Dark sector at Belle II

XIII Meeting on B Physics – *Marseille, 1-3 October 2018*

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on behalf of the Belle II Collaboration

Istituto Nazionale di Fisica Nucleare

Outline

- The Belle II experiment at SuperKEKB collider
- Phase 2 Running
- Dark Matter at Belle II
  - Dark Photons
  - Axion Like Particles
  - Muonic Forces
- Summary & Outlook

B-Factories: the high intensity frontier

B-factories: dedicated experiments at *e^+e^- asymmetric-energy colliders* for the production of quantum coherent $B\bar{B}$ pairs $\rightarrow$ **CPV studies**.

$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\bar{B}$$

First generation of B-factories

at the KEKB collider, (KEK, Japan)

at the PEP II collider (SLAC, California)

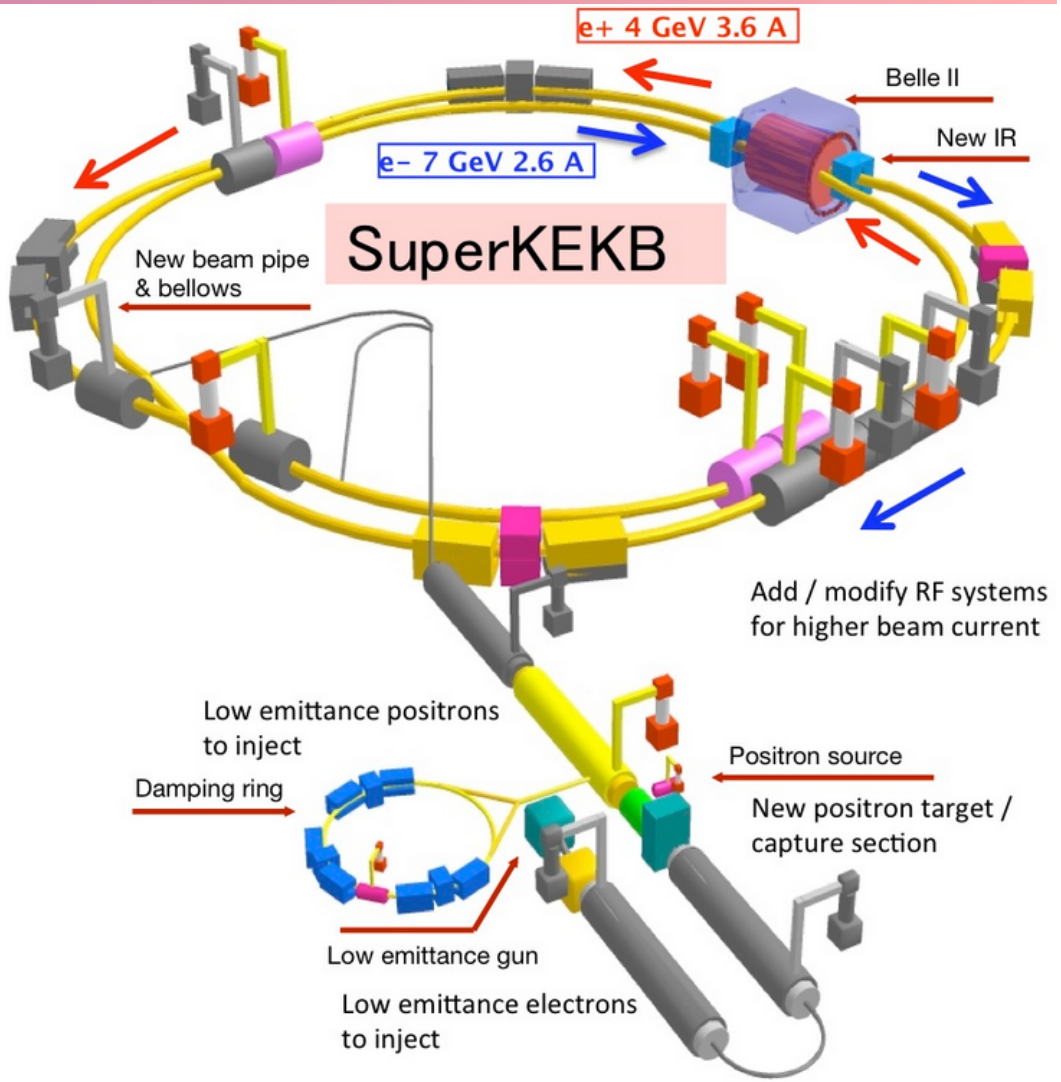
Belle II $\rightarrow$ x50 the data set of its predecessor!

Rich Physics Program

- SM test, precision flavor physics
- Rare/suppressed/forbidden processes
- Search for new light particle states
- *light DARK SECTOR*

SuperKEKB

- Second generation B-Factory, it will provide **the world highest luminosity,** applying the *large crossing angle nano-beams scheme.*
  (P.Raimondi for SuperB,
  M. Bona et al., arXiv:0709.0451)



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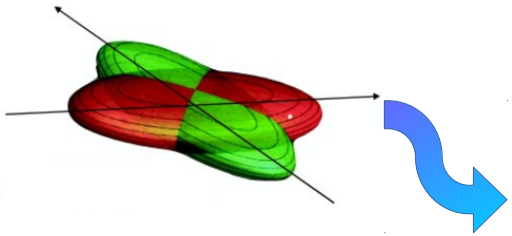
KEKB



I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

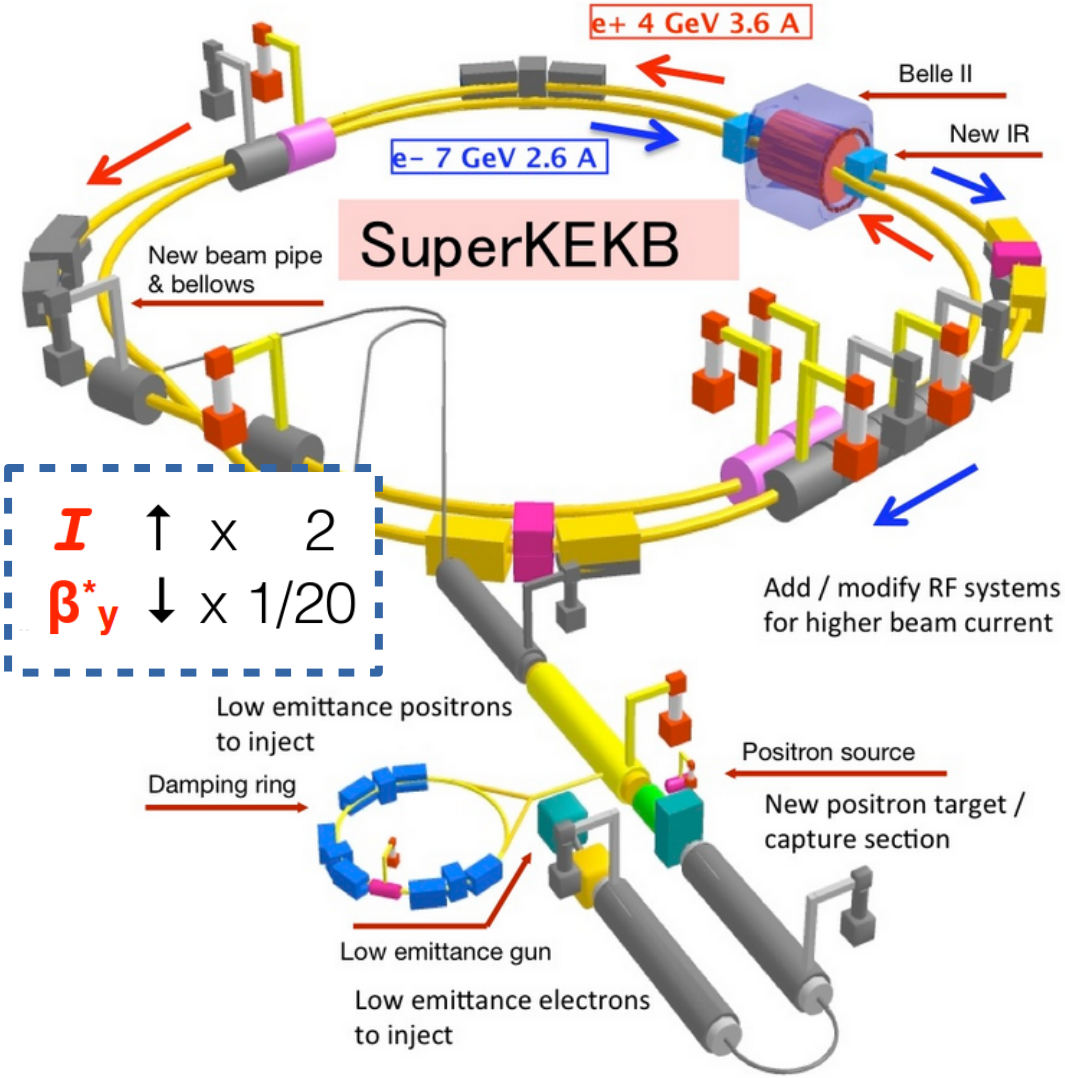
SuperKEKB

I (A): ~ 3.6/2.6

β^*_y (mm): ~ 0.27/0.3

I ↑ x 2

β^*_y ↓ x 1/20



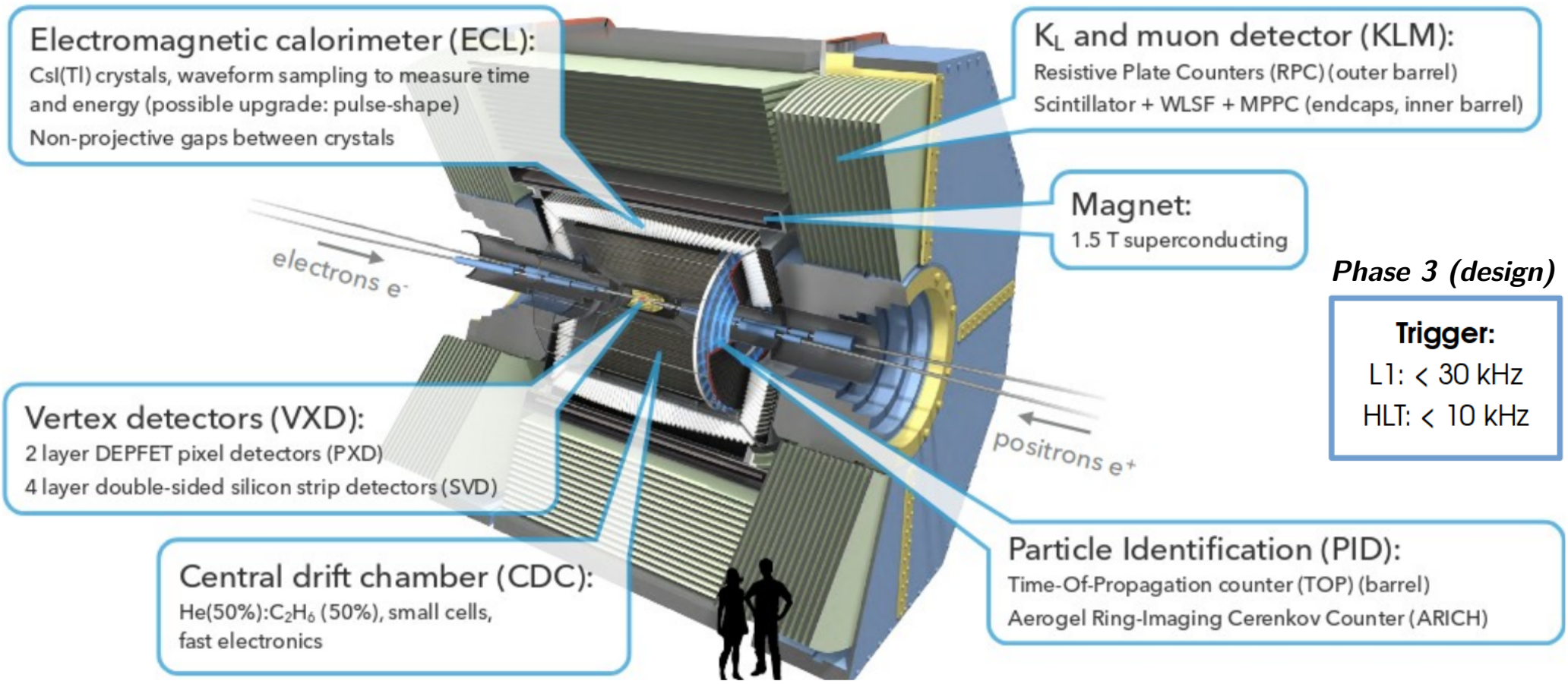
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma^*_y}{\sigma^*_x}\right)\frac{I_\pm \xi_{y\pm}}{\beta^*_{y\pm}}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor; beam current; beam-beam parameter; geometrical reduction factors; beam aspect ratio at the IP; vertical beta-function at the IP

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

The Belle II Detector

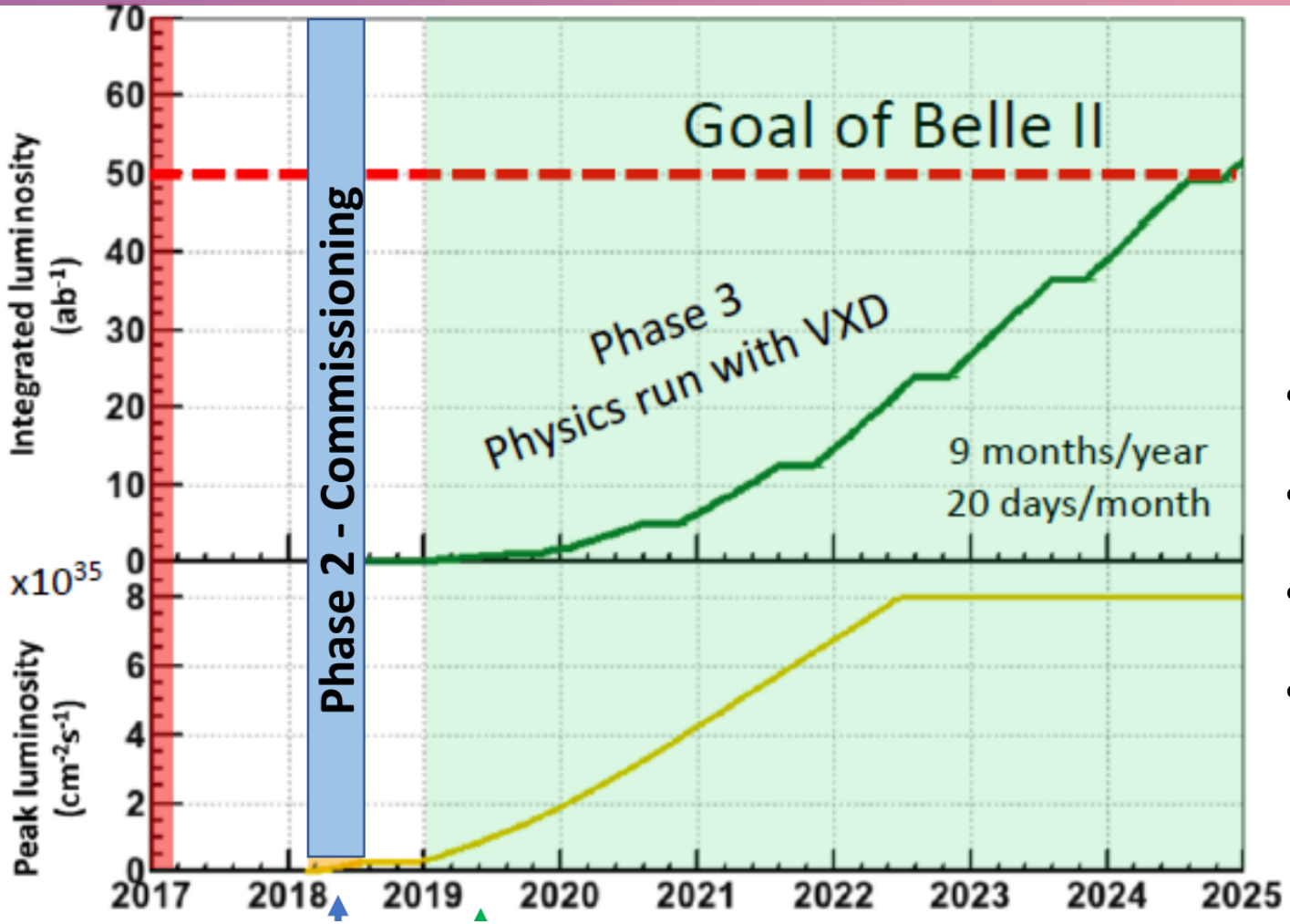
- The Belle II detector has better resolution, PID and capability to cope with higher background



Phase 3 (design)

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

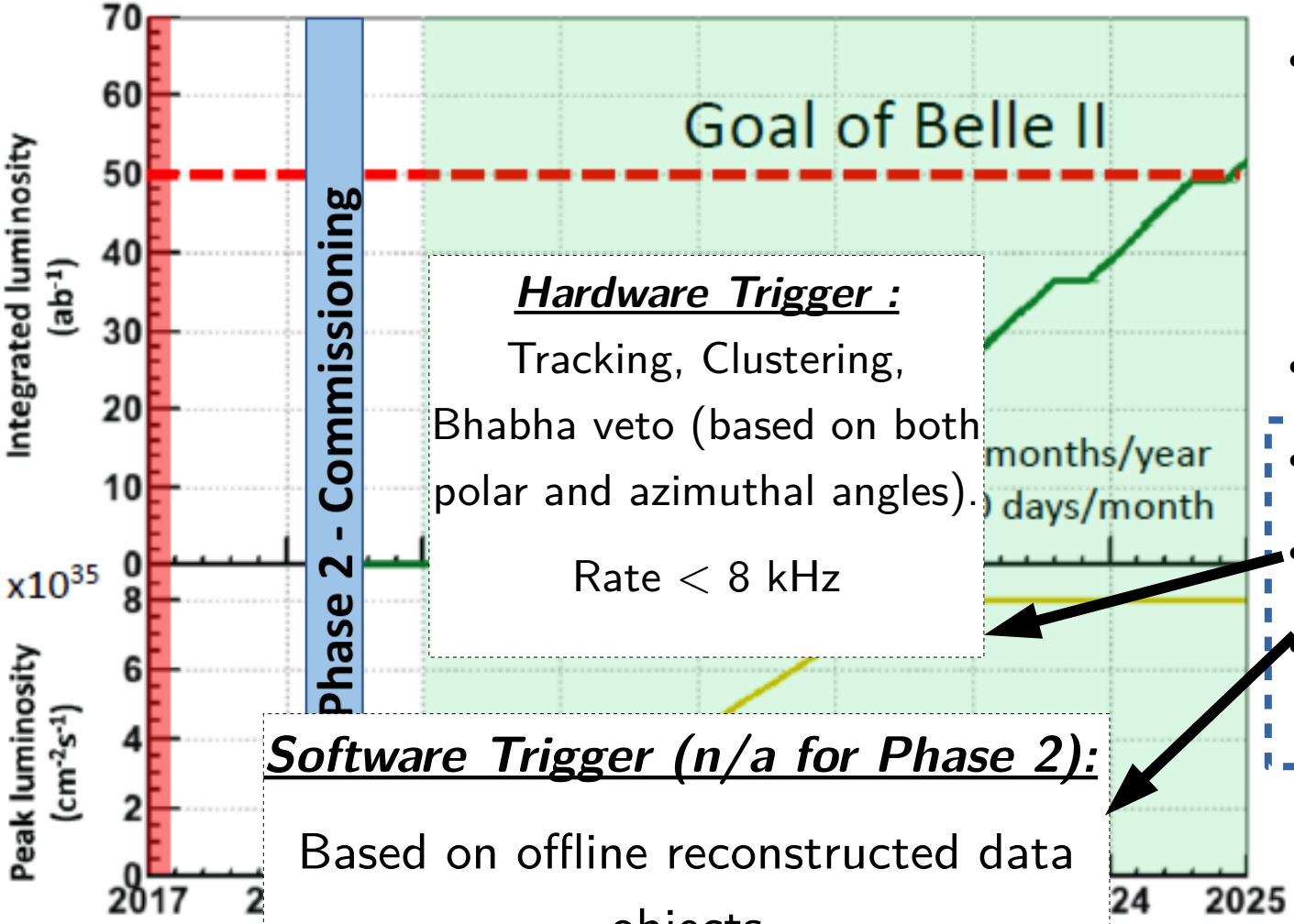
Belle II Data Taking: Phase 2



Phase 2 (April-July 2018): *Commissioning of the machine, detector and software*

- 1/8th VXD
- Lower backgrounds
- Flexible hardware triggers
- Pass-through software trigger

Belle II Data Taking: Phase 2



Hardware Trigger :

Tracking, Clustering, Bhabha veto (based on both polar and azimuthal angles).

Rate $<$ 8 kHz

Software Trigger (n/a for Phase 2):

Based on offline reconstructed data objects

- ***Phase 2 (April-July 2018):*** *Commissioning of the machine, detector and software*
- 1/8th VXD

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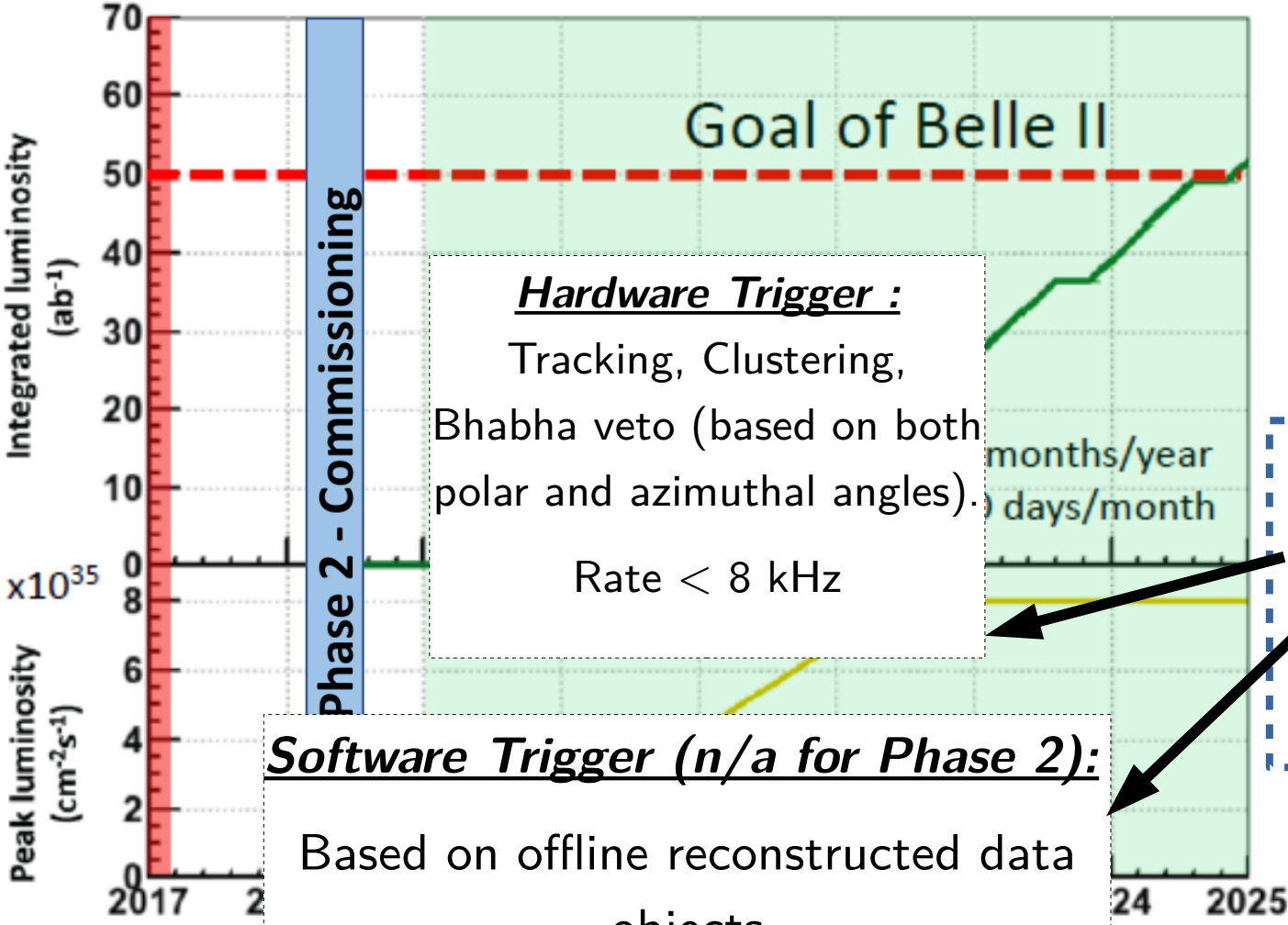
- Flexible hardware triggers
- Pass-through software trigger

Good conditions for Dark Sector Searches

Belle II Data Taking: Phase 3



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- Pass-through software trigger

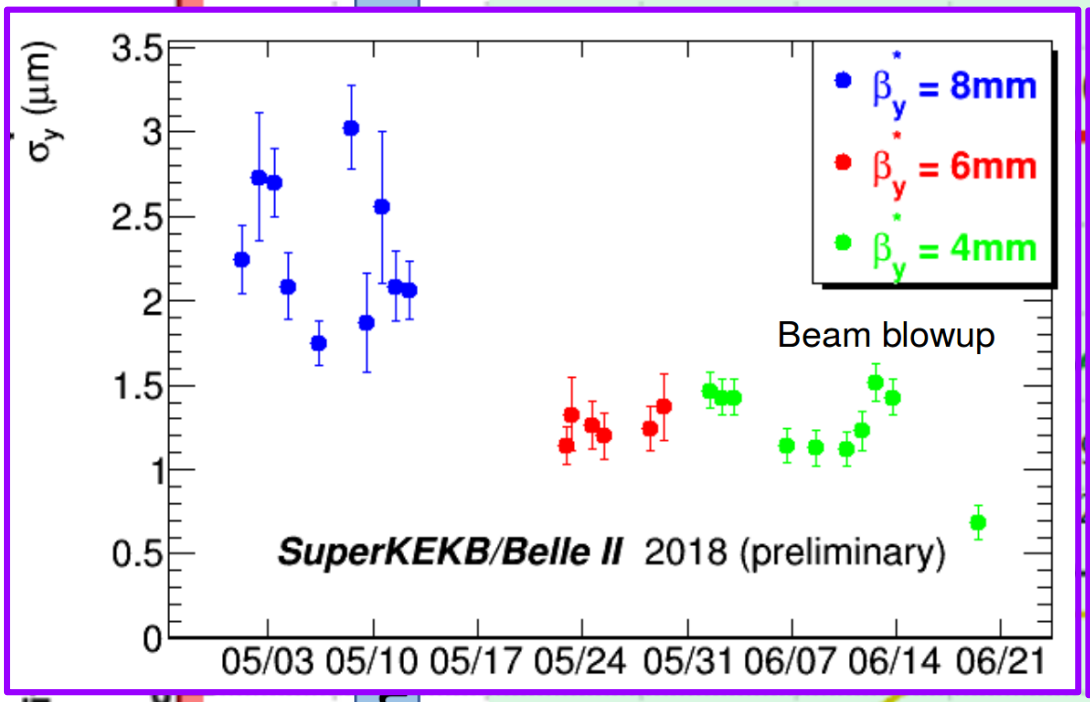
Good conditions for Dark Sector Searches

Phase 3: Run with full detector at peak luminosity, $L = 8 \cdot 10^{35}$ cm^{-2} s^{-1}

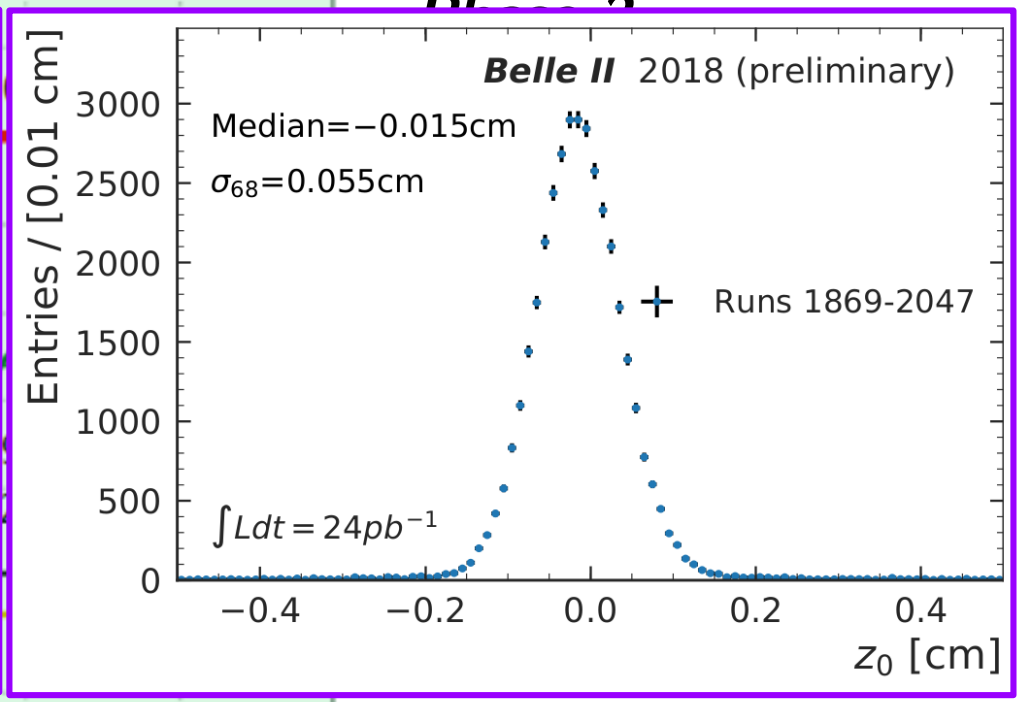
GOAL: collect 50 ab^{-1}

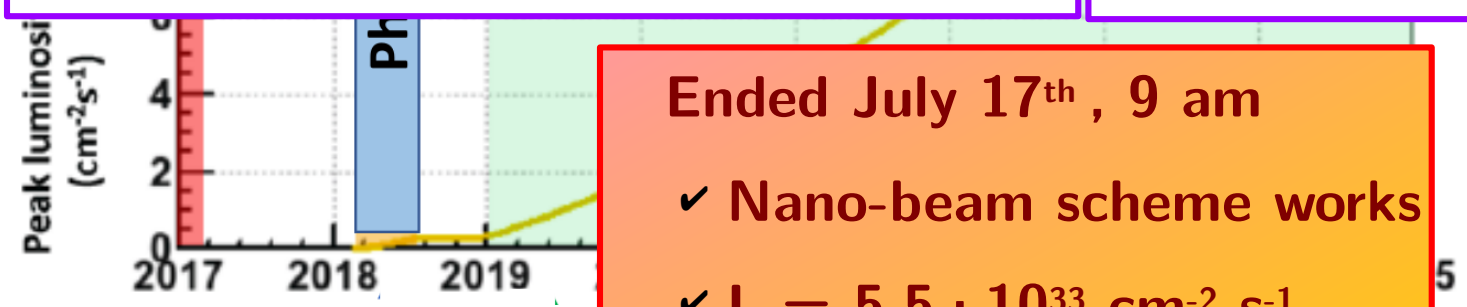
Belle II Performances

Vertical beam size



Longitudinal IP position



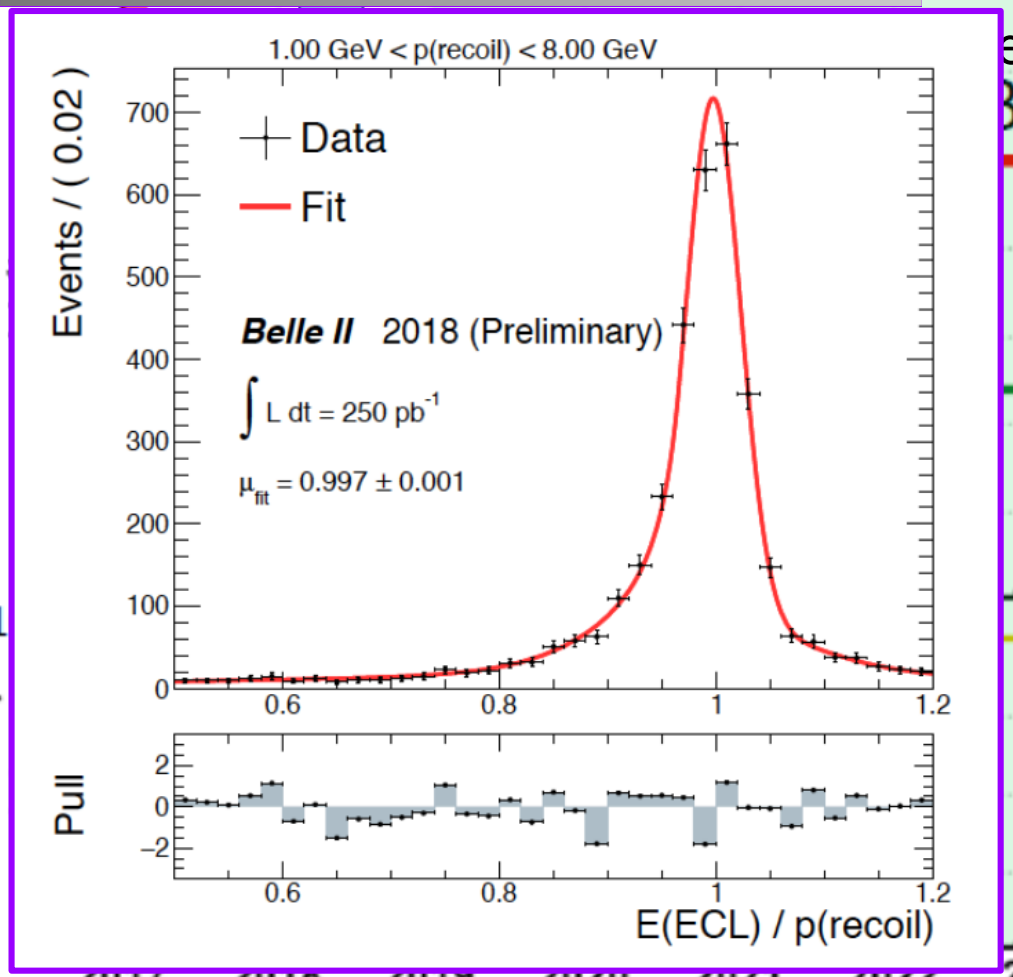


Ended July 17th , 9 am

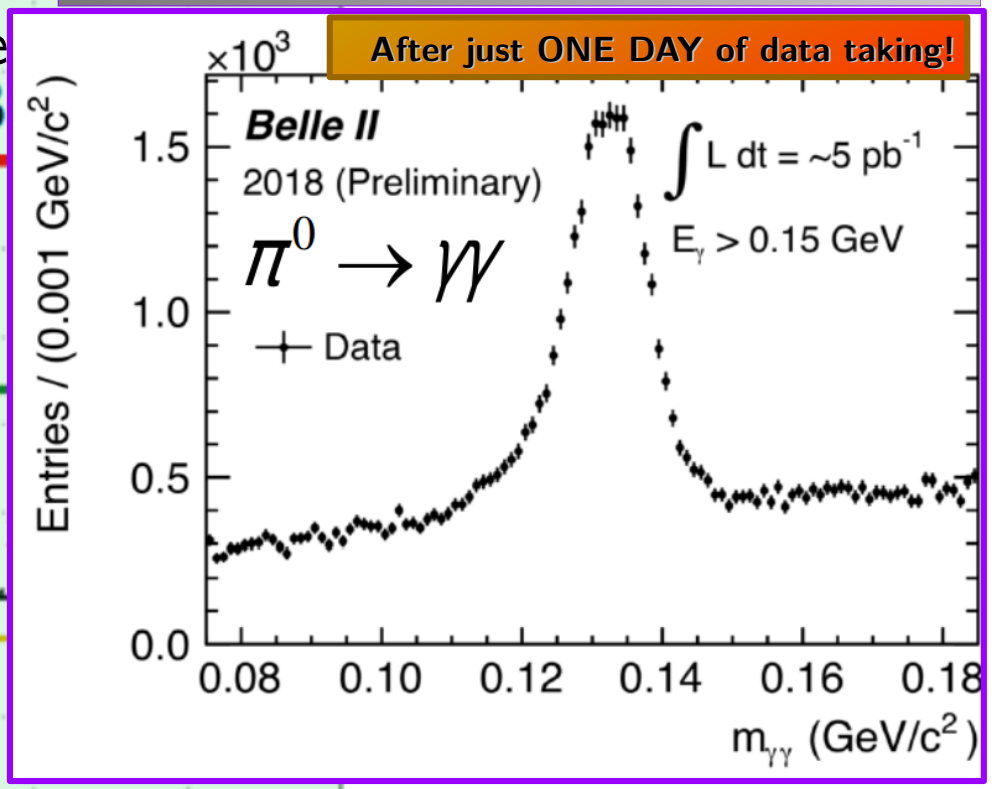
- ✔ **Nano-beam scheme works**
- ✔ **L = 5.5 · 10^{33} cm^{-2} s^{-1}**
- ✔ **Collected 0.472 fb^{-1}**

Belle II Performances: photon reconstruction

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



$\pi^0 \to \gamma\gamma$



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

$e^+e^- \to \gamma\ ALPS \to \gamma(\gamma\gamma)$

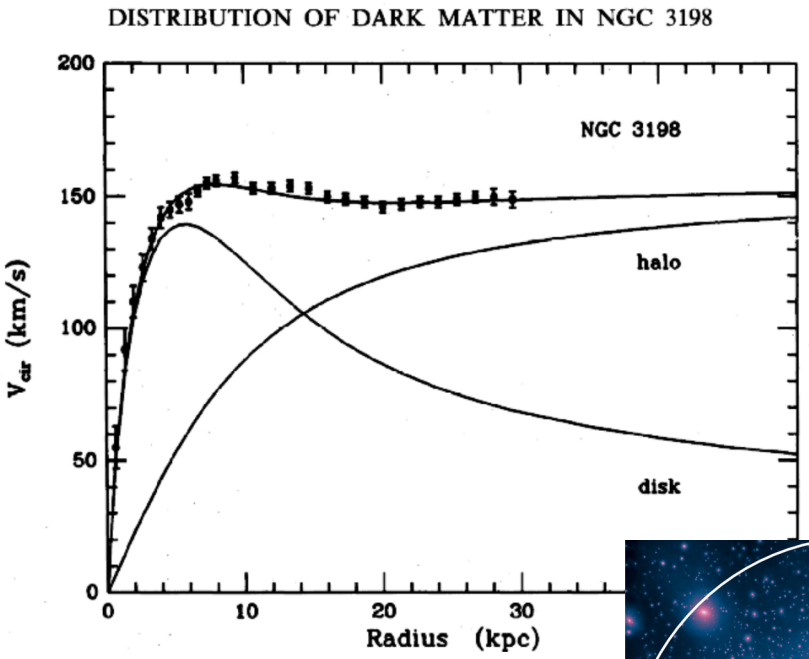
GOOD CONDITIONS for DARK SEARCHES

- ✔ Tracking and cluster L1 trigger
- ✔ Bhabha veto L1
- ✔ Single Photon L1 trigger

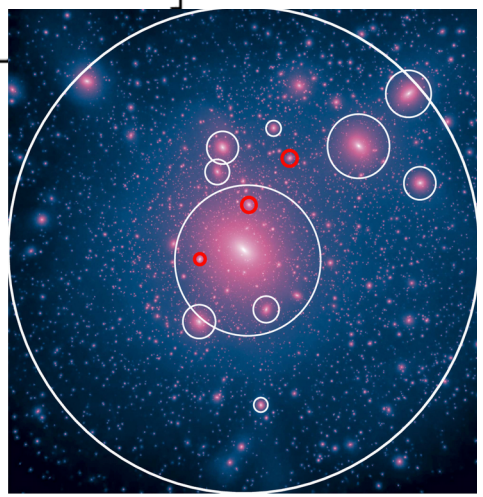
Dark Sector: Introduction

- Many astrophysical observations provide evidence for the existence of a kind of matter that does not interact with the SM (*mostly* gravitational interaction) → ***dark matter***

Flat rotational curves



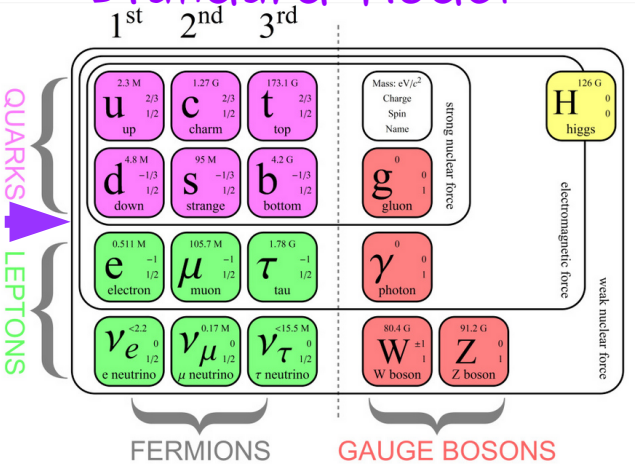
- Possible sub-GeV scale scenario: *light dark sector* weakly coupled to SM through a light ***mediator X***
  - Vector portal → Dark Photon A'
  - Scalar portal → Dark Higgs/Scalars
  - Pseudo-scalar portal → Axion Like Particles (ALPs)
  - Neutrino portal → Sterile Neutrinos



A Milky-Way-size dark-matter halo and its subhalos (circled), produced in simulations [Caterpillar Project, Griffen et al. 2016], AAS.

X

Standard Model



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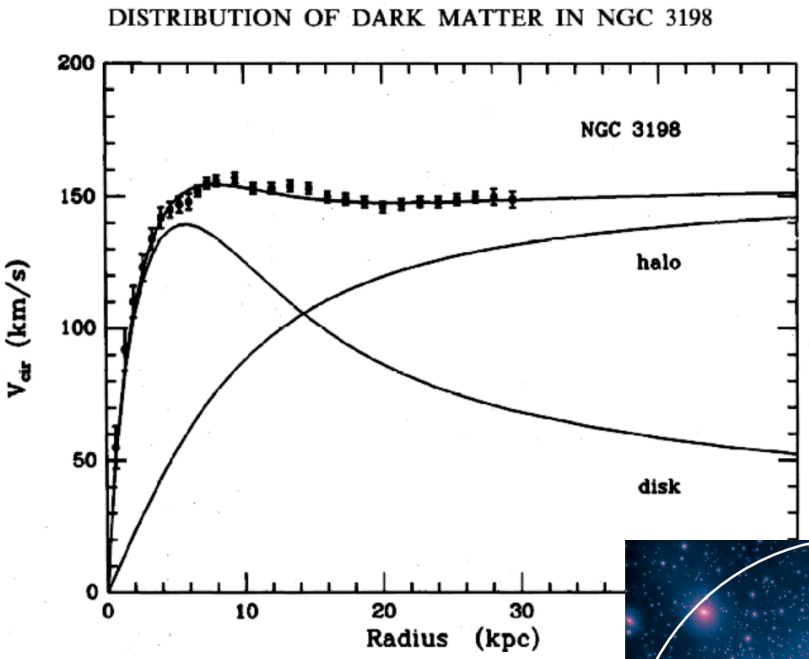

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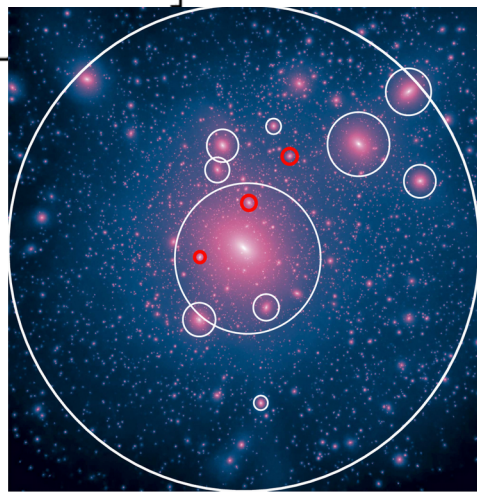
Phase 2 benchmark



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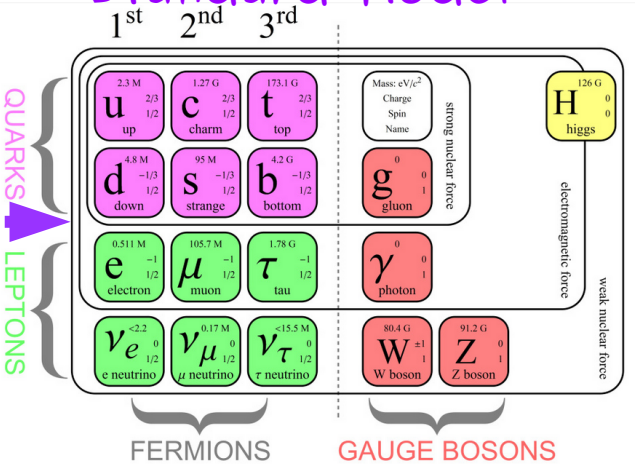
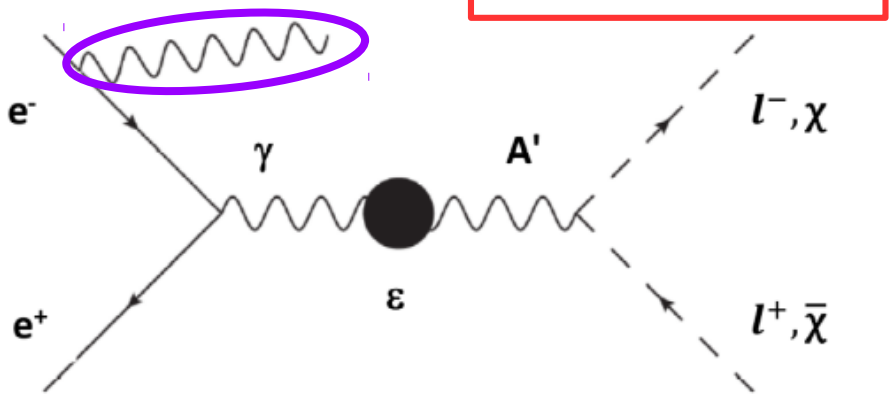


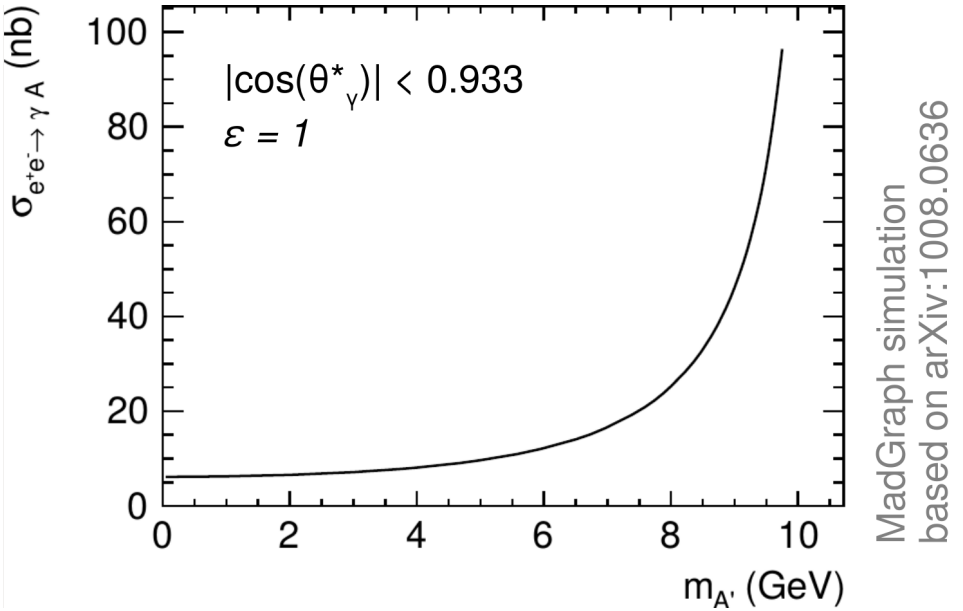
Vector portal: the Dark Photon

- A possible extension of the SM include a new massive ($m_{A'}$) gauge boson A' of spin = 1 coupling to the SM through the kinetic mixing with strength ε → the ***dark photon***
- At e^+e^- colliders we investigate the ISR production ***$e^+e^- \to \gamma$ A'***.

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

Batell et al. (2009), arXiv:0903.0363





- If $m_\chi > 1/2\ m_{A'}$ → A' can decay only to SM particle

  $e^+e^- \to \gamma\ l^+l^-$ visible decays→ not competitive for Phase 2

- If $m_\chi < 1/2\ m_{A'}$ → A' can decay into DM particle

  $e^+e^- \to \gamma$ + inv invisible decays → single photon search

Dark Photon to Invisible

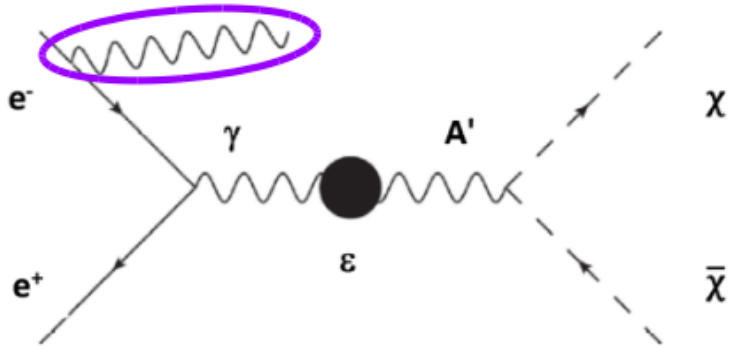
- Signal Signature:
  - select events with a single, monochromatic, high energetic *ISR photon*
  - Look for a bump in the reconstructed photon energy $E_\gamma = (s - m^2_{A'})/2\sqrt{s}$

    → only one photon in the detector requires a dedicated ***single photon trigger.***

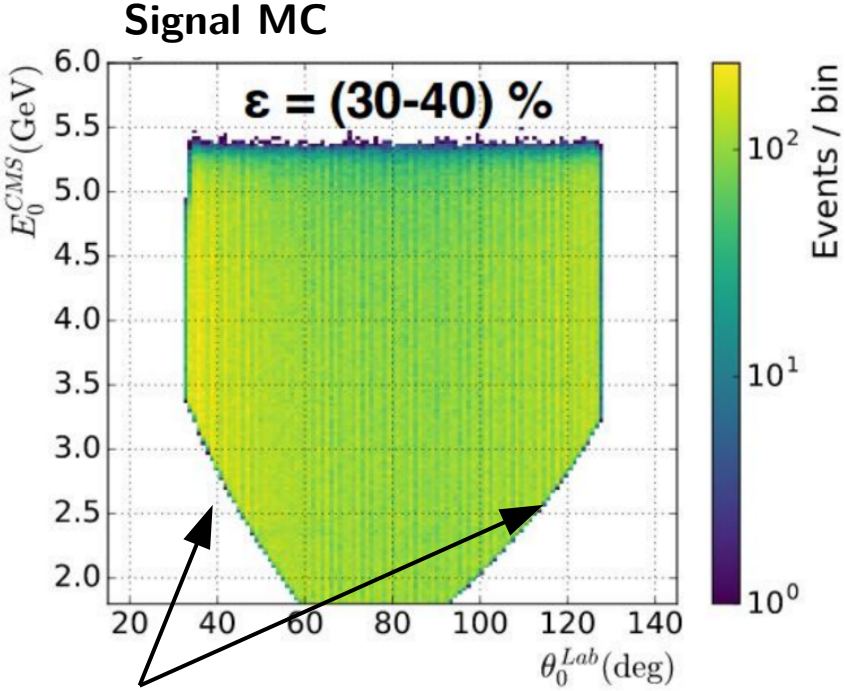
(@Belle was not available, ~10% BaBar data)

Belle II Phase 3 (Designed)

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



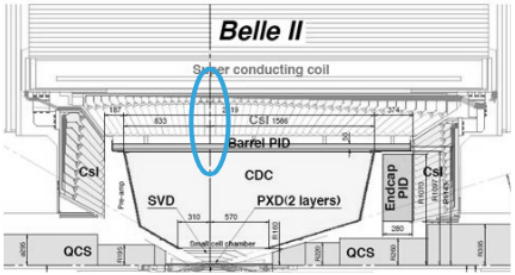
- Discriminant variables: E^*_γ, θ_γ



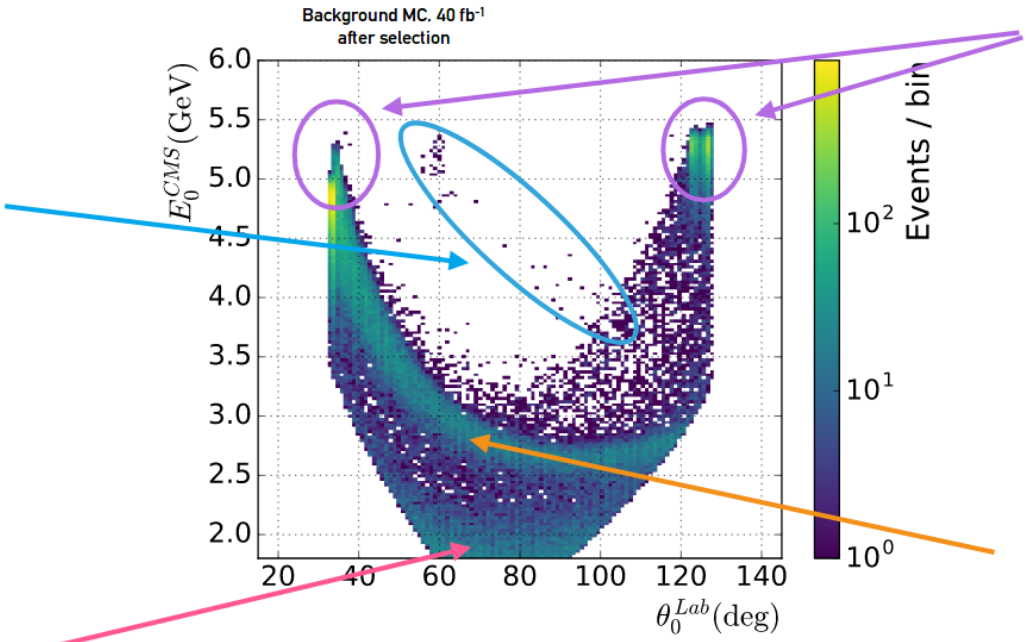
Effect of selection on E(θ) for background rejection

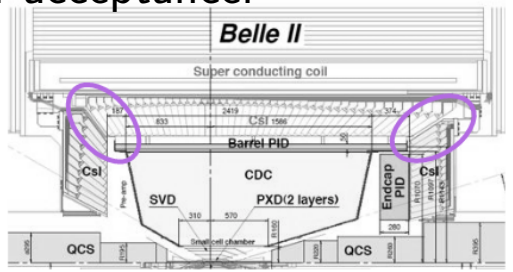
Dark Photon to Invisible: Backgrounds

- Background dominated by QED processes:
  - $e^+e^- \to \gamma\gamma(\gamma)$ where one photon is not detected (ECL gaps) and the second out of acceptance
  - radiative Bhabha $e^+e^- \to e^+e^-\,\gamma(\gamma)$ with the electron-positron pair out of acceptance.



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

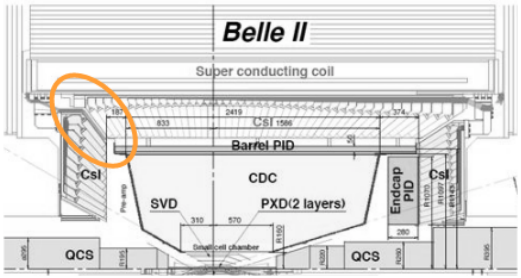




ee→2γ
1γ in ECL BWD or FWD gap

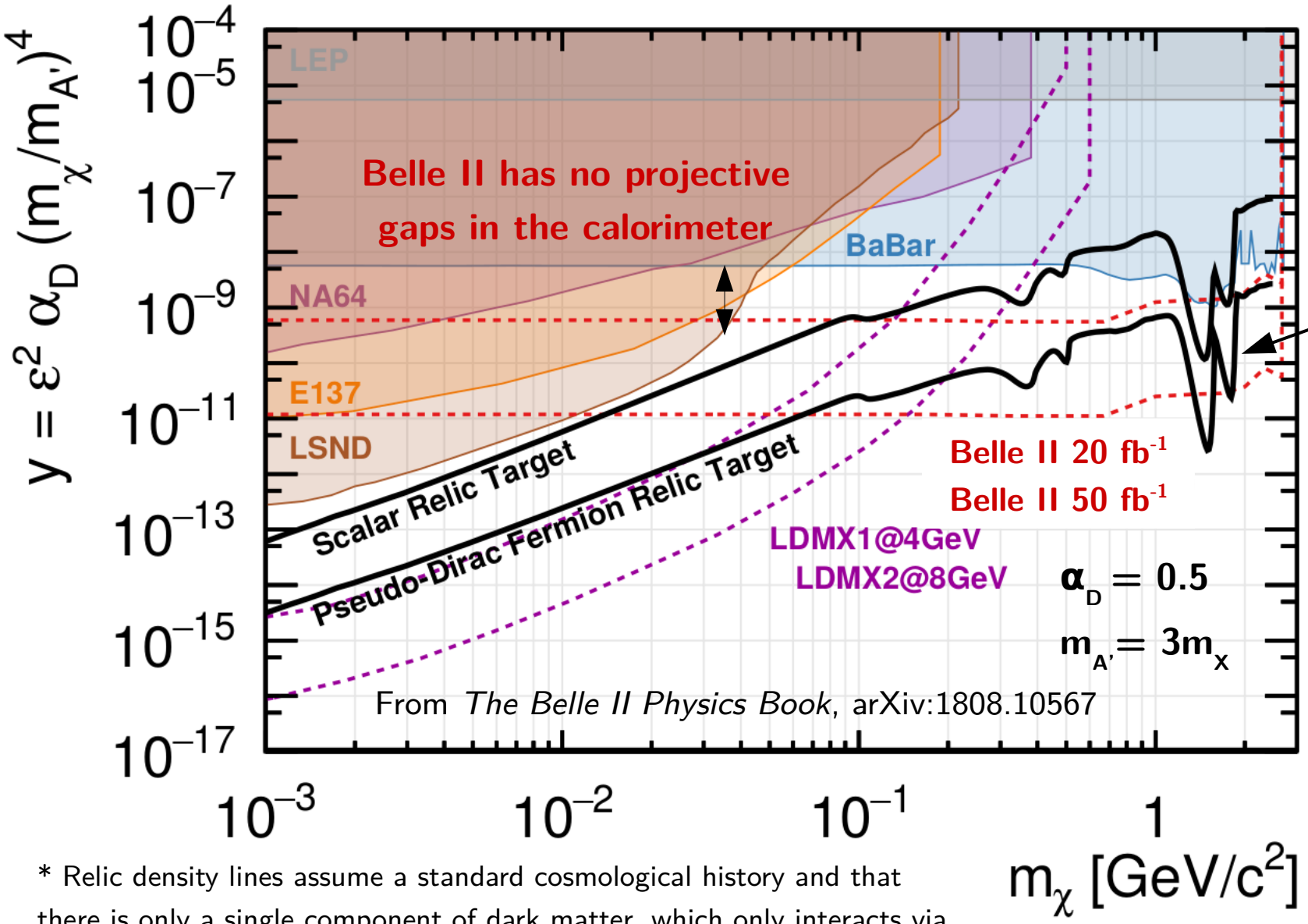
ee→eeγ
both electrons
out of tracking acceptance

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



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

Dark Photon to Invisible: Sensitivity



Limits from relic Dark Matter density *

J. Alexander et al. (2016), arXiv:1608.08632
Natalia Toro, private communication (2017)
J. P. Lees et al., BaBar (2017), arXiv:1702.0332

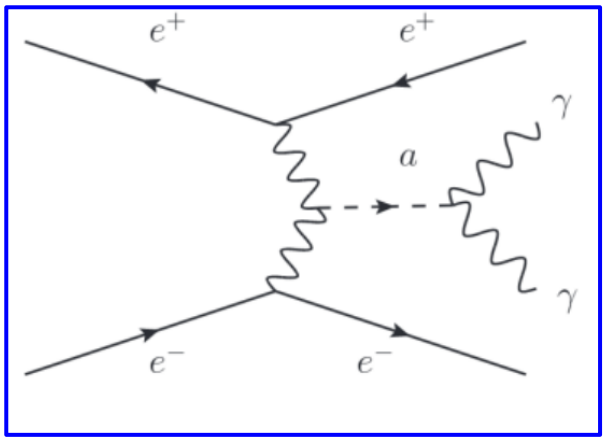
* Relic density lines assume a standard cosmological history and that there is only a single component of dark matter, which only interacts via Dark Photon exchange.

Axion Like Particles (ALPs)

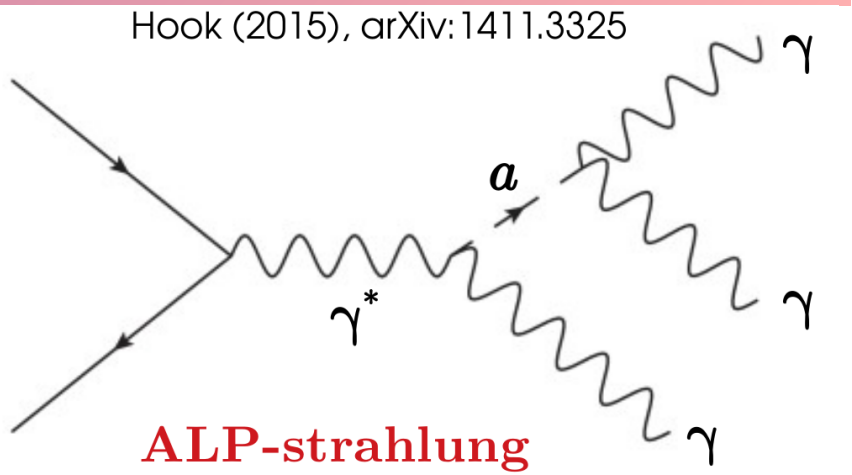
- Axion Like Particles are pseudo-scalars coupling to bosons
- Unlike for QCD Axions, there is no relation between the coupling and the mass
- Explored photon coupling $g_{a\gamma\gamma}$ in *ALP-strahlung* processes

  (*photon fusion:* sensitivity under study)

- $\tau = 1/m_a^2 g^2_{a\gamma\gamma}$
  - Displaced vertex
  - Long-lived particle

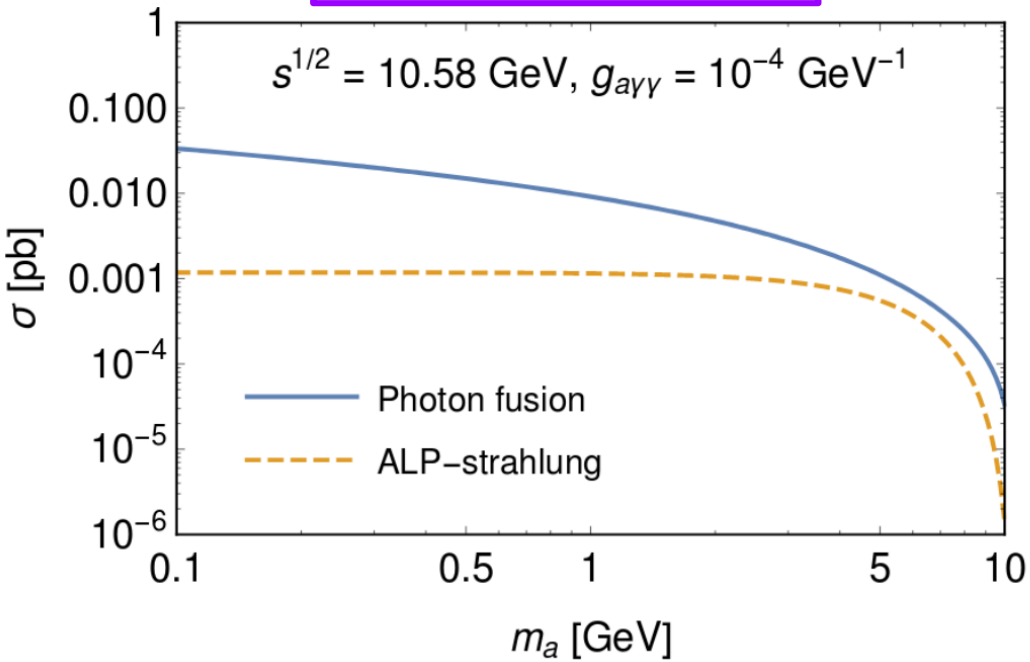


Hook (2015), arXiv:1411.3325



ALP-strahlung

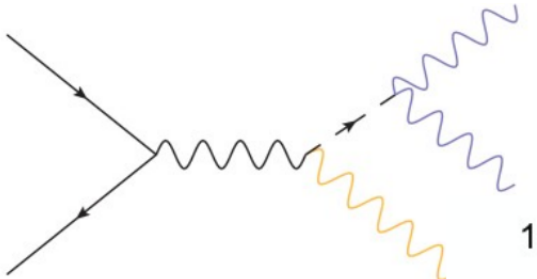
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



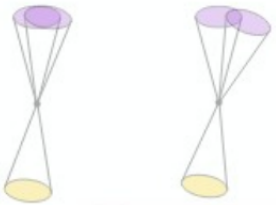
ALPs: Experimental Signature

- Signal signatures: 3γ final state, several topologies → 4 categories
- ALPS may also decay to invisible (DM) → single photon topology

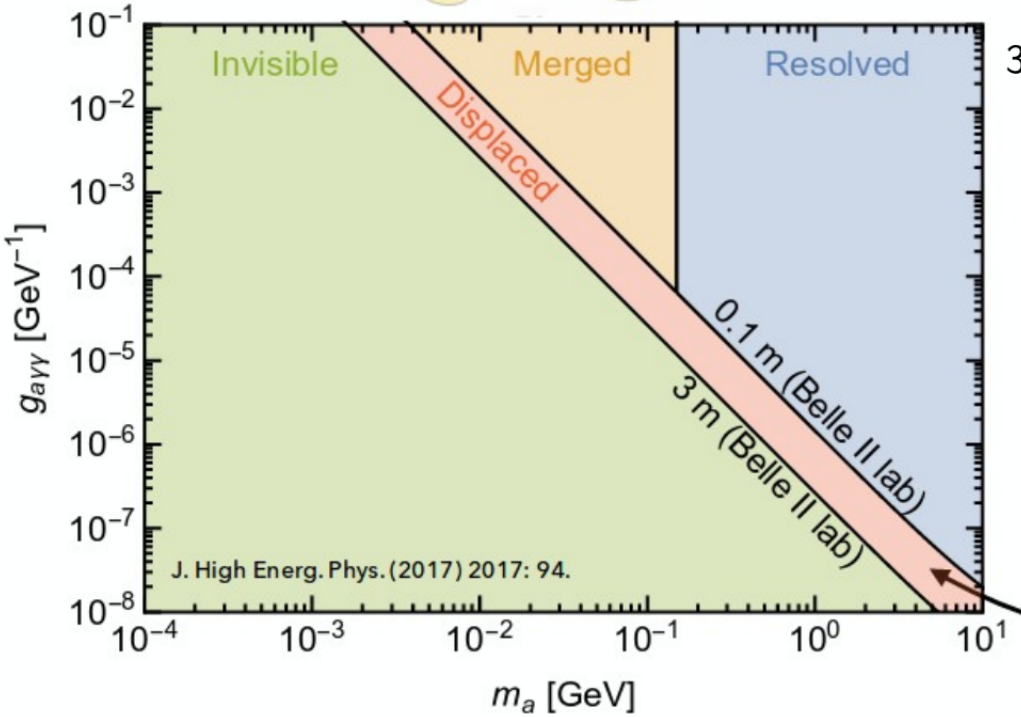
Backgrounds: $e^+e^- \to \gamma\gamma(\gamma)$ and pair conversion $\gamma \to e^+e^-$ outside the tracking volume



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



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

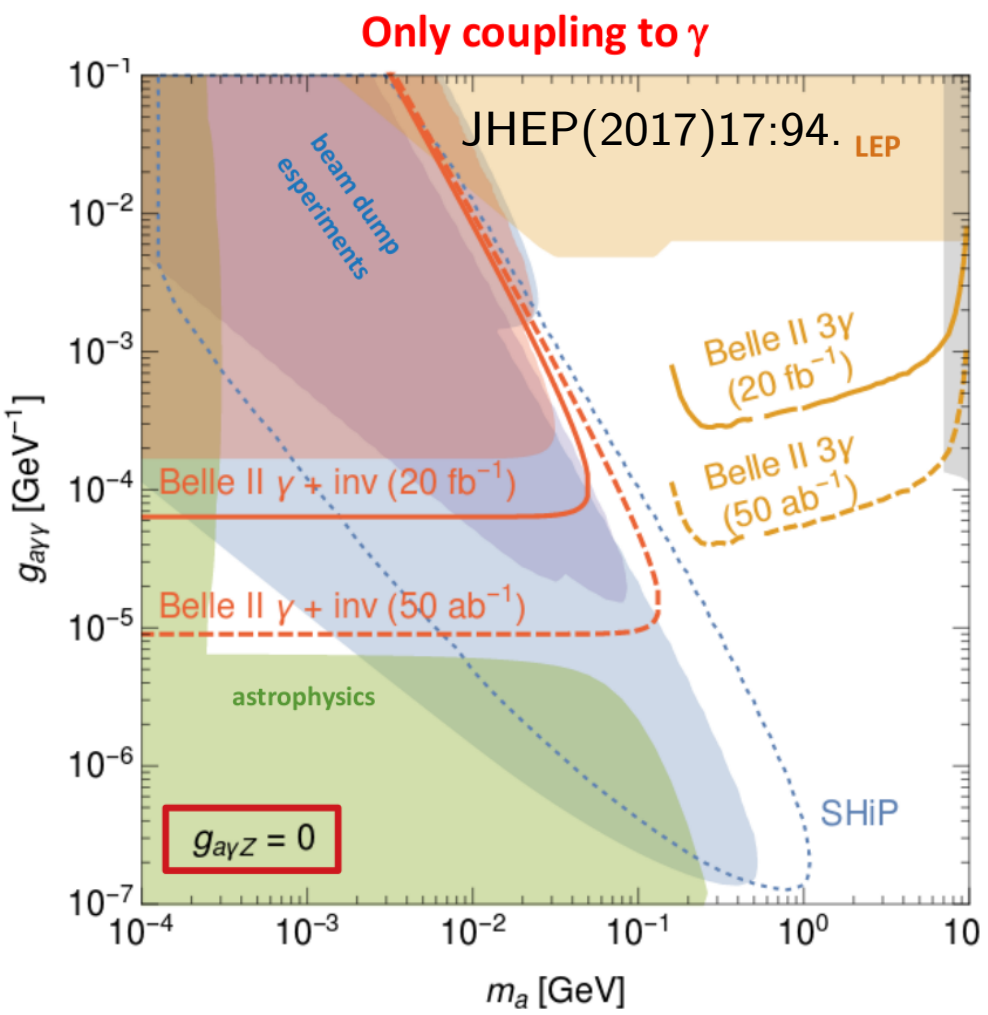


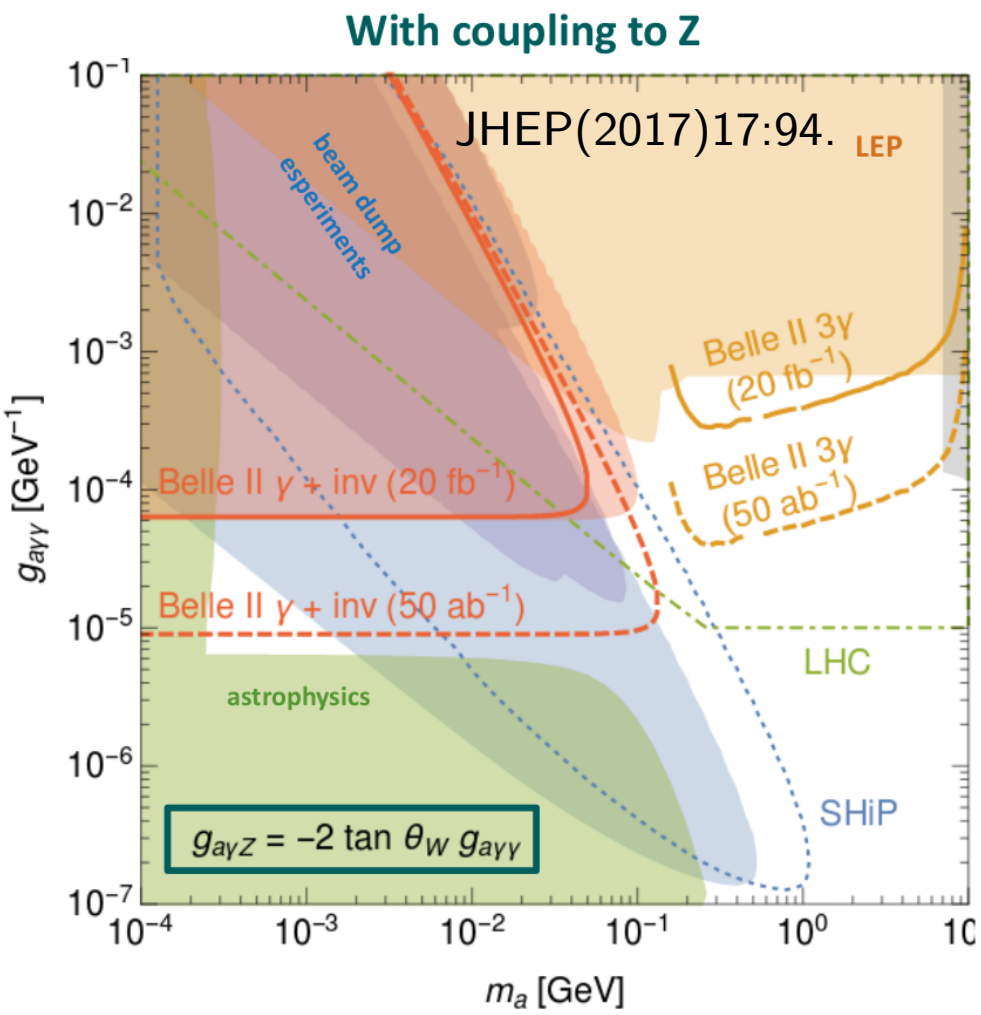
For **resolved** case:
3 clusters with $E_{CM} > 0.25$ GeV
Peak in $\gamma\gamma$ mass spectrum

Three **resolved**, high energetic photons.

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

ALPs: Sensitivity



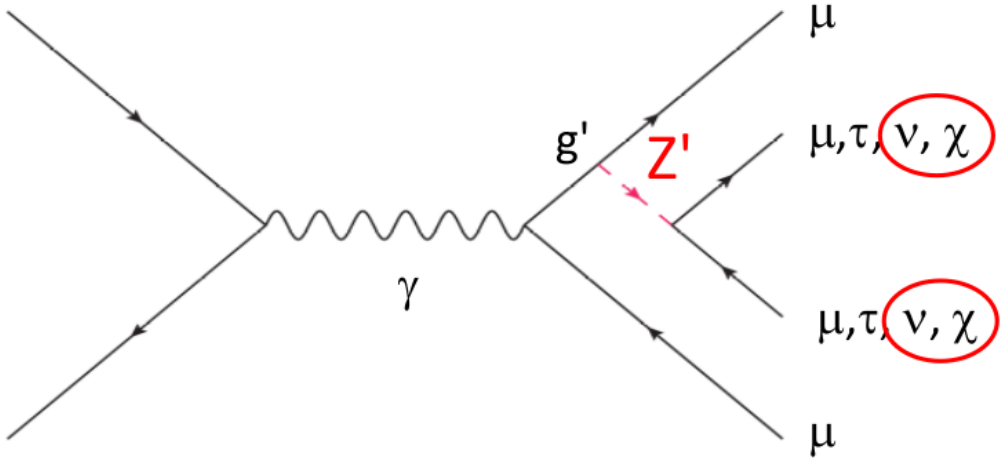


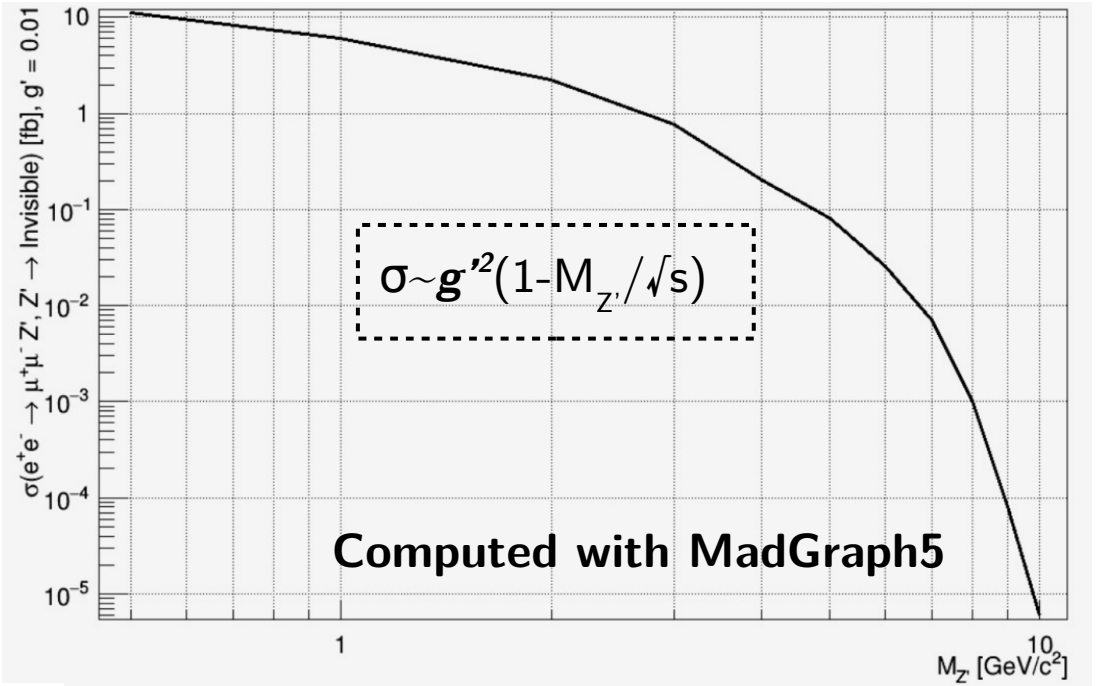
Z' to Invisible: L_μ-L_τ model

- New gauge boson Z' coupling only to the **2nd and 3rd** generation of leptons (L_μ-L_τ)

  Detecting the L_μ-L_τ gauge boson at Belle II, arXiv:1702.01497

- Invisible signature investigated for the first time in the process $e^+e^- \to \mu^+\mu^- Z'$ + *missing energy*
- May explain the $(g\text{-}2)_\mu$ anomaly
- BR(Z'→ inv) may be enhanced by the presence of kinematically accessible DM (e.g. sterile neutrinos)





Shuve et al. (2014), arXiv:1403.2727

Branching ratios:

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

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

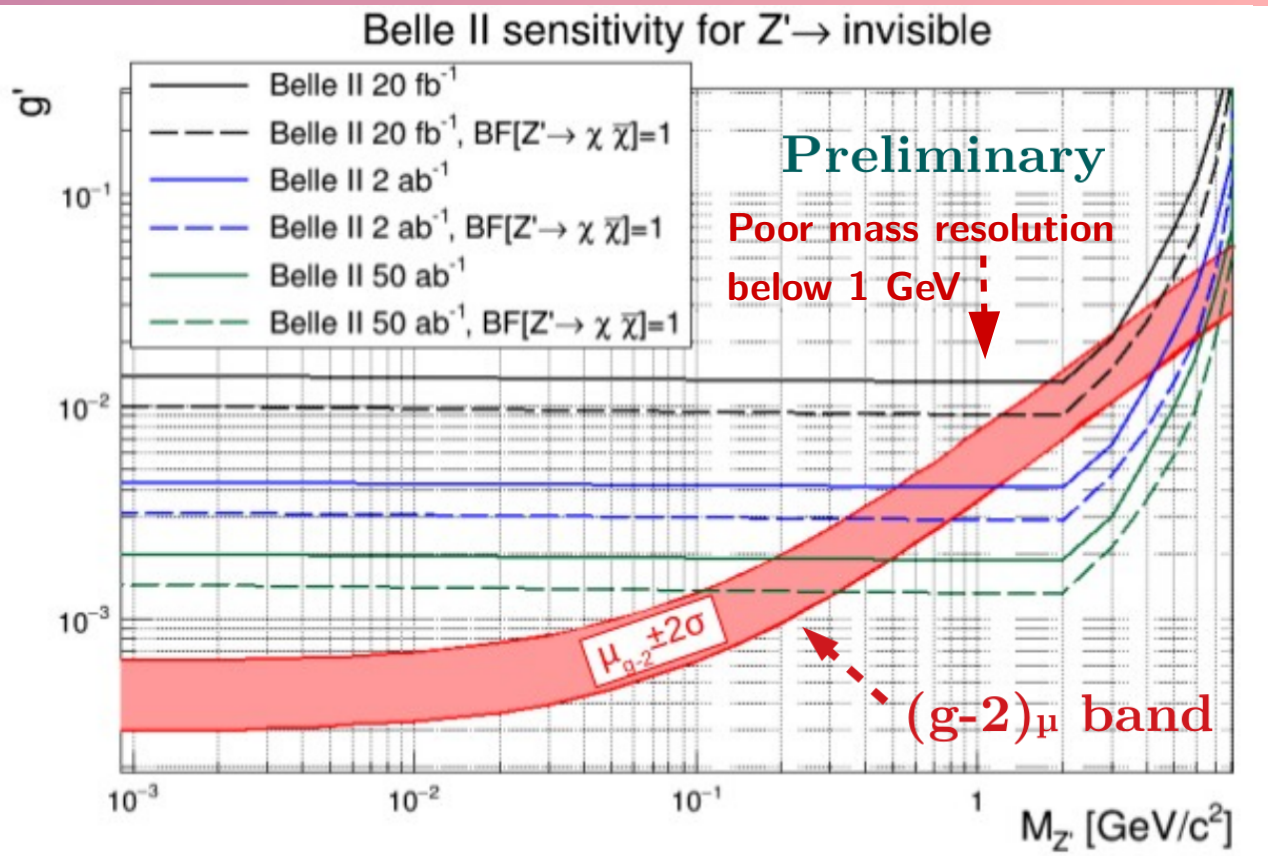
$$M_{Z'} > 2M_\tau \to \Gamma(Z' \to \text{inv.}) \sim 1/3$$

* If LDMA is accessible, BR(Z'→ DM)~1

Z' to Invisible: Experimental Signature

- Reconstruct the recoil against a $\mu^+\mu^-$ pair and looks for a peak in the recoil mass spectrum. (Additionally require nothing in the rest of event)
- Simulated and reconstructed several Z' masses between 0.1 -10 GeV
- Backgrounds mainly from radiative QED processes:

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

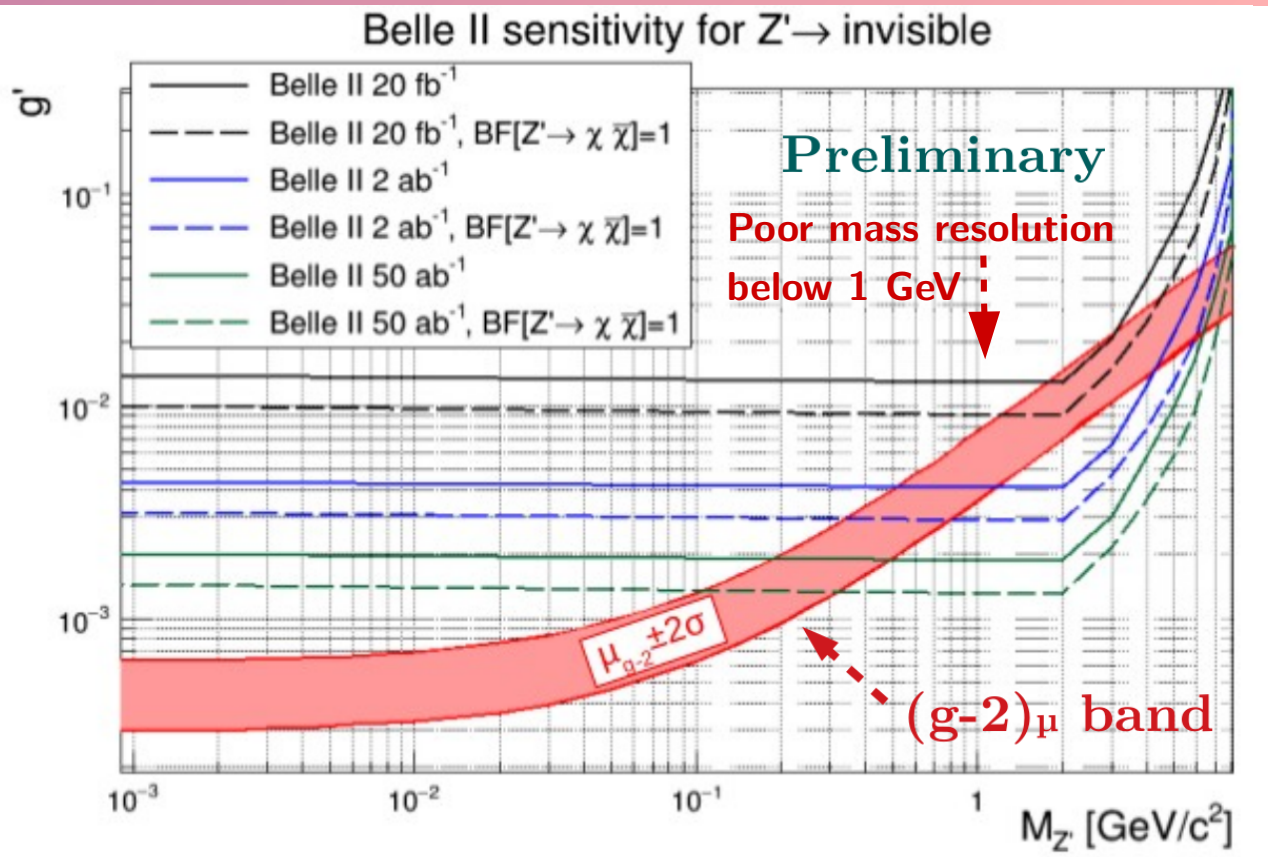


- The above upper limits (90% CL) take into account the calculate Z' cross section, signal efficiencies and background rejection (the selection is NOT optimized yet)
- Visible decays of Z' $\to \mu^+\mu^-$ will be competitive in Phase 3 (currently lead by BaBar measurement)

Z' to Invisible: Experimental Signature

- Reconstruct the recoil against a $\mu^+\mu^-$ pair and looks for a peak in the recoil mass spectrum. (Additionally require nothing in the rest of event)
- Simulated and reconstructed several Z' masses between 0.1 -10 GeV
- Backgrounds mainly from radiative QED processes:

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



- Furthermore, it will be possible to search for a **Lepton Flavor violating Z'**:

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)**

Summary

- Belle II Phase 2 finished less than 3 months ago
- Successful commissioning of SuperKEKB and Belle II detector, achieved peak luminosity $L_{MAX} = 5.5 \cdot 10^{33}\ cm^{-2}\ s^{-1}$ and collected $L_{INT} = 0.472\ fb^{-1}$
- Extensive studies on hardware L1 trigger have been performed (both on tracks and neutrals)
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→Dedicated Dark Sector triggers and improved performances may bring to *new world leading sensitivity* for dark sector searches even with a small data set

(20 fb^{-1} will hopefully come soon next year!)

- Invisible Dark Photon
- ALPs
- Z' to invisible (+ LFV Z')

Furthermore

- Magnetic monopole
- Invisible $\Upsilon(1S)$ decays
- Muonic dark forces
- Dark Higgs/Higgstrahlung
- Dark scalars
- Inelastic Dark Matter
- Long-lived particles
- ...

For further details see *The Belle II Physics Book*, arXiv:1808.10567

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- Early

Phase 3 running with the full detector, higher luminosity, will start soon (February 2019) …

STAY TUNED!

→De

impro

world

searches even with a small data set

(20 fb^{-1} will hopefully come soon next year!)

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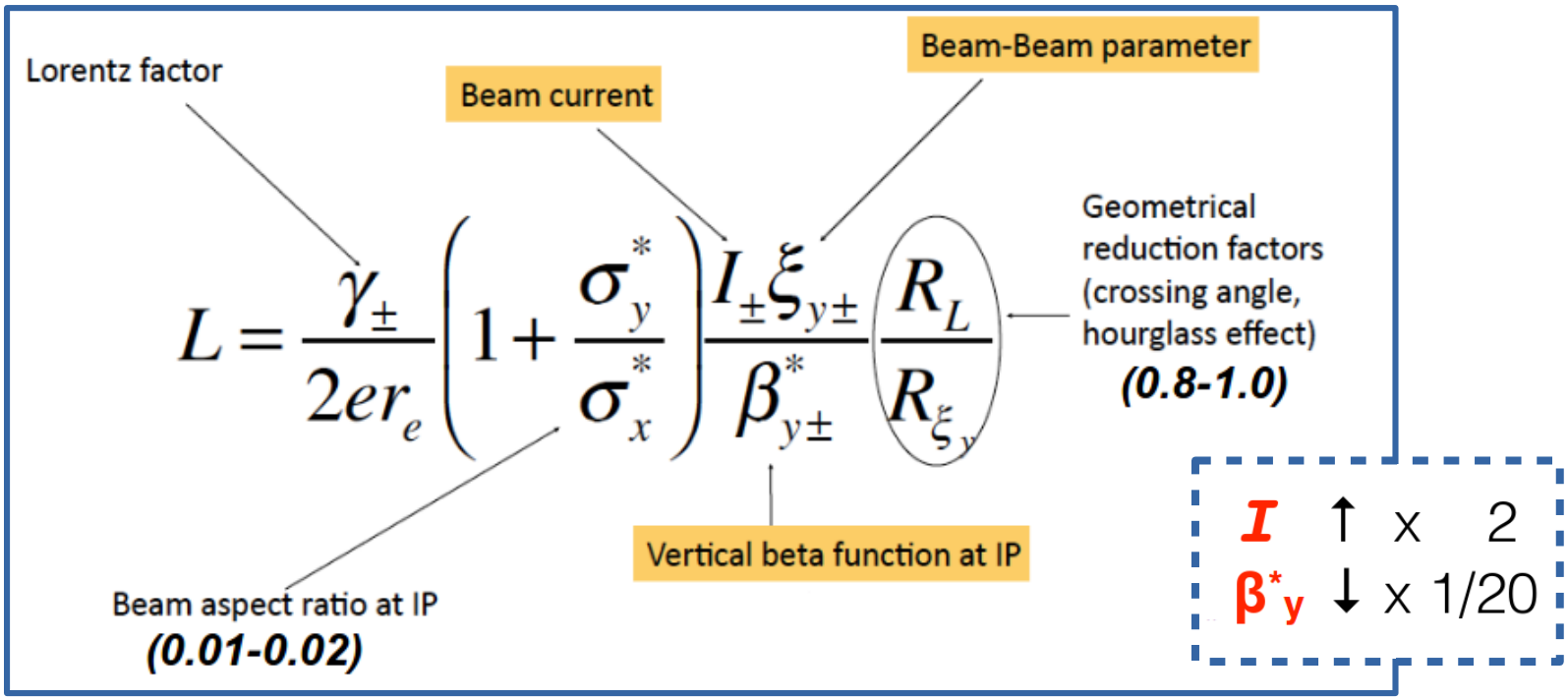
- …

Backup

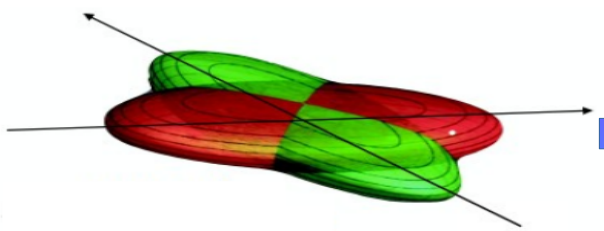
SuperKEKB Numbers

2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.20×10^{-4}	4.55×10^{-4}		
σ_δ	$7.92(7.53)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

Nano-beam Scheme



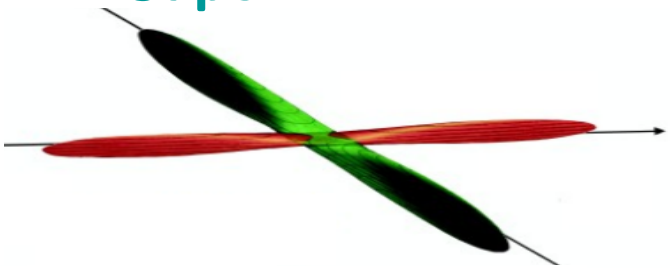
KEKB



I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

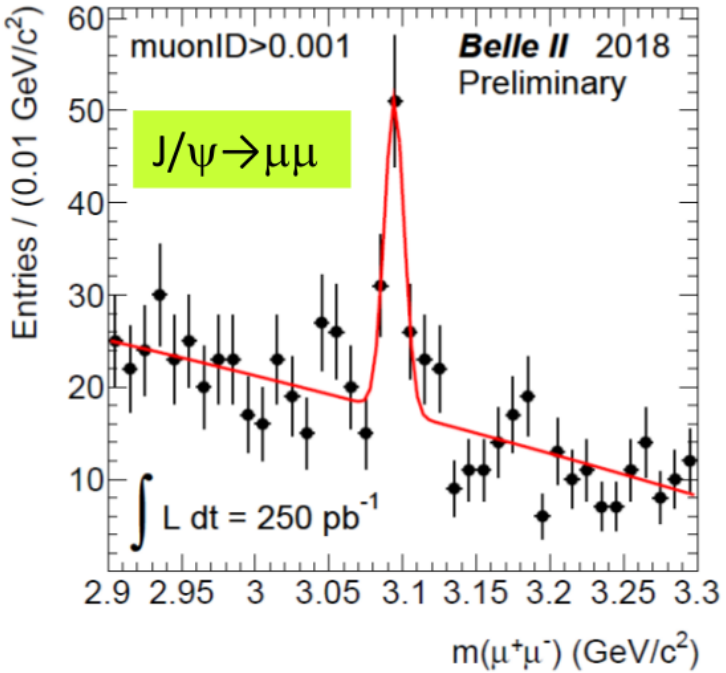
SuperKEKB

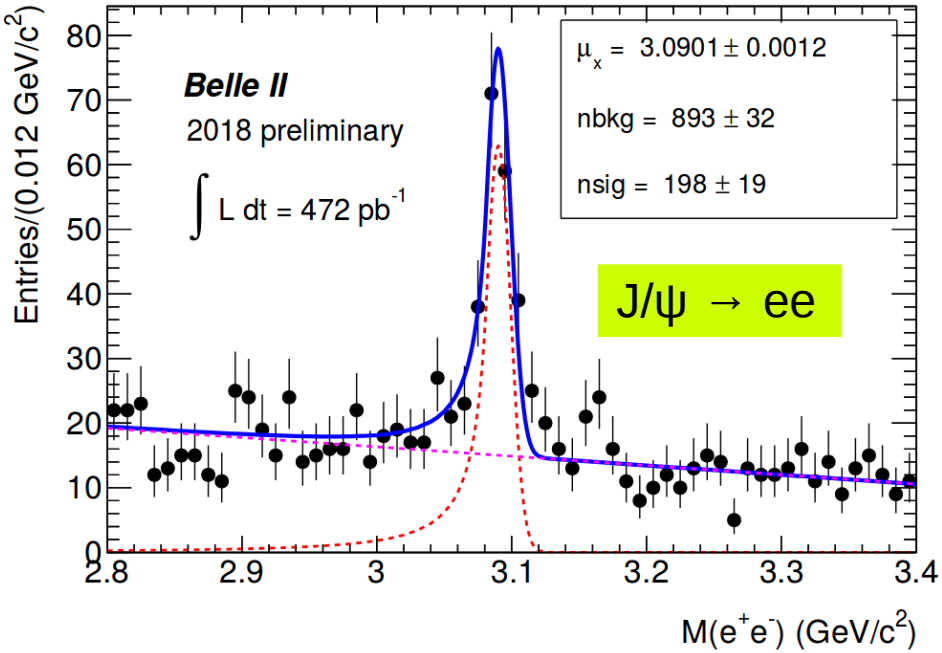


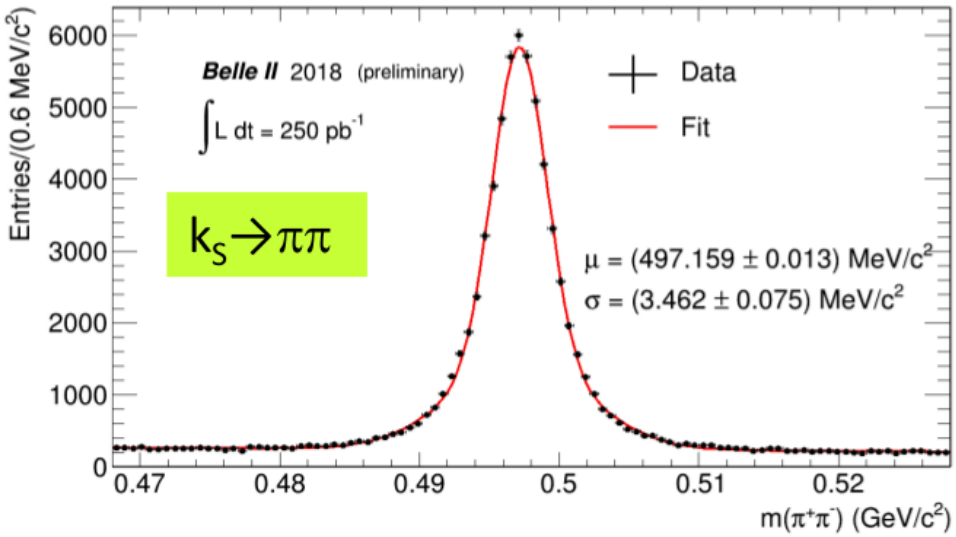
I (A): ~ 3.6/2.6

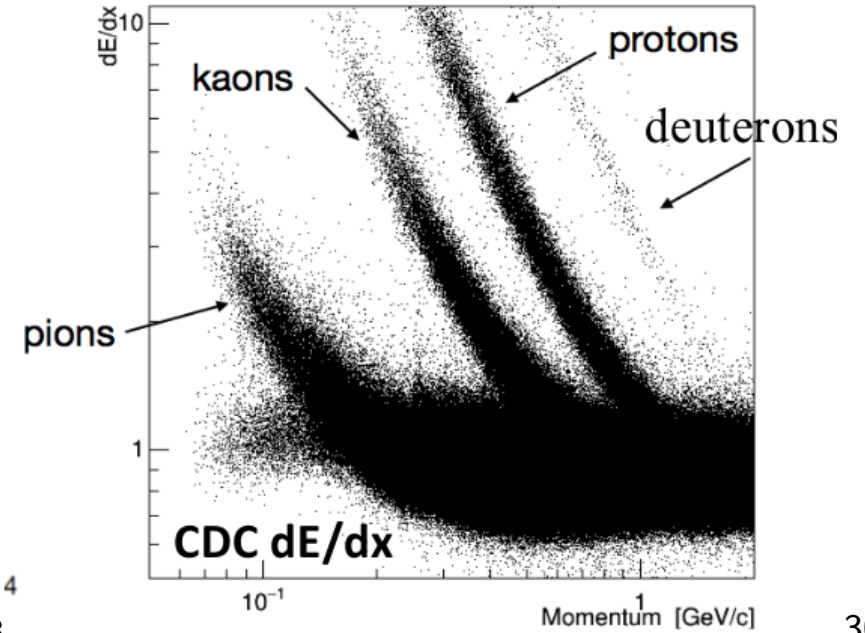
β^*_y (mm): ~ 0.27/0.3

Some Belle II Performances

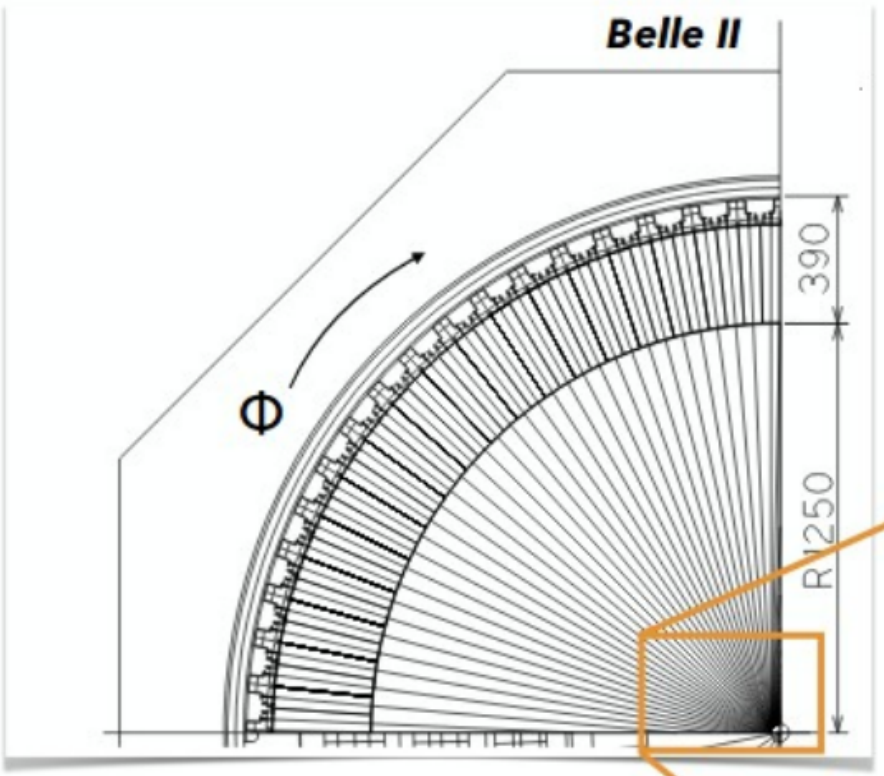








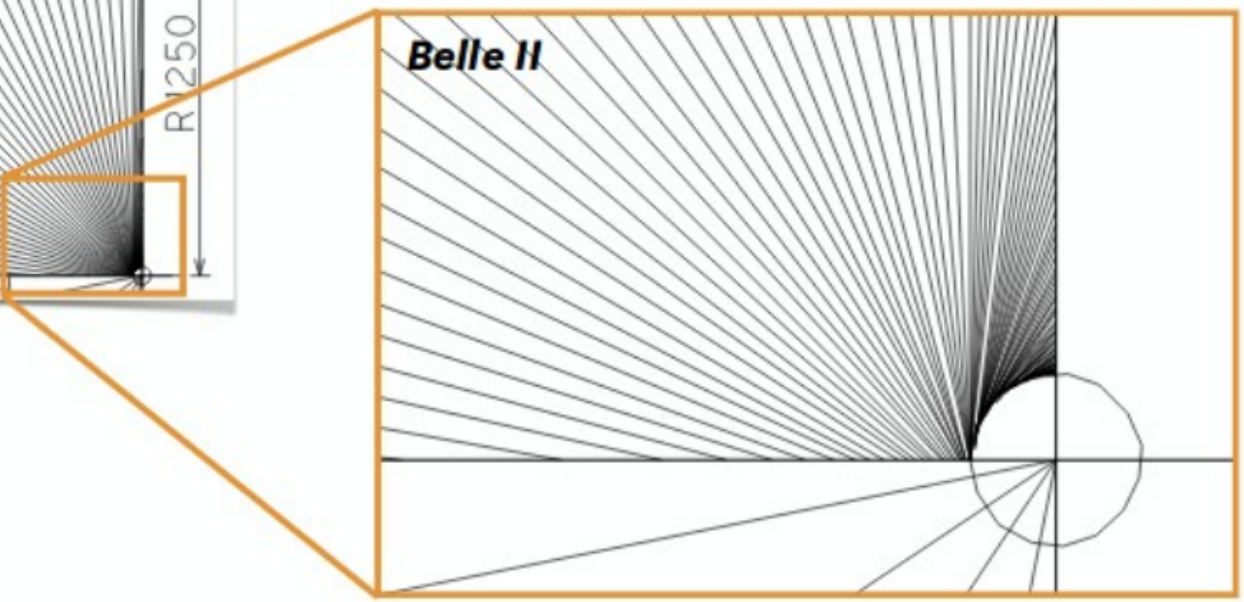
Belle II Electromagnetic Calorimeter (ECL)



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

→ more hermetic

→ more efficient



Dark Photon to leptons: Sensitivity

From Belle II Physics Book, arXiv:1808.10567

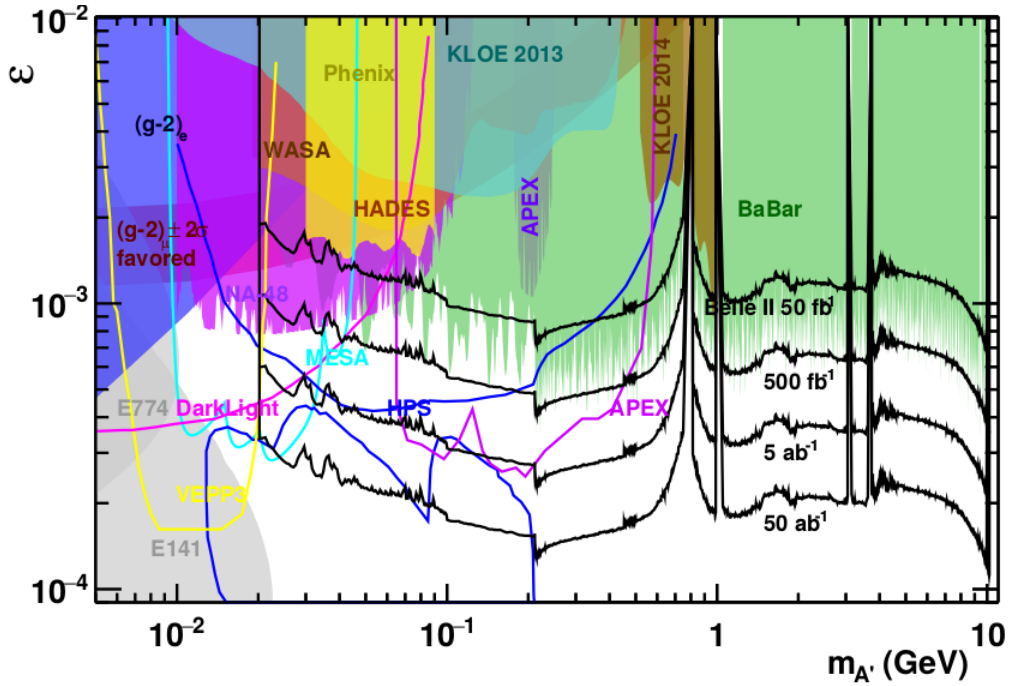


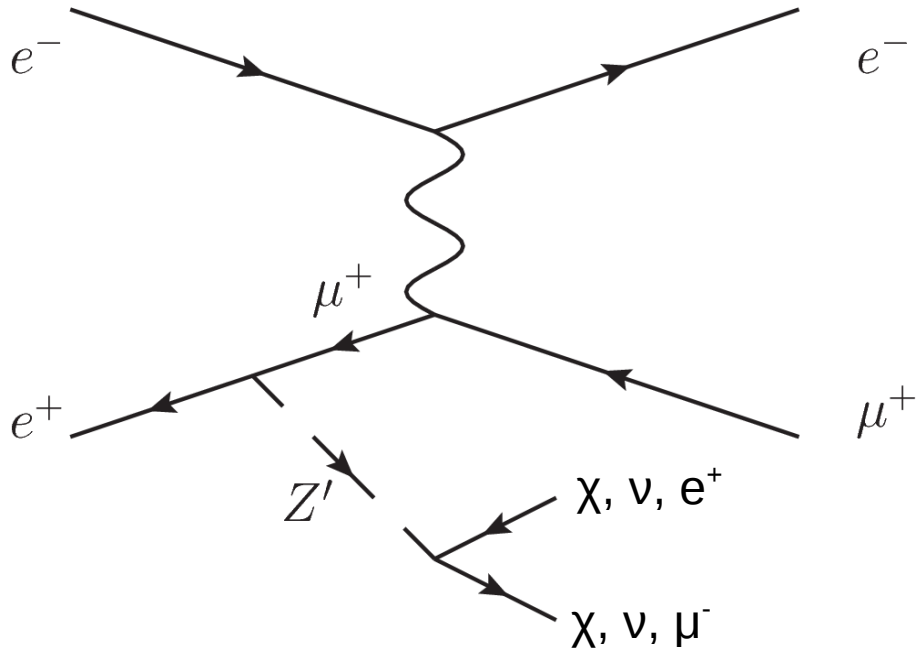
Fig. 211: Existing exclusion regions (90% CL) on the dark photon mixing parameter ε and mass $M_{A'}$ (solid regions) for $A' \to \ell\ell$, with projected limits for Belle II and other future experiments (lines)

LFV Z': invisible and visible channel

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

What if DM violates Lepton Flavour?

One can imagine, for example, eμ coupling



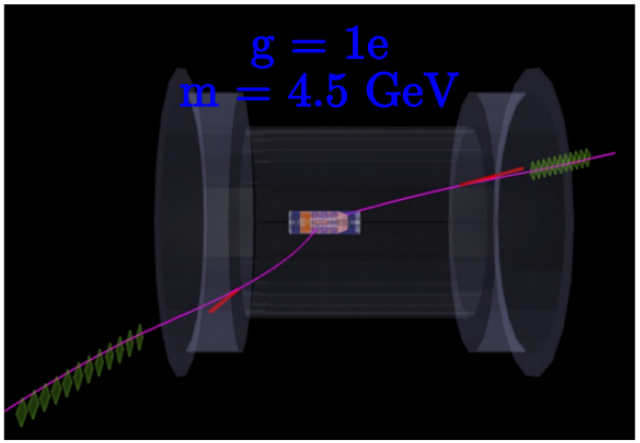
$e^+ e^- \to e^+ \mu^- Z'$; $Z' \to$ invisible

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

$e^+ e^- \to e^+ \mu^- Z'$; $Z' \to e^+ \mu^-$ **+ c.c.**

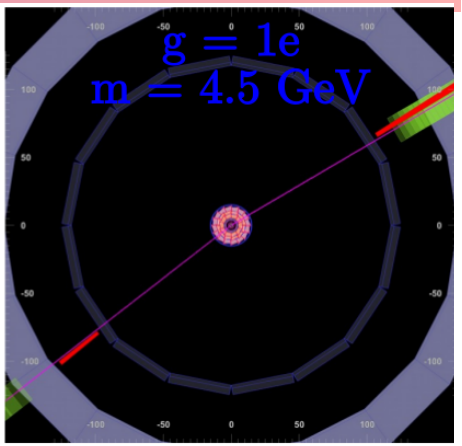
no SM background

Magnetic Monopoles



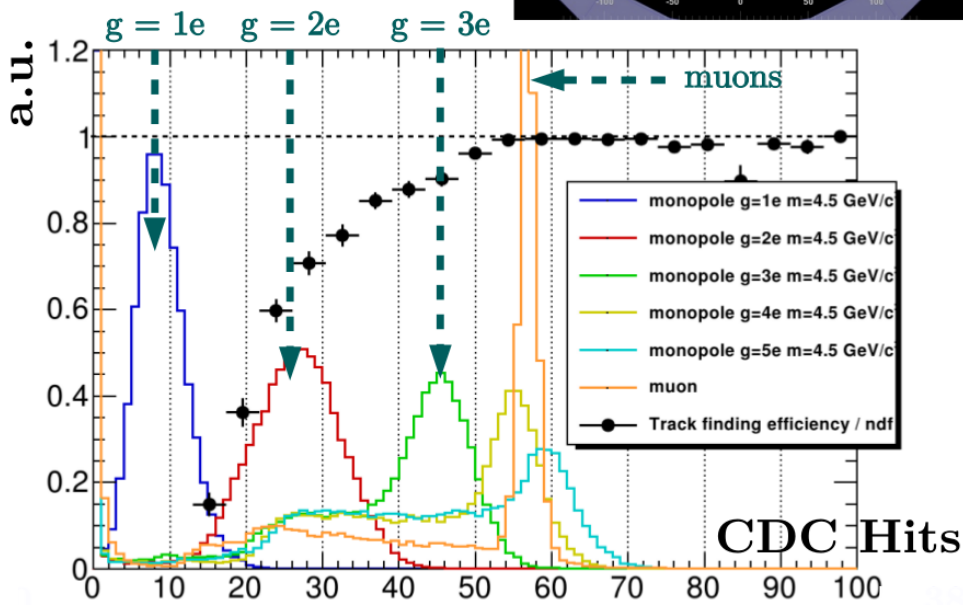
Minimal magnetic charge
from Dirac quantization: $g_D = 68.5e$

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



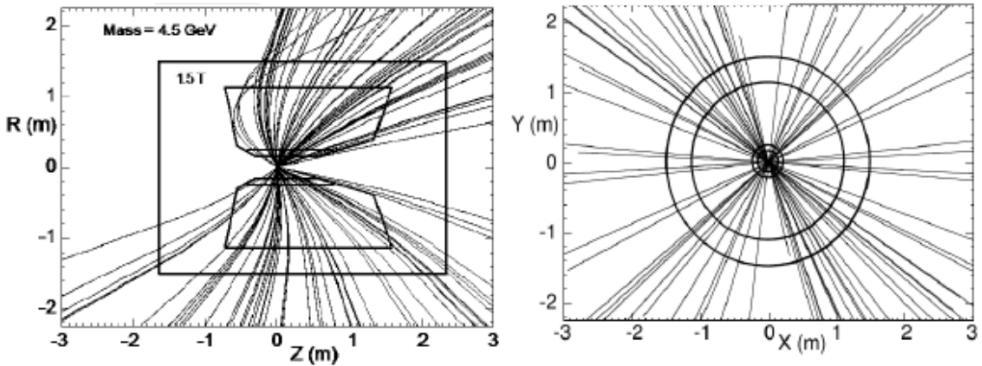
... but not-relativistic at Belle II:

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

→ few hits in the CDC

→ **needed a dedicated tracking**

(+ parabolic tracks)



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

Other Dark Sector and Exotic Searches

Visible Dark Photon decays

*Off-shell Dark Photon decays

Long-lived neutral particle decays

Dark Scalar:

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

*Magnetic Monopoles

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

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

Muonic Dark Force:

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

LFV:

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

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

*** Phase 2 benchmark**

Further details are provided in *The Belle II Physics Book*, arXiv:1808.10567 [hep-ex]