Dark Sector Searches with Belle II

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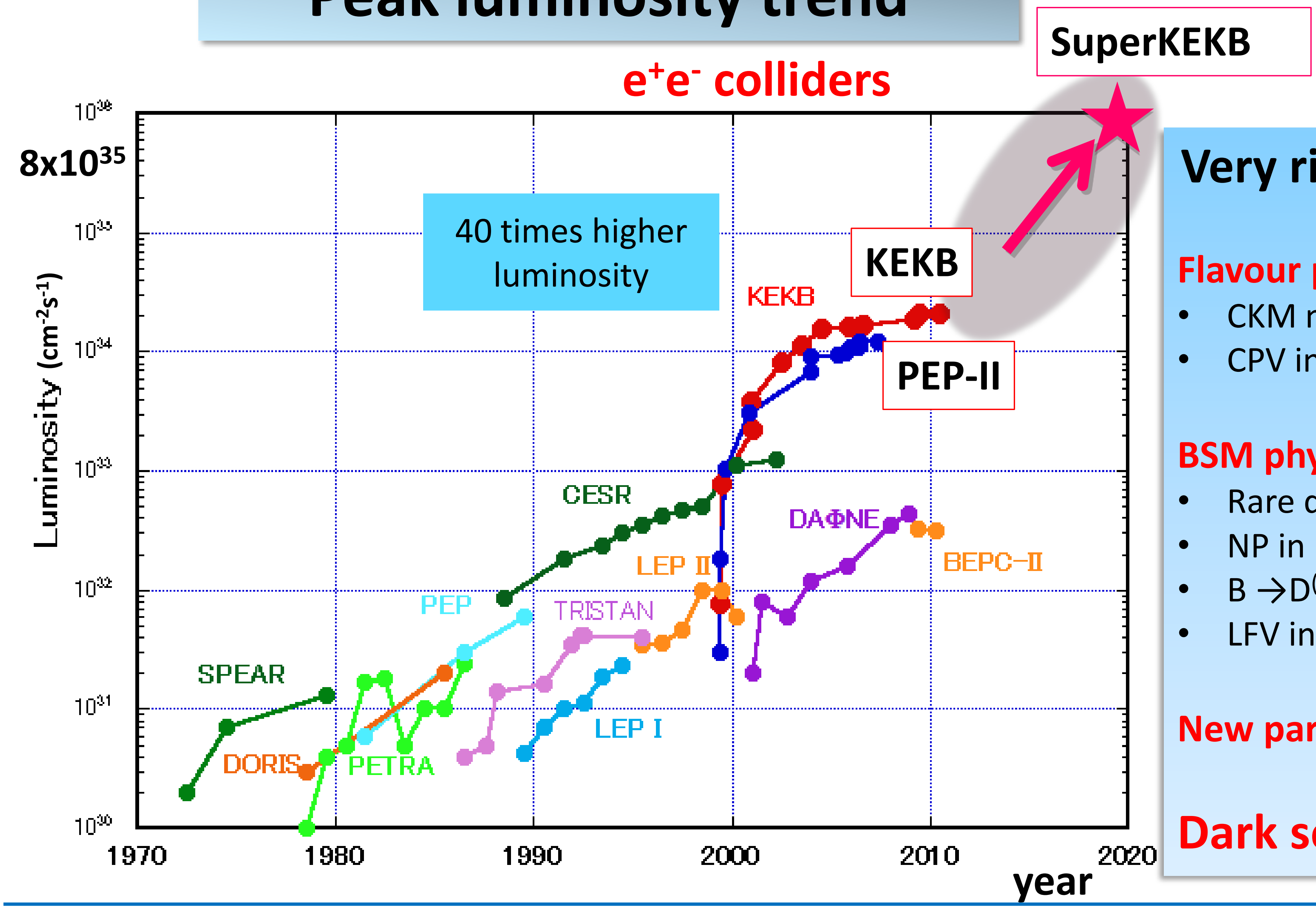
INFN – Roma 3

on behalf of the Belle II Collaboration

<u>OUTLINE OF THE TALK</u>

- Belle II and SuperKEKB
- Search of the invisible dark photon
- Search of ALP
- Search of Z' (invisible)
- Search of magnetic monopoles
- Summary

Peak luminosity trend



Very rich physics program

Flavour physics

- CKM matrix
- CPV in B deacys

BSM physics

- Rare decays
- NP in loops in $b \to s\gamma$, $b \to sll$
- $B \to D^{(*)}\tau\nu$
- LFV in τ decays

New particles (quarkonium)

Dark sector

From KEKB to SuperKEKB

Beam-beam parameter

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_\pm}\frac{N_\mp \beta_y^*}{\sigma_y^*(\sigma_x^* + \sigma_y^*)} R_{\xi_{y\pm}} \propto \frac{N_\mp}{\sigma_x^*}\sqrt{\frac{\beta_y^*}{\varepsilon_y}},$$

Lorentz factor

Beam current

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

Classical electron radius

Beam size ratio@IP
1 ~ 2 % (flat beam)

Vertical beta function@IP

Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 ~ 1 (short bunch)

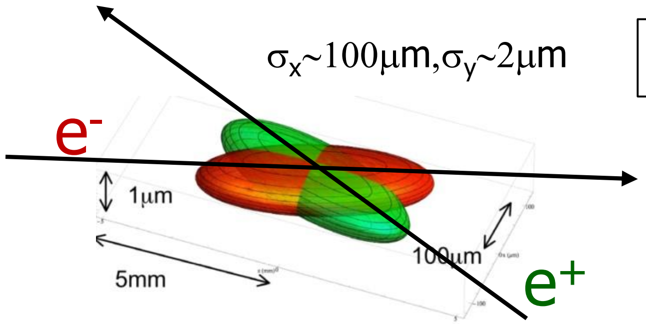
x20

x2

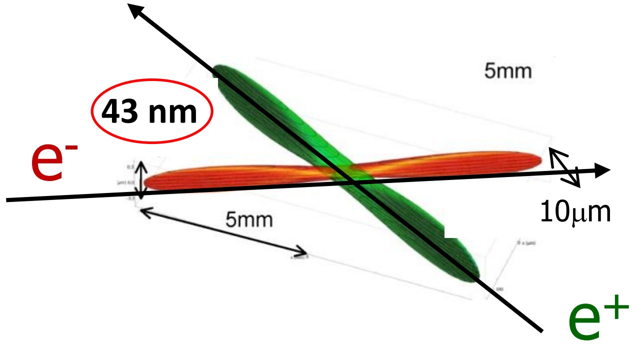
β^*_y=0.27/0.30 mm

$I_{+/-}$=3.6/2.6 A

(1) Smaller β_y^*
(2) Increase beam currents
(3) Increase ξ_y

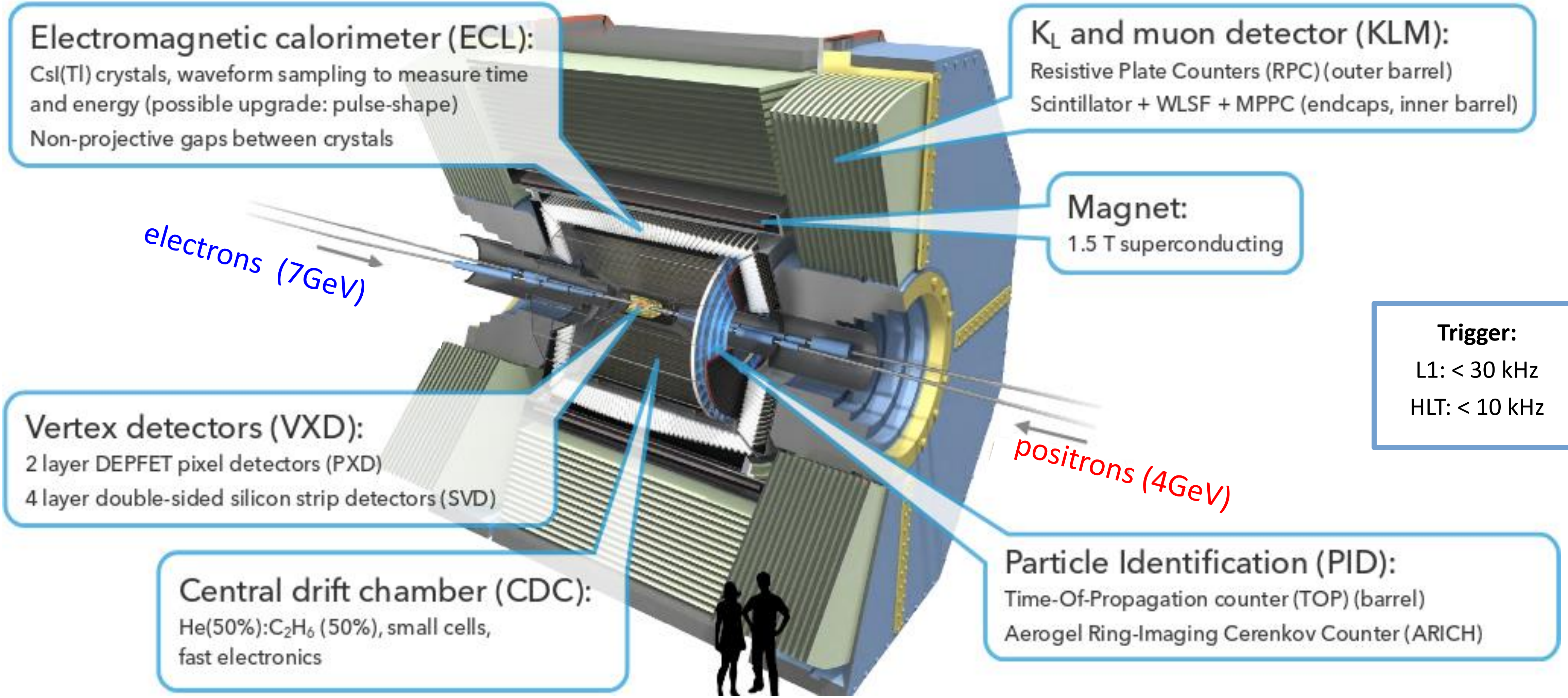


Nano-Beam scheme



... For a 40x increase in intensity you have to make the beam as thin as a few x100 atomic layers

Belle II detector

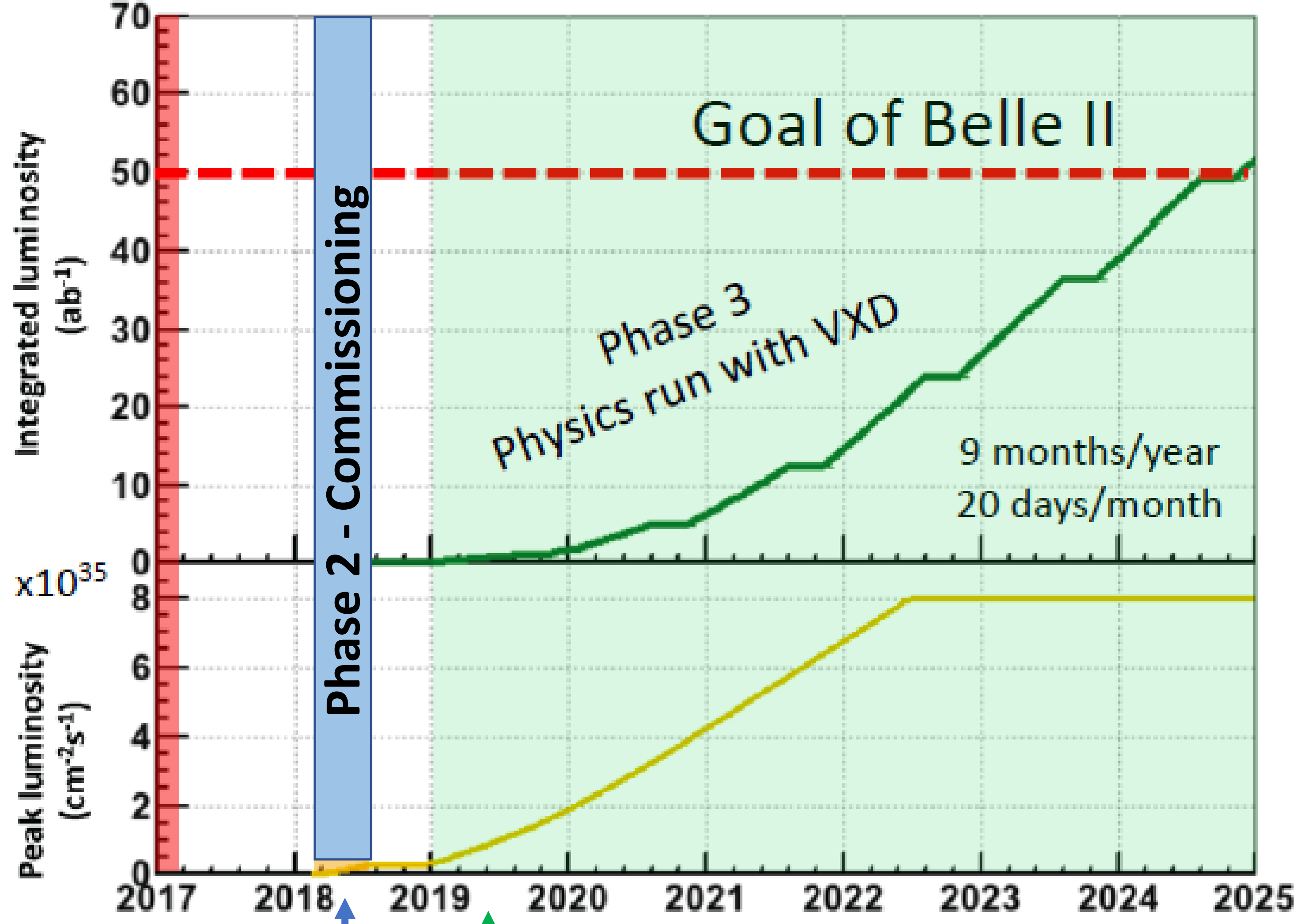


Trigger:
L1: < 30 kHz
HLT: < 10 kHz

Belle II vs Belle

better resolution, PID and capability to cope with higher background

Belle II data taking plan



Phase 2

Phase 3

Phase 2

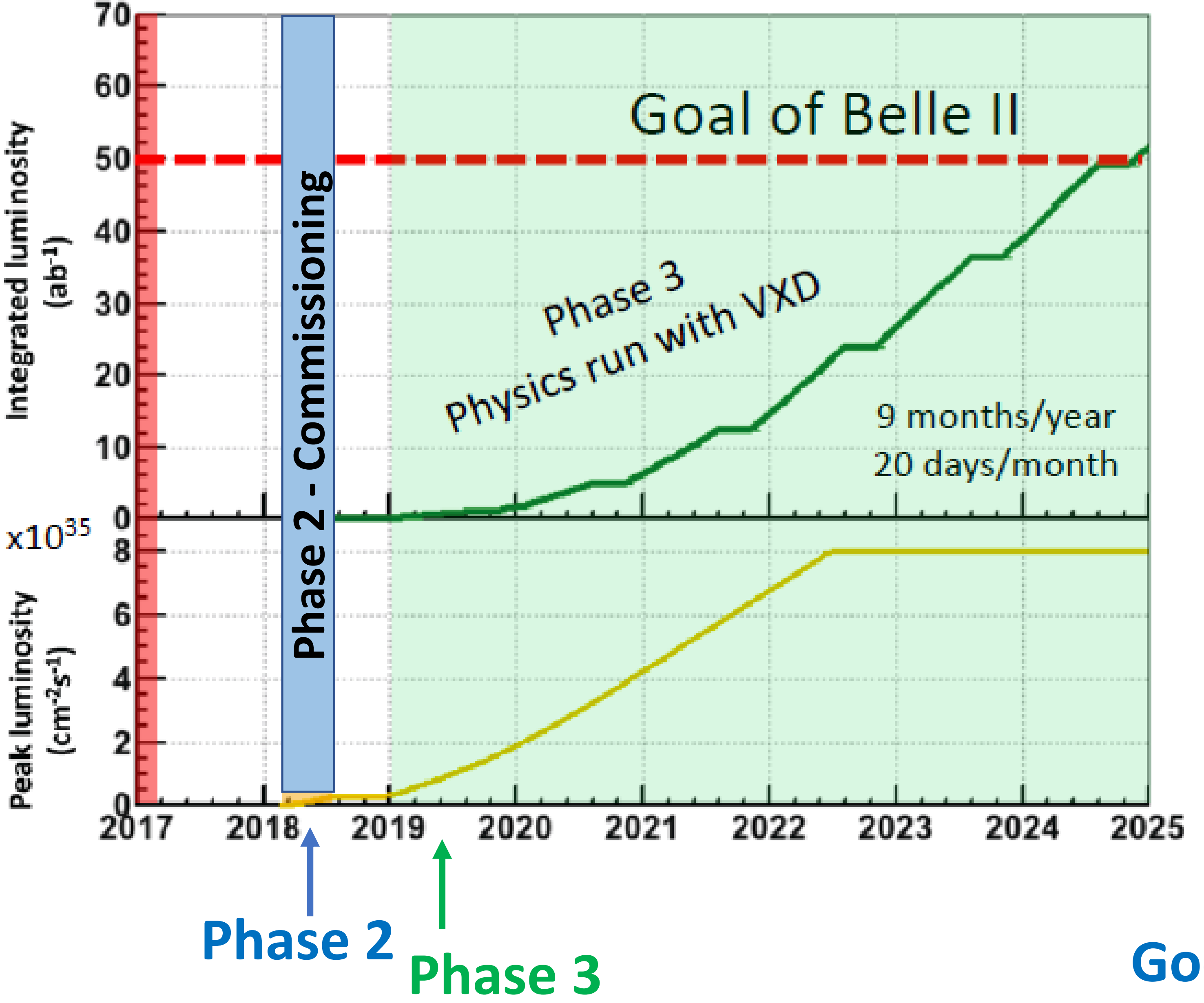
- 1/8 of vertex detector
- Low backgrounds
- Pass-through HLT (software) trigger

Good conditions for dark searches

Phase 3

- L ≈ 50 ab^{-1} with the full detector

Belle II data taking plan: today



Phase 2

Phase 2 finished July 17th 9 am

- **Nano-beam scheme works!**
- **$L=5.5\times10^{33}\ cm^{-2}s^{-1}$ achieved**
- **$L_{int} > 0.5\ fb^{-1}$ collected**

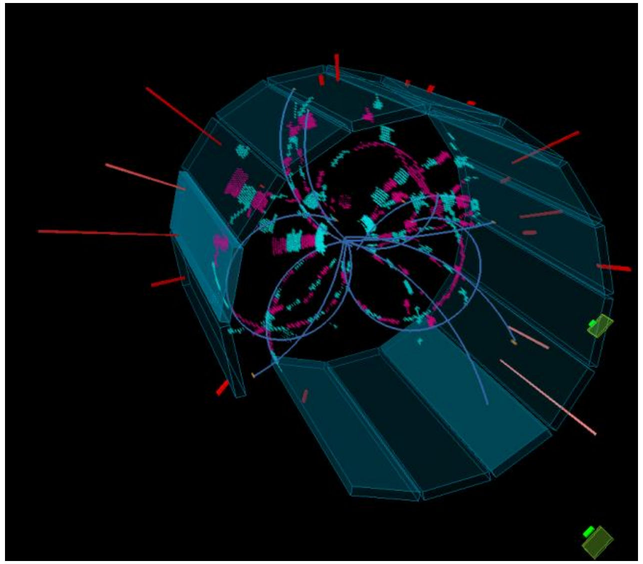
- 1/8 of vertex detector
- Low backgrounds
- Pass-through HLT (software) trigger

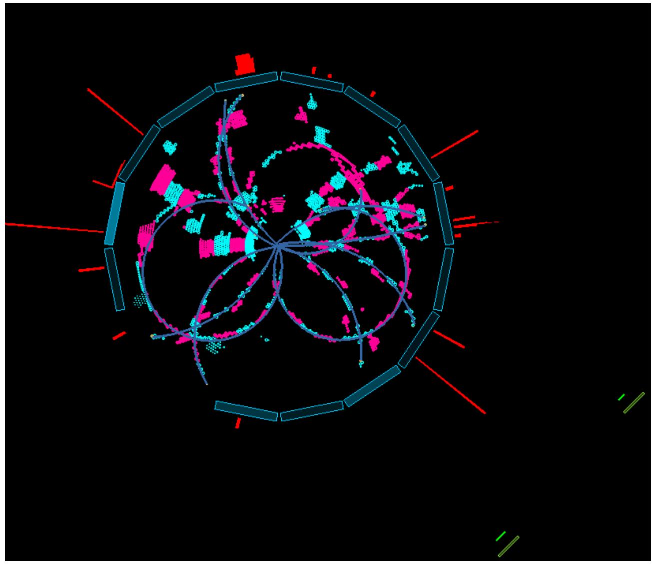
- ❑ Tracking and clustering L1 trigger
- ❑ Bhabha veto L1 trigger
- ❑ Some single photon L1 trigger

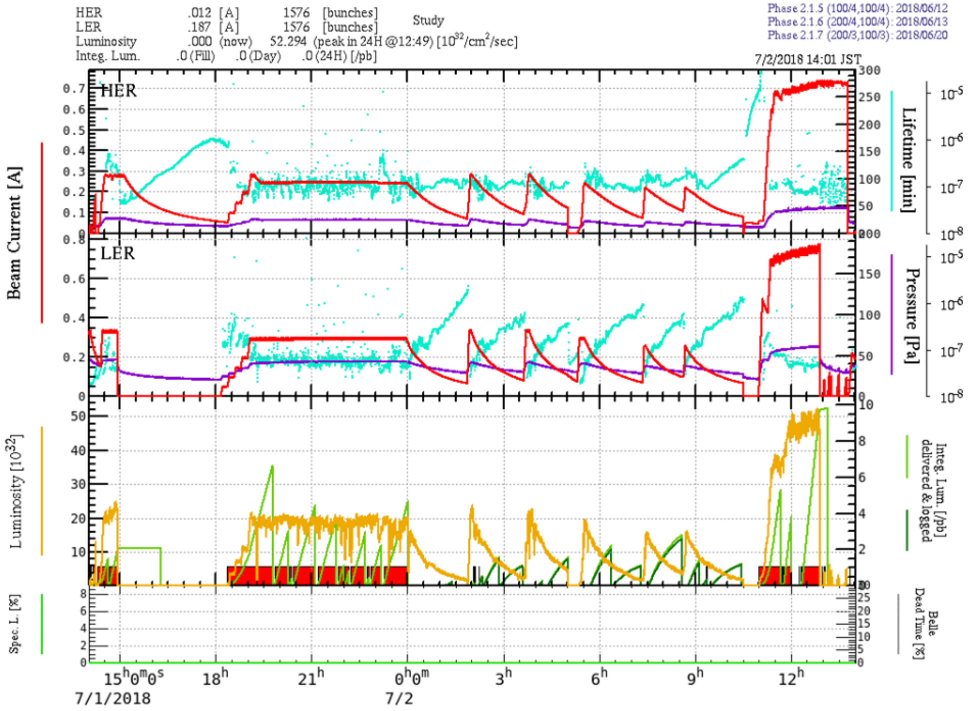
Good conditions for dark searches

Belle II & SuperKEKB Phase 2

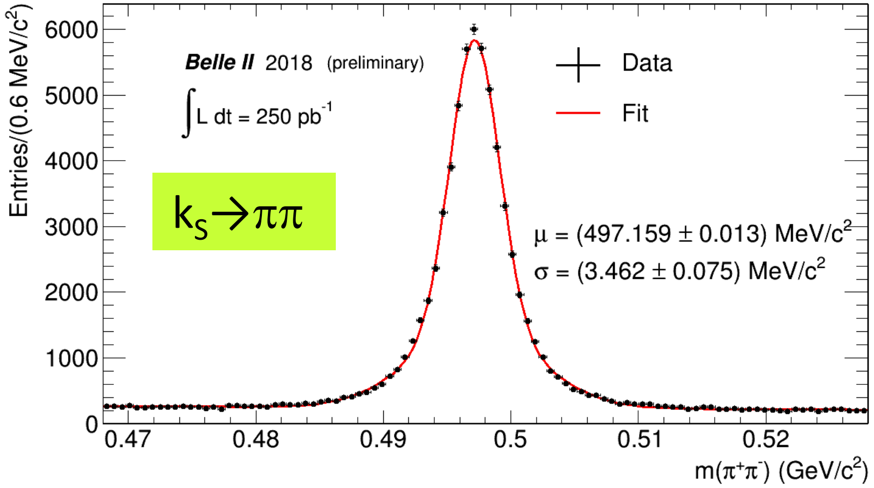
Start of collisions: April 25th

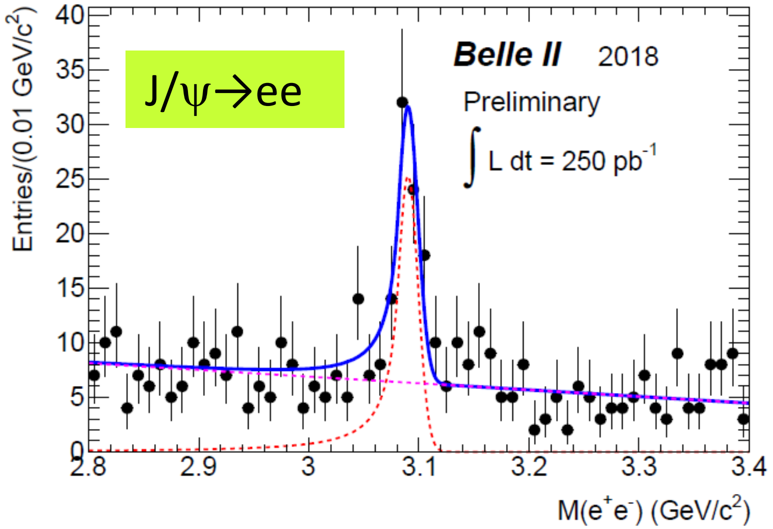


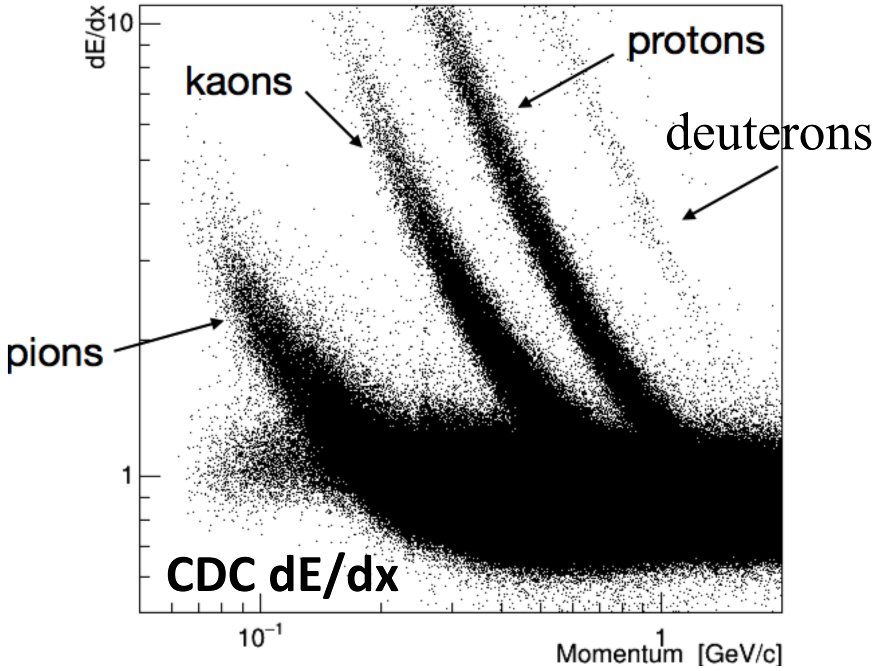


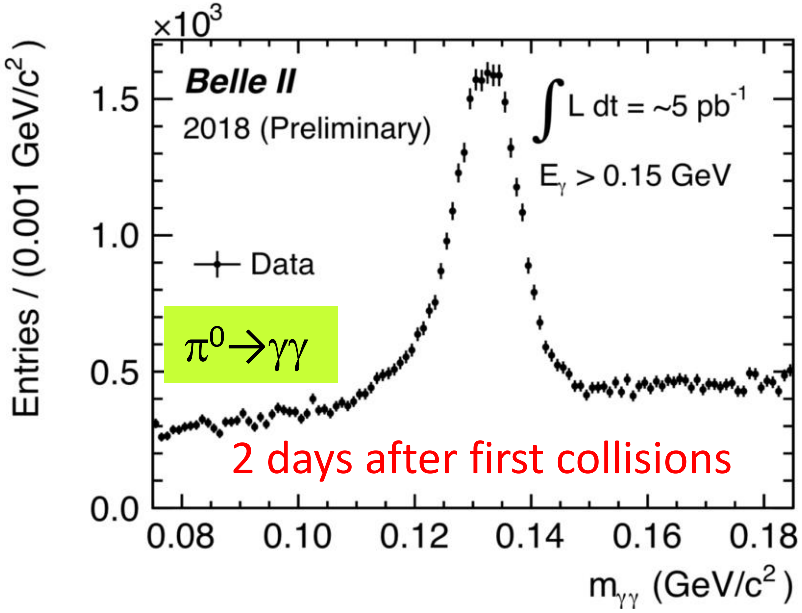


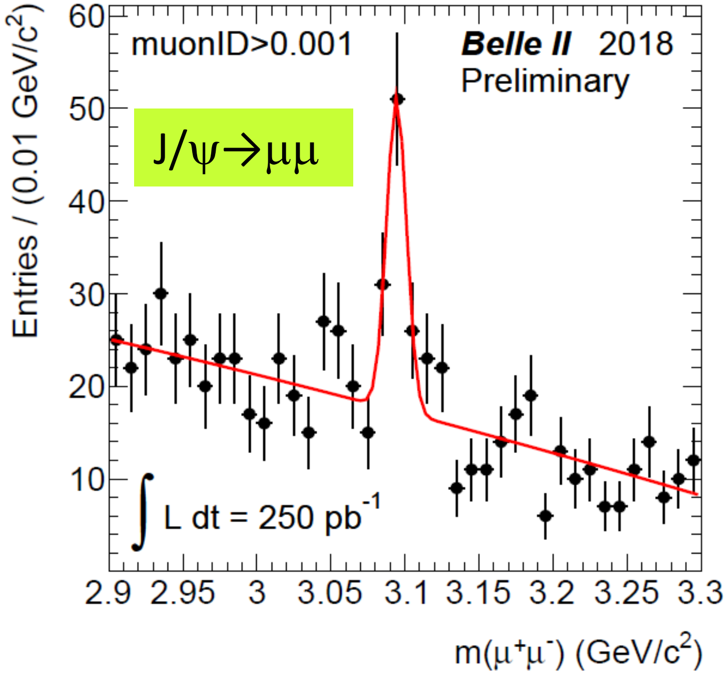
Belle II performance snapshots

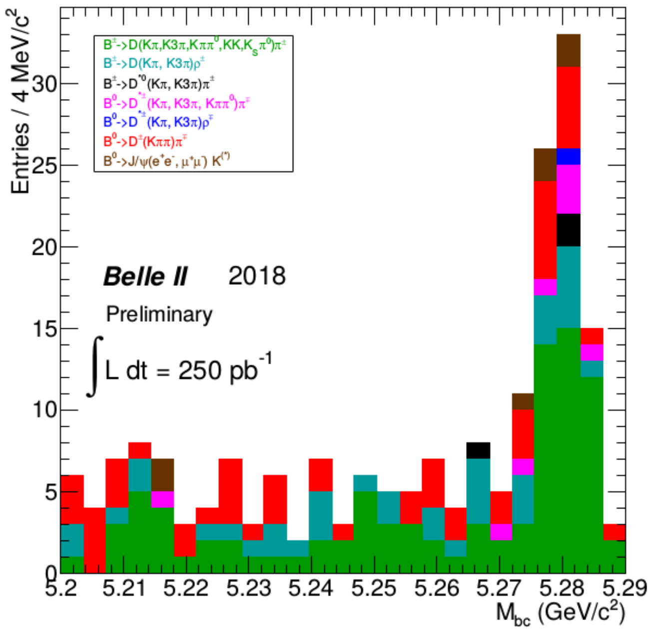








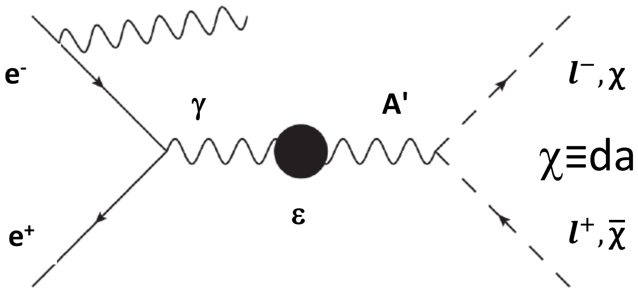




Dark photon: introduction

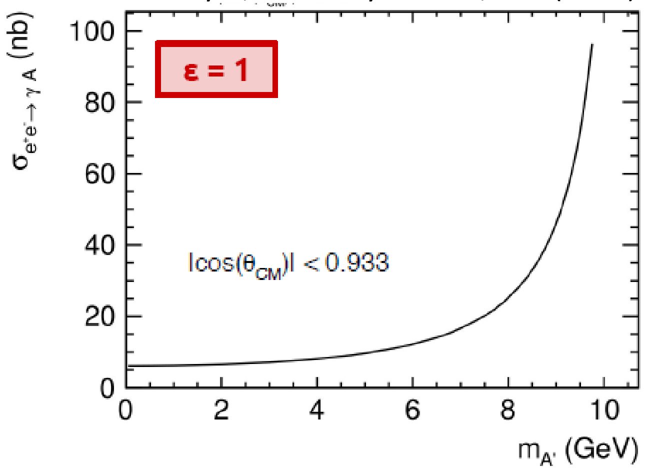
Some astrophysical observations suggest the possibility of the existence of a new light (GeV scale) hidden dark sector with a mediator A′ (dark photon), weakly coupled to the Standard Model via kinetic mixing, and light dark matter.

At e^+e^- colliders



χ≡dark matter particle

P. Fayet, Phys. Lett. B **95**, 285 (1980),
P.Fayet, Nucl. Phys. B **187**, 184 (1981)



two basic scenarios depending on **A′** vs matter mass relationship

$m_\chi > 1/2\ m_{A'} \Rightarrow$ A′ visible decays (SM particles)

$A' \to l^+ l^-$
$A' \to \pi^+\pi^-$
h′ A′ dark higgstrahlung

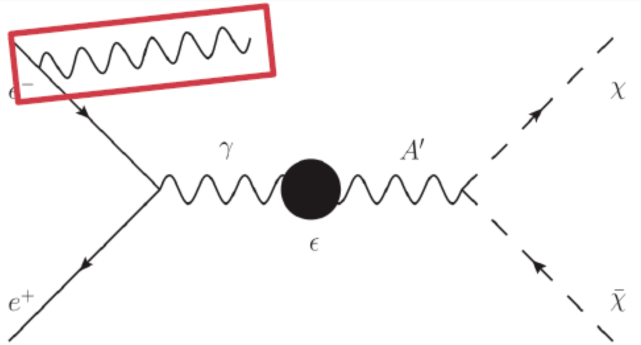
$\to$ $h' \to A'A'$, $A'A'A' \to 6\ l^{\pm} + \pi^{\pm}$
$\to$ A′+missing

$m_\chi < 1/2\ m_{A'} \Rightarrow$ A′ invisible decays to LDMA

$A' \to \chi\bar{\chi}$

access to light dark matter particles

Invisible dark photon: experimental signature



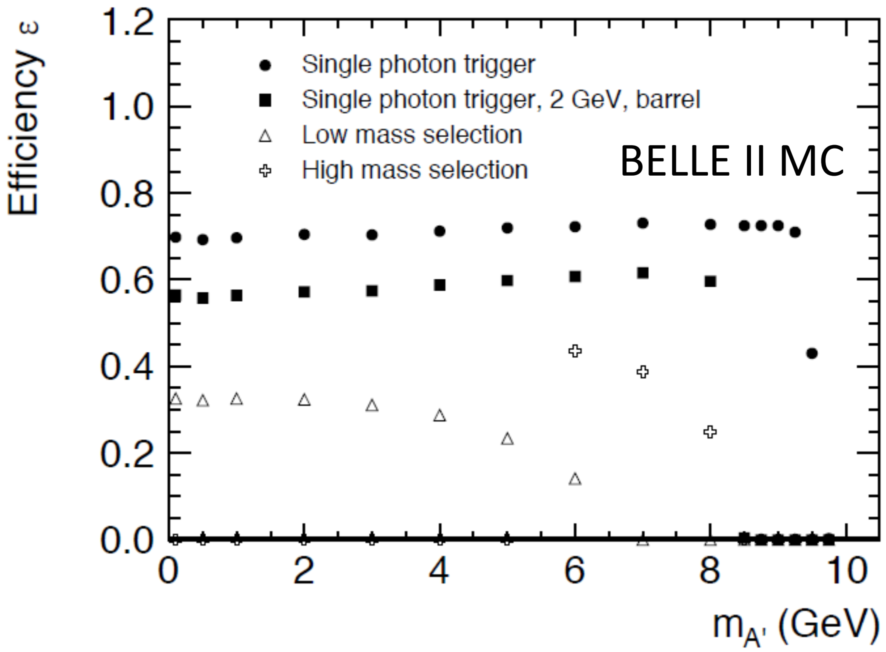
Only **one photon** in the detector.

Needs a **single photon trigger**

(*not available in Belle, ≈ 10% of data in BaBar*)

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

→ Bump in recoil mass or photon energy

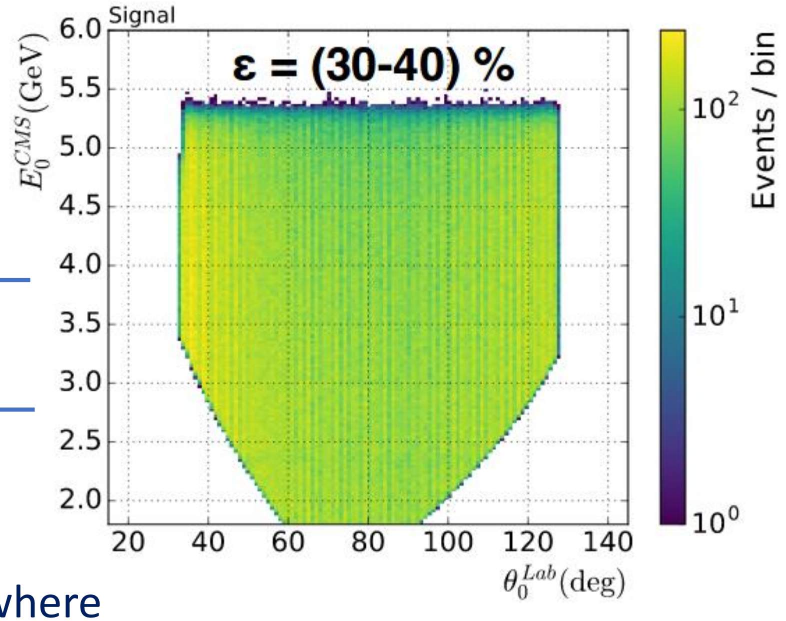


Limited mainly by acceptance

Backgrounds

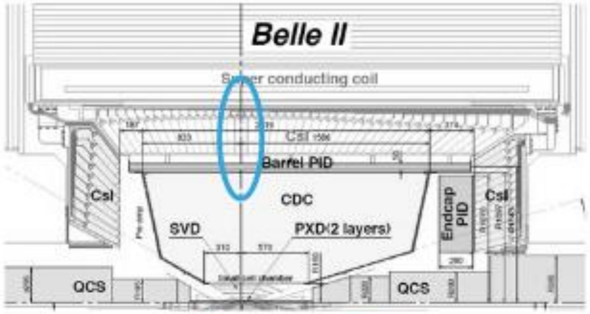
$e^+e^- \rightarrow e^+e^-\gamma(\gamma)$, $e^+e^- \rightarrow \gamma\gamma(\gamma)$

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)

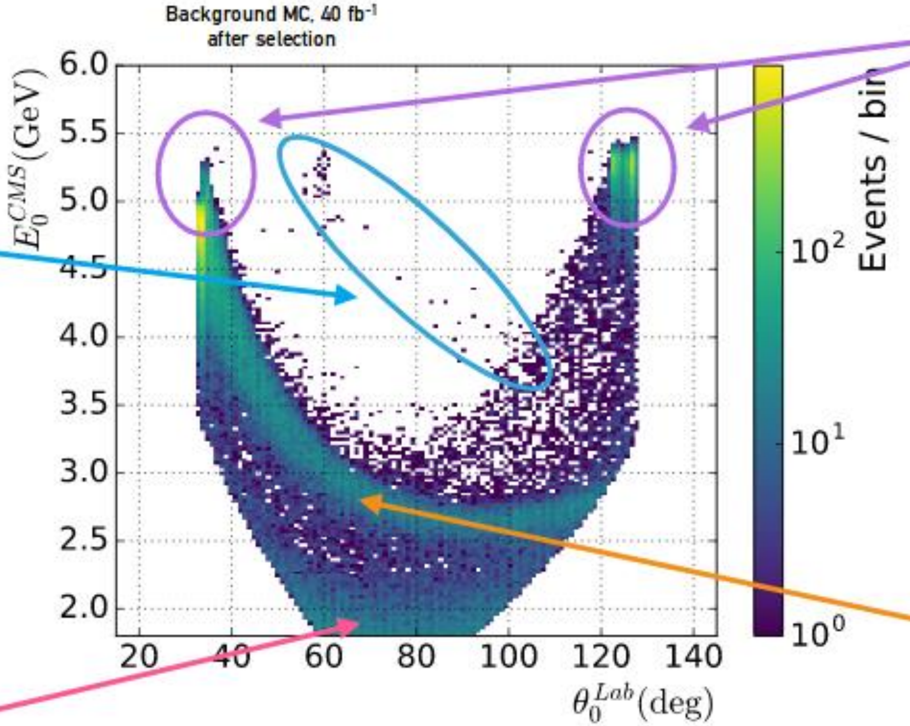


Probably not sustainable in deep Phase 3, where some prescaling or threshold adjustment will be needed

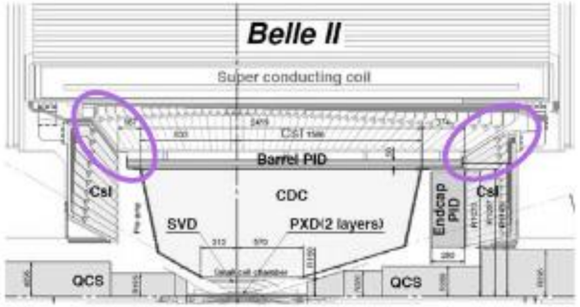
Invisible dark photon: backgrounds



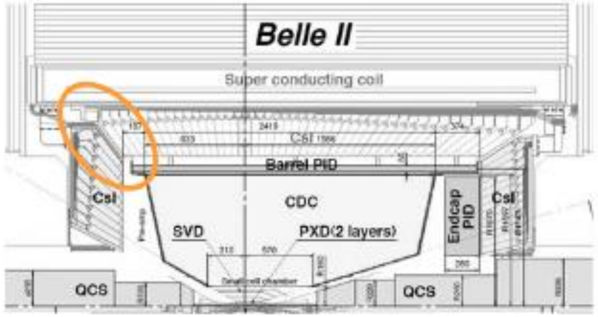
ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance



ee→eeγ
both electrons
out of tracking acceptance



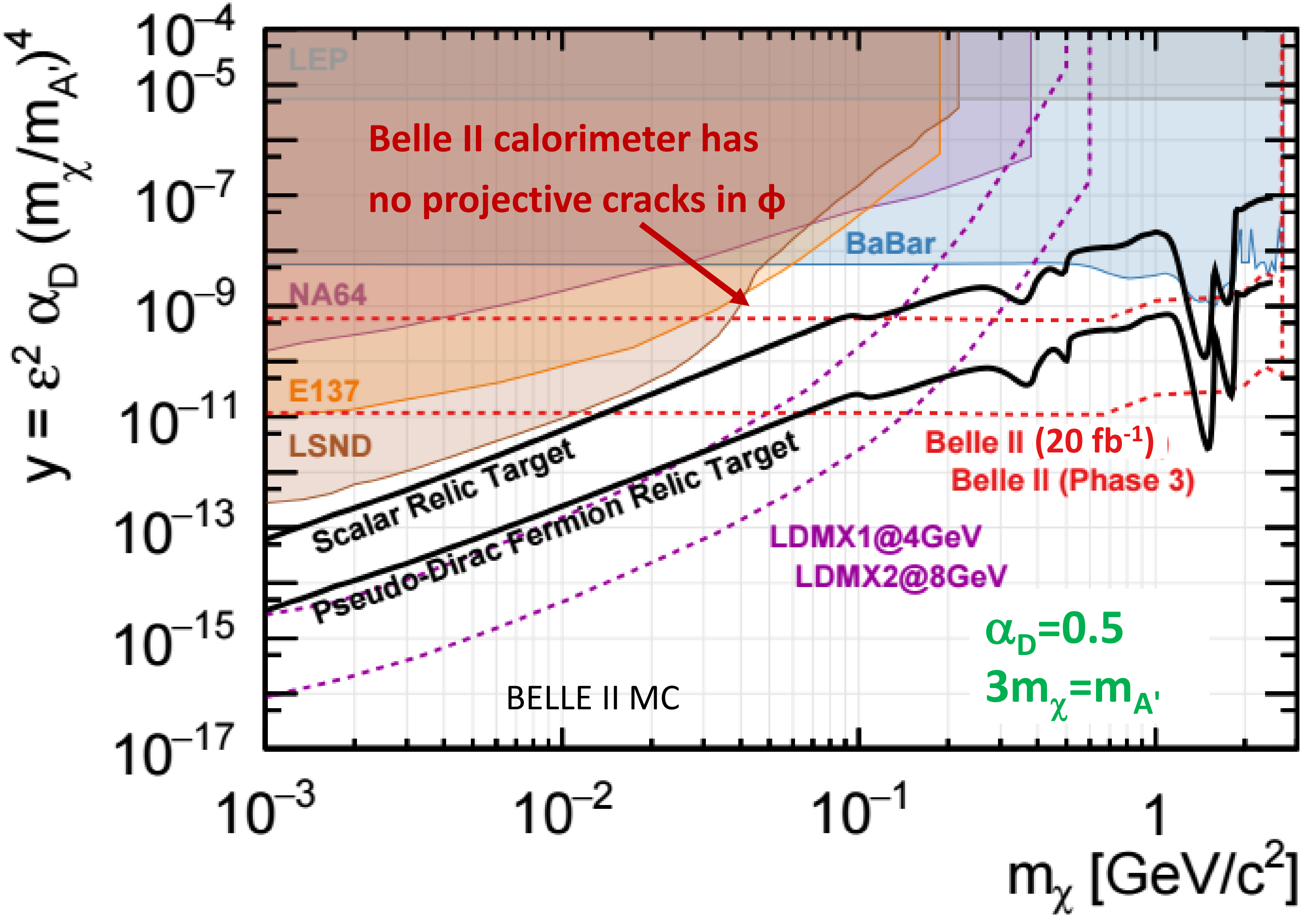
ee→2γ
1γ in ECL BWD or FWD gap



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

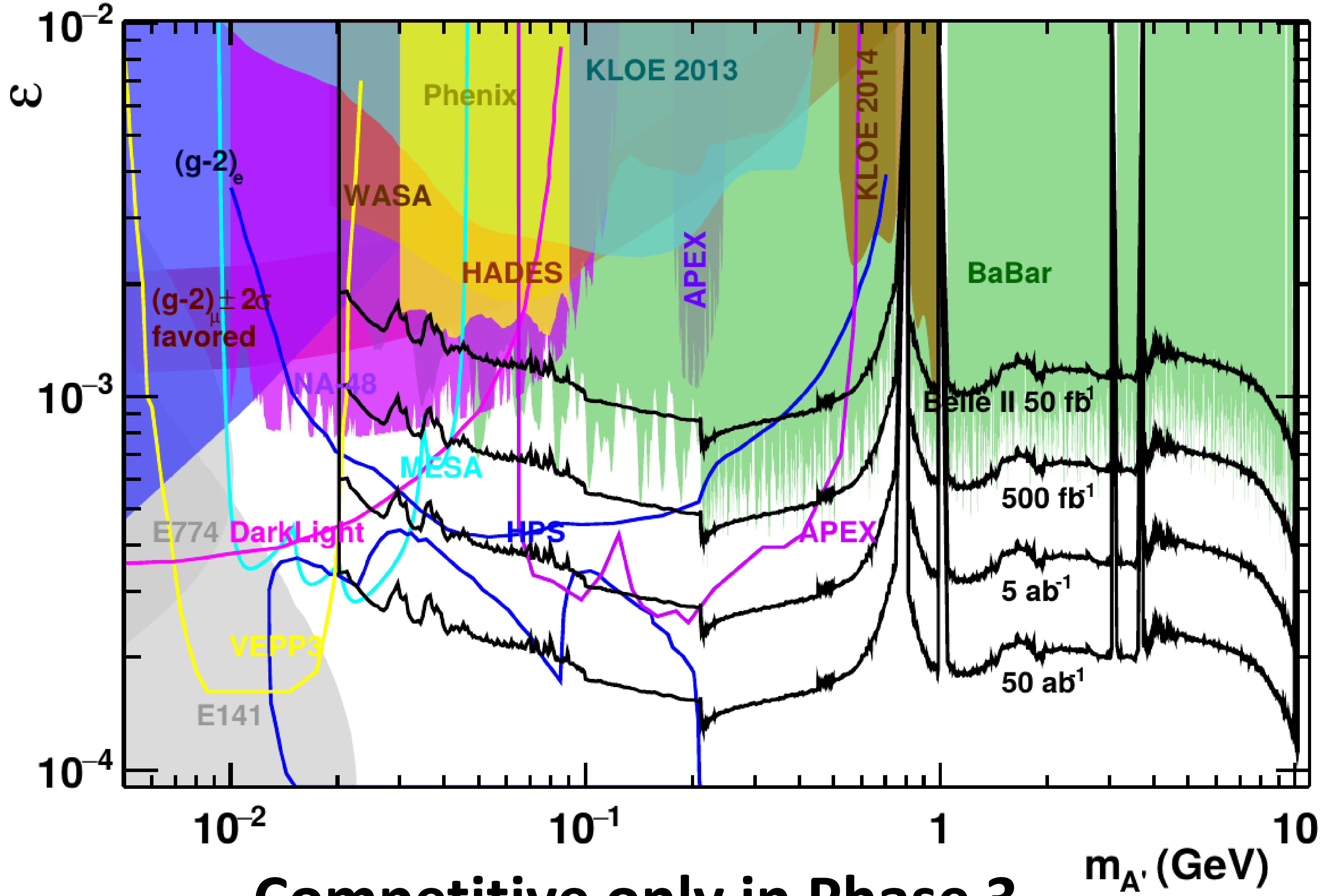
Crucial usage of KLM to veto photons in ECL gaps

Invisible dark photon: sensitivity



Lower trigger threshold wrt BaBar

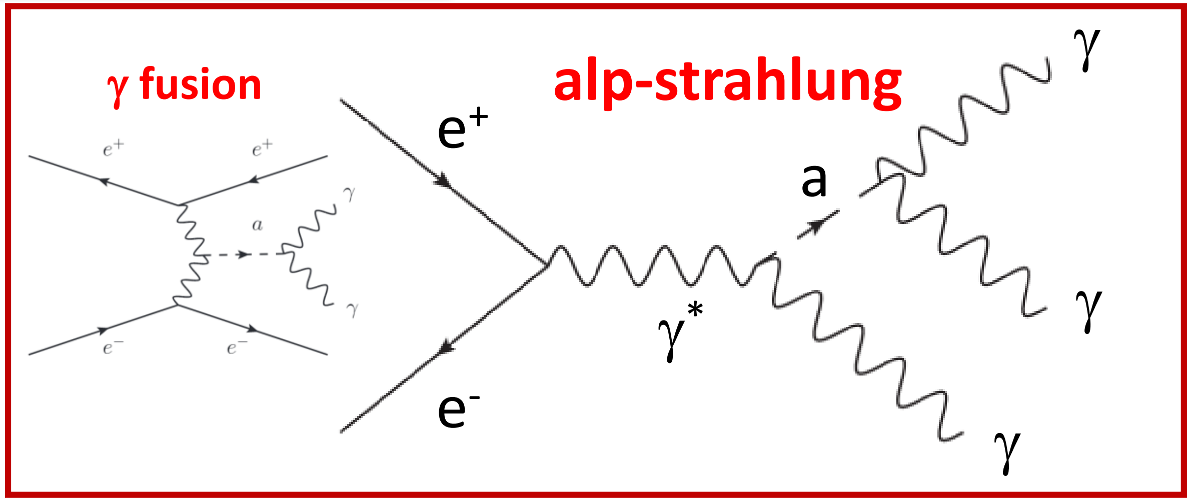
Visible dark photon: sensitivity



Competitive only in Phase 3

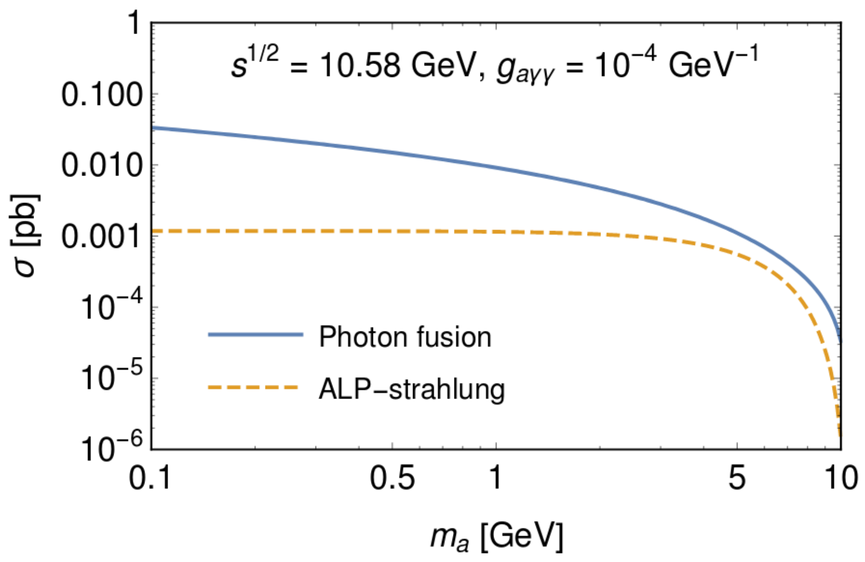
Axion Like Particles (ALPs)

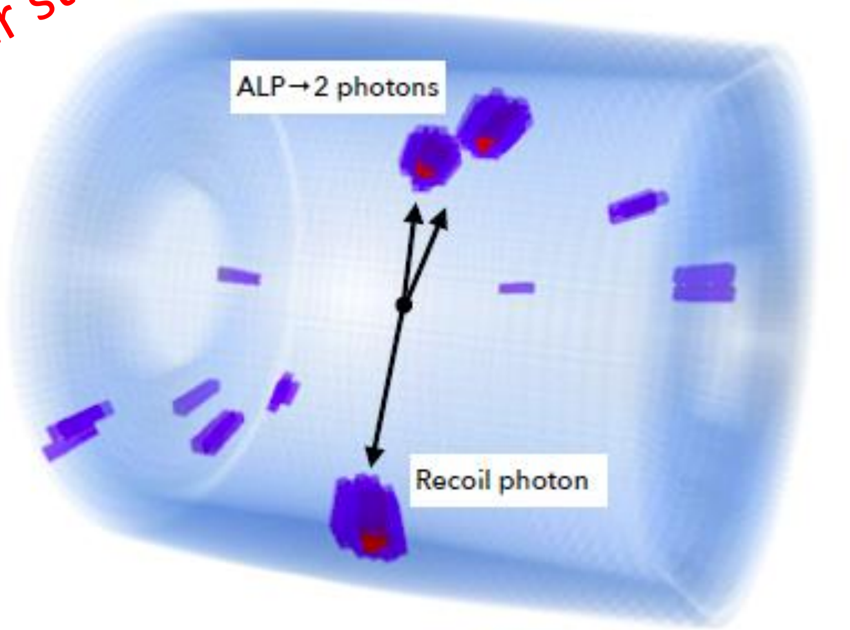
- Pseudo-scalars particles which couple to bosons.
- Differently from QCD axions, no relation between mass and coupling
- Focus on coupling to photons: $g_{a\gamma\gamma}$
- Alp-strahlung + photon fusion production mechanisms
- $\tau \sim 1 / g_{a\gamma\gamma}^2 \, m_a^3$
- No results at B factories yet



3 γ topology

photon fusion sensitivity under study

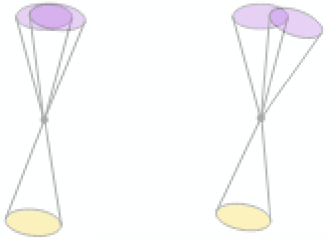


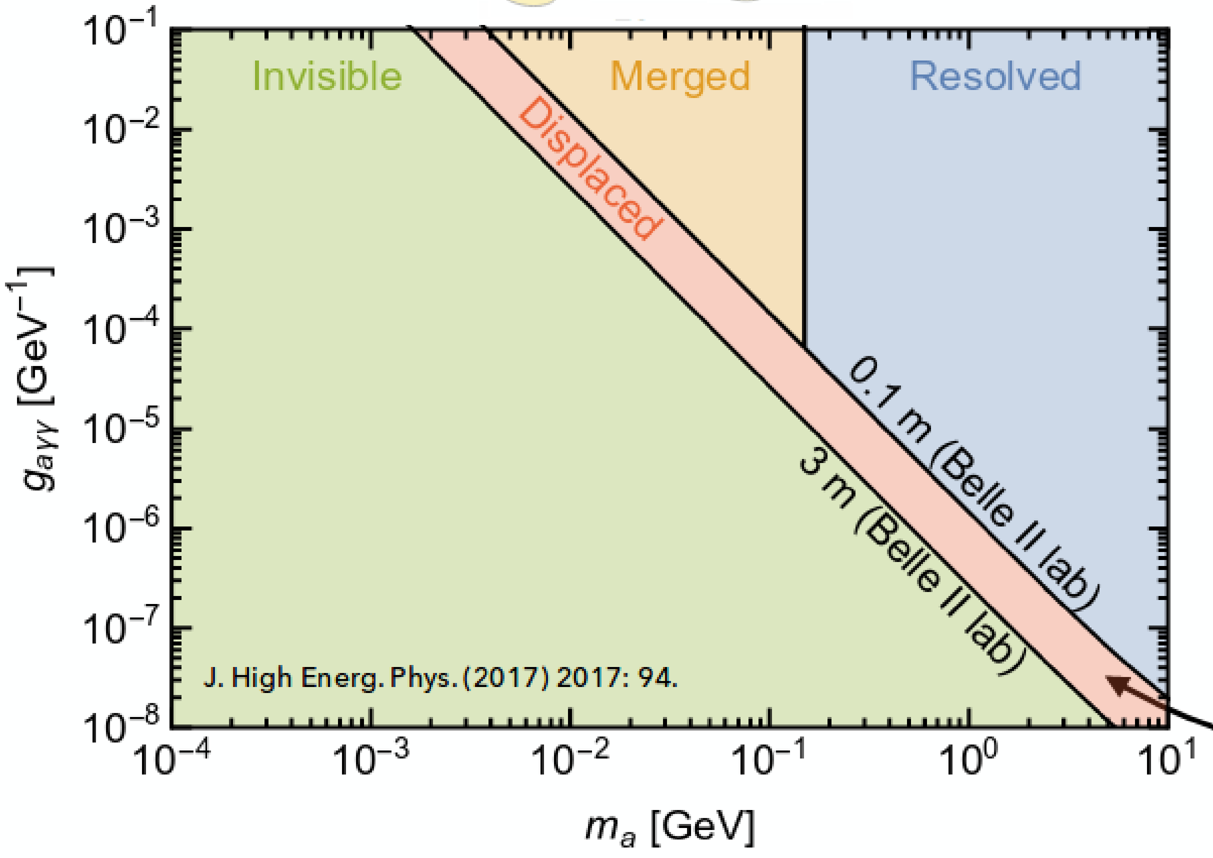


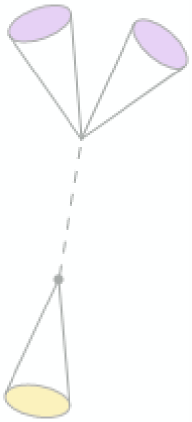
Axion Like Particles (ALPs): signal

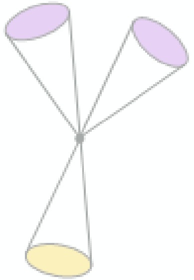
3 γ topology, but…

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









Three **resolved**, high energetic photons.

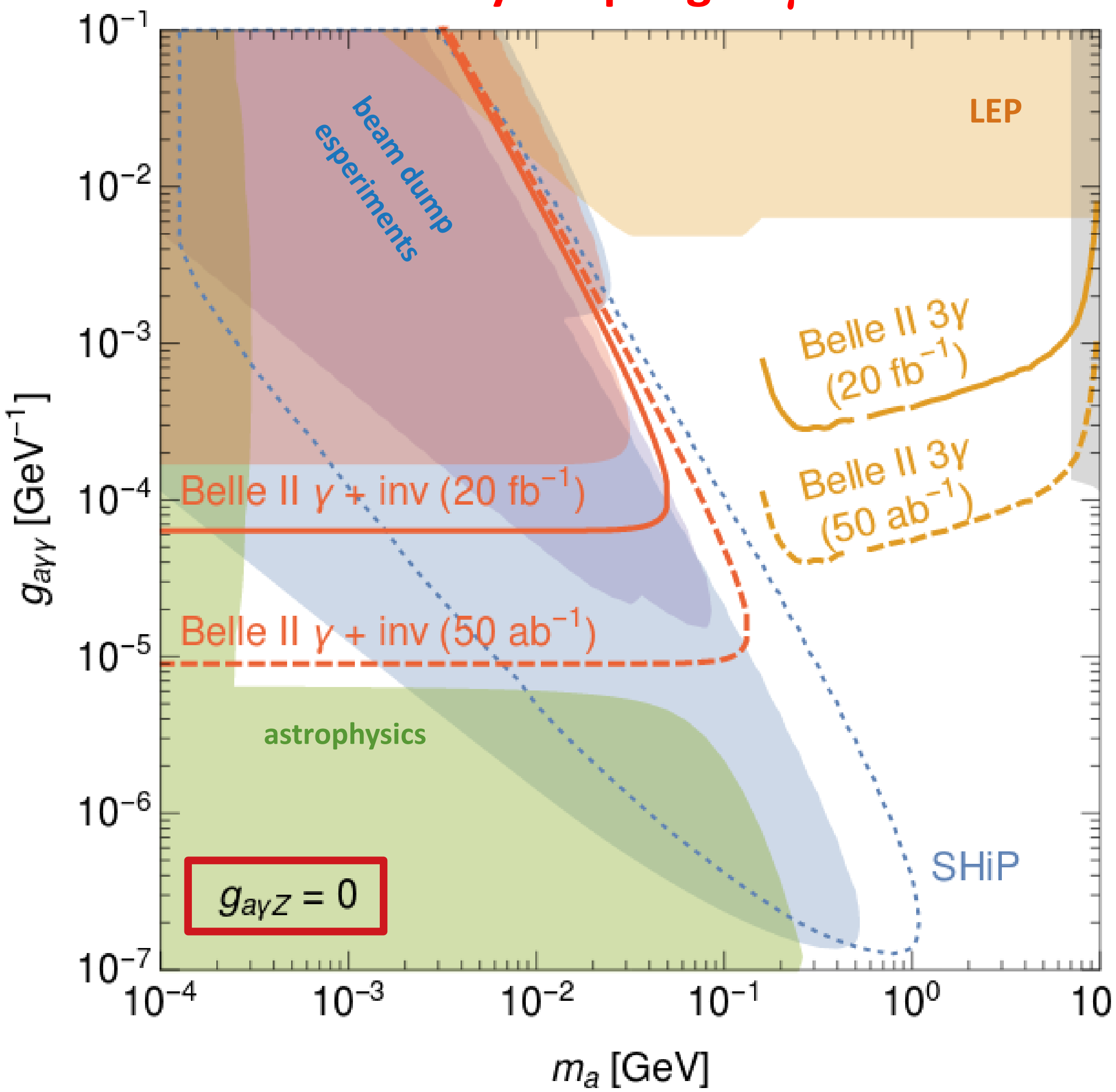
ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

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

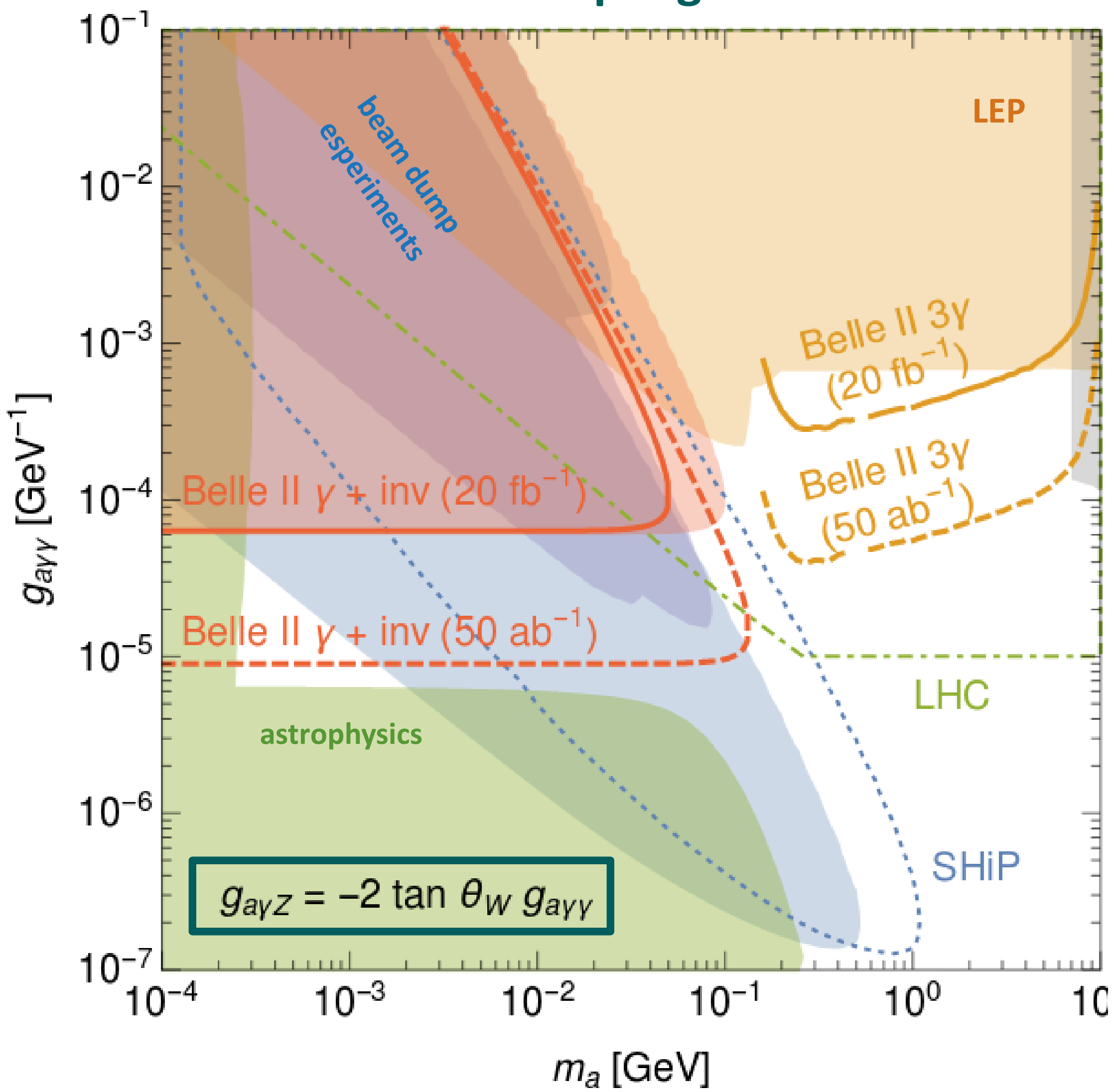
ALPs can also decay to DM → single photon topology

Axion Like Particles (ALPs): sensitivity

Only coupling to γ

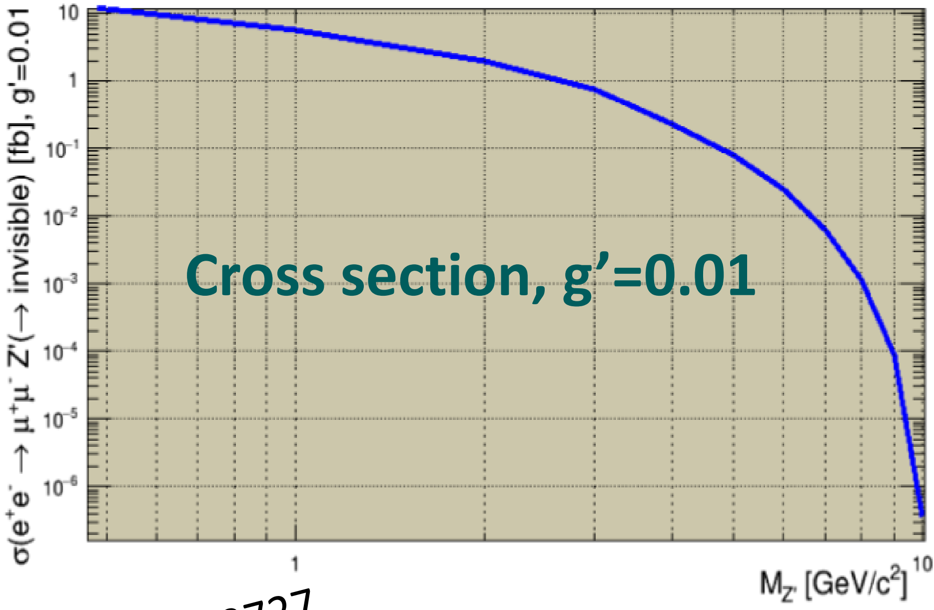


With coupling to Z

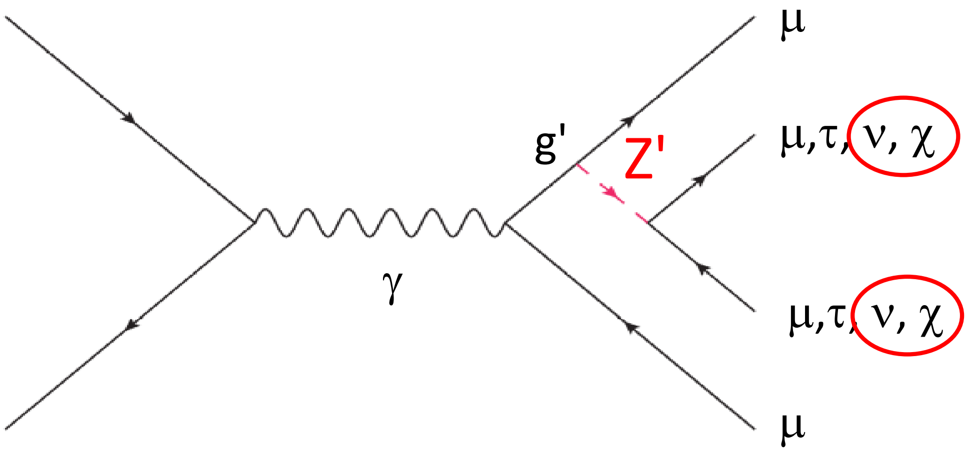


L_μ - L_τ: Z' invisible decay

- A new gauge boson Z' which couples only to the 2° and 3° lepton family
- May explain $(g-2)_\mu$
- Invisible decay channel to be explored for the first time
- Invisible decay channel BR possibly enhanced by the presence of kinematically accessible dark matter (e.g. sterile neutrinos)
- Sometimes invoked to explain EDGES results



Shuve et al. (2014), arXiv 1408.2727



Invisible Branching Ratios

Branching ratios to SM ν's:

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

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

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

If LDMA kinematically available → ≈ 1

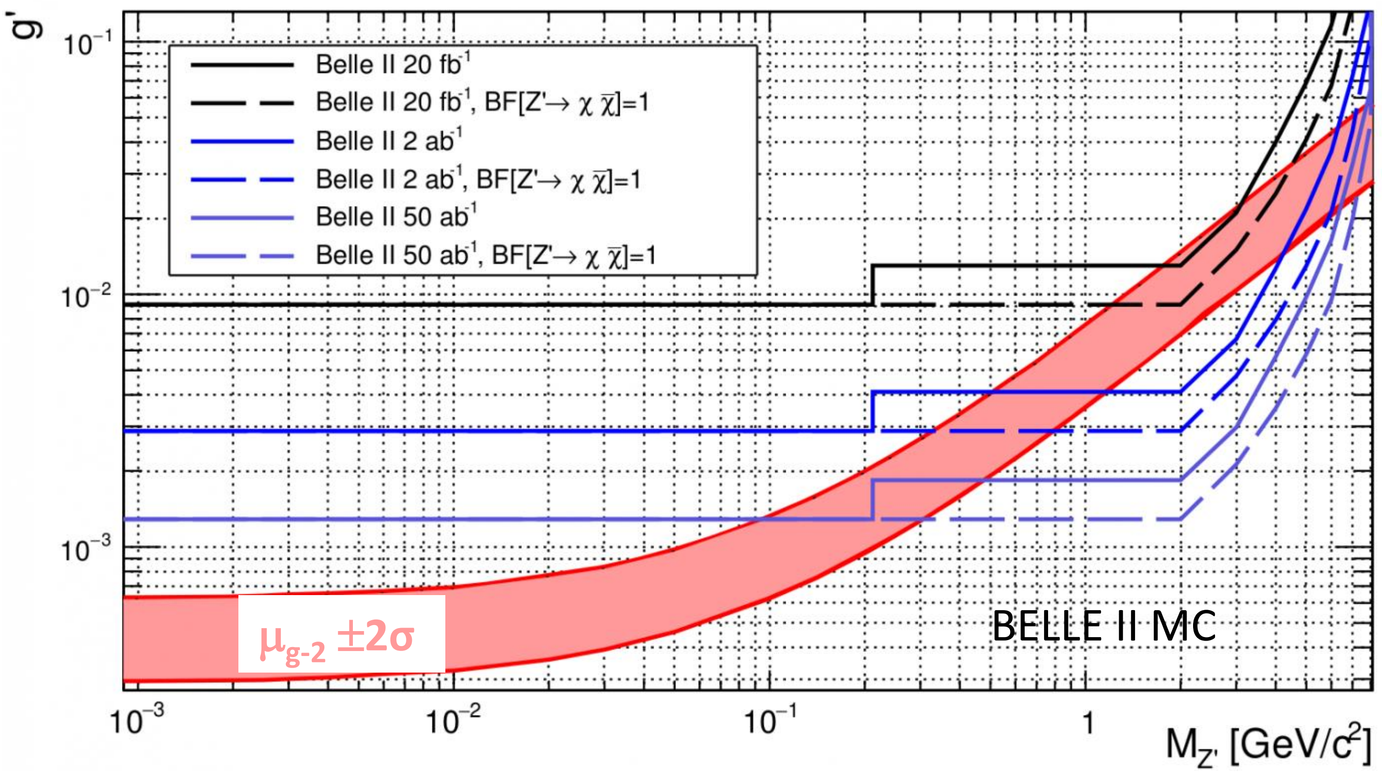
L_μ - L_τ, Z' invisible decay sensitivity

Look for bumps in recoil mass against a $\mu^+\mu^-$ pair

Main backgrounds:

$e^+e^- \to \mu^+\mu^- (\gamma)$
$e^+e^- \to \tau^+\tau^- (\gamma), \tau^\pm \to \mu^\pm\nu\nu$
$e^+e^- \to e^+e^- \mu^+\mu^-$

Belle II expected sensitivity for Z' → invisible



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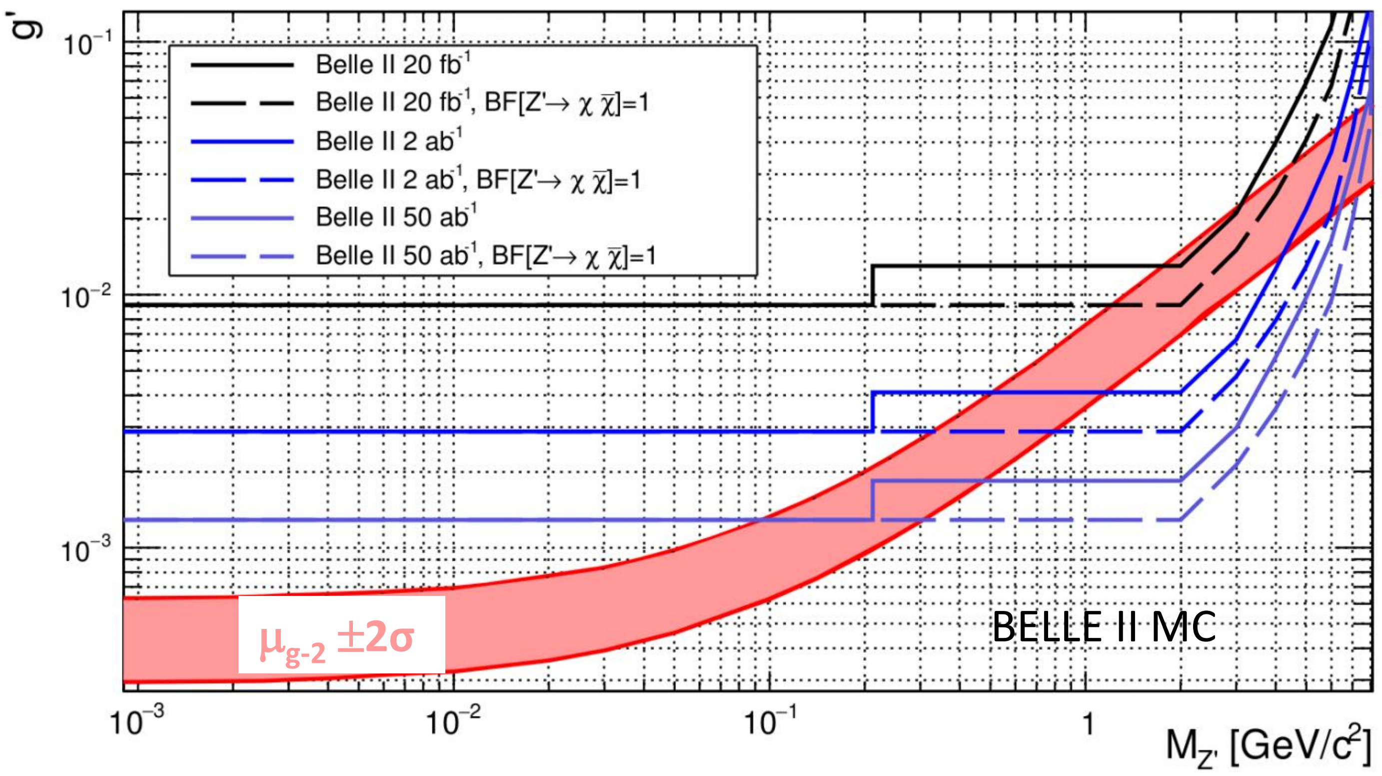

Z'→ visible decay (muonic dark force)

$e^+e^- \to \mu^+\mu^- Z'$; $Z' \to \mu^+\mu^-$ will be competitive in Phase 3 (due to BaBar result)

L_μ - L_τ, Z' invisible decay sensitivity

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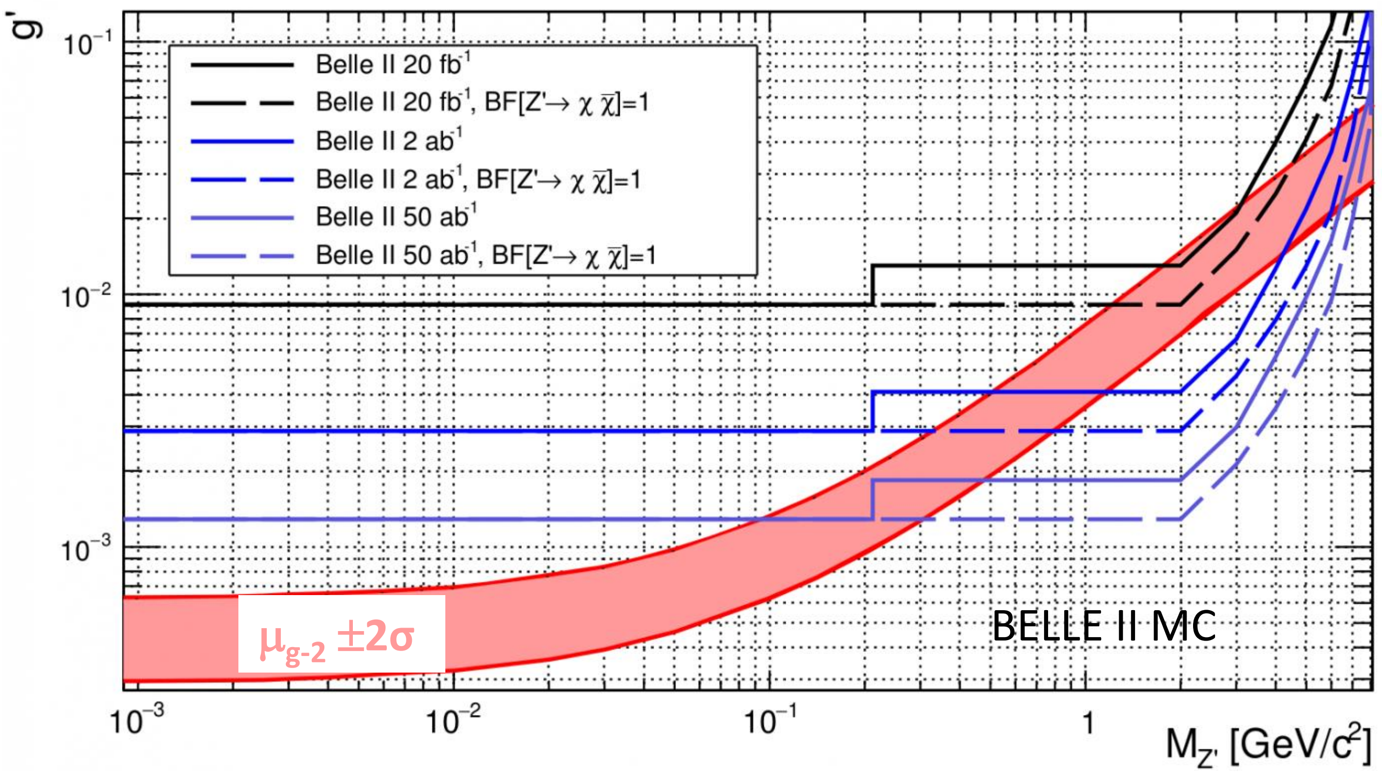


Additional possibility

LFV Z' (eμ coupling)

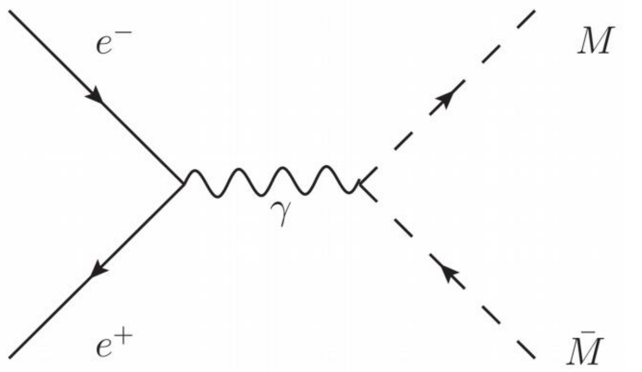
$e^+ e^- \to e^+ \mu^- Z'$; $Z' \to$ invisible

$e^+ e^- \to e^+ \mu^- Z'$; $Z' \to e^+ \mu^-$ (no SM background)

Z'→ visible decay (muonic dark force)

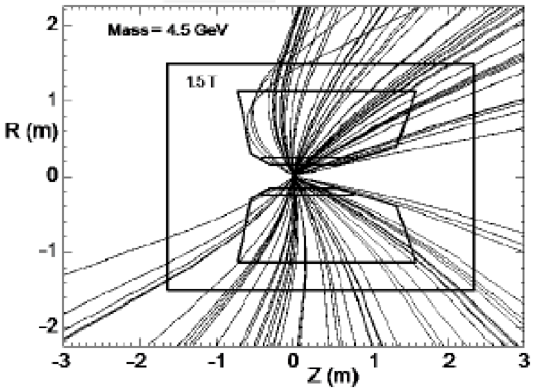
$e^+ e^- \to \mu^+ \mu^- Z'$; $Z' \to \mu^+ \mu^-$ will be competitive in Phase 3 (due to BaBar result)

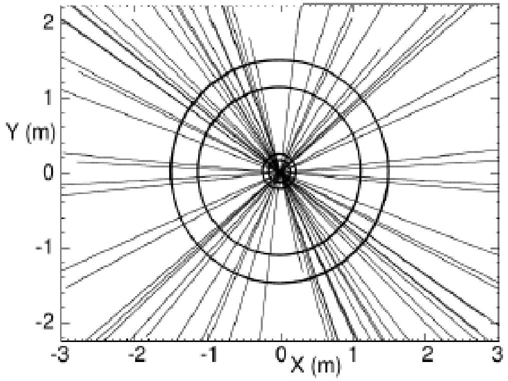
Magnetic monopoles

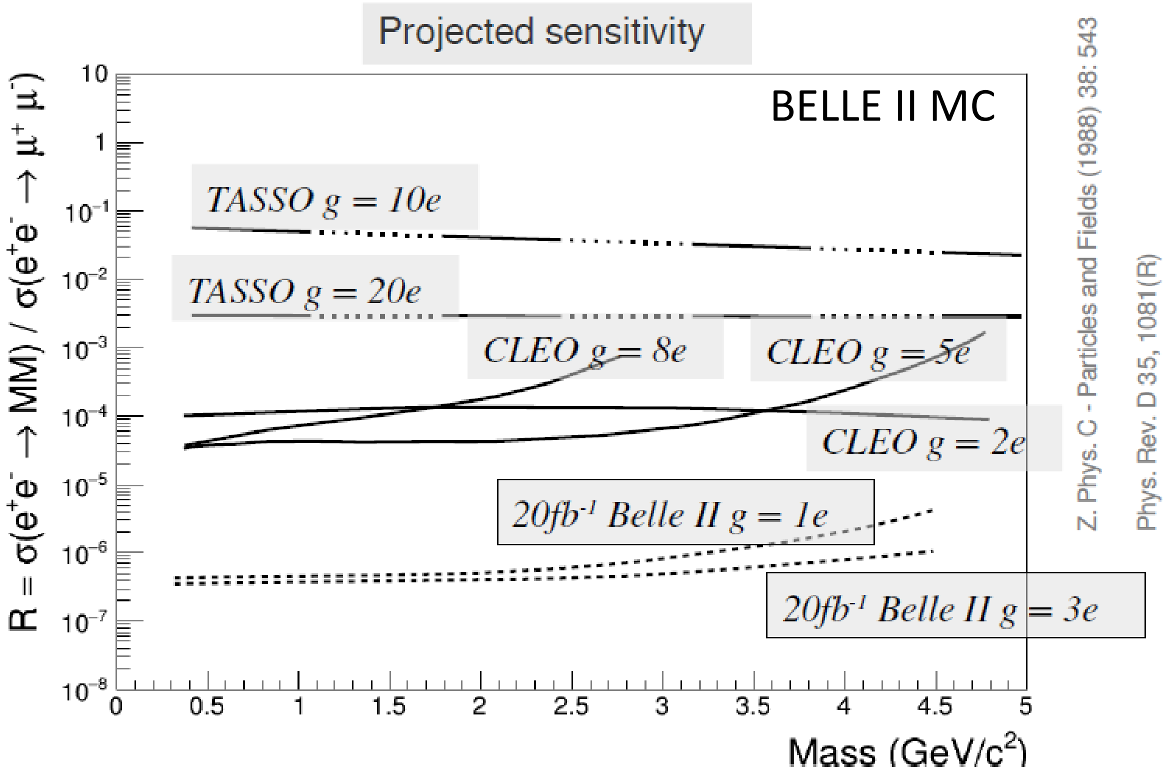


- Particle carrying magnetic charge
- Recent searches for magnetic charges g > 68.5e
- Small charges g < 10e are not excluded
- Weaker ionisation due to absence of $1/\beta^2$ factor for magnetic charges
- Tracks are straight in XY and curved in RZ
- They need a dedicated tracking (parabolas rather than helices)

$$z(s) = z_0 + \frac{p_z}{p_T}s + \frac{gBm}{2p_T^2}s^2$$







Summary

- Belle II Phase2 finished one week ago
- Early data taking mostly devoted to commissioning
- $L_{int} > 0.5\ fb^{-1}$, with $L_{MAX} = 5.5x10^{33} cm^{-2}s^{-1}$
- Hardware L1 trigger extensively studied (both tracks and neutrals)
- Resonances, b-physics and charm physics «rediscovered»

Some dark sector searches may lead to interesting new limits even with small data sets

- ➢ **Invisible dark photon search**
- ➢ **ALP search**
- ➢ **Z' to invisible search**
- ➢ **Z' LFV search**
- ➢ **Magnetic monopoles search**

They will be performed in the next months, aiming at more sensitive results in (the beginning of) Phase 3

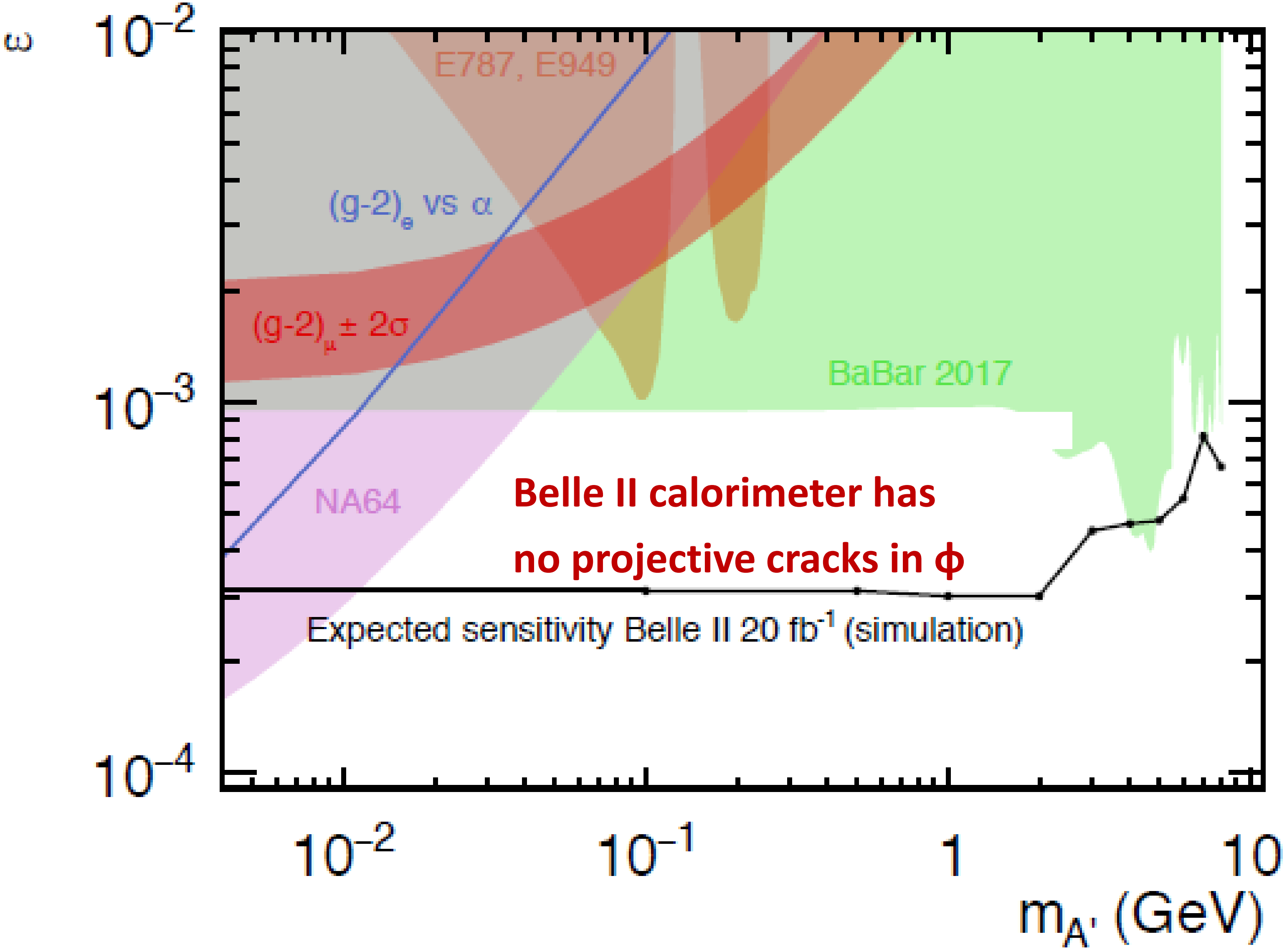
<u>Not even mentioned</u>

- Y(1S) to invisible
- muonic dark force
- dark Higgs
- dark Higgsstrahlung
- dark scalars
- inelastic dark matter
- long-lived particles
- …

Phase 3 (full detector, higher luminosity) will start in February 2019

SPARE SLIDES

Invisible dark photon: sensitivity

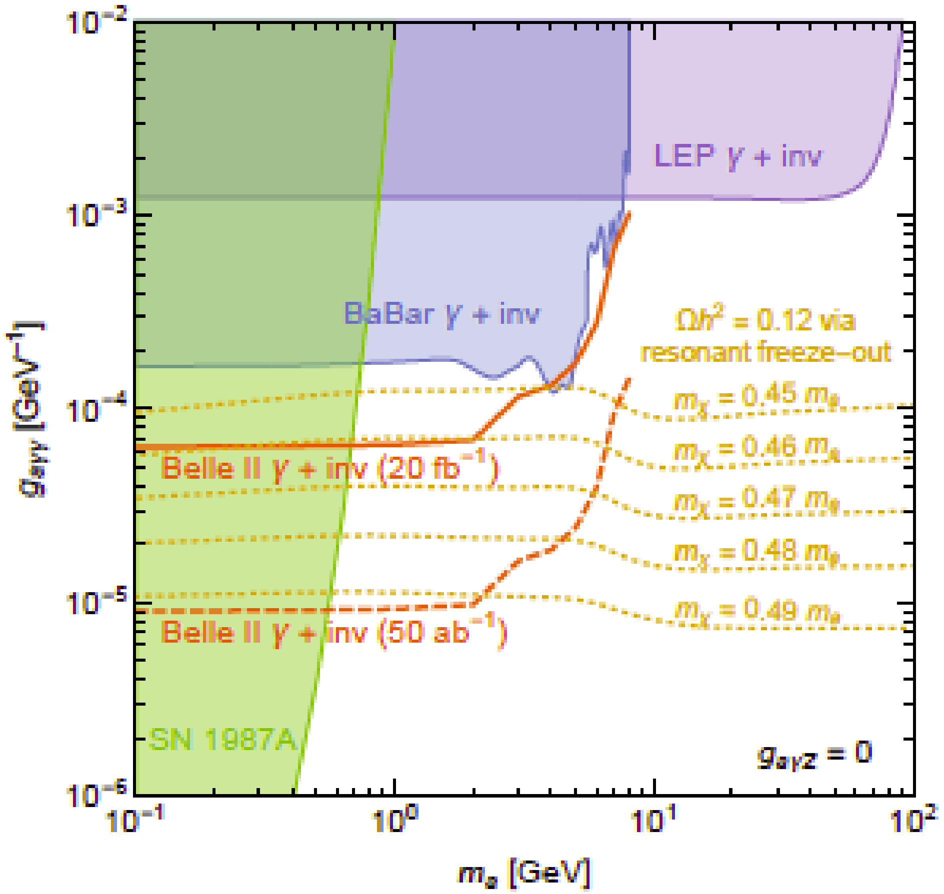


Belle II calorimeter has no projective cracks in ϕ

Lower trigger threshold wrt BaBar

Axion Like Particles (ALPs): sensitivity

ALP → DM decay



Z' LFV: invisible + visible

What if symmetries of SM are not kept in the Dark Sector?

What if DM violates Lepton Flavour?

One can imagine, for example, $e\mu$ coupling

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

Dominant background: $e^+e^- \rightarrow \tau^+\tau^- (\gamma)$, $\tau^\pm \rightarrow \mu^\pm, e^\pm \nu\nu$

$e^+ e^- \rightarrow e^+ \mu^{--} Z'$; $Z' \rightarrow e^+ \mu^-$ **+ c.c.**

no SM background