# Prospects for long-lived particle searches at Belle II.

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on behalf of the Belle II collaboration

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

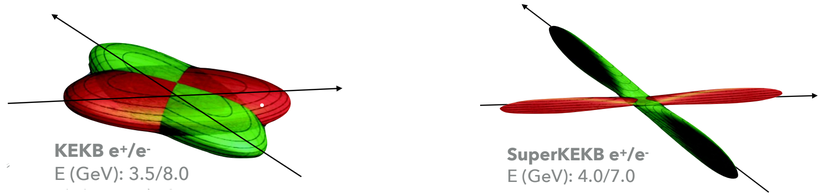
Belle II

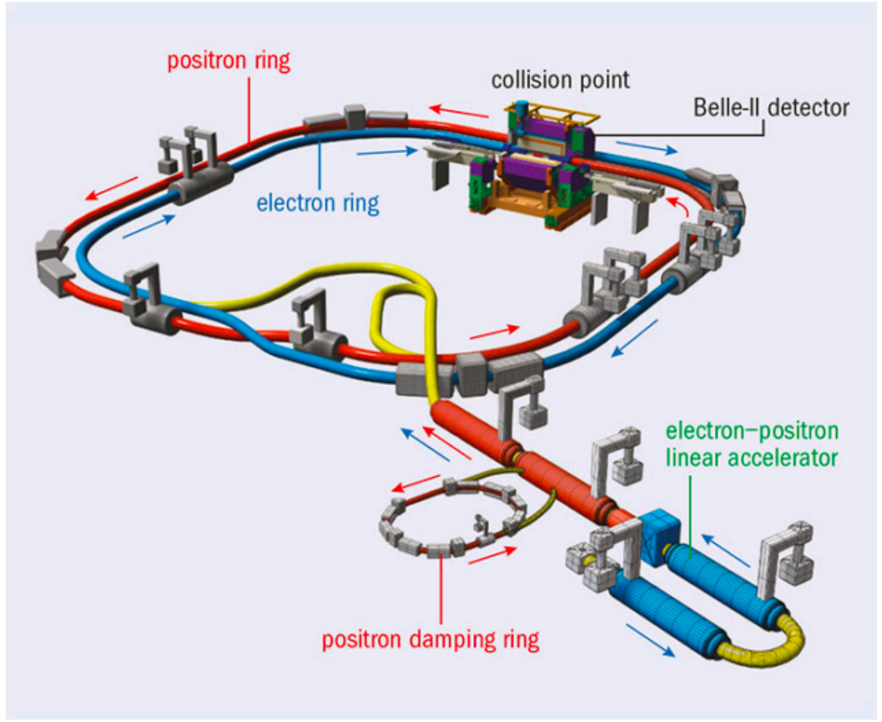
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

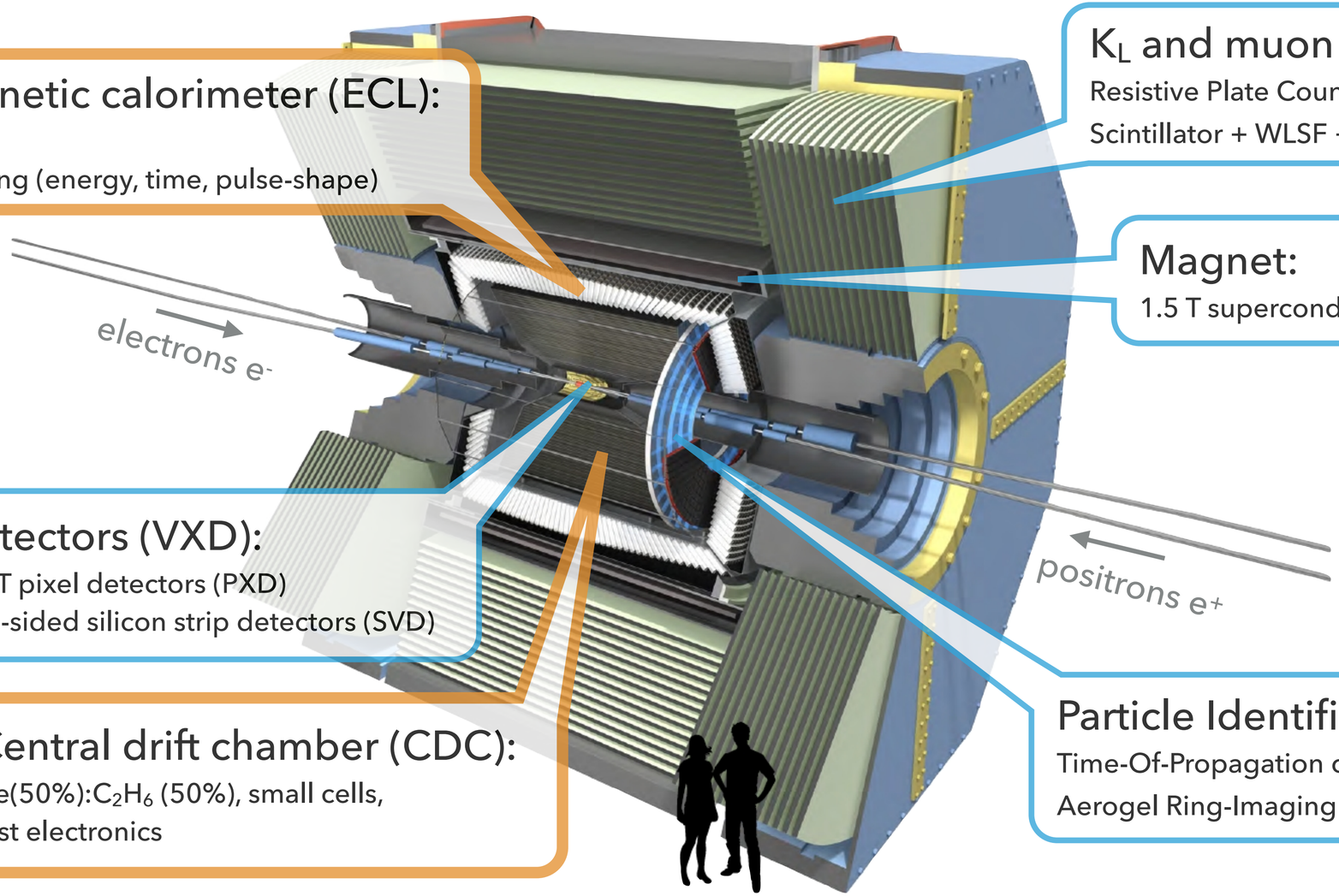
# Super B-factory accelerator: SuperKEKB

- Asymmetric beam energies:
  e.g. 7.0 GeV ($e^-$) / 4.0 GeV ($e^+$)
- Large crossing angle of 83 mrad
- Major upgrade to the accelerator with 30× the KEKB design luminosity ($6\times10^{35}$ $cm^{-2}s^{-1}$, 50 $ab^{-1}$ (50× Belle))
  - 1.5× higher beam currents, 20× smaller beam spot ($\sigma_y$=50 nm)
- Record: $3.12\times10^{34}$ $cm^{-2}s^{-1}$ (June 22 2021)
- Total dataset up to now: 213 $fb^{-1}$

# Super B-factory detector: Belle II




## Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, 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

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

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

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

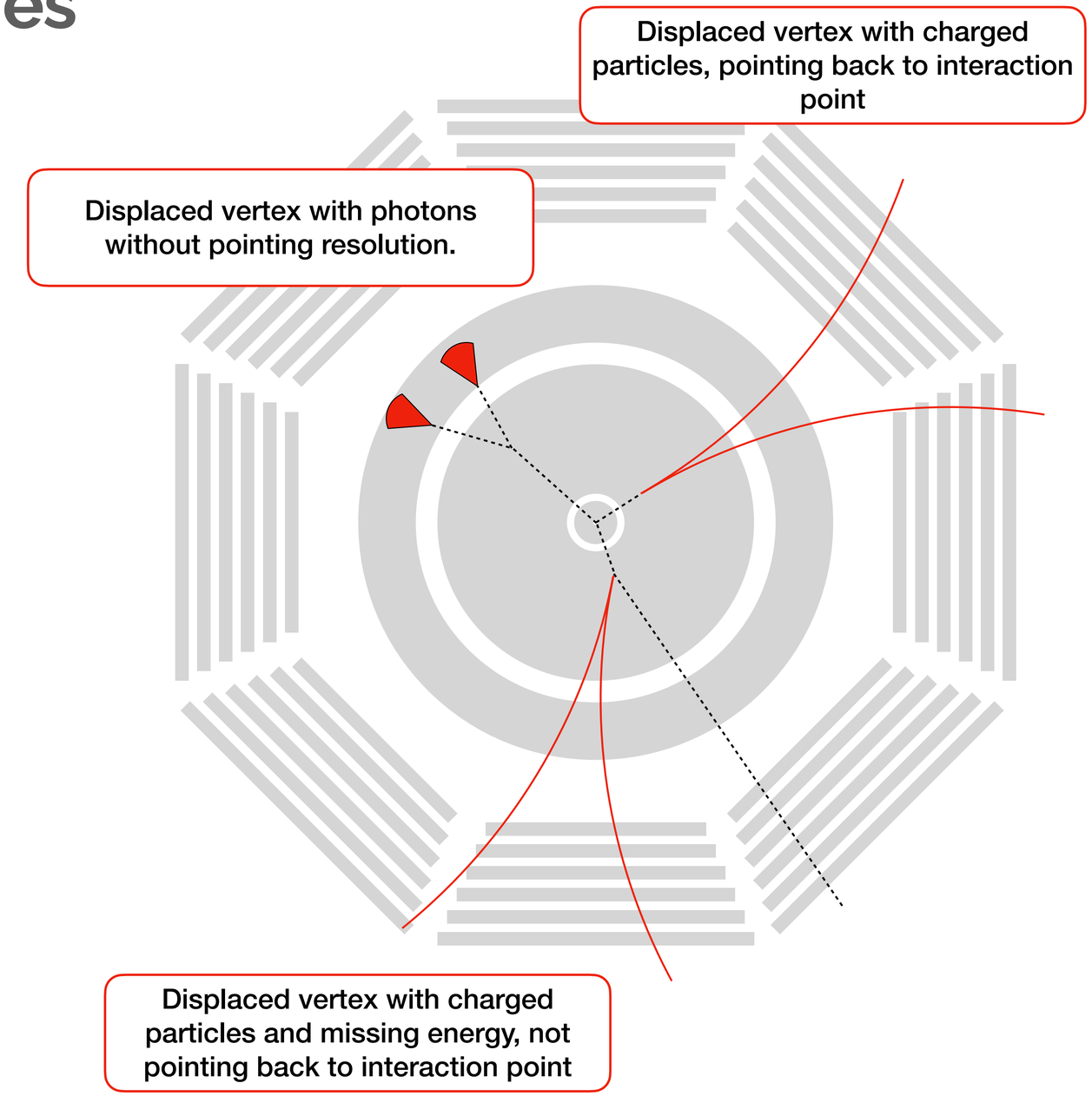
## Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

# Long-lived particle (LLP) signatures

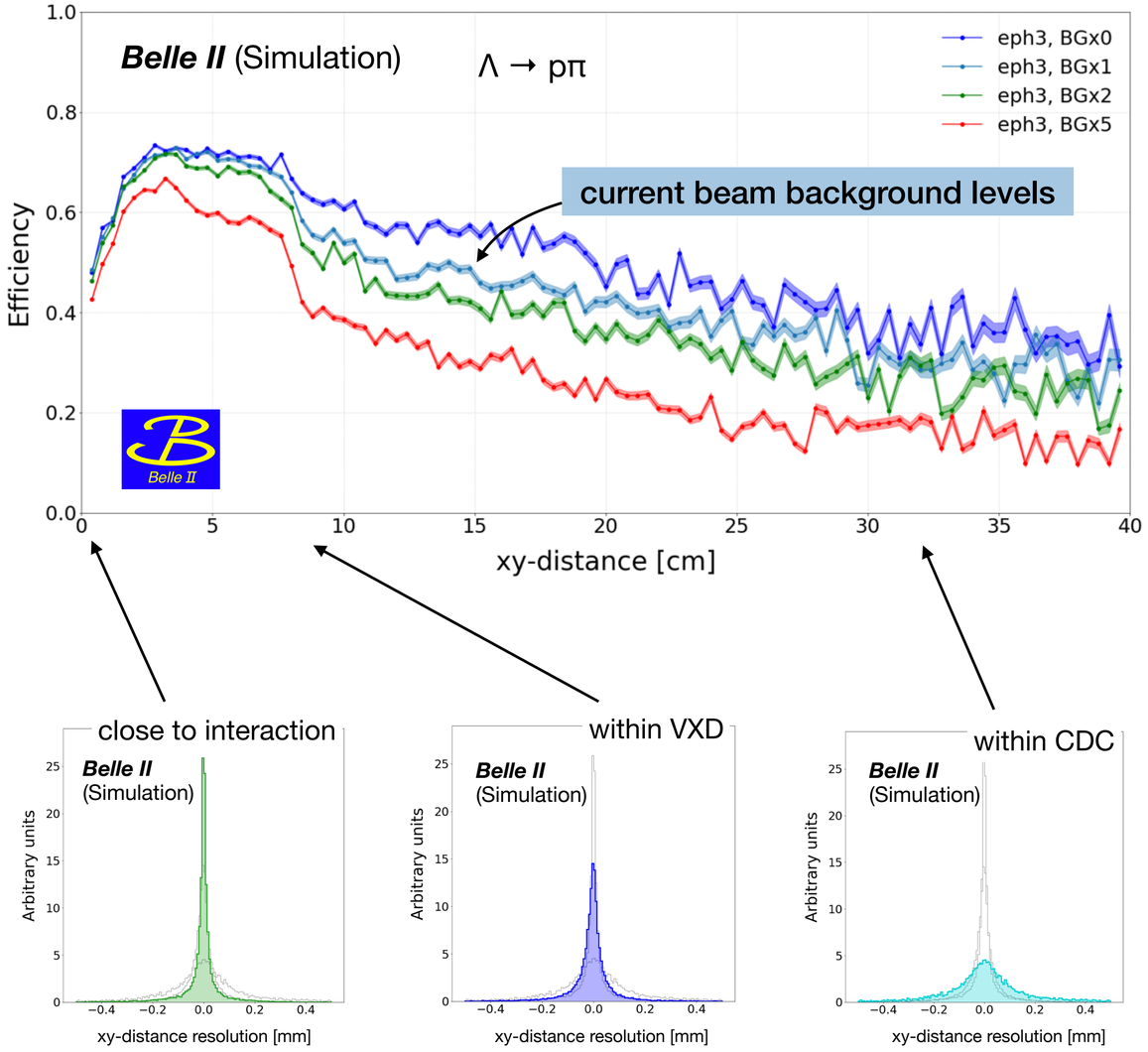
- LLPs from B meson decays:
  - Mediator mass limited by meson mass (~5 GeV)
  - Couplings to top quarks or W bosons (dark Higgs, ALPs)

- LLPs in $e^+e^-$ collisions:
  - Mediator mass limited to collision energy (~10 GeV)
  - Coupling to photons or leptons (dark photons, ALPs)



# Long-lived particle performance

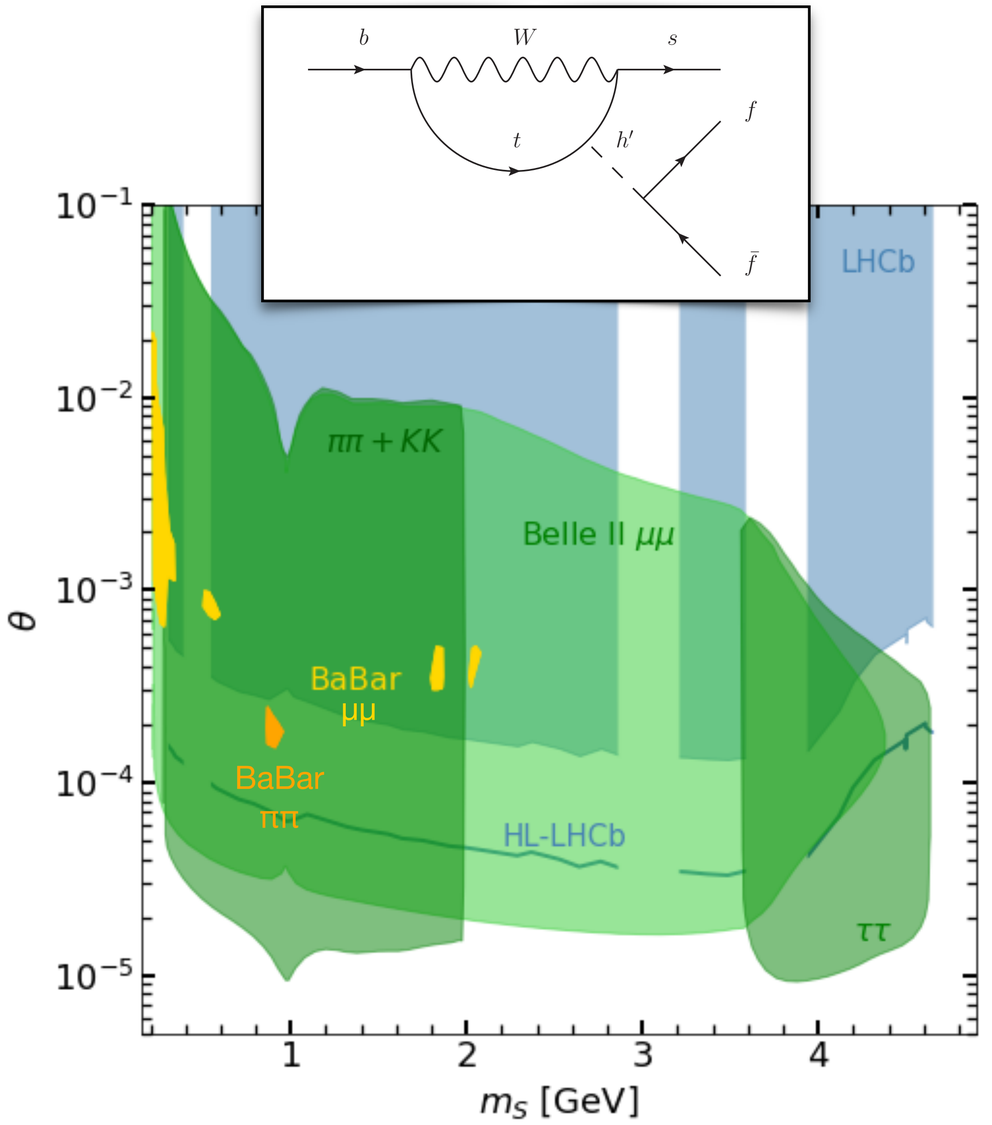
- Tracking:
  - Vertex efficiency >30% out to ~60 cm
  - Vertex resolution <100µm
- Calorimeter (ECL):
  - Timing resolution ~2ns @ 2GeV
  - No longitudinal segmentation, coarse lateral segmentation → no pointing resolution
- Trigger
  - No dedicated displaced vertex track trigger, but can exploit the 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



# 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)

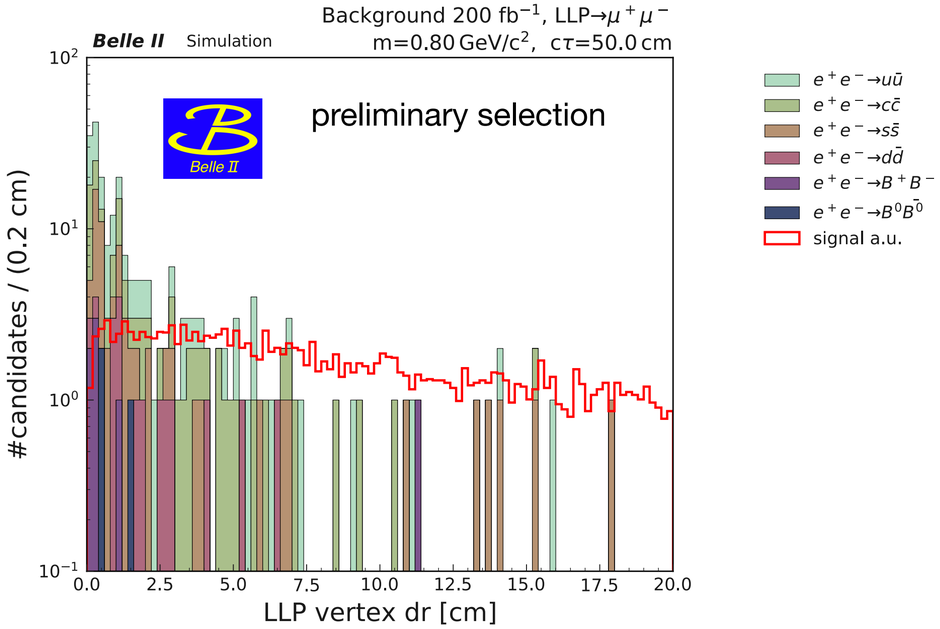
Belle II collaboration, "Search for B+→K+νν decays using an inclusive tagging method at Belle II" (arXiv:2104.1262)

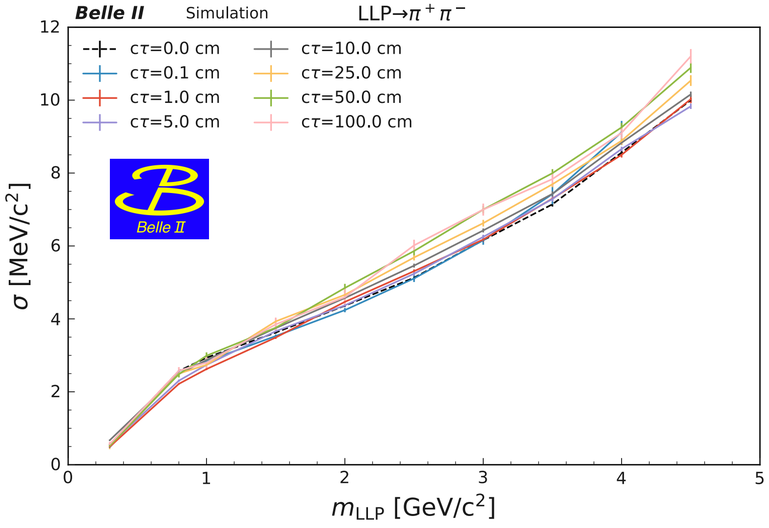


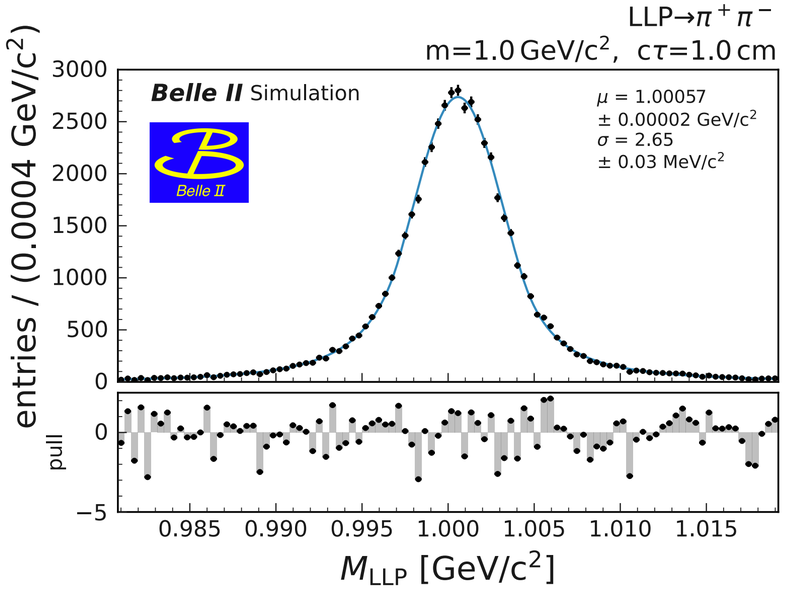

Filimonova, Schäfer, Westhoff, Phys. Rev. D 101, 095006 (2020), arXiv:1911.03490

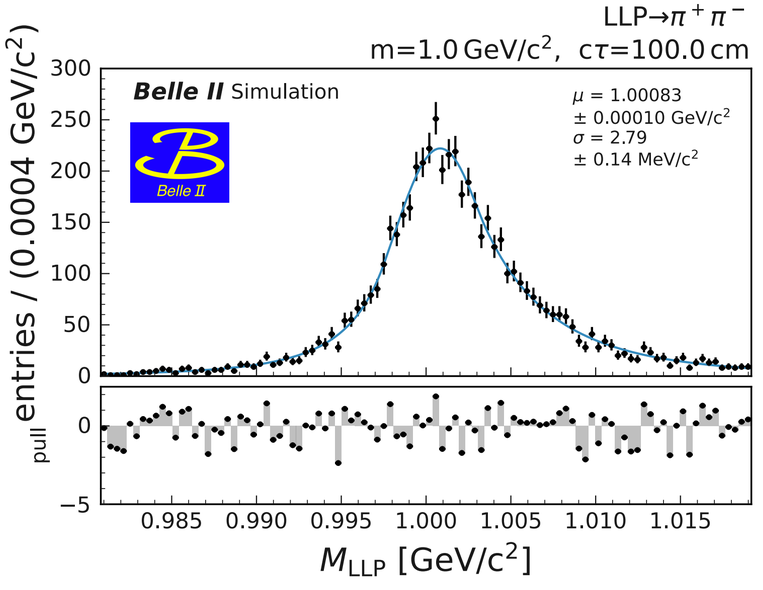
# B→Kh'

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



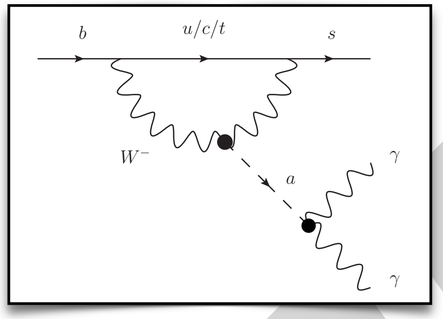



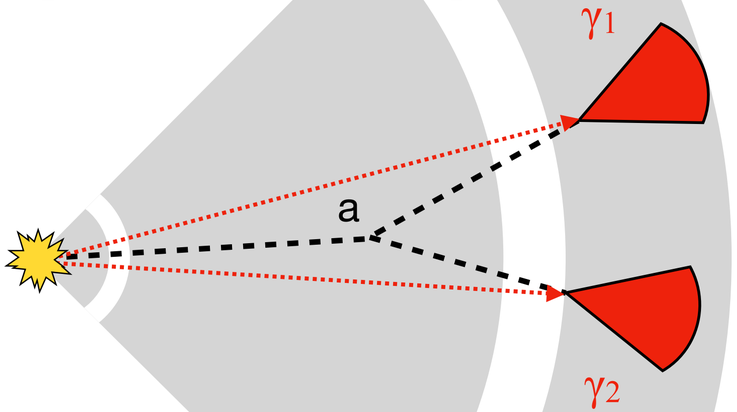
# B→Ka

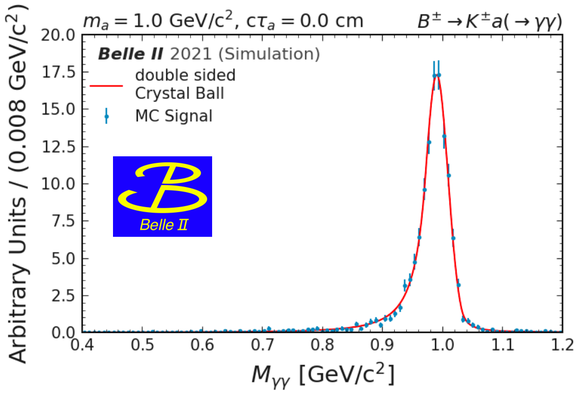
- Search for ALPs that predominantly couple to electroweak gauge bosons
- Dominant decay for $m_a \ll m_W$ into photons:

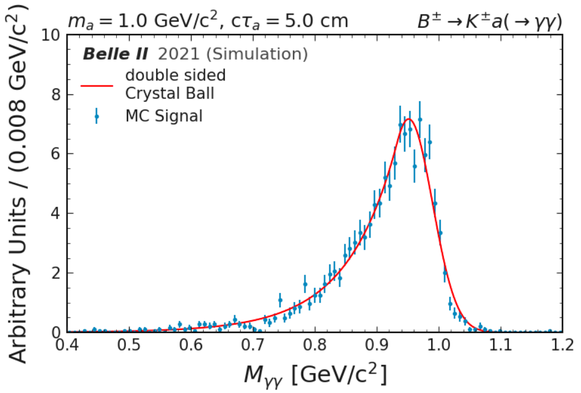
$$\Gamma(a \to \gamma\gamma) = \frac{g_{aW}^2 \sin^4\theta_W M_a^3}{64\pi}$$

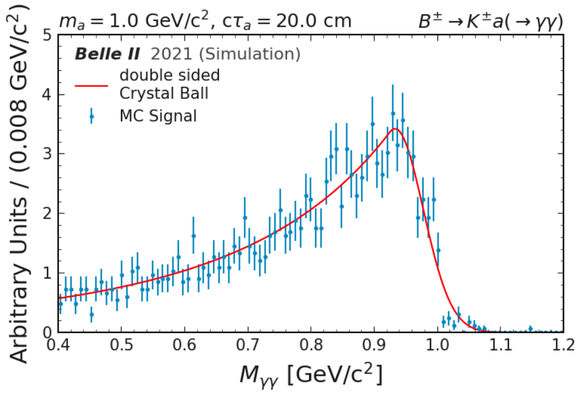
- Light ALPs naturally long-lived, but decay in general model-dependent

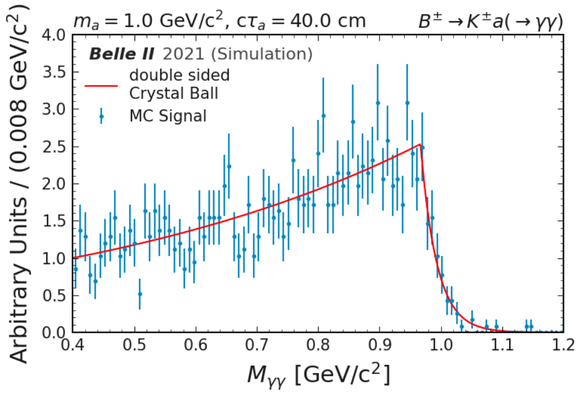


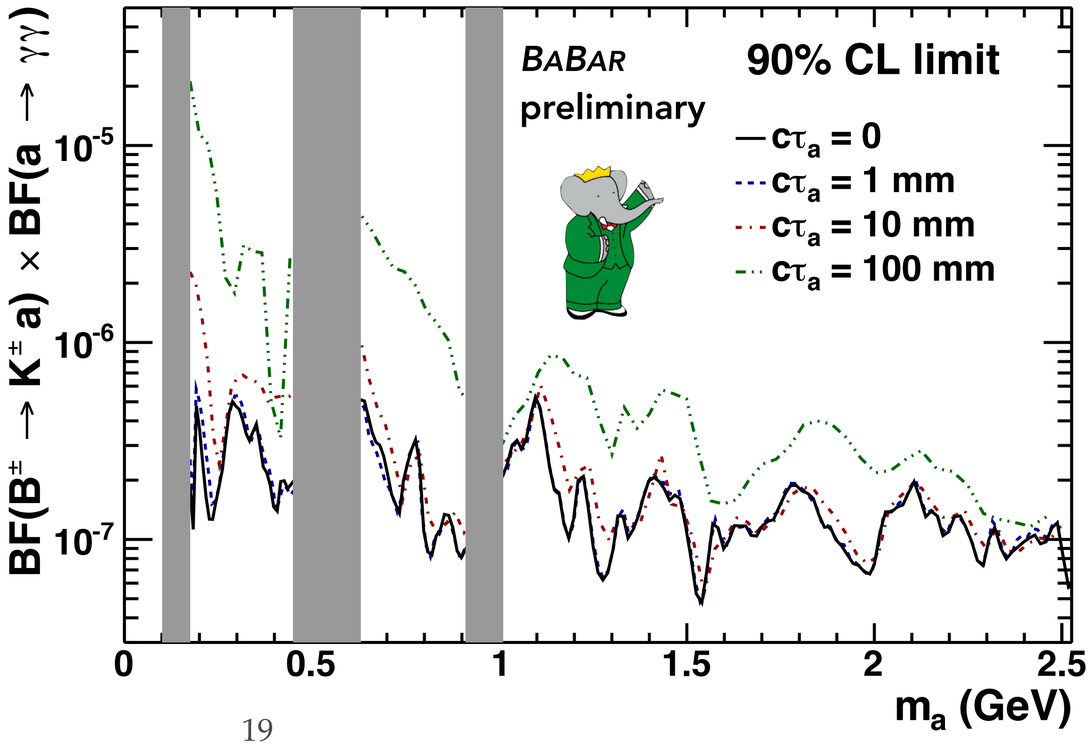



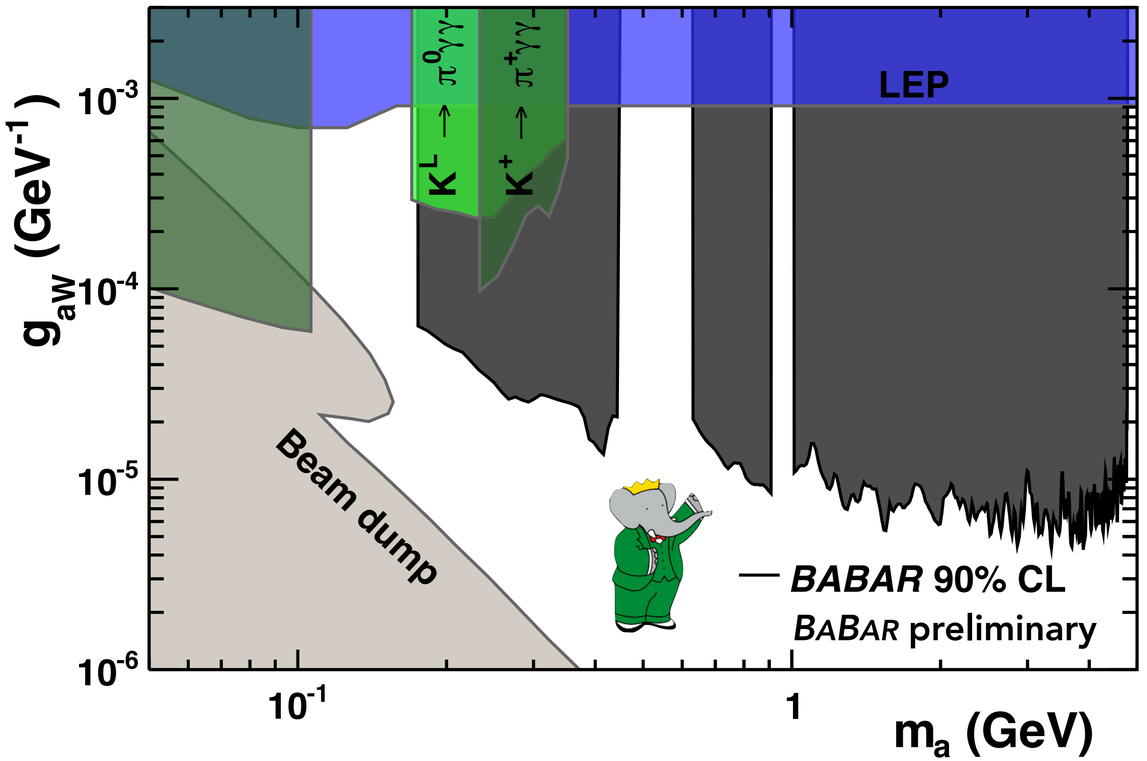



# B→Ka at BaBar

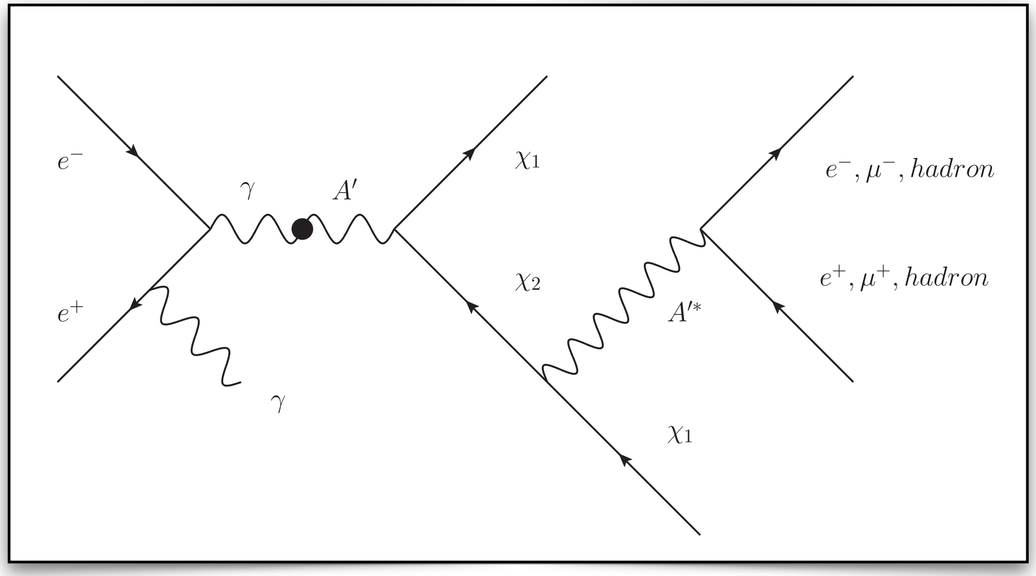




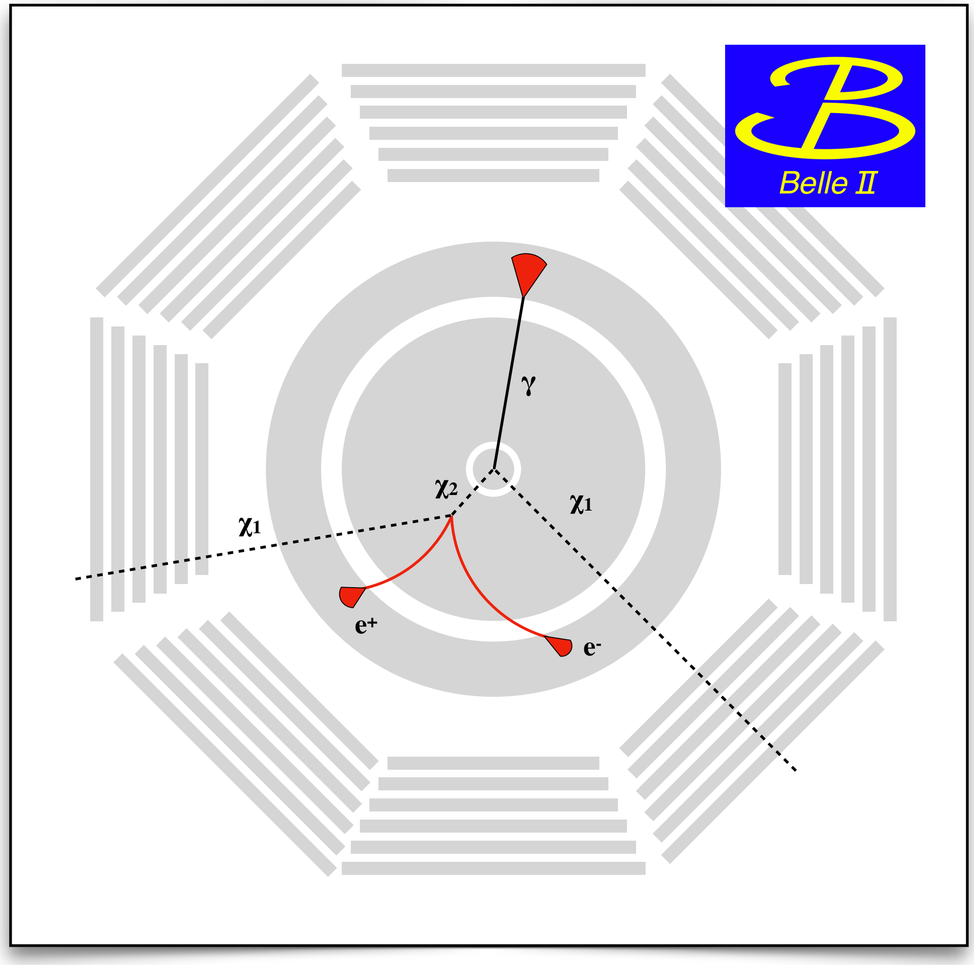




Shuve, ICHEP 2020, https://indico.cern.ch/event/868940/contributions/3814877/

# Inelastic Dark Matter




five free parameters:
- dark photon mass $m_{A'}$ (fixed relative to $m_{\chi 1}$)
- $\chi_1$ mass (stable dark matter candidate) (scan)
- mass difference $\Delta = m_{\chi 2} - m_{\chi 1}$ (categorical)
- dark coupling $\alpha_D$ (fixed to benchmarks)
- kinetic mixing parameter $\varepsilon$ (limit)



Duerr, **TF**, Hearty, Kahlhoefer, Schmidt-Hoberg, Tunney, *J. High Energ. Phys. 2020, 39 (2020)*, arXiv:1911.03176



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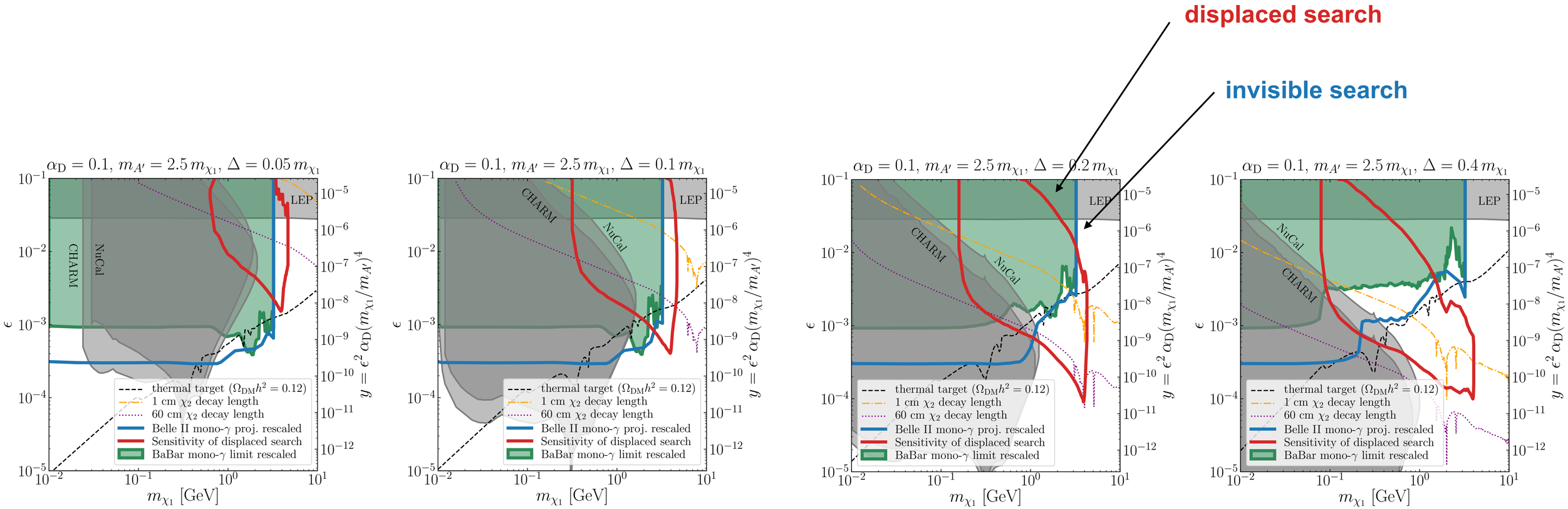


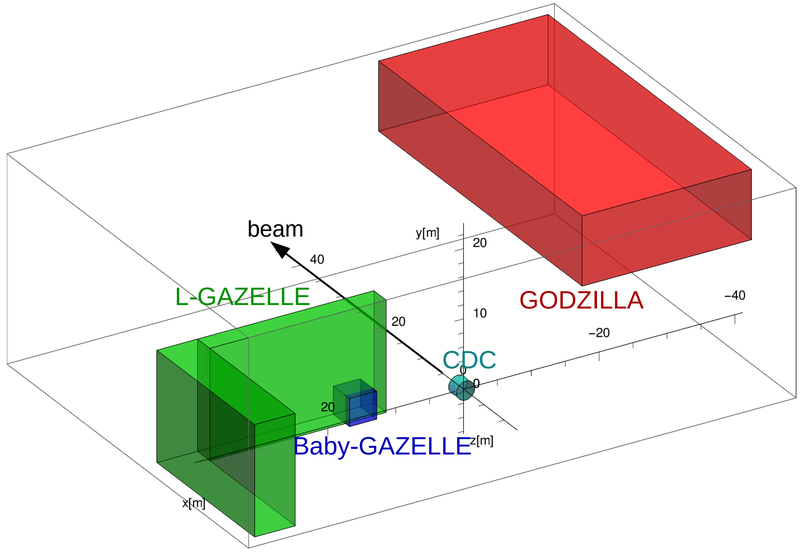
# GAZELLE

- Study “realistic” dedicated LLP detector near Belle II: GAZELLE*

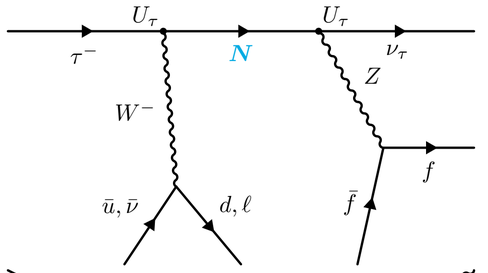
  *GAZELLE is the Approximately Zero-background Experiment for Long-Lived Exotics

- Three benchmarks studied (HNL, iDM, ALPs)

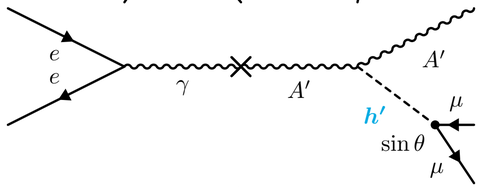
- No significant gain compared to Belle II due to moderate boost, and excellent solid angle coverage and low backgrounds for missing energy searches at Belle II



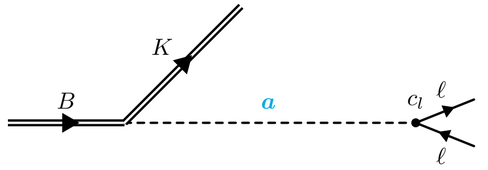

Clean $\tau$ production
⇒ HNLs: $N$




Displaced vertices
⇒ iDM: $h'$




Rare $B$ decays
⇒ ALPs: $a$

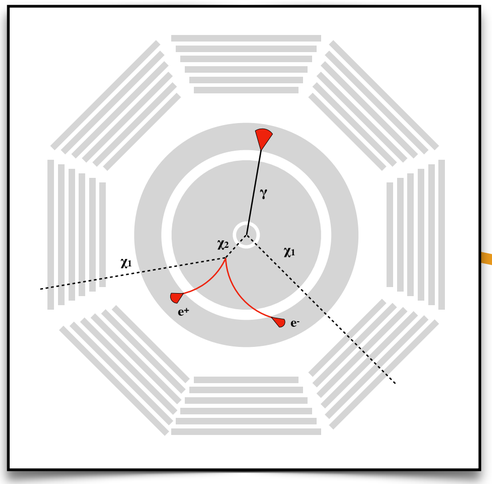


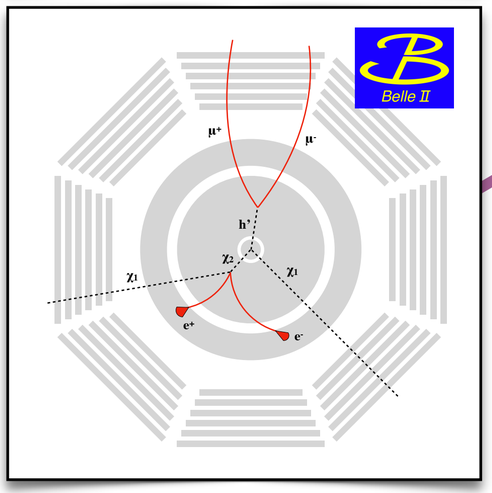
# Summary

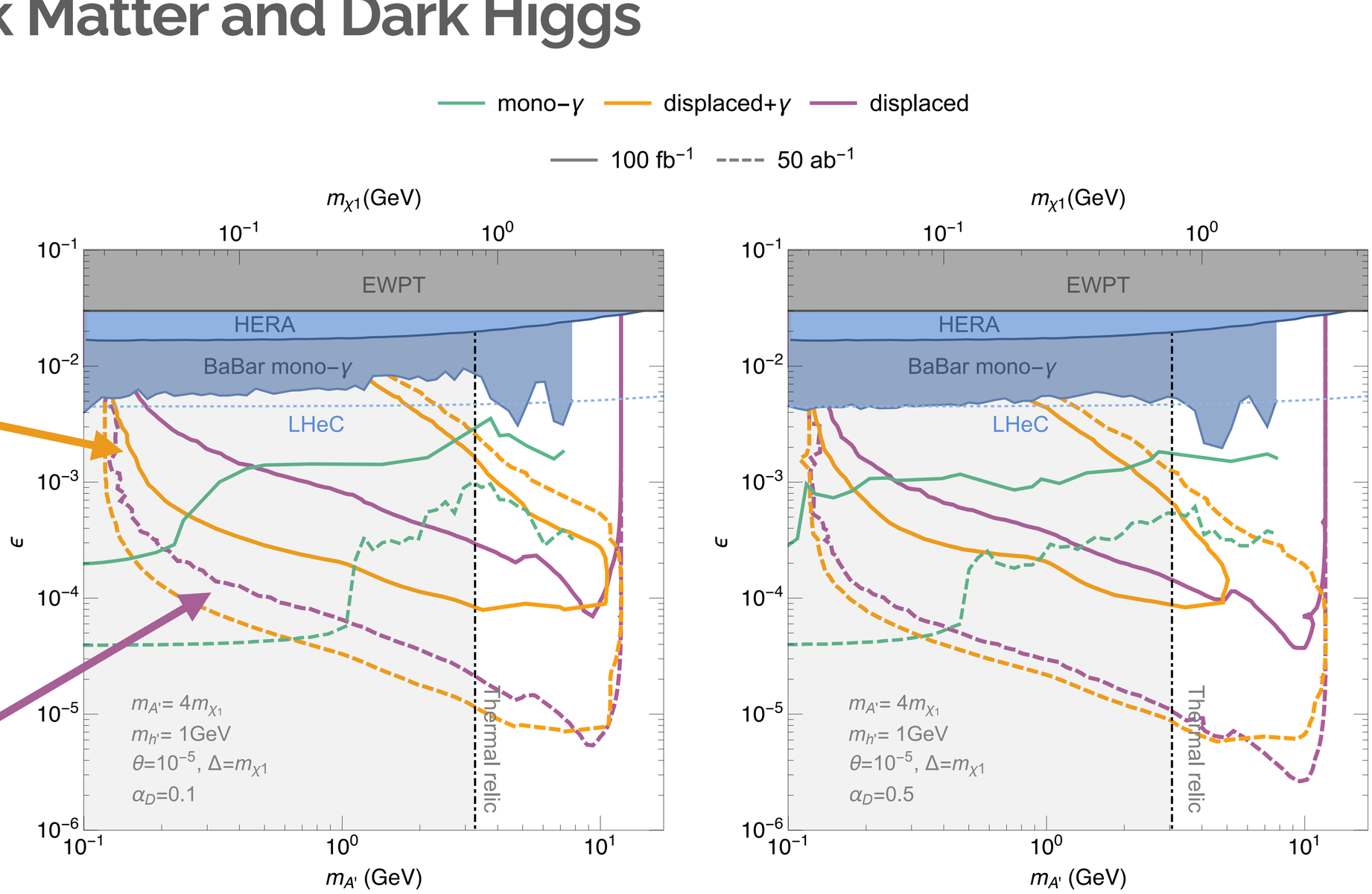
- Existing LLP triggers at Belle II rely on calorimeter information, dedicated LLP track trigger development has started
- Study of a possible dedicated LLP detector GAZELLE revealed excellent LLP sensitivity for Belle II itself
- Multiple searches with LLPs in the final state started using the existing 200 $fb^{-1}$ Belle II dataset: $B \rightarrow Kh'$, $B \rightarrow Ka$, inelastic DM, dark Higgs, …

# Backup

# Inelastic Dark Matter and Dark Higgs




Duerr, **TF**, Garcia-Cely, Hearty, Schmidt-Hoberg, *J. High Energ. Phys.* **2021,** 146 (2021), arXiv:2012.08595