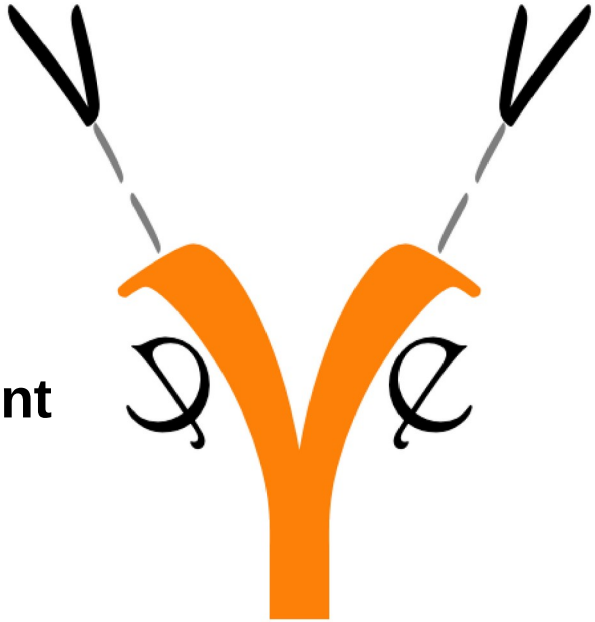
Nikhef



GAZELLE

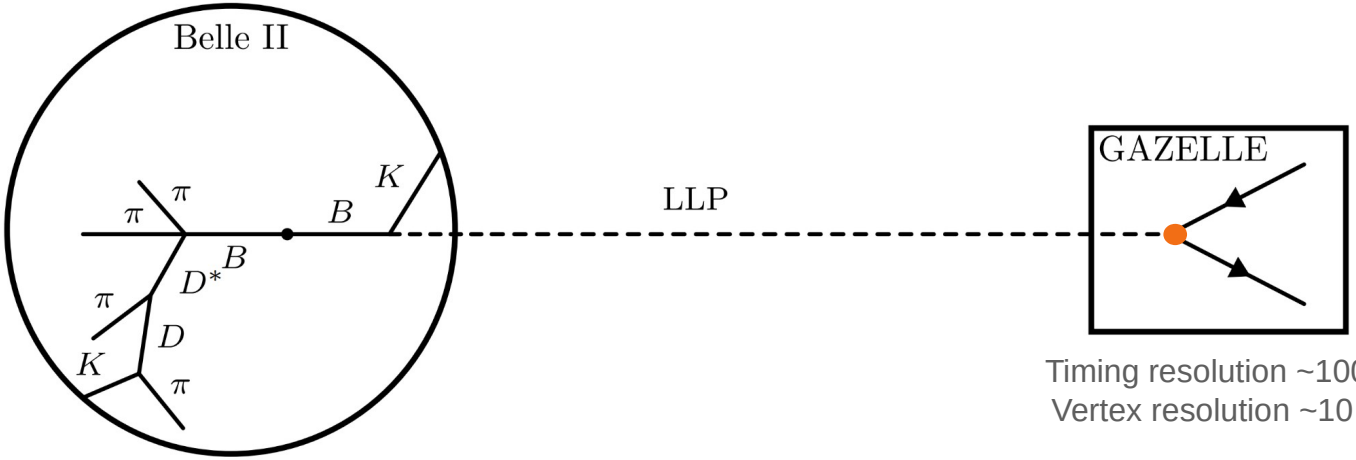
An Approximately Zero-background Experiment for Long-Lived Exotics at Belle II

Anastasiia Filimonova

Belle II workshop
8 Sep 2021, Vienna

Based on the SnowMass2021 Contributed Paper [2105.12962] with S. Dreyer, T. Ferber, C. Garcia-Cely, C. Hearty, S. Longo, R. Schäfer K. Schmidt-Hoberg, M. Tammaro, K. Trabelsi, S. Westhoff and J. Zupan.

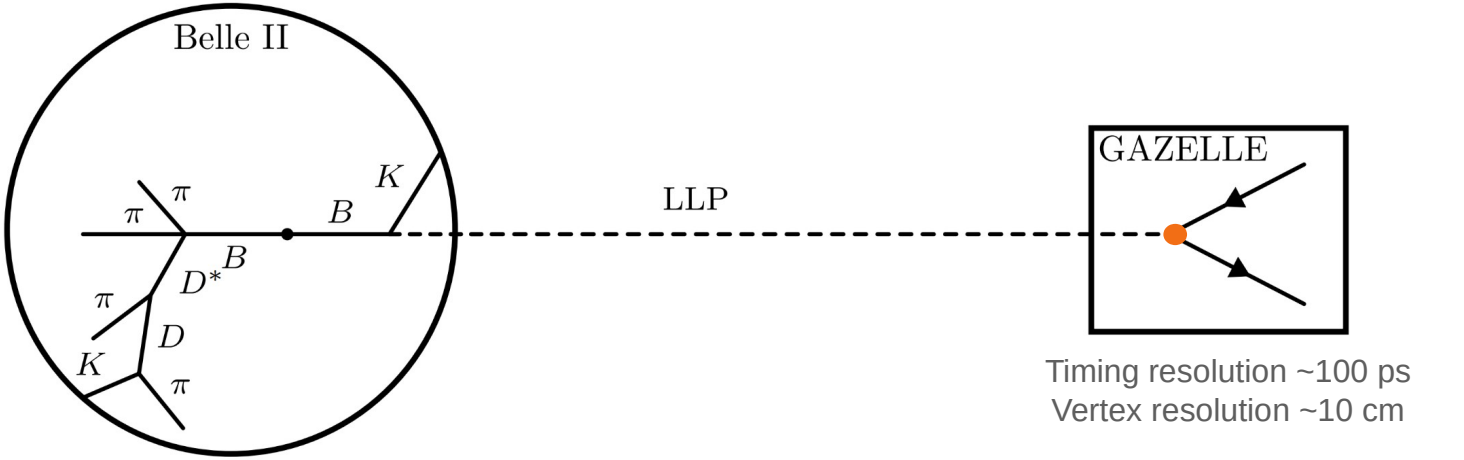
A far-distance detector for longer lifetimes



Timing resolution ~100 ps
Vertex resolution ~10 cm

No calorimetry required = cheap!

A far-distance detector for longer lifetimes



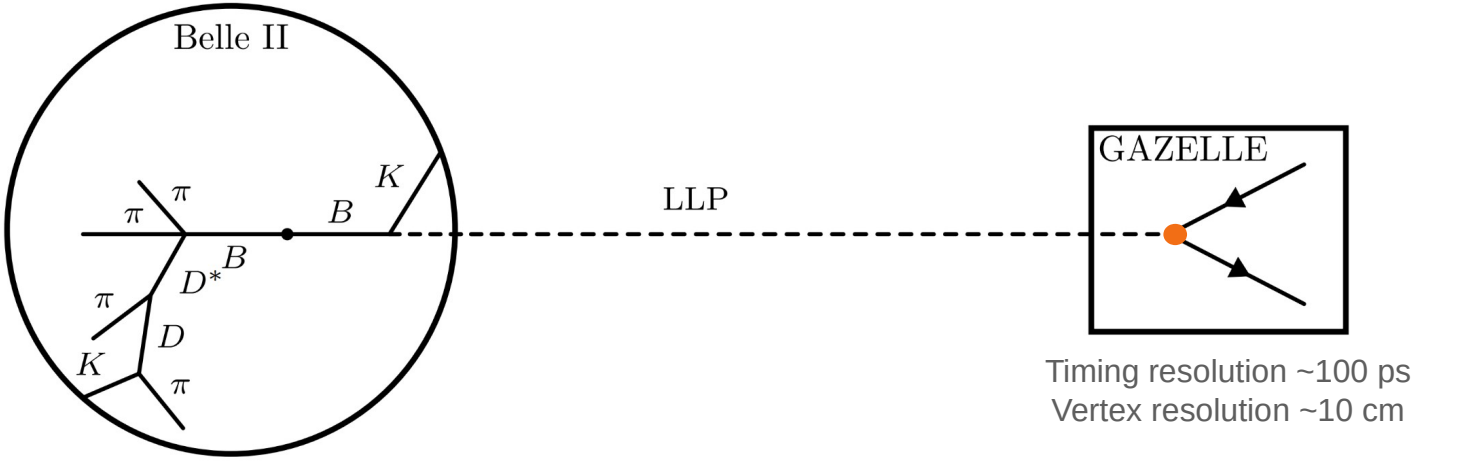
Timing resolution ~100 ps
Vertex resolution ~10 cm

No calorimetry required = cheap!

Possible to reconstruct:

- Vertex
- Mass
- Track direction
- Pointing angle (moderate boost)
- Absolute time (synchronize with Belle II)

A far-distance detector for longer lifetimes



Timing resolution ~100 ps
Vertex resolution ~10 cm

No calorimetry required = cheap!

Possible to reconstruct:

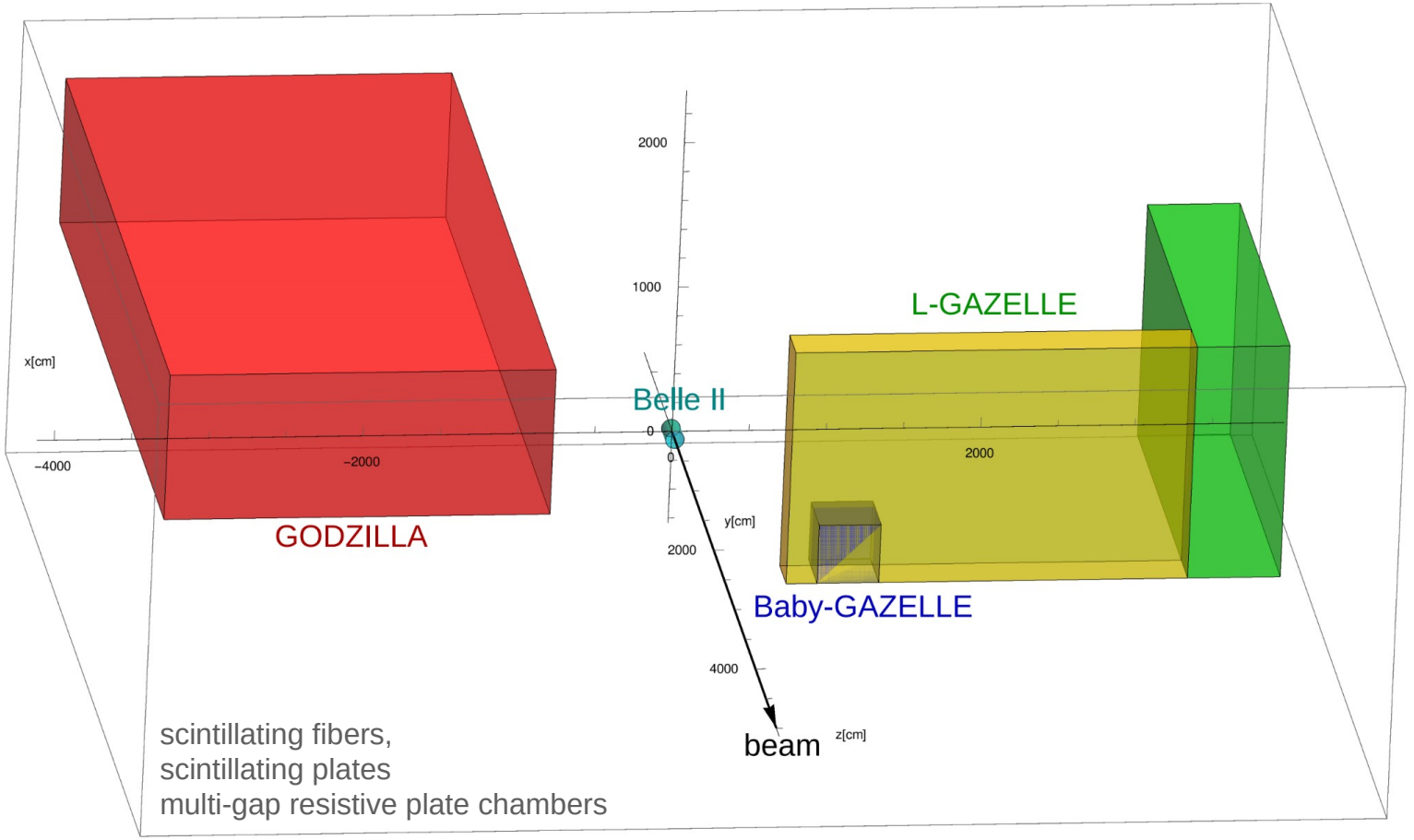
- Vertex
- Mass
- Track direction
- Pointing angle (moderate boost)
- Absolute time (synchronize with Belle II)

Almost zero background

Tsukuba hall can be used?

Tsukuba hall can be used?

GAZELLE: three possible configurations

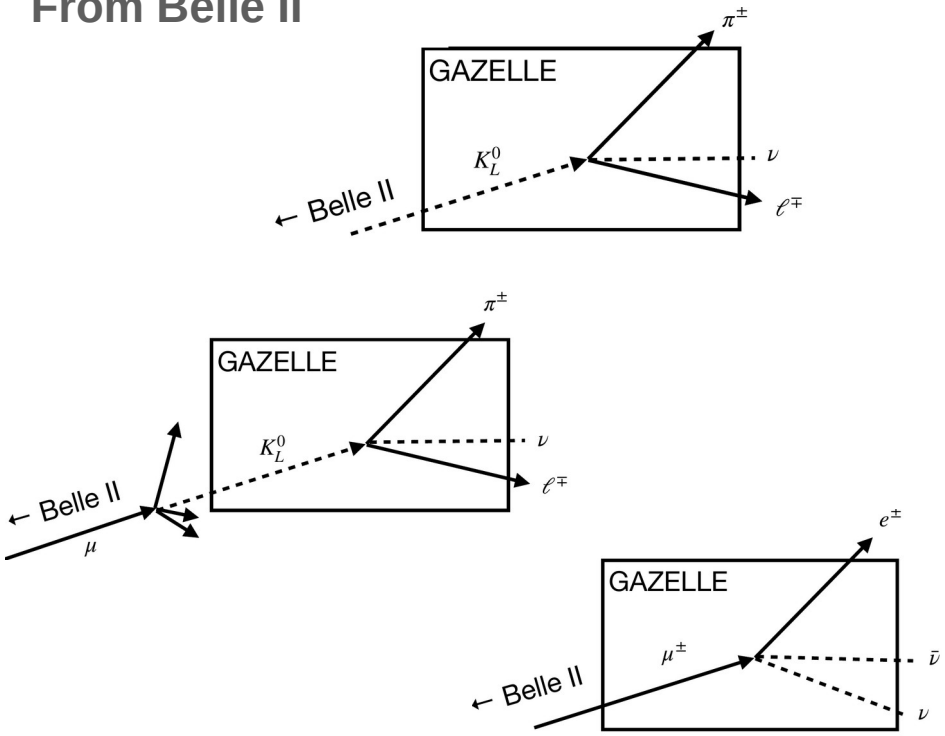


scintillating fibers,
scintillating plates
multi-gap resistive plate chambers

Main backgrounds

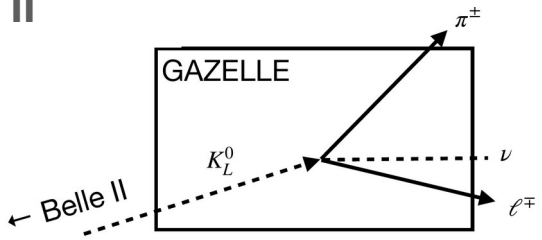
Main backgrounds

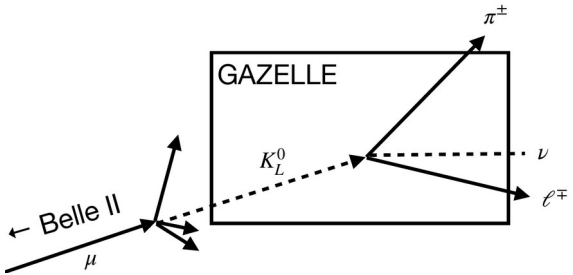
From Belle II

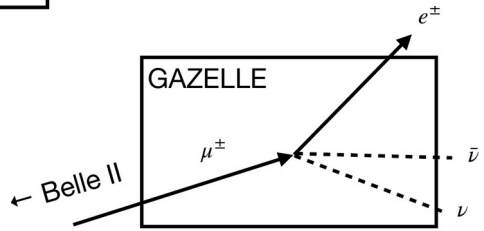


Main backgrounds

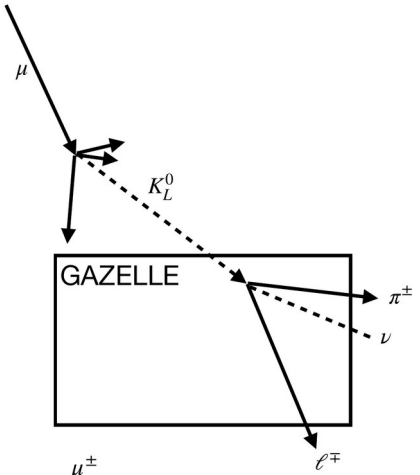
From Belle II

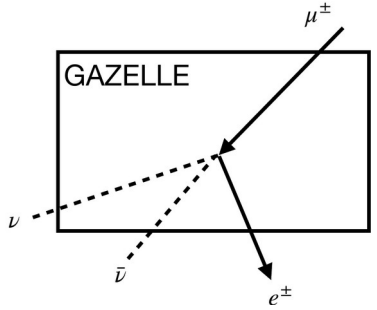






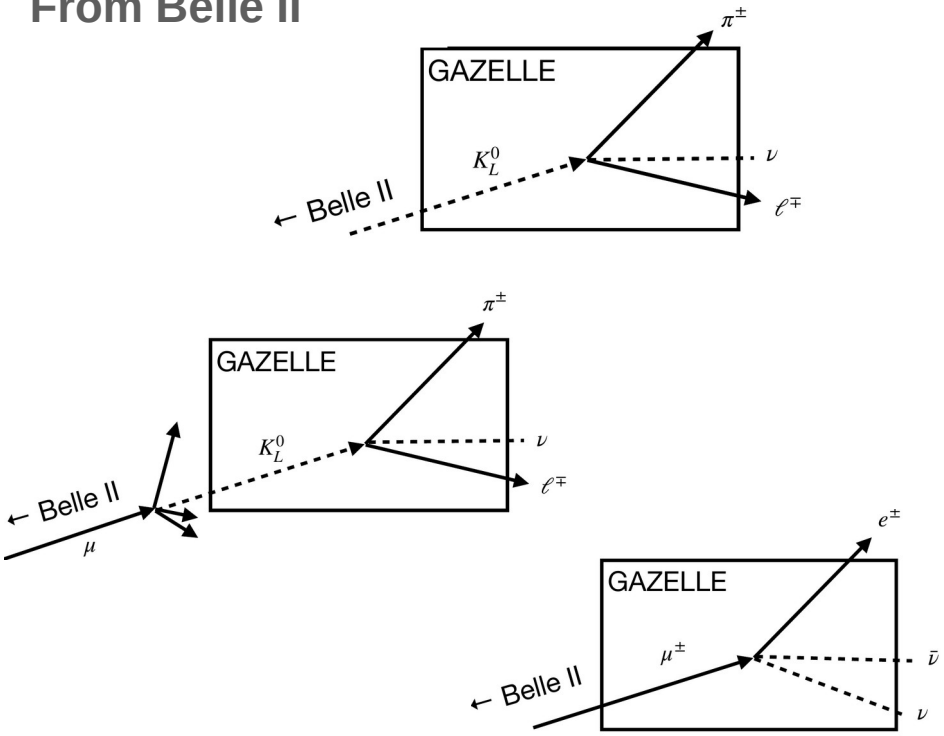
Cosmics



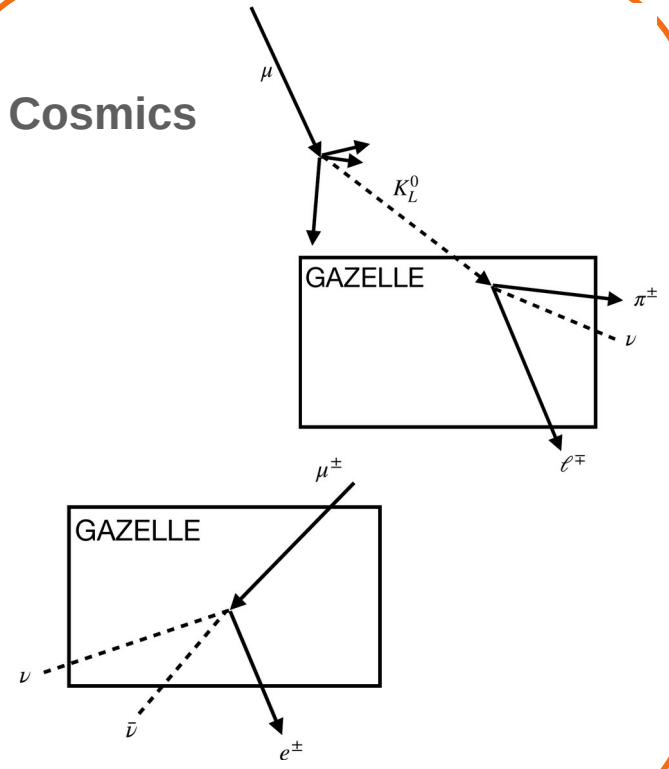


Main backgrounds

From Belle II



Cosmics



Almost never point to Belle II

Probability of an LLP to decay inside GAZELLE

$$P_i = \exp\left(-\frac{\ell_i^{in}}{\gamma\beta_i c\tau}\right) - \exp\left(-\frac{\ell_i^{in} + D}{\gamma\beta_i c\tau}\right)$$

Probability of an LLP to decay inside GAZELLE

$$P_i = \exp\left(-\frac{\ell_i^{in}}{\gamma\beta_i c\tau}\right) - \exp\left(-\frac{\ell_i^{in} + D}{\gamma\beta_i c\tau}\right)$$

$$\gamma\beta_i c\tau \gg \ell_i^{in},\ D \quad \Rightarrow \quad \langle P\rangle = \frac{1}{N}\sum_{i=1}^{N} P_i \approx \Omega \times \frac{D}{\gamma\beta c\tau}$$

Probability of an LLP to decay inside GAZELLE

$$P_i = \exp\left(-\frac{\ell_i^{in}}{\gamma\beta_i c\tau}\right) - \exp\left(-\frac{\ell_i^{in} + D}{\gamma\beta_i c\tau}\right)$$

$$\gamma\beta_i c\tau \gg \ell_i^{in},\ D \quad \Rightarrow \quad \langle P \rangle = \frac{1}{N}\sum_{i=1}^{N} P_i \approx \Omega \times \frac{D}{\gamma\beta c\tau}$$

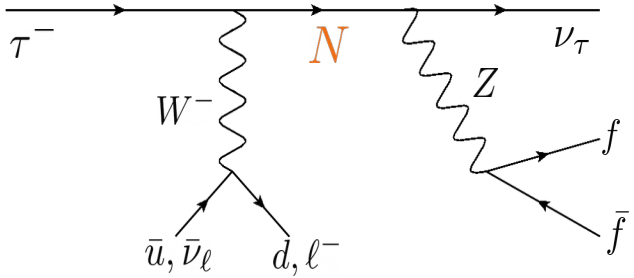
Detector	Belle II	Baby-GAZELLE	L-GAZELLE	GODZILLA
$\Omega \times D$	7 sr m	0.2 sr m	3 sr m	3.4 sr m

Benchmark models with long-lived particles

*

Benchmark models with long-lived particles

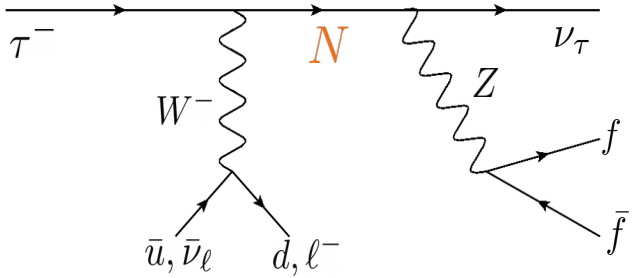
HNL: τ decays



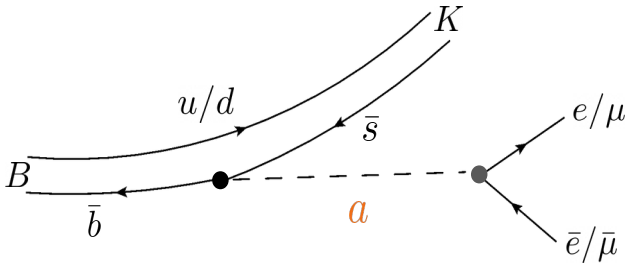
*

Benchmark models with long-lived particles

HNL: τ decays



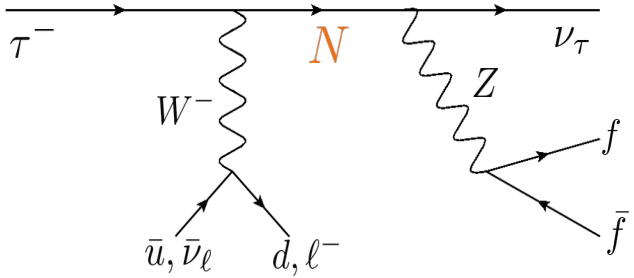
ALP: rare B decays



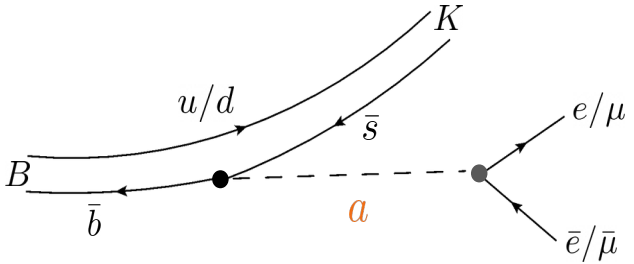
*

Benchmark models with long-lived particles

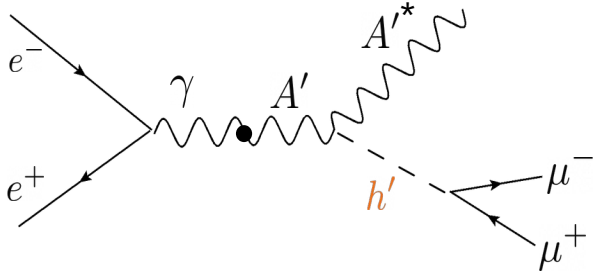
HNL: τ decays



ALP: rare B decays

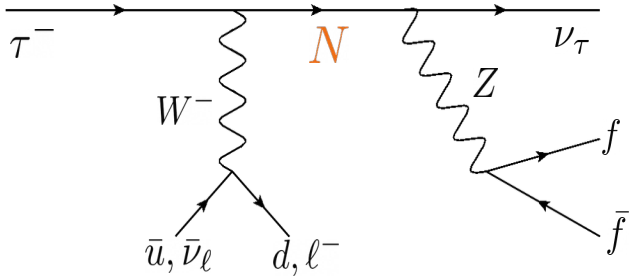


IDM: direct production

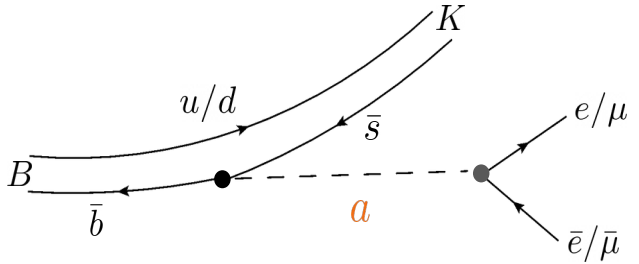


Benchmark models with long-lived particles

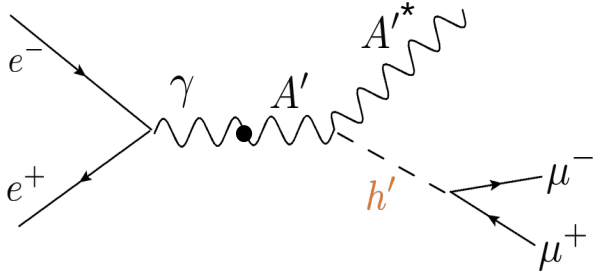
HNL: τ decays



ALP: rare B decays



IDM: direct production

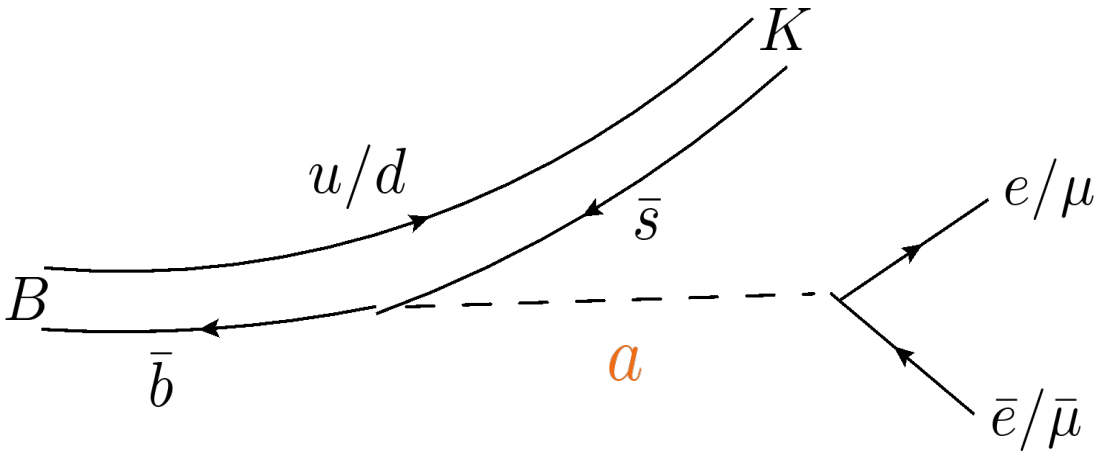


ALP model

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

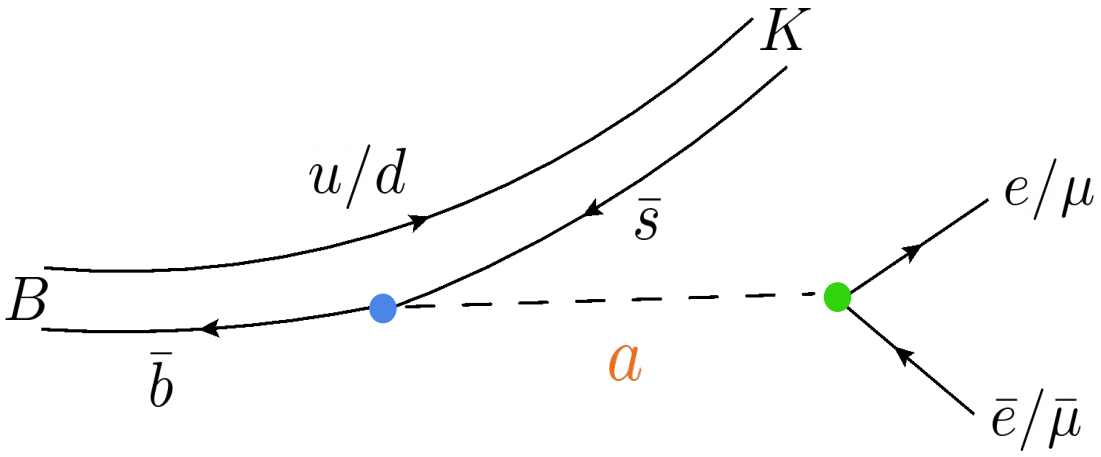
ALP model

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



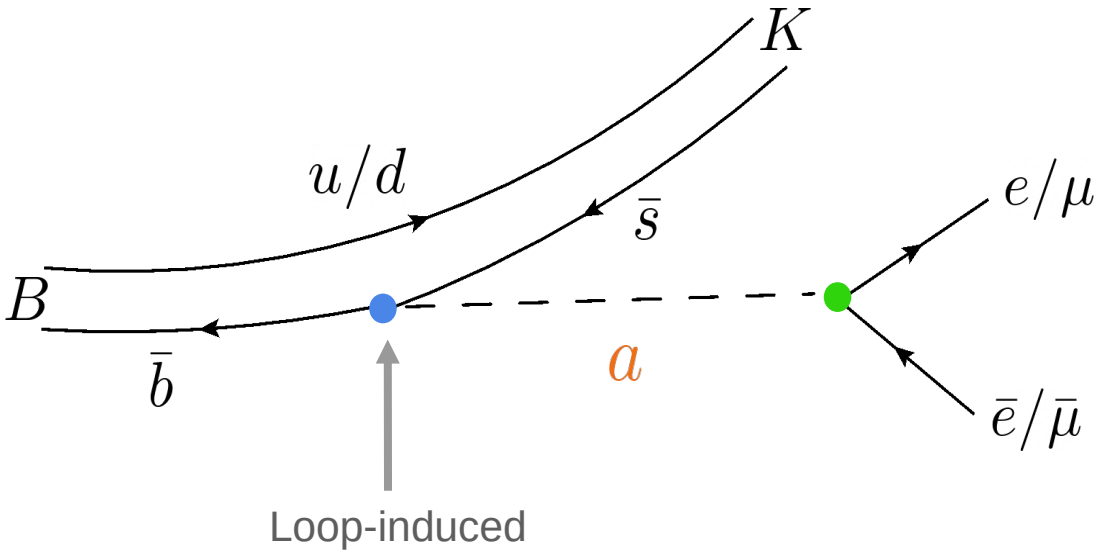
ALP model

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



ALP model

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

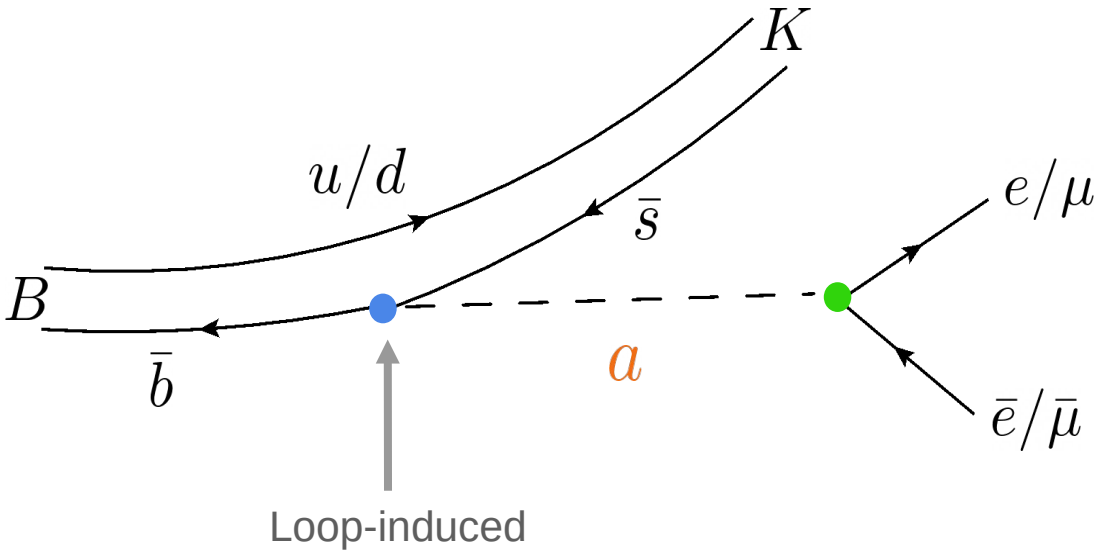


ALP model

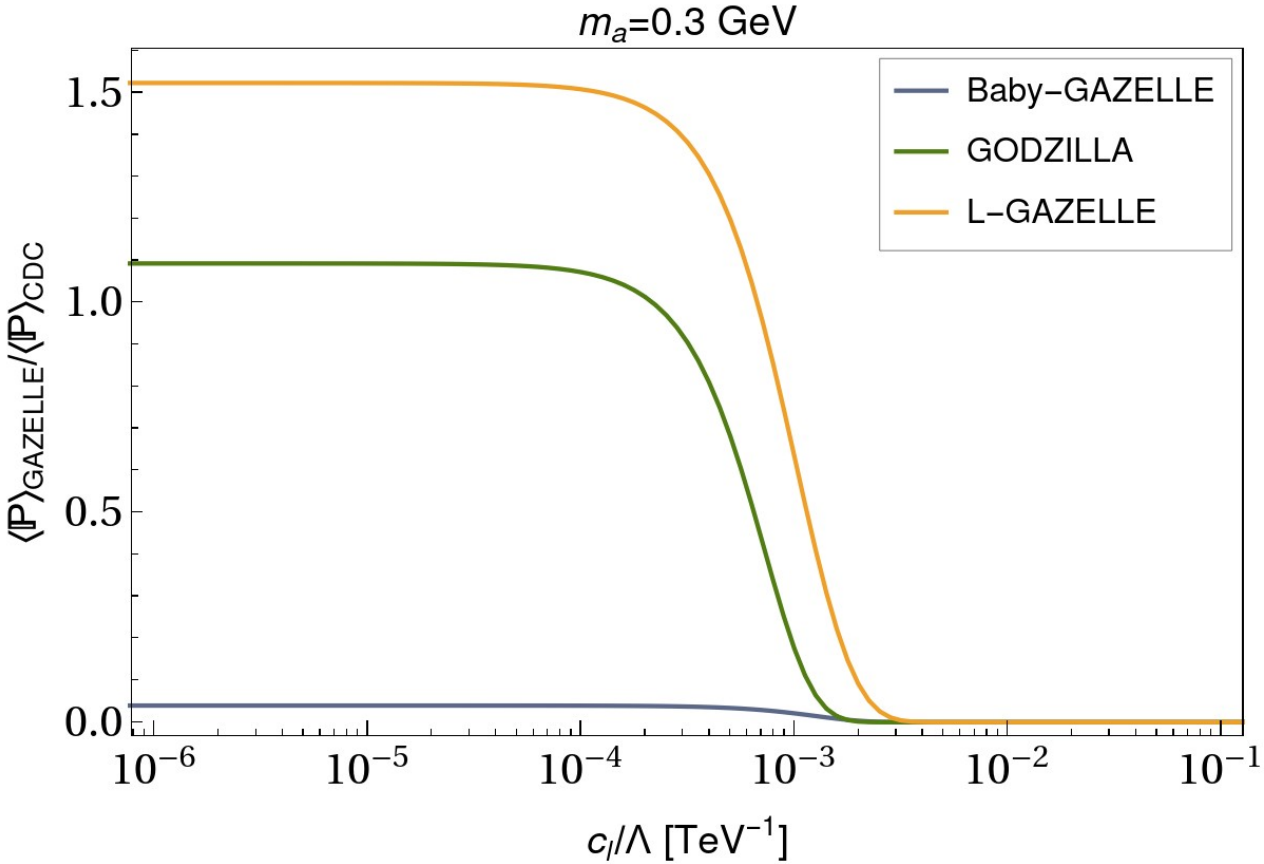
$$\mathcal{L} = -2 g_{sb} \frac{\partial^\mu a}{\Lambda} \bar{s} \gamma_\mu b_L + \frac{c_\ell}{2} \frac{\partial^\mu a}{\Lambda} \bar{\ell} \gamma_\mu \gamma_5 \ell$$

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

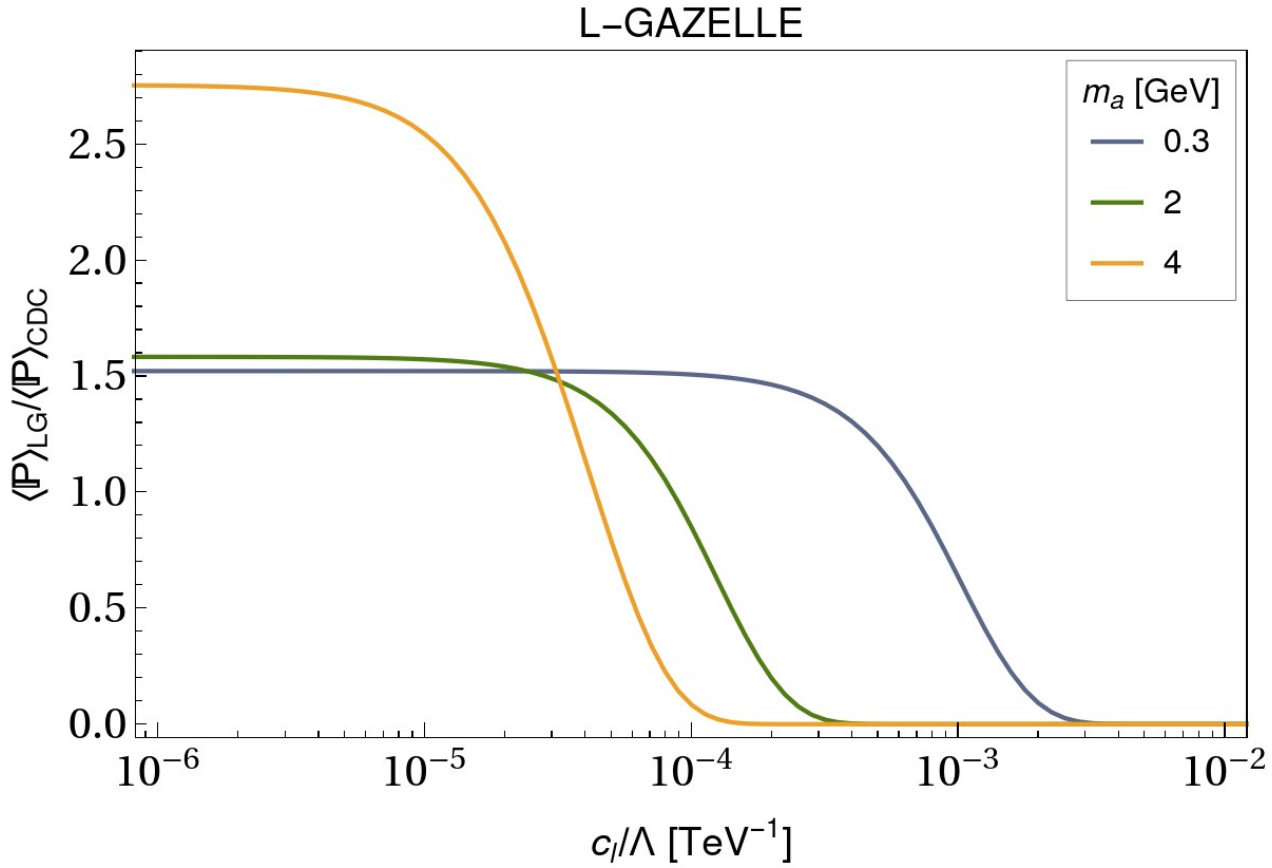
BaBar, invisible search [1303.7465]



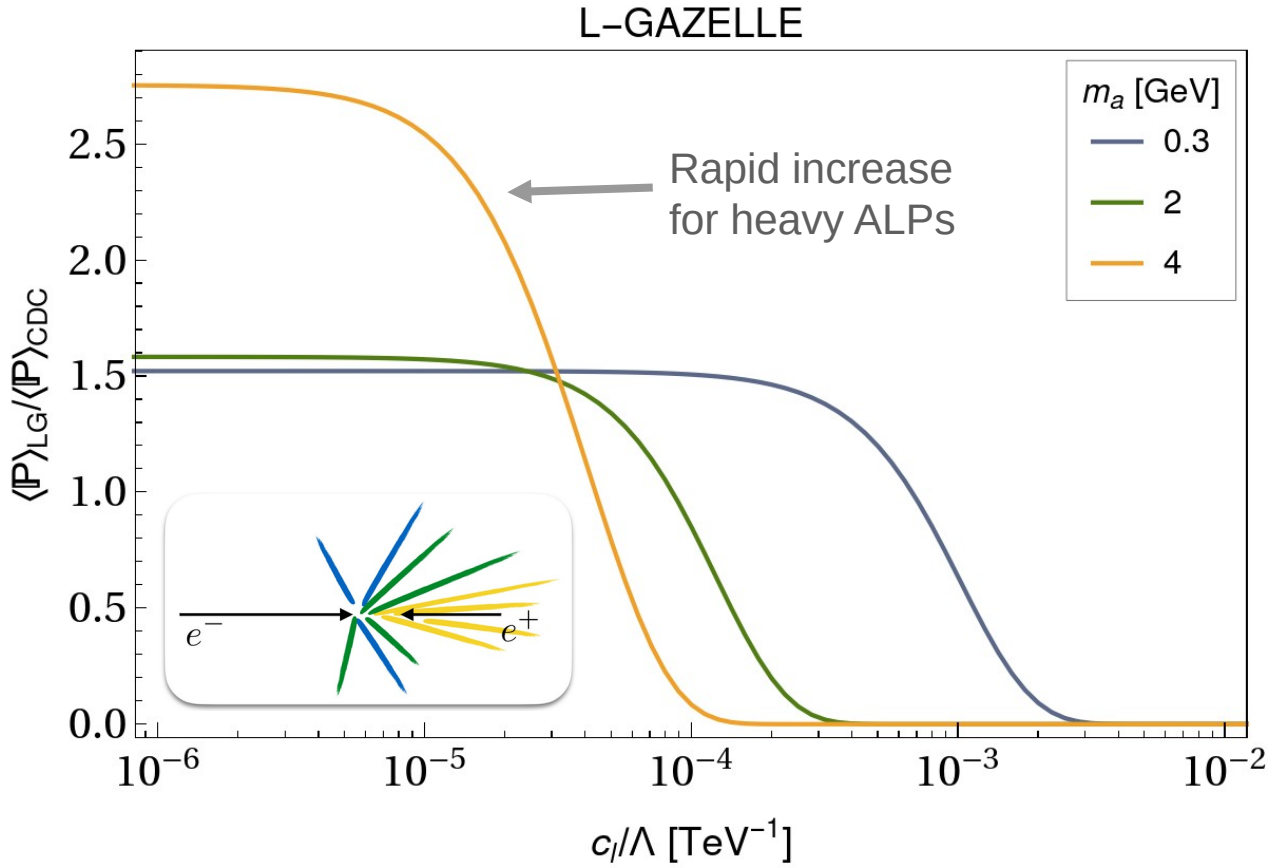
ALP decays inside different GAZELLE configurations



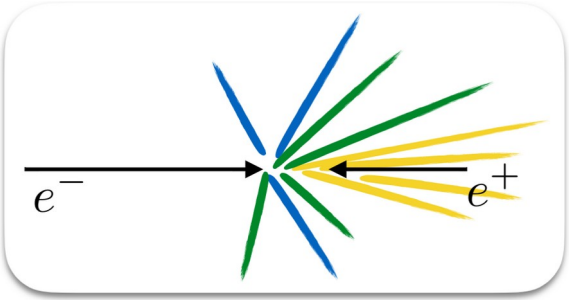
ALP decays inside L-GAZELLE

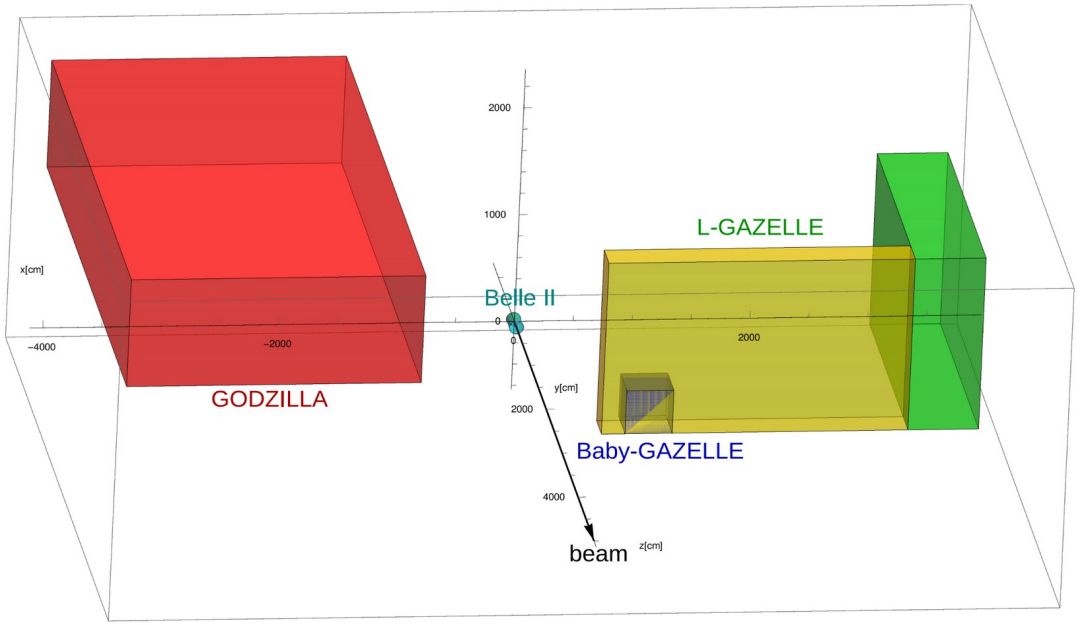


ALP decays inside L-GAZELLE

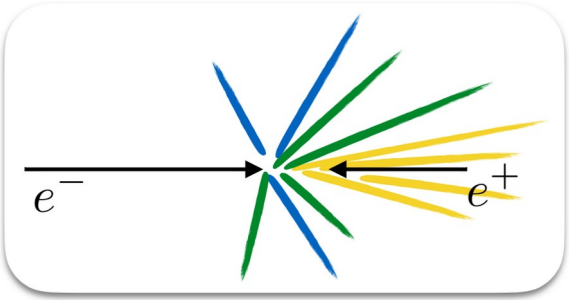


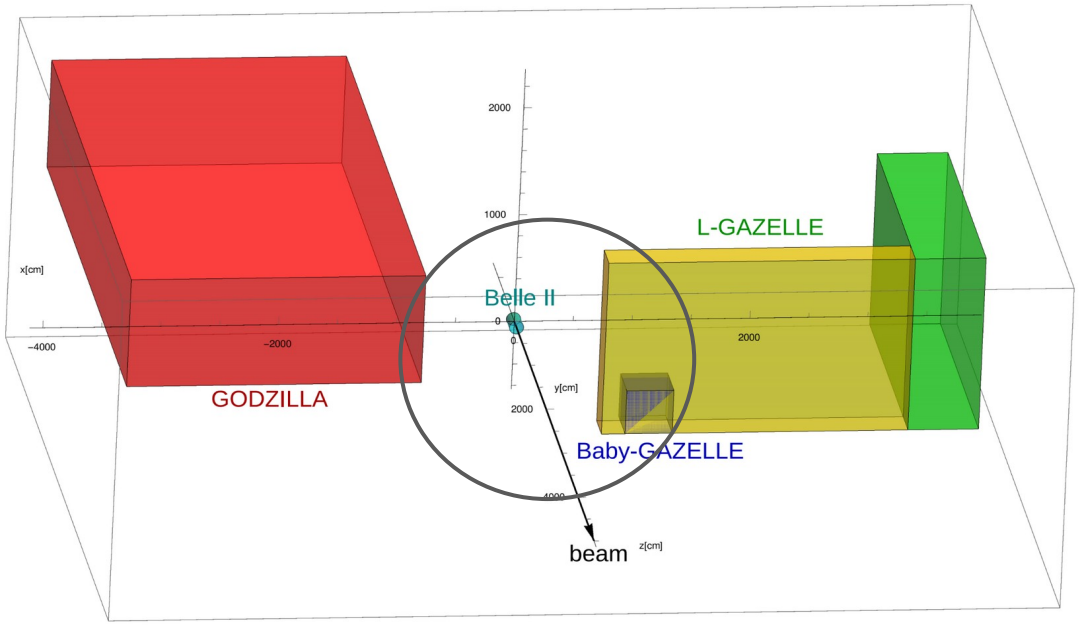
Heavy ALPs fly in the forward direction





Heavy ALPs fly in the forward direction



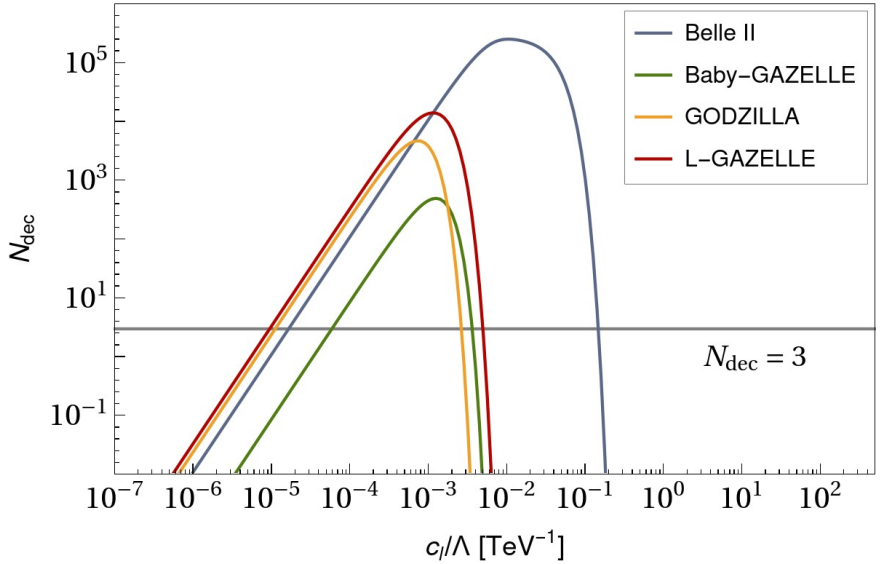


When it comes to numbers...

Projected reach of L-GAZELLE and Belle II for the ALP coupling $c_\ell/\Lambda\,[\mathrm{TeV}^{-1}]$

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

m_a=0.3 GeV



When it comes to numbers...

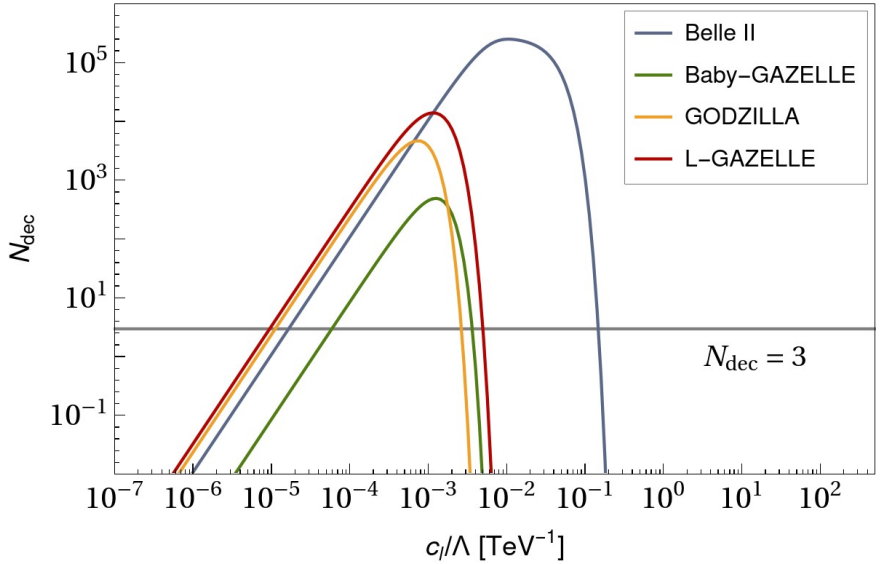
Projected reach of L-GAZELLE and Belle II for the ALP coupling $c_\ell/\Lambda\,[\mathrm{TeV}^{-1}]$

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

Assumptions:

- Zero background
- 100% efficiency

m_a=0.3 GeV



When it comes to numbers...

Projected reach of L-GAZELLE and Belle II for the ALP coupling $c_\ell/\Lambda\,[\mathrm{TeV}^{-1}]$

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

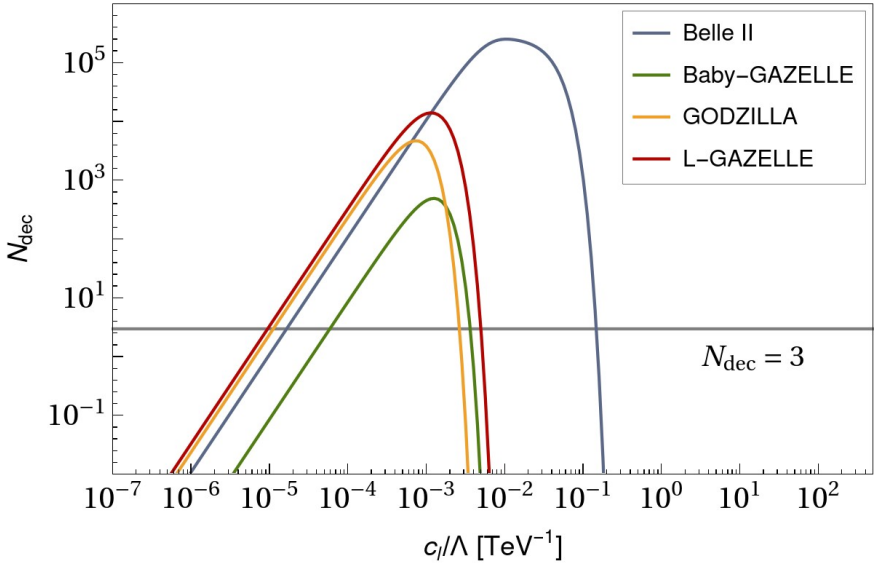
Assumptions:

- Zero background
- 100% efficiency

O(1) improvement over Belle II*

*Realistic background might slightly change the picture

m_a=0.3 GeV



More models for GAZELLE

Emerging jets (e.g. models with dark showers)

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

e.g. Schwaller et al. 1502.05409

Models with forward enhancement

$$e^+e^- \to \gamma a,\ \gamma A'$$

e.g. An et al. 1510.05020, Chen et al. 2001.04382, Fayet hep-ph/0702176

Quirks

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

e.g. Kang, Luty 0805.4642

Soft boms

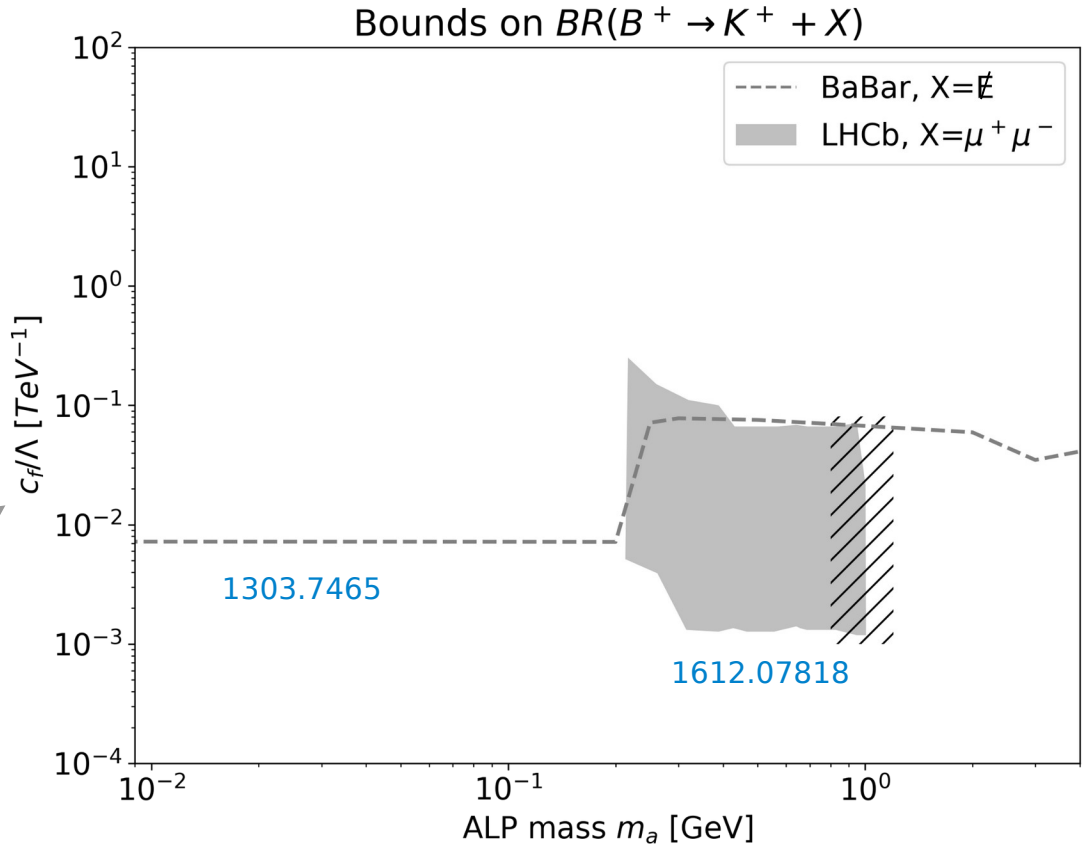
E.g. S. Knapen et al. 1612.00850

And more?

Visible and invisible searches are complementary

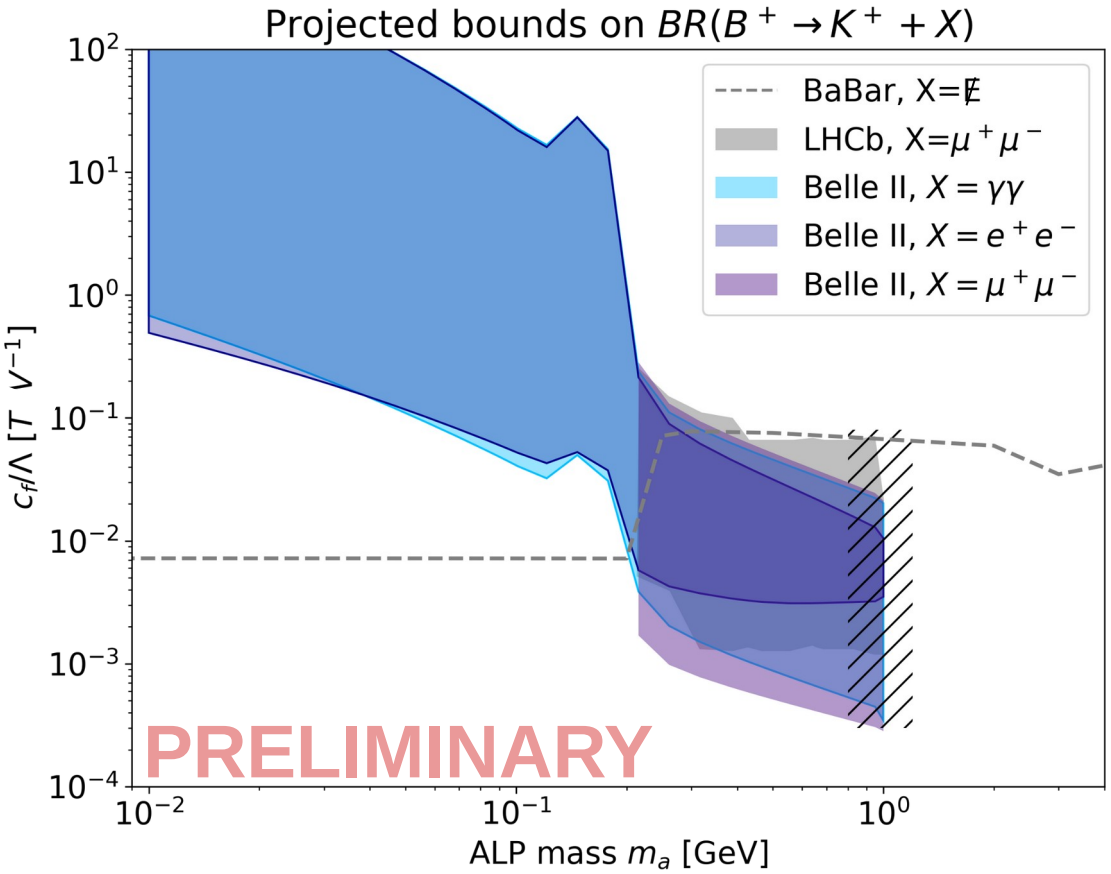
Work in progress with
R. Schäfer,
T. Ferber,
and S. Westhoff

Fundamental coupling at Λ=1 TeV



Belle II itself is an excellent LLP detector

Work in progress with
R. Schäfer,
T. Ferber,
and S. Westhoff



Take-home messages

- GAZELLE gives O(1) improvement over Belle II

- **Belle II is a great LLP detector**
  - Large acceptance, little background
  - Complementarity of invisible and displaced searches

- Viable far detector at Belle II should:
  - Have decent angular coverage
  - Be placed far from the interaction point
  - Be put where the target LLP go (e.g., along the beam line)
  - The larger LLP boost, the thicker
  - Belle II can be used to trigger it

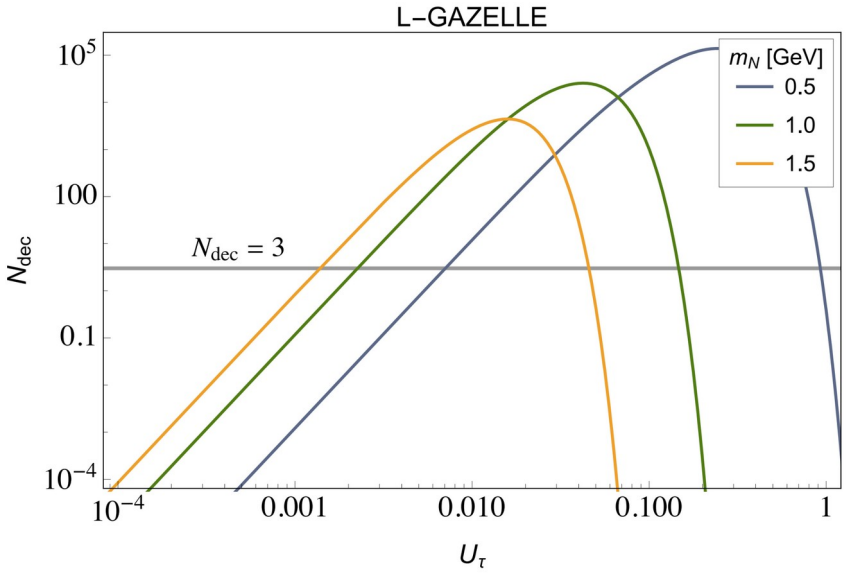
Backup

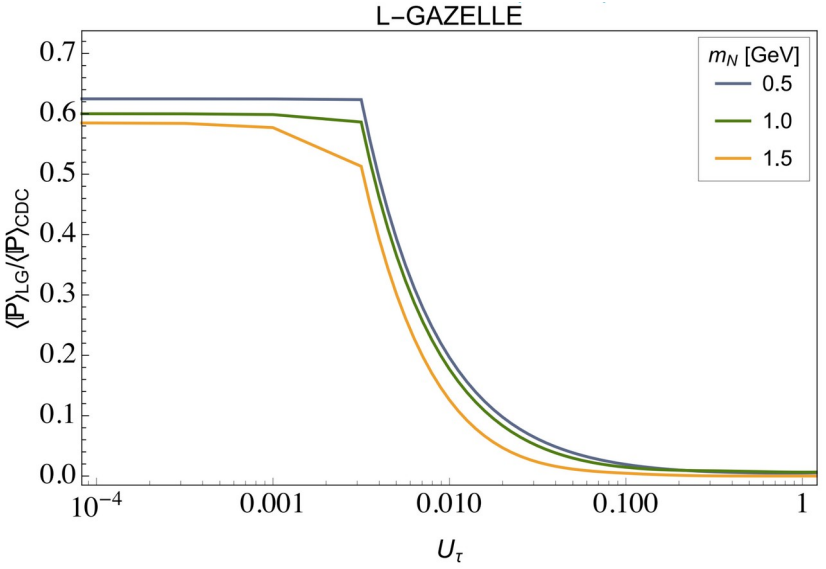
HNLs at GAZELLE

$$\Gamma(N \to \nu_\tau \ell \bar{\ell}) \sim m_N^5 |U_\tau|^2$$

Projected reach of L-GAZELLE and Belle II for the mixing angle U_τ

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



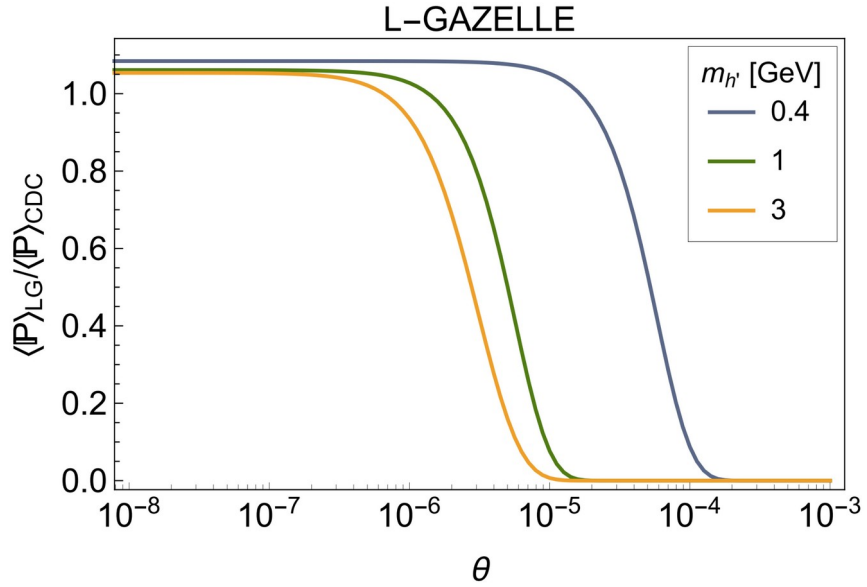


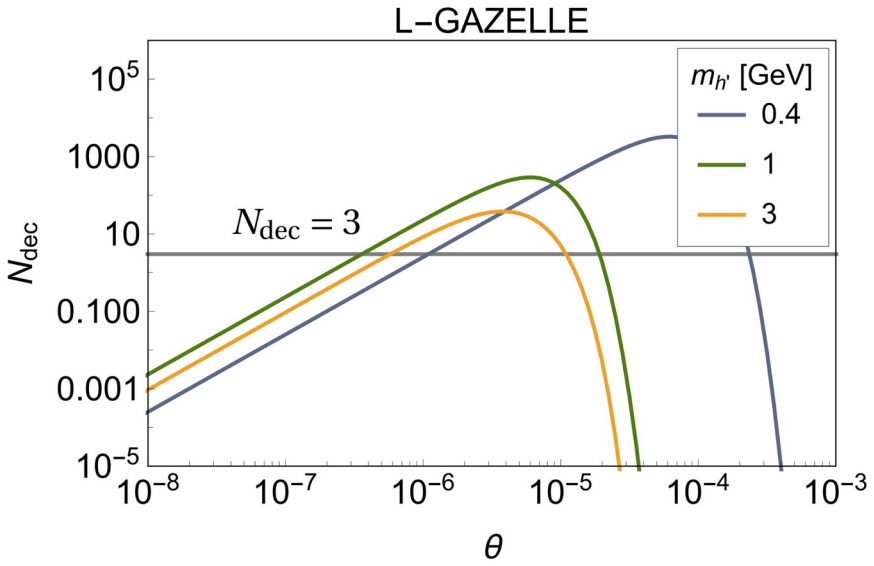
IDM at GAZELLE

$$\Gamma_{h' \to \mu^+\mu^-} = \frac{\sin^2\theta\, G_F\, m_{h'}\, m_\mu^2}{4\sqrt{2}\,\pi} \left(1 - \frac{4m_\mu^2}{m_{h'}^2}\right)^{\frac{3}{2}}$$

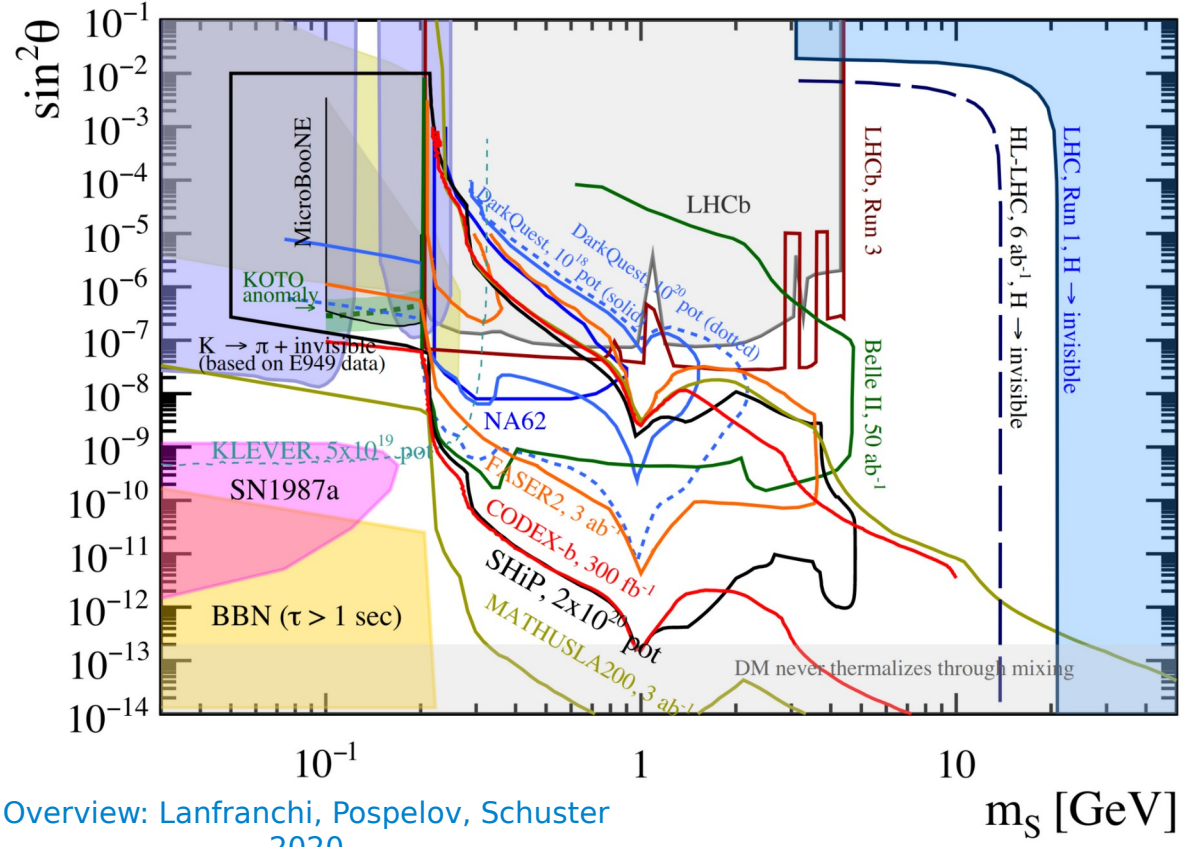
Projected reach of L-GAZELLE and Belle II for the mixing angle θ

$m_{h'}$ [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





Dark scalars: the complete picture



Overview: Lanfranchi, Pospelov, Schuster 2020