

# Vectorlike leptons and long-lived bosons at the LHC

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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:

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

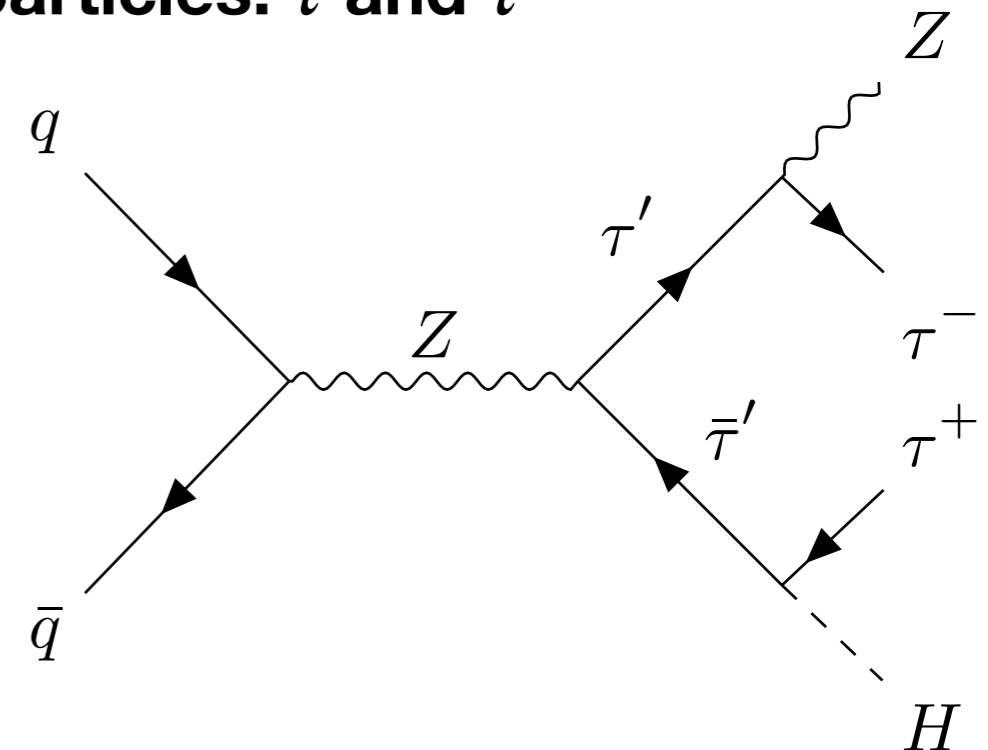
Mass mixing  $\rightarrow$  **physical particles:  $\tau$  and  $\tau'$**

- Mass eigenstate  $\tau'$  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  $m_{\tau'} \lesssim 176$  GeV

ATLAS collaboration, arXiv:1506.01291



ATLAS-CONF-2022-044

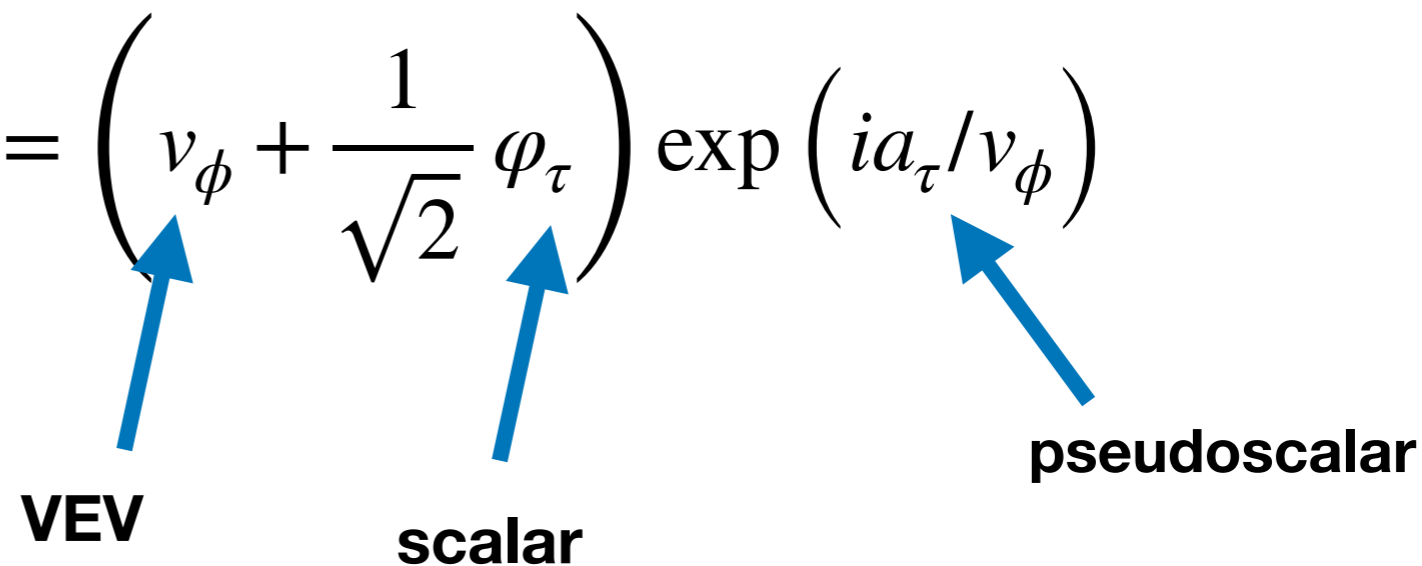
# Long-lived particles from vectorlike leptons

## How are vectorlike leptons connected to long-lived particles?

- Consider complex scalar  $\phi$  coupled to VLL
- Most general Yukawa interaction:

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

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

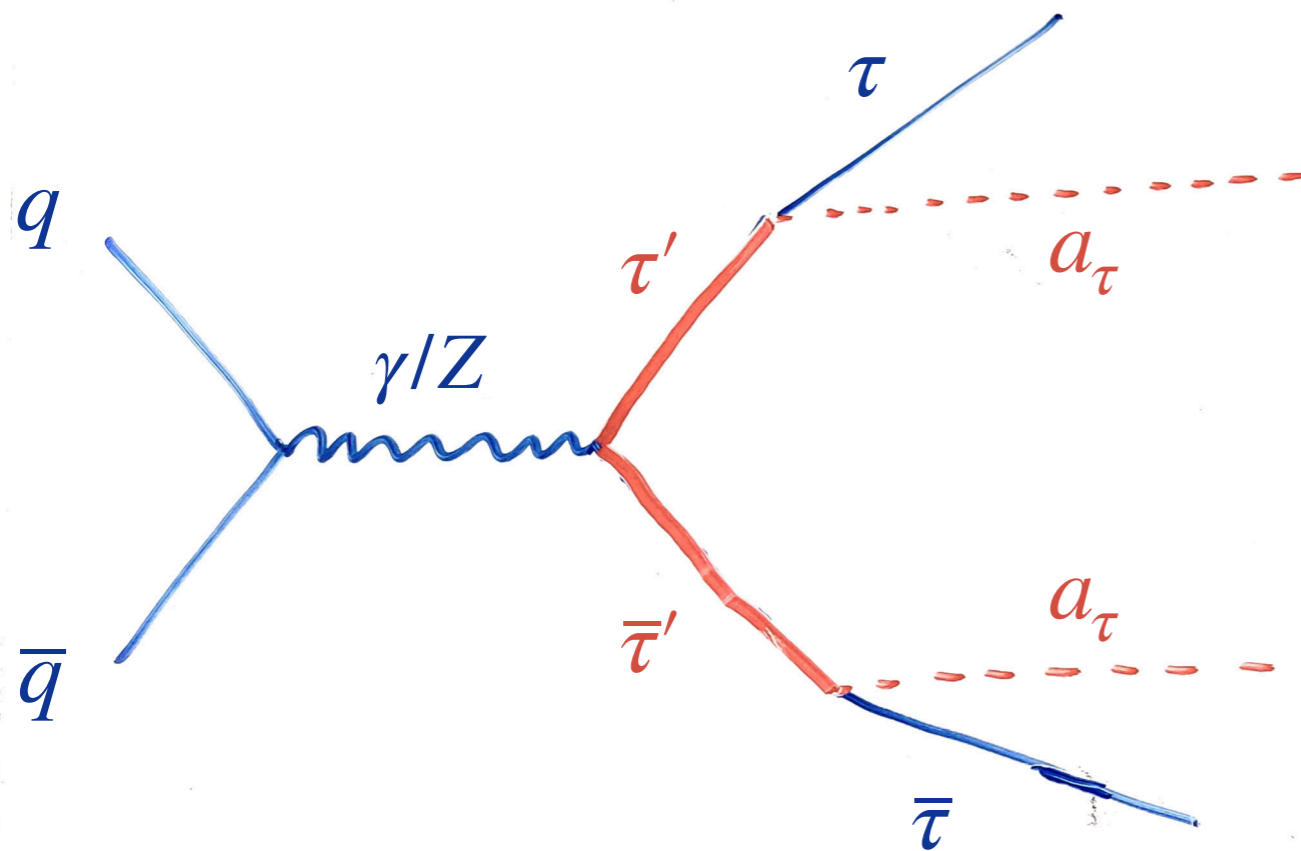
- After scalar acquires vev:  $\phi = \left( v_{\phi} + \frac{1}{\sqrt{2}} \varphi_{\tau} \right) \exp \left( i a_{\tau} / v_{\phi} \right)$   


VEV                      scalar                      pseudoscalar

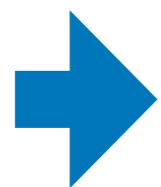
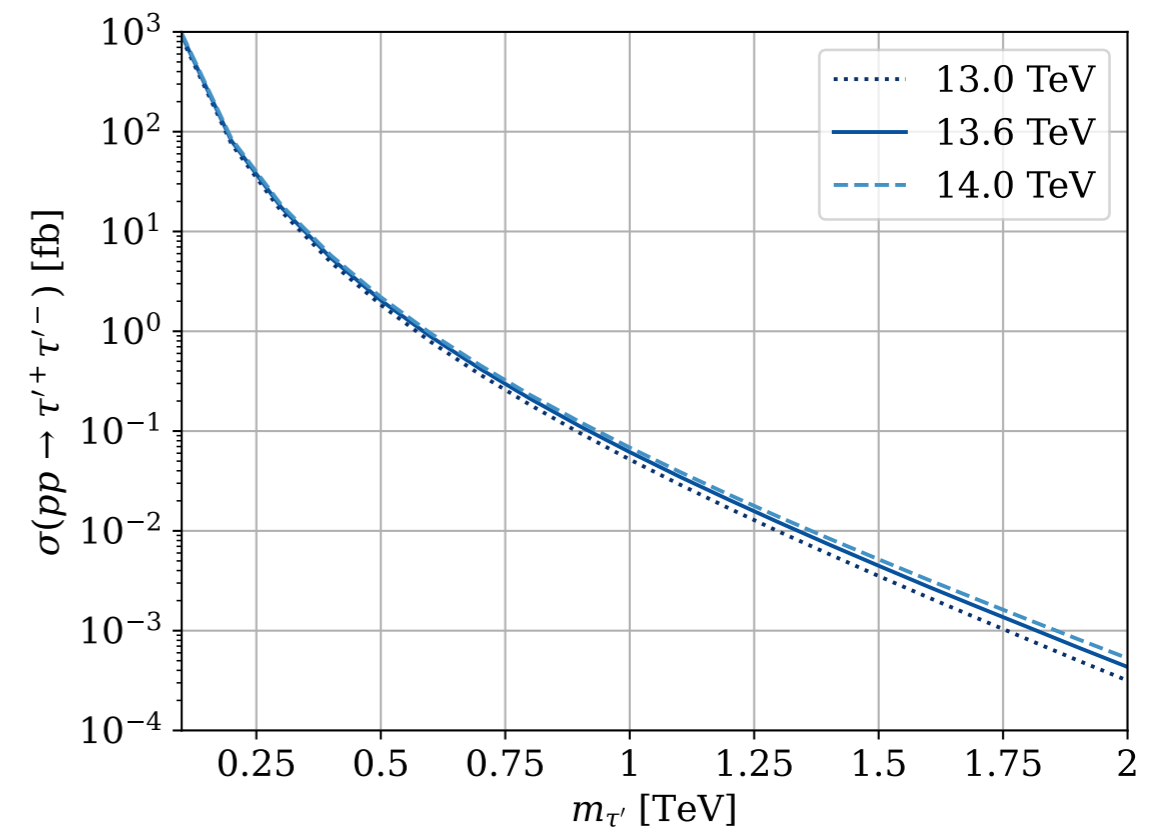
➔ Large parameter space with BR ( $\tau' \rightarrow \tau a_{\tau}$ )  $\approx 100\%$

# Long-lived particle production

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



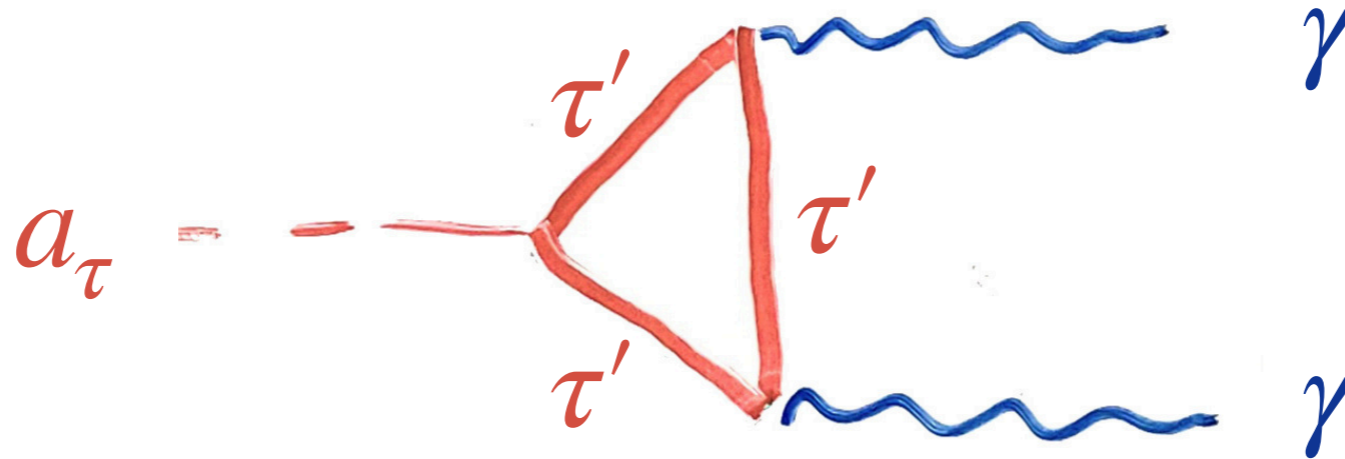
Production cross section



Potential LHC reach in  $\tau'$  mass to well above 1 TeV

# Long-lived particle decay

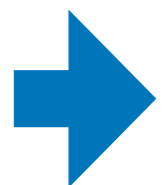
- Rich pheno with signals with many taus or photons
- Particularly interesting: **dominant decay mode**  $a_\tau \rightarrow \gamma\gamma$  **via heavy**  $\tau'$  **loop**



- Heavy VLL in the loop leads to **macroscopic**  $a_\tau$  **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,  $a_\tau$  picks up large boost ( $\sim 100$  for example above)



**Majority of decays can be meters from interaction point**

# Search for LLPs in muon system

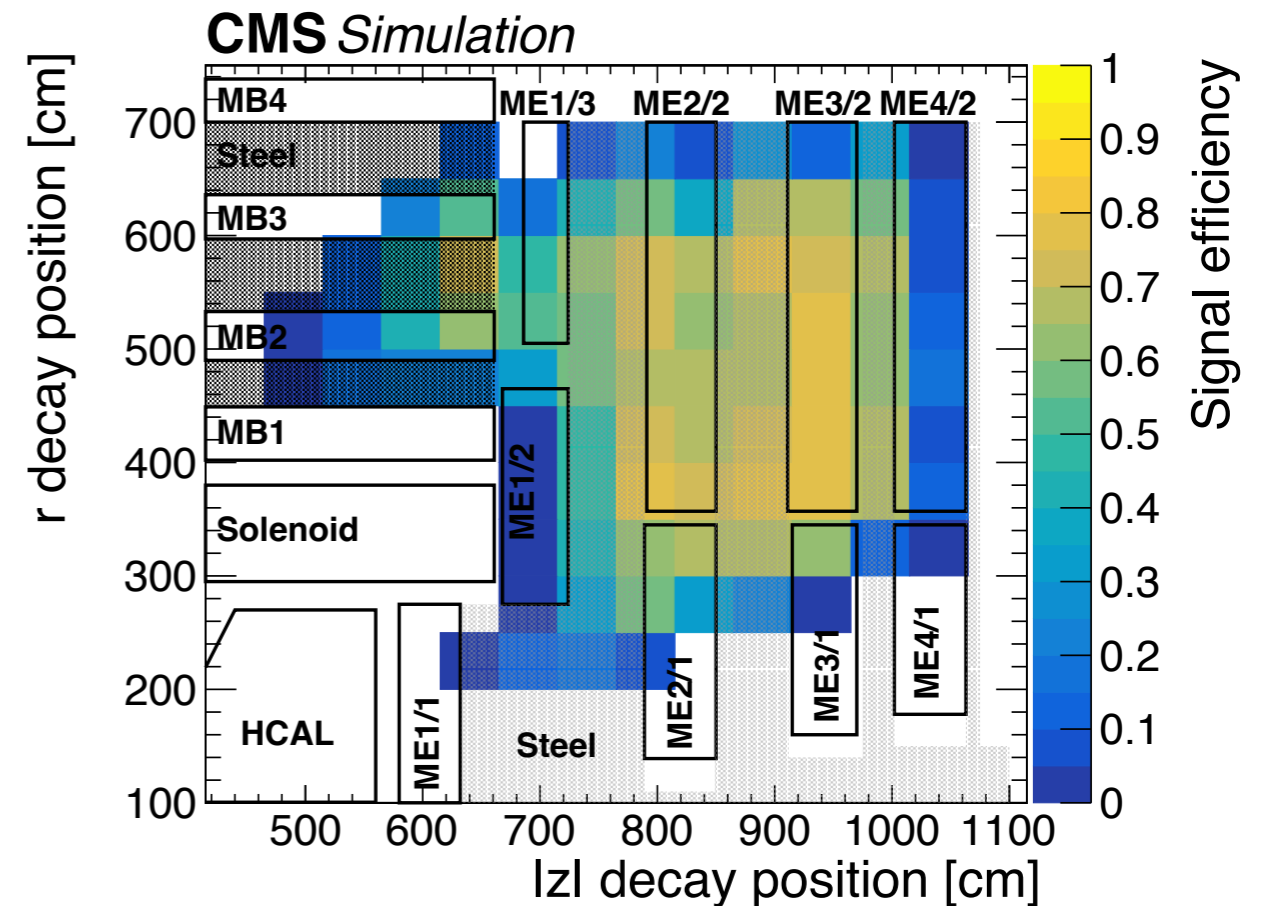
**The muon system is several meters away!**

- 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

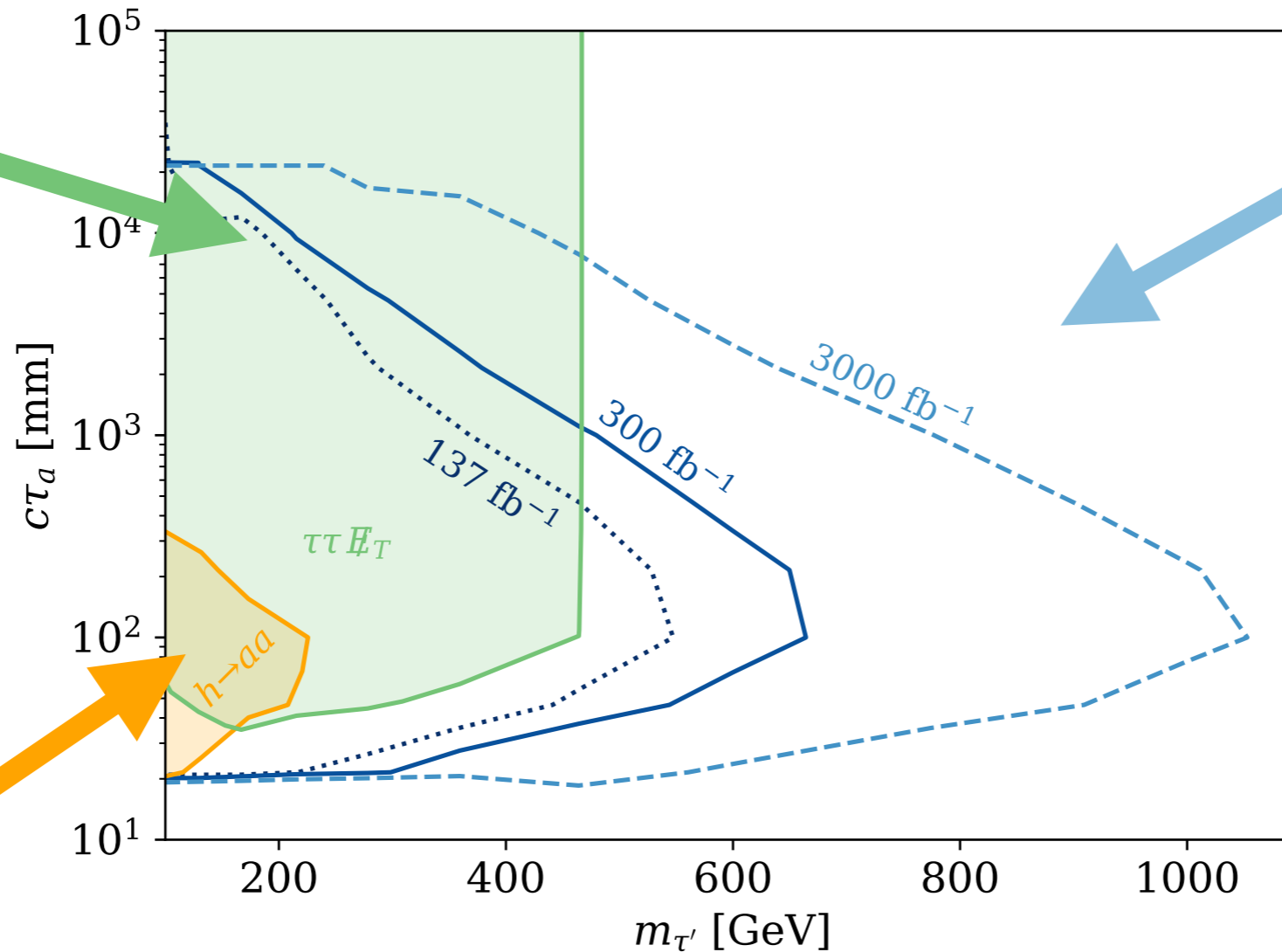
**Unique sensitivity to decay positions several meters away from  
interaction point**

# Projected LLP sensitivity in muon system

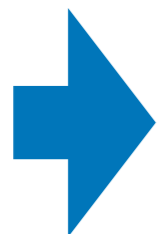
- Motivated by VLL+LLP model, **propose a search for LLPs in the muon system in association with prompt taus**
- Include full muon system with barrel + endcaps, leverage prompt taus for trigger and background suppression

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  $a_\tau$ 
    - ➔ Rich final states with many taus or photons
  - Majority of  $a_\tau$ 's typically decay meters from the interaction point
  - Searches in muon chambers improve greatly over existing constraints