CRC-TRR-257

Physics Potential of a Far Detector at Belle II

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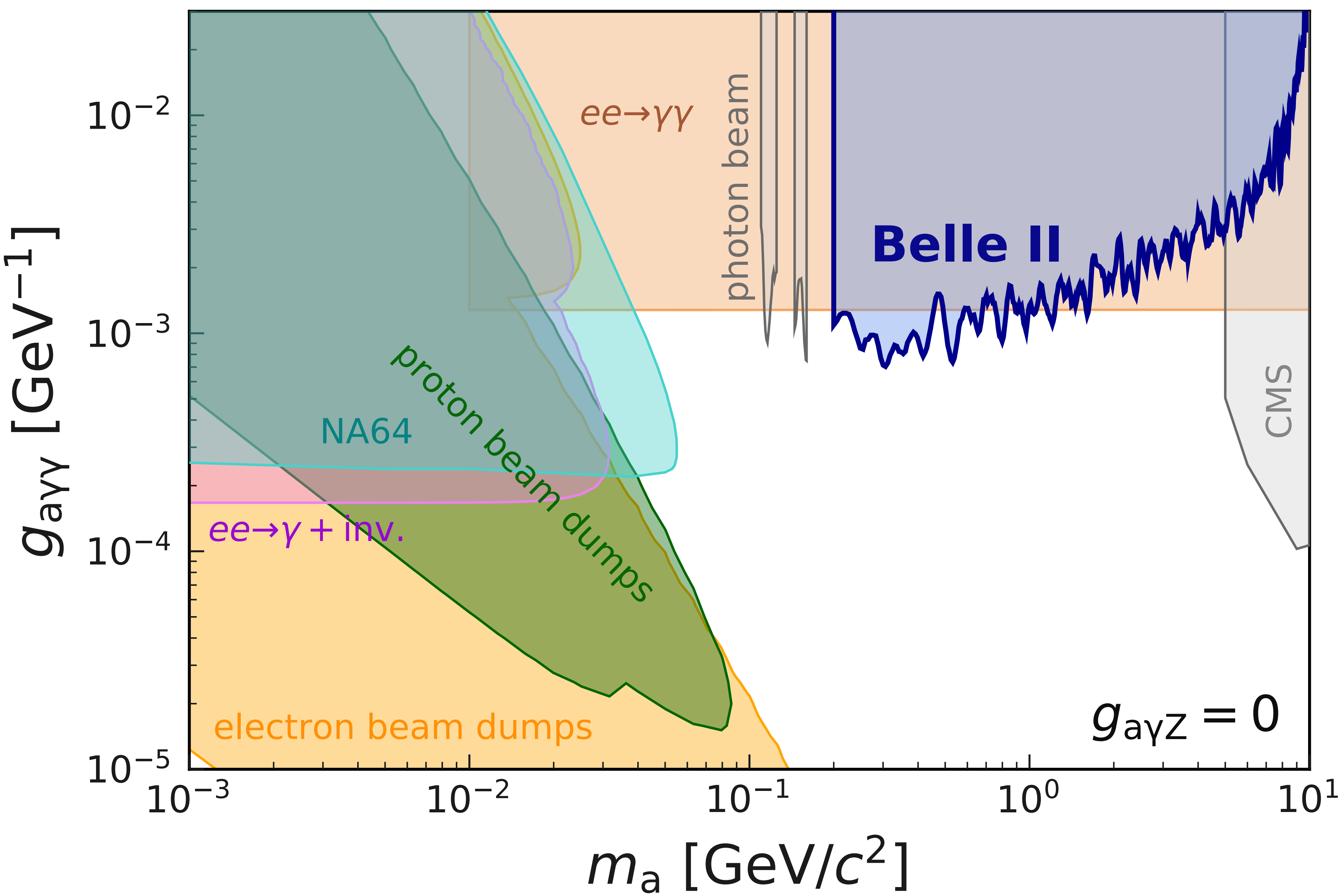
Heidelberg University

ILC WG Dark Sectors | June 16, 2021 | online

First ALP search at Belle II

$$e^+e^- \to a\,\gamma \to (\gamma\gamma)\gamma$$



Belle II 2007.13071

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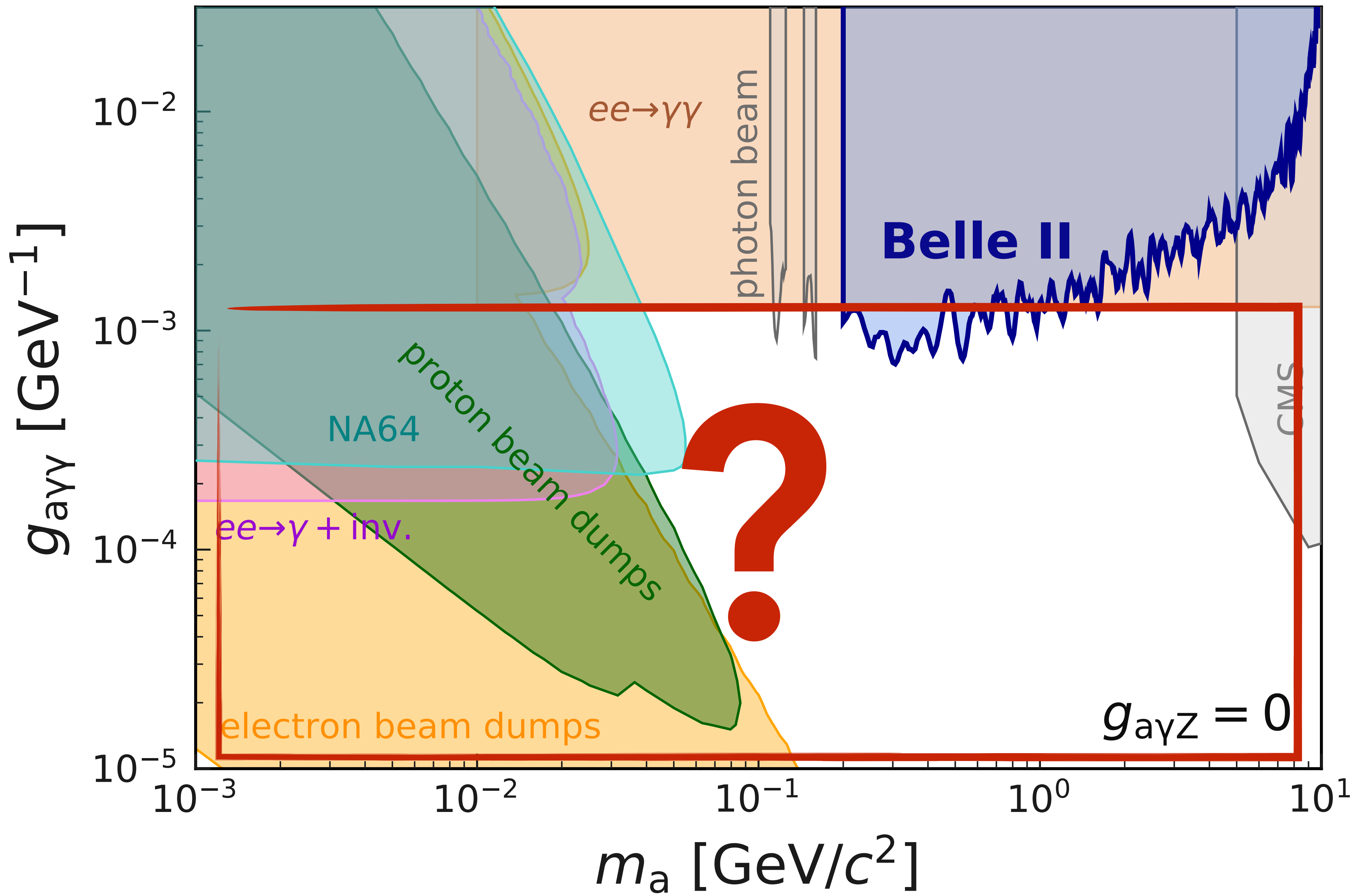


Belle II 2007.13071

GAZELLE

the

Approximately **Z**ero-Background **E**xperiment
for **L**ong-**L**ived **E**xotics

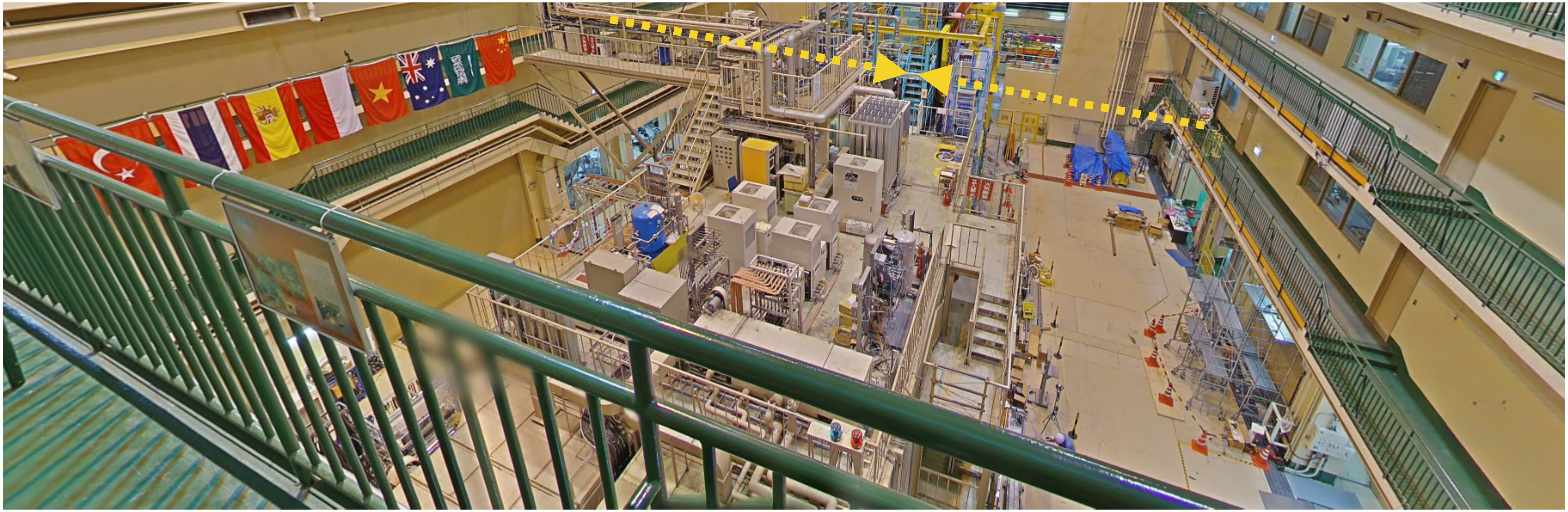
Belle II: S. Dreyer, T. Ferber, C. Hearty, S. Longo, K. Trabelsi

Theory: A. Filimonova, R. Schaefer, K. Schmidt-Hoberg, M. Tammaro, S. Westhoff, J. Zupan

Study of realistic options for far detectors around Belle II.

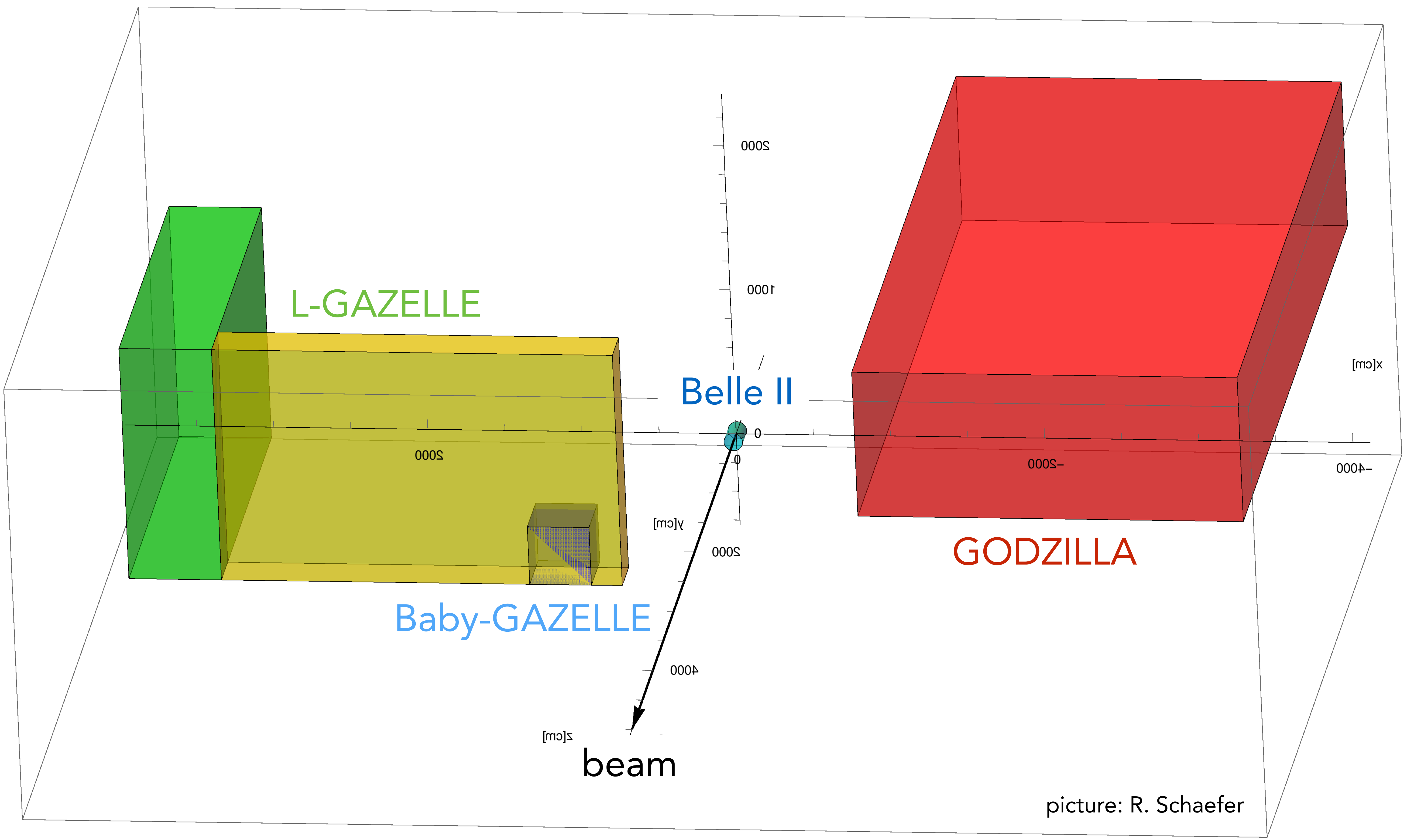
arXiv:2105.12962

Tsukuba Hall @ KEK

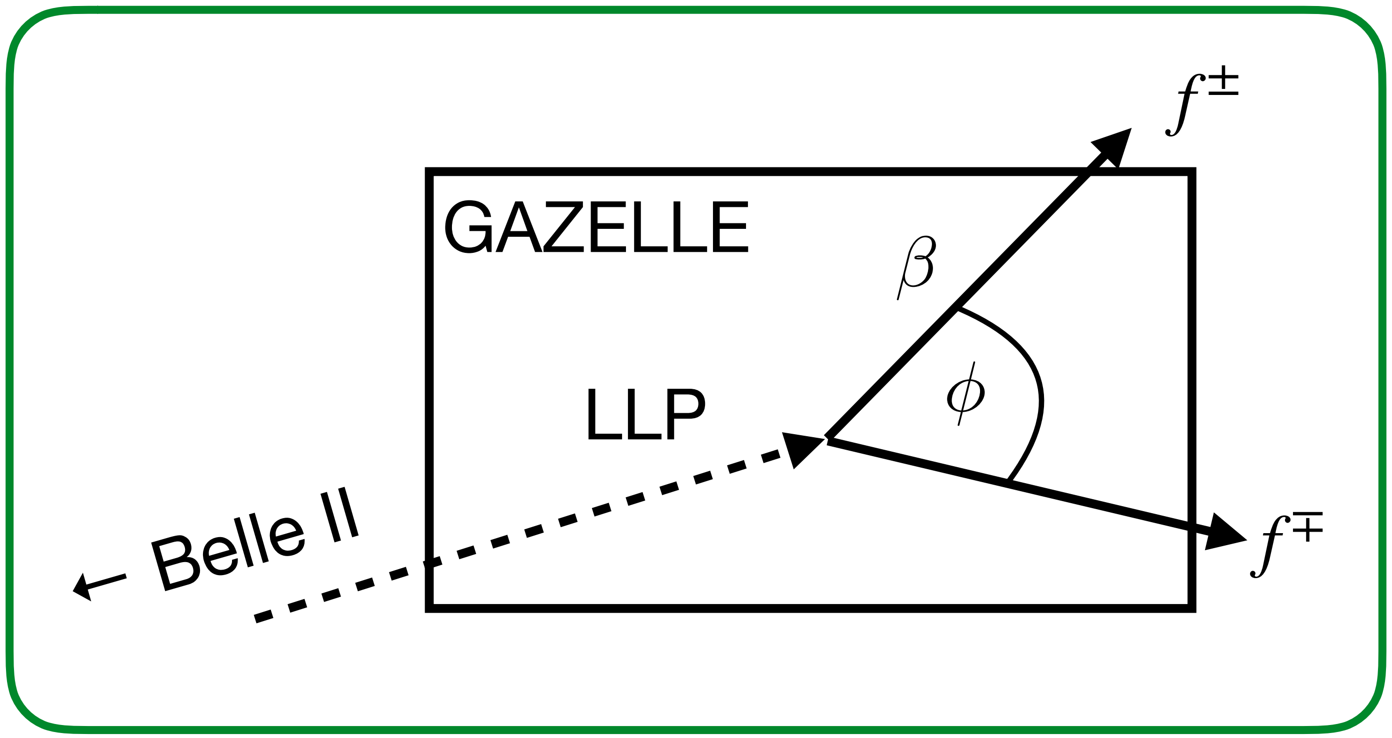


picture: Belle II collaboration

Design options far detectors



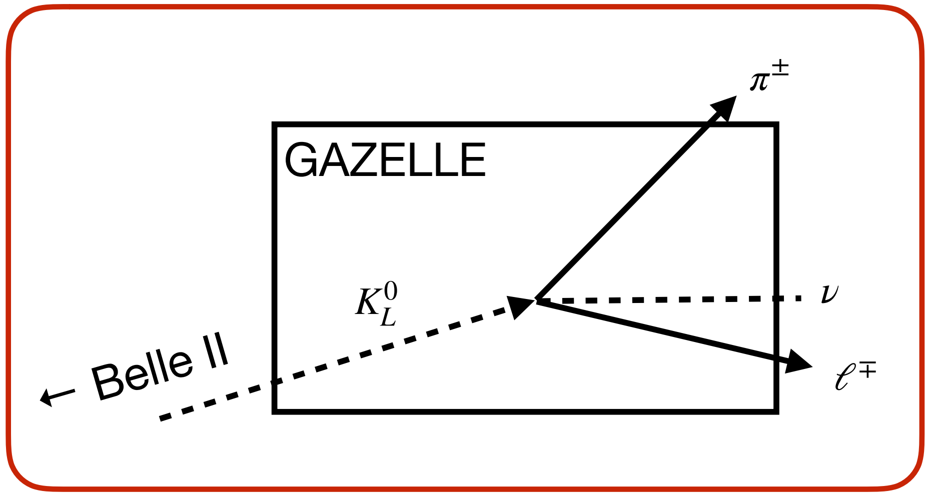
Search target



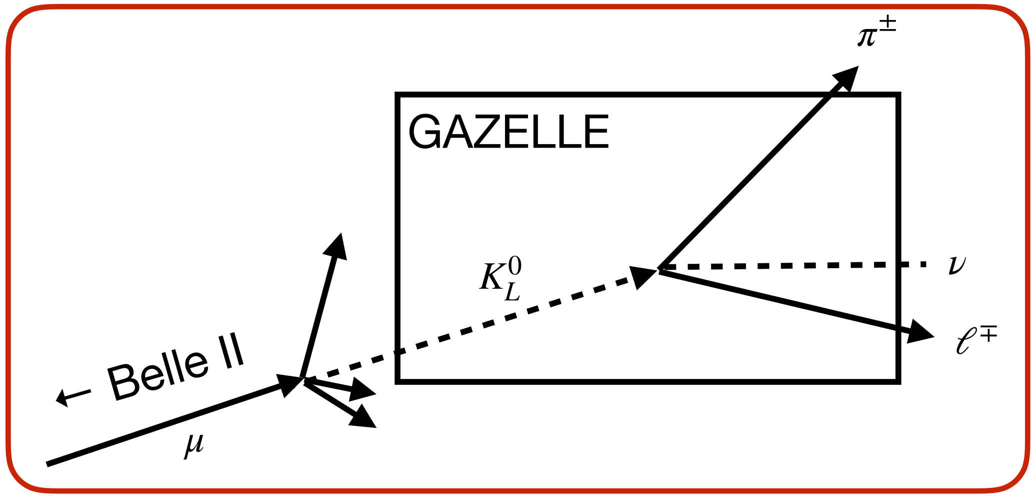
- precise measurement of LLP direction
- reconstruction of LLP mass (β , ϕ)
- GAZELLE and Belle II trigger each other

Background

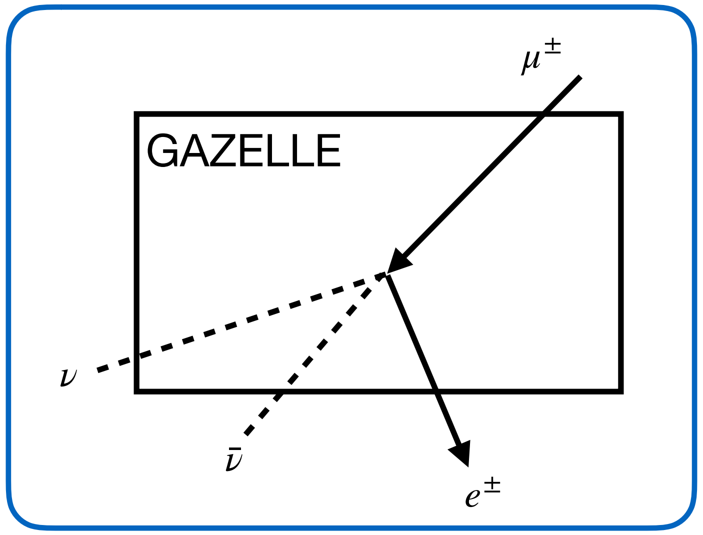
direct kaons



kaons from muons

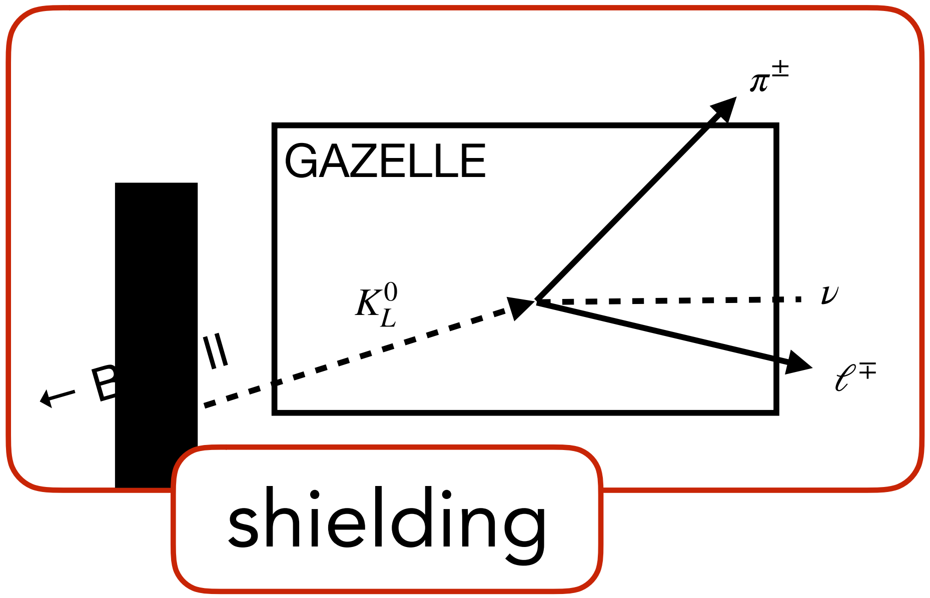


cosmics

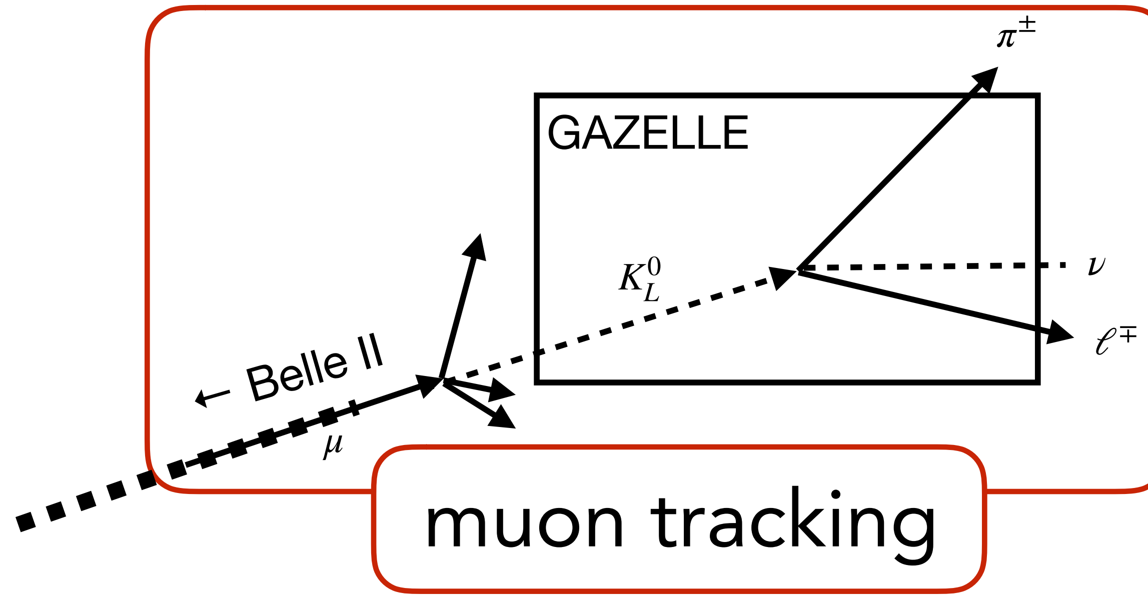


Background rejection

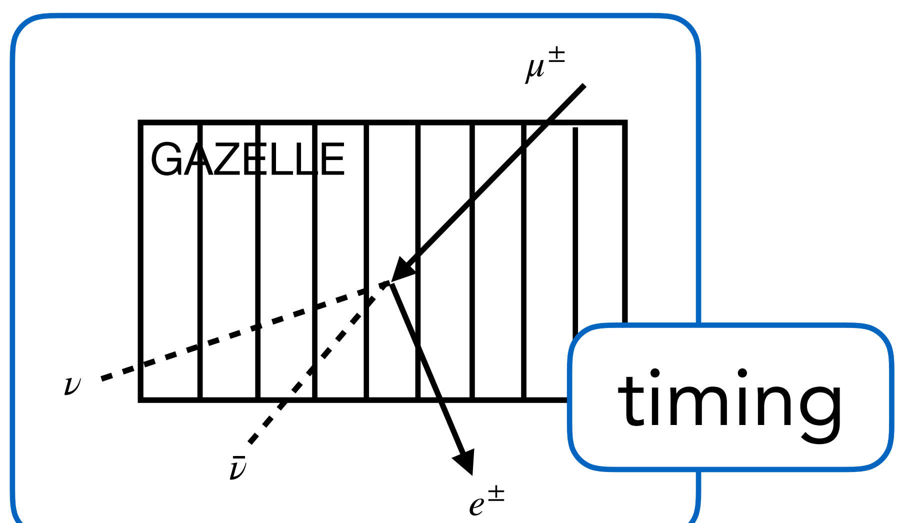
direct kaons



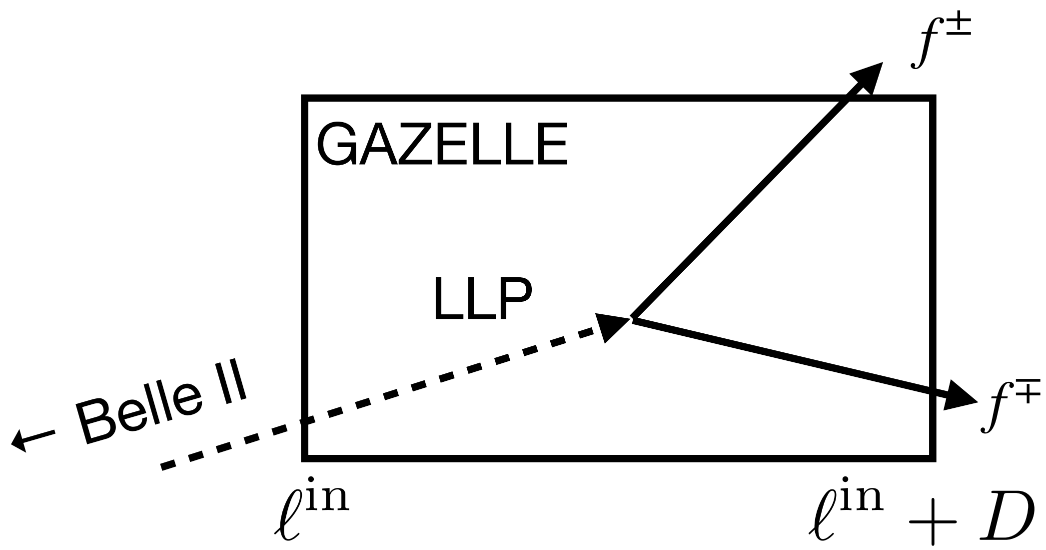
kaons from muons



cosmics



LLP decays inside GAZELLE



decay length

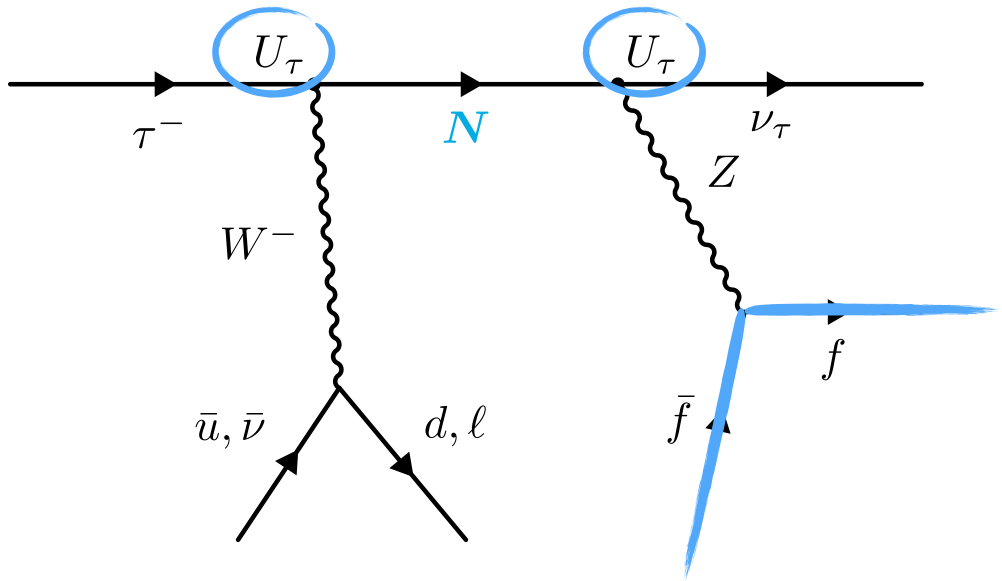
$d = \langle \beta\gamma \rangle c\tau$

- decay probability: $$\mathbb{P}(\ell^{in}) = \exp\left(-\frac{\ell^{in}}{d}\right) - \exp\left(-\frac{\ell^{in} + D}{d}\right)$$
- long lifetimes ($d \gg \ell^{in}, D$): $\langle \mathbb{P} \rangle \approx \frac{\Omega}{4\pi}\frac{D}{d}$

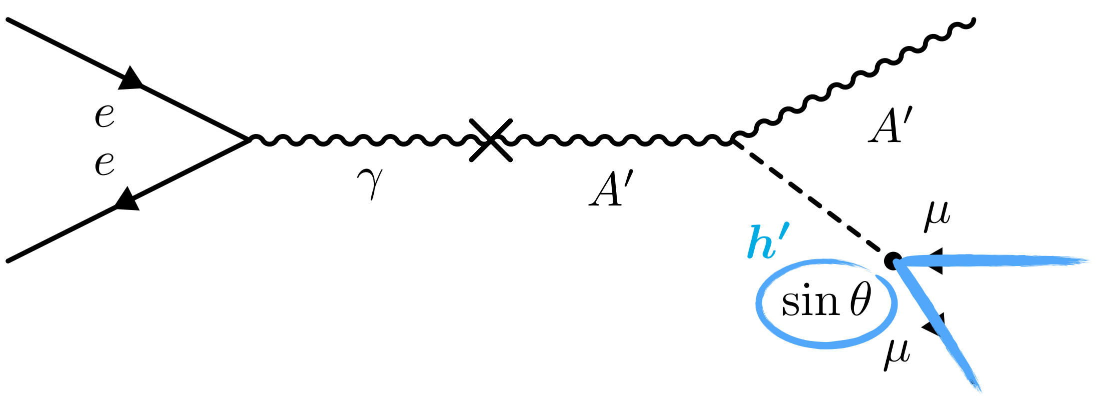
	Belle II	Baby-G.	L-GAZELLE	GODZILLA
$\Omega \times D$ [sr m] :	7	0.2	3	3.4

LLP benchmarks

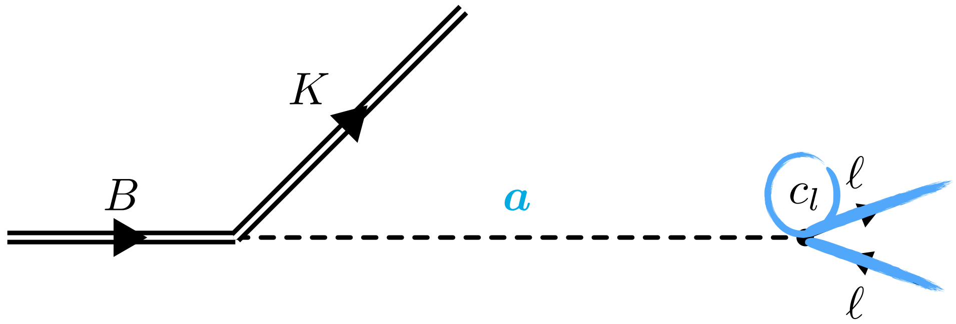
- Heavy neutral lepton



- Dark scalar
  (inelastic dark matter)



- Axion-like particle



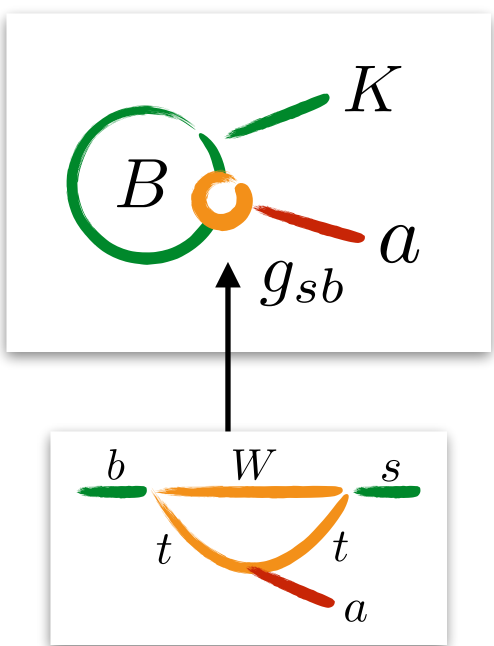
ALPs

$$\mathcal{L} = -2g_{sb}\frac{\partial^\mu a}{\Lambda}\bar{s}\gamma_\mu b_L + \frac{c_\ell}{2}\frac{\partial^\mu a}{\Lambda}\bar{\ell}\gamma_\mu\gamma_5\ell$$

rate

lifetime

- upper bound on production rate: $B \to K + \text{inv.}$

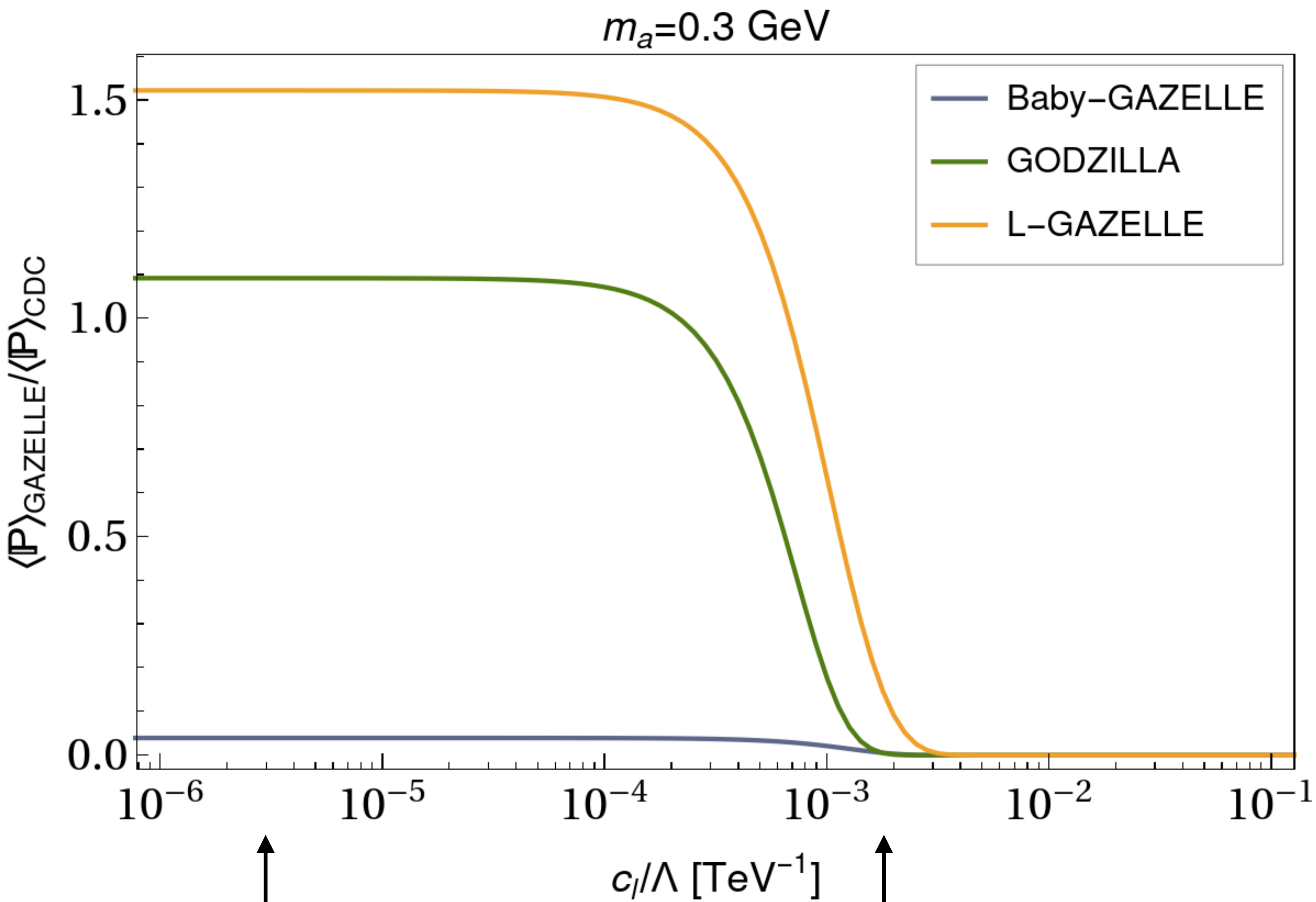


$$g_{sb} \lesssim 10^{-9}$$

BaBar 1303.7465

B > K + inv. at Belle II (in progress):
Ferber, Filimonova, Schaefer, Westhoff

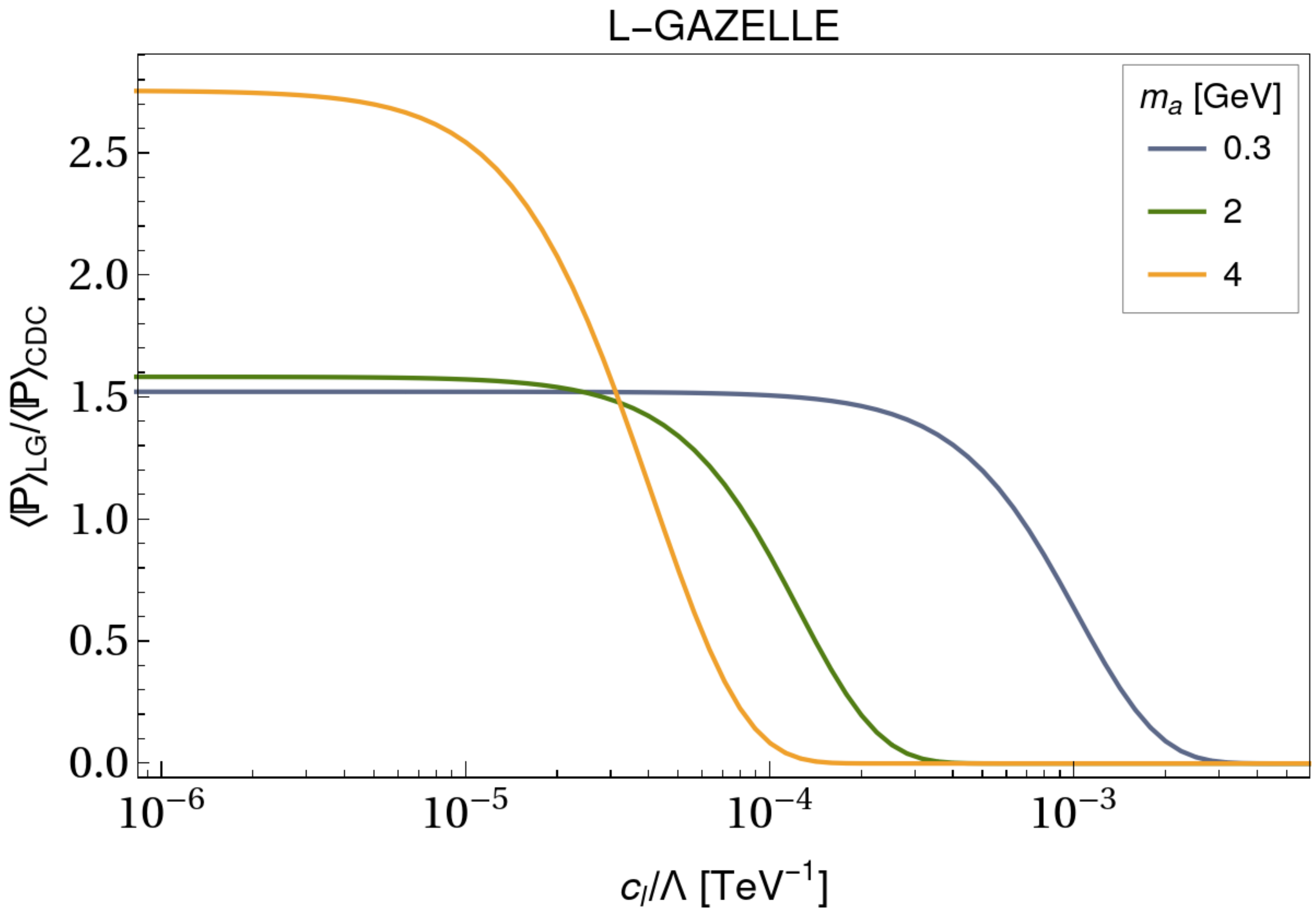
Decay probability GAZELLE vs. Belle II

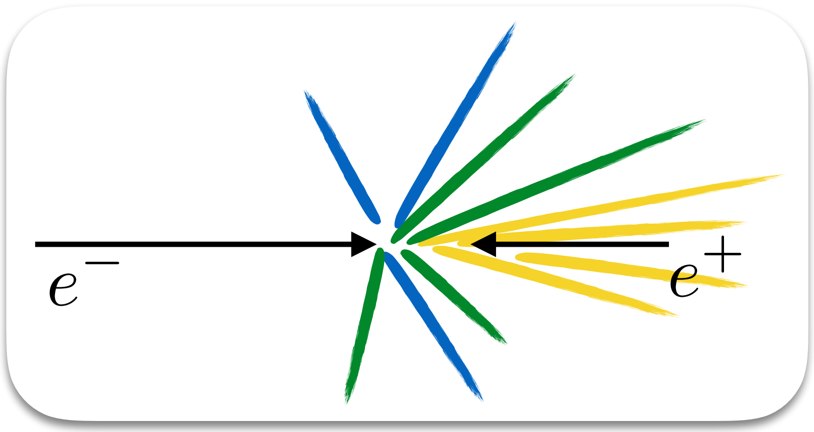


$$\langle\mathbb{P}\rangle \approx \frac{\Omega}{4\pi}\frac{D}{d}$$

$$\langle\mathbb{P}\rangle \sim \exp\left(-\frac{\ell^{\rm in}}{d}\right)$$

Sensitivity to ALP-lepton coupling





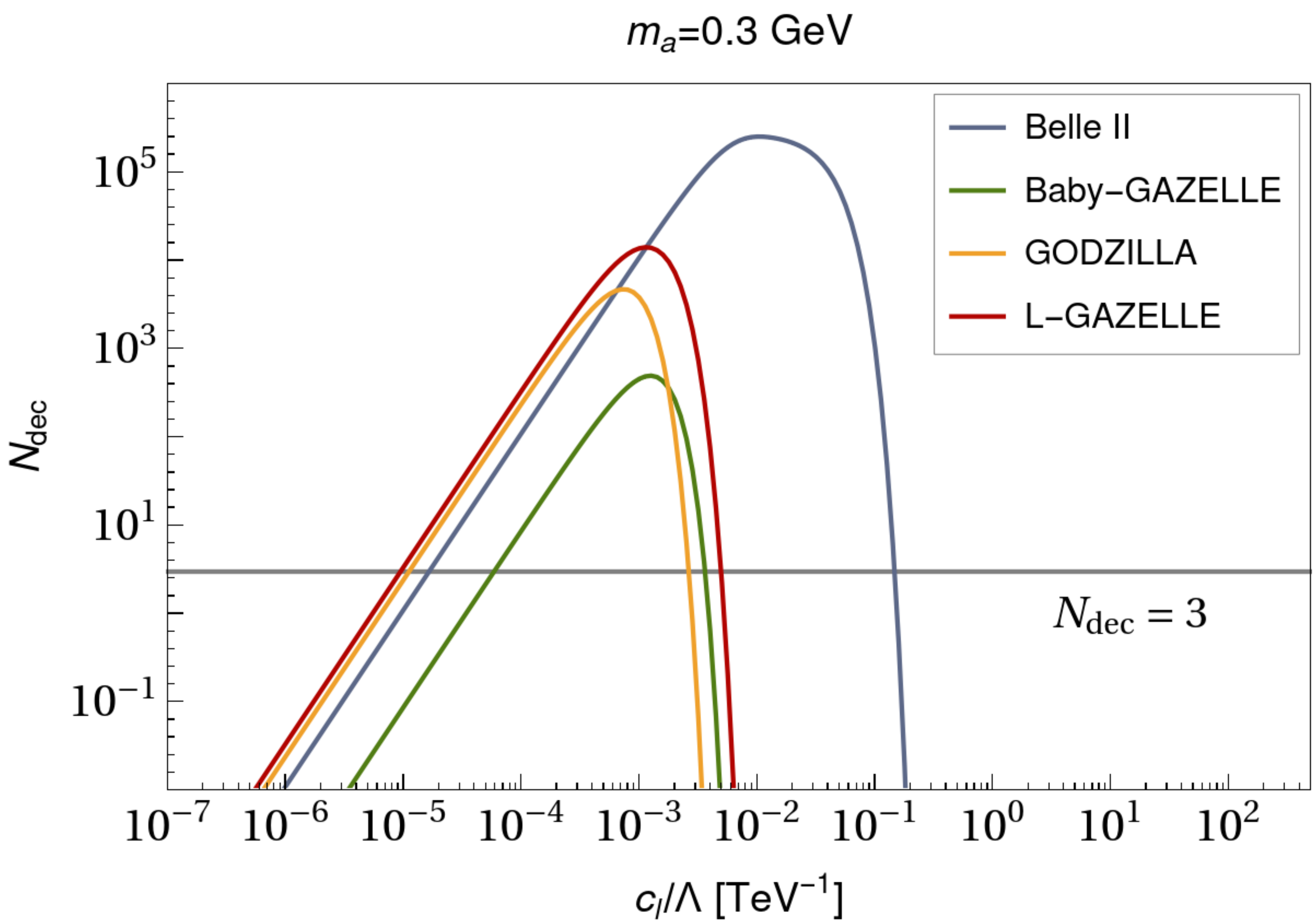
improved sensitivity in forward region

Projected upper bounds on c_ℓ/Λ [TeV^{-1}]

m_a [GeV]	g_{sb}	L-GAZELLE	Belle II	LG/Belle II
0.3	3.9×10^{-9}	9.4×10^{-6}	1.6×10^{-5}	0.57
2.0	3.8×10^{-9}	1.1×10^{-6}	1.9×10^{-6}	0.56
4.0	3.5×10^{-9}	2.7×10^{-7}	6.4×10^{-7}	0.43

- 95% C.L.
- zero background
- 100% efficiency

ALP lifetime reach



proper lifetime

$$c\tau_a \sim \frac{1}{c_\ell^2}\frac{\Lambda^2}{m_a^2}$$

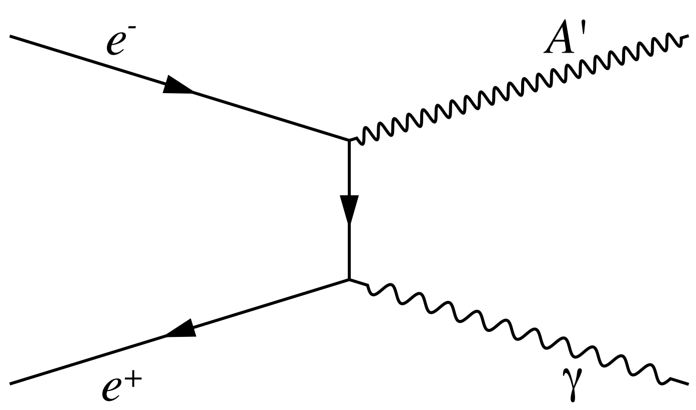
No ‚gap‘ between Belle II and GAZELLE.

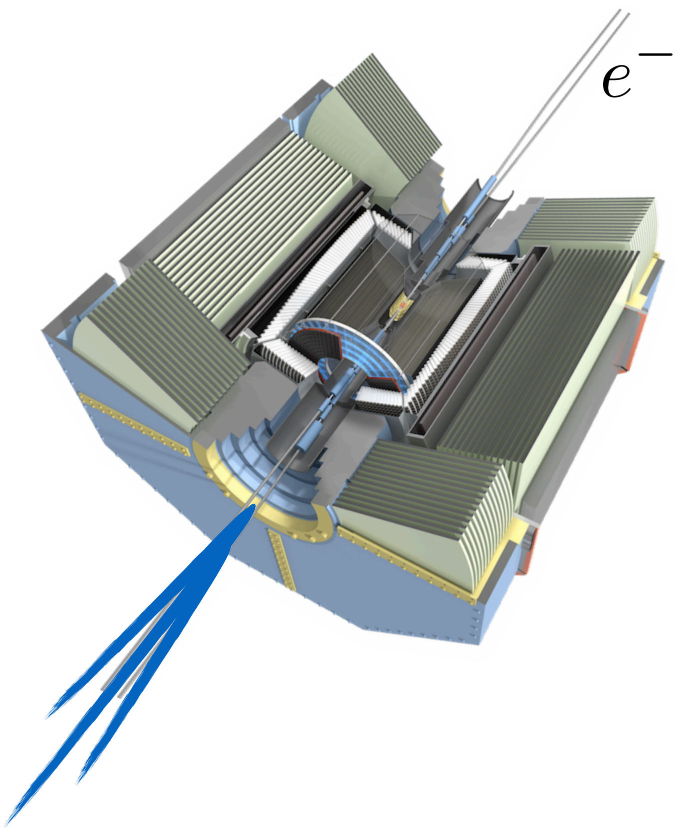
Forward physics

- example: dark photon

An et al. 1510.05020

Chen et al. 2001.04382





- forward enhancement

Fayet hep-ph/0702176

$$\frac{d\sigma}{d\cos\theta} = 2\pi\epsilon^2\alpha^2 \frac{\left(s+m_{A'}^2\right)^2 + \left(s-m_{A'}^2\right)^2 \cos^2\theta}{s\left(s-m_{A'}^2\right)\left(s\sin^2\theta + 4m_e^2\right)},$$

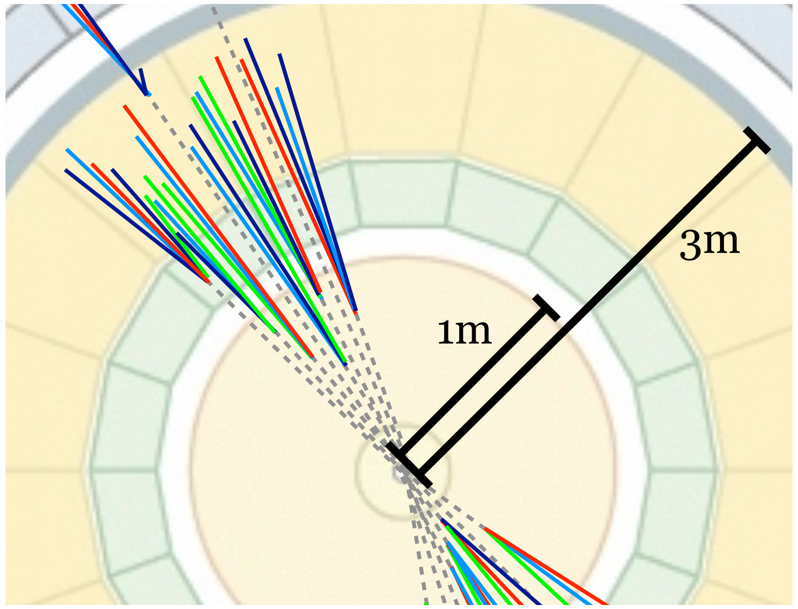
Expect O(1) sensitivity gain with detector in forward region.

Confining dark sectors

- dark showers:

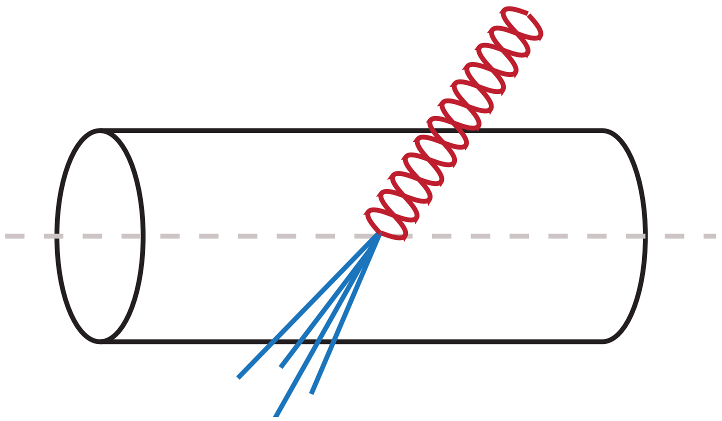
$$e^+e^- \to q_D\bar{q}_D \to \pi_D\pi_D \to \text{jets}$$

emerging jets e.g. Schwaller et al. 1502.05409



- quirks:

$$e^+e^- \to Q_D\bar{Q}_D \to \text{string}$$



flux tubes $\ell \sim \frac{E_{\rm kin}}{\Lambda_{\rm IR}^2} \sim 10\,\mathrm{m}\,\frac{E_{\rm kin}}{10\,\mathrm{GeV}}\left(\frac{10\,\mathrm{eV}}{\Lambda_{\rm IR}}\right)^2.$ e.g. Kang, Luty 0805.4642

Enhanced detection volume for macroscopic objects.

Lessons learned: Belle II / GAZELLE

Sensitivity of far detector versus near detector relies on

$$\langle \mathbb{P} \rangle \approx \frac{\Omega}{4\pi} \frac{D}{\langle \beta\gamma \rangle c\tau}$$

- acceptance: high at near detector > hard to beat
- positioning: small boost in e+e- collisions > forward region
- LLP boost: rather low > close and thin is OK
- background: moderate (expected), signal-dependent

Lessons learned: general

Sensitivity of far detector versus near detector relies on

$$\langle \mathbb{P} \rangle \approx \frac{\Omega}{4\pi} \frac{D}{\langle \beta\gamma \rangle c\tau}$$

- acceptance: *the further away the larger*
- positioning: *put it where the LLPs go*
- LLP boost: *the larger the thicker*
- background: *less is more ;)*

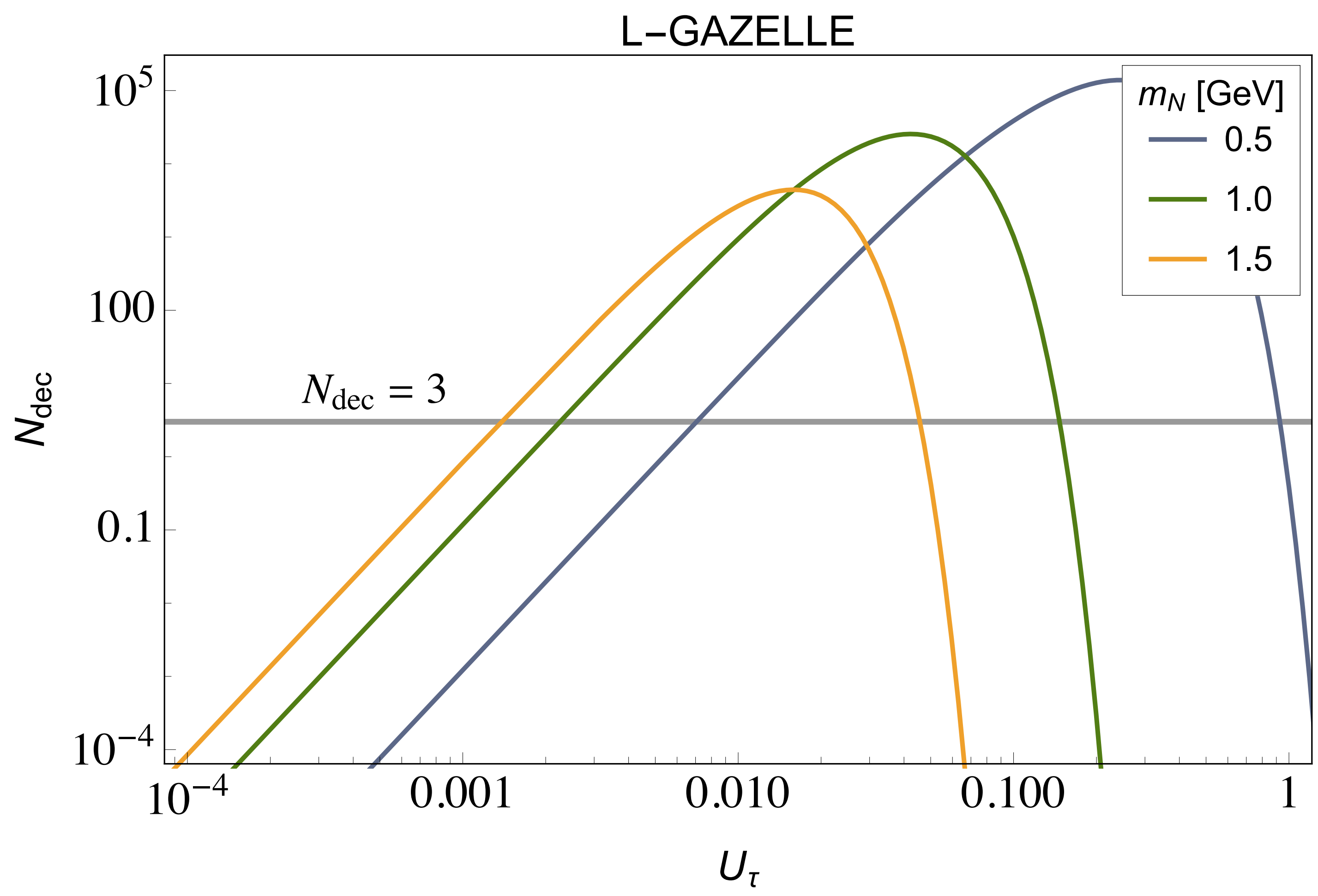
Benefits of Belle II / GAZELLE / ILC?

- Belle II itself is an LLP detector (high acceptance, low boost).
- With GAZELLE, O(1) sensitivity gain (at long lifetimes).
- No sensitivity gap at intermediate LLP lifetimes.
- Belle II's missing energy ~ GAZELLE's displaced vertices.
- Belle II and GAZELLE can trigger each other.
  (background rejection, signal characterization)

Thank you!

Backup

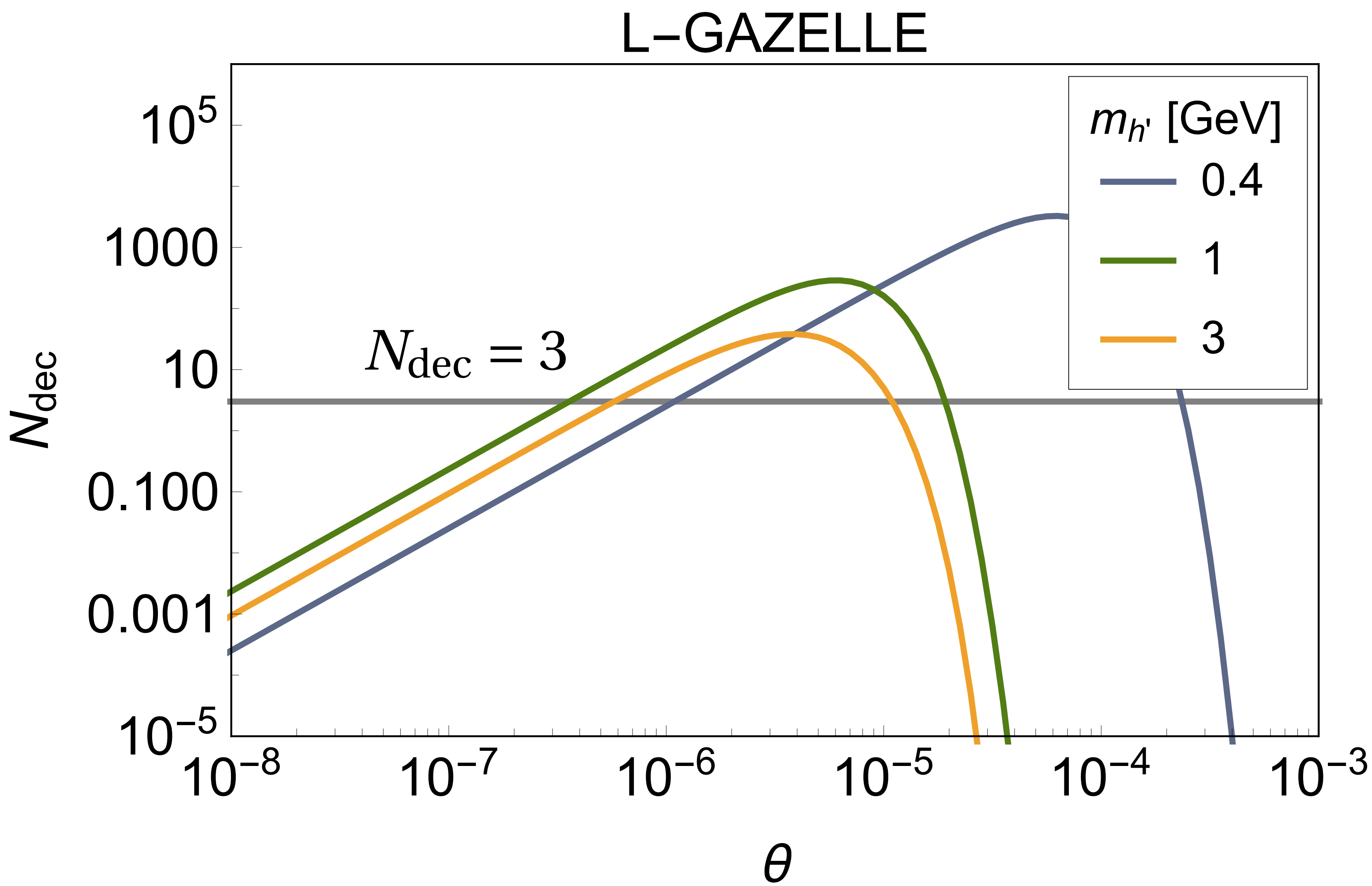
Heavy neutral leptons



Higher BR to leptons for large HNL mass: $\Gamma(N \to \nu_\tau \ell \bar{\ell}) \sim m_N^5 |U_\tau|^2$

m_N [GeV]	L-GAZELLE	Belle II	LG/Belle II
0.5	7.1×10^{-3}	2.0×10^{-3}	3.6
1.0	2.2×10^{-3}	1.1×10^{-3}	2.0
1.5	1.4×10^{-3}	1.6×10^{-3}	0.85

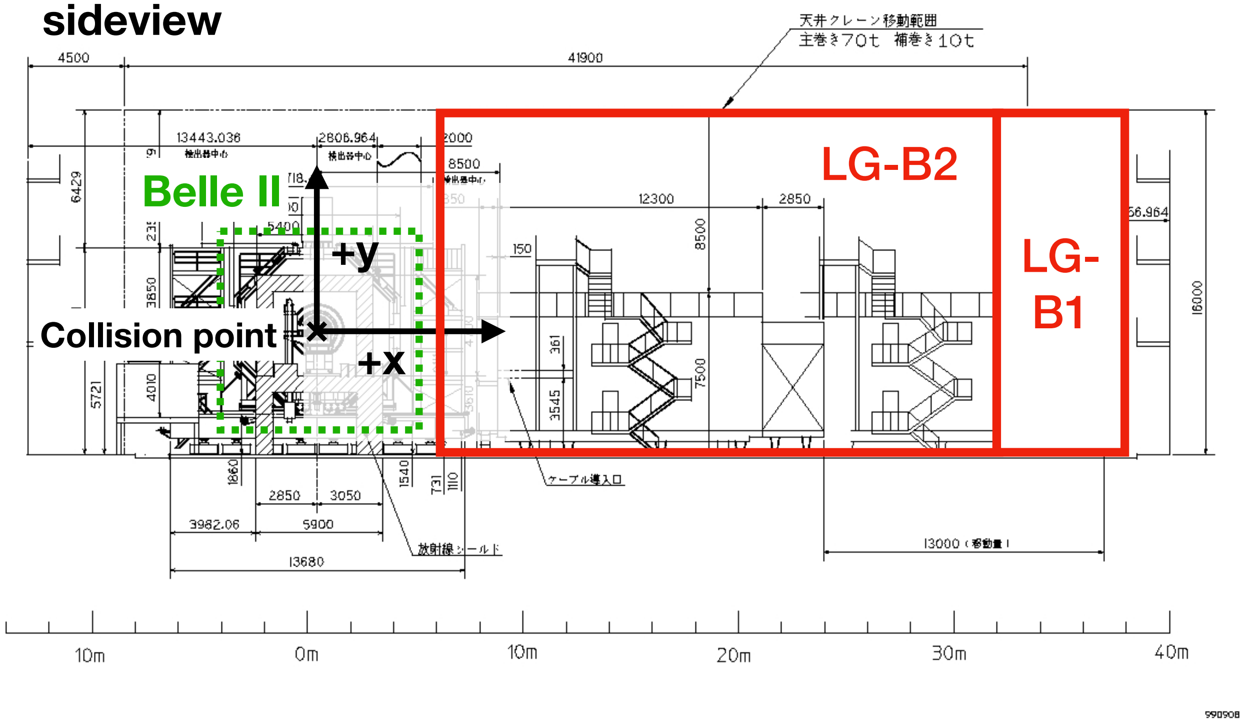
Dark Higgs (iDM)



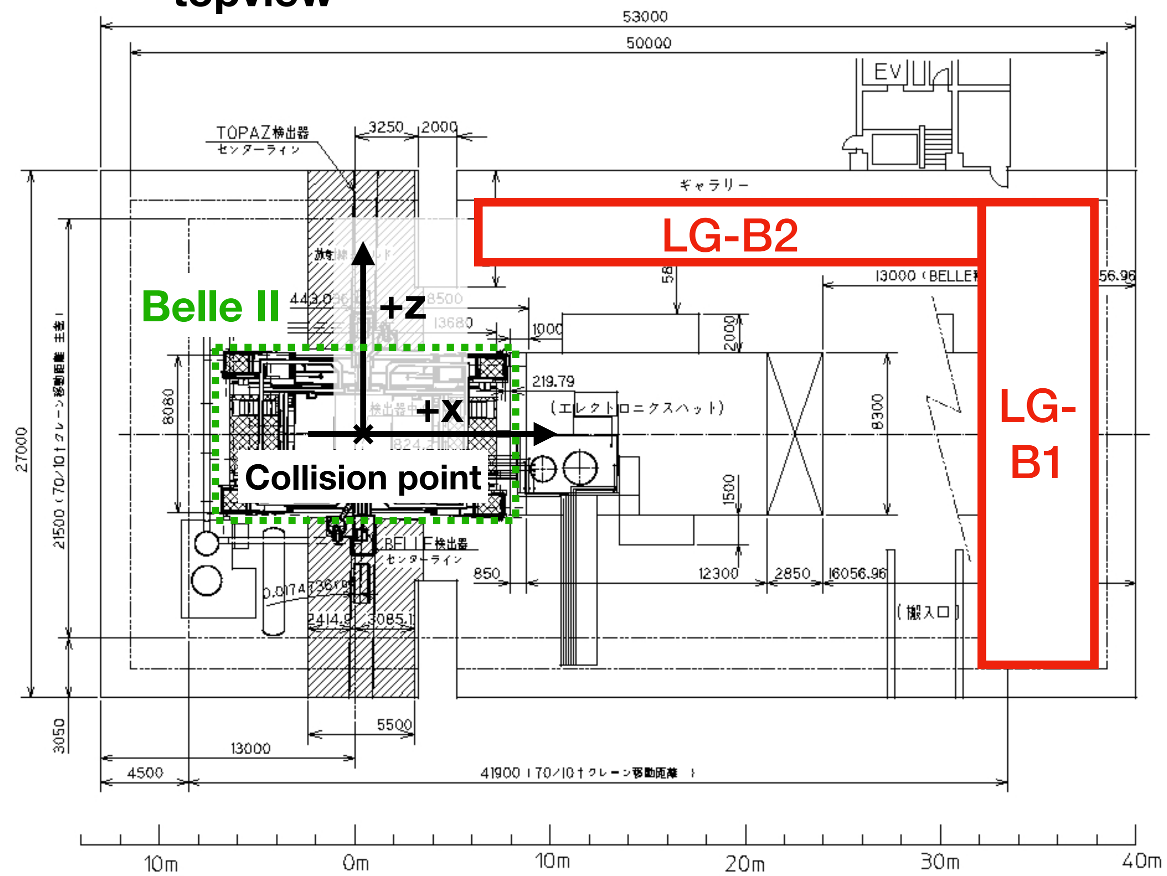
$m_{h'}$ [GeV]	L-GAZELLE	Belle II	LG/Belle II
0.4	1.10×10^{-6}	1.14×10^{-6}	0.96
1.0	3.6×10^{-7}	3.7×10^{-7}	0.97
3.0	5.8×10^{-7}	5.8×10^{-7}	0.99

L-GAZELLE positioning

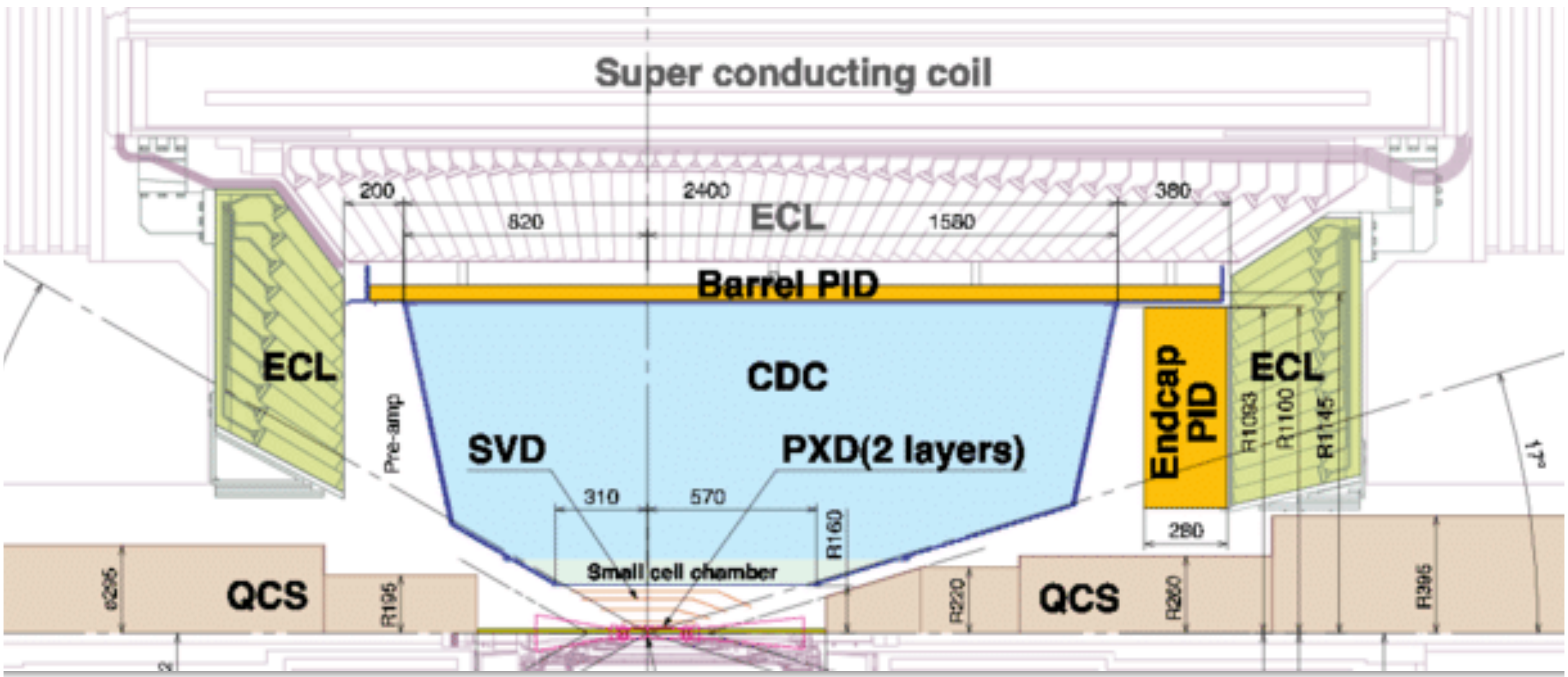
sideview



topview

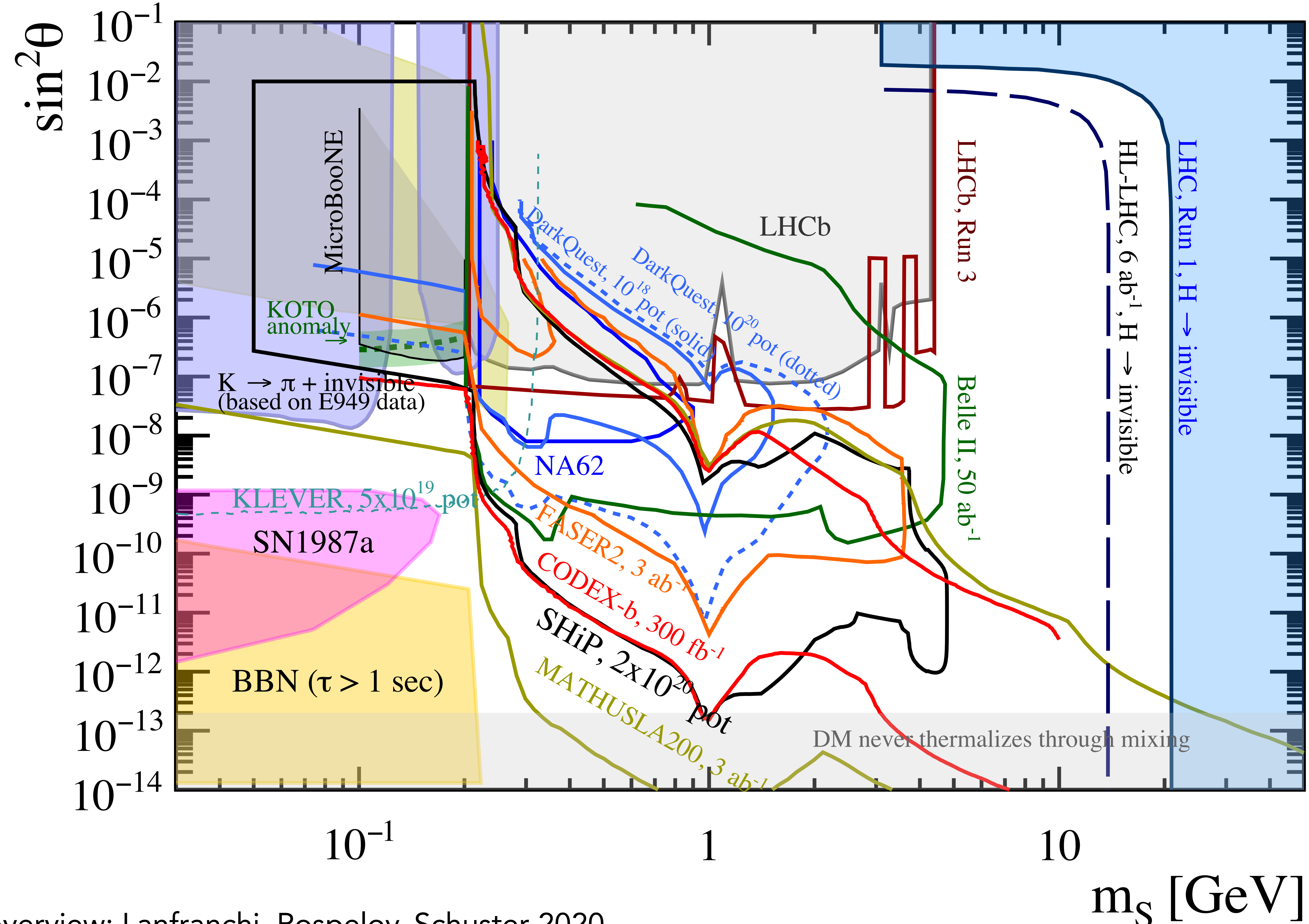


Belle II detector



picture: Belle II collaboration

Long-lived dark scalars



overview: Lanfranchi, Pospelov, Schuster 2020