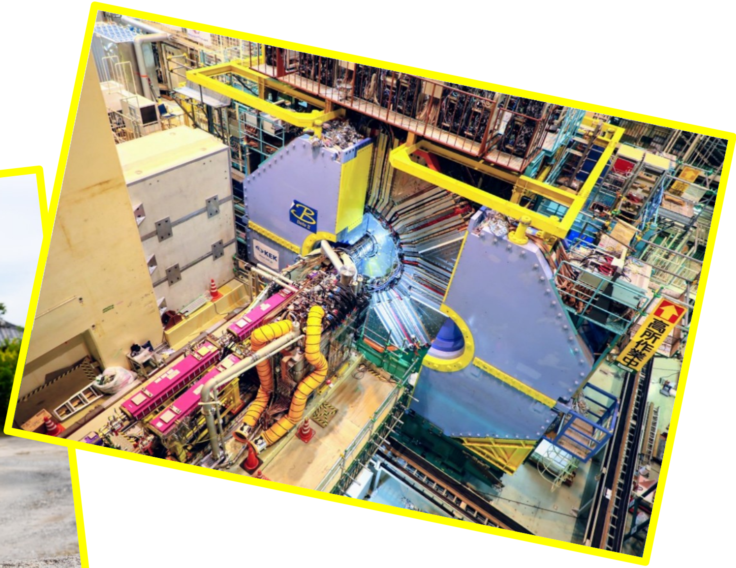
Dark Sector physics at Belle II



Giacomo De Pietro

INFN Roma Tre

INFN ROMA TRE

for the Belle II collaboration

Belle II

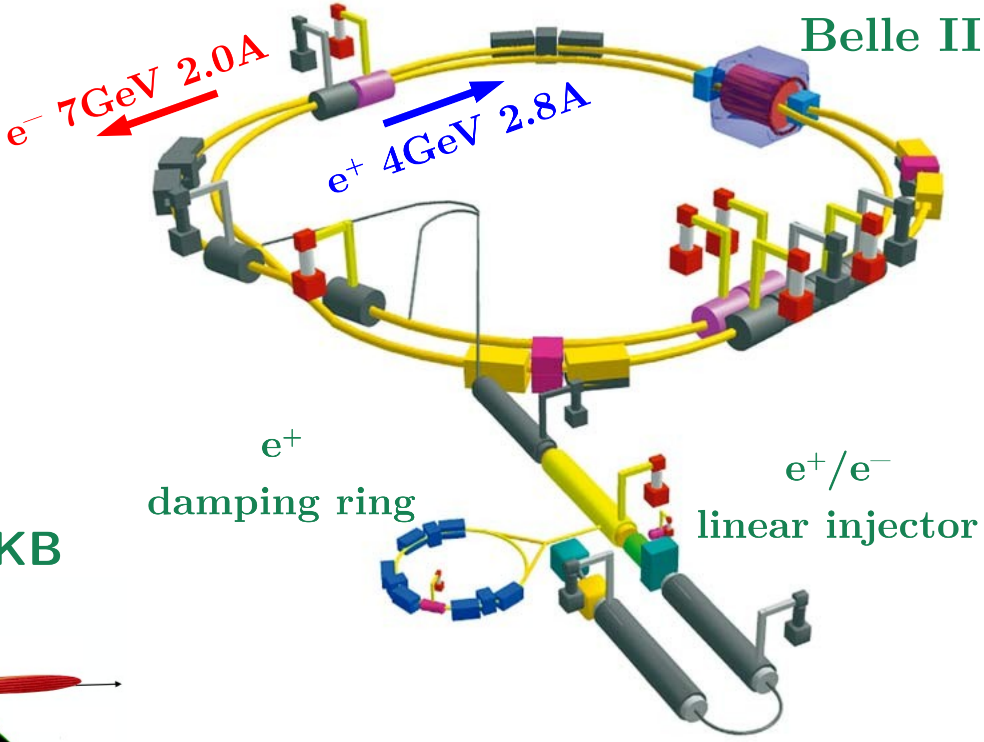
Dark Matter 2021: From the Smallest to the Largest Scales

13-16 September 2021

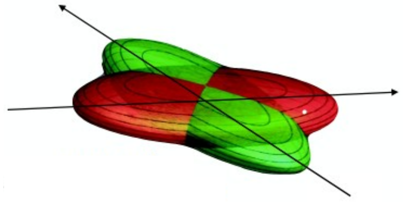
SuperKEKB: a new Intensity Frontier machine

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

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



KEKB



nano-beam
scheme

SuperKEKB

I (A): ~ 1.6/1.2

β^*_y (mm): ~ 5.9/5.9

I (A): ~ 2.8/2.0

β^*_y (mm): ~ 0.27/0.3

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

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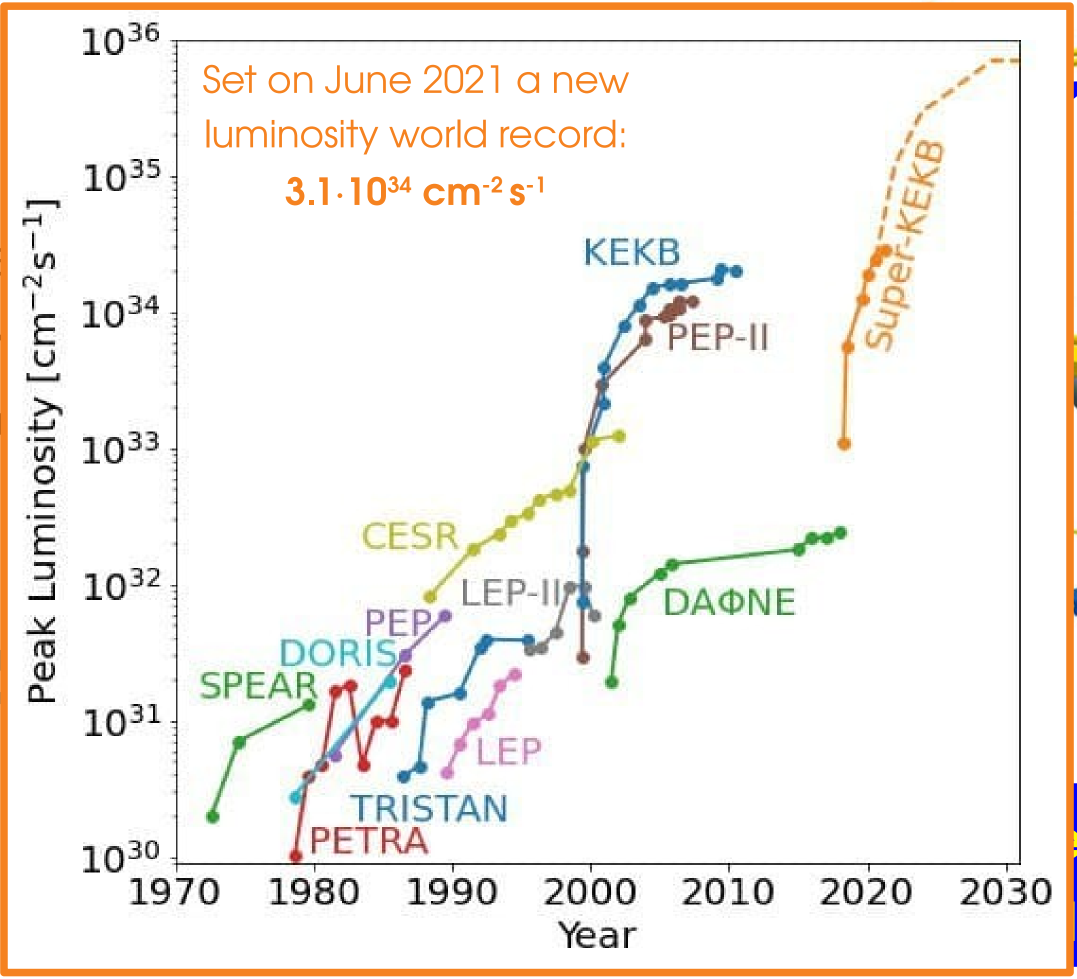
located at KEK

It's an asymme

operating mair

(Υ(4S), but foreseen r



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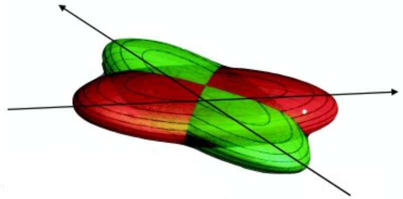

I (A): ~ 1.6/1.2

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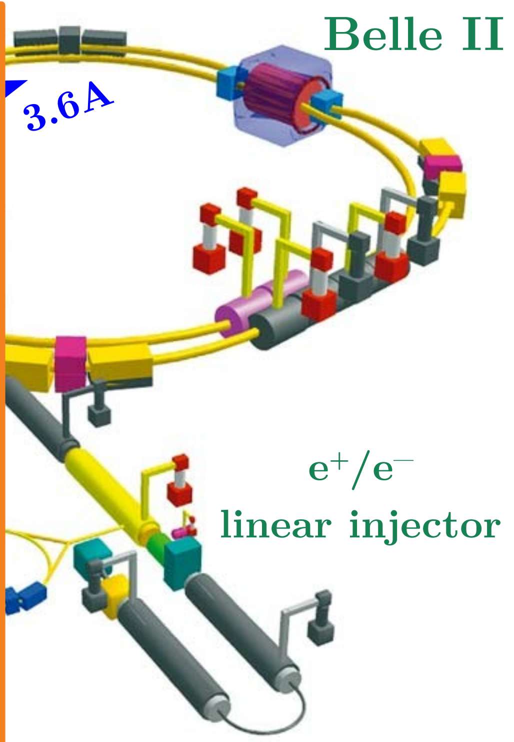


ak luminosity:

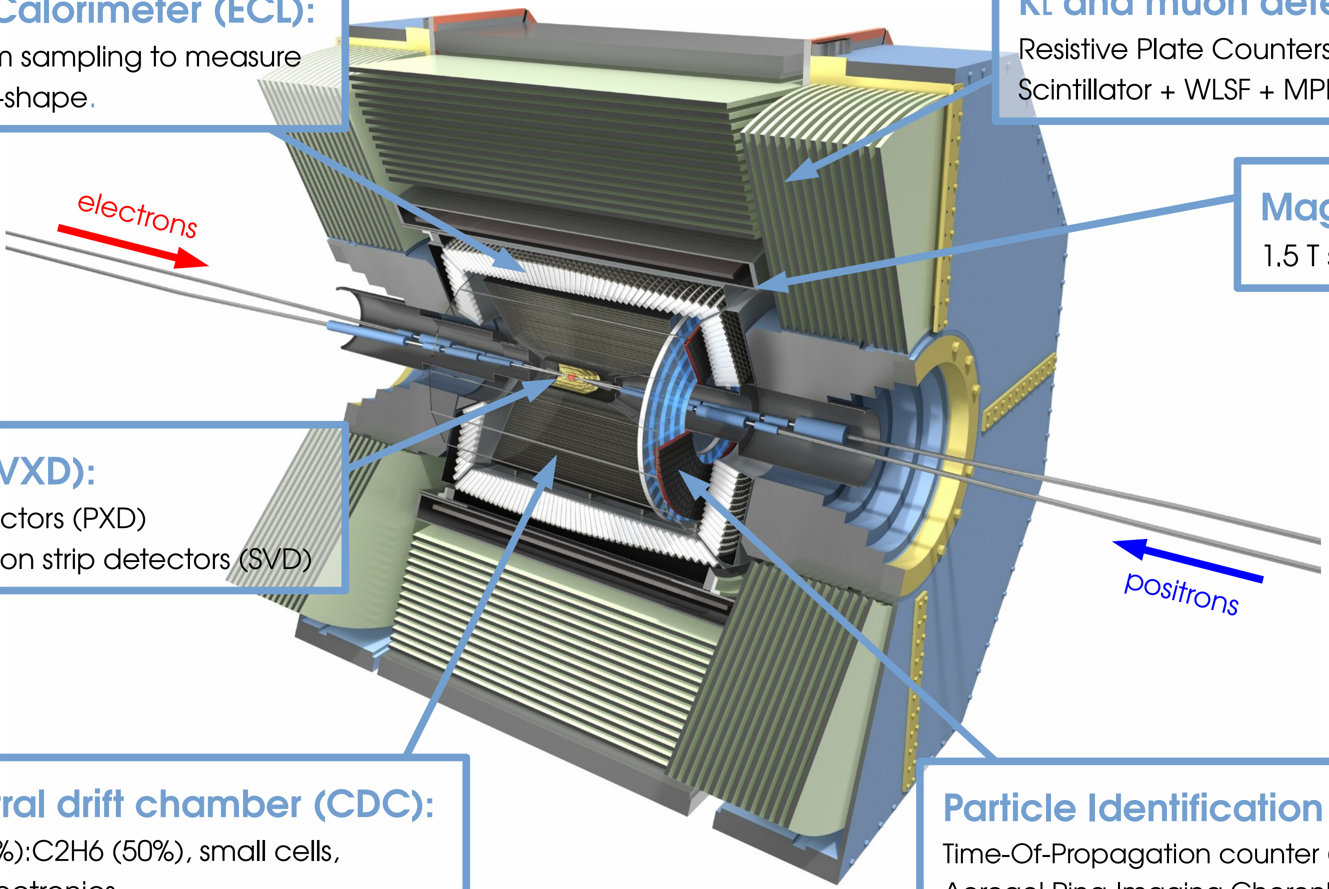
0^{35} cm^{-2} s^{-1}

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)

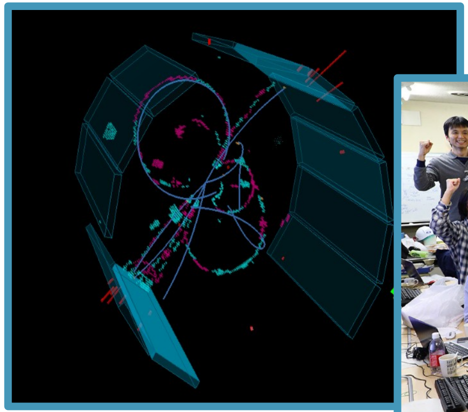
Trigger rate limits:
Hardware: < 30 kHz
Software: < 10 kHz

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

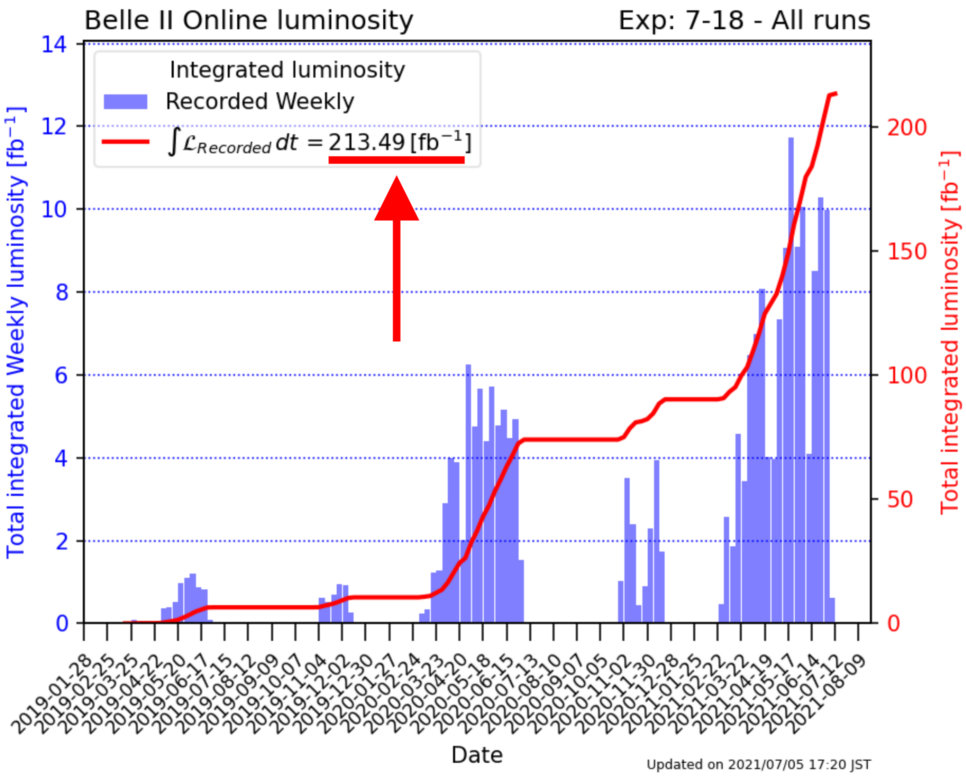


Collected 0.5 fb^{-1} in 2018 (pilot run)

Collected more than 200 fb^{-1} since 2019

SupeKEKB peak performance:

I (LER/HER): 690/830 mA; β^*_y: 1 mm



Goal: collect up to 50 ab^{-1} in a decade!

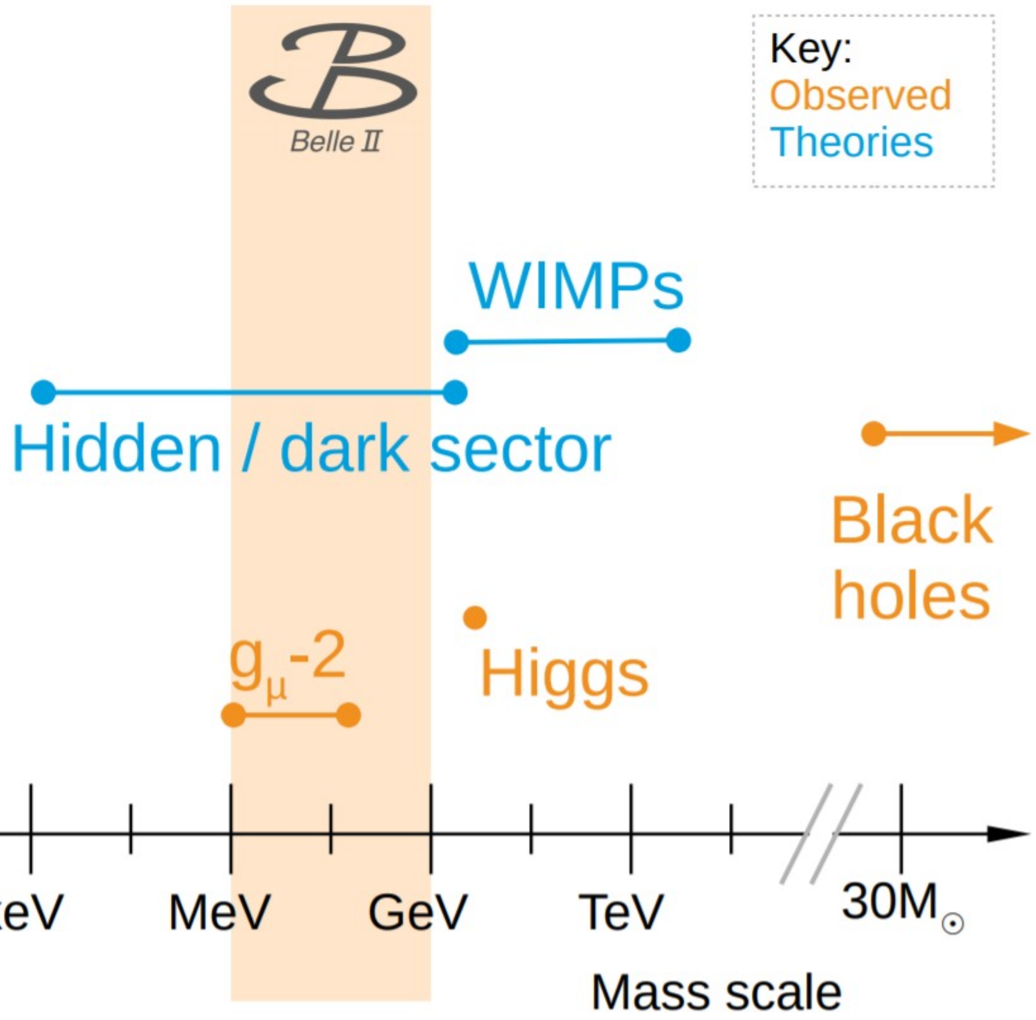
Dark Matter

It is "dark".

It exists...

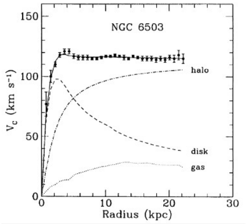
Many experimental techniques
to probe the Dark Matter existence:

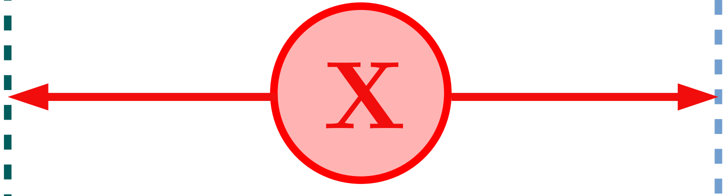
- **production at colliders.**



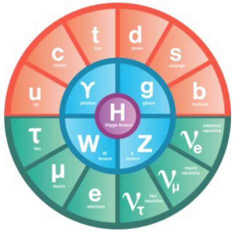
Dark Matter coupling to SM

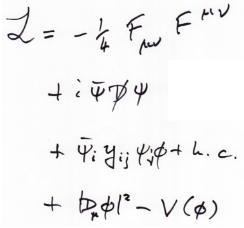
Dark Matter





Standard Model





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

Vector portal → Dark Photon / Z'

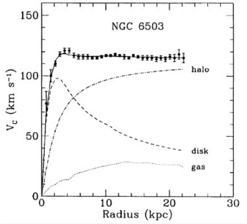
Scalar portal → Dark Higgs / Dark Scalar

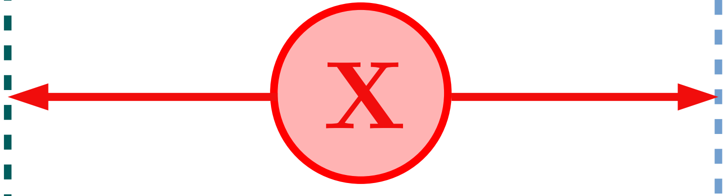
Pseudoscalar portal → Axion-Like Particles

Neutrino portal → Sterile Neutrinos

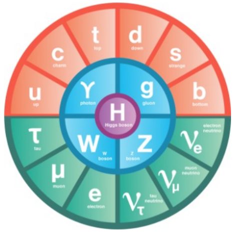
Dark Matter coupling to SM

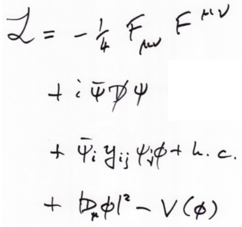
Dark Matter





Standard Model





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

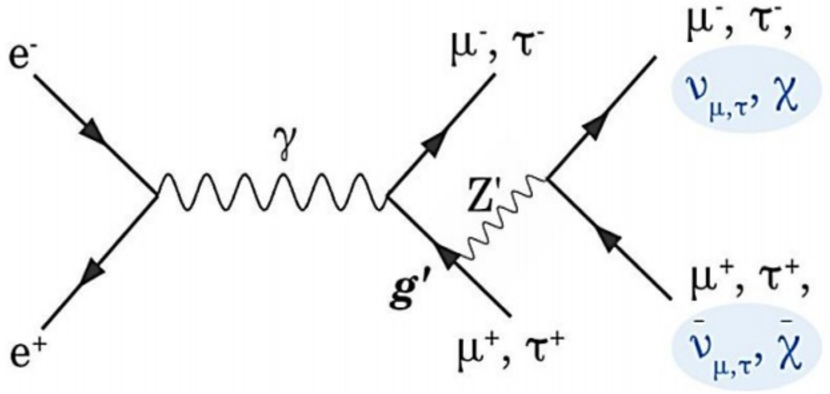
New light gauge boson Z' coupling only to **2nd and 3rd** generation of leptons (**$L\mu - L\tau$ model**):

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

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

g′ is the coupling constant introduced by the model

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 $m_{Z'} < 2m_\mu$.

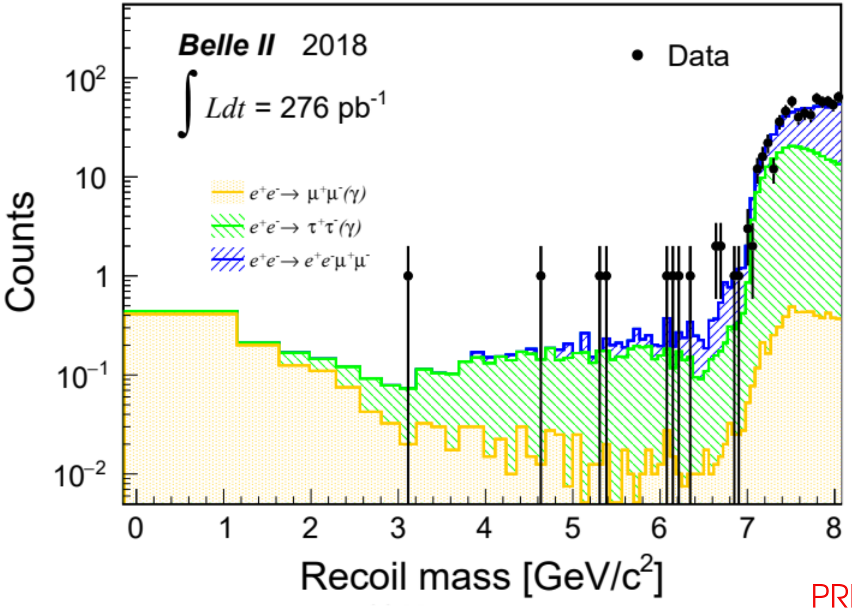
First physics paper by Belle II:
PRL 124 (2020) 141801

$L_\mu - L_\tau$ 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 system recoiling against the dimuon pair;
- nothing else in the rest of the event.



PRL 124 (2020) 141801

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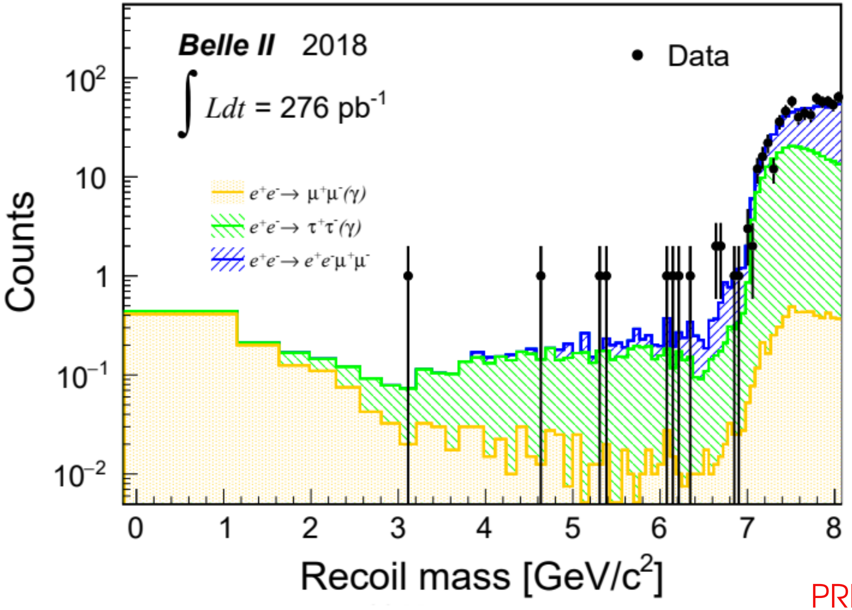
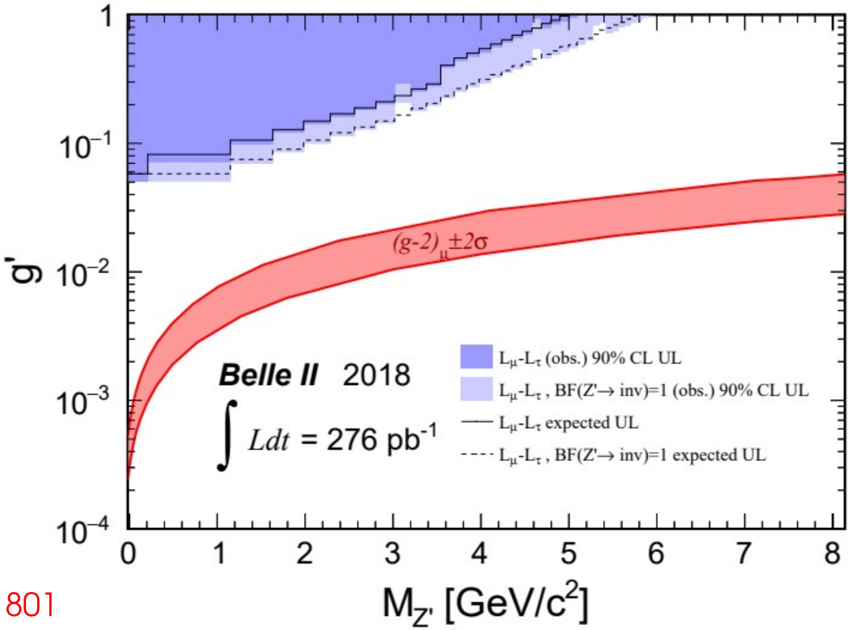


90% CL upper limit on the g′ coupling constant

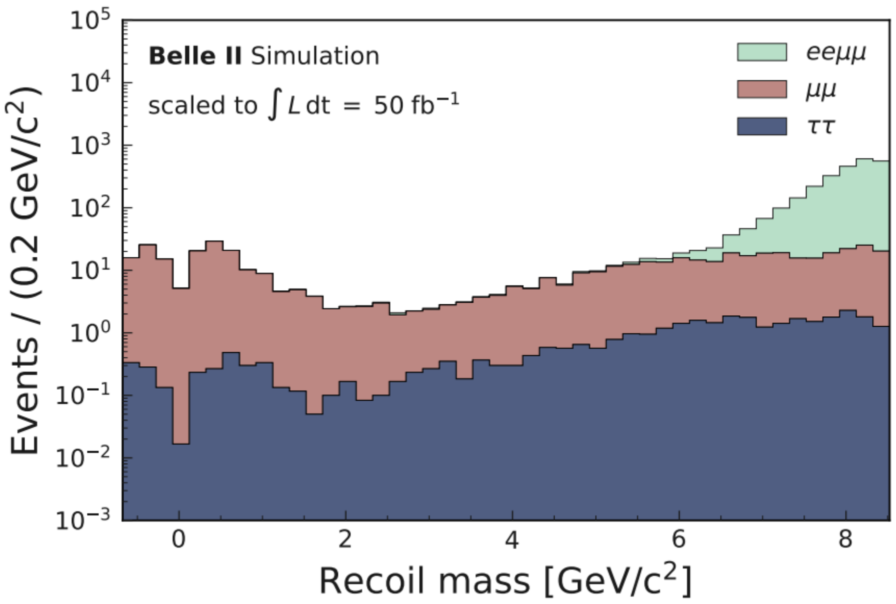


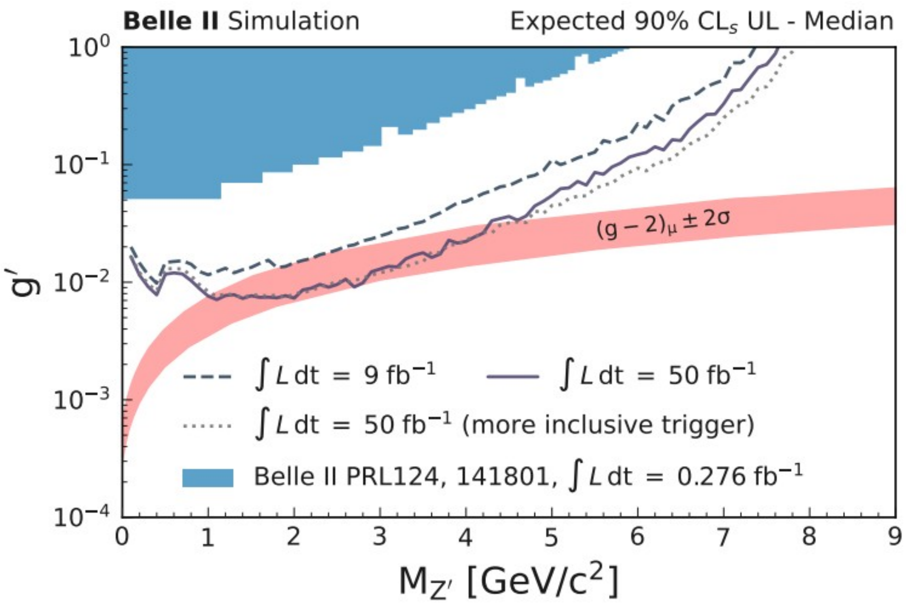
PRL 124 (2020) 141801

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





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

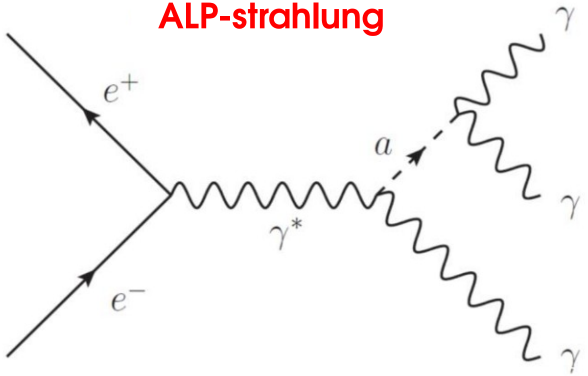
Axion-Like Particles: a → γγ

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

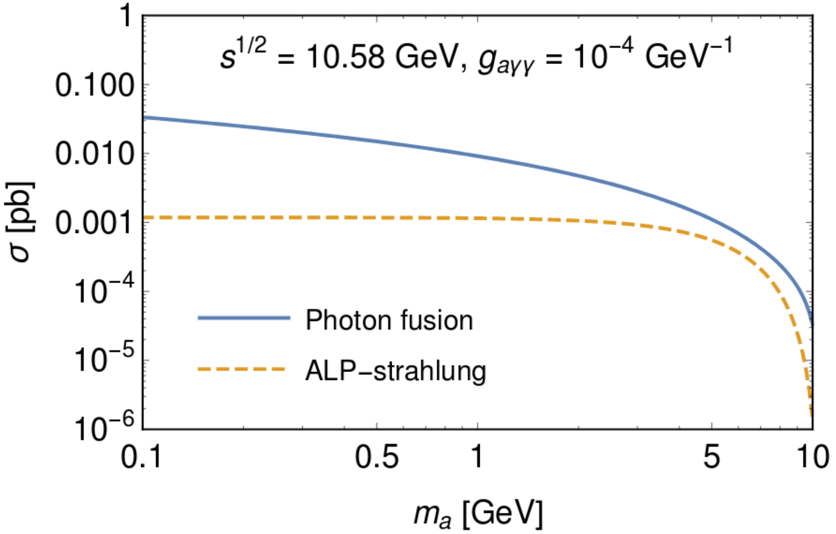
Belle II focused on the **coupling to photons**:

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

ALP-strahlung



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



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

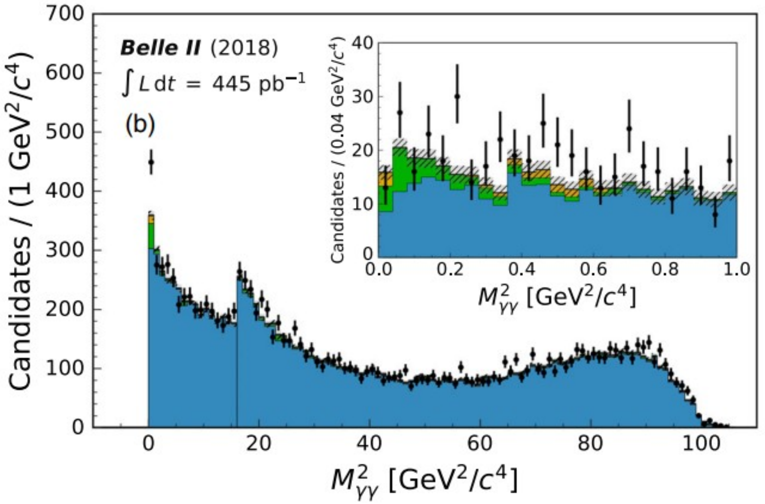
First search at B-factories

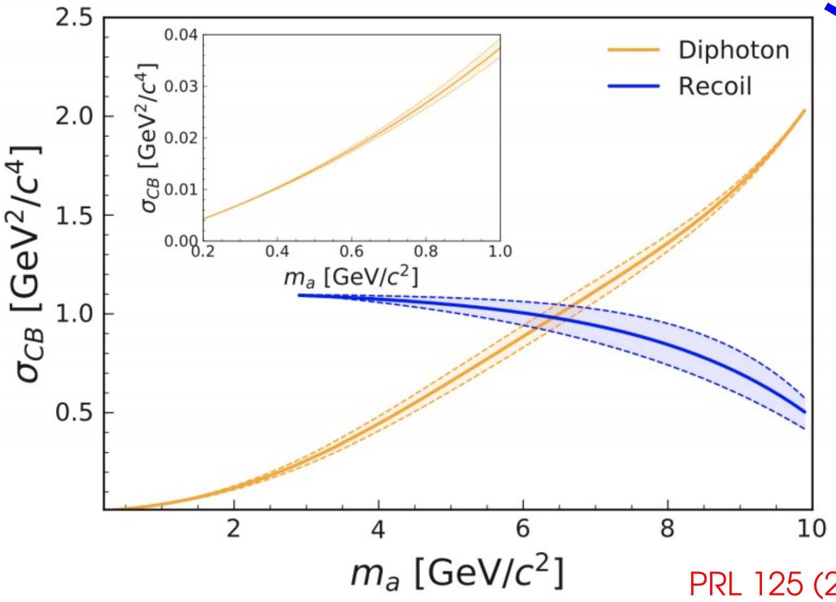
Axion-Like Particles: a → γγ

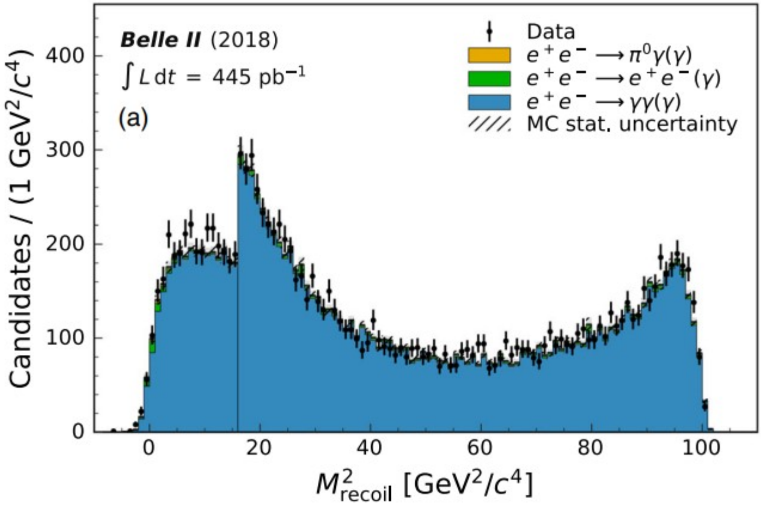
Select events with no charged tracks consisting of 3 isolated photons with a total invariant mass consistent with $\mathbf{s}^{1/2}$.

Search strategy optimized to maximize ALP sensitivity:

- low ALP mass → diphoton mass spectrum;
- high ALP mass → recoil mass spectrum.





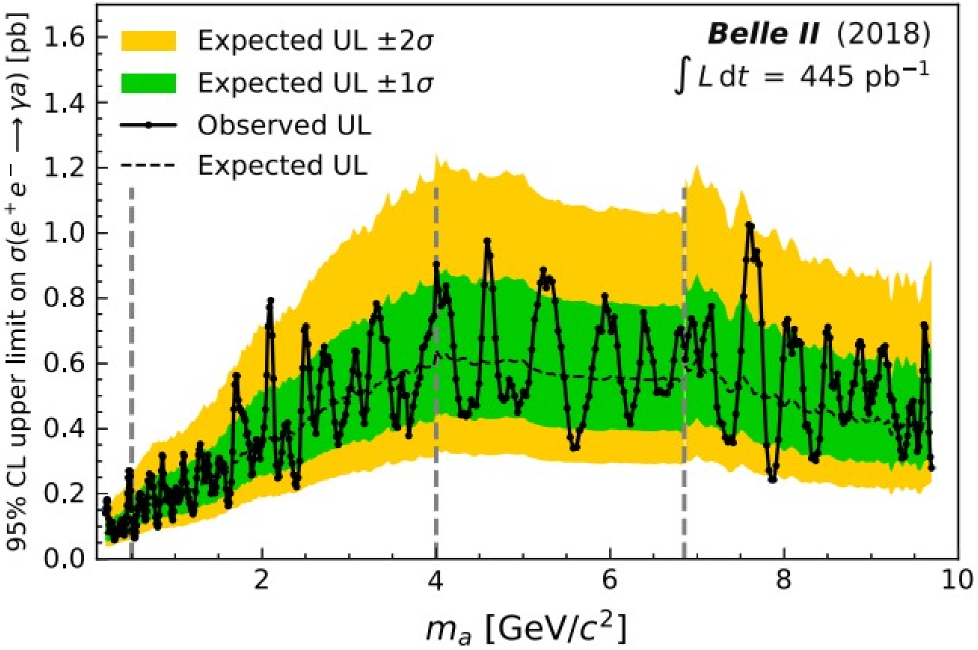


PRL 125 (2020) 161806

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 σ).



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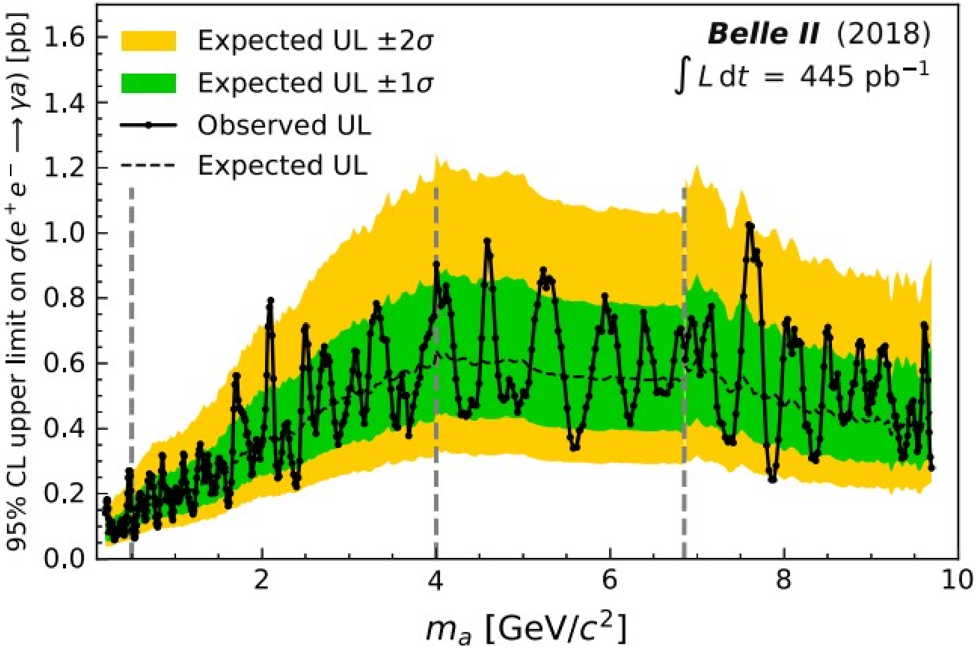
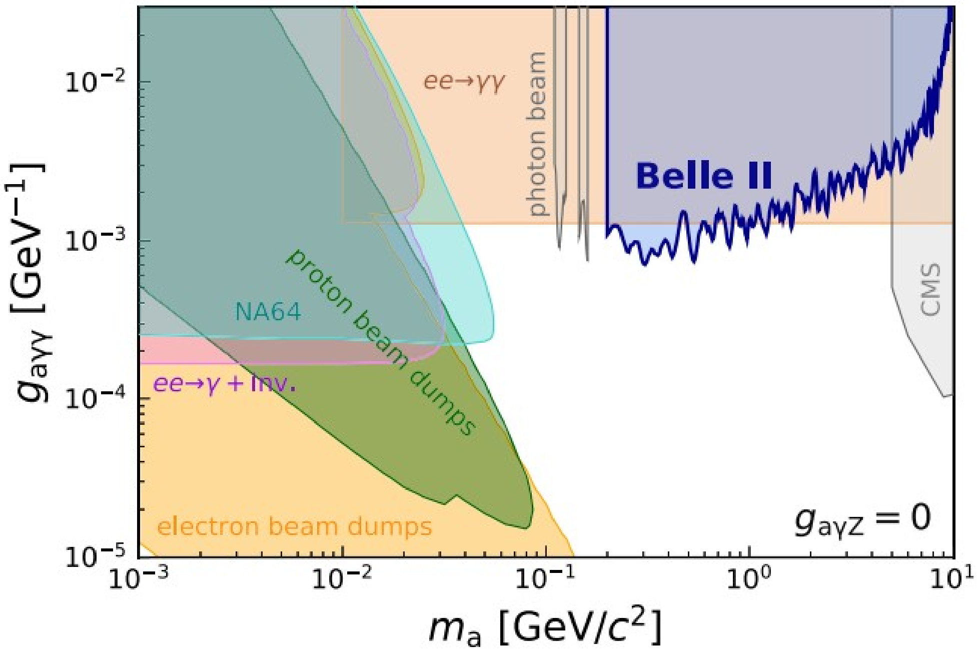
$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{QED}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$





PRL 125 (2020) 161806

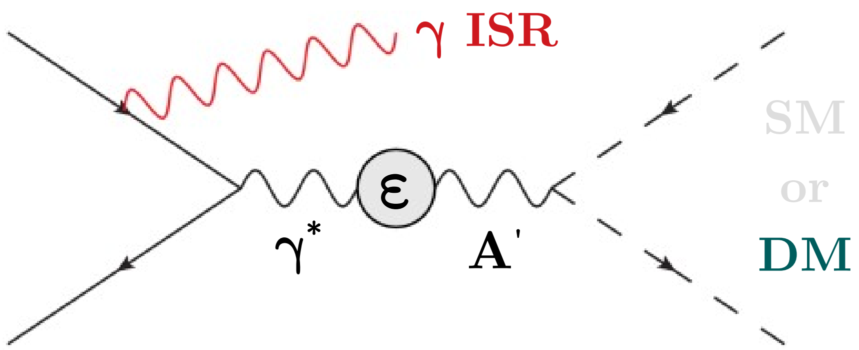
Dark Photon: invisible decay

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*

If $m_{DM} < ½\, m_{A'}$, the A' decays into an invisible final state.



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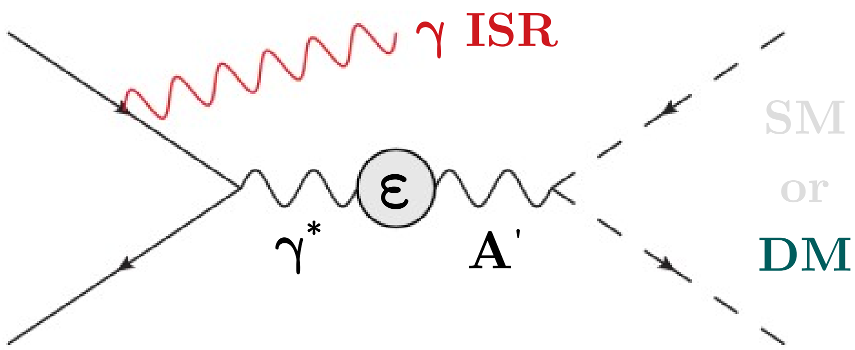
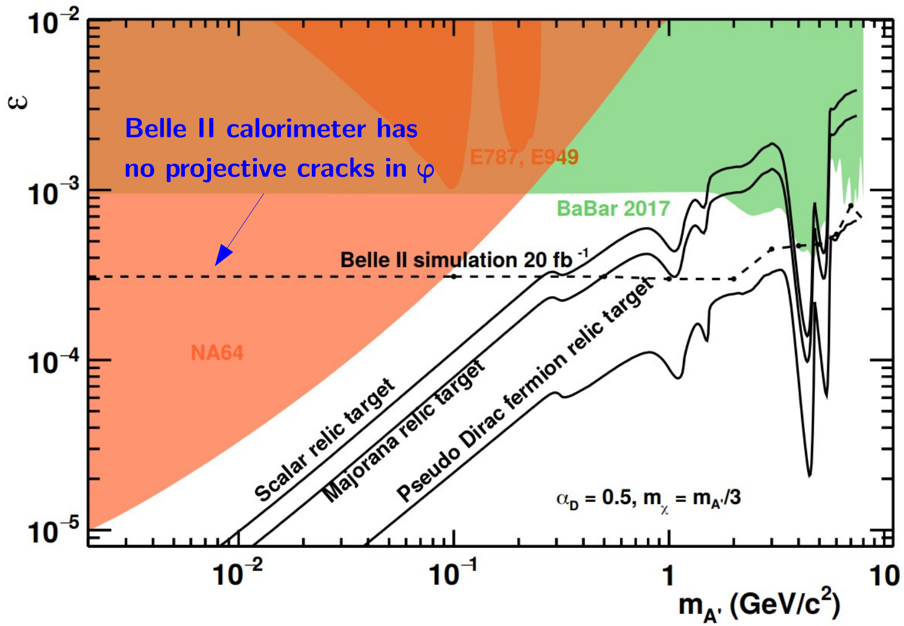


Signal signature:

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

Necessary a special **single photon trigger**

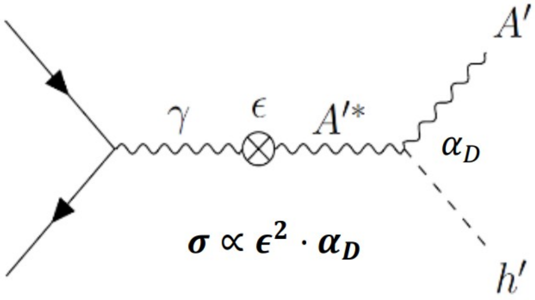
(not available in Belle, only ~10% of all data in BaBar)



Dark Higgsstrahlung

Dark Photon 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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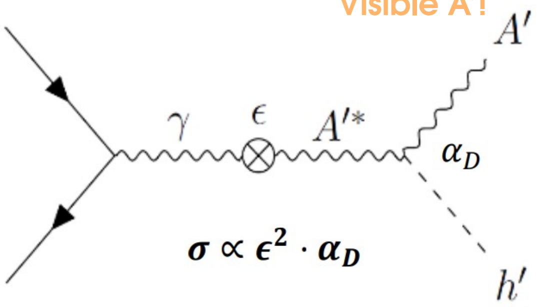
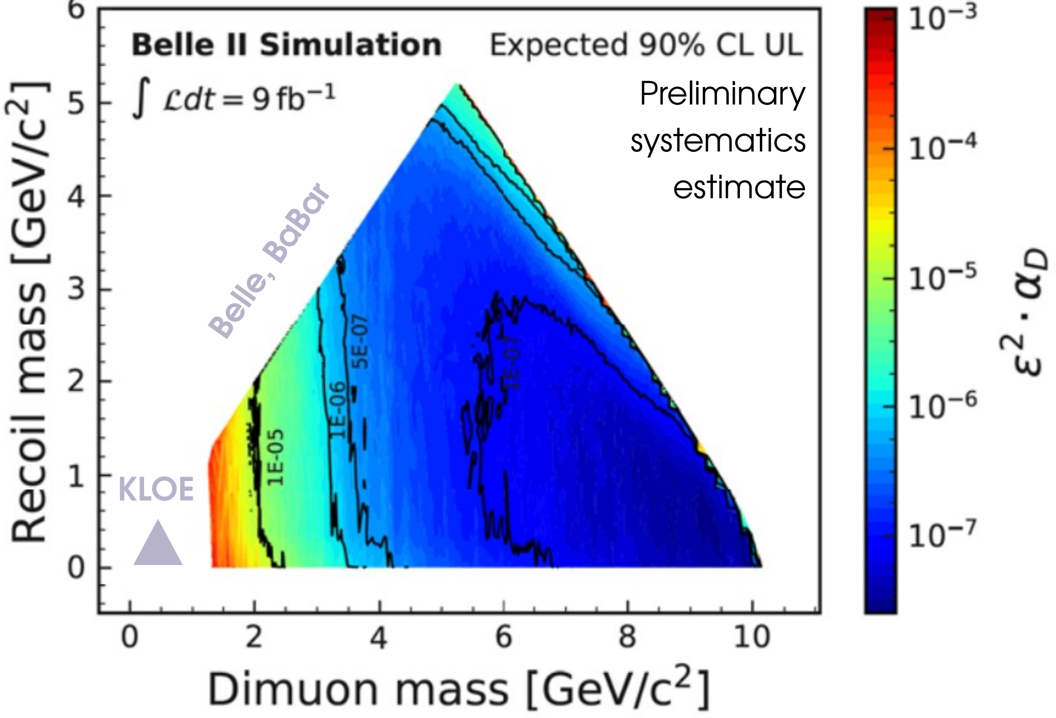
Visible A'!



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



At Belle II we are exploring the case with a long living h' (**mh' < mA'**), constrained only by **KLOE**:

Babusci et al. (2015), PLB 747 (2015) 265-372

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

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

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

Other ongoing Dark Sector searches @ Belle II

Dark Photon visible decays

Dark Scalar:

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

Dark Matter from B decays:

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

$$B^+ \to K^+ a(\to \gamma \gamma)$$

Inelastic Dark Matter (LLP)

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 MeV-GeV mass range in the coming years;
- ✓ Belle II collected up to now more than 200 fb^{-1} of collisions data;
- ✓ First results with early data (2018 pilot run: 0.5 fb^{-1}) 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:
  - A' $\rightarrow$ invisible search;
  - Dark Higgsstrahlung.

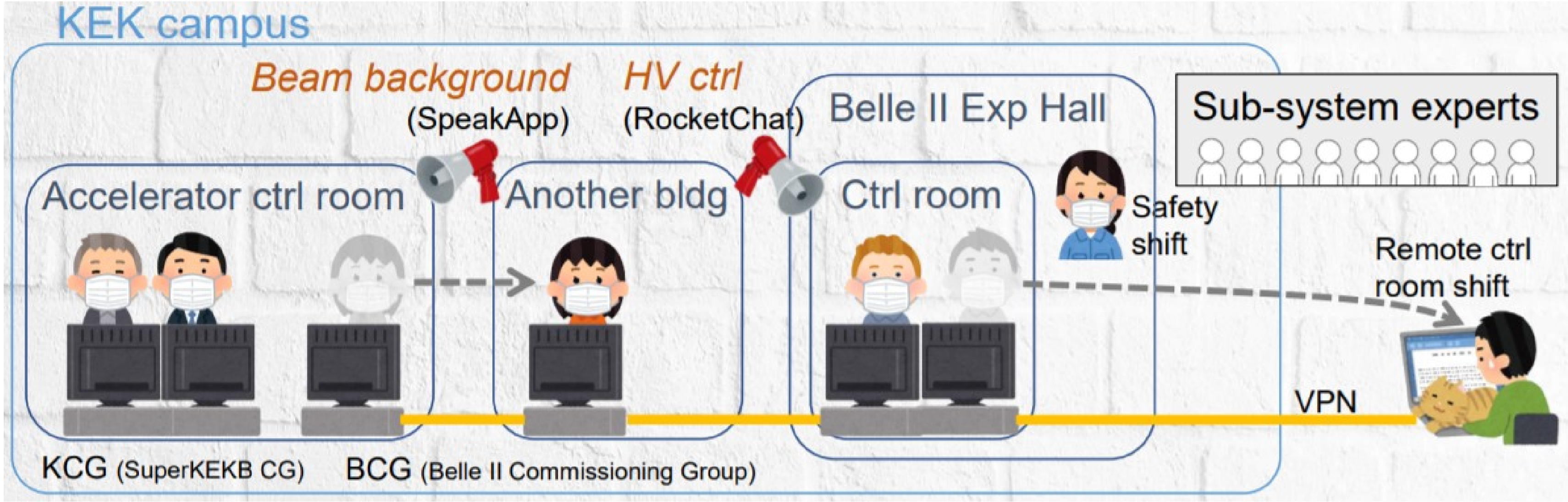
Thank you
for your
attention

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

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		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
$\frac{\epsilon_y}{\epsilon_x}$ (%)	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.)	$10° < \theta_e^* < 170°$, $E_e^* > 0.15\,\text{GeV}$	BABAYAGA.NLO
$e^+e^-(\gamma)$	74.4	$p_e > 0.5\,\text{GeV}/c$ and e in ECL	-
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta_\gamma^* < 170°$, $E_\gamma^* > 0.15\,\text{GeV}$	BABAYAGA.NLO
$\gamma\gamma(\gamma)$	3.30	$E_\gamma > 0.5\,\text{GeV}$ in ECL	-
$\mu^+\mu^-(\gamma)$	1.148	-	KKMC
$\mu^+\mu^-(\gamma)$	0.831	$p_\mu > 0.5\,\text{GeV}/c$ in CDC	-
$\mu^+\mu^-\gamma(\gamma)$	0.242	$p_\mu > 0.5\,\text{GeV}$ in CDC, $\geq 1\ \gamma\ (E_\gamma > 0.5\,\text{GeV})$ in ECL	-
$\tau^+\tau^-(\gamma)$	0.919	-	KKMC
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-	KKMC
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\text{GeV}/c^2$	AAFH
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5\,\text{GeV}/c^2$	AAFH

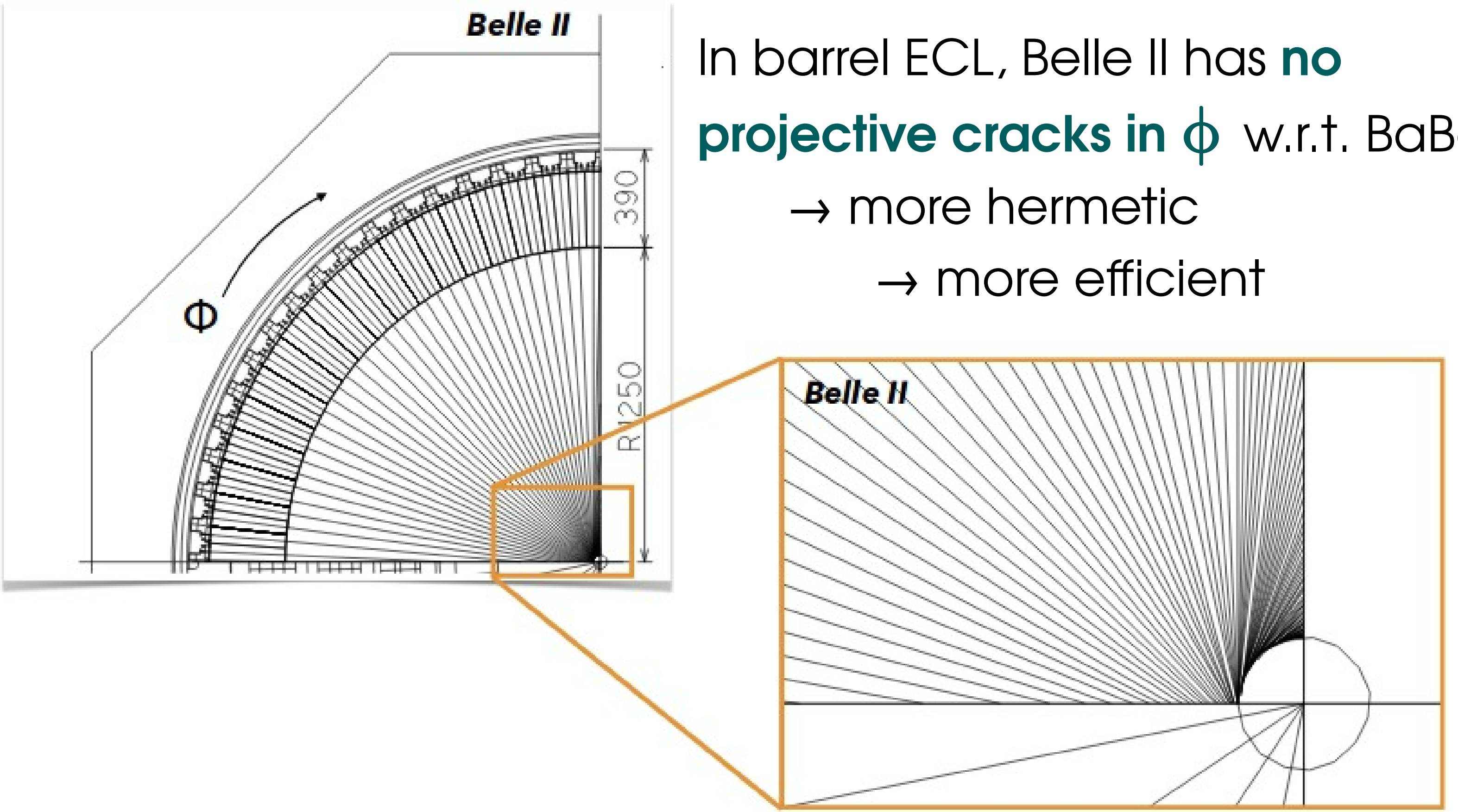
E. Kou, P. Urquijo et al.,
arXiv:1808.10567

Electromagnetic Calorimeter (ECL)

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

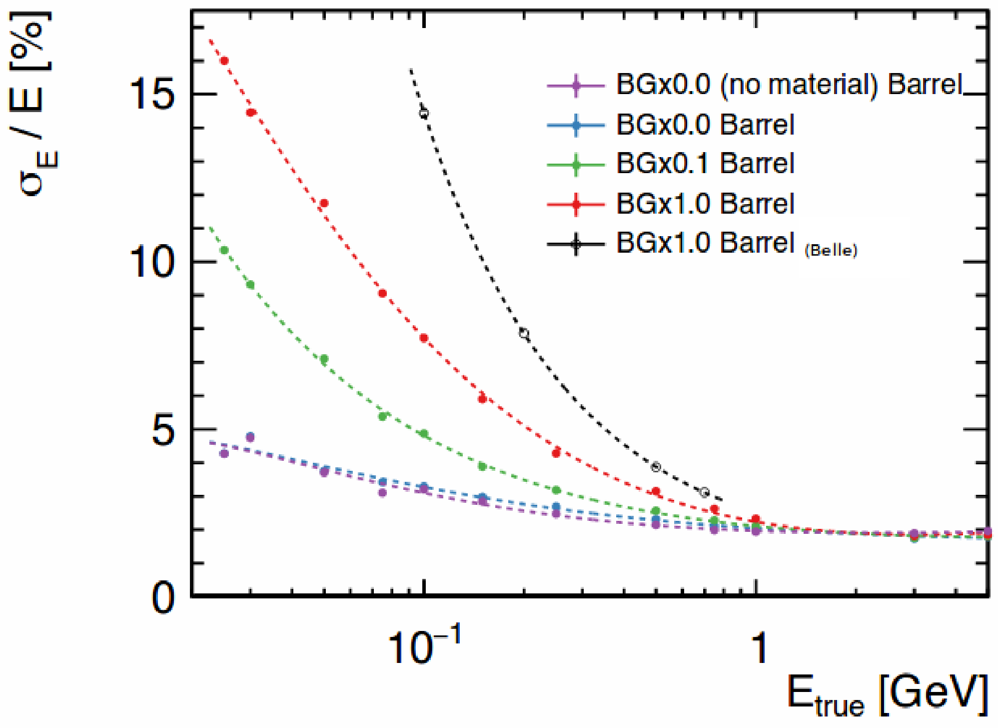
→ more hermetic

→ more efficient

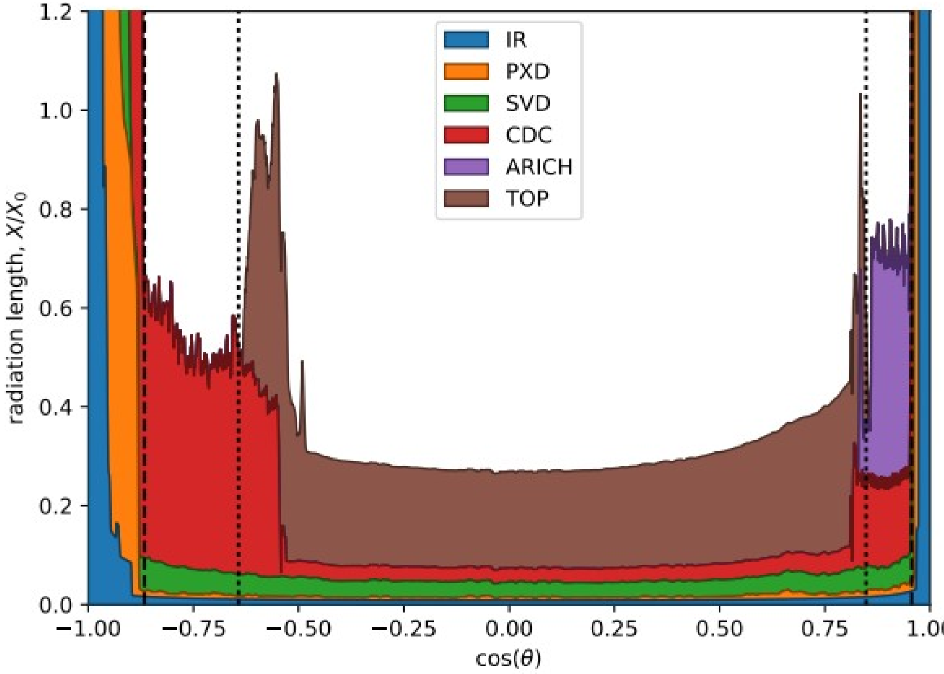


Electromagnetic Calorimeter (ECL)

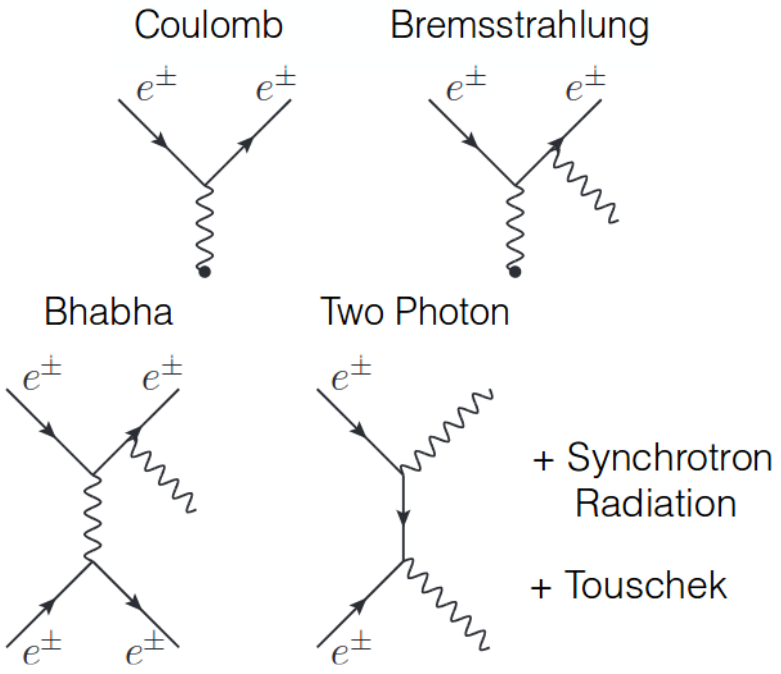
Energy resolution in Belle II barrel:

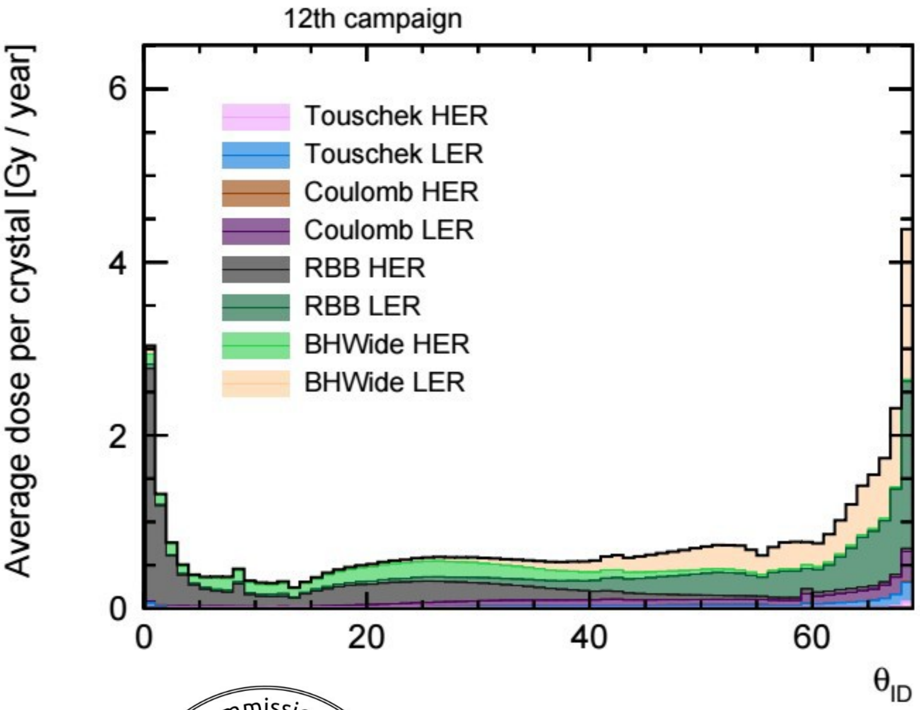


Material budget in front of ECL:



Beam background





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!

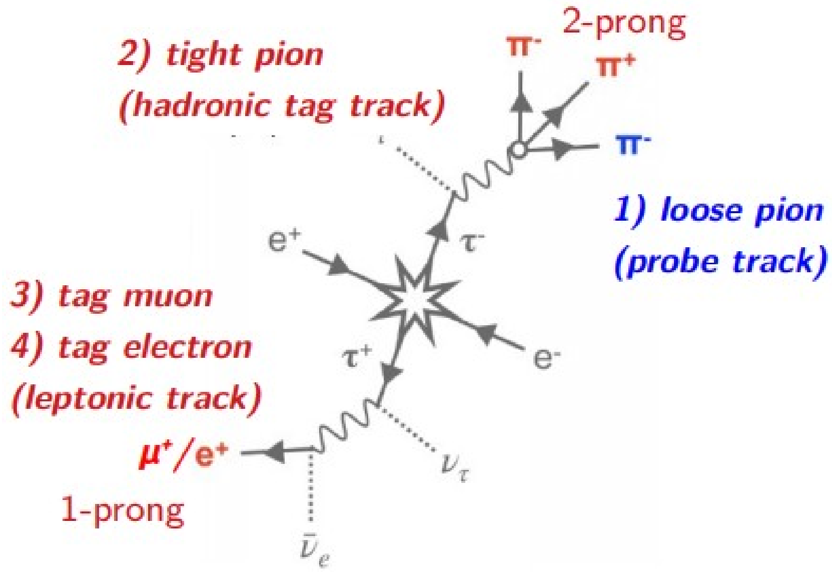
See P. Lewis et al.: 10.1016/j.nima.2018.05.071

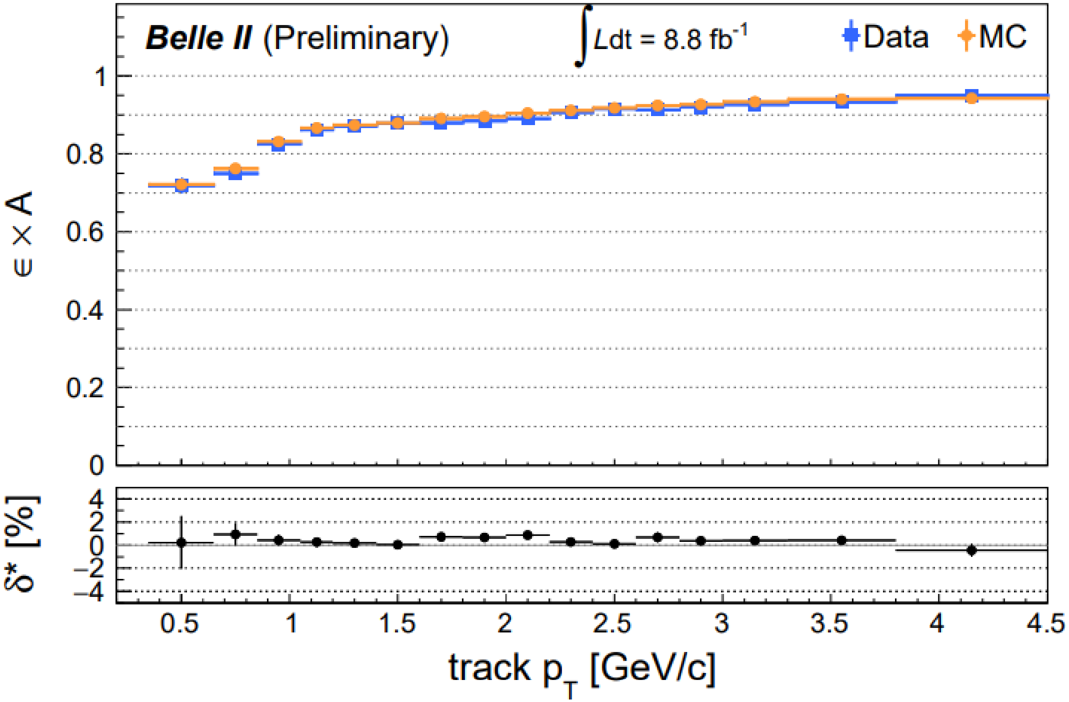
Tracking performance

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

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

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





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

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

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

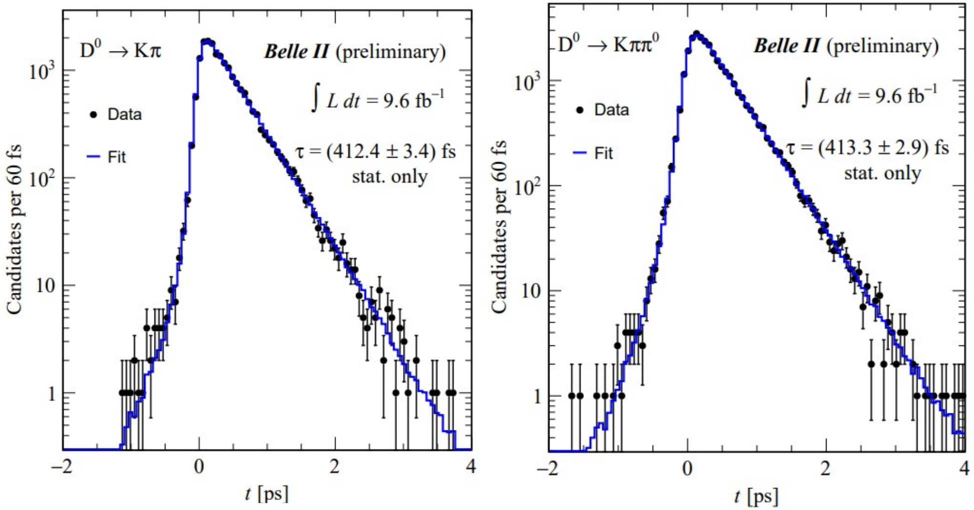
Vertexing performance

D^0 lifetime:

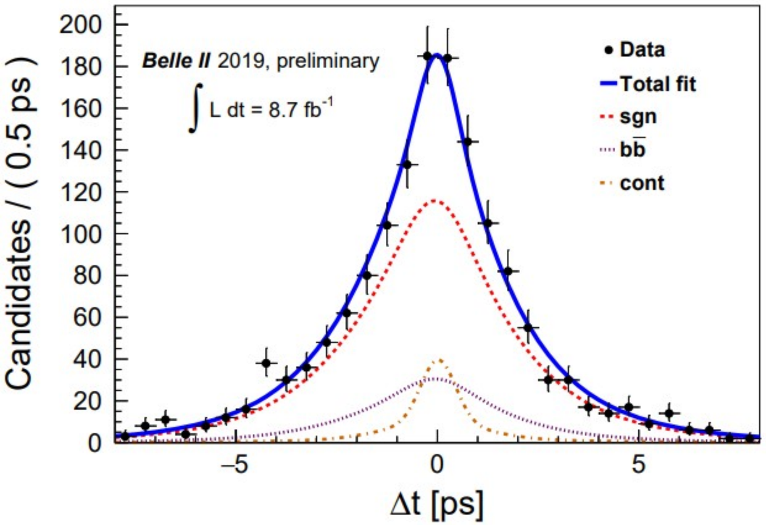
- measurement with 3 channels: $K^-\pi^+$, $K^-\pi^+$, $K^-\pi^+\pi^-\pi^-$
- estimated vertex resolution: $\sim$ **40 μm**;

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

(world average: (410.1 ± 1.5) fs



arXiv:2005.07507



B^0 lifetime:

- smaller boost $\beta\gamma$: 0.42 (Belle) $\rightarrow$ 0.28 (Belle II);
- average distance between B-mesons: 200 μm $\rightarrow$ 130 μm;

- hadronic channels: $B^0 \rightarrow D^{(*)-}\pi^+/\rho^+$;
- estimated resolutions: $\Delta t \sim 1$ ps $\rightarrow$ **$\Delta z \sim$ 80 μm**

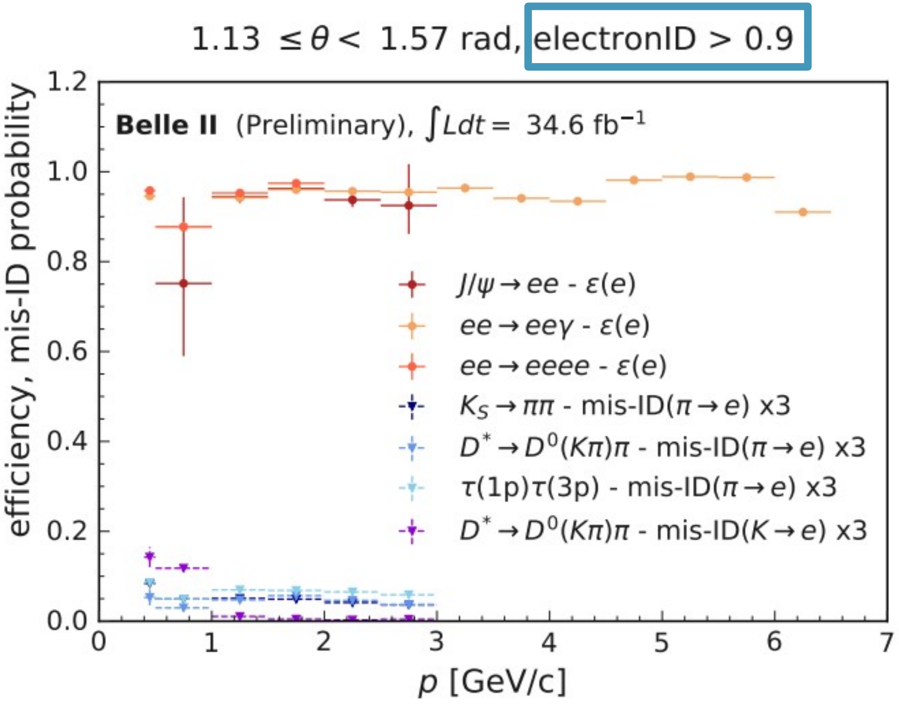
$\rightarrow \tau(B^0) = (1.48 \pm 0.28_{stat} \pm 0.06_{syst})$ ps

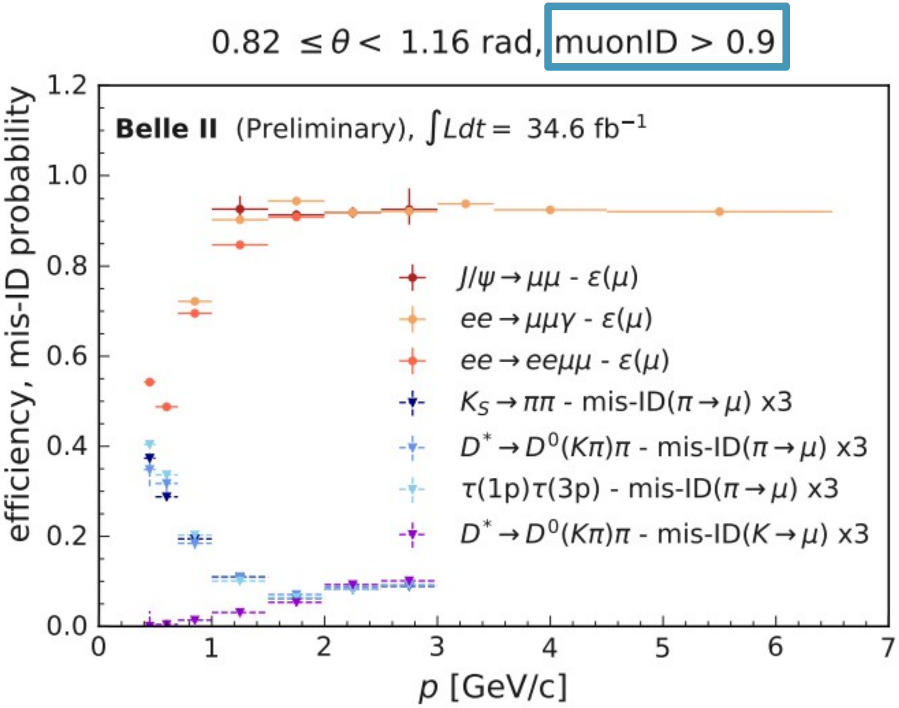
(world average: (1.519 ± 0.004) ps

Particle identification: leptons

Several fully reconstructed channels are used:

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



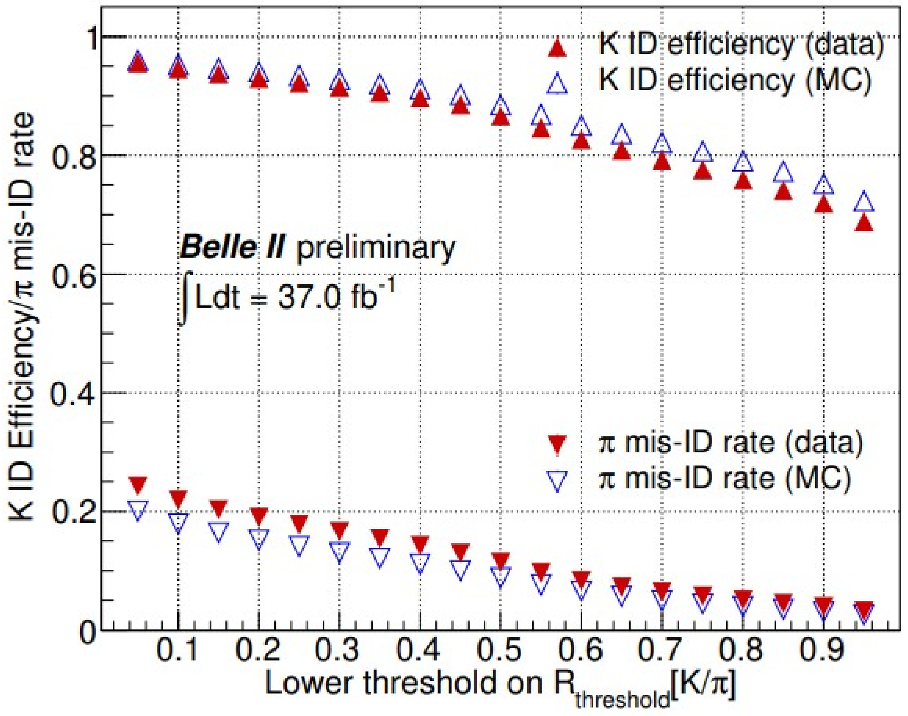


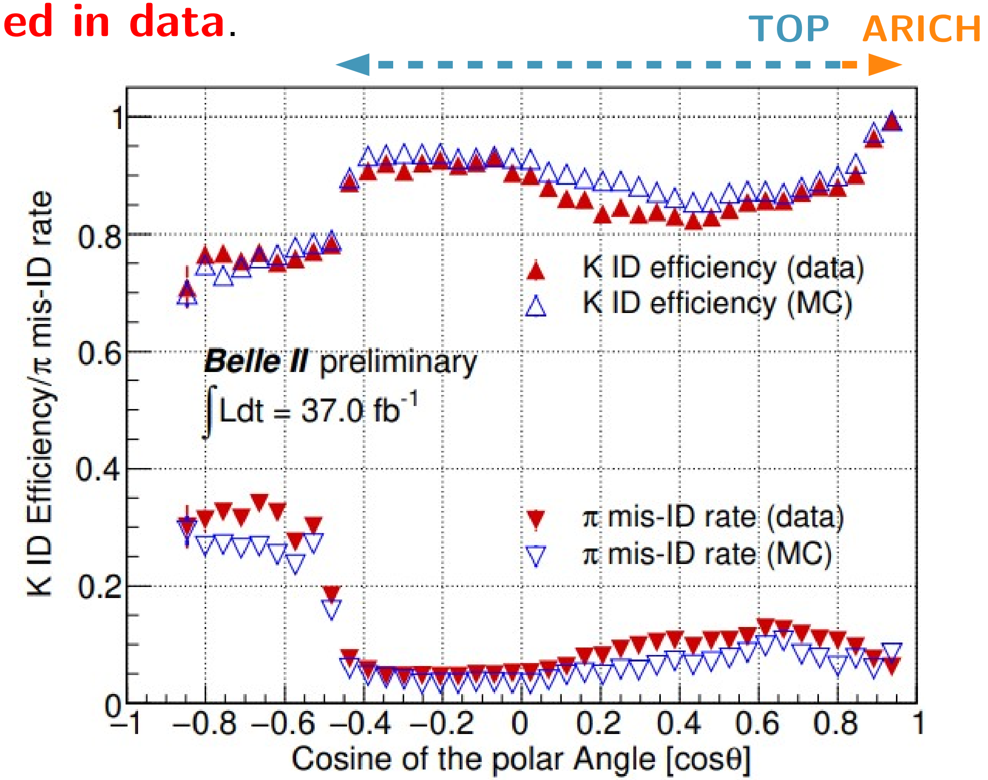
$$\text{leptonID} = \mathcal{L}_{\text{lepton}} \,/\, (\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p)$$

Particle identification: hadrons

Fully reconstructed channels are used:

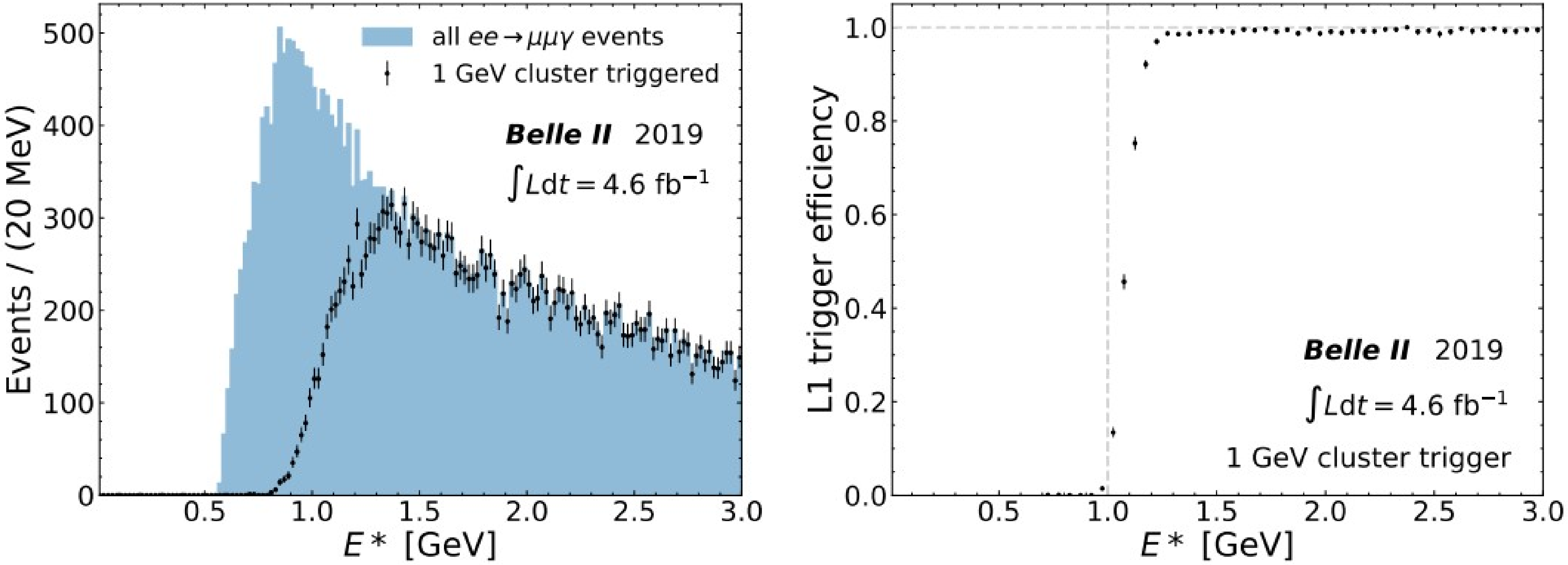
- $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$;
- slow π tags the D^0 flavour $\to$ **K** and π **identified in data**.





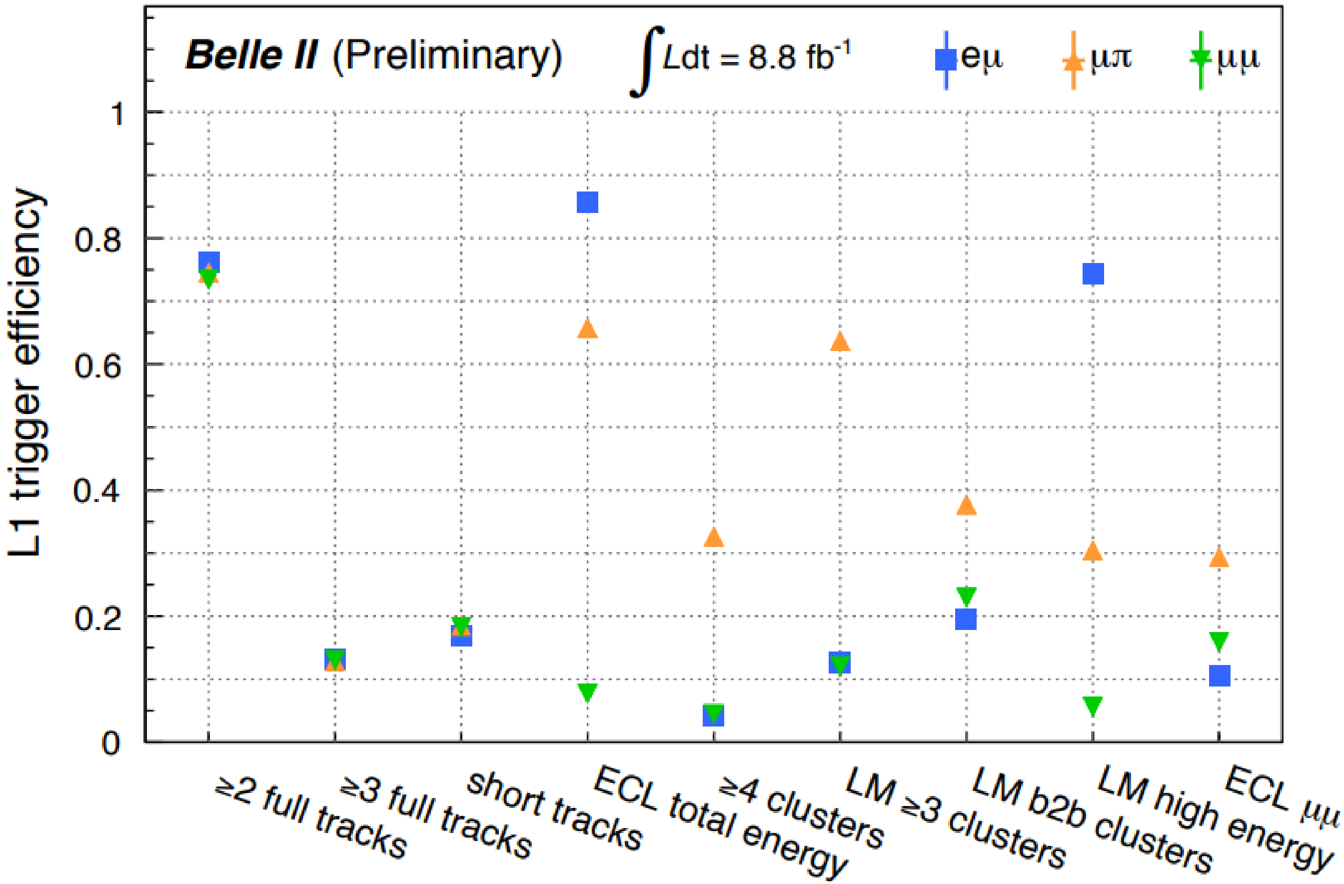
$$K/\pi\text{-ID} = \mathcal{L}_{K/\pi} / (\mathcal{L}_\pi + \mathcal{L}_K)$$

Single Photon Trigger



L1 (hardware) trigger

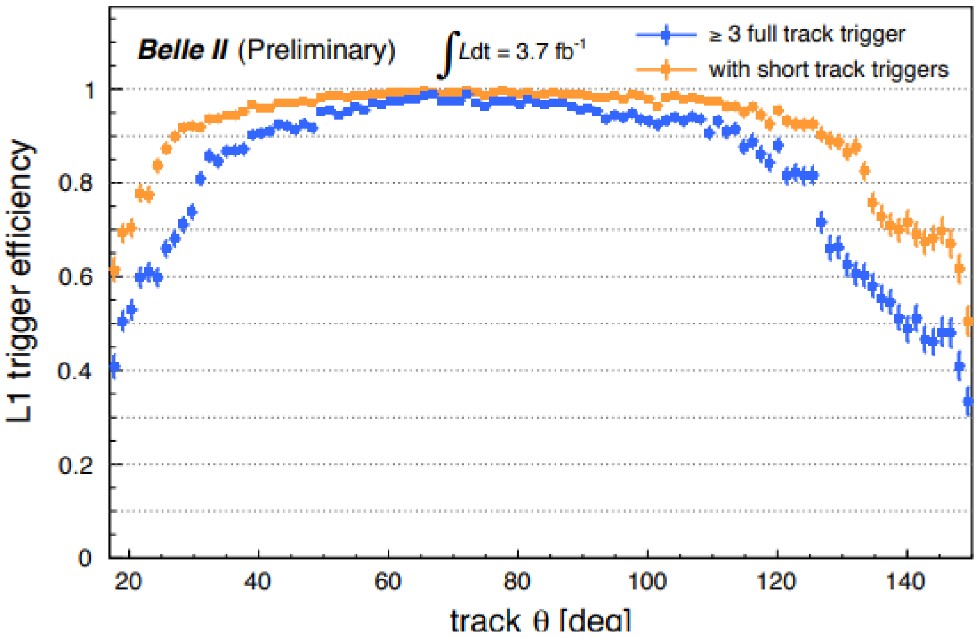
Low Multiplicity Triggers

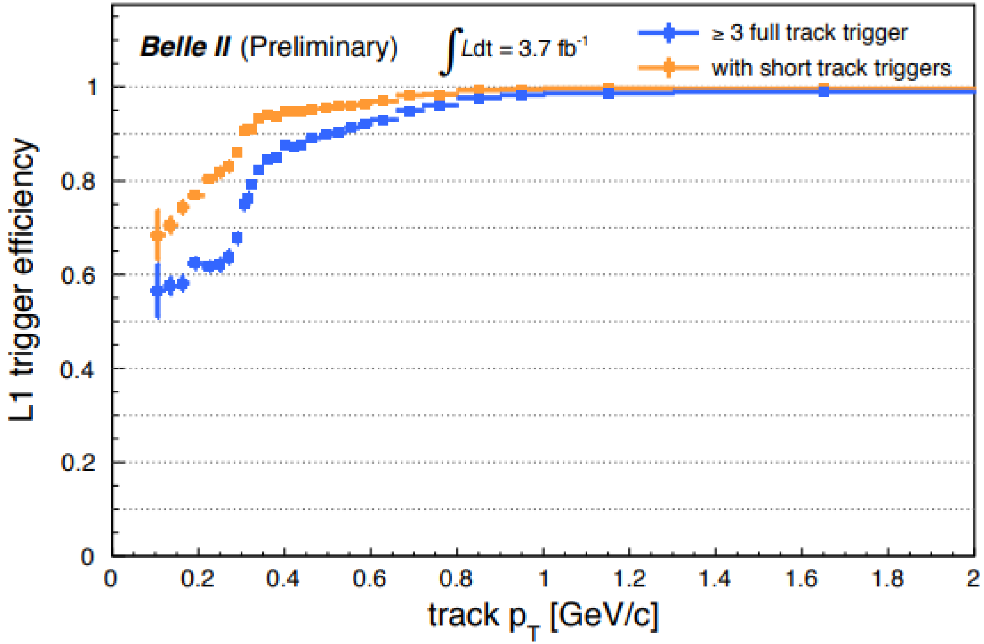


L1 (hardware) trigger

Measurement done with τ-pair events, 1x1 topology

Low Multiplicity Triggers

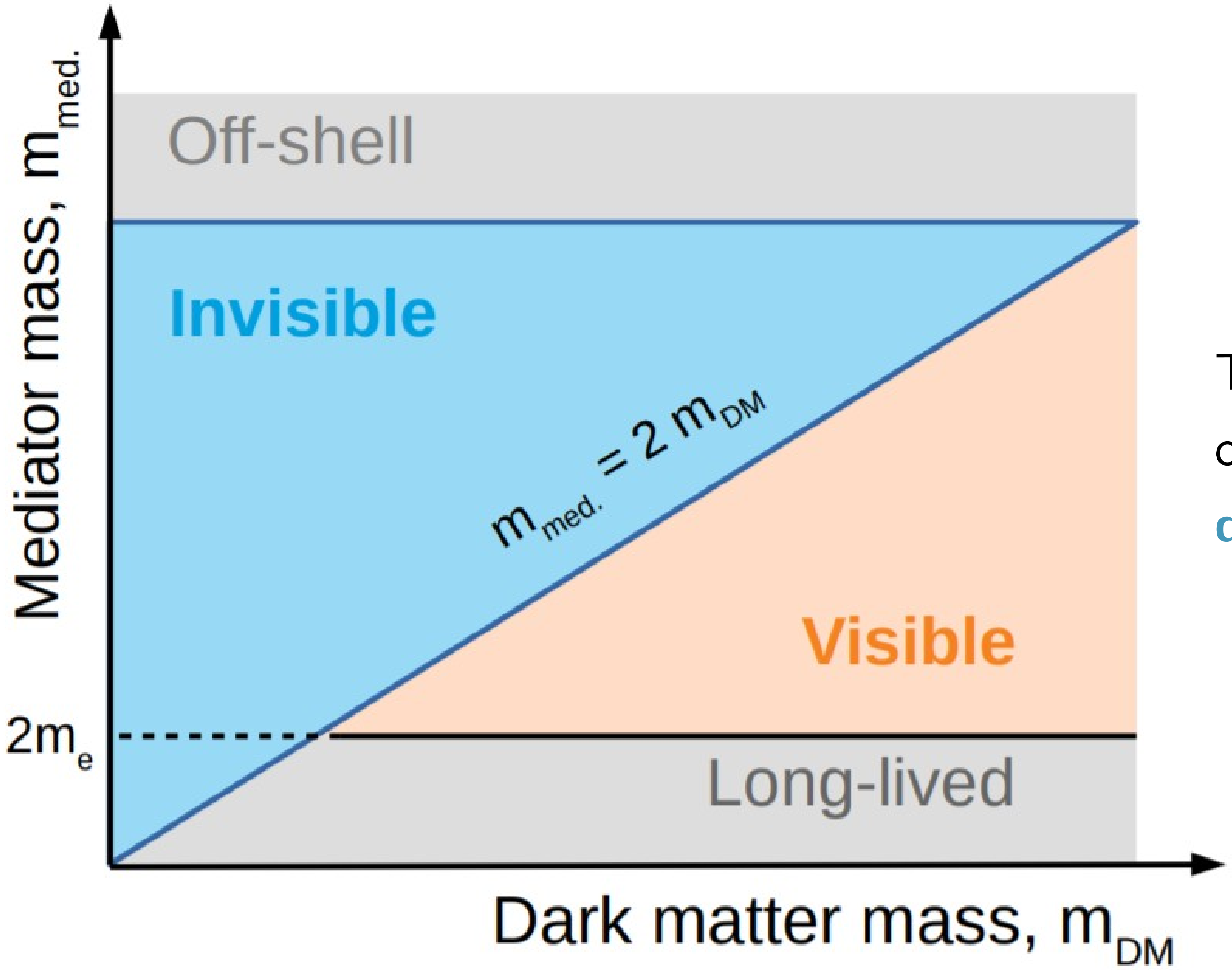




Measurement done with τ-pair events, 1x1 topology

L1 (hardware) trigger

A rule of thumb...



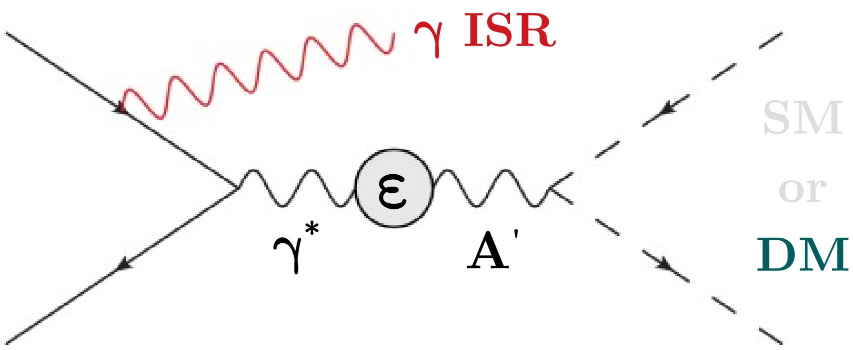
The masses of the mediator and of the DM candidates lead to **different type of searches**.

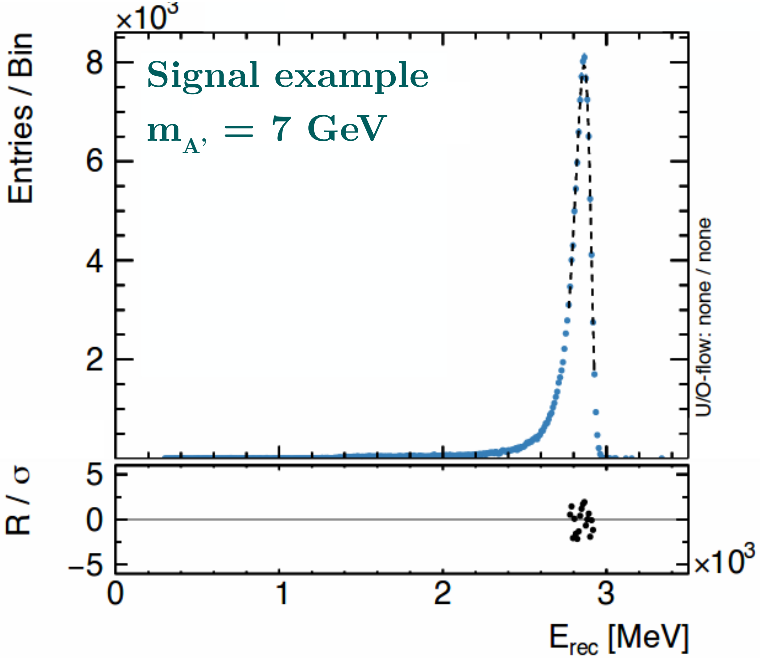
Dark Photon: invisible decay (signal)

Signal signature:

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

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





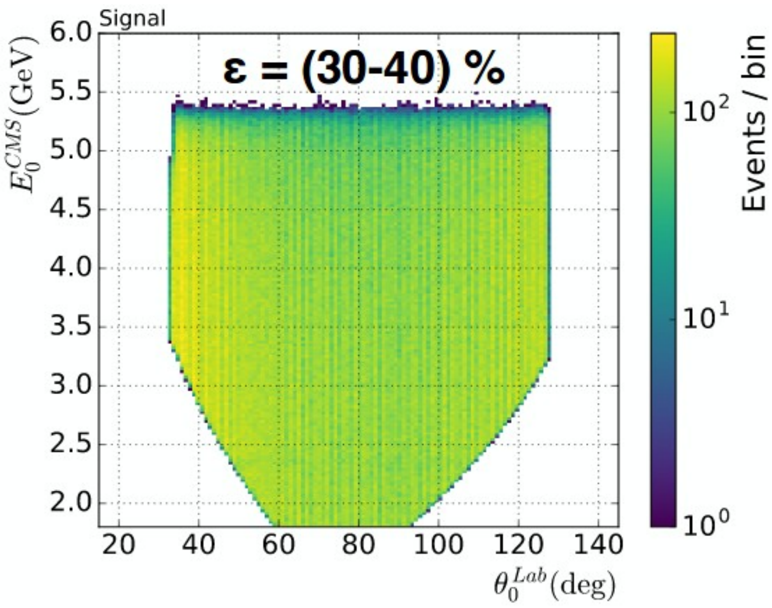
Needed a special **single photon trigger**

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

Dark Photon: invisible decay (signal)

Discriminant variables:

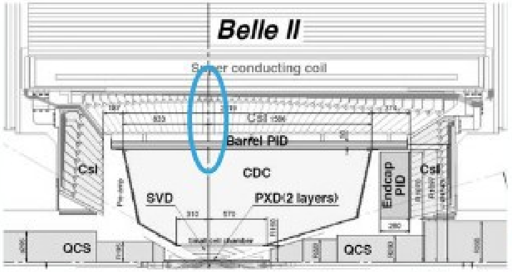
E_{CMS} vs. polar angle of "single photon"



Signal signature:

peak in E_{CMS} (horizontal band)

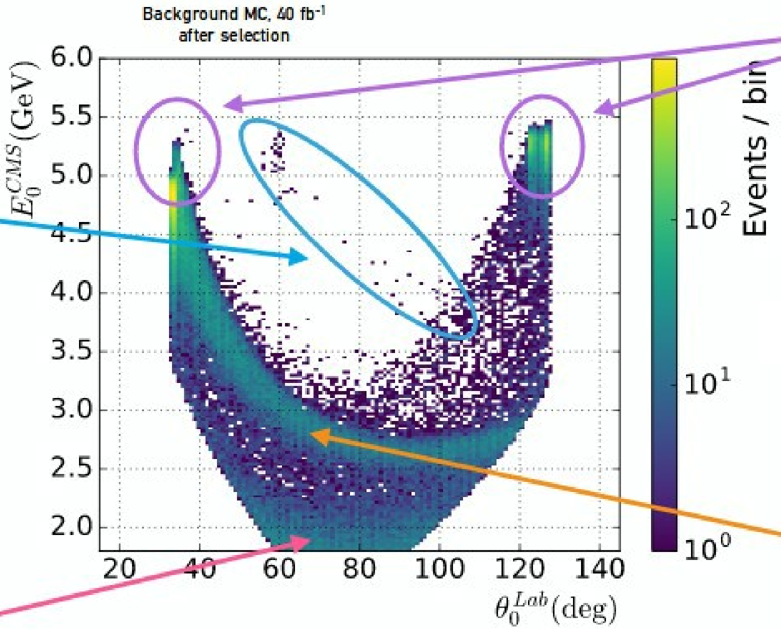
Dark Photon: invisible decay (background)



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

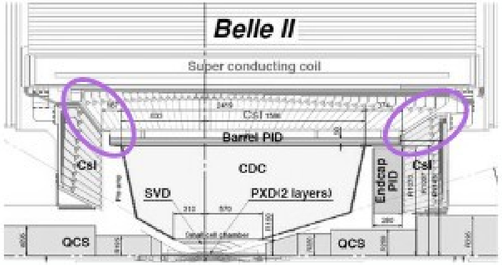
Discriminant variables:

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

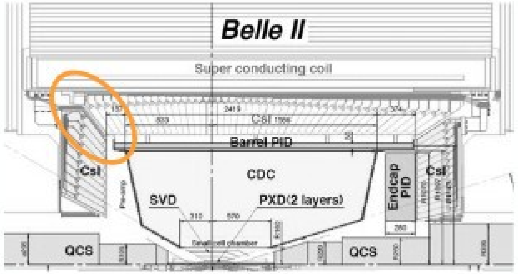


Signal signature:

peak in E_{CMS} (horizontal band)



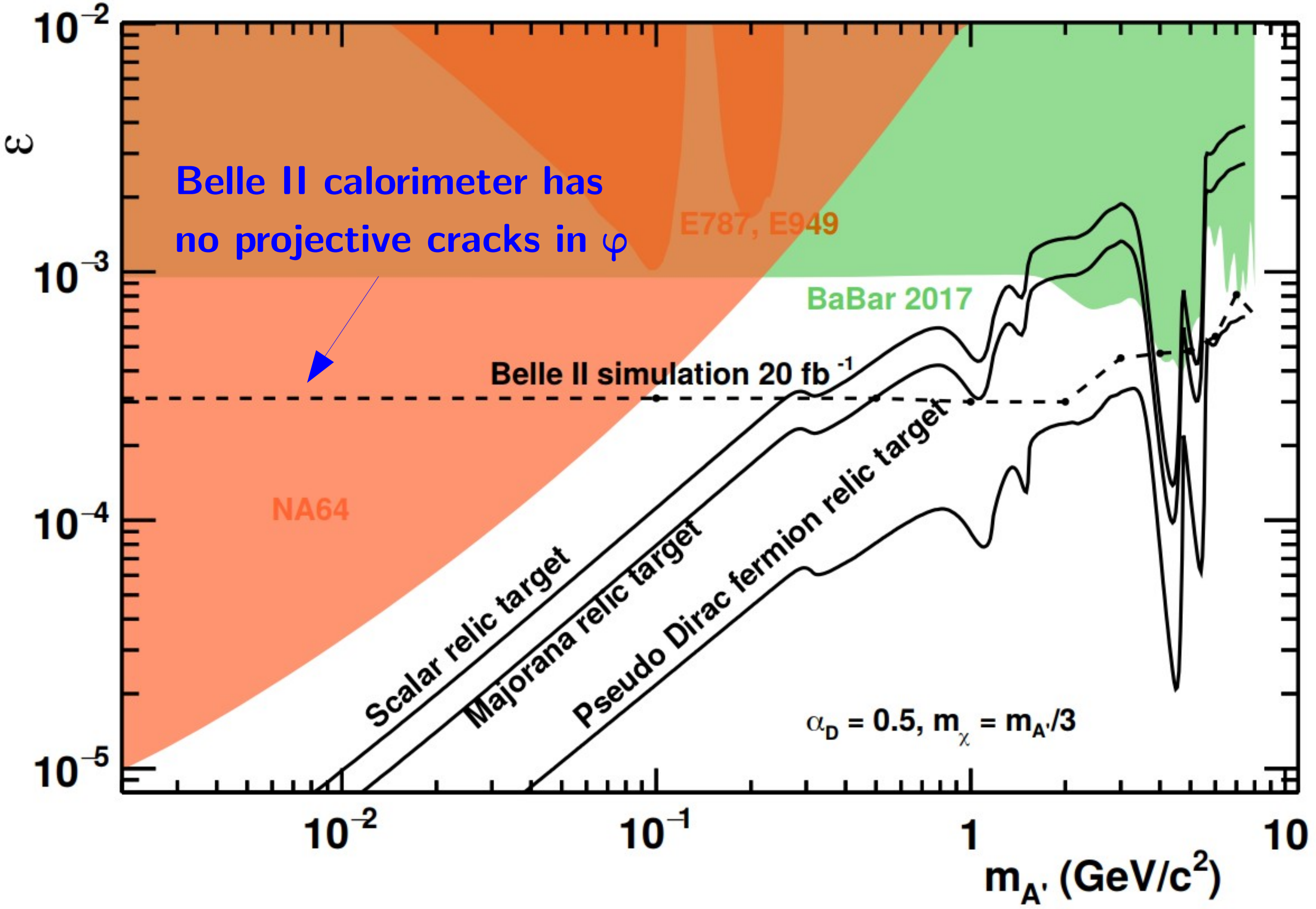
ee→2γ
1γ in ECL BWD or FWD gap

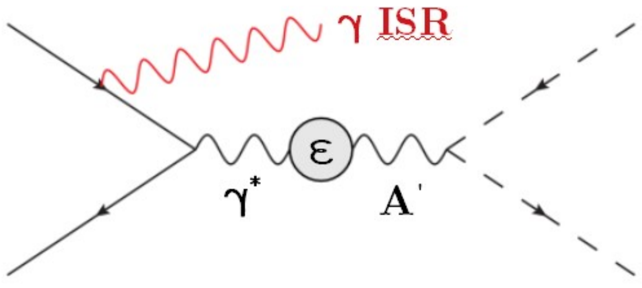


ee→3γ
1γ in ECL BWD gap
1γ out of ECL acceptance

ee→eeγ
both electrons
out of tracking acceptance

Dark Photon: invisible decay

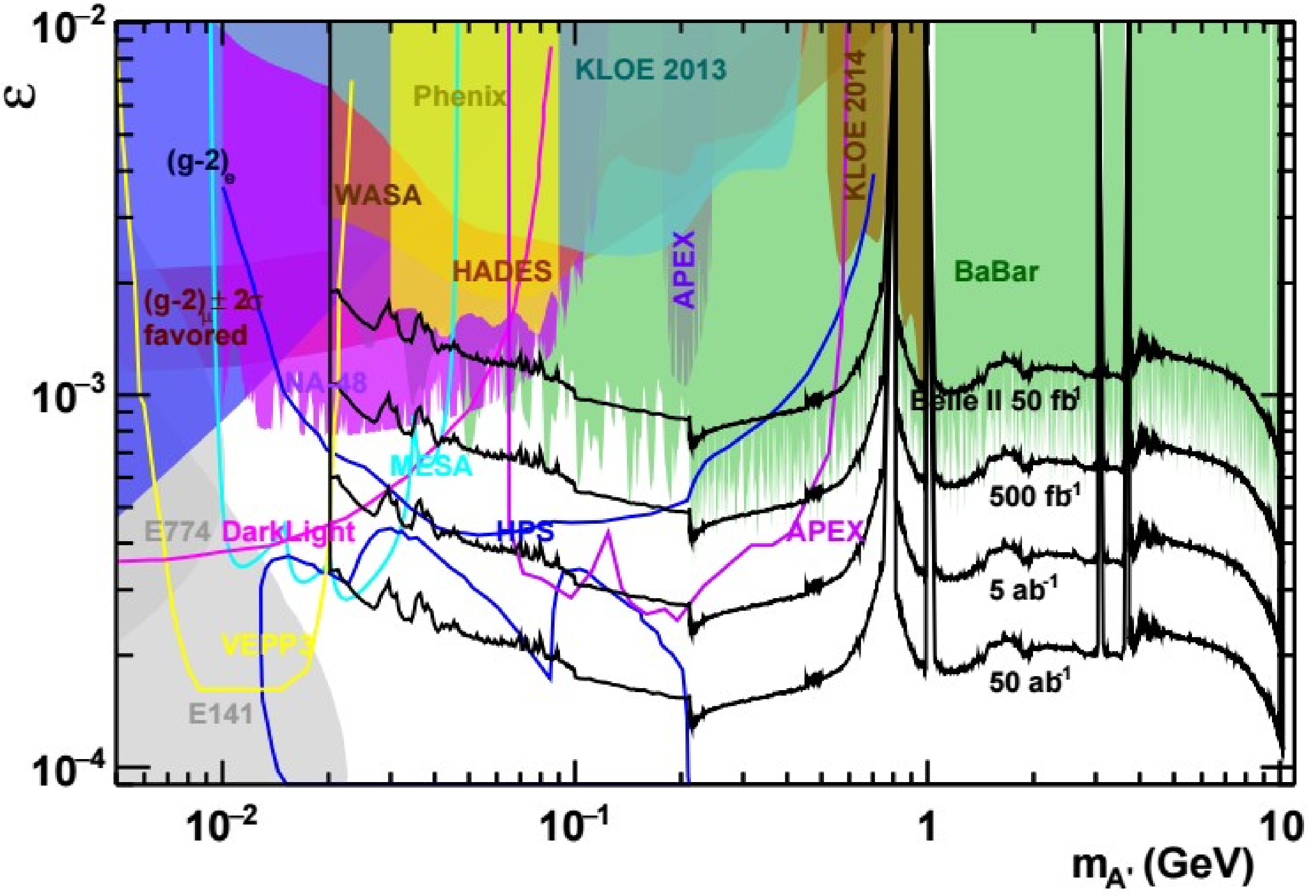




Single photon search: needed a **special trigger logic**:

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

Dark Photon: leptonic decay



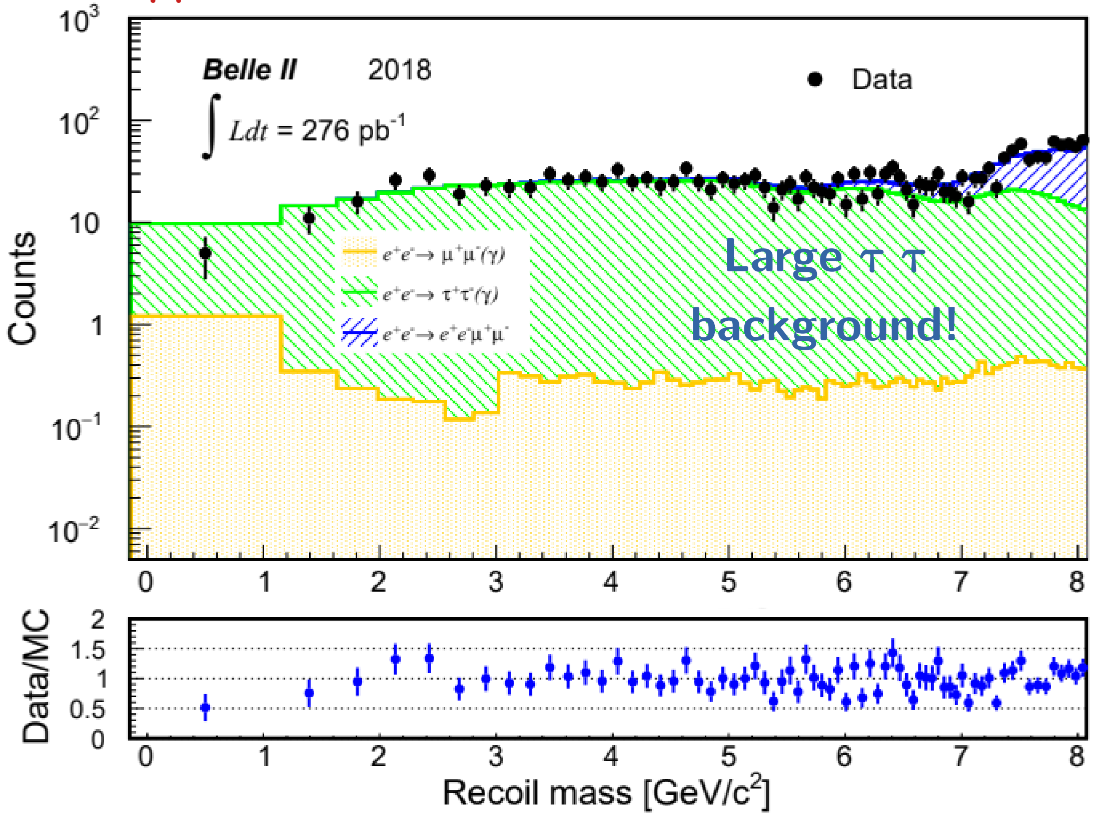
Look for a bump in the e^+e^- or $\mu^+\mu^-$ invariant mass over a (large) QED background

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.

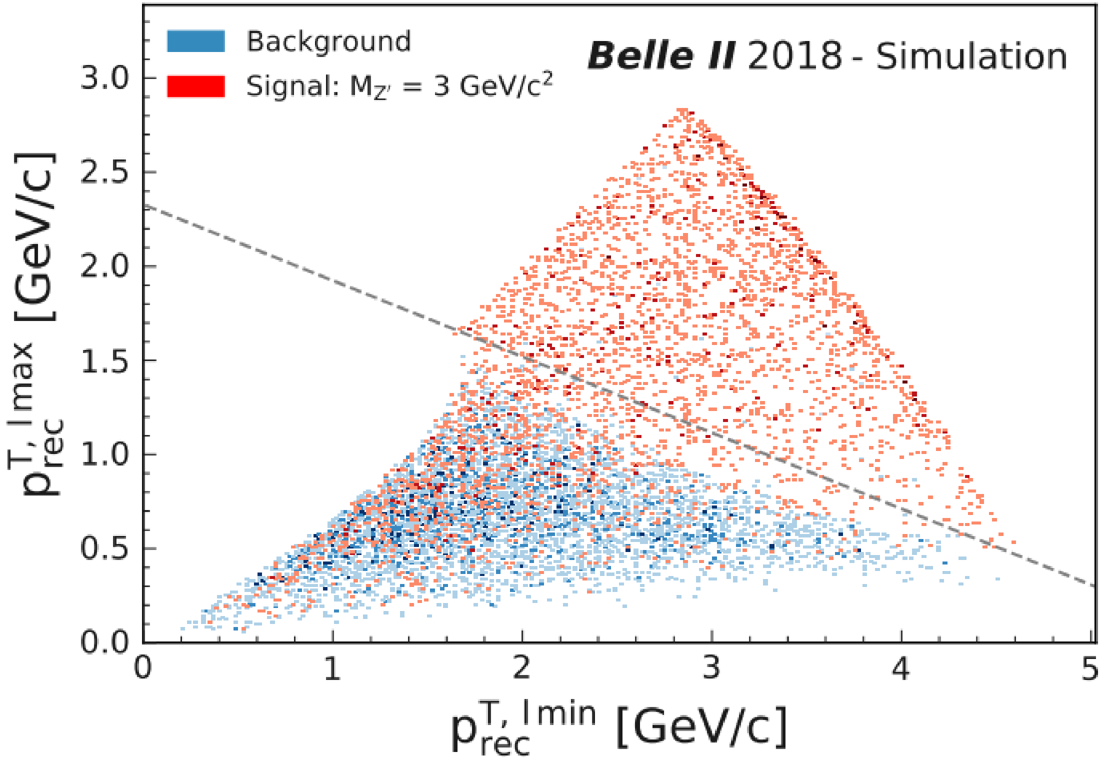
NB: all the corrections are evaluated on independent control samples!

PRL 124 (2020) 141801

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.

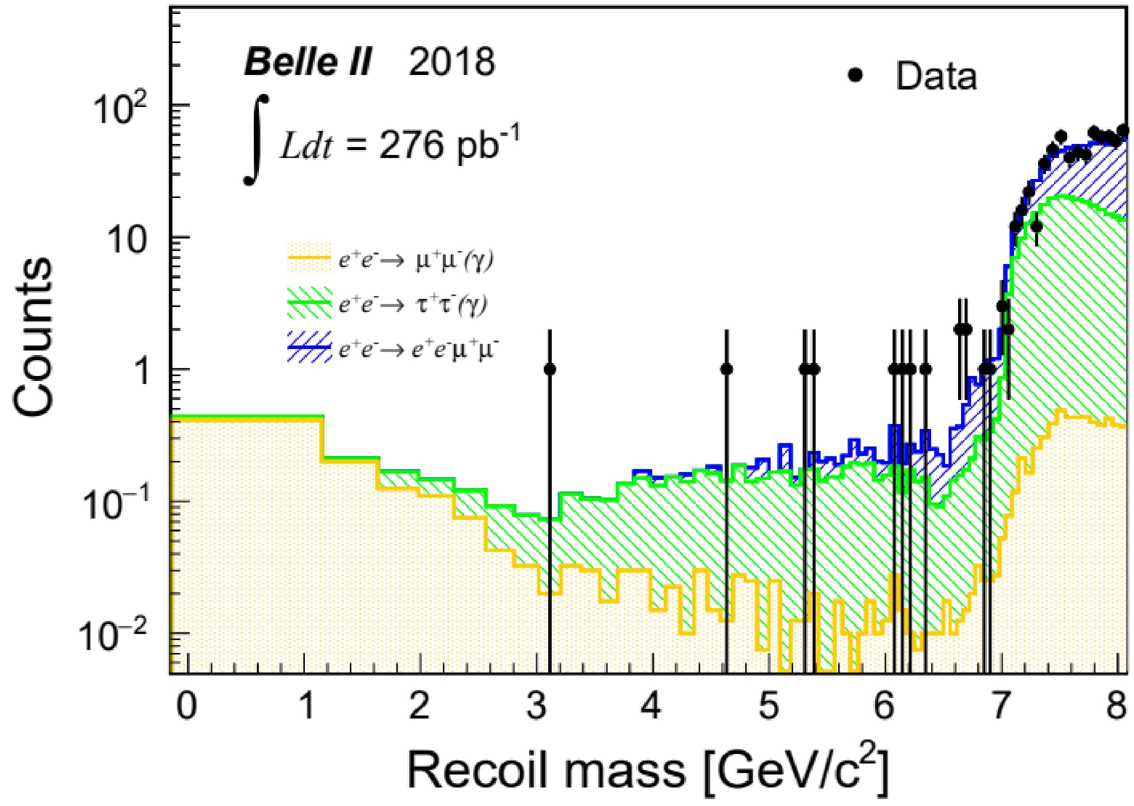


We optimized the selection in each recoil mass bin by choosing the best cuts that maximizes a given figure of merit (**hand-made multivariate approach**).

PRL 124 (2020) 141801

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... :(

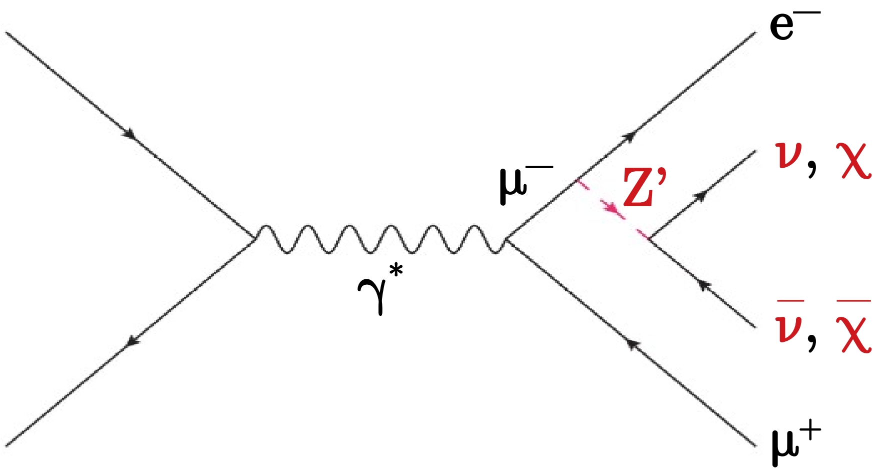
PRL 124 (2020) 141801

And why not considering a LFV Z'?

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

We considered only the invisible decay.

I. Galon et al. (2016), *arXiv:1610.08060*

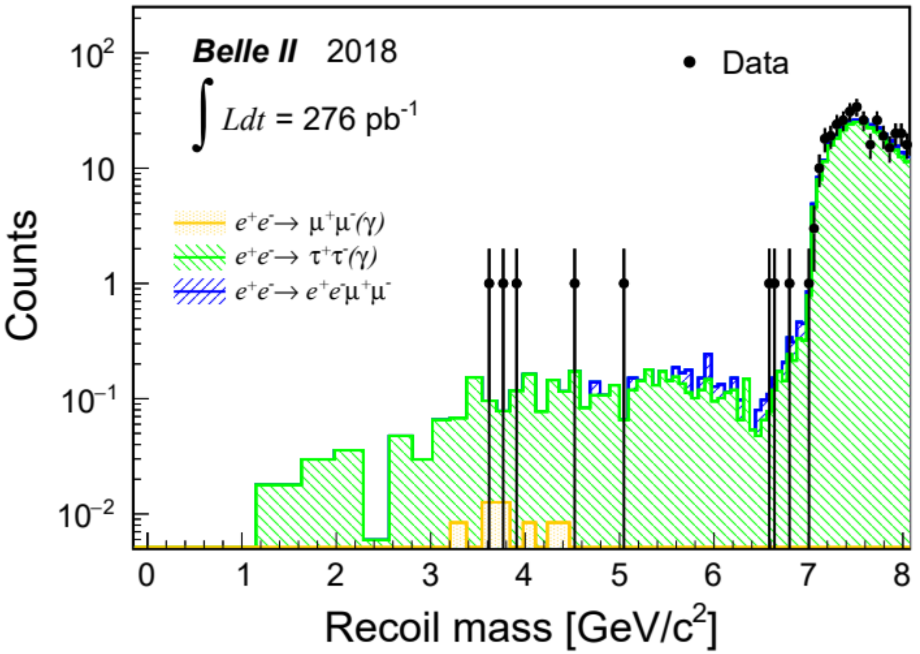


Unfortunately, the model we were using showed some issues (too large width for the Z', etc.).

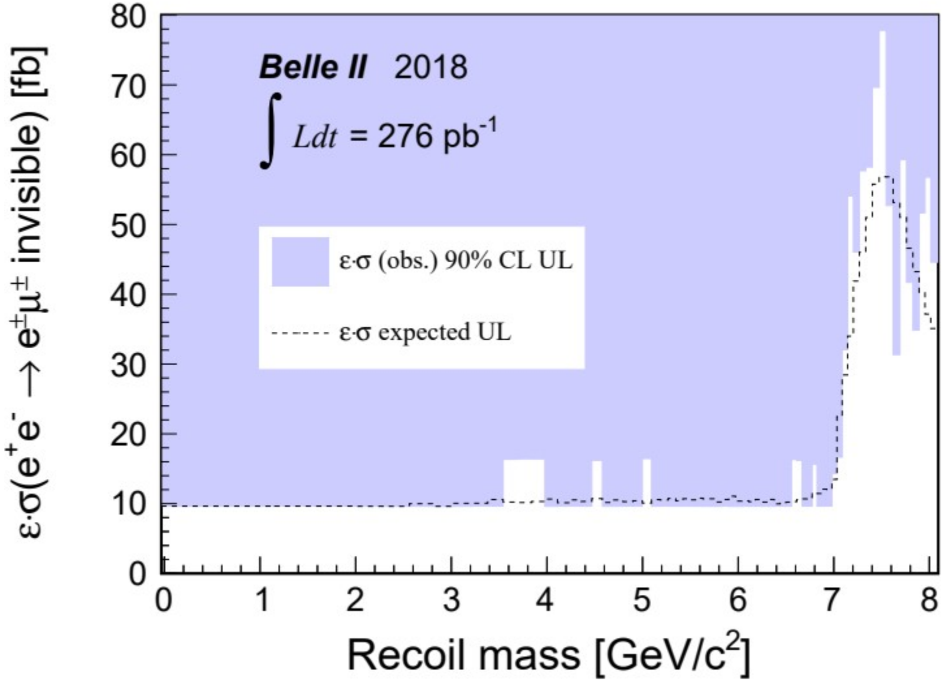
We decided to drop the signal model
and we opted for a model-independent search!

LFV Z'

eμ final state

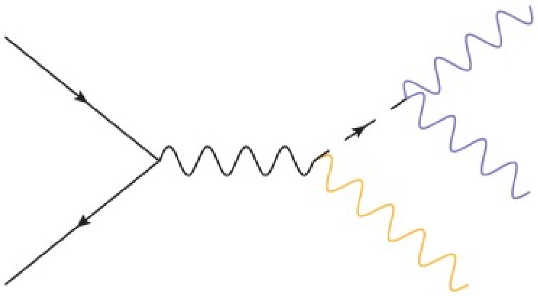


We can set limits on a coupling constant if a theoretical model is provided!



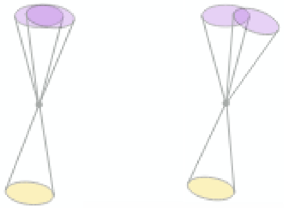
PRL 124 (2020) 141801

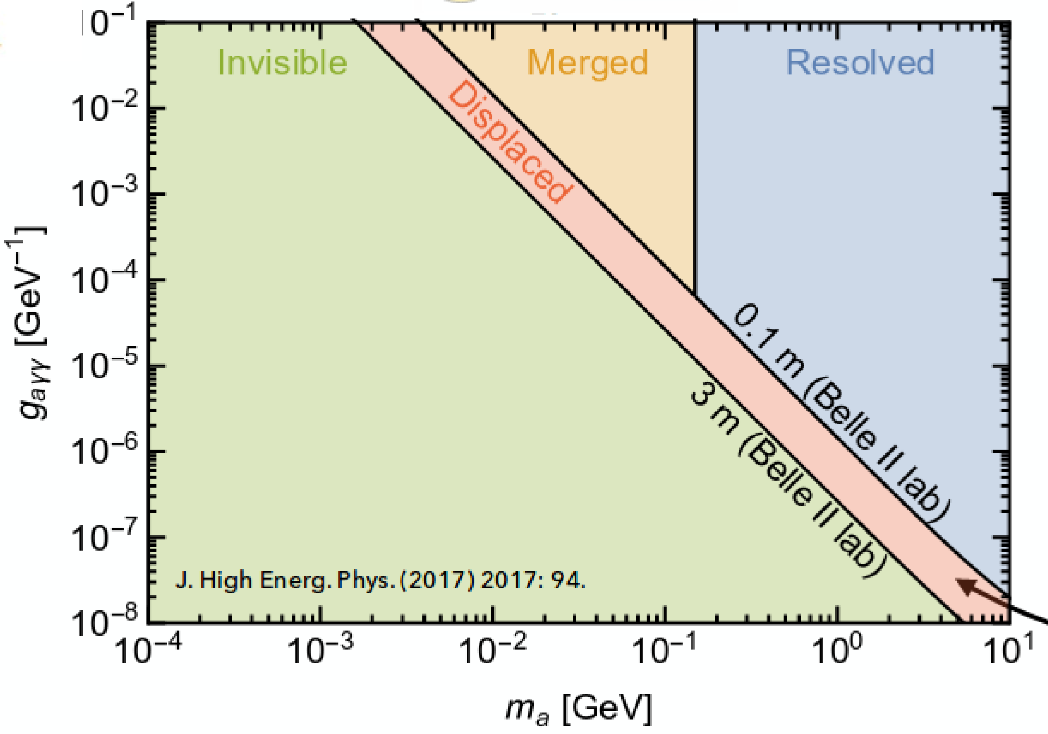
Axion-Like Particles (signal)



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

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



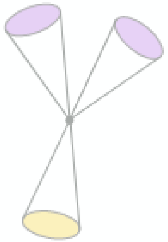


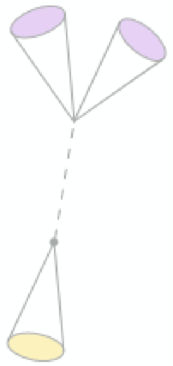
For **resolved** case:

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

Peak in $\gamma\gamma$ mass spectrum

Three **resolved**, high energetic photons.





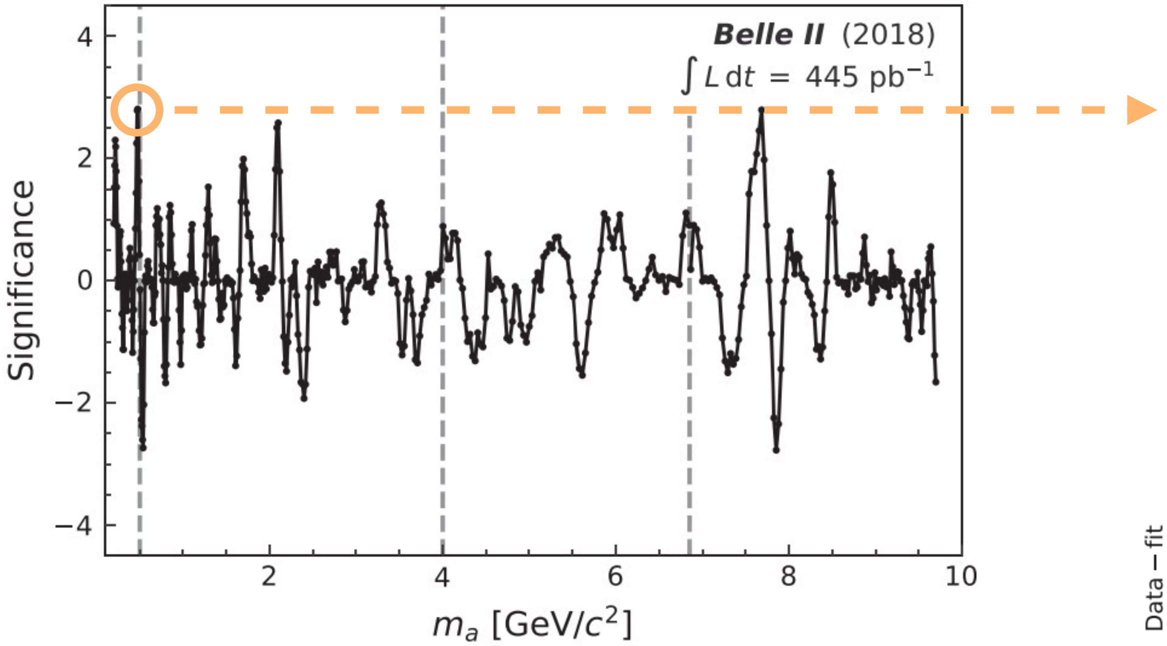
ALP decays outside of the detector or decays into **invisible** particles: Single photon final state.

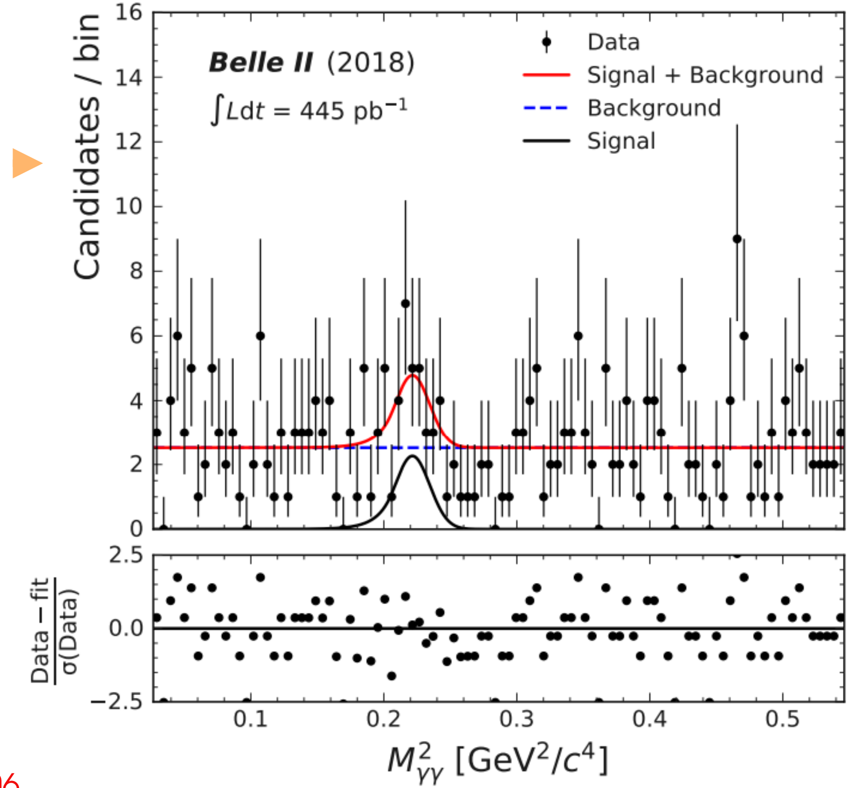
The searches for invisible and visible ALP decays veto this region.

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

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 σ**).





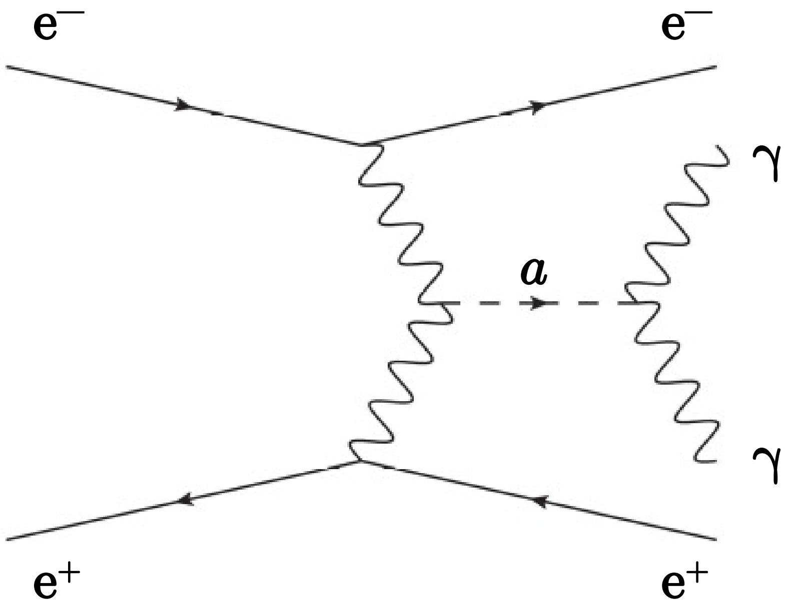
PRL 125 (2020) 161806

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

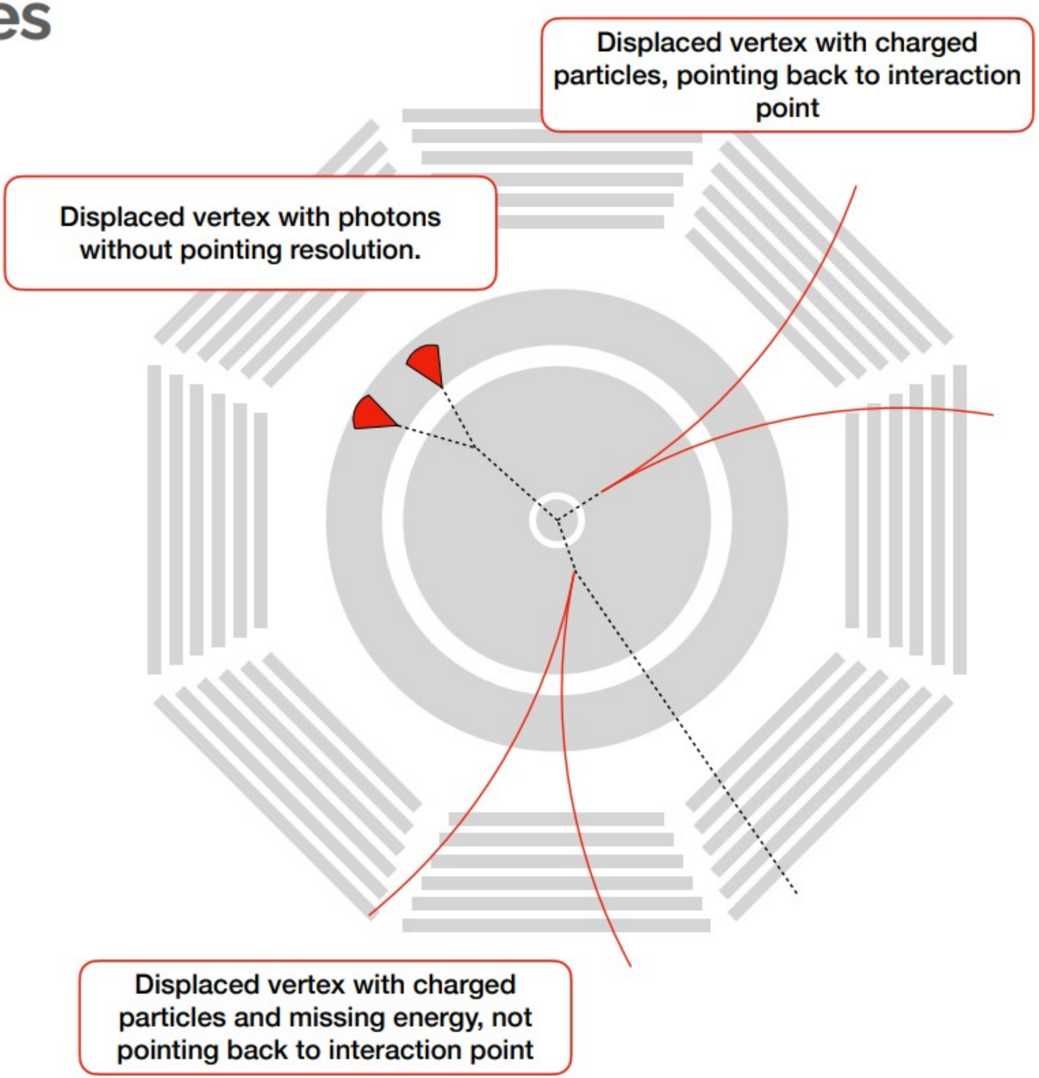


Pro: resolved clusters

Con: very low energetic photons

Long-lived particle (LLP) signatures

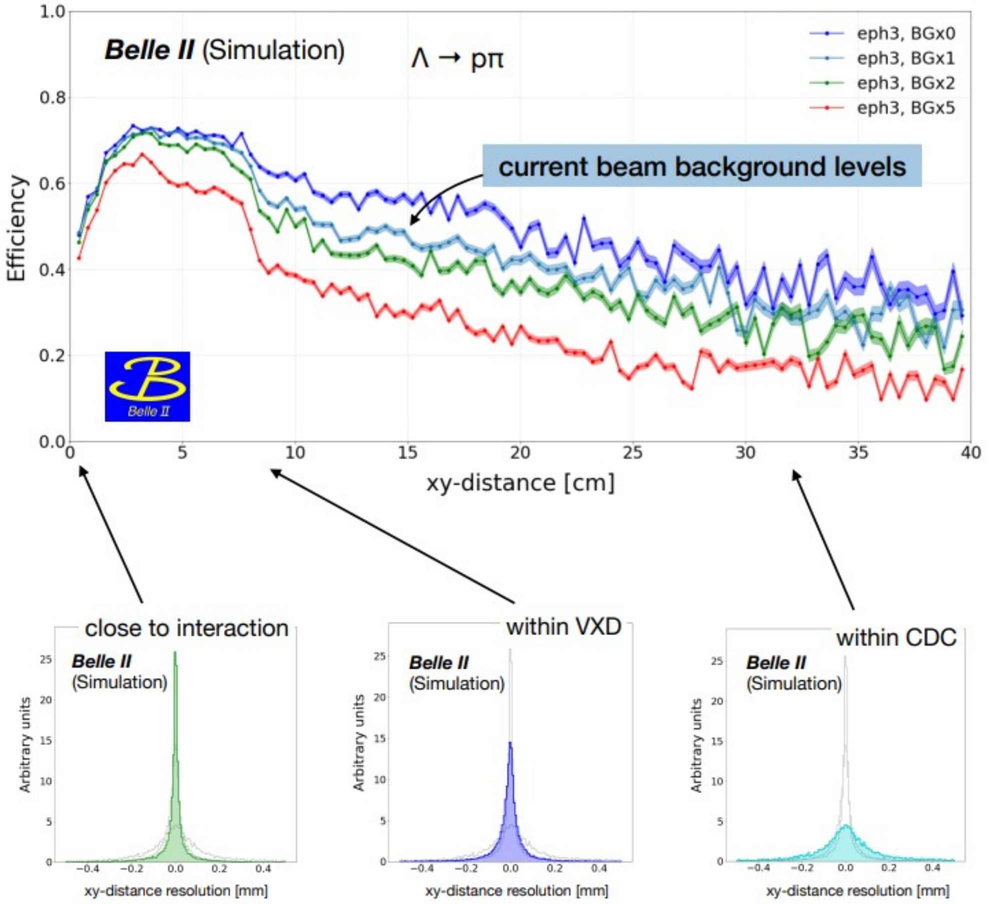
- LLPs from B meson decays:
  - Mediator mass limited by meson mass (~5 GeV)
  - Couplings to top quarks or W bosons (dark Higgs, ALPs)
- LLPs in e^+e^- collisions:
  - Mediator mass limited to collision energy (~10 GeV)
  - Coupling to photons or leptons (dark photons, ALPs)



From T. Ferber @ EPS-HEP 2021

Long-lived particle performance

- Tracking:
  - Vertex efficiency >30% out to ~60 cm
  - Vertex resolution <100µm
- Calorimeter (ECL):
  - Timing resolution ~2ns @ 2GeV
  - No longitudinal segmentation, coarse lateral segmentation → no pointing resolution
- Trigger
  - No dedicated displaced vertex track trigger, but can exploit the other B for searches in B decays (at Belle II, B's come from $\Upsilon(4S) \to B\bar{B}$)
  - Calorimeter triggers are efficient if there are electrons or photons in the final state

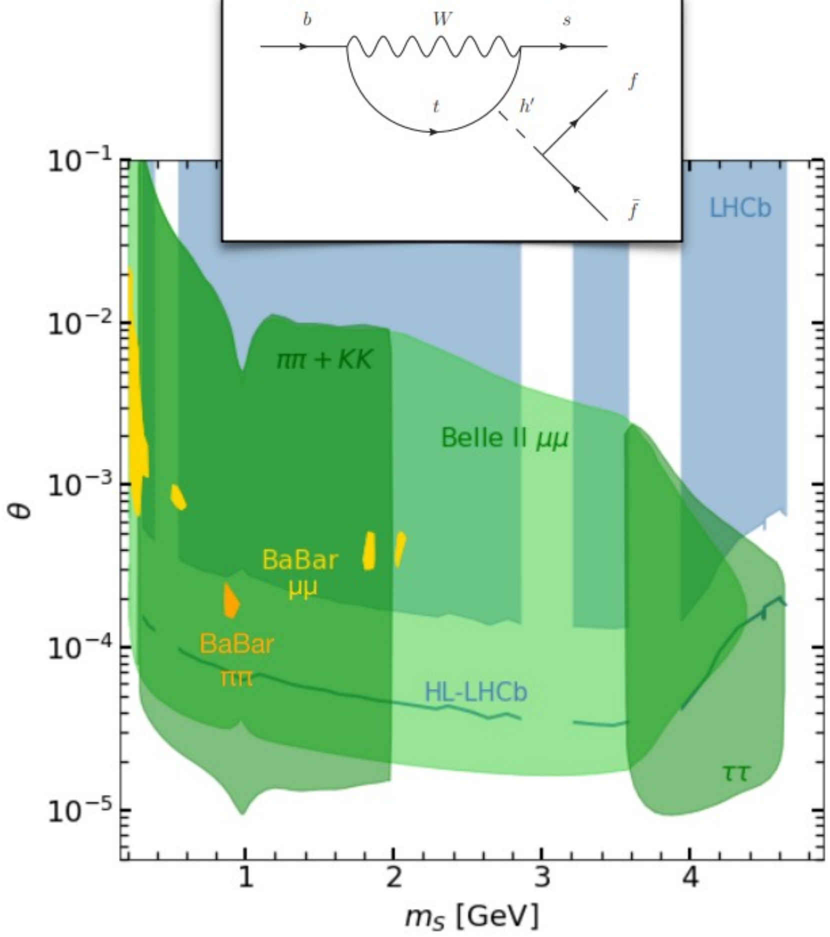


From T. Ferber @ EPS-HEP 2021

B→Kh'

- h' is long-lived
- m_{xx} peak hunt on small smooth background (x = (e), μ, π, K)
- LHCb and Belle II complementary due to very different B momenta, BaBar search is inclusive and recast is not competitive
- Reach towards even smaller mixing angle θ by searching for B→K+invisible
  - Recasting existing B→Kνν SM limits untrivial (3-body vs 2-body final state)

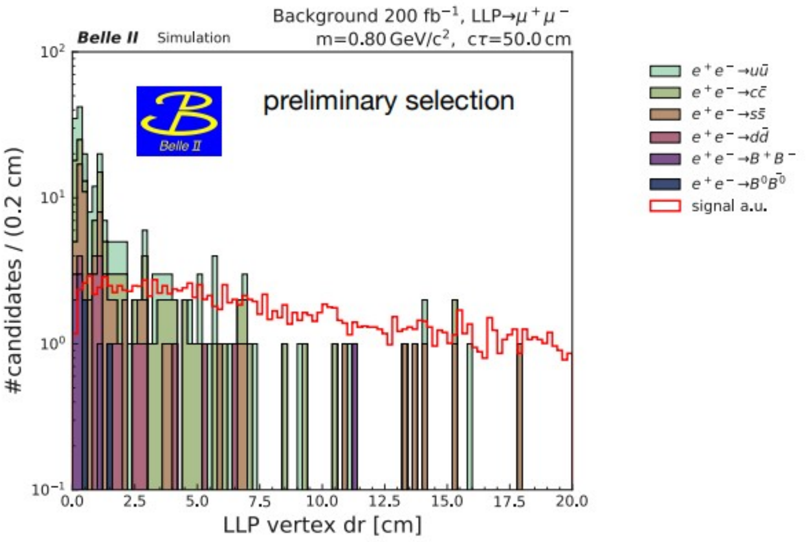
Belle II collaboration, "Search for B+→K+νν decays using an inclusive tagging method at Belle II" (arXiv:2104.1262)

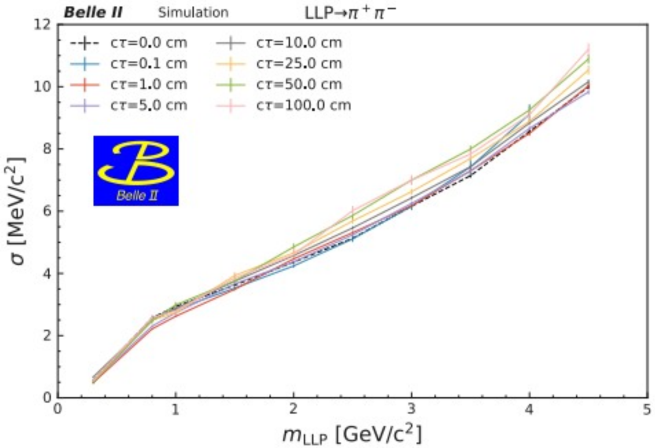


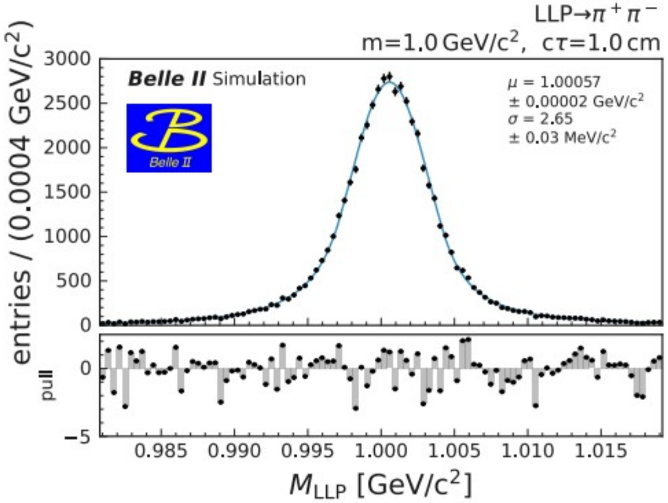
Filimonova, Schäfer, Westhoff, Phys. Rev. D 101, 095006 (2020), arXiv:1911.03490

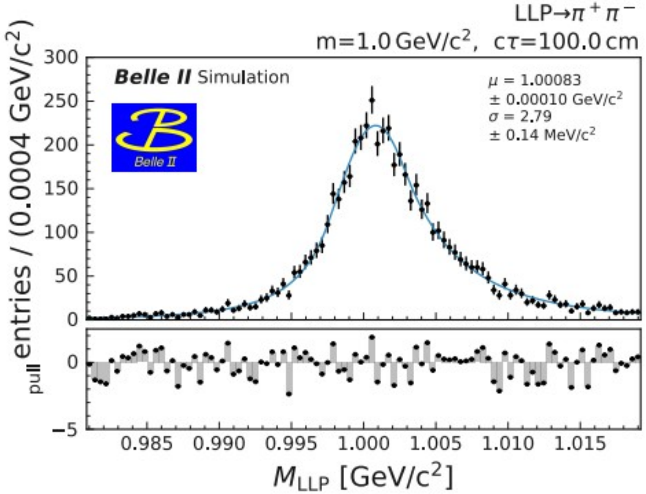
B→Kh’

- Event selection is very clean, but not quite at zero background
- Mild lifetime dependence on mass resolution and mass asymmetries









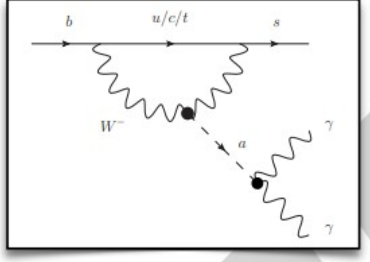
From T. Ferber @ EPS-HEP 2021

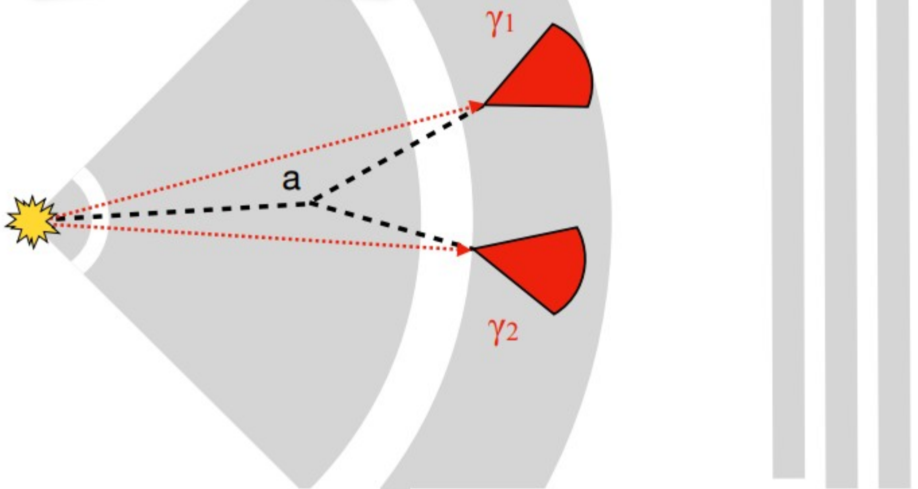
B→Ka

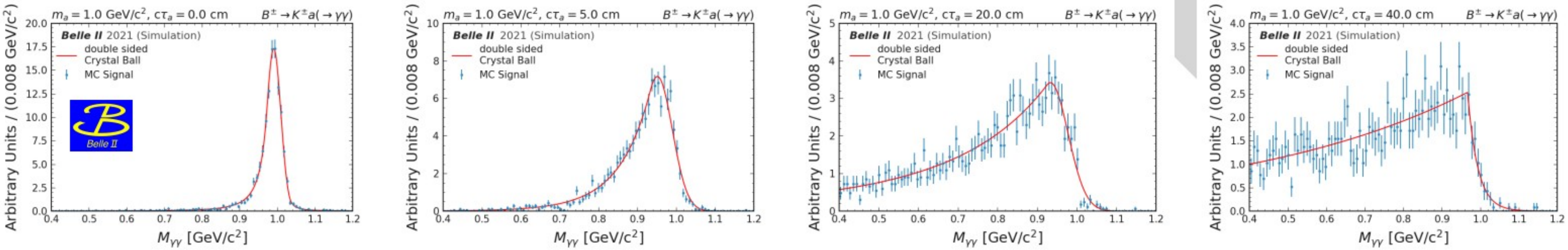
- Search for ALPs that predominantly couple to electroweak gauge bosons
- Dominant decay for $m_a \ll m_W$ into photons:

$$\Gamma(a \to \gamma\gamma) = \frac{g_{aW}^2 \sin^4 \theta_W M_a^3}{64\pi}$$

- Light ALPs naturally long-lived, but decay in general model-dependent





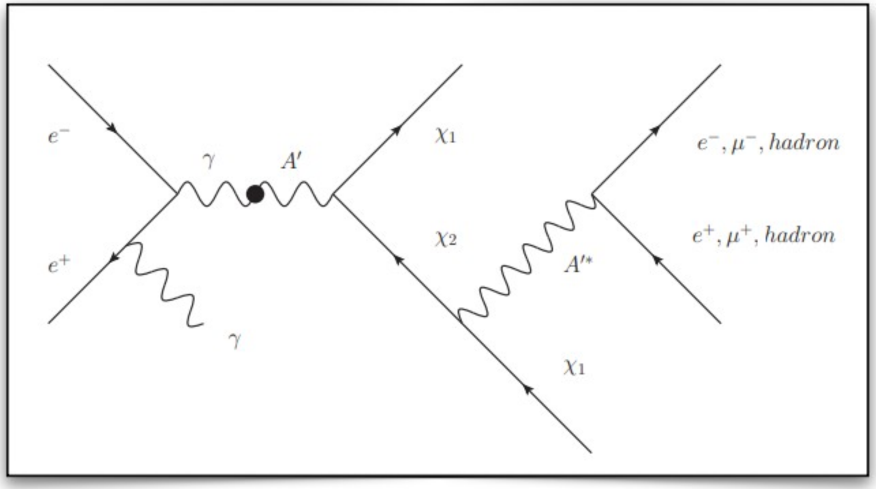


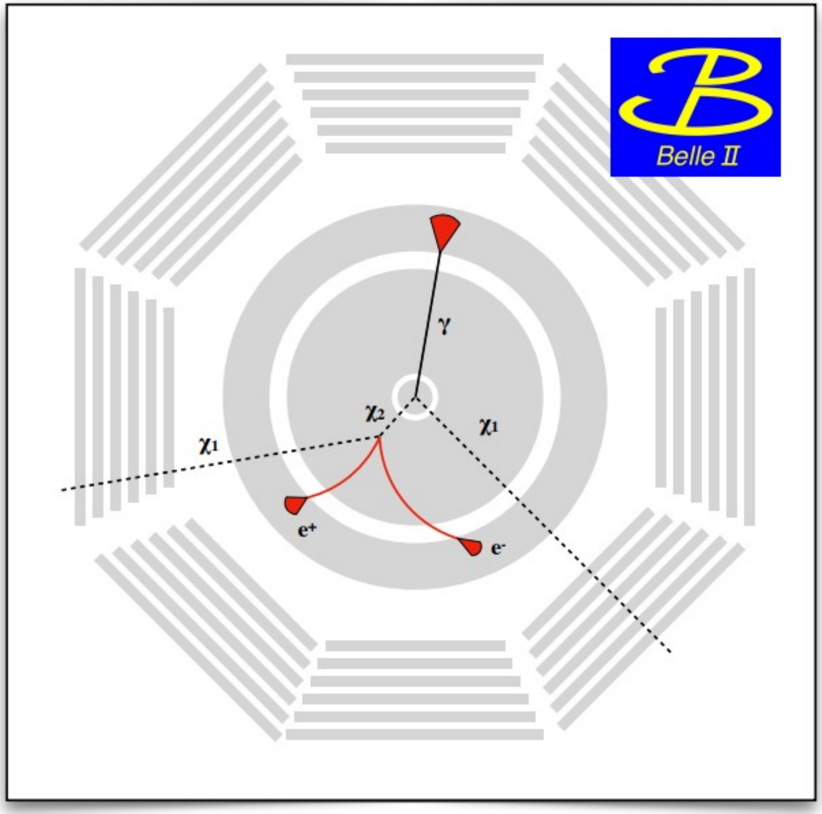
G. De Pietro

From T. Ferber @ EPS-HEP 2021

Inelastic Dark Matter

Duerr et al. (2020), *arXiv:1911.03176*



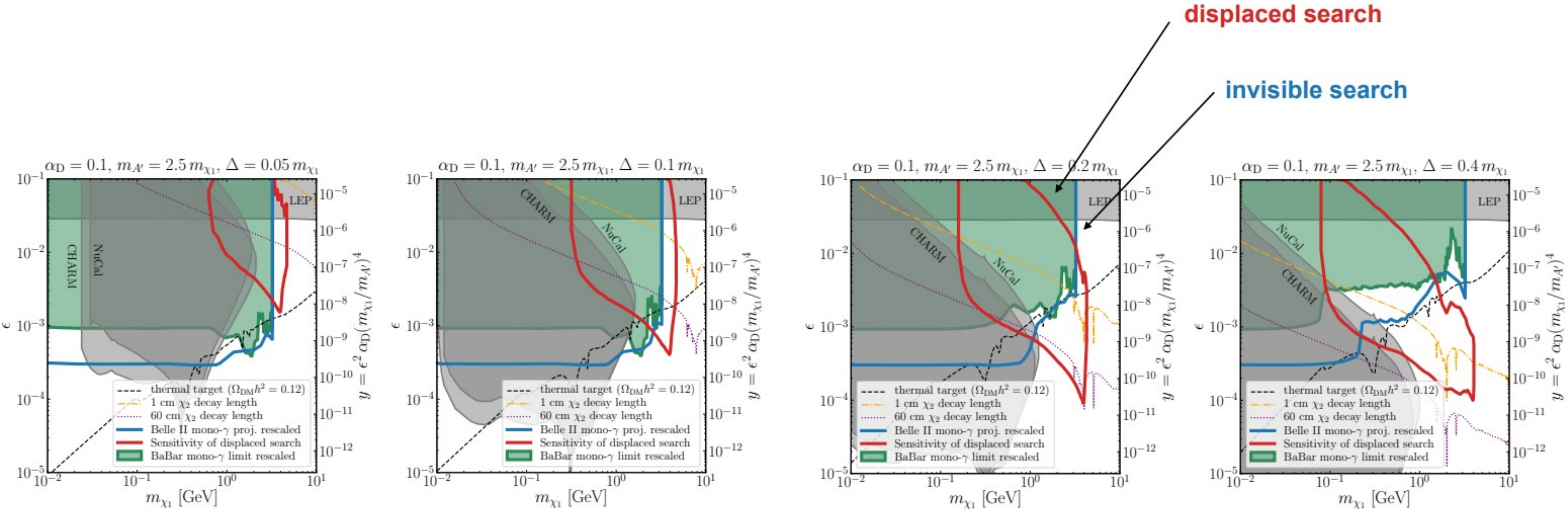


five free parameters:

- dark photon mass $m_{A'}$ (fixed relative to $m_{\chi 1}$)
- χ_1 mass (stable dark matter candidate) (scan)
- mass difference $\Delta = m_{\chi 2} - m_{\chi 1}$ (categorical)
- dark coupling α_D (fixed to benchmarks)
- kinetic mixing parameter ε (limit)

Inelastic Dark Matter

Duerr et al. (2020), *arXiv:1911.03176*



increased mass splitting