Dark Sector searches at Belle II: first results and future prospects

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INFN ROMA TRE

Belle II

New Physics in the Dark @ Roma Tre

21 February 2020

Outline

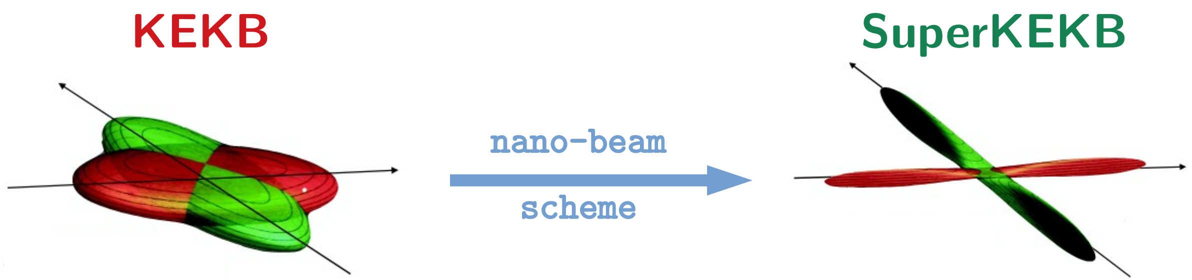
- ✔ Belle II and SuperKEKB
- ✔ Dark matter and dark mediators
- ✔ Search for an invisibly decaying Z'
- ✔ Review of other ongoing searches

SuperKEKB and Belle II

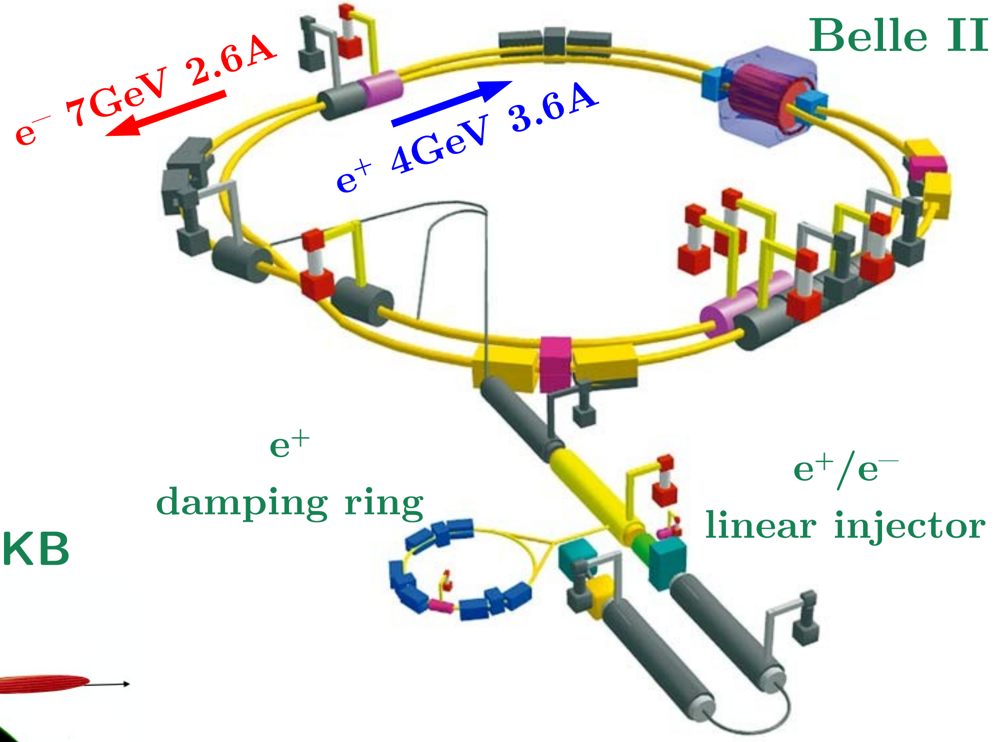
SuperKEKB: an Intensity Frontier machine

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

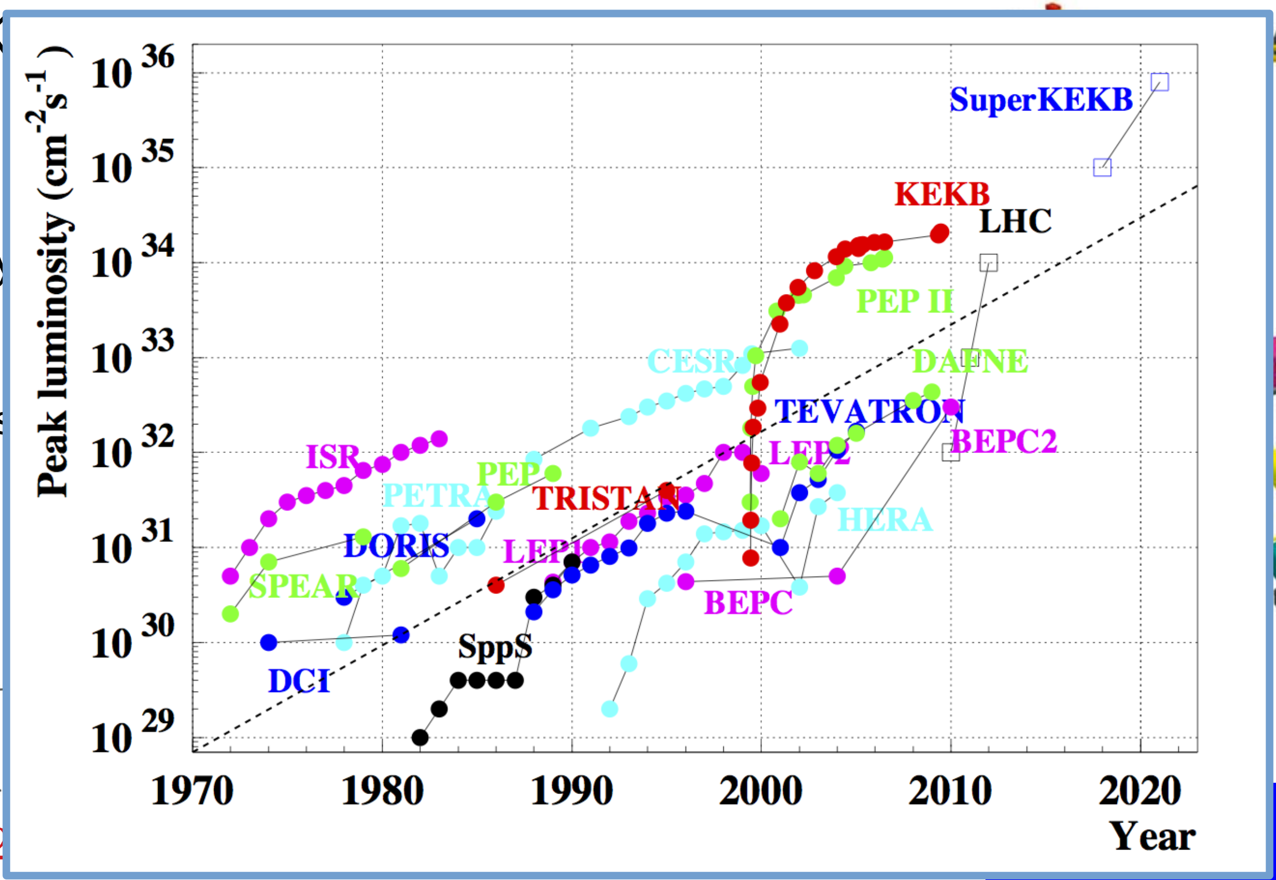
SuperKEK

located at

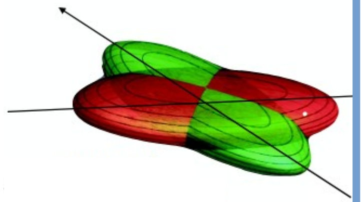
It's an asy

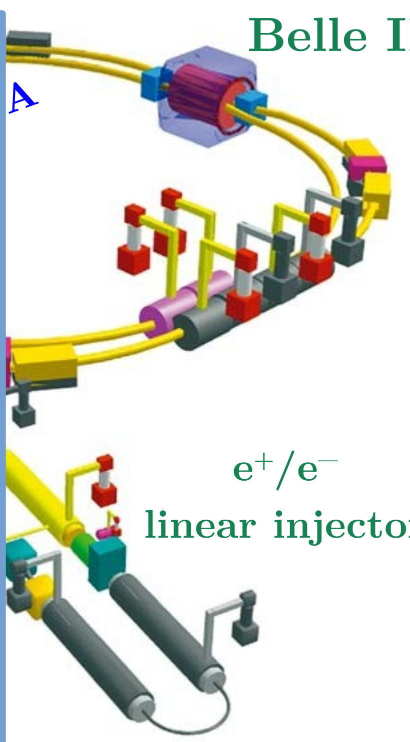
operating

(ϒ(4S), but poss



KEKB





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β^*_y (mm): ~ 5.9/5.9

β^*_y (mm): ~ 0.27/0.3

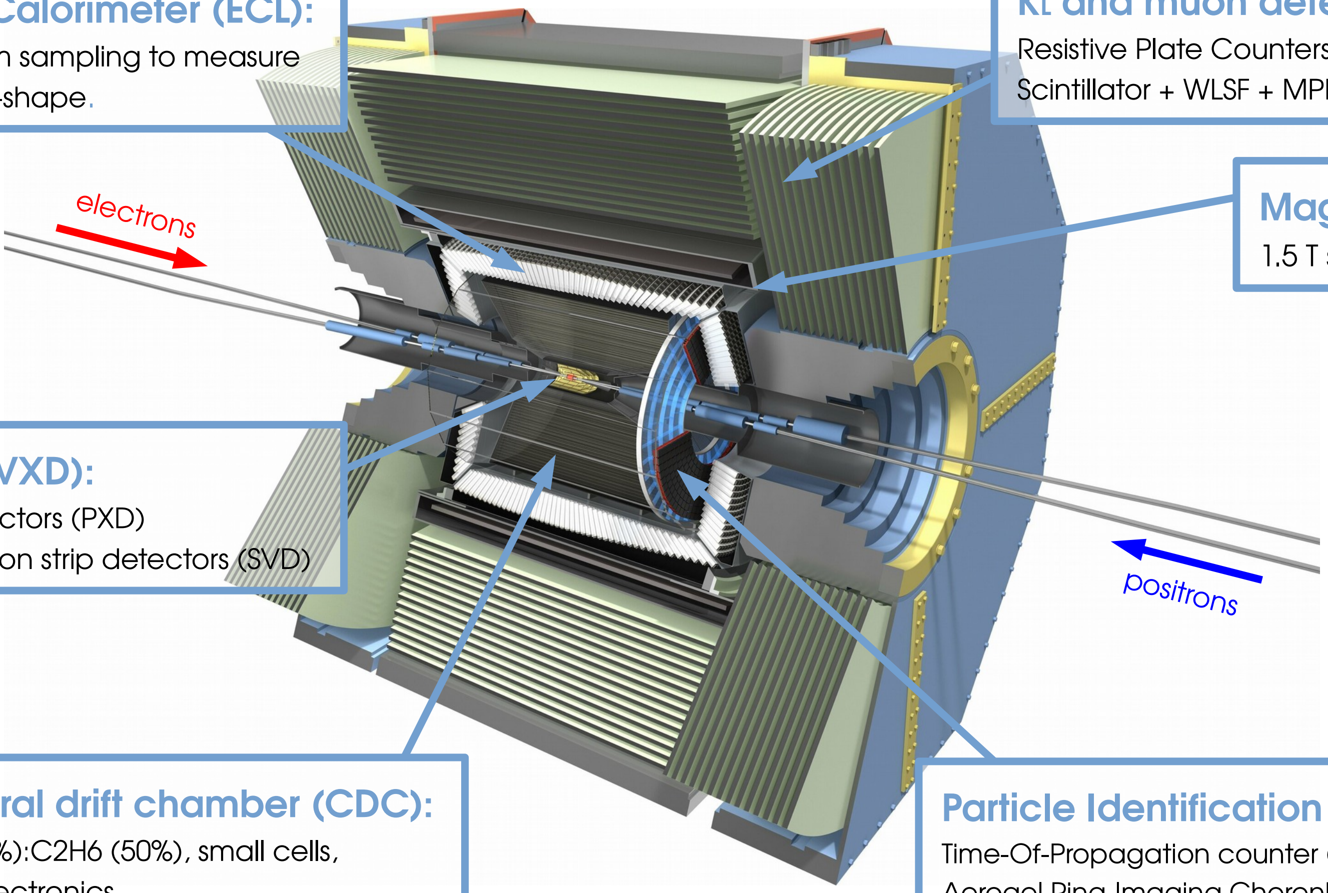
luminosity:

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

Belle II detector

Electromagnetic Calorimeter (ECL):
CsI(Tl) crystals, waveform sampling to measure time, energy, and pulse-shape.

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)



Magnet:
1.5 T superconducting

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

Trigger:
Hardware: $<$ 30 kHz
Software: $<$ 10 kHz

Central drift chamber (CDC):
He(50%):C2H6 (50%), small cells, fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

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.)	$10° < \theta_e^* < 170°$, $E_e^* > 0.15\,\text{GeV}$	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\text{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta_\gamma^* < 170°$, $E_\gamma^* > 0.15\,\text{GeV}$	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\text{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\text{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\text{GeV}$ in CDC, $\geq 1\ \gamma\ (E_\gamma > 0.5\,\text{GeV})$ 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.)	$W_{\ell\ell} > 0.5\,\text{GeV}/c^2$	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\text{GeV}/c^2$	AAFH

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

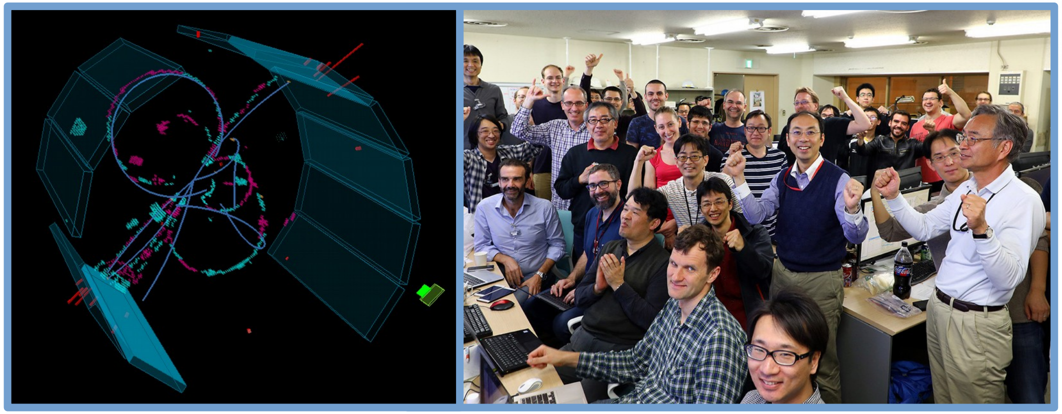
First period of data taking: Phase 2

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

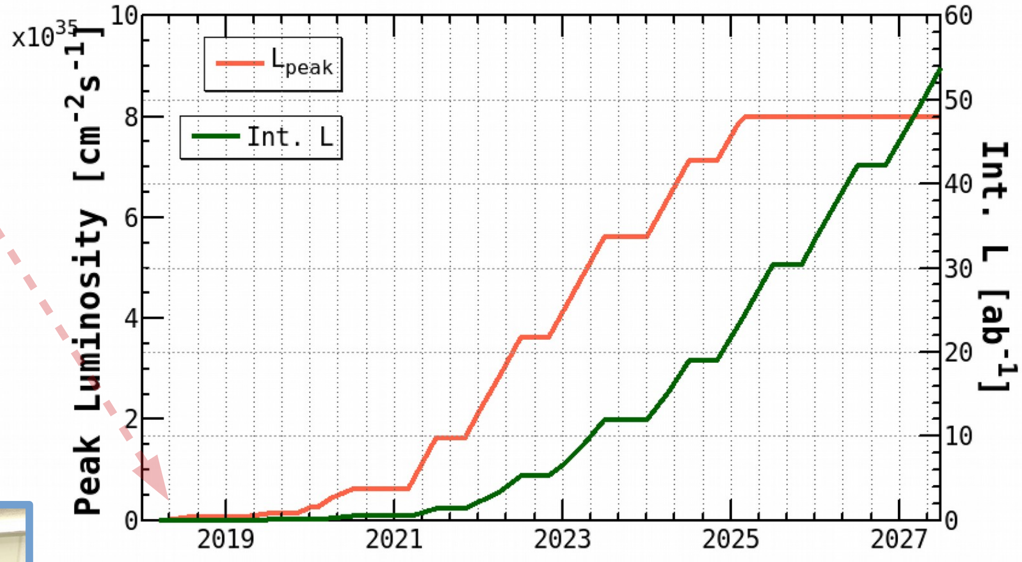
Belle II had partial **VXD detector**

Main goals:

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



First collisions: 26th April 2018

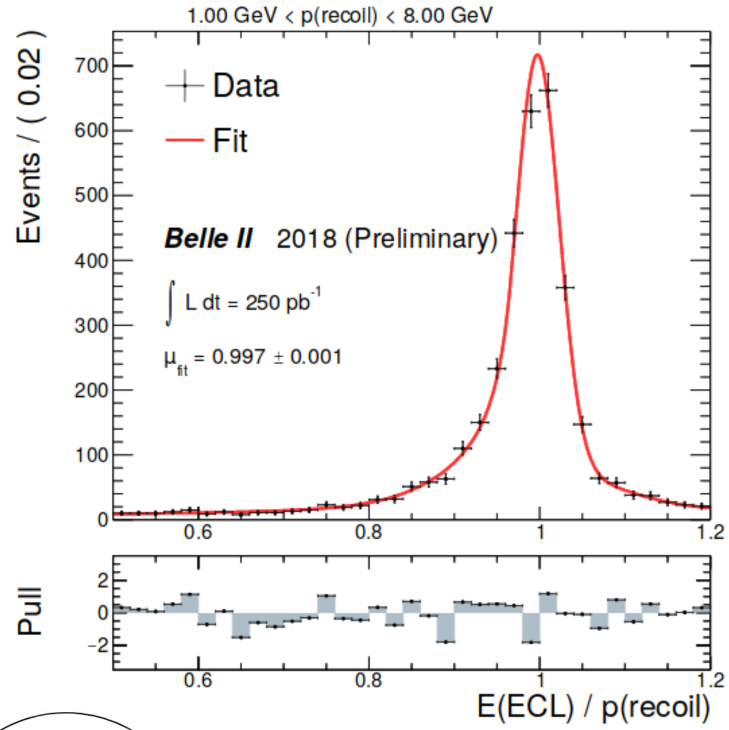


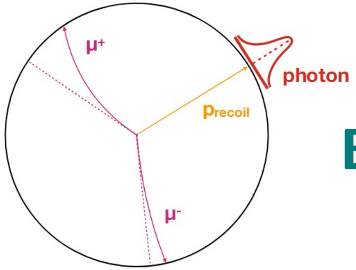
Phase 2:
0.5 fb^{-1}

Phase 3:
50 ab^{-1}

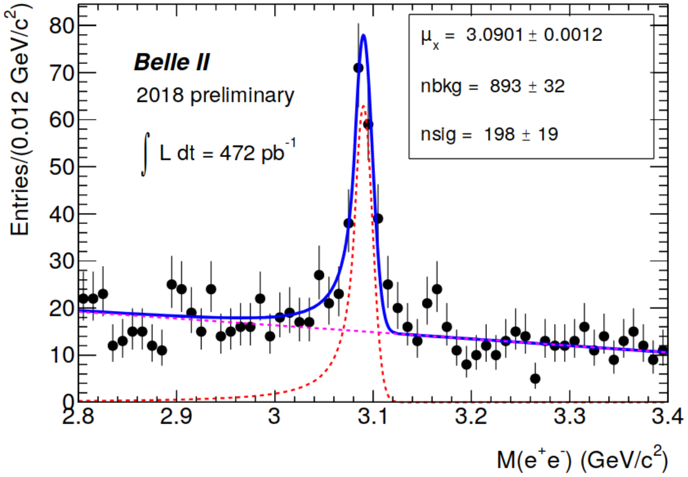
Instant luminosity achieved: $5.5 \cdot 10^{33}$ cm^{-2} s^{-1}

Highlights from Phase 2

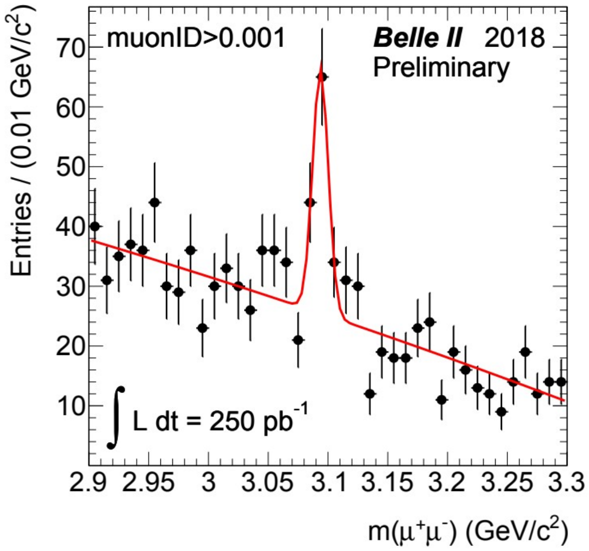




Excellent photon resolution



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

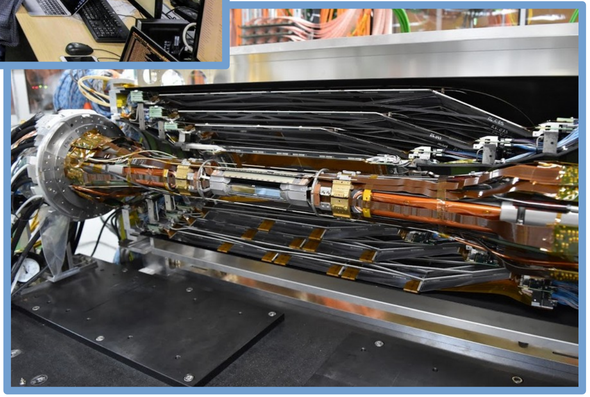


$J/\Psi \to \mu^+\mu^-$

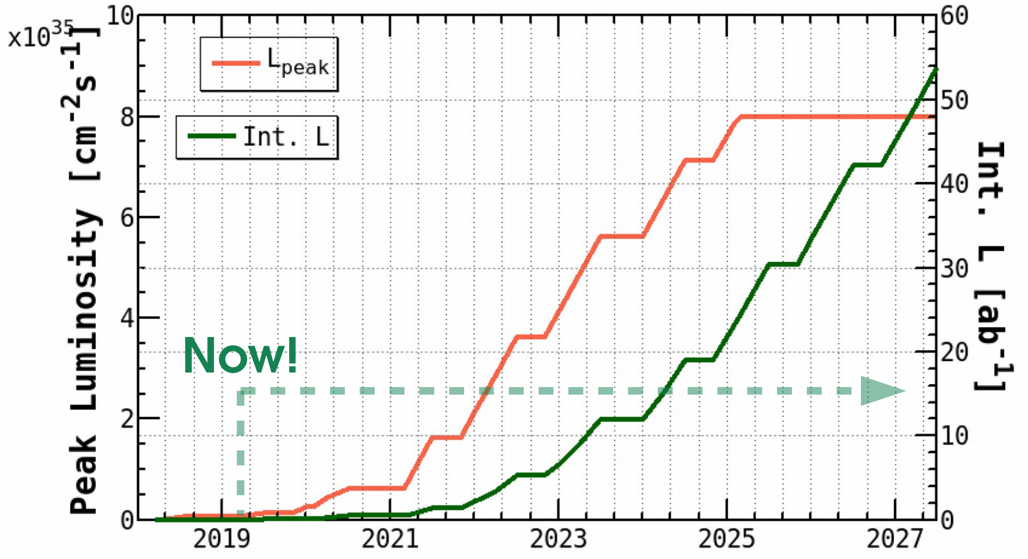
Phase 3

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

New first collisions (25th March 2019)



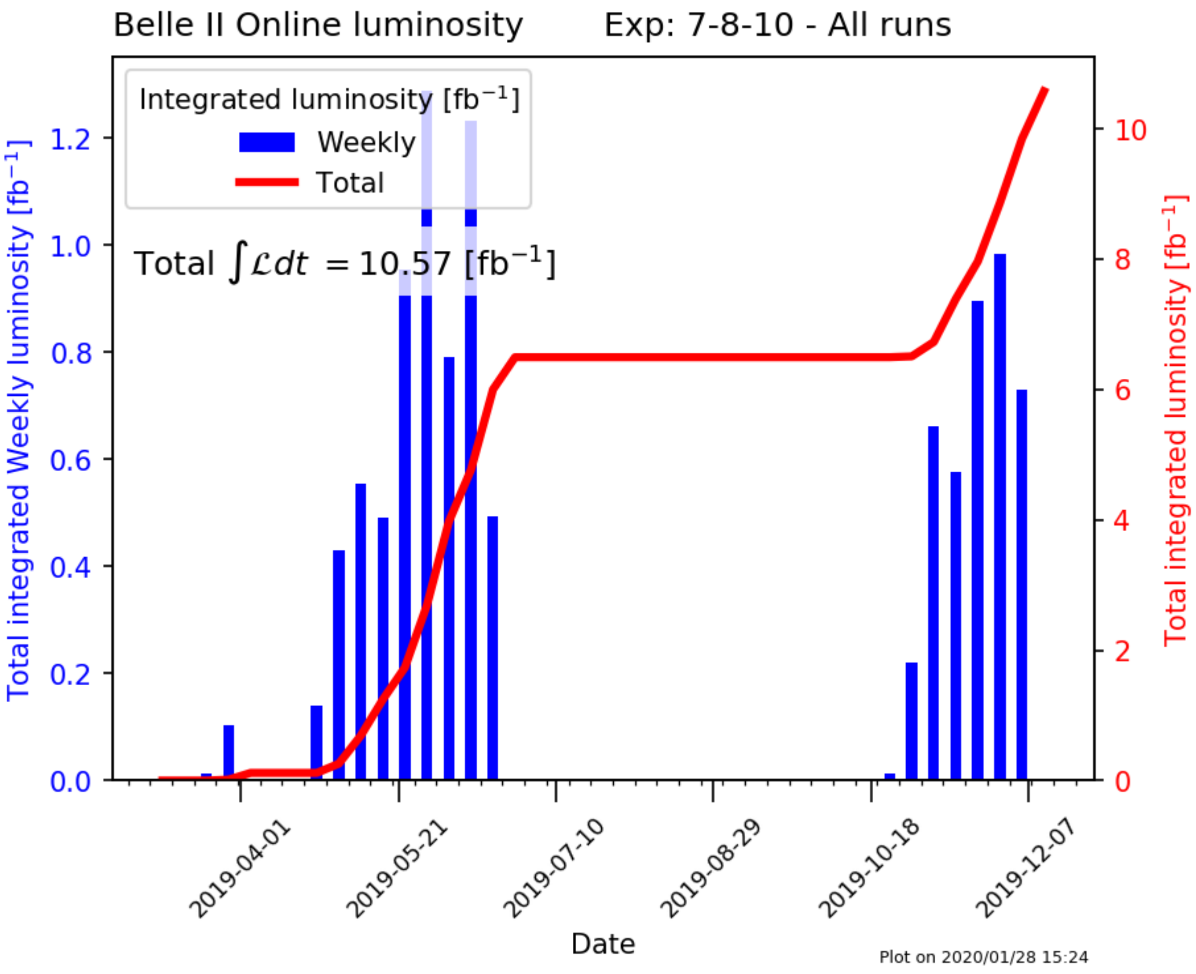
Full angular coverage with PXD and SVD installed



Phase 2: 0.5 fb^{-1}

Phase 3: 50 ab^{-1}

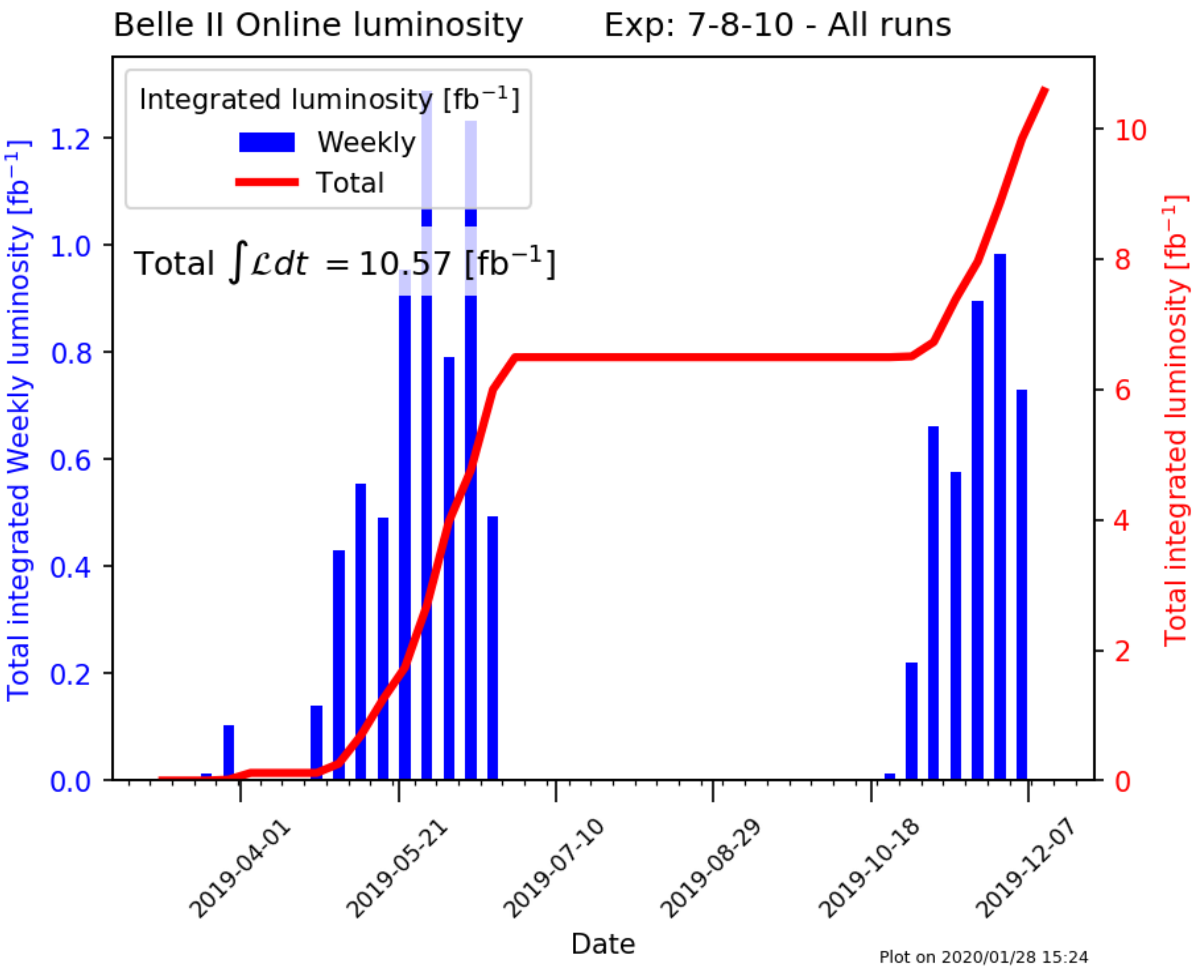
Phase 3



We collected **10.5 fb^{-1}** of data in 2019.

First physics results based on 2019 data will be presented at Moriond 2020.

Phase 3



We collected **10.5 fb^{-1}** of data in 2019.

First physics results based on 2019 data will be presented at Moriond 2020.

First physics results based on 2018 data are already available!

Dark Sector

Dark Matter

It is “dark”.

It may exists...

A lot of experimental technique to probe the Dark Matter existance:

- production at colliders;
- indirect astronomic searches;
- direct underground searches.

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A lot of experimental technique to probe the Dark Matter existance:

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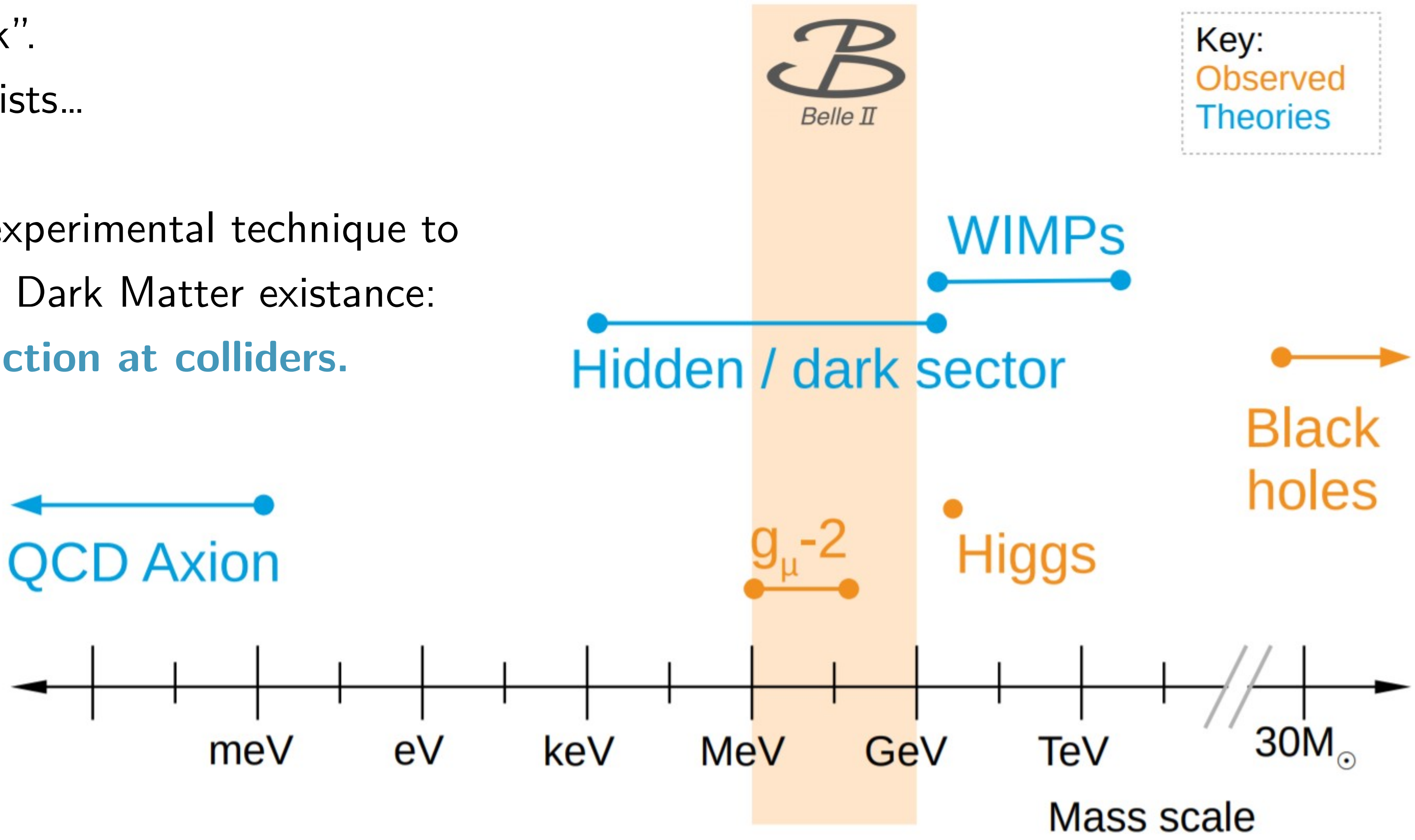
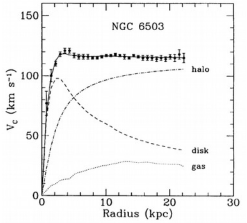
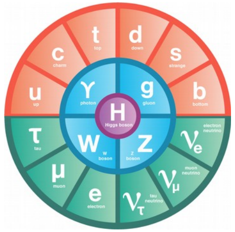


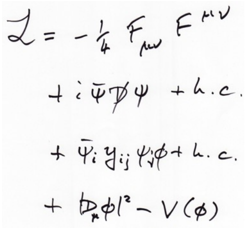
Dark Matter coupling to SM



Dark Matter

X

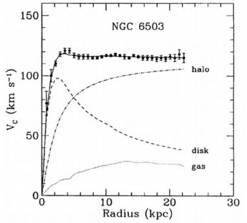




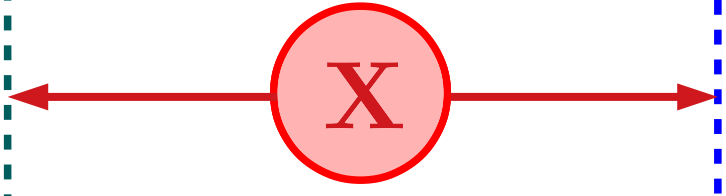
Standard Model

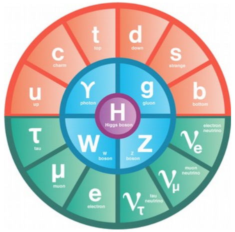
Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

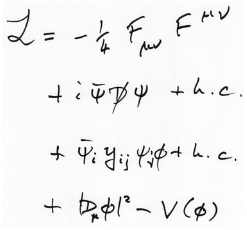
Dark Matter coupling to SM



Dark Matter







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

Vector portal $\rightarrow$ Dark Photon

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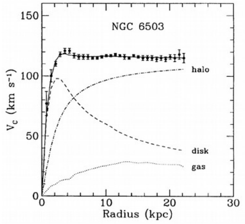
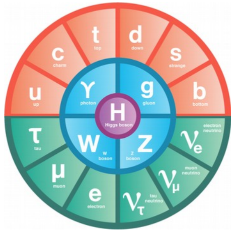
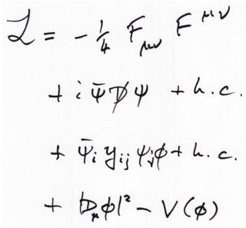


Dark Matter

X





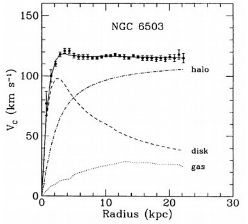
Standard Model

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

Vector portal → Dark Photon

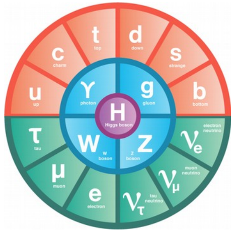
Scalar portal → Dark Higgs/Scalars

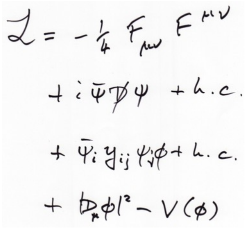
Dark Matter coupling to SM



Dark Matter

X





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Pseudoscalar portal → Axion-Like Particles

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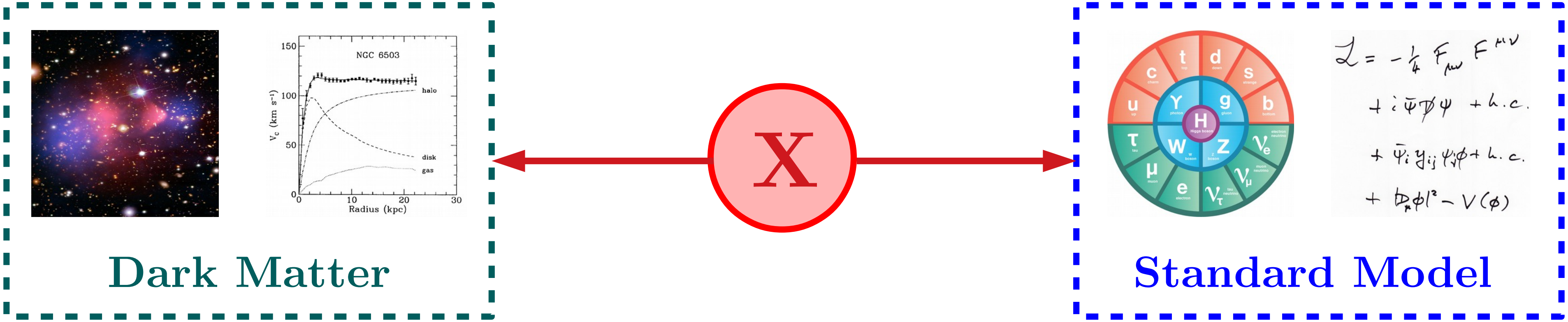


Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

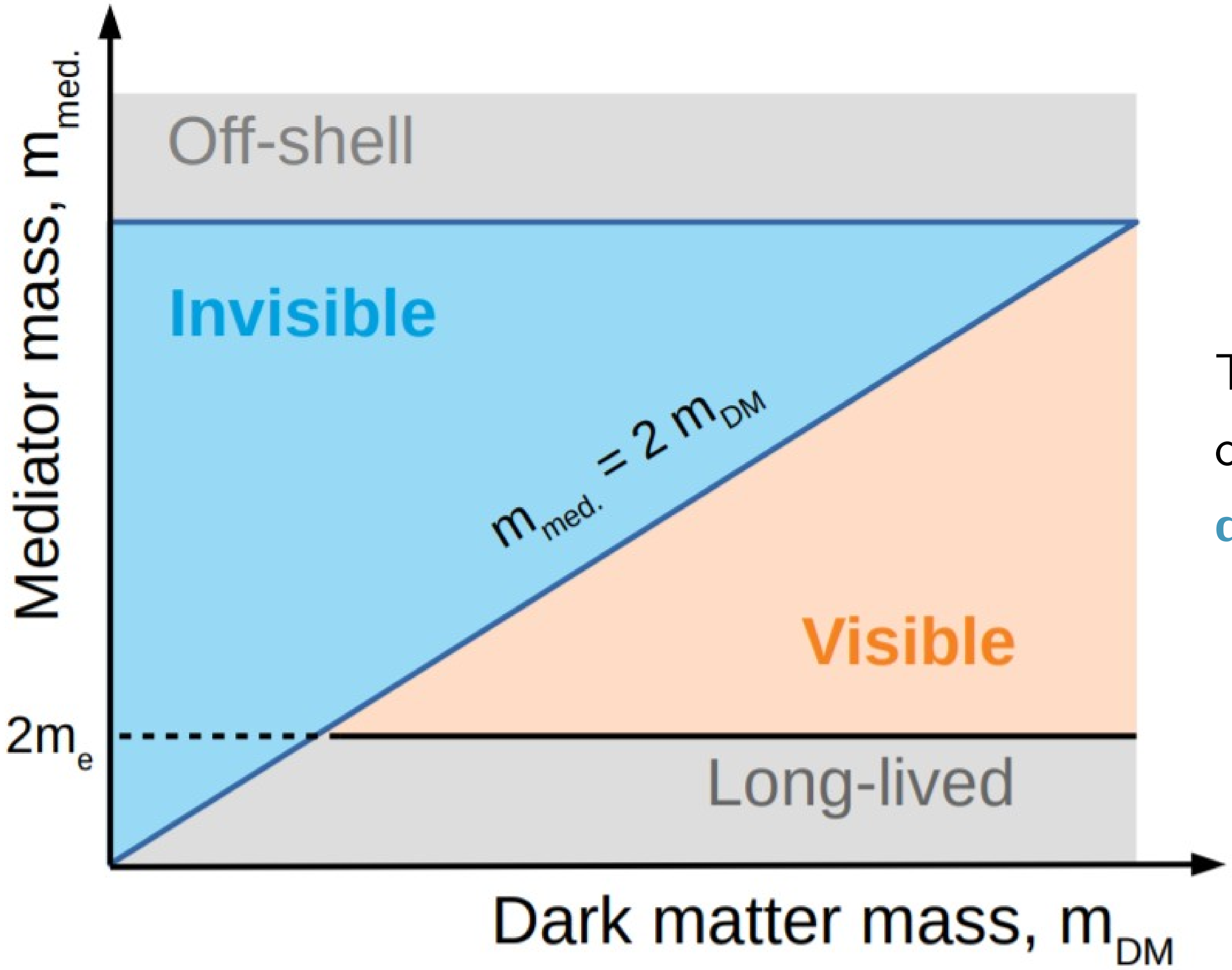
Vector portal $\rightarrow$ Dark Photon

Scalar portal $\rightarrow$ Dark Higgs/Scalars

Pseudoscalar portal $\rightarrow$ Axion-Like Particles

Neutrino portal $\rightarrow$ Sterile Neutrinos

A rule of thumb...



The masses of the mediator and of the DM candidates lead to **different type of searches**.

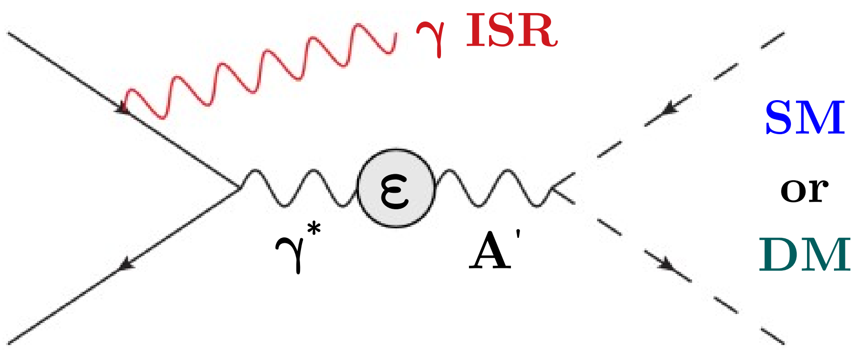
Search for an invisibly decaying Z’

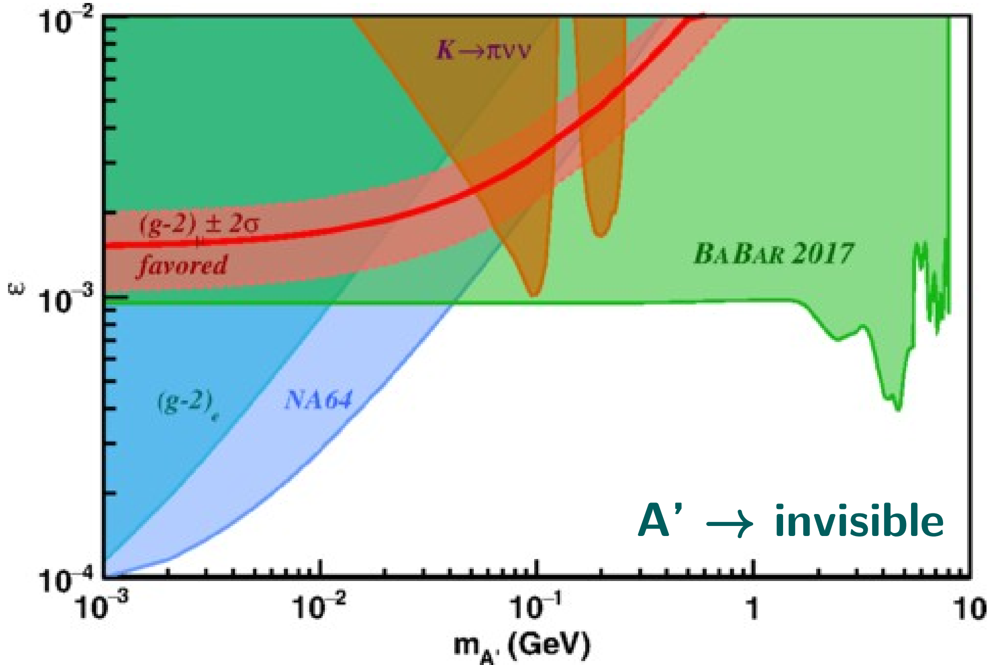
Dark Photon

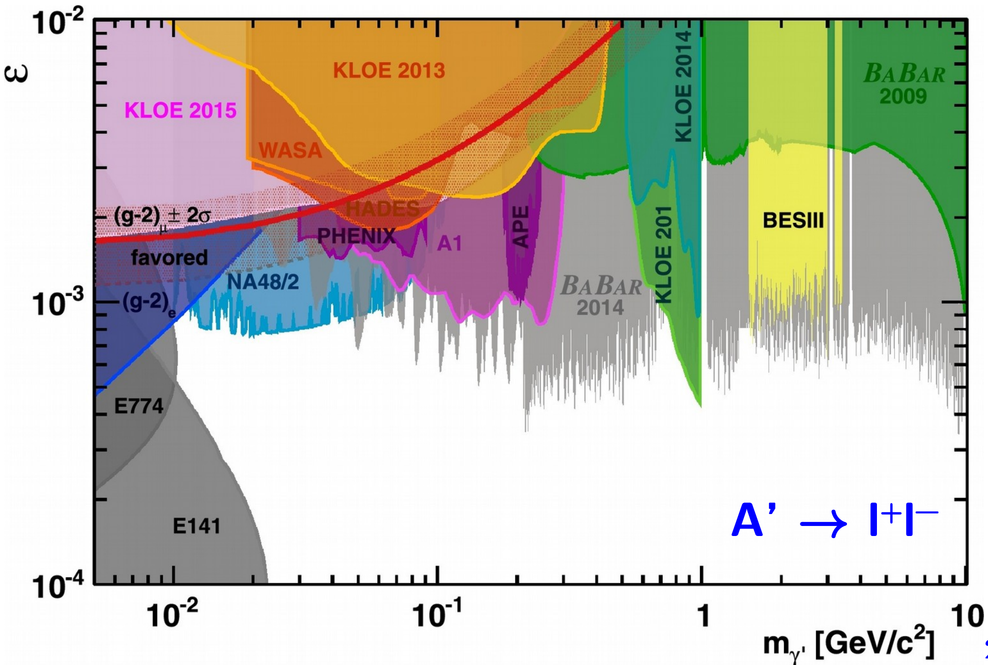
A massive Dark Photon **A'** can mix with SM with coupling strength ε:

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

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





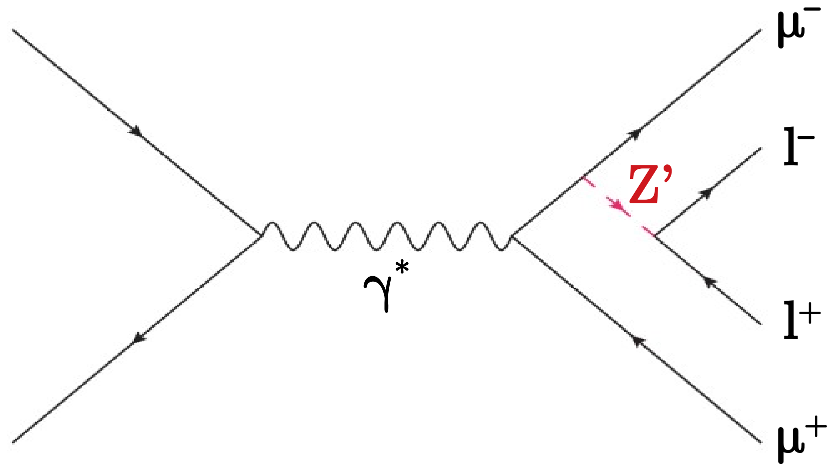


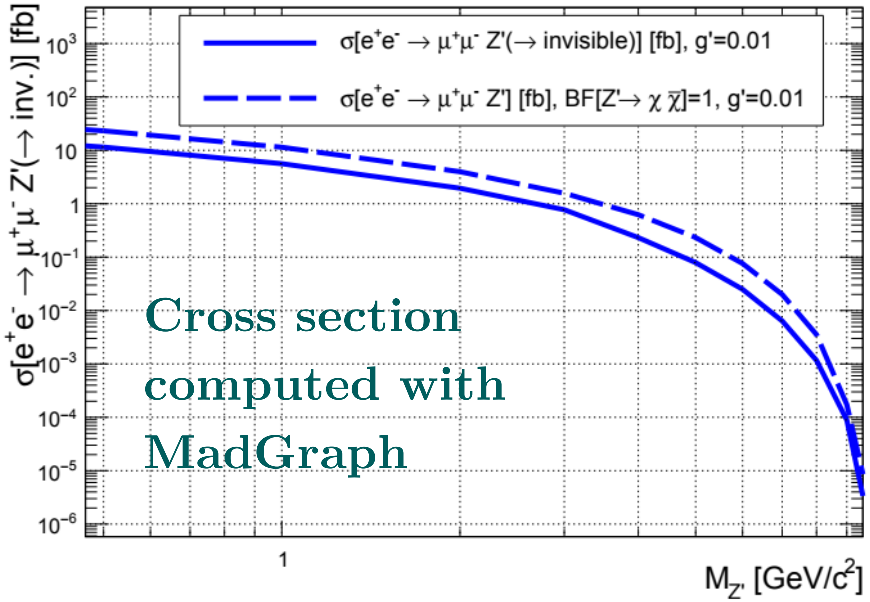
A different "Dark Photon": $L_\mu - L_\tau$ model

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*





Interesting to be studied because the existance of such kind of boson could explain some of the current anomalies:

$(g\text{-}2)_\mu$ $R(D^{(*)})$ $R(K^{(*)})$

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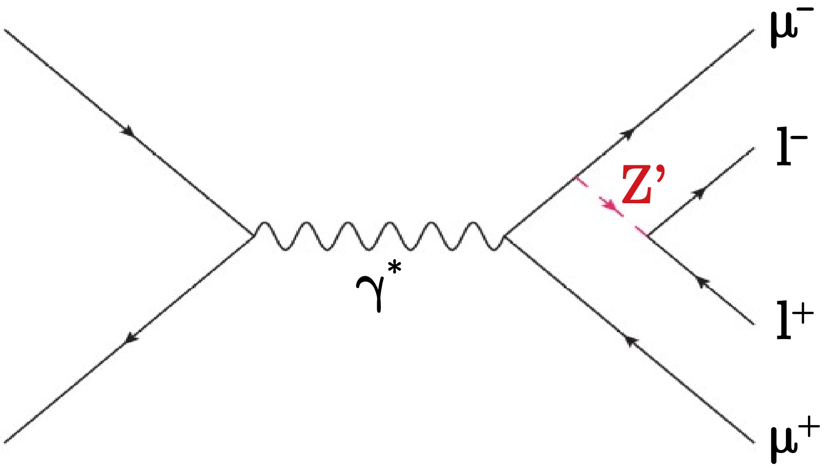

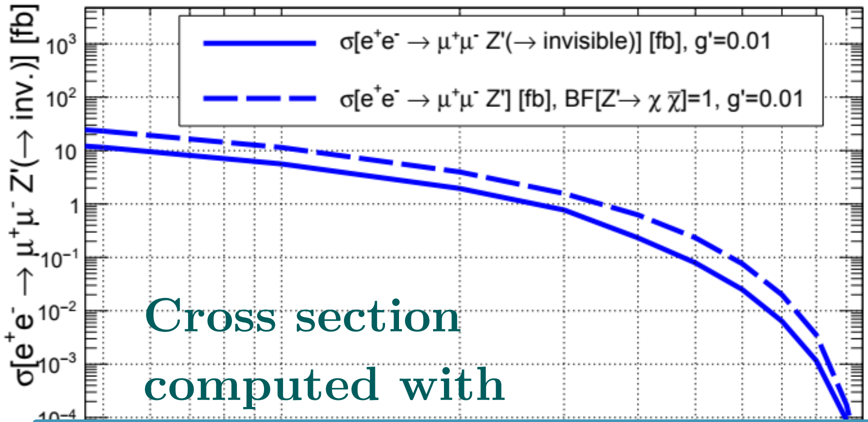

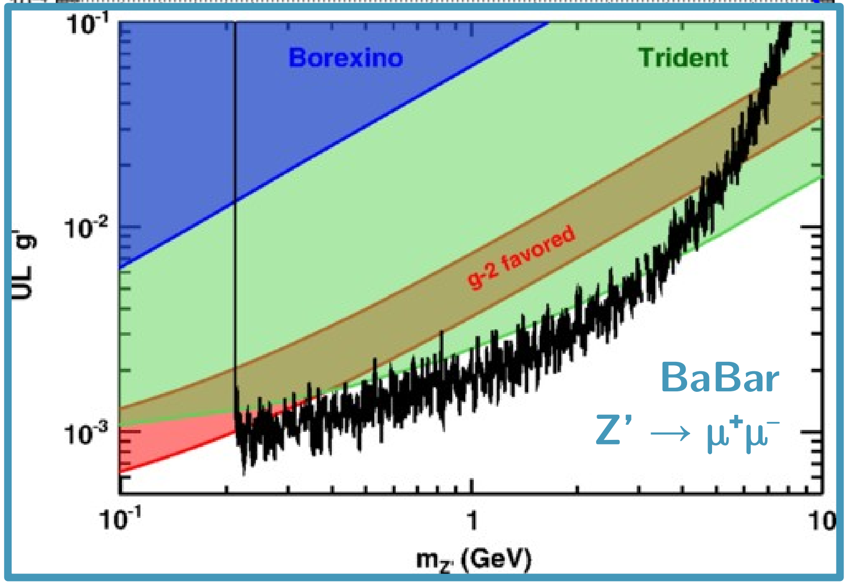

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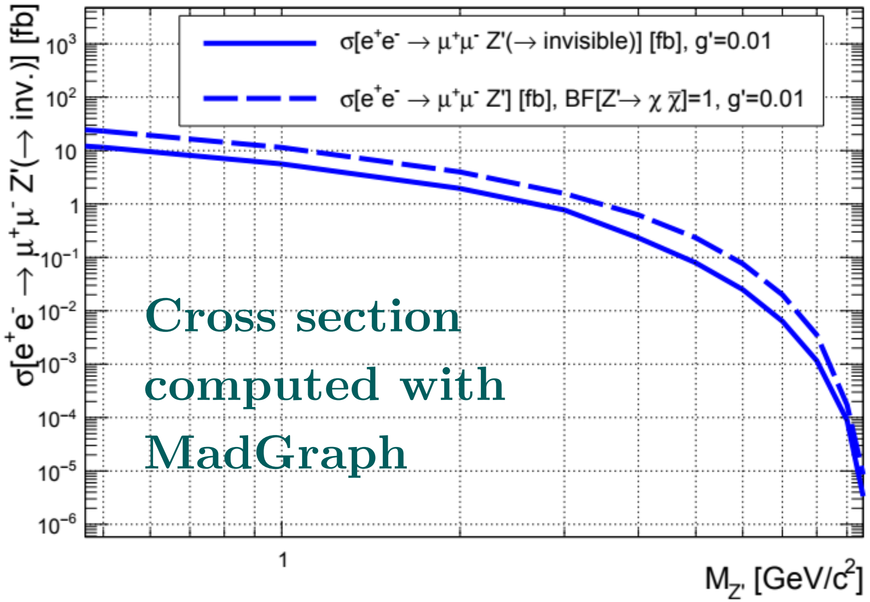
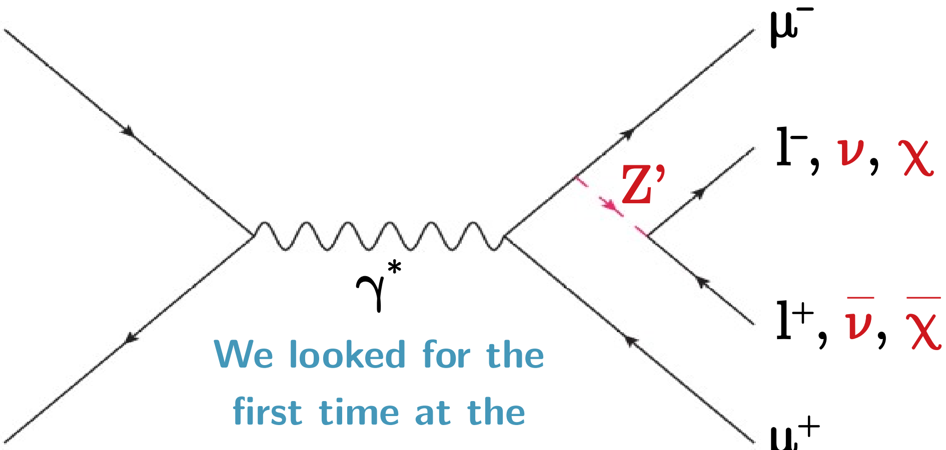




We looked for the first time at the invisible final state!

Branching ratios to invisible:

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

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

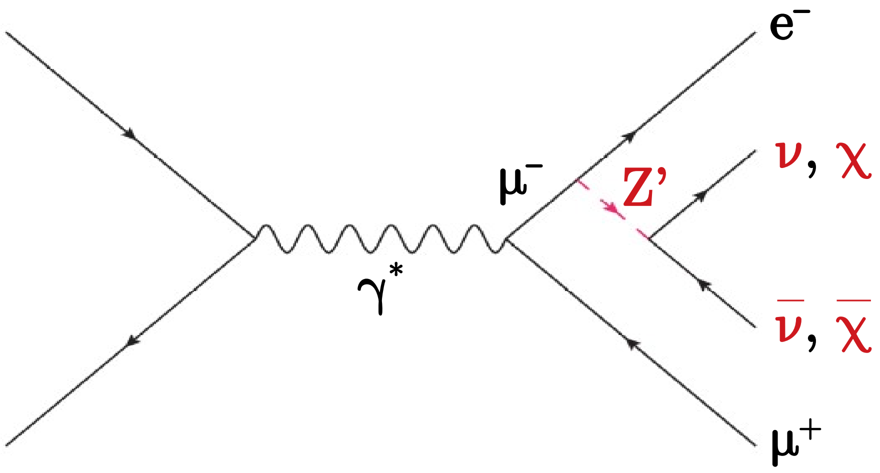
$M_{Z'} > 2M_\tau \rightarrow \Gamma(Z' \rightarrow \text{inv.}) \sim 1/3$

And why not considering a LFV Z'?

We considered only the $e-\mu$ coupling.

We considered only the invisible decay.

I. Galon et al., arXiv:1610.08060



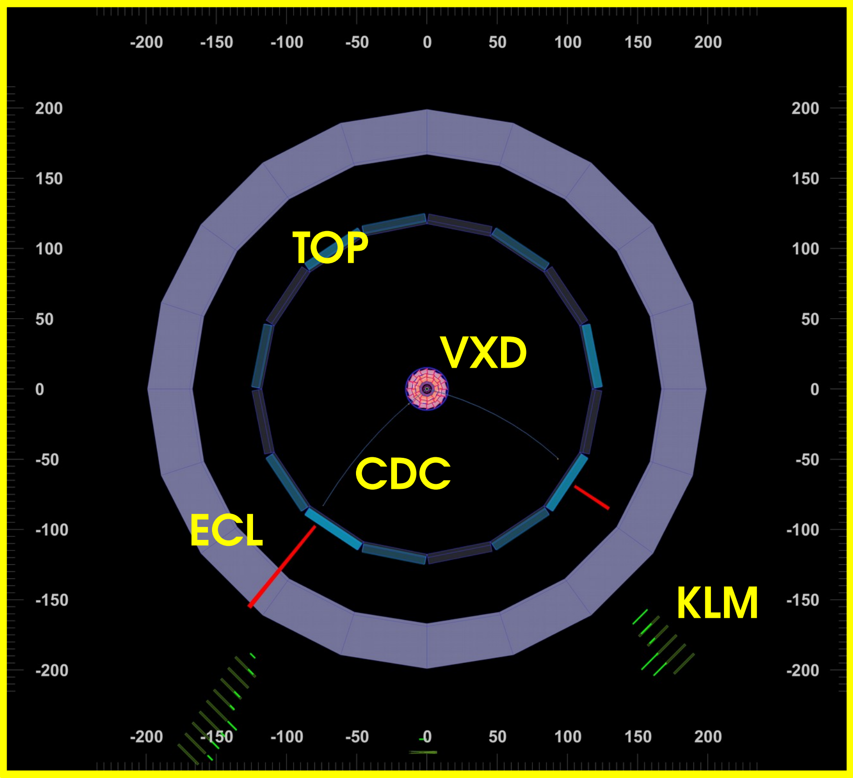
Unfortunately, the model we were using showed some issues (too large width for the Z', etc.).

We decided to drop the signal model and we opted for a model-independent search!

Z’ → invisible: analysis strategy

Invisible decay: reconstruct the recoil mass w.r.t. a muon pair (electron-muon pair) and look for a peak in the recoil mass spectrum.

Additionally: ~ nothing in the rest of the event.



Belle II transverse plane: event display of a reconstructed event from **Phase 2 data**

Belle II, arXiv:1912.1127 (submitted to PRL)

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Expected background events:

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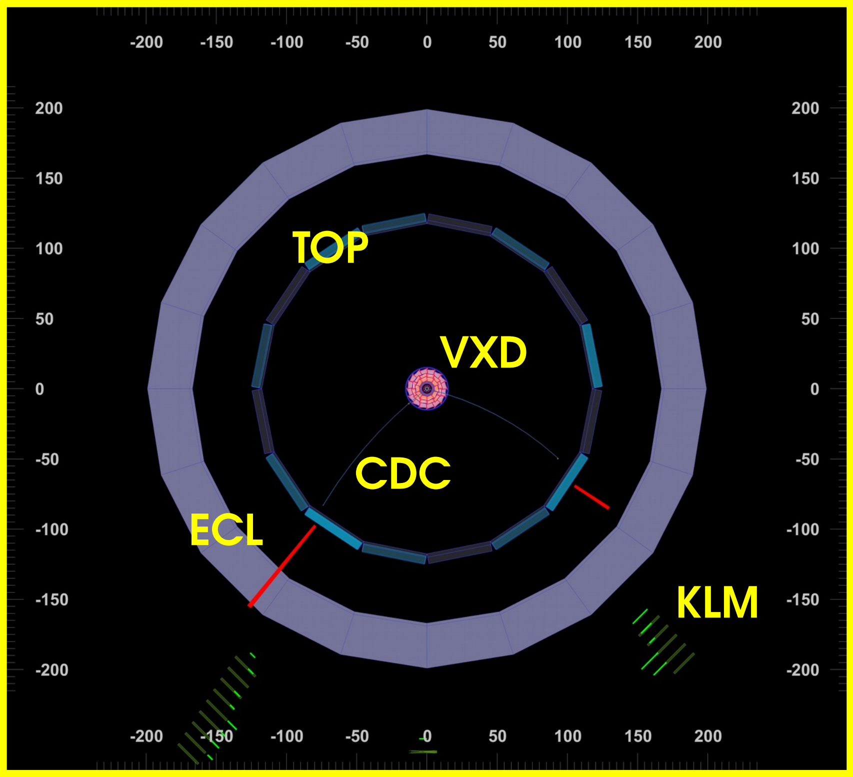
- $e^+ e^- \to e^+ e^- \mu^+ \mu^-$



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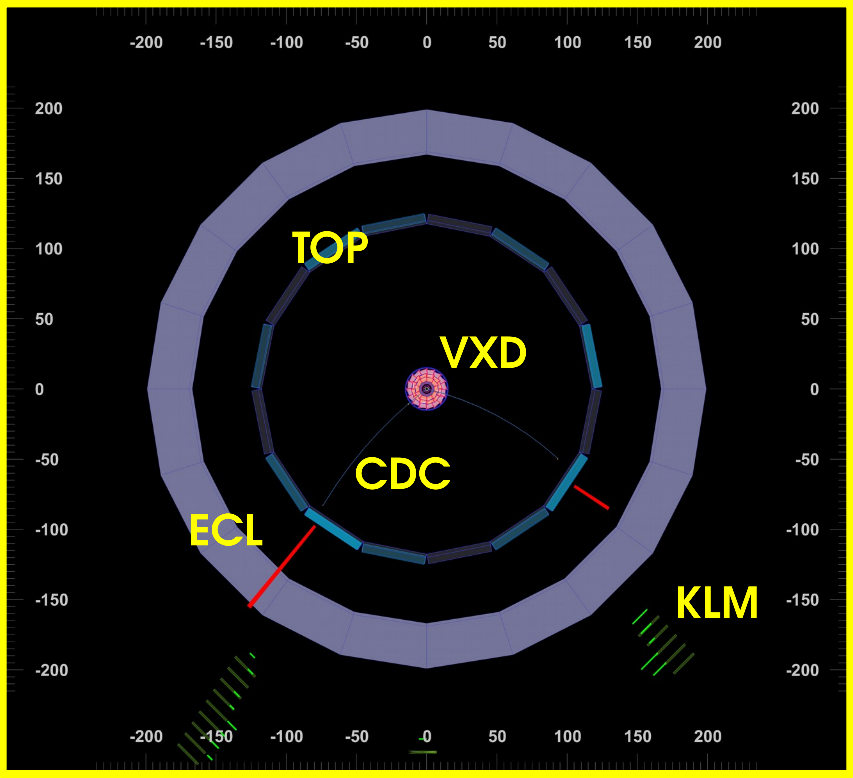
We optimized the selections for the "standard" Z';
we applied (almost) the same selections for the LFV case.



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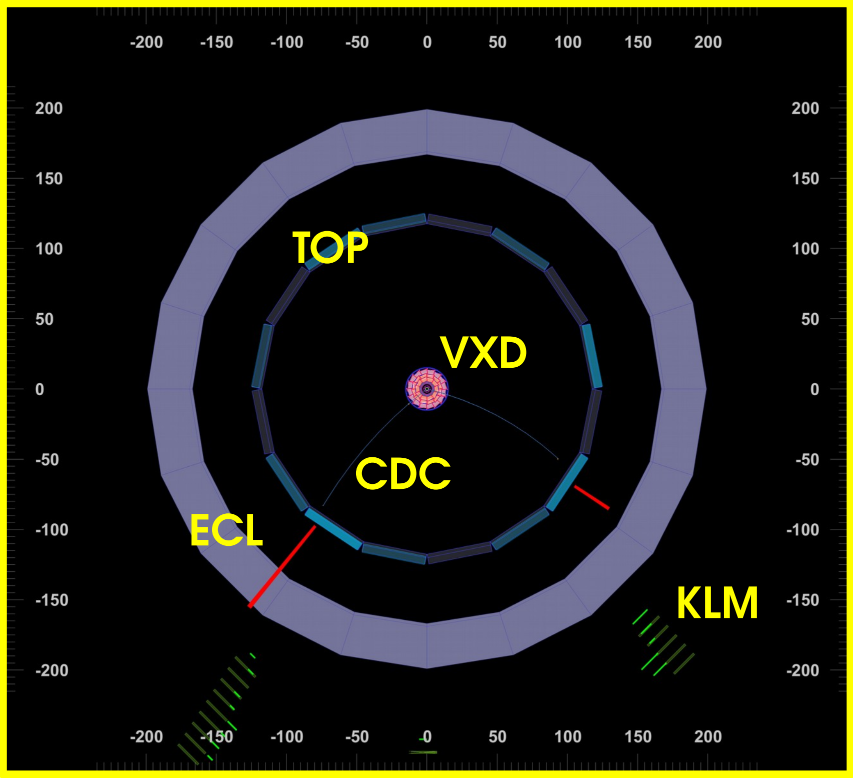
We optimized the selections for the "standard" Z';
we applied (almost) the same selections for the LFV case.

We extracted, using a Bayesian approach, a 90% CL upper limit on g' ($\varepsilon \cdot \sigma$ for the LFV Z').



Belle II transverse plane: event display of a reconstructed event from **Phase 2 data**

Belle II, arXiv:1912.1127 (submitted to PRL)

Used data set

For these analyses we used the 2018 data set: 496 pb^{-1} of collisions data.

But...

Belle II, arXiv:1912.1127 (submitted to PRL)

Used data set

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But...

- due to trigger issues, only 276 pb^{-1} of collisions data were usable for our purposes;

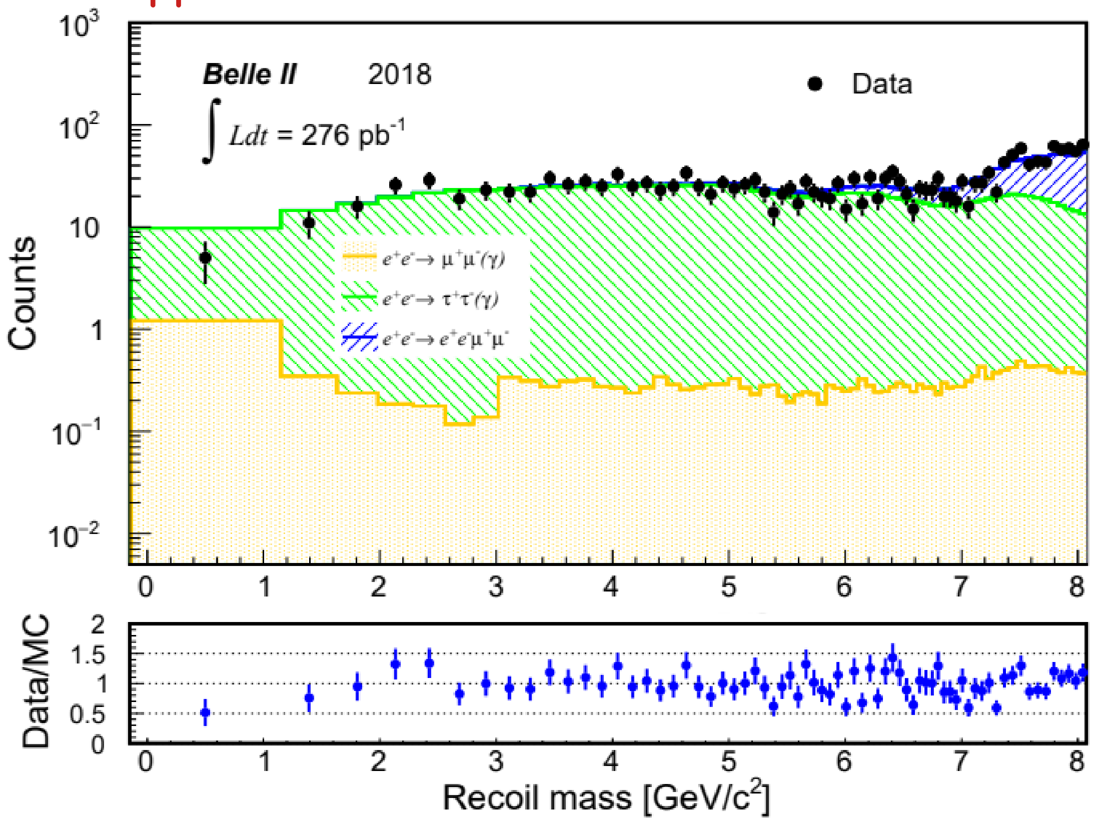
- the KLM subdetector faced severe firmware issues in 2018;
  $\rightarrow$ we identified the muons using the electromagnetic calorimeter;

- commisioning run: the detector performance had to be carefully evaluated;
  $\rightarrow$ found a large discrepancy between collisions and MC simulated data,
  not understood the source...

Belle II, arXiv:1912.1127 (submitted to PRL)

Recoil mass spectrum (after basic selections)

μμ final state



We found a deficit of data w.r.t. to MC (-35%)...

After having applied trigger and tracking corrections, in addition to a 65% correction, we obtain a very good agreement between data and MC.

NB: all the corrections are evaluated on indipendent control samples!

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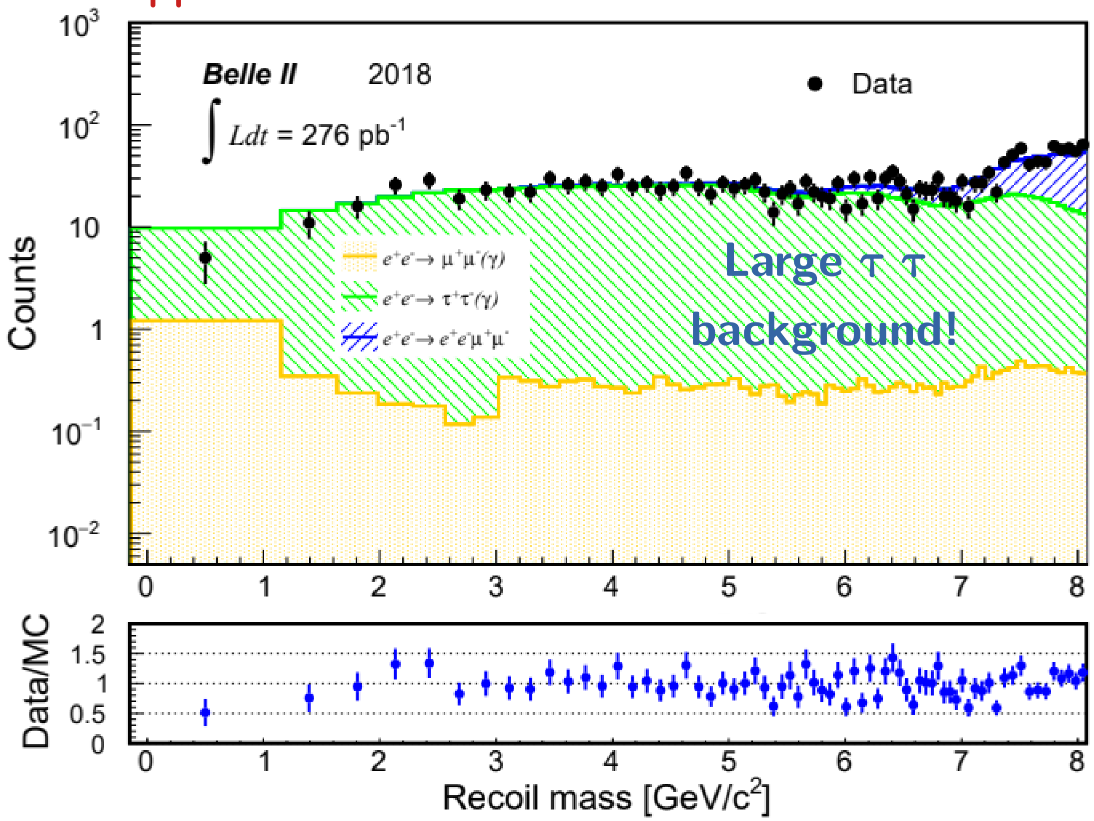

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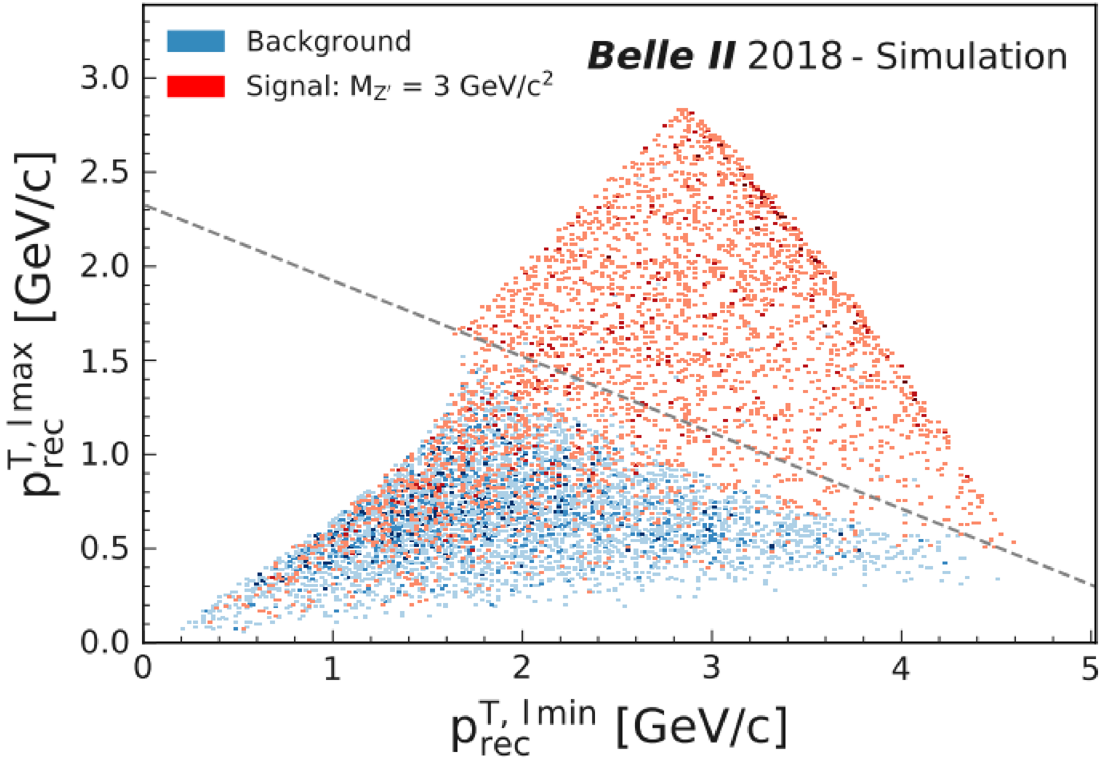
Belle II, arXiv:1912.1127 (submitted to PRL)

Suppression of the $\tau\tau$ background

The largest background component is due to $\tau\tau$ events: needed a special technique to suppress it!

$\rightarrow$ Studied several variables, isolated the most discriminating ones between generated signal and background samples.

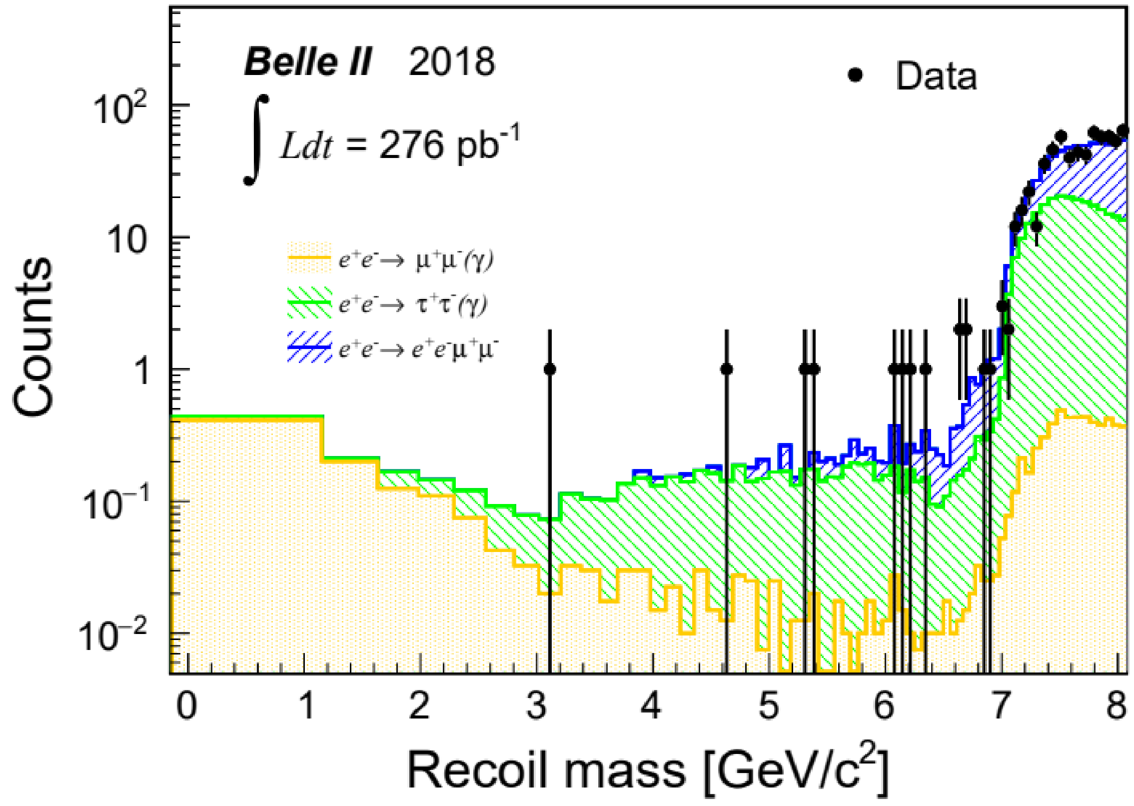


We optimized the selection in each recoil mass bin by choosing the best cuts that maximizes a given figure of merit (**hand-made multivariate approach**).

Belle II, arXiv:1912.1127 (submitted to PRL)

$\tau\tau$ background suppressed

$\mu\mu$ final state



Suppression of the $\tau\tau$ background very effective up to 7 GeV (then, **$ee\mu\mu$** events start to be dominant).

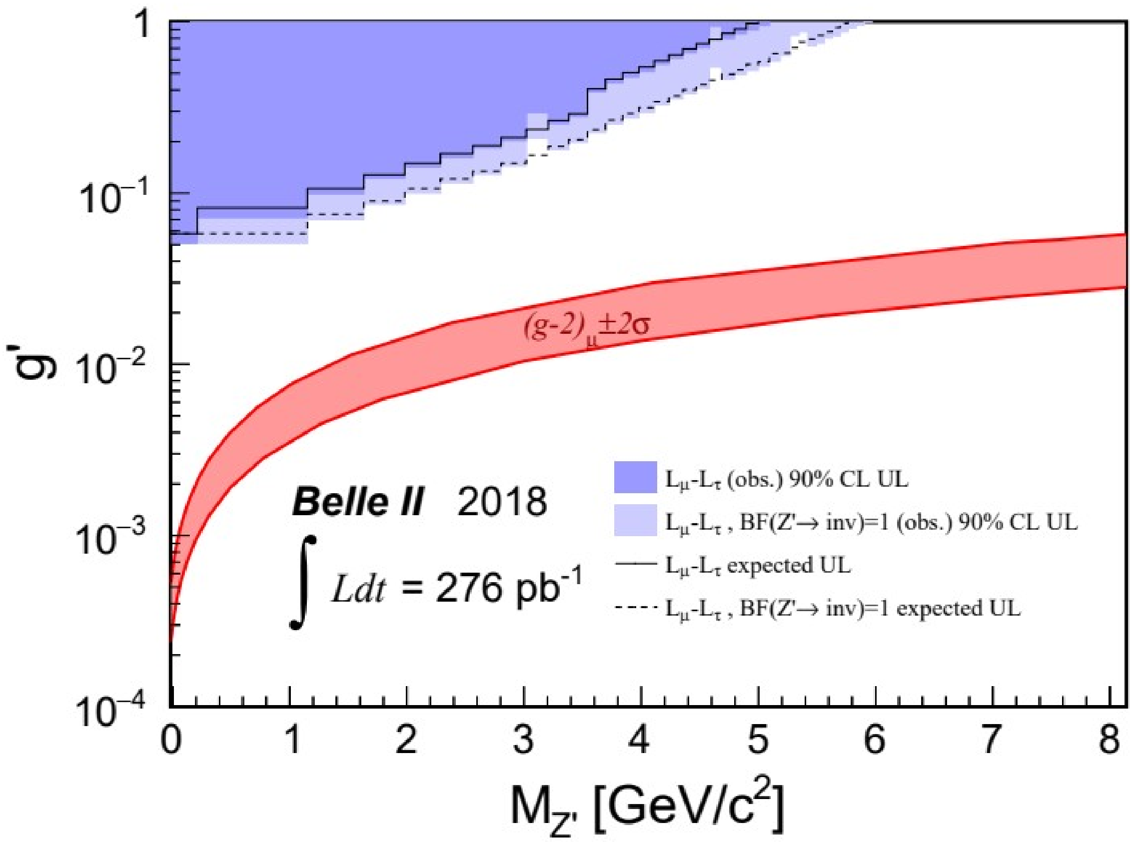
Signal efficiency between 3% and 5%.

No (local) anomalies observed... :(

Belle II, arXiv:1912.1127 (submitted to PRL)

Upper limits

μμ final state



We set 90% CL upper limits using a Bayesian approach and a Poisson counting technique.

Systematic uncertainties:

Source	$\mu^+\mu^-$
Trigger efficiency	6%
Tracking efficiency	4%
PID	4%
Luminosity	0.7%
τ suppression (background)	22%
Background before τ suppression	2%
Discrepancy in $\mu\mu$ yield (signal)	12.5%

Belle II, arXiv:1912.1127 (submitted to PRL)

Upper limits

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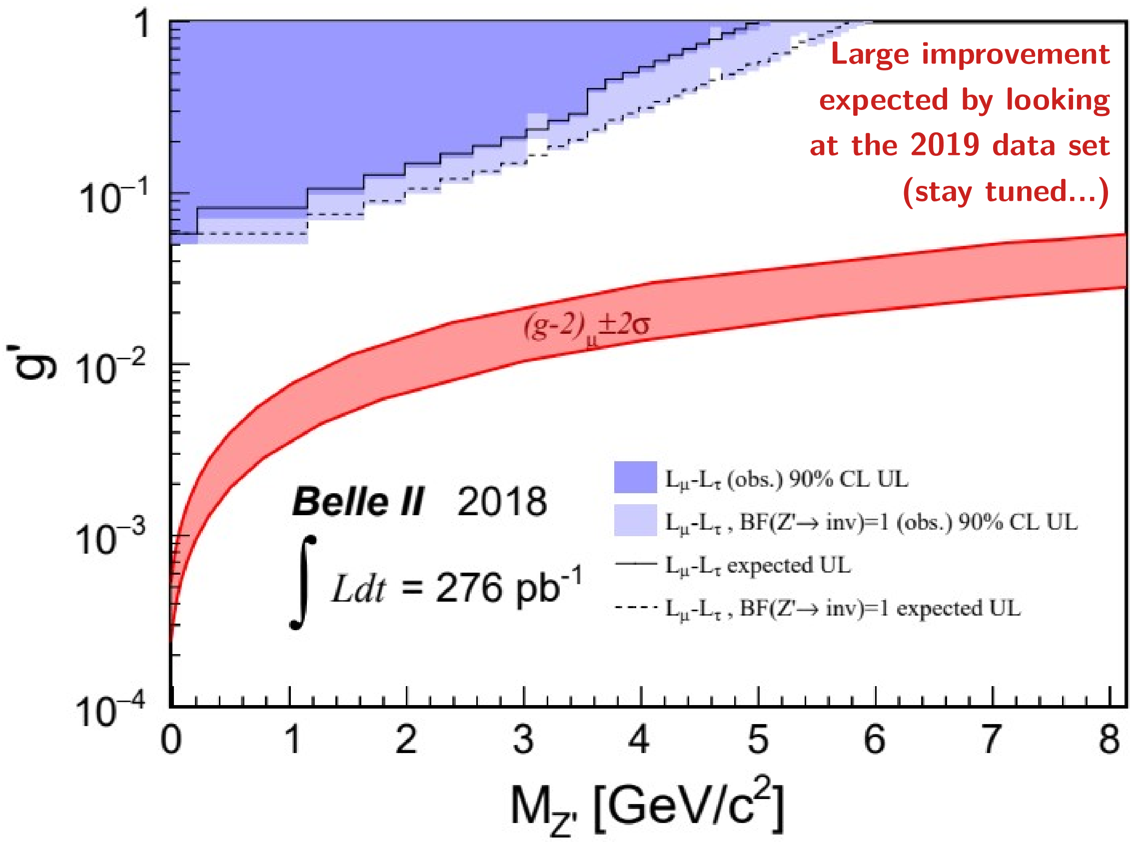

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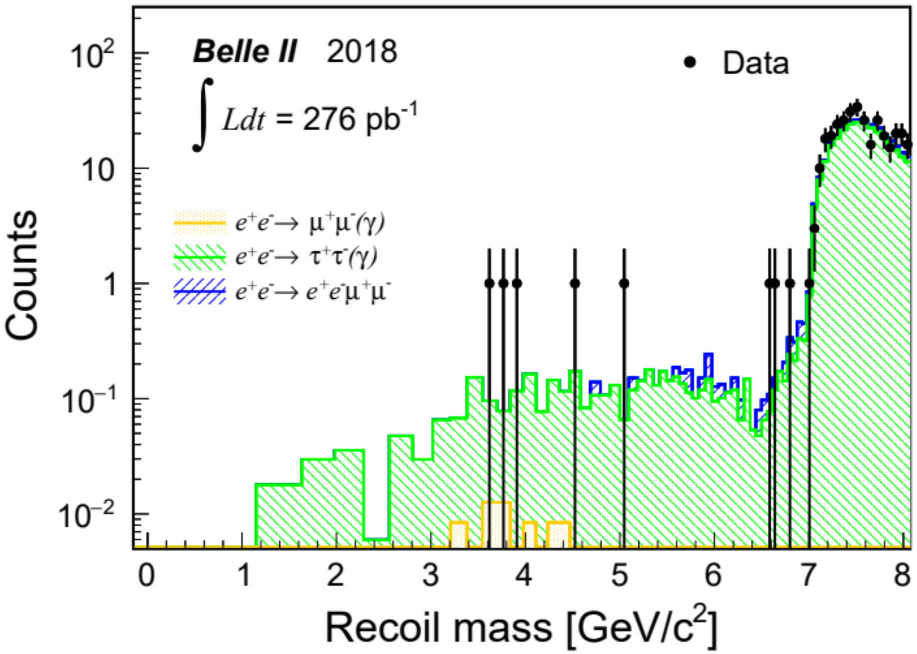
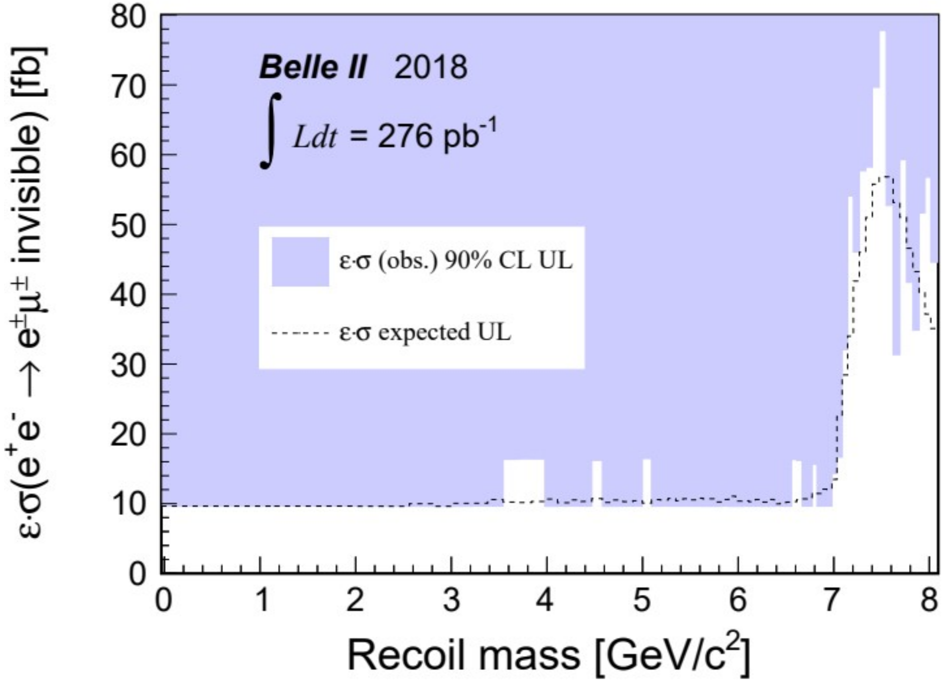
Belle II, arXiv:1912.1127 (submitted to PRL)

LFV Z'

eμ final state



We can set limits on a coupling constant if a theoretical model is provided!



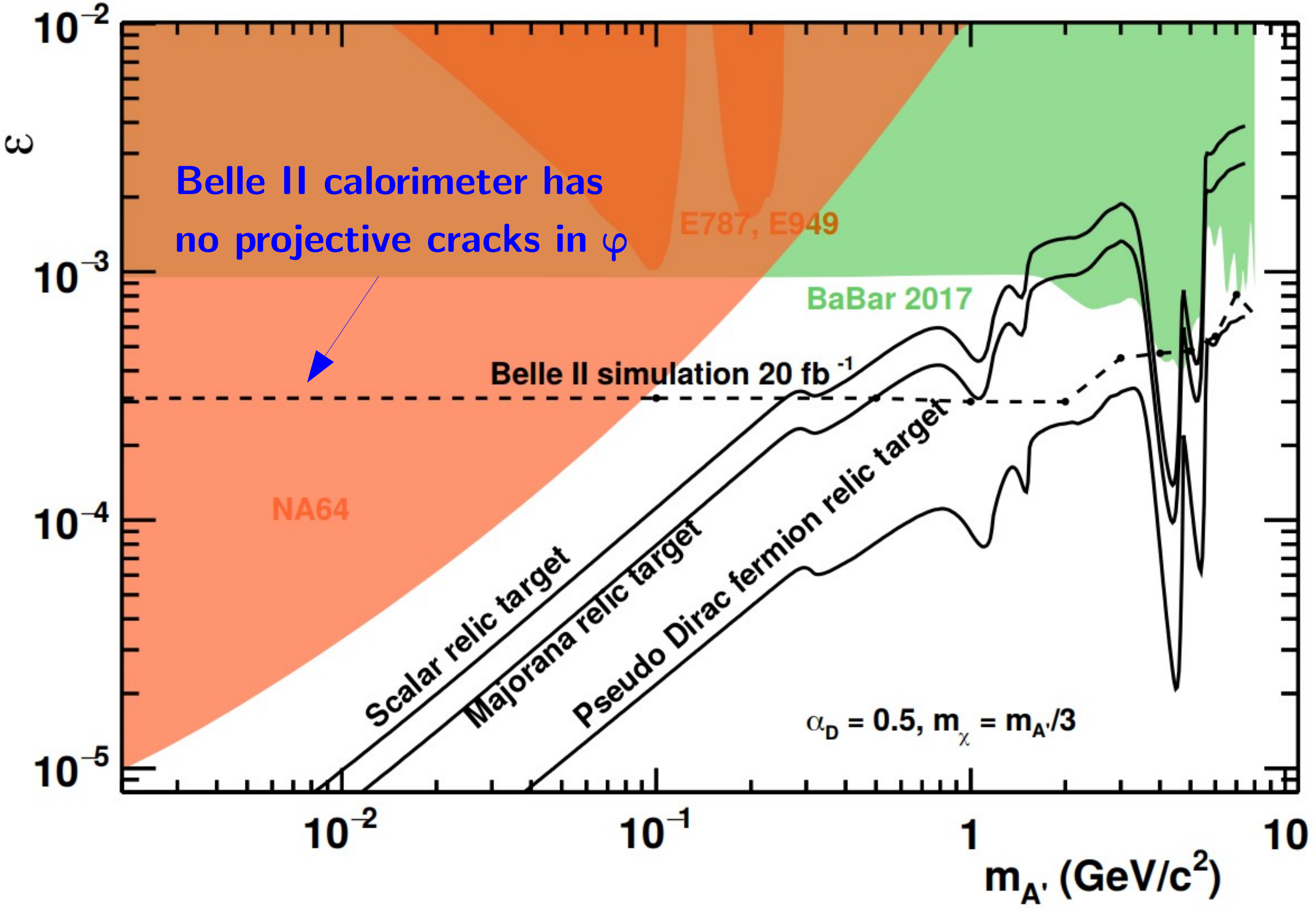
Belle II, arXiv:1912.1127 (submitted to PRL)

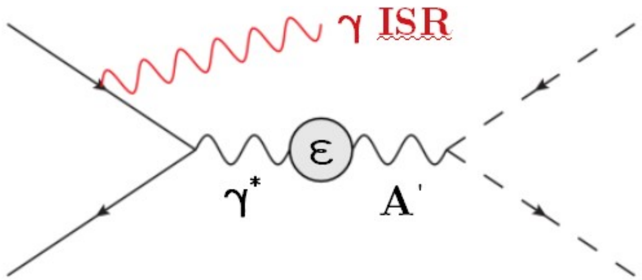
Other ongoing searches

Dark Photon


S/N 16
S/N 23
INFN
LNF-RM3
INFN
LNF-RM3
Z AXIS
Z AXIS
JTAG
JTAG
Phi
Phi AXI

Dark Photon: invisible decay

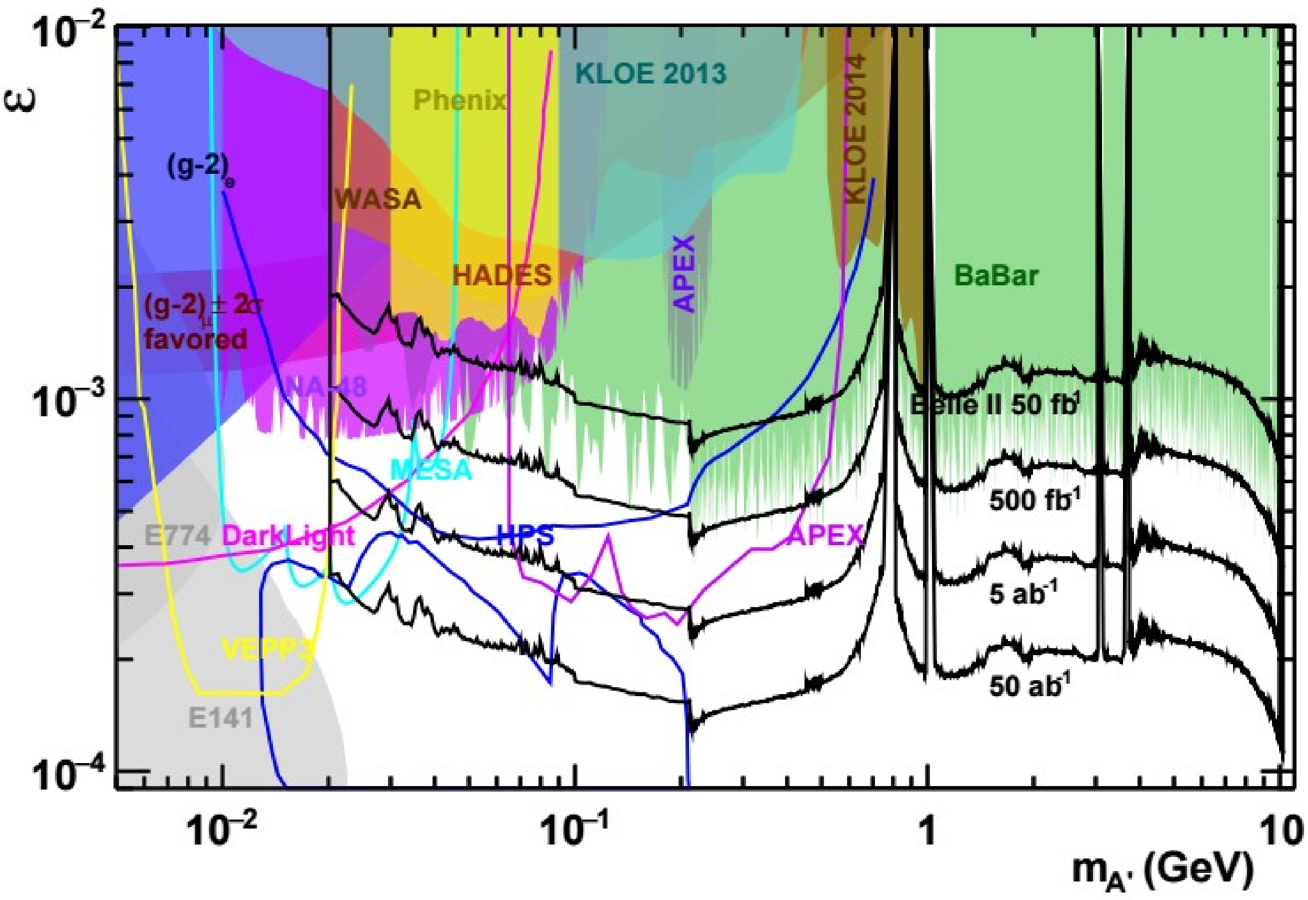




Single photon search: needed a **special trigger logic**:

- ready for Belle II;
- not available in Belle;
- partially available in BaBar.

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.

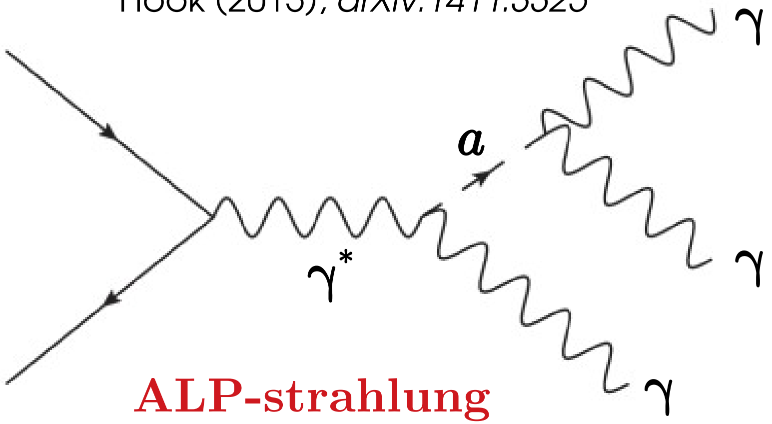
Unlike QCD Axions, ALPs have no relation between mass and coupling.

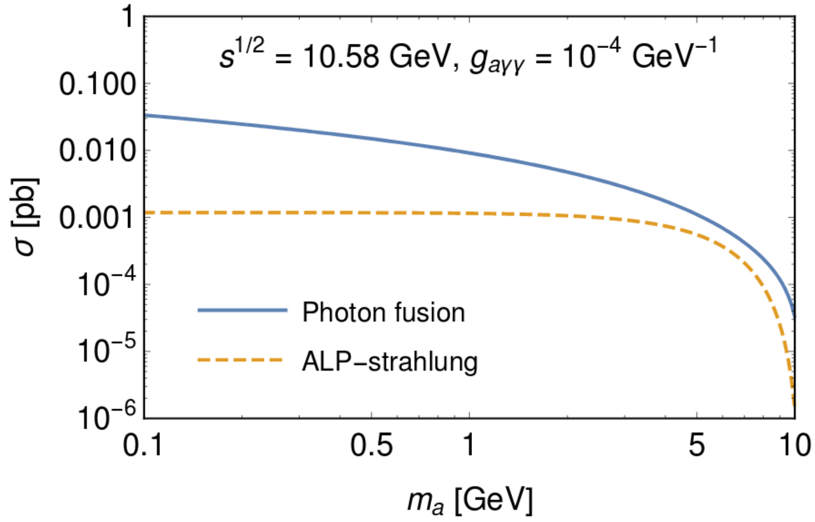
I will focus on the **coupling to photons**:

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

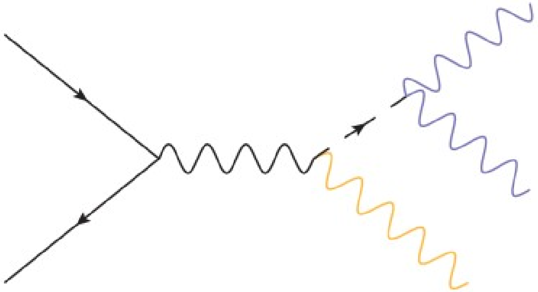
Belle II will study the **ALP-strahlung** case (low sensitivity to photon fusion production)

Hook (2015), *arXiv:1411.3325*

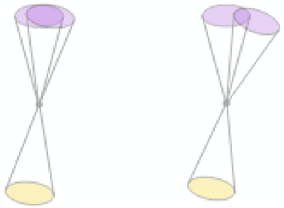




Axion-Like Particles (signal)



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

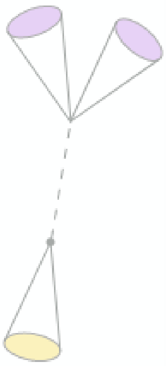


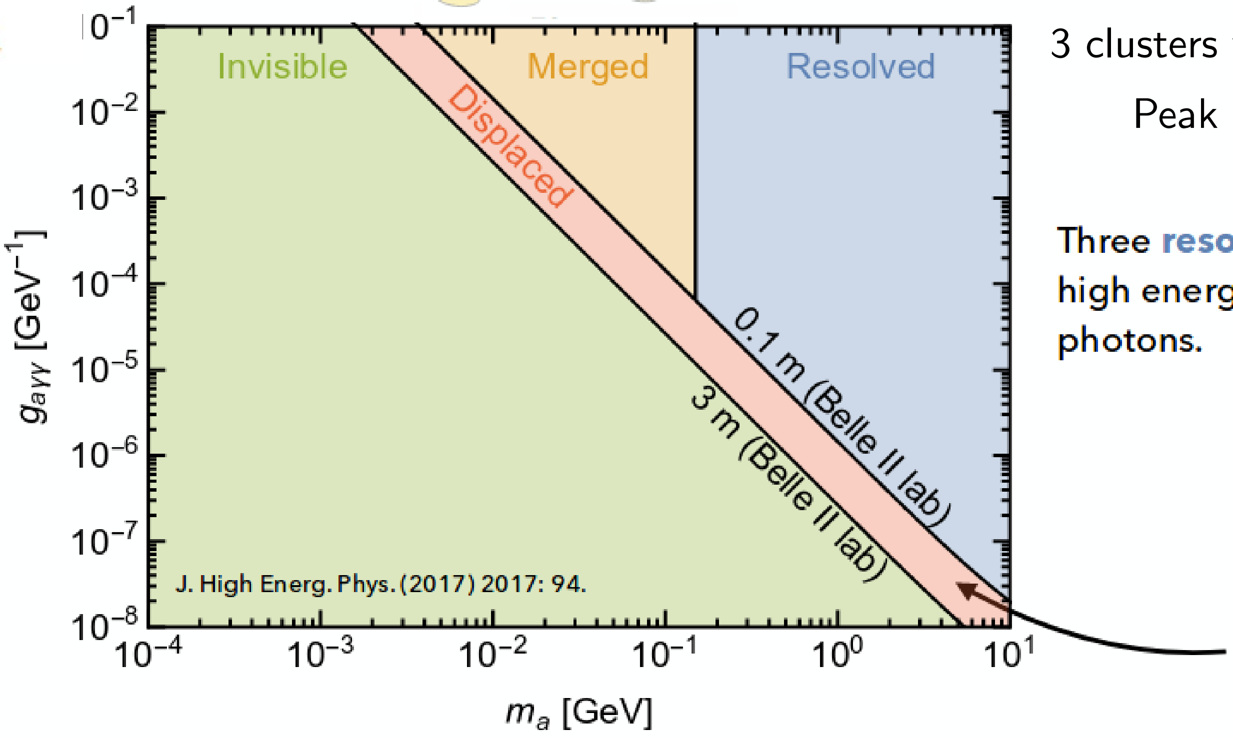
$$\tau_a \sim 1/g_{a\gamma\gamma}^2 m_a^3$$

For **resolved** case:

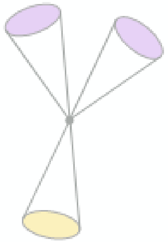
3 clusters with $E_{CM} > 0.25$ GeV

Peak in $\gamma\gamma$ mass spectrum





Three **resolved**, high energetic photons.



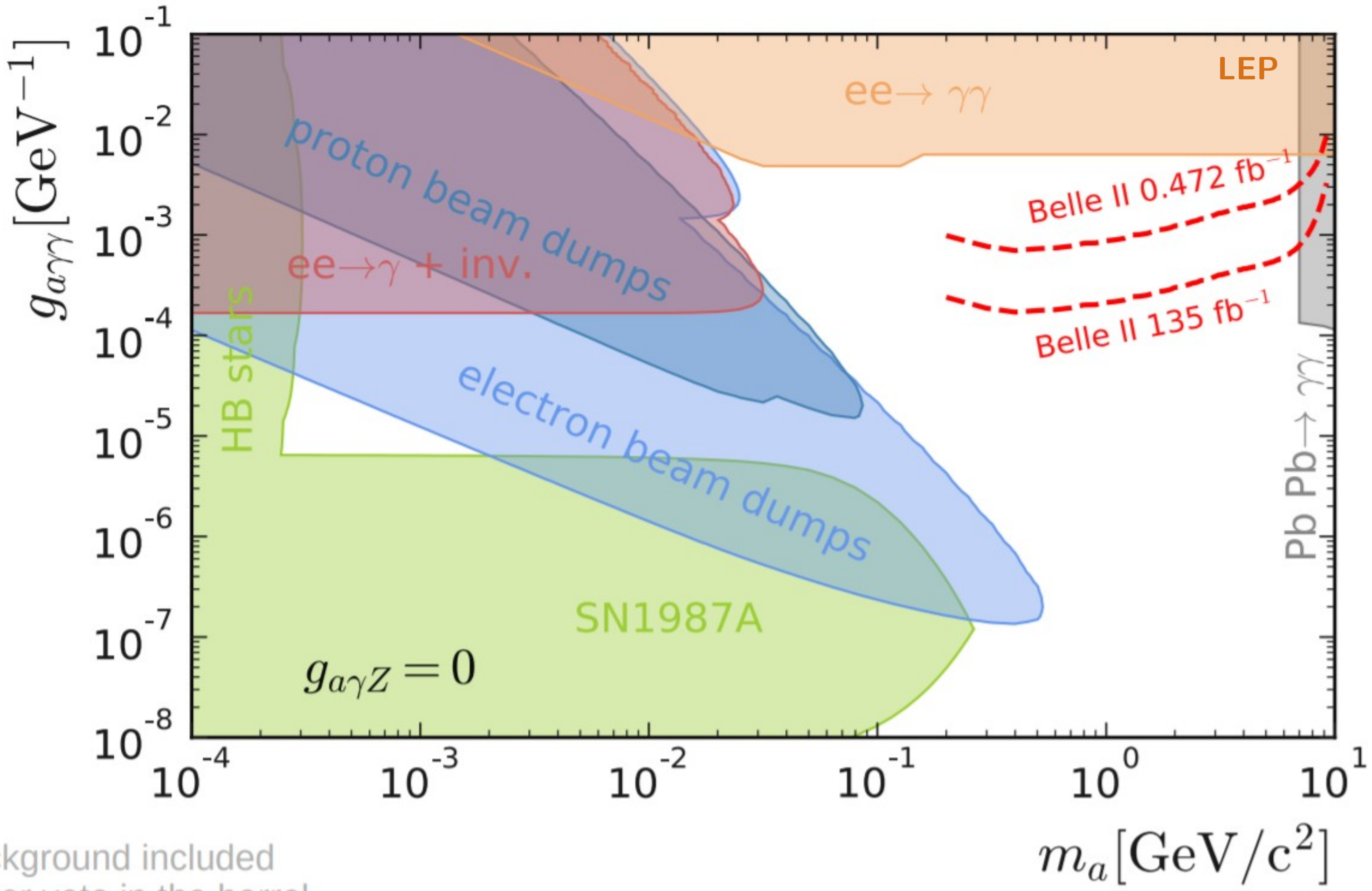
ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

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

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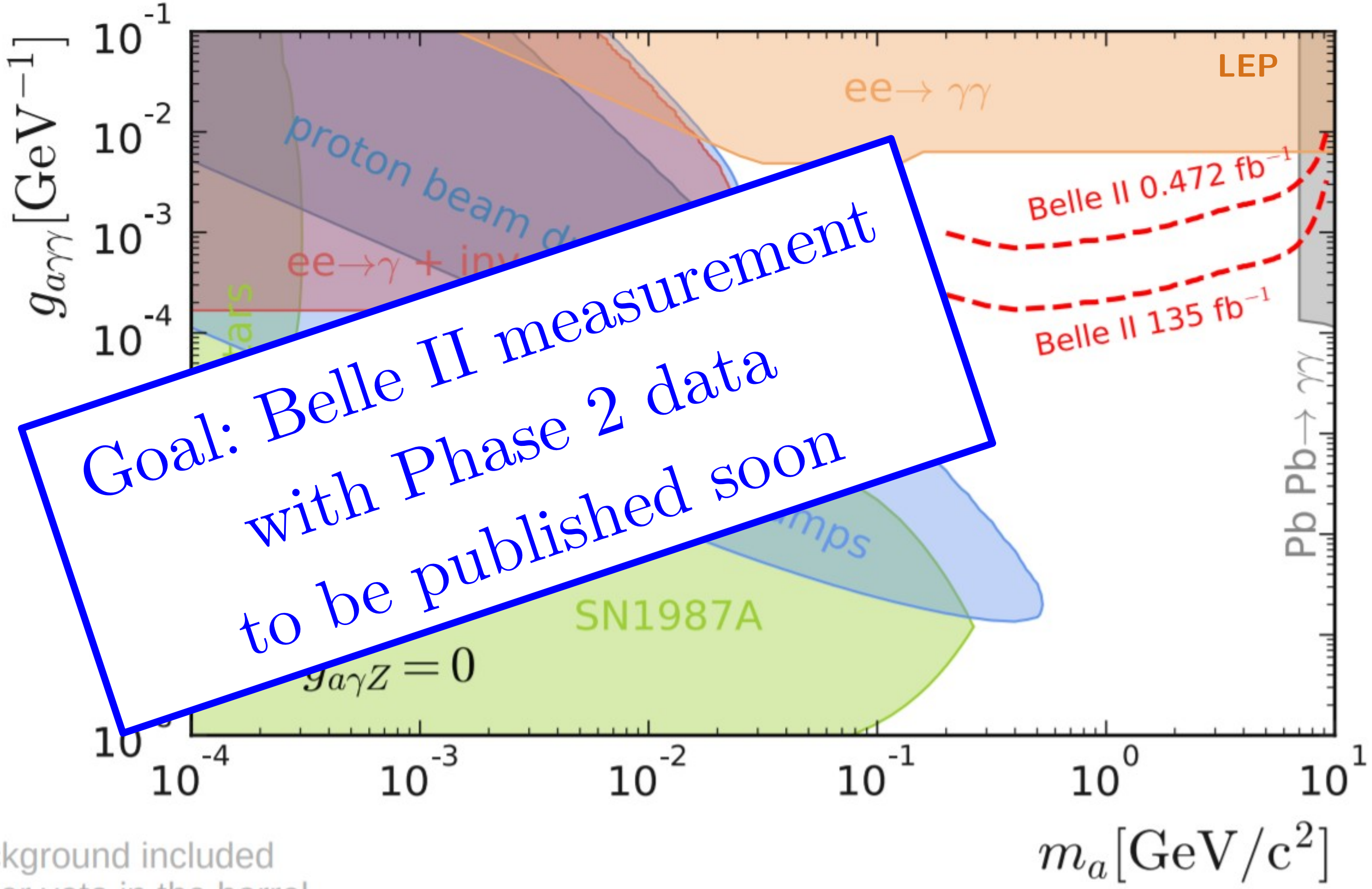

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Dark Higgs-strahlung

Dark Higgsstrahlung

General remarks

The dark photon mass could be generated via a spontaneous symmetry breaking mechanism, adding a dark Higgs boson *h*' to the theory.

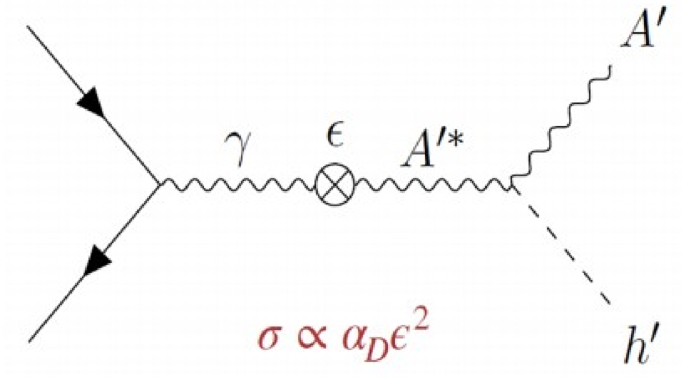
In a minimal scenario: a single dark photon A' and a single dark Higgs boson h'.

The *h'* could be produced in the Higgsstrahlung process, which is also sensitive to the dark sector coupling constant α_D

Different scenarios depending on the mass hypothesis.

Focus on $m_{h'} < m_{A'}$ case:

- 2 charged particle in the final state plus missing energy.



$$e^+e^- \rightarrow A'^* \rightarrow h' A' \;\; (\hookrightarrow \mu^+\mu^-)$$

Signal:

- A peak in the *Recoil mass vs. Di-muon mass* phase space.

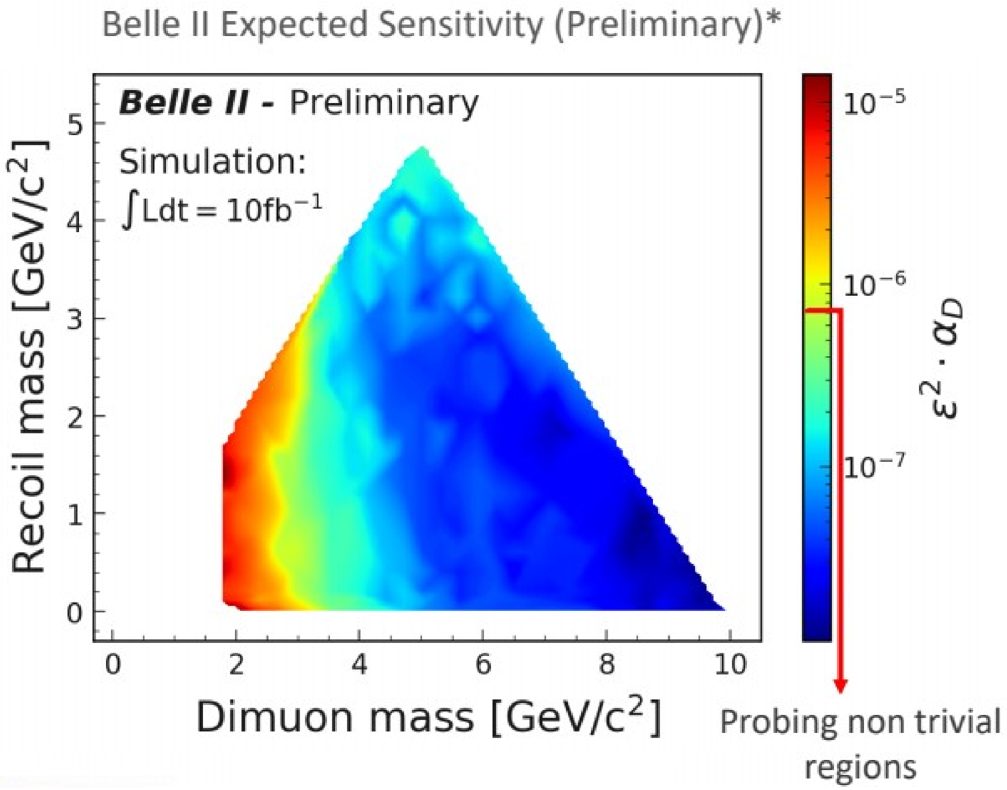
Background:

- Everything with 2 particles identified as muons and missing momentum: $\mu\mu\gamma,\ \tau\tau\gamma,\ ee\mu\mu,\ \pi\pi\gamma$

Courtesy from M. Campajola

Dark Higgsstrahlung

Expected sensitivity



Belle II can be competitive with early Phase 3 dataset (~10 fb^{-1}).

Still unconstrained region in $\epsilon^2\, \alpha_D$. Beyond the KLOE coverage.

90% C.L. UL on ϵ^2 in Dark Photon searches lies in $\sim 5 \cdot 10^{-7}$ regime

*No systematics into account.

Courtesy from M. Campajola

Conclusions

Other dark sector and exotic searches

Dark Photon decays

- invisible decay
- leptonic decays
- hadronic decays?

Long-living neutral particle decays

Dark Scalar:

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

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

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

Other Z' decays:

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

... and many others!

More details in The Belle II Physics Book

arXiv:1808.10567

Other dark sector and exotic searches

Dark Photon decays

invisible decay

leptonic decays

hadronic decays?

Long-living neutral particle decays

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… and many others!

Analyses in which Roma Tre is involved

(+ $Z' \rightarrow$ invisible, Dark Higgs-strahlung, LFV decay $\tau^+ \rightarrow \mu^+ \mu^- \mu^+$)

Summary

- ✔ Belle II at the SuperKEKB facility started operations in 2018, collecting 0.5 fb^{-1} of collisions data in 2018 and other 10.5 fb^{-1} in 2019

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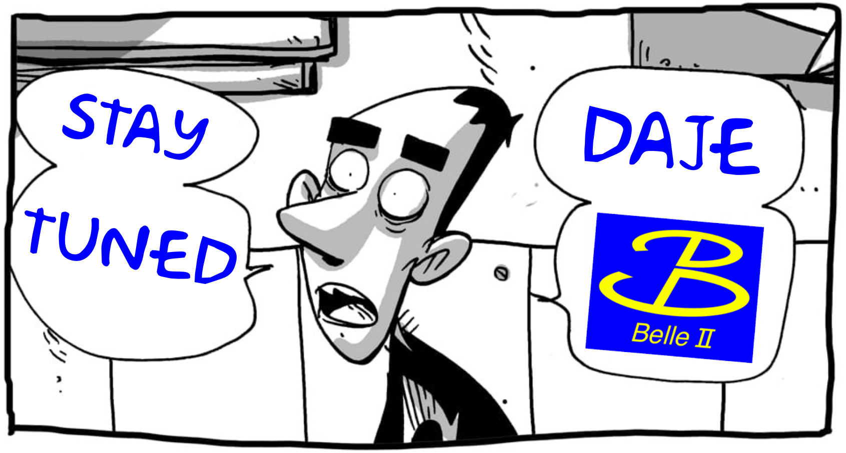


Thank you
for your
attention

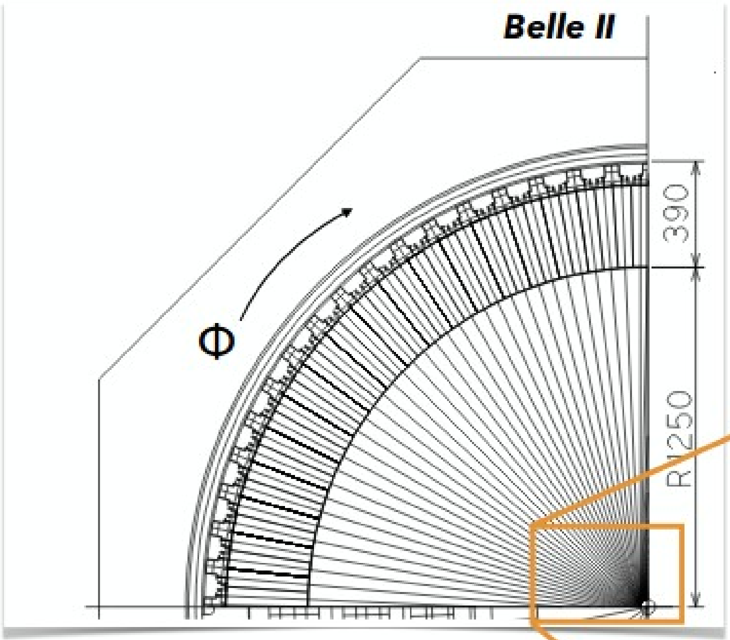
Backup slides

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

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

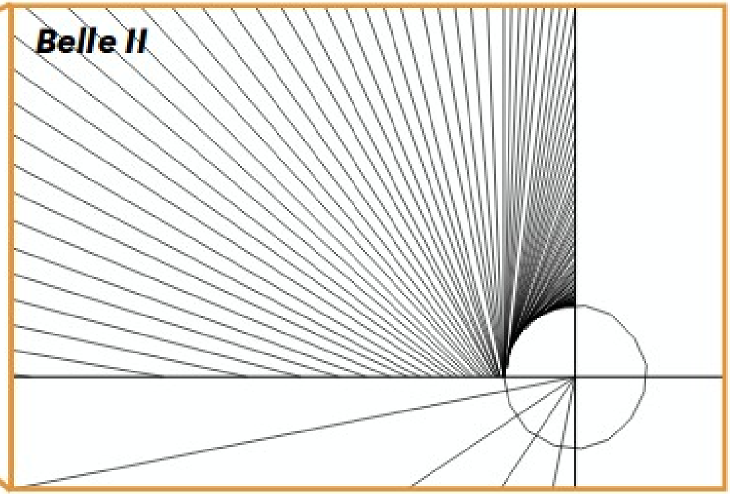
Electromagnetic Calorimeter (ECL)



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

→ more hermetic

→ more efficient



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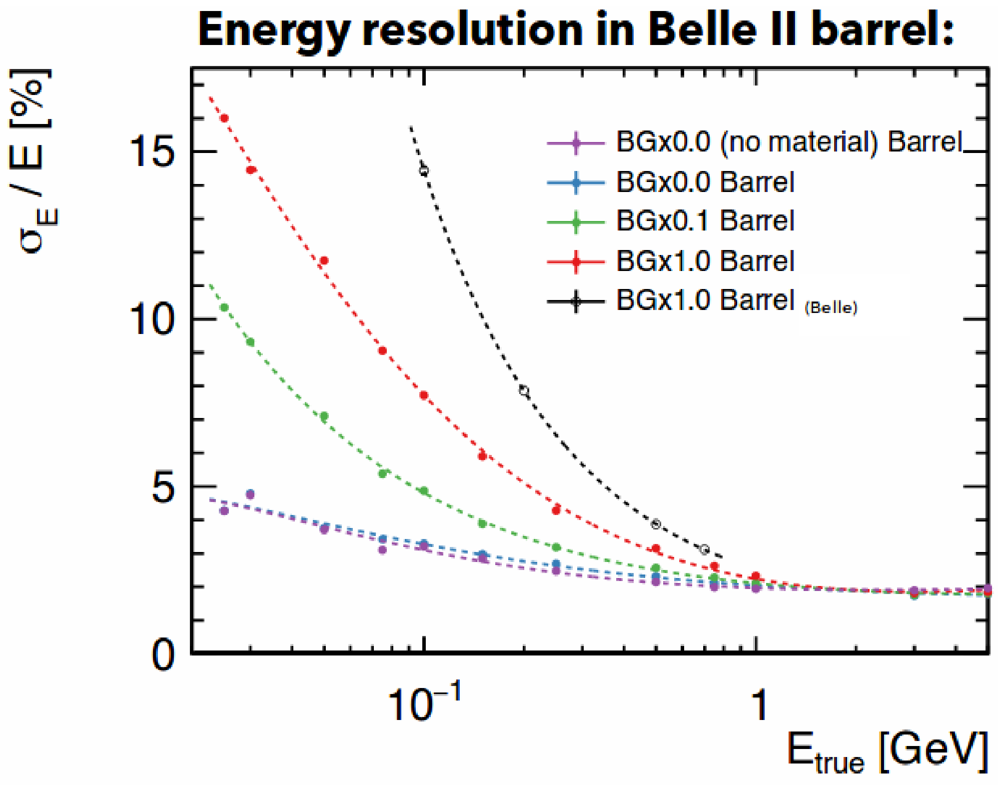
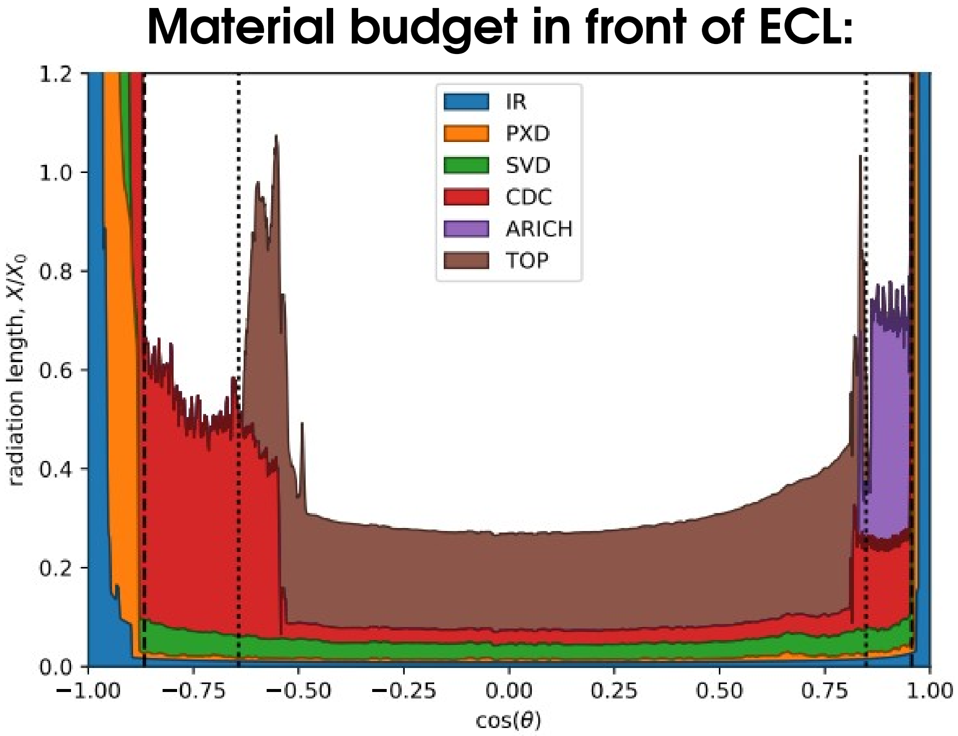
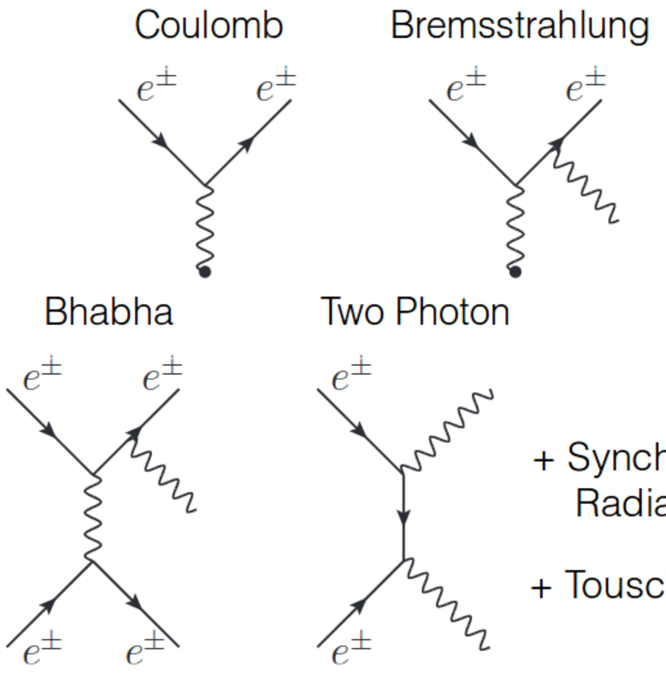


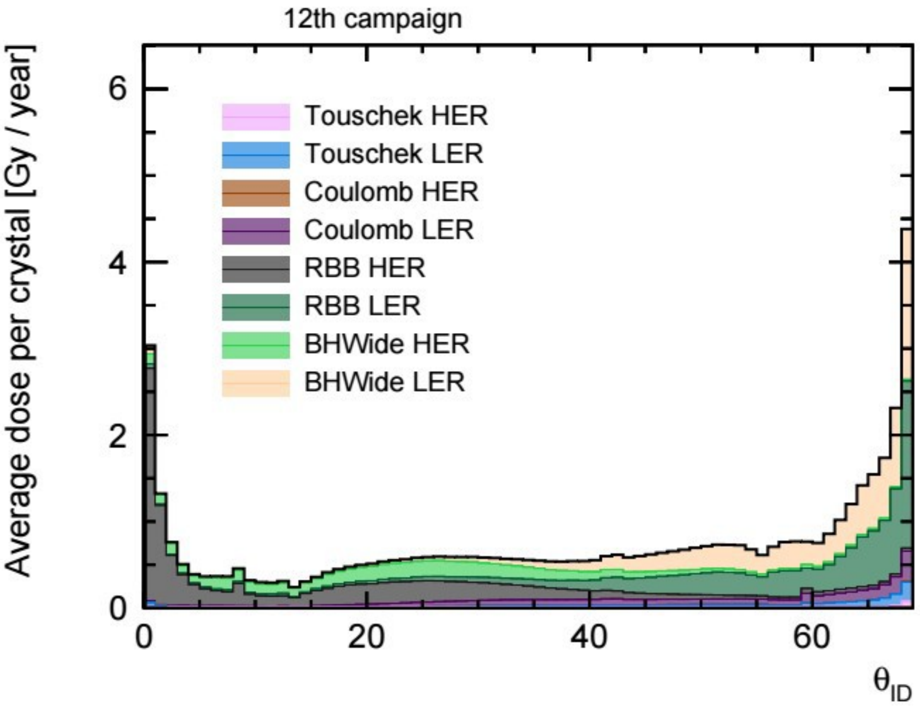


Beam background



+ Synchrotron Radiation

+ Touschek



Effects from beam background:

→ degrades calorimeter resolution.

→ radiation damage.

→ pile-up and event size.

→ physics background

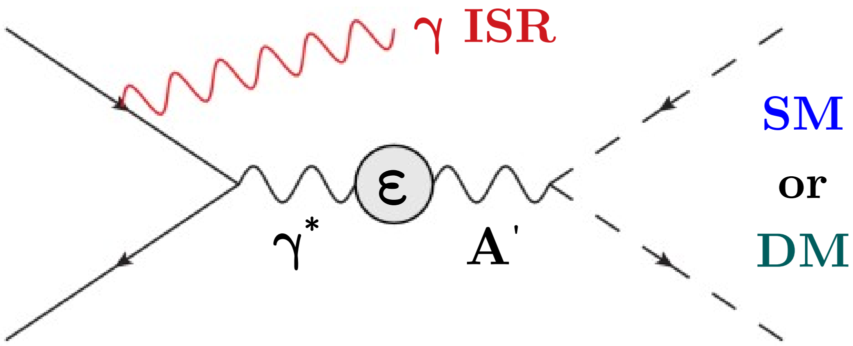
BEAST: dedicated systems for continuous beam background measurement and monitoring!

Dark Photon

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

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

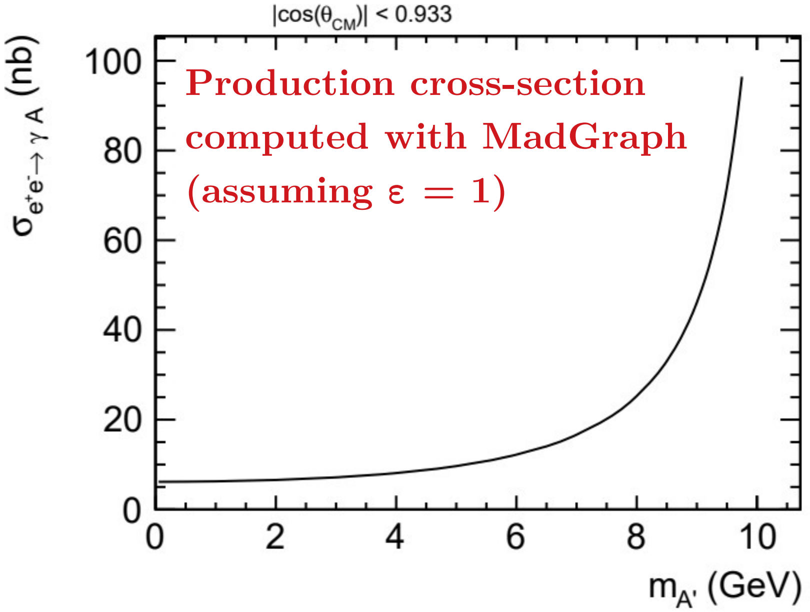
Batell et al. (2009), *arXiv:0903.0363*



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**

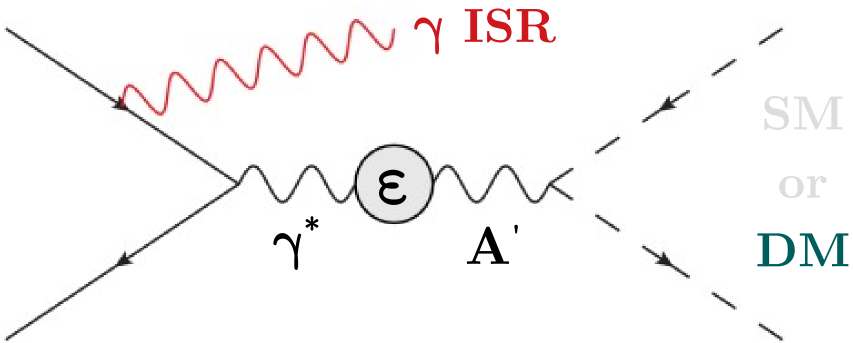


Dark Photon: invisible decay (signal)

Signal signature:

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

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



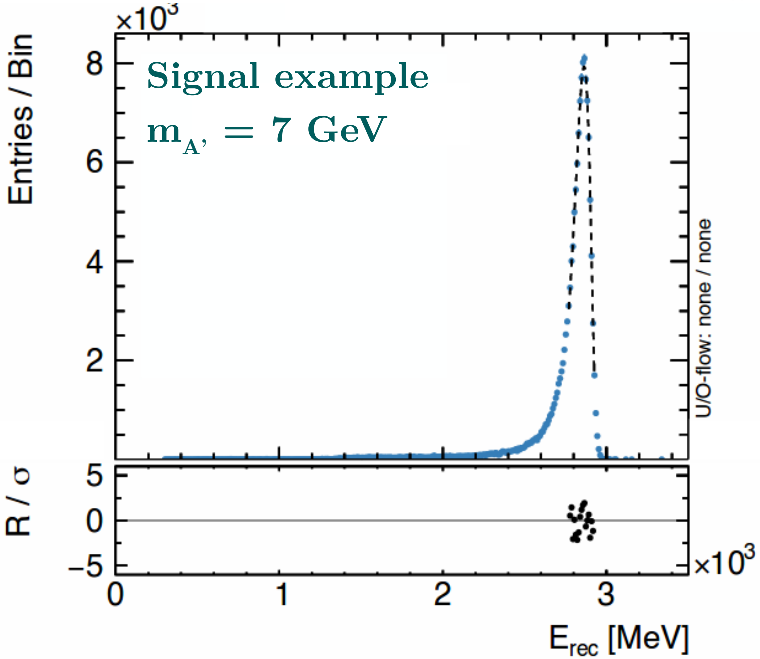
Needed a special **single photon trigger**

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

Trigger logic	L1 rate at full luminosity
E > 1 GeV + 2^{nd} 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?

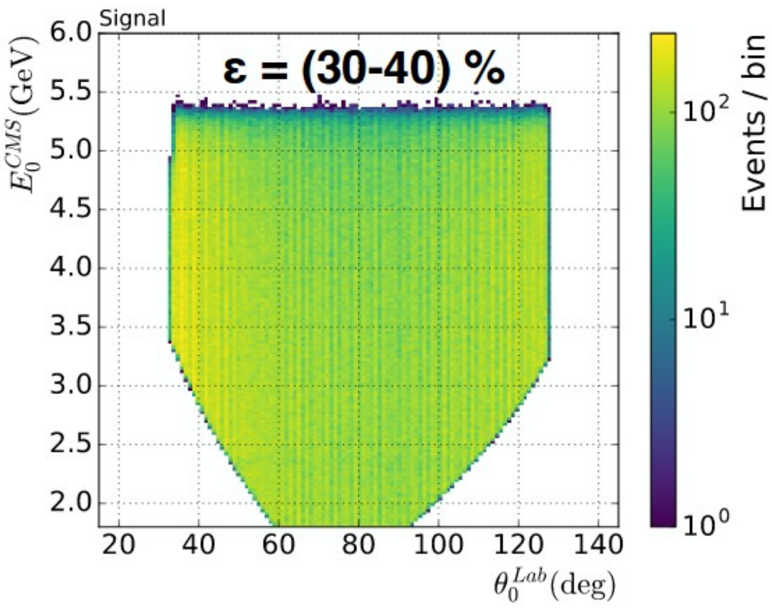


Belle II MC Preliminary

Dark Photon: invisible decay (signal)

Discriminant variables:

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



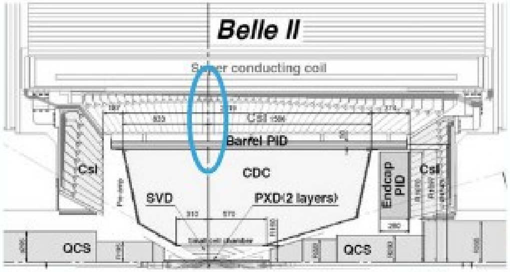
Signal signature:

peak in E_{CMS} (horizontal band)

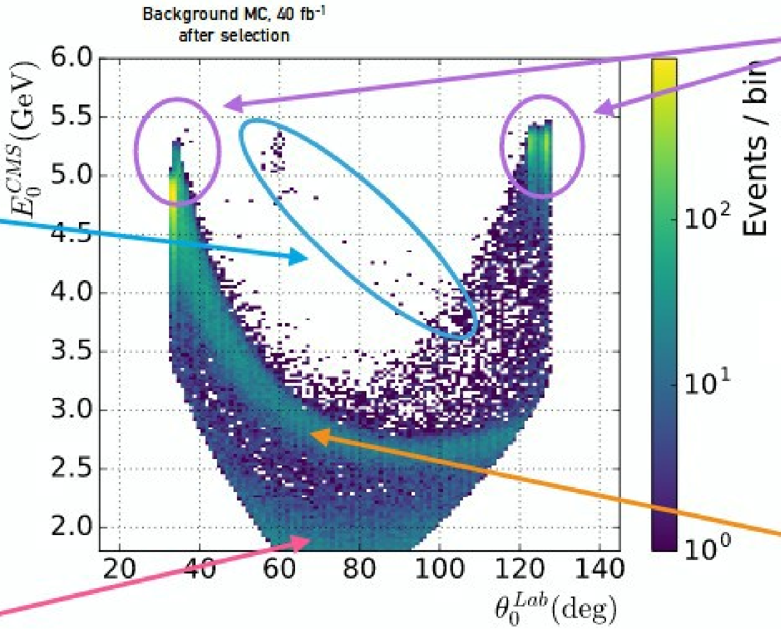
Dark Photon: invisible decay (background)

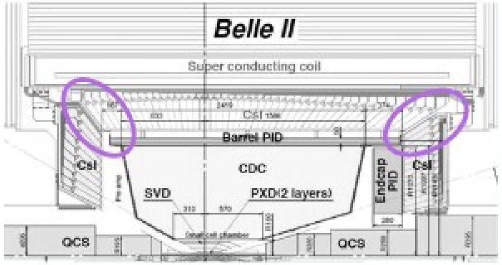
Discriminant variables:

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

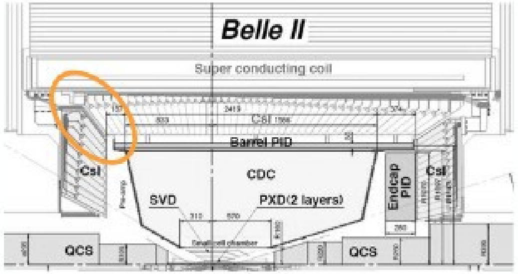


ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance





ee→2γ
1γ in ECL BWD or FWD gap

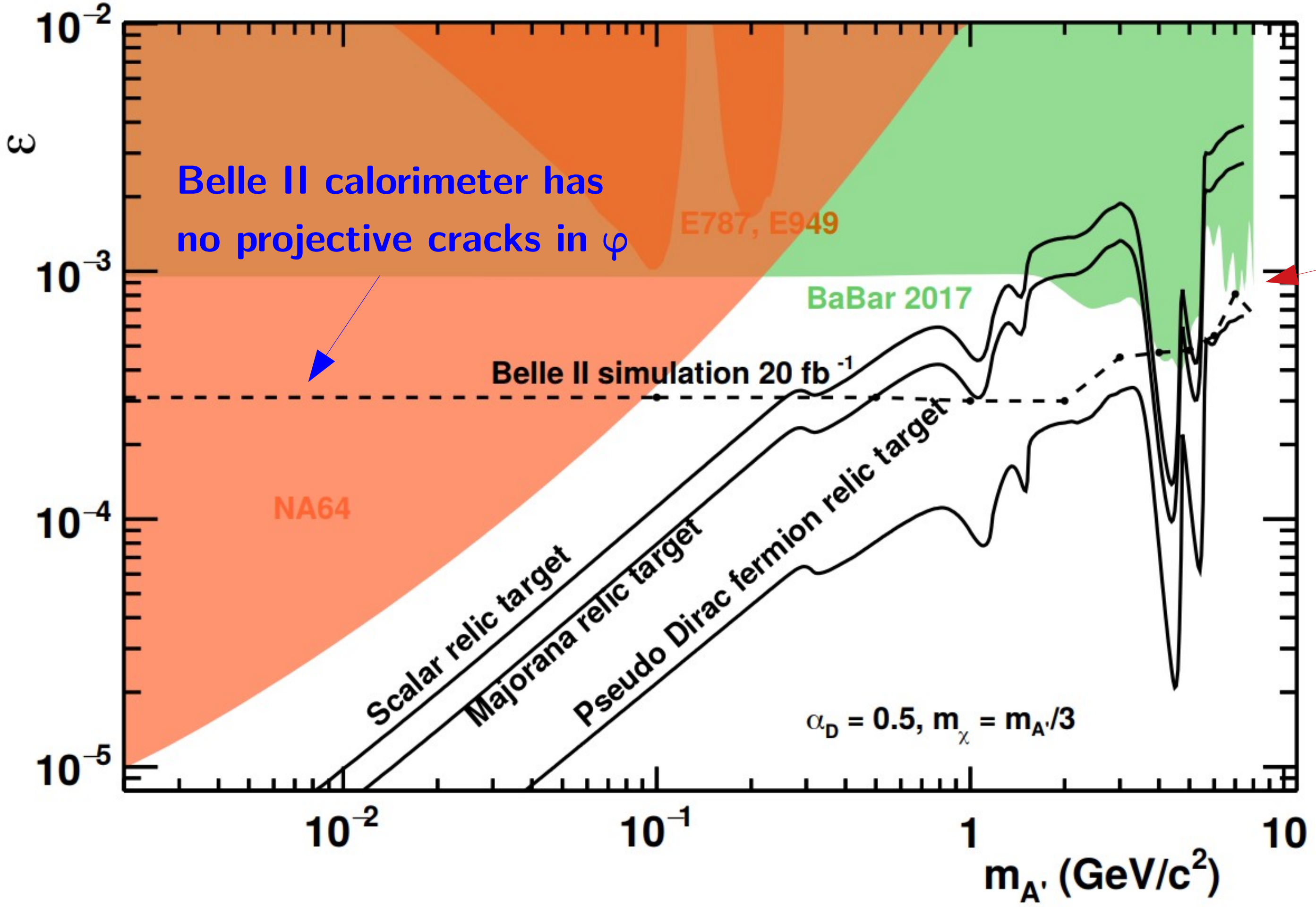


ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

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

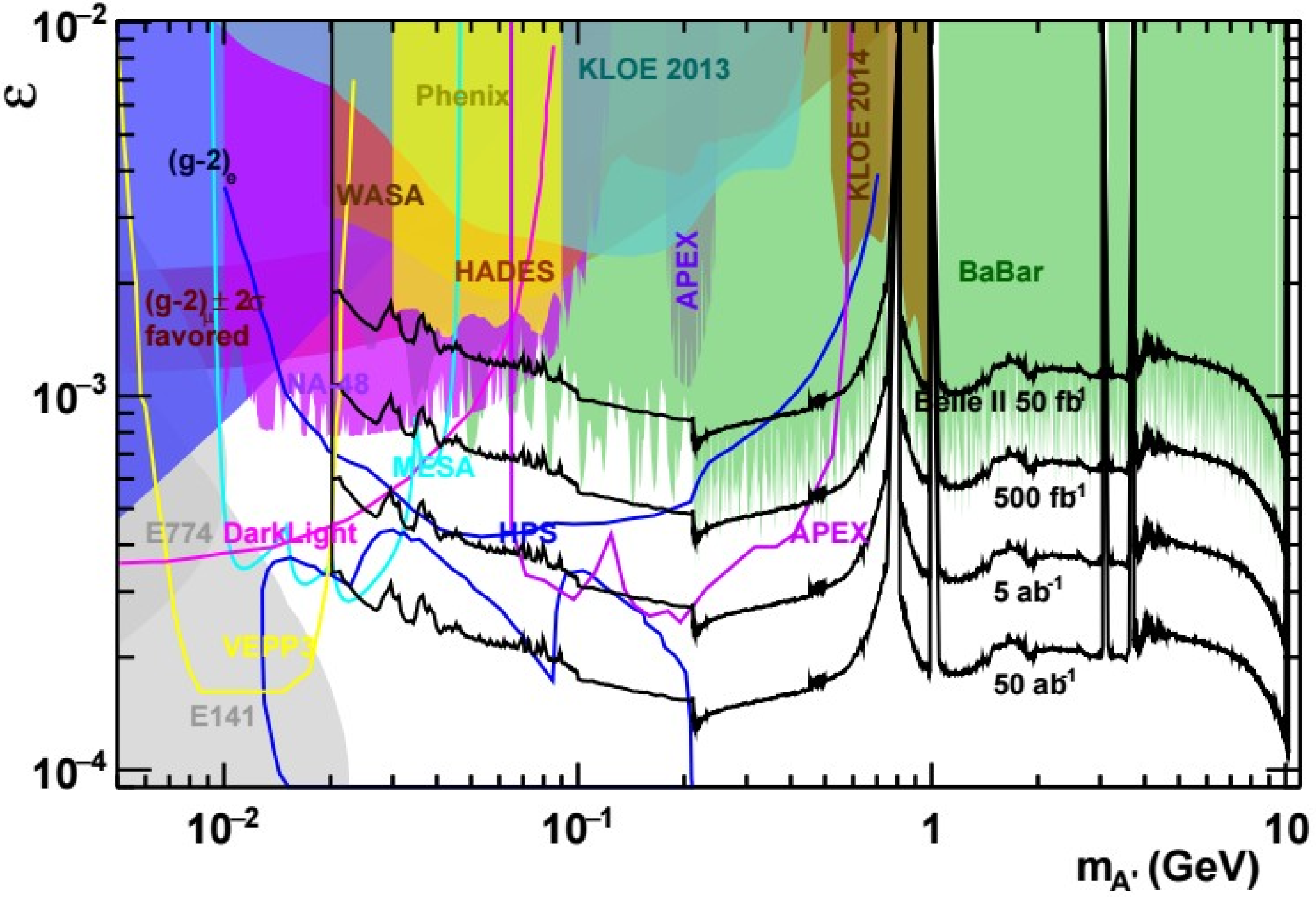
J. Alexander et al. (2016), *arXiv:1608.08632*

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



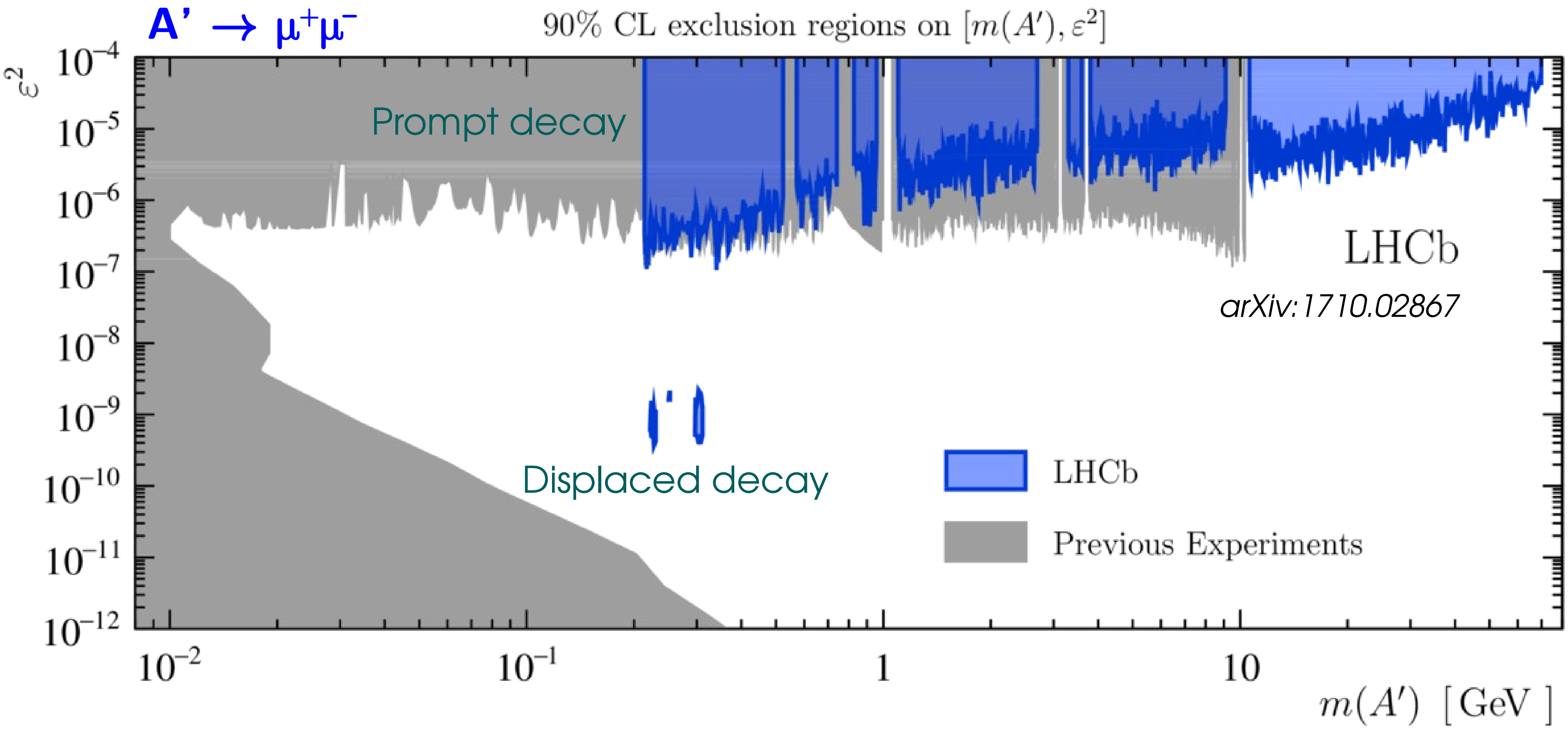
Look for a bump in the e^+e^- or $\mu^+\mu^-$ invariant mass over a (large) QED background

Belle II sensitivity is obtained by scaling the BaBar measurement:

- expected better invariant mass resolution

- expected better triggers

Dark Photon: muonic decay @ LHCb



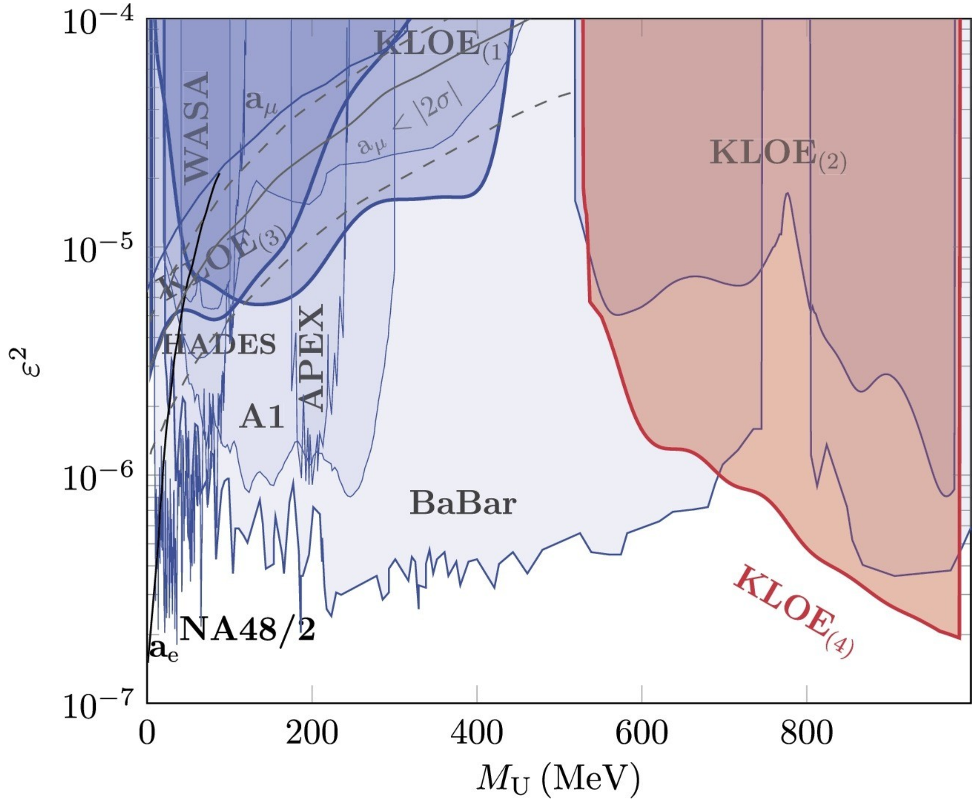
Dark Photon: hadronic decay

Very interesting final state...

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

... but quite challenging!

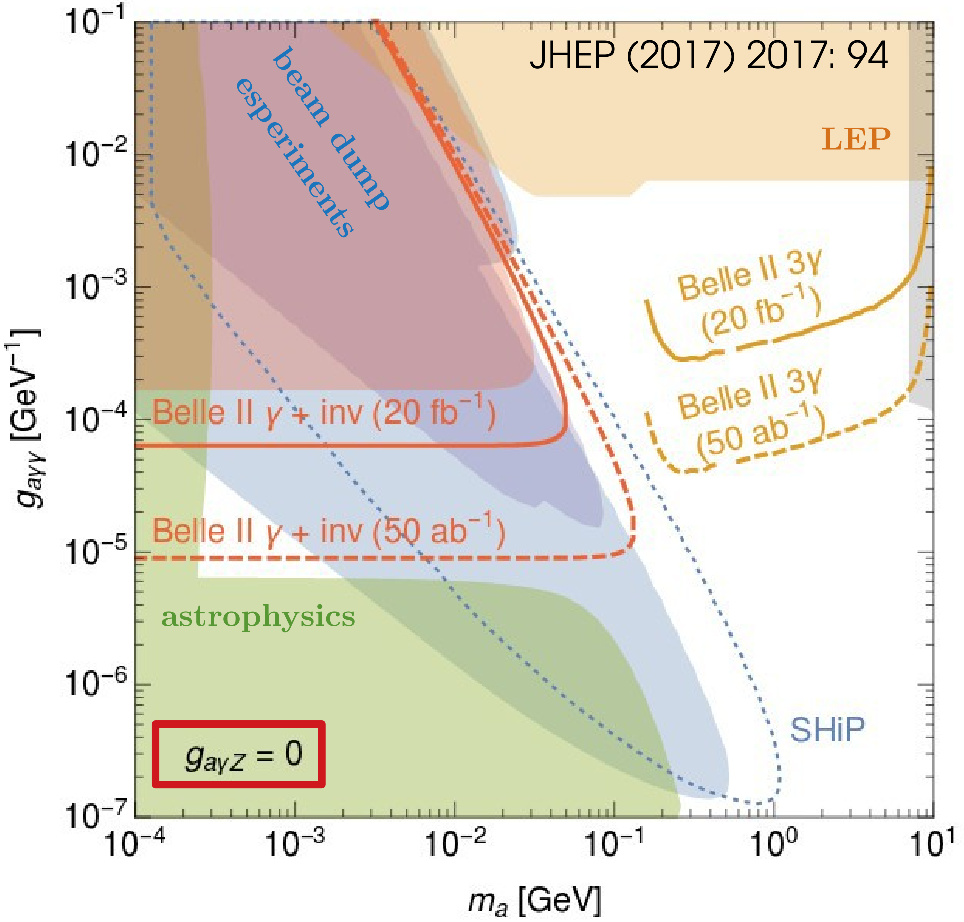
- due to large available phase space + hadronization, many final states must be considered
- background from hadronic events



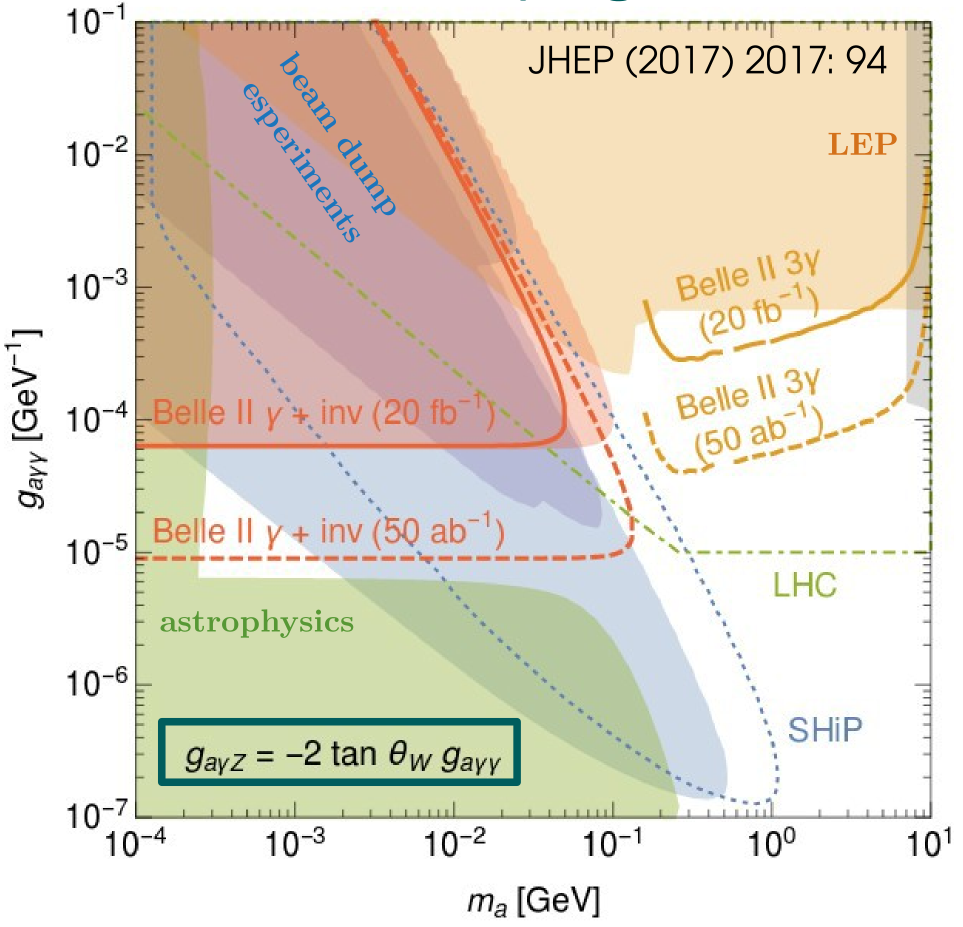
We aim to cover $m_{A'} > 1$ GeV

Axion-Like Particles (sensitivity)

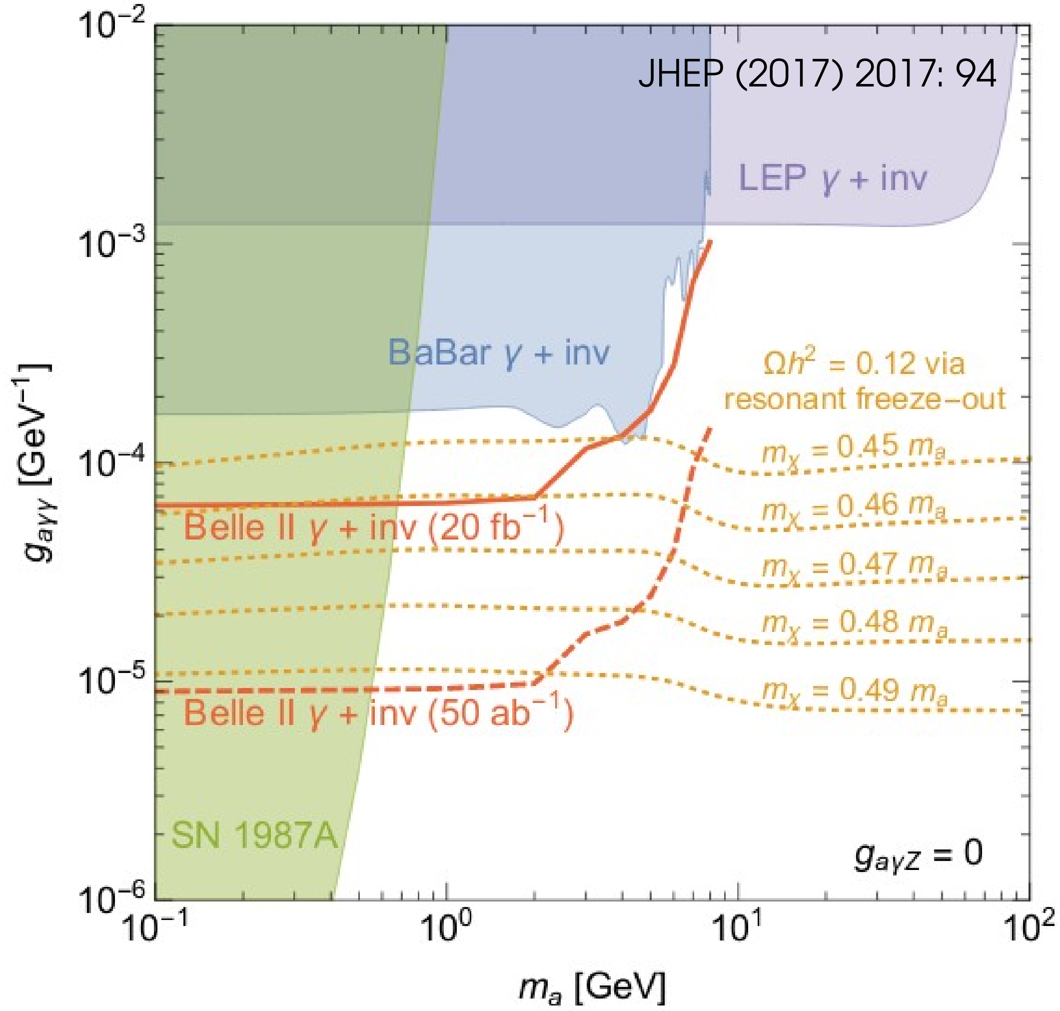
Only coupling to γ



With coupling to Z



Axion-like Particles: invisible decay

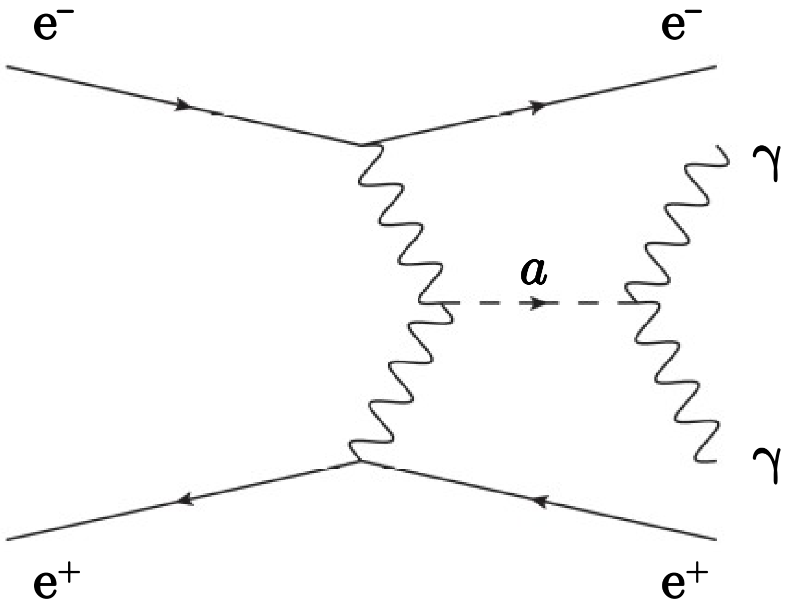


ALPs: low-mass region

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.

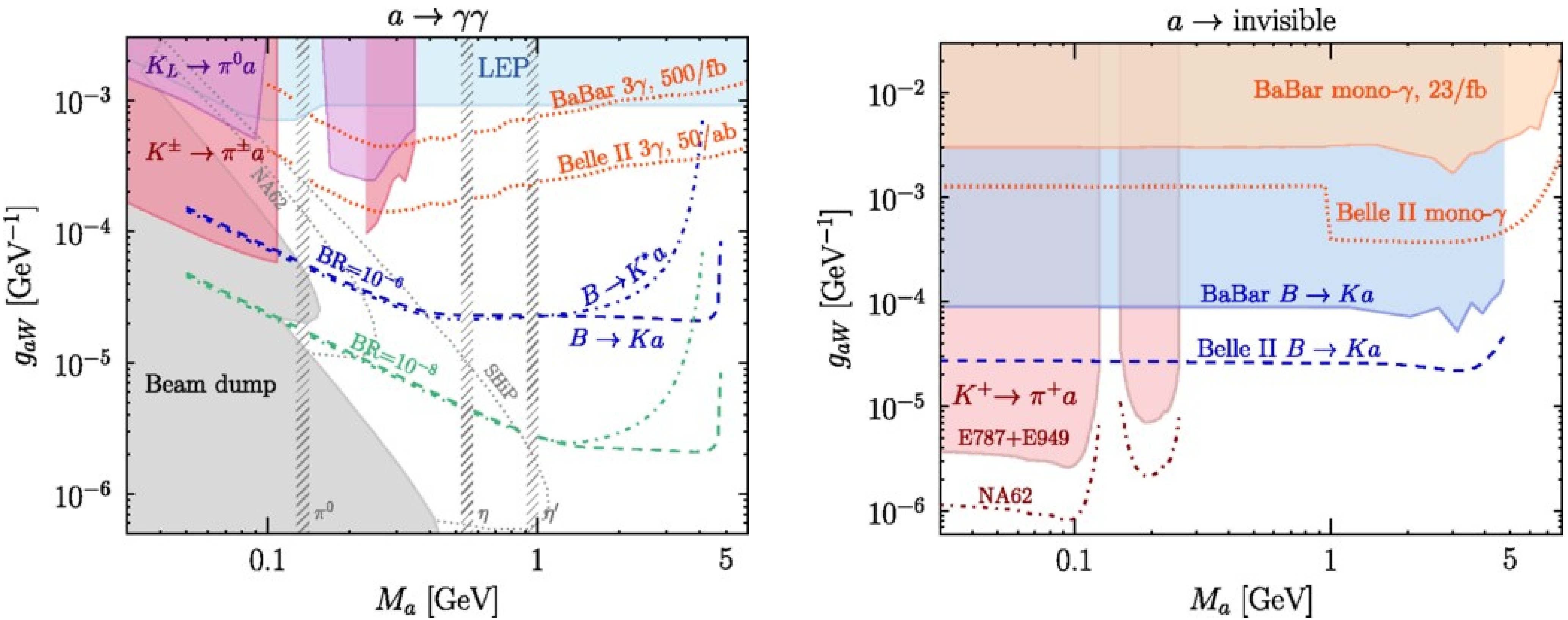
ALP-fusion



Pro: resolved clusters

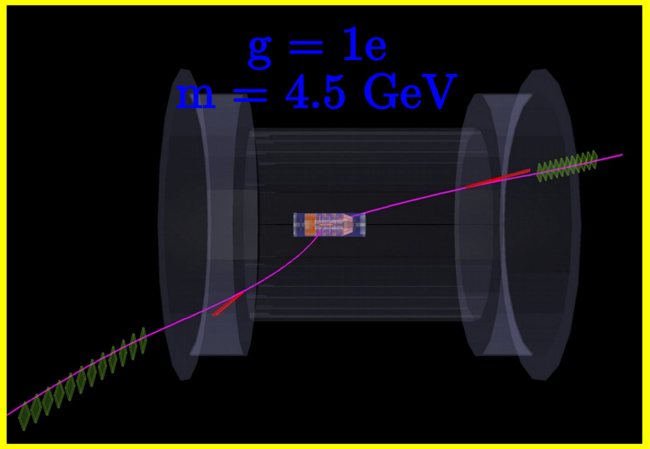
Con: very low energetic photons

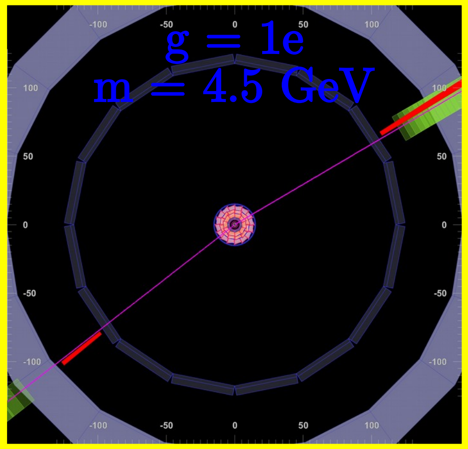
Axion-like Particles from B decays



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

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

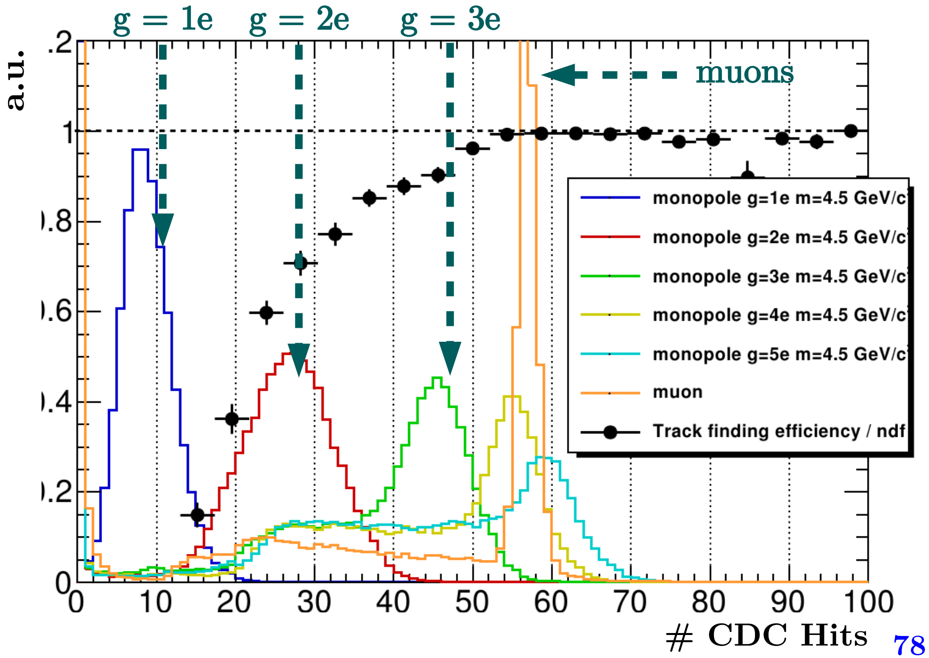
→ few hits in the CDC

→ **needed a dedicated tracking**

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

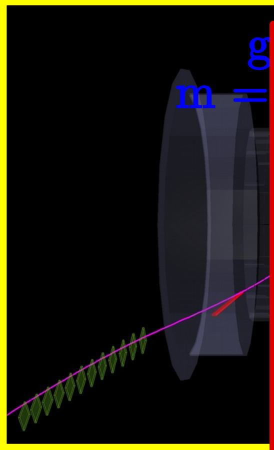
Lower magnetic charge not ruled out

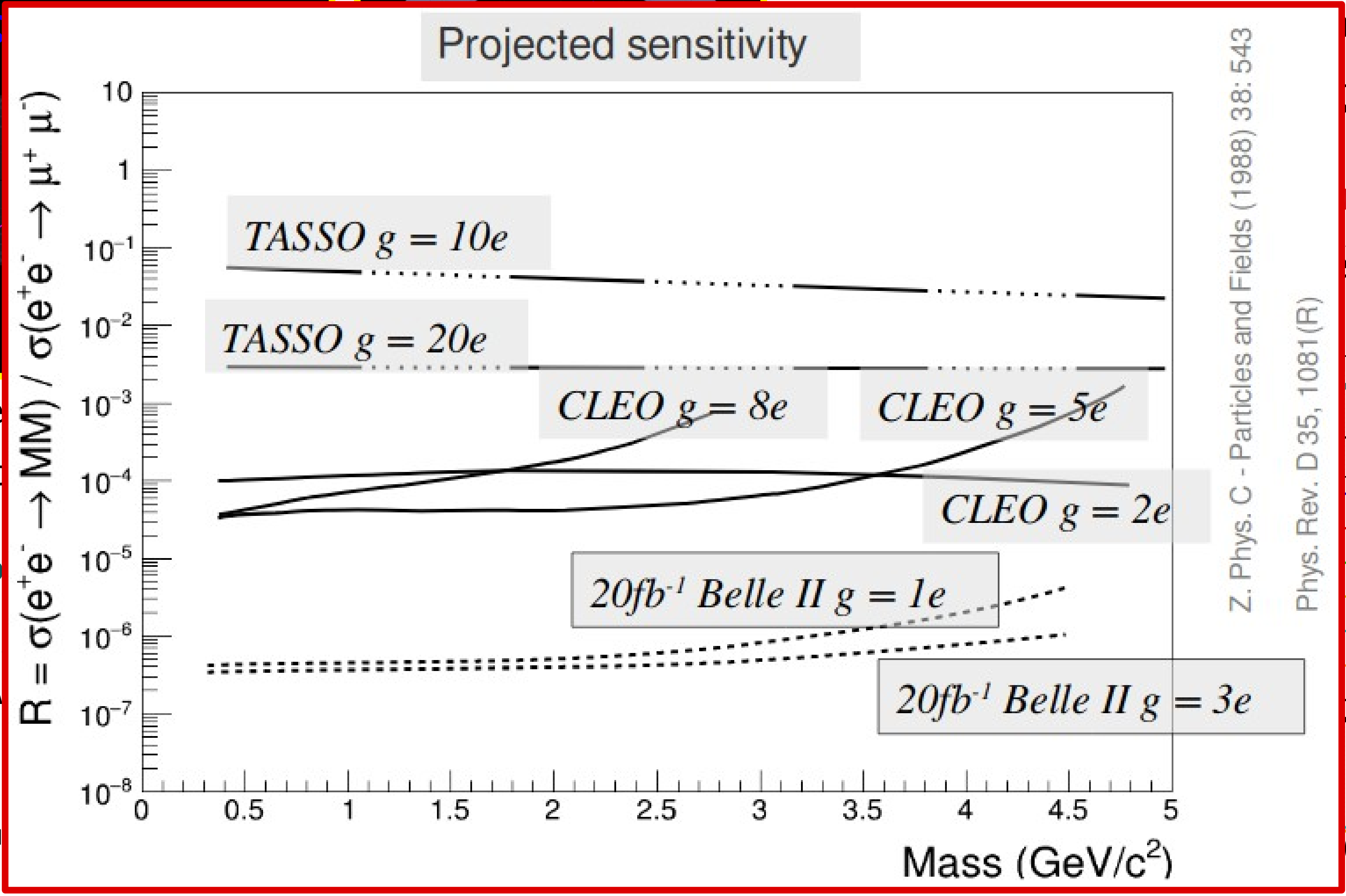
(and not covered at ∼GeV scale)



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

Magnetic monopoles





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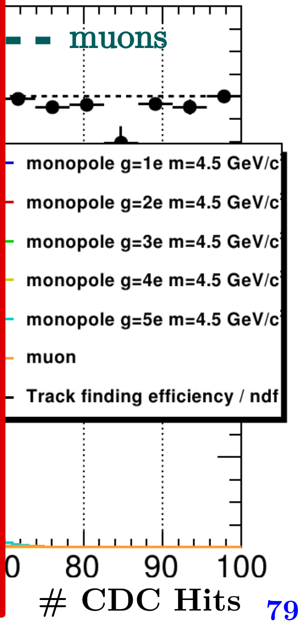

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monopo

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Complementa