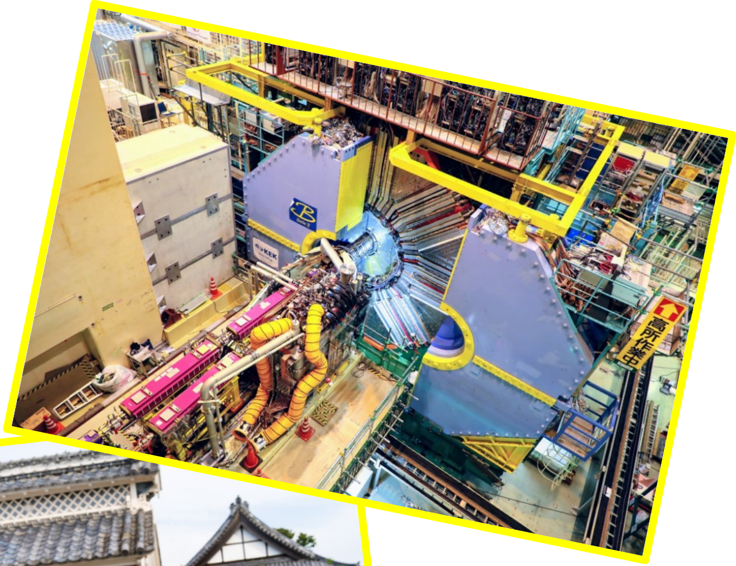


# Dark Sector searches at Belle II


**Giacomo De Pietro**

*INFN Roma Tre*

INFN ROMA TRE


Belle II

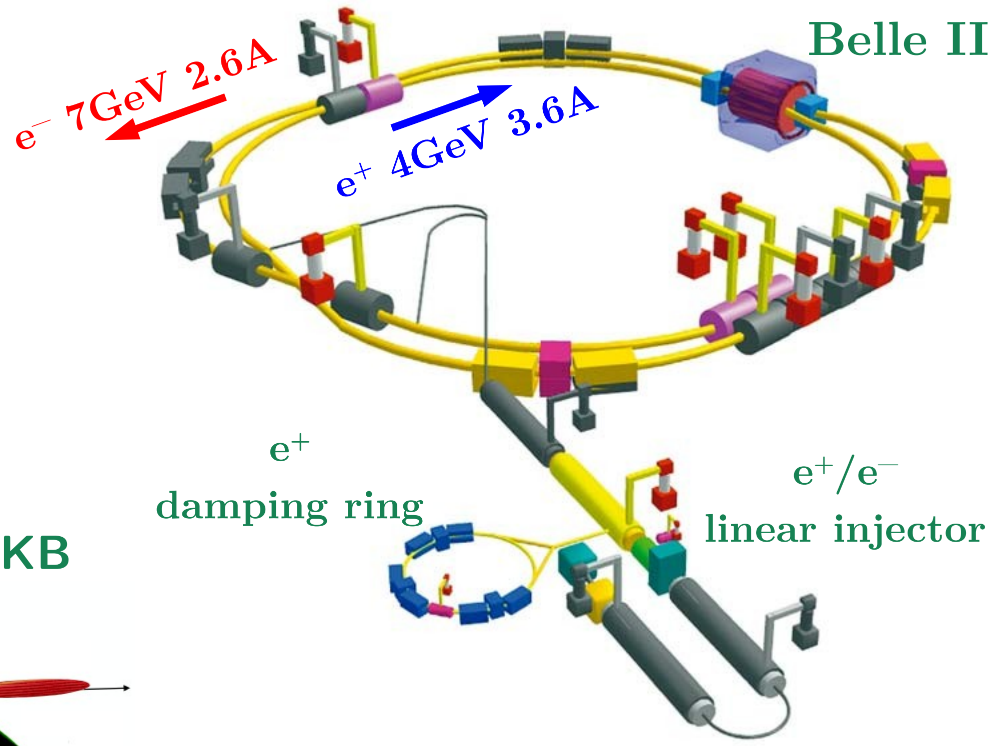
## 55th Rencontres de Moriond Electroweak Interactions and Unified Theories

## 20-27 March 2021

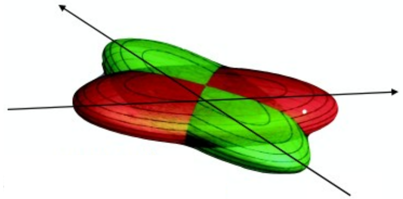
# SuperKEKB: a new Intensity Frontier machine

SuperKEKB is a **super** B-factory
located at KEK (Tsukuba, Japan)

It's an asymmetric $e^+e^-$ collider
operating mainly at **10.58 GeV**
( **$\Upsilon$(4S)**, but possible runs from $\Upsilon$(2S) to $\Upsilon$(6S) )




**KEKB**



I (A): ~ 1.6/1.2

$\beta^*_y$ (mm): ~ 5.9/5.9

nano-beam → scheme

**SuperKEKB**

I (A): ~ 3.6/2.6

$\beta^*_y$ (mm): ~ 0.27/0.3

**30x peak luminosity:**
**$6 \cdot 10^{35}$ cm$^{-2}$ s$^{-1}$**

# SuperKEKB: a new Intensity Frontier machine

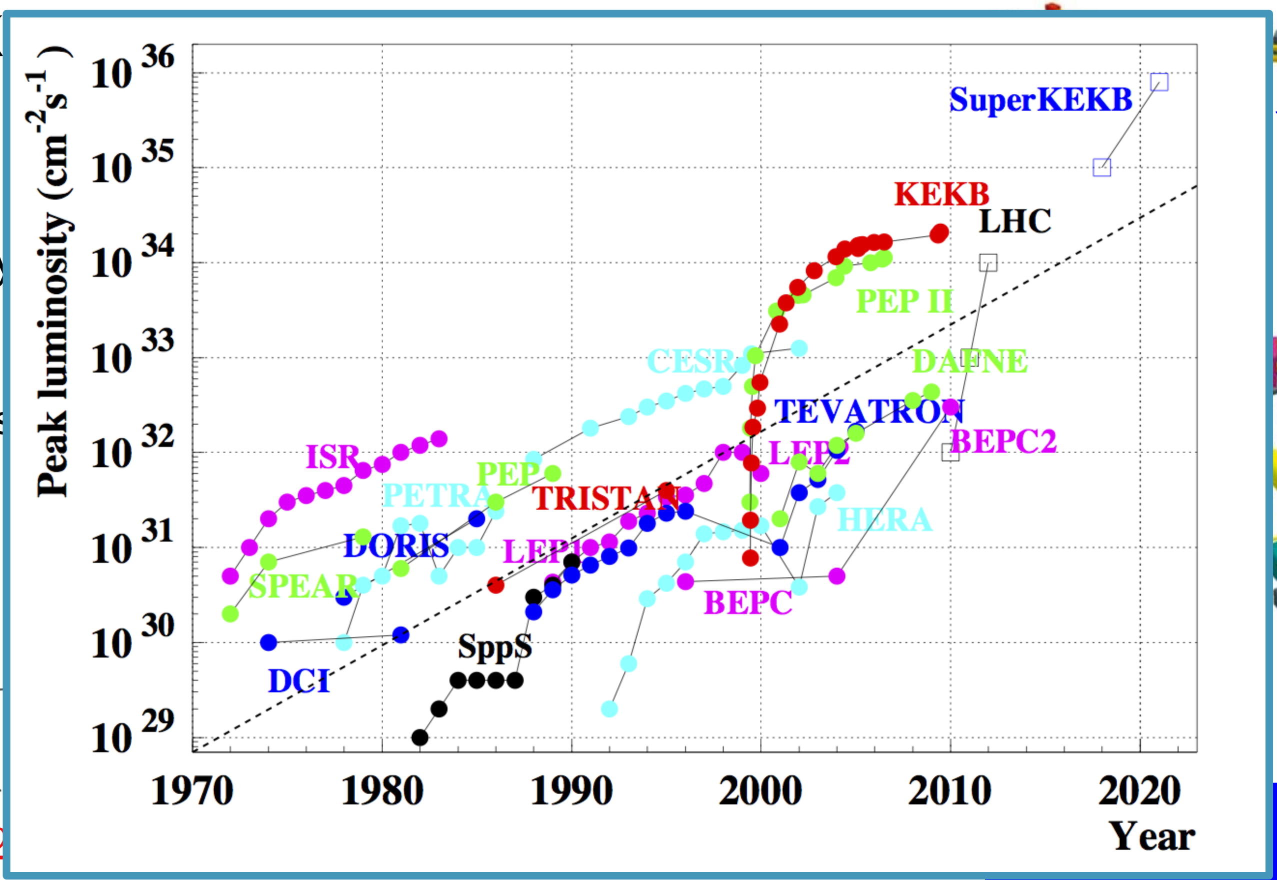
SuperKEK

located at

It's an asy

operating

( $\Upsilon$**(4S)**, but poss

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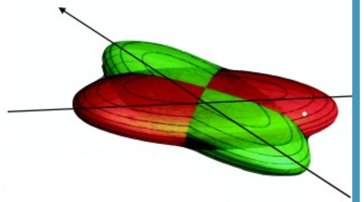
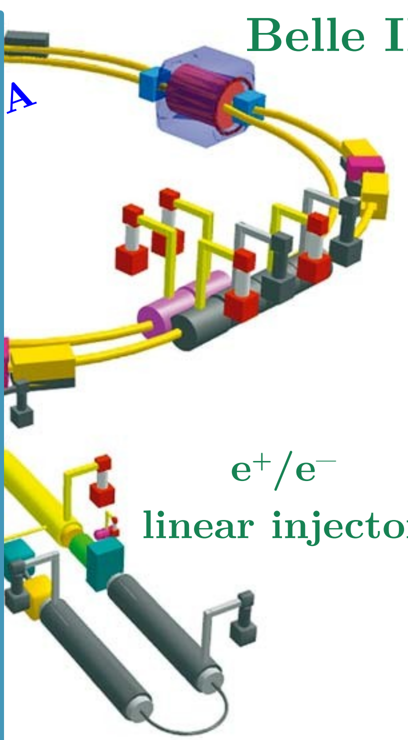





I (A): ~ 1.6/1.2

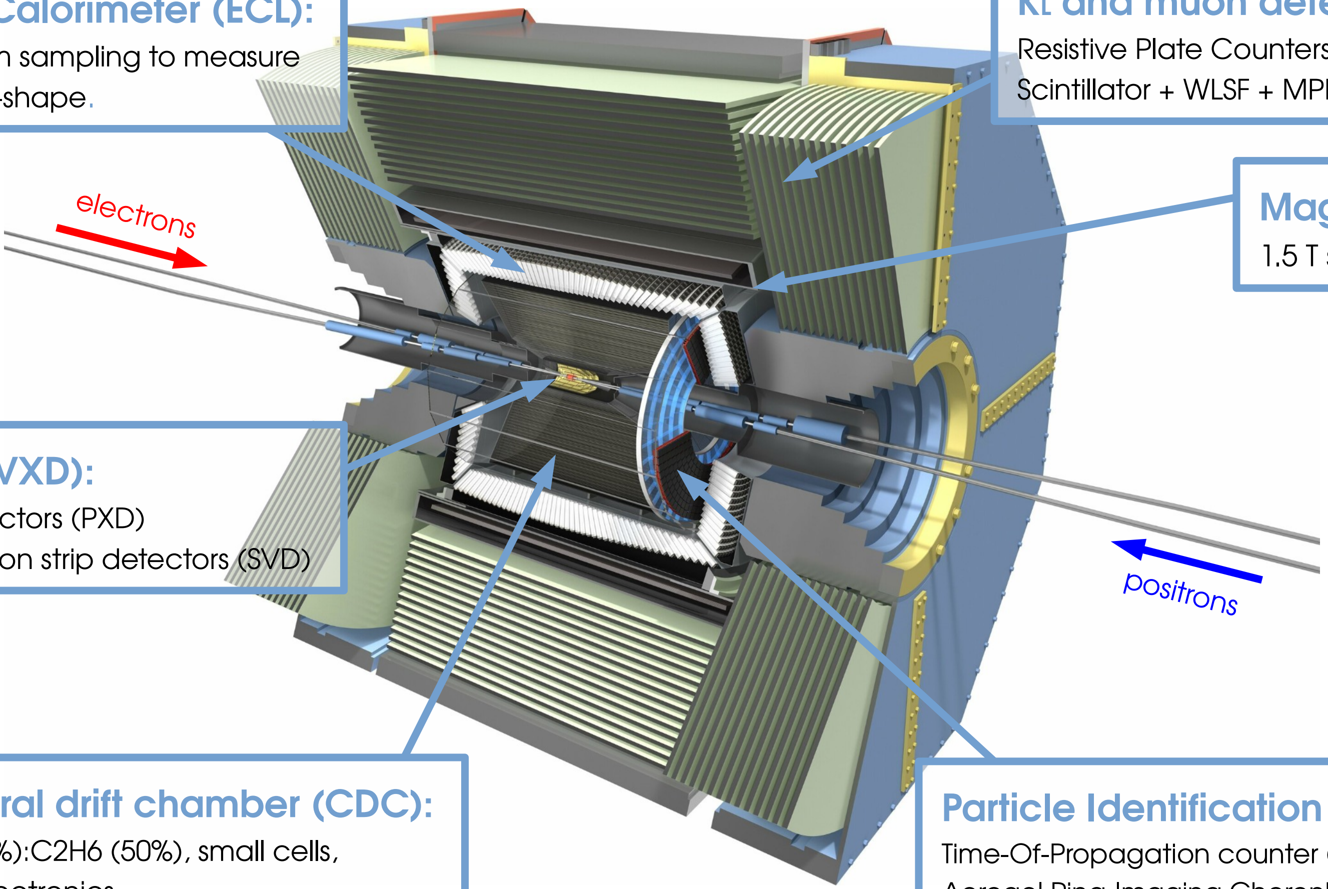
$\beta^*_y$ (mm): ~ 5.9/5.9

$\beta^*_y$ (mm): ~ 0.27/0.3

**luminosity:**

**$6 \cdot 10^{35}$ $cm^{-2}$ $s^{-1}$**

# 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)

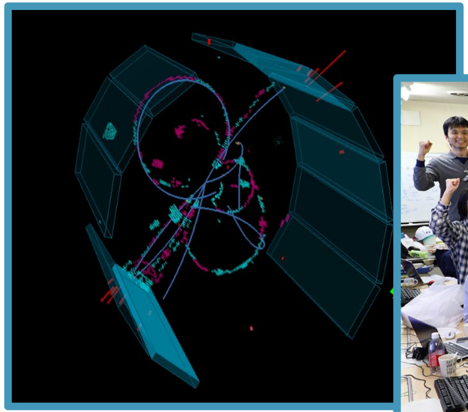
**Trigger:**
Hardware: < 30 kHz
Software: < 10 kHz

**Central drift chamber (CDC):**
He(50%):$C_2H_6$ (50%), small cells, fast electronics

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

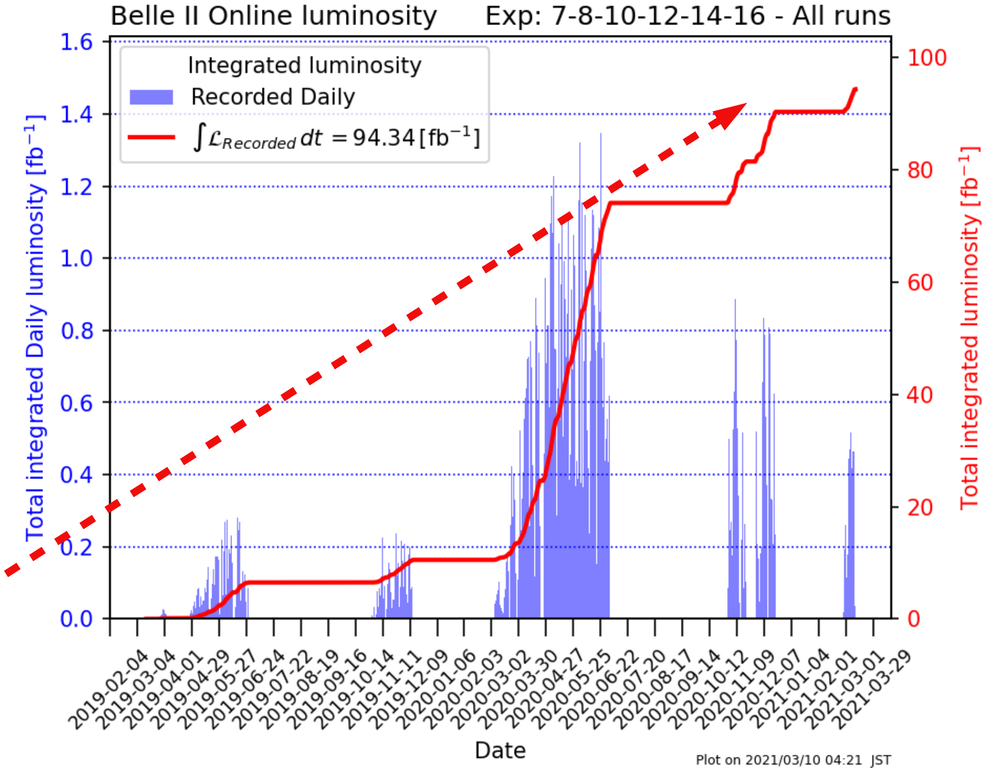
# SuperKEKB and Belle II operations

First collisions: 26th April 2018



Collected 0.5 $fb^{-1}$ in 2018 (pilot run)

Collected about 94 $fb^{-1}$ since 2019




## Goal: collect up to 50 $ab^{-1}$!

# Dark Matter

It is "dark".

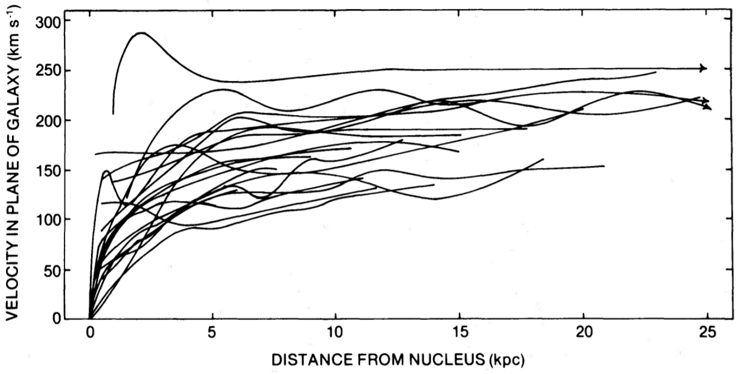
It exists...

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

# Dark Matter

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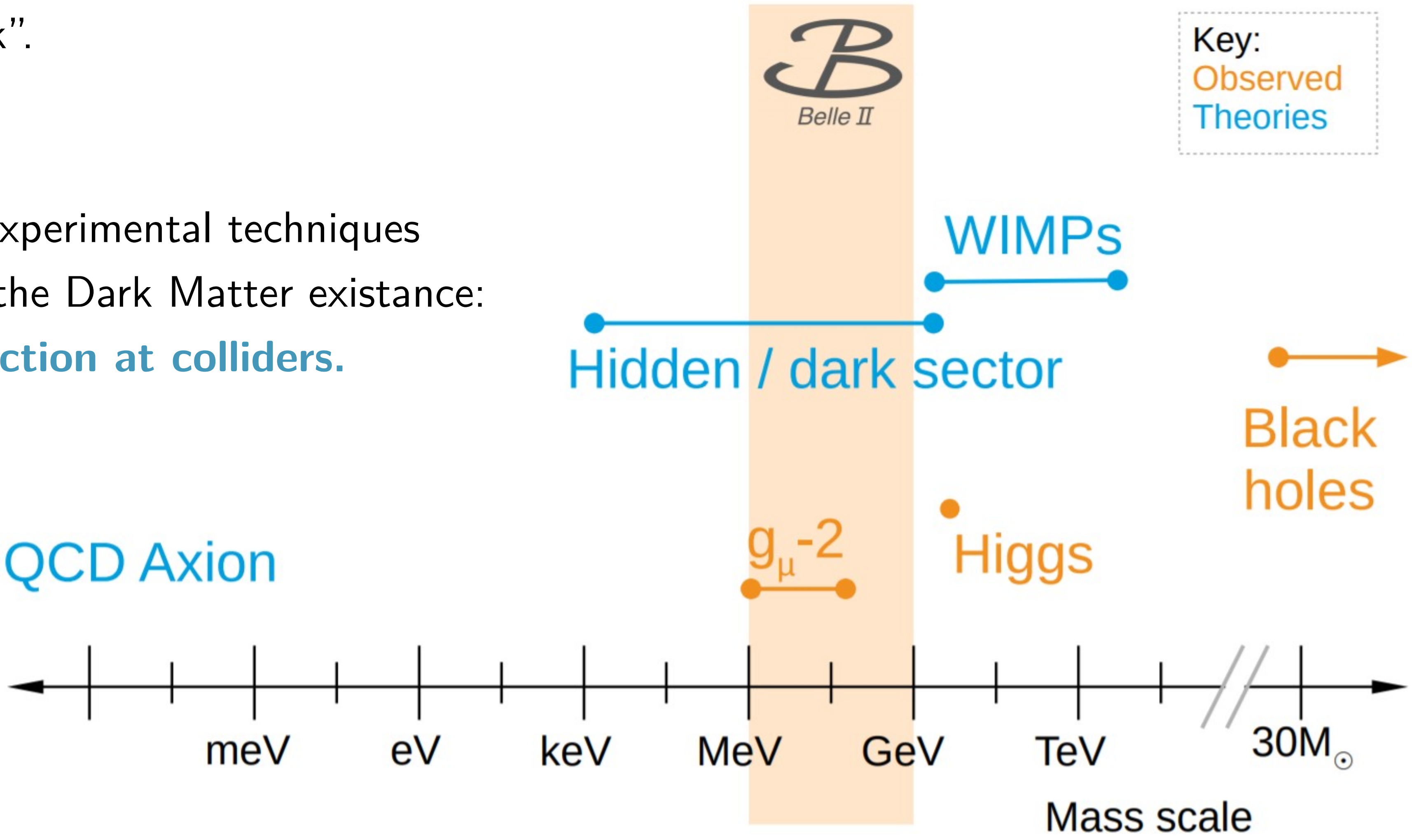
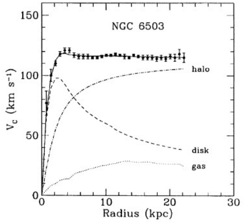
A lot of experimental techniques
to probe the Dark Matter existance:

- **production at colliders.**



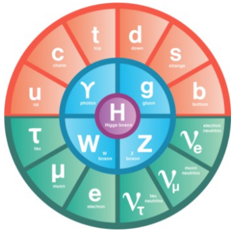
# Dark Matter coupling to SM

Dark Matter




**X**

Standard Model




$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Different possible portals between **Dark Matter** and **Standard Model**

depending on the **dark mediator X**:

Vector portal → Dark Photon / Z'

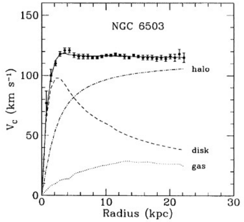
Scalar portal → Dark Higgs / Dark Scalar

Pseudoscalar portal → Axion-Like Particles

Neutrino portal → Sterile Neutrinos

# Dark Matter coupling to SM

Dark Matter

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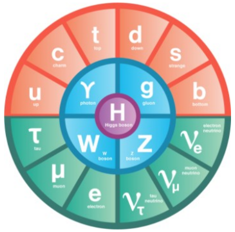


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Different possible portals between **Dark Matter** and **Standard Model** depending on the **dark mediator X**:

Vector portal → Dark Photon / **Z'**

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Pseudoscalar portal → **Axion-Like Particles**

Neutrino portal → Sterile Neutrinos

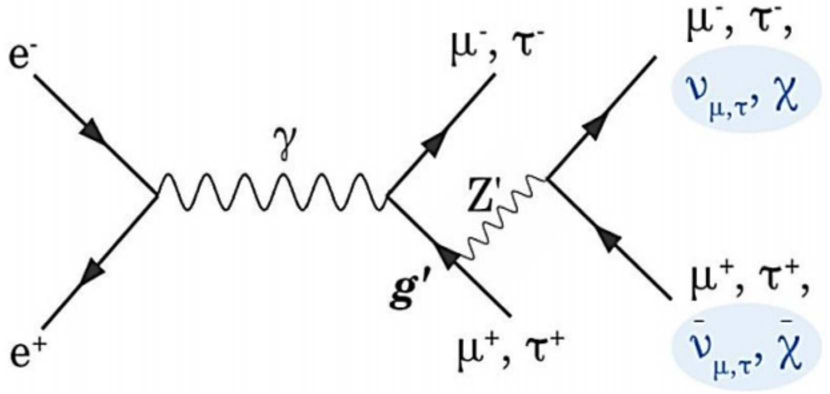
# $L_\mu - L_\tau$ model: Z' to invisible

New light gauge boson Z' coupling only to **2nd and 3rd** generation of leptons (**$L\mu - L\tau$ model**):

$$\mathcal{L} = \sum_{\ell = \mu, \tau, \nu_{\mu,L}, \nu_{\tau,L}} \theta g' \bar{\ell} \gamma^\mu Z'_\mu \ell$$

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

It may explain:
- DM puzzle;
- $(g\text{-}2)_\mu$ anomaly;
- R(K) and R(K*) anomalies.




Invisible decay studied here for the first time

Looking for an invisibly decaying Z' produced with a pair of muons:
- Z' can decay to neutrinos or light DM if kinematically accessible;
- BF(Z' $\rightarrow$ invisible) $= 1$ if $m_{Z'} < 2m_\mu$.

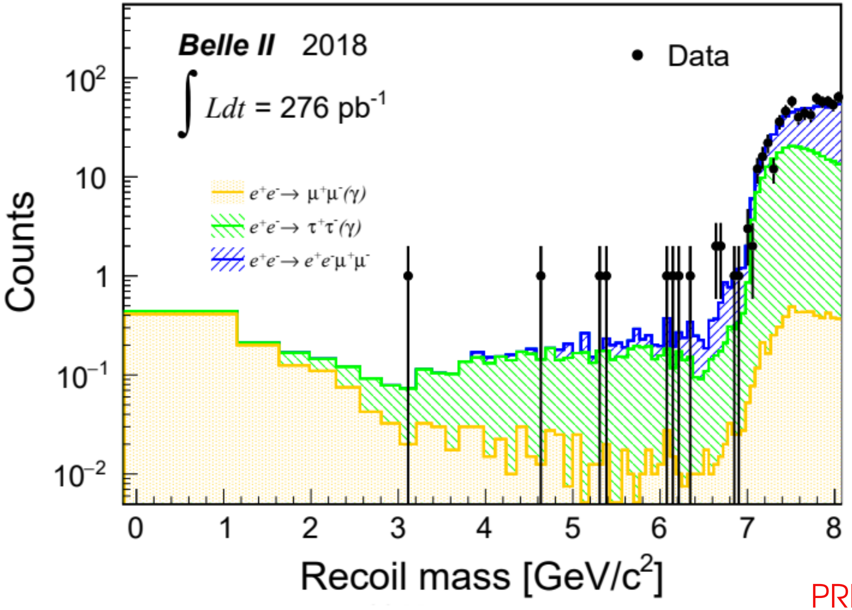
**First physics paper by Belle II:**
PRL 124 (2020) 141801

# $L_\mu - L_\tau$ model: Z' to invisible

Measurement done using **2018 pilot run data**: only 276 $pb^{-1}$ usable due to trigger conditions.

Looking for:

- a peak in the mass distribution of the recoiling system against the dimuon pair;
- nothing else in the rest of the event.




PRL 124 (2020) 141801

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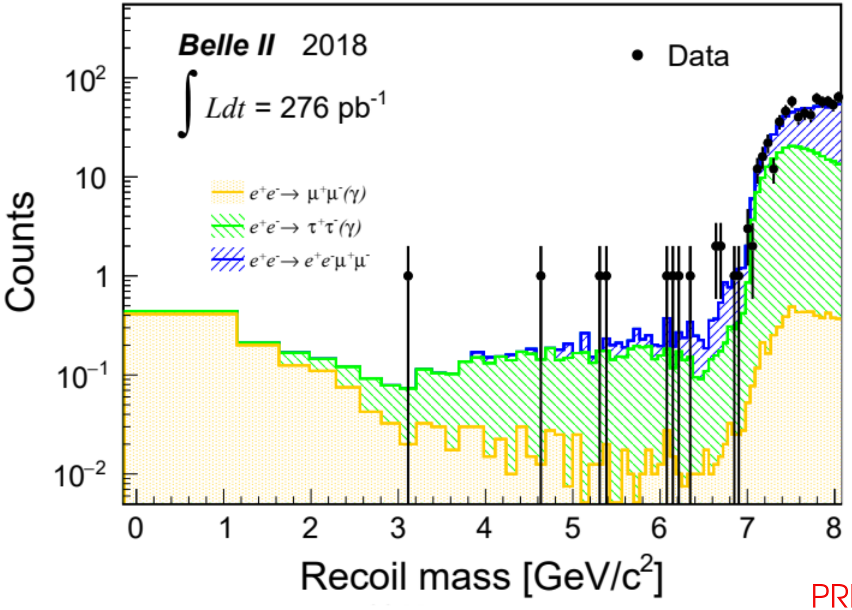
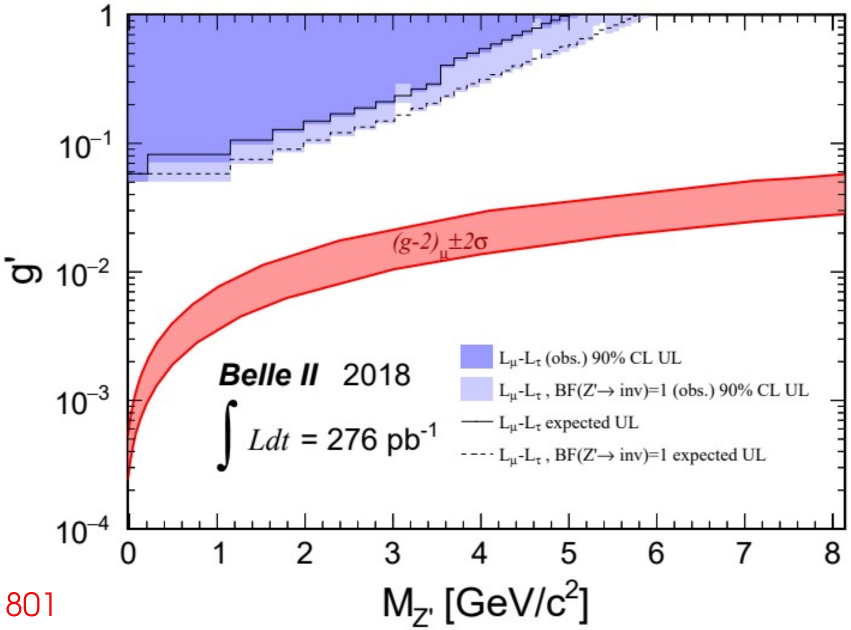



90% CL upper limit on the g′ coupling constant

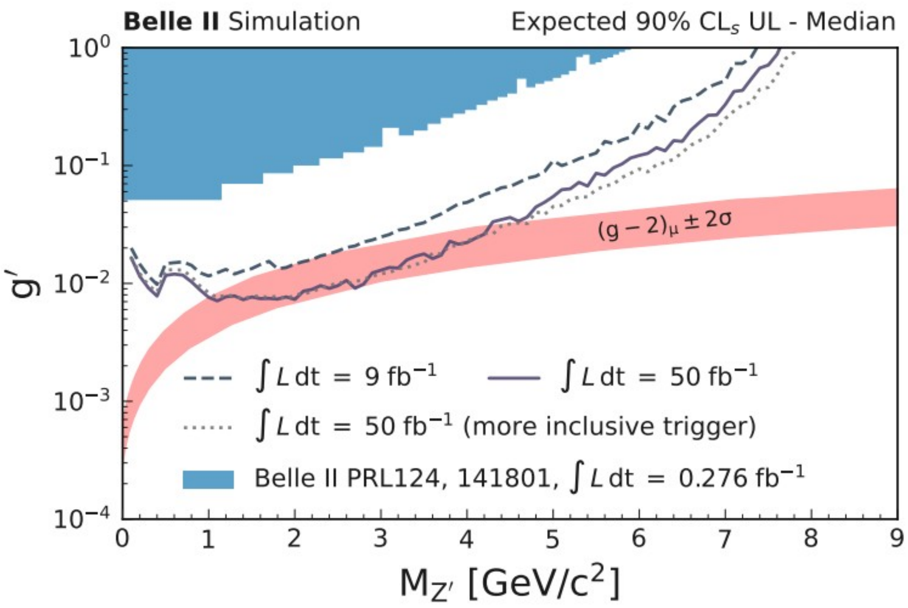



PRL 124 (2020) 141801

# $L_\mu - L_\tau$ model: Z' to invisible

Short term projections including several improvements:

- much higher integrated luminosity (already on tape);
- analysis improvements (better muonID, MVA selection);
- new triggers.




Starting to probe the $(g-2)_\mu$ band already with 50 $fb^{-1}$.

*Preliminary (conservative) systematics considered here.*

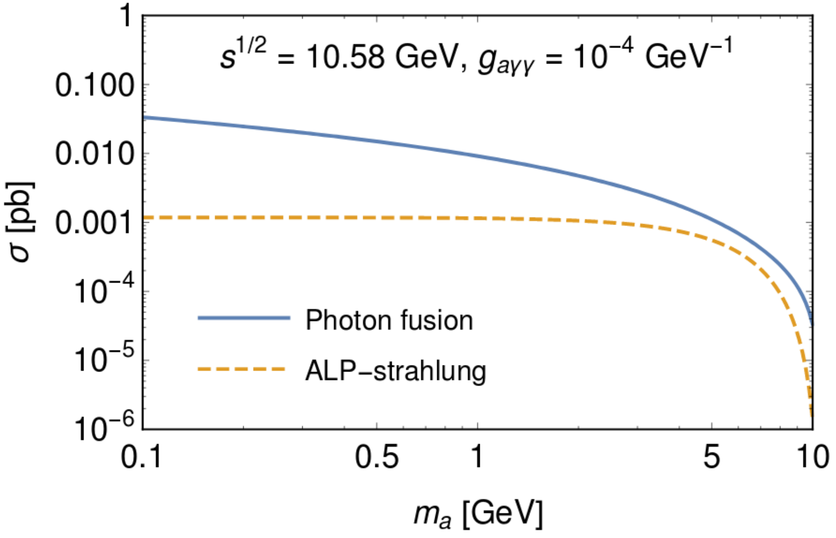
# Axion-Like Particles: a → γγ

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

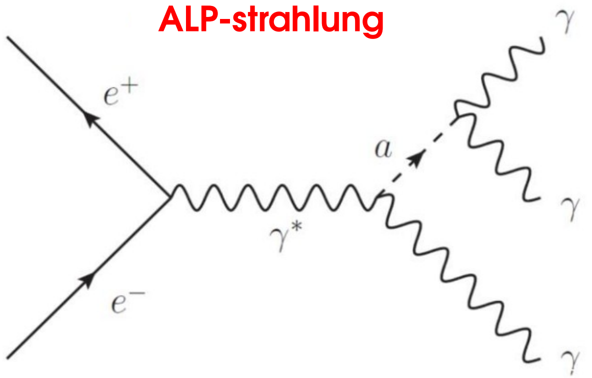
Belle II focused on the **coupling to photons**:

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

Dolan et al. (2017), *arXiv:1708.00009*




ALP-strahlung



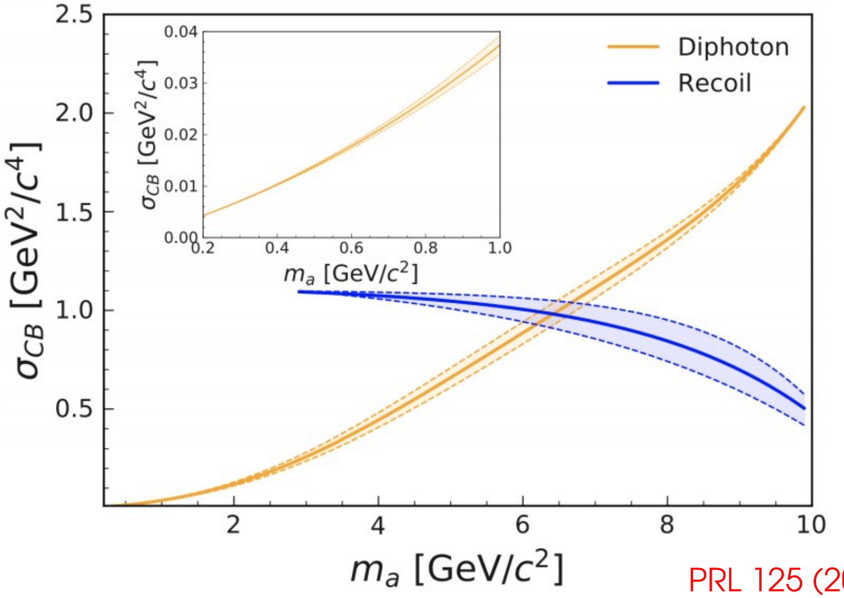

**Investigating the photon coupling $g_{a\gamma\gamma}$ in ALP-strahlung**

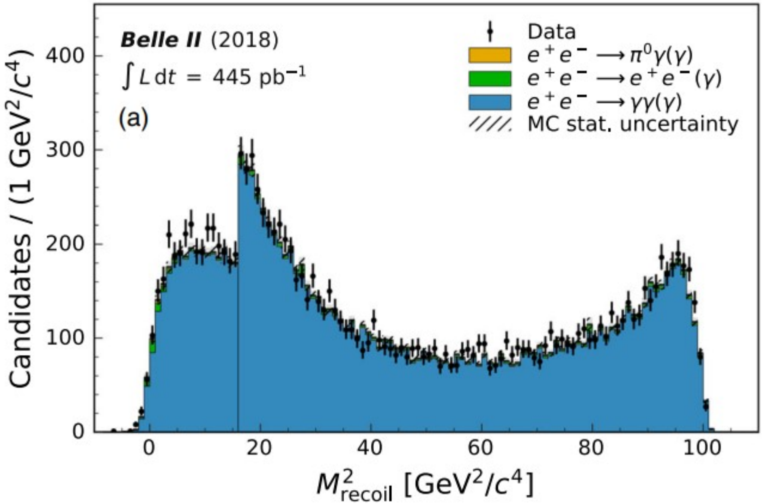
**First search at B-factories**

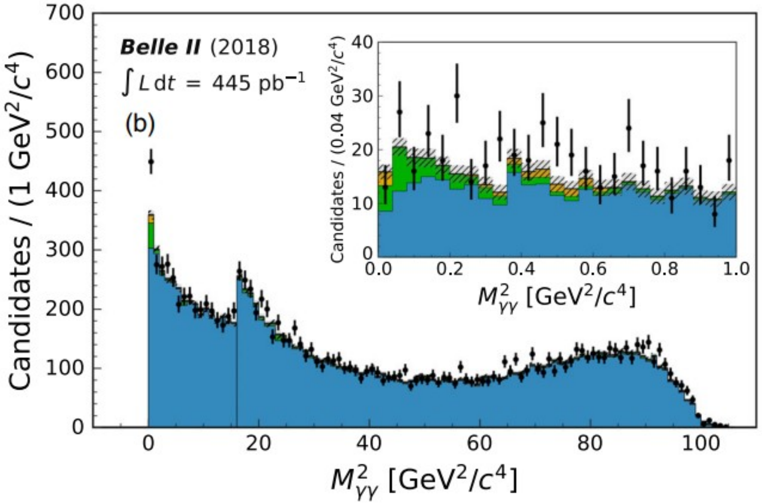
# Axion-Like Particles: a $\to \gamma\gamma$

Select fully neutral events consisting of 3 isolated photons with a total invariant mass consistent with $\mathbf{s}^{1/2}$.

Search strategy optimized to maximize ALP sensitivity:
- low ALP mass $\to$ recoil mass spectrum;
- high ALP mass $\to$ diphoton mass spectrum.



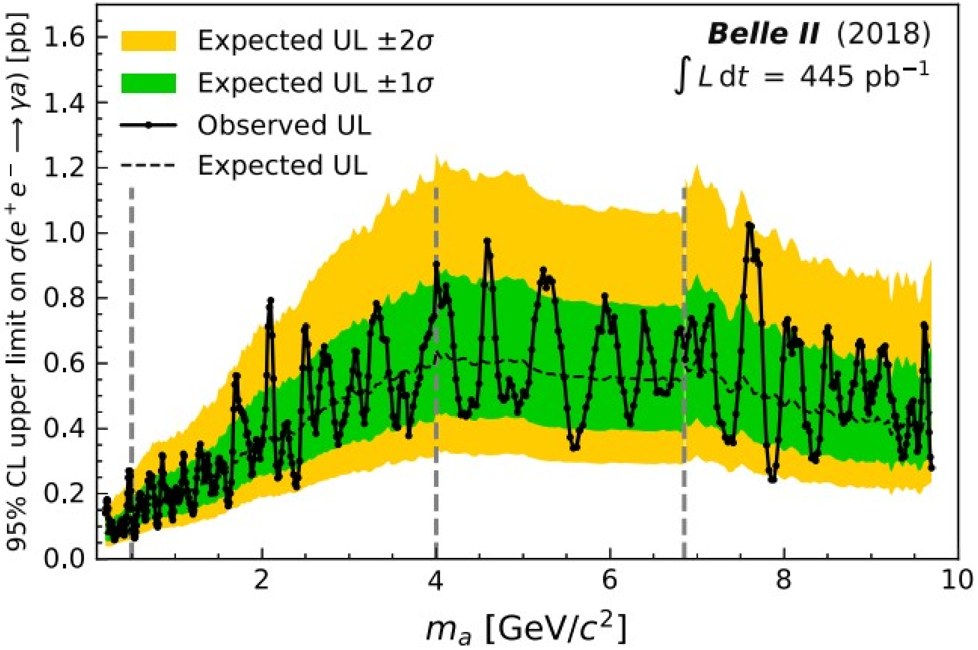




PRL 125 (2020) 161806

# Axion-Like Particles: $a \to \gamma\gamma$

Search conducted with 445 pb-1 of 2018 pilot run data:

- 500 fits in sliding ranges with steps of half mass resolution;
- no excess observed (largest local significance: 2.8 $\sigma$).




PRL 125 (2020) 161806

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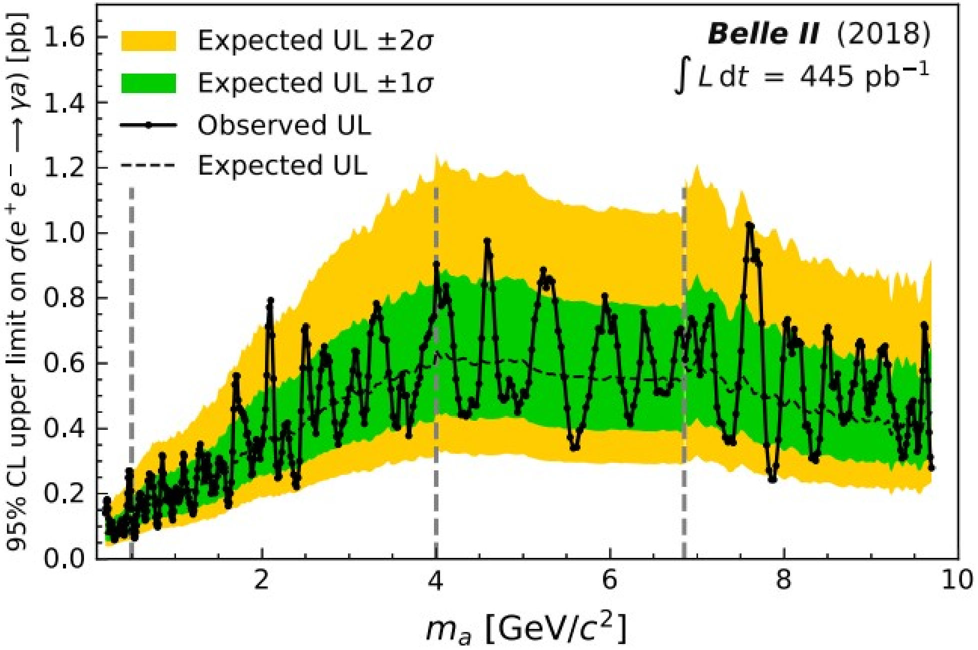
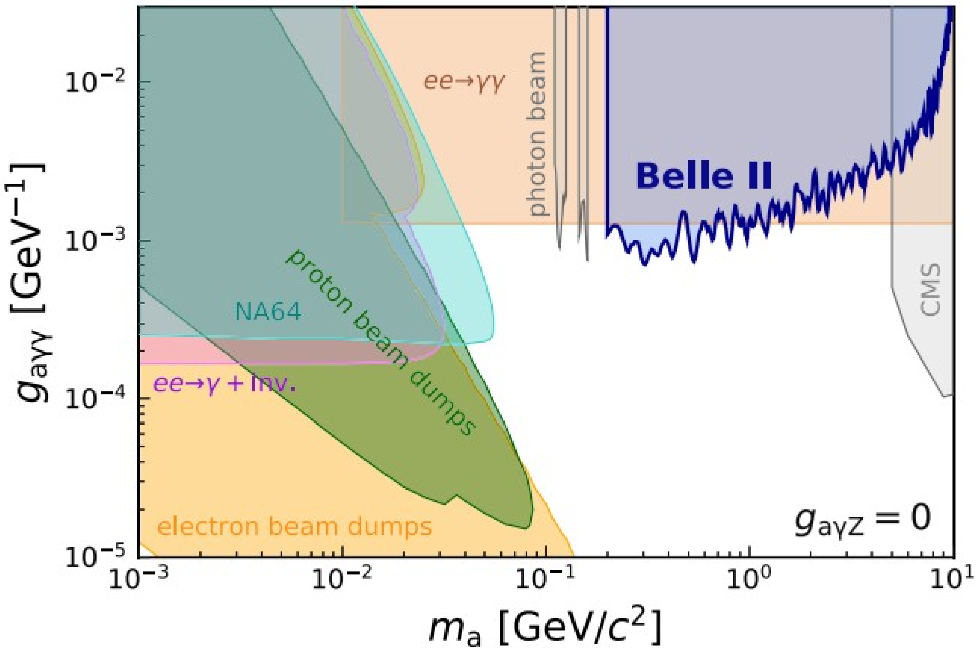
$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{QED}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$



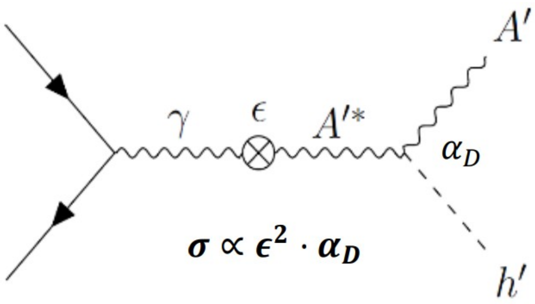




PRL 125 (2020) 161806

# Dark Higgsstrahlung

Dark Photon (A') mass could be generated via a spontaneous symmetry breaking mechanism, adding a Dark Higgs boson (h') to the model:

- Dark Higgsstrahlung process: $e^+ e^- \rightarrow A'^* \rightarrow A'\ h'$



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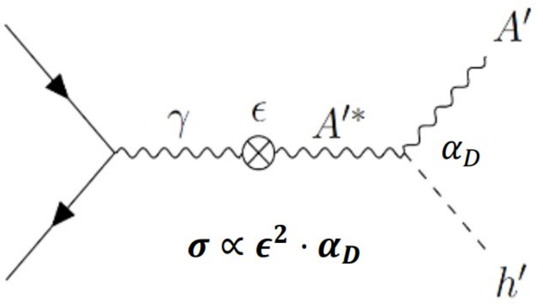
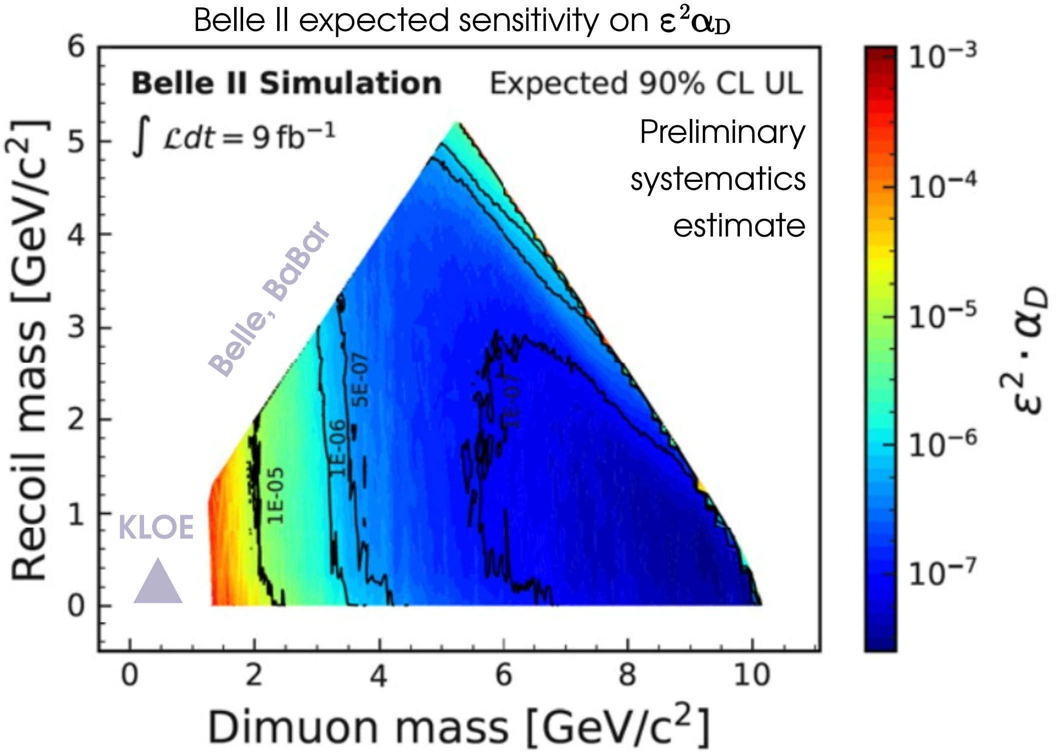



At Belle II we are exploring the invisible h' decay ($m_{h'} < m_{A'}$), constrained only by KLOE:

$$e^+ e^- \to A'^* \to A'(\to \mu^+ \mu^-)\ h'(\to \text{inv.})$$

Very promising results even considering only the 2019 dataset (9 fb$^{-1}$):

- accessing an unconstrained region beyond the KLOE coverage;
- probing non-trivial $\varepsilon^2 \alpha_D$ couplings.

# Other ongoing Dark Sector searches @ Belle II

Dark Photon (A') decays

- invisible decay
- leptonic decays

Dark Scalar:

- $e^+ e^- \to \tau^+ \tau^- S(\to l^+ l^-)$

Dark Scalar with displaced vertex:

- $B^+ \to K^+ S(\to l^+ l^-)$

Inelastic Dark Matter

Other Z' decays:

- $e^+ e^- \to \mu^+ \mu^- Z'(\to \mu^+ \mu^-)$
- $e^+ e^- \to \mu^+ \mu^- Z'(\to \tau^+ \tau^-)$

Magnetic monopoles

... and many others!

# Summary

- Belle II has a broad and active program to explore the Dark Sector;
- We successfully started operations in 2018; up to now we collected $> 90$ fb$^{-1}$ of data;
- First results with early data (2018 pilot run) are published:
  - Z' $\rightarrow$ invisible search (PRL 124 (2020) 141801);
  - ALP $\rightarrow \gamma\gamma$ search (PRL 125 (2020) 161806);


Thank you for your attention

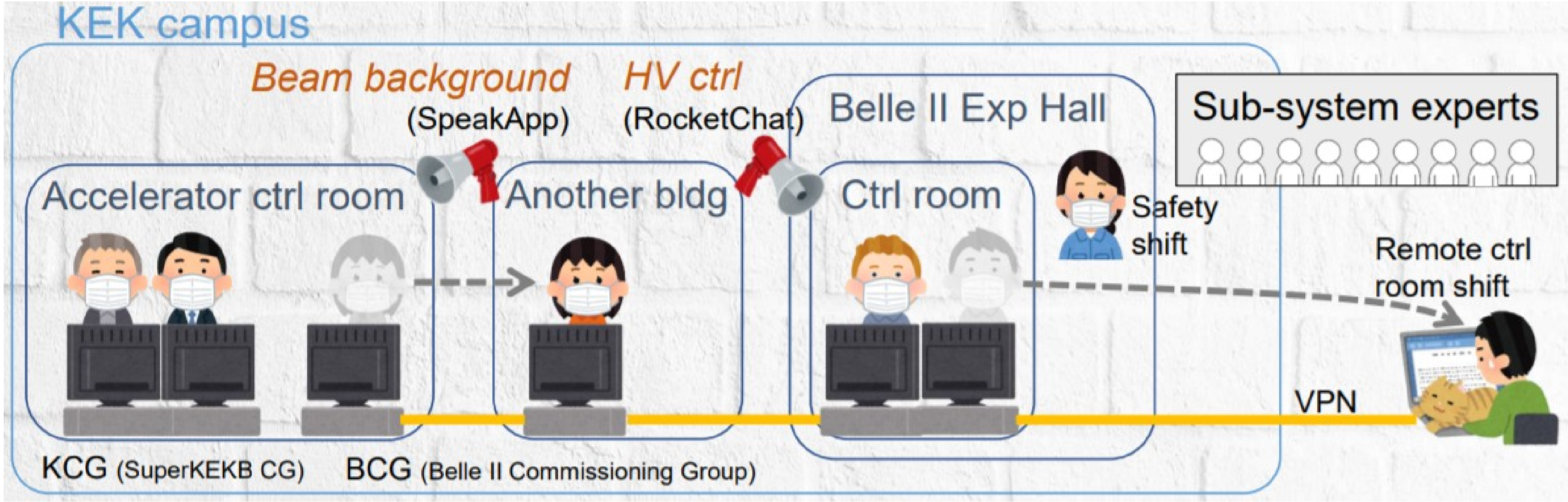

Backup
slides
S/N 16
S/N 23
INFN
LNF-RM3
Z AXIS
JTAG
Phi AXIS

# Taking data during the 2020 pandemic...

**Non-stop operations with COVID-19 pandemic**:

- social distancing requirements;
- strong developments for close to or fully **remote sub-system operations**;
- **huge commitments from japanese colleagues and residents in Japan**;

$\rightarrow$ only 40 persons on site from March to July.




courtesy of K. Matsuoka

Belle II data taking efficiency: **85%**

# SuperKEKB machine parameters

| Parameter | KEKB Design | KEKB Achieved | SuperKEKB Design |
|---|---|---|---|
| Energy (GeV) (LER/HER) | 3.5/8.0 | 3.5/8.0 | $\boxed{4.0/7.0}$ |
| $\beta_y^*$ (mm) | 10/10 | 5.9/5.9 | 0.27/0.30 |
| $\beta_x^*$ (mm) | 330/330 | 1200/1200 | 32/25 |
| $\varepsilon_x$ (nm) | 18/18 | 18/24 | 3.2/5.3 |
| $\frac{\varepsilon_y}{\varepsilon_x}$ (%) | 1 | 0.85/0.64 | 0.27/0.24 |
| $\sigma_y$ ($\mu$m) | 1.9 | 0.94 $\xrightarrow{1/20}$ | 0.048/0.062 |
| $\xi_y$ | 0.052 | 0.129/0.090 | 0.09/0.081 |
| $\sigma_z$ (mm) | 4 | 6/7 | 6/5 |
| $I_{beam}$ (A) | 2.6/1.1 | 1.64/1.19 $\xrightarrow{x2}$ | 3.6/2.6 |
| $N_{bunches}$ | 5000 | 1584 | 2500 |
| Luminosity ($10^{34} cm^{-2} s^{-1}$) | 1.0 | 2.11 $\xrightarrow{x40}$ | 80 |

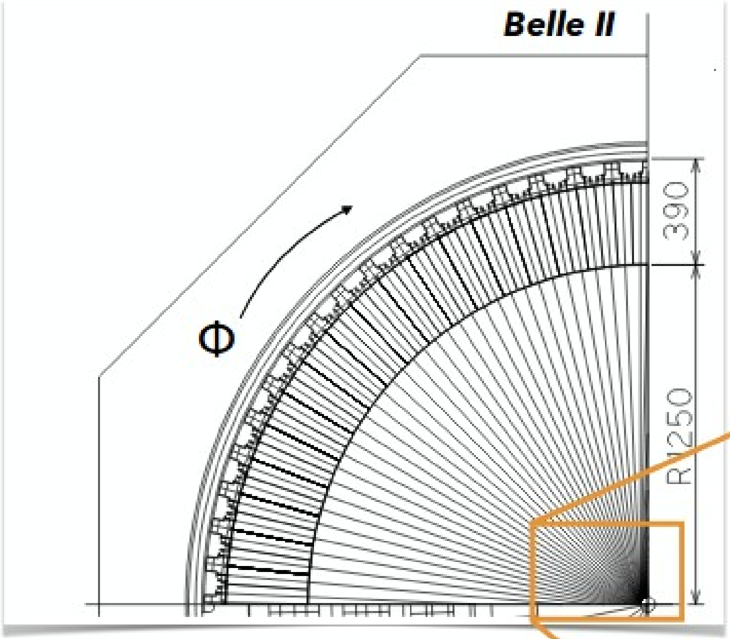
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

# Cross sections at a B-factory

| Physics process | Cross section [nb] | Selection Criteria | Reference |
|---|---|---|---|
| $\Upsilon(4S)$ | $1.110 \pm 0.008$ | - | [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 |
| $e^+e^-(\gamma)$ | $300 \pm 3$ (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 | - |
| $\gamma\gamma(\gamma)$ | $4.99 \pm 0.05$ (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 |
| $\nu\bar{\nu}(\gamma)$ | $0.25 \times 10^{-3}$ | - | KKMC |
| $e^+e^-e^+e^-$ | $39.7 \pm 0.1$ (MC stat.) | $W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$ | AAFH |
| $e^+e^-\mu^+\mu^-$ | $18.9 \pm 0.1$ (MC stat.) | $W_{\ell\ell} > 0.5\,\mathrm{GeV}/c^2$ | AAFH |

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

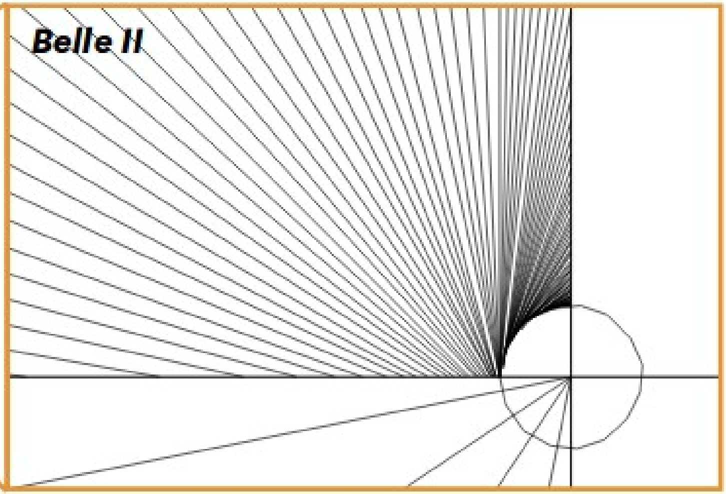
# Electromagnetic Calorimeter (ECL)




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

→ more hermetic

→ more efficient



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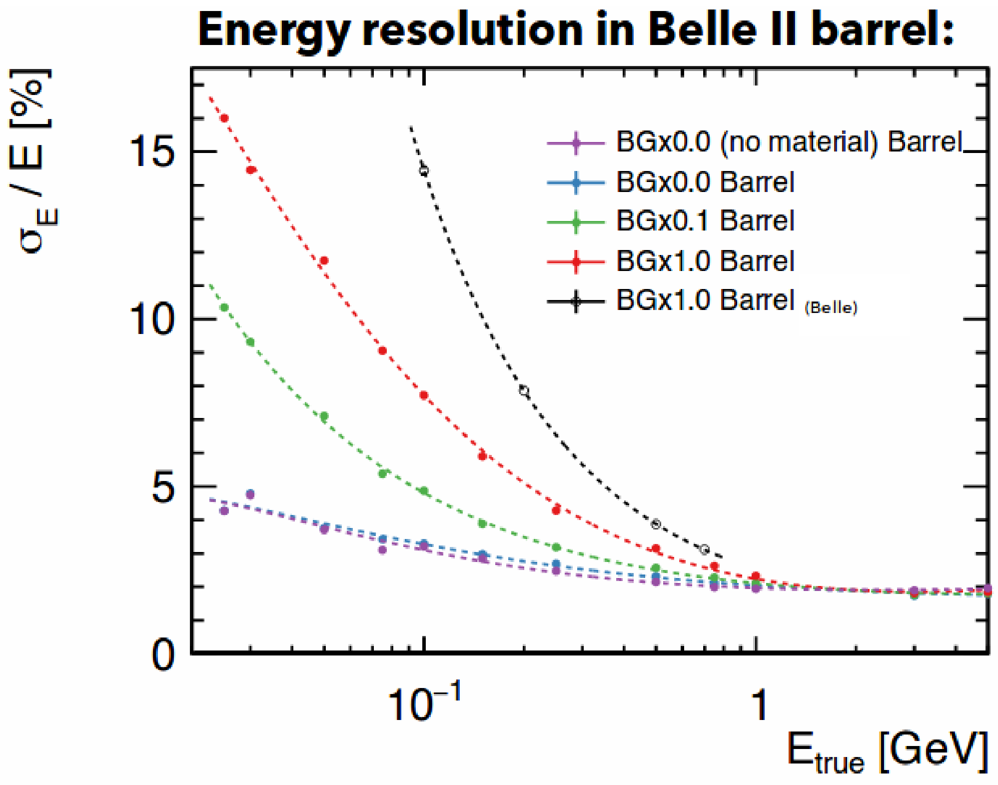
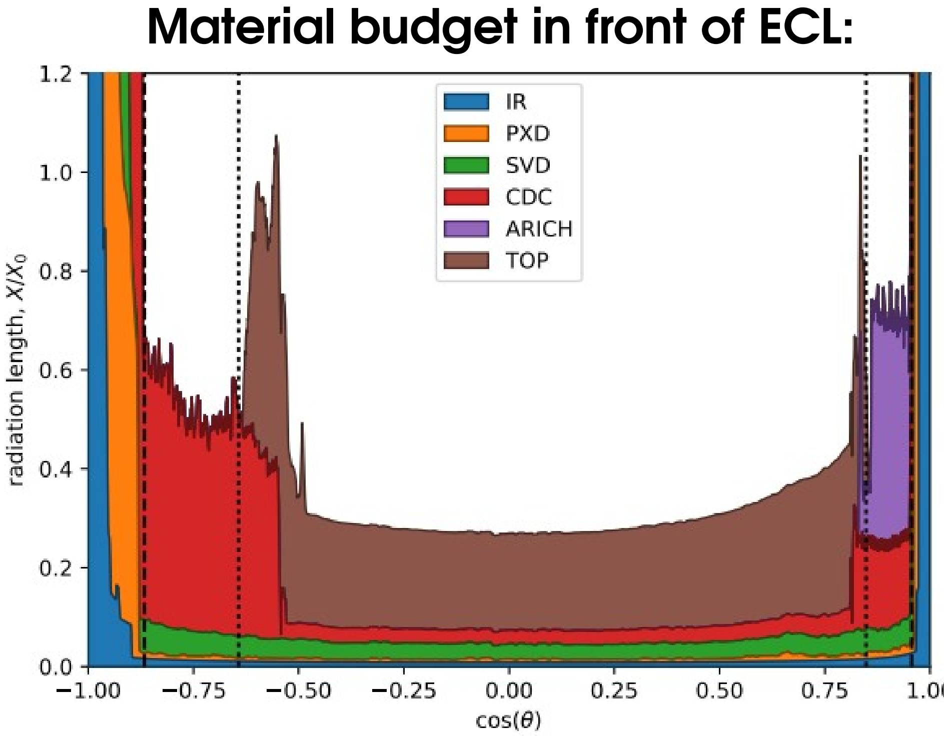
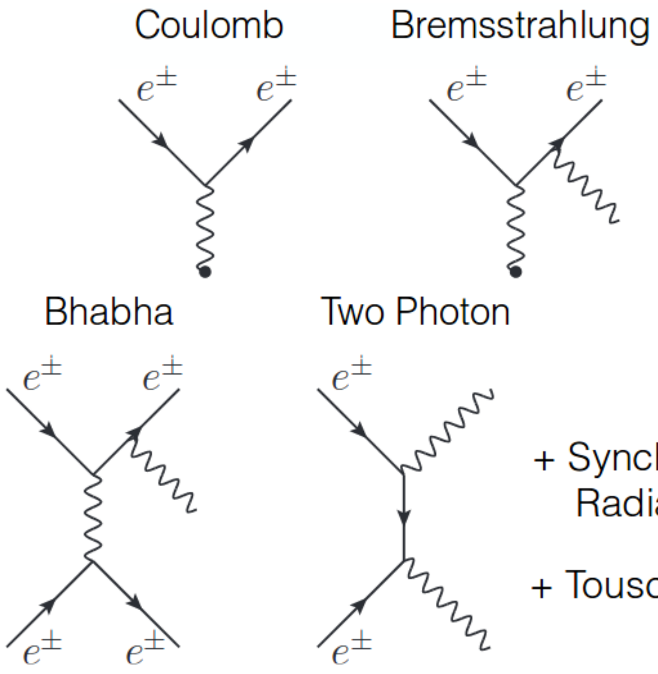


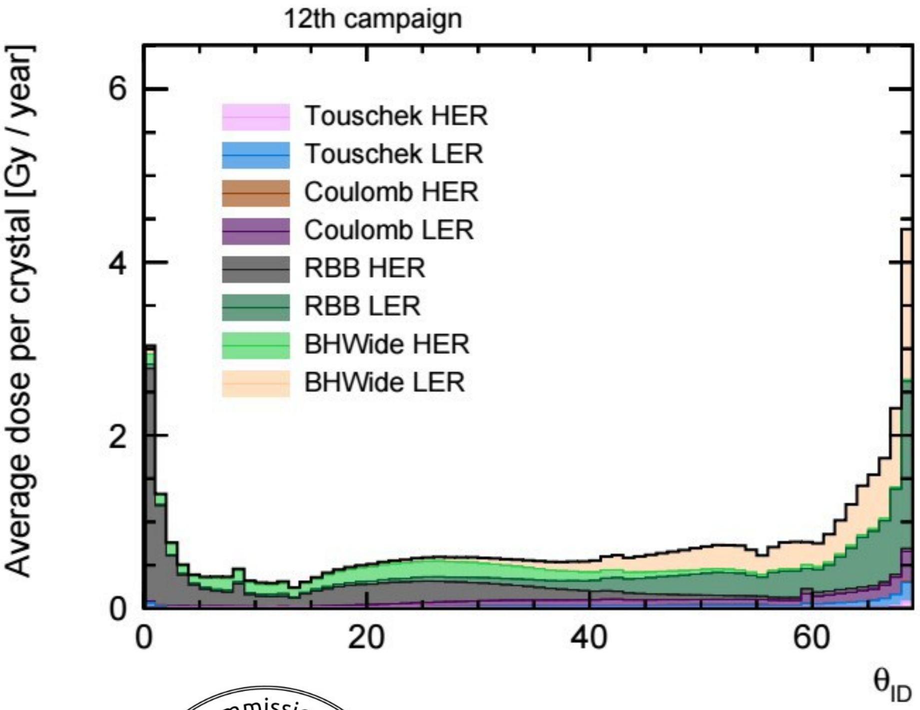



# Beam background




+ Synchrotron Radiation

+ Touschek




**Effects from beam background:**

→ degrades calorimeter resolution.

→ radiation damage.

→ pile-up and event size.

→ physics background

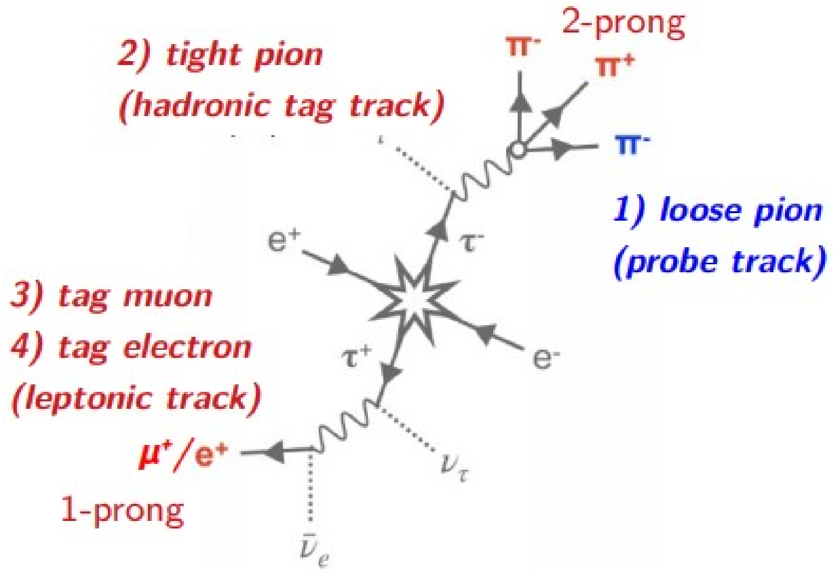
**BEAST**: dedicated systems for continuous beam background measurement and monitoring!

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

# Tracking performance

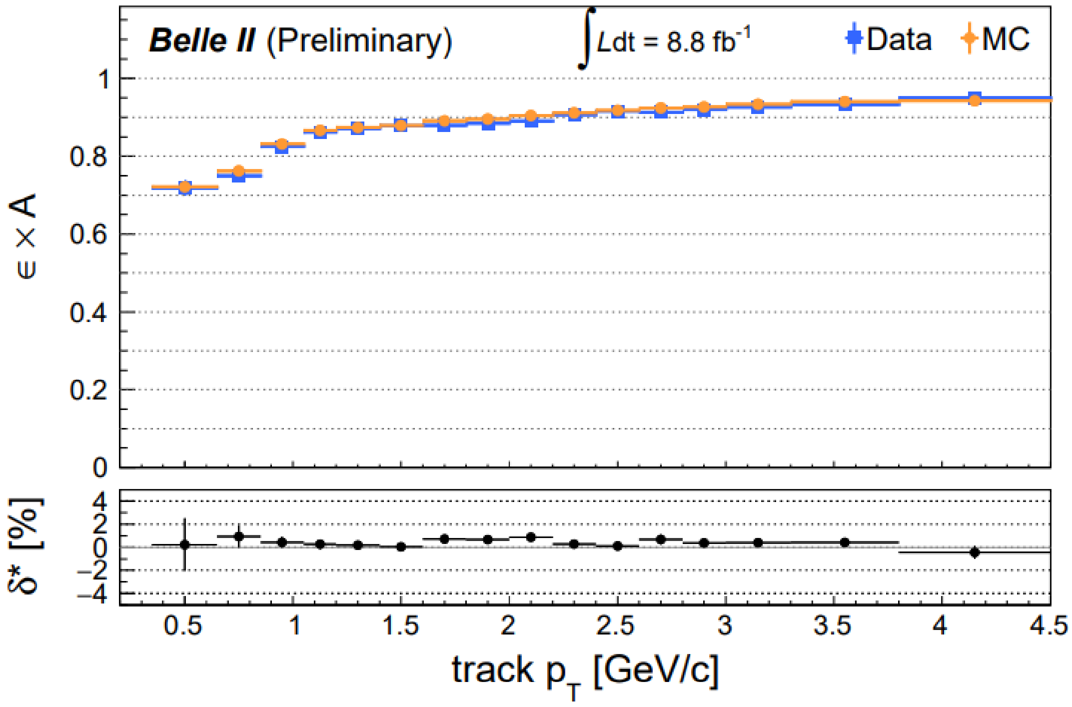
**Tag & probe** technique with events $e^+e^- \to \tau^+\tau^-$:

- 4 charged tracks expected;
- leptonID tags the event;
- 3 prongs provide the probe.




$\varepsilon = N_{evts}(4 \text{ tracks}) \,/\, [N_{evts}(4 \text{ tracks}) + N_{evts}(3 \text{ tracks})]$

Track finding paper: arXiv:2003.12466
Performance plots: BELLE2-NOTE-PL-2020-014




Similar technique to evaluate **fake rate per track**:

$$r_{fake} = (0.97 \pm 0.34_{stat} \pm 0.06_{syst})\ \%$$

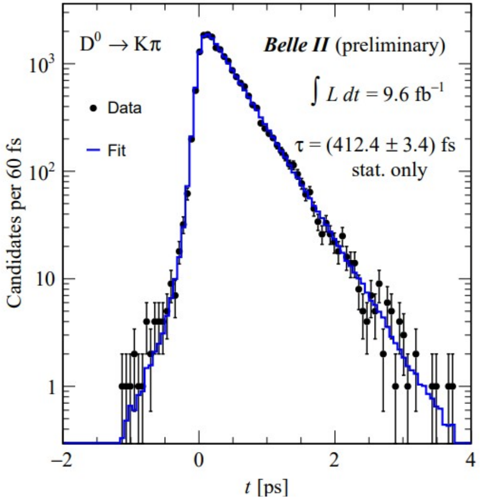
# Vertexing performance

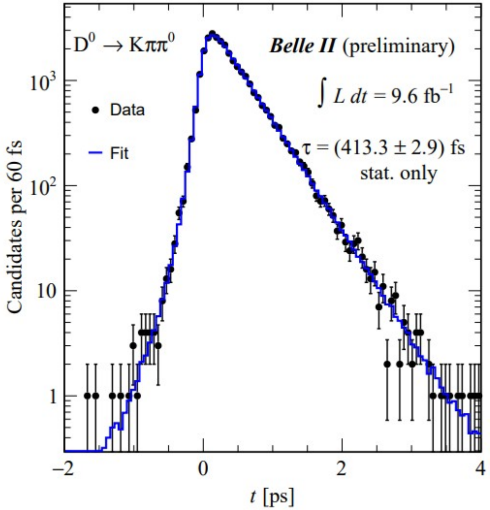
## $D^0$ lifetime:

- measurement with 3 channels: $K^-\pi^+$, $K^-\pi^+$, $K^-\pi^+\pi^-\pi^-$
- estimated vertex resolution: ~ **40 μm**;

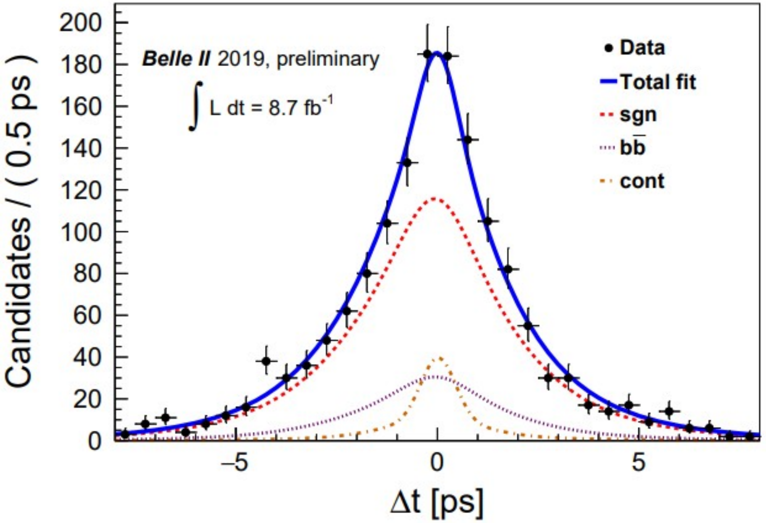
$\rightarrow \tau(D^0) = (412.3 \pm 2.0_{stat})$ fs

(world average: (410.1 ± 1.5) fs)




arXiv:2005.07507




## $B^0$ lifetime:

- smaller boost βγ: 0.42 (Belle) → 0.28 (Belle II);
- average distance between B-mesons: 200 μm → 130 μm;

- hadronic channels: $B^0 \rightarrow D^{(*)-}\pi^+/\rho^+$;
- estimated resolutions: Δt ~ 1 ps → **Δz ~ 80 μm**

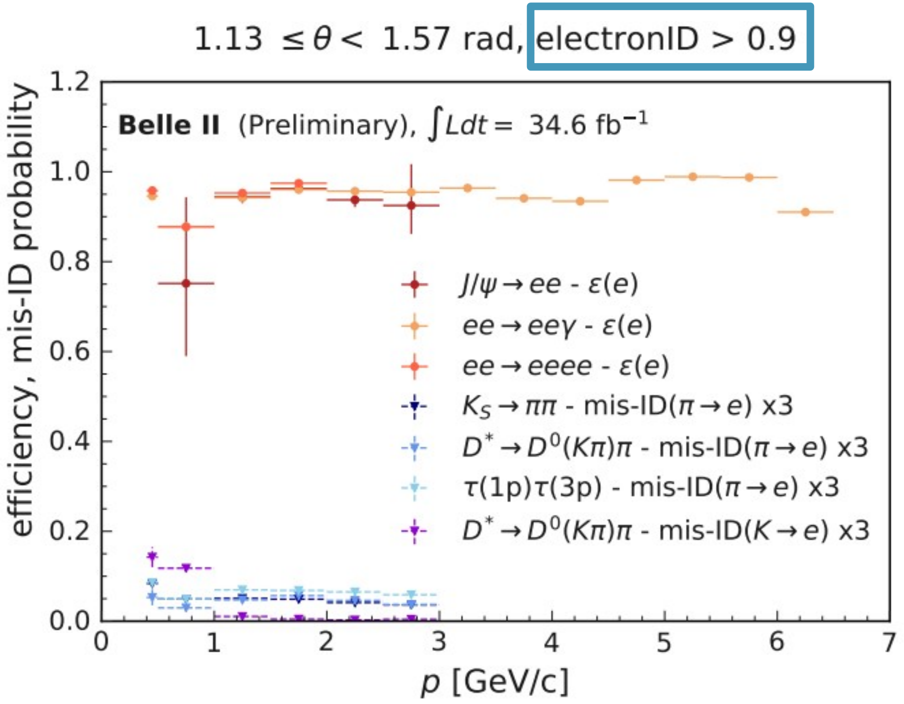
$\rightarrow \tau(B^0) = (1.48 \pm 0.28_{stat} \pm 0.06_{syst})$ ps

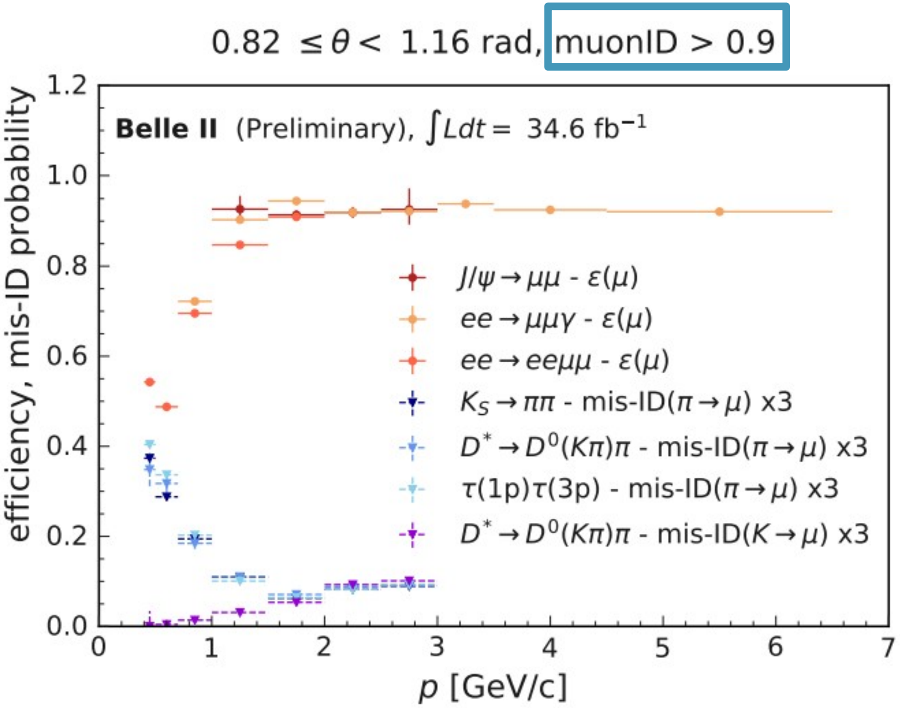
(world average: (1.519 ± 0.004) ps)

# Particle identification: leptons

Several fully reconstructed channels are used:

- extract both efficiency & mis-ID probability **from data**;
- measured for various leptonID and angular acceptance.



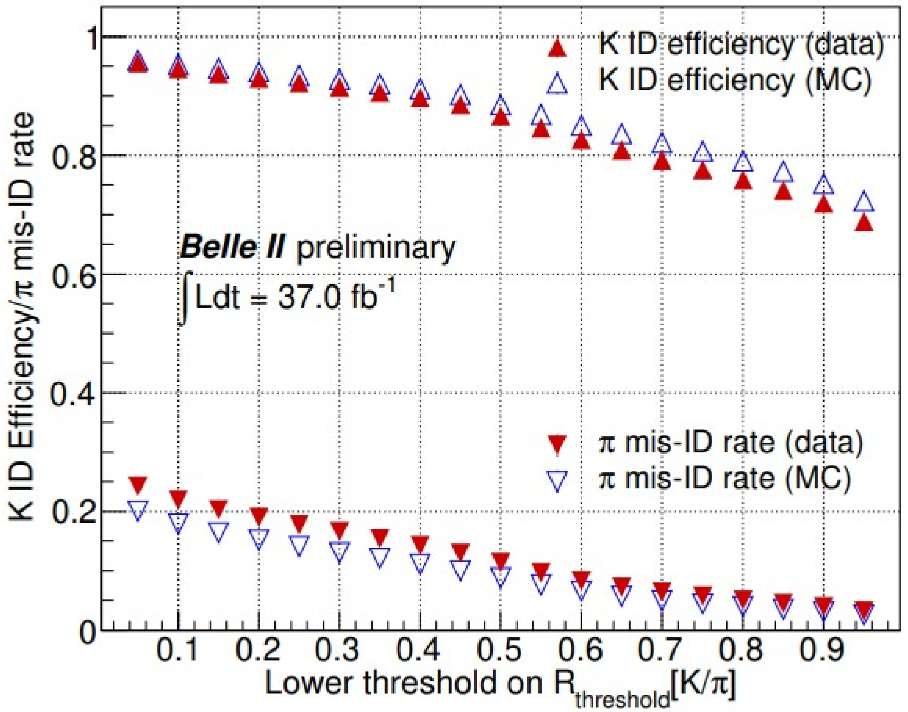



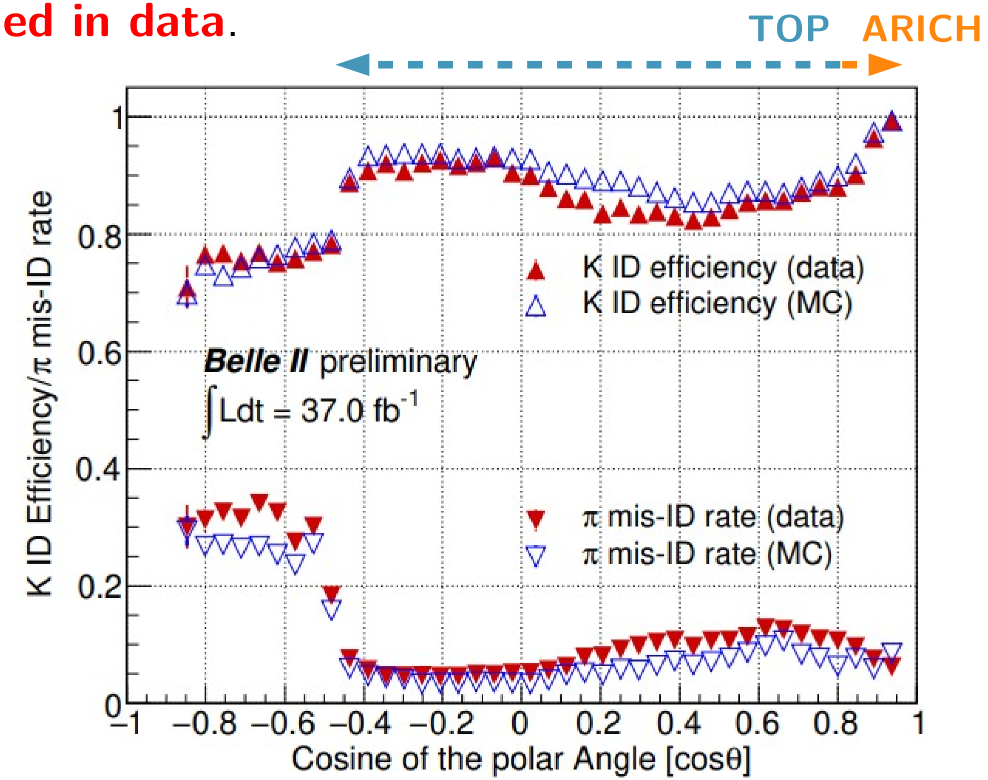

$$\text{leptonID} = \mathcal{L}_{\text{lepton}} \,/\, (\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p)$$

# Particle identification: hadrons

Fully reconstructed channels are used:

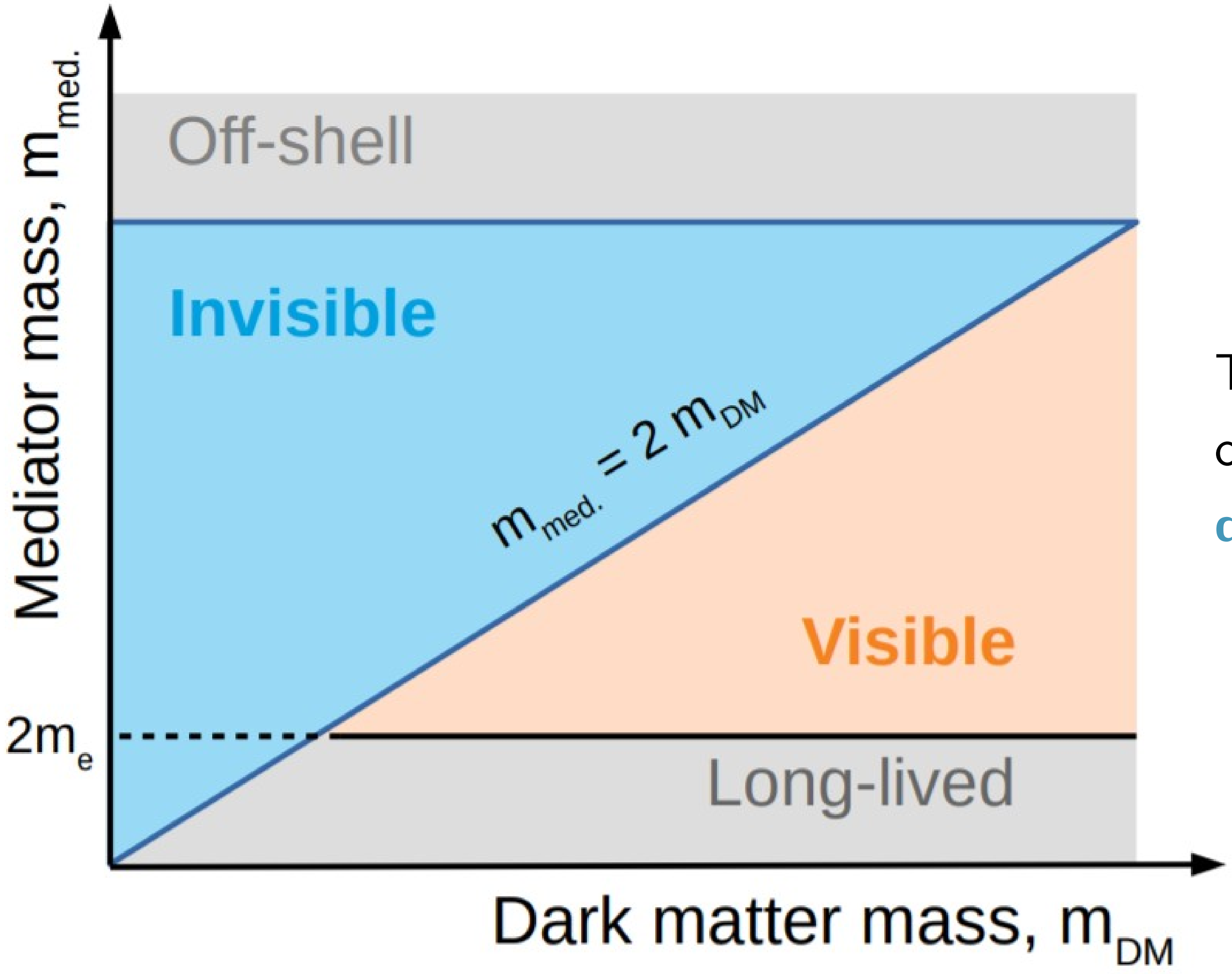
- $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$;
- slow $\pi$ tags the $D^0$ flavour $\to$ $K$ and $\pi$ **identified in data**.




$$K/\pi\text{-ID} = \mathcal{L}_{K/\pi} \,/\, (\mathcal{L}_\pi + \mathcal{L}_K)$$

# A rule of thumb...



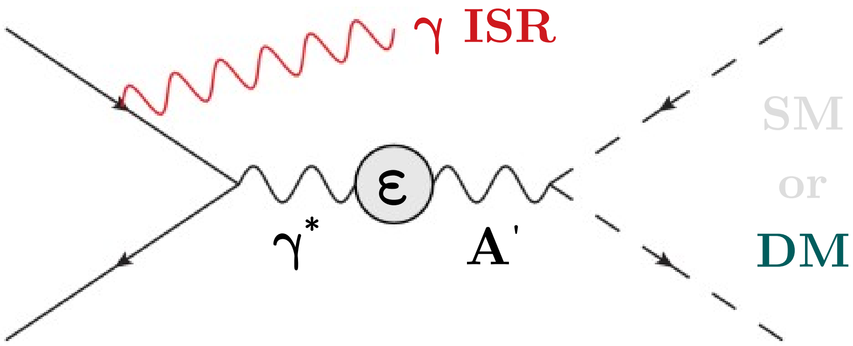

The masses of the mediator and of the DM candidates lead to **different type of searches**.

# Dark Photon: invisible decay (signal)

**Signal signature:**

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

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



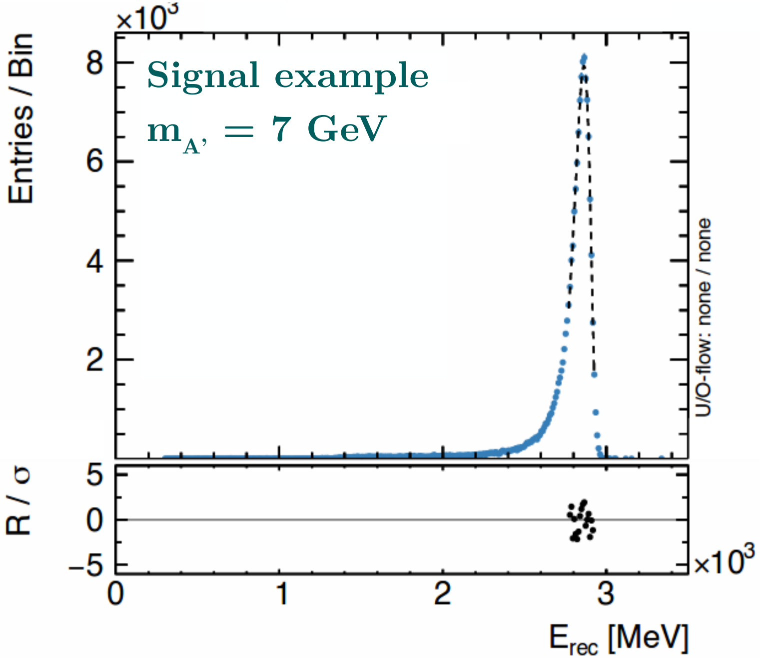

Needed a special **single photon trigger**

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

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

Max. L1 rate: < 30 kHz

**Sustainable for entire Phase 3?**

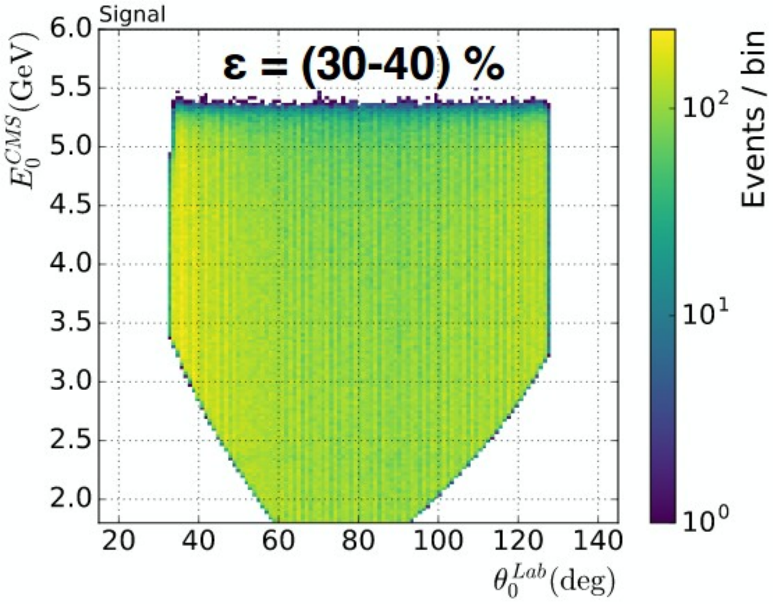



Belle II MC Preliminary

# Dark Photon: invisible decay (signal)

Discriminant variables:

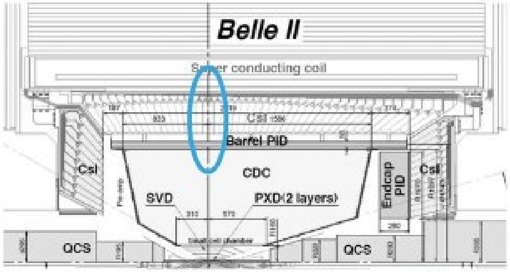
$E_{CMS}$ vs. polar angle of "single photon"




Signal signature:

**peak in $E_{CMS}$ (horizontal band)**

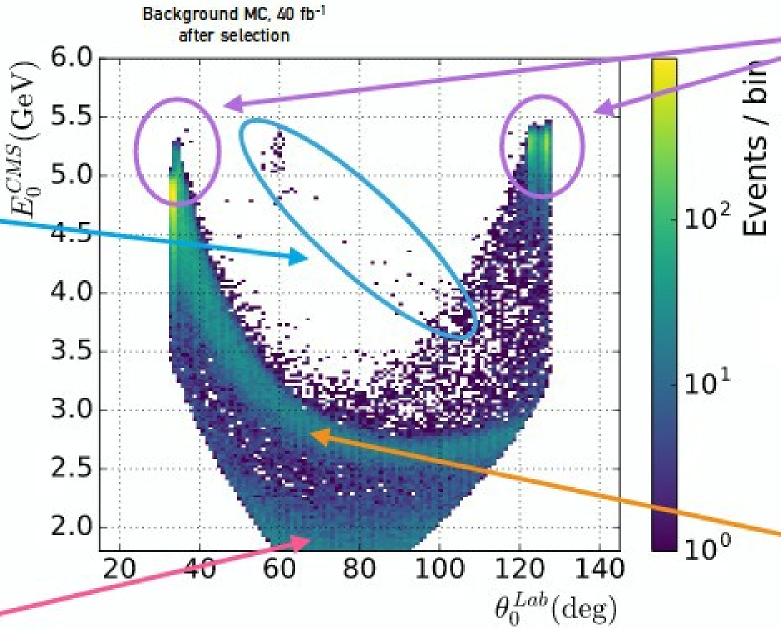
# Dark Photon: invisible decay (background)




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

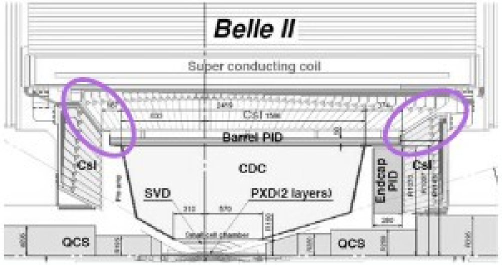
Discriminant variables:

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

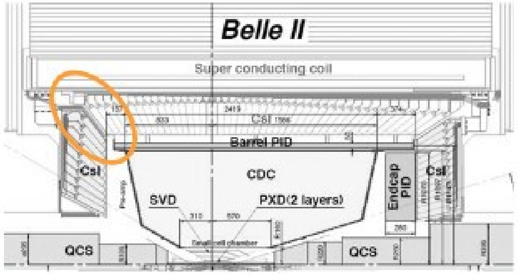



Signal signature:

**peak in $E_{CMS}$ (horizontal band)**



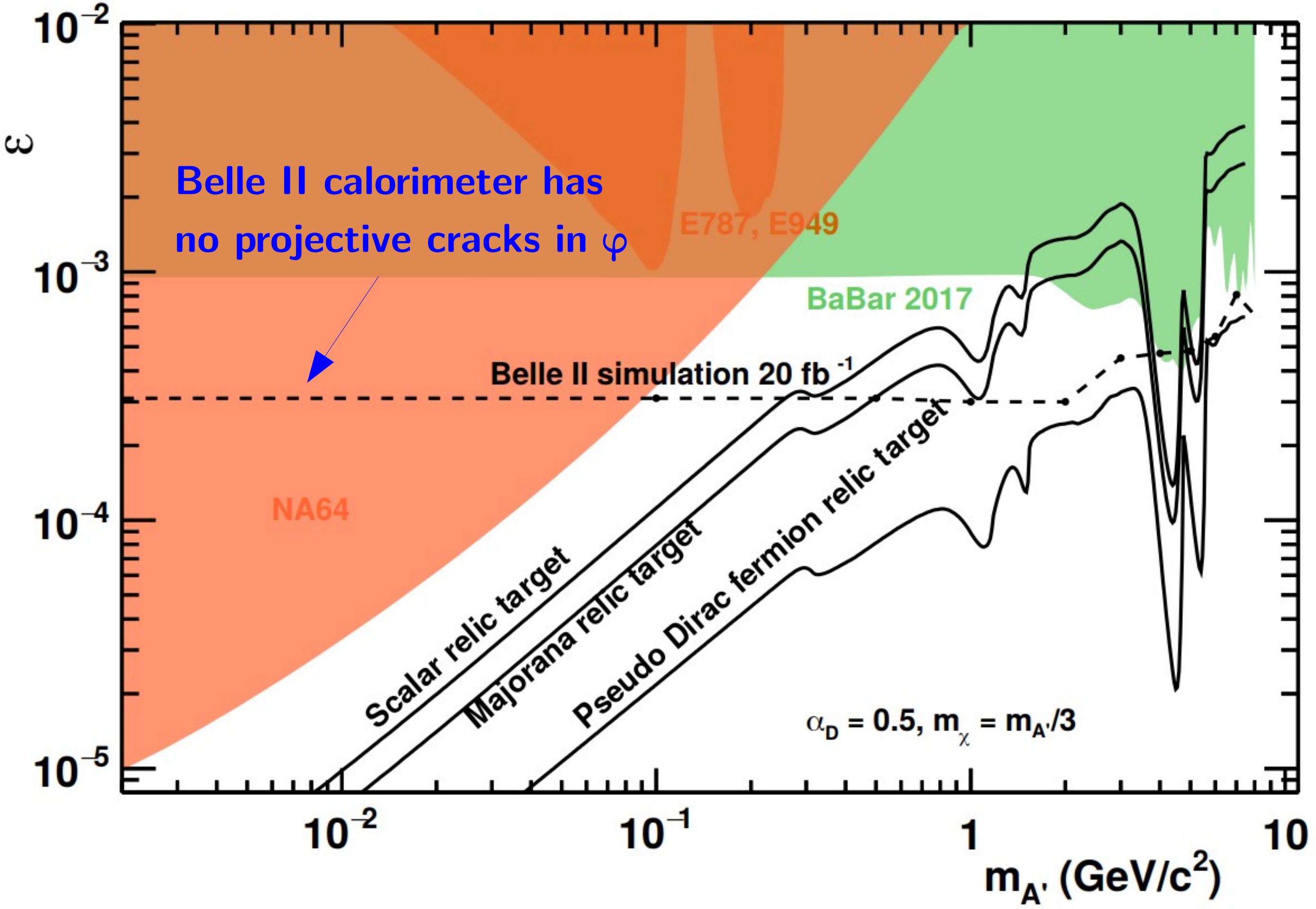

**ee→2γ**
1γ in ECL BWD or FWD gap

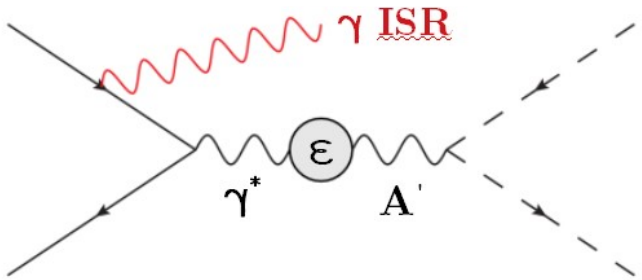



**ee→3γ**
1γ in ECL BWD gap
1γ out of ECL acceptance

**ee→eeγ**
both electrons
out of tracking acceptance

# Dark Photon: invisible decay

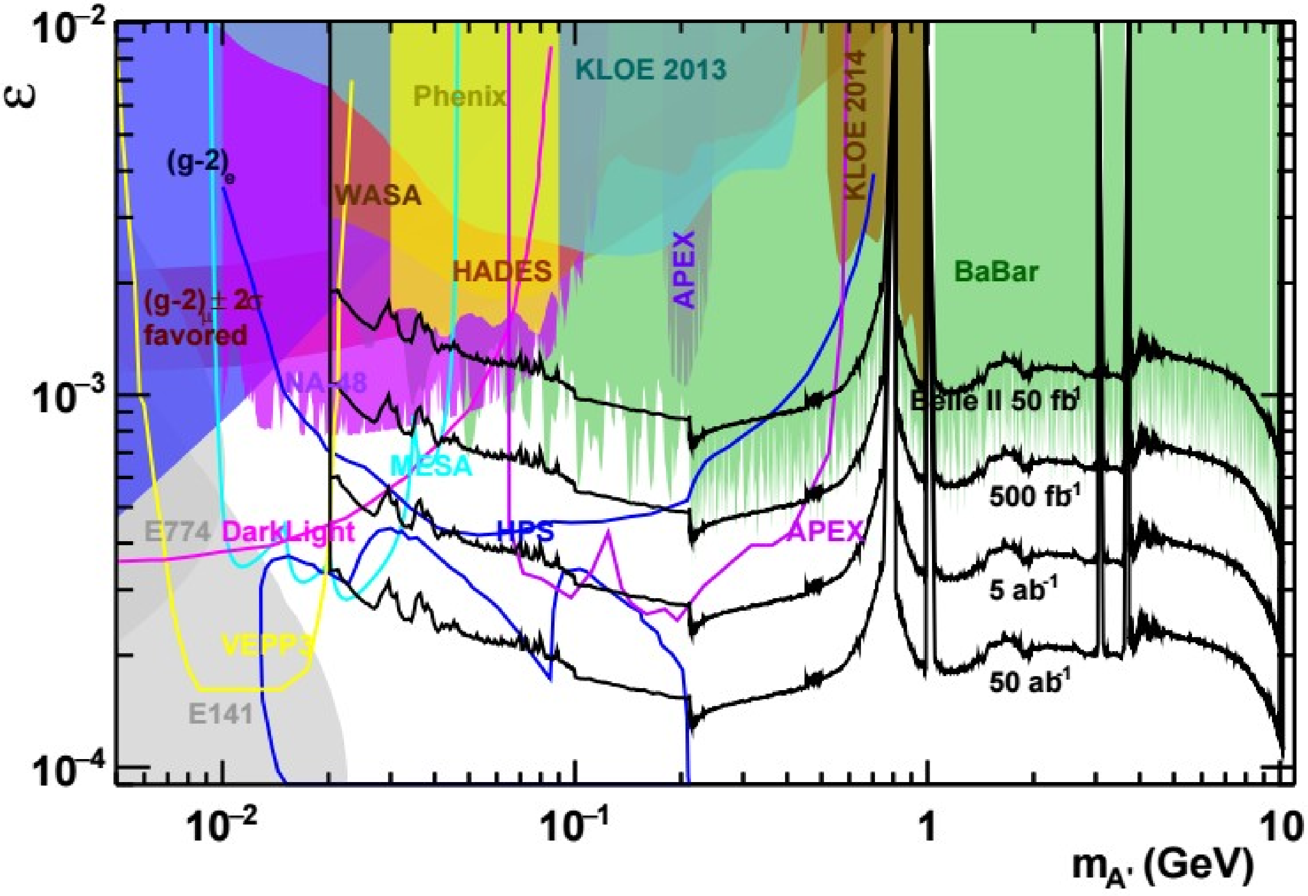



Single photon search: needed a **special trigger logic**:

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

# Dark Photon: leptonic decay



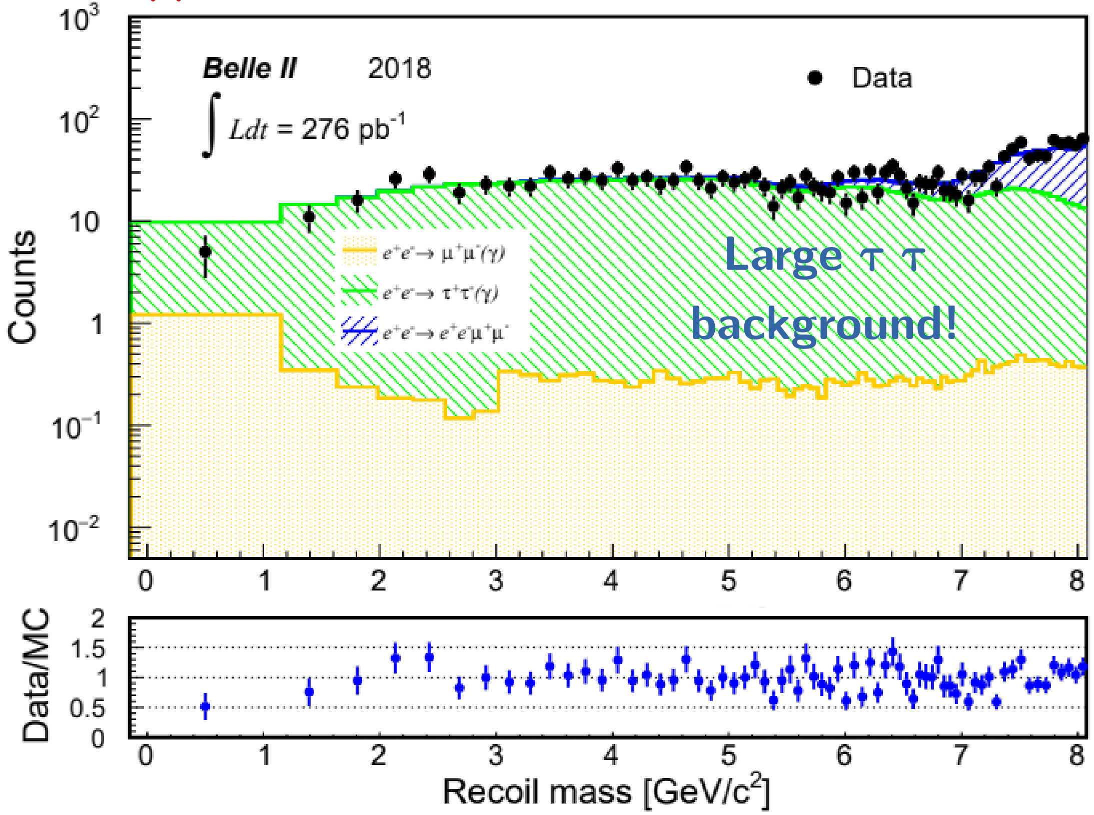

Look for a bump in the $e^+e^-$ or $\mu^+\mu^-$ invariant mass over a (large) QED background

Belle II sensitivity is obtained by scaling the BaBar measurement:

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

# 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!

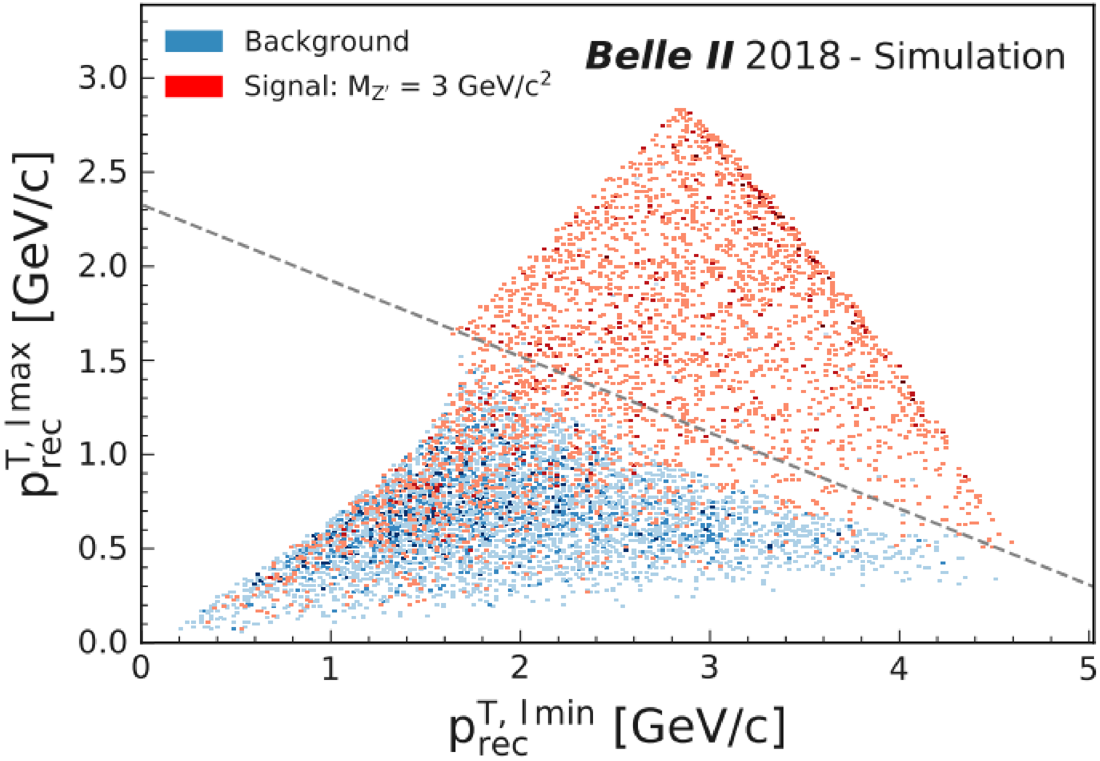


Belle II, arXiv:1912.1127 (submitted to PRL)

# 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.

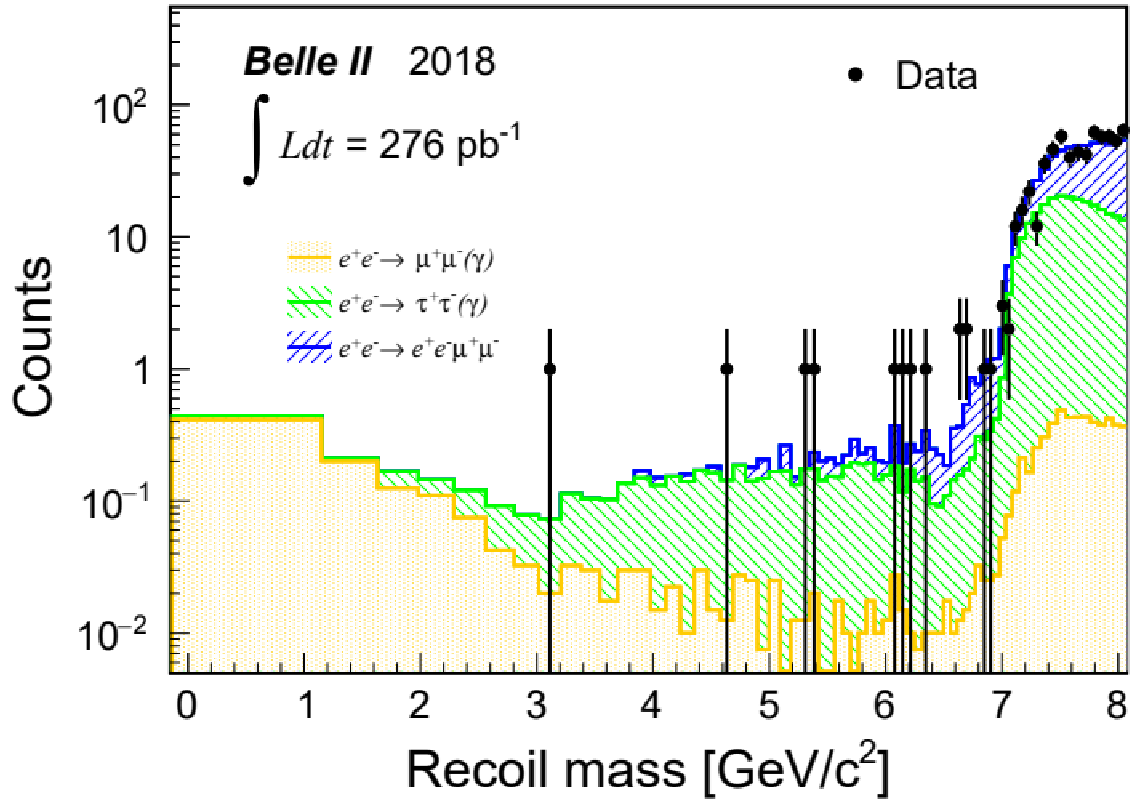



We optimized the selection in each recoil mass bin by choosing the best cuts that maximizes a given figure of merit (**hand-made multivariate approach**).

Belle II, arXiv:1912.1127 (submitted to PRL)

# $\tau\tau$ 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... :(**



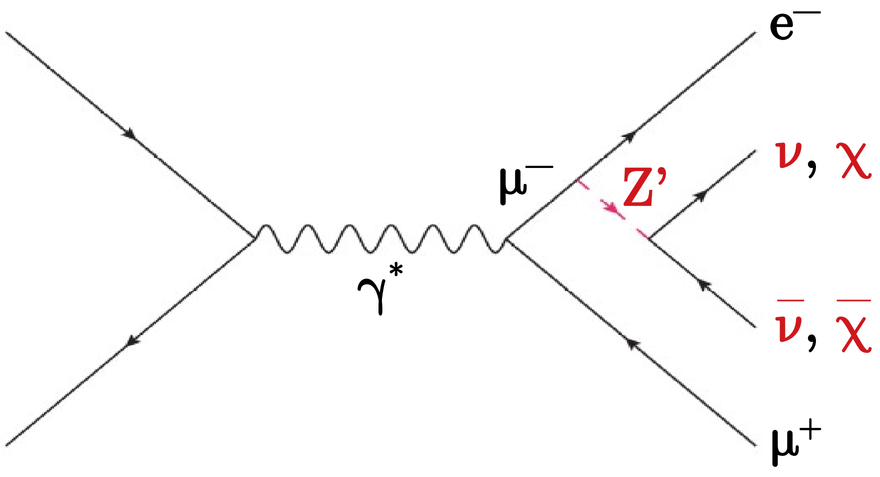
Belle II, arXiv:1912.1127 (submitted to PRL)

# And why not considering a LFV Z'?

We considered only the $\mathrm{e}-\mu$ coupling.

We considered only the invisible decay.

I. Galon et al., arXiv:1610.08060

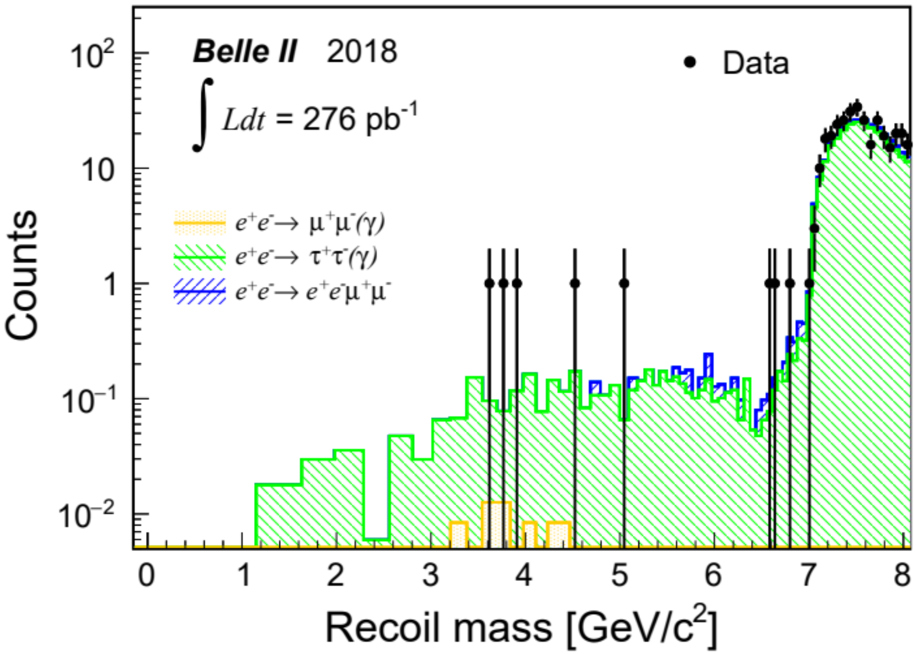



Unfortunately, the model we were using showed some issues (too large width for the Z', etc.).

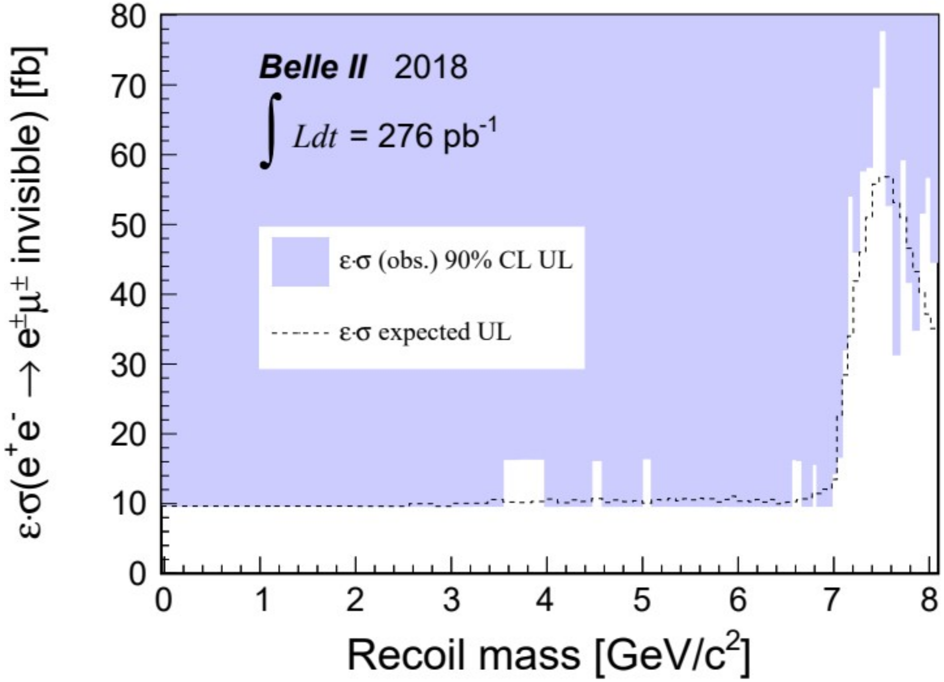
**We decided to drop the signal model**
**and we opted for a model-independent search!**

# LFV Z'

eμ final state



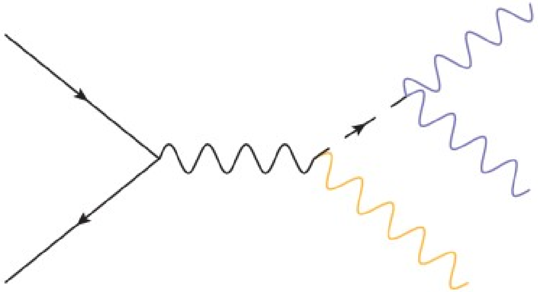

We can set limits on a coupling constant if a theoretical model is provided!



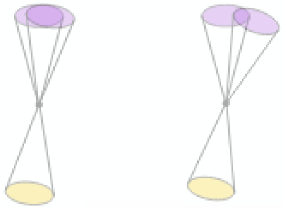



Belle II, arXiv:1912.1127 (submitted to PRL)

# Axion-Like Particles (signal)



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

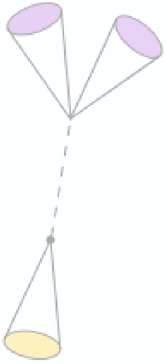


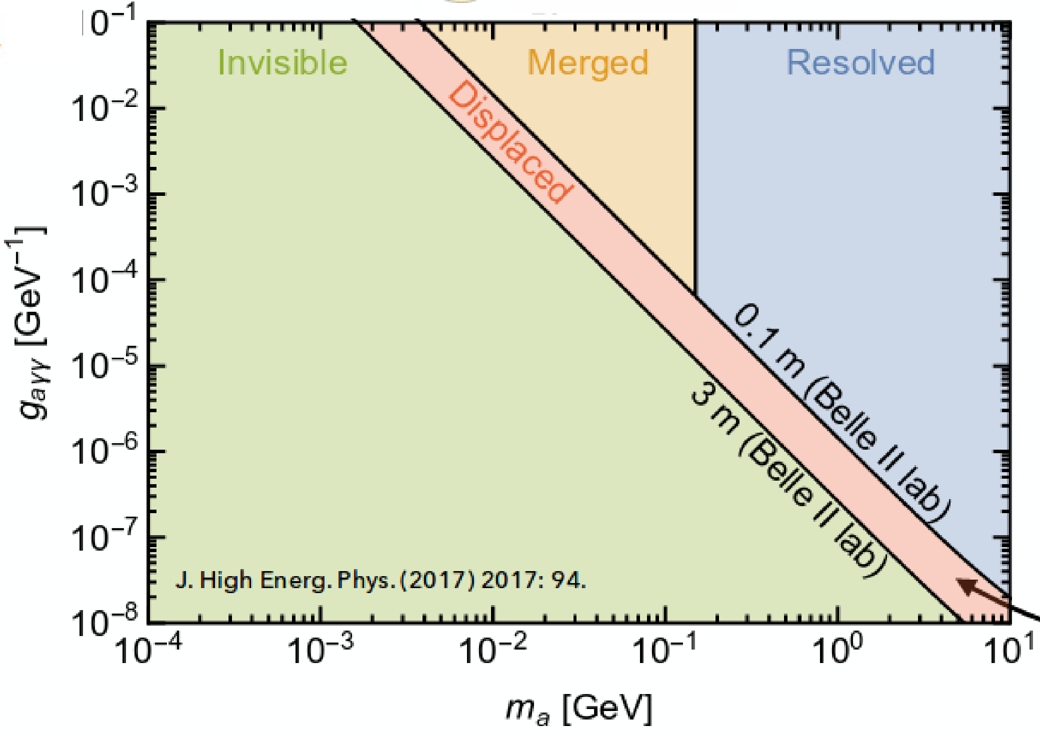
$$\boxed{\tau_a \sim 1/g^2_{a\gamma\gamma} m^3_a}$$

For **resolved** case:

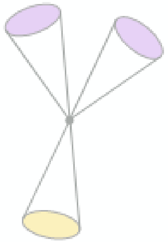
3 clusters with $E_{CM} > 0.25$ GeV

Peak in $\gamma\gamma$ mass spectrum






Three **resolved**, high energetic photons.



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

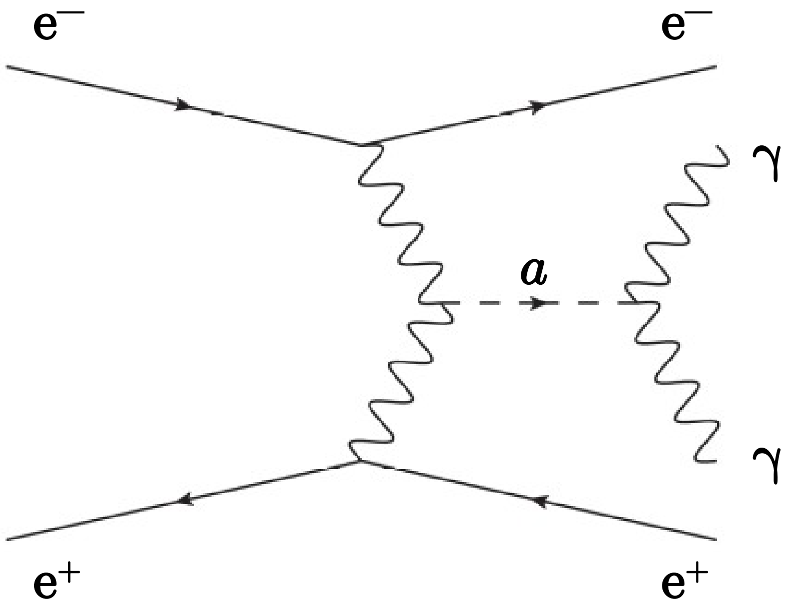
The searches for invisible and visible ALP decays veto this region.

# 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.

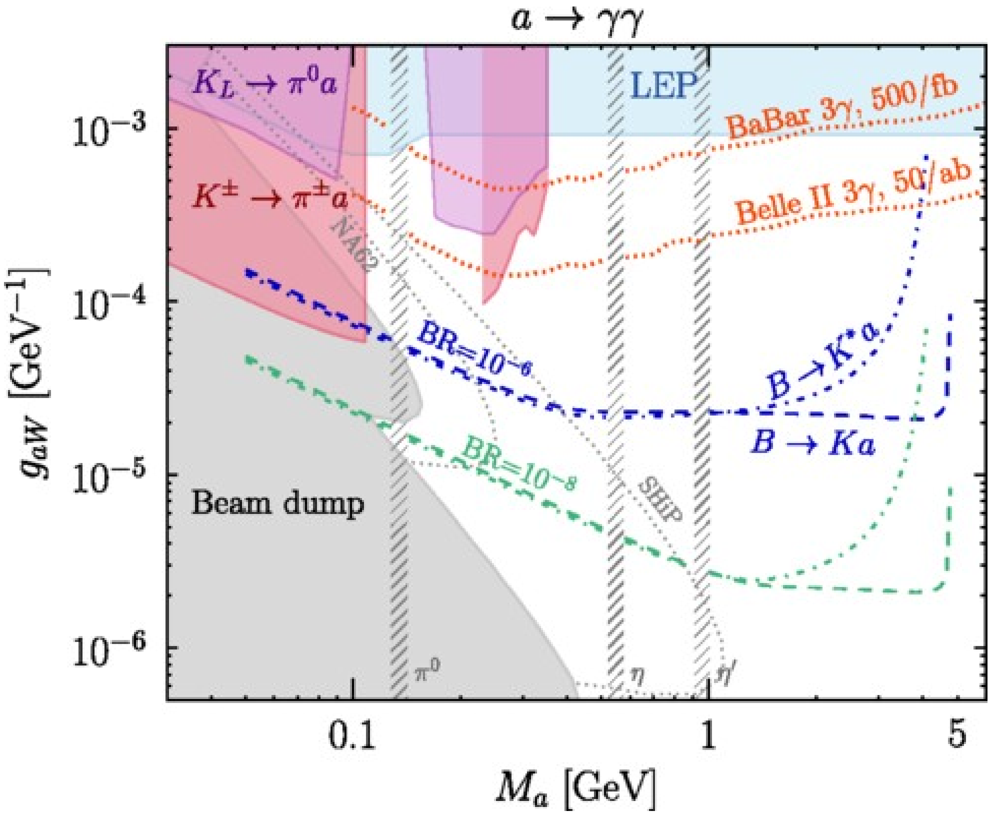
**ALP-fusion**

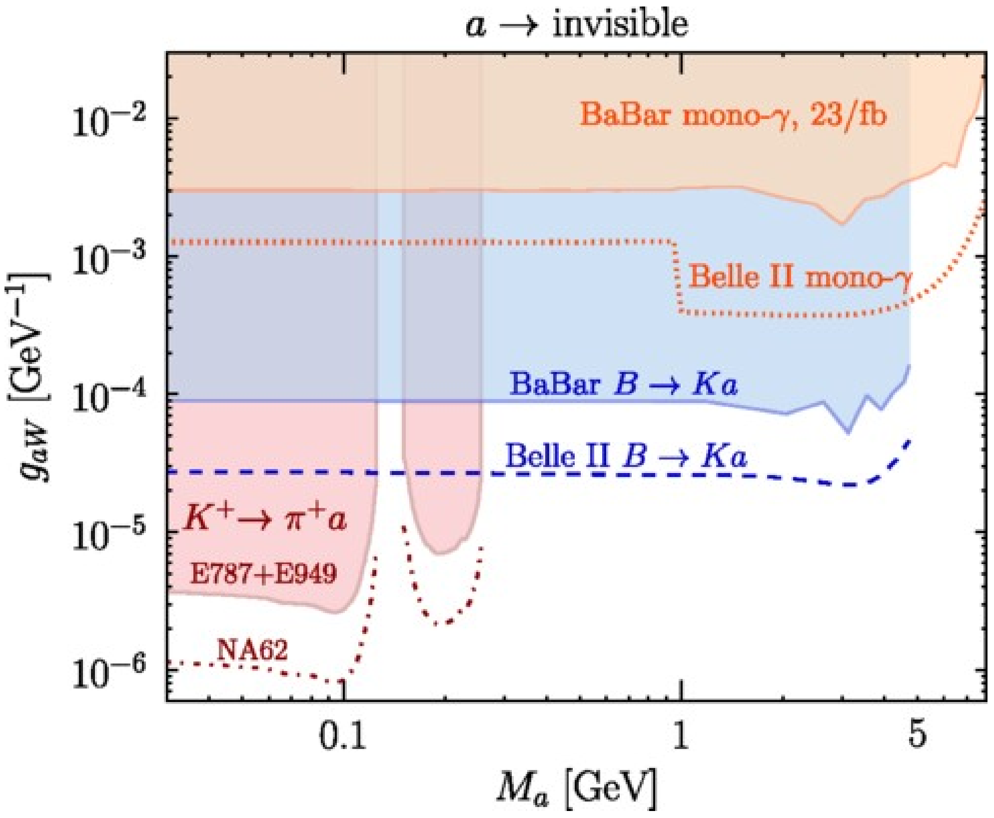



**Pro:** resolved clusters

**Con:** very low energetic photons

# Axion-like Particles from B decays




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