Dark Sector searches at Belle II

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INFN ROMA TRE

for the Belle II Collaboration

Belle II

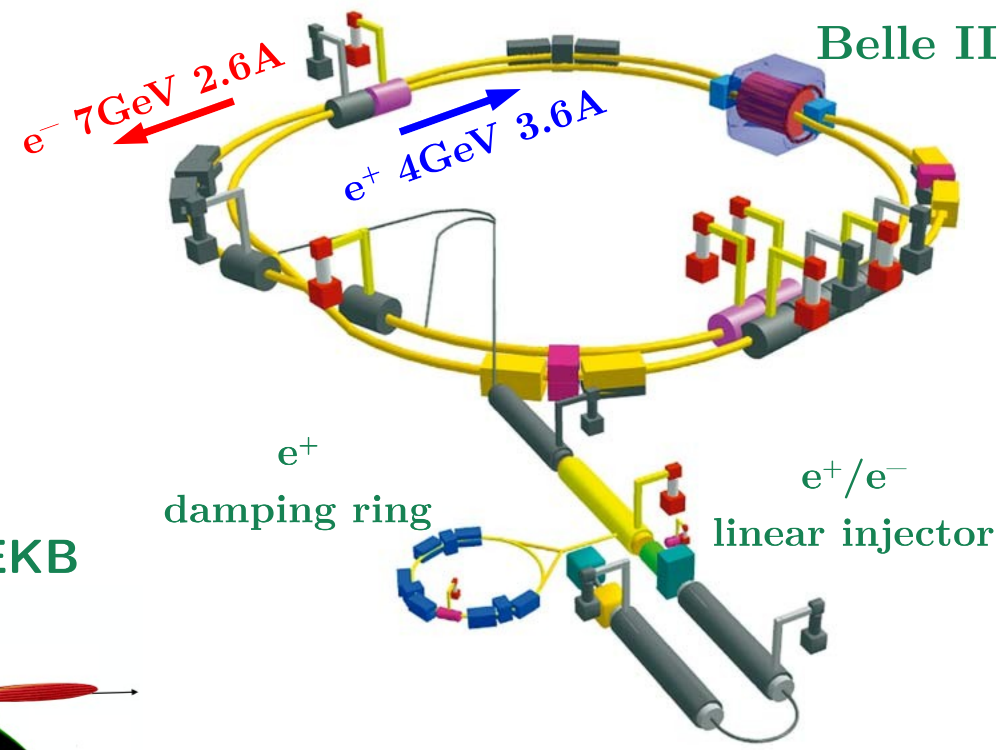
Dark Side of the Universe (DSU) @ Buenos Aires
15 - 19 July 2019


SuperKEKB
and
Belle II
S/N 16
S/N 23
INFN
LNF-RM3
Z AXIS
JTAG
Phi

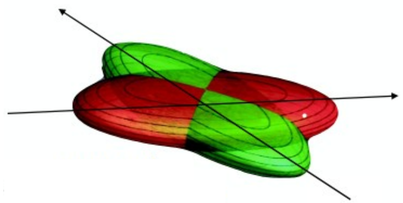
SuperKEKB: an Intensity Frontier machine

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



nano-beam scheme

SuperKEKB

I (A): ~ 1.6/1.2
β^*_y (mm): ~ 5.9/5.9

I (A): ~ 3.6/2.6
β^*_y (mm): ~ 0.27/0.3

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

SuperKEKB: an Intensity Frontier machine

Belle II

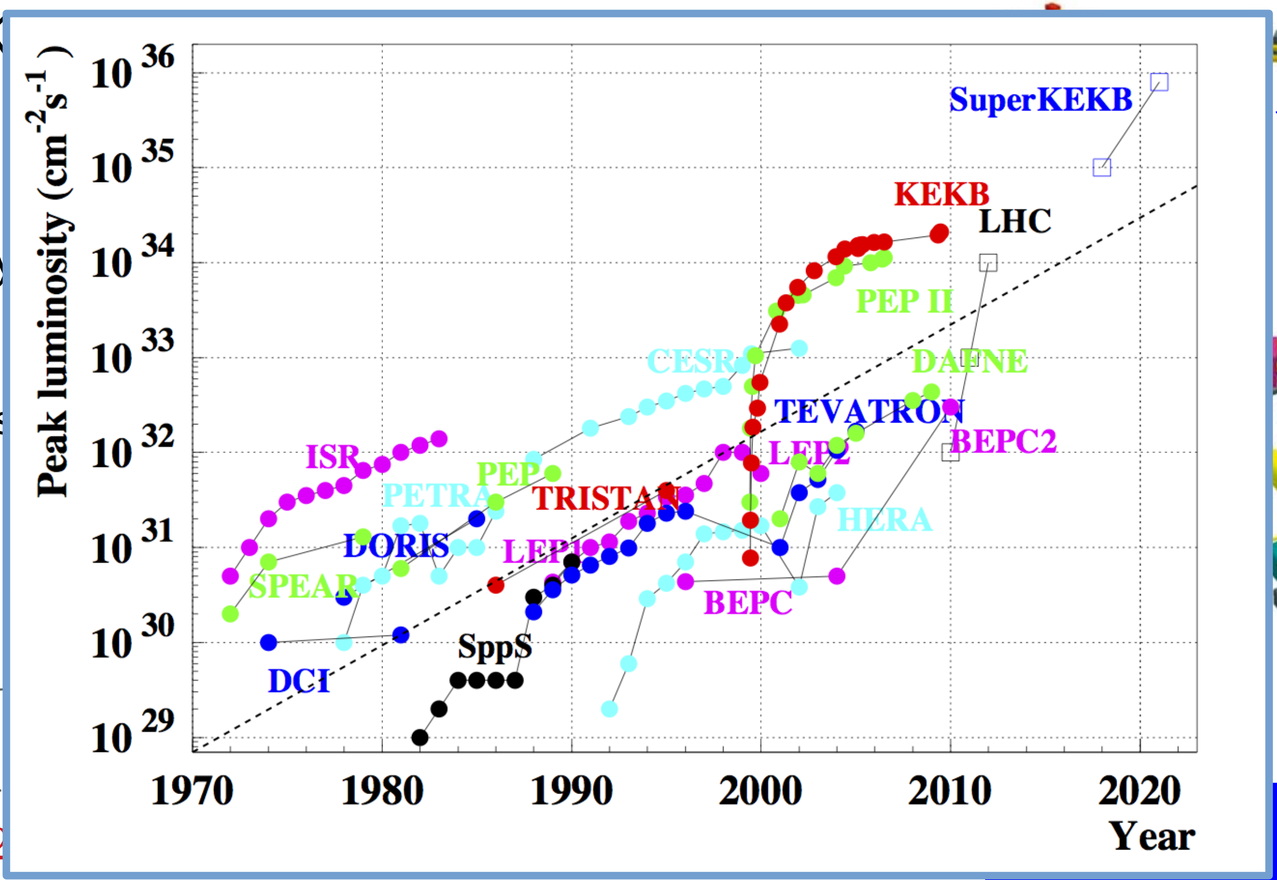
SuperKEK

located at

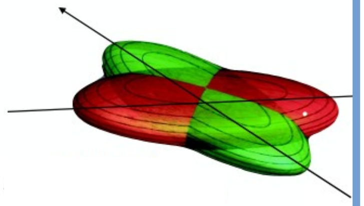
It's an asy

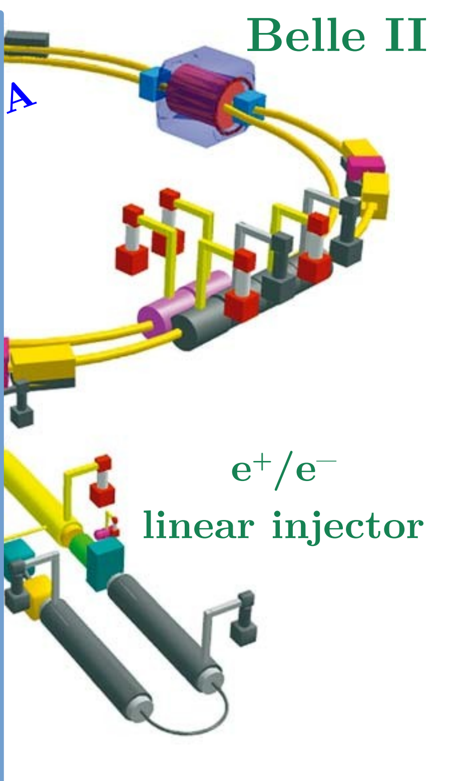
operating

(Υ(4S), but poss



KEKB





I (A): ~ 1.6/1.2

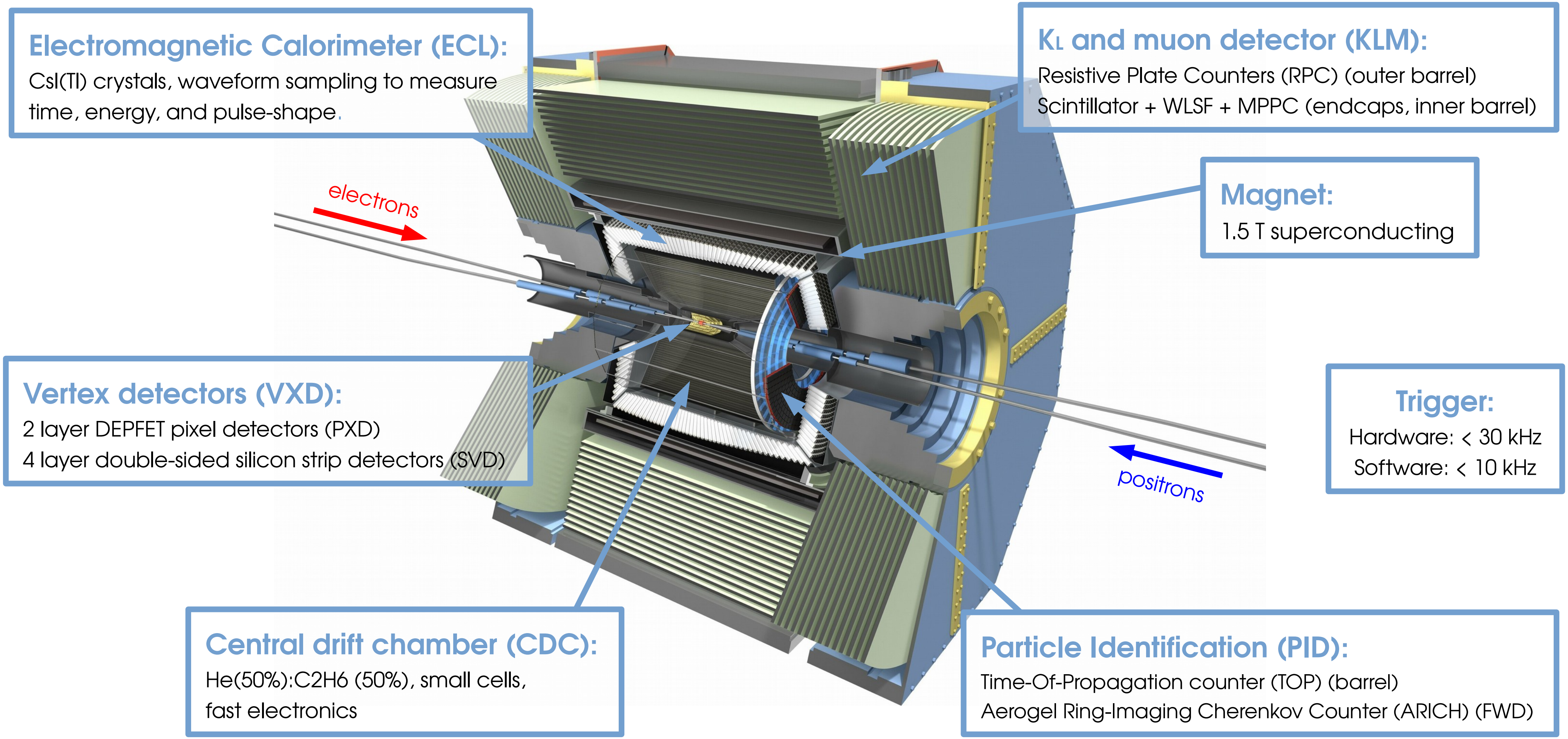
β^*_y (mm): ~ 5.9/5.9

β^*_y (mm): ~ 0.27/0.3

luminosity:

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

Belle II detector



Cross sections at a B-factory

Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 0.008	-	[2]
$u\bar{u}(\gamma)$	1.61	-	KKMC
$d\bar{d}(\gamma)$	0.40	-	KKMC
$s\bar{s}(\gamma)$	0.38	-	KKMC
$c\bar{c}(\gamma)$	1.30	-	KKMC
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta_e^* < 170°$, $E_e^* > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\mathrm{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta_\gamma^* < 170°$, $E_\gamma^* > 0.15\,\mathrm{GeV}$	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\mathrm{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\mathrm{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\mathrm{GeV}$ in CDC, $\geq 1\ \gamma\ (E_\gamma > 0.5\,\mathrm{GeV})$ in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	KKMC
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$	AAFH

E. Kou, P. Urquijo et al., arXiv:1808.10567

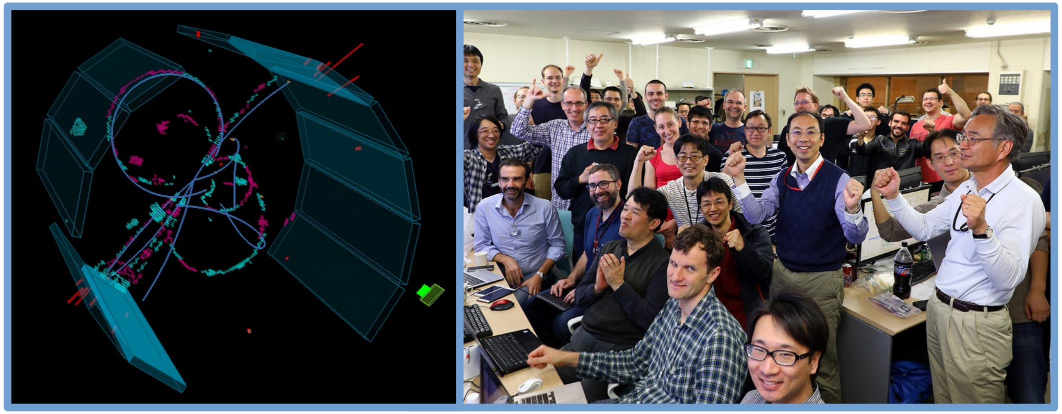
First period of data taking: Phase 2

During the Phase 2 run (**2018**)

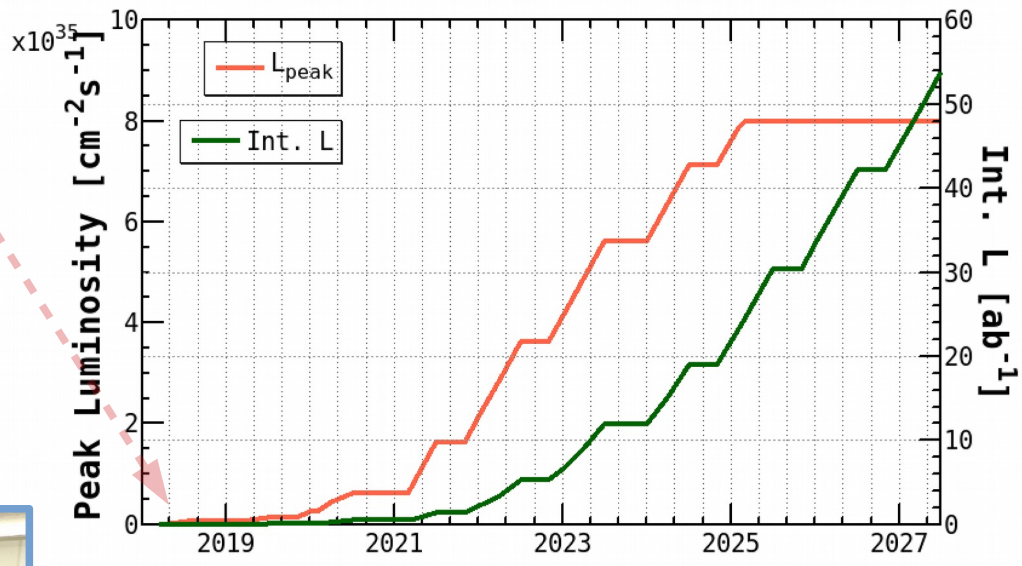
Belle II had partial **VXD detector**

Main goals:

- accelerator commissioning
- measure beam background
- detector commissioning
- **dark sector physics**



First collisions: 26th April 2018

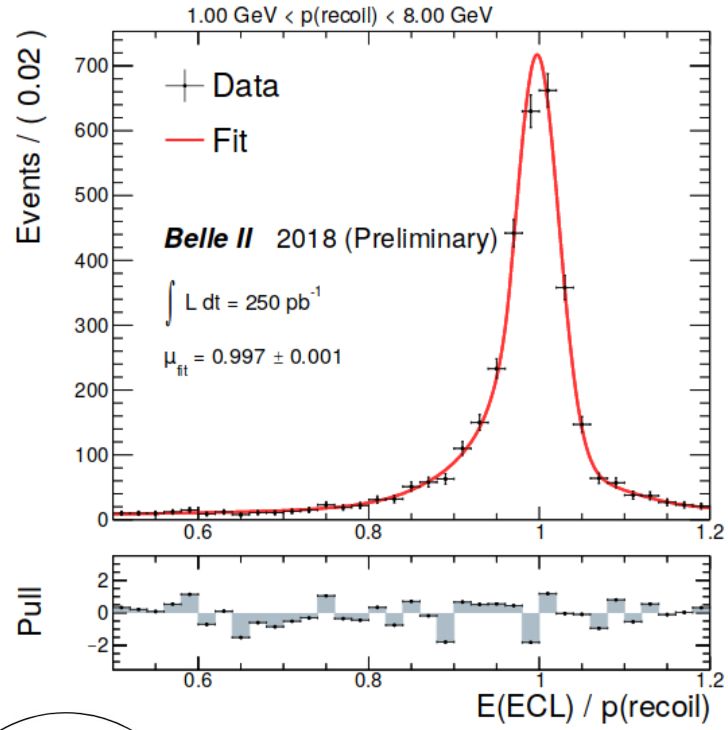


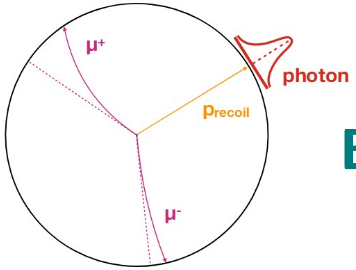
Phase 2: **0.5 fb^{-1}**

Phase 3: **50 ab^{-1}**

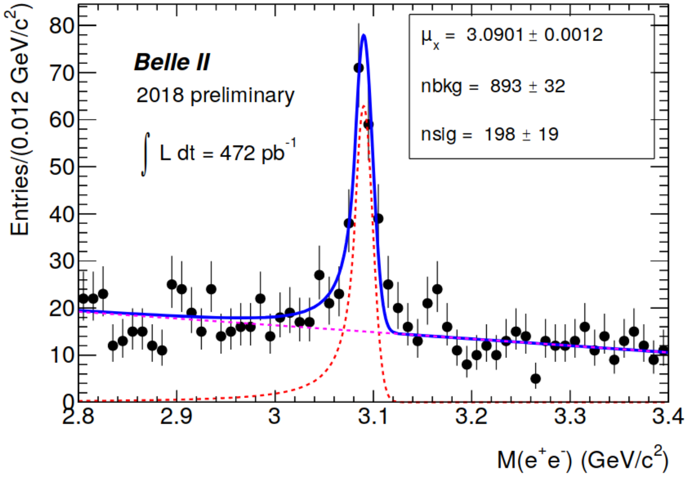
Instant luminosity achieved: $5.5 \cdot 10^{33}$ cm^{-2} s^{-1}

Highlights from Phase 2

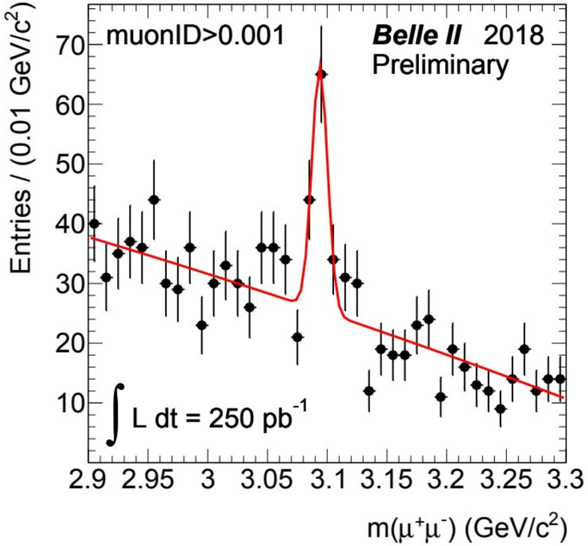




Excellent photon resolution



$J/\Psi \to e^+e^-$

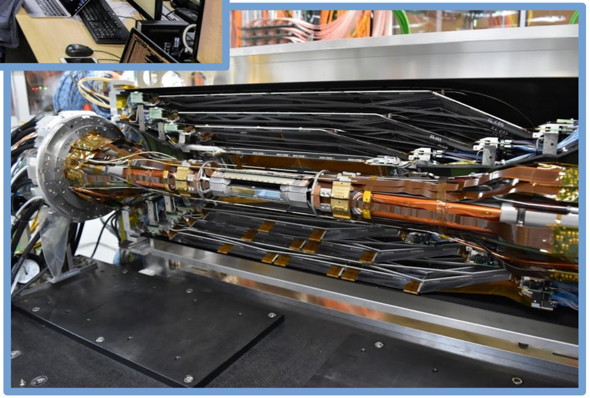


$J/\Psi \to \mu^+\mu^-$

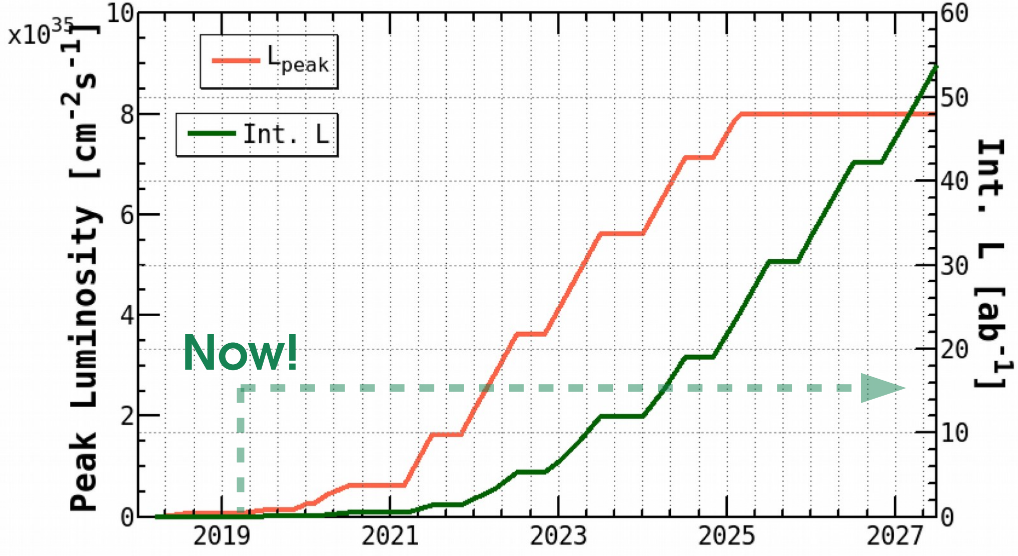
Phase 3

Goal: integrate up to 50 ab^{-1} of data

New first collisions (25th March 2019)



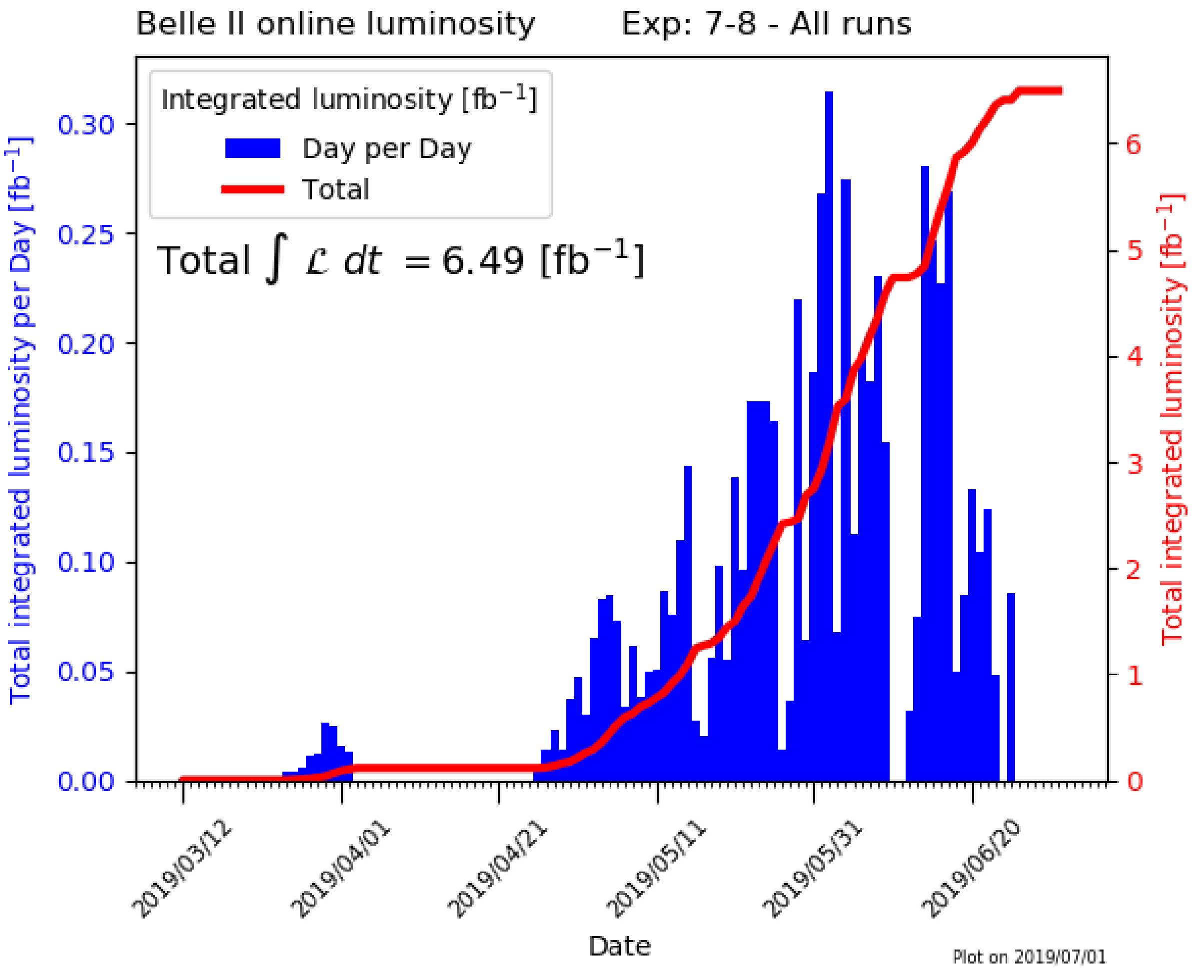
Full angular coverage with PXD and SVD installed



Phase 2:
0.5 fb^{-1}

Phase 3:
50 ab^{-1}

Phase 3

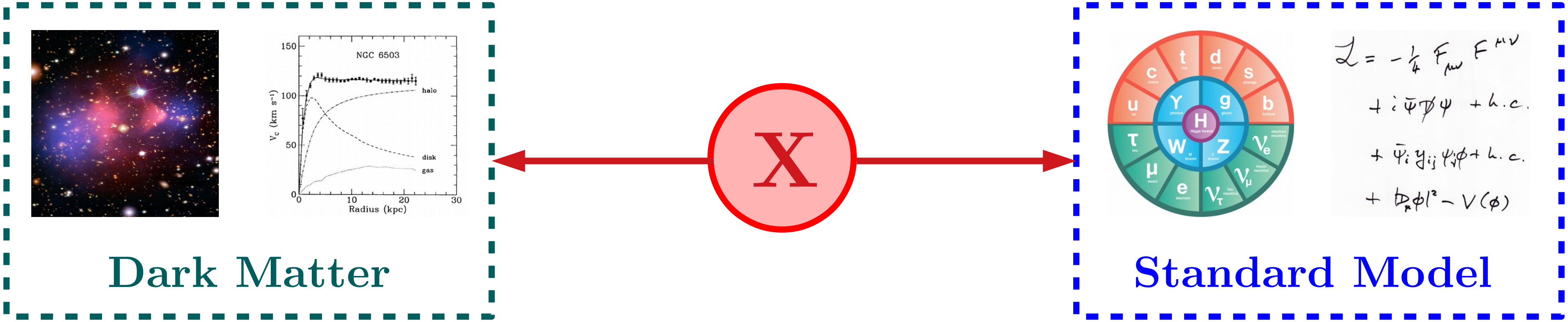


Spring run just finished:
we collected **6.5 fb^{-1}** of data!

→ First rediscoveries shown
at **EPS last week**!

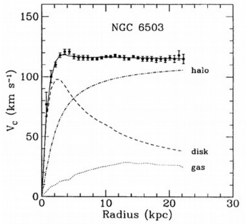
→ First physics results to be shown
at **LP in August**!

Dark Matter coupling to SM



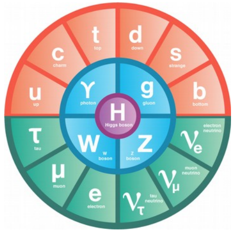
Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

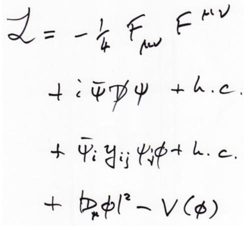
Dark Matter coupling to SM



Dark Matter

X



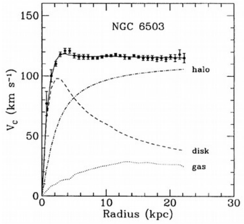


Standard Model

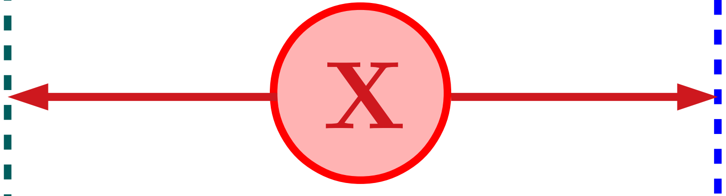
Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

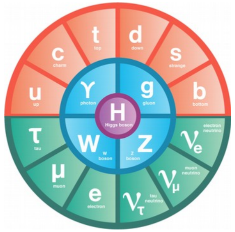
Vector portal $\rightarrow$ Dark Photon

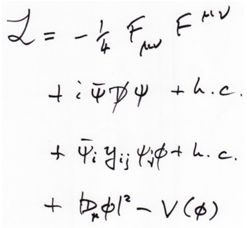
Dark Matter coupling to SM

Dark Matter







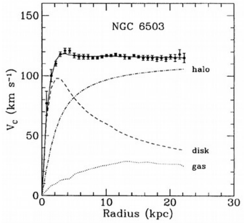
Standard Model

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

Vector portal → Dark Photon

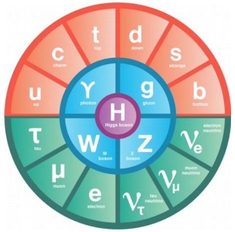
Scalar portal → Dark Higgs/Scalars

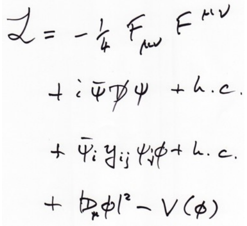
Dark Matter coupling to SM



Dark Matter

X





Standard Model

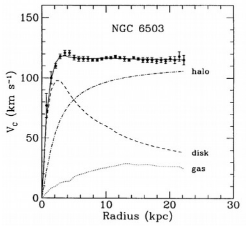
Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

Vector portal → Dark Photon

Scalar portal → Dark Higgs/Scalars

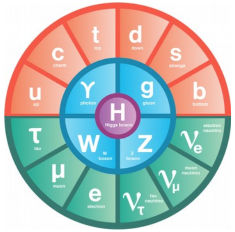
Pseudoscalar portal → Axion-Like Particles

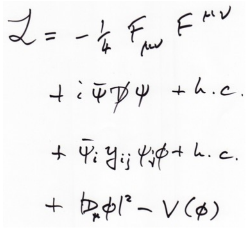
Dark Matter coupling to SM



Dark Matter

X





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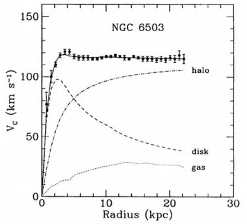
Vector portal $\rightarrow$ Dark Photon

Scalar portal $\rightarrow$ Dark Higgs/Scalars

Pseudoscalar portal $\rightarrow$ Axion-Like Particles

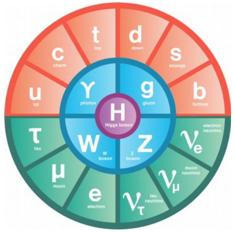
Neutrino portal $\rightarrow$ Sterile Neutrinos

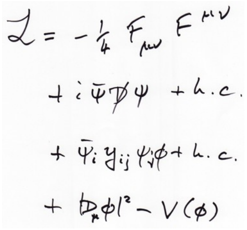
Dark Matter coupling to SM

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

Competitive studies with low statistics!

Dark Photons

Dark Photon

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

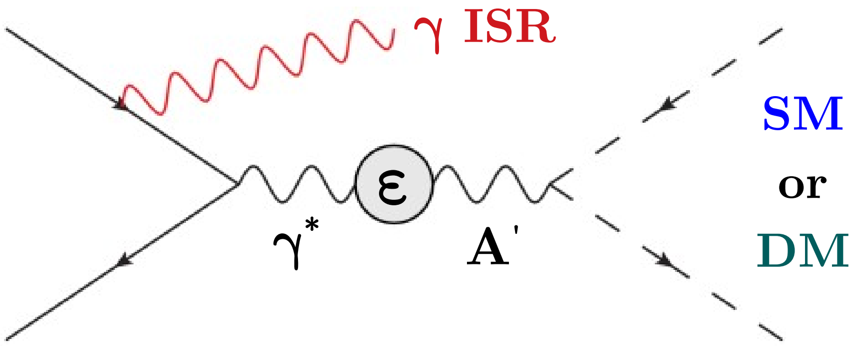
$$\mathcal{L} \supset \epsilon A_\mu J^\mu_{\mathrm{SM}}$$

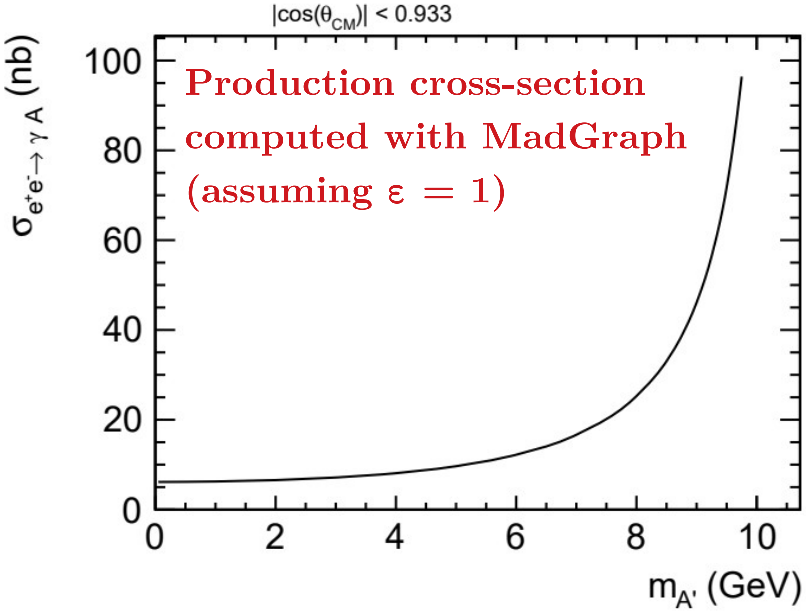
Batell et al. (2009), *arXiv:0903.0363*

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**



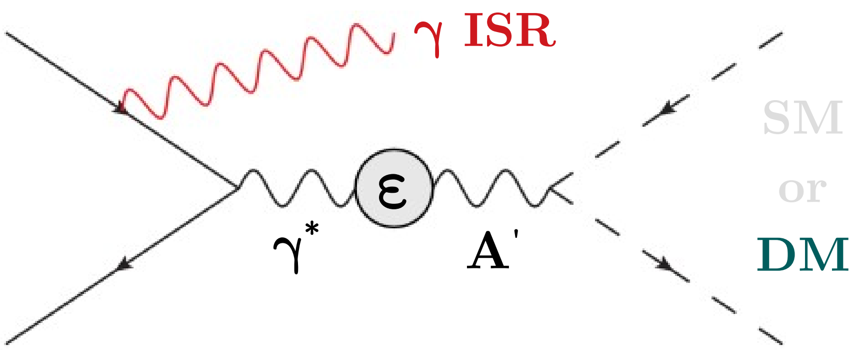


Dark Photon: invisible decay (signal)

Signal signature:

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

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



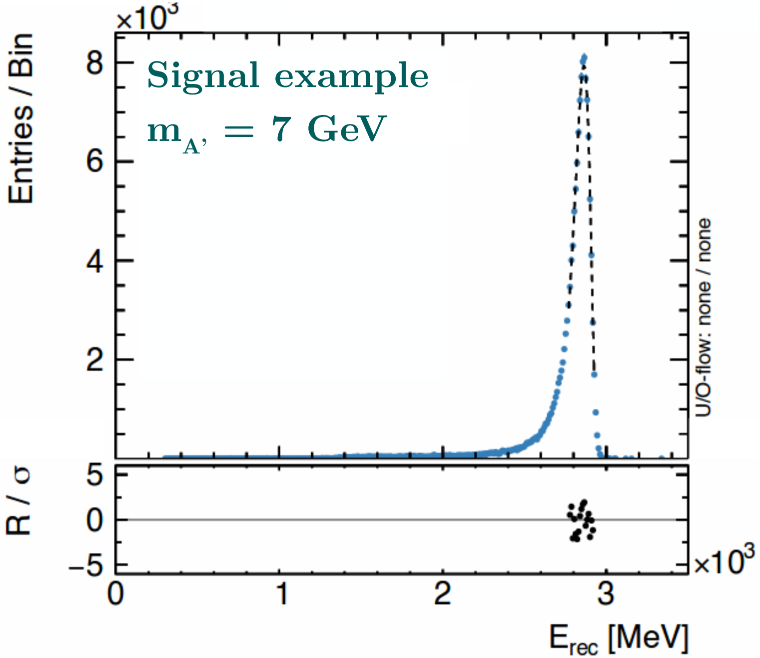
Needed a special **single photon trigger**

(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 entire Phase 3?

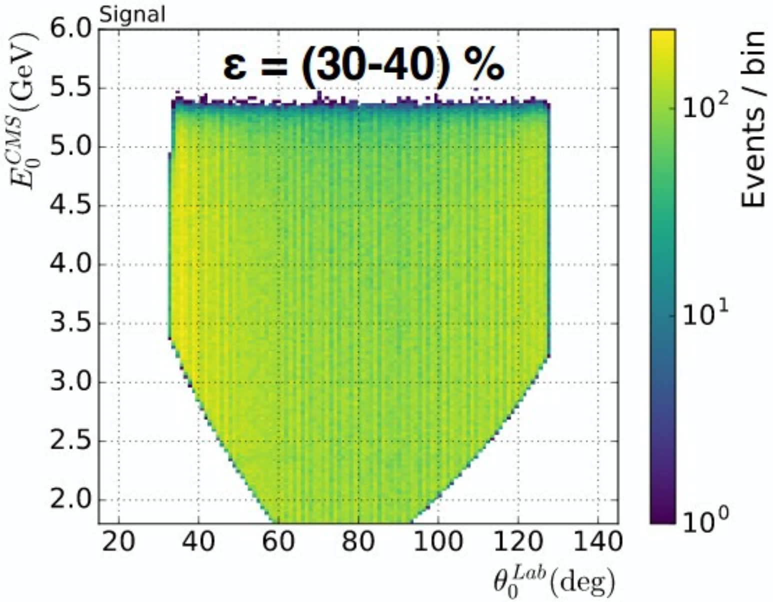


Belle II MC Preliminary

Dark Photon: invisible decay (signal)

Discriminant variables:

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



Signal signature:

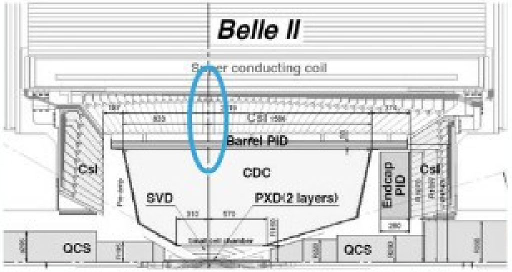
peak in E_{CMS} (horizontal band)

Dark Photon: invisible decay (background)

Belle II

Discriminant variables:

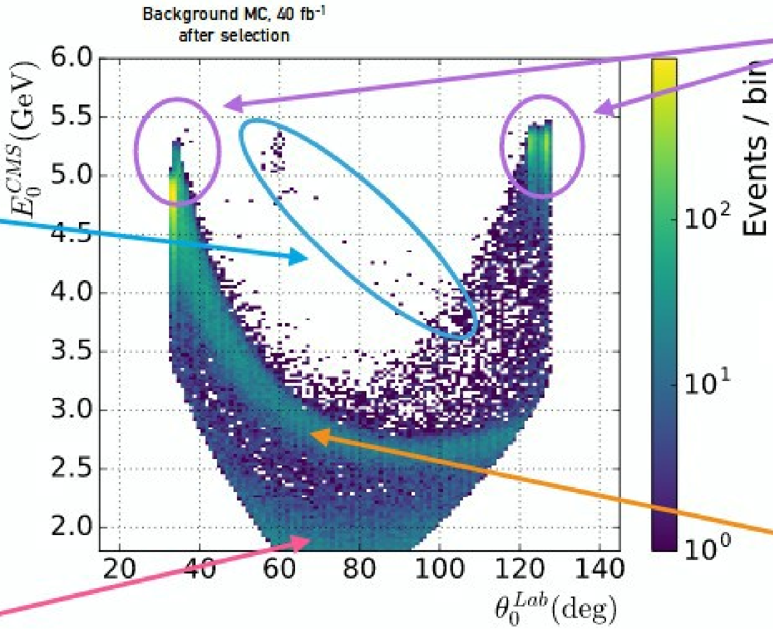
E_{CMS} vs. polar angle of "single photon"

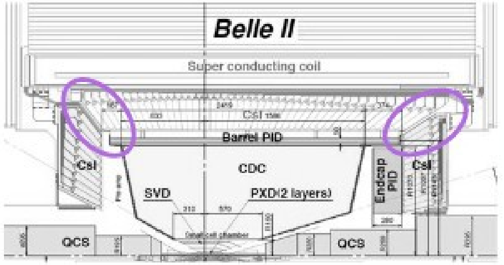


ee→2γ and 3γ

1γ in ECL 90° gap

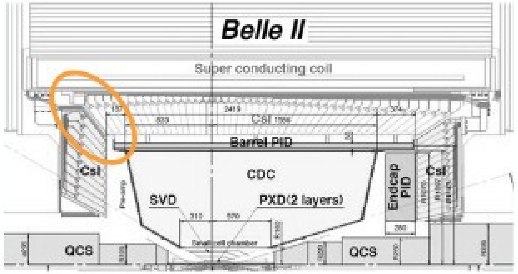
1γ out of ECL acceptance





ee→2γ

1γ in ECL BWD or FWD gap



ee→3γ

1γ in ECL BWD gap

1γ out of ECL acceptance

ee→eeγ

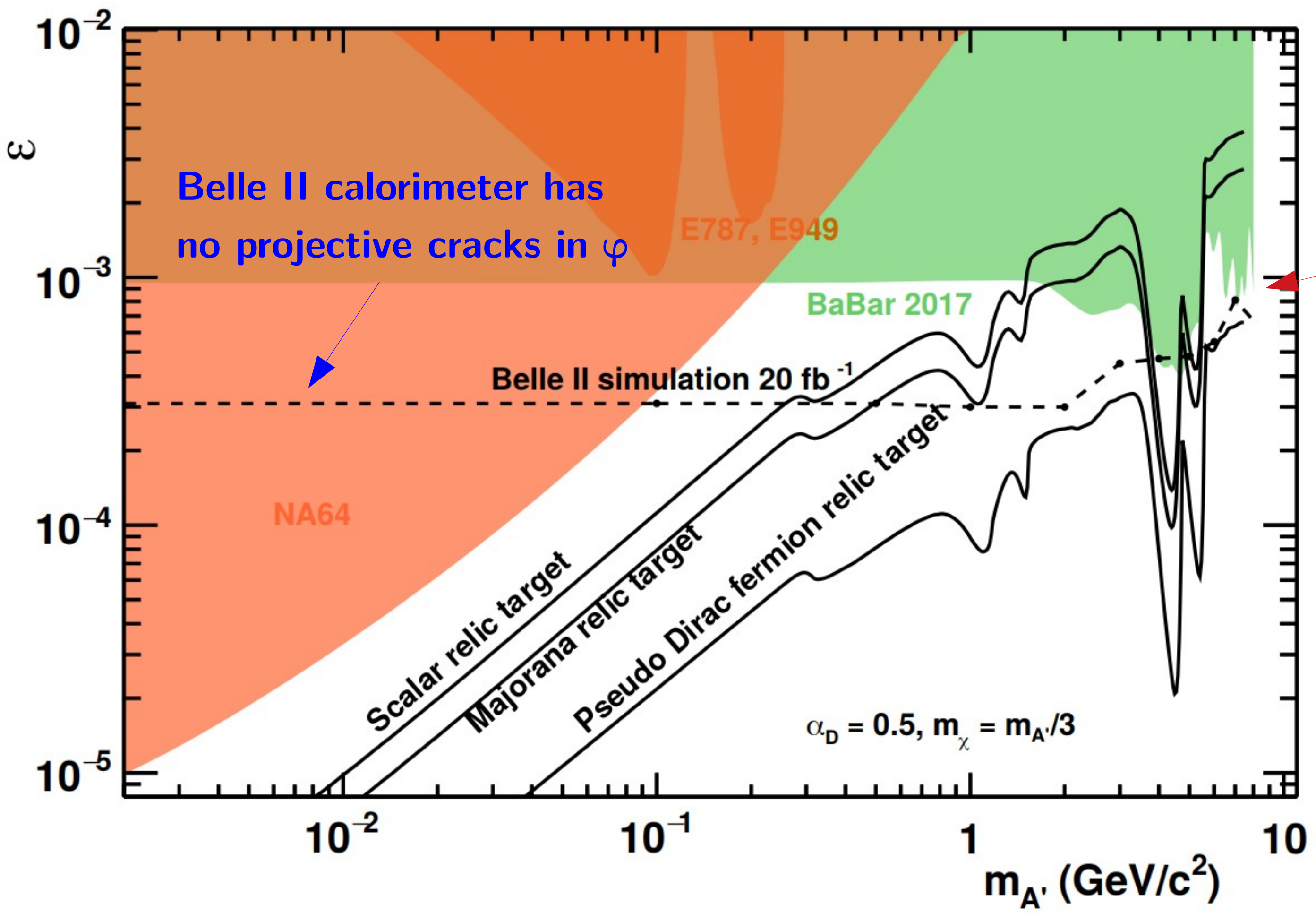
both electrons

out of tracking acceptance

Signal signature:

peak in E_{CMS} (horizontal band)

Dark Photon: invisible decay (sensitivity)



Belle II calorimeter has no projective cracks in φ

Lower trigger threshold wrt BaBar

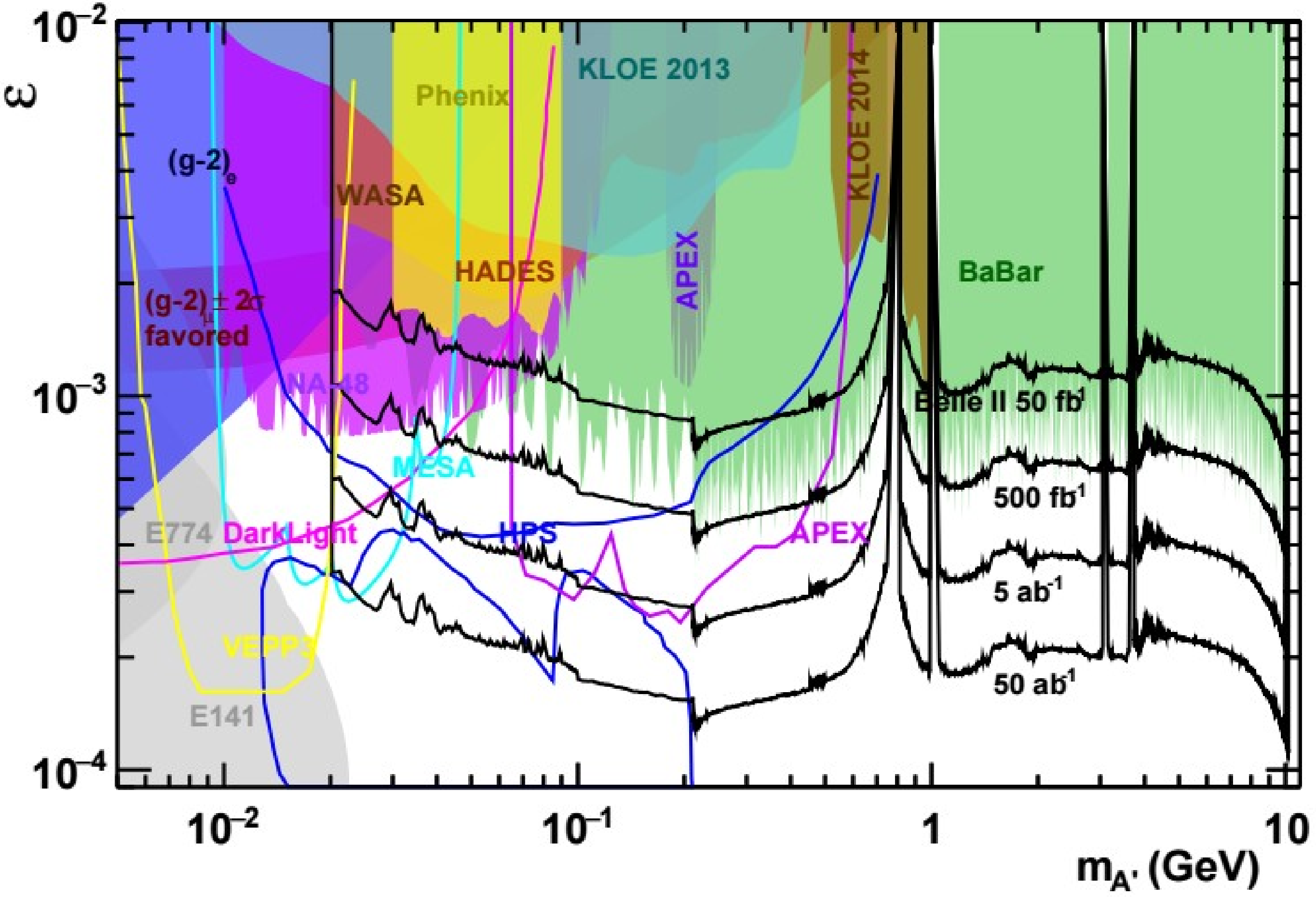
J. Alexander et al. (2016), *arXiv:1608.08632*

N. Toro, private communication (2017)

J. P. Lees et al., BaBar (2017), *arXiv:1702.0332*

The Belle II Physics Book, *arXiv:1808.10567*

Dark Photon: leptonic decay



Look for a bump in the e^+e^- or $\mu^+\mu^-$ invariant mass over a (large) QED background

Belle II sensitivity is obtained by scaling the BaBar measurement:

- **expected better invariant mass resolution**
- **expected better triggers**

Axion-like Particles

Axion-Like Particles

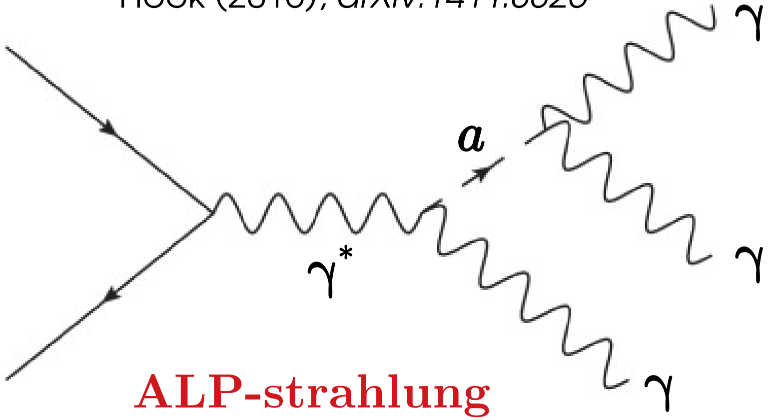
Axion-Like Particles (ALPs) are pseudo-scalars and couple to bosons.
Unlike QCD Axions, ALPs have no relation between mass and coupling.

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

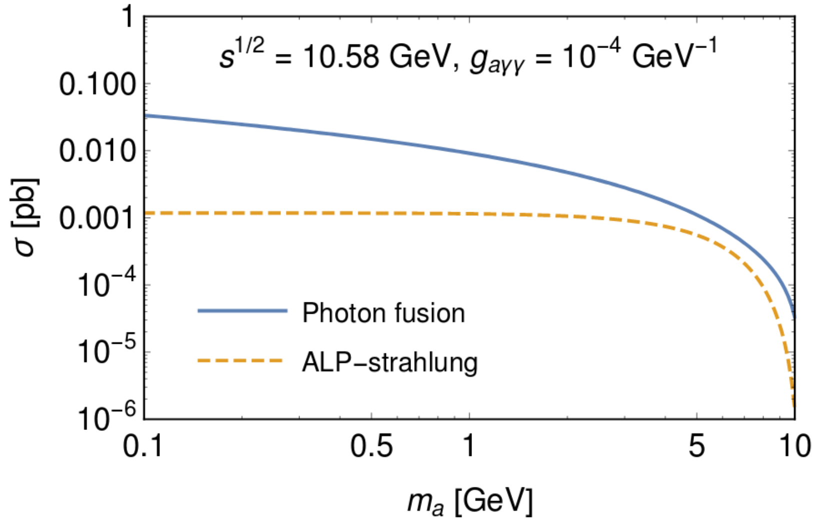
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad \tau_a \sim 1/g^2_{a\gamma\gamma} m_a^3$$

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

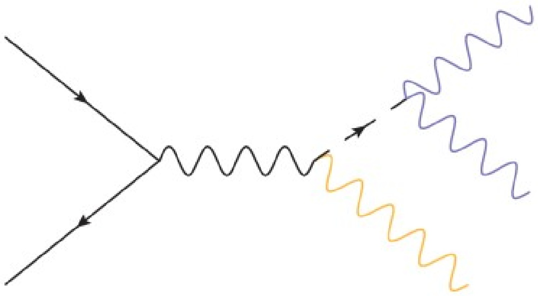
Hook (2015), *arXiv:1411.3325*



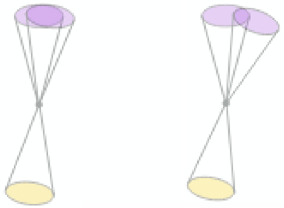
ALP-strahlung



Axion-Like Particles (signal)



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

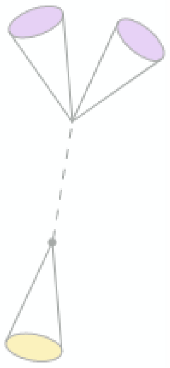


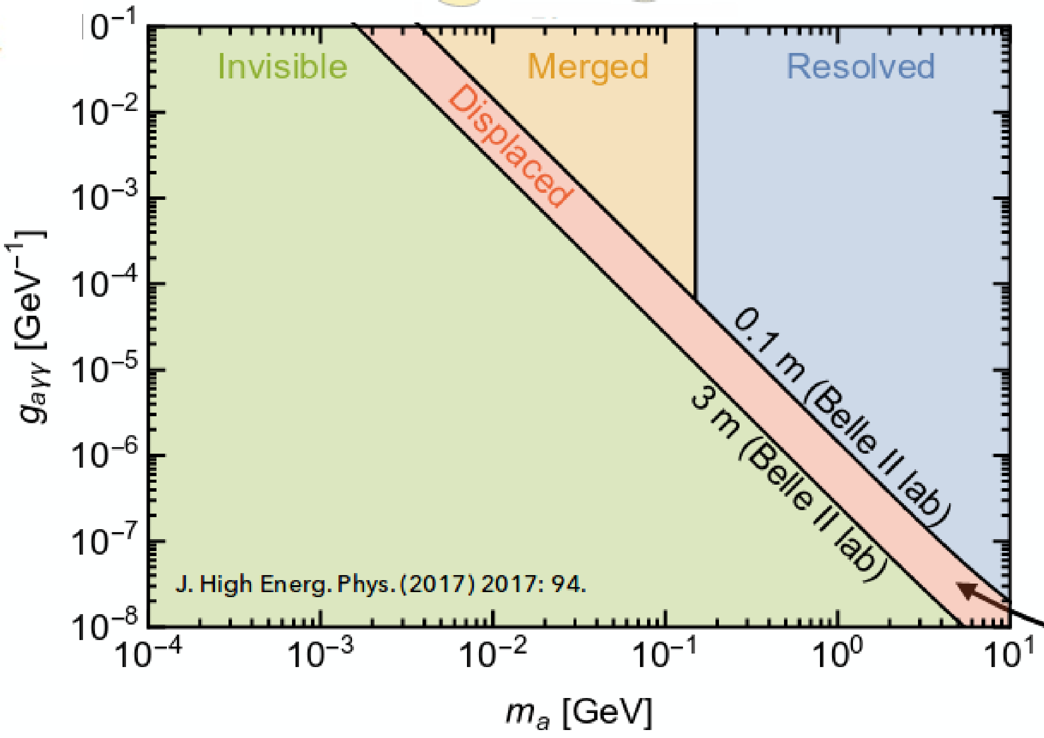
$$\tau_a \sim 1/g_{a\gamma\gamma}^2 m_a^3$$

For **resolved** case:

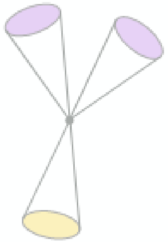
3 clusters with $E_{CM} > 0.25$ GeV

Peak in $\gamma\gamma$ mass spectrum





Three **resolved**, high energetic photons.

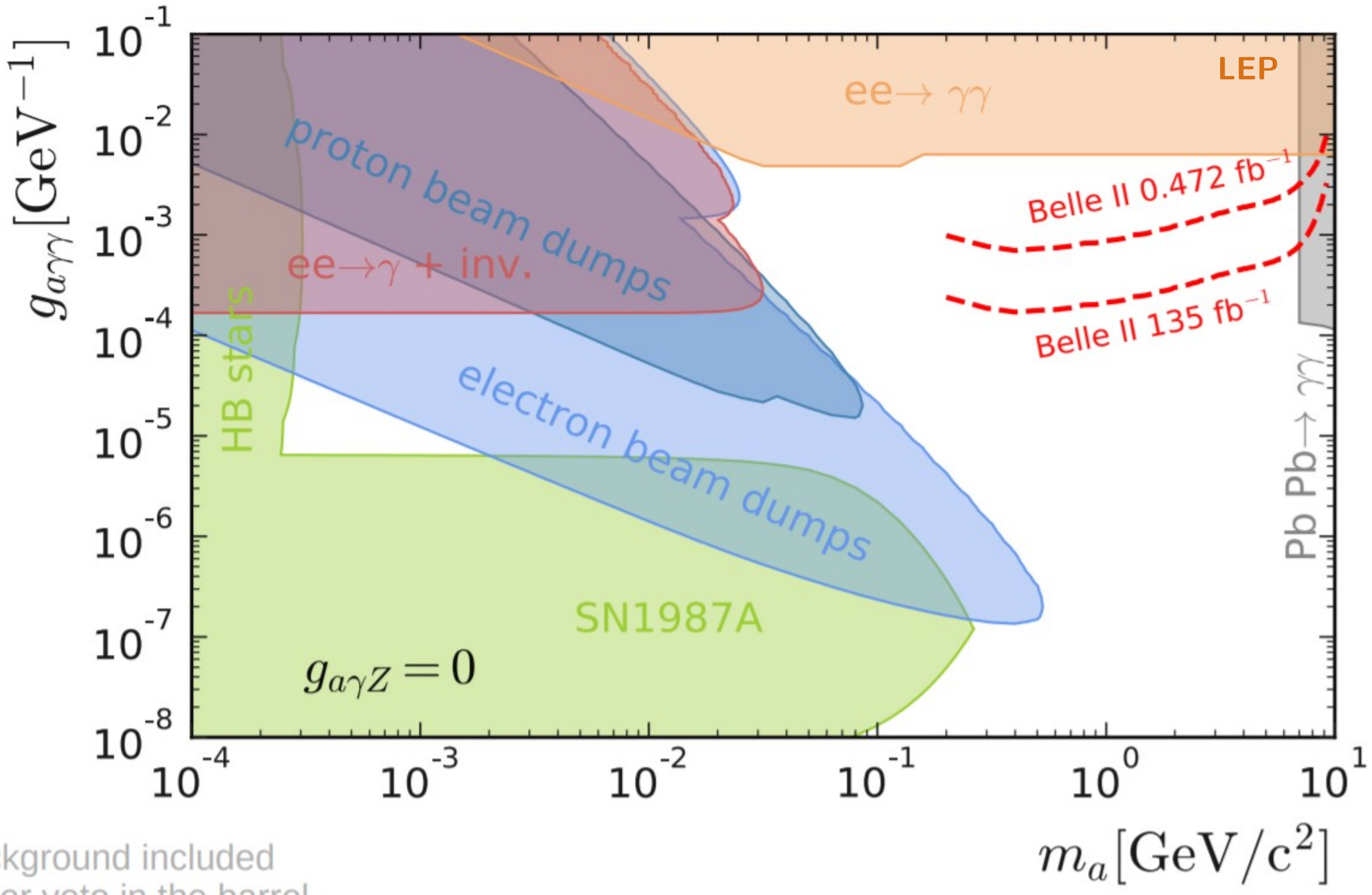


ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

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

Axion-Like Particles (sensitivity)

We expect to improve the current limits for $m_a > 100$ MeV



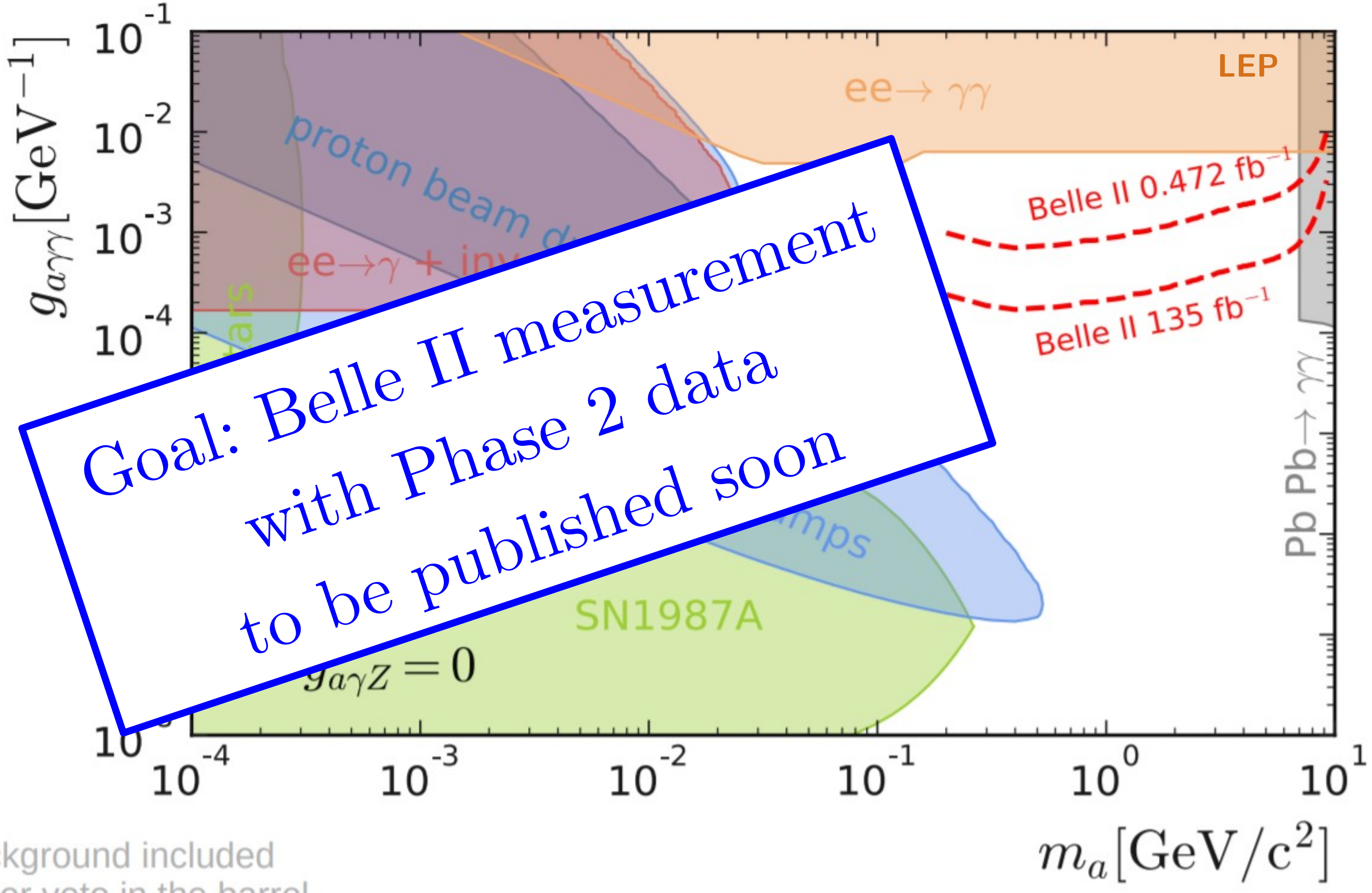
No systematics.
Only (dominant) ee→γγγ background included
135fb -1 assumes no γγ trigger veto in the barrel

Axion-Like Particles (sensitivity)

Belle II

We expect to improve the current limits for

$m_a > 100$ MeV



Goal: Belle II measurement with Phase 2 data to be published soon

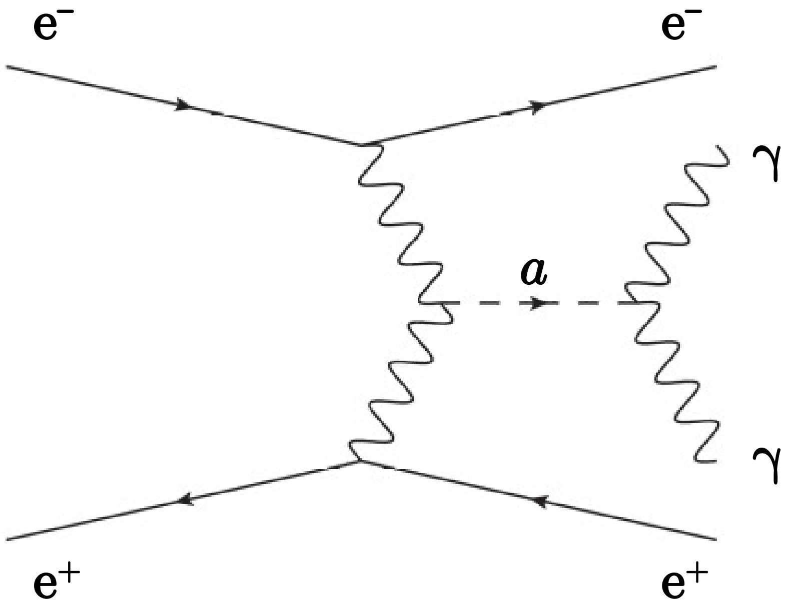
No systematics.
Only (dominant) ee→γγγ background included
135fb -1 assumes no γγ trigger veto in the barrel

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 energetic photons

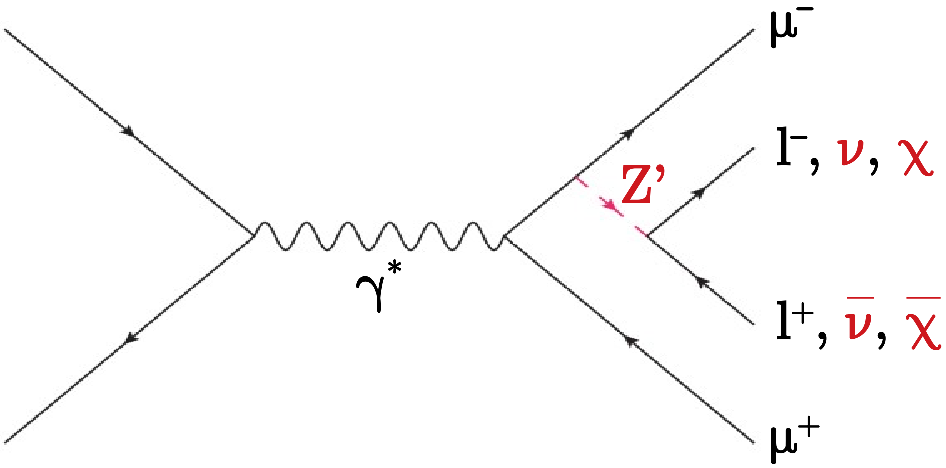

Other exotic searches
S/N 16
S/N 23
INFN
LNF-RM3
Z AXIS
JTAG
Phi

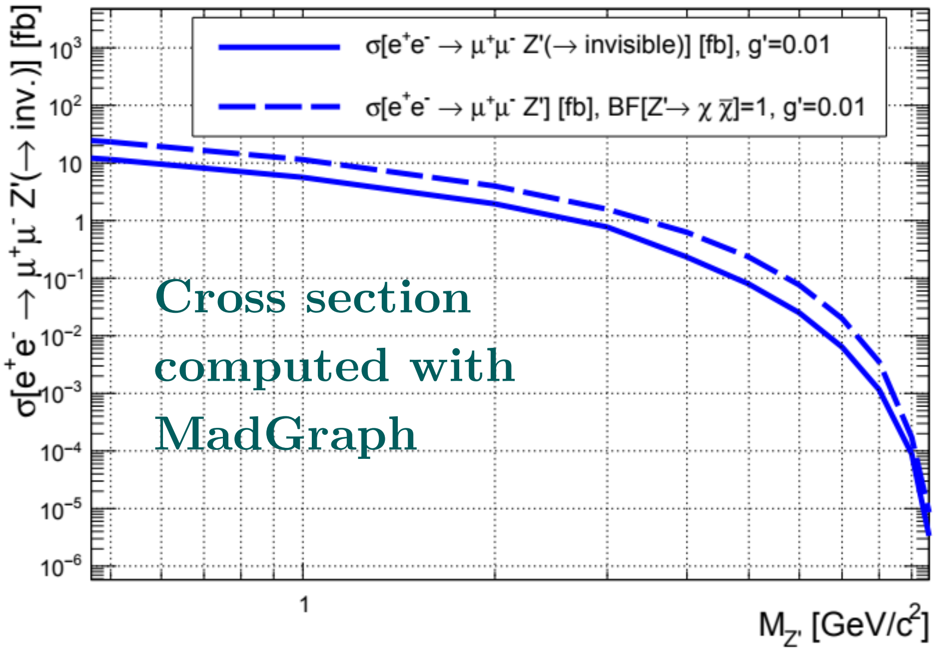
Muonic Dark Force: invisible decay

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

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

Shuve et al. (2014), *arXiv:1403.2727*





Branching ratios:

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

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

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

Muonic Dark Force: invisible decay

Belle II

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:

~ nothing in the rest of the event

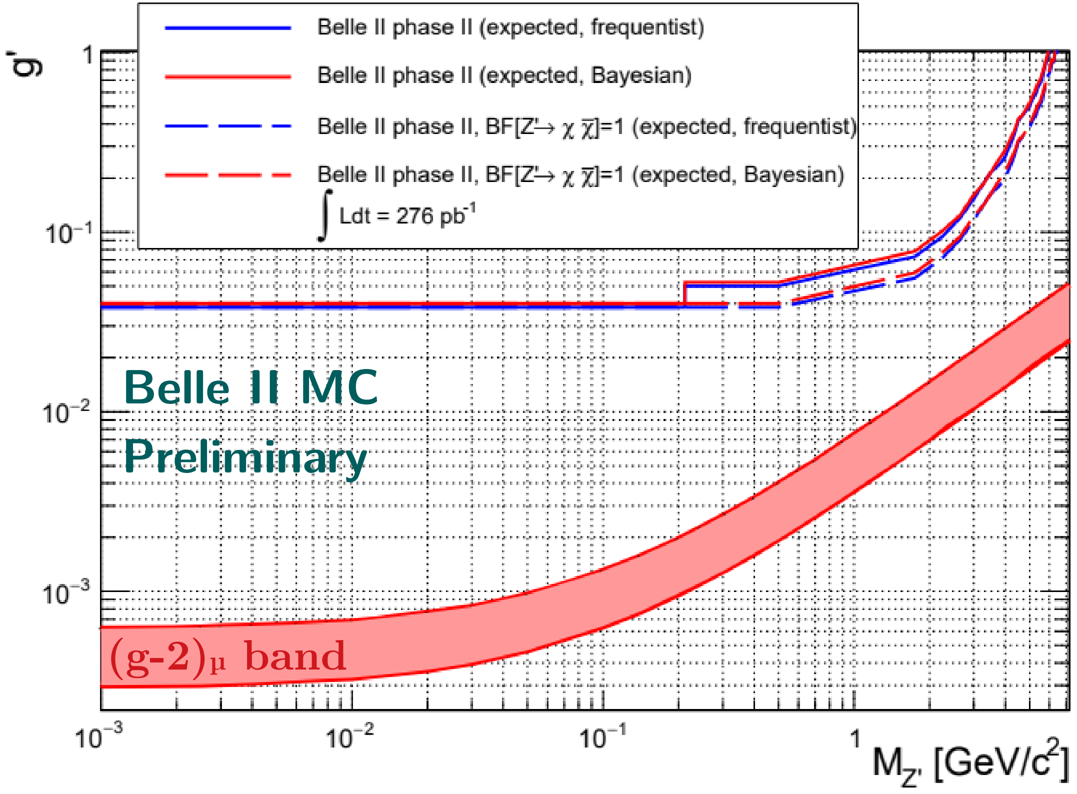
Considered several **mass hypothesis for Z'** with full simulation and reconstruction

Considered the **main backgrounds**:

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

$e^+ e^- \to \tau^+ \tau^-$

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



Trigger + tracking + PID + mass resolution systematics already included here (10%)

Possible additional systematics on background estimate not included (0-30%)

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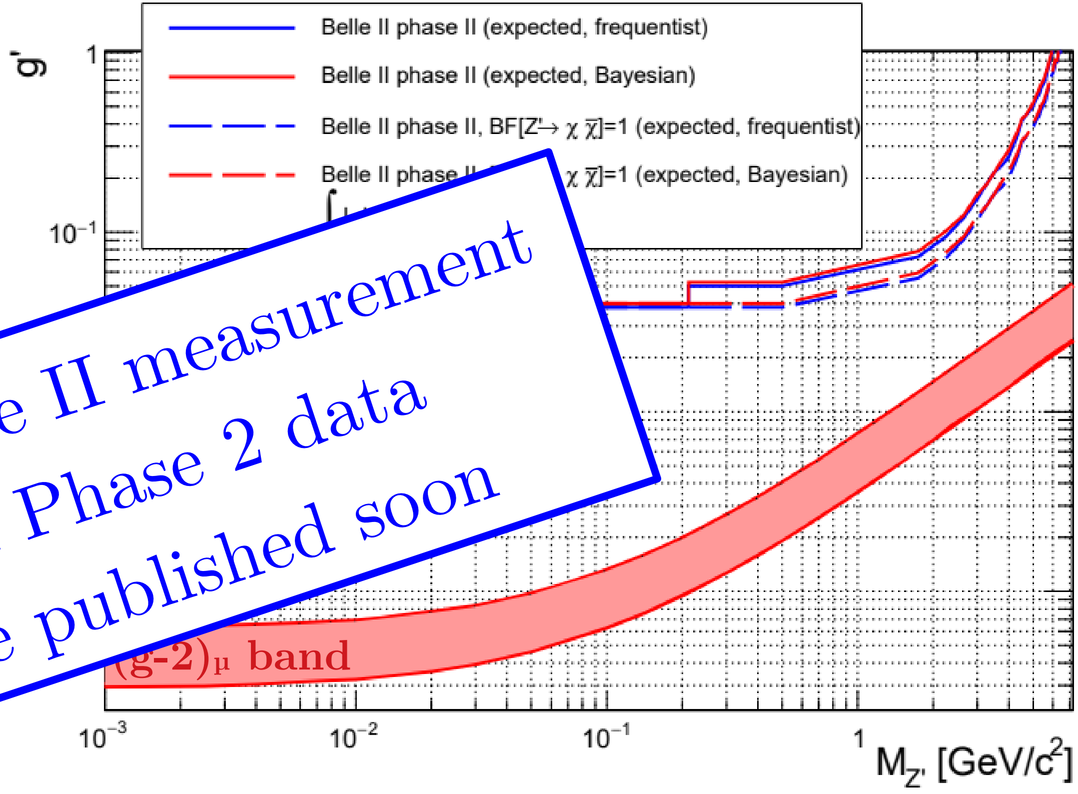
C
mai
e^+
e^+ e
$e^+ e^-$ —

Goal: Belle II measurement with Phase 2 data to be published soon



Trigger + tracking + PID + mass resolution systematics already included here (10%)

Possible additional systematics on background estimate not included (0-30%)

Dark Sector and LFV

We are also considering a different model, in which a Z' boson couples to all leptons and we allow for **Lepton Flavour Violation**

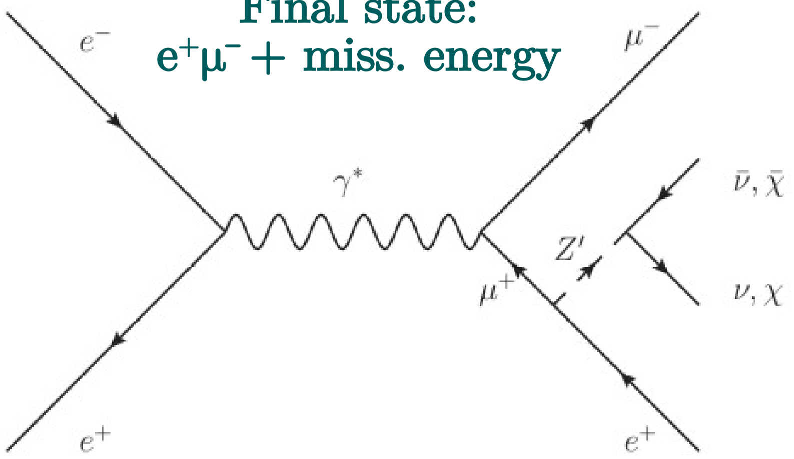
See I. Galon et al.: *arXiv:1610.08060, arXiv:1701.08767*

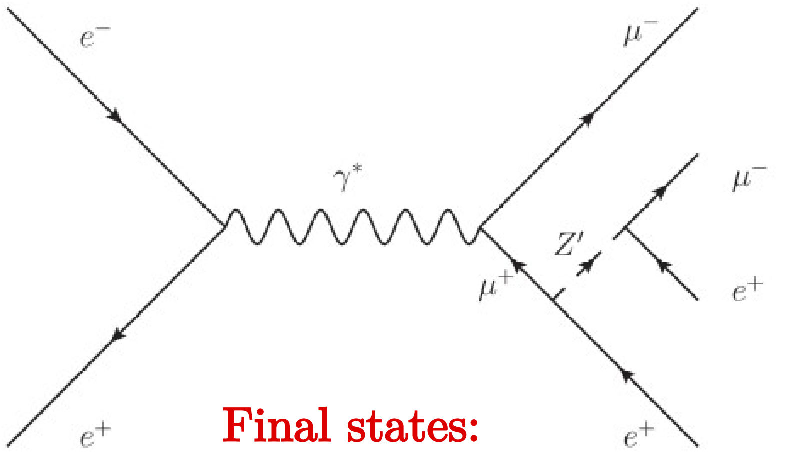
Complementarity with searches for:

- low mass Z'
- charged LFV

Low background from SM processes!

Final state:
$e^+\mu^- +$ miss. energy





Final states:
$e^+e^+\mu^-\mu^-$; $e^+e^-\mu^+\mu^-$

Dark Sector and LFV

We are also consi... del,

in whi... ns

... on

... 1701.08767

Goal: Belle II measurement with Phase 2 data to be published soon

C... tarity with searches for:

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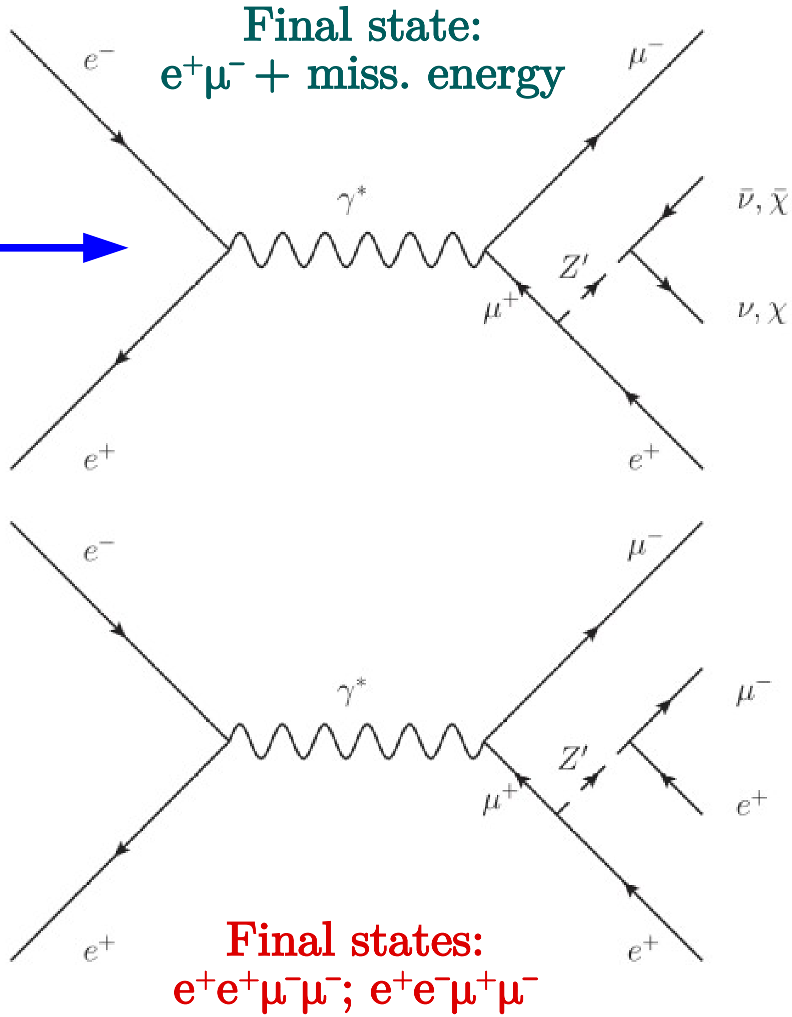
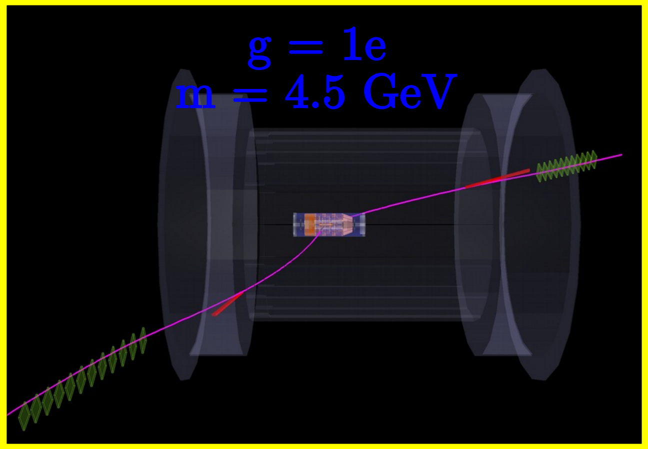
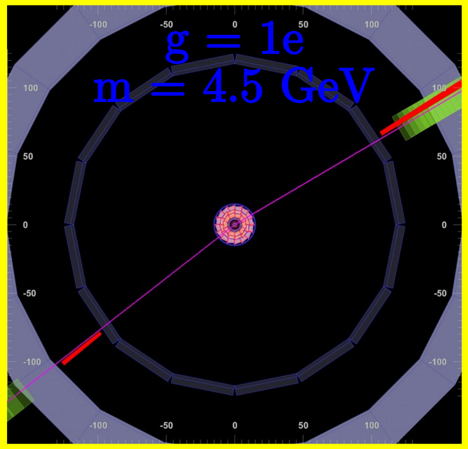


Magnetic monopoles





Interesting predictions (*arXiv:1707.05295*) for monopoles with **g ∼ 1e** and **m = 4.5 GeV**...

... but not-relativistic at Belle II:

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

→ few hits in the CDC

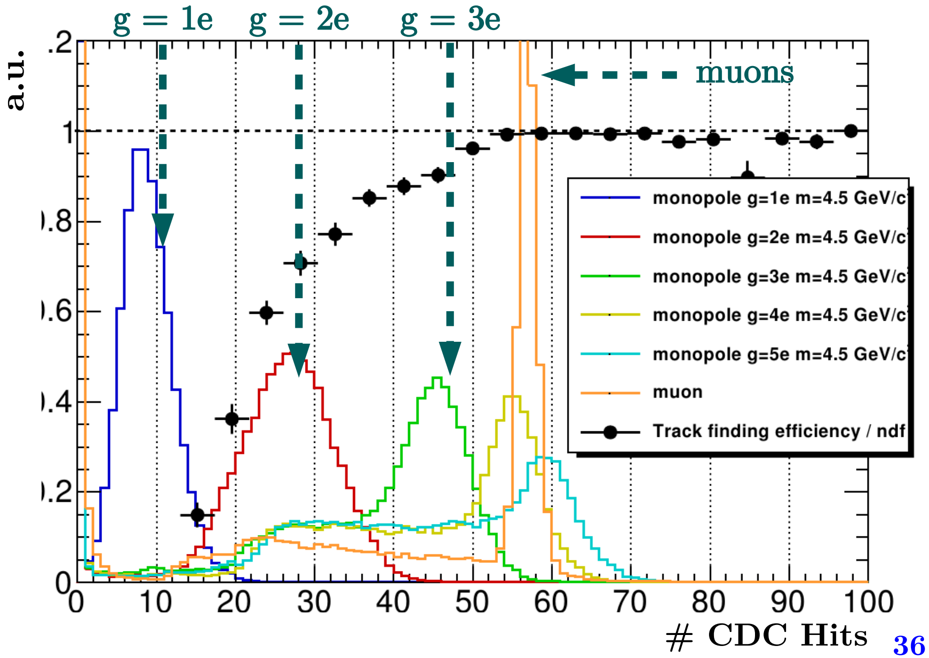
→ **needed a dedicated tracking**

Complementary search using our PXD: K. Dort et al., arXiv:1906.04942

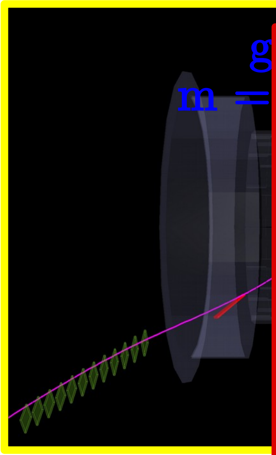
Minimal magnetic charge from Dirac quantization: $g_D = 68.5e$

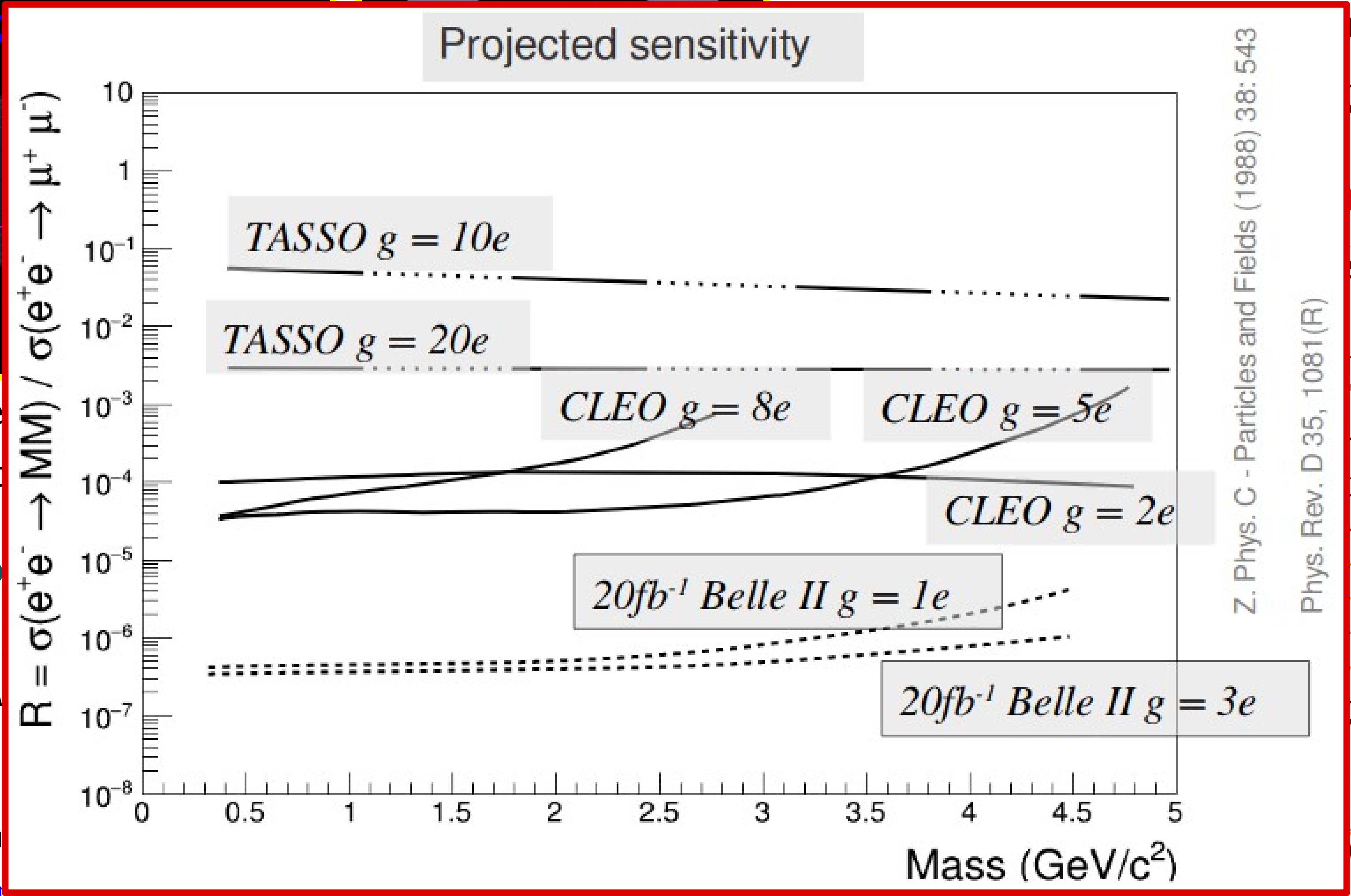
Lower magnetic charge not ruled out

(and not covered at ∼GeV scale)



Magnetic monopoles





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$_D = 68.5e$

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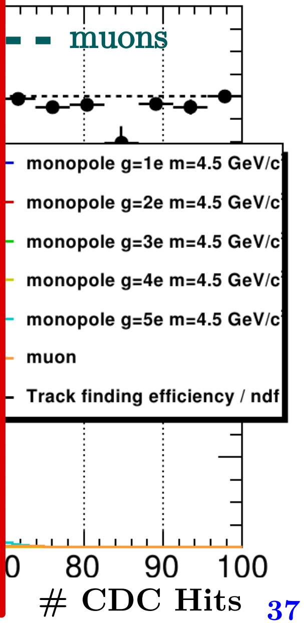
V scale)



Intere

monopo

… but no

→ no 1

→ few

→ **n**

Complementa

Other dark sector and exotic searches

Visible Dark Photon decays

also $\tau^+\tau^-$ final state!

Off-shell Dark Photon decays

Long-lived neutral particle decays

Dark Scalar:

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

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

$\Upsilon(3S) \to \Upsilon(1S)\,\pi^+\pi^-$
$\Upsilon(2S) \to \Upsilon(1S)\,\pi^+\pi^-$

Muonic Dark Force:

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

... and many others!

More details in The Belle II Physics Book

arXiv:1808.10567

Summary

- ✔ Belle II at the SuperKEKB facility started operations in 2018, collecting 0.5 fb^{-1} of collisions data in 2018 and other 6.5 fb^{-1} in 2019

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Summary

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- Dedicated triggers for a rich program of Dark Sector and exotic searches at Belle II
- Already a small dataset will give world leading sensitivity for several Dark Sector searches
- First results (ALPs, Z', etc.) are currently under internal review and they will be published soon

Thank you for your attention

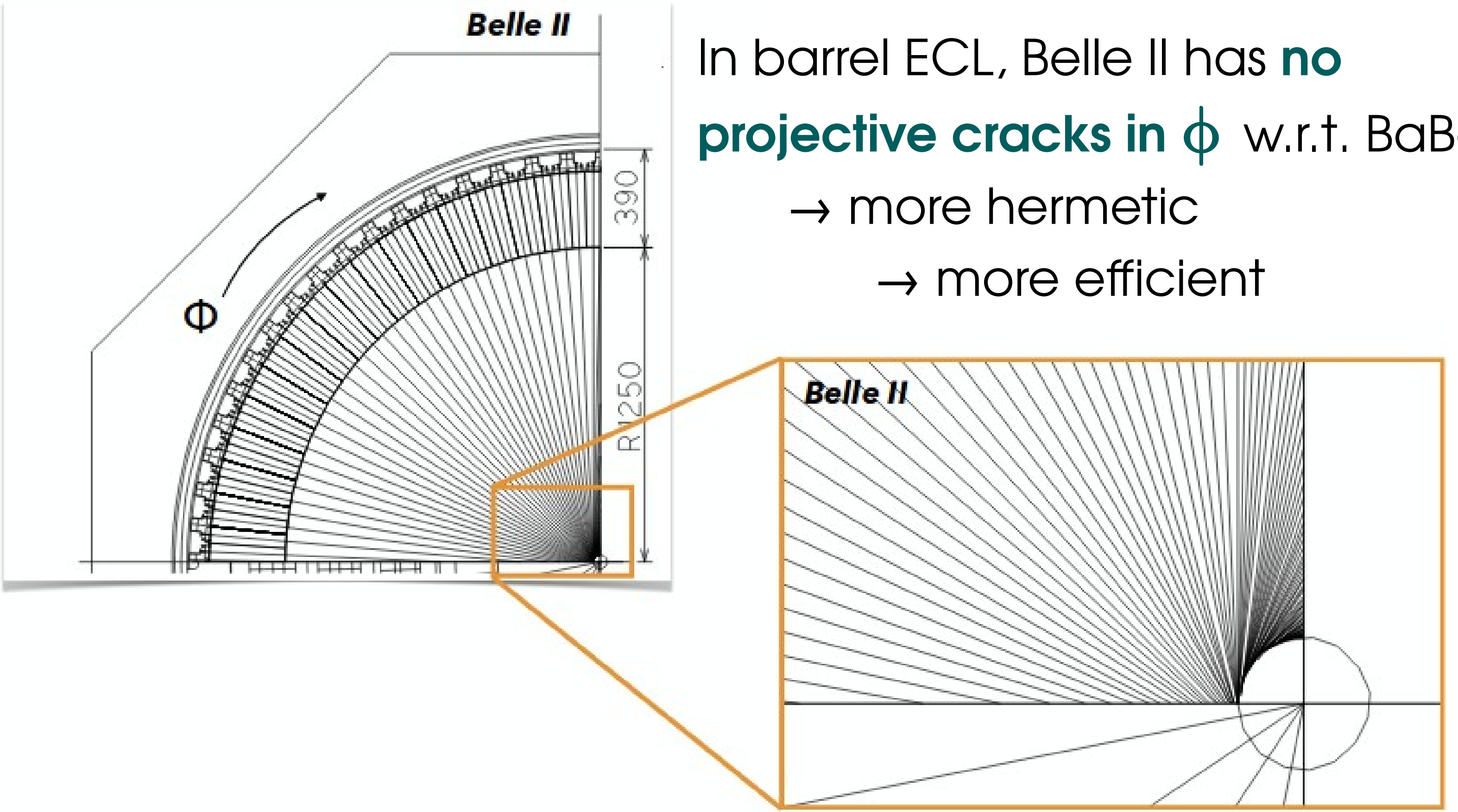
Backup slides

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
$\frac{\varepsilon_y}{\varepsilon_x}$ (%)	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

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

Electromagnetic Calorimeter (ECL)



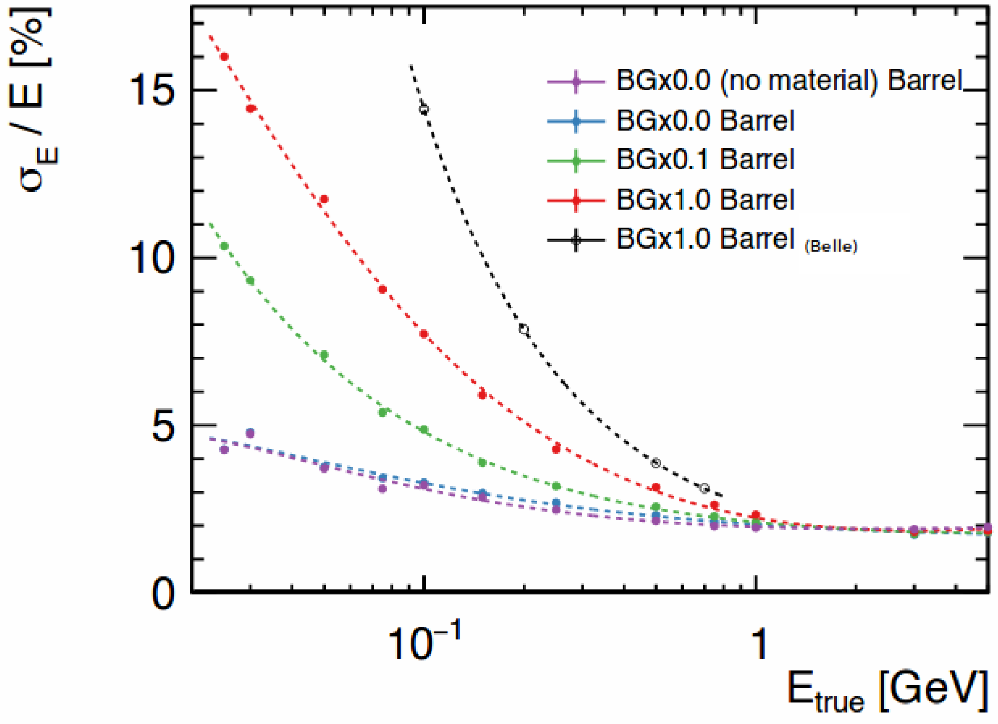
In barrel ECL, Belle II has **no projective cracks in ϕ** w.r.t. BaBar:

$\rightarrow$ more hermetic

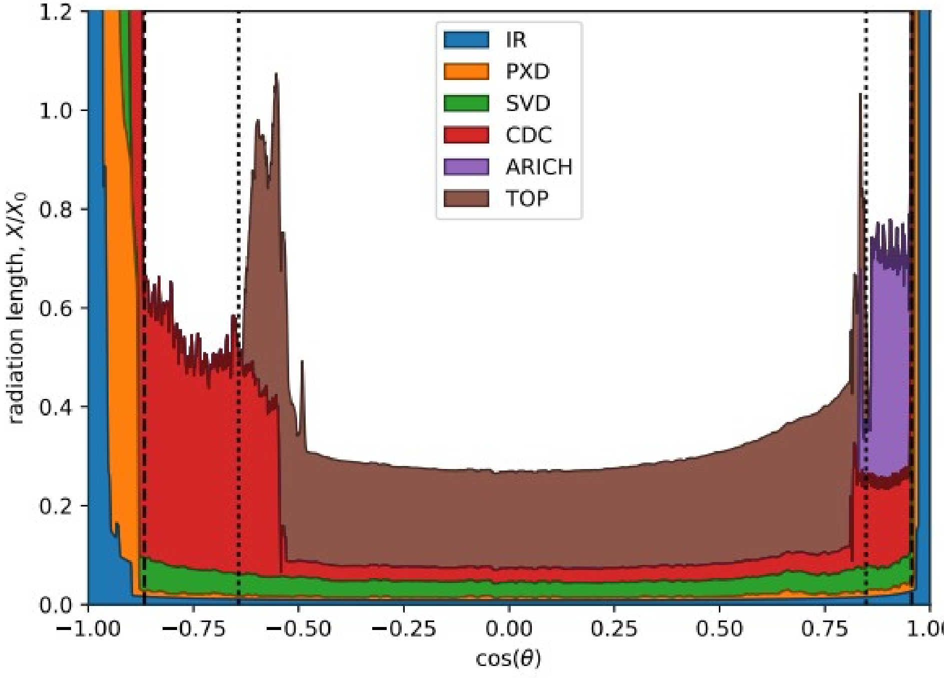
$\rightarrow$ more efficient

Electromagnetic Calorimeter (ECL)

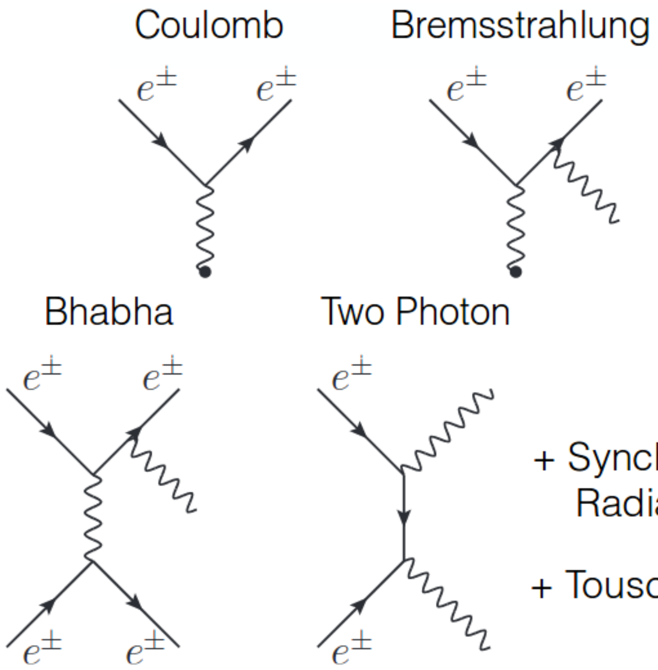
Energy resolution in Belle II barrel:



Material budget in front of ECL:

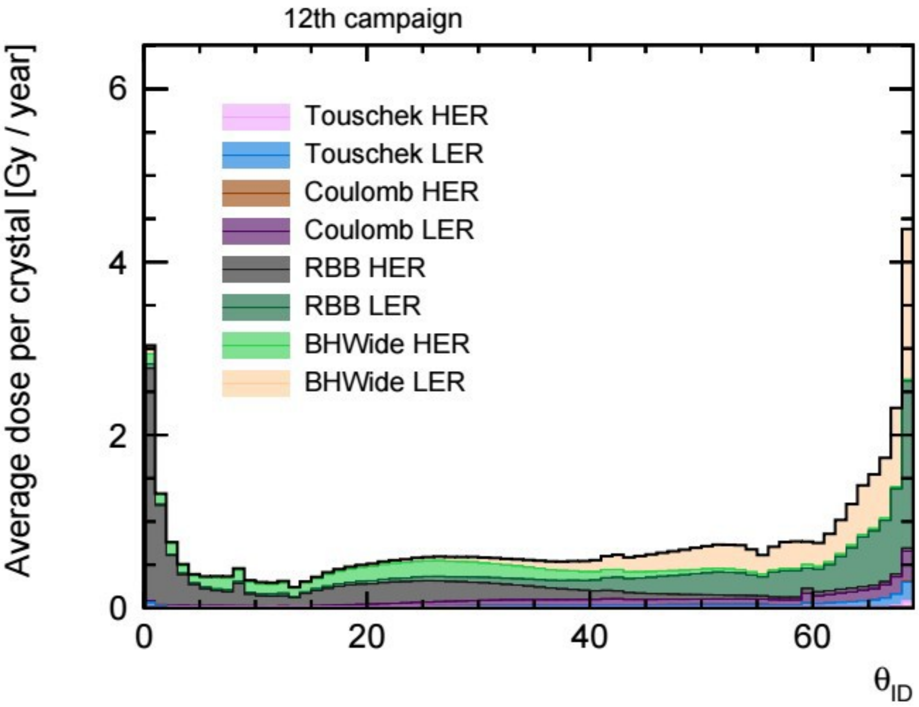


Beam background



+ Synchrotron Radiation

+ Touschek



Effects from beam background:

→ degrades calorimeter resolution.

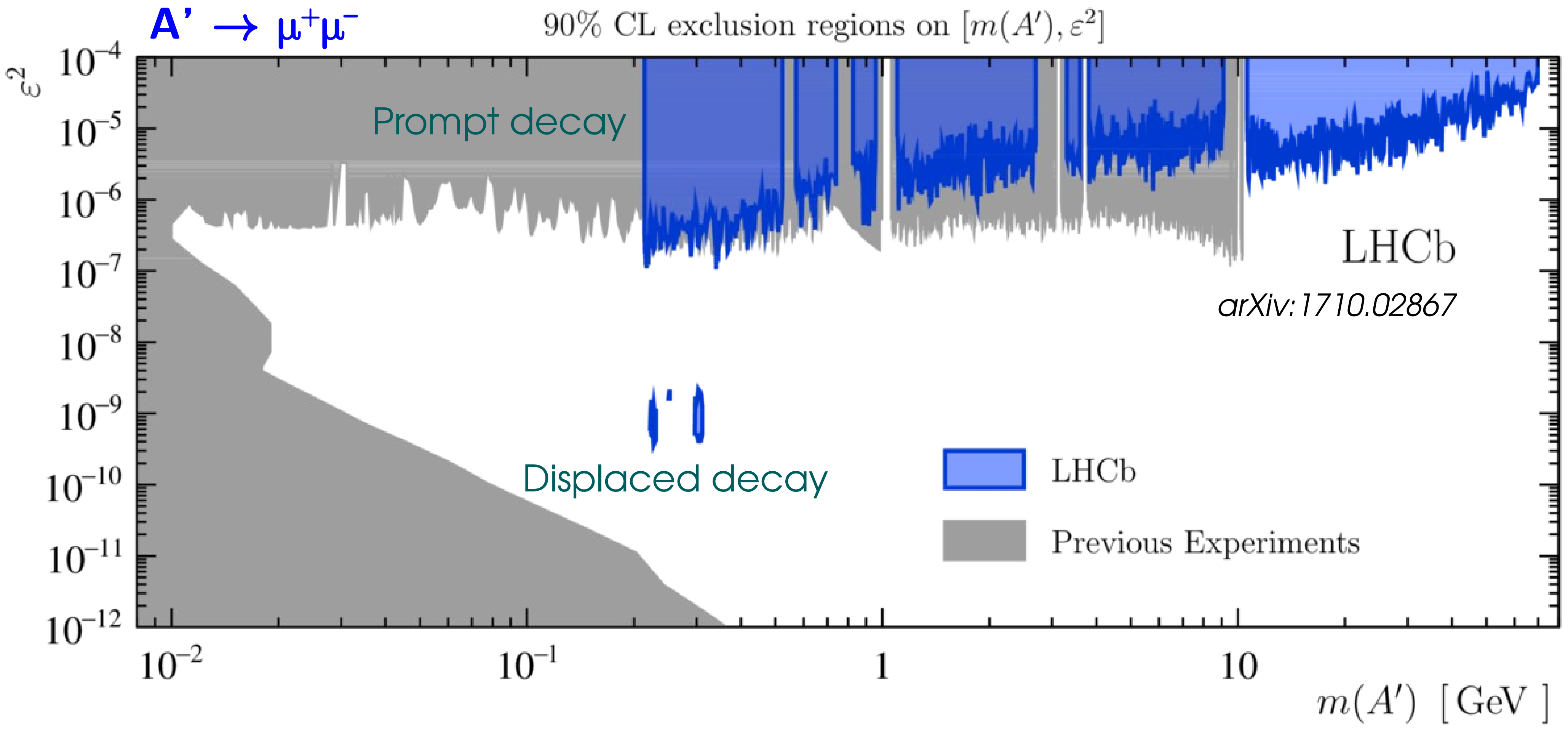
→ radiation damage.

→ pile-up and event size.

→ physics background

BEAST: dedicated systems for continuous beam background measurement and monitoring!

Dark Photon: muonic decay @ LHCb



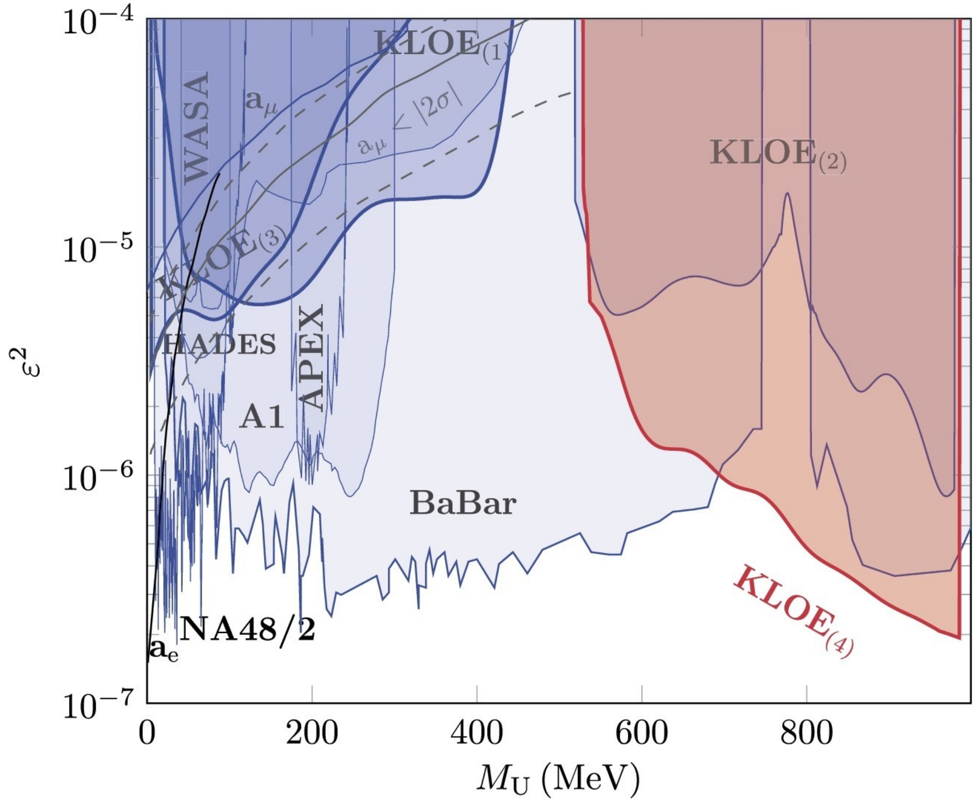
Dark Photon: hadronic decay

Very interesting final state...

- searched only by KLOE
  ($A' \rightarrow \pi^+\pi^-$)
- covered only the region $m_{A'} < 1$ GeV

... but quite challenging!

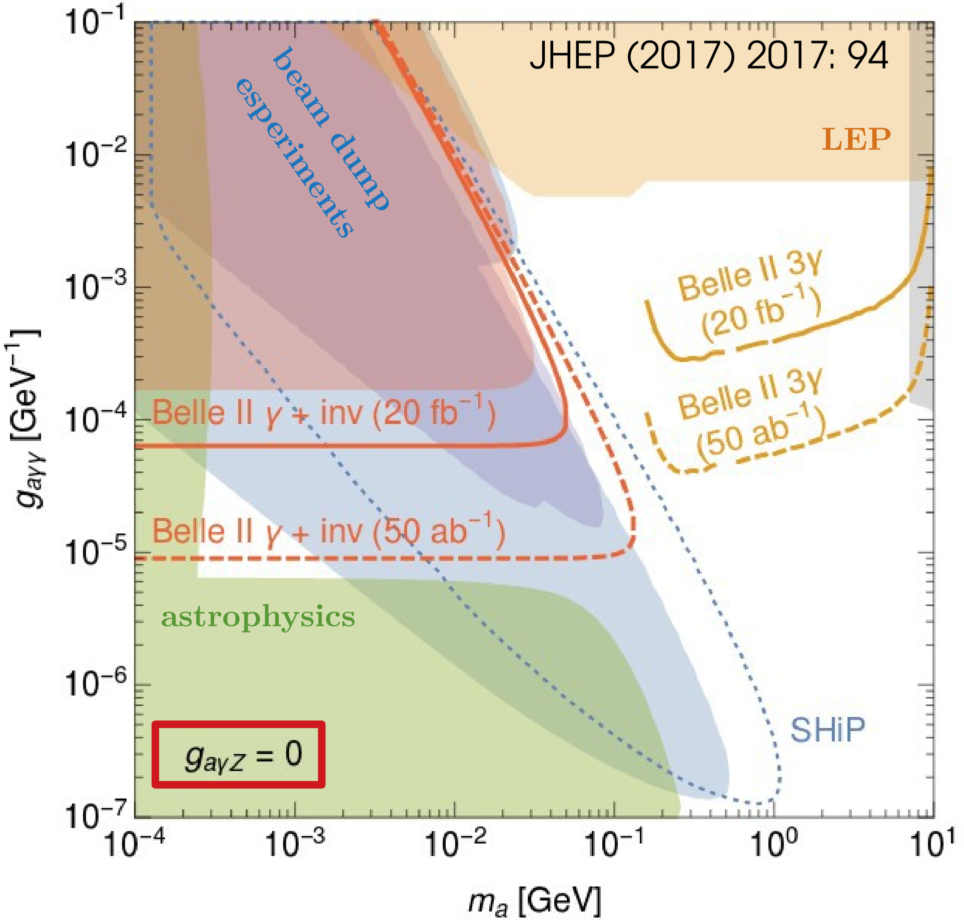
- due to large available phase space + hadronization, many final states must be considered
- background from hadronic events



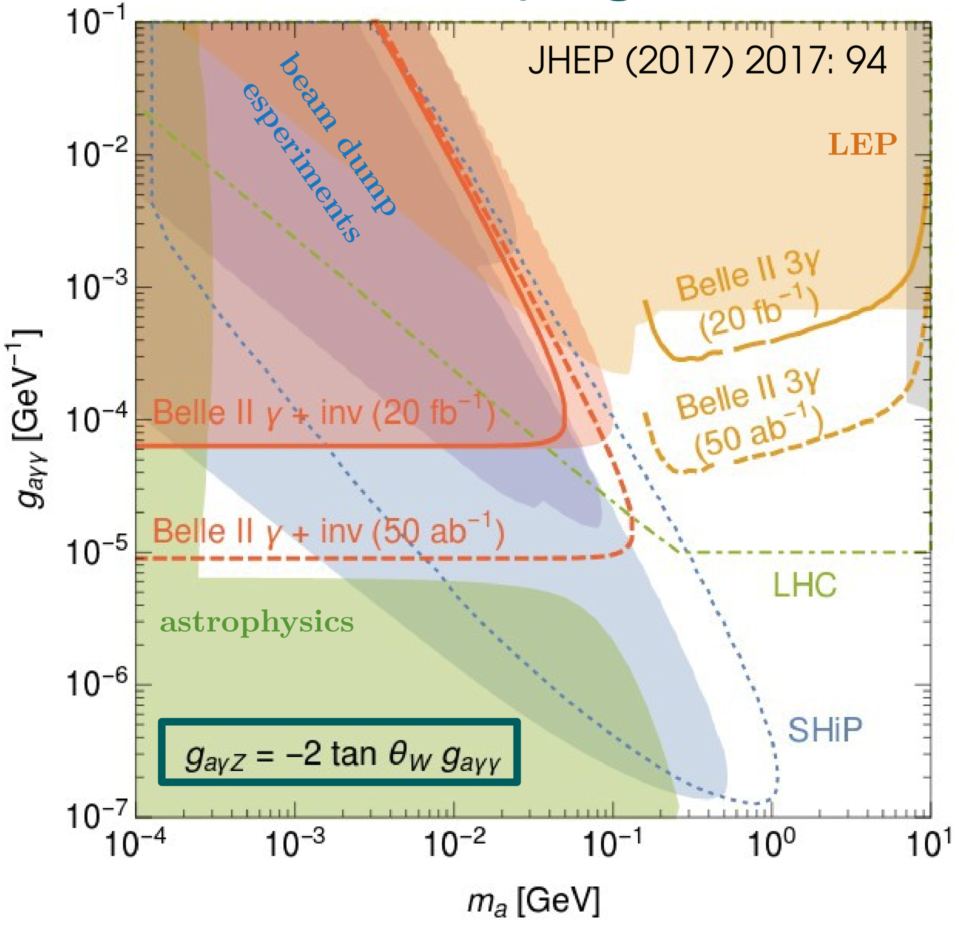
We aim to cover $m_{A'} > 1$ GeV

Axion-Like Particles (sensitivity)

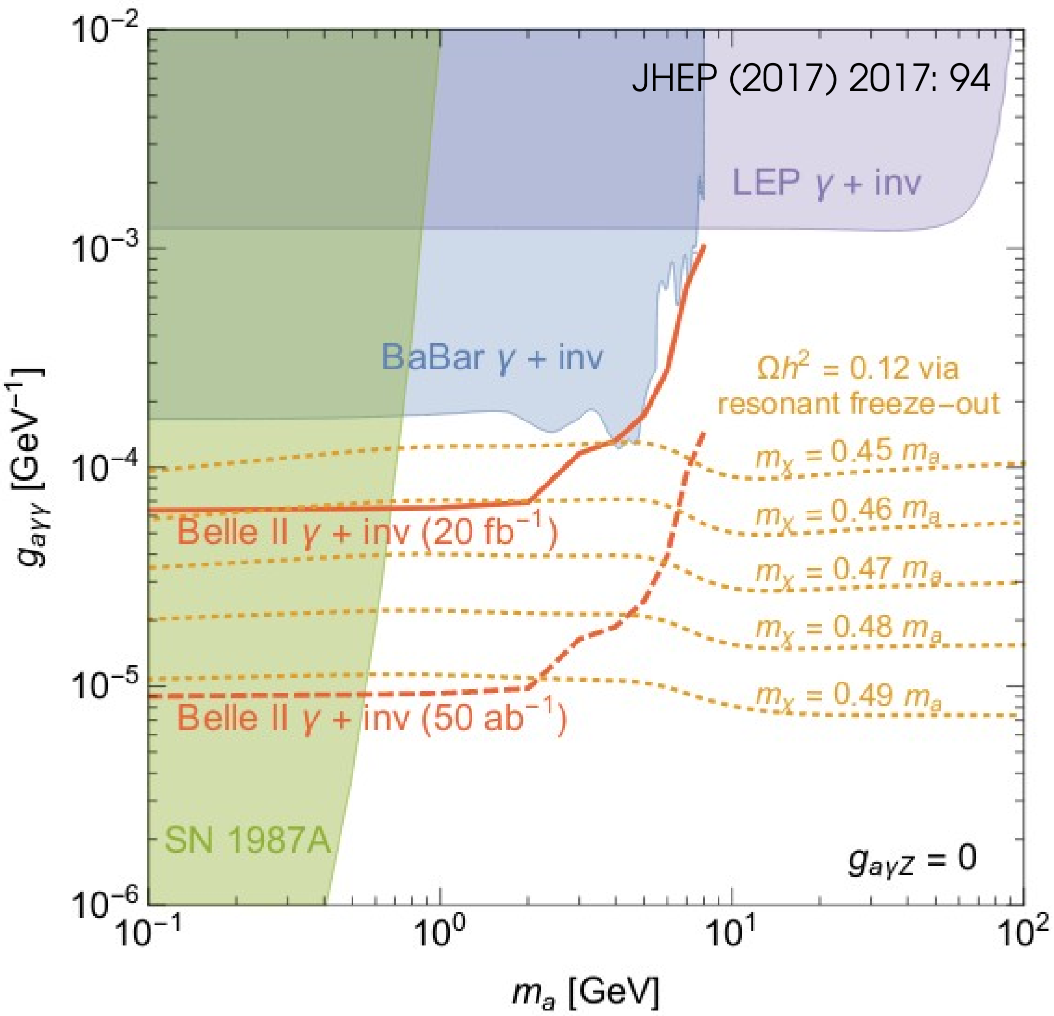
Only coupling to γ



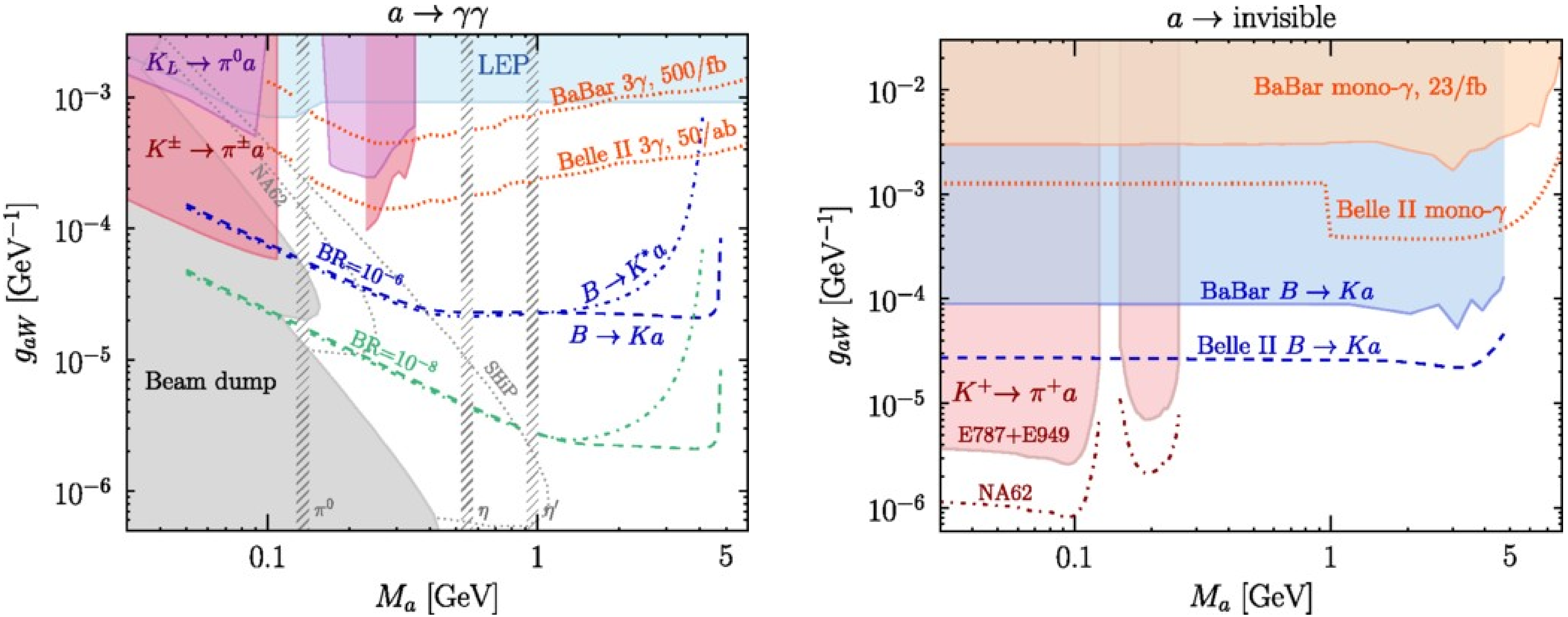
With coupling to Z



Axion-like Particles: invisible decay



Axion-like Particles from B decays



Izaguirre et al. (2017), *arXiv:1611.09355*