Long-lived Particles

1) What are long-lived particles?

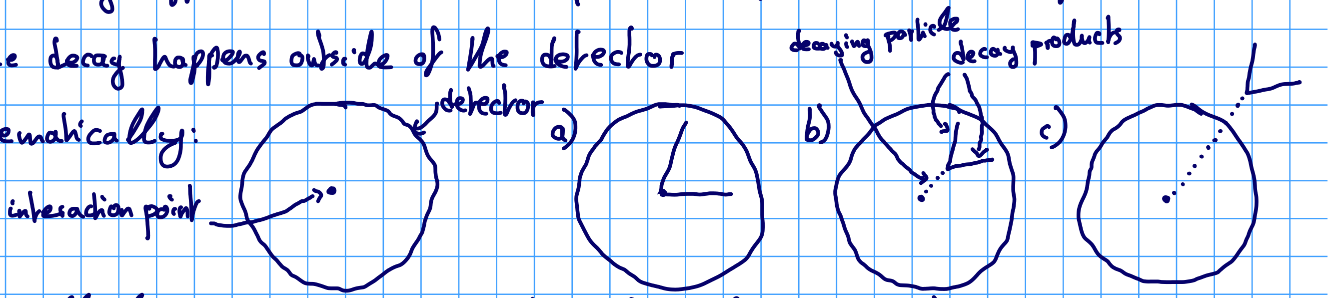
- For the timeline of any particle decay in any detector, we have 3 cases:

  a) the decay happens so close to the interaction point that we cannot distinguish from it happening here

  b) the decay happens in the detector but further out from the interaction point

  c) the decay happens outside of the detector

  Schematically:



  We call these decays a) prompt b) displaced and c) missing or outside
  (Searches for scenario c) are often called missing energy or missing momentum searches)

  By long-lived particles (LLPs), we mean particles that do not decay promptly.

  Often, we also mean that they still decay within the detector → scenario b)

- When are particles long-lived?

  lifetime $\tau \sim \frac{1}{\Gamma}$ decay width: Particles live long when their decays are suppressed

  The longevity of particles depends on the detector / experiment: decay length $d_{lab} = \underbrace{\gamma\beta}_{\text{boost}} c\tau$

  For example, a particle with $m = 0.5\,\frac{\text{GeV}}{c^2}$ and $\tau = 50\,\text{ns}$

  flies an average of 40 cm at Belle II (a B factory) but 20m at LHCb.

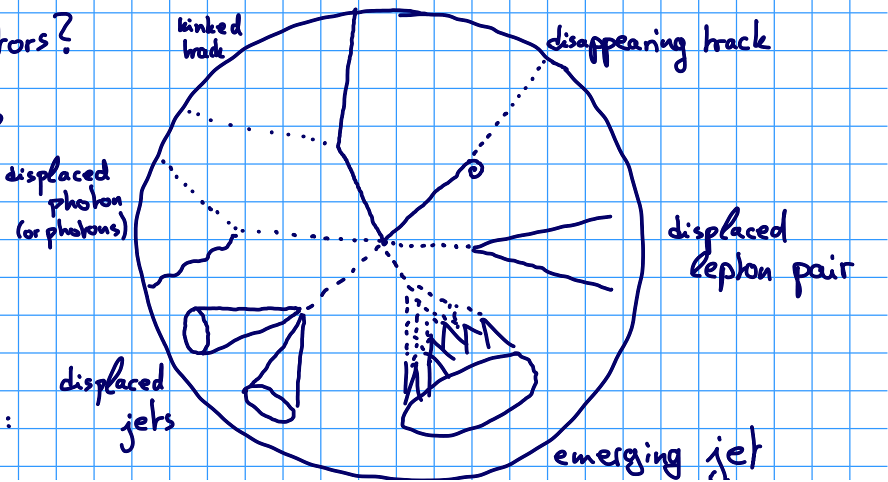
  → displaced decay in one detector, missing momentum in the other

- Why do we care for LLPs?
  - we have good ways to explore high mass regimes, LLPs allow us to probe small couplings
  - most models (next section!) have LLPs in some form or some parts of parameter space
  - even the Standard Model has LLPs: n, K_L (our example above), K_S, $\pi^\pm$, $\mu^\pm$, …

- How do LLPs look in detectors?

  Depending on the structure make-up of the detector, these signatures are seen in different ways.

  These are (schematically) some examples of features to look for:



2) Models or Where do we get our LLPs from?

Astrophysical and cosmological observations show us the need for particle dark matter.

The fact that we have not detected it yet tells us it is coupled to the Standard Model very weakly.

→ We have a need for mediators to weakly couple the dark sector to the Standard Model.

We can construct "portals" between the sectors by constructing gauge-invariant operators in both sectors and combining them: $\mathcal{L}_{\text{mediation}} \sim \sum_{k,\ell} \frac{\mathcal{O}^{(k)}_{NP}\,\mathcal{O}^{(\ell)}_{SM}}{\Lambda^{k+\ell-4}}$ with $\mathcal{O}^{(i)}$ operator of dimension i

Common low-dimensional portals:

- Scalar portal: $\mathcal{L} \supset \mu S H^\dagger H + \lambda S^2 H^\dagger H$
- Vector portal: $\mathcal{L} \supset \varepsilon F_{\mu\nu} F'^{\mu\nu}$
- Neutrino portal: $\mathcal{L} \supset y_n L H N$

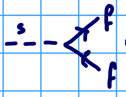
} dim = 4

- Axion (-like) portal: $\mathcal{L} \supset \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu}$ } dim = 5

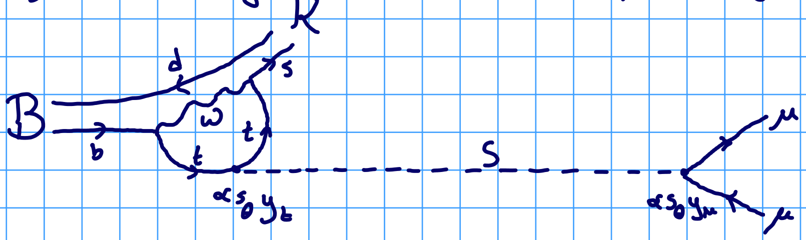
· Scalar Portal:

Singlet scalar S: $\mathcal{L}_{\text{mediation}} = (\mu S + \lambda^2 S^2)\, H^\dagger H$

after electroweak symmetry breaking, S and H mix into the Standard Model Higgs + new scalar s

⟶ Scalar S gains coupling to Standard Model suppressed by mixing s_θ  $\propto s_\theta y_f$

for example:

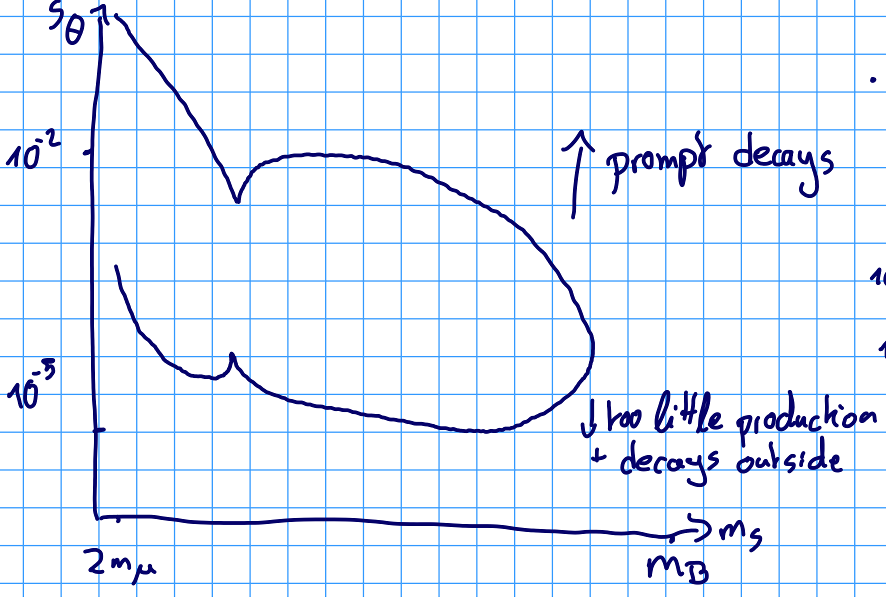


The S-decay is suppressed with regards to the S-production

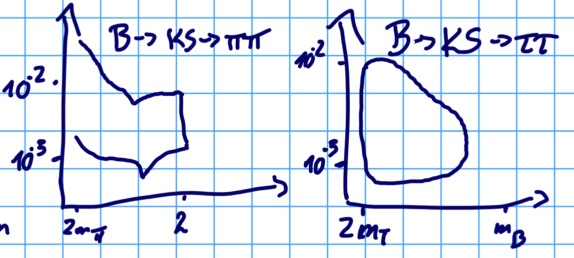
Let's take this model as an example:

at Belle II: vertex resolution 500 μm (minimum decay length) → $s_\theta \sim 10^{-2}$

depth of tracker: ~1 m (maximum decay length → $s_\theta \sim 10^{-5}$



· shape depends on lifetime + decay products

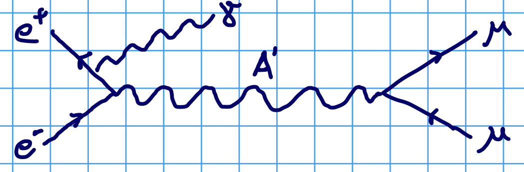


- Vector Portal:

massive new vector boson (called dark photon A' or Z' depending on the mass range) from an additional $U(1)$ symmetry $\mathcal{L} \supset \varepsilon F^{\mu\nu} F'_{\mu\nu}$ (kinetic mixing)

mixes with photon (and Z) to gain their couplings

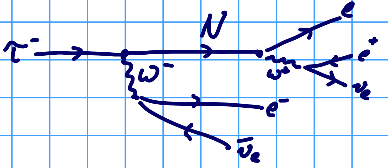
for example:



While this decay is not enhanced like the scalar portal's, there are many e^+e^- colliders where this has a good chance of happening + being observed anyway

- Neutrino Portal:

Heavy neutral lepton (HNL) N: $\mathcal{L} \supset y_n LHN$ for example:



N mixes with standard neutrinos to gain their couplings (suppressed by the mixing)

For heavy N, this naturally gives small couplings, such that N becomes long-lived

This "portal" is also used to explain neutrino masses + oscillations

- Axion (-like) portal

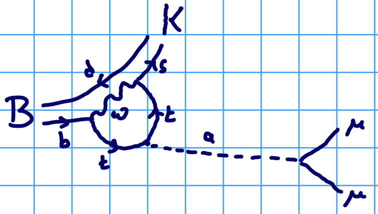
First constructed to solve the strong CP problem, axions couple to the topological gluon term $\mathcal{L} \supset \frac{a}{f_a} \tilde{G}^a_{\mu\nu} G^{a\mu\nu}$ where $\tilde{G}^{a\mu\nu} = \varepsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma}$

More generally, axion-like particles (ALPs) couple to topological gauge terms + derivatively to fermions

$$\mathcal{L} \supset \frac{a}{f_A} \tilde{F}_{\mu\nu} F^{\mu\nu} + c_{ff} \frac{\partial_\mu a}{f_f} \bar{f} \gamma^\mu \gamma^5 f$$

ALPs are natural LLPs, because in most UV models, f_A / f_f are very large scales

Due to the derivative fermion coupling, the decay of the ALP to fermions goes with their momentum and thus mass hierarchically. Thus, like the scalar case:



- There are many more models + many more complicated iterations of these (but these are a good overview and often used)