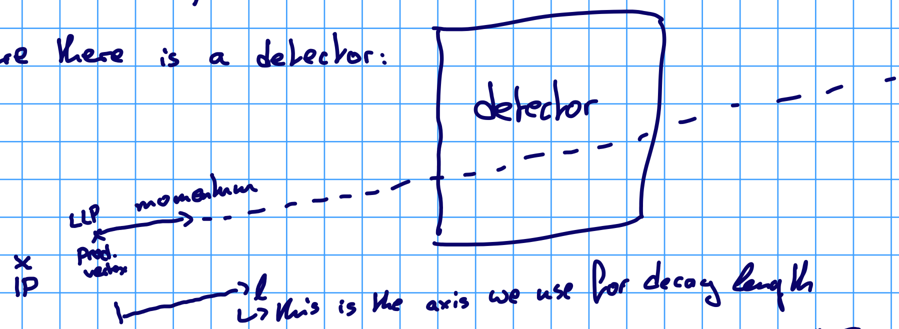
Long-lived Particles (3)

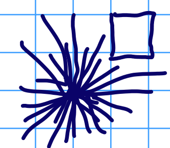
Now, how to analyse how good GAZELLE is?

Our situation is: somewhere an LLP is produced, it has momentum in some direction and somewhere there is a detector:



↳ this is the axis we use for decay length

The first thing to note is that the LLP can miss the detector:



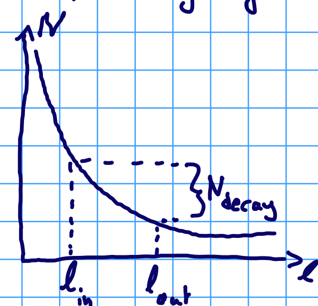
When the LLP is produced isotropically: $\mathbb{P}_{angular} = \frac{\Omega_{det}}{4\pi}$

For this we check whether the ray of the particle intersects with any points in the detector

If the LLP's ray intersects with the detector, we need to consult the exponential decay law

$N_{remain}(t) = N_0 \cdot e^{-t/\tau}$ or, in our case more usefully, $\frac{N(l)}{N_0} = e^{-\frac{l}{\gamma\beta c\tau}}$ ← length of flight; $\gamma\beta c\tau$: boost, proper decay length

Now the rate of LLPs decaying within the detector is given by the difference between the rate of LLPs still undecayed before entering the detector and those that still haven't decayed after leaving it again. We can calculate the point of entry & exit together with the intersection from above, such that



$$\mathbb{P}_{temporal} = e^{-\frac{l_{in}}{\gamma\beta c\tau}} - e^{-\frac{l_{out}}{\gamma\beta c\tau}}$$

The probability that a single LLP decays within a detector is then

$$\mathbb{P} = \mathbb{P}_{ang} \cdot \mathbb{P}_{tmp} = \begin{cases} 0 & \text{if particle misses detector} \\ e^{-\frac{l_{in}}{\gamma\beta c\tau}} - e^{-\frac{l_{out}}{\gamma\beta c\tau}} & \text{if particle enters detector at } l_{in} \text{ and exits at } l_{out} \end{cases}$$

To assess the GAZELLEs' discovery potential, we generate events for several benchmark models and masses that produce our long-lived particle. For each such event, we evaluate $\mathbb{P}$ and average them:

$$\langle \mathbb{P} \rangle = \frac{1}{N} \sum_i \mathbb{P}_i$$

For discovering something, we of course need more than $\langle \mathbb{P} \rangle$.

Let us consider the number of events N expected to be produced / measured:

$$N = N_0 \times Br(\text{LLP production}) \times \langle \mathbb{P} \rangle \times Br(\text{LLP decay}) \times \varepsilon$$

- N_0: number of total events ($\sim$ luminosity) $5 \cdot 10^{10}$ $B\bar{B}$-pairs for Belle II runtime
- $Br(\text{LLP production})$: model-dependent probability that LLP is produced (may look more complicated)
- $\langle \mathbb{P} \rangle$: model- and detector-dependent probability that the decay happens within the detector
- $Br(\text{LLP decay})$: model-dependent probability that LLP decays to the right final state (here: charged particle pairs)
- ε: efficiency detector-dependent measure of likelihood that event is recognised as the right event (we assume 100% here)

If we assume that there is no background, we need 3 events of signal for 95% confidence.

Benchmark Models:

We want these models to have an LLP, be well-motivated and with good chances at Belle II / GAZELLE

HNL

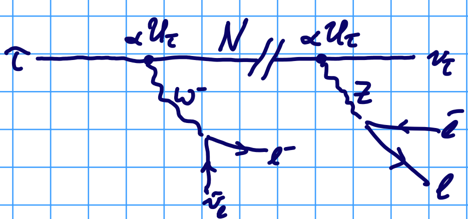
Heavy Neutral Lepton N produced from abundant τ's

$$\mathcal{L} \supset \sum_\alpha c_\alpha (\bar{L}_\alpha \tilde{H}) N$$

(N: sterile neutrino/HNL)

$\rightsquigarrow \nu'_\alpha = \nu_\alpha + U_\alpha N$

flavour eigenstate neutrino is part N

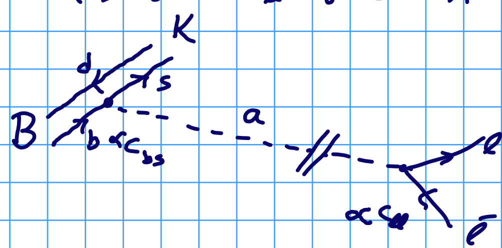


ALP

Axion-like particle a produced from abundant B's

effective low-energy ALP-couplings:

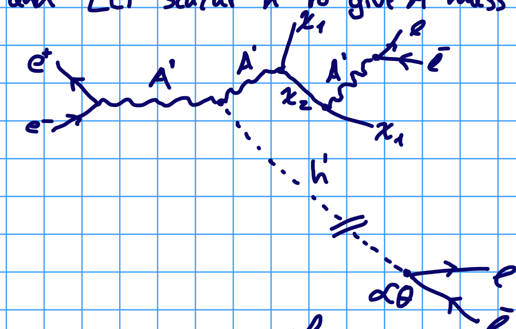
$$\mathcal{L} \supset (c_{bs}\, \bar{b}\gamma^\mu P_L s + c_{\ell\ell}\, \bar{\ell}\gamma^\mu P_L \ell) \frac{\partial_\mu a}{\Lambda}$$



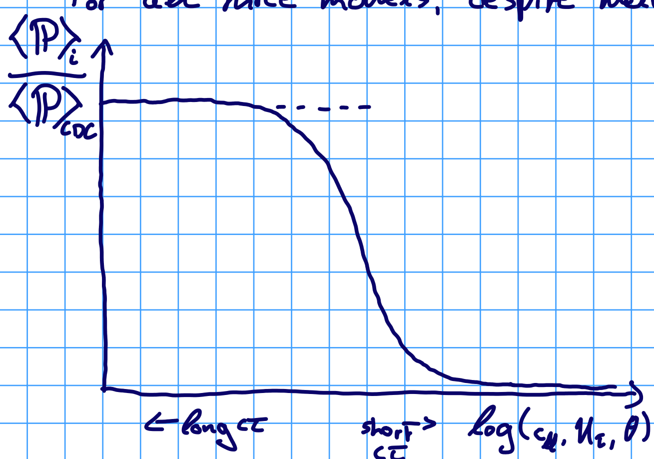
iDM

inelastic dark matter produced directly from e^+e^--collision

has vector mediator A', dark fermions χ_1, χ_2 and LLP scalar h' to give A' mass



For all three models, despite their different productions and decays, we see similar behaviours in $\langle \mathbb{P} \rangle$ and N:

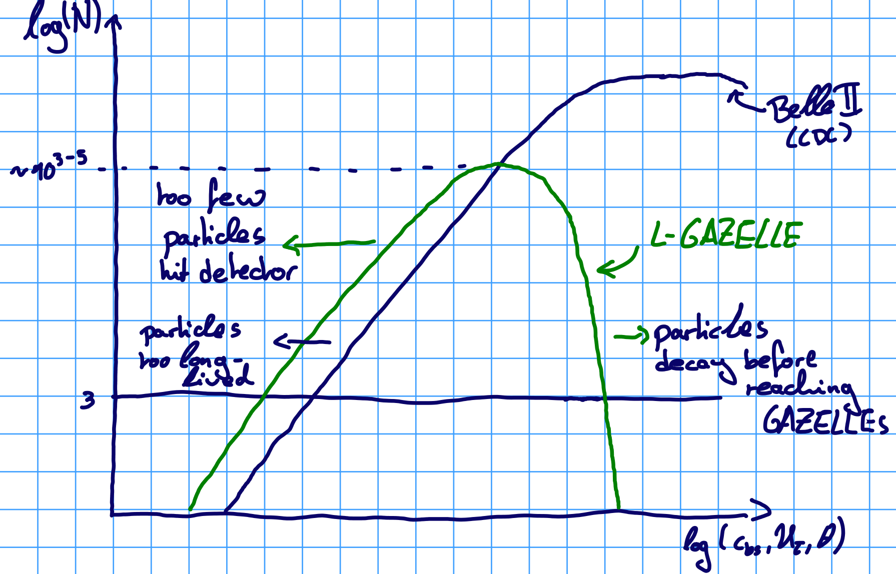


max value (%)	HNL	ALP	iDM
BabyGAZELLE	4	5-10	4
L-GAZELLE	60	150-300	105
GODZILLA	100	110	110

In ALP and iDM the position of the slope is greatly mass-dependent, in HNLs not

Side Note: why are the ALP values so spread out?

- B-mesons are forward boosted
- some ALPs near kinematic endpoint
- Baby- & L-GAZELLE are forward detectors



→ GAZELLE can make improvements over Belle II, but just $\mathcal{O}(1)$

So why is it not better? Since we are in a low-boost detector, we can approximate

$$\langle \mathbb{P} \rangle = \langle \mathbb{P}_{ang} \rangle \times \langle \mathbb{P}_{temp} \rangle = \langle \mathbb{P}_{ag} \rangle \times \left\langle e^{-\frac{l_{in}}{\beta\gamma c\tau}} - e^{-\frac{l_{out}}{\beta\gamma c\tau}} \right\rangle$$

$$\approx \frac{\Omega}{4\pi} \times \frac{l_{out} - l_{in}}{\beta\gamma c\tau}$$ "fiducial acceptance"

$\Omega \times D$ ← detector thickness as approximation for $l_{out} - l_{in}$

Belle II's CDC	7 sr × m	
Baby GAZELLE	0.2 sr × m	→ is much too small to compete
L-GAZELLE	3 sr × m	do similarly well as Belle II, as we saw
GODZILLA	3.4 sr × m	

→ Takeaways:
- Solid angle is very important
- A clean environment in terms of background helps a lot
- Belle II may not need GAZELLE, but other detectors would surely benefit
- If we explore all available production channels, we may find that a low Br at a low-energy collider still could give us good detection capacities
- To explore higher mass LLPs, we may have to
  - build the ILC or FCCee, etc.
  - work at messier environments

↳ then we need all our ingenuity!