

Physics reach of

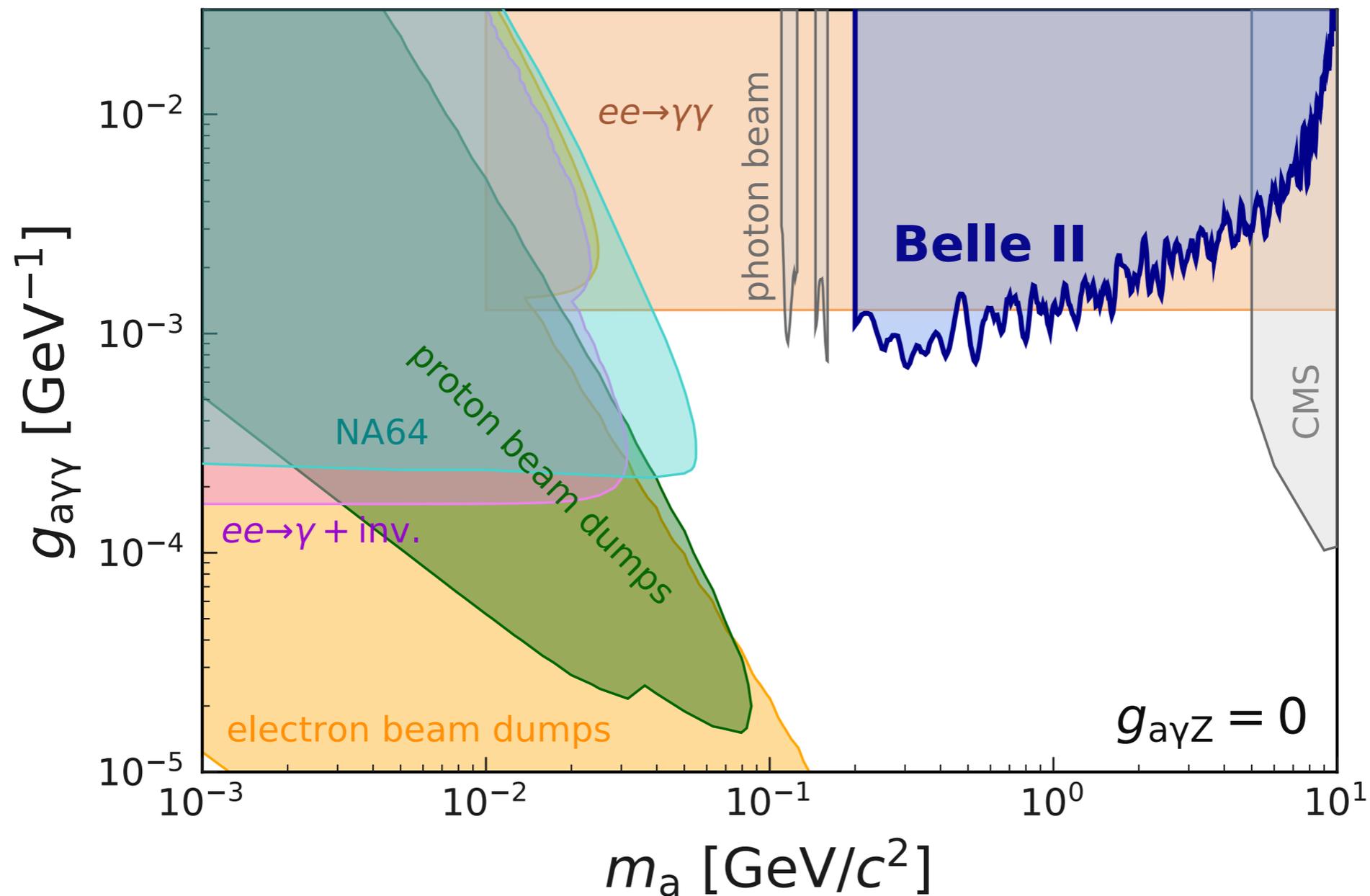
A Long-Lived-Particle Detector at Belle II

and prospects for the ILC

Susanne Westhoff
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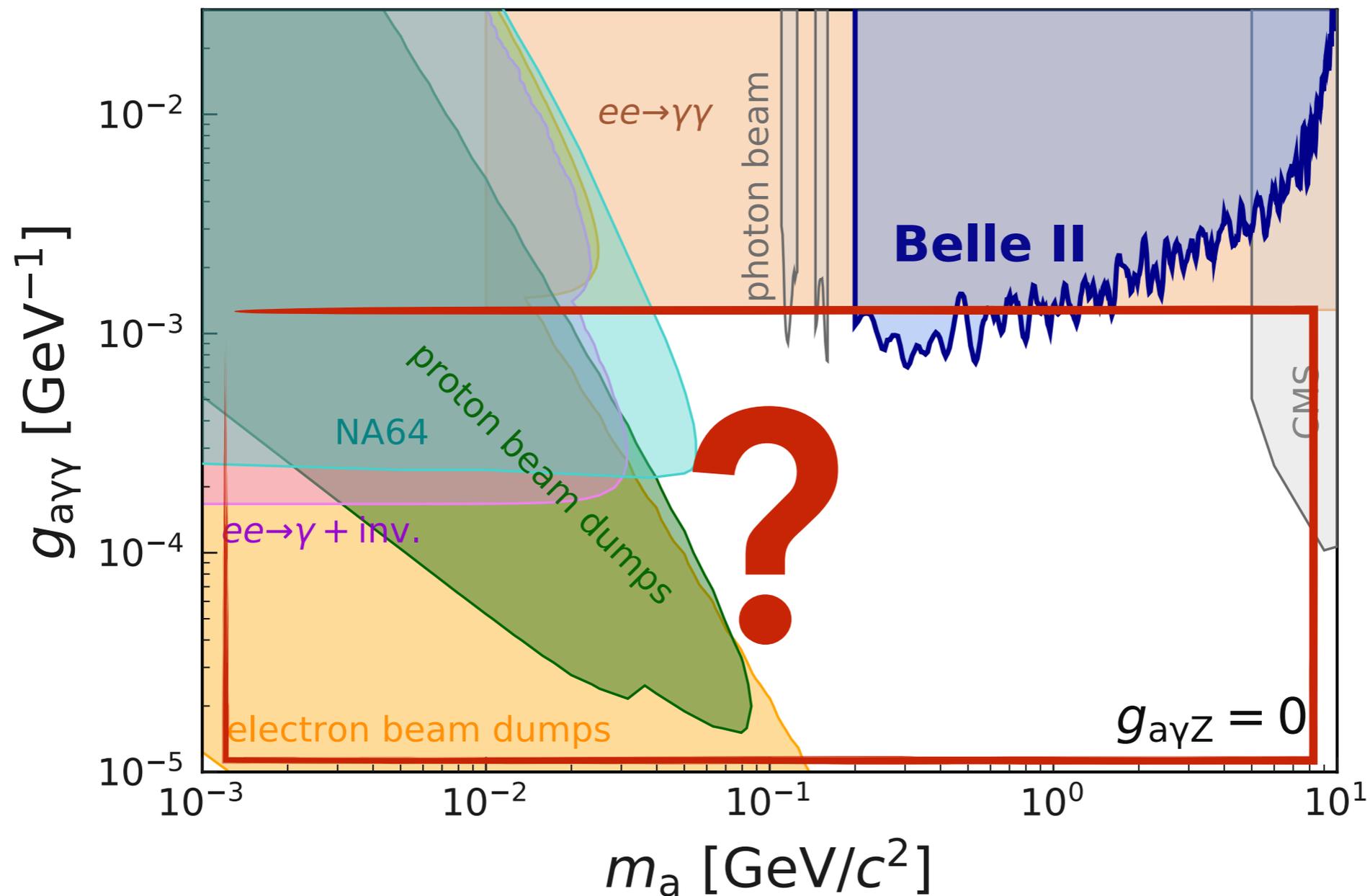
Belle II's first search for light new particles

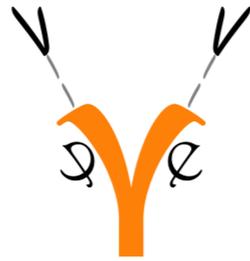
$$e^+e^- \rightarrow a\gamma \rightarrow (\gamma\gamma)\gamma$$



Belle II's first search for light new particles

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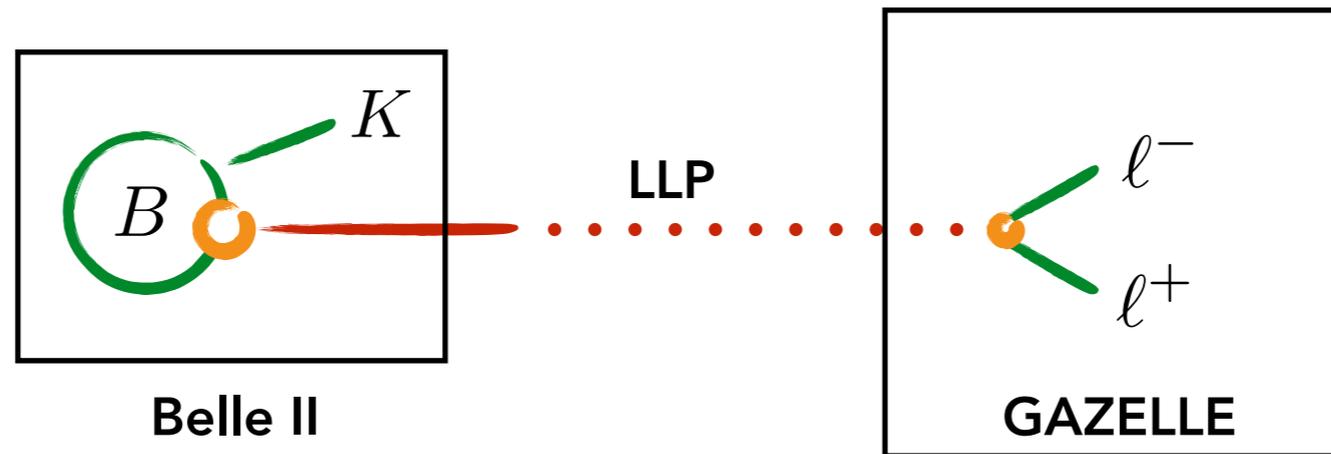




GAZELLE

the

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



Study of realistic options for far detectors around Belle II.

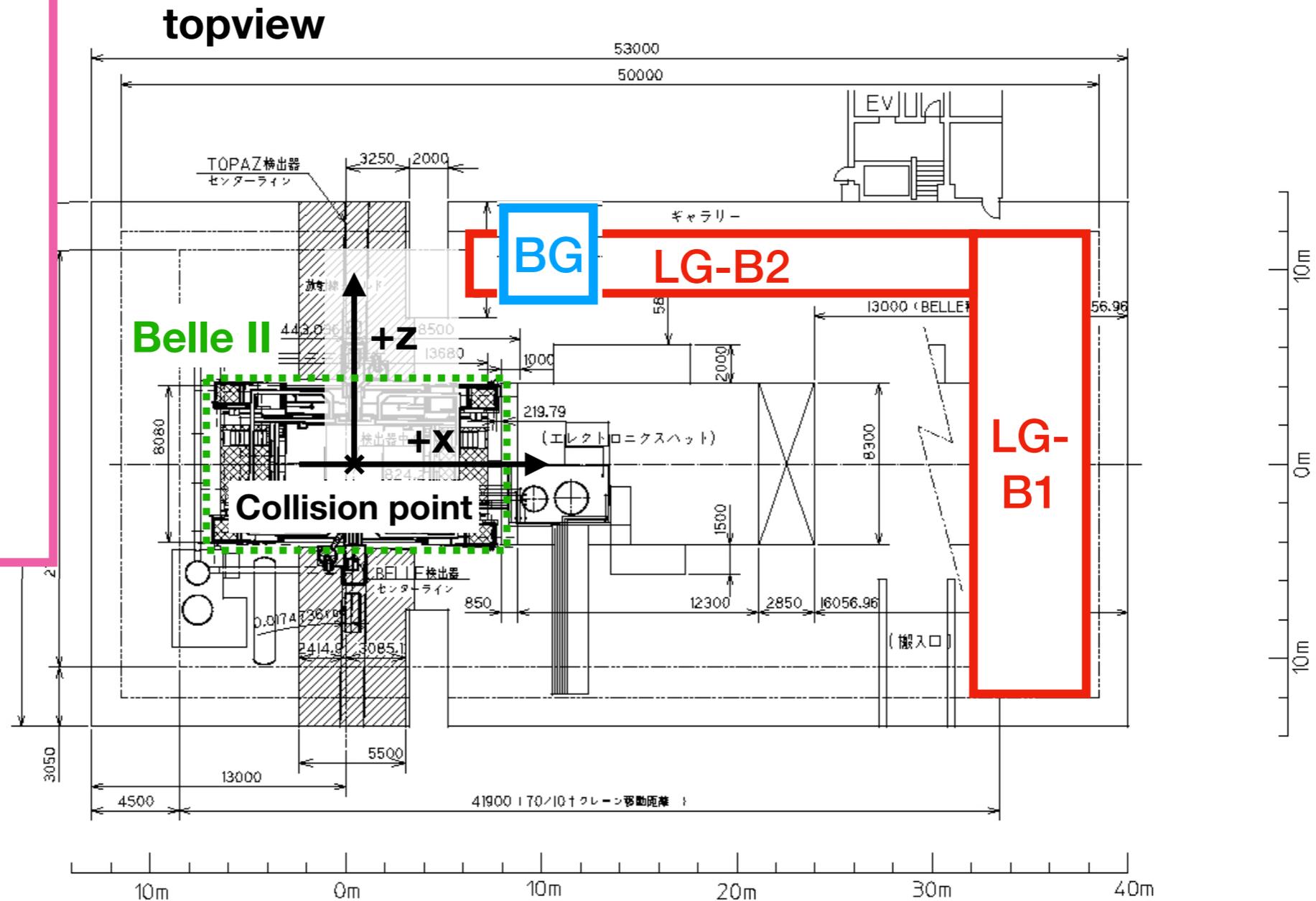
arXiv: 2105.12962

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

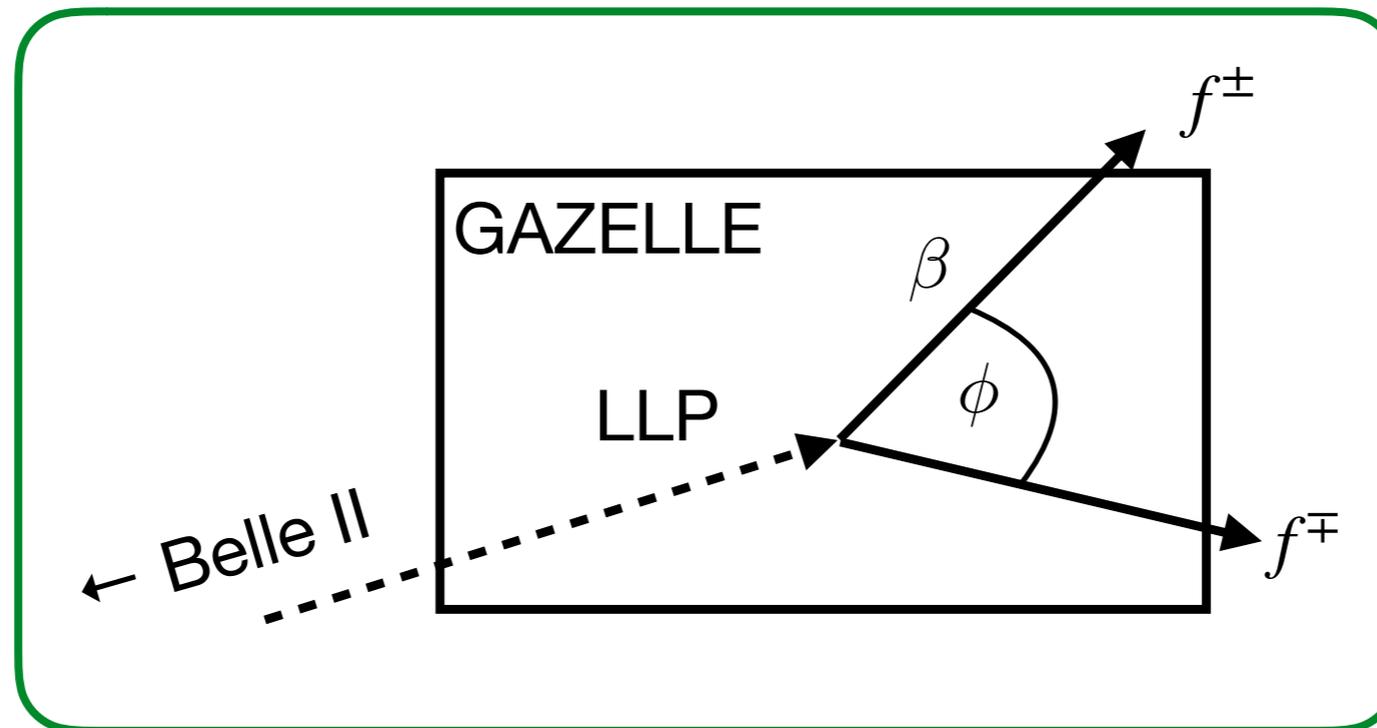
Theory: A. Filimonova, R. Schaefer, K. Schmidt-Hoberg, M. Tamaro, S. Westhoff, J. Zupan

Design options for detectors

GZ



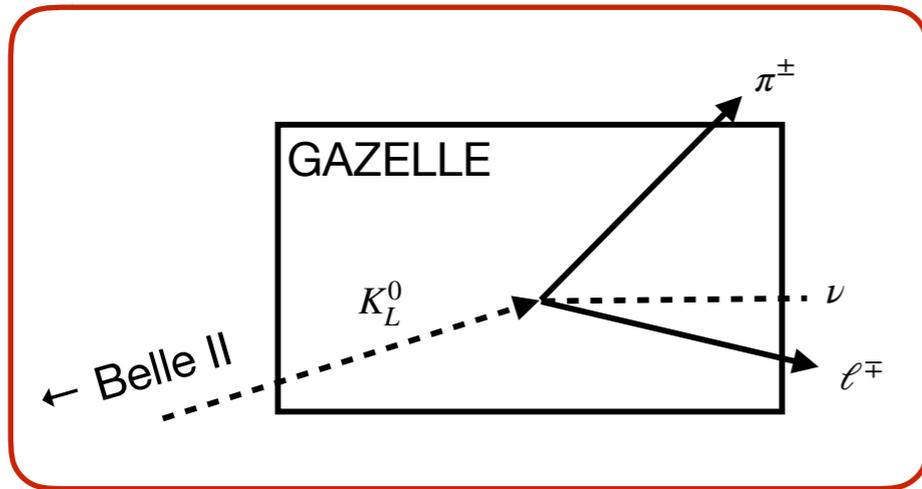
Search target



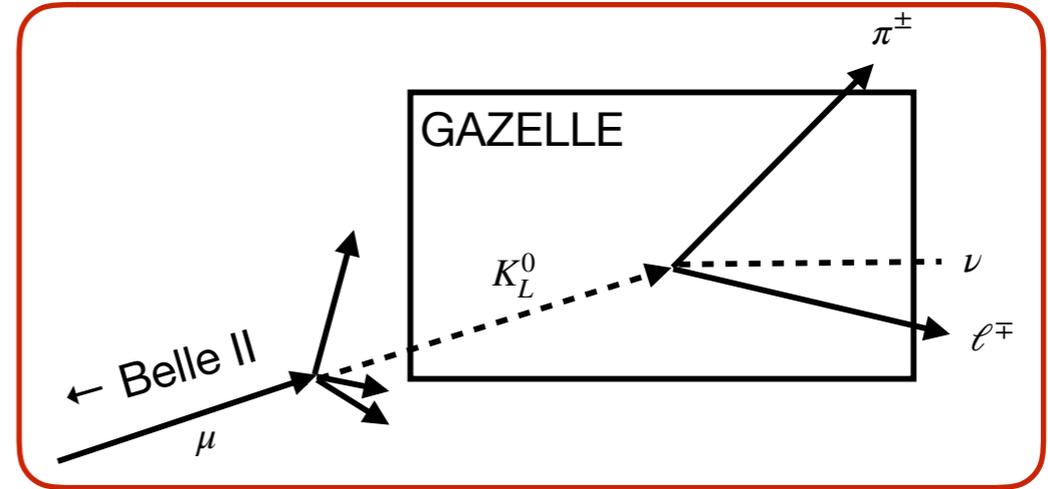
- precise measurement of LLP direction
- reconstruction of LLP mass (β, ϕ)
- GAZELLE and Belle II can trigger each other

Background

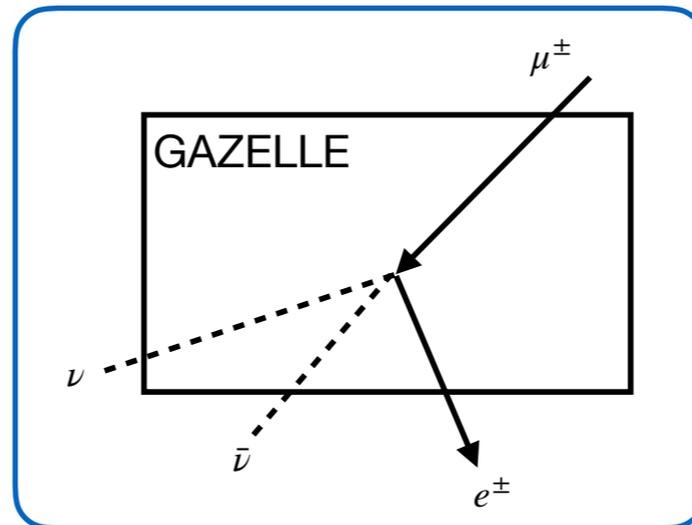
direct kaons



kaons from muons

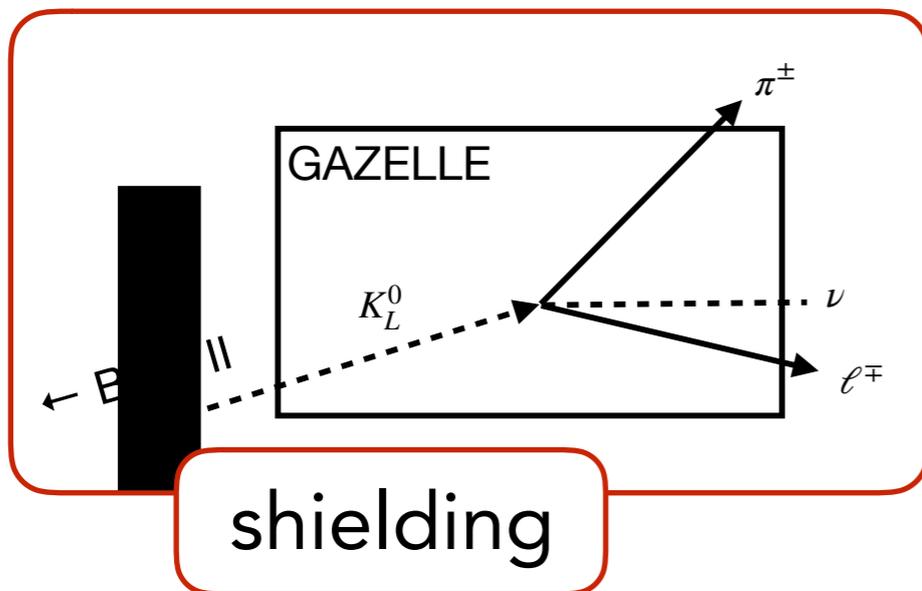


cosmics

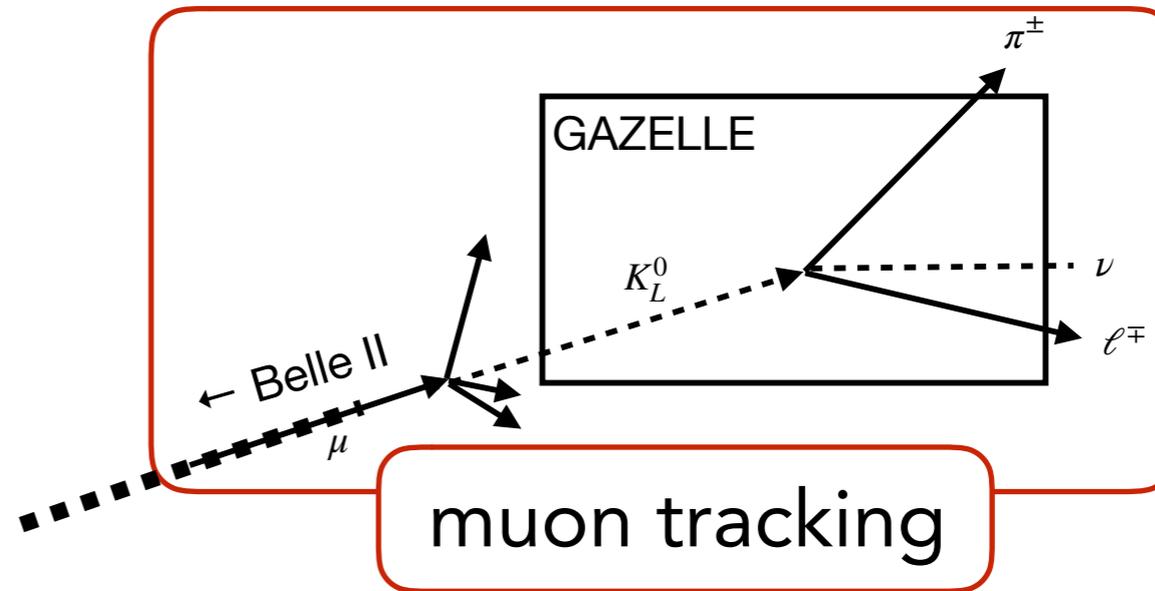


Background rejection

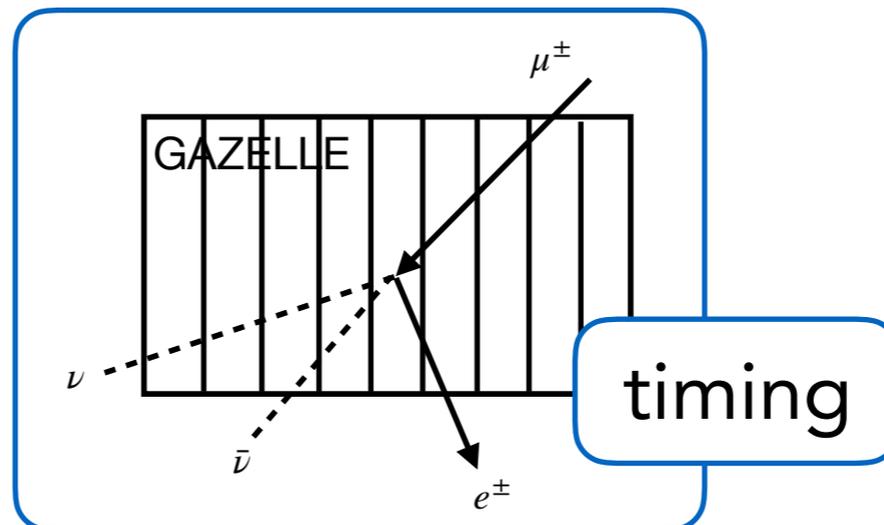
direct kaons



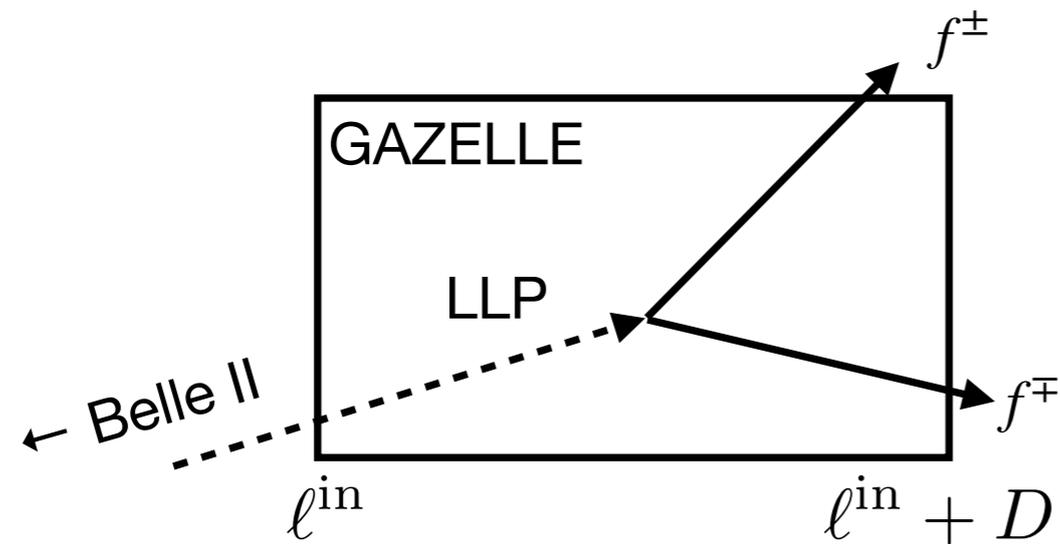
kaons from muons



cosmics



LLP decays inside GAZELLE



decay length

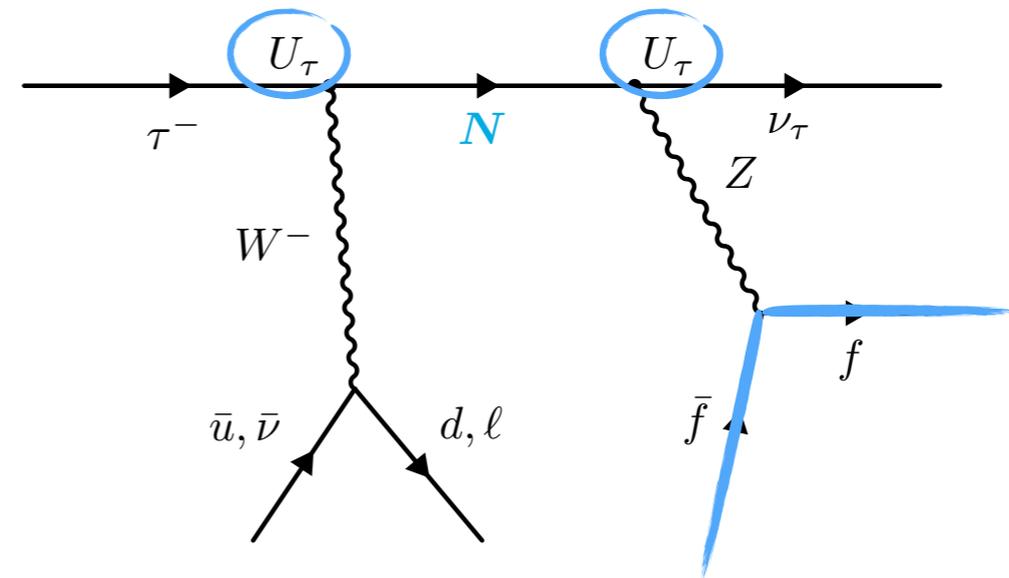
$$d = \langle \beta \gamma \rangle c \tau$$

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

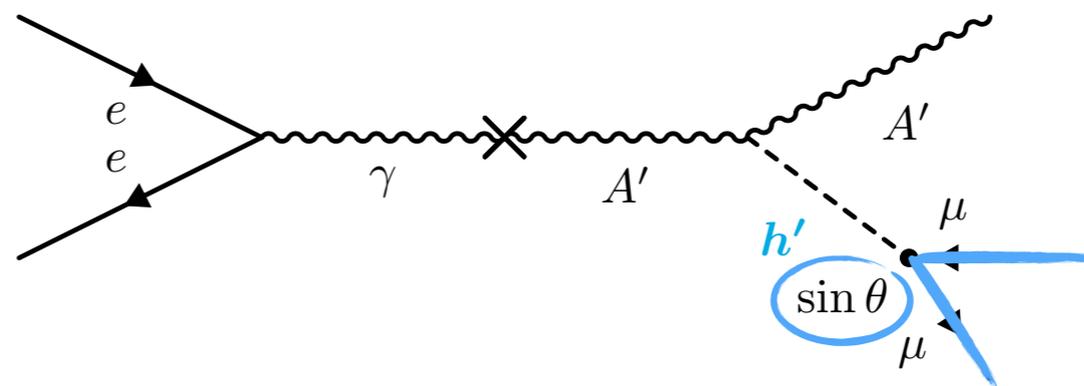
	Belle II	Baby-G.	L-GAZELLE	GODZILLA
$\Omega \times D$ [sr m] :	7	0.2	3	3.4

LLP benchmarks

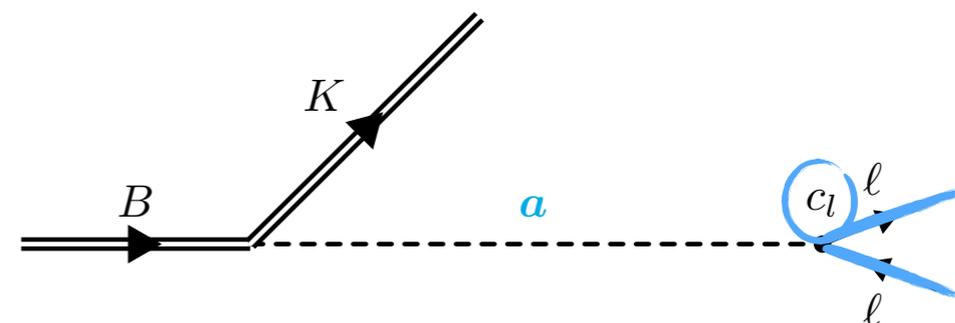
- Heavy neutral lepton



- Dark scalar
(inelastic dark matter)



- Axion-like particle

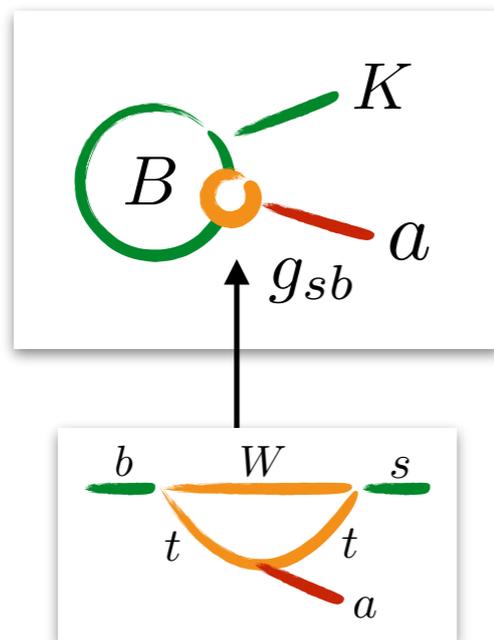


Axion-like particles (ALPs)

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

rate
lifetime

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

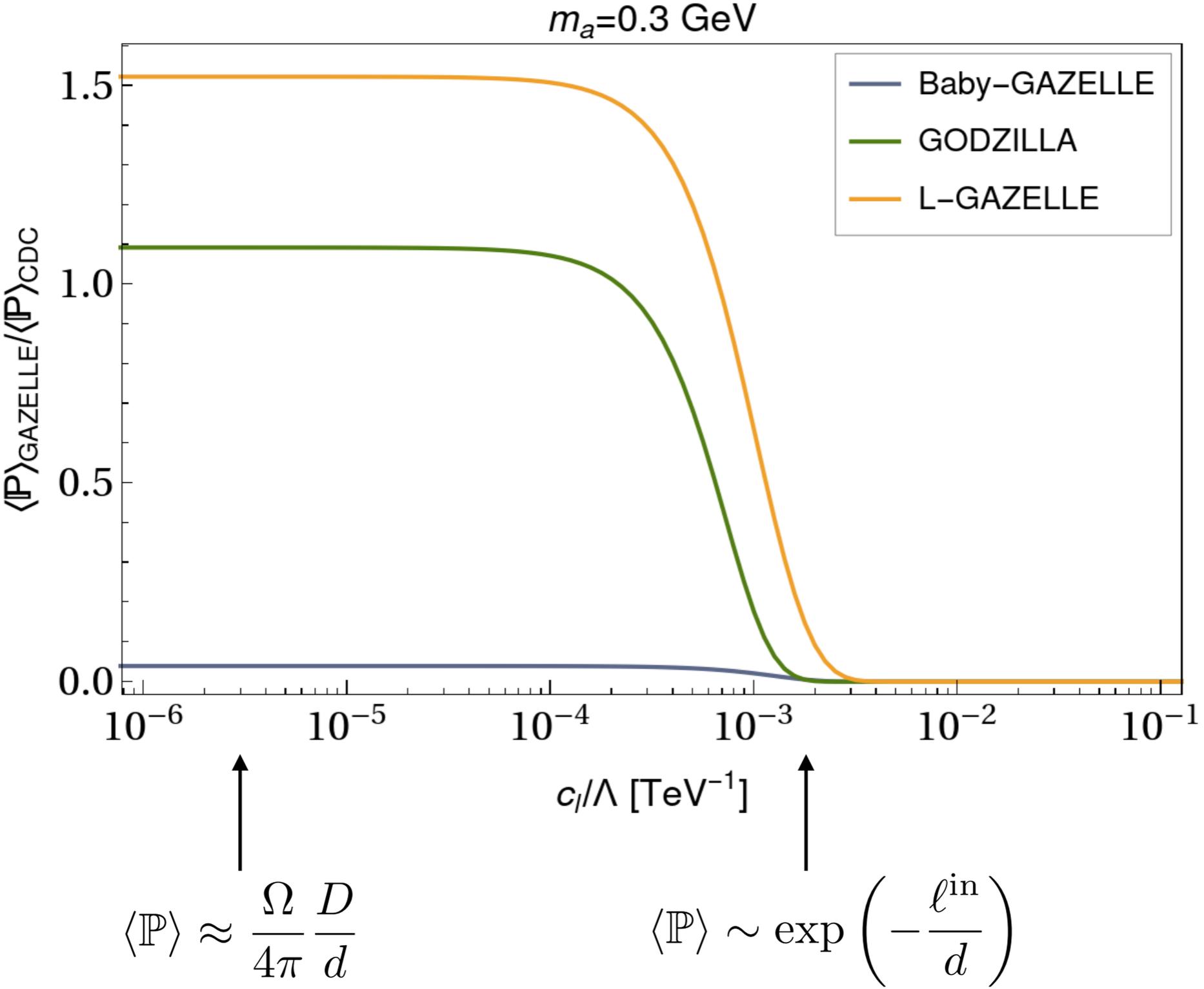


$$g_{sb} \lesssim 10^{-5}$$

BaBar 1303.7465 (recast)

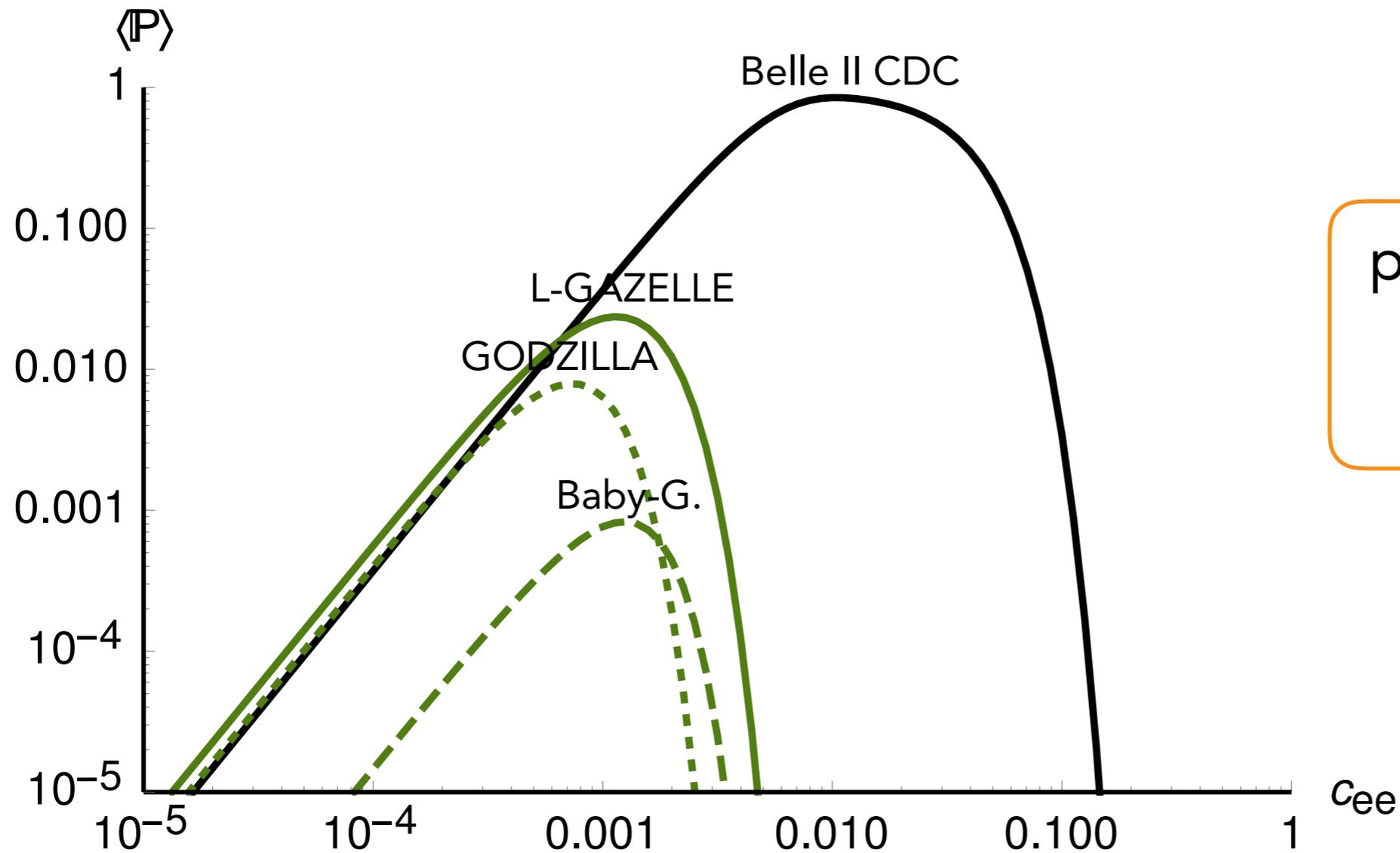
$B > K + \text{inv.}$ at Belle II (in progress):
Ferber, Filimonova, Schaefer, Westhoff

Decay probability GAZELLE vs. Belle II



ALP lifetime reach

$m_a = 0.3 \text{ GeV}$



proper lifetime

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

No sensitivity gap between Belle II and GAZELLE.

Lessons learned

LLP sensitivity of far detector versus near detector relies on

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

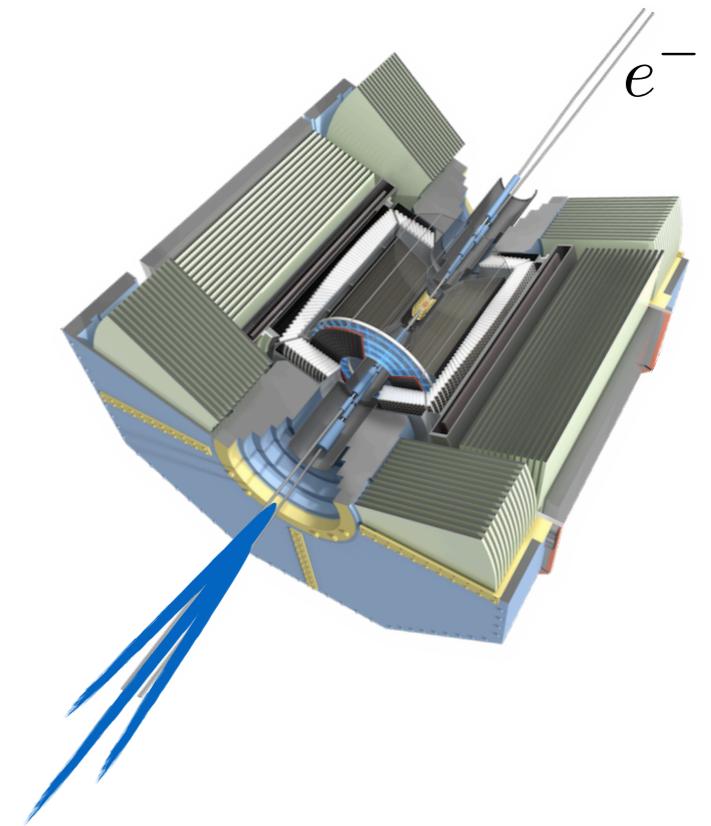
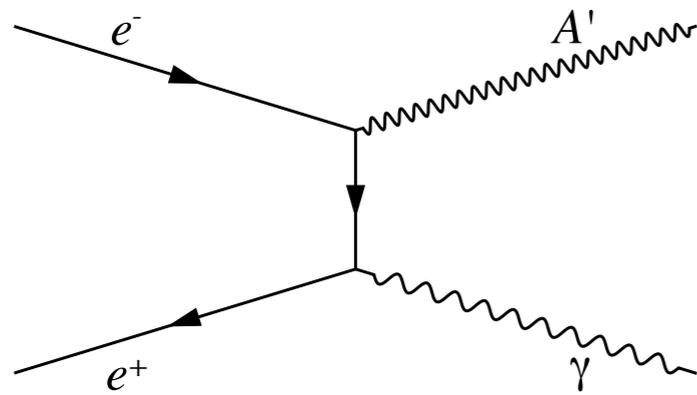
- acceptance: *the further away the larger*
- positioning: *Belle II: forward (boost), ILC: central (model-dep.)*
- LLP boost: *the larger the boost the thicker the detector*
- signatures: *displaced vertex (far) — missing energy (main)*

Forward physics at e+e- colliders

- example: dark photon

An et al. 1510.05020

Chen et al. 2001.04382



- forward enhancement

Fayet hep-ph/0702176

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

Belle II: expect O(1) sensitivity gain with forward far detector.

An off-beam far detector at the ILC?

ILC versus Belle II:

- larger LLP boost

$$d_{\text{ILC}} \approx 10 d_{\text{BII}} \text{ (light LLPs)}$$

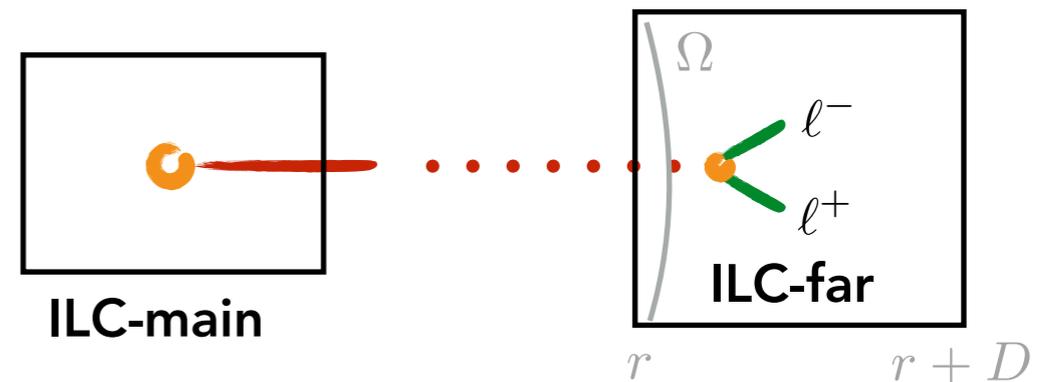
larger relative rate ILC-far/main

- different LLP production

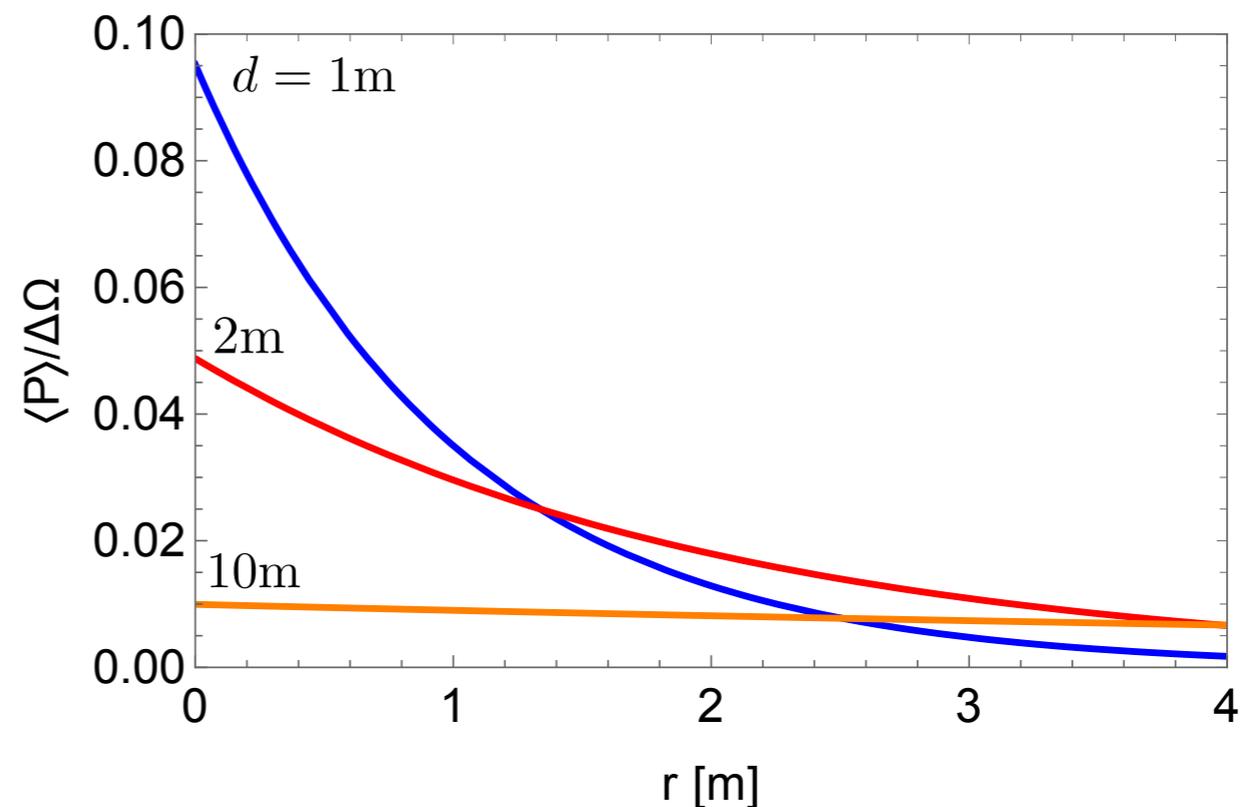
Z/Higgs decays, VBF, LLP+photon

Similar to Belle II:

- ILC-far should be large (high acceptance at ILC-main)
- close by is better than far away (optimize geometric acceptance)



$D=0.1\text{m}$



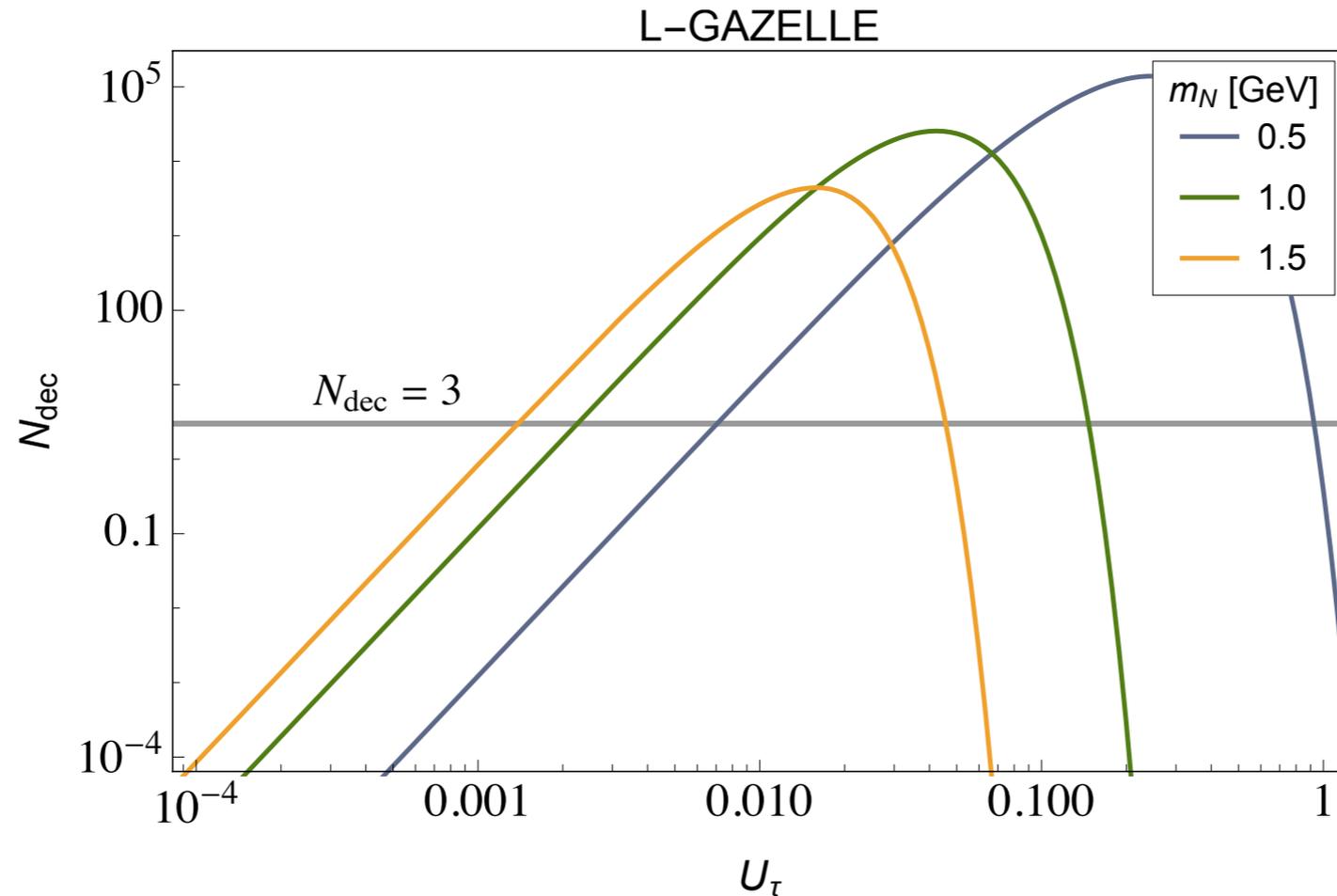
Conclusions: far detector at ILC

- ILD itself should be a great LLP detector.
(high acceptance, clean environment)
- Sensitivity gain of far detector larger than at Belle II.
(LLPs produced with higher boost)
- Explore new production channels.
(Higgs, electroweak, top (ILC-500))
- Signal coincidence:
missing energy (main) - displaced vertices (far).
- Main and far detector can trigger each other.
(background rejection, signal characterization).

Thank you!

Backup

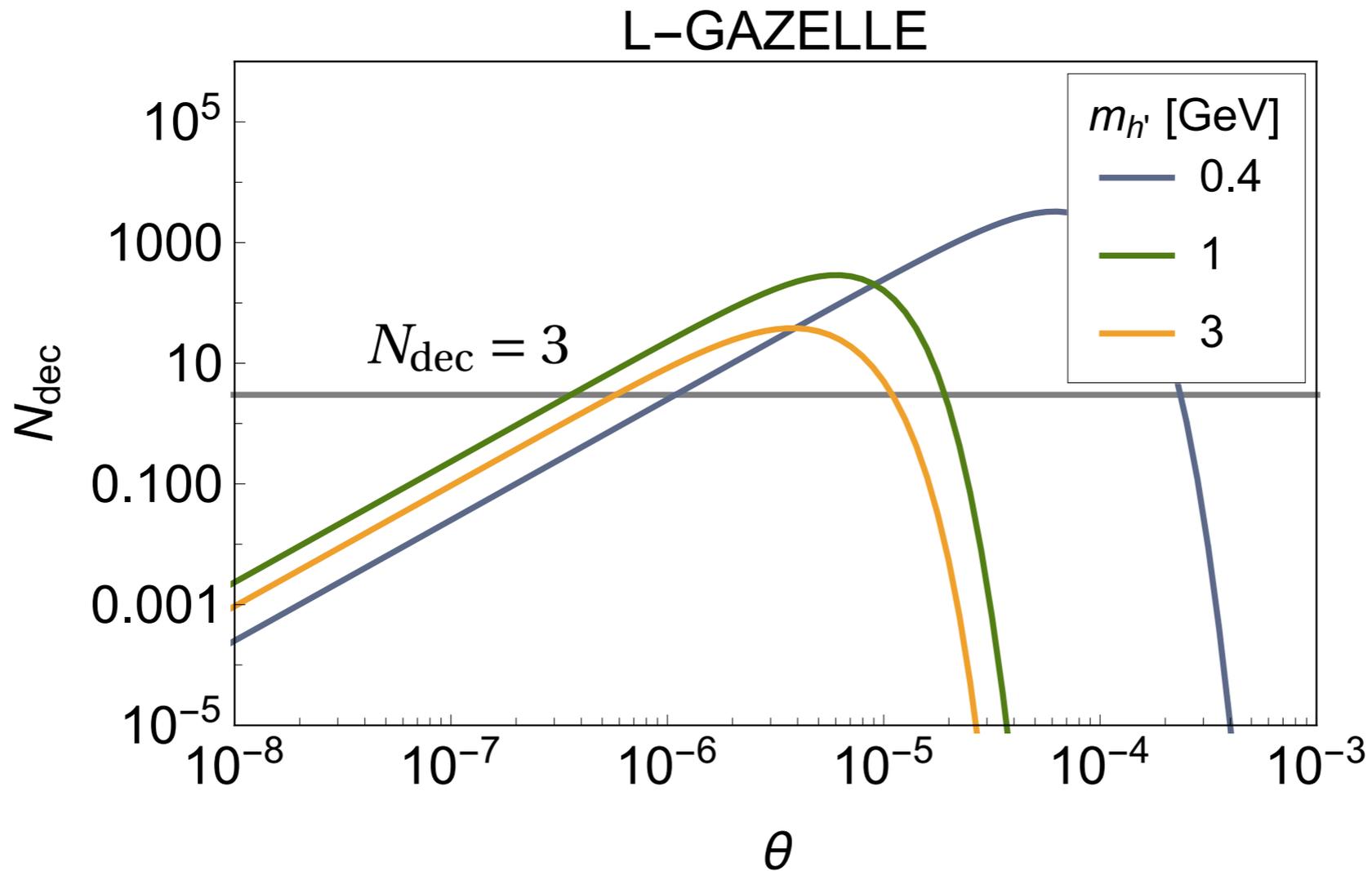
Heavy neutral leptons



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

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)



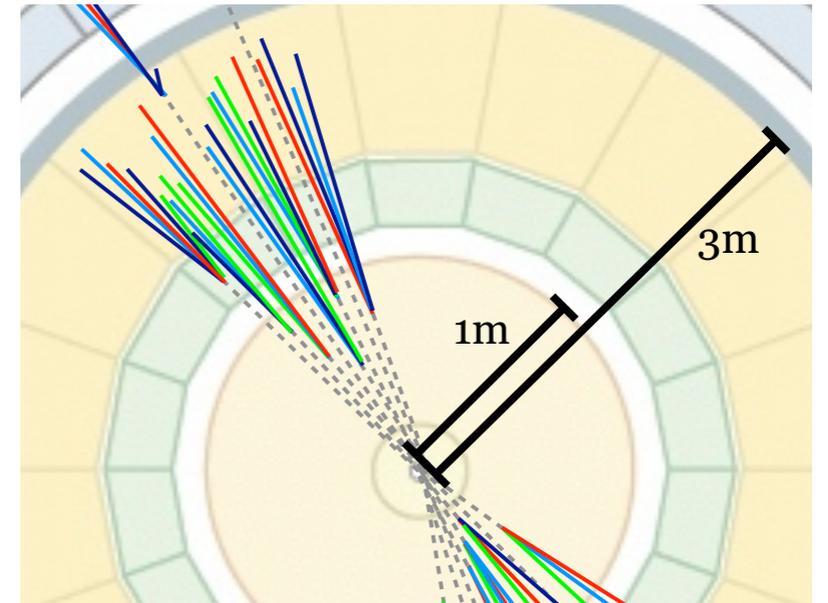
$m_{h'}$ [GeV]	L-GAZELLE	Belle II	LG/Belle II
0.4	1.10×10^{-6}	1.14×10^{-6}	0.96
1.0	3.6×10^{-7}	3.7×10^{-7}	0.97
3.0	5.8×10^{-7}	5.8×10^{-7}	0.99

Confining dark sectors

- dark showers:

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

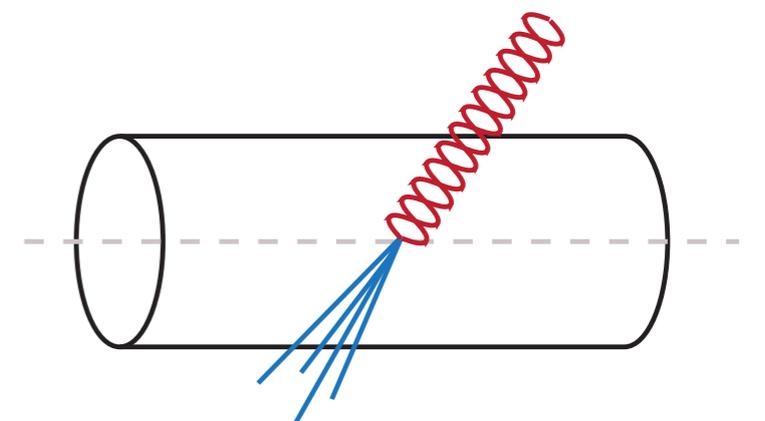
emerging jets e.g. Schwaller et al. 1502.05409



- quirks:

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

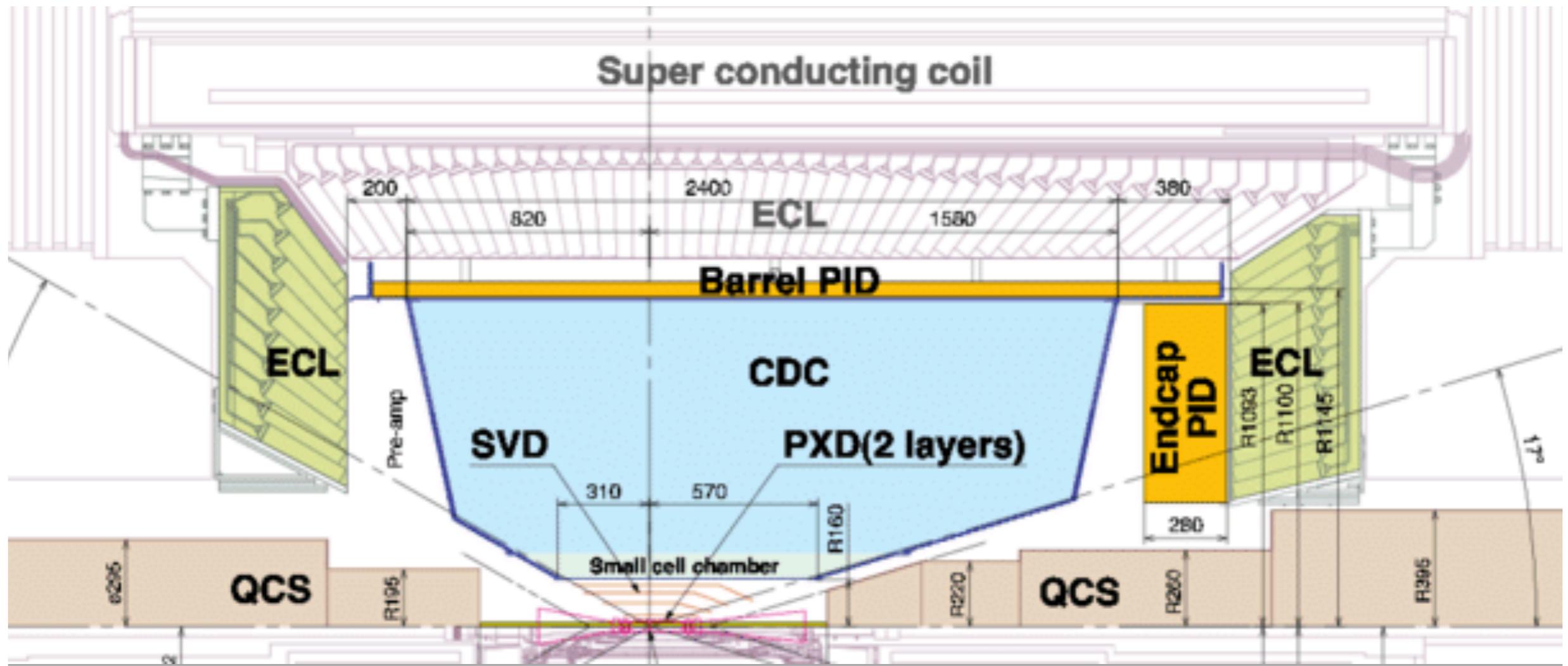
flux tubes $\ell \sim \frac{E_{\text{kin}}}{\Lambda_{\text{IR}}^2} \sim 10 \text{ m} \frac{E_{\text{kin}}}{10 \text{ GeV}} \left(\frac{10 \text{ eV}}{\Lambda_{\text{IR}}} \right)^2.$



e.g. Kang, Luty 0805.4642

Enhanced detection volume for macroscopic objects.

Belle II detector



picture: Belle II collaboration

Long-lived dark scalars

