Light long-lived particles at colliders

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based on

ongoing work, arXiv:2303.XXXXX with Bogdan Dobrescu

JHEP 12 (2022) 005, arXiv:2203.08824 with Kai Böse, Torben Ferber, Christopher Hearty, Felix Kahlhoefer, Alessandro Morandini and Kai Schmidt-Hoberg

New physics off the beaten track

- **LHC has collected an enormous amount of data already:**

  $137\ \mathrm{fb}^{-1}$ in Run 2; on its way to collecting $300\ \mathrm{fb}^{-1}$ in Run 3

- Still, this is **only a small fraction** of the final luminosity goal

Conservative view: discovery potential scales as $\sqrt{\text{luminosity}}$

Not true if we keep looking in new places!

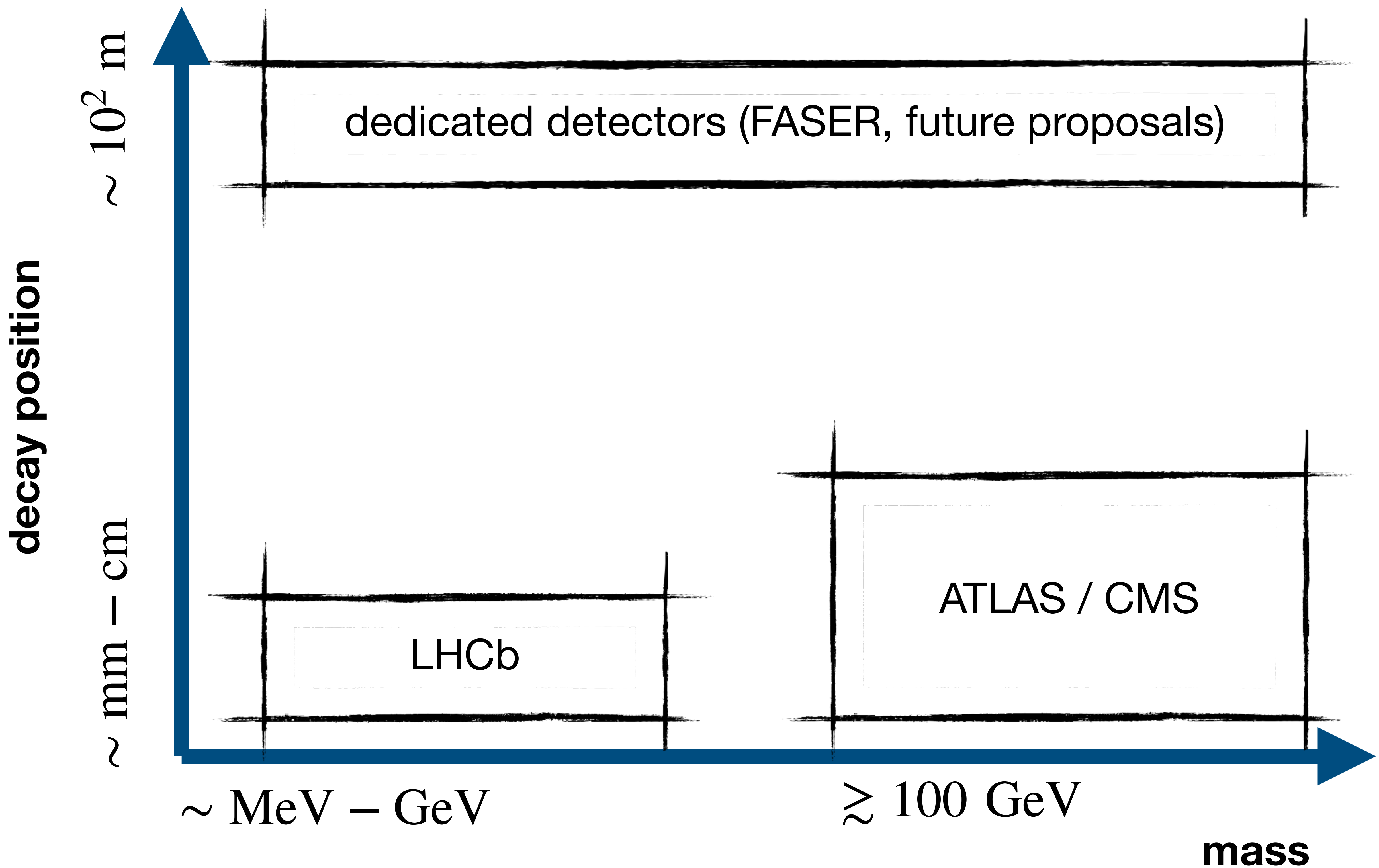
Active frontier with a great deal of recent progress:

Long-lived particles

i.e. particles with macroscopic decay lengths of $\mathcal{O}(\mathrm{mm})$ to $\mathcal{O}(\mathrm{km})$

Landscape of displaced decays

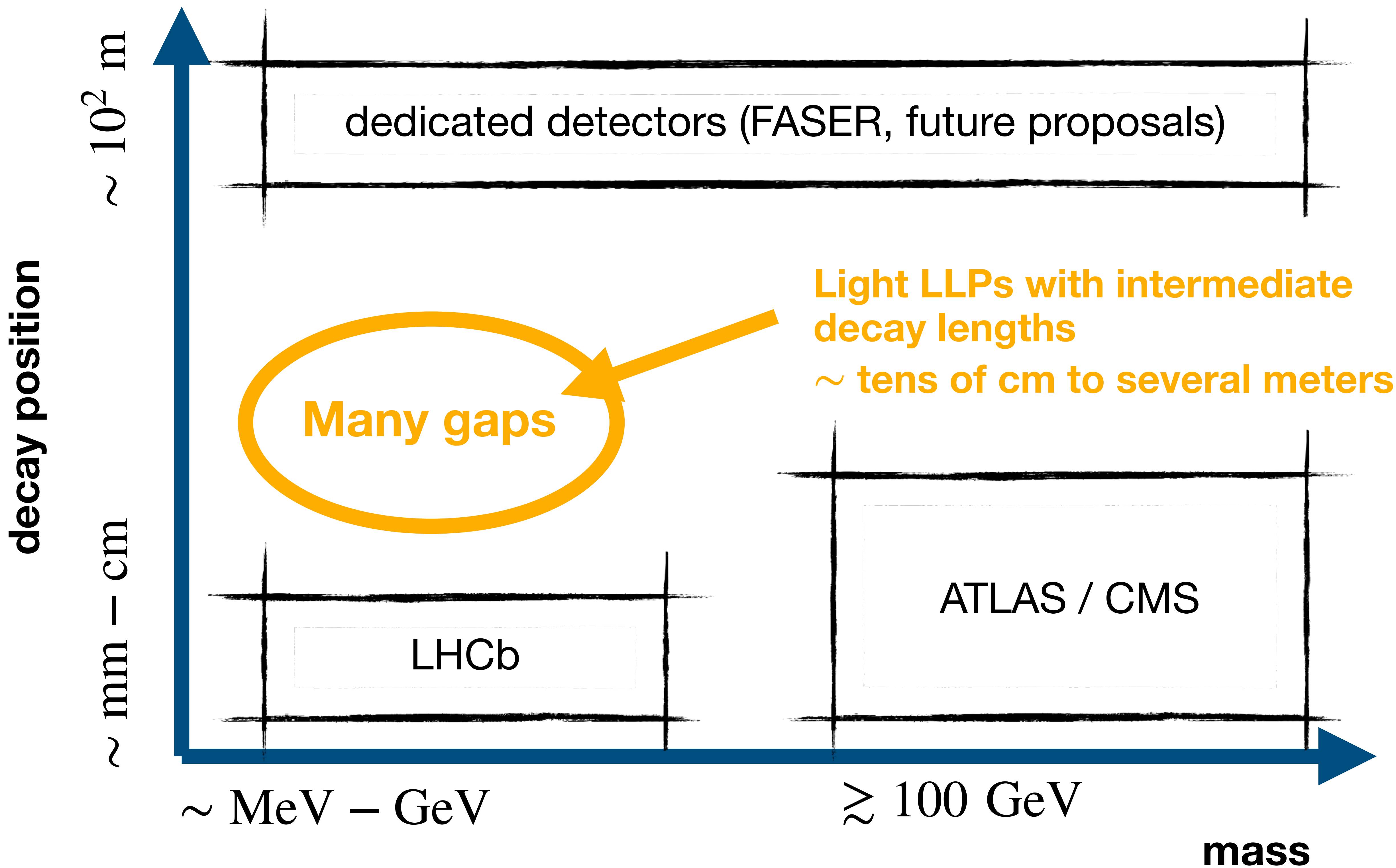
Organize approximately by mass and decay position



see e.g. Alimena et al., 1903.04497 for review

Landscape of displaced decays

Organize approximately by mass and decay position



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Light long-lived particles

In this talk: Two different ways to close this gap, illustrated with two models

Light LLPs from vectorlike leptons at the LHC, in particular **in the muon chambers**

Light LLPs from strongly interacting dark sector at **Belle II**

- **In both cases**, detectors are used in new, creative ways that they were not originally intended for.
- **In both cases**, light particles are long-lived due to a mass hierarchy.

Vectorlike fermions

What heavy new physics could drive a macroscopic LLP lifetime?

- Heavy new **bosons**: second part of this talk
- Heavy new **fermions:** have to be **vectorlike**
  (left- and right-handed fields have the gauge charges)

  due to stringent constraints on new chiral fermions

  - Vectorlike fermions among the simplest possible additions to the SM
  - Novel form of matter
  - Part of a large number of top-down BSM models
    (grand unification, compositeness, extra dimensions …)

⇨ Most minimal possibility: **Singlet vectorlike lepton** $\mathscr{E}$

Vectorlike leptons: standard story

- Gauge eigenstates: **vectorlike lepton** $\underbrace{\mathscr{E}_L, \mathscr{E}_R}$

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

  see e.g. Kumar & Martin, 1510.03456

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

$$-m_{\mathscr{E}\mathscr{E}}\,\overline{\mathscr{E}}_L\,\mathscr{E}_R - m_{\mathscr{E}3}\,\overline{\mathscr{E}}_L\,e^3_R - y_3\,H\,\overline{\ell}^3_L\,e_R + \mathrm{H.c.}$$

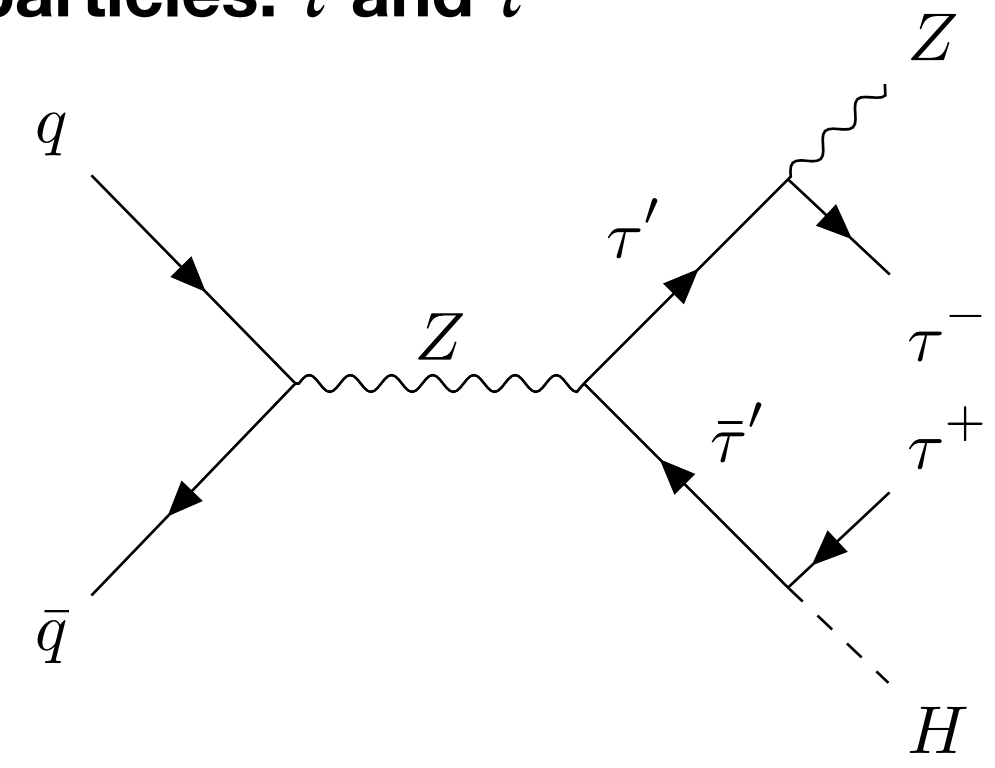
Mass mixing ➡ **physical particles: τ and τ'**

- Mass eigenstate τ' decays via channels

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

➡ 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 can vectorlike leptons be connected to long-lived particles?

- Consider complex scalar ϕ, responsible for VLL mass
- Most general Yukawa interaction:

$$-\phi\,\overline{\mathscr{E}}_L\left(y_{\mathscr{E}}\,e^{i\beta_{\mathscr{E}}}\,\mathscr{E}_R + y_o\,e^{i\beta_o}\,e_R^3\right) + \mathrm{H.c.}$$

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

- After scalar acquires vacuum expectation value:

$$\phi = \left(v_\phi + \frac{1}{\sqrt{2}}\varphi_\tau\right)\exp\left(ia_\tau/v_\phi\right)$$

pseudoscalar

VEV **scalar**

Long-lived particles from vectorlike leptons

- **VEVs v_H, v_ϕ and explicit mass terms $m_{\mathscr{E}\mathscr{E}}$, $m_{\mathscr{E}3}$ control mixing** with SM third generation

$$\left(\overline{e}_L^3\,,\ \overline{\mathscr{E}}_L\right)\begin{pmatrix} y_3\, v_H & 0 \\ m_{\mathscr{E}3} + y_o\, e^{i\beta_o}\, v_\phi & m_{\mathscr{E}\mathscr{E}} + y_{\mathscr{E}}\, e^{i\beta_{\mathscr{E}}}\, v_\phi \end{pmatrix}\begin{pmatrix} e_R^3 \\ \mathscr{E}_R \end{pmatrix}$$

$$\begin{pmatrix} e_{L,R}^3 \\ \mathscr{E}_{L,R} \end{pmatrix} = \begin{pmatrix} c_{L,R} & s_{L,R} \\ -s_{L,R} & c_{L,R} \end{pmatrix}\begin{pmatrix} \tau_{L,R} \\ \tau'_{L,R} \end{pmatrix}$$

Constraint on mixing angle: $s_L < 0.037$ from $\dfrac{B(Z \to \tau^+\tau^-)}{B(Z \to \ell^+\ell^-)}$

- **Interesting new BSM decay modes** of VLL mass eigenstate:

$$\tau' \to \tau a_\tau\,, \quad \tau' \to \tau\varphi_\tau$$

in addition to standard SM modes $\tau' \to \tau Z,\ \tau' \to \tau h,\ \tau' \to \nu W$

Long-lived particles from vectorlike leptons

Case 1: Pseudo-Goldstone limit: entire mass of VLL is generated by ϕ

➡ a_τ is naturally light pseudo-Goldstone boson

- Ratio of BSM-to-SM branching fractions of VLL is set purely by VEVs, independent of Yukawa coupling:

$$\frac{\Gamma\left(\tau' \to \tau a_\tau\right)}{\Gamma\left(\tau' \to \mathrm{SM}\right)} = \frac{v_H^2}{4v_\phi^2}\left(1 + \frac{M_h^2}{2m_{\tau'}^2} + O(M_h^4/m_{\tau'}^4)\right)$$

explored in ongoing separate project

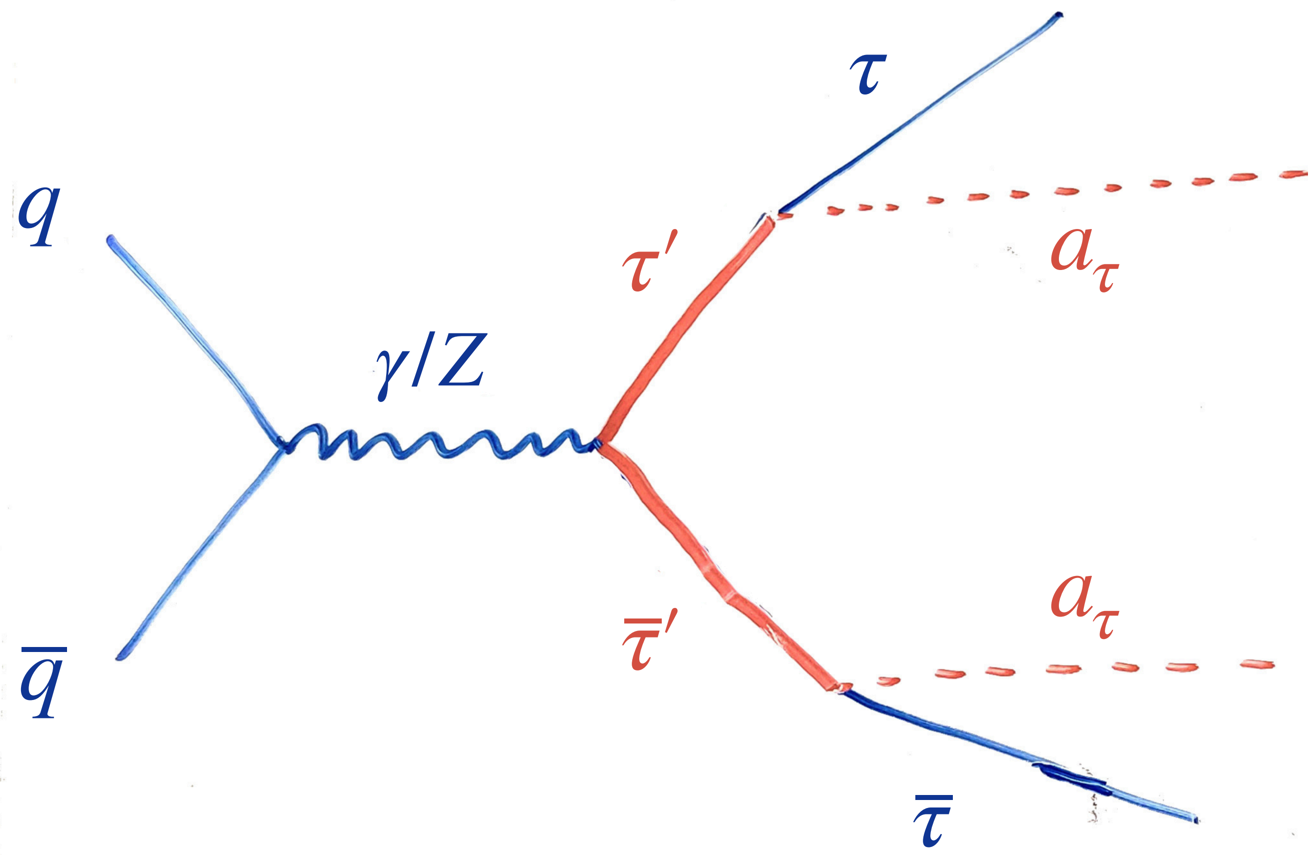
In this talk focus on:

Case 2: With explicit mass terms $m_{\mathscr{E}\mathscr{E}}, m_{\mathscr{E}3}$

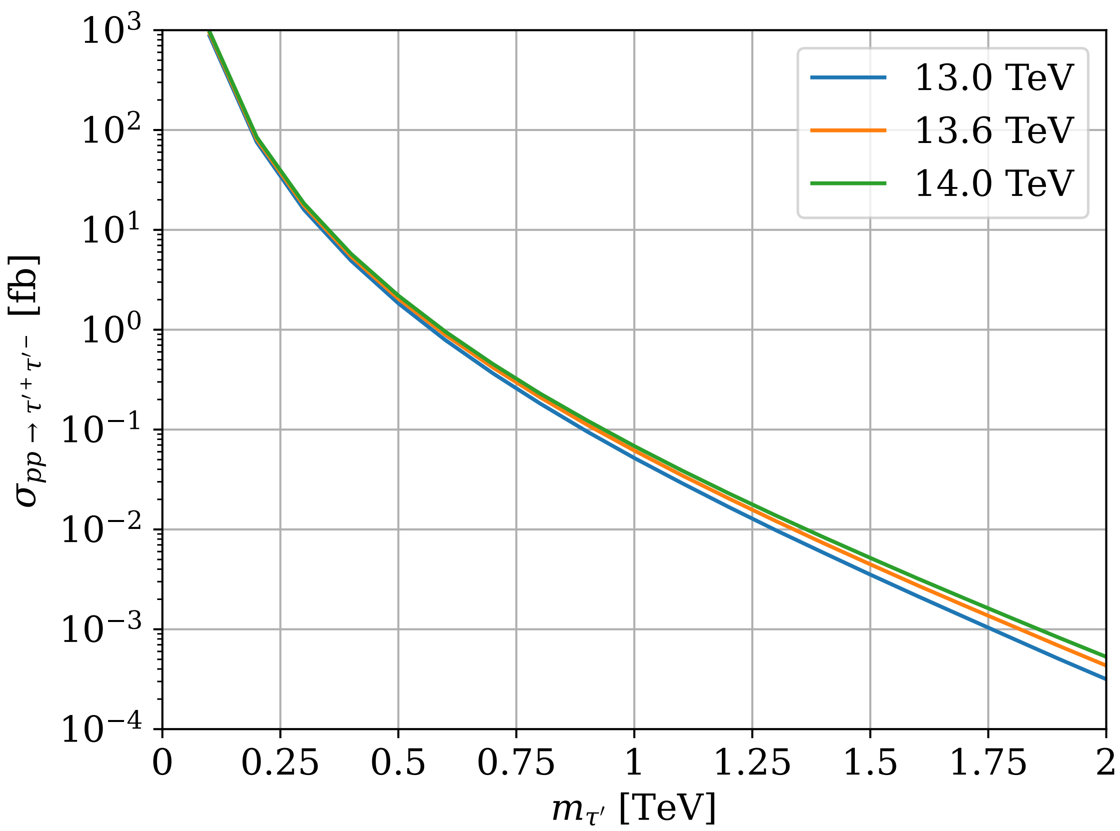
➡ **Large parameter space with** $\mathrm{BR}\left(\tau' \to \tau a_\tau\right) \approx 100\ \%$

Long-lived particle production

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



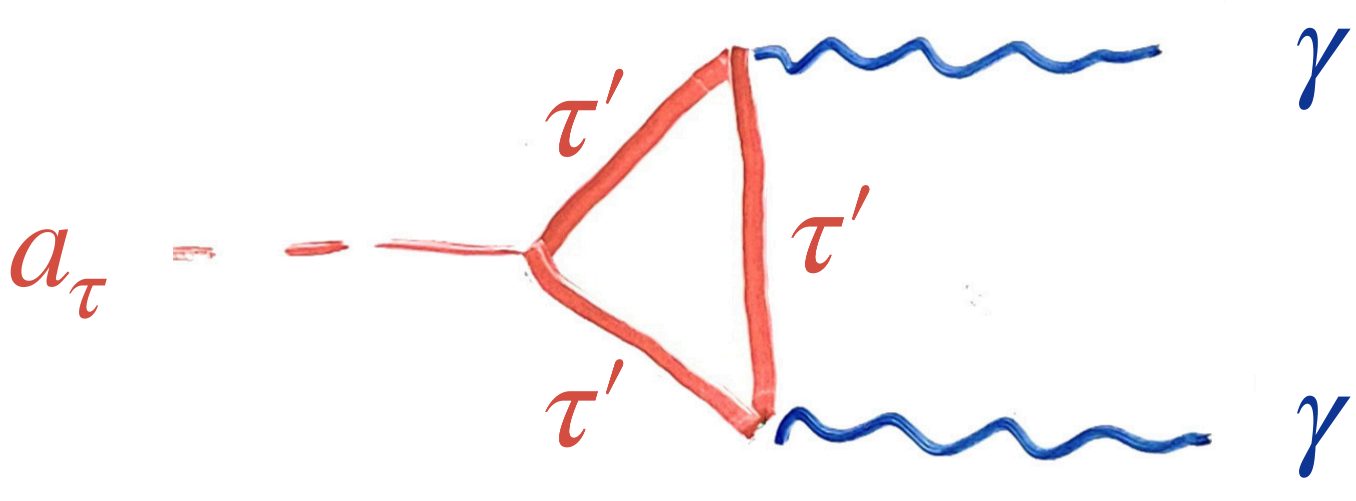
Production cross section



Potential LHC reach in τ' mass to well above $1\ \mathrm{TeV}$

Long-lived particle decay

- If a_τ is lighter than τ', its **dominant decay mode is $a_\tau \to \gamma\gamma$ via heavy τ' loop**



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

$$c\tau_a = 0.23\ \mathrm{m} \times \left(\frac{0.1}{y_{\tau'}}\right)^2 \left(\frac{1\ \mathrm{GeV}}{m_{a_\tau}}\right)^3 \left(\frac{m_{\tau'}}{400\ \mathrm{GeV}}\right)^2$$

- In addition, a_τ picks up substantial boost

Majority of decays can easily occur meters from the interaction point

Search for LLPs in muon system

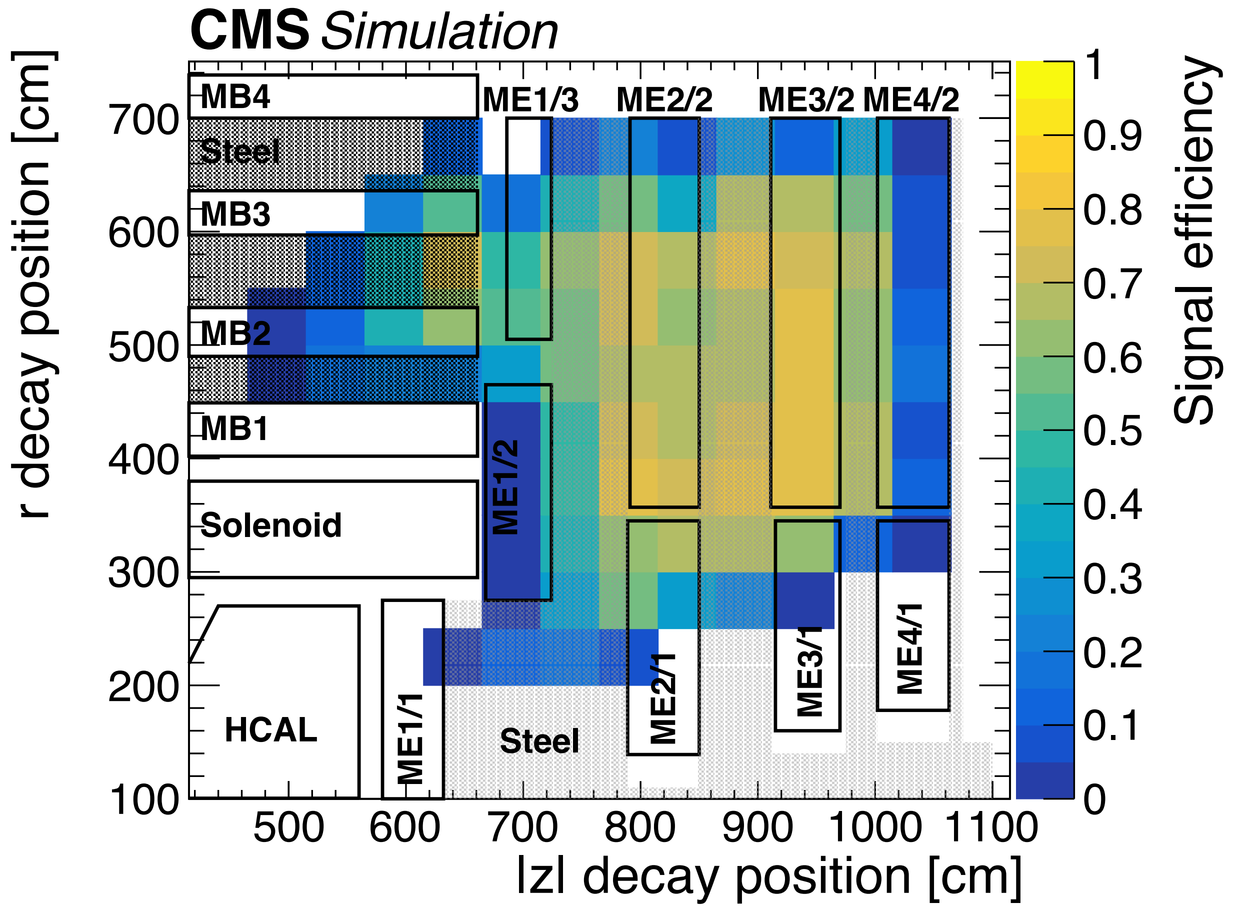
The muon system is several meters away!

- 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

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

$$\Delta\phi(\mathrm{cluster}, \vec{\mathrm{p}}_{\mathrm{T}}^{\mathrm{miss}}) < 0.75$$



Sensitivity depends on LLP energy, not on mass

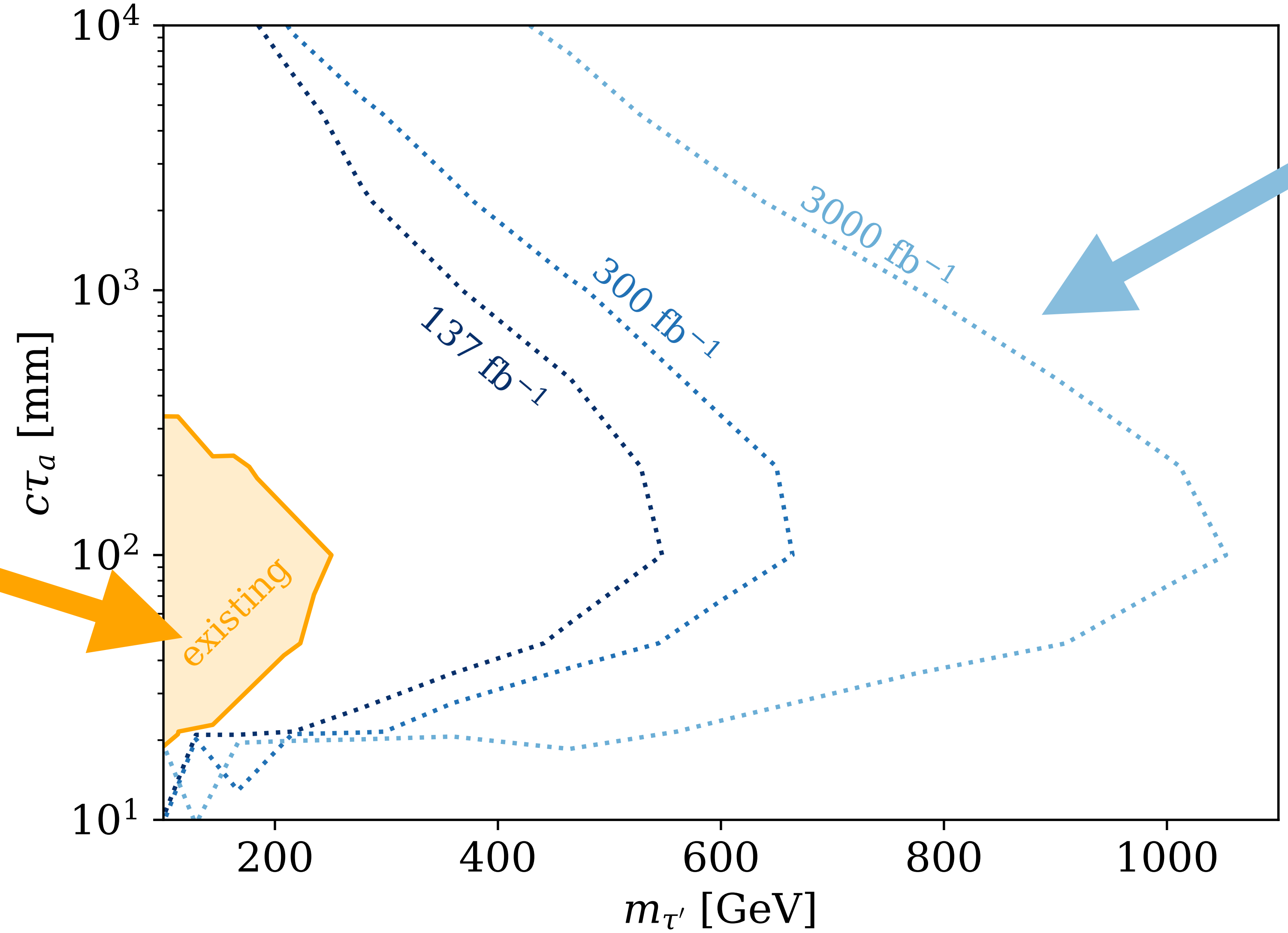
CMS collaboration, 2107.04838

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

Existing CMS search for LLPs in muon system 2107.04838



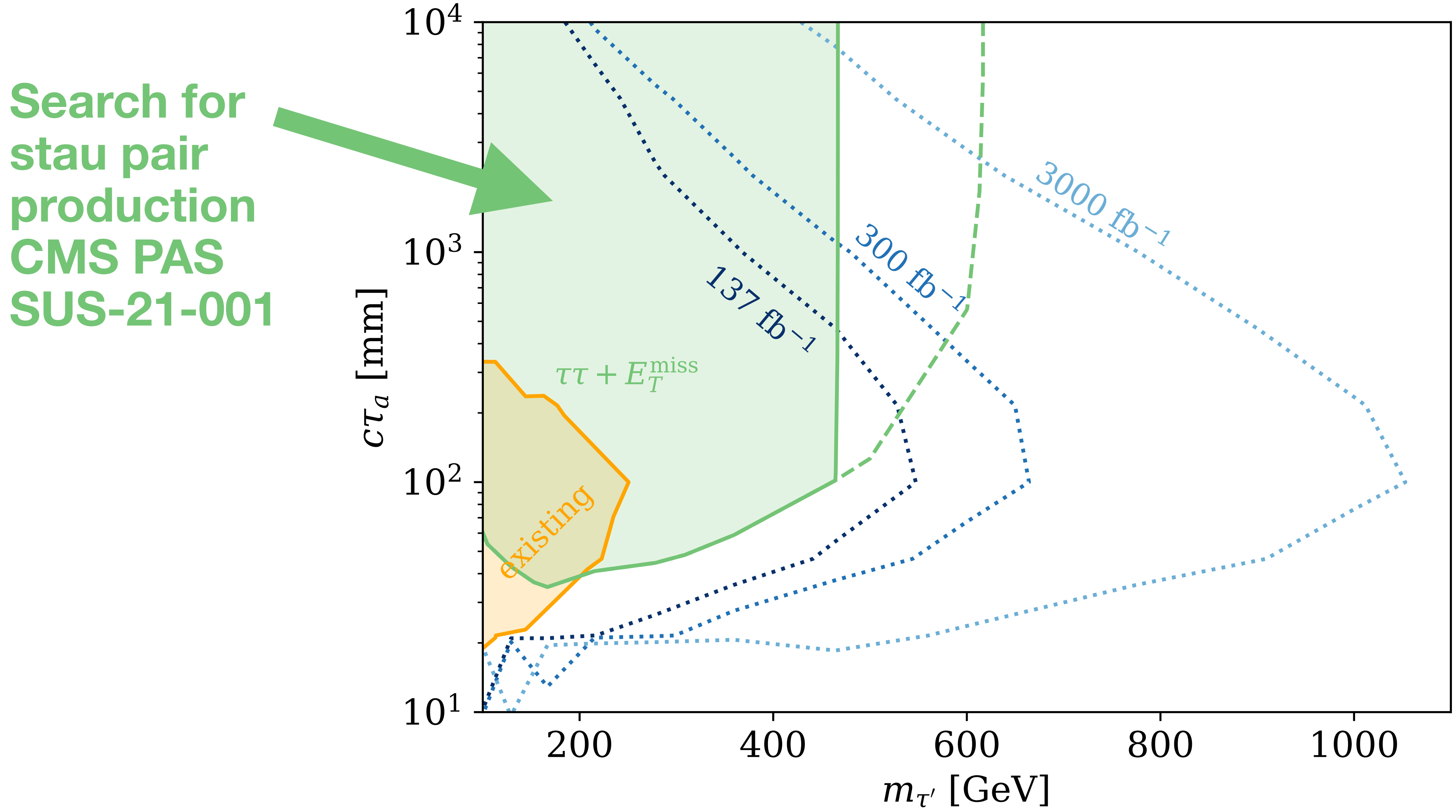
Projected limit for search in muon system barrel + endcaps with tau triggers

Vast improvement over sensitivity of existing search

Complementarity with missing energy searches

- LLPs decaying to photons after the ECAL **appear as missing energy**

complementary constraint from missing energy searches



LLP search superior for shorter lifetimes and higher VLL masses and scales more favorably with luminosity

Light LLPs

Intermediate LLP decay lengths $\sim$ tens of centimeters to meters are challenging to cover at the LHC

One possibility (we just saw):

Use parts of the detector in novel ways
and avoid vertex reconstruction

Other possibility:

Different experiments,

in particular B factories

Dark sector searches at the intensity frontier

Belle II experiment at SuperKEKB e^+e^- collider with $\sqrt{s} \sim 10.6 \text{ GeV}$

- Among the world-leading probes of B mesons (along with LHCb)
- Very well suited also for searching for light LLPs beyond the SM

see e.g. Belle II physics book, arXiv:1808.10567

- **Advantages over LHCb with respect to light LLPs:**
  - Longer decay lengths in the lab system covered (up to $\sim 60 \text{ cm}$)
  - Typically lower LLP boost due to smaller c.o.m. energy

→ sensitive to much longer proper decay lengths

→ **Particularly striking example: dark showers**

Strongly interacting dark sector with effective portal

- Dark showers occur in **strongly interacting dark sectors** resembling SM QCD sector:

$$\mathscr{L}_{\text{dark QCD}} \supset -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a} + \overline{q_\text{d}} i \not{D} q_\text{d} - \overline{q_\text{d}} M_q q_\text{d}$$

- **Below the dark confinement scale**:

Dark pions π_d are excellent DM candidates. see e.g. Kribs & Neal arXiv:1604.04627 for review
Dark vector mesons ρ_d are generically unstable:
can set dark pion relic abundance via "forbidden" annihilations $\pi_\text{d}\pi_\text{d} \to \rho_\text{d}\rho_\text{d}$
gives rise to **visible signals at accelerator experiments** EB et al. arXiv:1907.04346

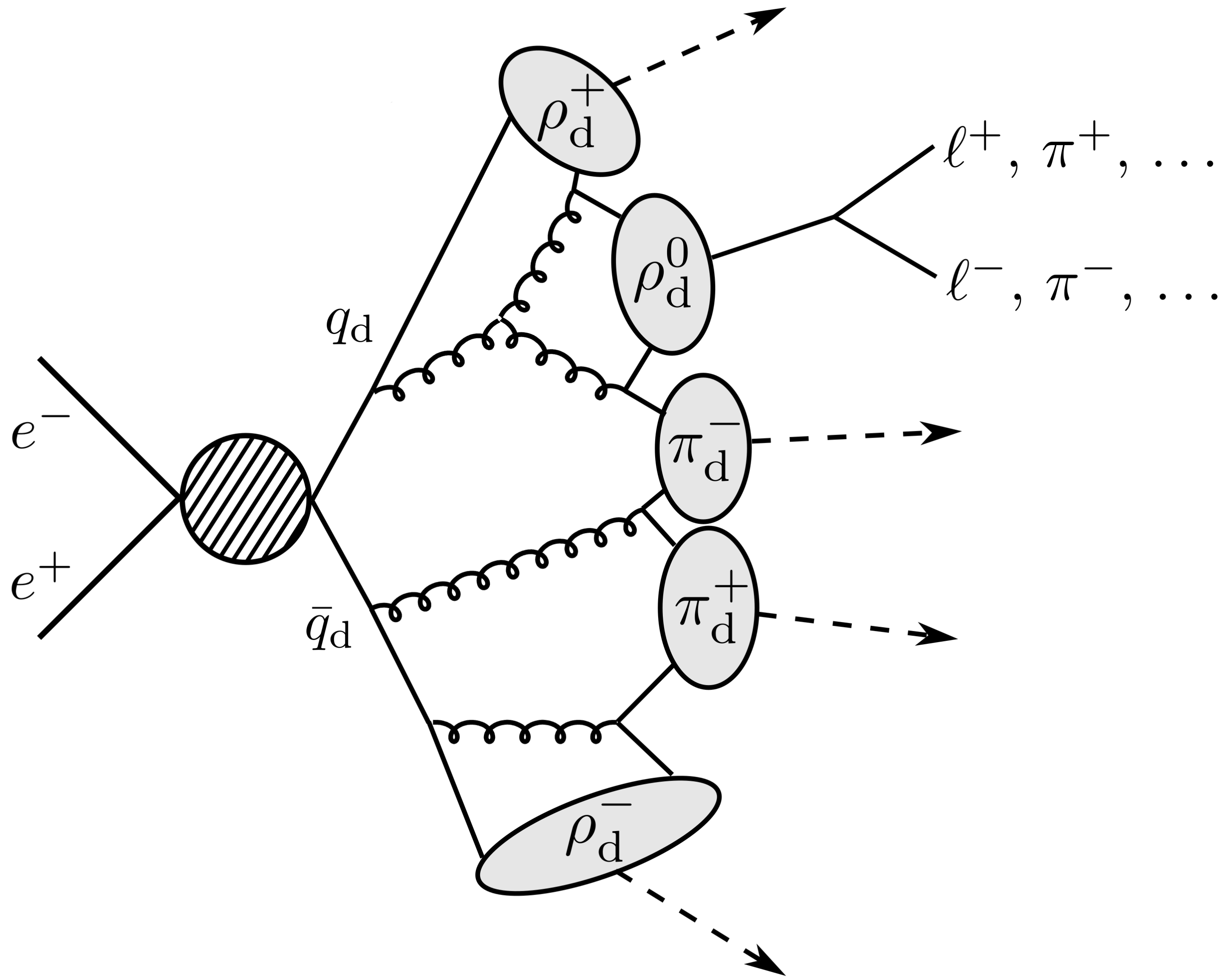
- Mediator with mass $\gg \sqrt{s}_{\text{Belle II}}$ can be described by an **effective interaction** between dark quarks and SM fermions:

$$\mathscr{L}_{\text{eff}} \supset \frac{1}{\Lambda^2} \sum_f q_f \bar{f} \gamma^\mu f \bar{q}_\text{d} \gamma_\mu q_\text{d}$$

Λ : **scale of the effective interaction**

Dark showers at Belle II

- If dark confinement scale $\ll \sqrt{s}$, production of dark quarks via effective interaction leads to **dark shower** and production of dark mesons



- Rate of dark shower production through effective operator scales as

$$\sigma(e^+e^- \to q_{\rm d}\bar{q}_{\rm d}) \propto \frac{s}{\Lambda^4}$$

- The $\rho_{\rm d}^0$ mesons decay to visible SM particles with decay length

$$c\tau_{\rho_{\rm d}^0} \propto \frac{\Lambda^4}{m_{\rho_{\rm d}}^5}$$

Parameter space of low-energy effective theory only consists of Λ and $m_{\rho_{\rm d}}$.

- **Signature of light dark showers:**

  (multiple) displaced decays
  number varying from event to event

Displaced vertex search at Belle II

- No dedicated search for dark showers at B factories yet, but **model-independent searches for LLPs**
- **Prospective search for displaced vertices at Belle II**
  Duerr et al., arXiv:1911.03176 and arXiv:2012.08595, and EB et al. arXiv:2203.08824

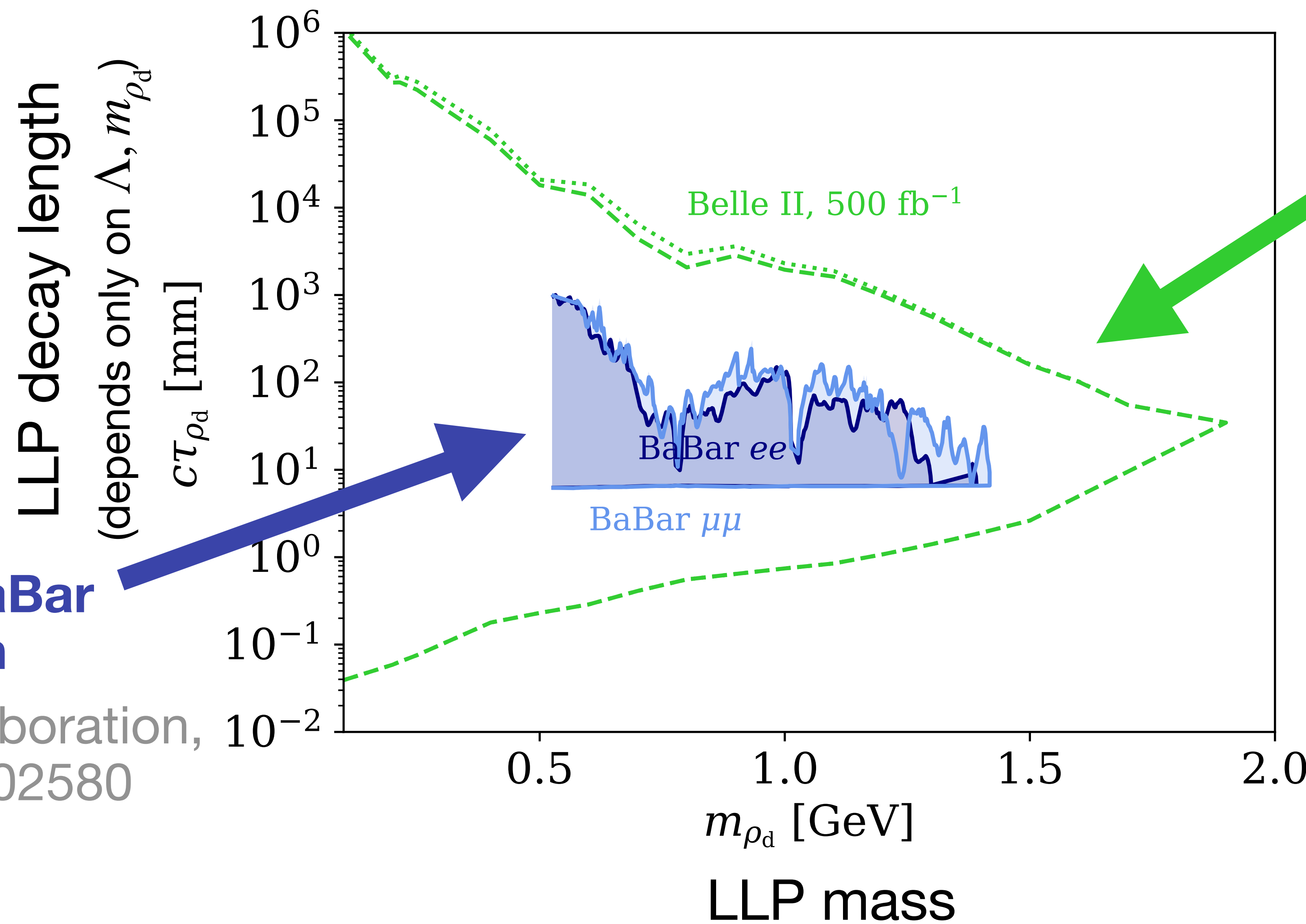
  Signature: displaced decays to pairs of oppositely charged leptons, pions or kaons
  Transverse distance $0.2\ \text{cm} < R < 60\ \text{cm}$
  Trigger on sum of energy depositions ($E > 1\ \text{GeV}$), two tracks or one high-p_T muon
  Selection criteria:

electron pairs	muon pairs
$p(e^+),\ p(e^-) > 0.1$ GeV	$p(\mu^+),\ p(\mu^-) > 0.05$ GeV
$m_{e^+e^-} > 0.03$ GeV	$m_{\mu^+\mu^-} < 0.48$ GeV *or* $m_{\mu^+\mu^-} > 0.52$ GeV
$\alpha(e^+, e^-) > 0.025$ rad	
Displaced vertex position	
$0.2\ \text{cm} < R < 0.9\ \text{cm}$ *or* $17\ \text{cm} < R < 60\ \text{cm}$	$0.2\ \text{cm} < R < 60\ \text{cm}$
$-55\ \text{cm} \leq z \leq 140\ \text{cm}$	
$17^\circ \leq \theta_{\text{lab}} \leq 150^\circ$	

- **Negligible background expected**

Belle II LLP sensitivity for dark showers

Projected sensitivity for dark showers of model-agnostic Belle II search



Projected limit on dark showers from DV search at Belle II

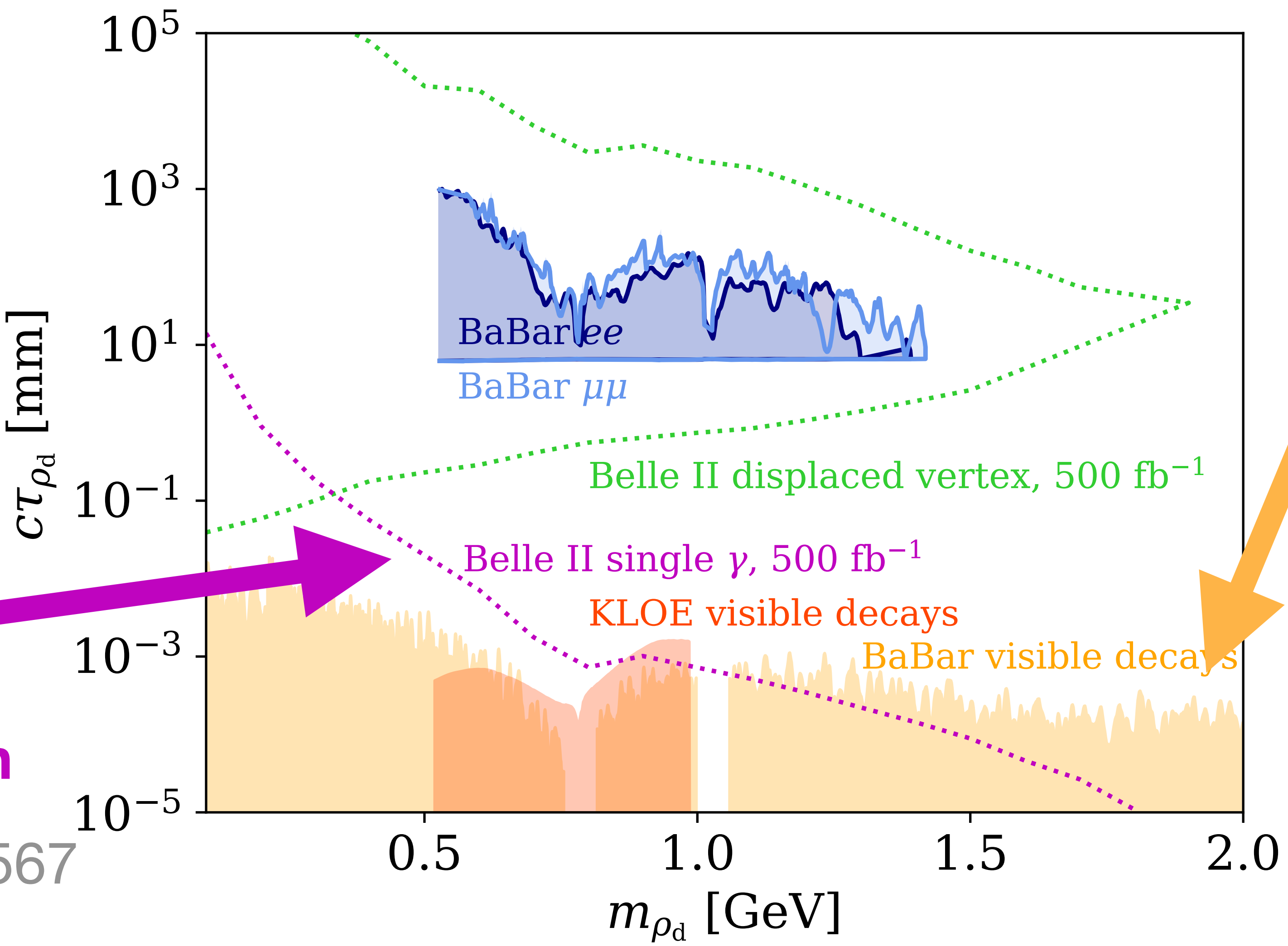
Existing BaBar LLP search

BaBar collaboration, arXiv:1502.02580

Displaced vertex search at Belle II can greatly improve over BaBar in cosmologically viable parameter space even with just $500\ \mathrm{fb}^{-1}$ of data.

Complementary constraints

Additional constraints on the low-energy effective theory:



Existing BaBar search for visible resonance

BaBar collaboration, arXiv:1406.2980

Belle II single photon projection

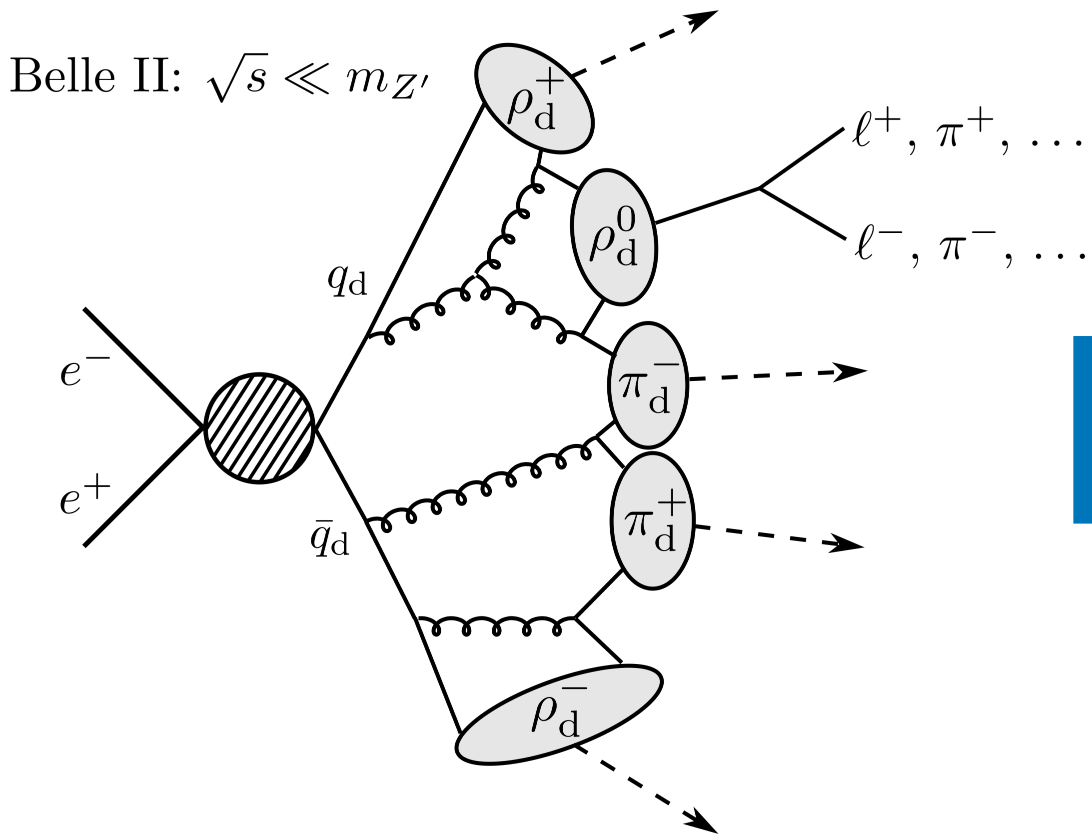
see arXiv:1808.10567

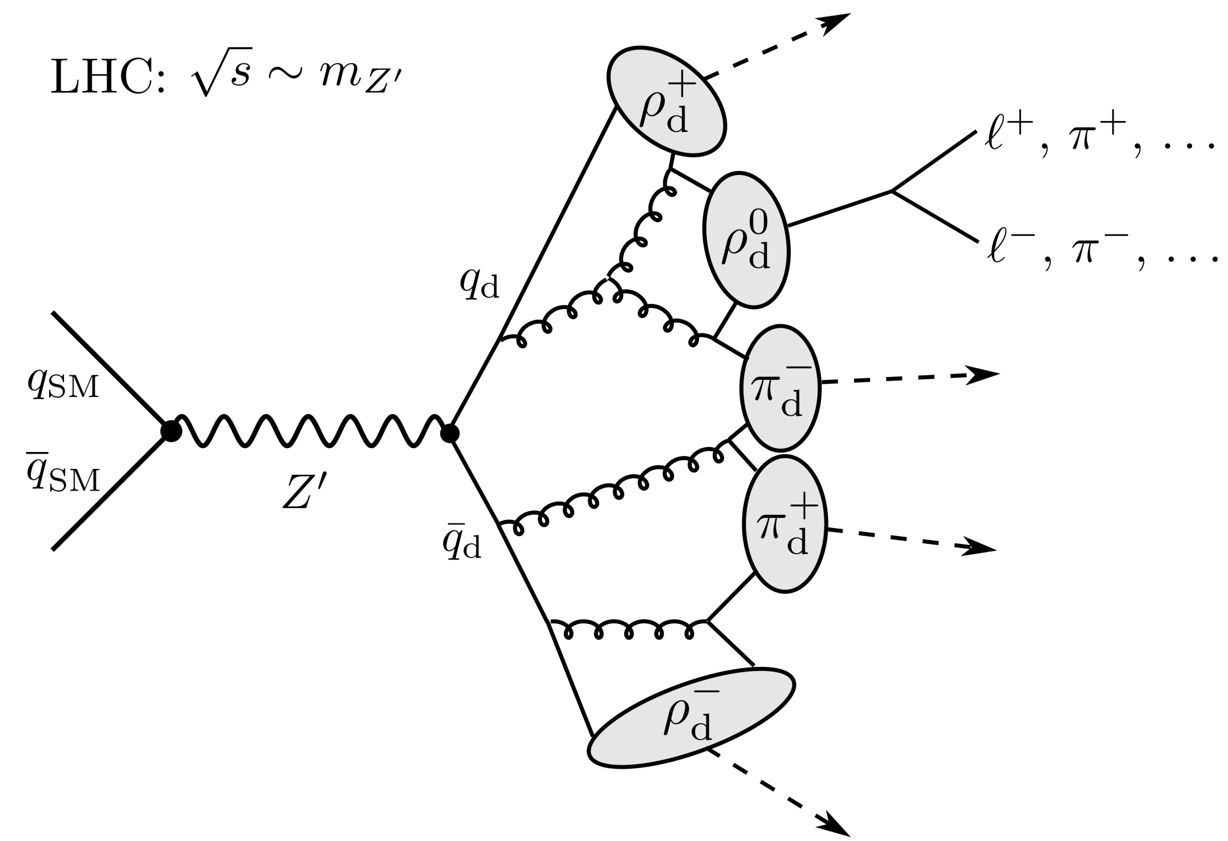
- Existing searches for **visible resonances** at BaBar and KLOE yield complementary constraints on **promptly decaying dark mesons.**
- Events with **invisible dark shower and ISR photon** lead to **single photon signal** with continuous energy spectrum.

  → Projection weaker than for bump hunt but competitive at small LLP mass

Belle II vs LHCb

How does Belle II compare to LHCb?





- Relevant LHCb search:
  model-agnostic search for displaced dimuon resonances

LHCb collaboration, arXiv:2007.03923

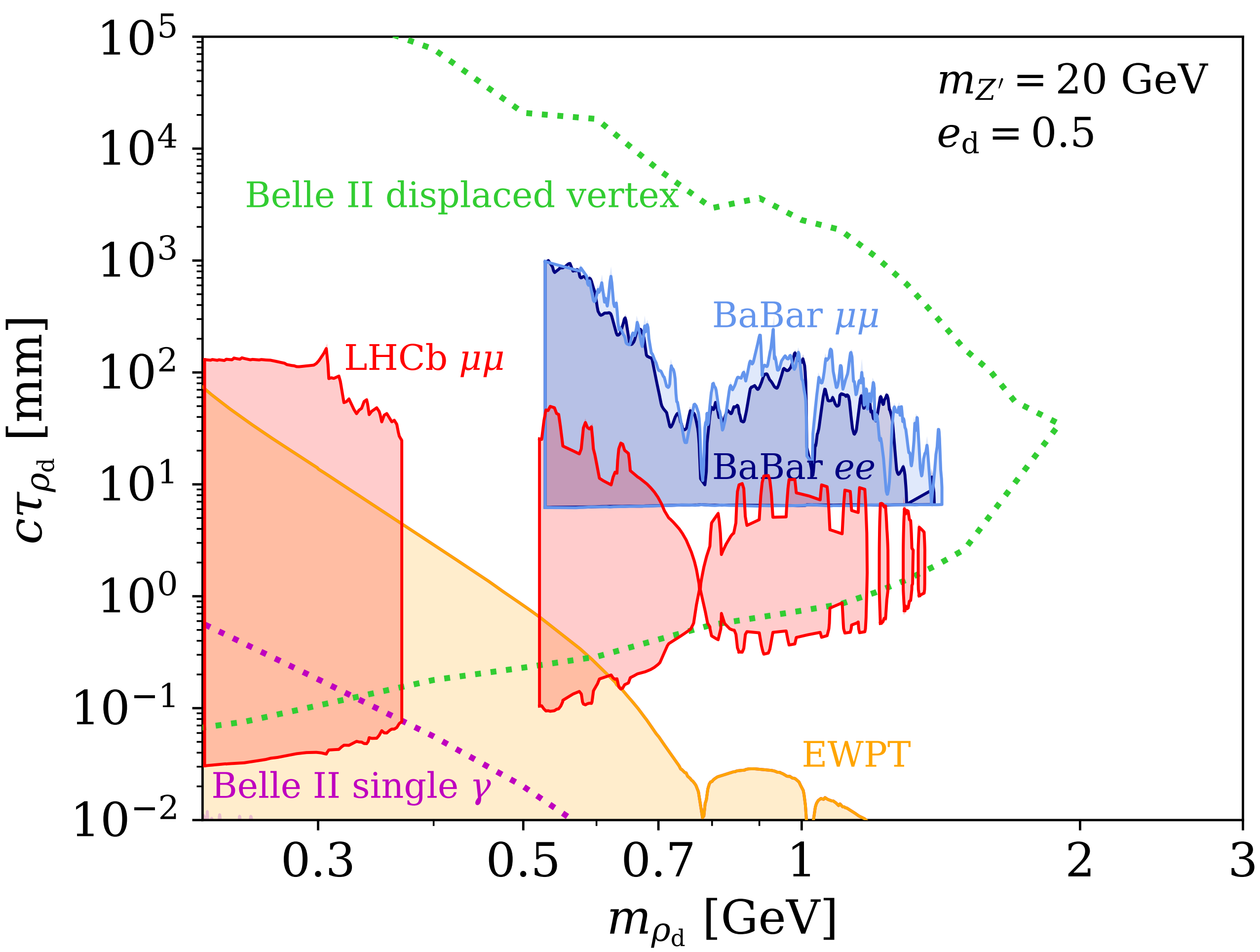
Belle II vs LHCb

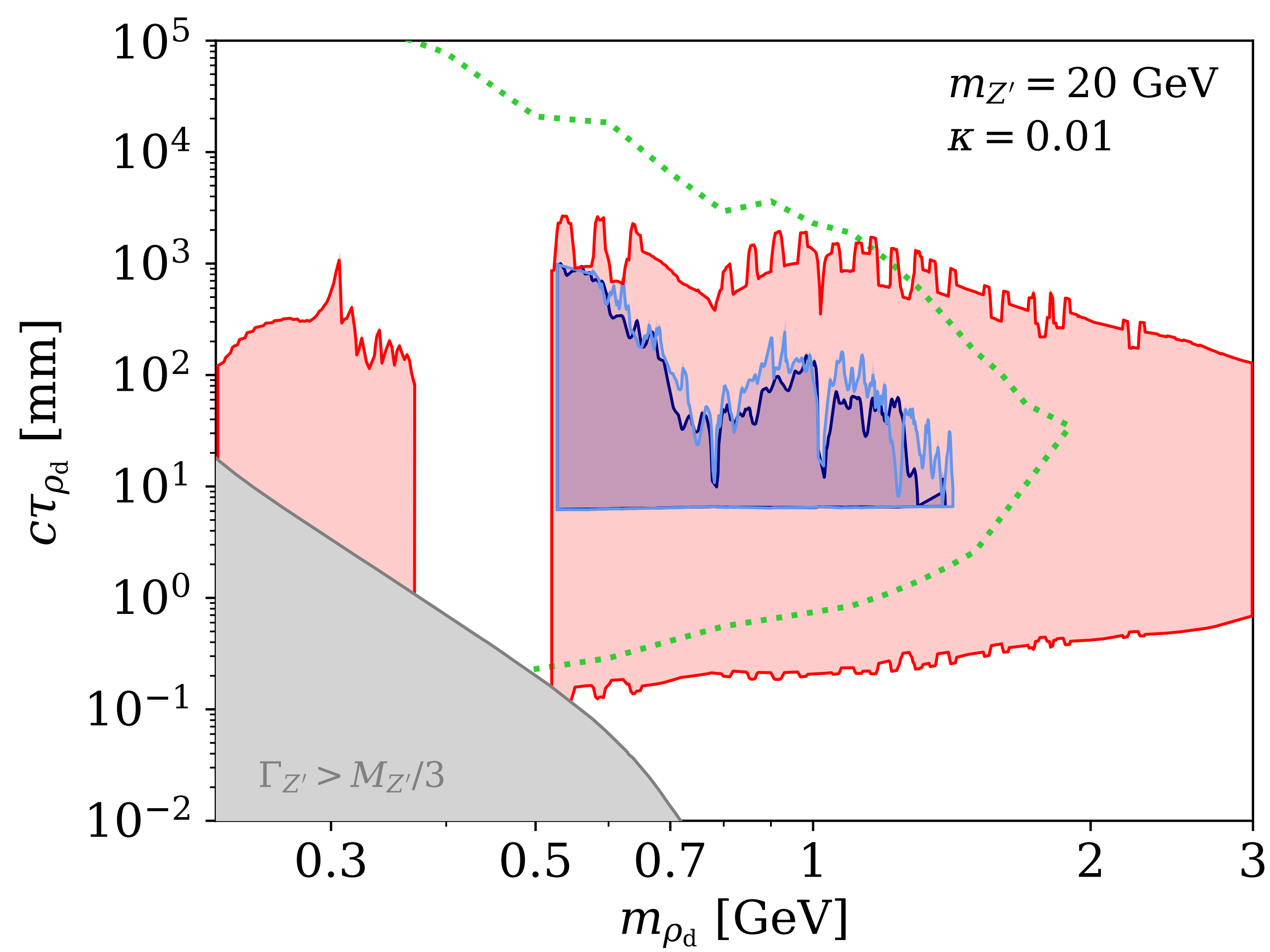
- LHCb sensitivity depends on combination of mediator couplings underlying

$$\Lambda = \frac{m_{Z'}}{\sqrt{e\kappa e_{\rm d}}}$$

Belle II favorable scenario

LHC favorable scenario





- **Belle II sensitive to much longer decay lengths ($c\tau \gtrsim \mathcal{O}(\text{meters})$)**
- Strong case for Belle II search even in least favorable scenario

Conclusions

- Long-lived particles are extremely well-motivated and could still be discovered at the LHC
- Rapidly expanding search program, but many remaining gaps
  → especially light LLPs, decay lengths $\sim$ meters
- Wealth of interesting models; here: VLL with LLP, dark showers
- Ways to close gap:
  - Creative use of existing detectors, in particular muon system
  - Other, lower-energy experiments, in particular Belle II