

Vectorlike leptons and long-lived bosons at the LHC

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Searching for long-lived particles at the LHC and beyond
CERN, June 20, 2023

based on

[arXiv:2304.08509](https://arxiv.org/abs/2304.08509) with Bogdan Dobrescu

Long-lived particles at the LHC

Long-lived particles

with **macroscopic decay lengths** $\gtrsim \mathcal{O}(\text{mm})$ among prime targets at the LHC

Most current searches geared towards short decay lengths (mm – cm) and large masses ($\gtrsim 100$ GeV) see e.g. Alimena et al., 1903.04497 for review

 **Gap at decay lengths of several meters** (especially for GeV-scale LLPs)

- **Light LLPs** naturally in this regime if decay **suppressed by heavy particle**

Generic example: **heavy new fermion**

- **has to be vectorlike**
i.e. same gauge charges for left- and right-handed fermions
- Most minimal possibility: **Singlet vectorlike lepton** \mathcal{E}

Vectorlike leptons: standard story

- Gauge eigenstates: **vectorlike lepton** $\mathcal{E}_L, \mathcal{E}_R$
 $(\mathbf{1}, \mathbf{1}, -1)$ under $SU(3) \times SU(2) \times U(1)$

see e.g. Kumar & Martin, 1510.03456

- Couplings of \mathcal{E} to third-generation leptons:

$$-m_{\mathcal{E}\mathcal{E}} \bar{\mathcal{E}}_L \mathcal{E}_R - m_{\mathcal{E}3} \bar{\mathcal{E}}_L e_R^3 - y_3 H \bar{\mathcal{E}}_L^3 e_R + \text{H.c.}$$

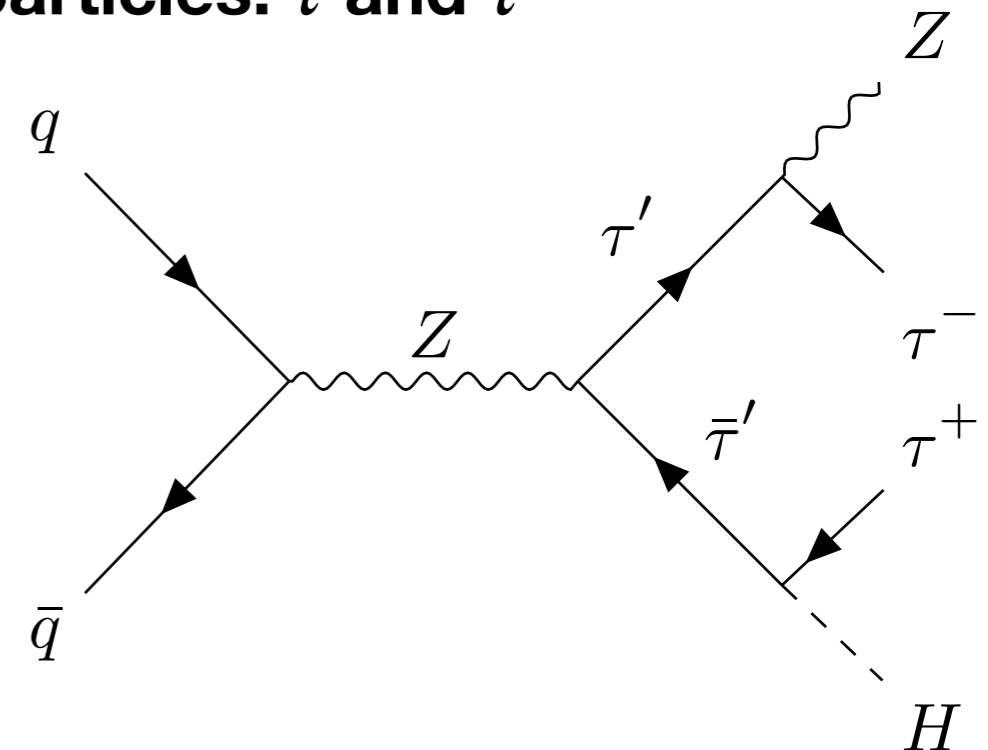
Mass mixing \rightarrow **physical particles: τ and τ'**

- Mass eigenstate τ' decays via channels

$$\tau' \rightarrow \tau Z, \tau' \rightarrow \tau h, \tau' \rightarrow \nu W$$

\rightarrow ATLAS and CMS searches exclude these standard VLLs if $m_{\tau'} \lesssim 176 \text{ GeV}$

ATLAS collaboration, arXiv:1506.01291



ATLAS-CONF-2022-044

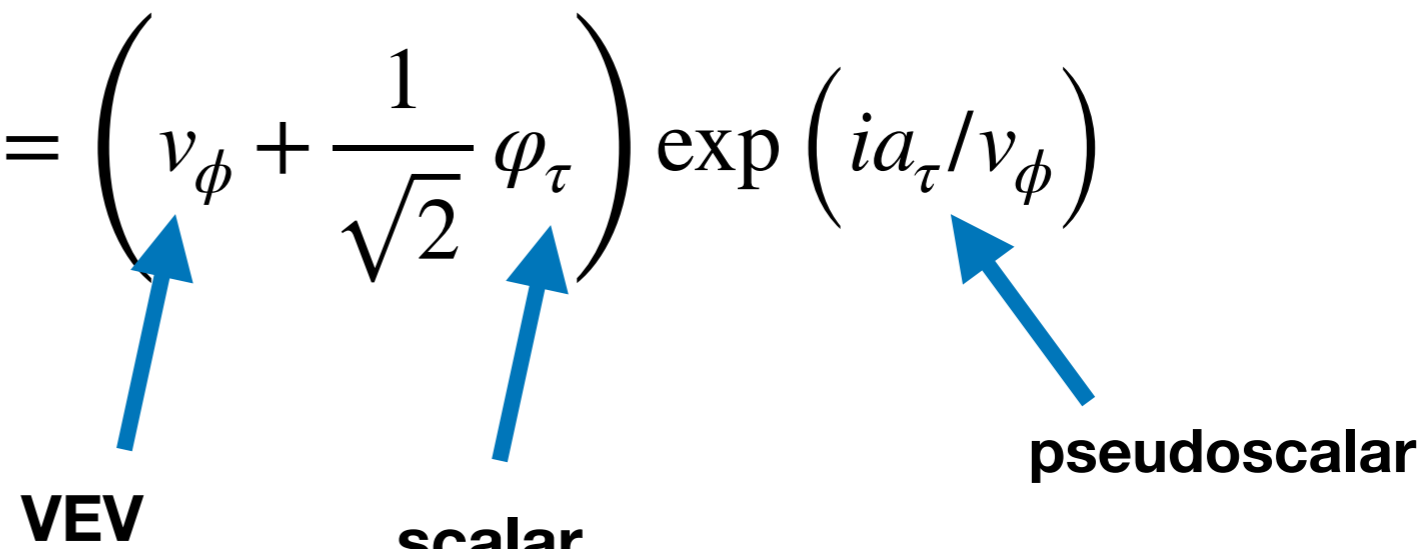
Long-lived particles from vectorlike leptons

How are vectorlike leptons connected to long-lived particles?

- Consider complex scalar ϕ coupled to VLL
- Most general Yukawa interaction:

$$-\phi \bar{\mathcal{E}}_L (y_{\mathcal{E}} e^{i\beta_{\mathcal{E}}} \mathcal{E}_R + y_o e^{i\beta_o} e_R^3) + \text{H.c.}$$

$$y_{\mathcal{E}}, y_o > 0 \quad \text{and} \quad 0 \leq \beta_{\mathcal{E}}, \beta_o < 2\pi$$

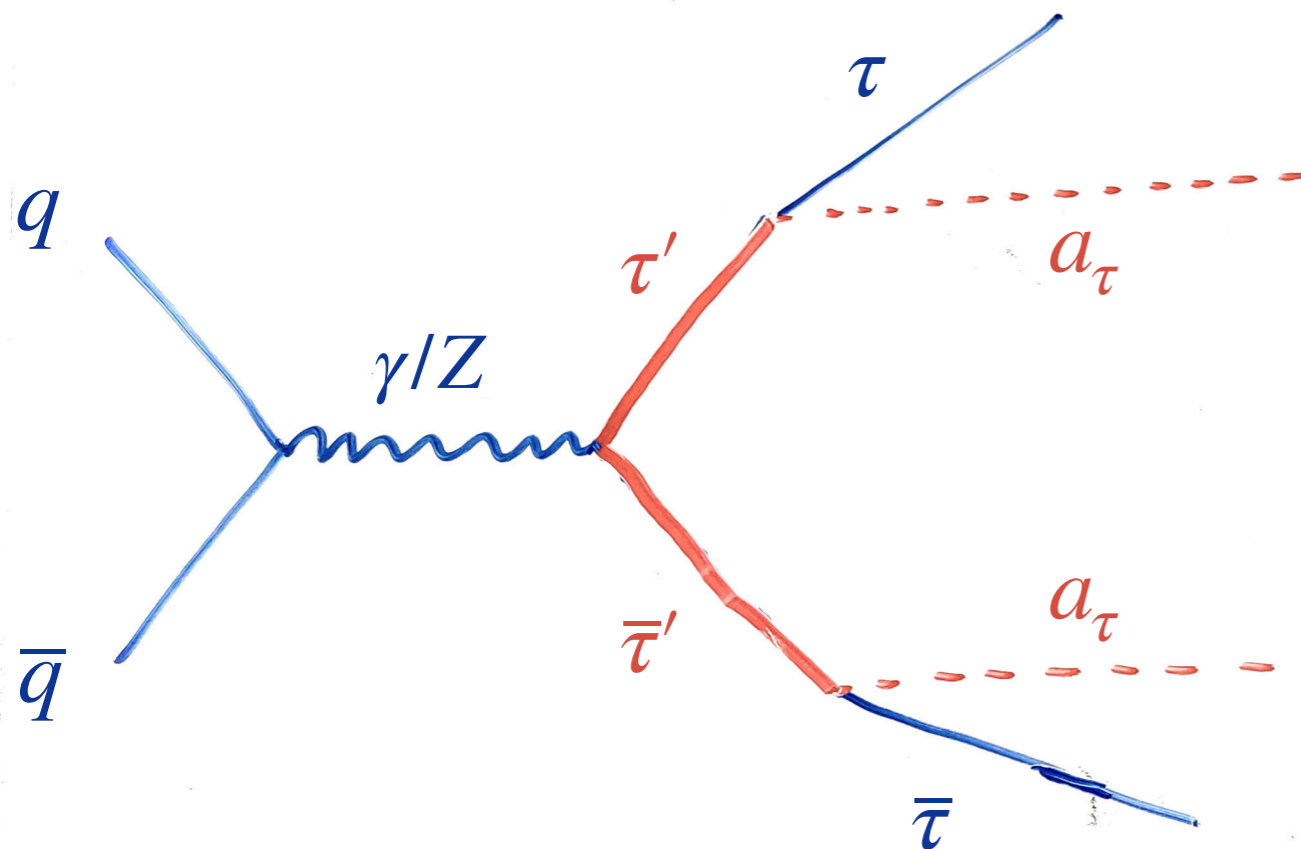
- After scalar acquires vev: $\phi = \left(v_{\phi} + \frac{1}{\sqrt{2}} \varphi_{\tau} \right) \exp \left(i a_{\tau} / v_{\phi} \right)$


VEV scalar pseudoscalar

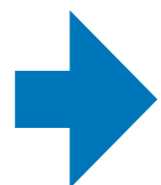
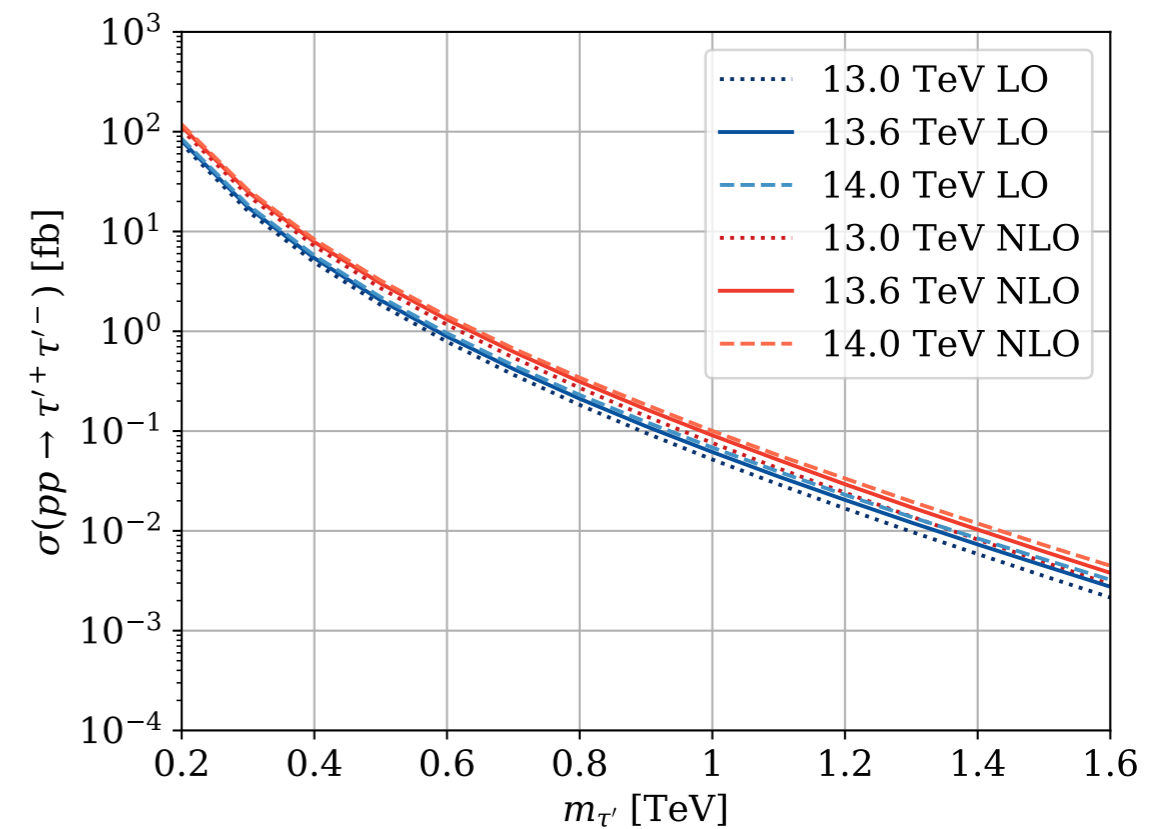
➔ Large parameter space with BR ($\tau' \rightarrow \tau a_{\tau}$) $\approx 100\%$

Long-lived particle production

Prompt VLL production
and decay $\tau' \rightarrow \tau a_\tau$



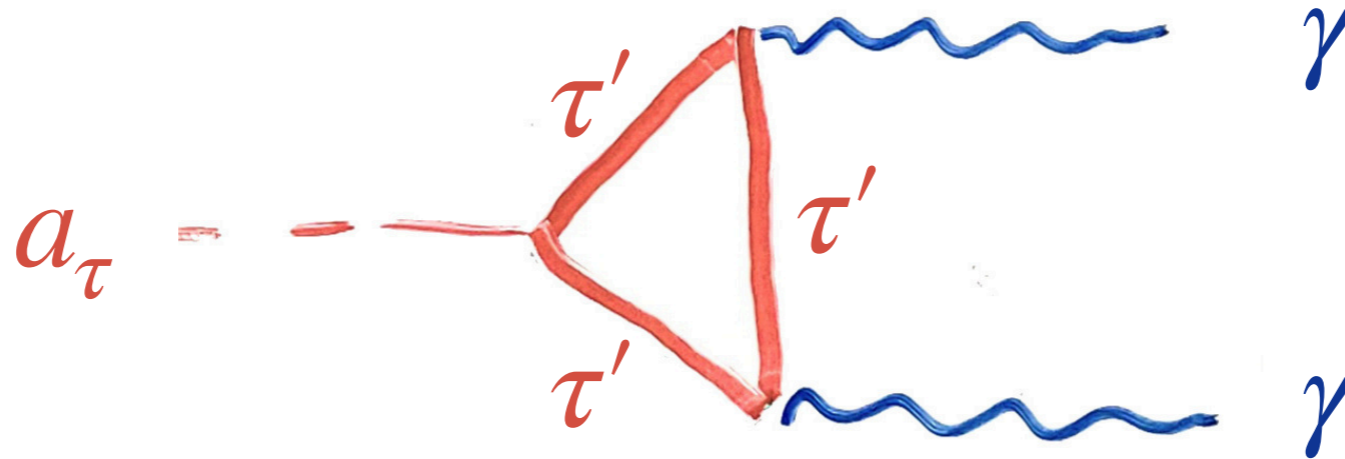
Production cross section



Potential LHC reach in τ' mass to well above 1 TeV

Long-lived particle decay

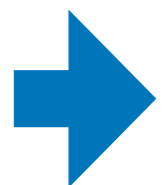
- Rich pheno with signals with many taus or photons
- Particularly interesting: **dominant decay mode** $a_\tau \rightarrow \gamma\gamma$ **via heavy** τ' **loop**



- Heavy VLL in the loop leads to **macroscopic** a_τ **decay length even for sizable couplings:**

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

- In addition, a_τ picks up large boost (~ 100 for example above)



Majority of decays can be meters from interaction point

Search for LLPs in muon system

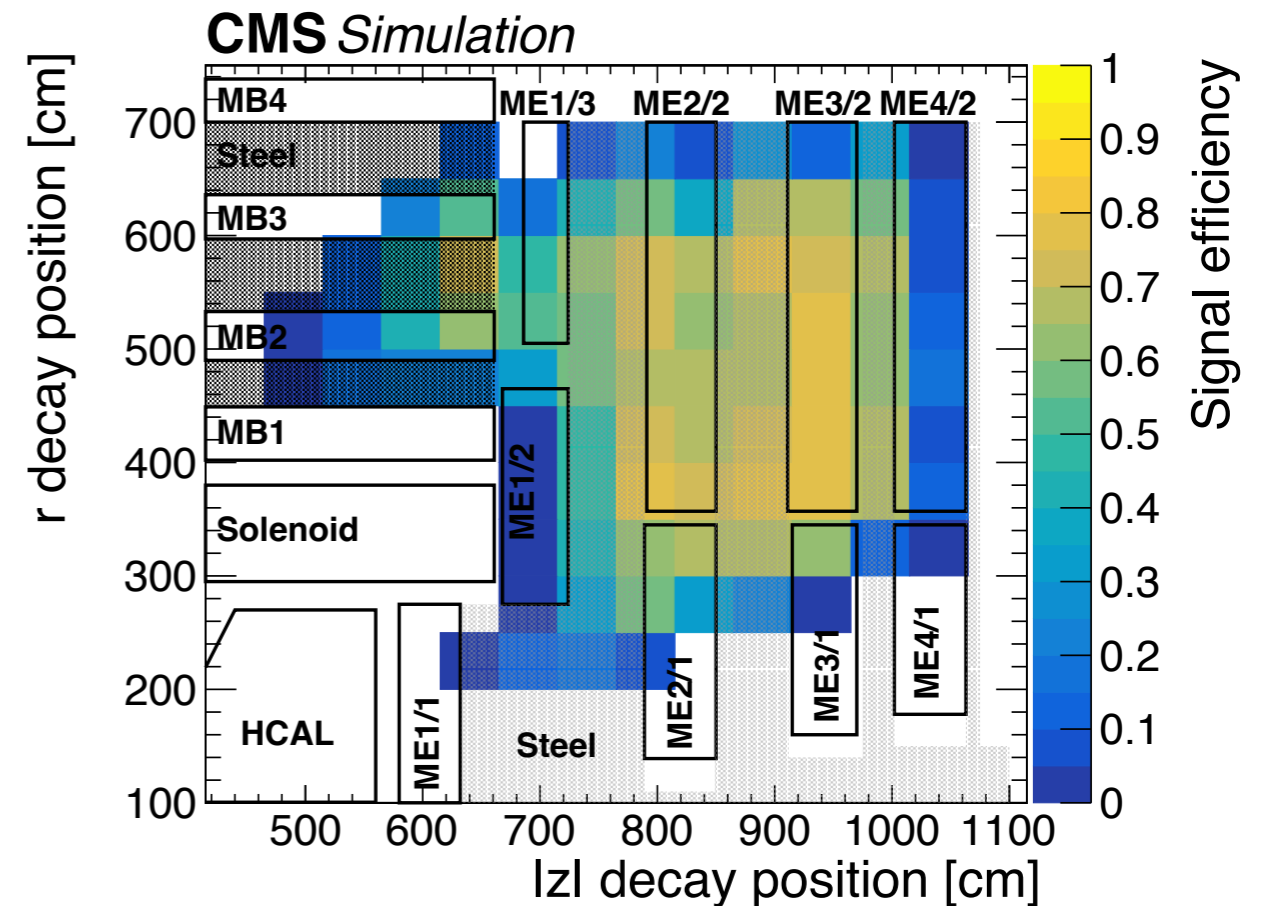
The muon system is several meters away!

- Recent CMS search [2107.04838](#) and ATLAS search [1811.07370](#)
- **CMS search** first search to use muon system like a calorimeter for LLPs

Look for cascade caused by LLP decay products

$$N_{\text{hits}} > 130$$

$$\Delta\phi(\text{cluster}, \vec{p}_T^{\text{miss}}) < 0.75$$



Sensitivity depends on LLP energy, not on mass

CMS collaboration, 2107.04838

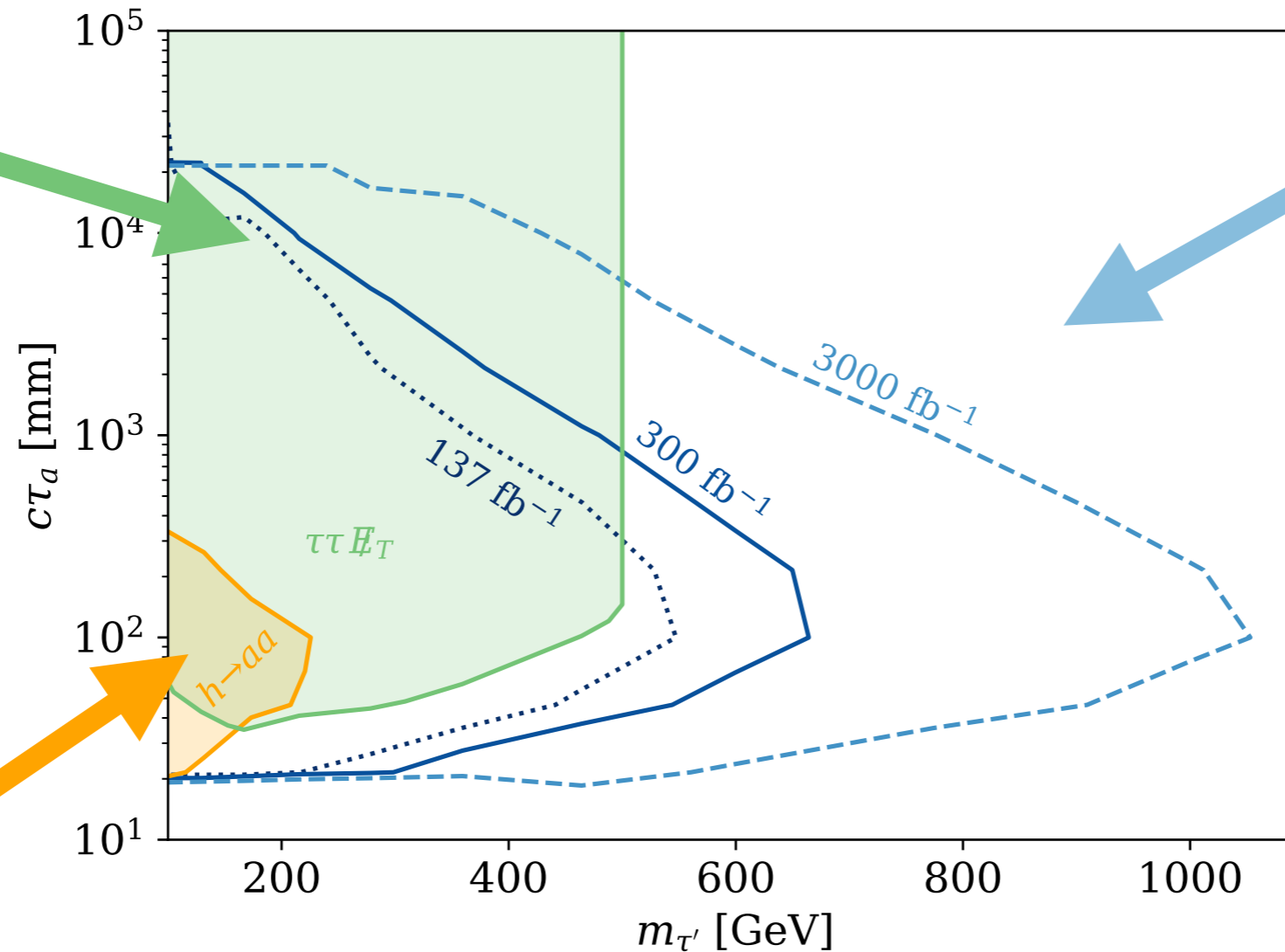
Unique sensitivity to decay positions several meters away from interaction point

Projected LLP sensitivity in muon system

- Motivated by VLL+LLP model, **propose a search for LLPs in the muon system in association with prompt taus**
- Include full muon system with barrel + endcaps, leverage prompt taus for trigger and background suppression

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

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



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

Vast improvement over existing constraints

Conclusions

- Long-lived particles are extremely well-motivated and among the primary targets at the LHC and other colliders now
- Rapidly expanding search program, but many remaining gaps
 - ➔ especially light LLPs, decay lengths \sim meters
- Wealth of interesting models that fall into this gap; in this talk:
 - Vectorlike leptons may decay primarily into pseudoscalars a_τ
 - ➔ Rich final states with many taus or photons
 - Majority of a_τ 's typically decay meters from the interaction point
 - Searches in muon chambers improve greatly over existing constraints