First data at Belle II: dark sector physics

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for the Belle II Collaboration

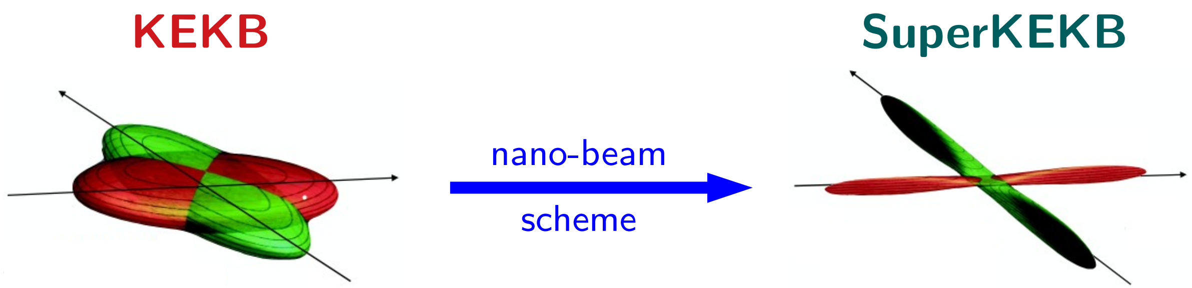
BEAUTY 2018 @ La Biodola (Elba island, Italy)

07-11 May 2018

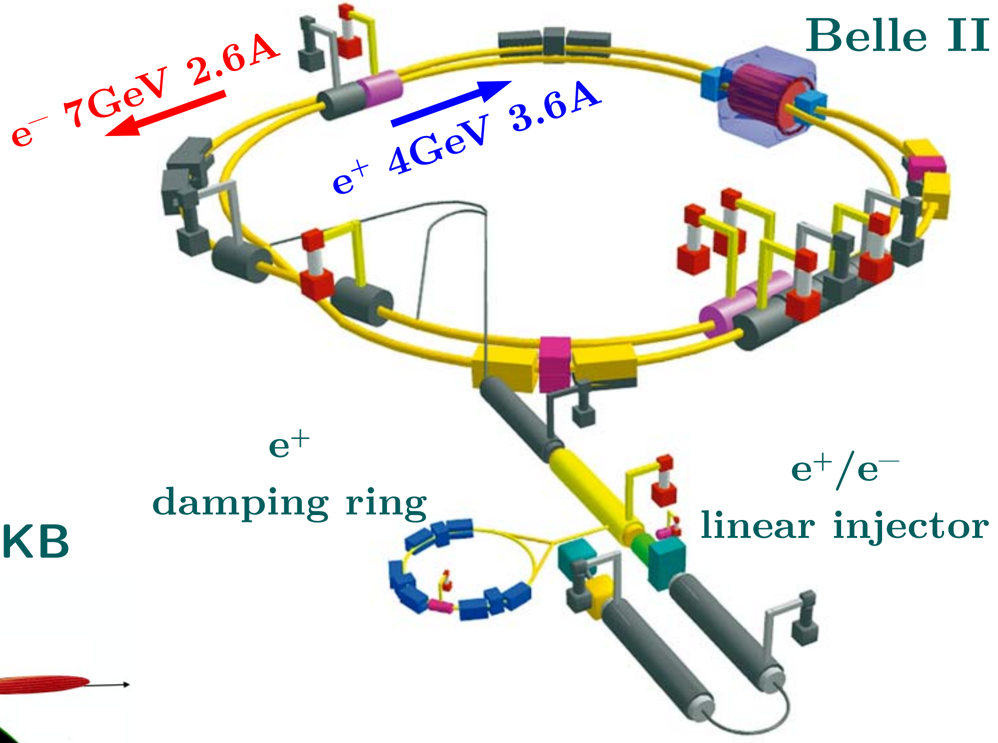
SuperKEKB: an Intensity Frontier machine

SuperKEKB is a super B-factory located at KEK (Tsukuba, Japan)

It's an asymmetric e^+e^- collider operating mainly at **10.58 GeV**
(**Υ(4S)**, but possible runs from Υ(2S) to Υ(6S))



KEKB	SuperKEKB
I (A): ~ 1.6/1.2	I (A): ~ 3.6/2.6
β^*_y (mm): ~ 5.9/5.9	β^*_y (mm): ~ 0.27/0.3



40x peak luminosity: $8 \cdot 10^{35}$ cm^{-2} s^{-1}

SuperKEKB: an Intensity Frontier machine

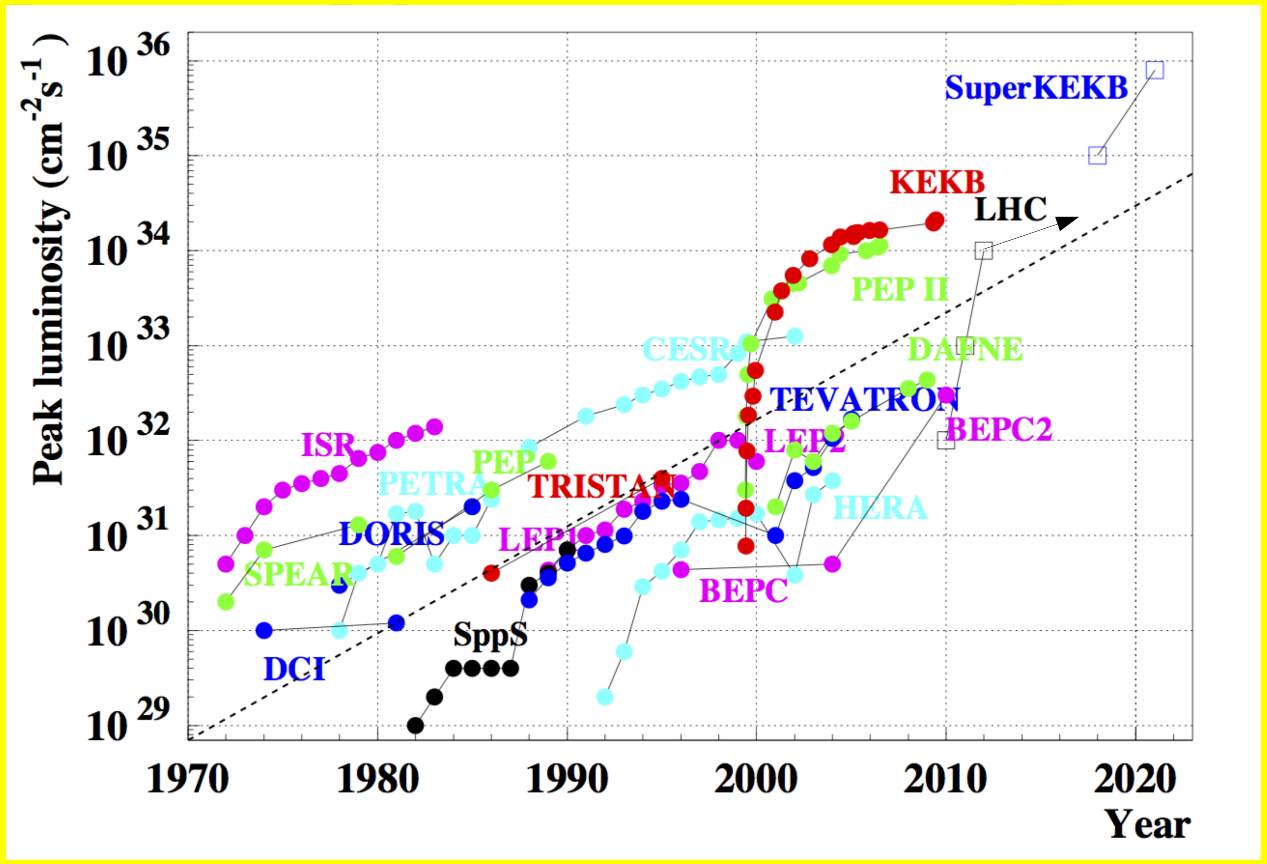
SuperKEK

located at

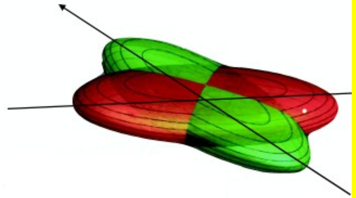
It's an asy

operating

(Υ(4S), but poss



KEKB



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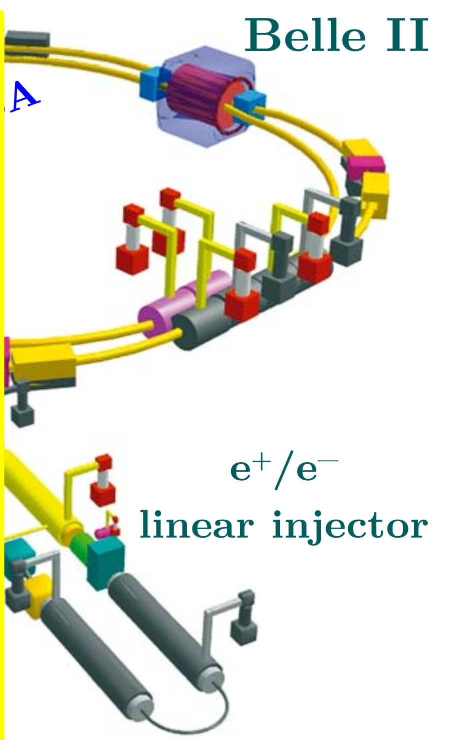
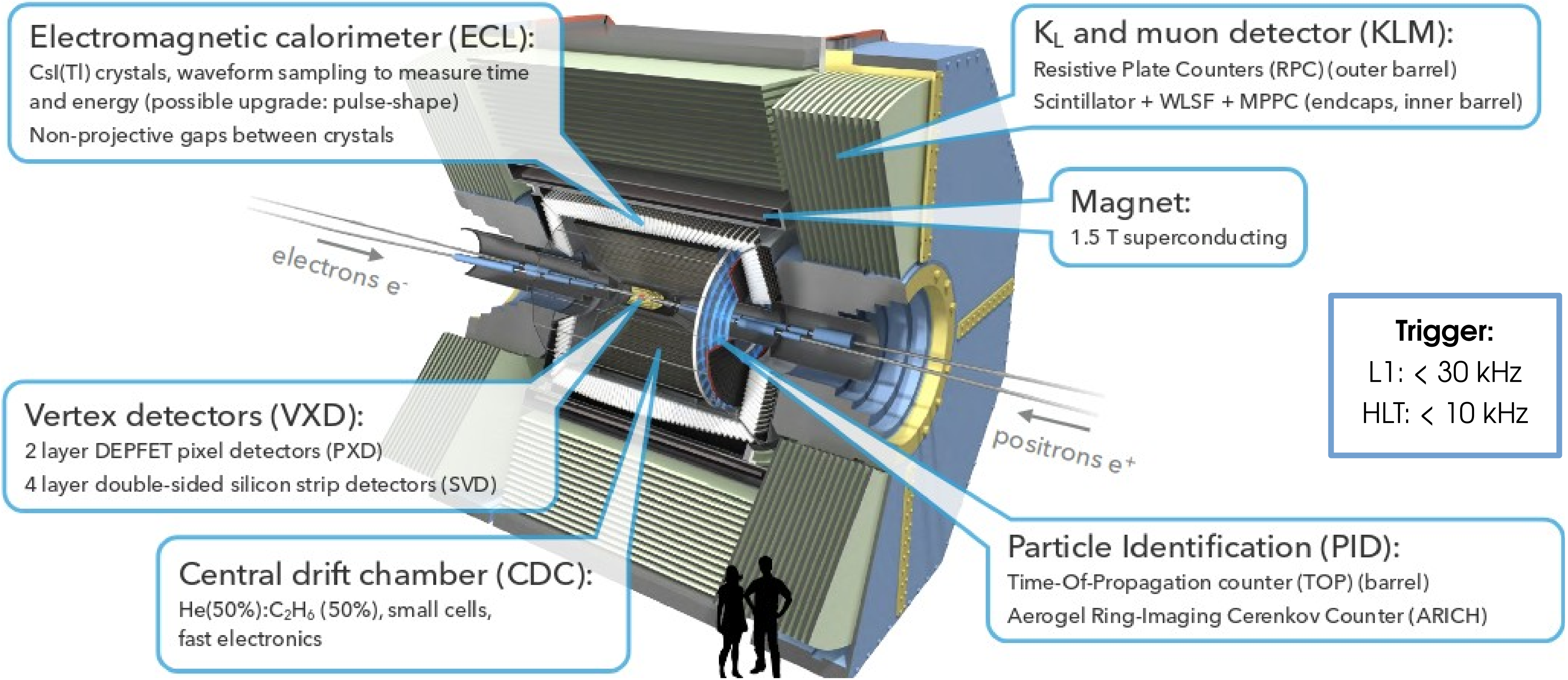


luminosity:

$8 \cdot 10^{35}$ cm^{-2} s^{-1}

Belle II detector



Trigger:

L1: < 30 kHz

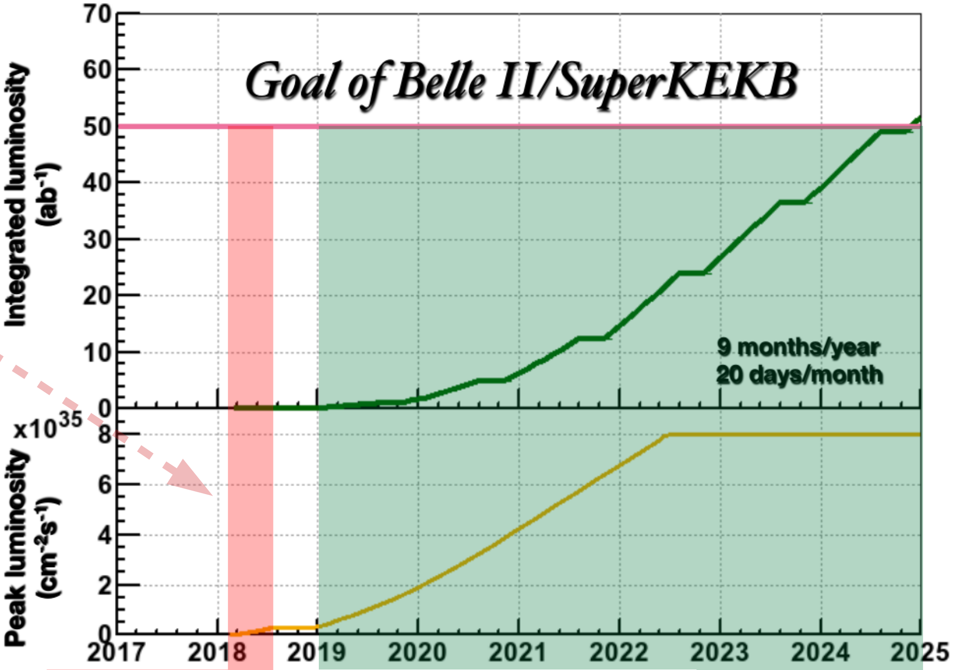
HLT: < 10 kHz

First period of data taking: Phase 2

During the Phase 2 run
(**ongoing now!**)
Belle II has **no VXD detector** installed

Main goals:

- nano-beam commissioning
- reach the KEKB peak luminosity and collect up to 20 fb^{-1} of data
- measure beam background
- **dark sector physics**
  $\rightarrow$ **new exotic trigger modes w.r.t. Belle (i.e. "single photon")**

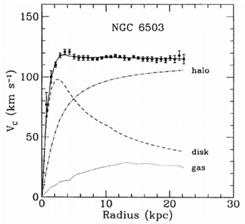


Phase 2: $\leq$ 20 fb^{-1}

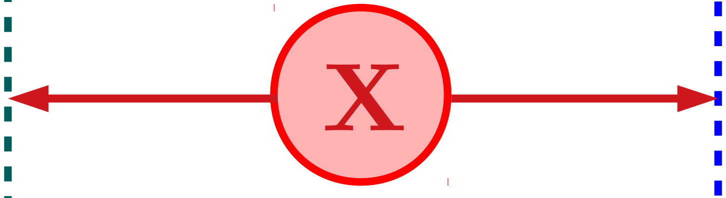
Phase 3: 50 ab^{-1}

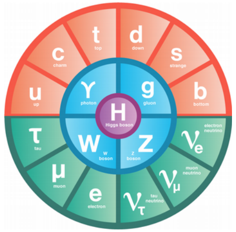
See Carlos' talk on Friday for info & news about Phase 2!

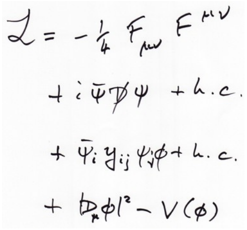
Dark Matter coupling to SM



Dark Matter



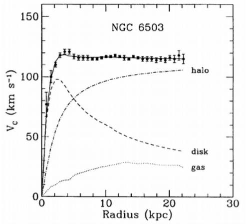




Standard Model

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

Dark Matter coupling to SM



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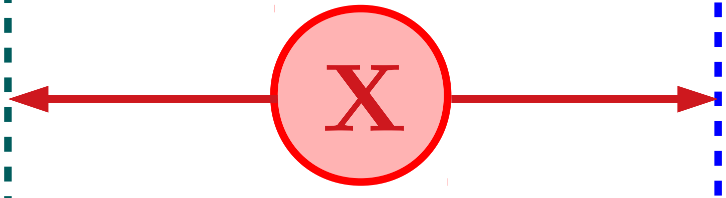

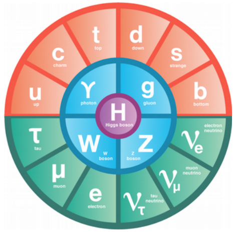

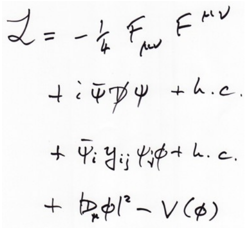

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Vector portal $\rightarrow$ Dark Photon

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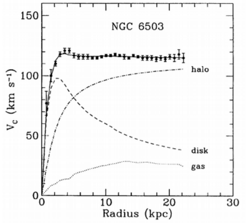
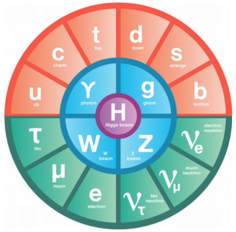
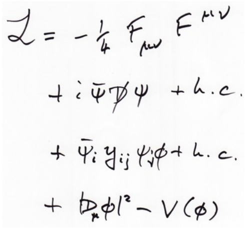


Dark Matter

X





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Vector portal → Dark Photon

Scalar portal → Dark Higgs/Scalars

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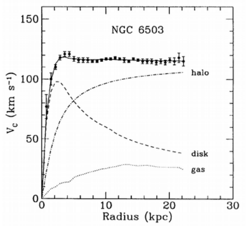

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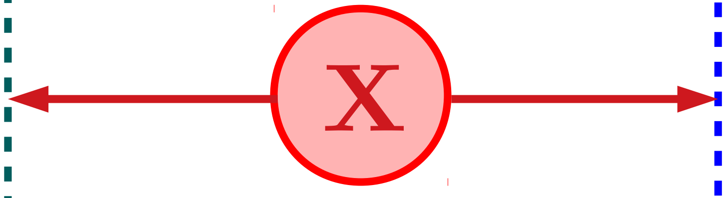

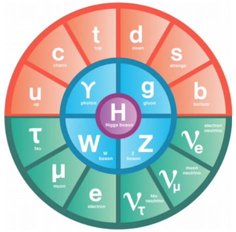

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Standard Model

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Pseudoscalar portal → Axion-Like Particles

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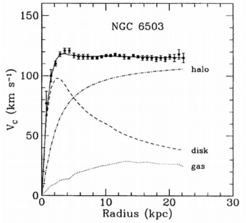

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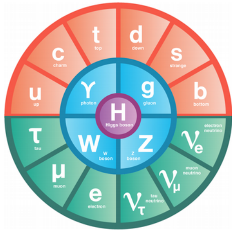

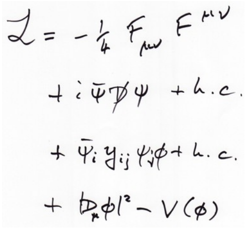

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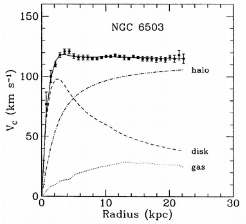

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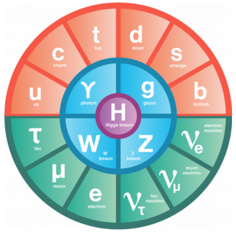

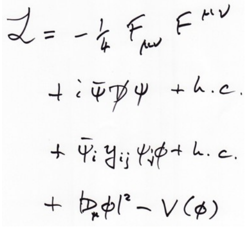

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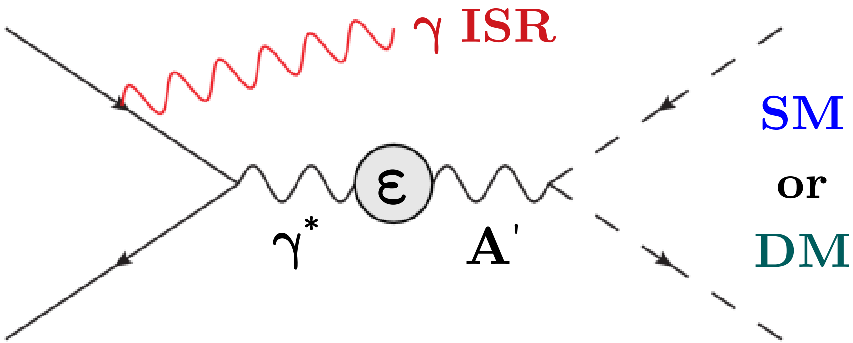
Competitive studies with Phase 2 data!

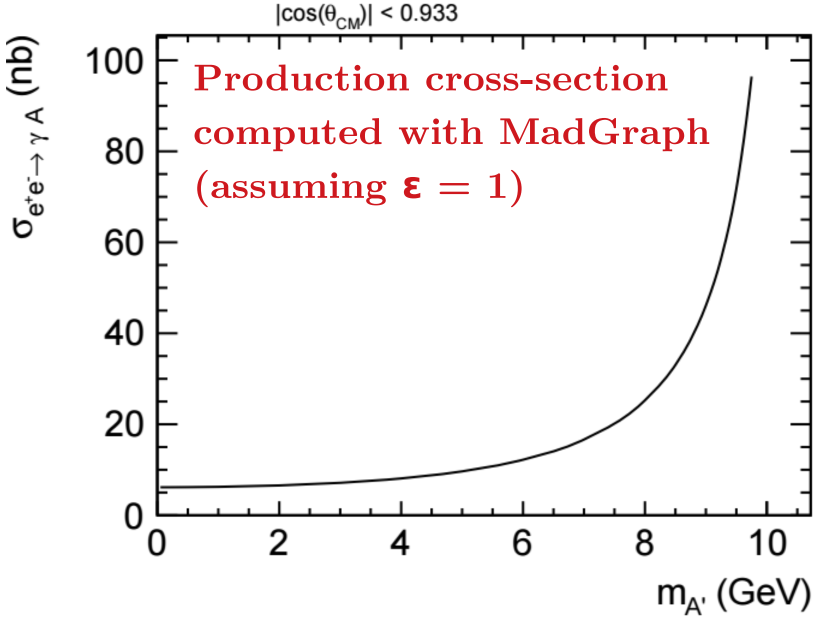
Dark Photon

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

$$\mathcal{L} \supset \varepsilon A'_\mu J^\mu_{\mathrm{SM}}$$

Batell et al. (2009), arXiv:0903.0363





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**

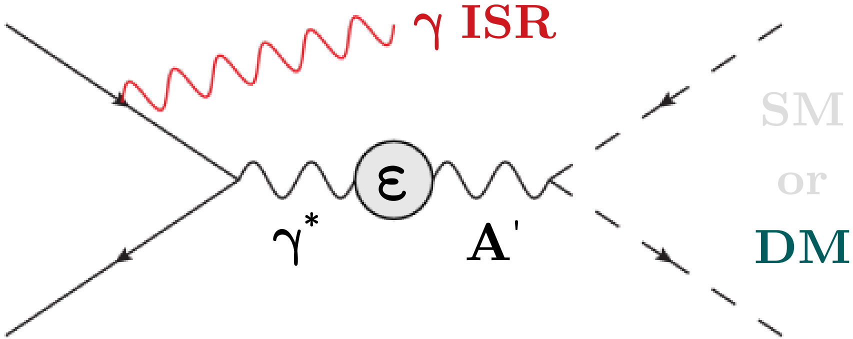
Dark Photon: invisible decay (signal)

Belle II

Signal signature:

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

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



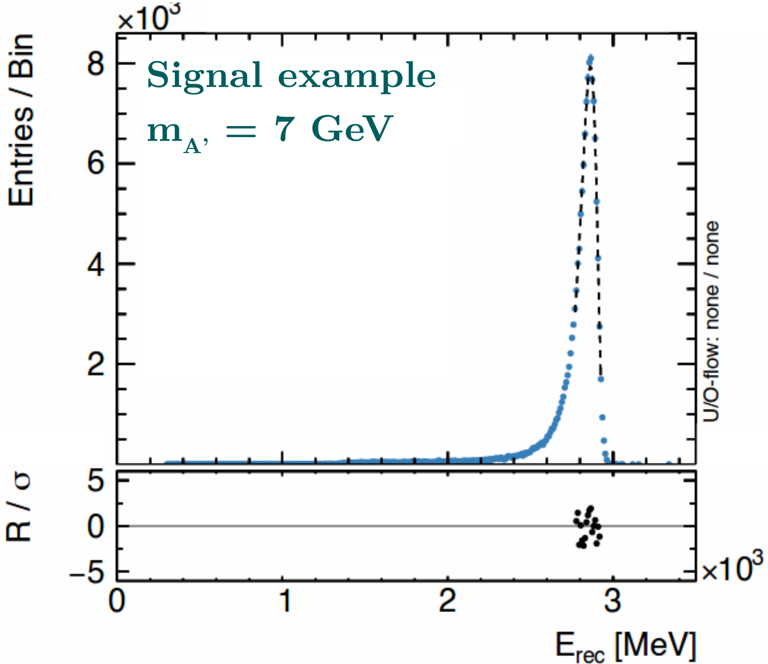
Needed a special **single photon trigger**

(not available in Belle, only ~10% of all data in BaBar)

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

Max. L1 rate: < 30 kHz

Sustainable for Phase 3?

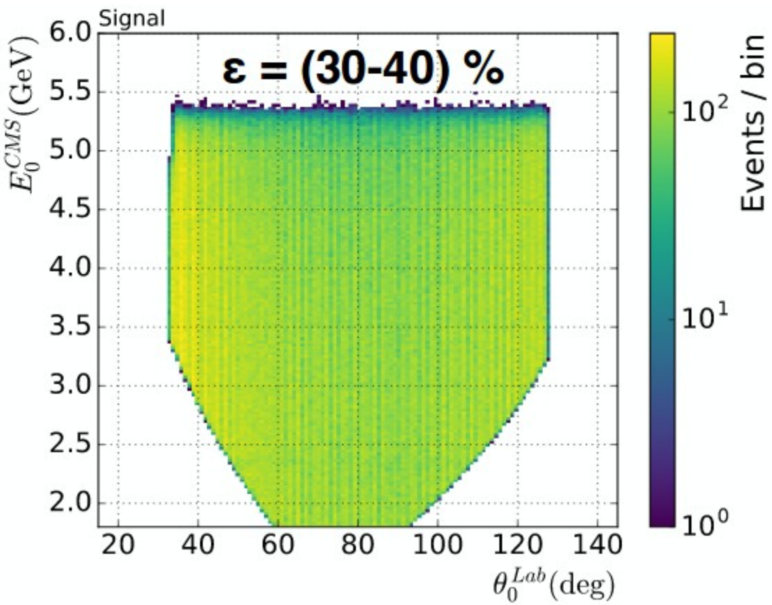


Belle II MC Preliminary

Dark Photon: invisible decay (signal)

Discriminant variables:

E_{CMS} vs. polar angle of “single photon”



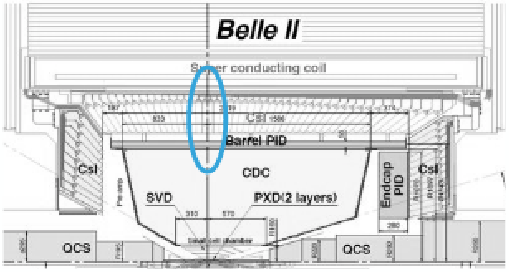
Signal signature:

peak in E_{CMS} (horizontal band)

Dark Photon: invisible decay (background)

Discriminant variables:

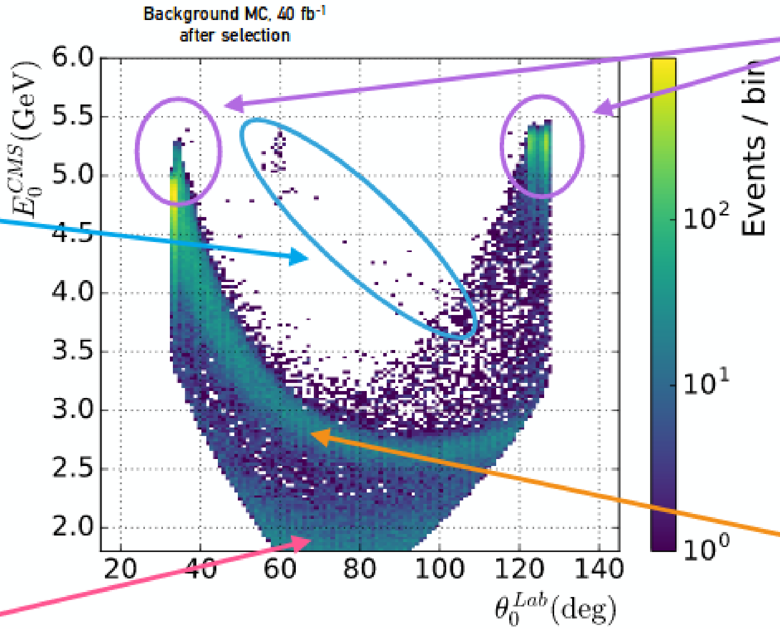
E_{CMS} vs. polar angle of "single photon"

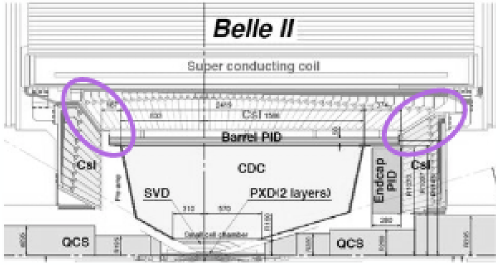


ee→2γ and 3γ

1γ in ECL 90° gap

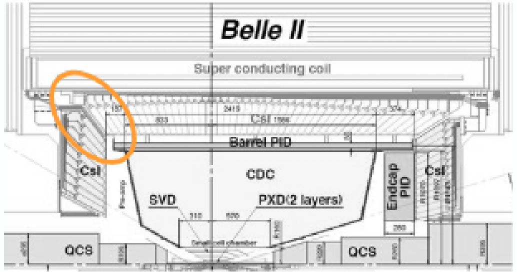
1γ out of ECL acceptance





ee→2γ

1γ in ECL BWD or FWD gap



ee→3γ

1γ in ECL BWD gap

1γ out of ECL acceptance

ee→eeγ

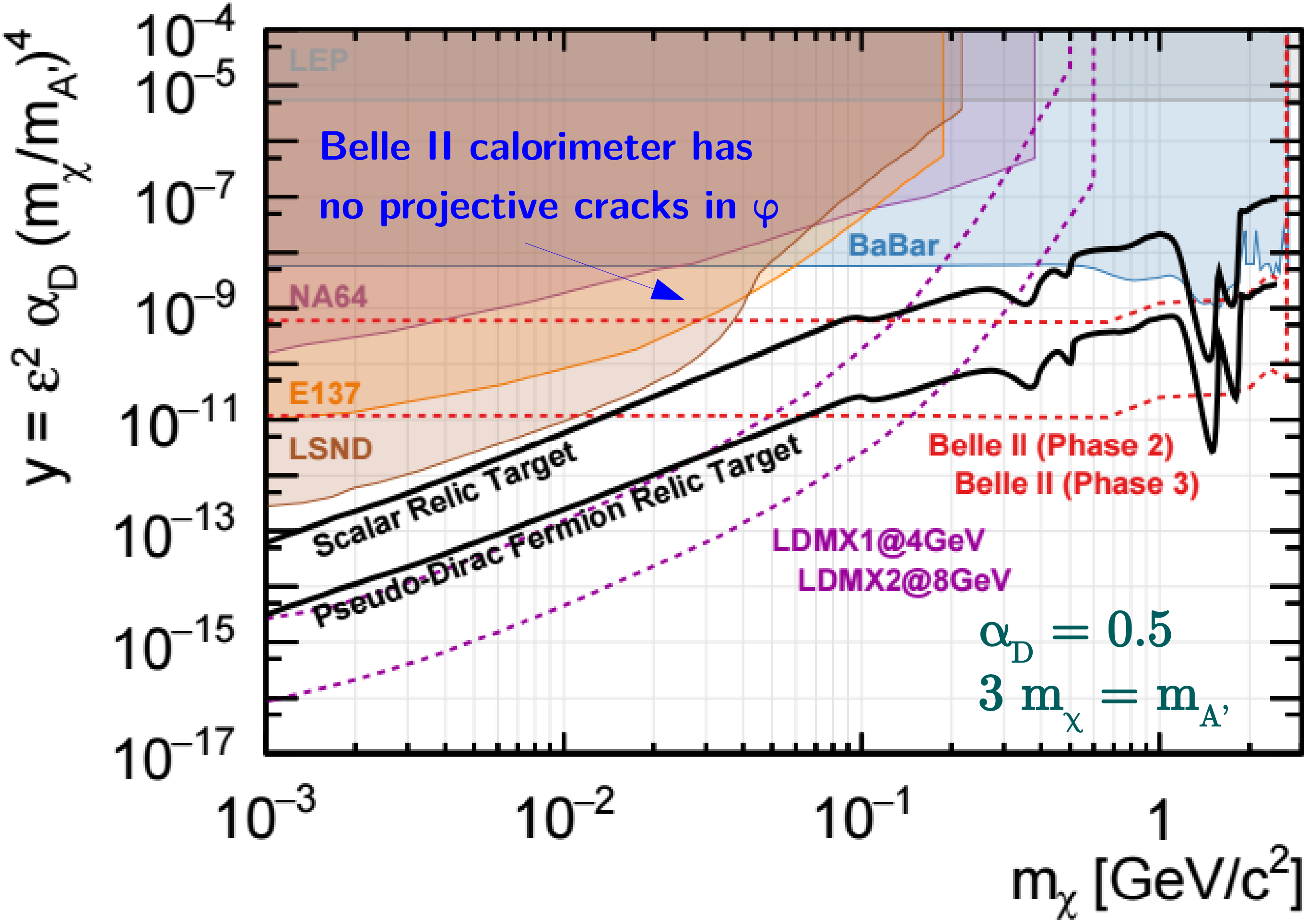
both electrons

out of tracking acceptance

Signal signature:

peak in E_{CMS} (horizontal band)

Dark Photon: invisible decay (sensitivity)



Lower trigger threshold wrt BaBar

J. Alexander et al. (2016), arXiv:1608.08632
Natalia Toro, private communication (2017)
J. P. Lees et al., BaBar (2017), arXiv:1702.0332
B2TIP, to be submitted in PTEP (2018)

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.

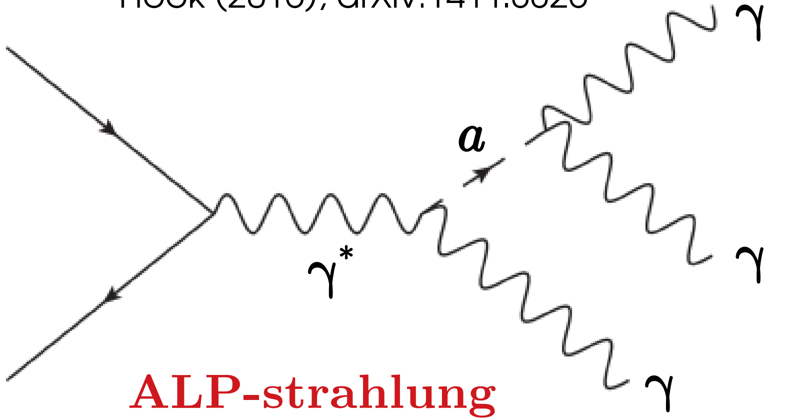
I will focus on the **coupling to photons**:

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

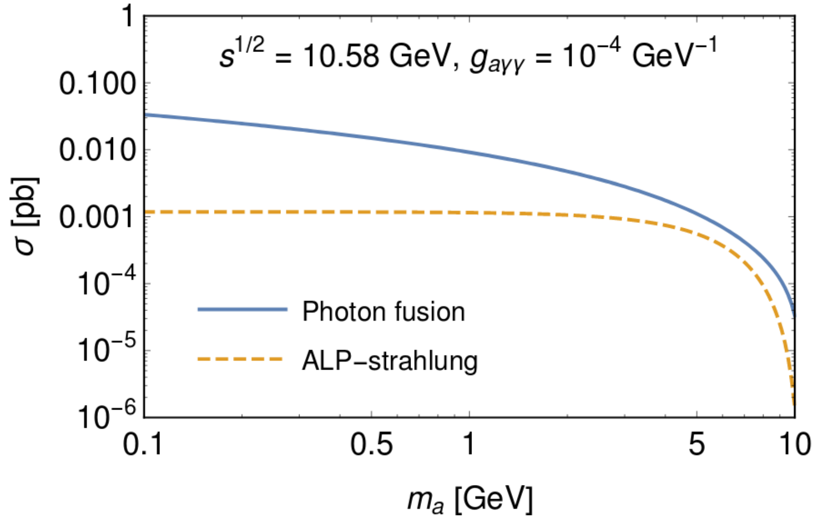
N.B. $\tau \sim 1 / g_{a\gamma\gamma}^{2} M_{a}^{3}$

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

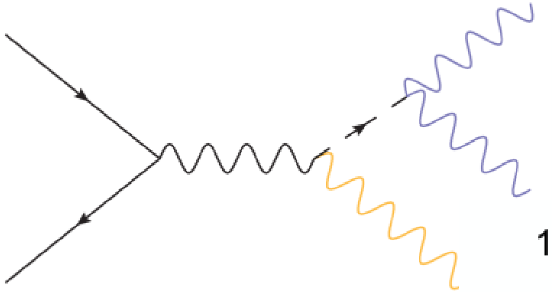
Hook (2015), arXiv:1411.3325



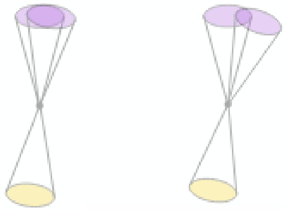
ALP-strahlung



Axion-Like Particles (signal)



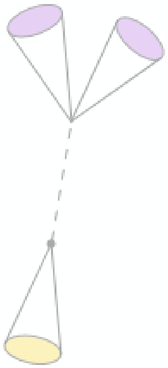
Two of the photons overlap or **merge**.

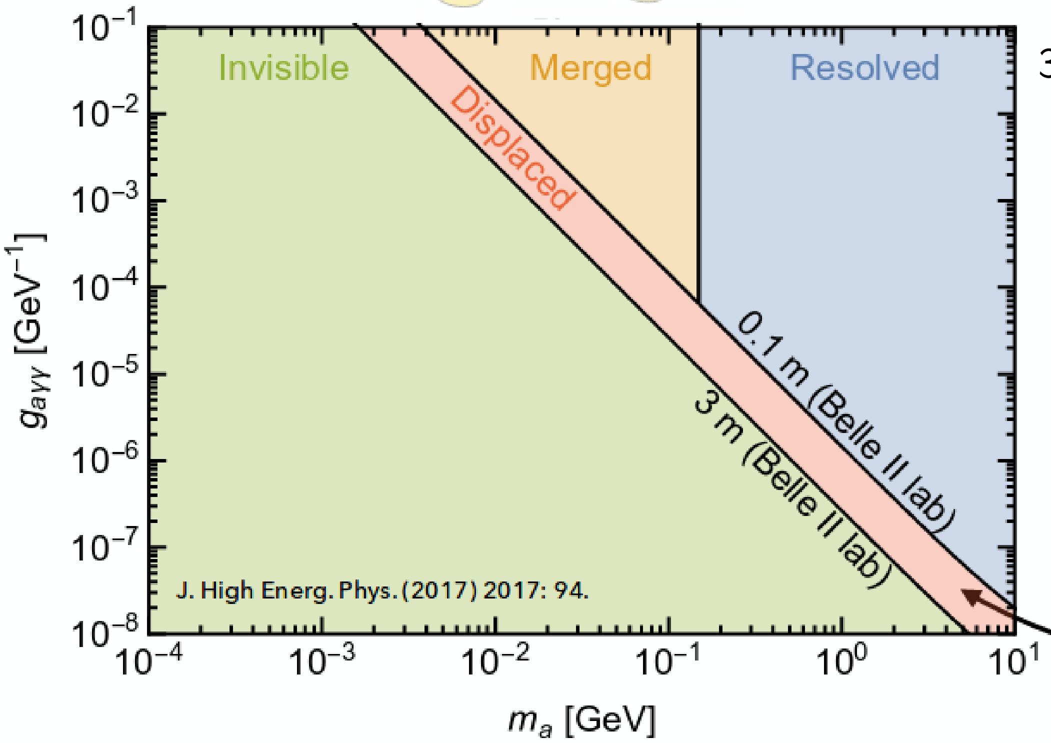


For **resolved** case:

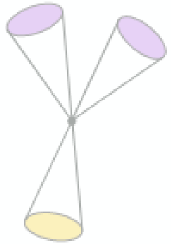
3 clusters with $E_{CM} > 0.25$ GeV

Peak in $\gamma\gamma$ mass spectrum





Three **resolved**, high energetic photons.

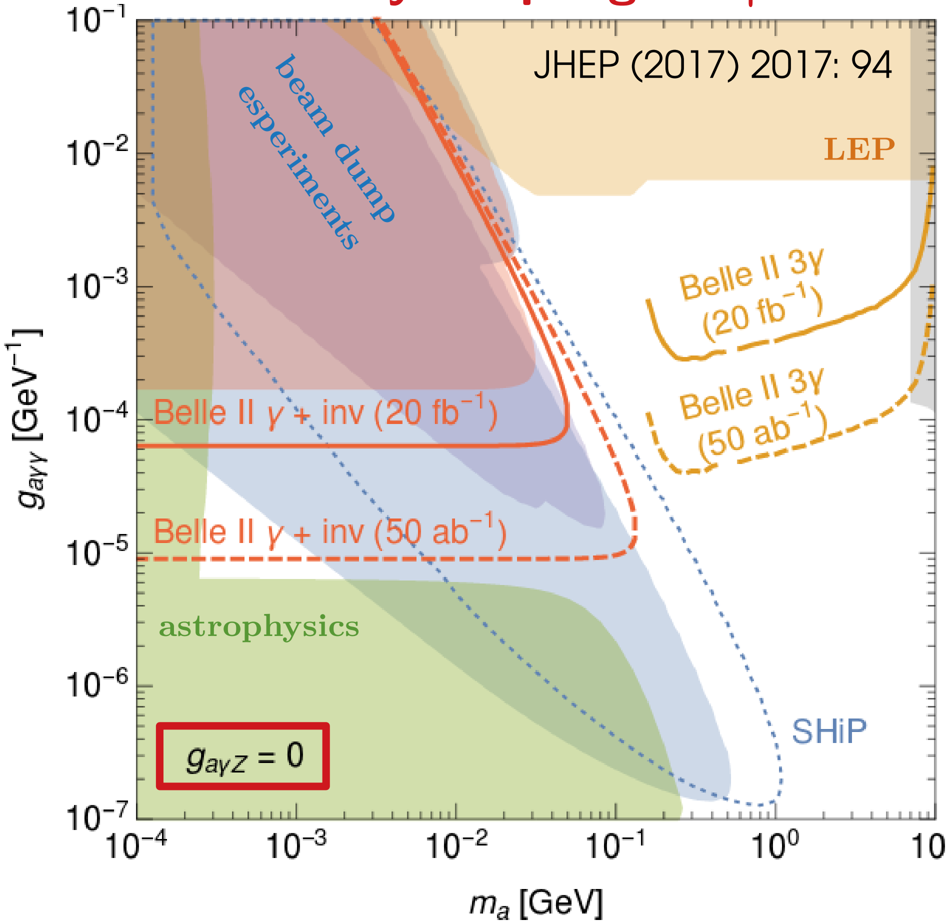


ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

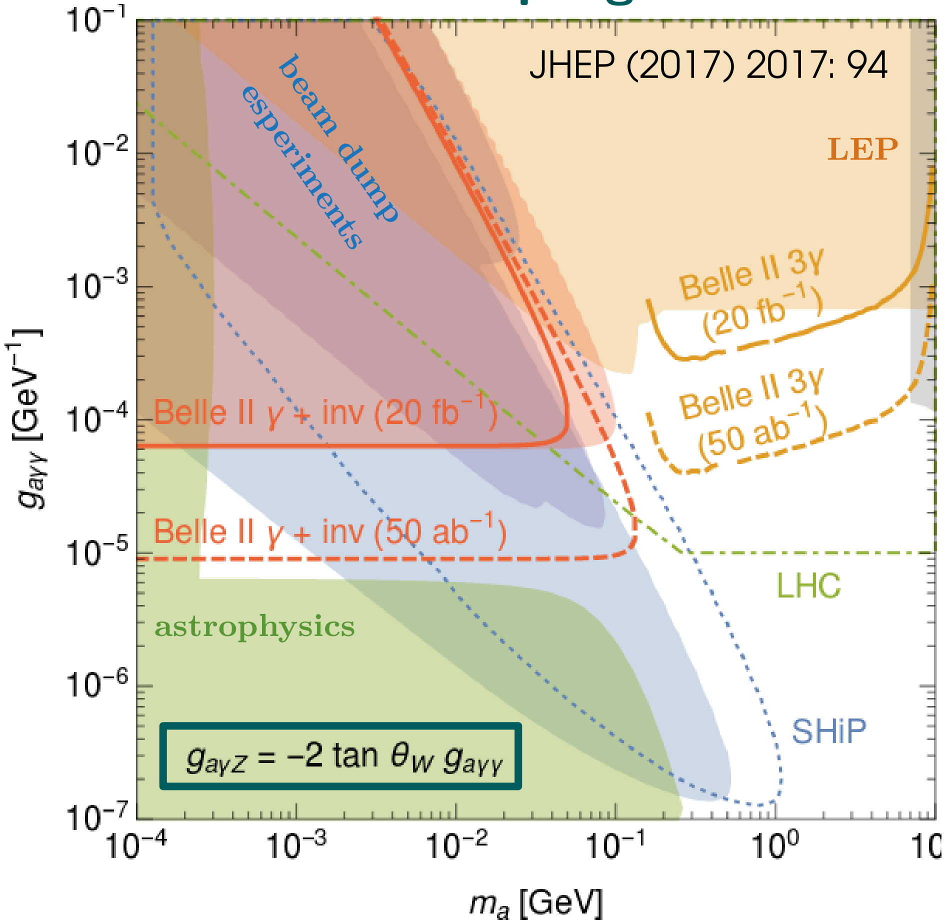
The searches for invisible and visible ALP decays veto this region.

Axion-Like Particles (sensitivity)

Only coupling to γ



With coupling to Z

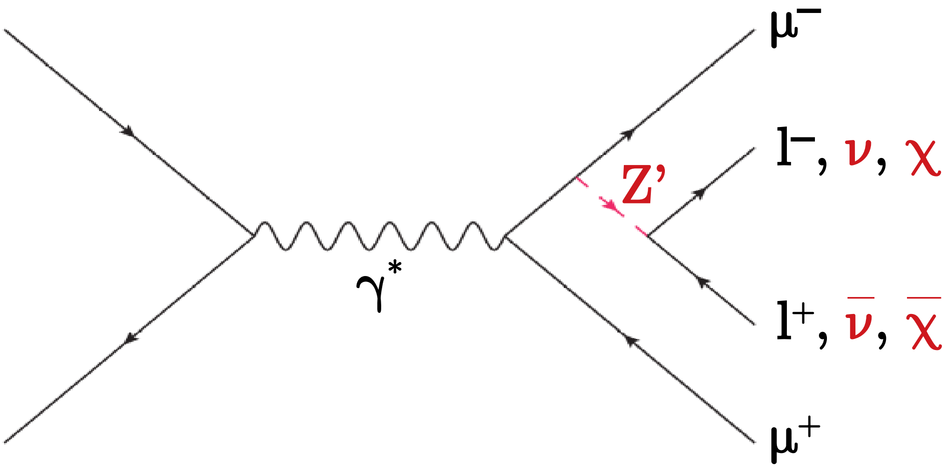


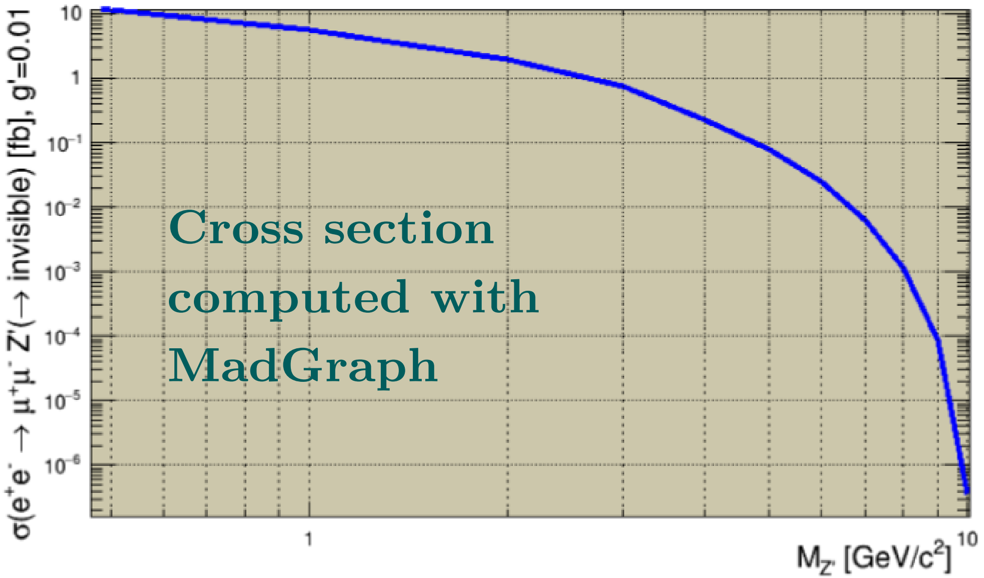
Muonic Dark Force: invisible decay

It's possible to consider a gauge boson Z' that couples only to **2nd and 3rd** leptonic generation (**$L_\mu - L_\tau$ model**)

$$\mathcal{L} = -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,L}\gamma^\mu Z'_\mu \nu_{\mu,L} + g'\bar{\nu}_{\tau,L}\gamma^\mu Z'_\mu \nu_{\tau,L}$$

Shuve et al. (2014), arXiv:1403.2727





Branching ratios:

$$M_{Z'} < 2M_\mu \to \Gamma(Z' \to \text{inv.}) = 1$$

$$2M_\mu < M_{Z'} < 2M_\tau \to \Gamma(Z' \to \text{inv.}) \sim 1/2$$

$$M_{Z'} > 2M_\tau \to \Gamma(Z' \to \text{inv.}) \sim 1/3$$

Muonic Dark Force: invisible decay

Invisible decay: reconstruct the recoil mass w.r.t. the two opposite-charged muons and look for a peak in the mass spectrum

Additional request:

$\sim$ nothing in the rest of the event

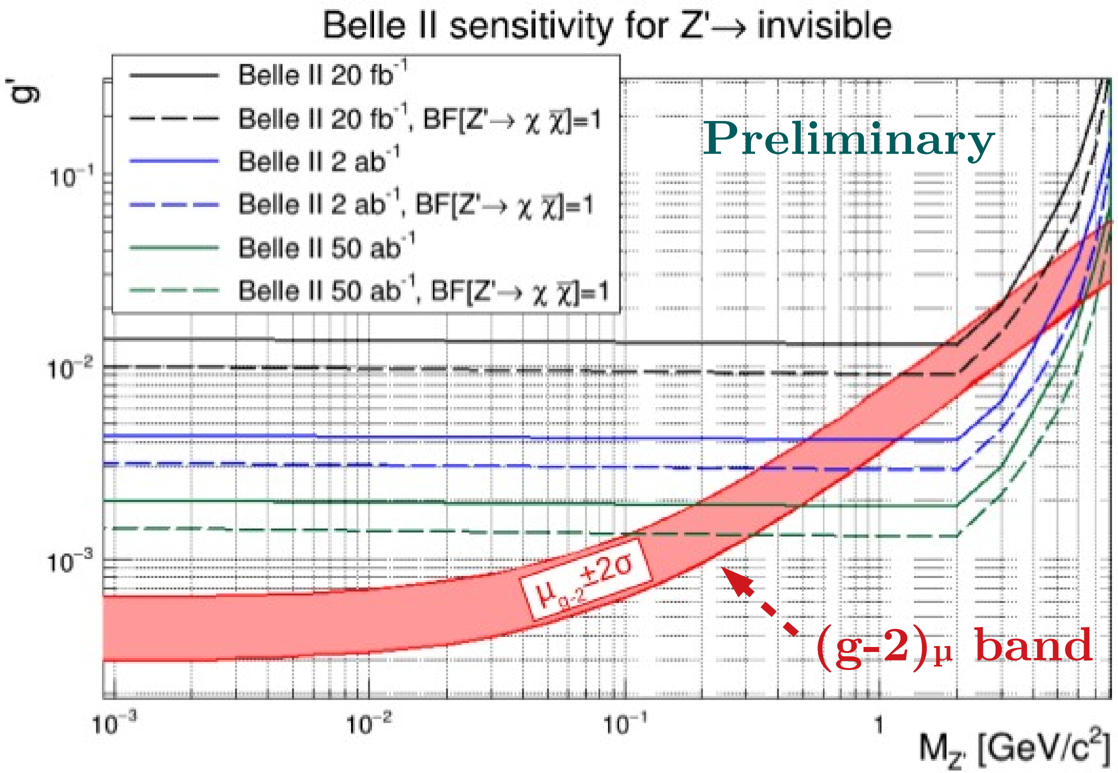
Considered several **mass hypothesis for Z'** with full simulation and reconstruction

Considered the **main backgrounds**:

$e^+ e^- \rightarrow \mu^+ \mu^-$

$e^+ e^- \rightarrow \tau^+ \tau^-$

$e^+ e^- \rightarrow e^+ e^- \mu^+ \mu^-$



The sensititivity plot is obatined considering Z' cross section, signal efficiency and background rejection (**the selection is not optimized**)

Other dark sector and exotic searches

Visible Dark Photon decays

*Off-shell Dark Photon decays

Long-lived neutral particle decays

Dark Scalar:

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

*Magnetic Monopoles

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

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

Muonic Dark Force:

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

LFV:

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

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

*** Competitive with Phase 2 data!**

More details at: B2TIP, to be submitted in PTEP (2018)

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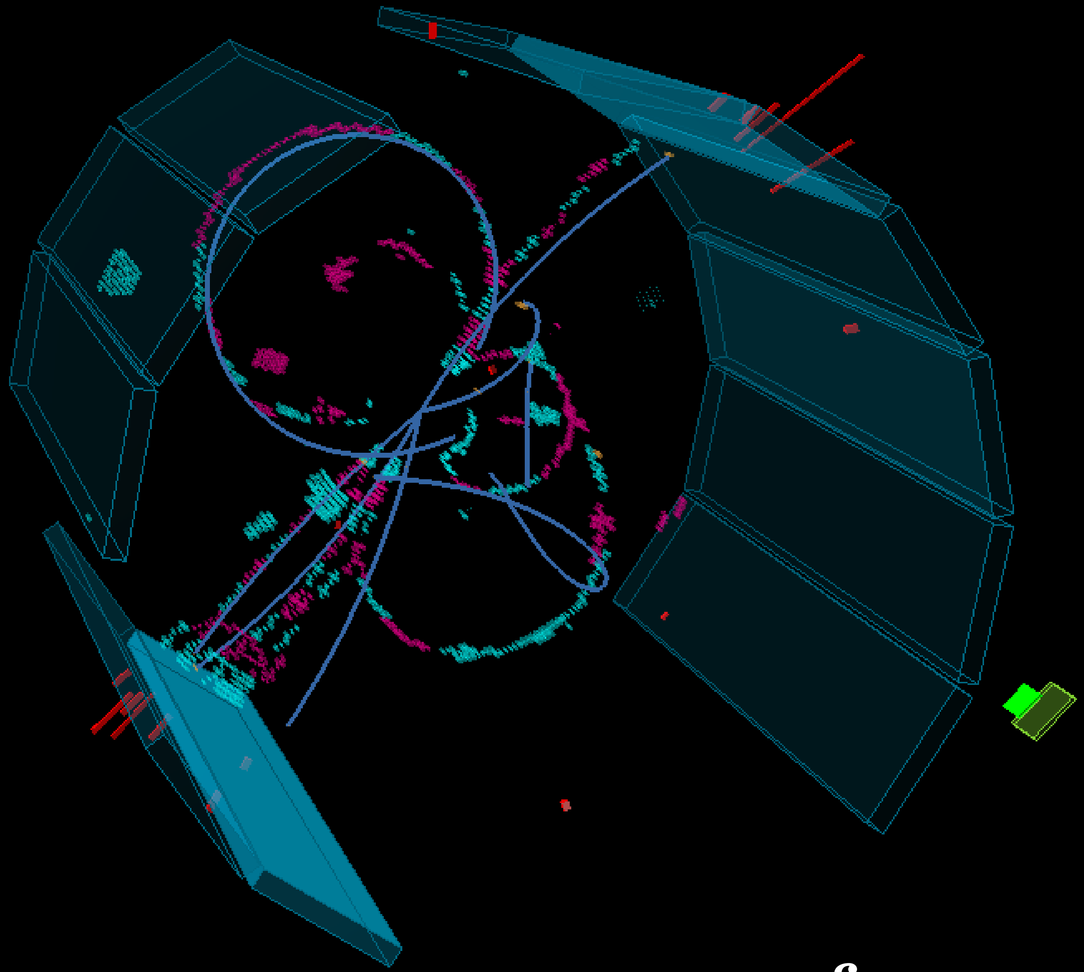
- Rich program of dark sector and exotics searches planned (magnetic monopoles, muonic dark forces, etc.)

- **And, the last but not the least...**

... the first hadronic event recorded at Belle II!



26th April 2018

Exp. 3; Run 125; Event 223

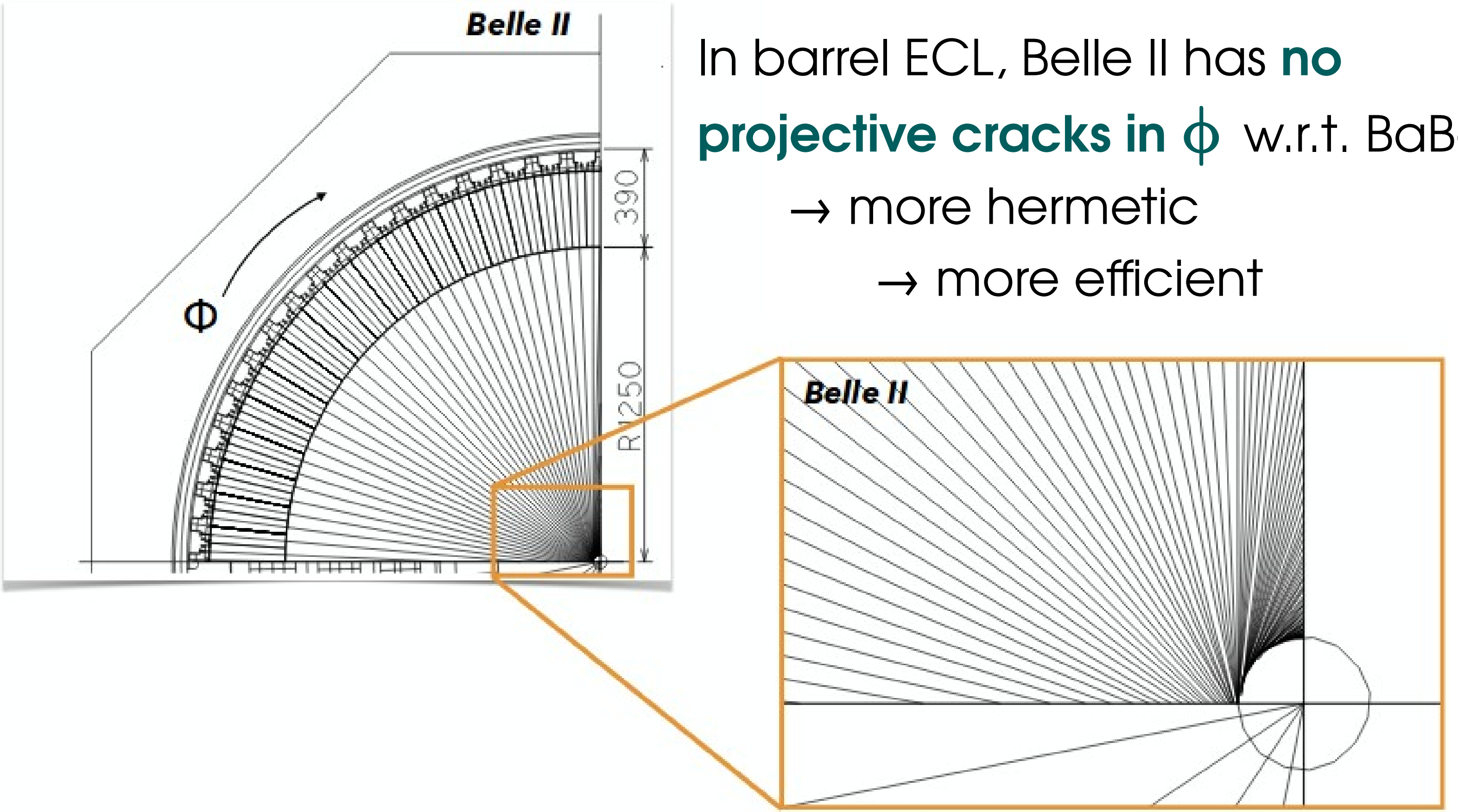
Thank you for your attention!

Backup slides

SuperKEKB machine parameters

Parameter	KEKB Design	KEKB Achieved	SuperKEKB Design
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.0
β_y^* (mm)	10/10	5.9/5.9	0.27/0.30
β_x^* (mm)	330/330	1200/1200	32/25
ϵ_x (nm)	18/18	18/24	3.2/5.3
$\frac{\epsilon_y}{\epsilon_x}$ (%)	1	0.85/0.64	0.27/0.24
σ_y (μm)	1.9	0.94 → 1/20	0.048/0.062
ξ_y	0.052	0.129/0.090	0.09/0.081
σ_z (mm)	4	6/7	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19 → x2	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity ($10^{34} cm^{-2} s^{-1}$)	1.0	2.11 → x40	80

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

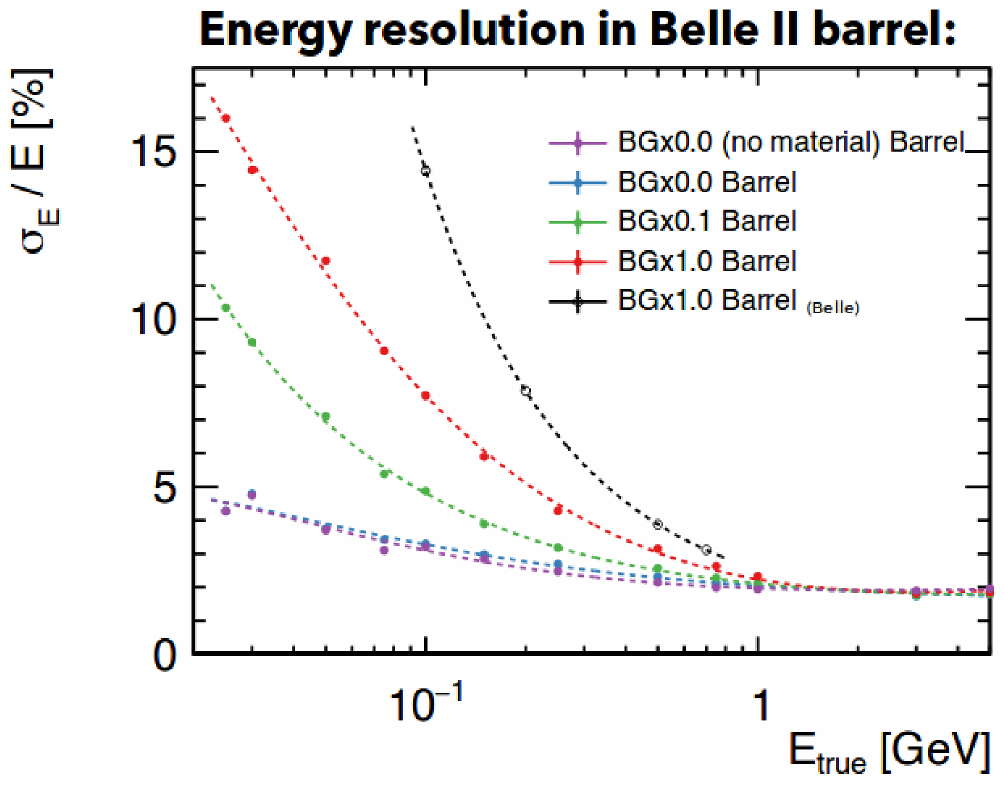


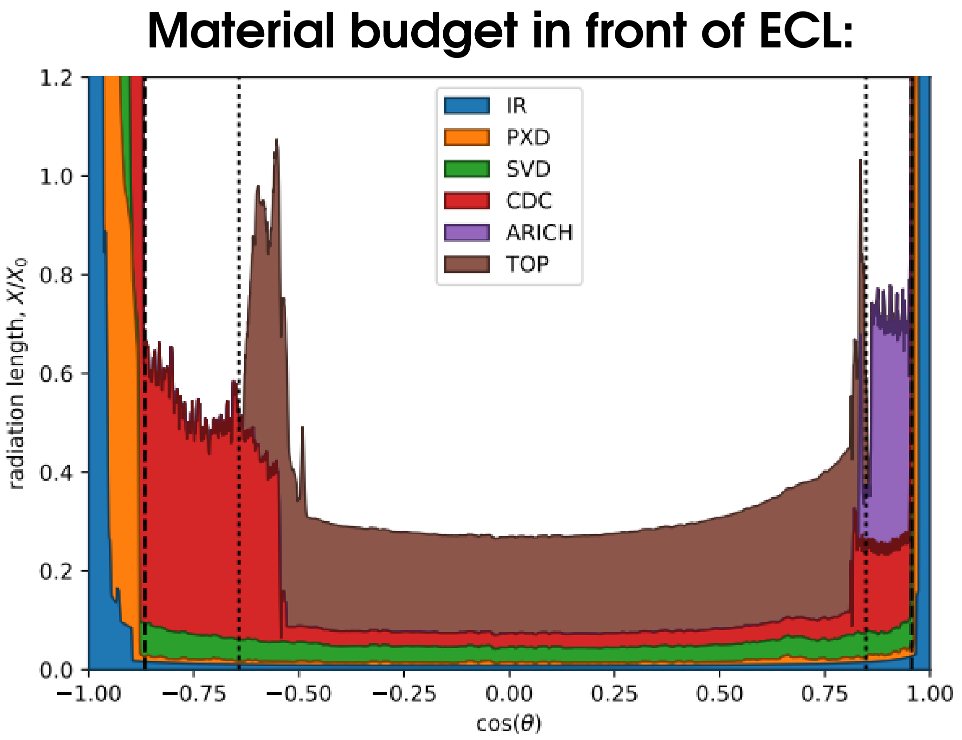
In barrel ECL, Belle II has **no projective cracks in ϕ** w.r.t. BaBar:

→ more hermetic

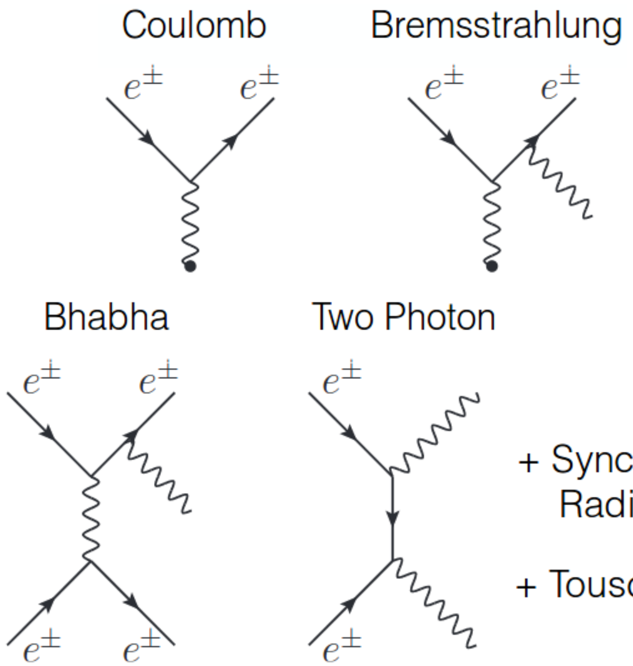
→ more efficient

Electromagnetic Calorimeter (ECL)



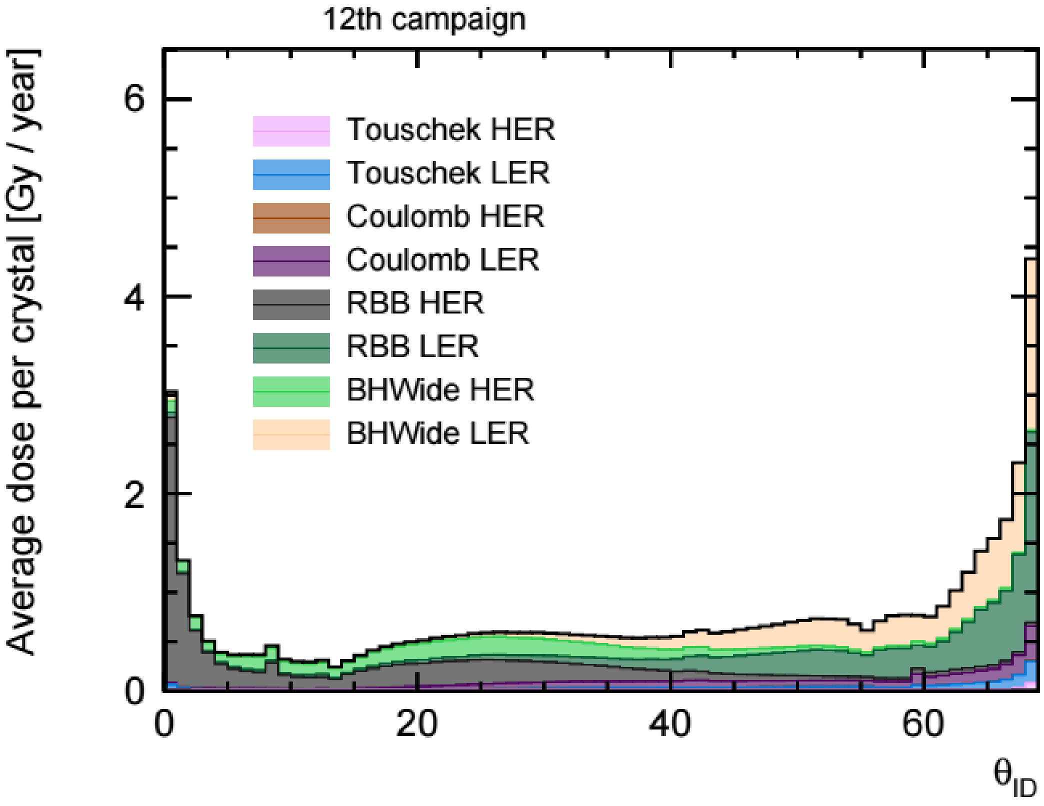


Beam background



+ Synchrotron Radiation

+ Touschek



Effects from beam background:

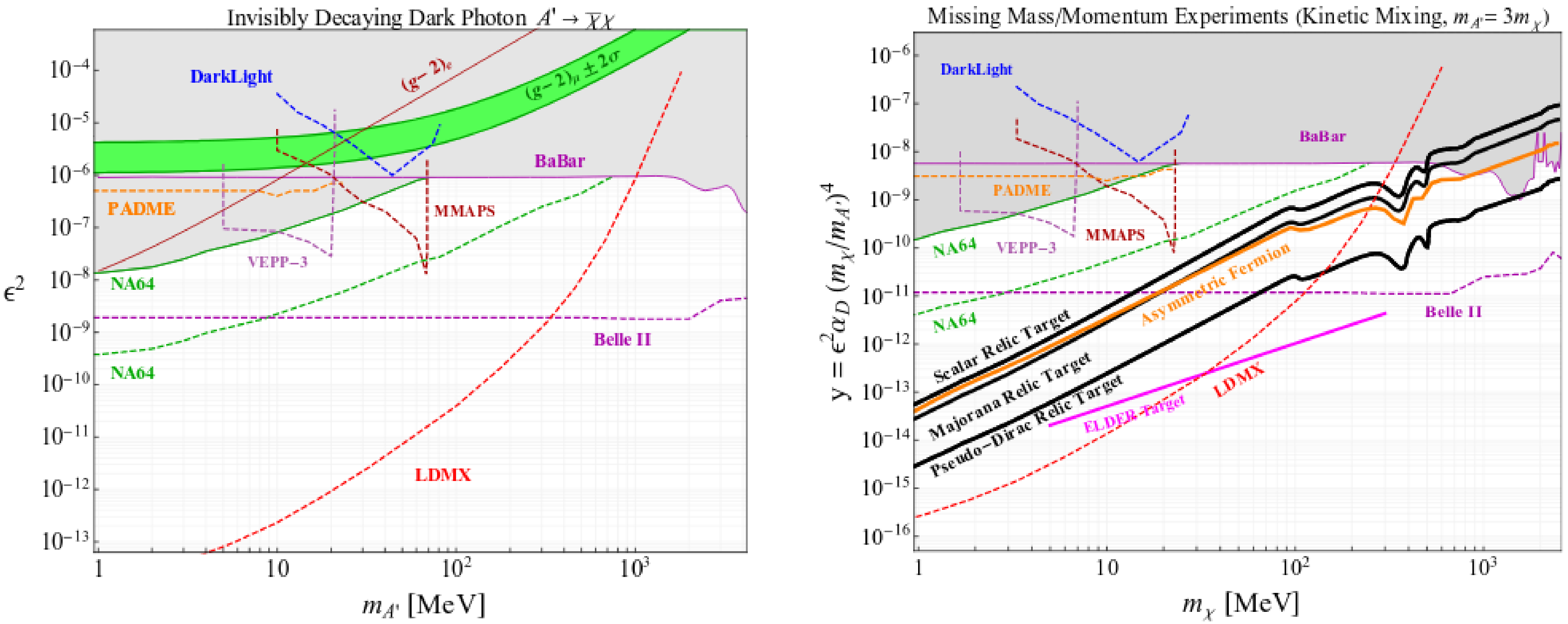
→ degrades calorimeter resolution.

→ radiation damage.

→ pile-up and event size.

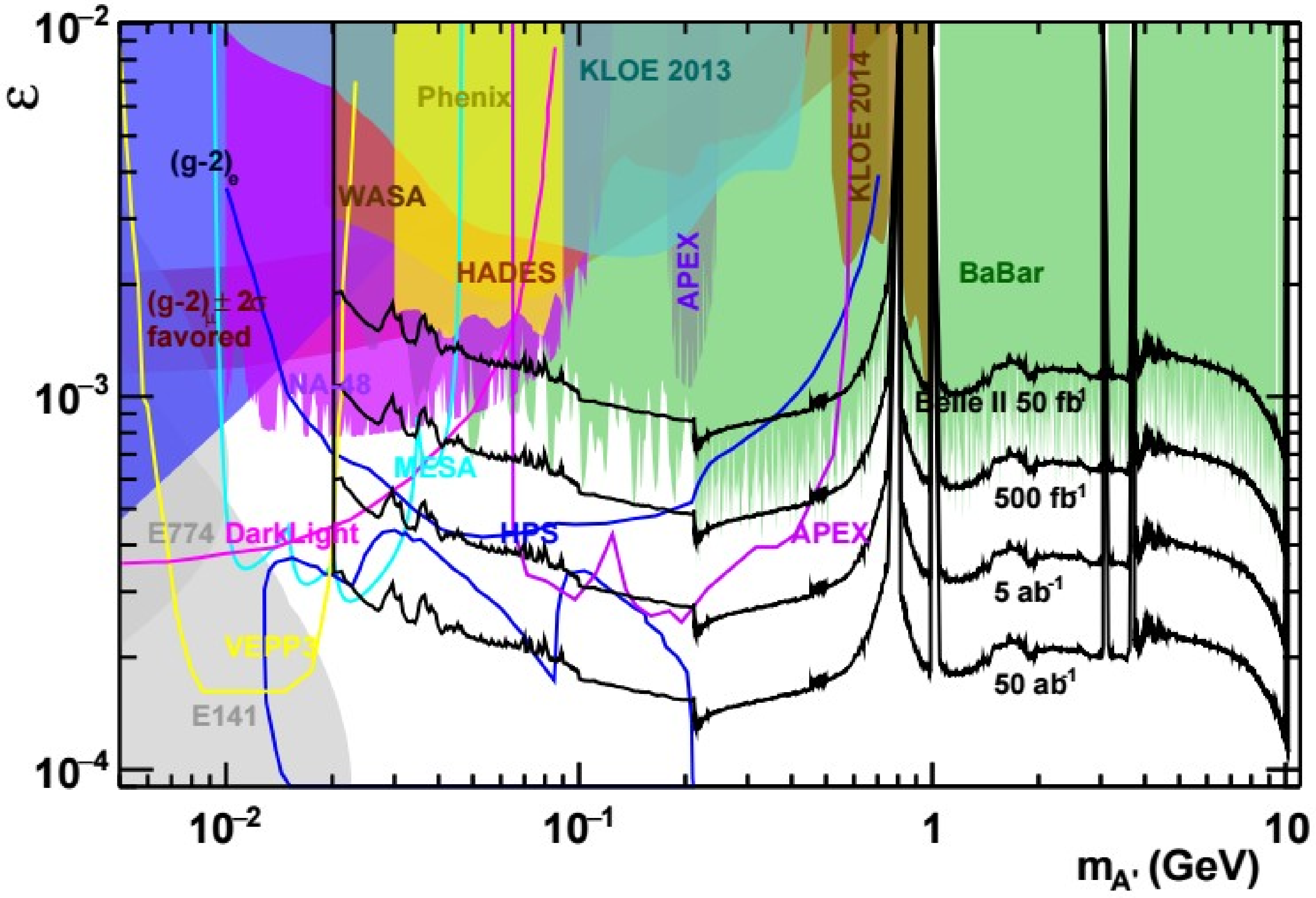
→ physics background

Dark Photon: invisible decay (prospects)



Battaglieri et al. (2017), arXiv:1707.04591

Dark Photon: visible decay

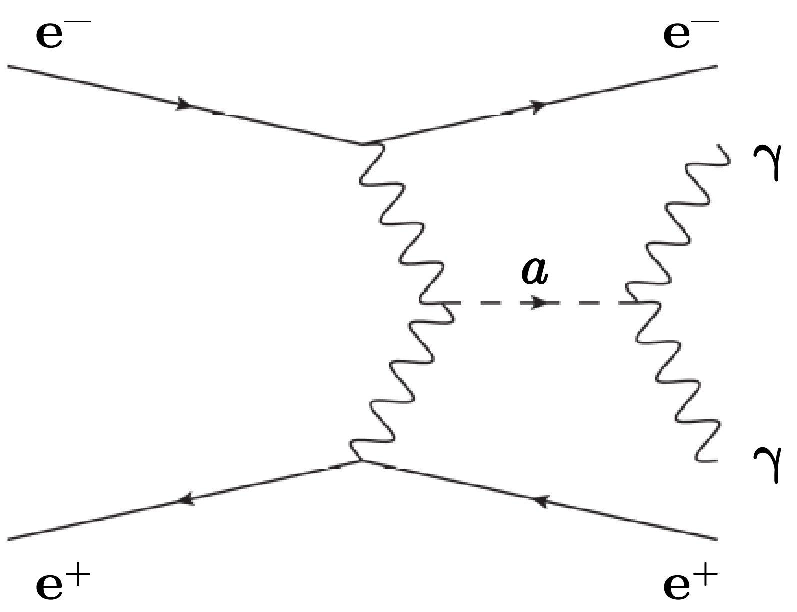


ALPs: low-mass region

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.

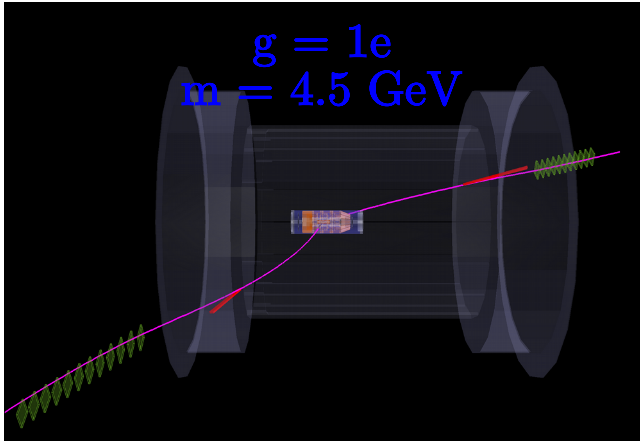
ALP-fusion



Pro: resolved clusters

Con: very low-energy photons

Magnetic monopoles

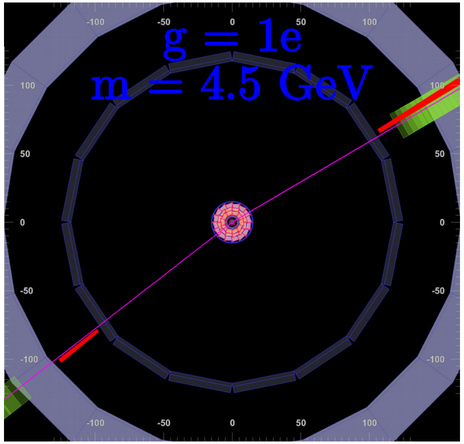


Minimal magnetic charge

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**

(+ parabolic tracks)