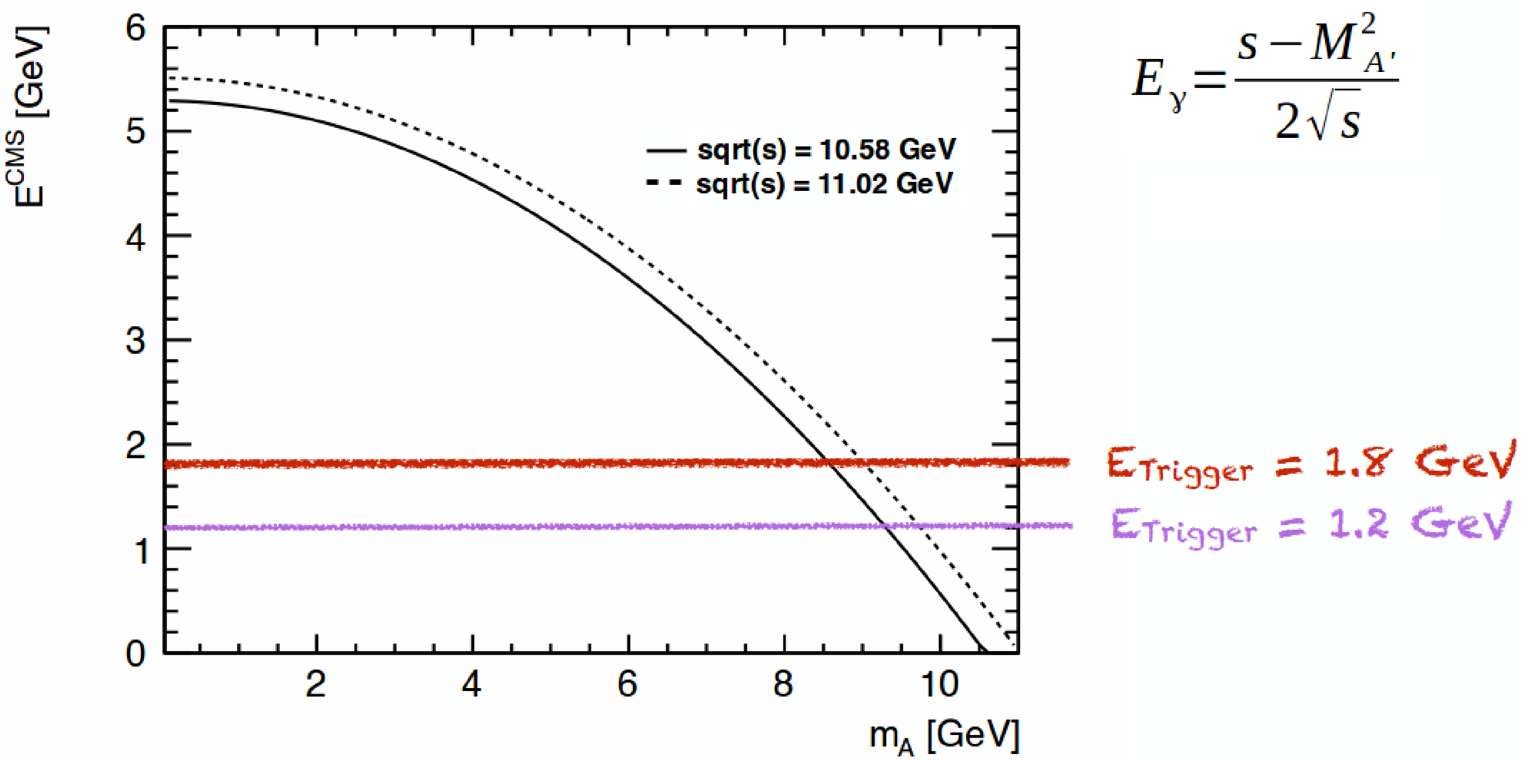
SM (if $m_{DM} > \frac{1}{2} m_{A'}$) → **visible decay**



Dark Photon: invisible decay (signal)

Signal signature:

- a single, mono-chromatic, high-E photon (**ISR photon**)
- a bump in the recoil mass:



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

Dark Photon: invisible decay (signal)

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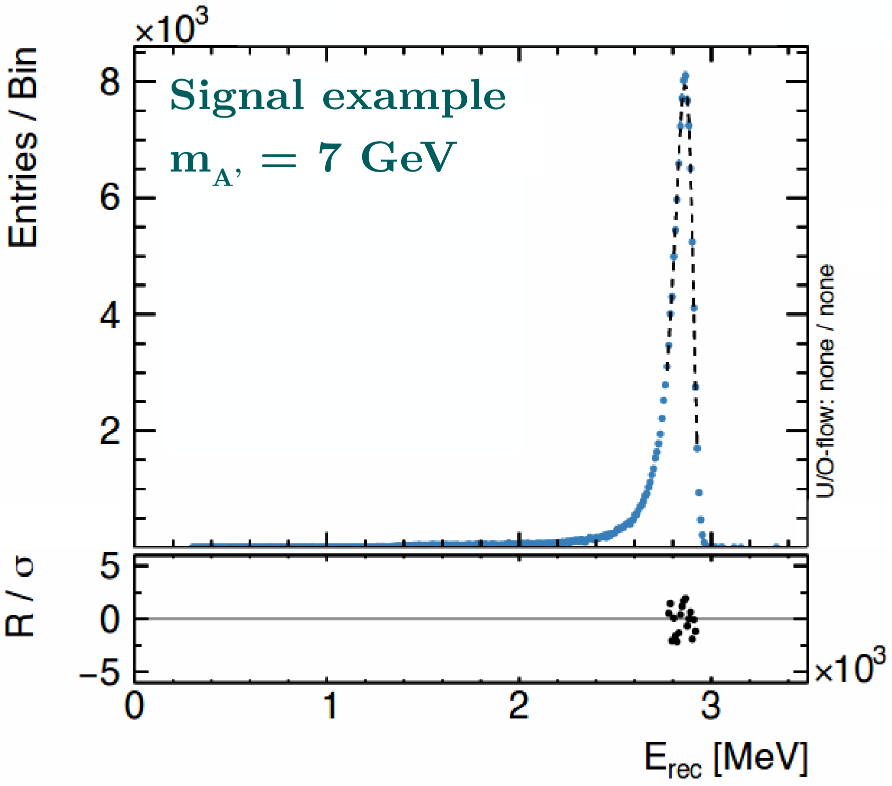
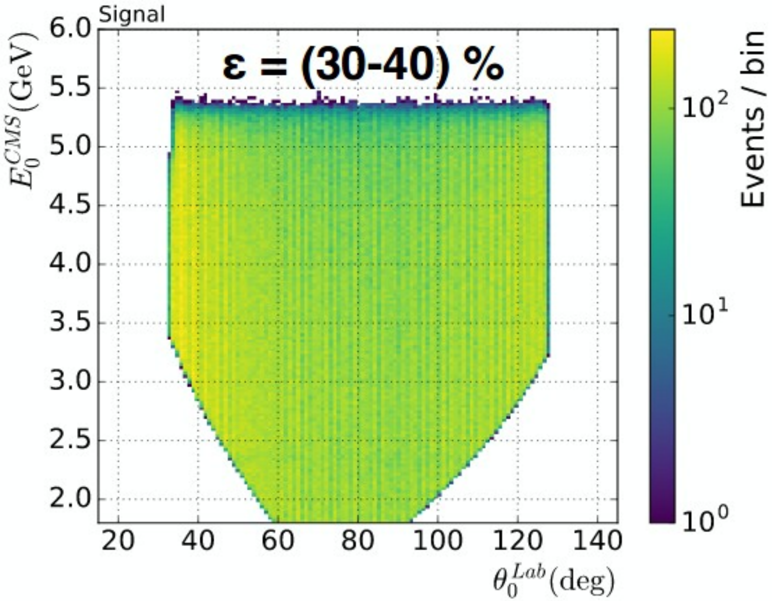
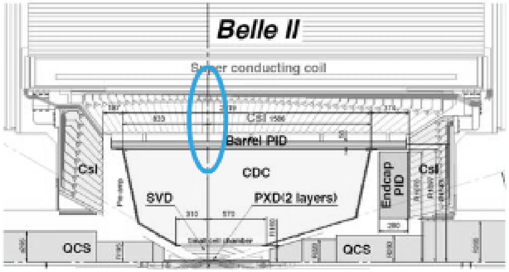




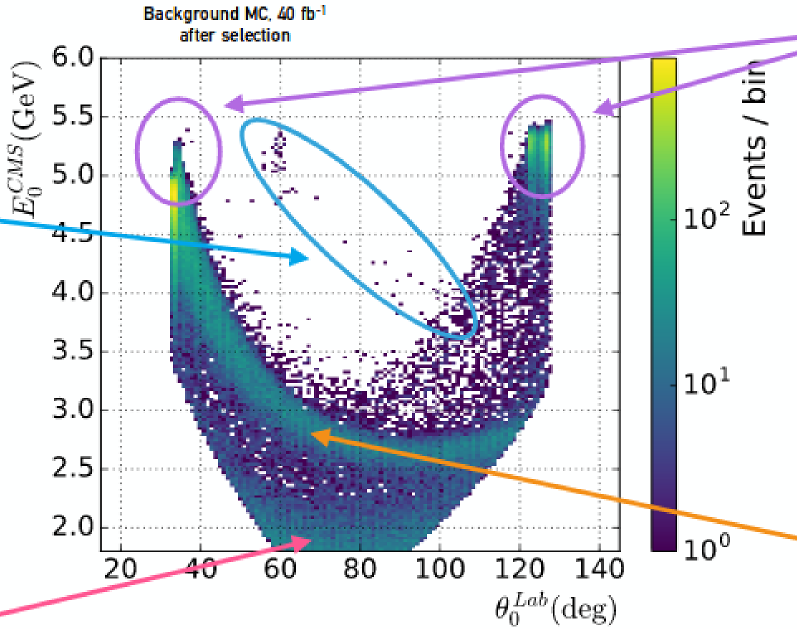
Signal signature:

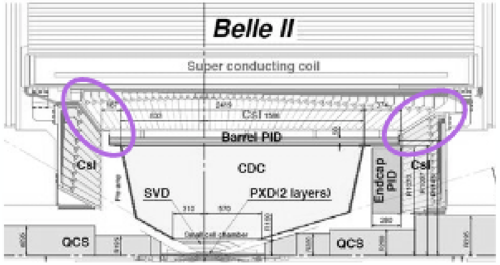
peak in E_{CMS} (horizontal band)

Dark Photon: invisible decay (background)

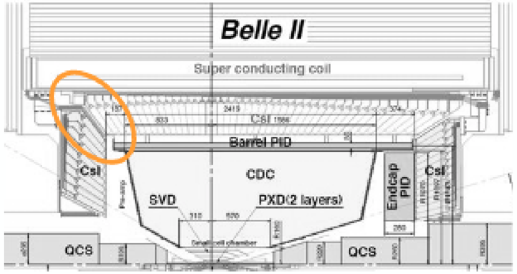


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance





ee→2γ
1γ in ECL BWD or FWD gap



ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance

Signal signature:
peak in E_{CMS} (horizontal band)

Single photon trigger

Trigger logic	L1 rate at full luminosity
E $>$ 1 GeV + 2^{nd} cluster E $<$ 300 MeV	4 kHz (barrel) 7 kHz (endcaps)
E $>$ 2 GeV + Bhabba & $\gamma\gamma$ vetoes	5 kHz (barrel)

Rates OK for Phase 2:

(max 8 kHz)

Max. L1 rate for Phase 3:

$<$ 30 kHz

Sustainable for Phase 3?

Single photon trigger

News from the Technical Board

of this morning (by Nakazawa-san)

Trigger for Dark

- Based on ECL trigger, number of isolated cluster and energy sum triggers
  - Number of isolated clusters
    - No timing, energy, position information
  - Energy sum in lab frame
  - Tracking triggers as veto
- Activated since this Monday runs (r2001-) with prescale factor 1.

2 B2TB 20180523, Dark Trigger

Bits

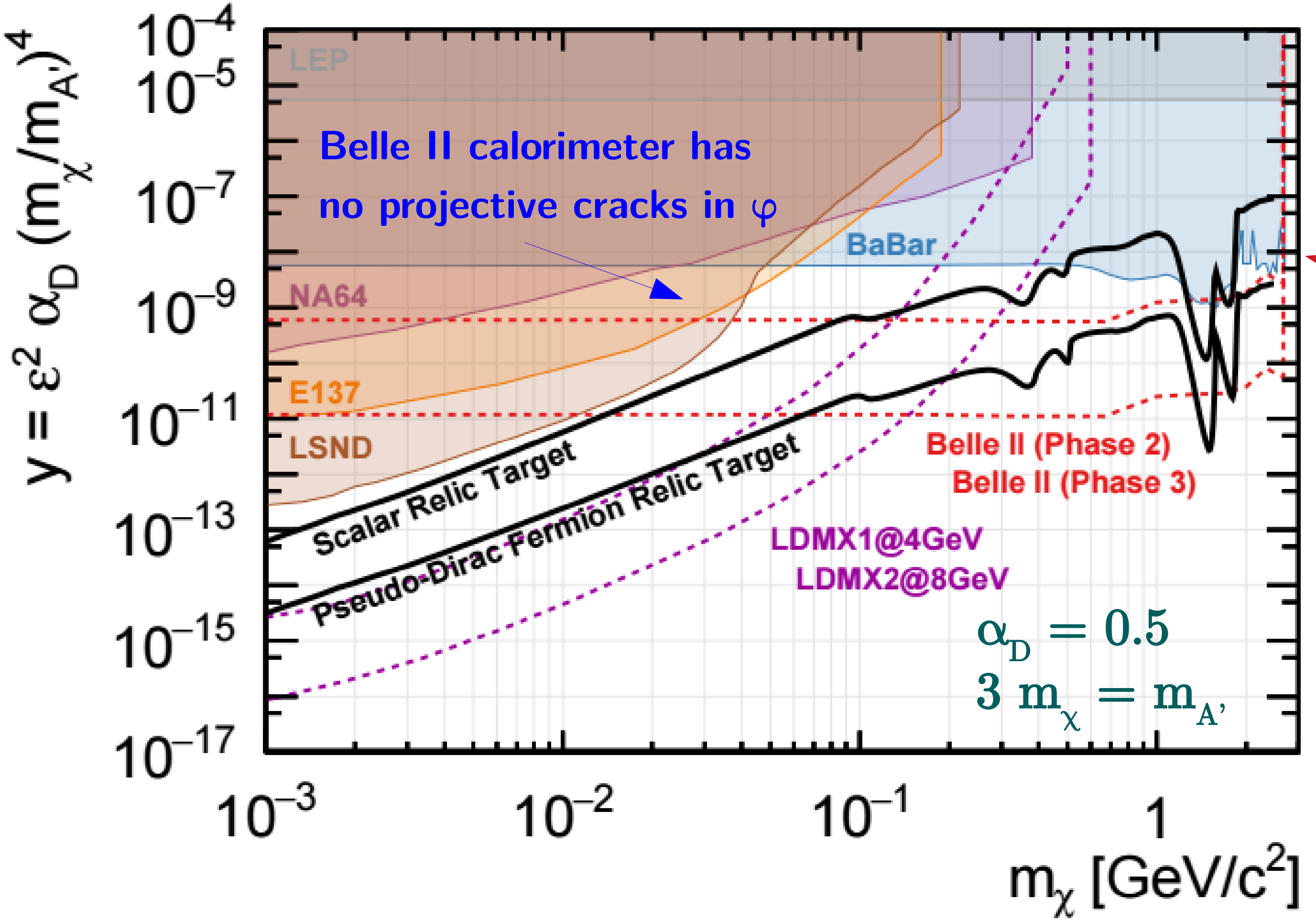
		Rate (Hz)
c1hie	clst=1 & energy > 1GeV	78.4
c1lume	clst=1 & energy > 3GeV	16.2
n1hie	clst=1 & energy > 1GeV & track=0	78.1
n1lume	clst=1 & energy > 3GeV & track=0	16.1
c3hie	clst=3 & energy > 1GeV	53.7
c3lume	clst=3 & energy > 3GeV	2.6
n3hie	clst=3 & energy > 1GeV & track=0	53.4
n3lume	clst=3 & energy > 3GeV & track=0	2.6

L1 rate = 378 Hz

3 B2TB 20180523, Dark Trigger

Dark Photon: invisible decay (sensitivity)

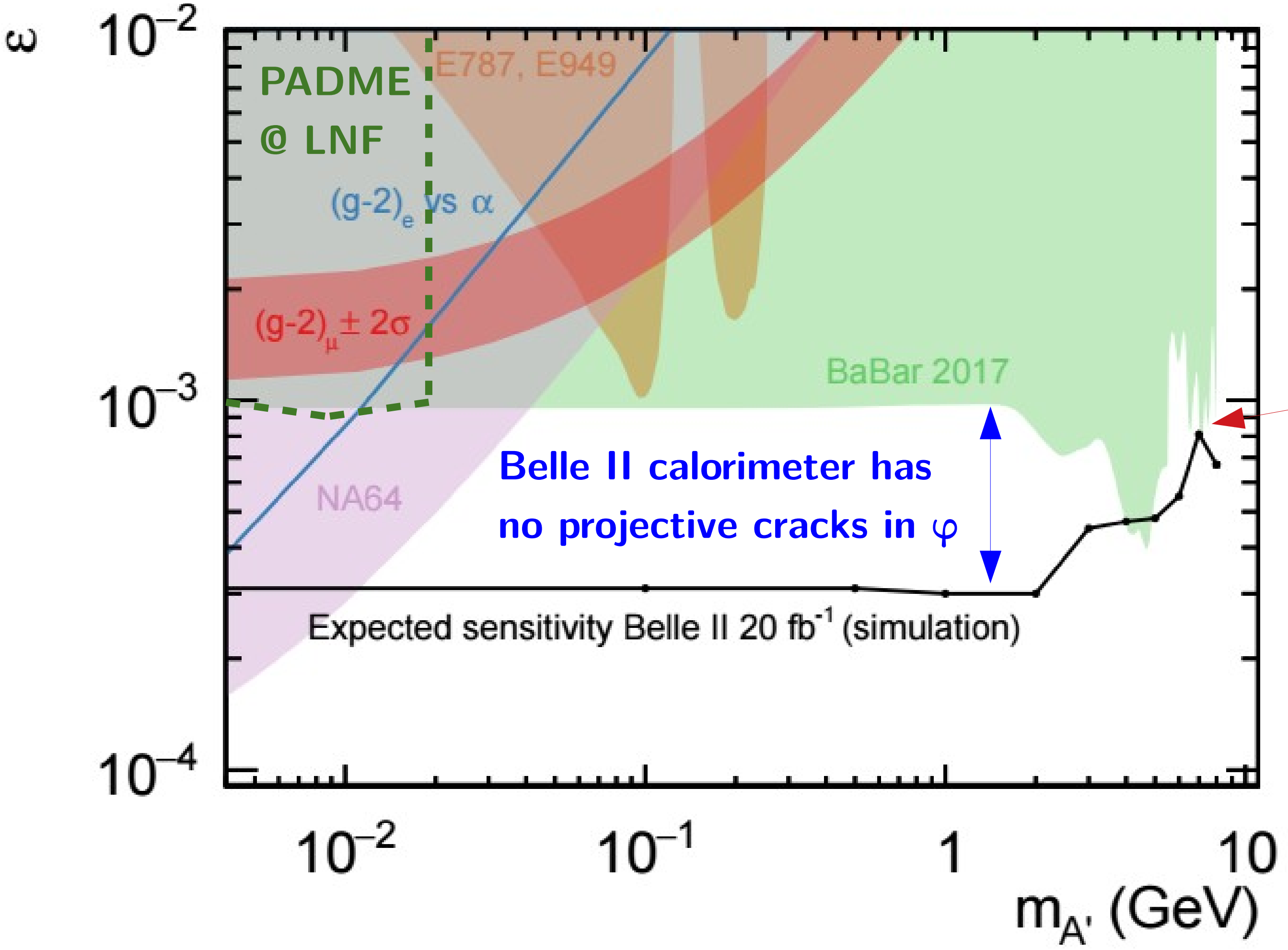
Belle II



Lower trigger threshold wrt BaBar

N.B.:
part of the BaBar data with Single photon trigger was below the 4S

Dark Photon: invisible decay (sensitivity)



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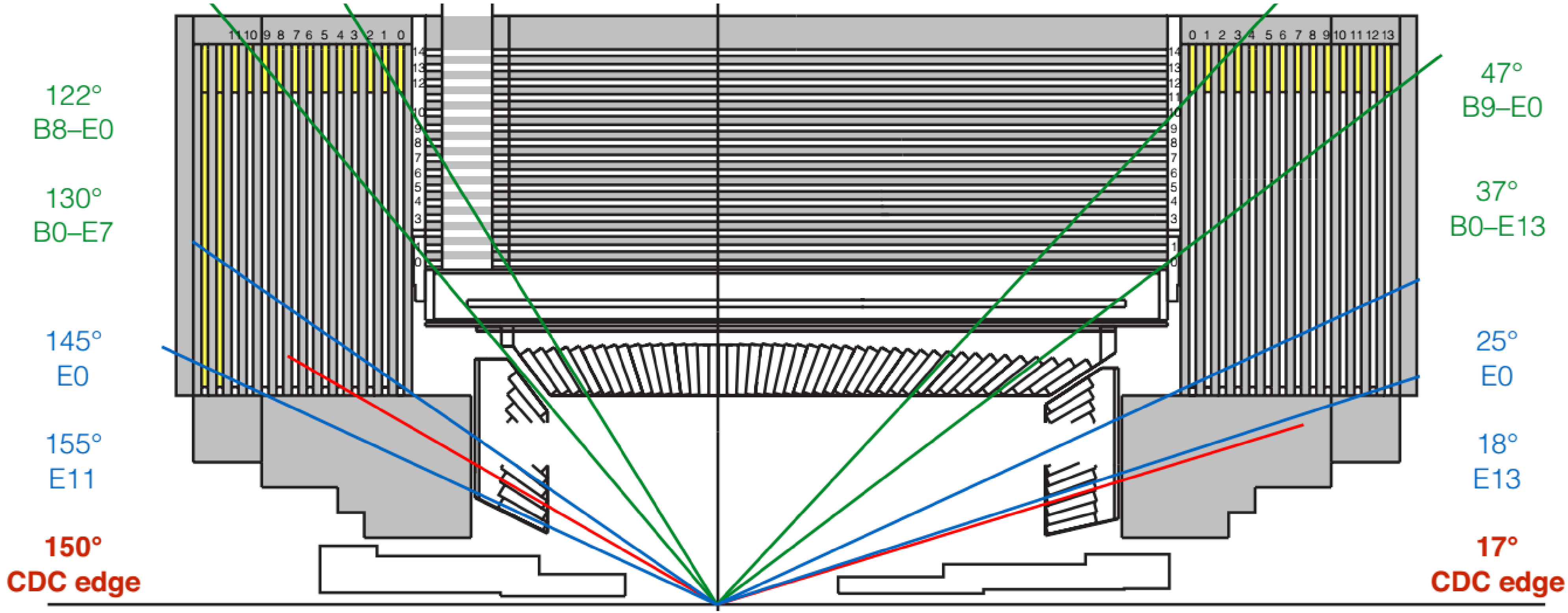
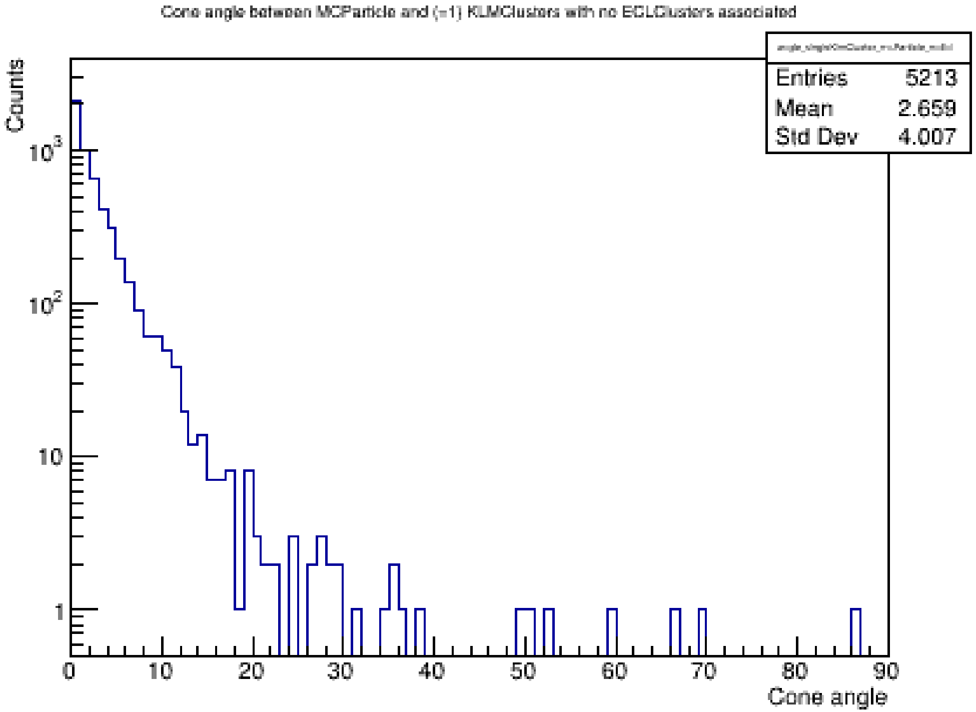
Dark Photon: the KLM veto

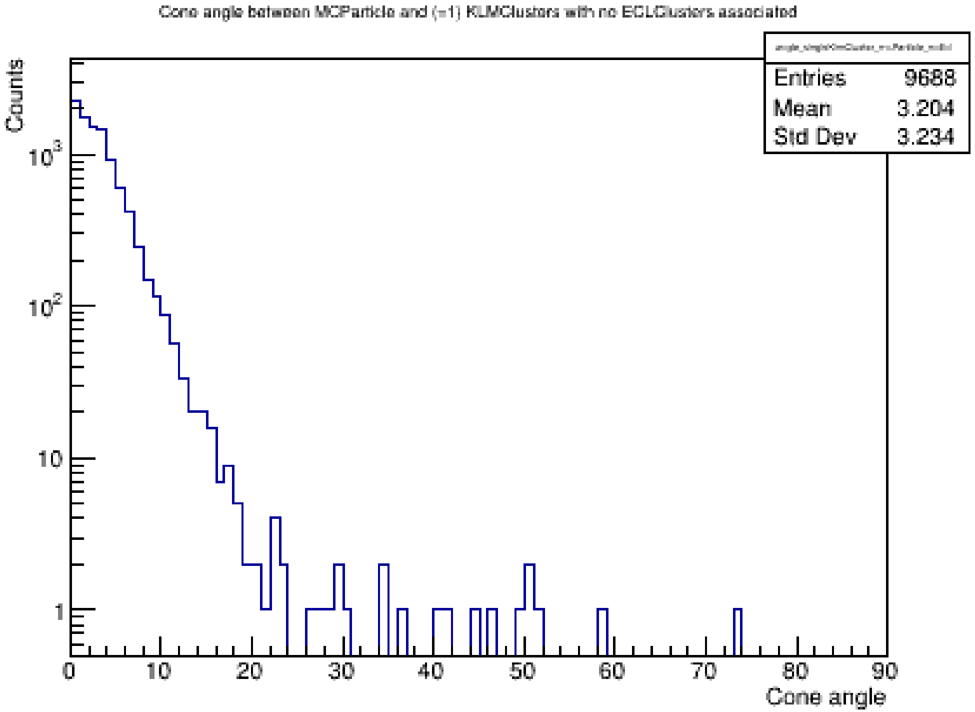


Dark Photon: the KLM veto

"Cone" angle between MCPhotons (with no ECLClusters associated) and KLMCluster associated



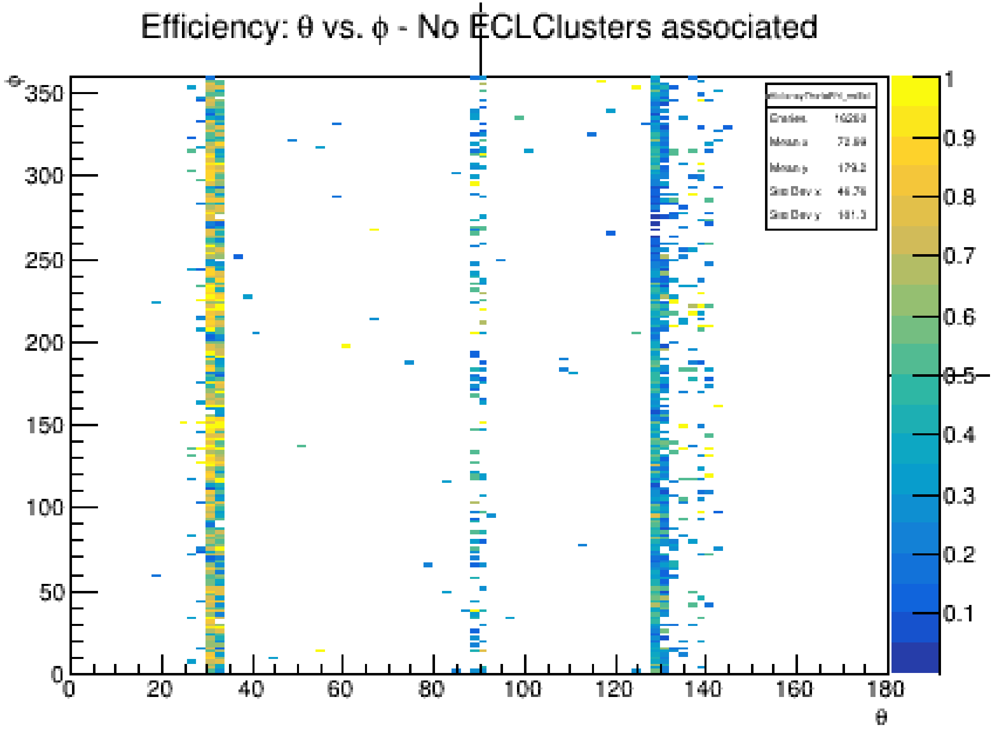
1 GeV < E < 2 GeV



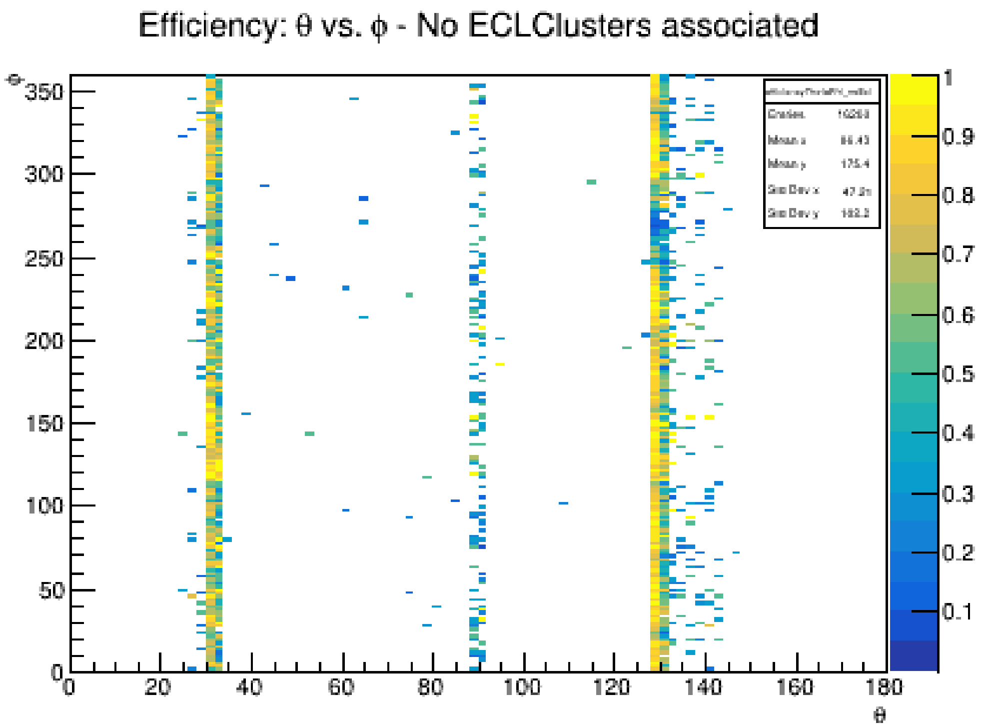
5 GeV < E < 6 GeV

Dark Photon: the KLM veto

$$\frac{\#\ \text{MCPhotons with} >0\ \text{KLMClusters \& 0 ECLClusters associated}}{\#\ \text{MCPhotons with 0 ECLClusters associated}}$$



1 GeV < E < 2 GeV



5 GeV < E < 6 GeV

theta and phi
of the MCPhoton

Dark Photon: the KLM veto

Strategies to measure the KLM efficiency with Phase 2 data:

- mu mu (g) events
- g g events, with 1 g not fully reconstructed in ECL

A (little) concern:

quality of scintillators data during Phase 2;

N.B.: the scintillators are CRUCIAL for this measurement!

Axion-Like Particles

Axion-Like Particles (ALPs) are pseudo-scalars and couple to bosons.

Unlike QCD Axions, ALPs have no relation between mass and coupling.

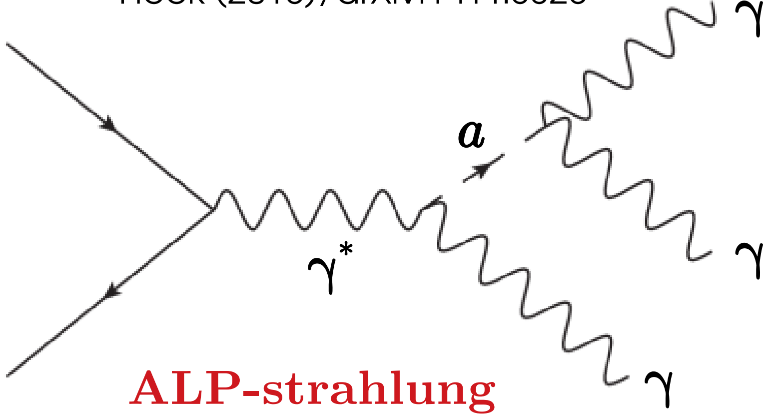
I will focus on the **coupling to photons**:

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

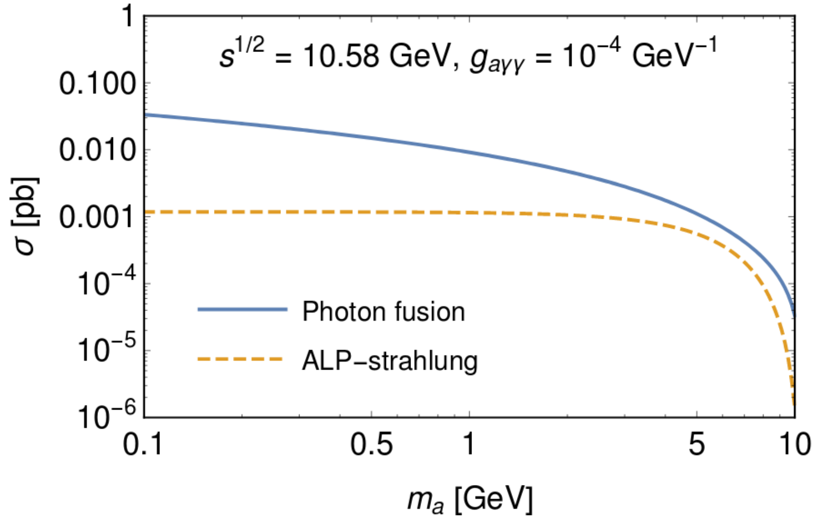
N.B. $\tau \sim 1 / g_{a\gamma\gamma}{}^2 M_a{}^3$

Belle II will study the **ALP-strahlung** case (low sensitivity to photon fusion production)

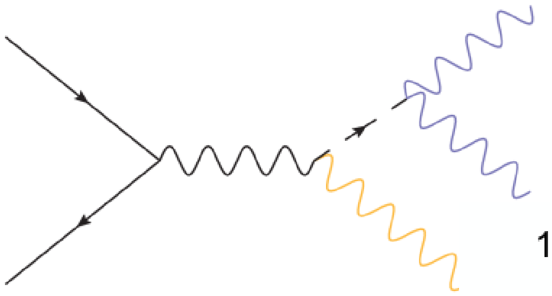
Hook (2015), arXiv:1411.3325



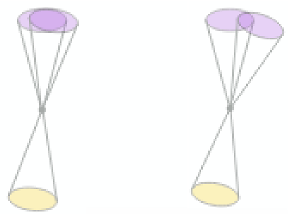
ALP-strahlung



Axion-Like Particles (signal)



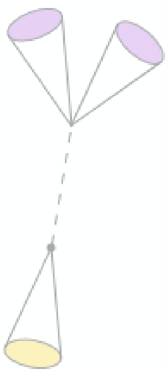
Two of the photons overlap or **merge**.

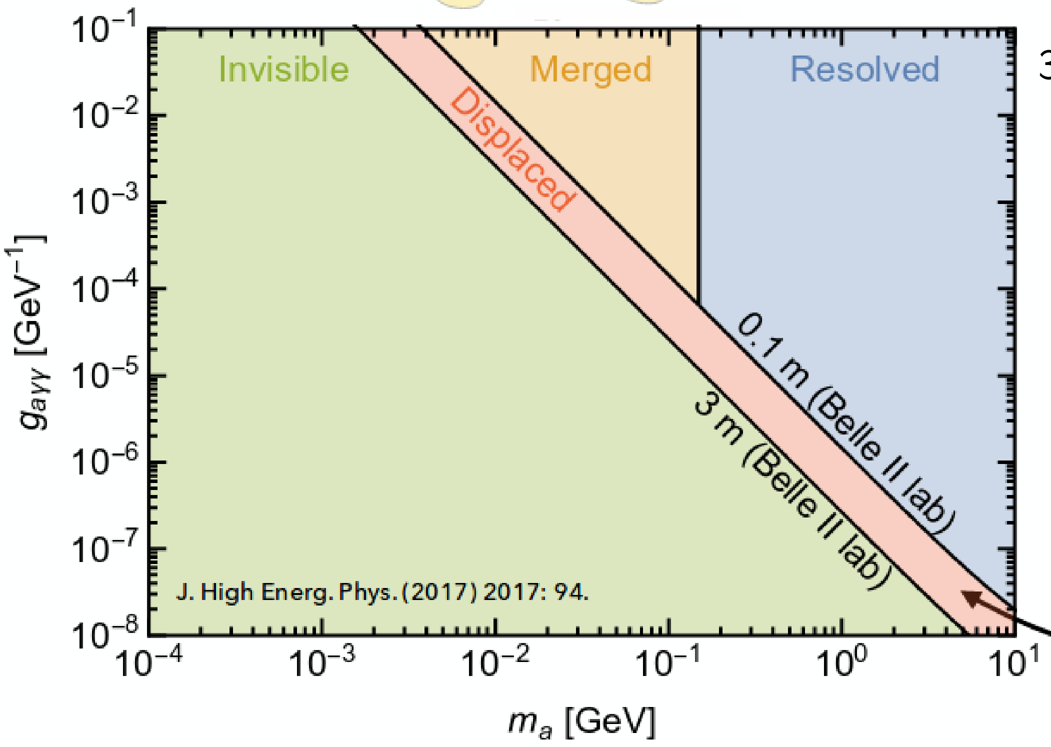


For **resolved** case:

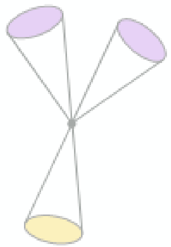
3 clusters with $E_{CM} > 0.25$ GeV

Peak in $\gamma\gamma$ mass spectrum





Three **resolved**, high energetic photons.

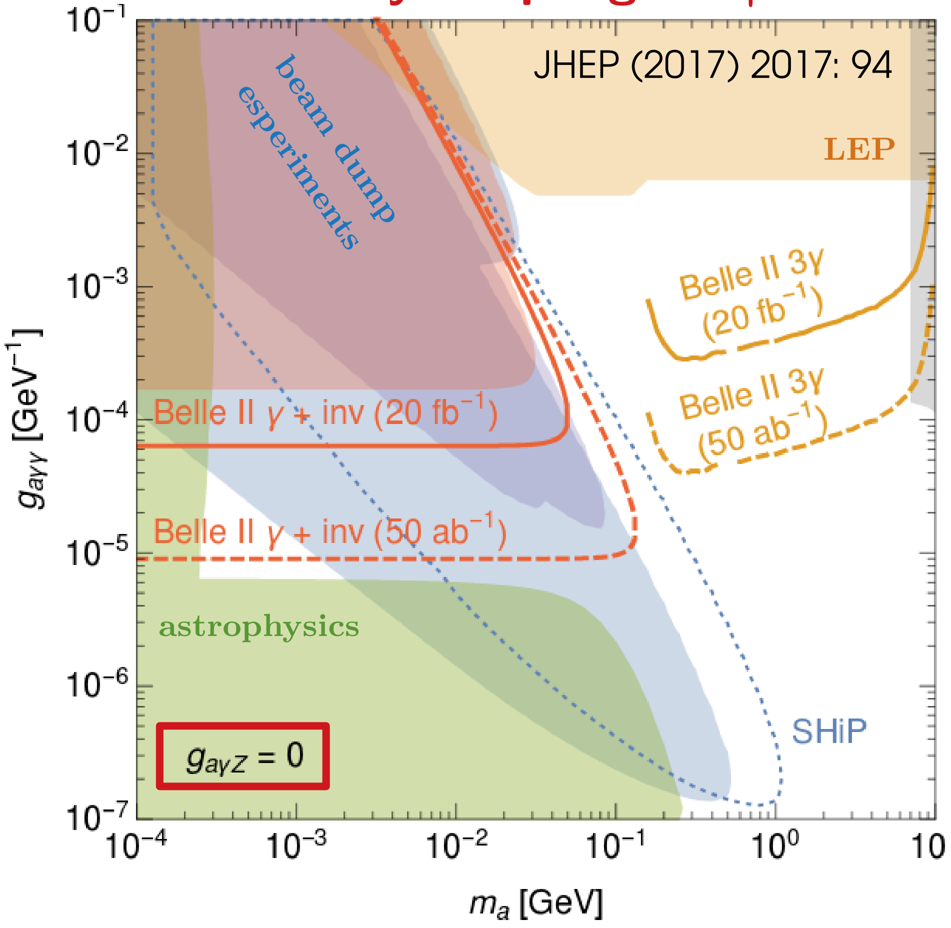


ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

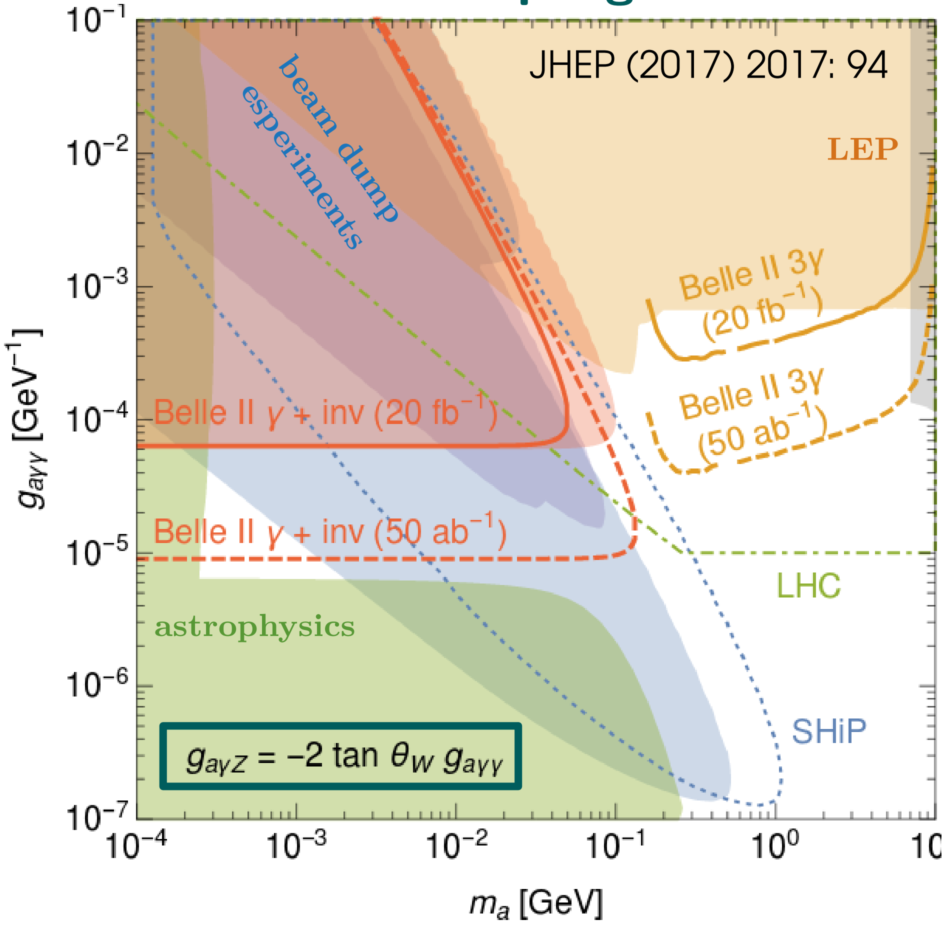
The searches for invisible and visible ALP decays veto this region.

Axion-Like Particles (sensitivity)

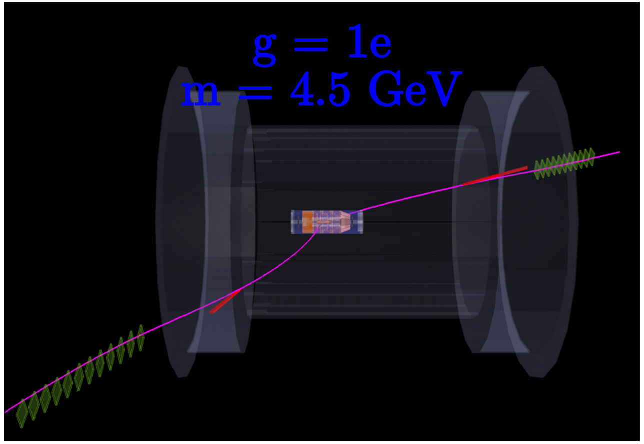
Only coupling to γ



With coupling to Z



Magnetic monopoles

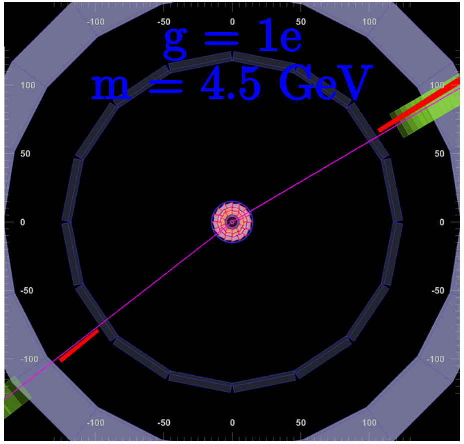


Minimal magnetic charge

from Dirac quantization: $g_D = 68.5e$

Lower magnetic charge is not ruled out

(and not covered at ~GeV scale)



Interesting predictions* for

g ~ e and **m = 4.5 GeV**...

* arXiv:1707.05295

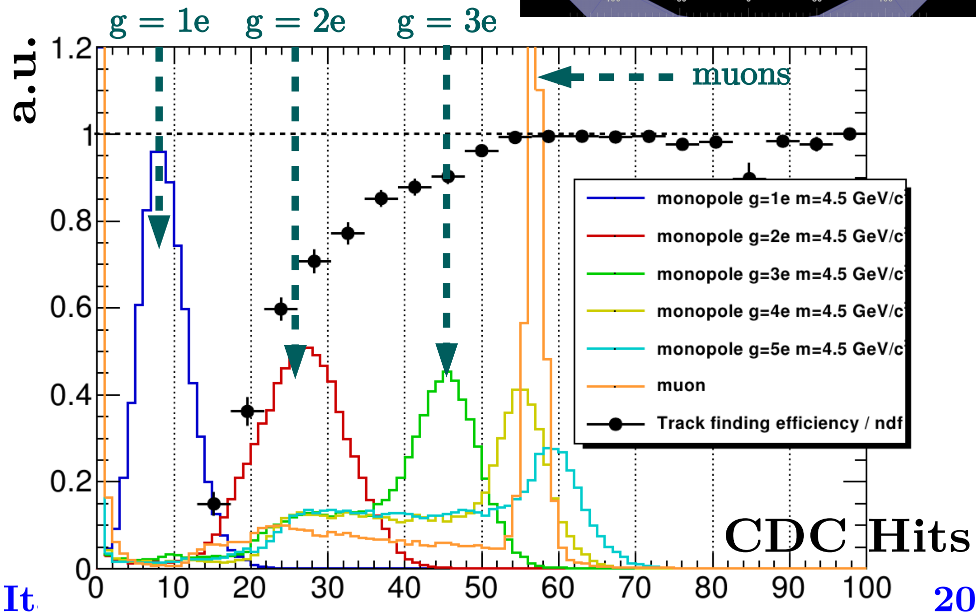
... but not-relativistic at Belle II:

→ no $1/\beta^2$ term in dE/dx for magnetic charges

→ few hits in the CDC

→ **needed a dedicated tracking**

(also because: "non-standard" tracks)



Other dark sector and exotic searches

Visible Dark Photon decays

Off-shell Dark Photon decays

Long-lived neutral particle decays

Dark Scalar:

$e^+ e^- \rightarrow \tau^+ \tau^- S$; $S \rightarrow l^+ l^-$

Invisible $\Upsilon(1S)$ decays via:

$\Upsilon(3S) \rightarrow \Upsilon(1S)\, \pi^+ \pi^-$

Muonic Dark Force:

*$e^+ e^- \rightarrow \mu^+ \mu^- Z'$; $Z' \rightarrow$ insivible

$e^+ e^- \rightarrow \mu^+ \mu^- Z'$; $Z' \rightarrow \mu^+ \mu^-$

LFV:

*$e^+ e^- \rightarrow e^+ \mu^- Z'$; $Z' \rightarrow$ invisible

*$e^+ e^- \rightarrow e^+ \mu^- Z'$; $Z' \rightarrow e^+ \mu^-$

* More details later in Enrico's talk!

Thank you for your attention!

Piramide Cestia

Porta San Paolo

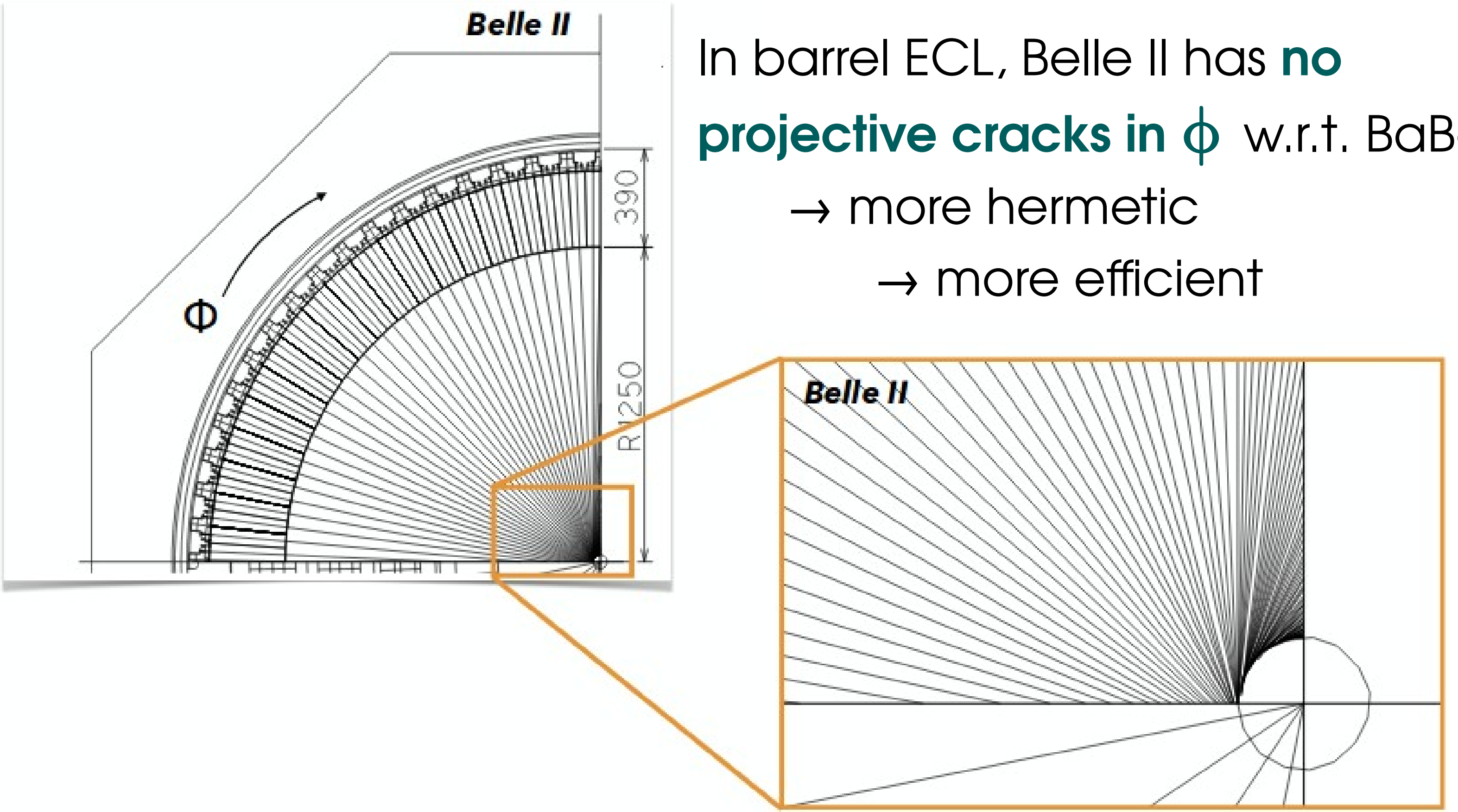
Dark portal

Backup slides

In barrel ECL, Belle II has **no projective cracks in ϕ** w.r.t. BaBar:

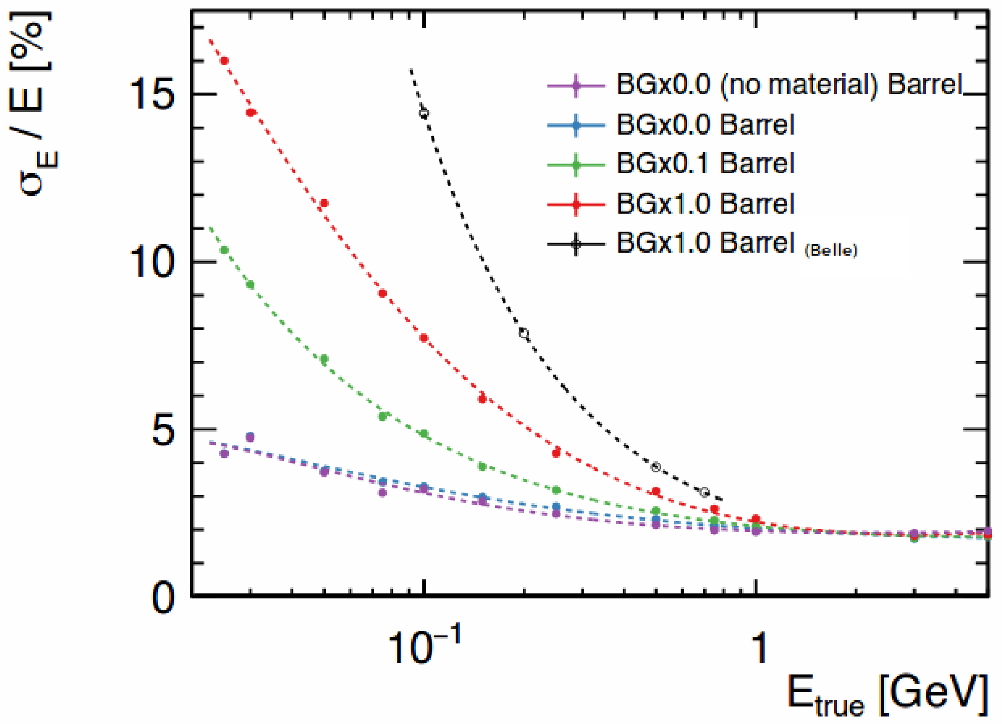
→ more hermetic

→ more efficient

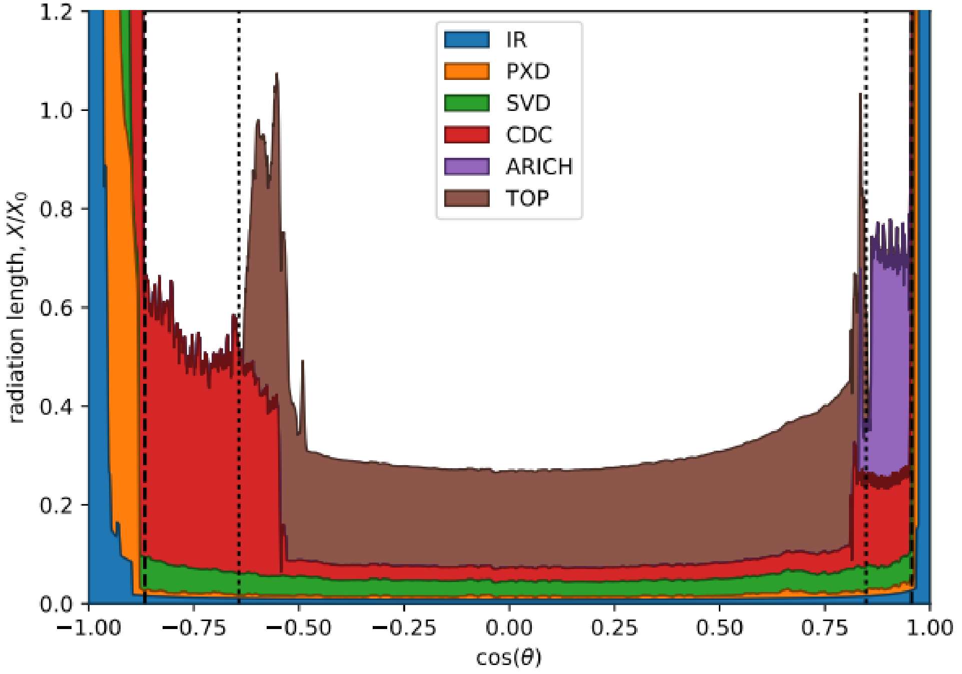


Electromagnetic Calorimeter (ECL)

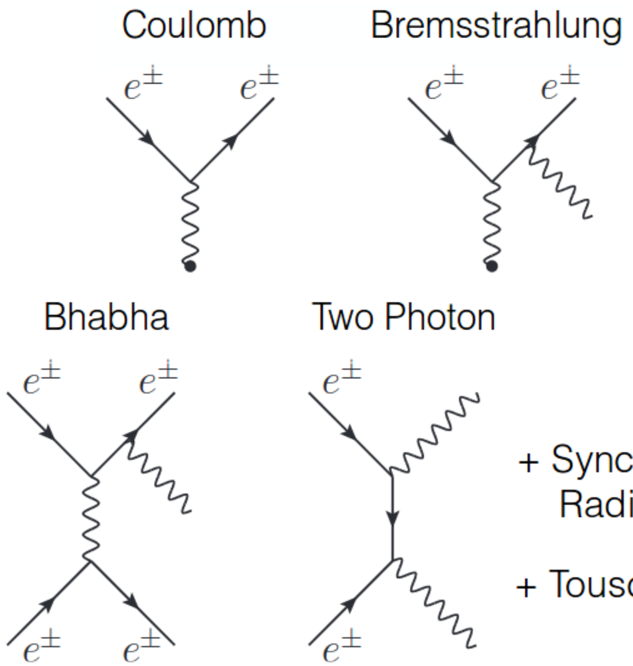
Energy resolution in Belle II barrel:



Material budget in front of ECL:

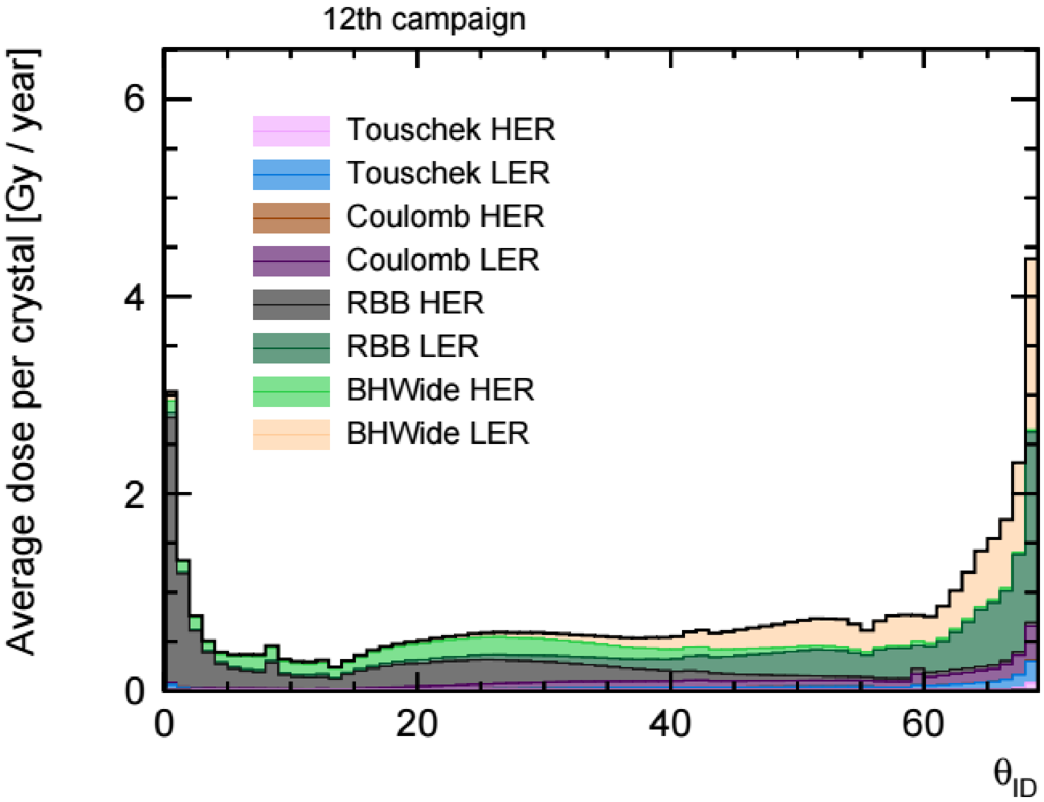


Beam background



+ Synchrotron Radiation

+ Touschek



Effects from beam background:

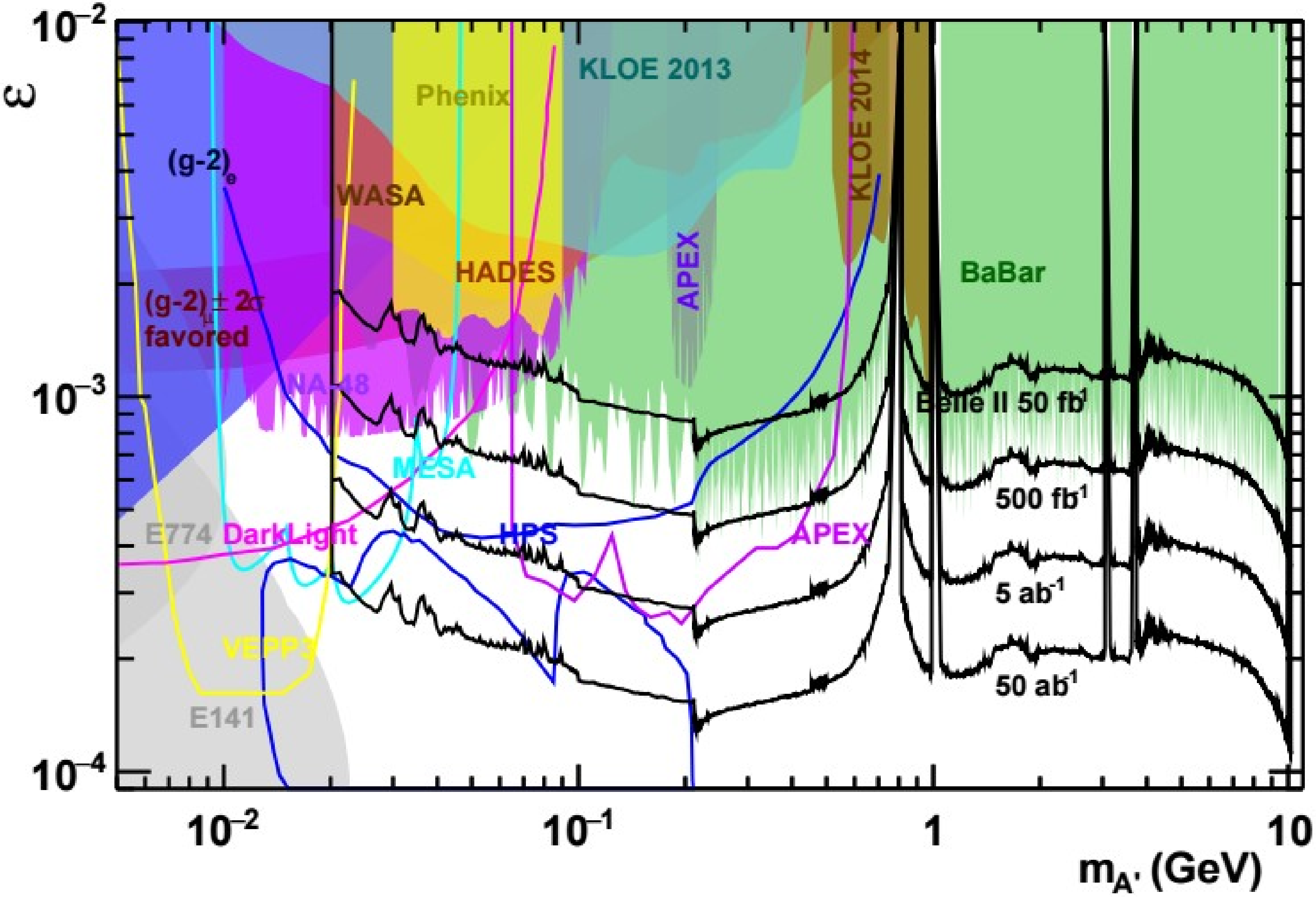
→ degrades calorimeter resolution.

→ radiation damage.

→ pile-up and event size.

→ physics background

Dark Photon: visible decay

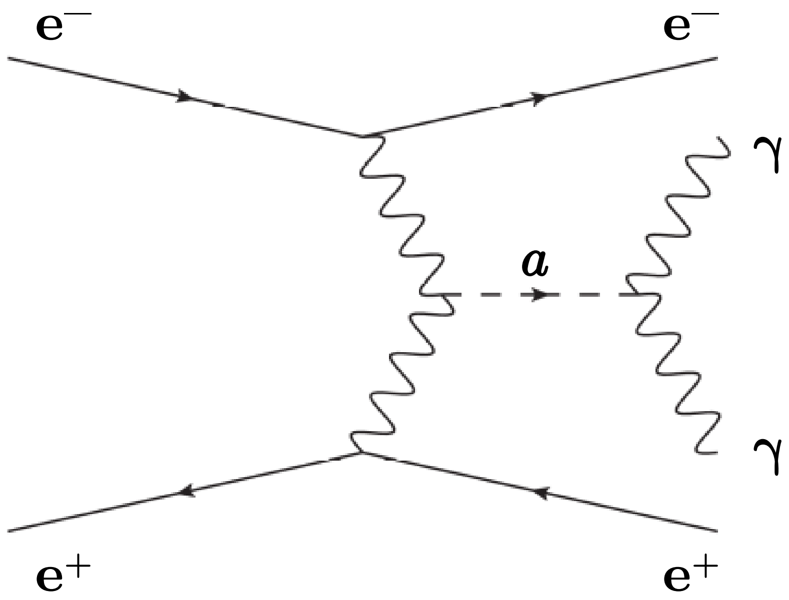


ALPs: low-mass region

Belle II: ALPs below 200 MeV?

- For ALP masses below ~200 MeV, the decay photons are reconstructed as one ECL cluster even in offline analysis. Currently under study:
  - Untagged (electrons not seen) ALP fusion production has a much higher cross section and produces ALPs with less boost (difficult to trigger).
  - Shower shapes for merged cluster are different, MVA based reconstruction has better separation power (but events have to pass L1 trigger).
  - Pair conversion of one decay photon costs statistics, but yields a distinctive four particle final state.

ALP-fusion



Pro: resolved clusters

Con: very low-energy photons