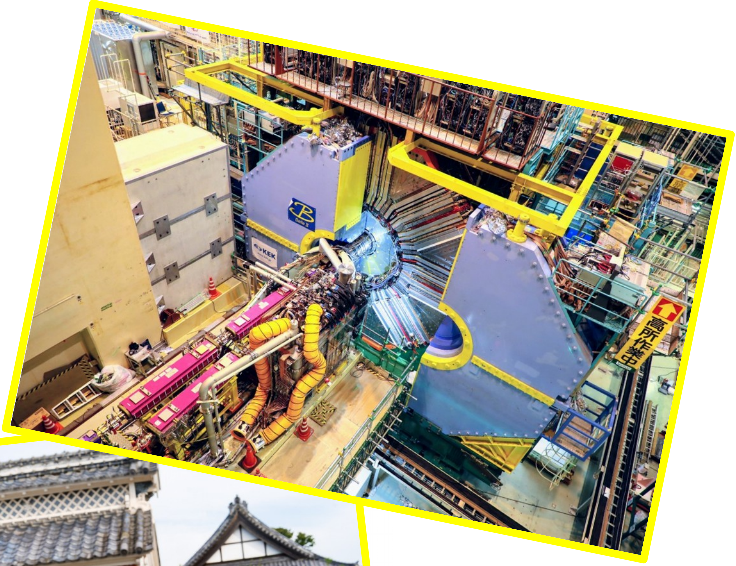


Dark Photon searches at the B-factories — a mini review —

Giacomo De Pietro

INFN ROMA TRE

Belle II

Phenomenology 2020 Symposium @ Pittsburgh

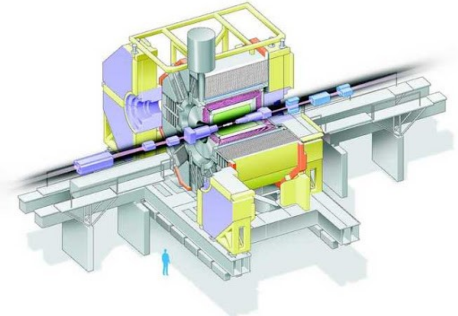
4-6 May 2020

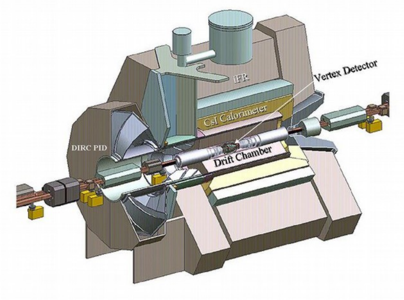
B-factories as Intensity Frontier experiments

B-factories are dedicated experiments at e^+e^- asymmetric-energy colliders for the production of quantum coherent $B\overline{B}$ pairs.

First generation of B-factories

(collected about 1.5 ab^{-1} of integrated luminosity)





BELLE

BABAR

The strenghts of a B-factory are:

- constrained kinematics;
- clean environment and lower background;
- hermetic detector;
- excellent PID capabilities;
- efficienct reconstruction of neutral particles.

B-factories as Intensity Frontier experiments

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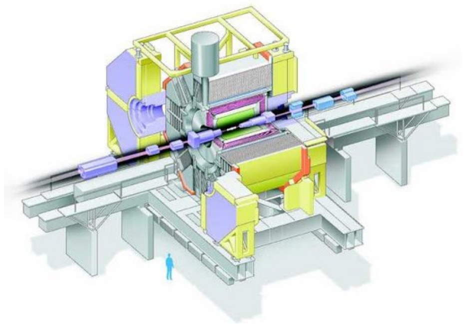
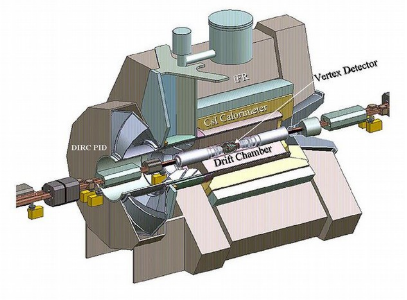
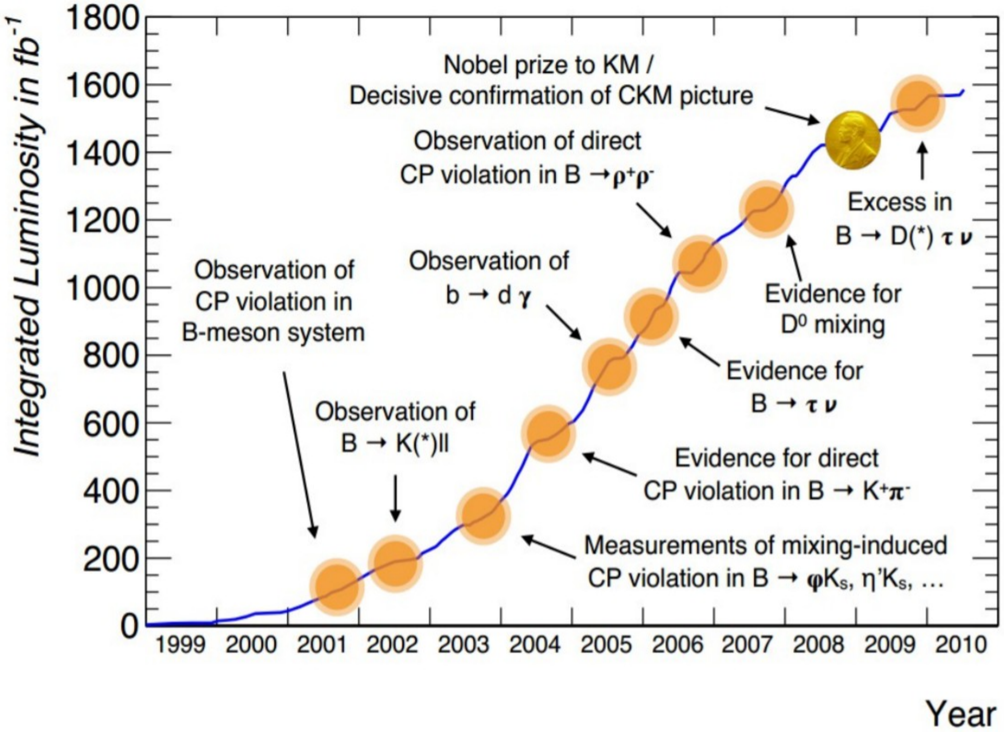




BELLE

BABAR

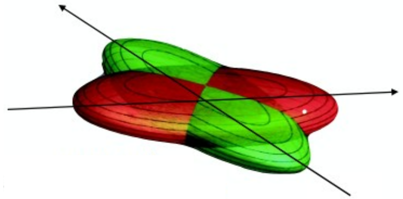


SuperKEKB: a new Intensity Frontier machine

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

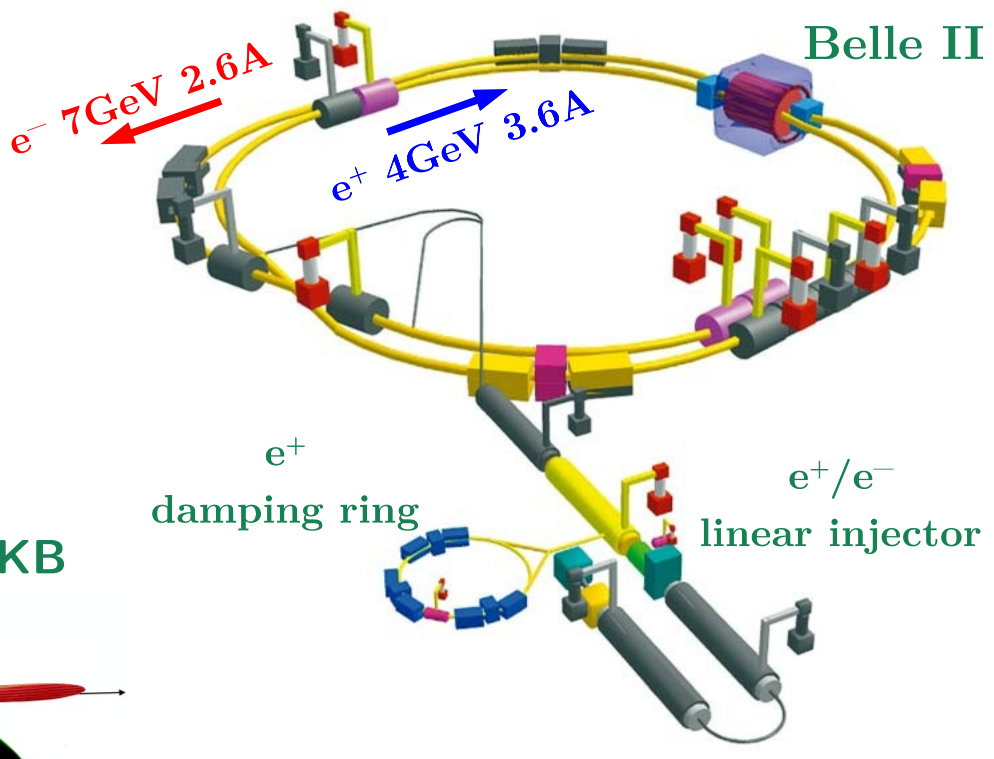
SuperKEKB

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



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

SuperKEKB: a new Intensity Frontier machine

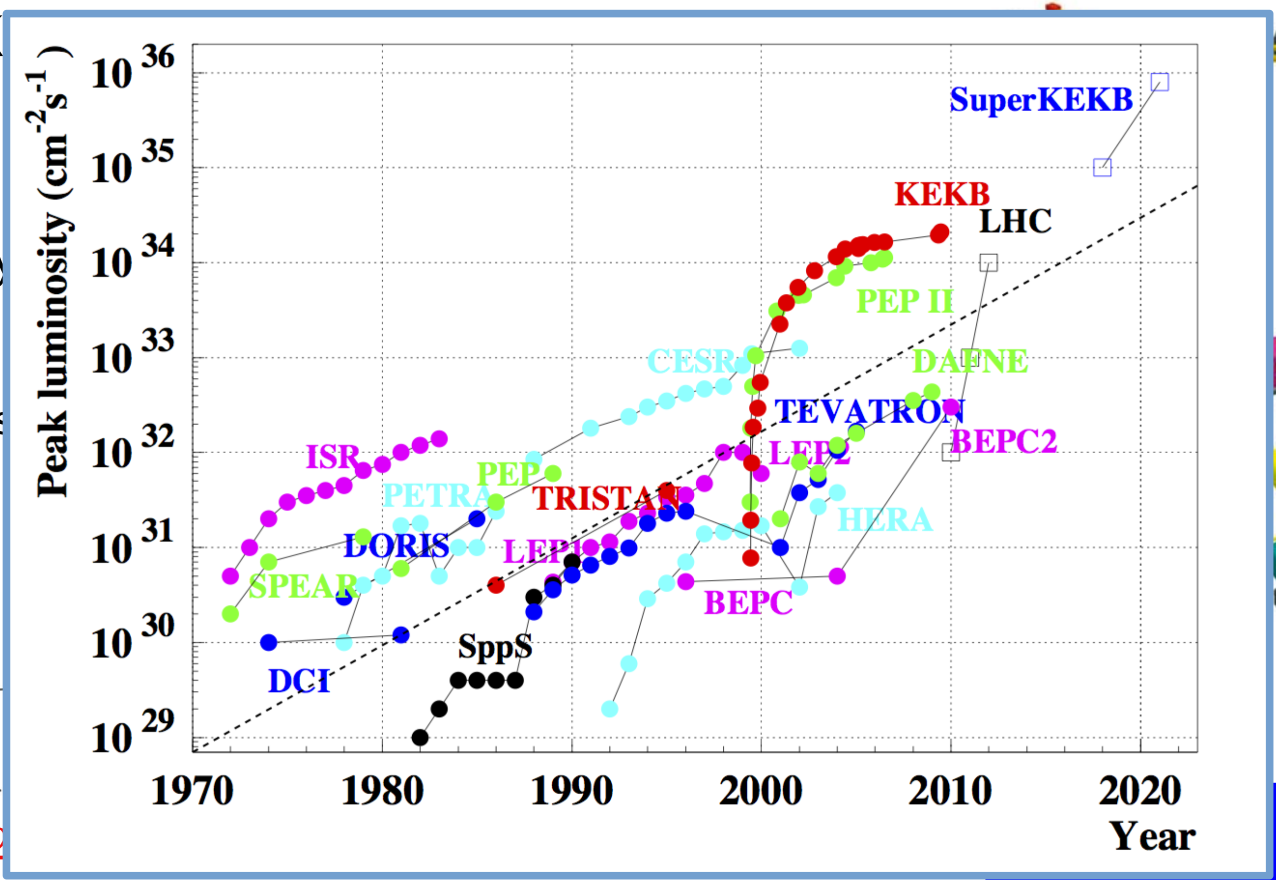
SuperKEK

located at

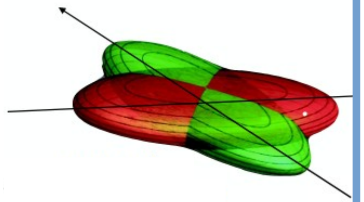
It's an asy

operating

(Υ(4S), but poss



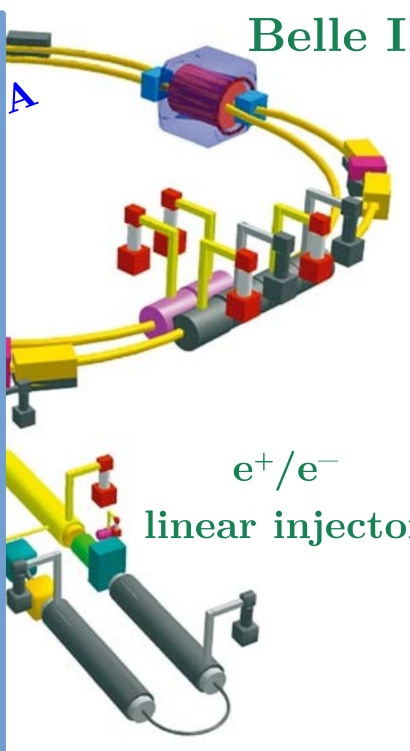
KEKB



I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

β^*_y (mm): ~ 0.27/0.3



Belle II

e^+/e^- linear injector

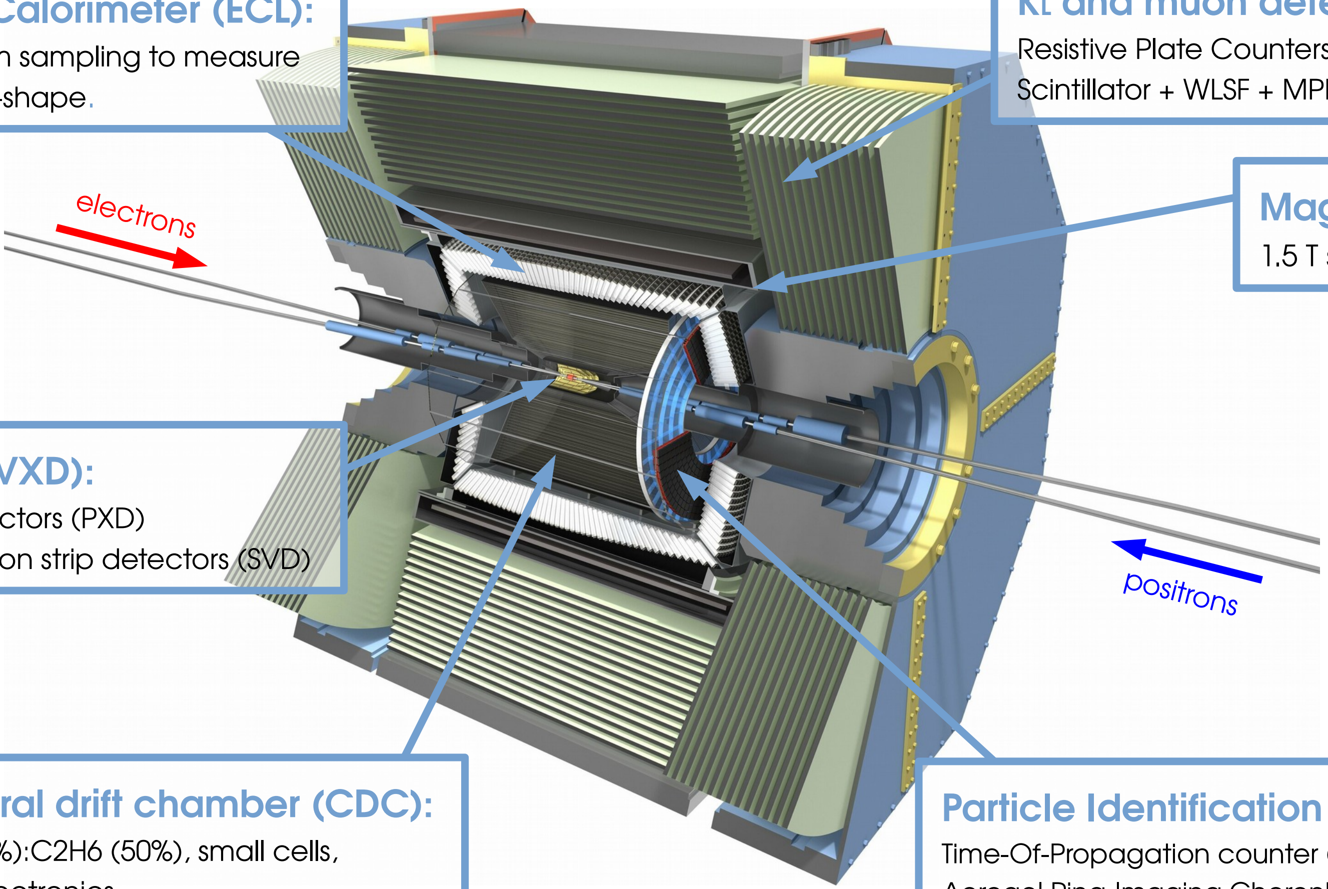
luminosity:

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

Belle II: a new Intensity Frontier 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)

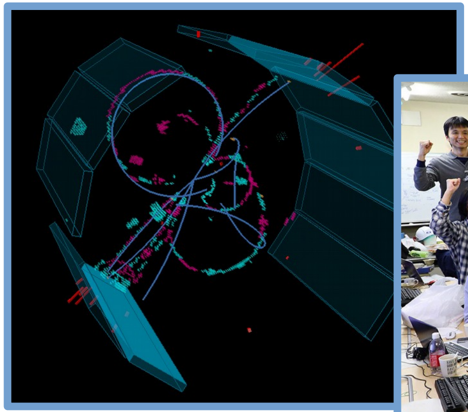
Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

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)

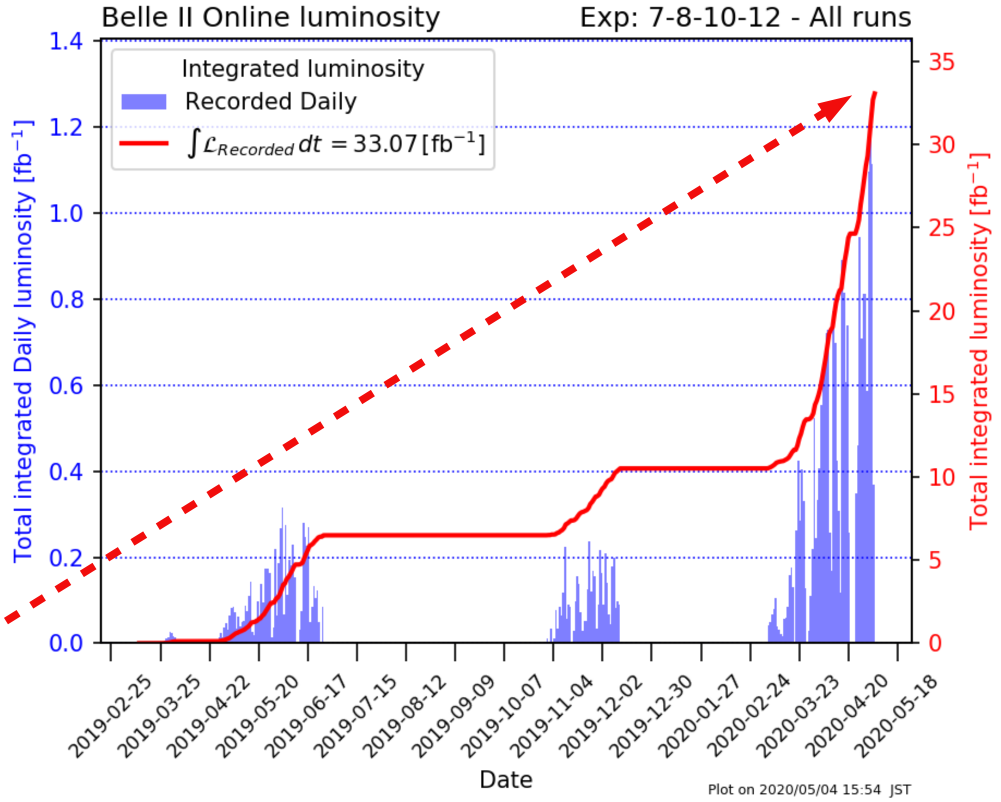
SuperKEKB and Belle II operations

First collisions: 26th April 2018



Collected 0.5 fb^{-1} in 2018

Collected about 33 fb^{-1} since 2019



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

Dark Matter

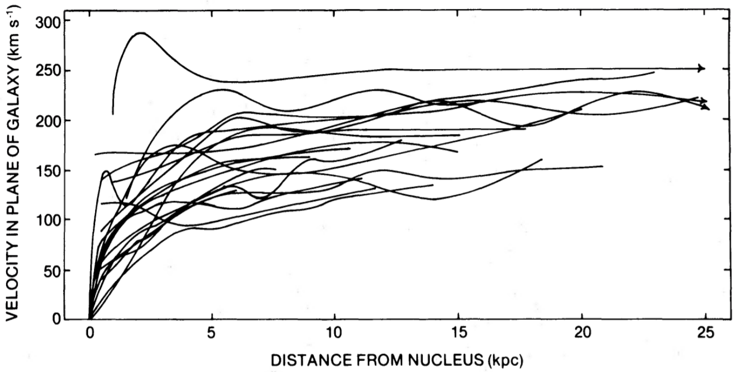
It is “dark”.

It exists...

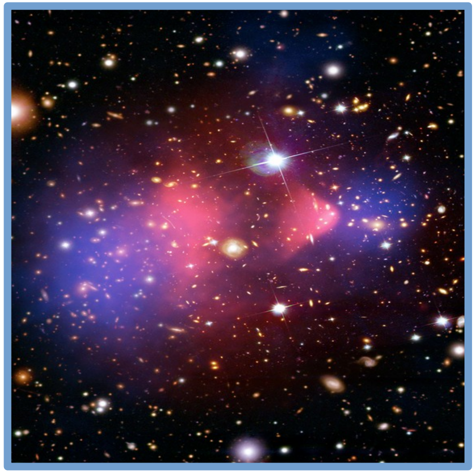
A lot of experimental techniques
to probe the Dark Matter existance:

- production at colliders;
- production at fixed target experiments;
- indirect astronomic searches;
- direct underground searches.

Rotational curves of the galaxies



Bullet clusters



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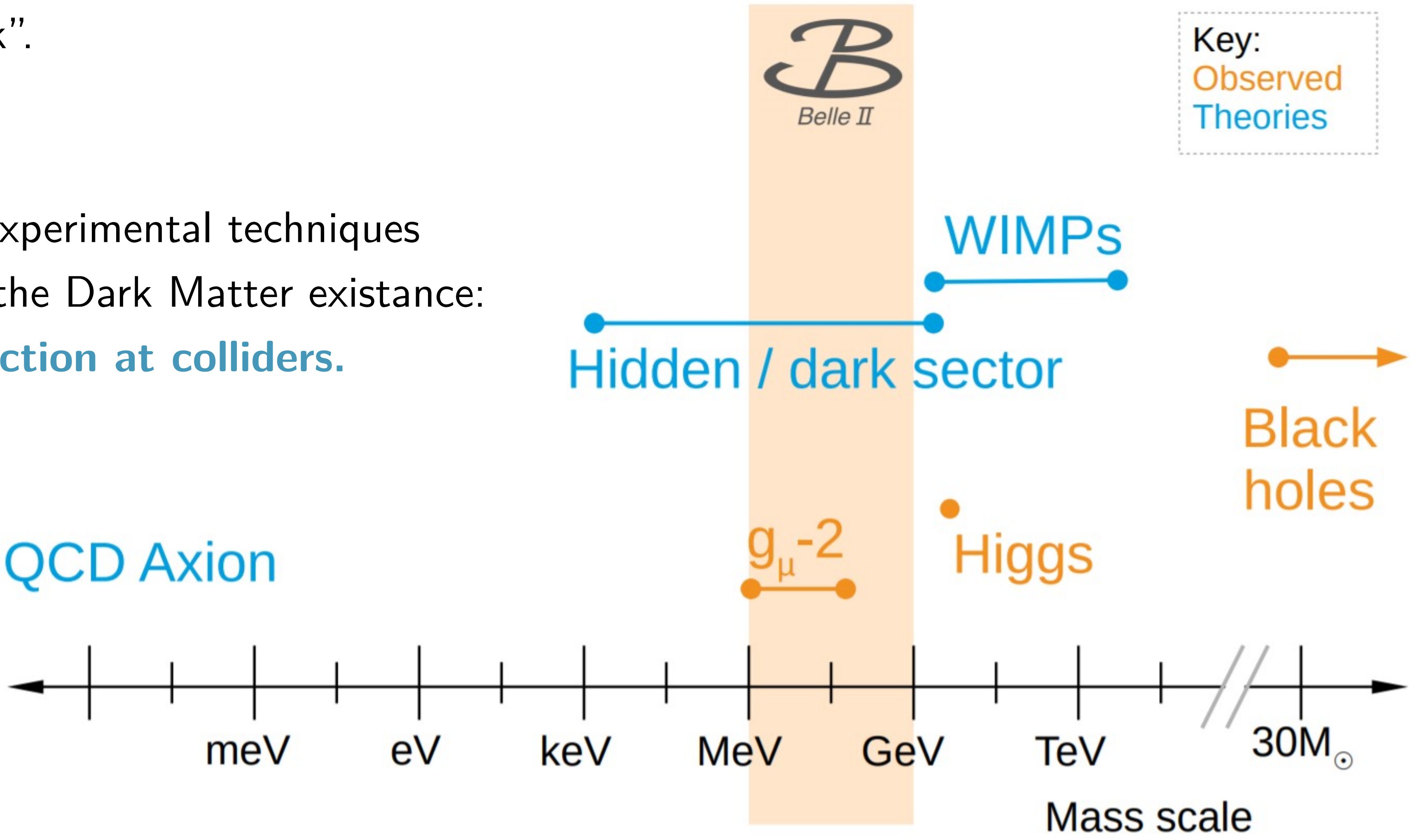
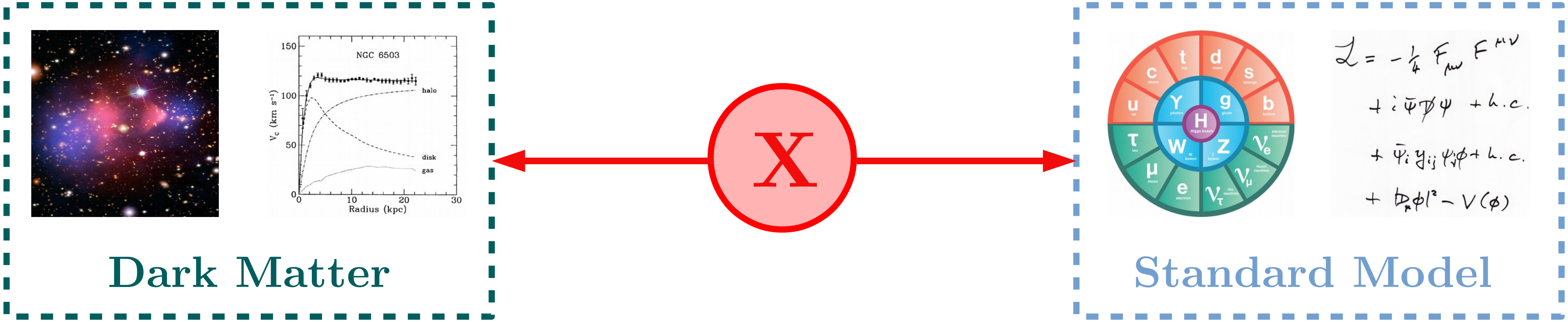


Dark Matter coupling to SM



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

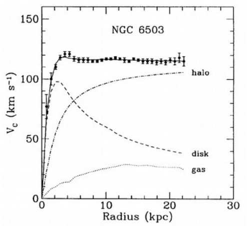
Vector portal → Dark Photon / Z'

Scalar portal → Dark Higgs / Dark Scalar

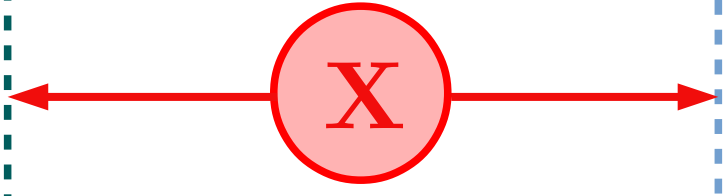
Pseudoscalar portal → Axion-Like Particles

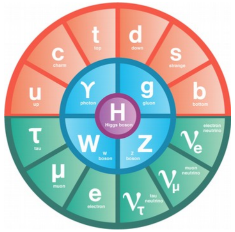
Neutrino portal → Sterile Neutrinos

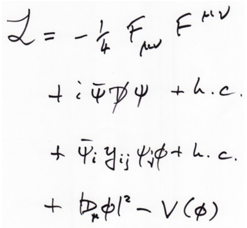
Dark Matter coupling to SM



Dark Matter







Standard Model

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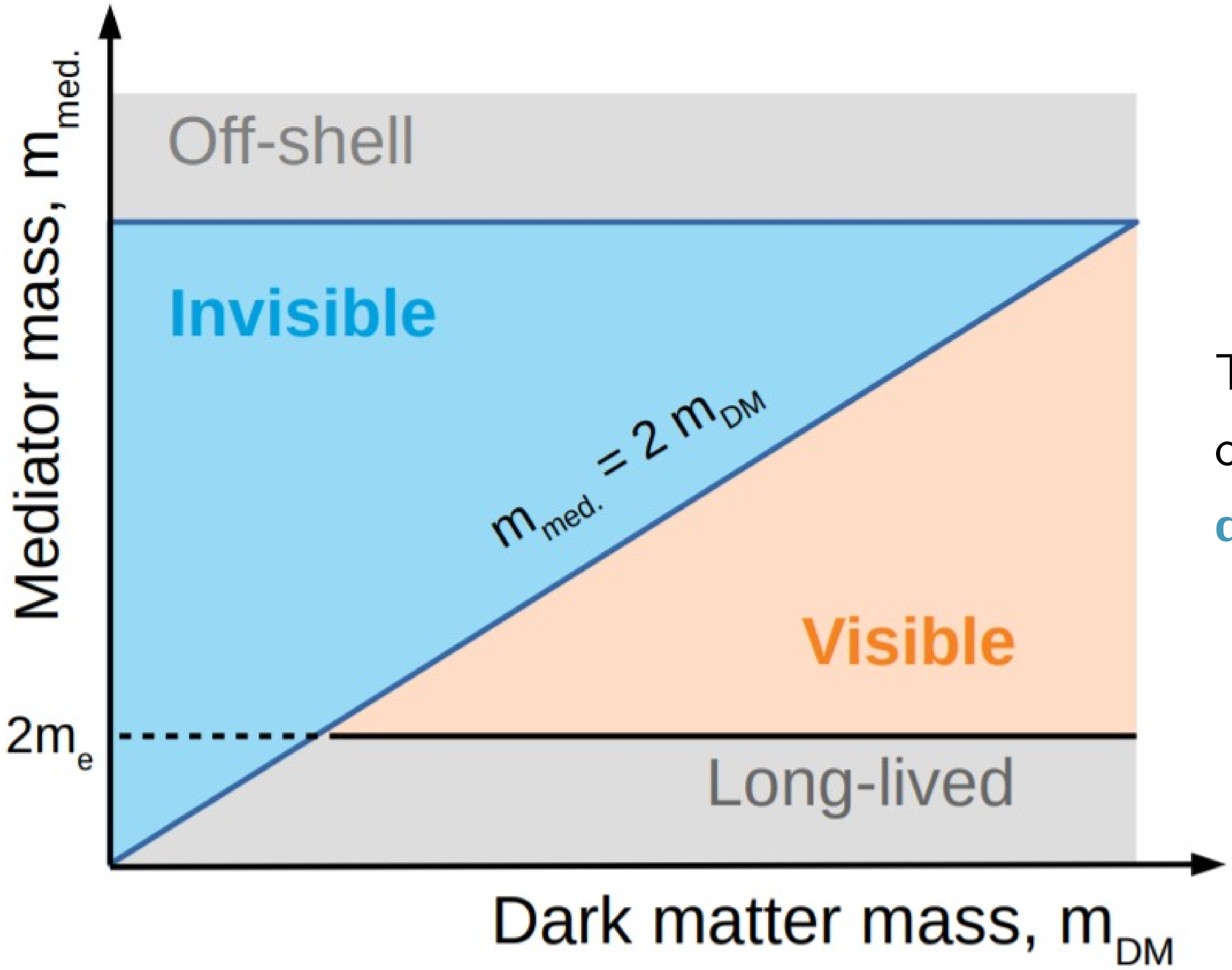
Vector portal → Dark Photon / Z'

Scalar portal → **Dark Higgs** / Dark Scalar

Pseudoscalar portal → Axion-Like Particles

Neutrino portal → Sterile Neutrinos

A rule of thumb...



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

Dark Photon

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

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

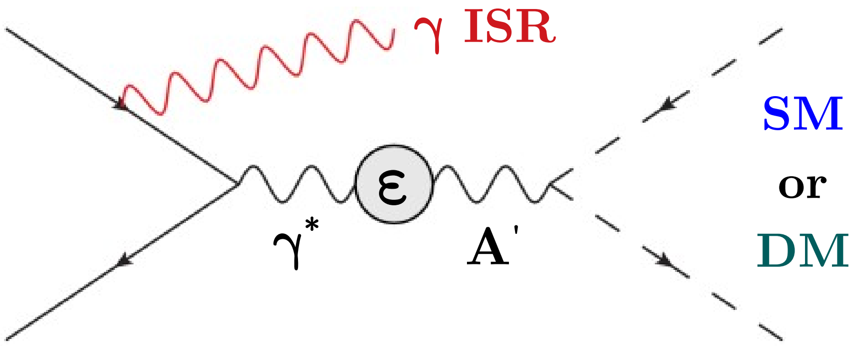
Batell et al. (2009), *arXiv:0903.0363*

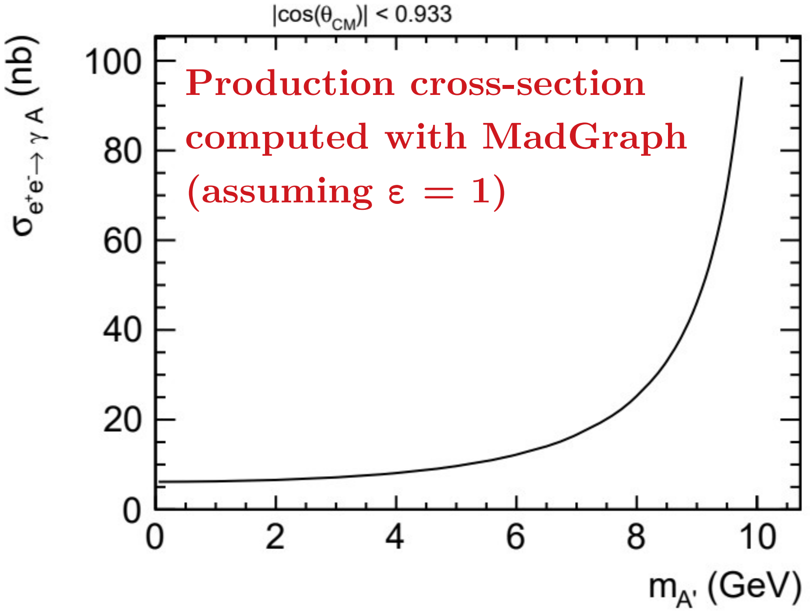
Depending on DM mass, a dark photon decays to:

DM (if $m_{DM} < ½\ m_{A'}$) → **invisible decay**

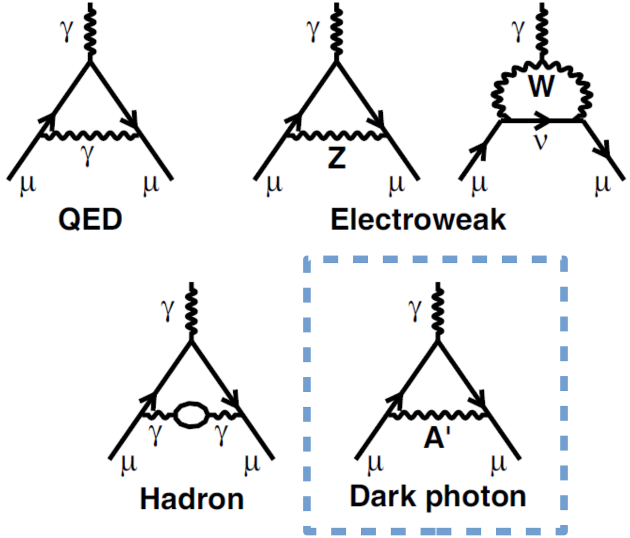
SM (if $m_{DM} > ½\ m_{A'}$) → **visible decay**

(only prompt decays probed at B-factories)

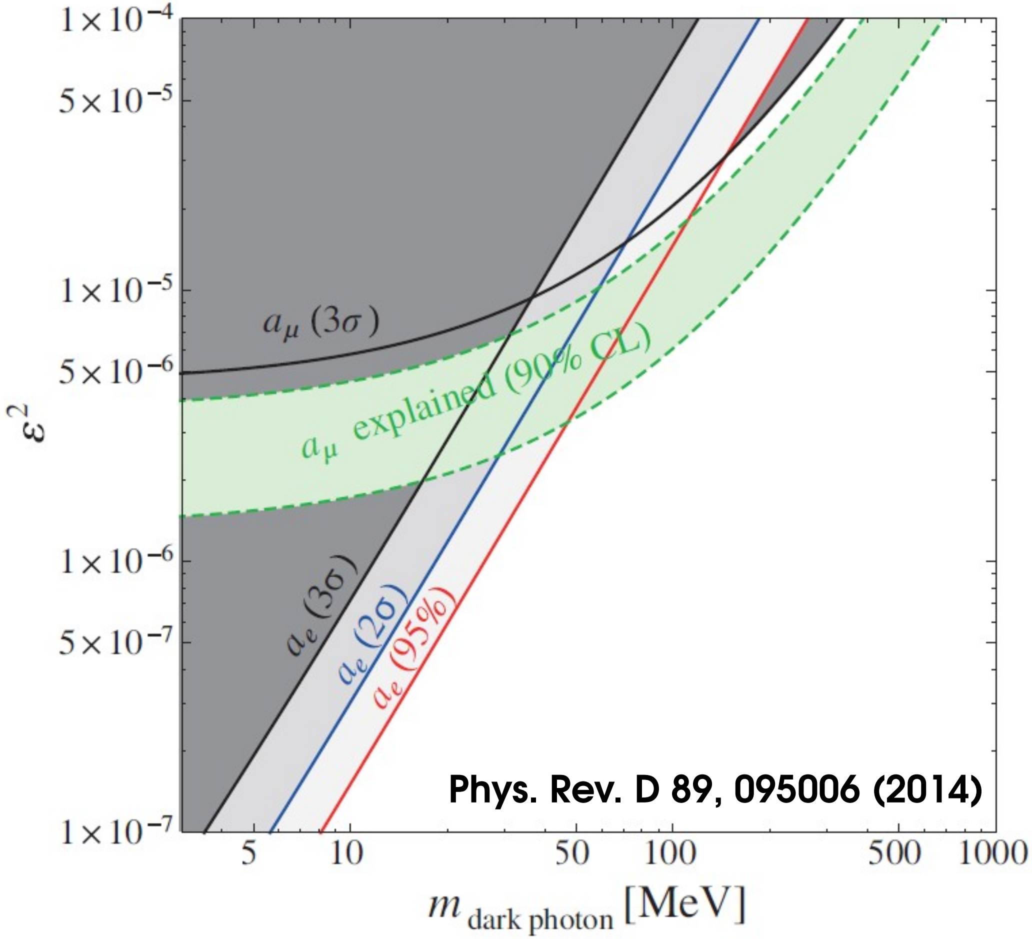




Dark Photon as a solution for the g-2 anomaly



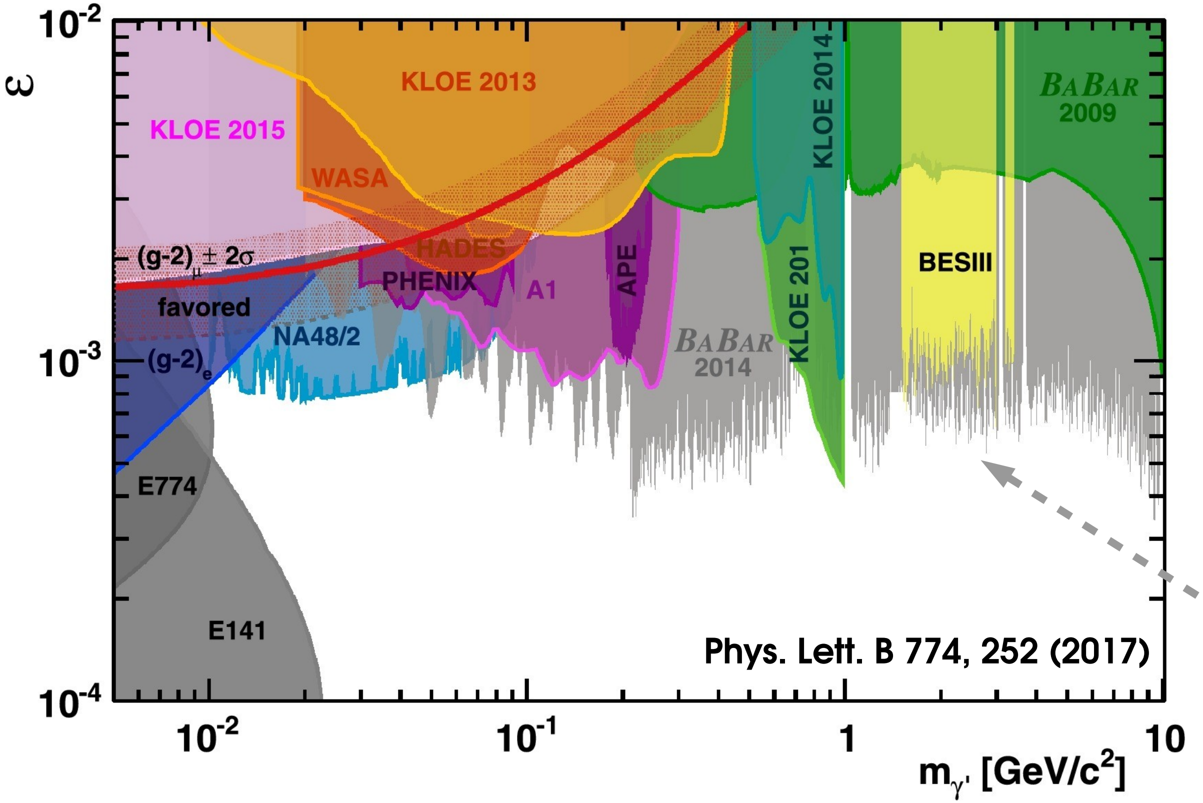
A Dark Photon below 10 GeV can provide a **solution** to the $(g\text{-}2)_\mu$ anomaly!



Phys. Rev. D 89, 095006 (2014)

A' $\rightarrow$ leptons: 2019 status

Analysis strategy: look for a peak on the invariant mass distribution of the dilepton pair over a large QED background.



A' → leptons: 2020 status

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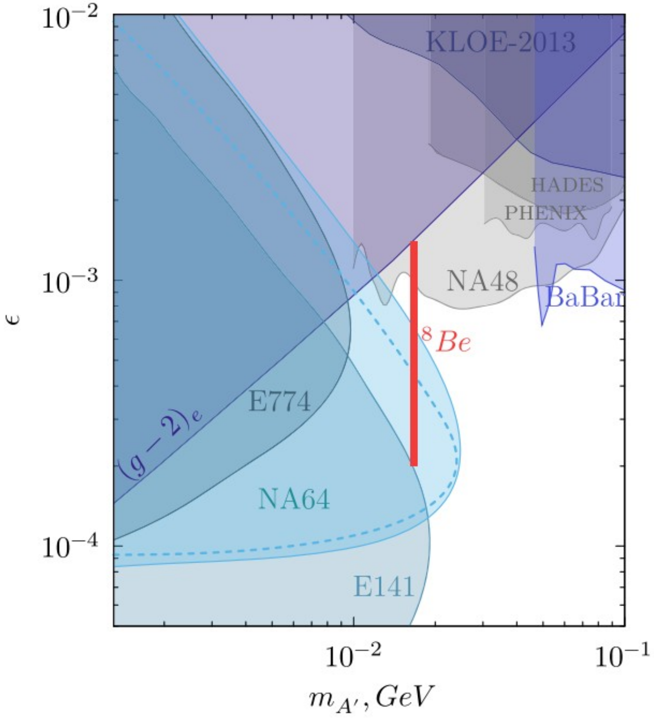
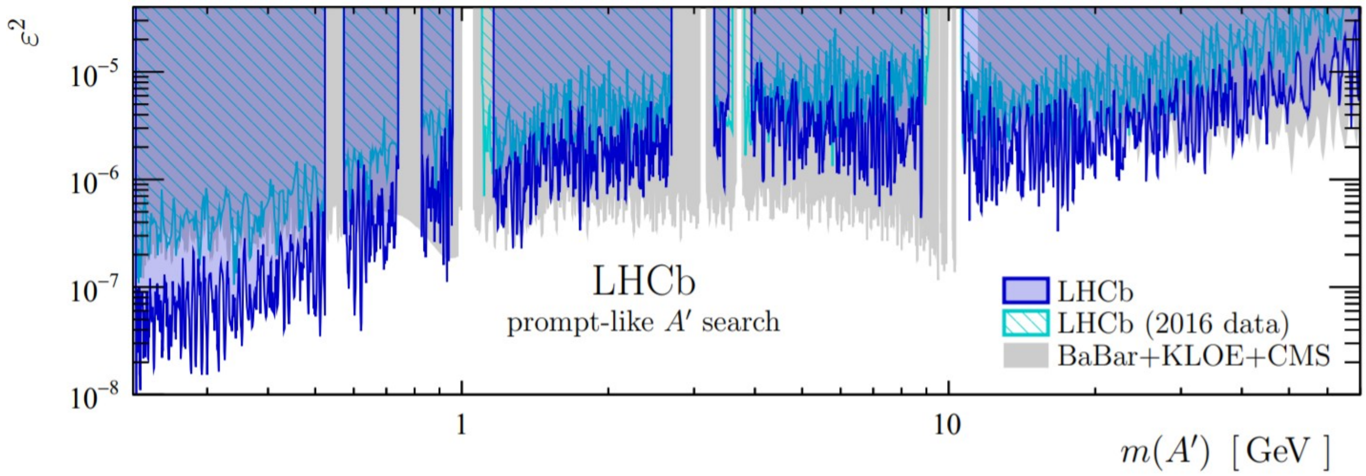


NA64, A' → $e^+ e^-$

Phys. Rev. Lett. 124, 041801 (2020)

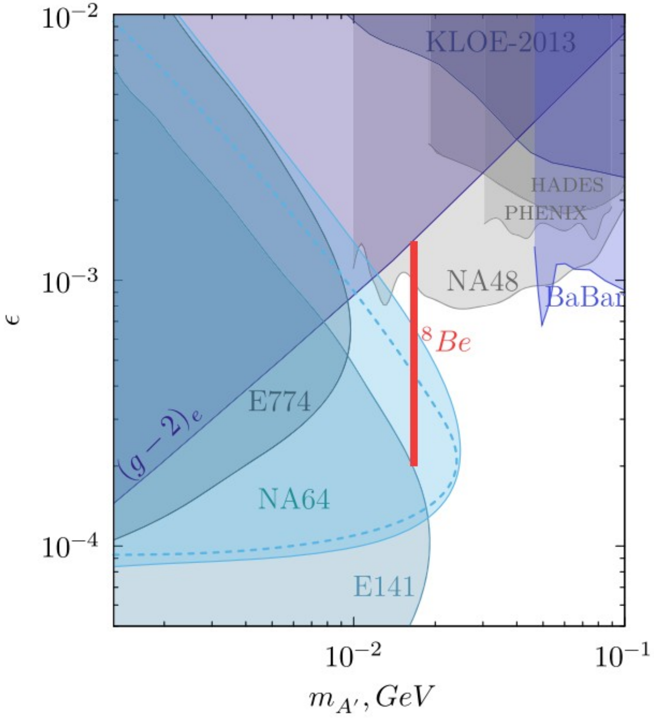
LHCb, A' → $\mu^+ \mu^-$

Phys. Rev. Lett. 124, 041801 (2020)



A' → leptons: Belle II sensitivity

Analysis strategy: look for a peak on the invariant mass distribution of the dilepton pair over a large QED background.



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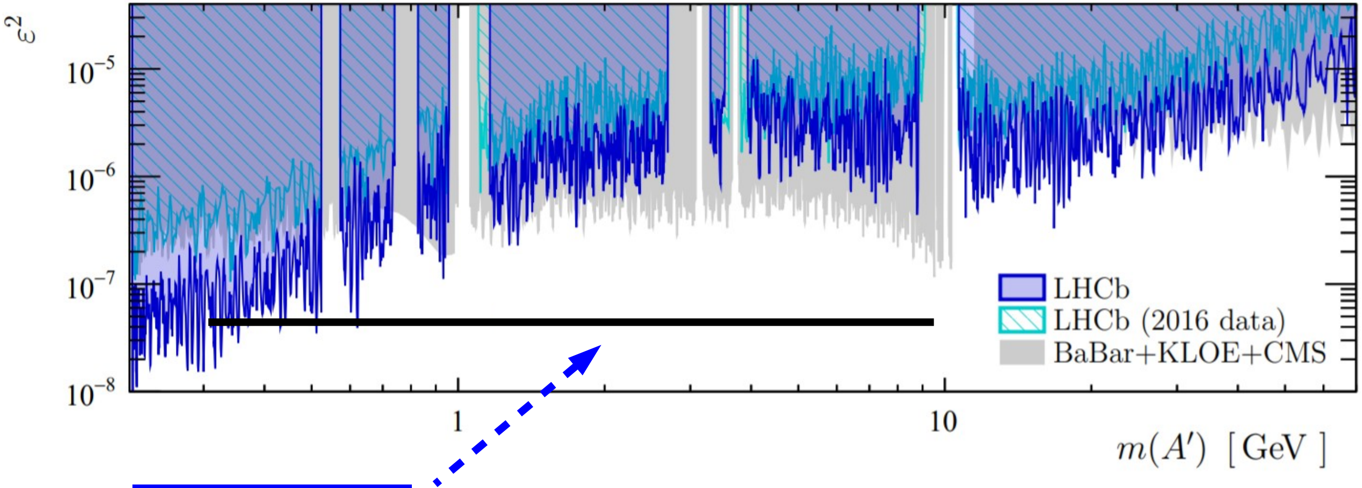
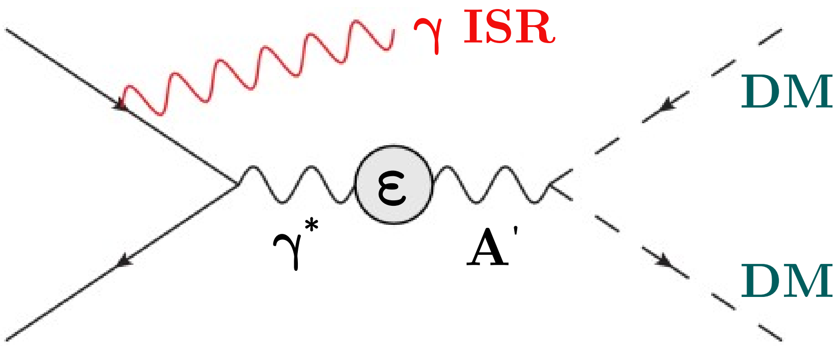


Belle II expected sensitivity with 50 ab^{-1}

A' → invisible: strategy

BaBar searched for the invisible decay of a dark photon.



On-shell dark photon ($m_{DM} < ½ \, m_{A'}$)

→ monochromatic **ISR** photon with:

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

Used about 50 fb^{-1} recorded with a dedicated single photon trigger in the final BaBar running period:

→ trigger threshold: $E_\gamma^{CM} > 1.5$ GeV

A' → invisible: background

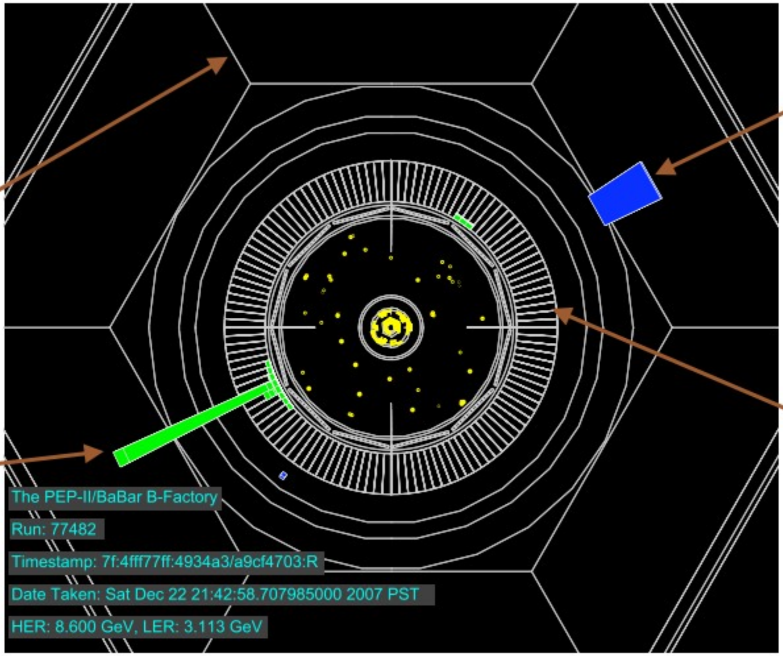
Main background component:

- $e^+e^- \to \gamma\gamma$, with a γ undetected

photon shower detected in muon system. Inefficiency produces single photon events.

no efficiency in muon system near sector boundaries

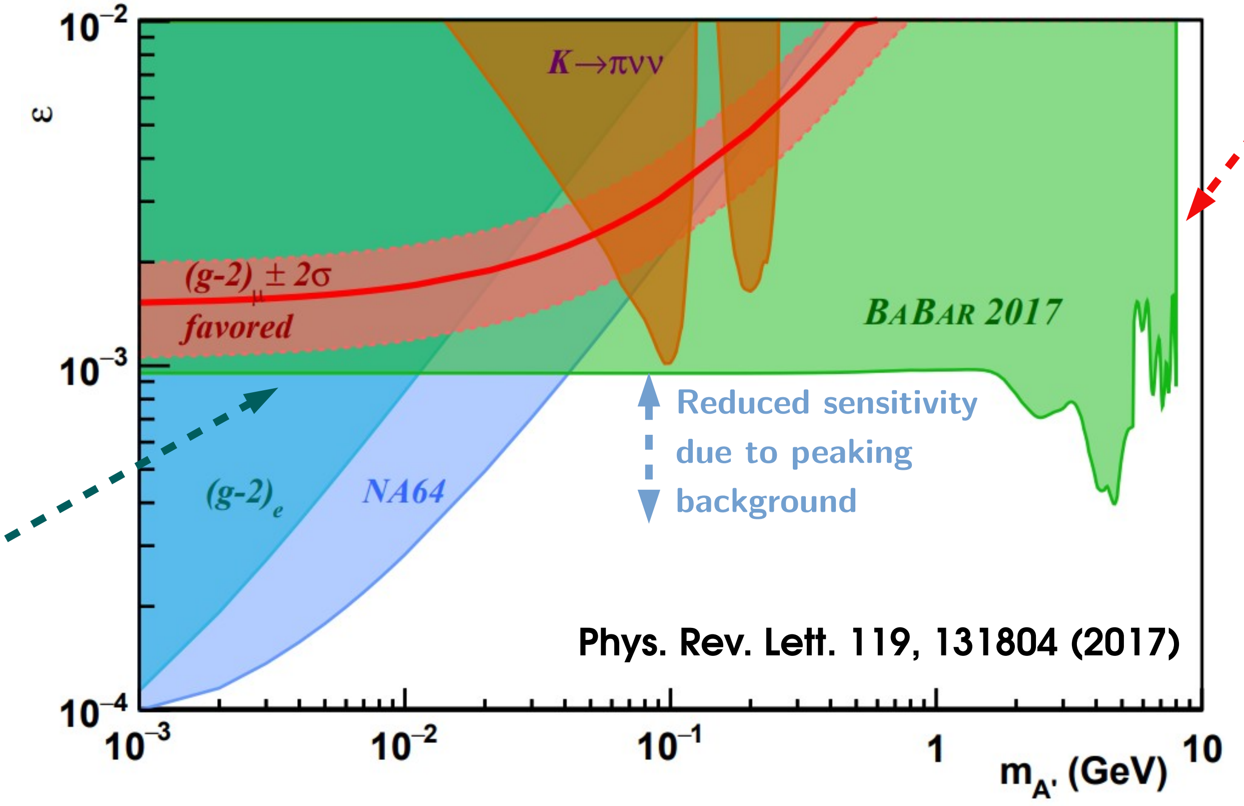
beam-energy photon shower



azimuthal gaps between crystals align with collision point

Also $e^+e^- \to e^+e^-\gamma$, neither $e^\pm$ in the detector.

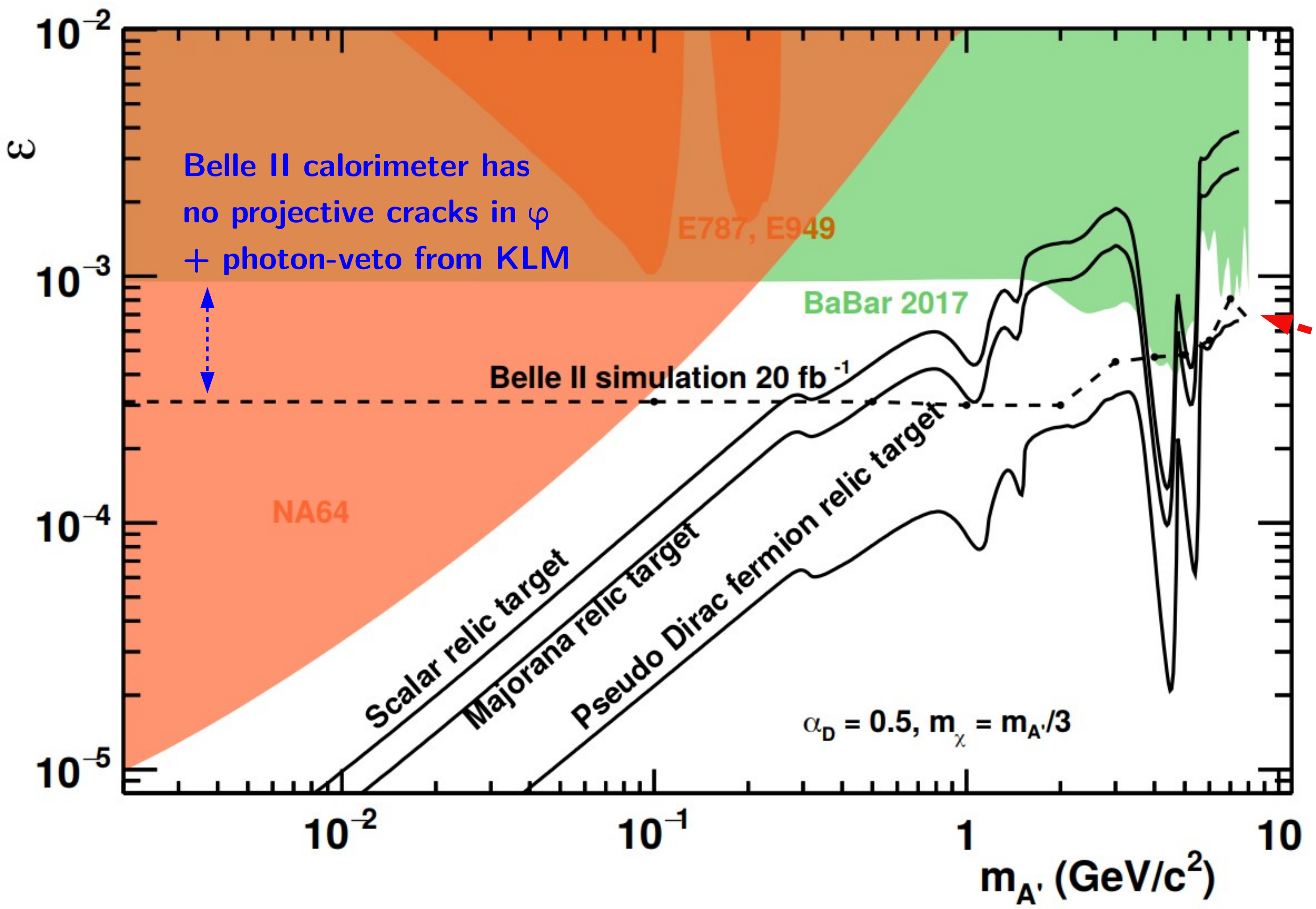
A' → invisible: results



Limited by beam energy and trigger threshold

Flat because one cannot resolve different masses here (single photon with ~beam energy)

A' → invisible: Belle II sensitivity



Trigger threshold lower than in BaBar

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

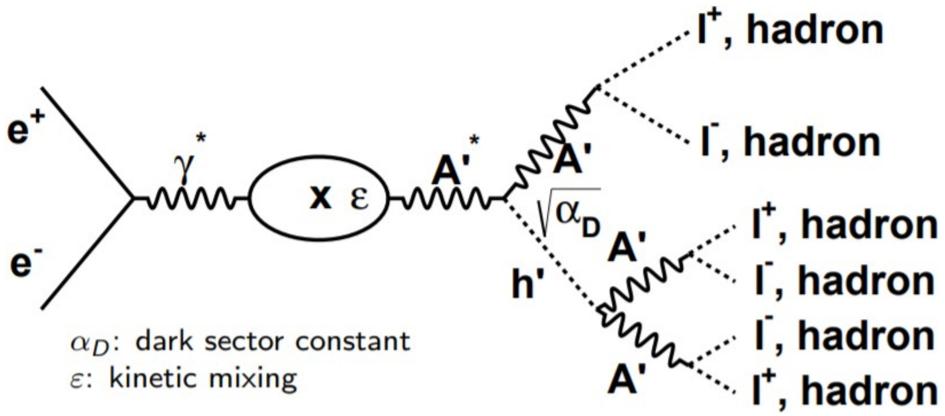
N. Toro, private communication (2017)

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

The Belle II Physics Book, *arXiv:1808.10567*

Dark Higgs-strahlung at Belle and BaBar

Belle and BaBar searched for the production of a Dark Photon (A') and a Dark Higgs (h') in the so-called Higgs-strahulung channel.



Assuming **prompt decays** for A' and h' and also $\mathbf{m_{h'} > 2m_{A'}}$.

If $\alpha_D = 1$, this is the most sensitive search for a Dark Photon!

Note: the Dark Photon mass could be generated via a spontaneous symmetry mechanism adding a Dark Higgs to the theory.

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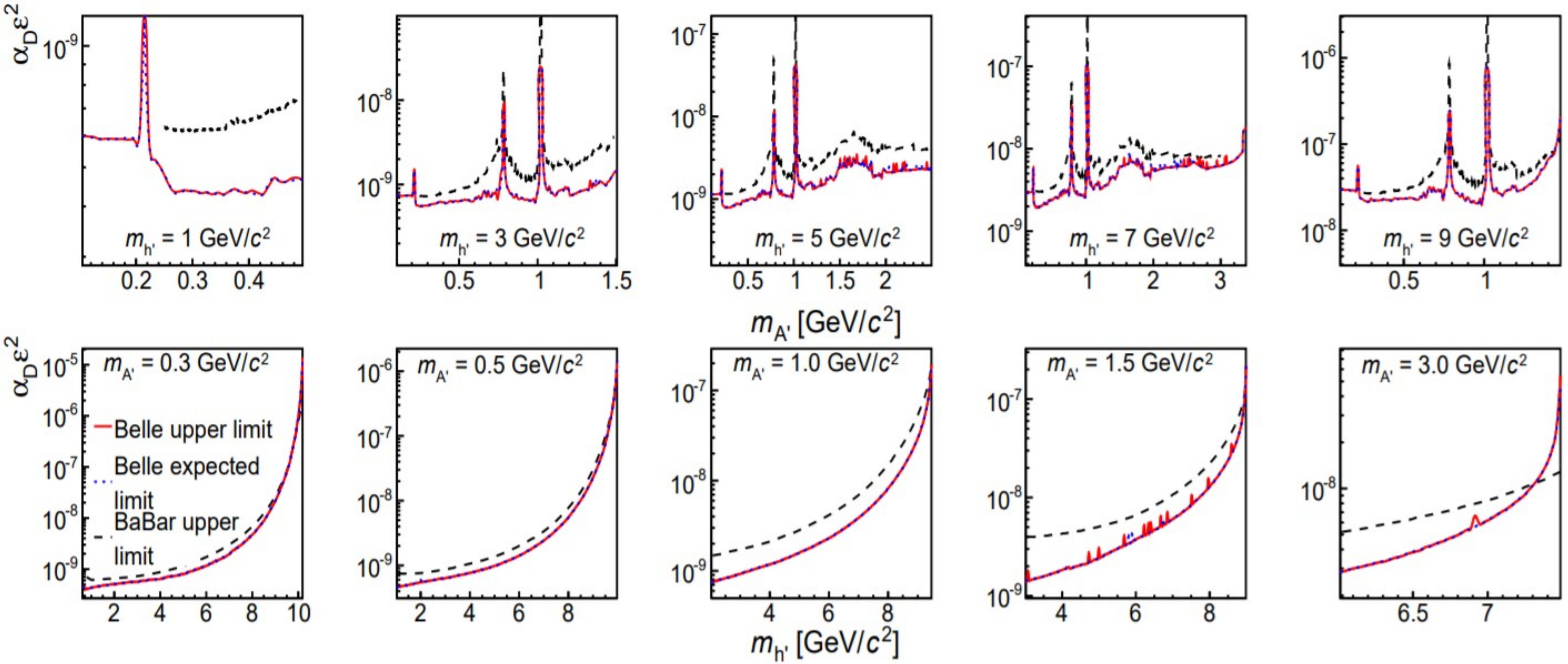
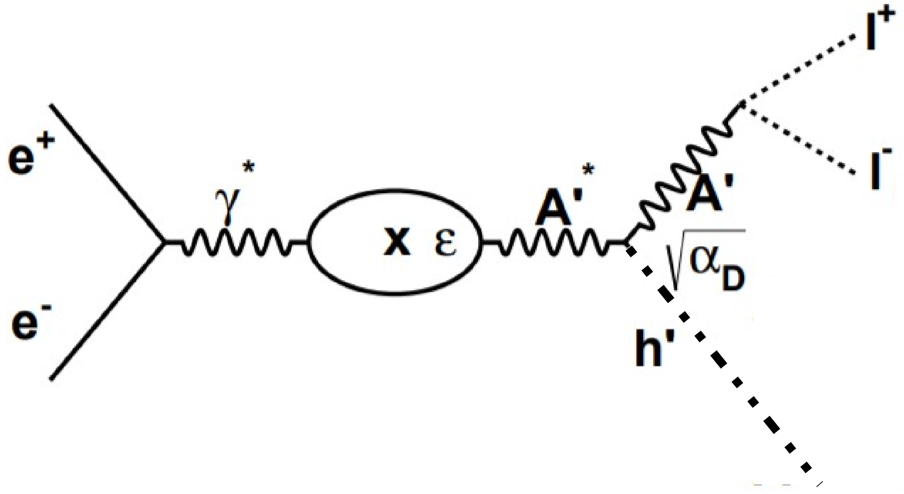


Phys. Rev. Lett. 114, 211801 (2015), Phys. Rev. Lett. 108, 211801 (2012)

Dark Higgs-strahlung at Belle II

Belle II is looking for a complementary case using the early data set:

if $m_{h'} < m_{A'}$, the h' is long-lived and **escapes detection**.



If $A' \to \mu^+ \mu^-$ we have 2 charged particles in the final state and missing energy:

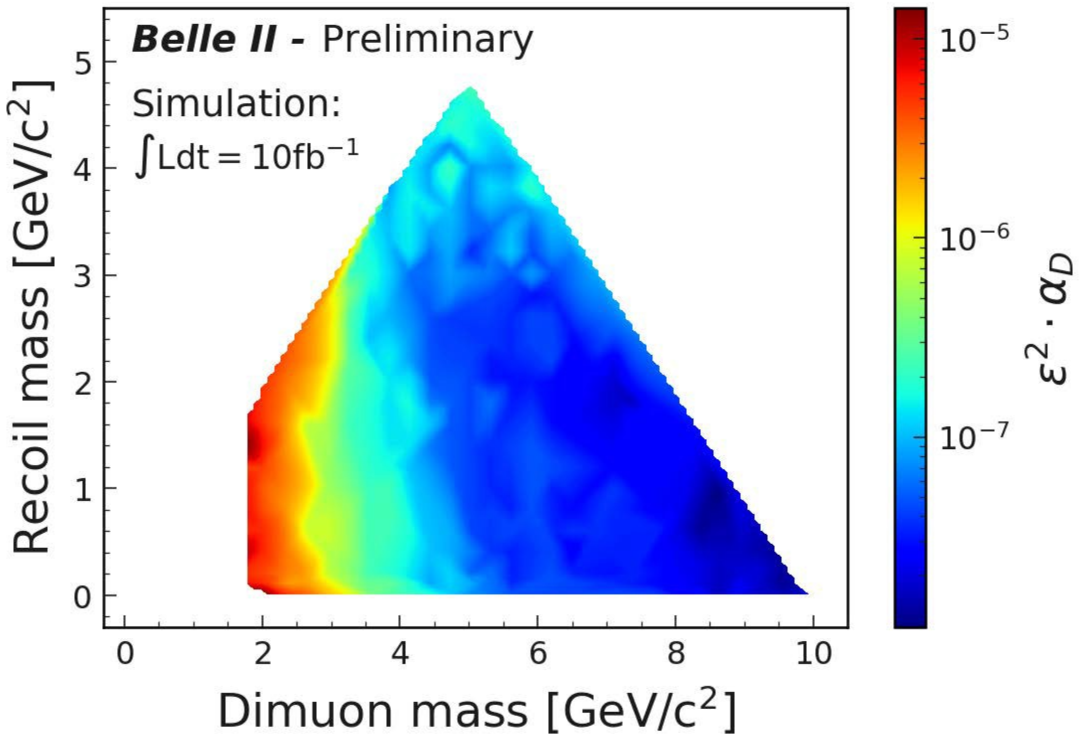
- looking for a peak in both **direct mass** (A') and **recoil mass** (h');
- only investigated by KLOE.

Dark Higgs-strahlung at Belle II

Belle II is looking for a complementary case using the early data set:

if $m_{h'} < m_{A'}$ the h' is long-lived and **escapes detection**.

No systematics into account.



Belle II can be competitive using the 2019 data set ($\sim$ 10 fb^{-1}).

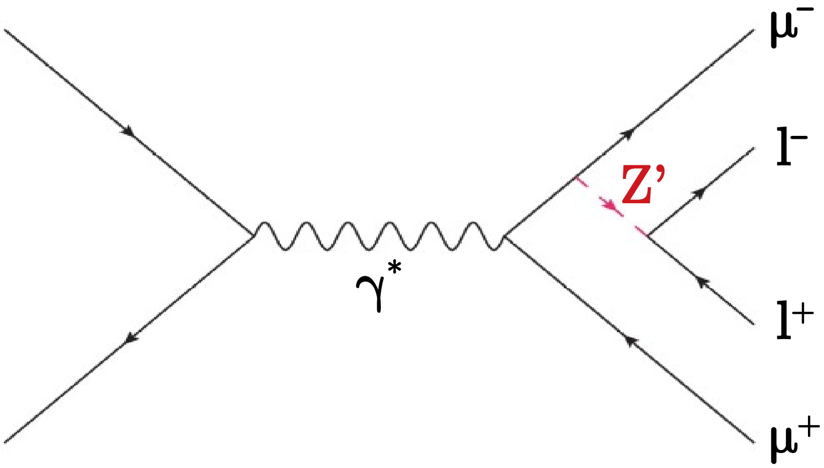
Still unconstrained region beyond the KLOE coverage.

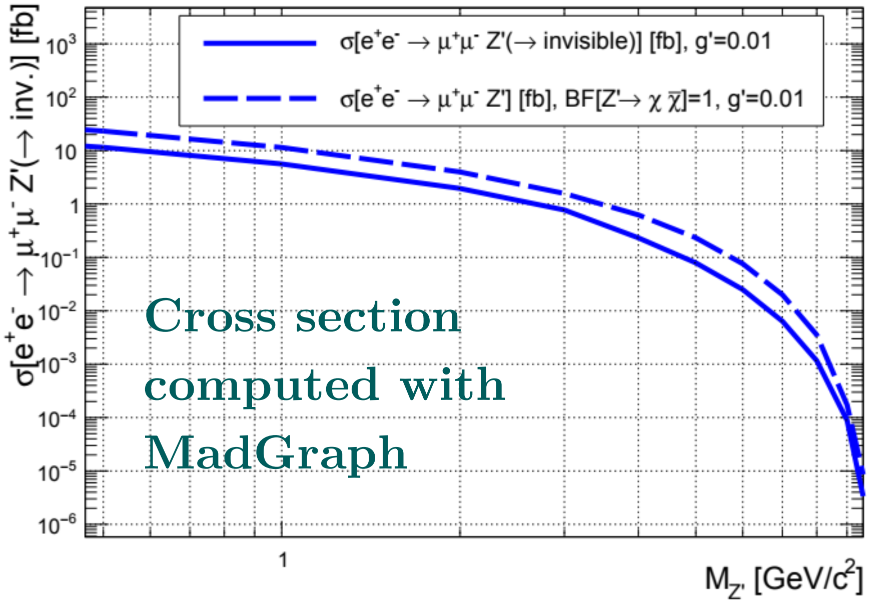
A different “Dark Photon”: $L_\mu - L_\tau$ model

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

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

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





Interesting because the existance of such a boson could explain some of the current anomalies:

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

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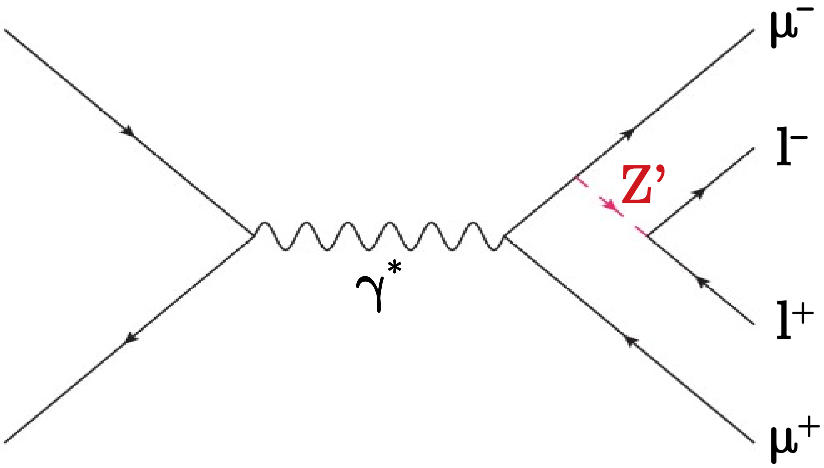
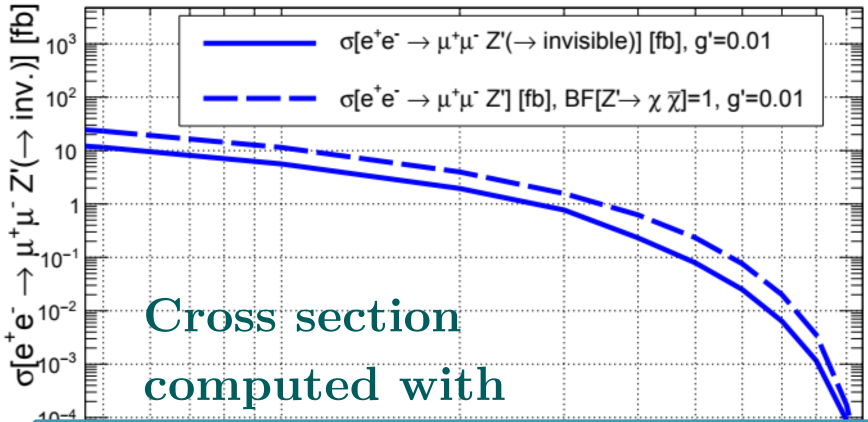
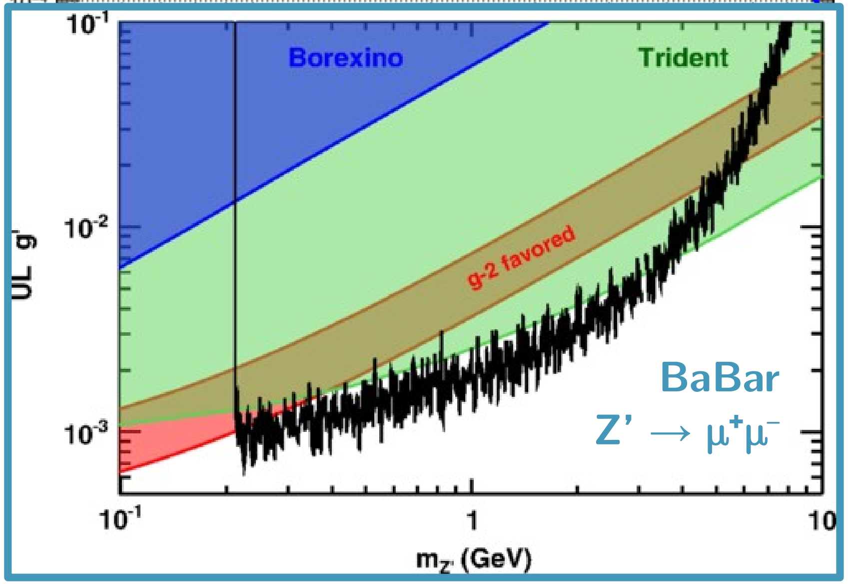




Cross section computed with



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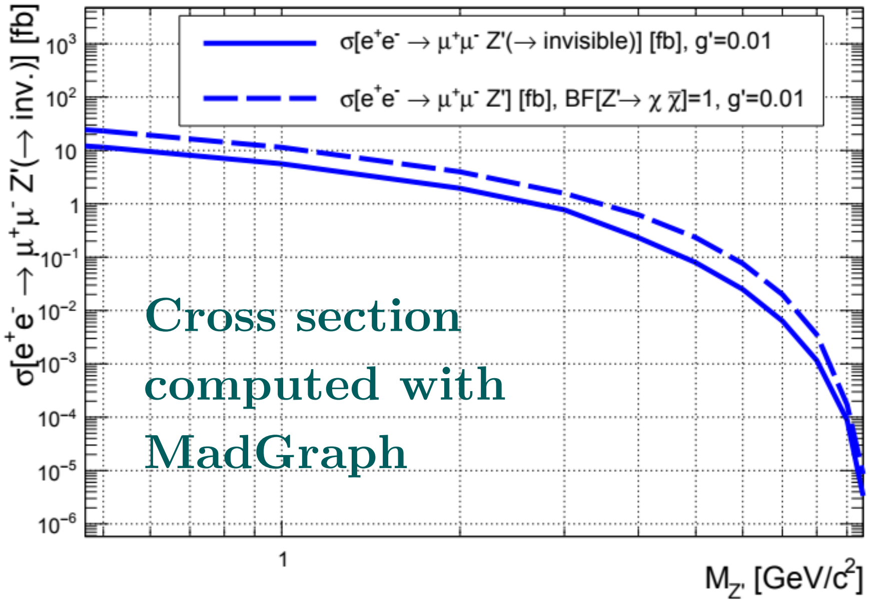
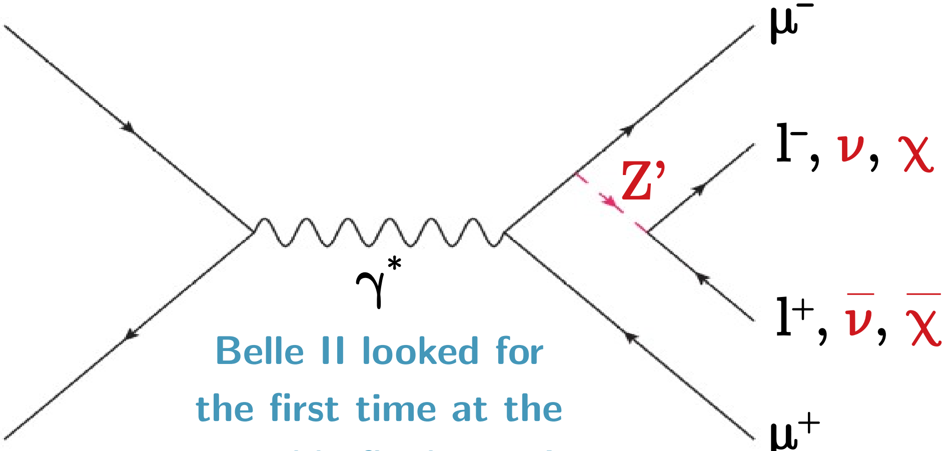
Shuve et al. (2014), *arXiv:1403.2727*



Cross section computed with MadGraph



Belle II looked for the first time at the invisible final state!

Branching ratios to invisible:

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

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

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

Z' → invisible: strategy

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

Also required ∼ nothing in the rest of the event.

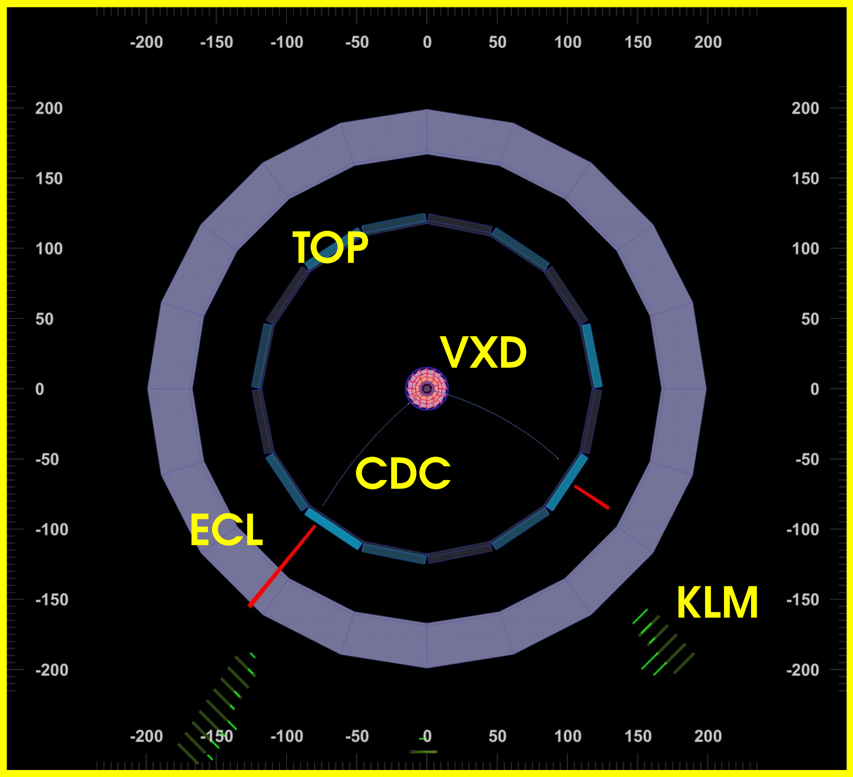
Expected background events:

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

Used 2018 data set (276 pb^{-1}):

first Belle II physics result!

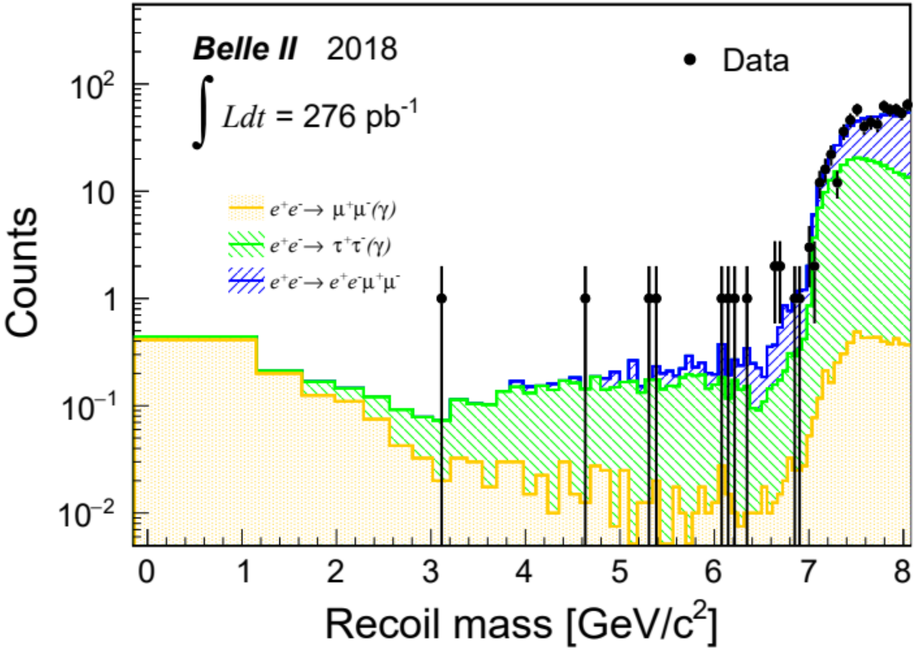
Phys. Rev. Lett. 124, 141801 (2020)



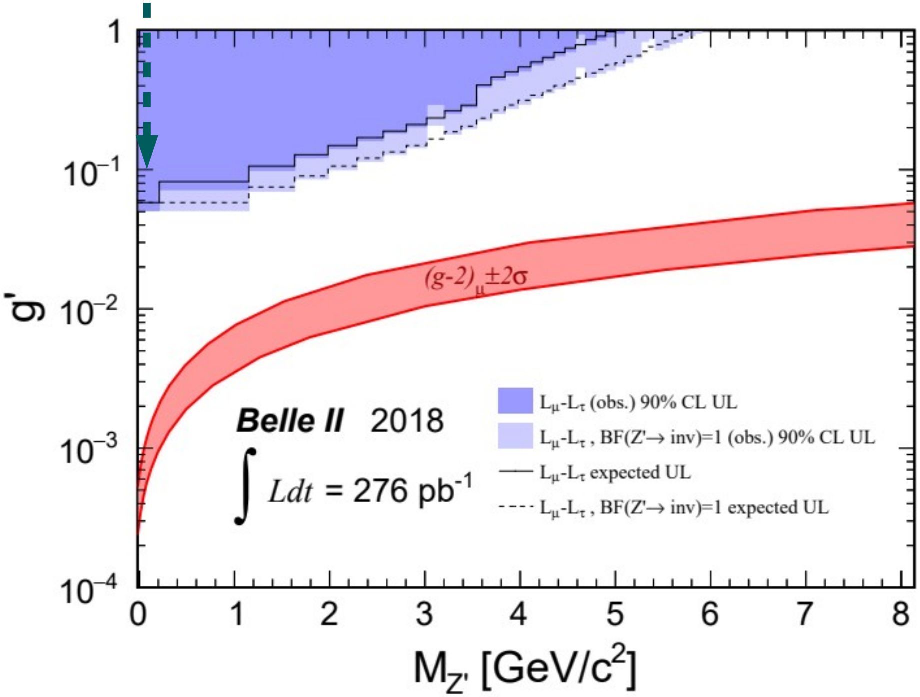
Belle II transverse plane: event display of a reconstructed event from **2018 data**

Z’ → invisible: results

Phys. Rev. Lett. 124, 141801 (2020)



Probed for the first time the region below the dimuon threshold!



Large improvement expected with 2019 data set: stay tuned!

Summary

- Most stringent limits on the Dark Photon mass and coupling in the GeV-range comes from the B-factories

- Belle II started the operations in 2018 and collected $> 33\ \mathrm{fb}^{-1}$ so far

  $\rightarrow$ The first physics result has been published: search for the invisible decay of a Z' boson, **Phys. Rev. Lett. 124, 141801 (2020)**

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

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

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

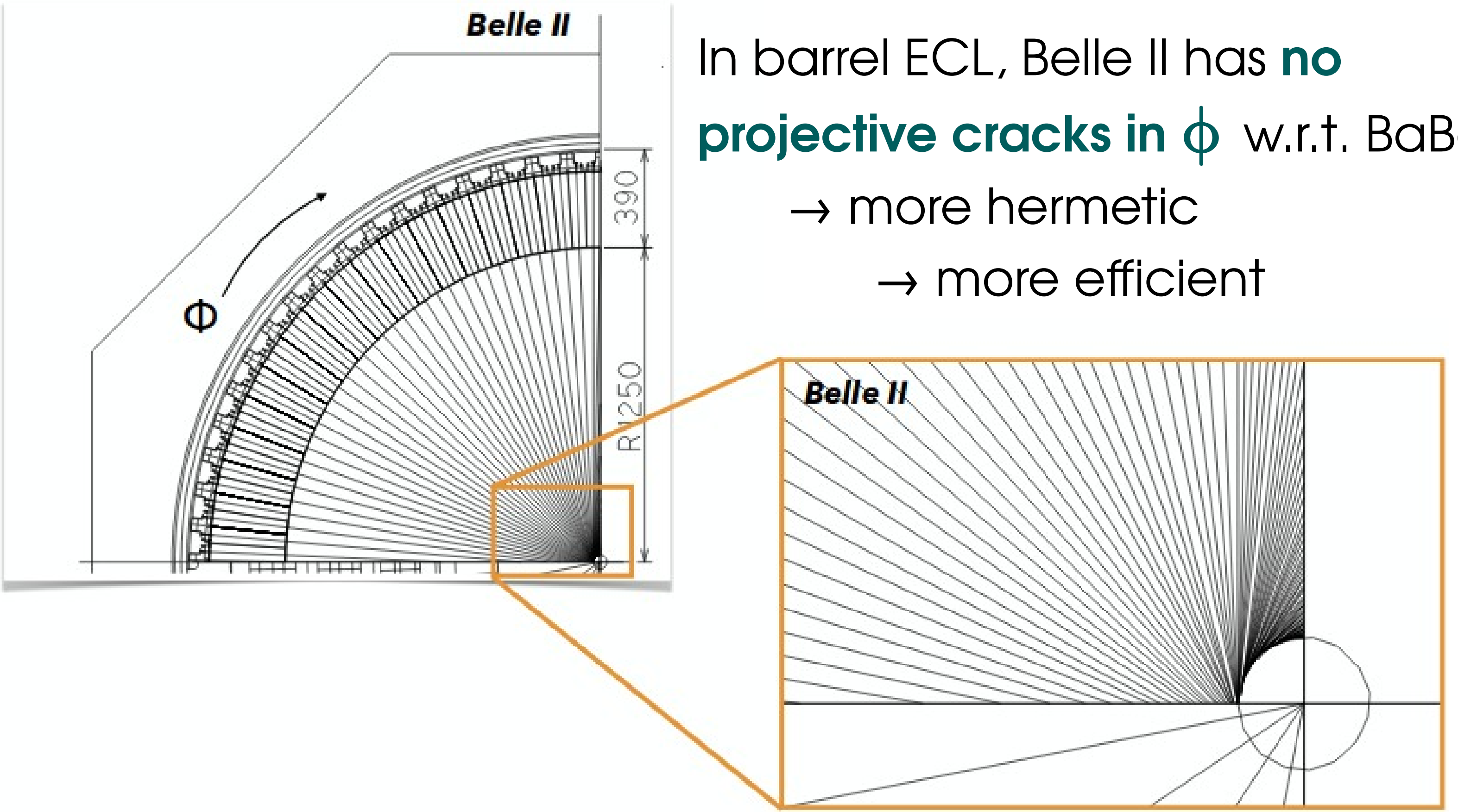
E. Kou, P. Urquijo et al., arXiv:1808.10567

Electromagnetic Calorimeter (ECL)

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

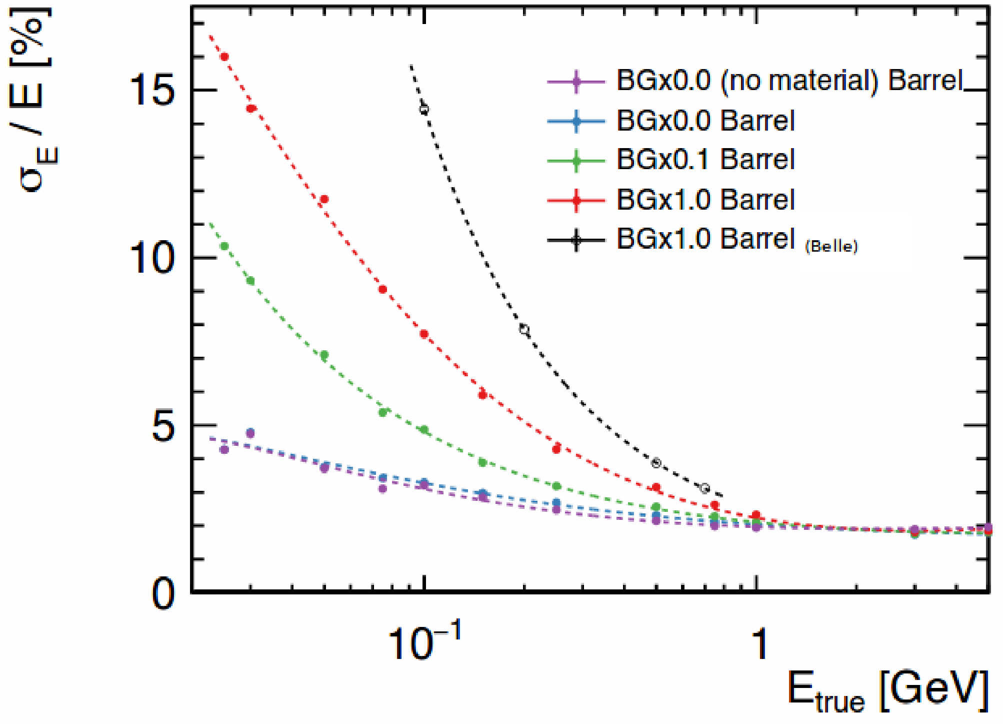
→ more hermetic

→ more efficient

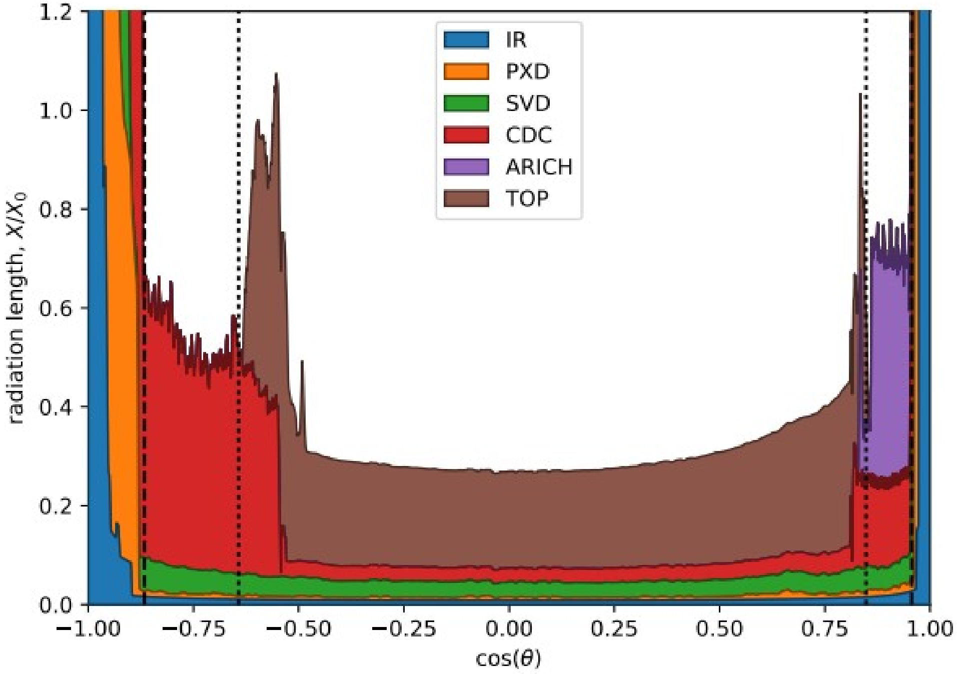


Electromagnetic Calorimeter (ECL)

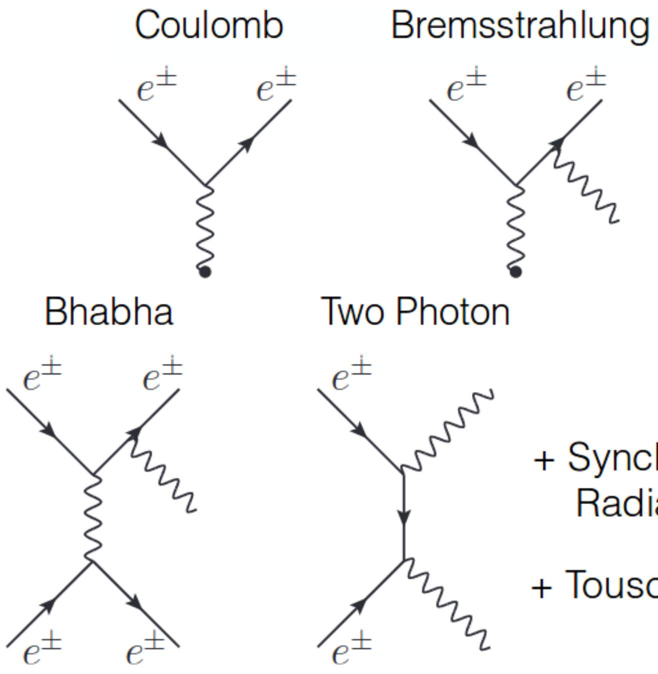
Energy resolution in Belle II barrel:



Material budget in front of ECL:

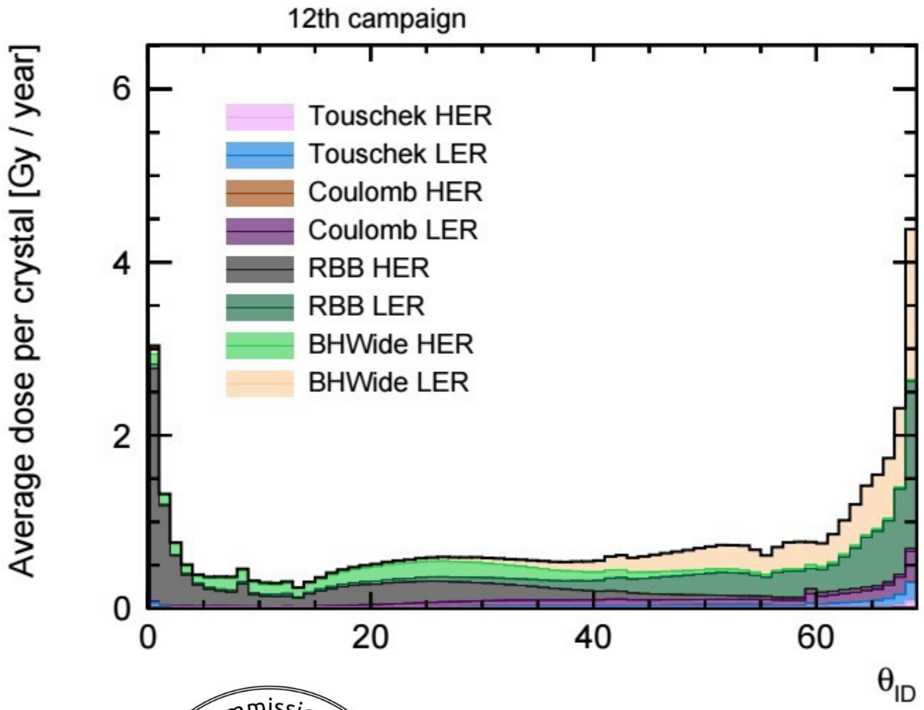


Beam background



+ Synchrotron Radiation

+ Touschek



Effects from beam background:

→ degrades calorimeter resolution.

→ radiation damage.

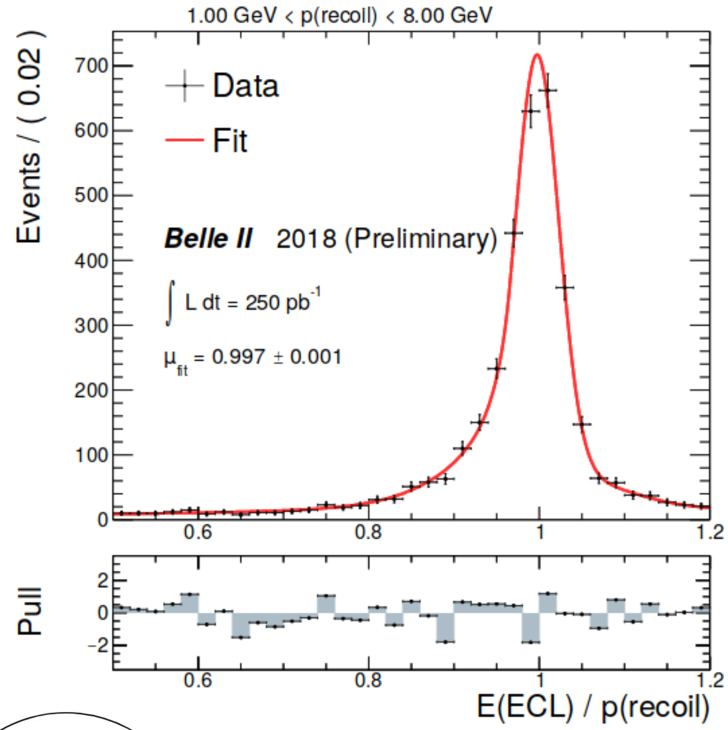
→ pile-up and event size.

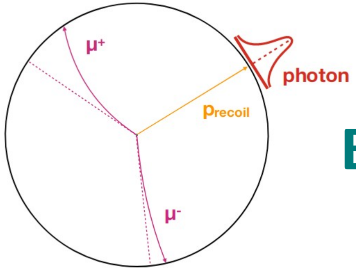
→ physics background

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

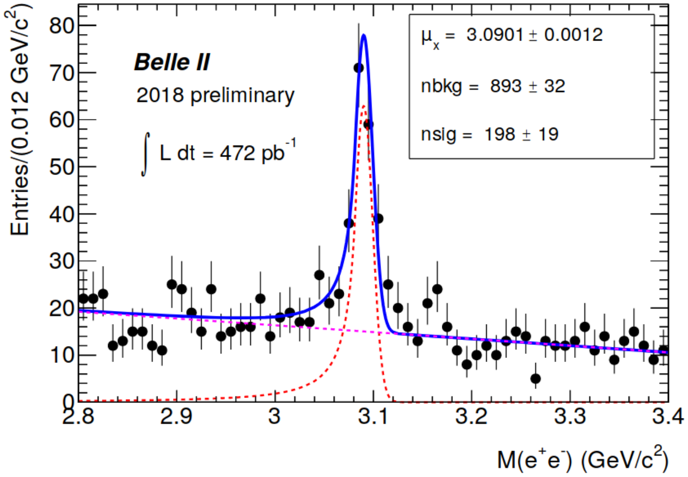
See P. Lewis et al.: 10.1016/j.nima.2018.05.071

Highlights from 2018



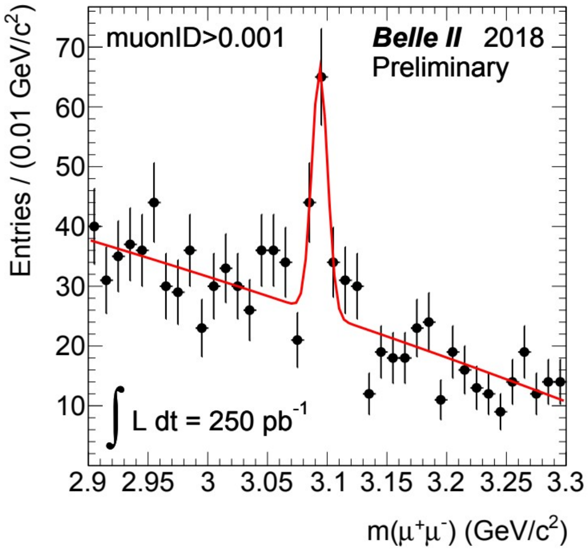


Excellent photon resolution



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

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

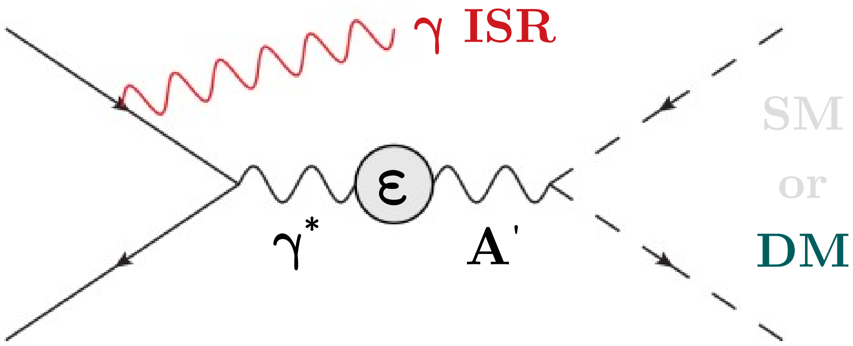


Dark Photon: invisible decay (signal)

Signal signature:

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

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



Needed a special **single photon trigger**

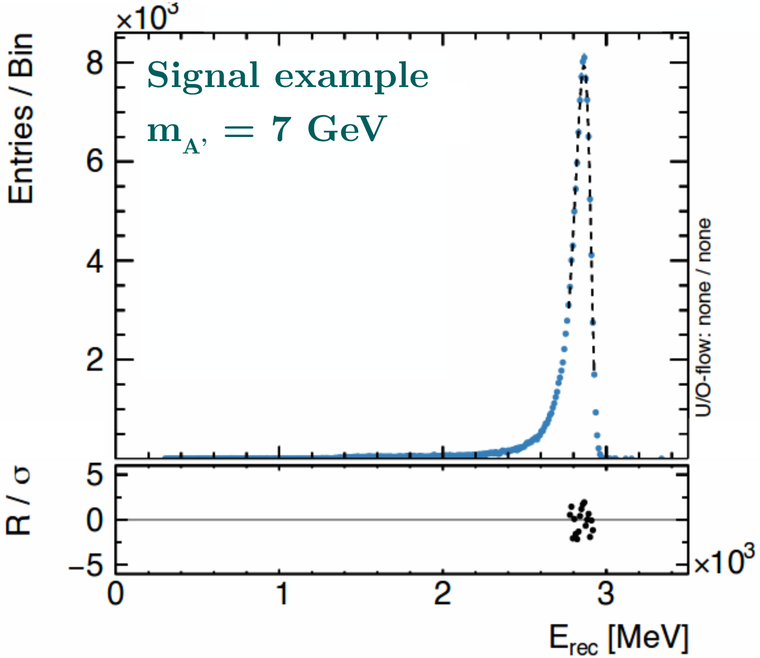
(not available in Belle, only ~10% of all data in BaBar)

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)

Belle II MC Preliminary

Max. L1 rate: < 30 kHz

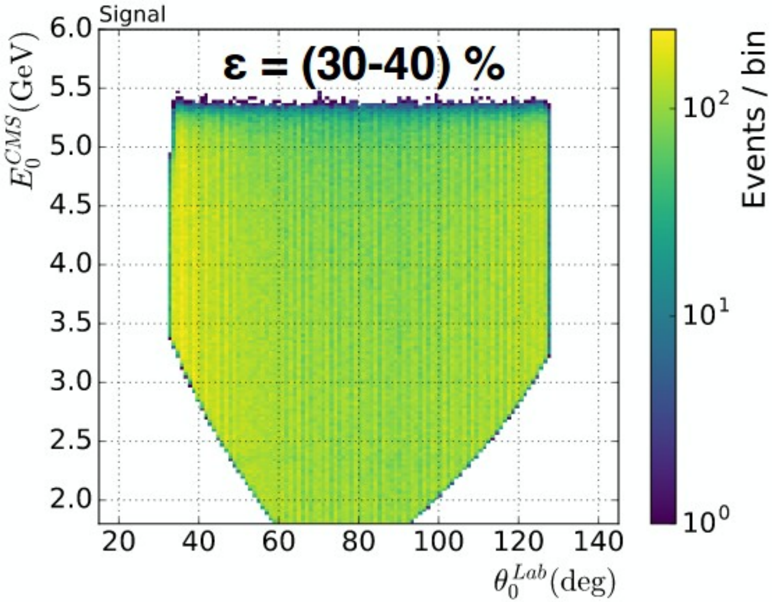
Sustainable for entire Phase 3?



Dark Photon: invisible decay (signal)

Discriminant variables:

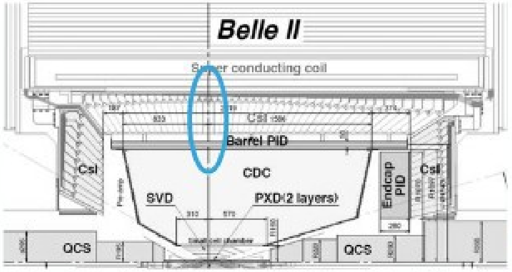
E_{CMS} vs. polar angle of "single photon"



Signal signature:

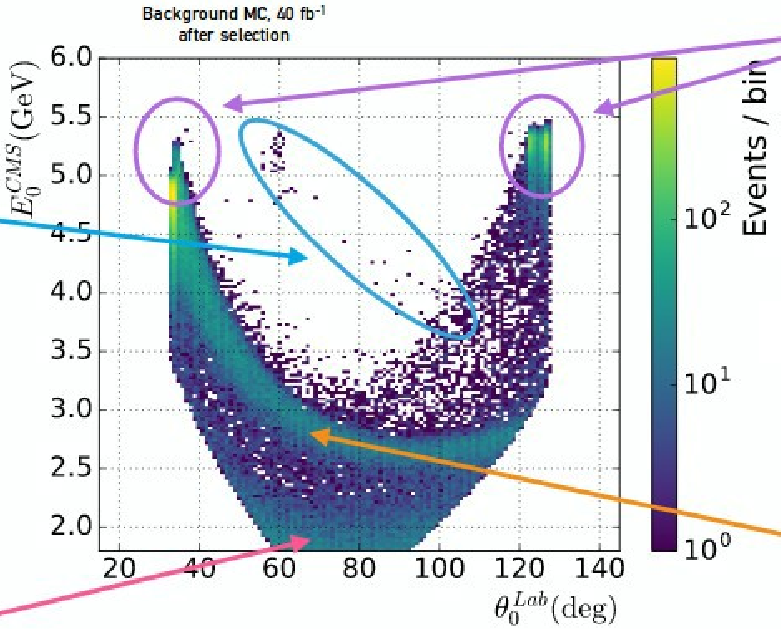
peak in E_{CMS} (horizontal band)

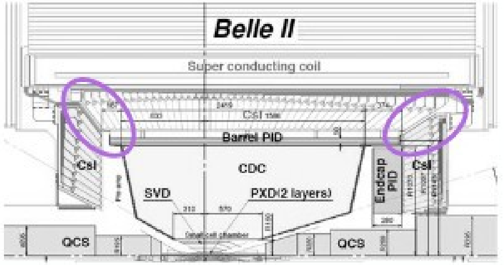
Dark Photon: invisible decay (background)



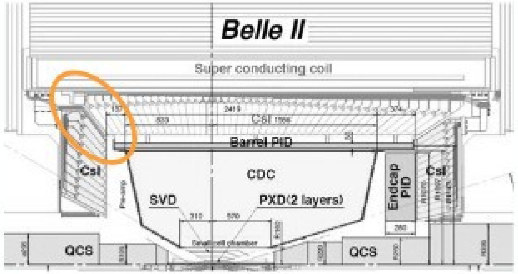
ee→2γ and 3γ
1γ in ECL 90° gap
1γ out of ECL acceptance

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





ee→2γ
1γ in ECL BWD or FWD gap



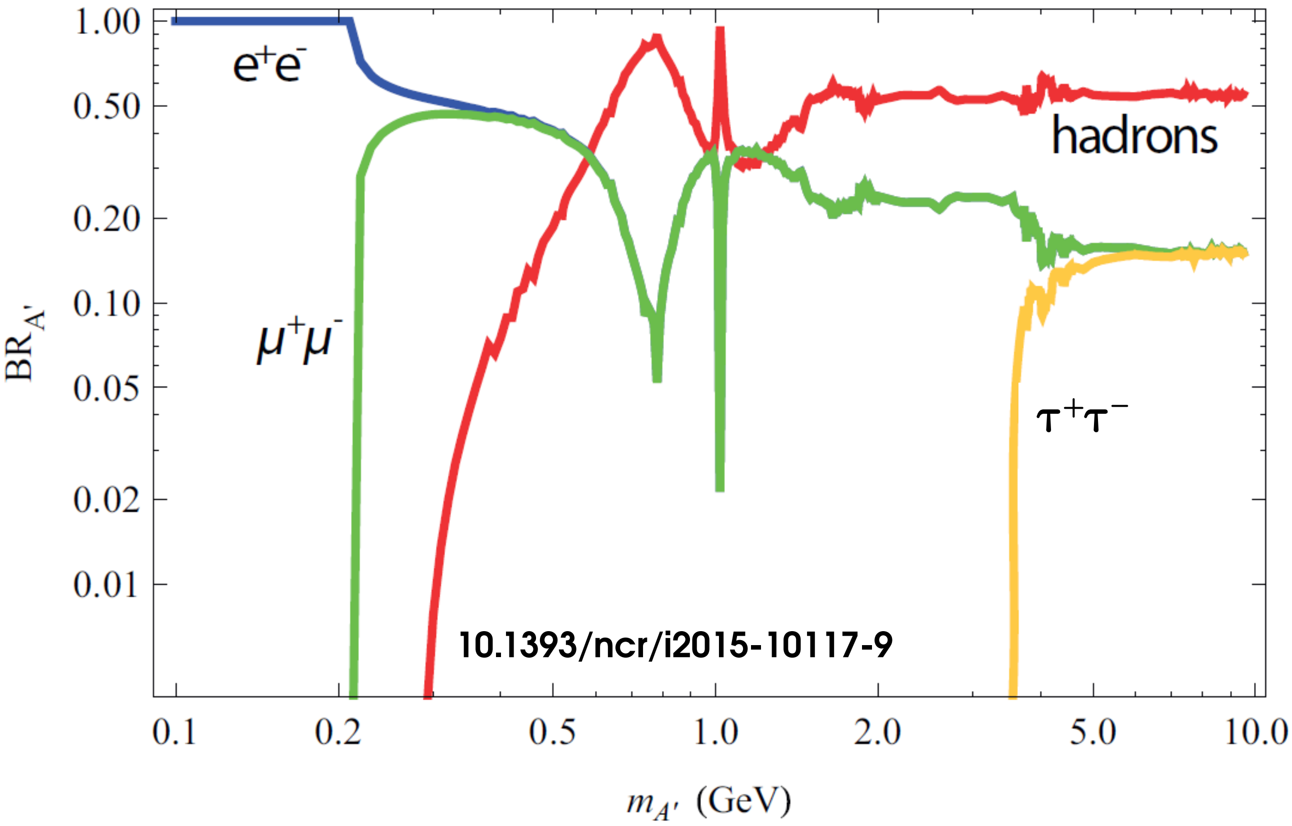
ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance

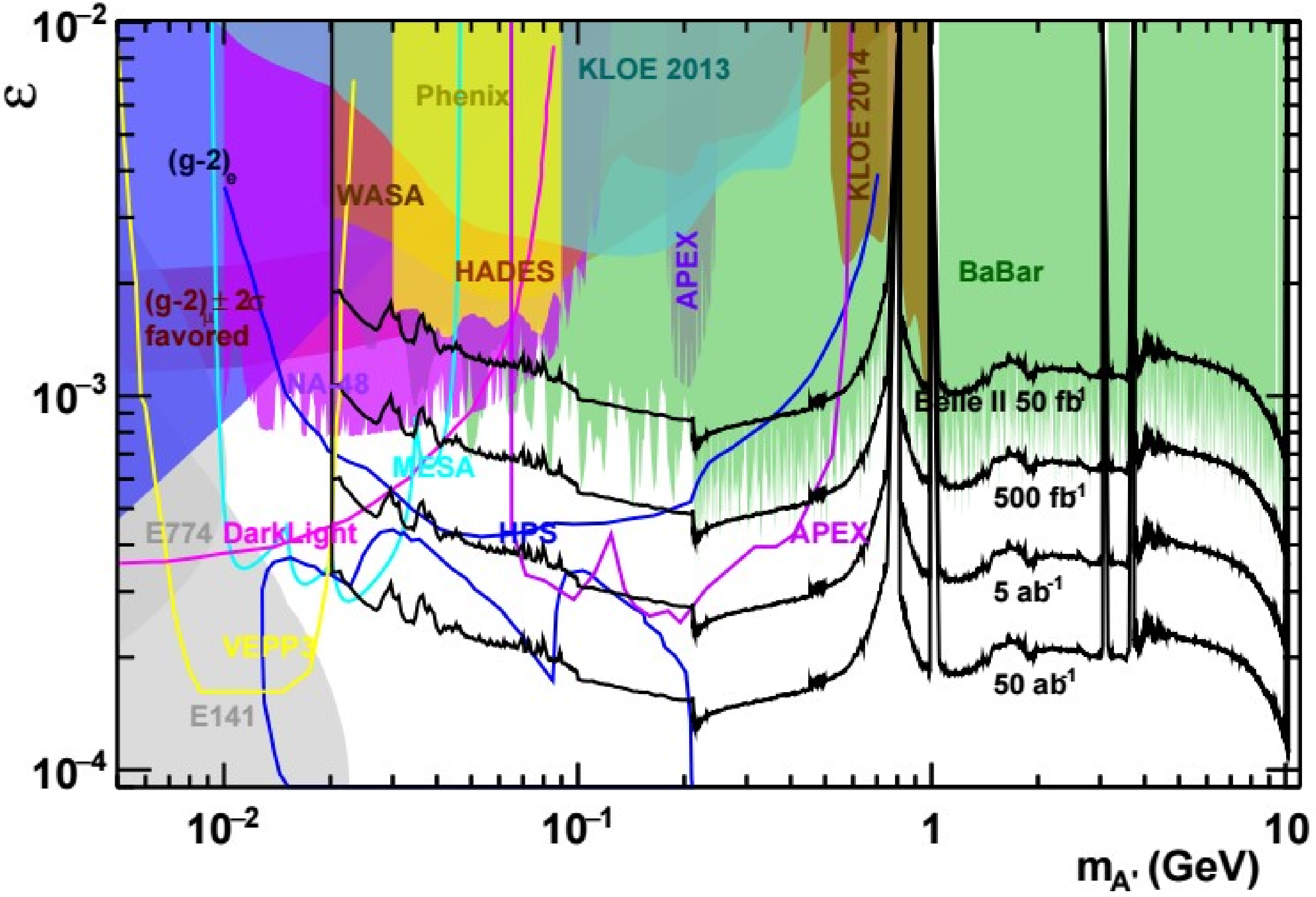
Signal signature:
peak in E_{CMS} (horizontal band)

A' → visible

Branching Fraction of a Dark Photon into visible final states.



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**

A' → hadrons: current status

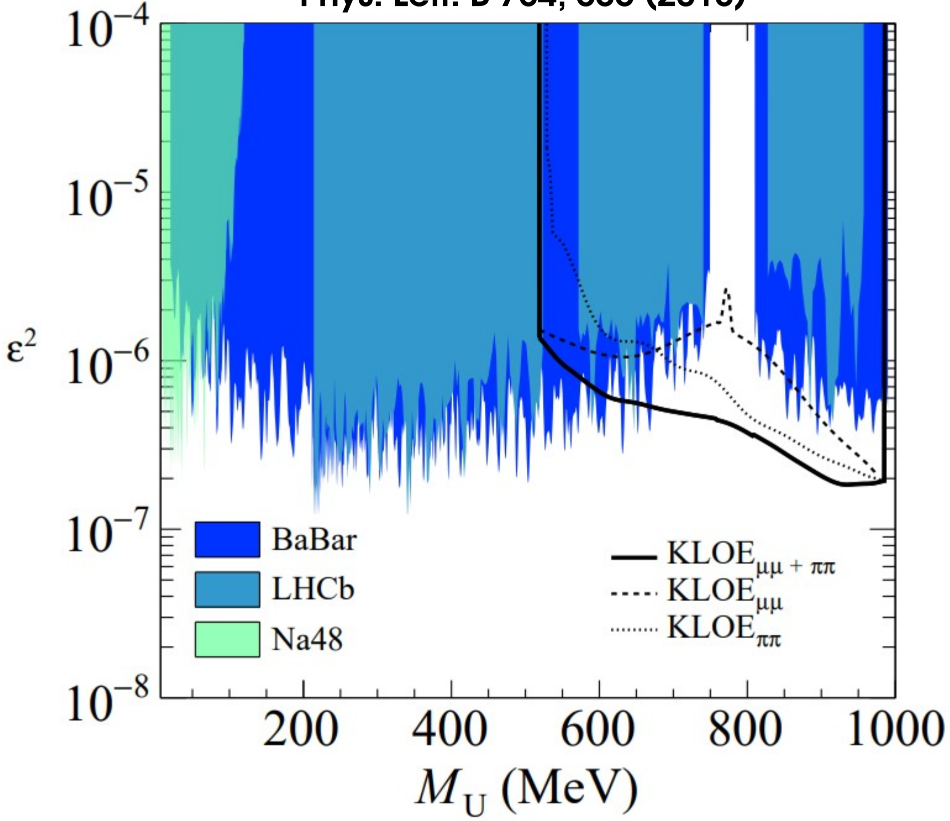
Very interesting final state...

- searched only by KLOE **(A' → $\pi^+\pi^-$)**
- 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

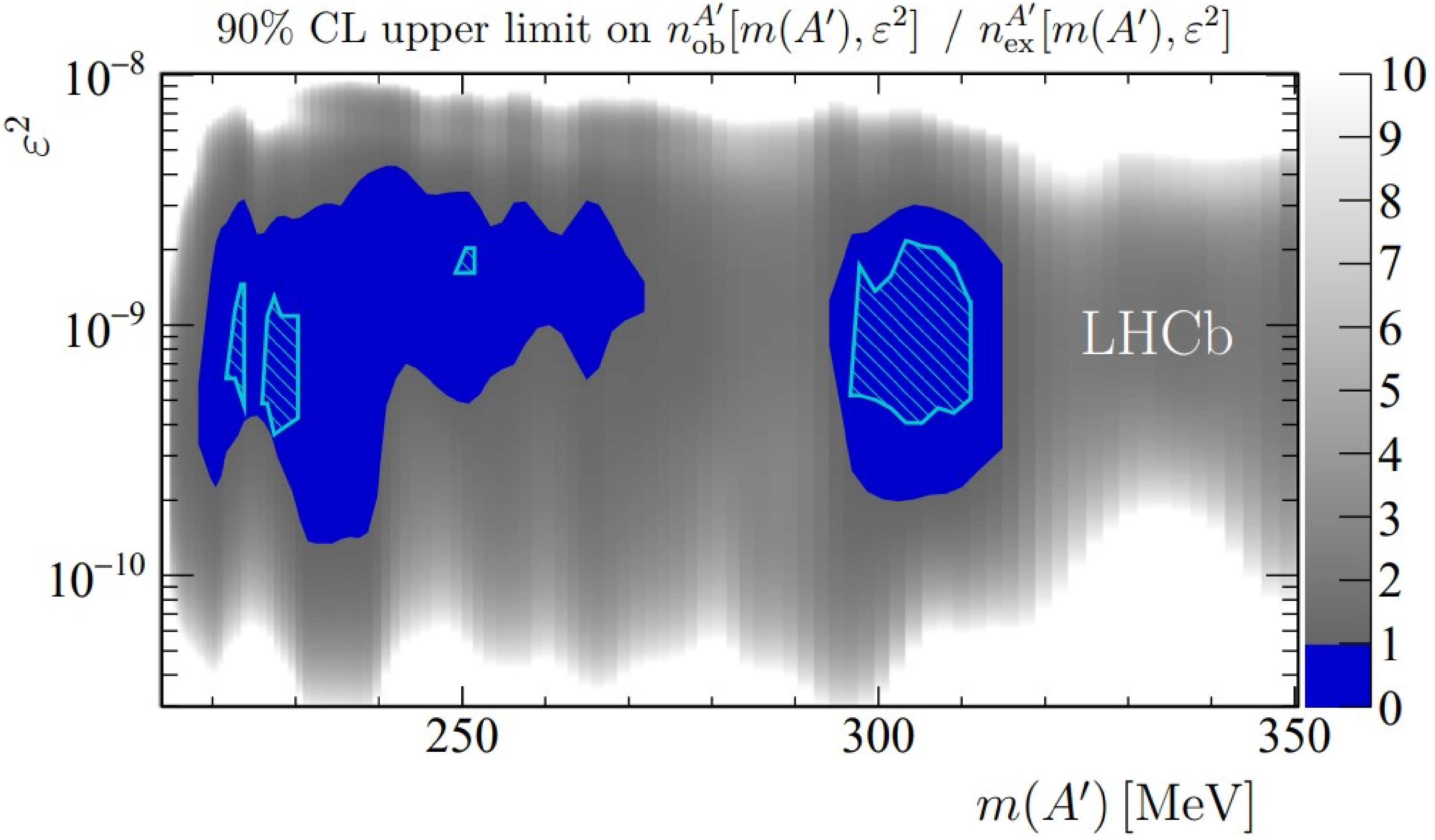
Phys. Lett. B 784, 336 (2018)



Belle II aims to cover $m_{A'} > 1$ GeV

Long-living Dark Photon

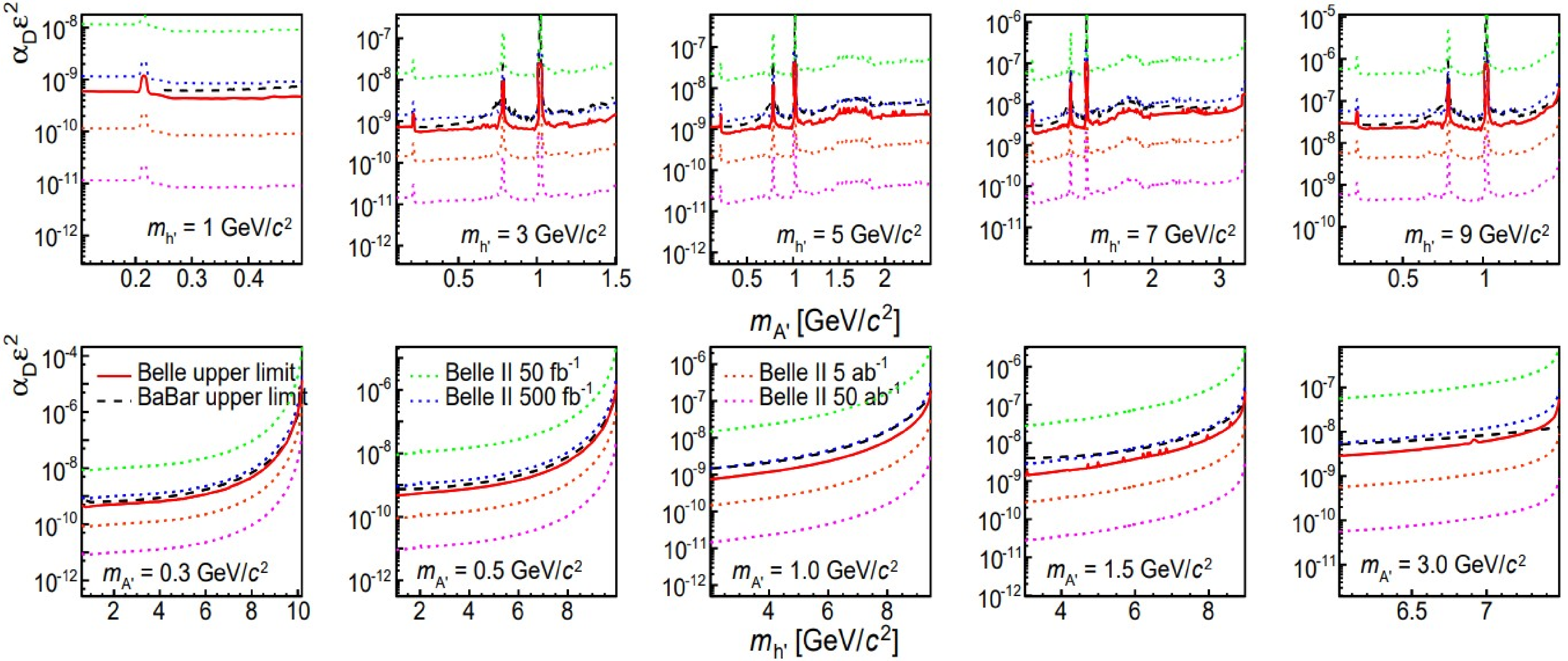
LHCb searched a long living Dark Photon decaying into a pair of muons.



Phys. Rev. Lett. 124, 041801 (2020)

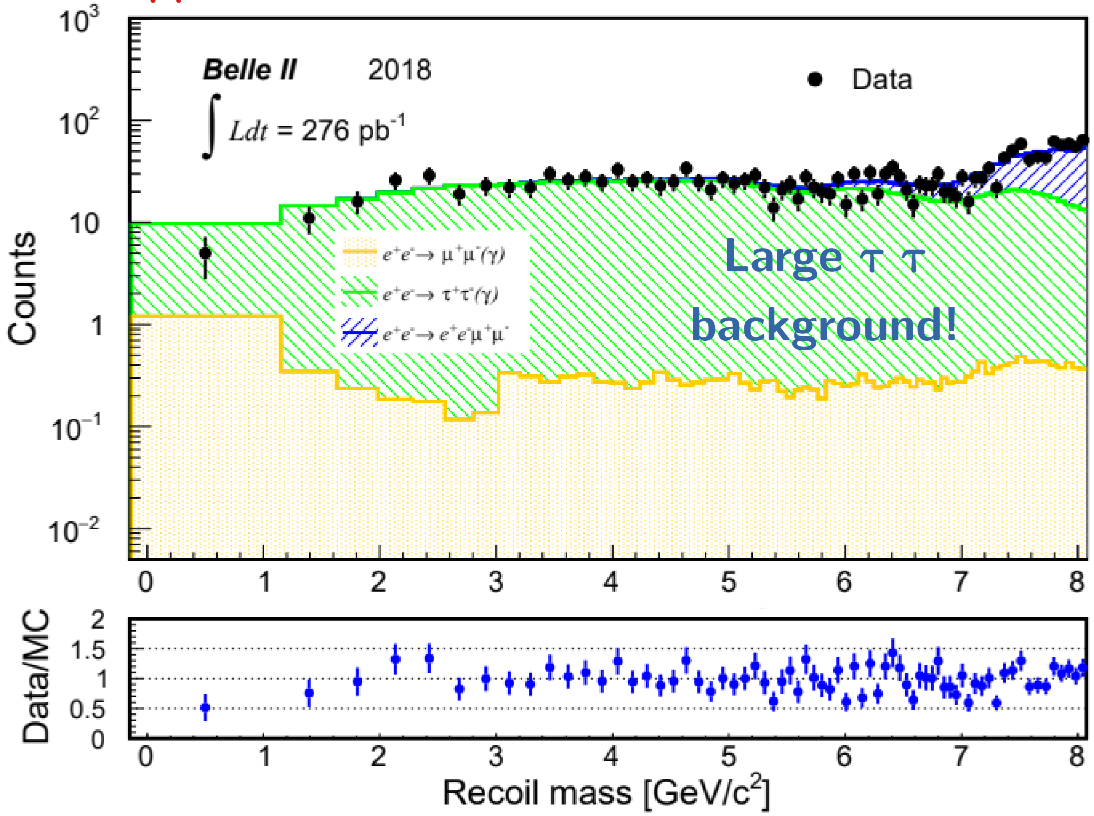
Dark Higgs-strahlung at Belle II

Belle II computed the expected sensitivity for the fully visibile final state (prompt decay and $m_{h'} > 2m_{A'}$) by scaling the Belle upper limits.



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.

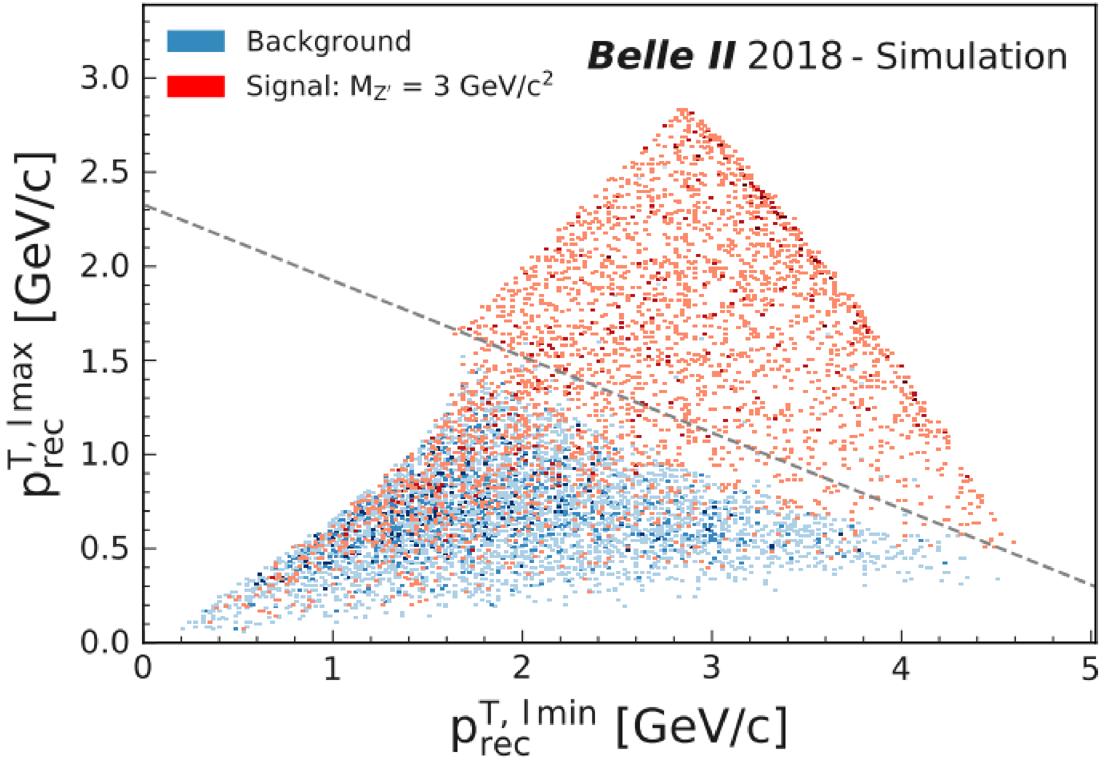
NB: all the corrections are evaluated on indipendent control samples!

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.

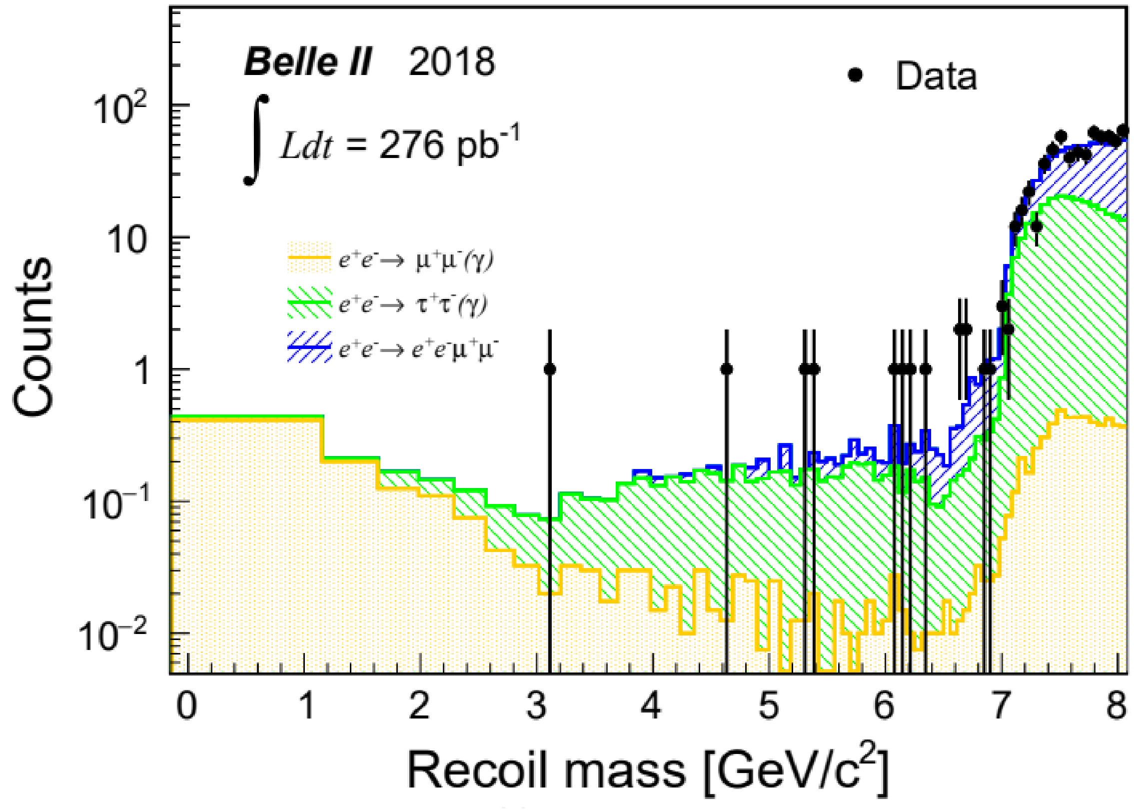


We optimized the selection in each recoil mass bin by choosing the best cuts that maximizes a given figure of merit (**hand-made multivariate approach**).

Belle II, arXiv:1912.1127 (submitted to PRL)

ττ background suppressed

μμ final state



Suppression of the ττ background very effective up to 7 GeV (then, **eeμμ** events start to be dominant).

Signal efficiency between 3% and 5%.

No (local) anomalies observed... :(

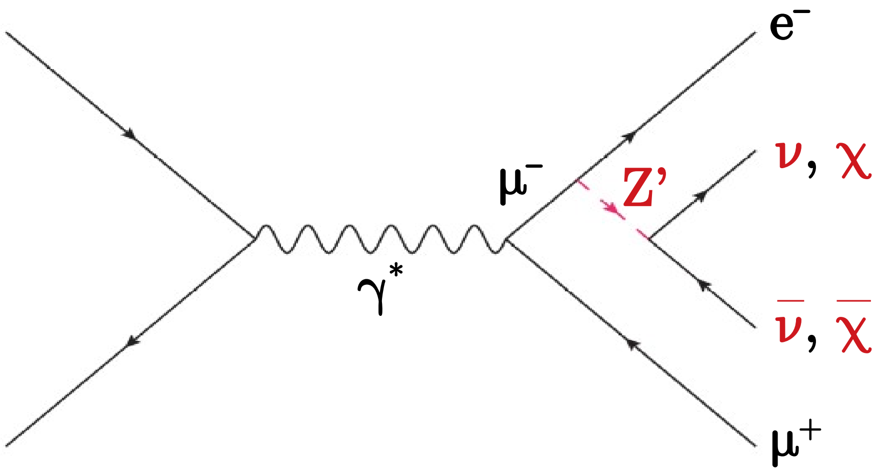
Belle II, arXiv:1912.1127 (submitted to PRL)

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

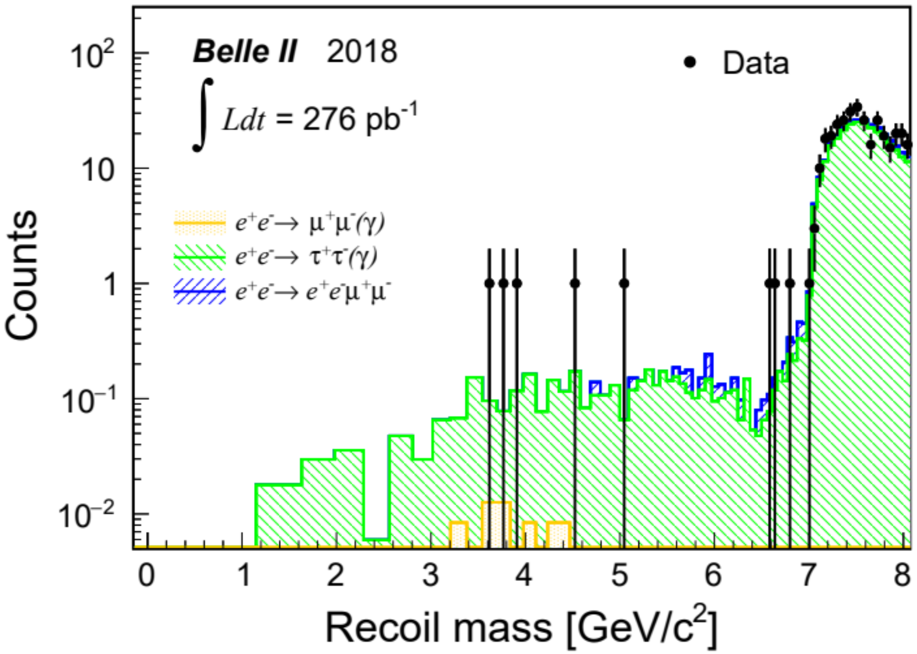


Unfortunately, the model we were using showed some issues (too large width for the Z', etc.).

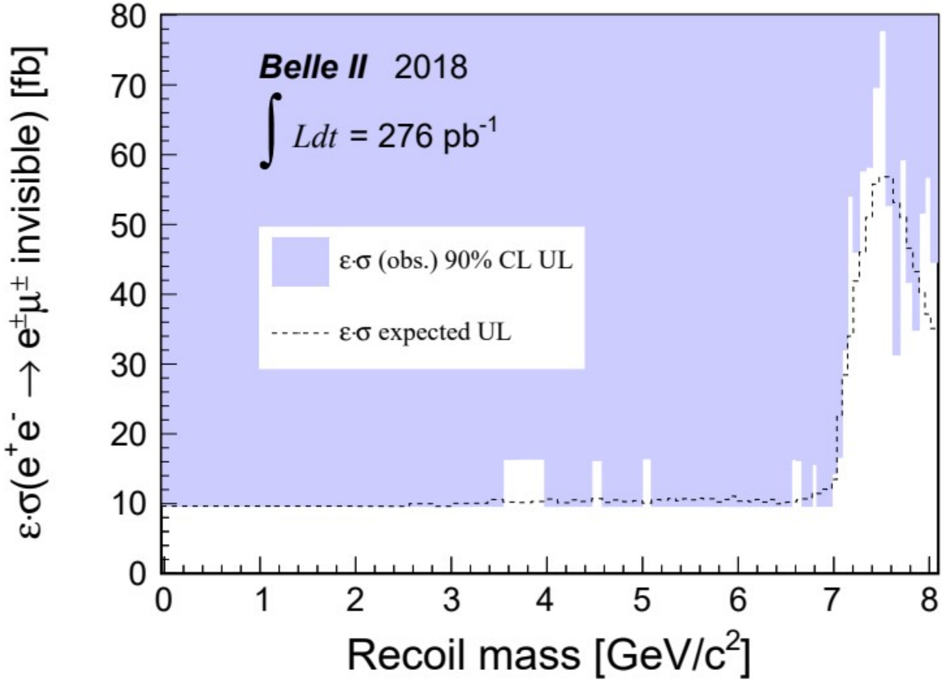
We decided to drop the signal model
and we opted for a model-independent search!

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)

Axion-Like Particles

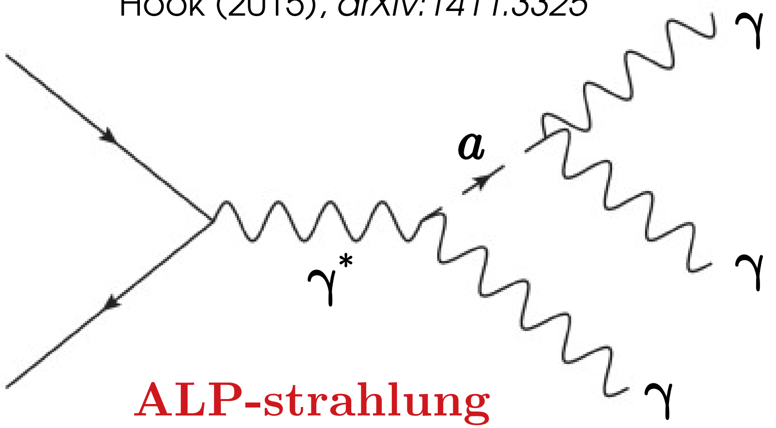
Axion-Like Particles (ALPs) are pseudo-scalars and couple to bosons.
Unlike QCD Axions, ALPs have no relation between mass and coupling.

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

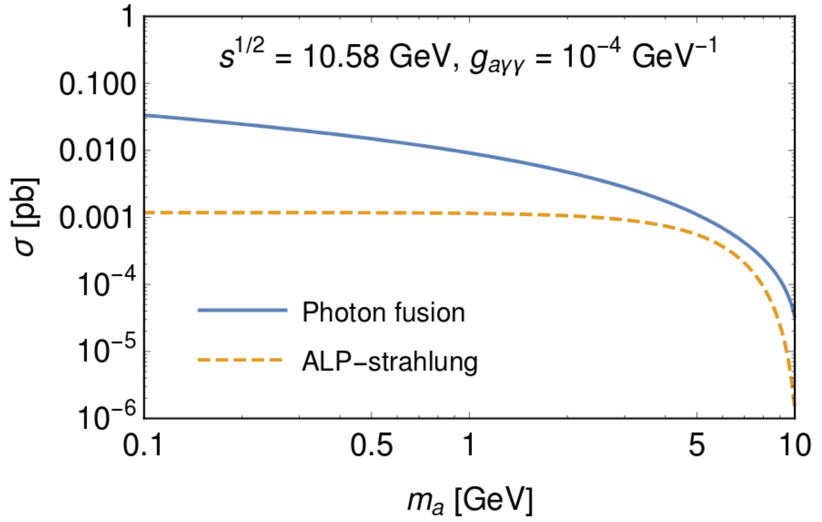
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad \tau_a \sim 1/g_{a\gamma\gamma}^2 m_a^3$$

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

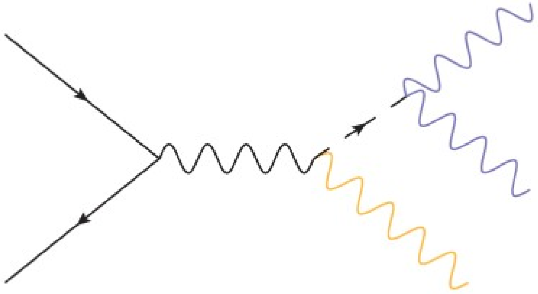
Hook (2015), *arXiv:1411.3325*

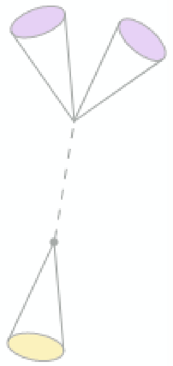


ALP-strahlung



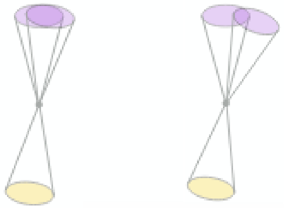
Axion-Like Particles (signal)

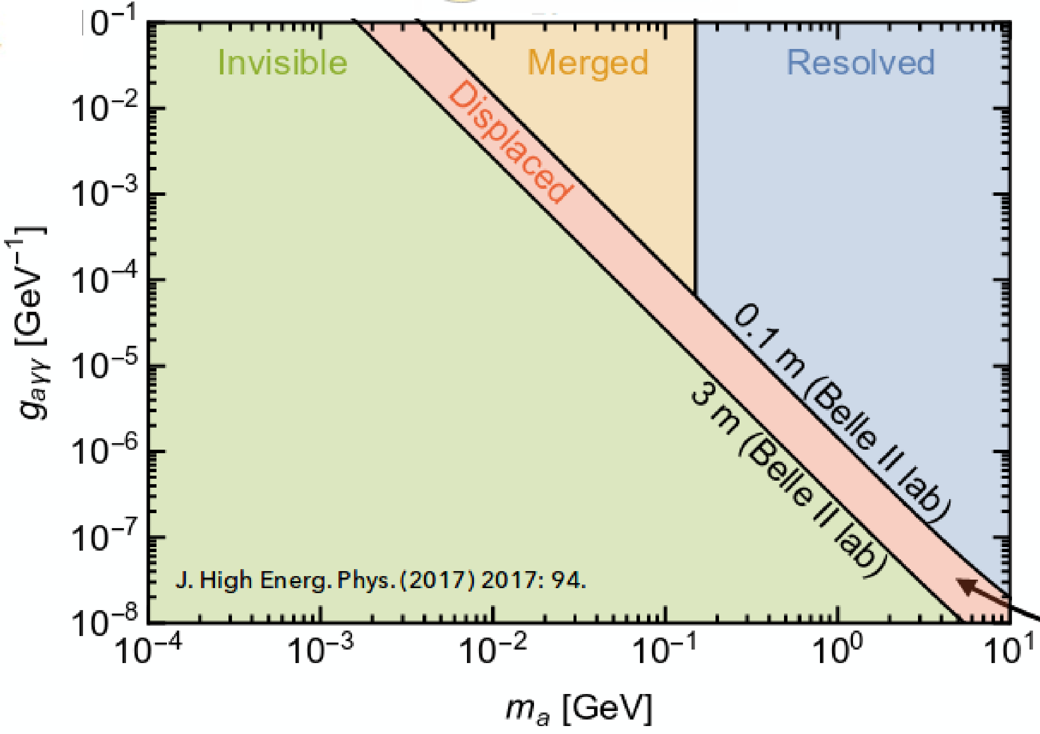




ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

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





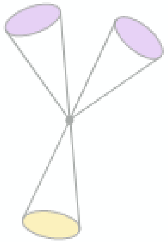
$$\tau_a \sim 1/g^2_{a\gamma\gamma} m^3_a$$

For **resolved** case:

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

Peak in $\gamma\gamma$ mass spectrum

Three **resolved**, high energetic photons.

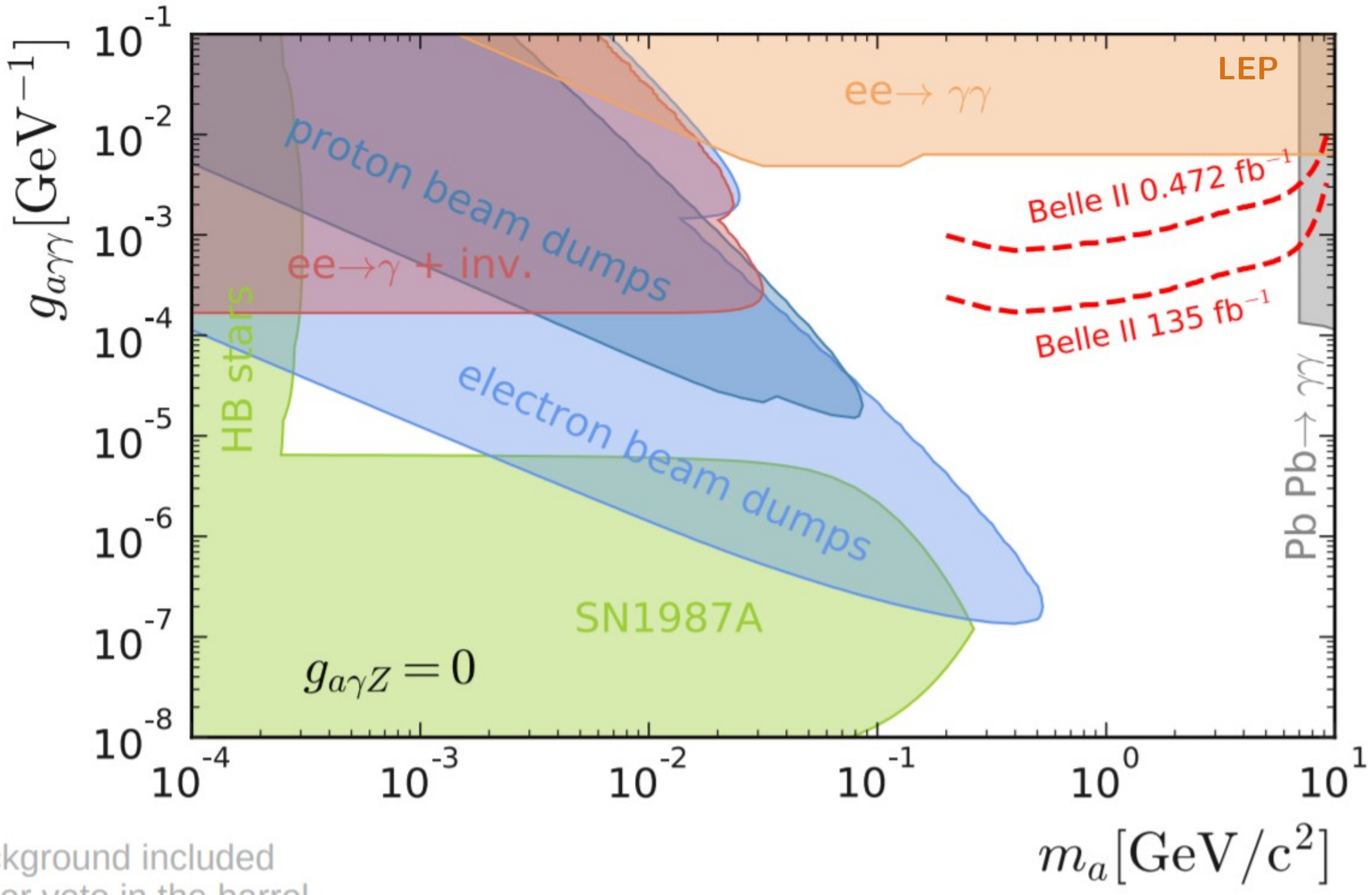


The searches for invisible and visible ALP decays veto this region.

Axion-Like Particles (sensitivity)

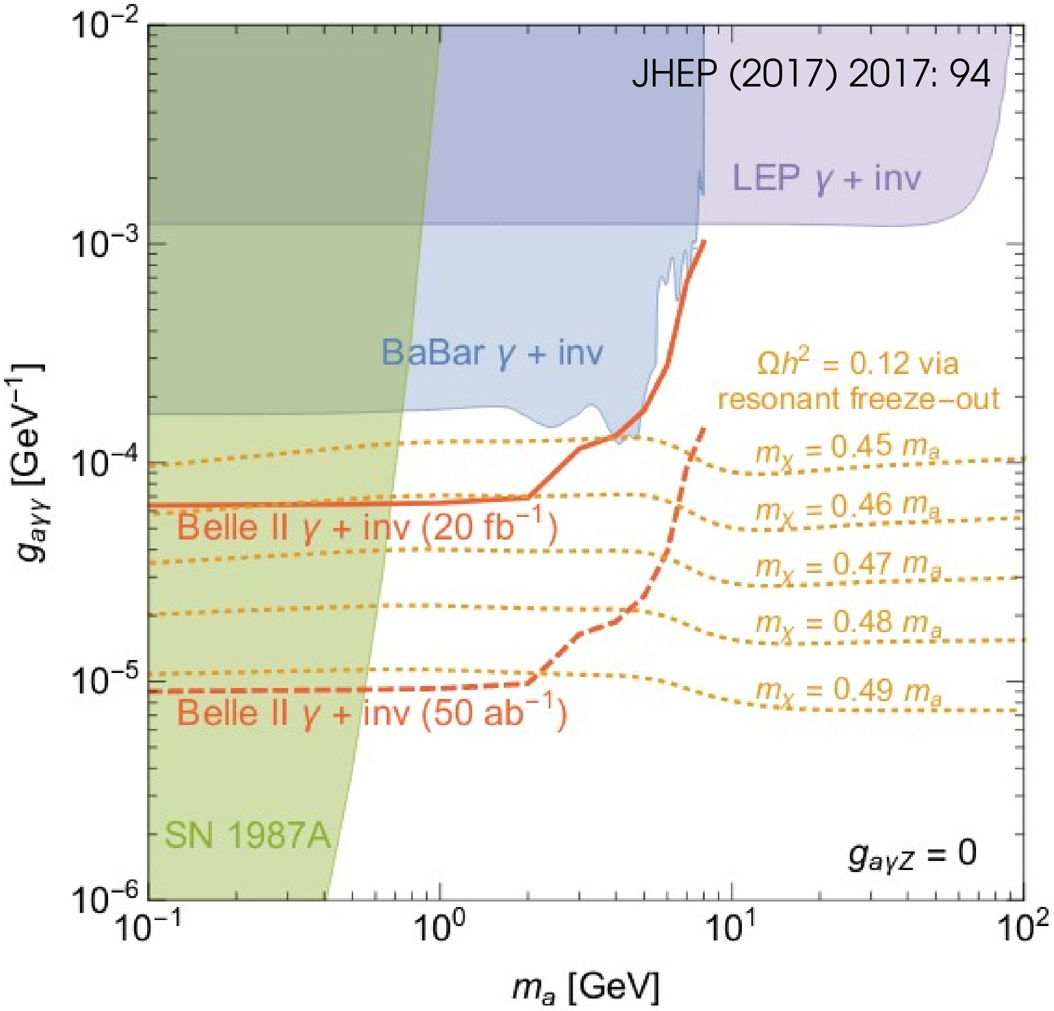
Belle II expects to improve the current limits for

$m_a > 100$ MeV



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

Axion-like Particles: invisible decay

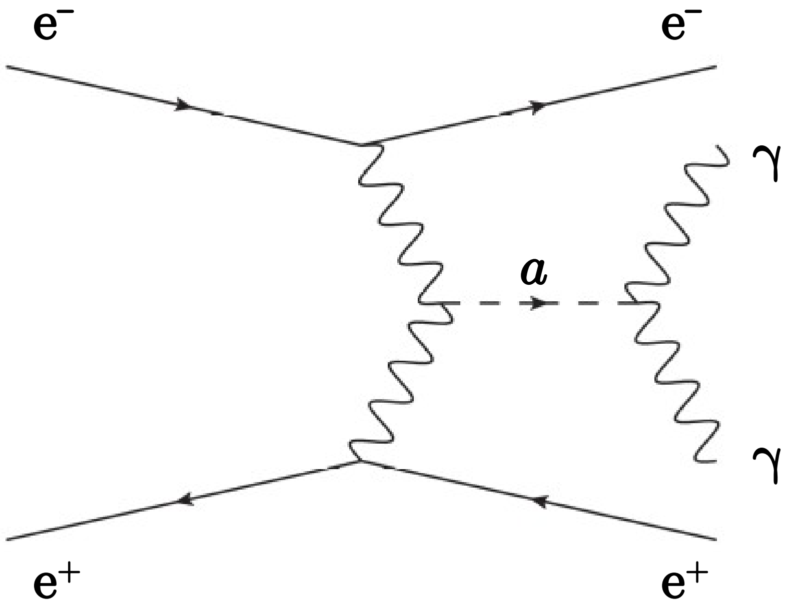


ALPs: low-mass region

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.

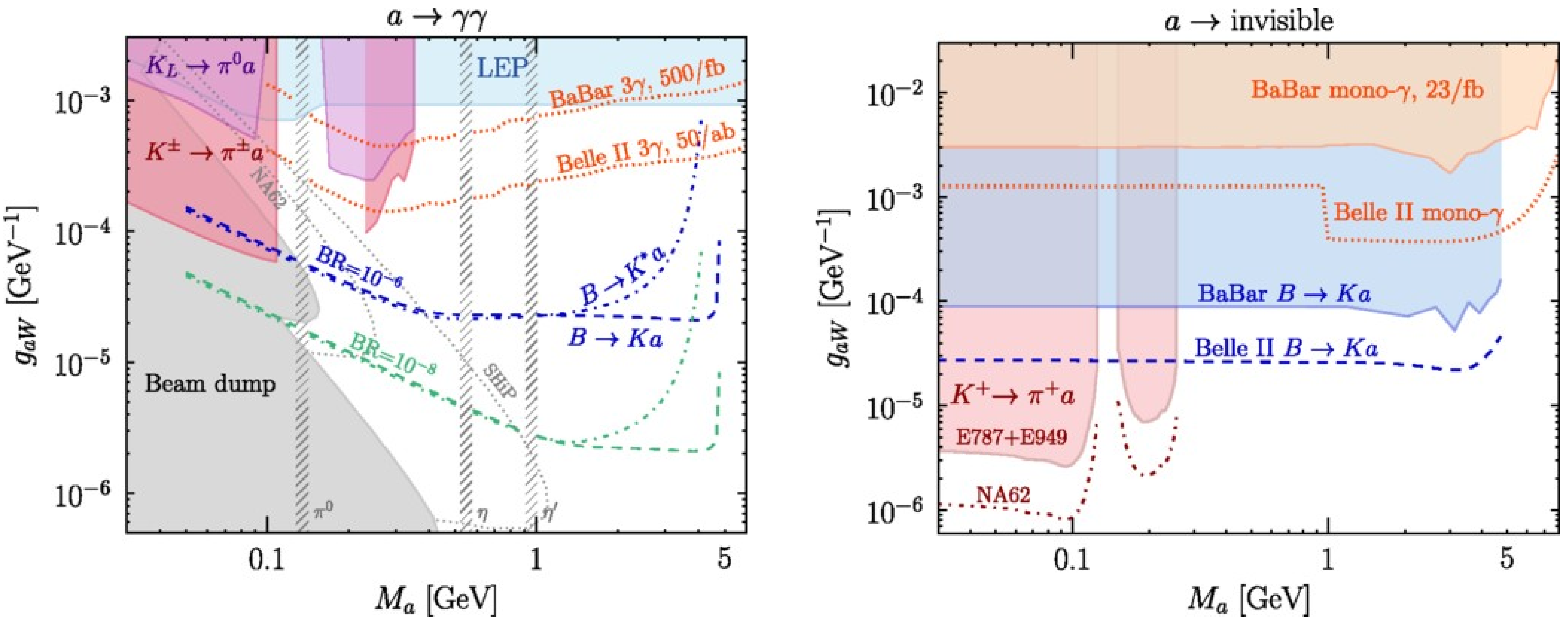
ALP-fusion



Pro: resolved clusters

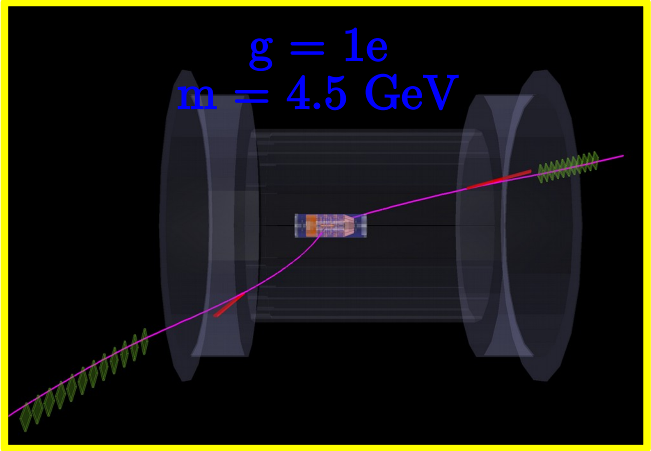
Con: very low energetic photons

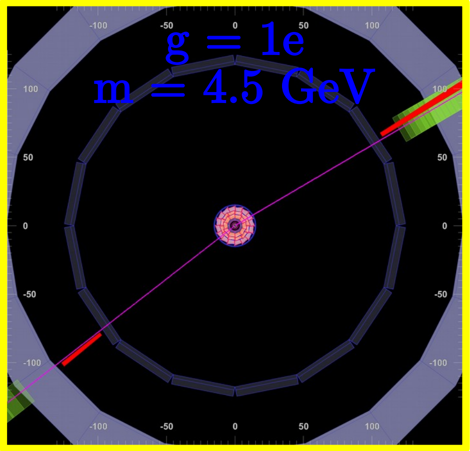
Axion-like Particles from B decays



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

Magnetic monopoles





Minimal magnetic charge

from Dirac quantization: $g_D = 68.5e$

Lower magnetic charge not ruled out

(and not covered at ~GeV scale)

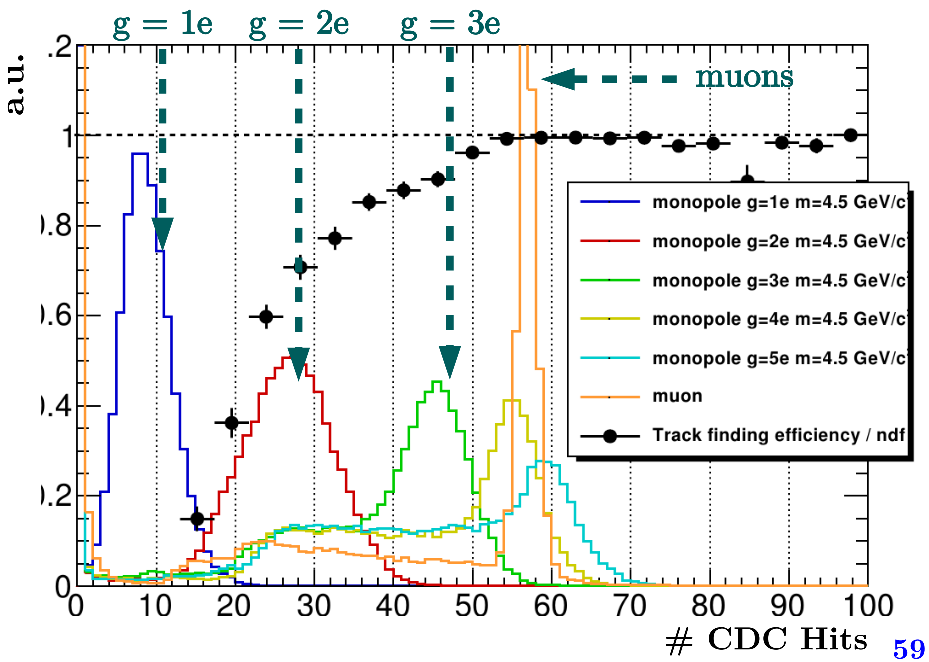
Interesting predictions (*arXiv:1707.05295*) for monopoles with **g ~ 1e** and **m = 4.5 GeV**...

... but not-relativistic at Belle II:

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

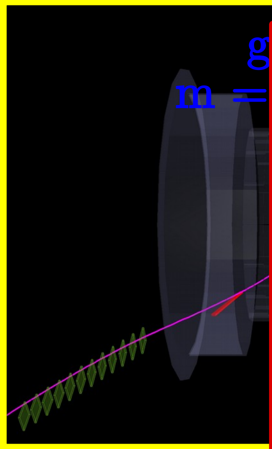
→ few hits in the CDC

→ **needed a dedicated tracking**



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

Magnetic monopoles



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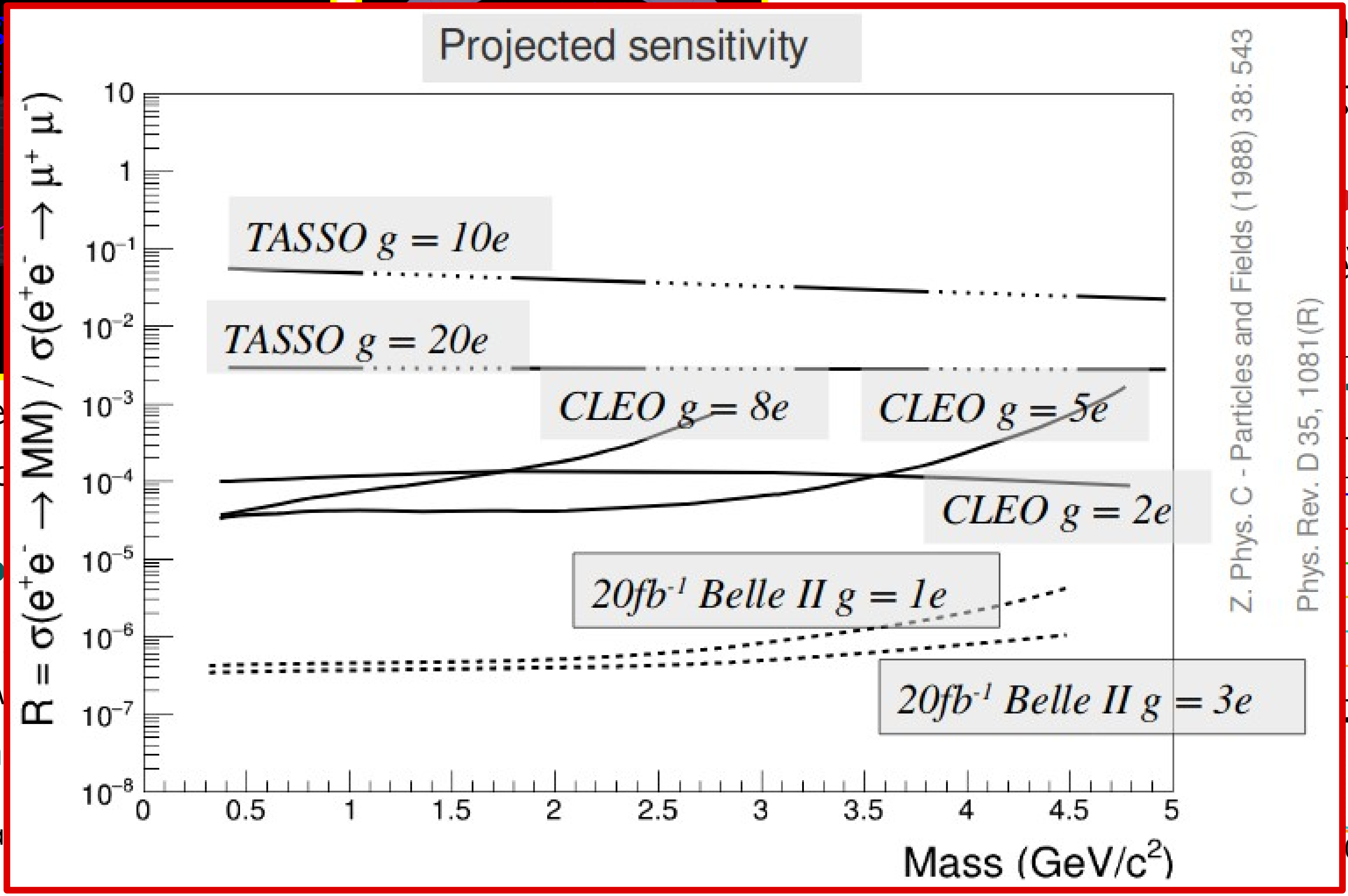
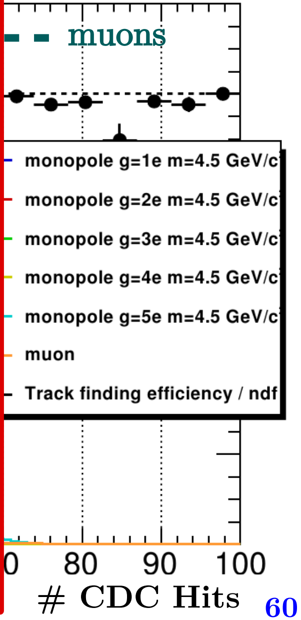
Complementa





Other Belle II 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

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