Long-lived Particles (2)

An Interlude on gauge invariance:

The Standard Model gauge group is $\underbrace{SU(3)_c}_{\text{strong interaction}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{electroweak interaction}}$

The intesactions are mediated by the gauge bosons $\underset{\text{(gluons)}}{G^a_\mu}$, W^i_μ and B_μ

Quarks are charged under $SU(3)$, left-handed fermions and the Higgs doublet under $SU(2)$ and fermions + the Higgs doublet under $U(1)$.

The fields transform as:

$$B_\mu \to B_\mu + \frac{2}{g_1} \partial_\mu \theta$$

$$W_\mu \to U W_\mu U^\dagger - \frac{2i}{g_2} U \partial_\mu U^\dagger$$

$$G_\mu \to V G_\mu V^\dagger - \frac{i}{g} V \partial_\mu V$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \to e^{i\theta} U \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R \to e^{2i\theta} e_R$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \to e^{i\theta} U V \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R \to e^{-\frac{4}{3}\theta} V u_R \qquad d_R \to e^{\frac{2}{3}\theta} V d_R$$

$$H \to e^{-i\theta} U H$$

With this in mind, let us revisit the portals:

$$F^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu \to \partial^\mu B^\nu + \cancel{\frac{2}{g_1} \partial^\mu \partial^\nu \theta} - \partial^\nu B^\mu - \cancel{\frac{2}{g_1} \partial^\nu \partial^\mu \theta} = \partial^\mu B^\nu - \partial^\nu B^\mu = F^{\mu\nu}$$

is gauge invariant while $W^{\mu\nu} \to U W^{\mu\nu} U^\dagger$ and $G^{\mu\nu} \to V G^{\mu\nu} V^\dagger$ are not

$$H^\dagger H \to (e^{-i\theta} U H)^\dagger (e^{-i\theta} U H) = e^{i\theta} H^\dagger \underbrace{U^\dagger U}_{1} H e^{-i\theta} = H^\dagger H \quad \text{is gauge invariant}$$

$$\bar{L} i \sigma_2 H^* \to \overline{(e^{i\theta} U L)}\, i\sigma_2 (e^{-i\theta} U H)^* \overset{[\dots]}{=} \bar{L} \underbrace{U^\dagger i\sigma_2 U^*}_{i\sigma_2} H^* \underbrace{e^{-i\theta} \cdot e^{i\theta}}_{1} = \bar{L} H^* \quad \text{is gauge invariant}$$

Note: the fermion currents $\bar{f} f$, $\bar{f} \gamma^\mu f$, etc. are also gauge invariant

They appear (if not outright defined then mixing-induced) in the scalar and vector portals:

$$\mathcal{L}_{\text{scalar}} \supset \mu \phi H^\dagger H + \lambda \phi^2 H^\dagger H \to \mathcal{L}_{\text{scalar}} \supset s_\theta y_f S \bar{f} f$$

$$\mathcal{L}_{\text{vector}} \supset \varepsilon F^{\mu\nu} F'_{\mu\nu} \to \mathcal{L}_{\text{vector}} \supset \frac{e\varepsilon}{\sqrt{1-\varepsilon^2}} V_\mu \bar{f} \gamma^\mu f$$

3) GAZELLE is the Approximately Zerobackground Experiment for Long-Lived Exotics

Idea: Can a far detector at Belle II improve its sensitivity to long-lived particles?

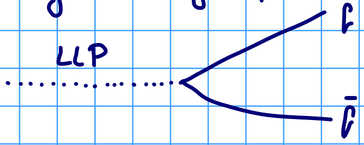
At the LHC there are many such proposals (MATHUSLA, CODEX-b, ...) and one such experiment (FASER) that promise to significantly increase the sensitivity to light & weakly coupled physics (->LLPs)

But the LHC and Belle II are also very different experiments. At Belle II, there is a cleaner background (e^+e^- vs. hadron collisions) and particles are less boosted (lower beam energies) so it is already an experiment better suited for LLP-searches.

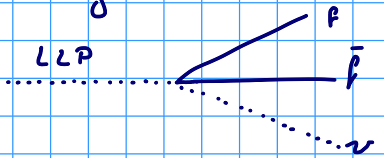
e.g. Scalar portal model: (roughly)

Detector Design:

In the benchmark models we consider (and many LLP models) the LLPs decay into final states containing to charged particles (and possibly additional neutral ones):
↳ which we will get to later



or



That means our detector will need to be able to detect charged tracks.

We need:
- position reconstruction ~ 10 cm
- timing resolution ~ 100 ps
- small latency ~ 1 μs
  ↳ to link triggers with Belle II

We do not need a calorimeter

This is possible + at a reasonable price for example with Scintillating Fibers, Scintillating Tiles or Multigap Resistive Plate Chambers (MRPCs)
↳ e.g. at LHCb
↳ e.g. at ATLAS
↳ e.g. at ALICE

This allows us to measure:
- the direction of particles
  ↳ the opening angle of decay products
    ↳ the direction of LLPs
- their velocity
  ↳ the mass of LLPs

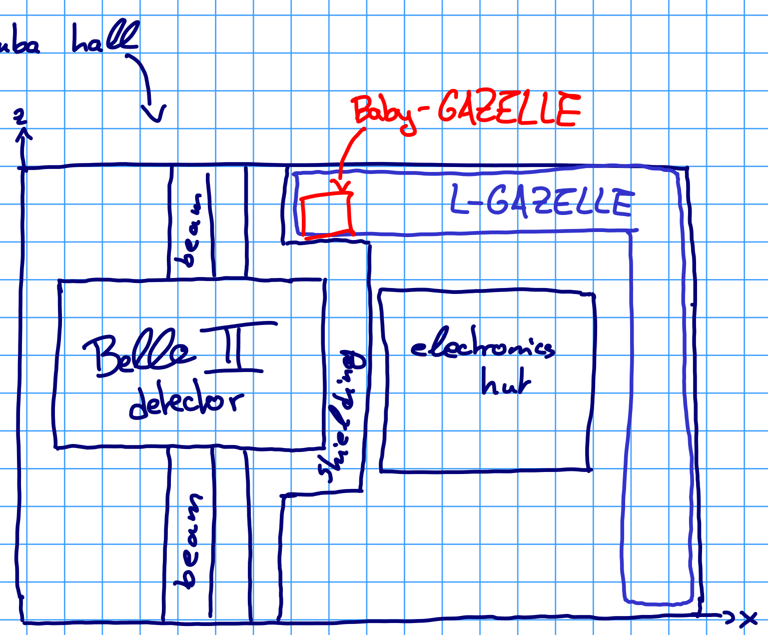
For background, we have to consider cosmic rays and particles from the e^+e^--collision

The above specifications help to reject backgrounds:

- track direction should point towards Belle II interaction point
- allow us to tell apart muon decay vs. decay to two leptons through timing
- check if the time of LLP measurement fits with an origin within Belle II

A full study would be needed, but we assume zero background events for now.

To choose the shape and placement of our detector, we need to consider the place where Belle II resides: Tsukuba hall



In this space, we place three designs:

- Baby GAZELLE, a $(4m)^3$ cube placed as close to Belle II as possible, just behind the shielding. 0.4 % angular coverage
- L-GAZELLE, ceiling-high detectors spanning the far and forward wall of Tsukuba hall with a thickness of 3 to 6 m. ~5% angular coverage
- GODZILLA, instead of within Tsukuba hall, this detector is its own building right outside on a free plot next to Tsukuba hall. ~ 1.4 % angular coverage

These 3 designs are
- possible within the existent constraints
- pretty representative for all possible designs