Theory perspective on long-lived particles

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Long-lived particles

- **Long-lived particles:** macroscopic decay length $\gtrsim \mathrm{mm}$
- 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

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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 **vectorlike** (left- and right-handed fields have same SM gauge charges)

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

$(\mathbf{1}, \mathbf{1}, -1)$ under SU(3)xSU(2)xU(1)

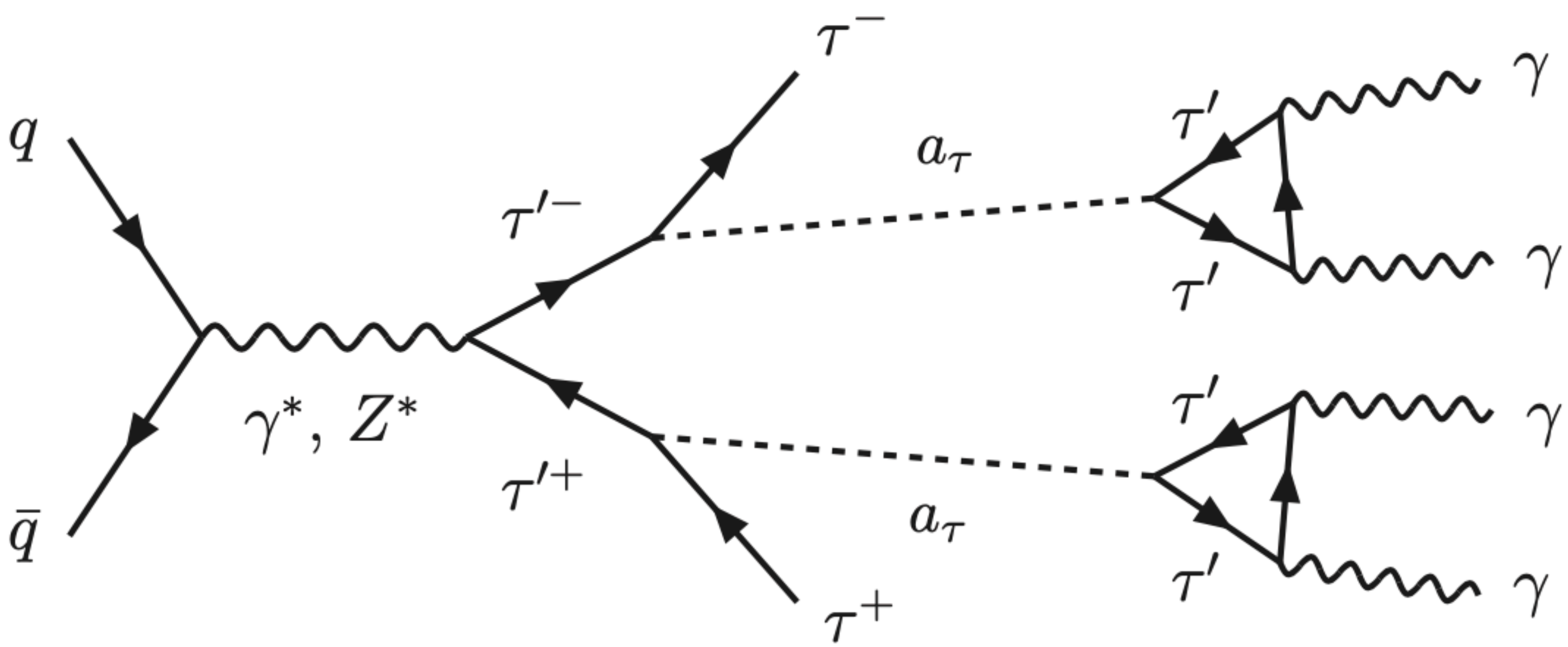
LLPs from vectorlike leptons

VLL $\mathscr{E}$ mixes with third-generation leptons ➡ **physical particles: τ and τ'**

If complex scalar ϕ coupled to VLL $\quad -\phi\, \overline{\mathscr{E}}_L \left(y_{\mathscr{E}}\, e^{i\beta_{\mathscr{E}}}\, \mathscr{E}_R + y_o\, e^{i\beta_o}\, e^3_R \right) + \mathrm{H.c.}$

➡ Dominant decay of VLL to long-lived pseudoscalar, $\tau' \to \tau\, a_\tau$

EB & Dobrescu, 2304.08509



$$c\tau_a = 4\ \mathrm{cm} \times \left(\frac{0.1}{y_{\tau'}}\right)^2 \left(\frac{2\ \mathrm{GeV}}{M_a}\right)^3 \left(\frac{m_{\tau'}}{500\ \mathrm{GeV}}\right)^2$$

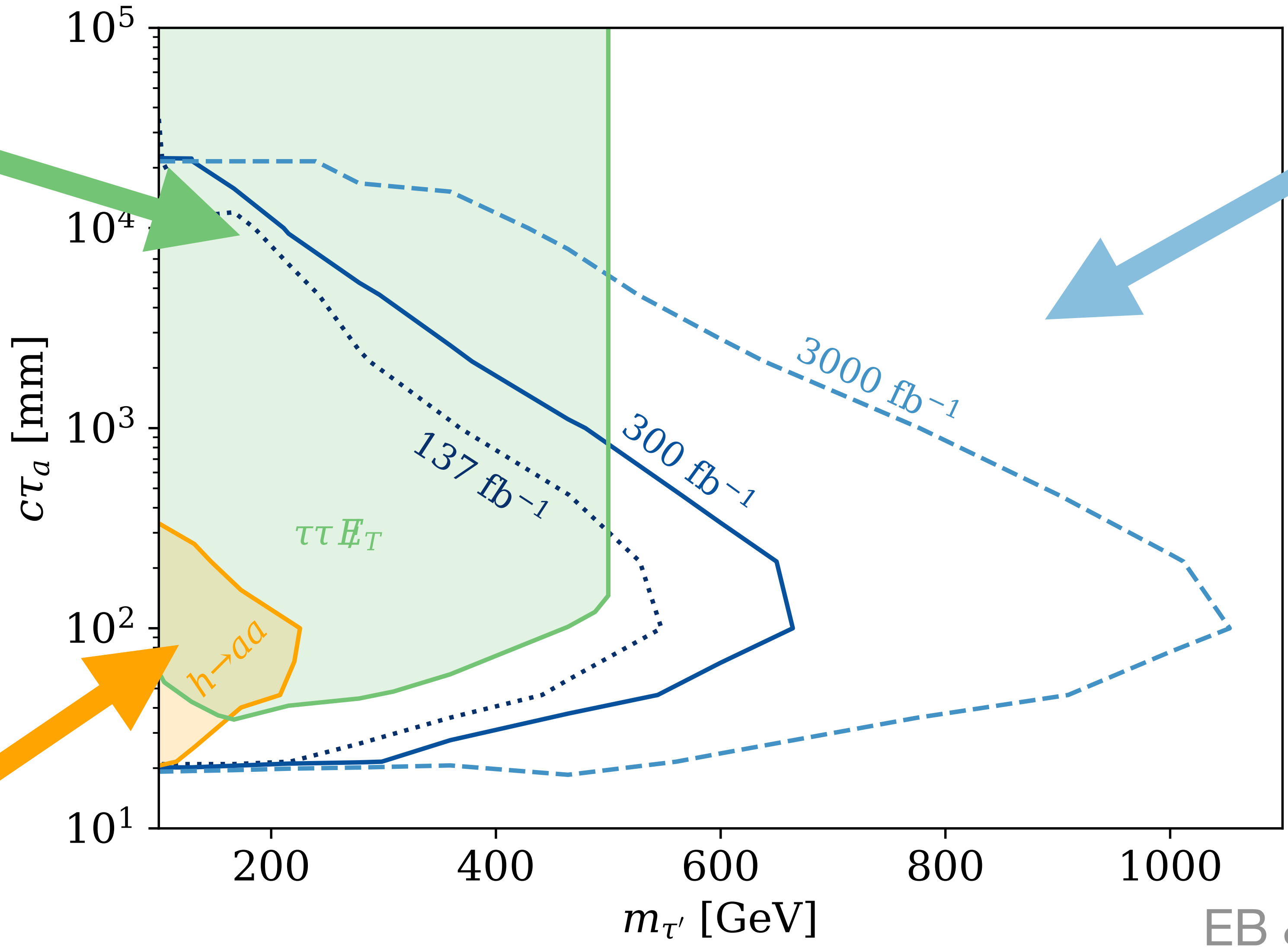
➡
- **One of the simplest examples of an LLP from new fermions**
- **Example of ALP model that can only be probed at the LHC**

LHC sensitivity to LLPs from VLLs

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

Search for stau pair production CMS PAS SUS-21-001

Existing CMS search for LLPs in muon system [2107.04838](2107.04838)



Projected limit for search in muon system barrel + endcaps with tau triggers

EB & Dobrescu, 2304.08509

- **If decay happens $\mathcal{O}(m)$ from int. point, muon system very sensitive**
- **Motivates searches sensitive to light LLP $\to \gamma\gamma$ 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:

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

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 ΔN_{eff}

  EB et al., 2204.01759

Dark radiation at the LHC

Example of concrete model: $\mathscr{L}_{\text{int}} = y_\ell \, B \, \bar{\ell}_R \, \chi$

EB, Kahlhoefer, Lucente, Morandini, 2204.01759

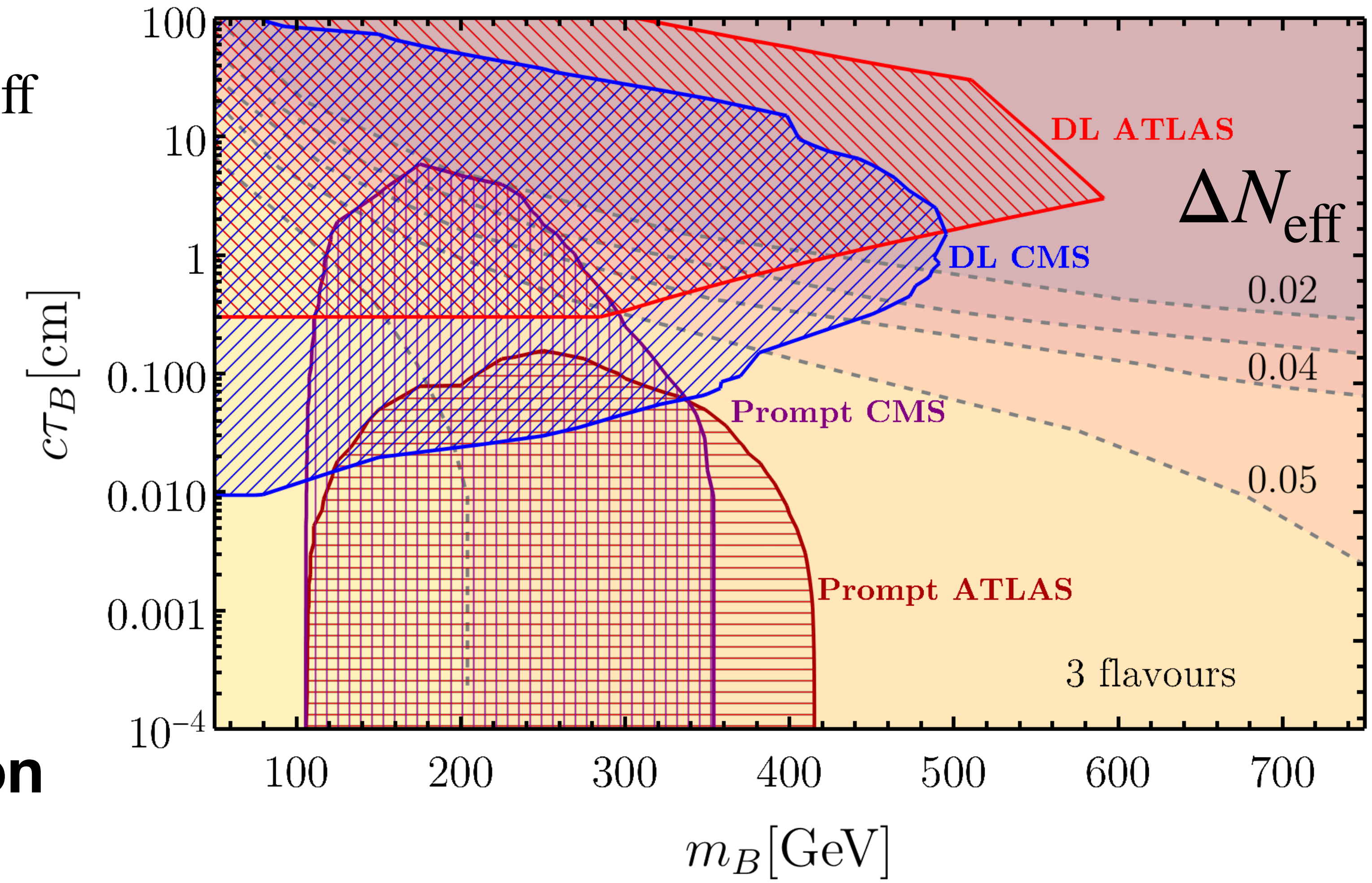
In the early Universe:

- Freeze-in of dark radiation χ via out-of-equilibrium decay of B
- χ contributes to ΔN_{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**

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_τ
- Muon chambers have excellent sensitivity to displaced $a_\tau \to \gamma\gamma$ 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