Theory perspective on long-lived particles

Elias Bernreuther

Fermilab

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Long-lived particles

- **Long-lived particles**: macroscopic decay length $\gtrsim \text{mm}$
- Very active frontier with a lot of recent progress
- Theoretically extremely well motivated, in particular deeply connected to cosmology

Ways for a particle to be long-lived:

\[ \Gamma \sim g^2 \frac{m^n}{M^{n-1}} \times \text{PS factor} \]

suppression by: tiny coupling, heavy scale, compressed phase space
Long-lived particles

- **Long-lived particles**: macroscopic decay length $\gtrsim 1\text{ mm}$
- Very active frontier with a lot of recent progress
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Ways for a particle to be long-lived:

$$\Gamma \sim g^2 \frac{m^n}{M^{n-1}} \times \text{PS factor}$$

suppression by: tiny coupling **heavy scale** compressed phase space
Long lifetime from heavy new particles

What heavy new physics could be behind a macroscopic LLP lifetime?

Heavy new bosons:

- Heavy squarks suppressing long-lived gaugino decays in split SUSY
  e.g. Gambino et al., hep-ph/0506214
- Heavy $Z'$ dark sector mediator mediating long-lived dark meson decays in dark QCD
  e.g. Li & Tsai, 1901.09936
- ...

Heavy new fermions:

Have to be \textbf{vectorlike} (left- and right-handed fields have same SM gauge charges)

Simplest example: \textbf{vectorlike lepton} $\mathcal{E}_L, \mathcal{E}_R$ see e.g. Kumar & Martin, 1510.03456

$(1, 1, -1)$ under SU(3)$\times$SU(2)$\times$U(1)
One of the simplest examples of an LLP from new fermions

Example of ALP model that can only be probed at the LHC
LHC sensitivity to LLPs from VLLs

Constraints and projections for displaced $a \rightarrow \gamma \gamma$ from vectorlike leptons

- If decay happens $\mathcal{O}(m)$ from int. point, muon system very sensitive
- Motivates searches sensitive to light LLP $\rightarrow \gamma \gamma$ at smaller displacements
LLP-cosmology connection

LLP models from cosmology, e.g.
- Dark matter co-annihilations
  e.g. Khoze et al., 1702.00750
- WIMP baryogenesis
  e.g. Cui & Sundrum, 1212.2973
- extended dark sectors with LLPs
  e.g. Strassler & Zurek, hep-ph/0604261

Numerical coincidence:

Width of LLPs comparable to Hubble rate at the electroweak scale:

$$c\tau \sim 1 \text{ cm} \quad \overset{\sim}{=} \quad \Gamma \sim 10^{-14} \text{ GeV} \quad \approx \quad H(T = 100 \text{ GeV})$$

Via freeze-in, out-of-equilibrium decays of LLPs can produce:

- **Dark matter**: LHC-scale $c\tau$ requires non-standard cosmology or light DM
  e.g. Calibbi et al., 2102.06221
  Decant et al., 2111.09321
- **Dark radiation**: LHC-scale $c\tau$ corresponds to (soon) accessible $\Delta N_{\text{eff}}$
  EB et al., 2204.01759
Dark radiation at the LHC

Example of concrete model: \[ \mathcal{L}_{\text{int}} = \gamma_{\ell} B \bar{\ell}_R \chi \]

In the early Universe:

- Freeze-in of dark radiation \( \chi \) via out-of-equilibrium decay of \( B \)
- \( \chi \) contributes to \( \Delta N_{\text{eff}} \)

At the LHC:

Same decay yields displaced leptons and MET

LHC-cosmology correlation

- LHC LLP searches complementary to CMB-S4 (target \( \Delta N_{\text{eff}} = 0.06 \))
- CMB-S4 observation would set target for LHC searches

EB, Kahlhoefer, Lucente, Morandini, 2204.01759
Conclusions

- **Long-lived particles** are extremely well-motivated and **among the primary targets** at the LHC now

- **Motivations**: models of dark sectors, baryogenesis, neutrino masses, SUSY, and many others

- **In this talk**:

  **Example of heavy new physics resulting in light LLP**:
  - Vectorlike leptons may decay primarily into pseudoscalars $a_\tau$
  - Muon chambers have excellent sensitivity to displaced $a_\tau \rightarrow \gamma\gamma$ decay
  - Currently little sensitivity to shorter decay lengths

  **Example of the interplay with cosmology**:
  - Production of dark radiation via decay of LLP
  - CMB-S4 could set target for LHC LLP searches