Dark Sector searches at Belle II
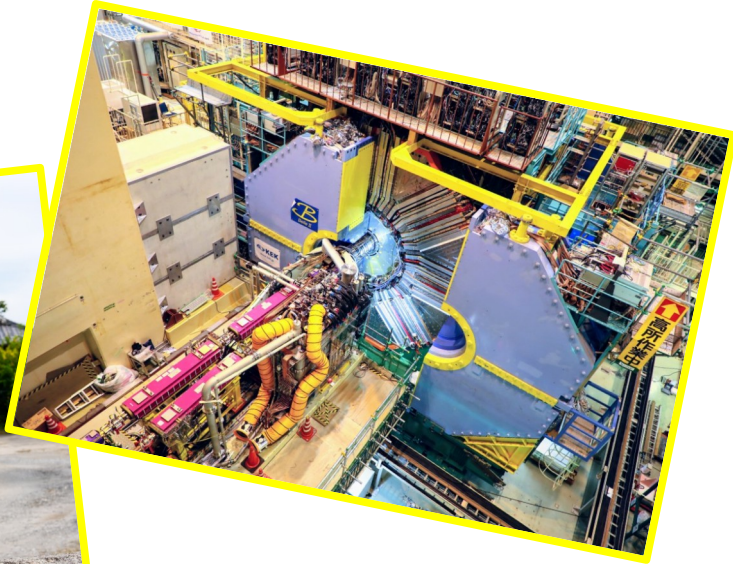
Giacomo De Pietro

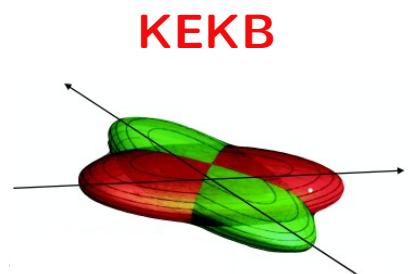*INFN Roma Tre*

SuperKEKB: a new Intensity Frontier machine

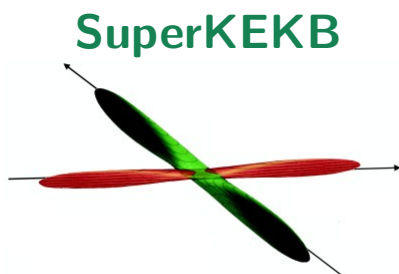SuperKEKB is an upgraded B-factory located at KEK (Tsukuba, Japan)

It's an asymmetric e^+e^- collider operating mainly at **10.58 GeV**

(**$\Upsilon(4S)$**, but foreseen runs from $\Upsilon(2S)$ to $\Upsilon(6S)$)

e^- 7GeV 2.0A
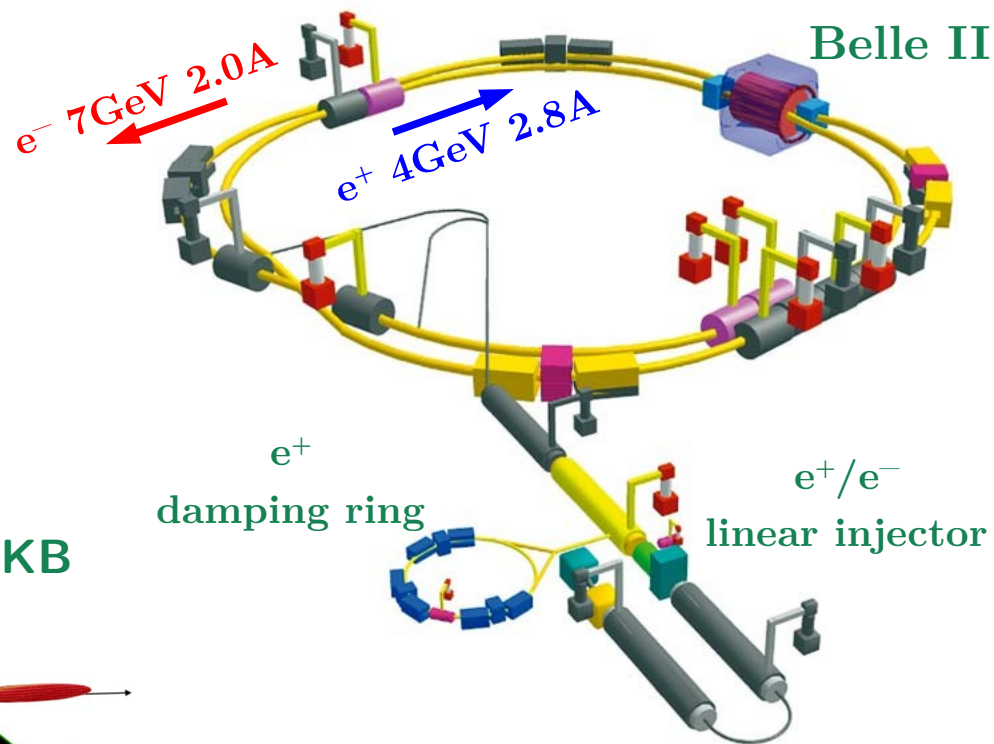
e^+ 4GeV 2.8A

Belle II

e^+ damping ring

e^+/e^- linear injector

KEKB

SuperKEKB

nano-beam scheme

I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

I (A): ~ 2.8/2.0

β^*_y (mm): ~ 0.27/0.3

30x peak luminosity:
$6 \cdot 10^{35}$ cm^{-2} s^{-1}
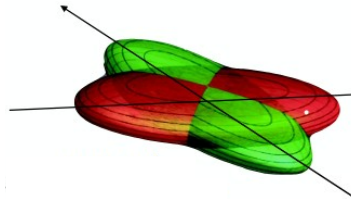
SuperKEKB: a new Intensity Frontier machine

SuperKEKB

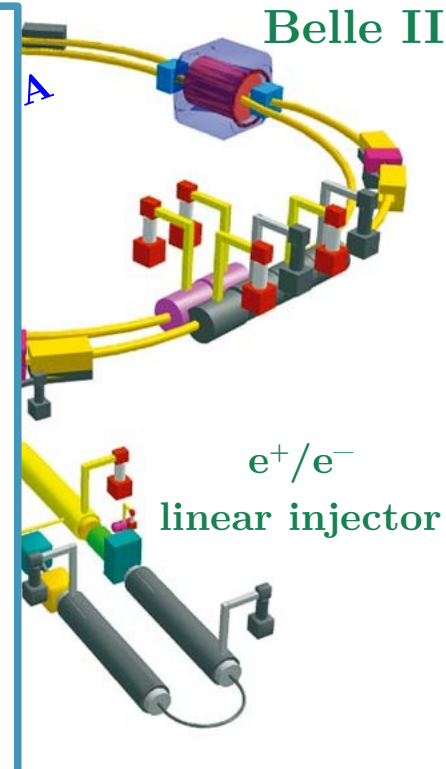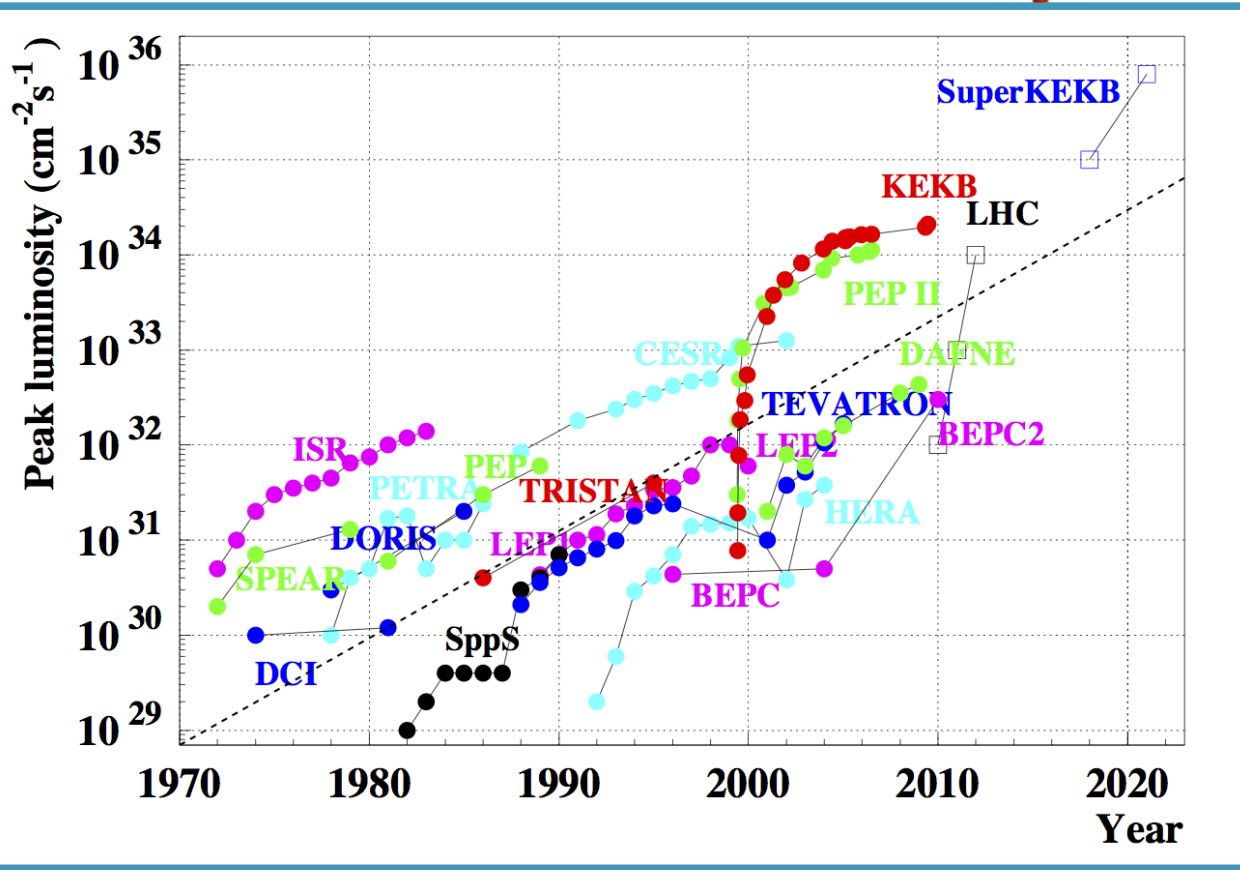located at

It's an asy

operating

($\Upsilon(4S)$, but fores

KEKB

I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

Belle II

e^+/e^-
linear injector

β^*_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

electrons

positrons

Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)
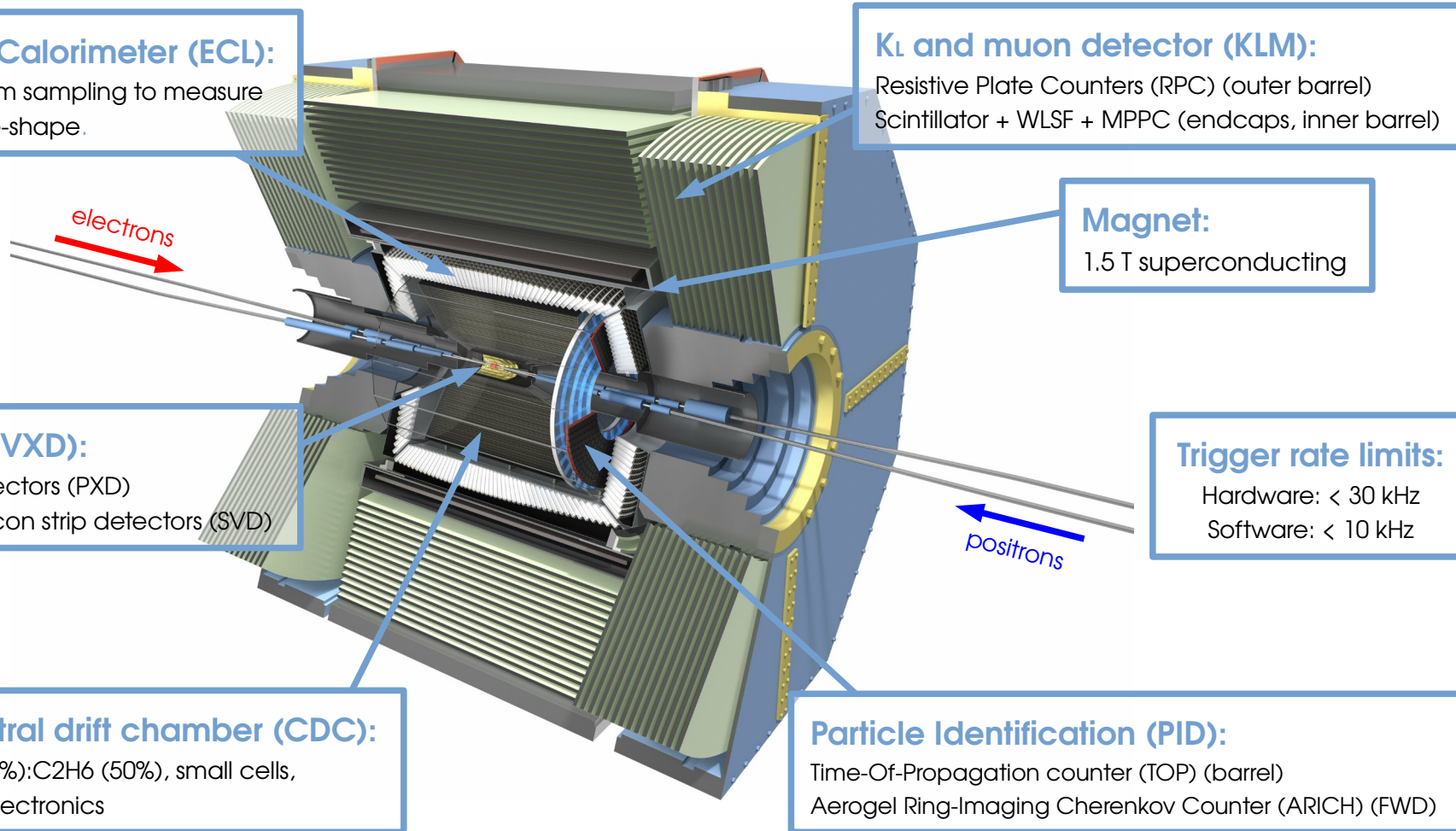
Trigger rate limits:
Hardware: < 30 kHz
Software: < 10 kHz

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)
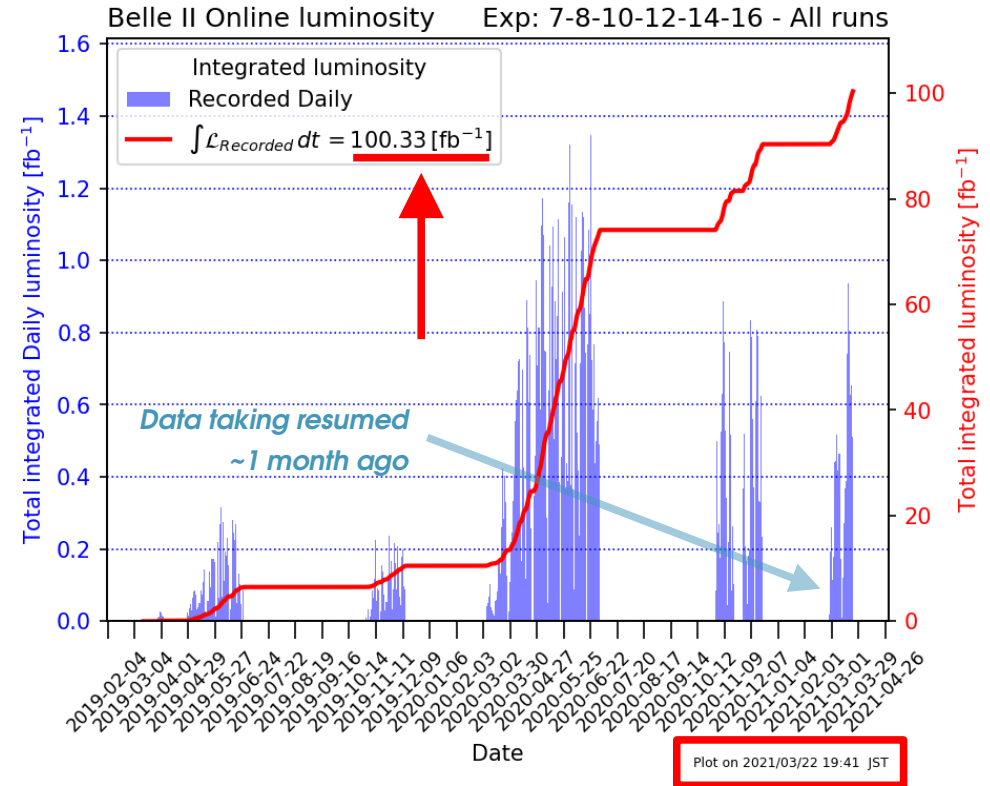
SuperKEKB and Belle II operations

First collisions: 26th April 2018

Collected 0.5 fb⁻¹ in 2018 (pilot run)

**Collected more than
100 fb⁻¹ since 2019**

Goal: collect up to 50 ab⁻¹!
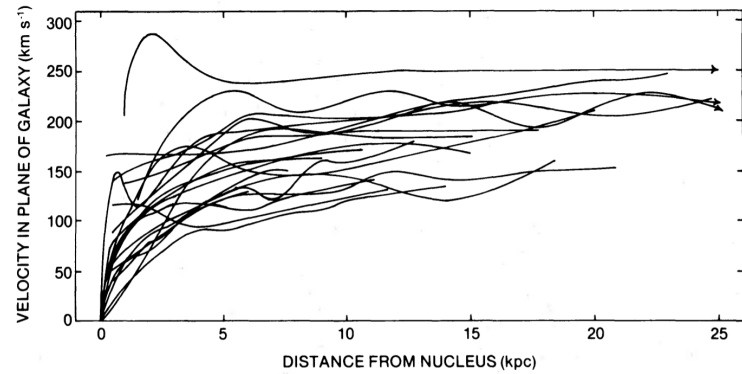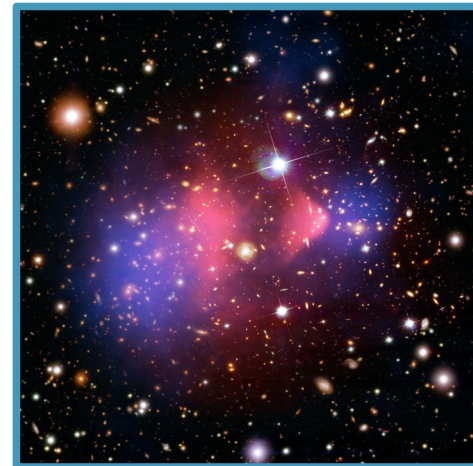
Dark Matter

It is "dark".

It exists...

A lot of experimental techniques
to probe the Dark Matter existence:
  - production at colliders;
  - production in fixed target experiments;
  - indirect astronomic searches;
  - direct underground searches.

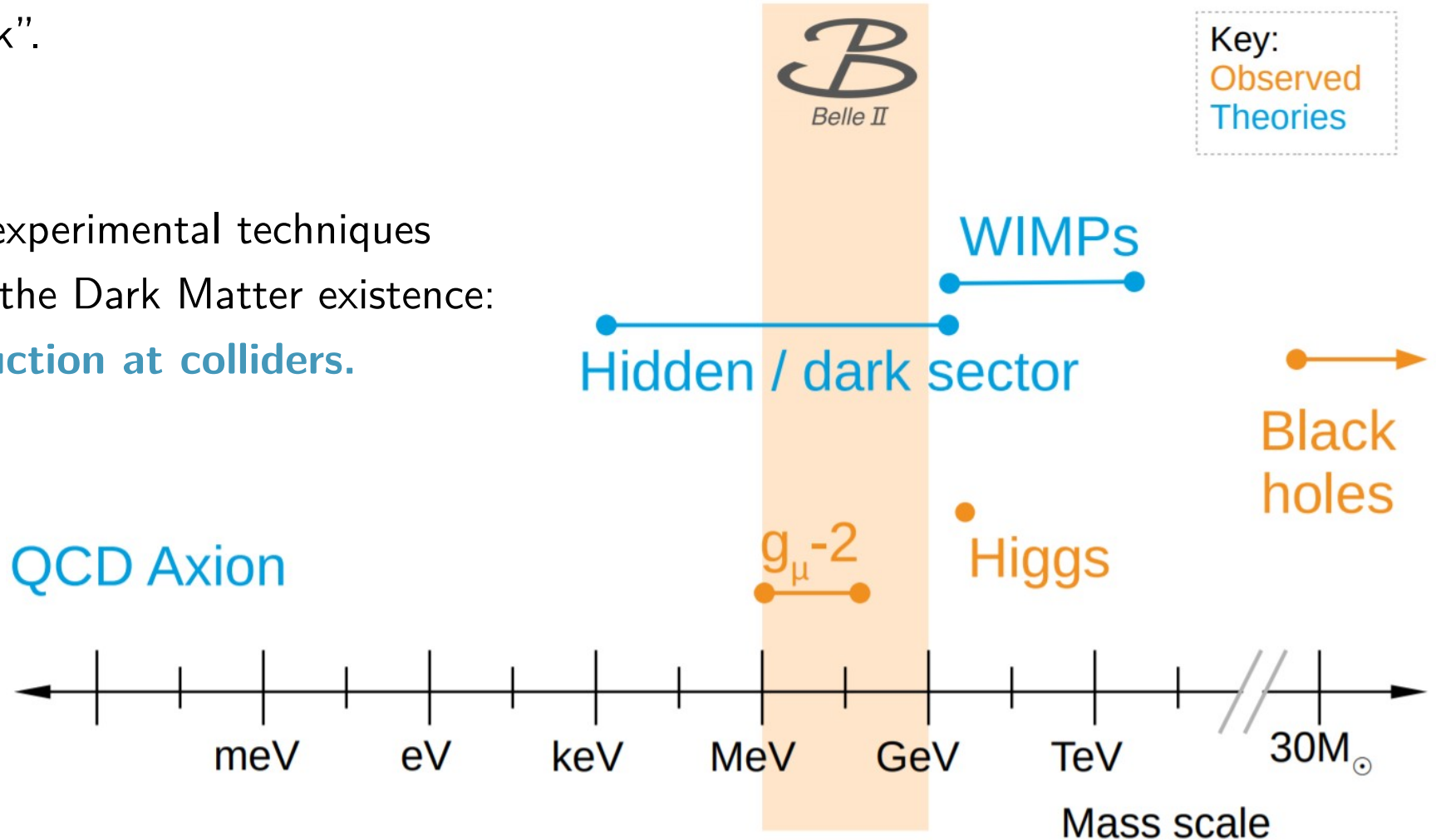Rotational curves of the galaxies

Bullet clusters

Dark Matter

It is "dark".
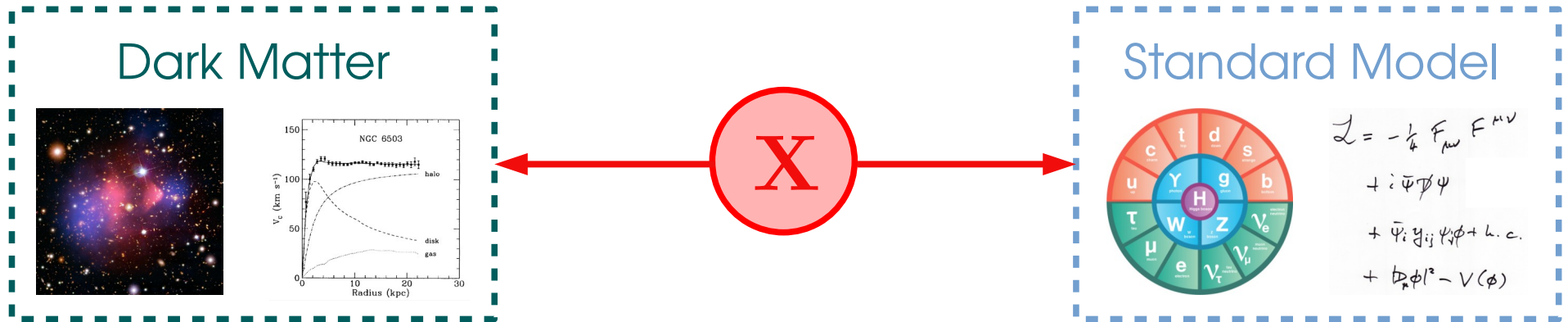It exists...

A lot of experimental techniques
to probe the Dark Matter existence:
- **production at colliders.**

Key:
Observed
Theories

WIMPs

Hidden / dark sector

QCD Axion

g_μ-2

Higgs

Black holes

meV   eV   keV   MeV   GeV   TeV   30M$_\odot$

Mass scale

Dark Matter coupling to SM

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

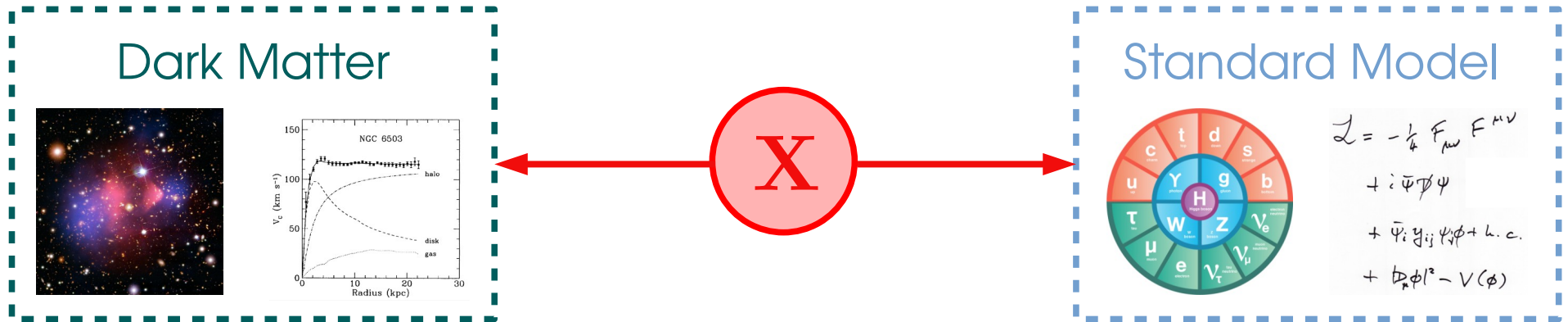depending on the **dark mediator X**:

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

X

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

Vector portal $\rightarrow$ Dark Photon / **Z'**

Scalar portal $\rightarrow$ **Dark Higgs** / Dark Scalar

Pseudoscalar portal $\rightarrow$ **Axion-Like Particles**

Neutrino portal $\rightarrow$ Sterile Neutrinos
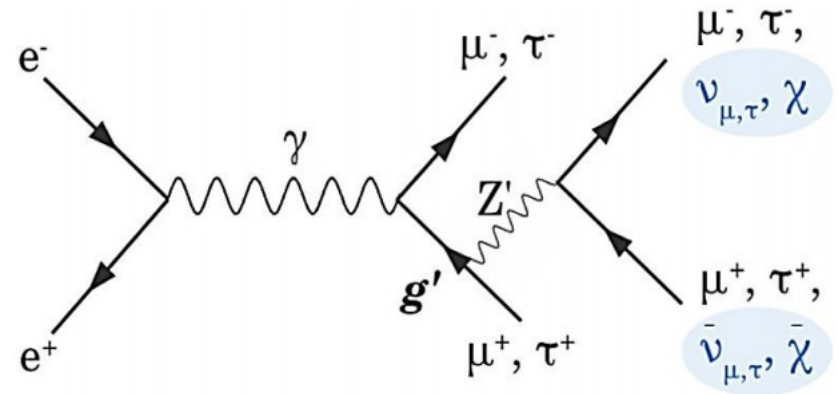
$\mathbf{L_\mu - L_\tau}$ model: Z' to invisible

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

g' is the coupling constant introduced by the model

It may explain:
- DM puzzle;
- $(g-2)_\mu$ 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;
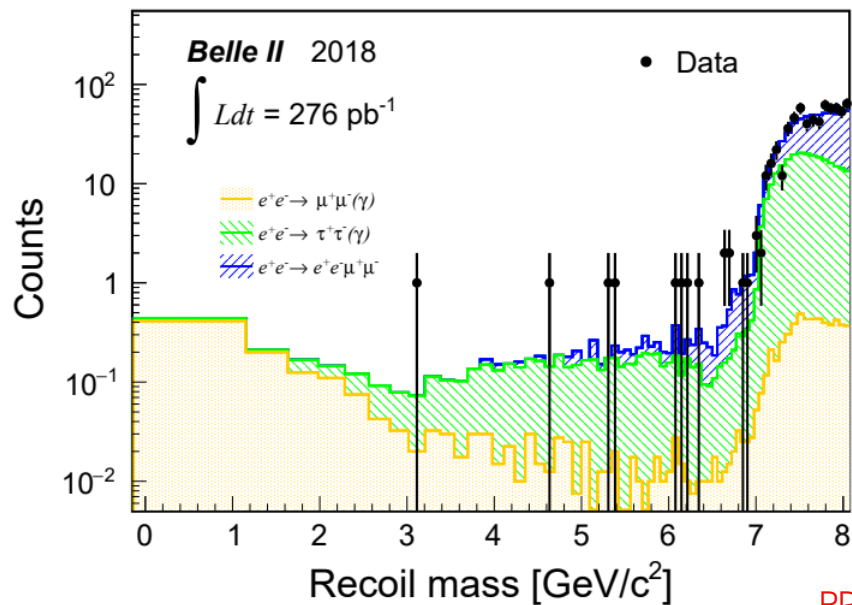- BF(Z' → invisible) = 1 if $m_{Z'} < 2m_\mu$.

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 system recoiling against the dimuon pair;
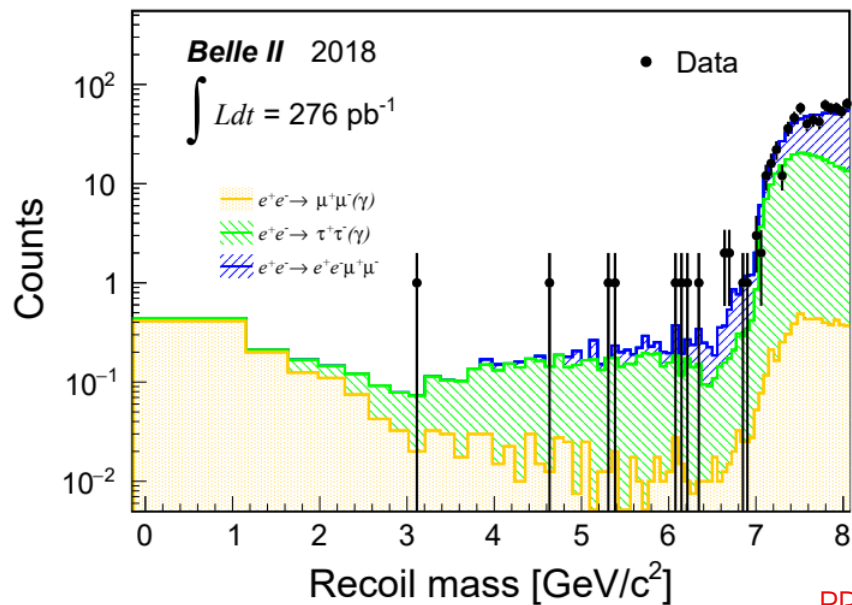- nothing else in the rest of the event.
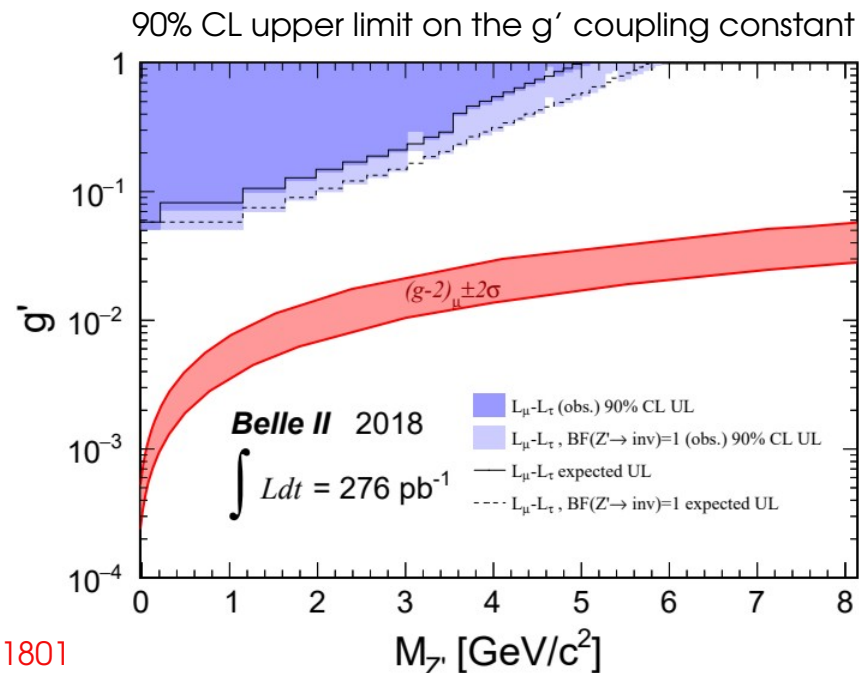
$L_\mu - L_\tau$ model: Z' to invisible

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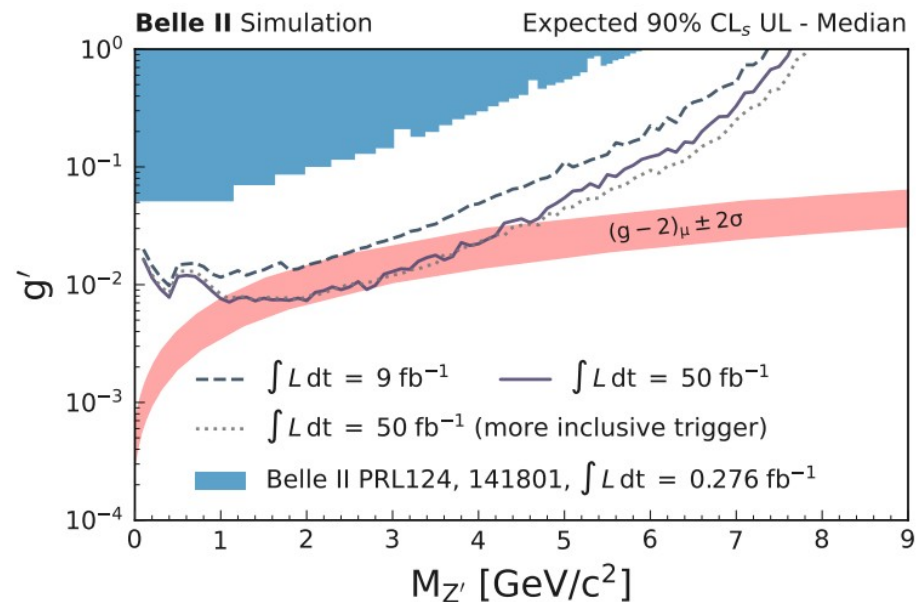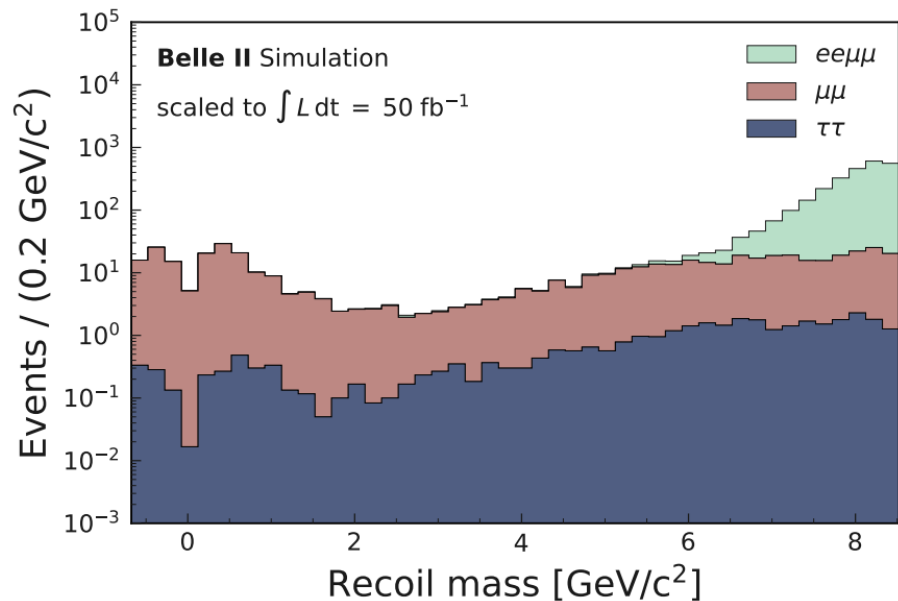- nothing else in the rest of the event.

$L_\mu - L_\tau$ 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 w.r.t. 2018 pilot run.

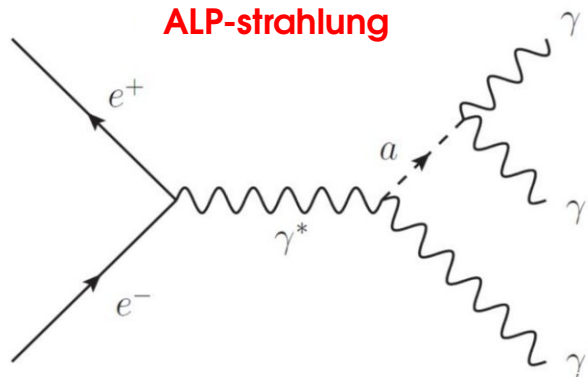**Starting to probe the $(g-2)_\mu$ band already with 50 fb^{-1}**

Axion-Like Particles: a → γγ

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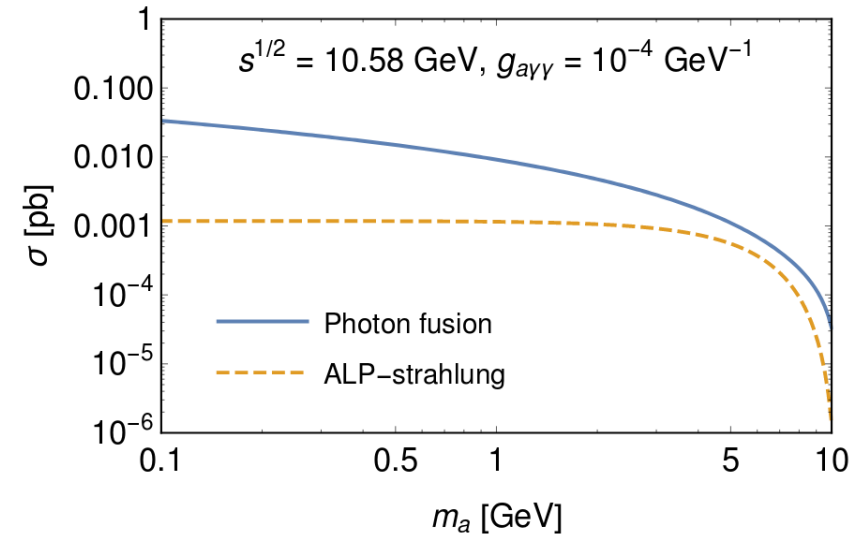
Unlike QCD Axions, ALPs have no relation between mass and coupling.

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

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

ALP-strahlung

Dolan et al. (2017), *arXiv:1709.00009*

$s^{1/2}$ = 10.58 GeV, $g_{a\gamma\gamma}$ = 10^{-4} GeV^{-1}

Photon fusion

ALP–strahlung

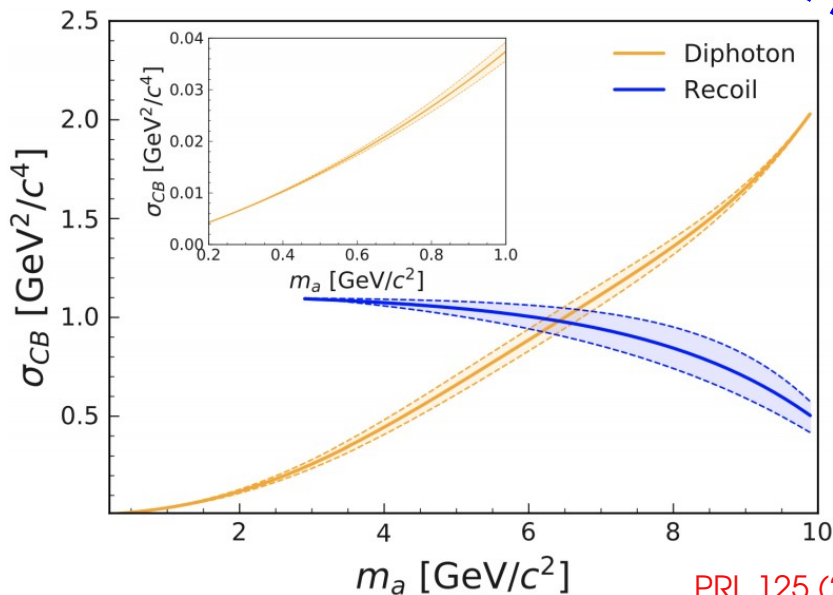**Investigating the photon coupling g$_{a\gamma\gamma}$ in ALP-strahlung**

First search at B-factories
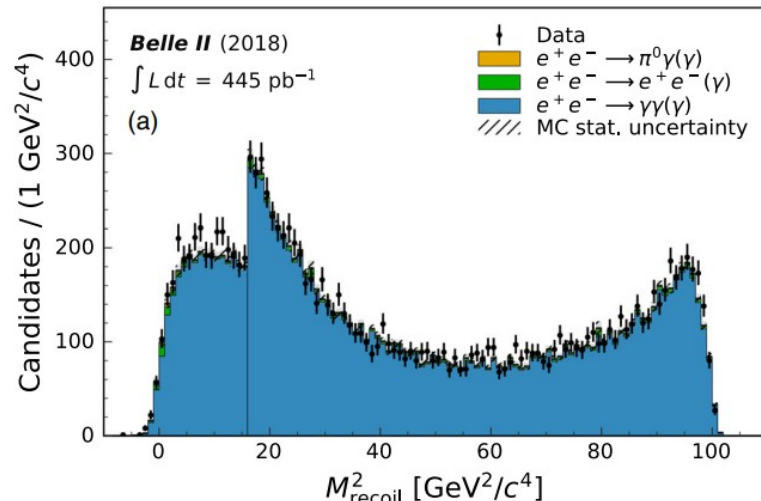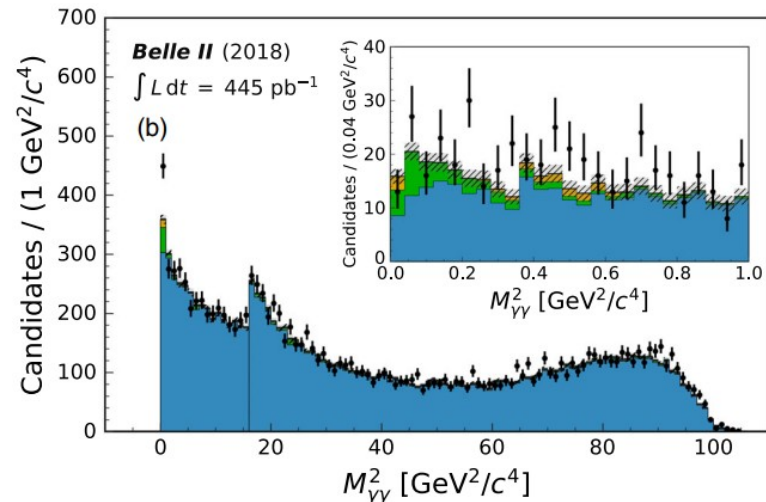
Axion-Like Particles: a → γγ

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

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

PRL 125 (2020) 161806

Axion-Like Particles: a → γγ

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 σ).
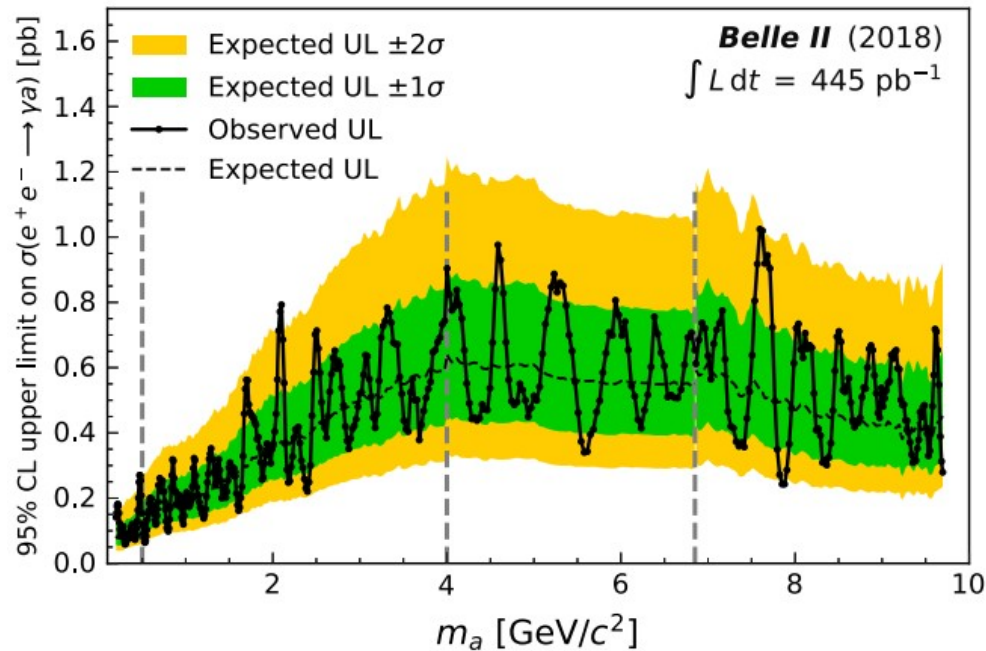
Axion-Like Particles: a → γγ

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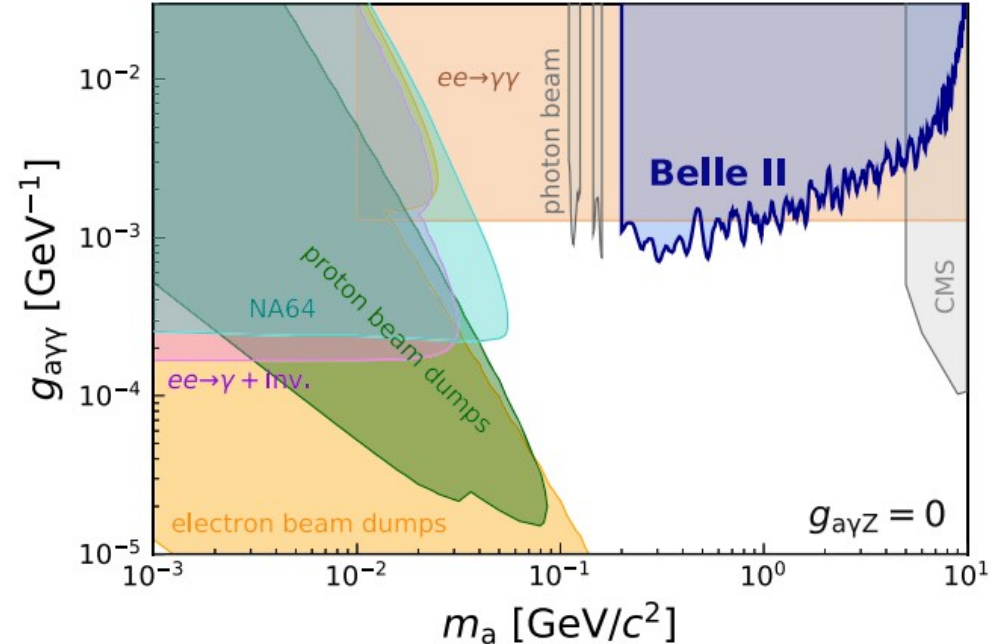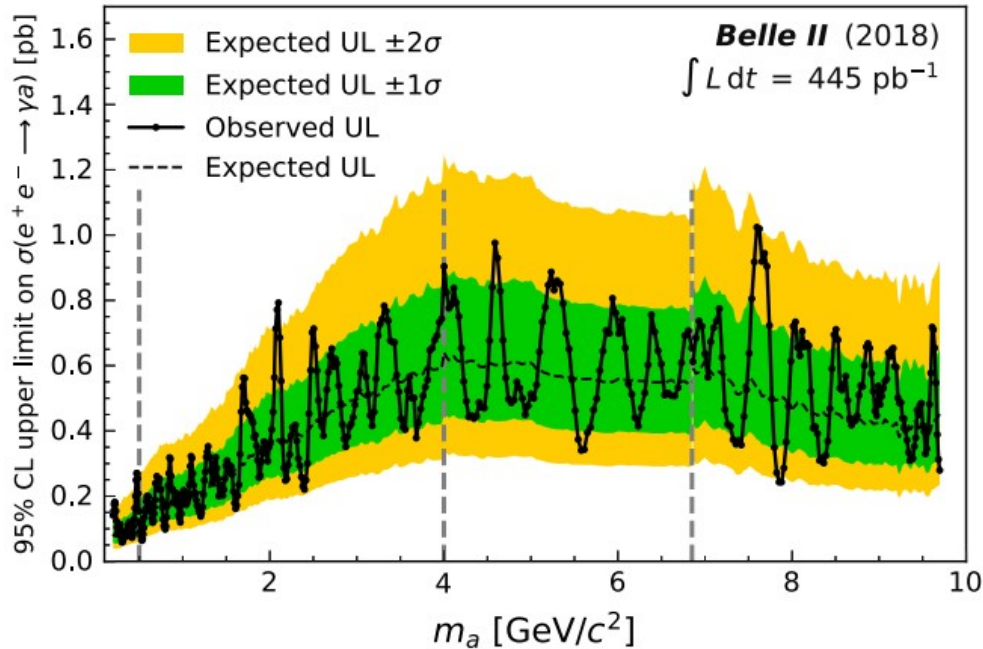- no excess observed (largest local significance: 2.8 σ).
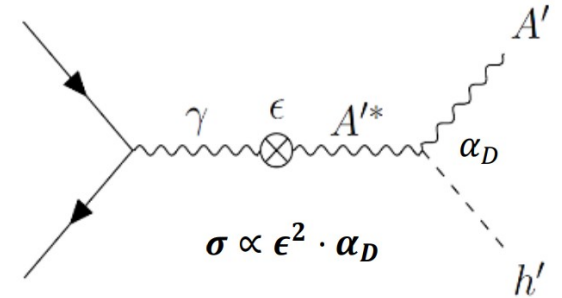
$$\sigma_a = \frac{g^2_{a\gamma\gamma}\alpha_{\mathrm{QED}}}{24}\left(1 - \frac{m^2_a}{s}\right)^3$$

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: $e^+ e^- \rightarrow A'^* \rightarrow A' \, h'$

Dark Higgsstrahlung

Dark Photon (A') mass could be generated via a spontaneous symmetry breaking mechanism, adding a Dark Higgs boson (h') to the model:
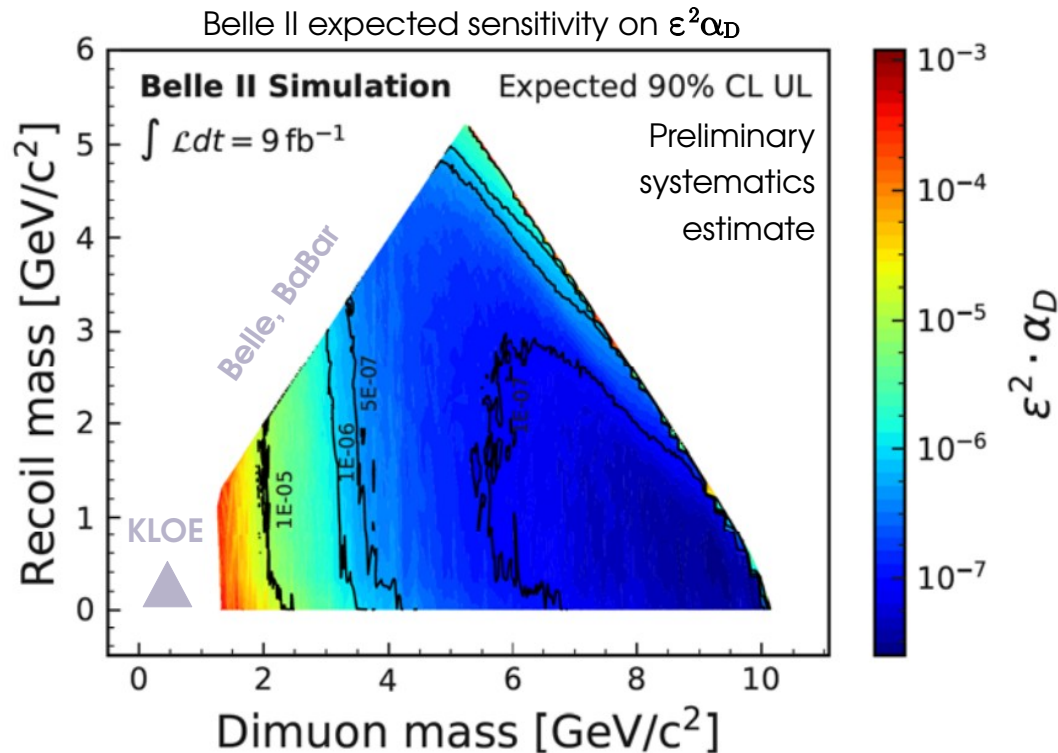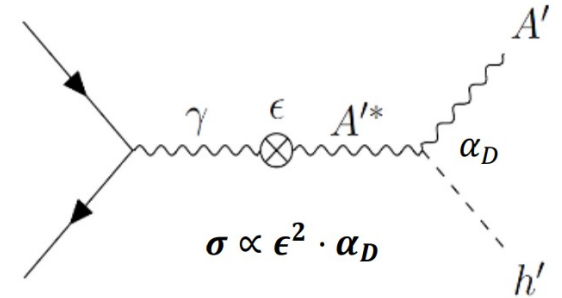
- Dark Higgsstrahlung process: $e^+ e^- \to A'^* \to A' \, h'$

$$\sigma \propto \epsilon^2 \cdot \alpha_D$$

Belle II expected sensitivity on $\epsilon^2 \alpha_D$

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

Babusci et al. (2015), arXiv:1501.06795

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

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

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

Other ongoing Dark Sector searches @ Belle II

Dark Photon (A') decays

invisible decay *coming soon*

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 will lead the field in the Dark Sector searches in the coming years;

- We successfully started operations in 2018; up to now we collected more than 100 fb^{-1} of collisions 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);

- Next results in the pipeline using the data collected since 2019:

    - Dark Higgsstrahlung;
    - A' $\rightarrow$ invisible search.
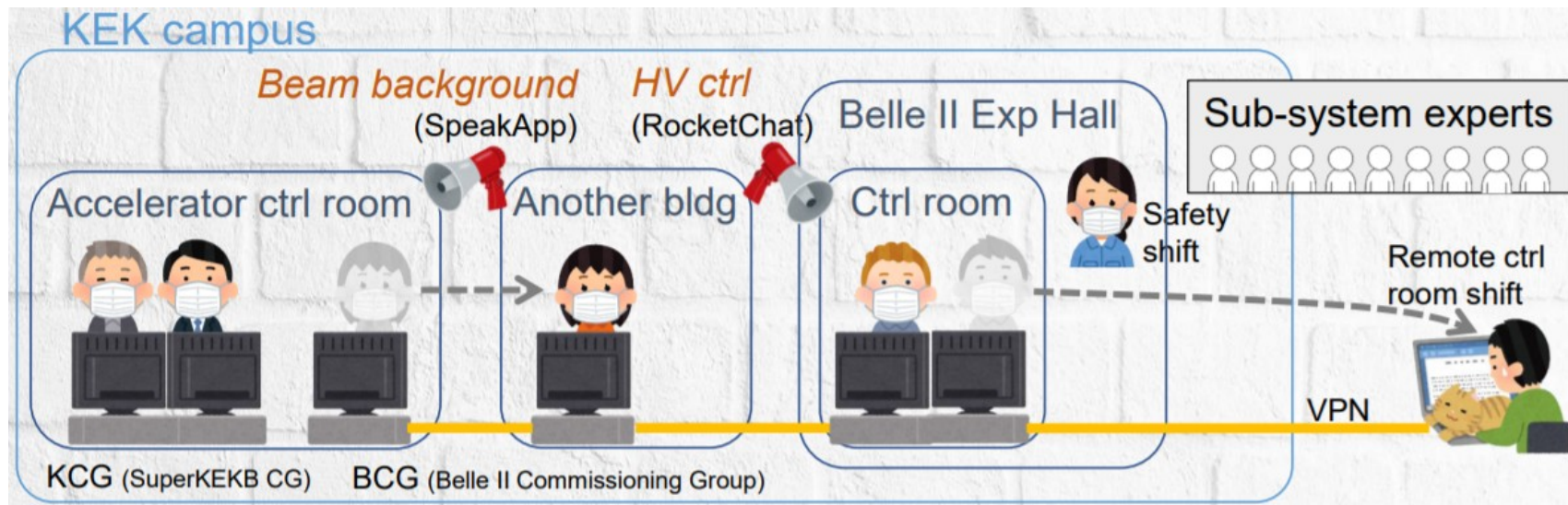
Thank you for your attention

Backup slides

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

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 $\xrightarrow{1/20}$	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 $\xrightarrow{x2}$	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity ($10^{34} cm^{-2} s^{-1}$)	1.0	2.11 $\xrightarrow{x40}$	80

$$L = \frac{\gamma_\pm}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi y\pm}}\right)$$
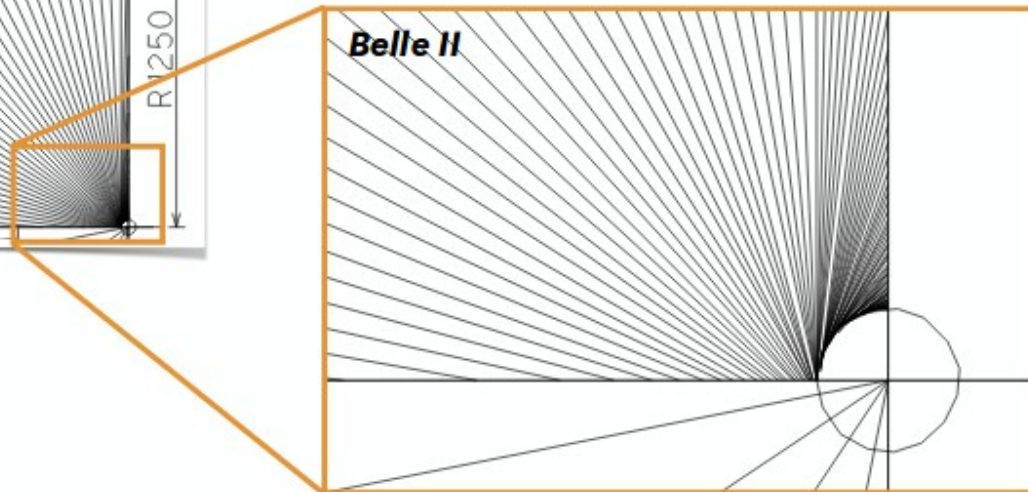
Cross sections at a B-factory

Physics process	Cross section [nb]	Selection Criteria	Reference
$\Upsilon(4S)$	1.110 ± 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

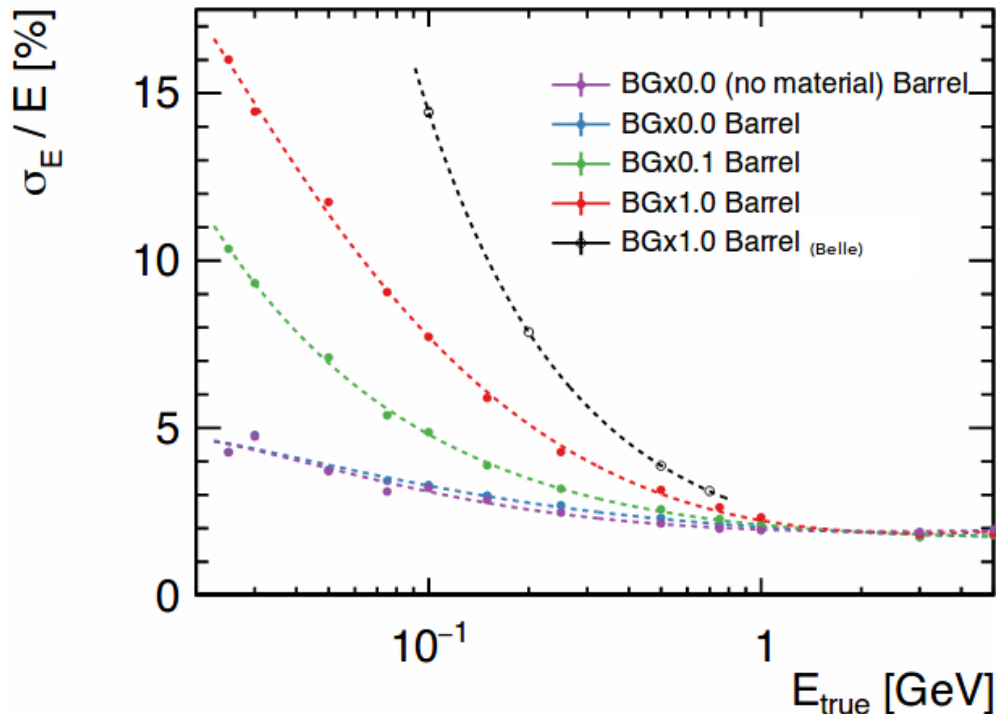# Electromagnetic Calorimeter (ECL)
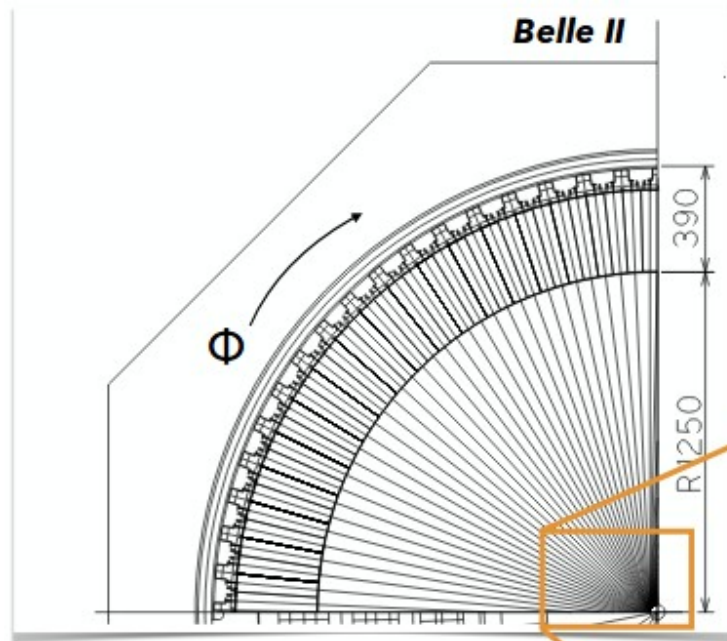
In barrel ECL, Belle II has **no projective cracks in ϕ** w.r.t. BaBar:
→ more hermetic
→ more efficient

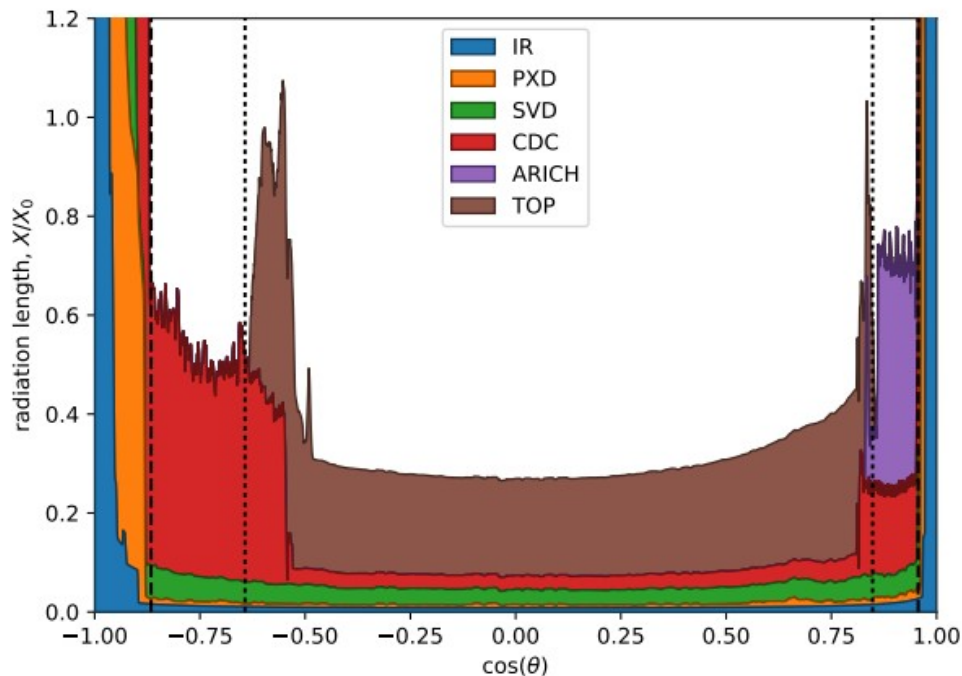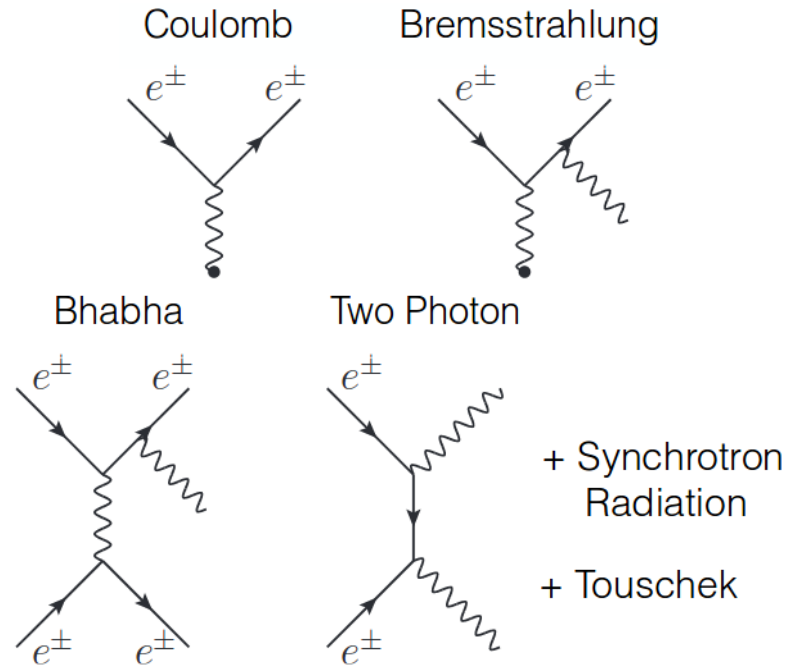# Electromagnetic Calorimeter (ECL)
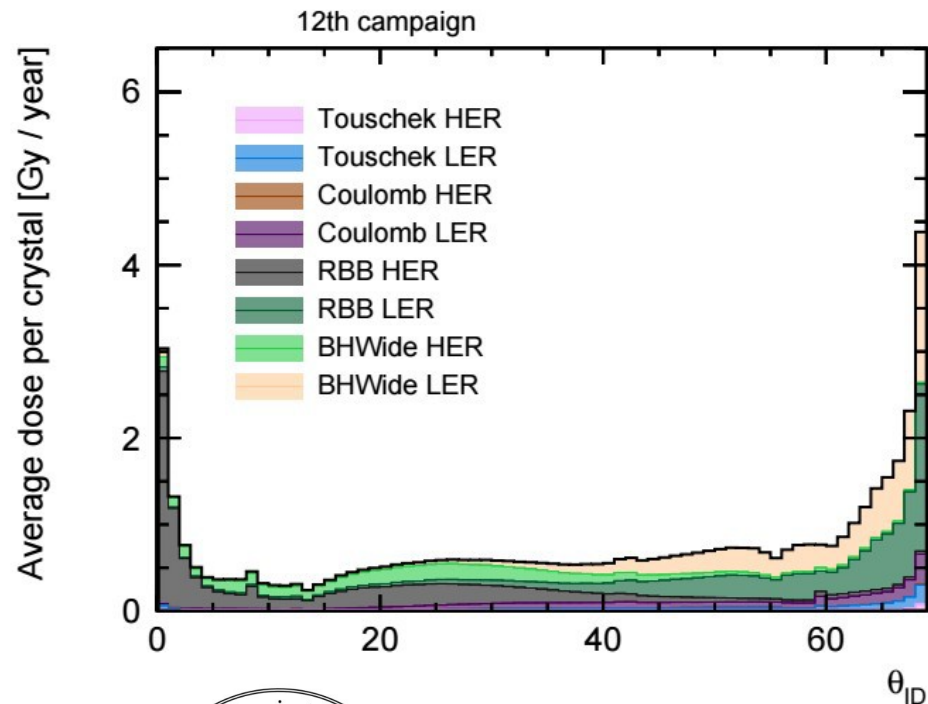

Energy resolution in Belle II barrel:

- BGx0.0 (no material) Barrel
- BGx0.0 Barrel
- BGx0.1 Barrel
- BGx1.0 Barrel
- BGx1.0 Barrel (Belle)

σ_E / E [%]

E_{true} [GeV]

Material budget in front of ECL:

- IR
- PXD
- SVD
- CDC
- ARICH
- TOP

radiation length, X/X_0

$\cos(\theta)$

Beam background

Coulomb

$e^\pm \quad e^\pm$

Bremsstrahlung

$e^\pm \quad e^\pm$

Bhabha

$e^\pm \quad e^\pm$

Two Photon

$e^\pm$

$e^\pm$

$e^\pm$

+ Synchrotron Radiation

+ Touschek

Effects from beam background:

→ degrades calorimeter resolution.

→ radiation damage.

→ pile-up and event size.

→ physics background

12th campaign

Average dose per crystal [Gy / year]

- Touschek HER
- Touschek LER
- Coulomb HER
- Coulomb LER
- RBB HER
- RBB LER
- BHWide HER
- BHWide LER

θ_{ID}

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 $e^+e^- \rightarrow \tau^+\tau^-$:

- 4 charged tracks expected;
- leptonID tags the event;
- 3 prongs provide the probe.
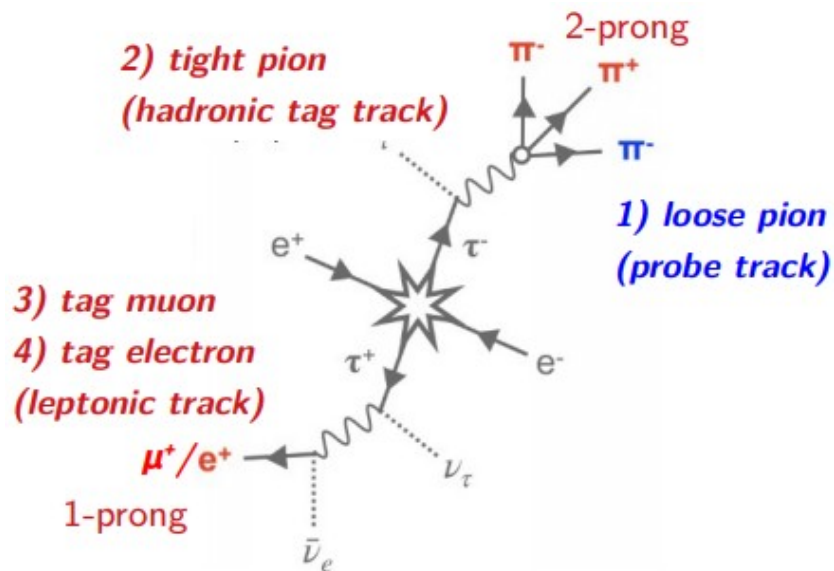
$\varepsilon = N_{evts}(4\ \text{tracks}) / \left[N_{evts}(4\ \text{tracks}) + N_{evts}(3\ \text{tracks}) \right]$
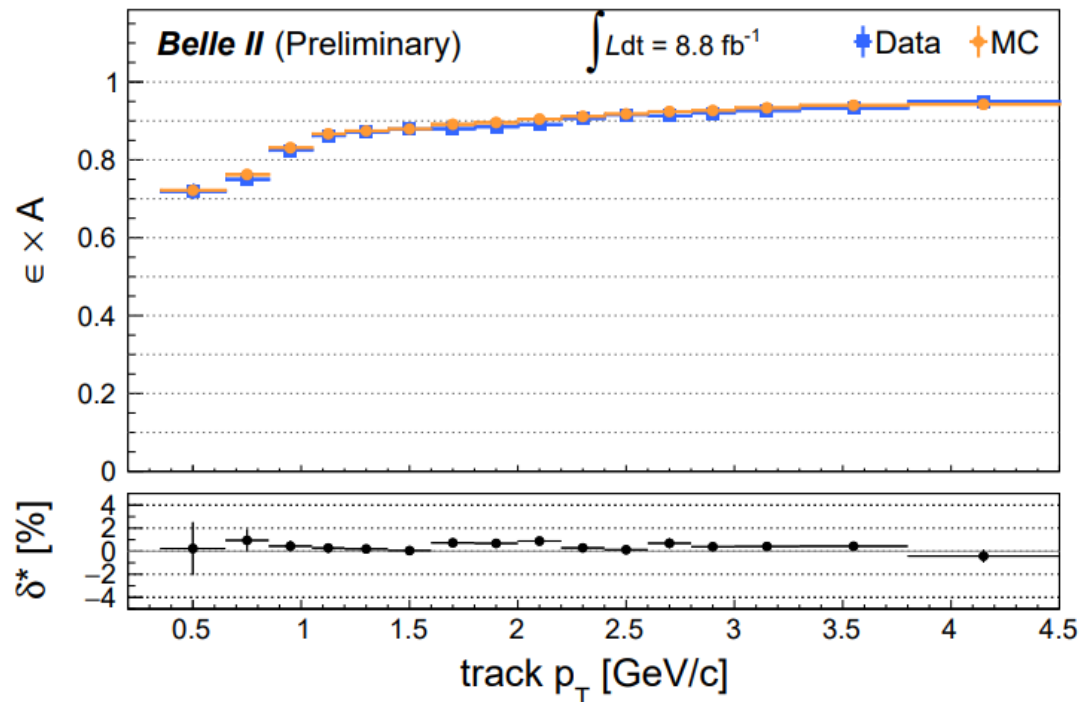
Similar technique to evaluate **fake rate per track**:
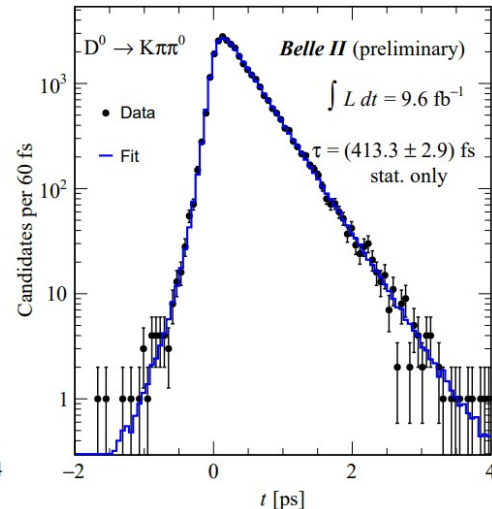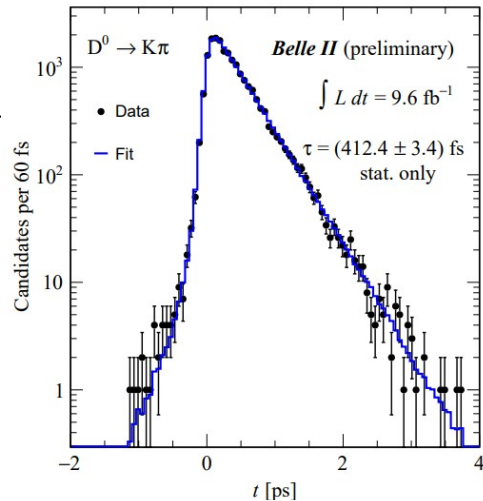
$$r_{fake} = (0.97 \pm 0.34_{stat} \pm 0.06_{syst})\ \%$$

Vertexing performance

D⁰ lifetime:

- measurement with 3 channels: $K^-\pi^+$, $K^-\pi^+$, $K^-\pi^+\pi^-\pi$

- estimated vertex resolution: ~ **40 μm**;

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

(world average: (410.1 ± 1.5) fs
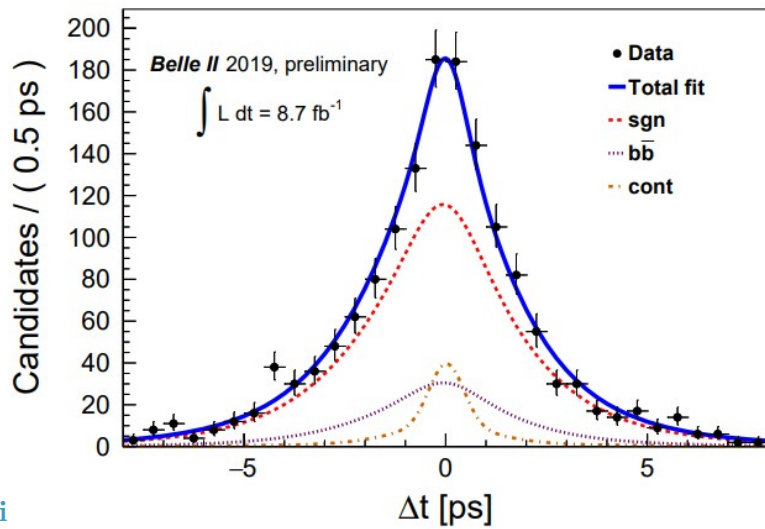
B⁰ lifetime:

- smaller boost $\beta\gamma$: 0.42 (Belle) → 0.28 (Belle II);

- average distance between B-mesons: 200 μm → 130 μm;

- hadronic channels: $B^0 \to D^{(*)-}\pi^+/\rho^+$;

- estimated resolutions: Δt ~ 1 ps → **Δz ~ 80 μm**

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

(world average: (1.519 ± 0.004) ps

G. De Pi

Particle identification: leptons

Several fully reconstructed channels are used:

- extract both efficiency & mis-ID probability **from data**;
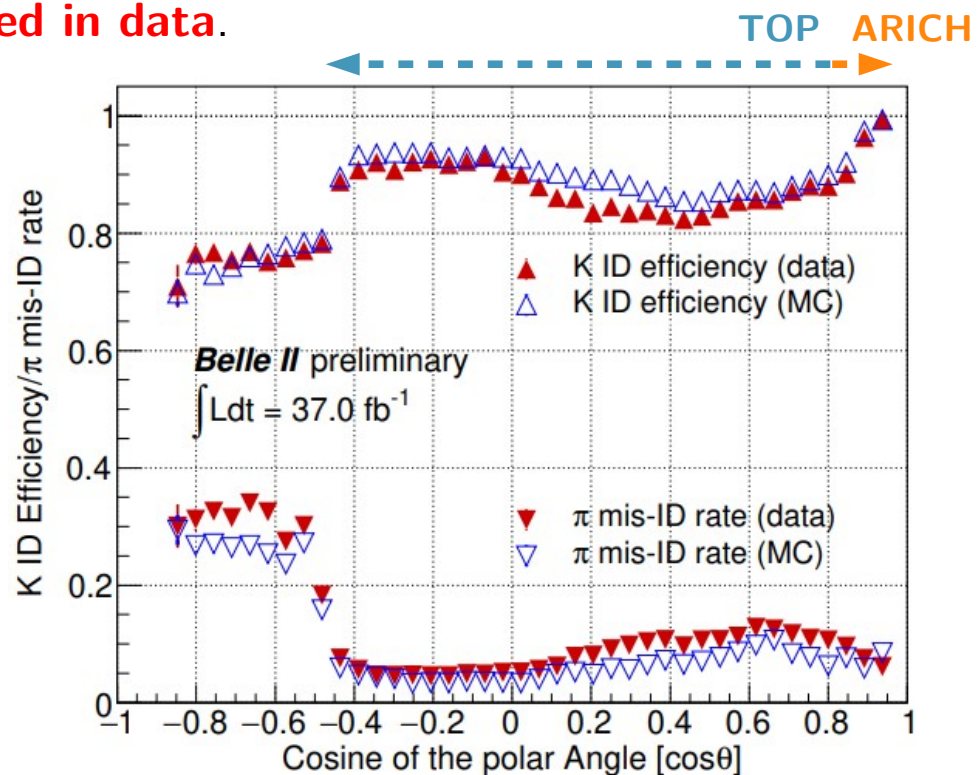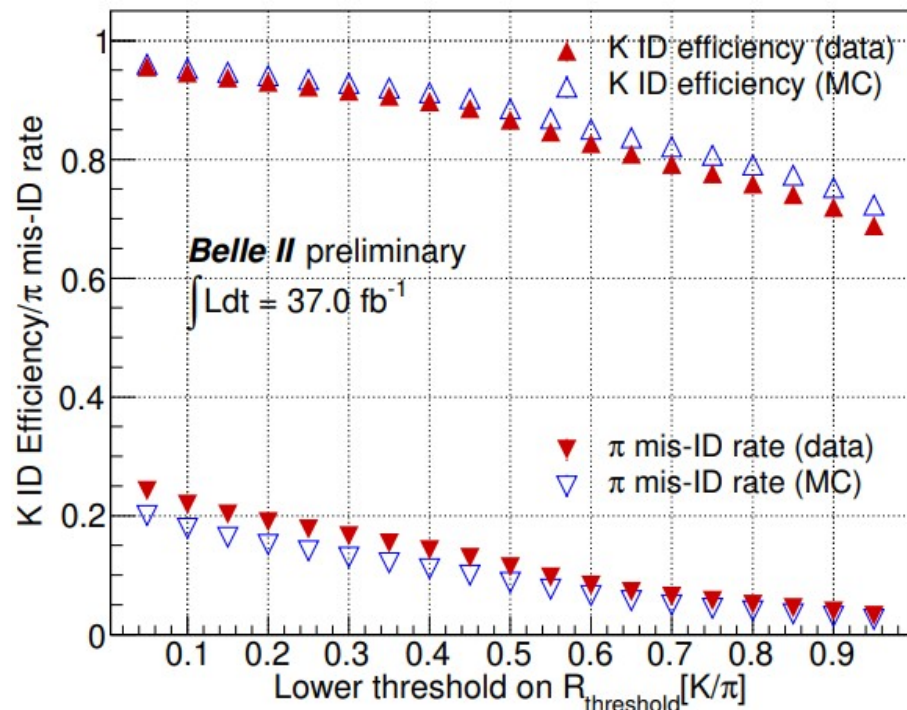- measured for various leptonID and angular acceptance.
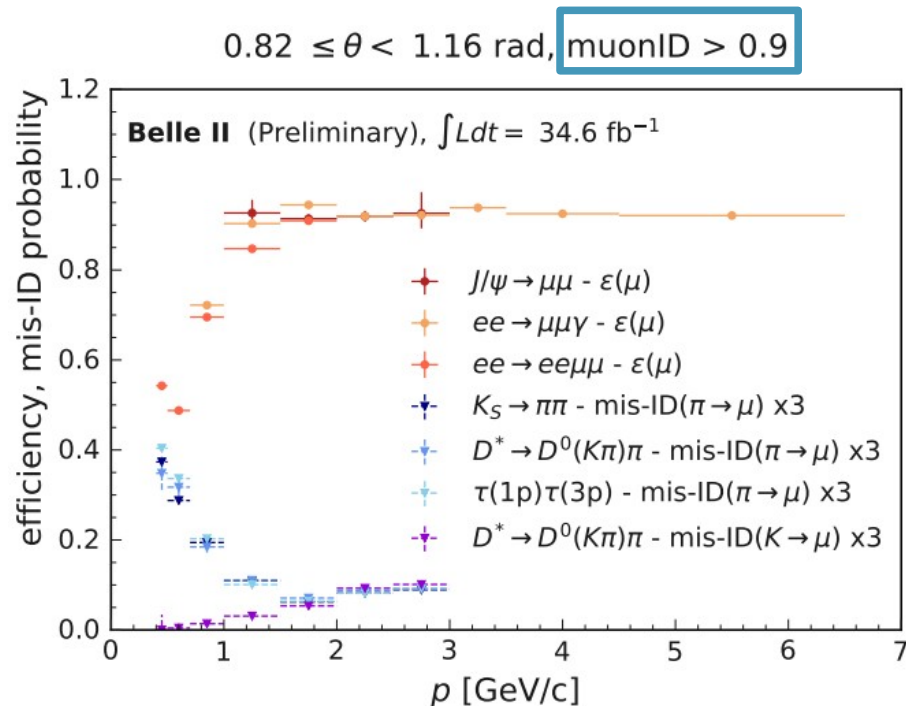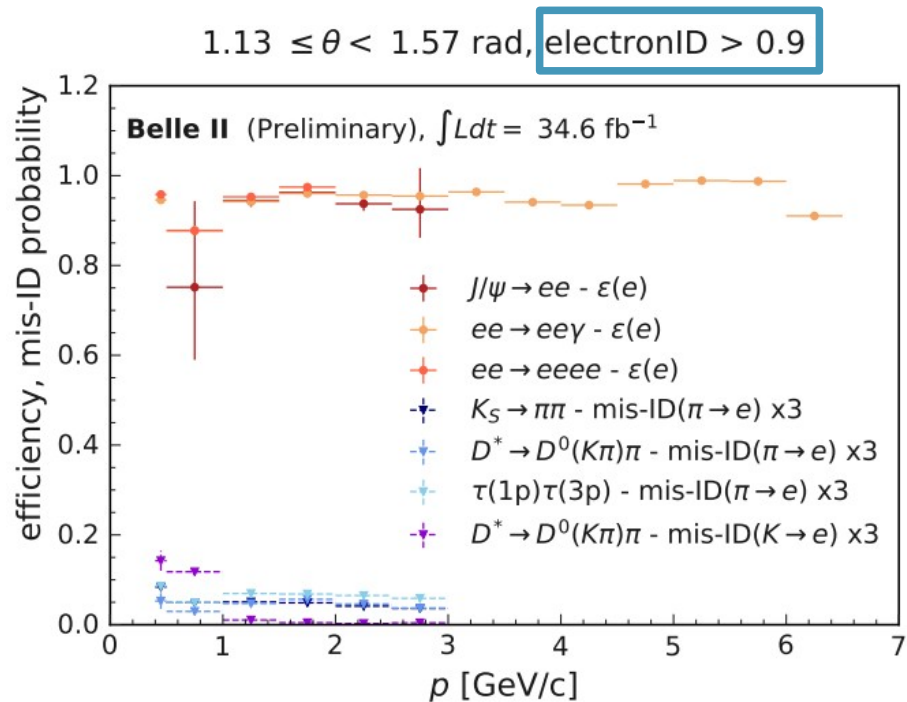
$$\text{leptonID} = \mathcal{L}_{\text{lepton}} / (\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p)$$
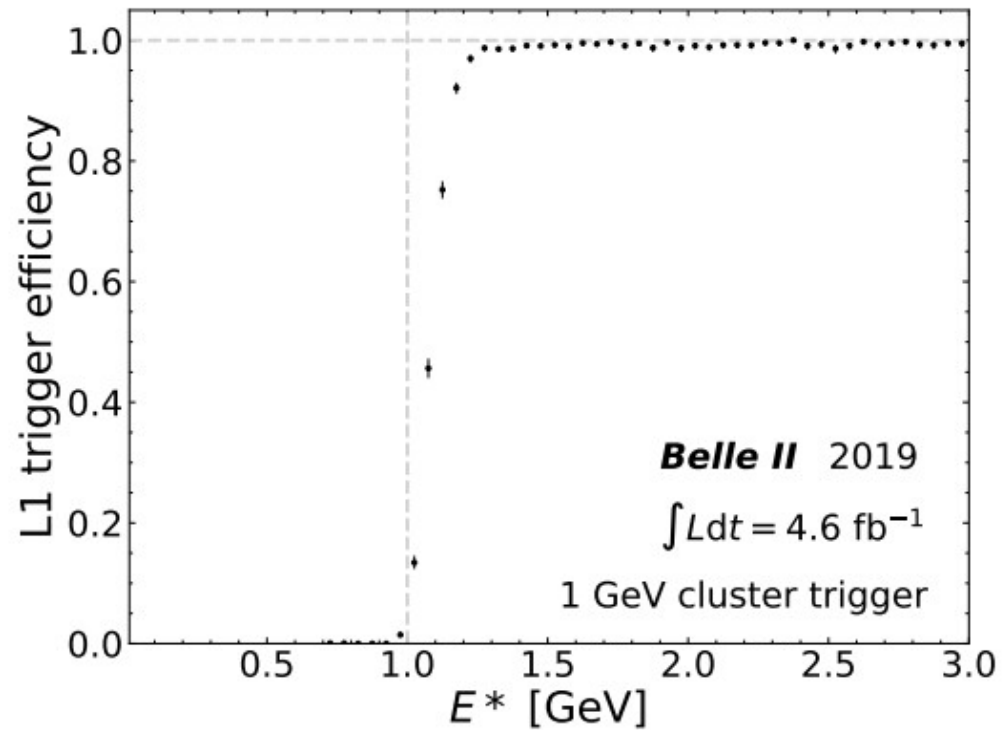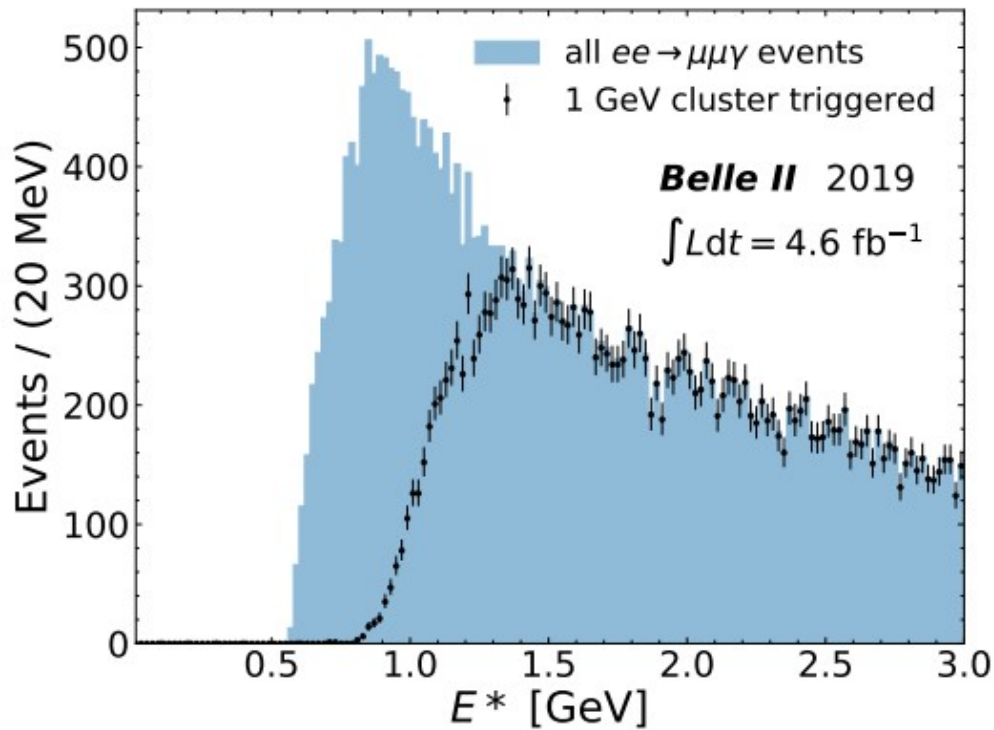
Particle identification: hadrons

Fully reconstructed channels are used:

- $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$;

- slow π tags the D^0 flavour $\rightarrow$ K and π **identified in data**.
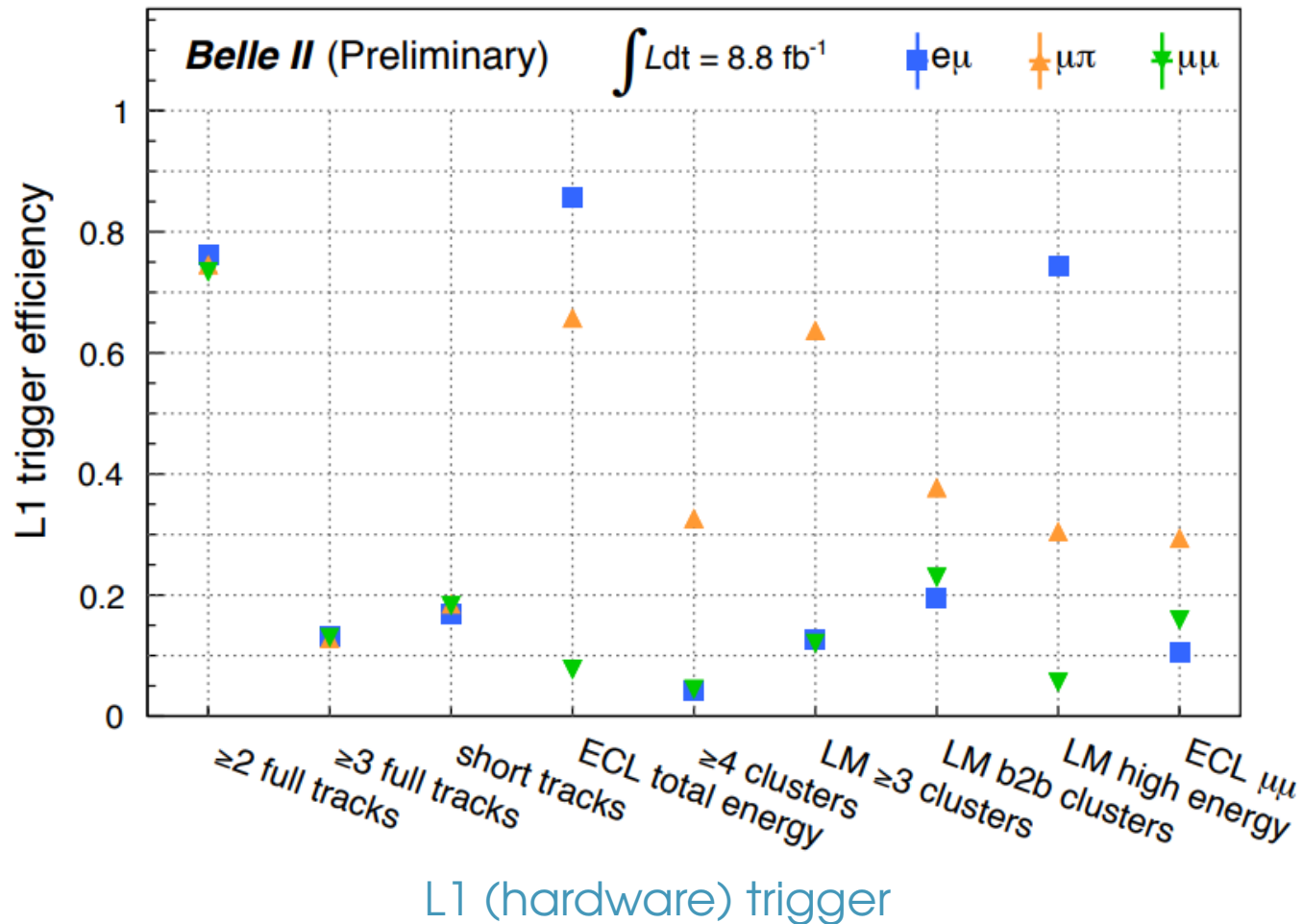
TOP ARICH

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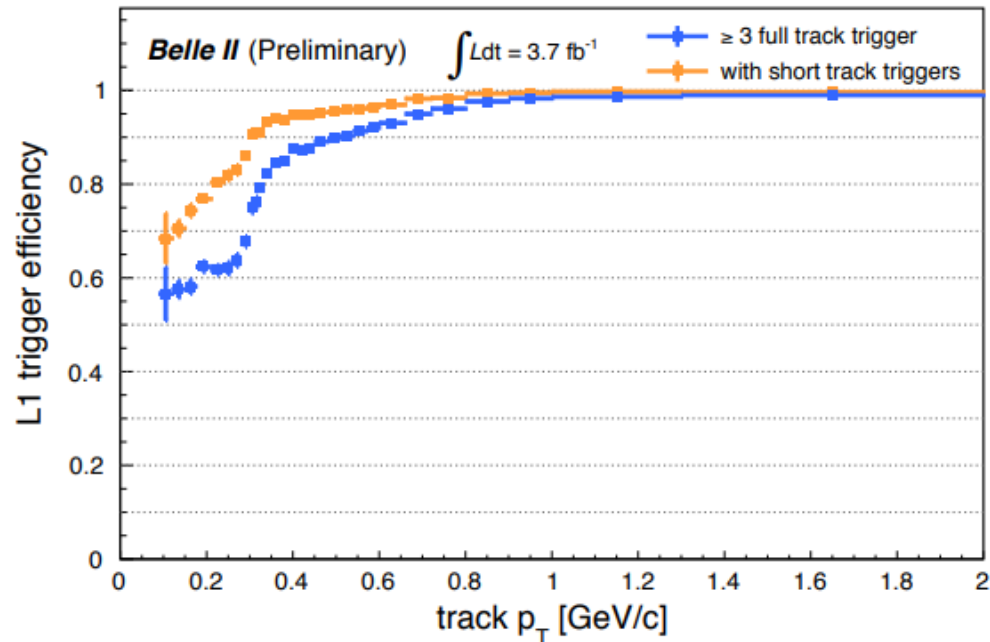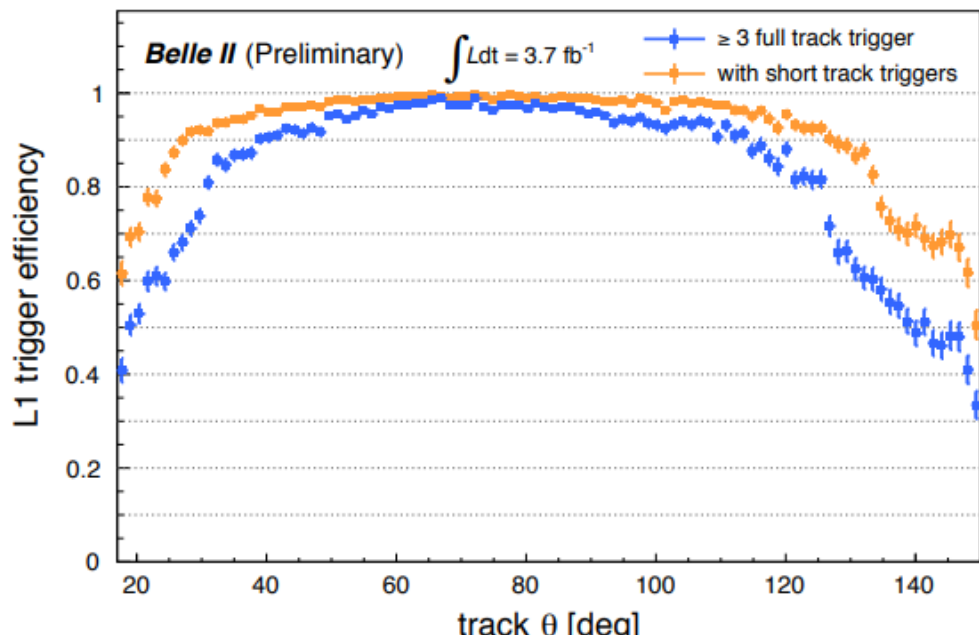
Single Photon Trigger

L1 (hardware) trigger

Low Multiplicity Triggers

Belle II (Preliminary) $\int L dt = 8.8\ \text{fb}^{-1}$ eμ   μπ   μμ

L1 trigger efficiency

≥2 full tracks, ≥3 full tracks, short tracks, ECL total energy, ≥4 clusters, LM ≥3 clusters, LM b2b clusters, LM high energy, ECL μμ

L1 (hardware) trigger

Measurement done
with τ-pair events,
1x1 topology

Low Multiplicity Triggers

Measurement done with τ-pair events,
1x1 topology

L1 (hardware) trigger

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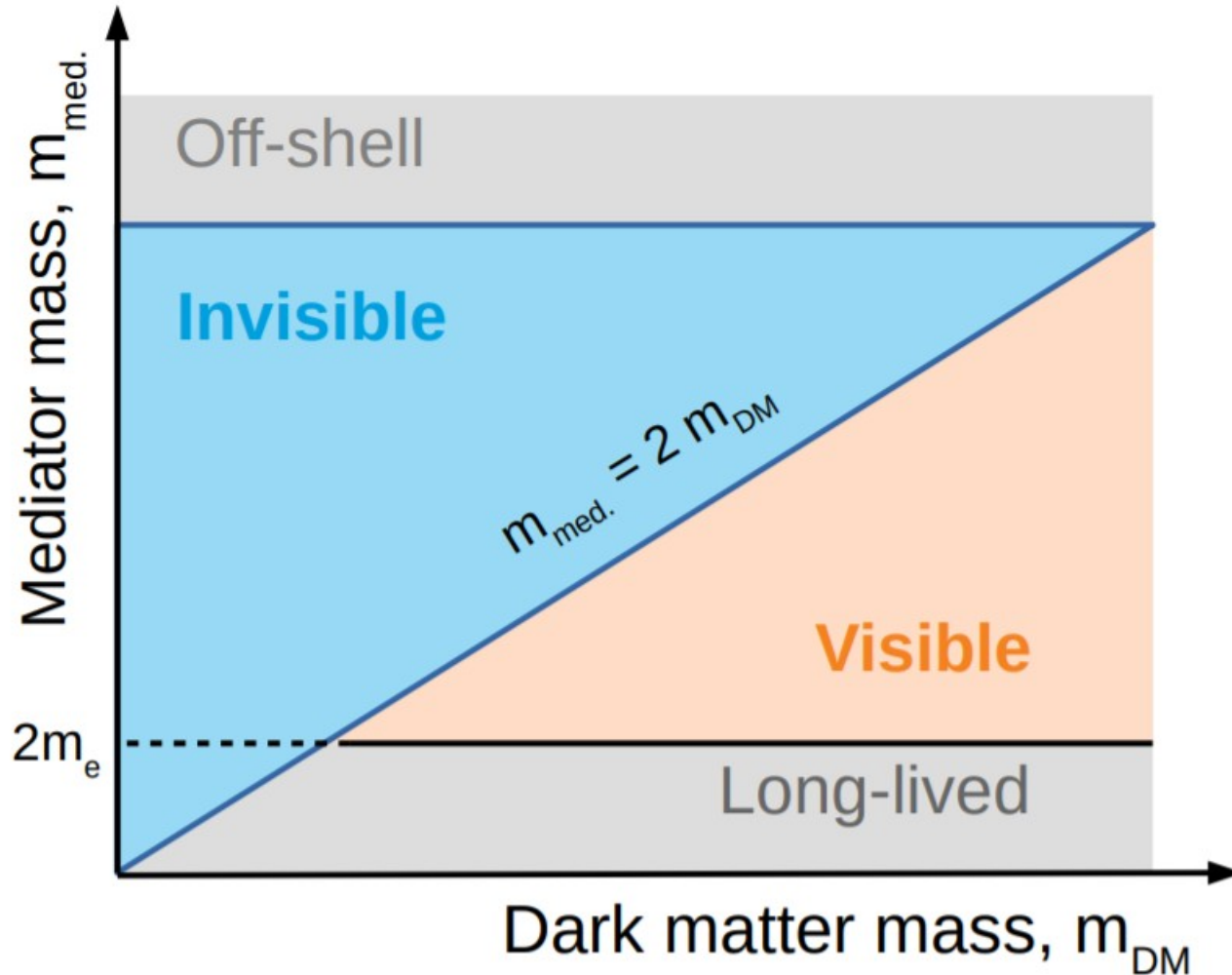
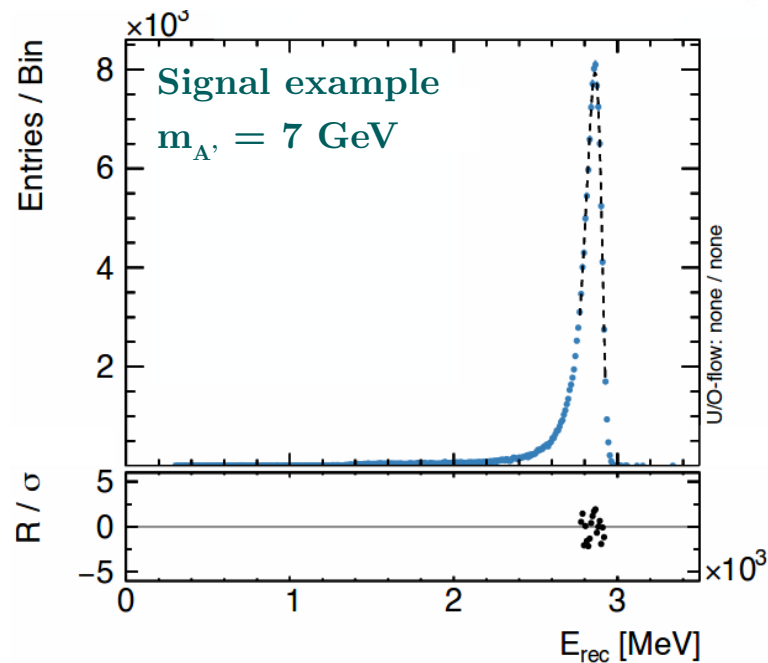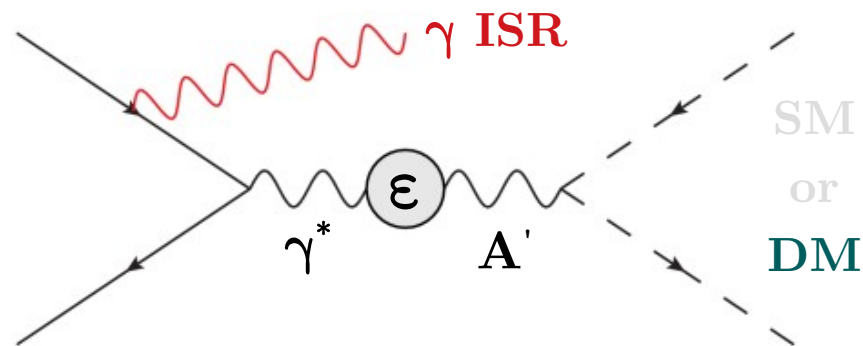The masses of the mediator and of the DM candidates lead to **different type of searches**.

Dark Photon: invisible decay (signal)

Signal signature:

- a single, mono-chromatic, high-E photon (**ISR photon**)

- a bump in the recoil mass:

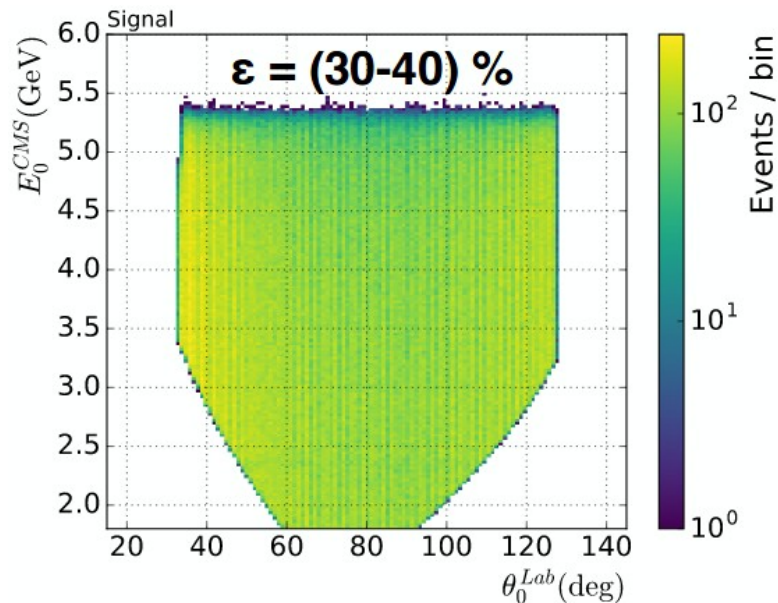$$E_\gamma = \frac{s - m_{A'}^2}{2\sqrt{s}}$$

Needed a special **single photon trigger**

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

Dark Photon: invisible decay (signal)

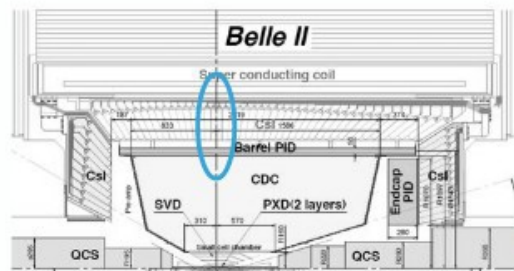Discriminant variables:

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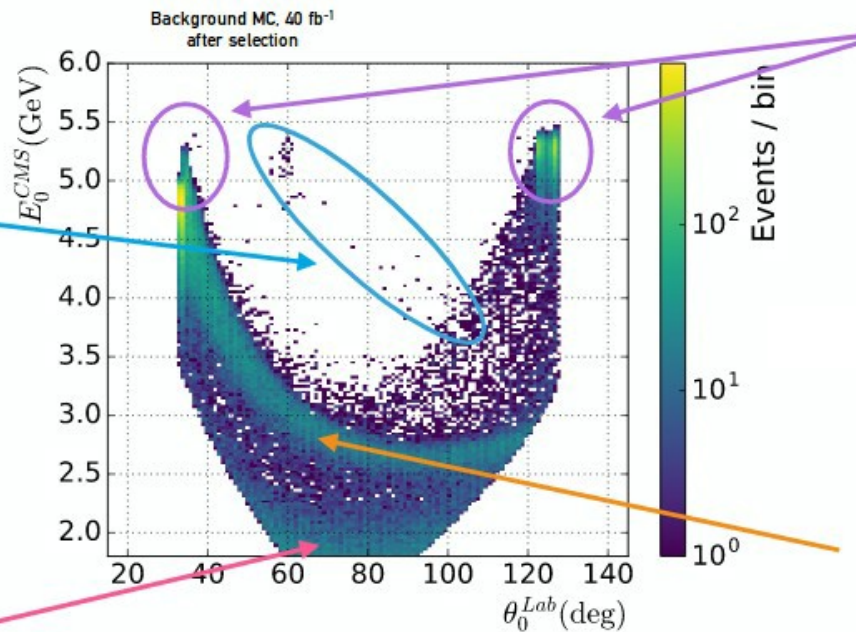

Signal signature:

peak in E_{CMS} (horizontal band)

Dark Photon: invisible decay (background)

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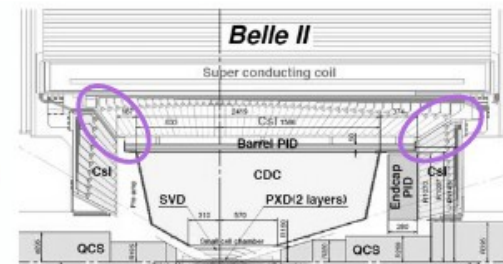
E_{CMS} vs. polar angle of "single photon"

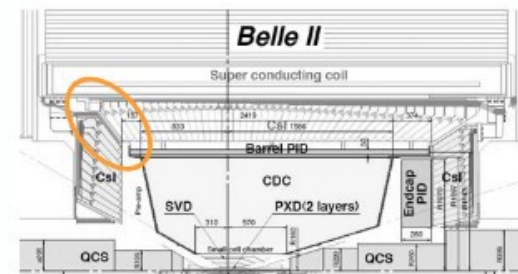**ee→2γ and 3γ**
1γ in ECL 90° gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance
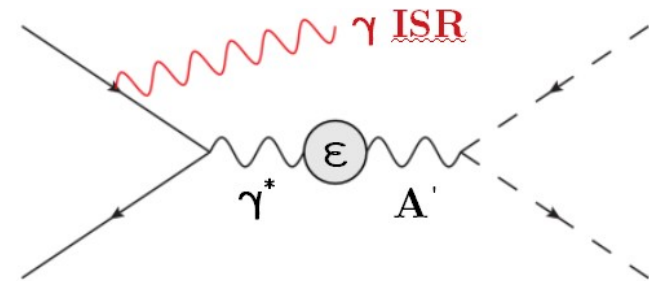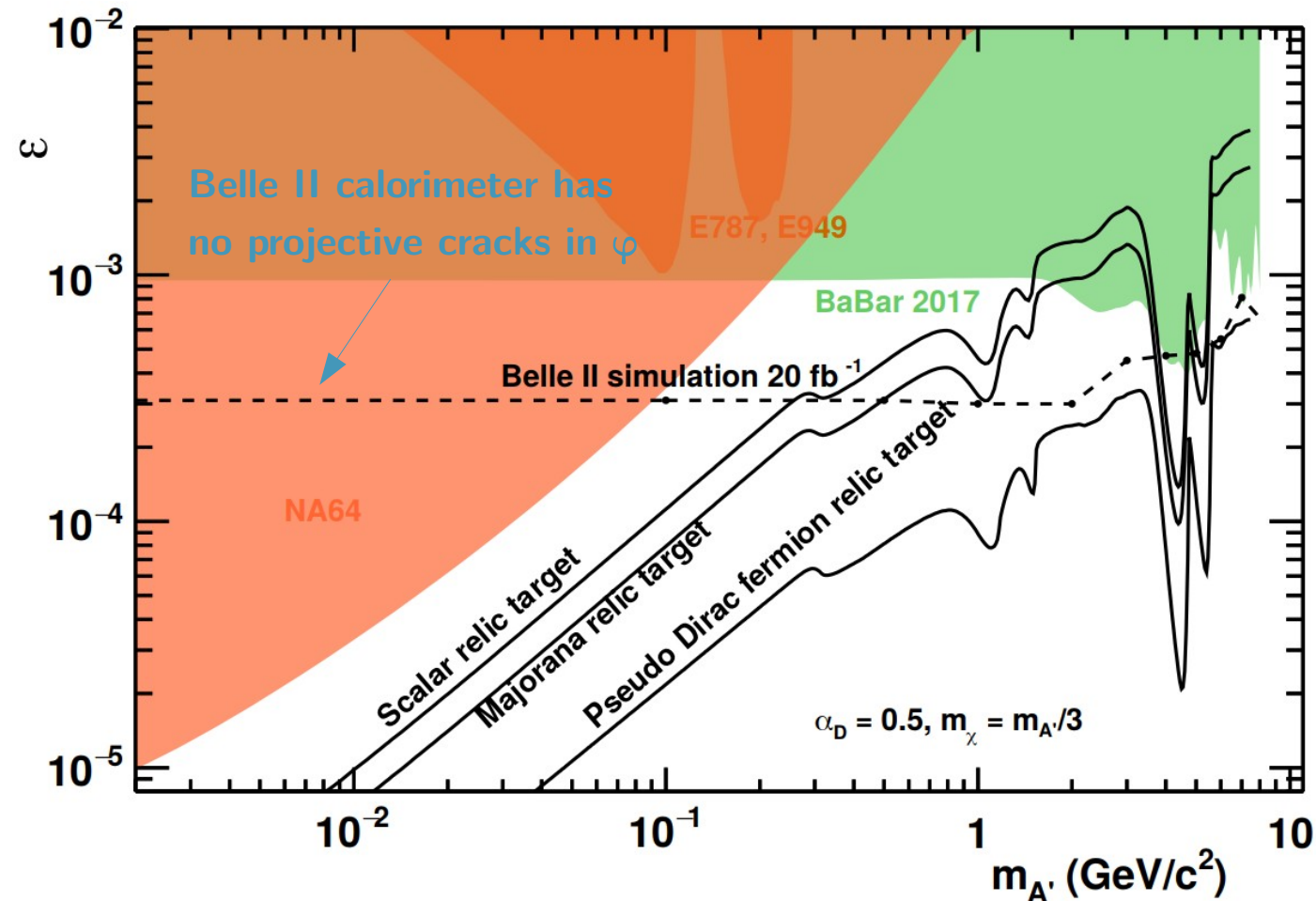
Signal signature:
peak in E_{CMS} (horizontal band)

ee→2γ
1γ in ECL BWD or FWD gap

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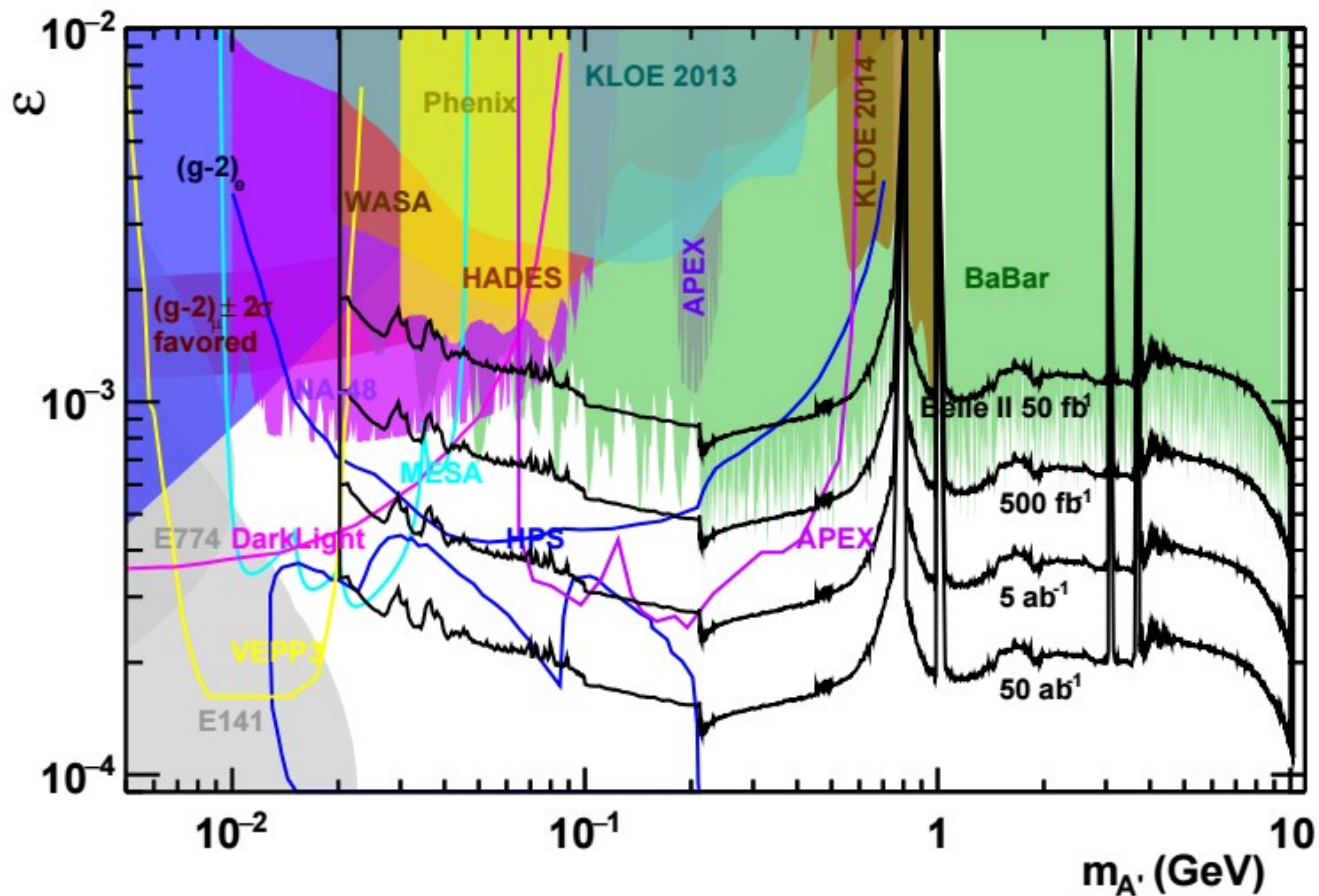1γ out of ECL acceptance

Dark Photon: invisible decay

Single photon search: needed a **special trigger logic**:
- ready for Belle II;
- not available in Belle;
- partially available in BaBar.
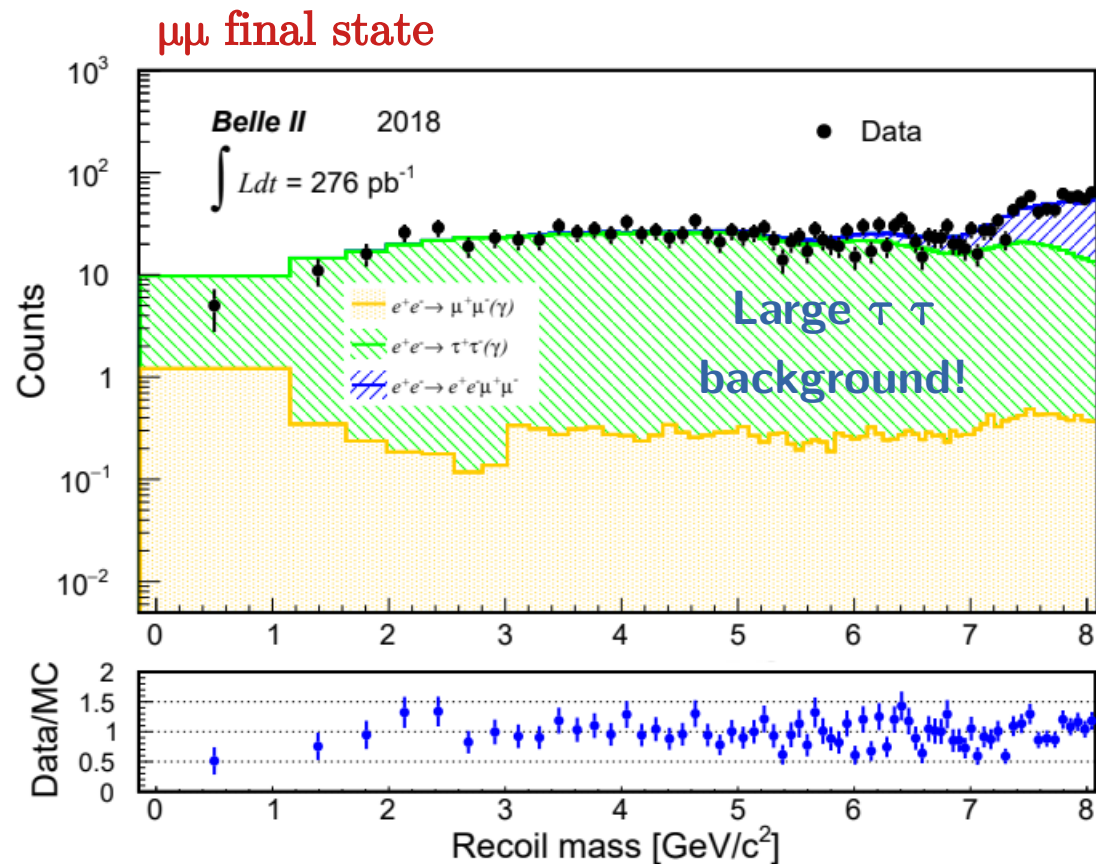
Dark Photon: leptonic decay

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

Belle II 2018
$\int L dt = 276 \text{ pb}^{-1}$

Data

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

Large τ τ background!

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 independent control samples!
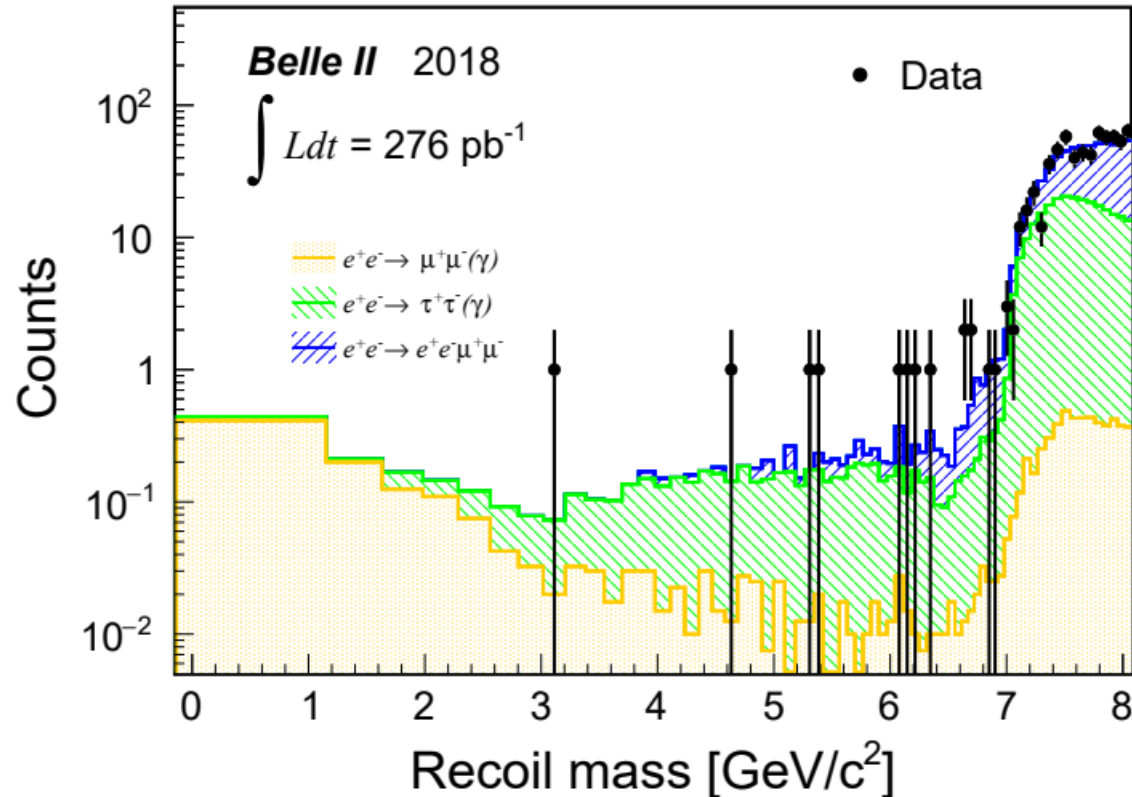
Suppression of the ττ background

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

→ Studied several variables, isolated the most discriminating ones between generated signal and background samples.
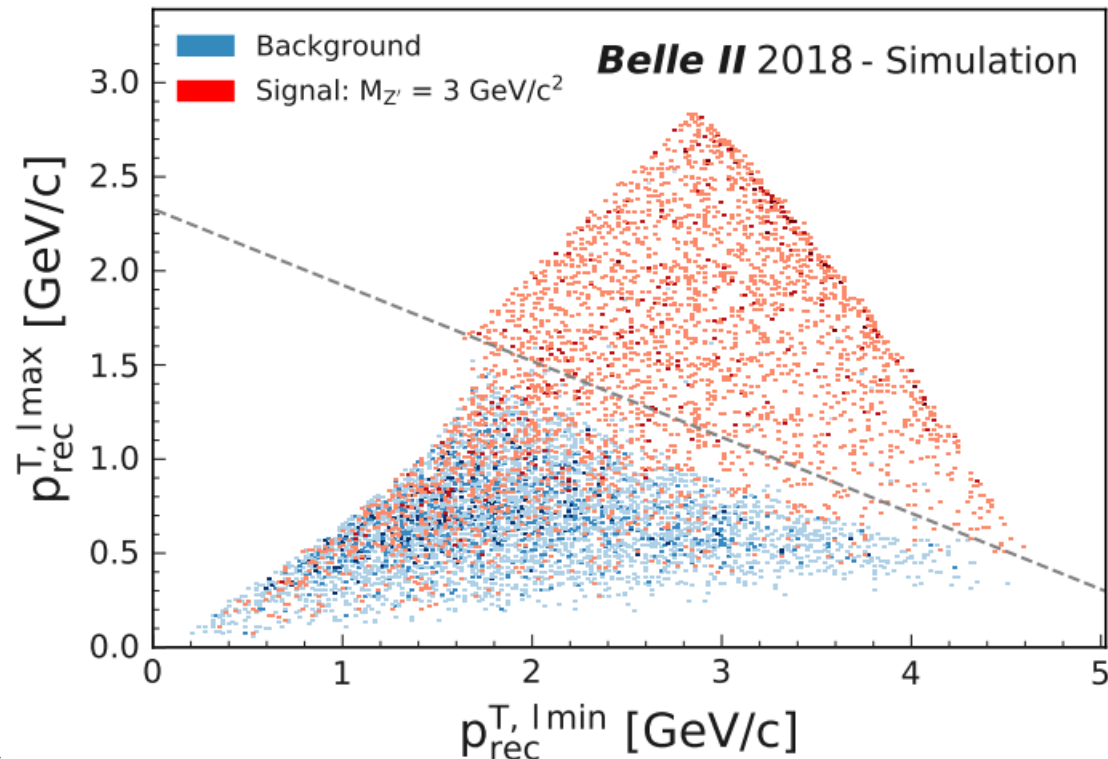
We optimized the selection in each recoil mass bin by choosing the best cuts that maximizes a given figure of merit (**hand-made multivariate approach**).

ττ background suppressed

μμ final state

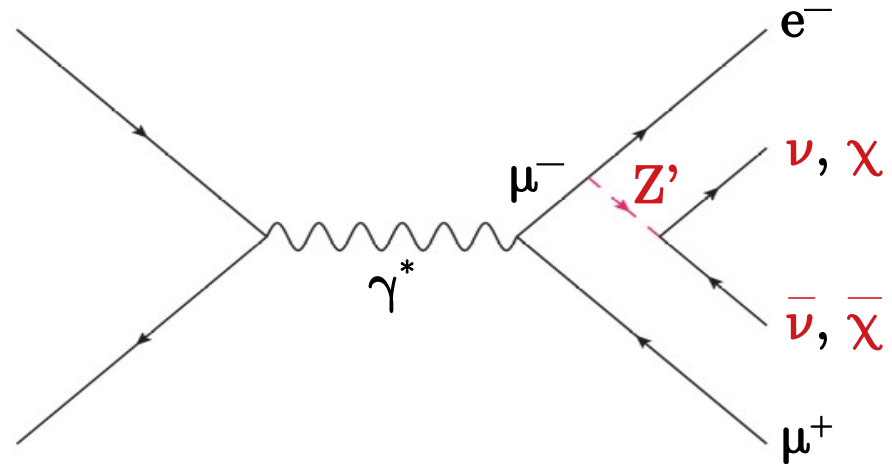Suppression of the ττ background very effective up to 7 GeV (then, ~~ee~~μμ events start to be dominant).

Signal efficiency between 3% and 5%.

No (local) anomalies observed… :(

And why not considering a LFV Z'?

We considered only the e−μ coupling.
We considered only the invisible decay.
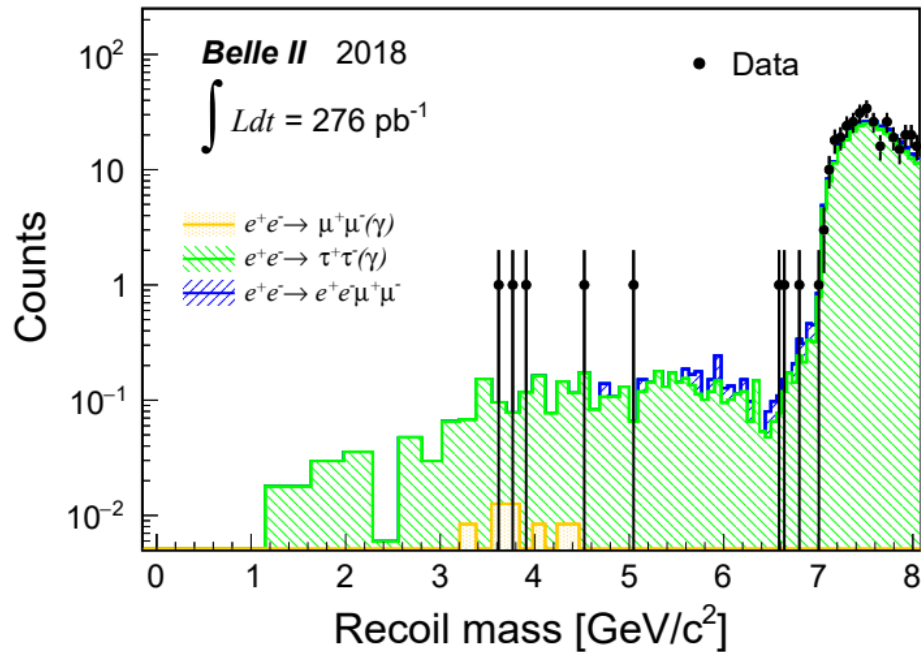
I. Galon et al. (2016), *arXiv:1610.08060*

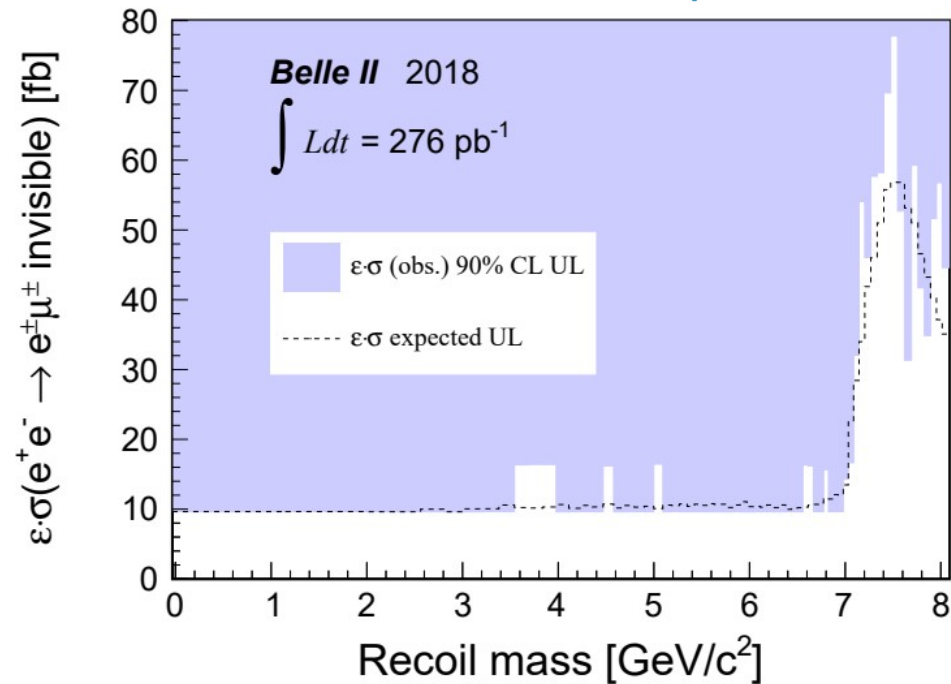Unfortunately, the model we were using showed some issues (too large width for the Z', etc.).

**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!**

Axion-Like Particles (signal)

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

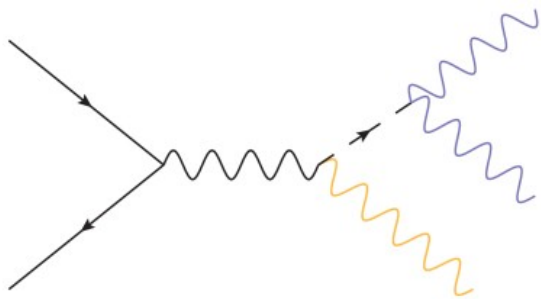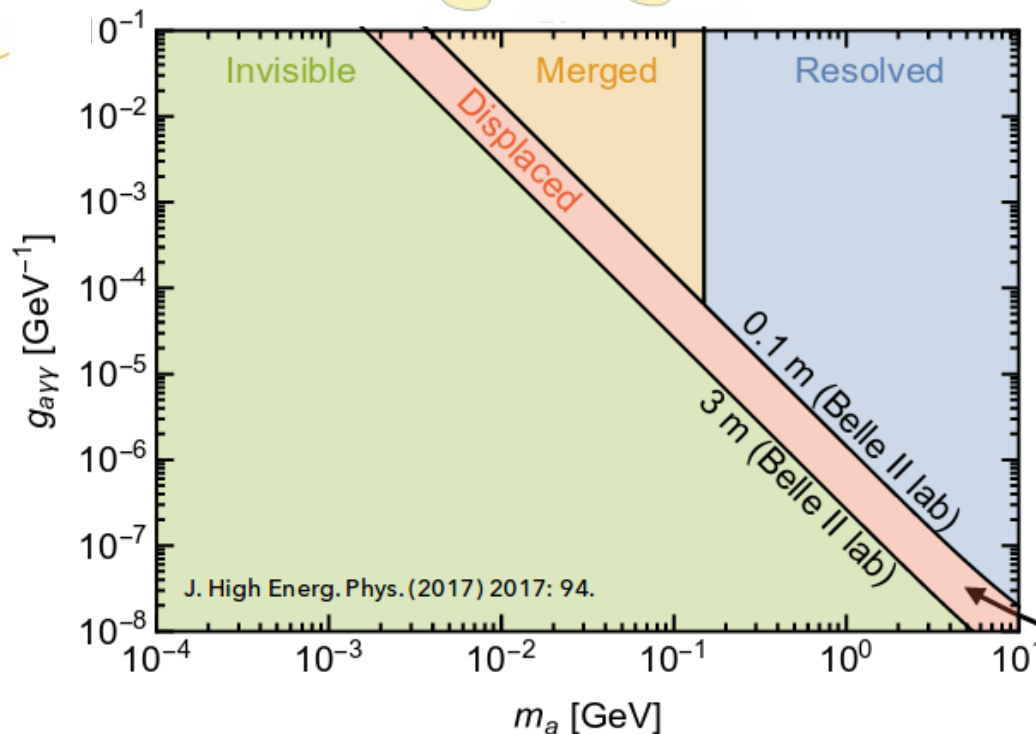For **resolved** case:

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

Peak in $\gamma\gamma$ mass spectrum

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

Invisible   Merged   Resolved

Displaced

$g_{a\gamma\gamma}$ [GeV^{-1}]

0.1 m (Belle II lab)

3 m (Belle II lab)

J. High Energ. Phys. (2017) 2017: 94.

m_a [GeV]

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: a → γγ

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 σ**).

PRL 125 (2020) 161806
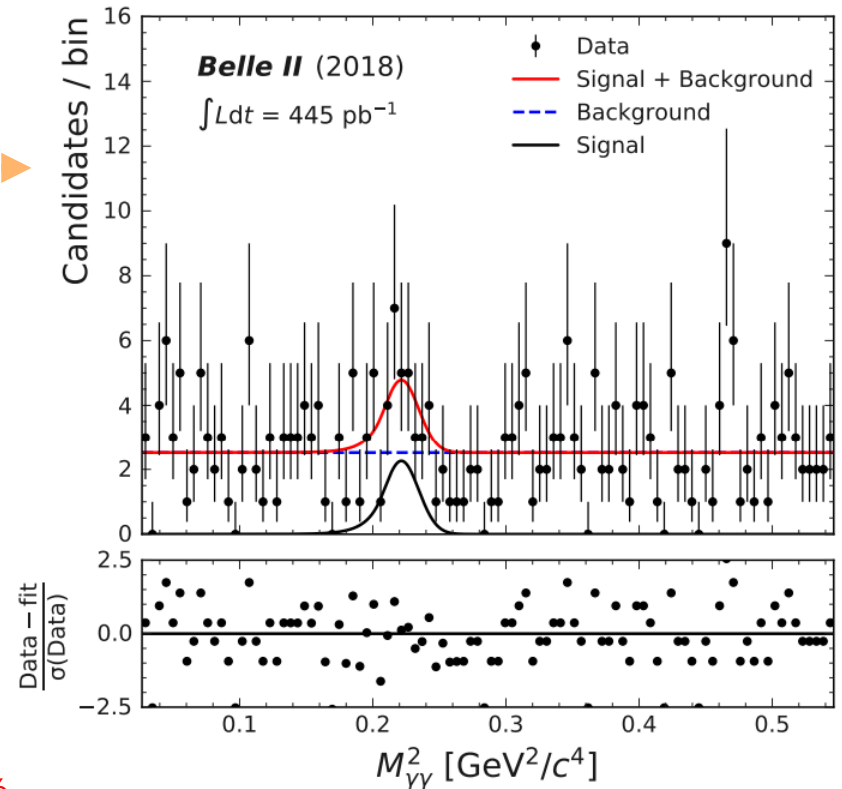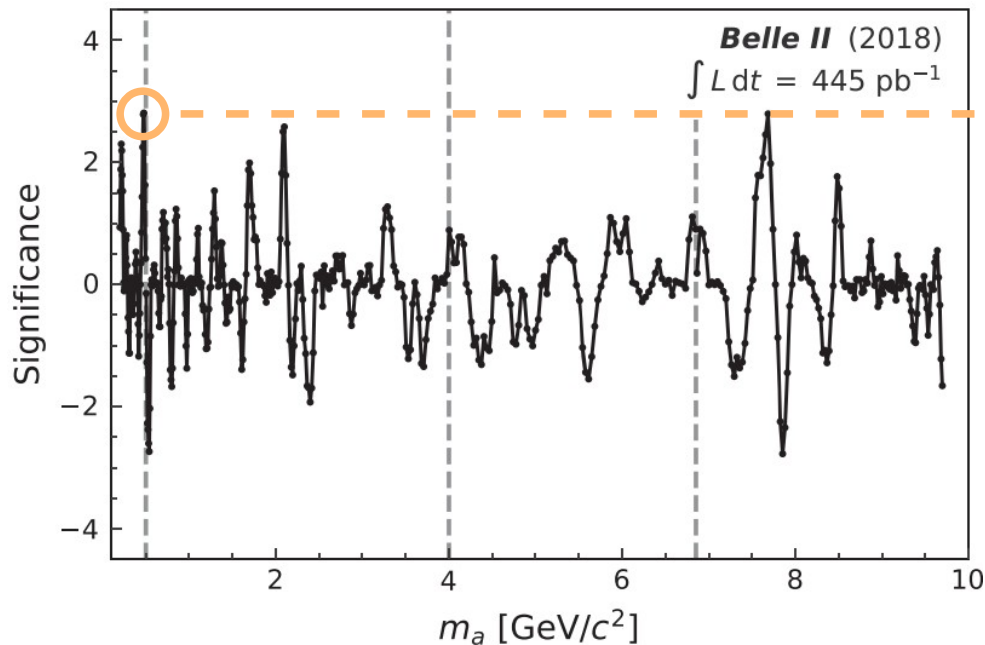
ALPs: low-mass region

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

e^- e^-

γ

a

γ

e^+ e^+
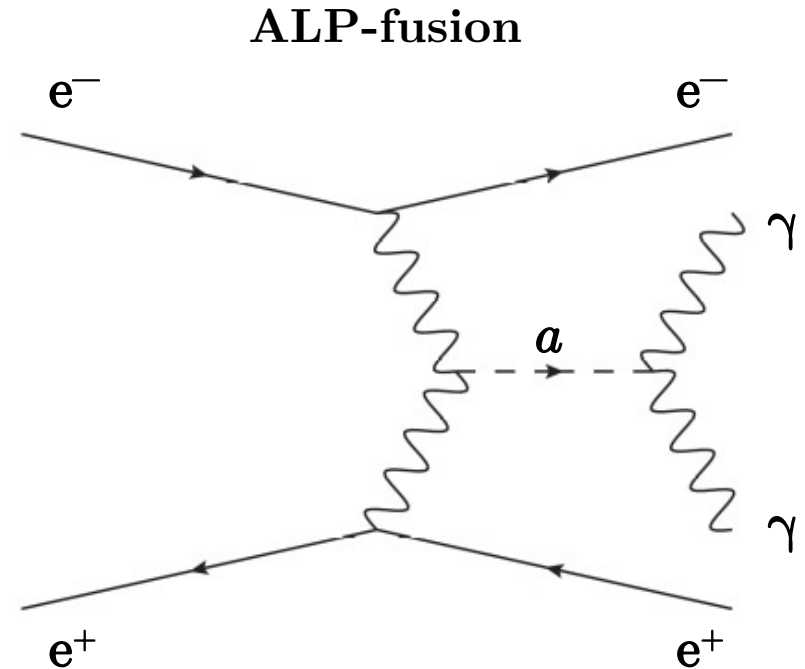
Pro: resolved clusters
Con: very low energetic photons

Axion-like Particles from B decays
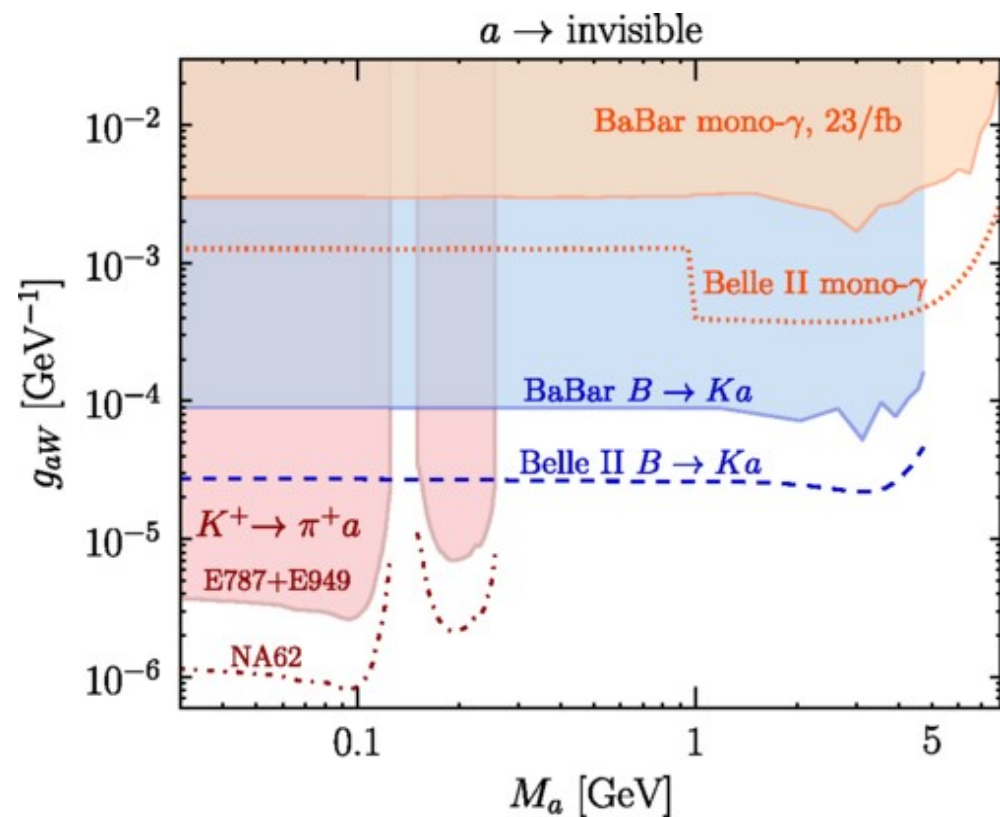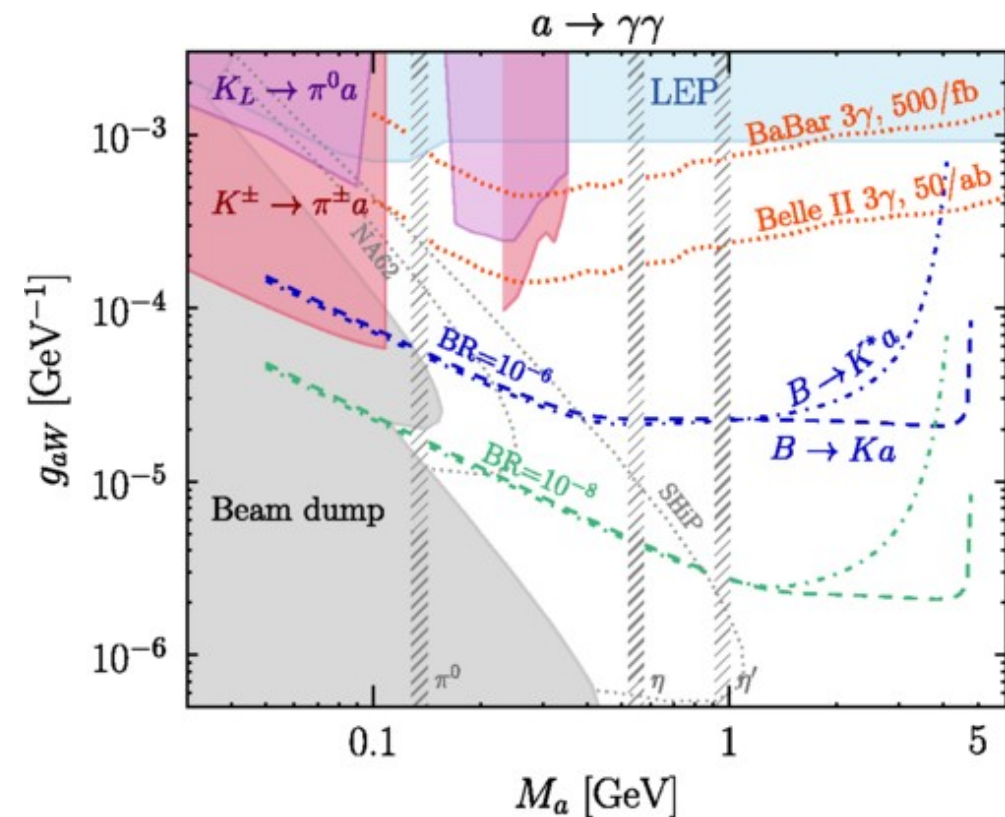
Izaguirre et al. (2017), *arXiv:1611.09355*