Environmentally aware displaced vertices

as a probe of the dark sector

based on arXiv:2304.08118

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LLP13 - CERN, 23/6/2023

Emmy Noether-Programm

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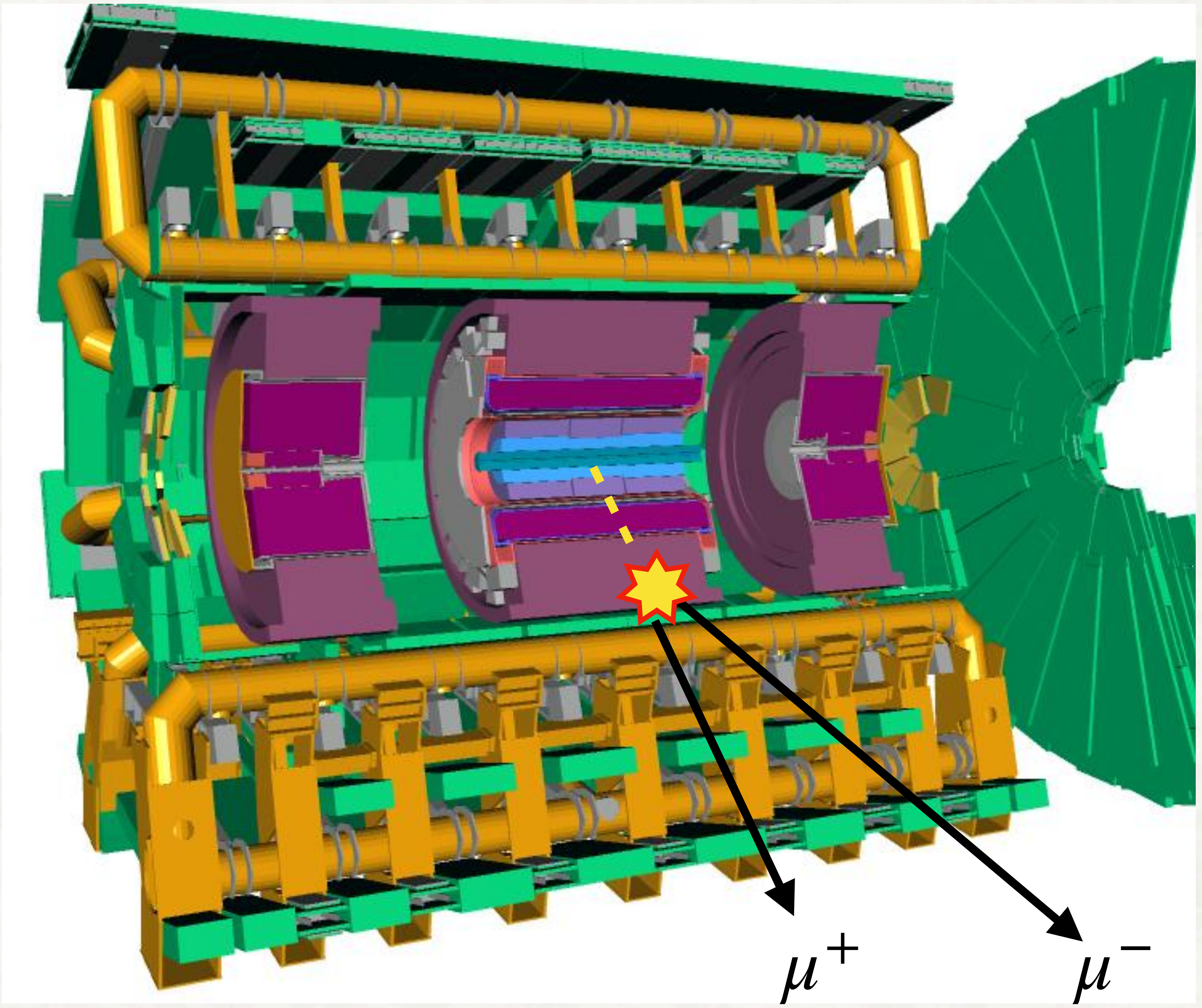
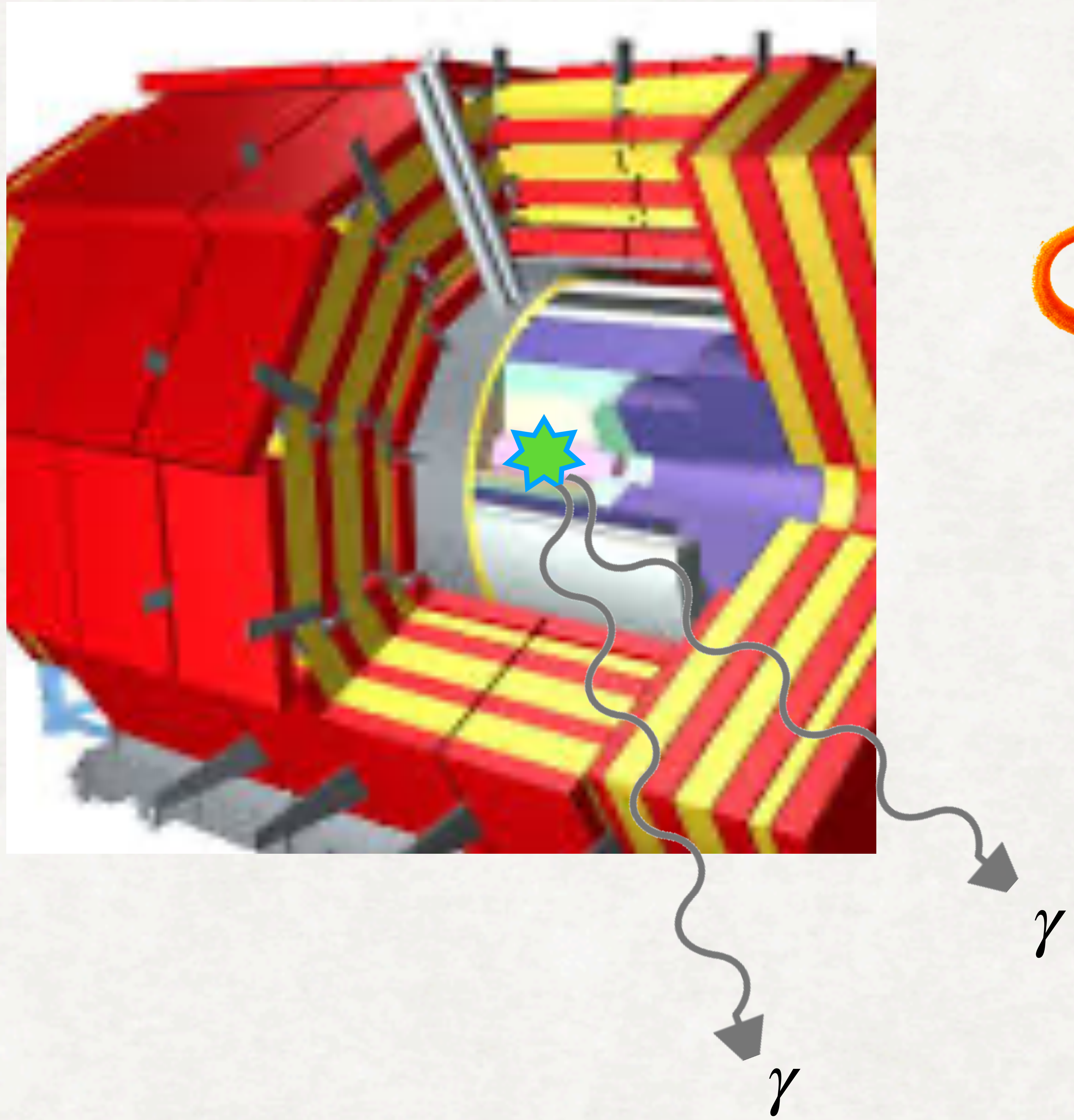
Imagine a particle whose properties like

- mass
- life-time
- branching ratios

change as a function of the environment density...



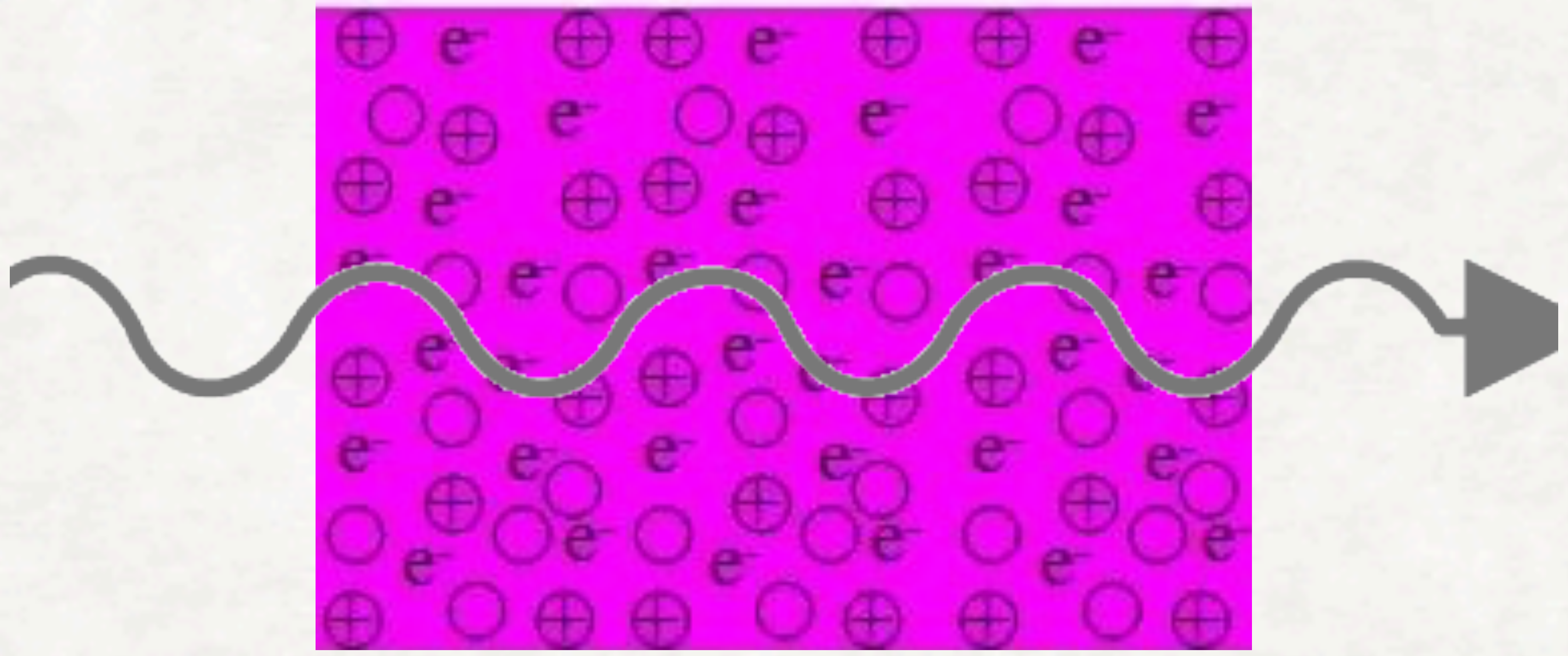


decaying to 2 muons
in the ATLAS calorimeters

but to 2 photons
in the CMS tracker

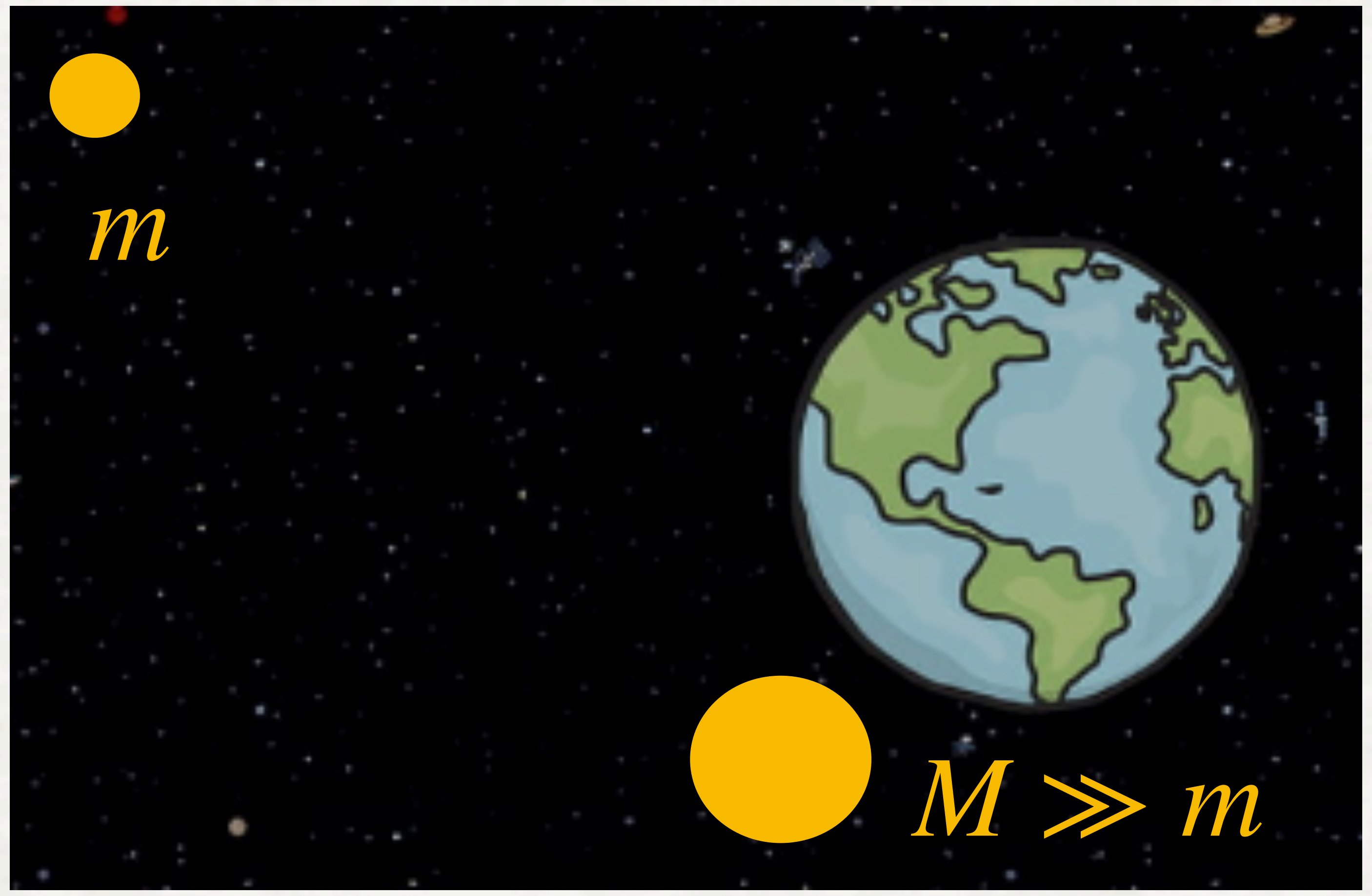
A familiar concept in other settings

Plasma physics



photon mass
$\propto$ plasma frequency
$\propto$ charge density

Modified cosmological models



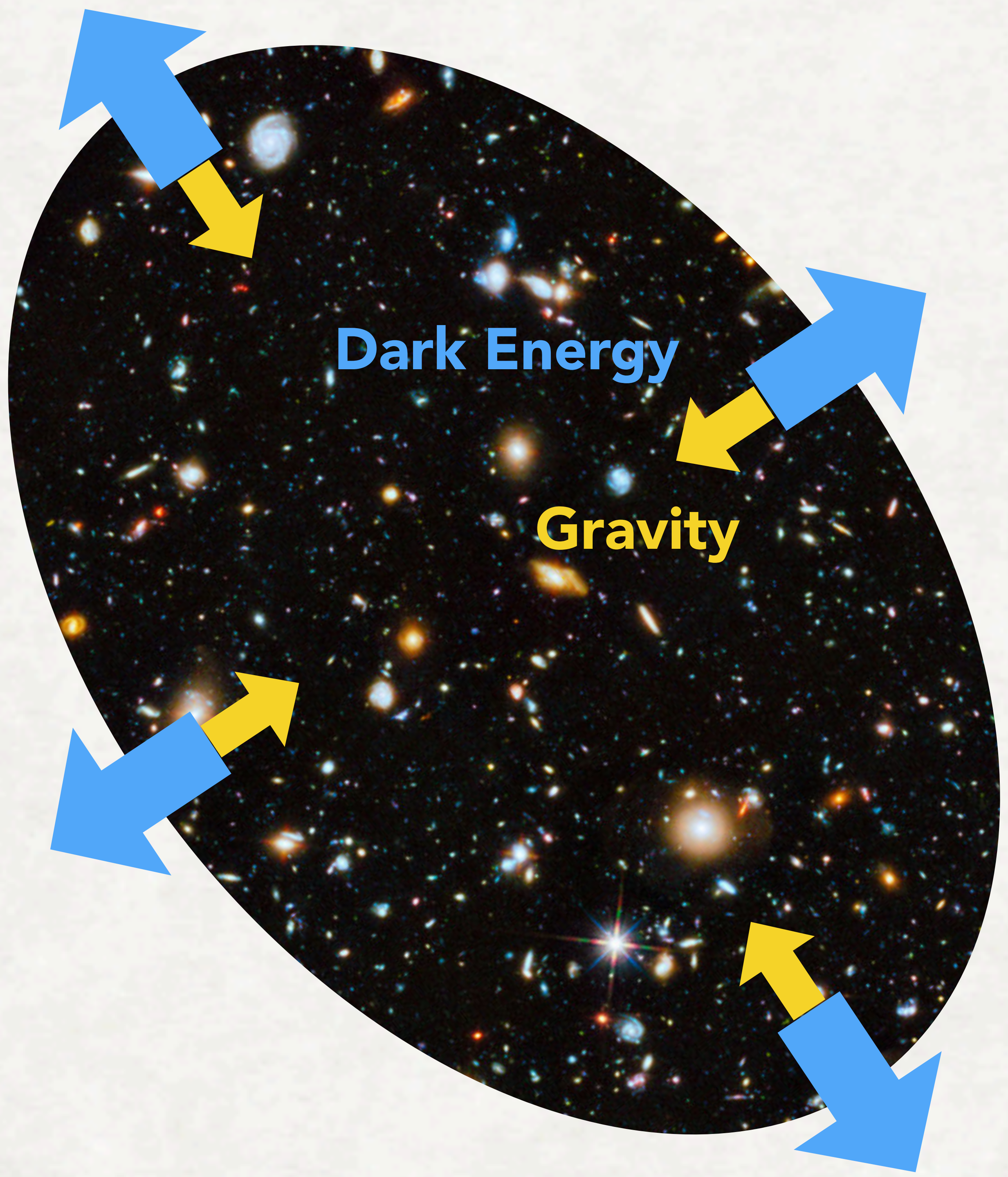
DE scalar mass
$\propto$ matter density

Motivation

Density dependence can arise in models with light scalars coupled to the Higgs (more on this later)

Original inspiration: studying the impact of ***Dark Energy*** models at the ***LHC***

Brax, et al, PRD 94, 084054 (2016) , ATLAS, JHEP 05 (2019) 142, Burrage, et al, JCAP 11 (2018) 036



One of the biggest unknowns with several unanswered questions:

➡ new particle or modified gravity?

➡ constant or dynamic?

➡ interacting with SM or not?

➡ microscopic nature?

Dark Energy scalars and screening

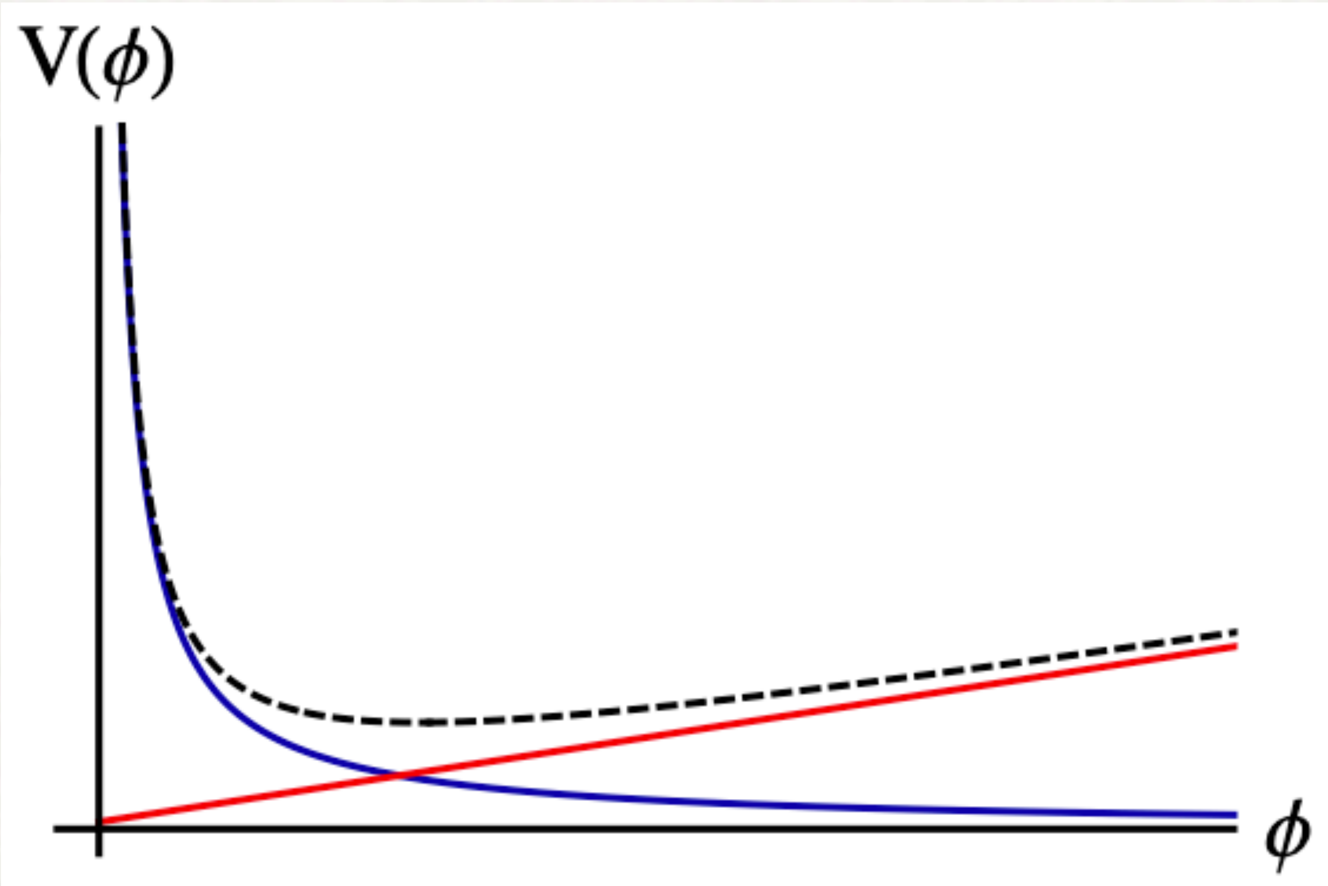
Simplest explanation: DE = Λ ⇒ cosmological constant problem

➡ make DE a dynamic field - simplest scenario DE = *light* scalar field

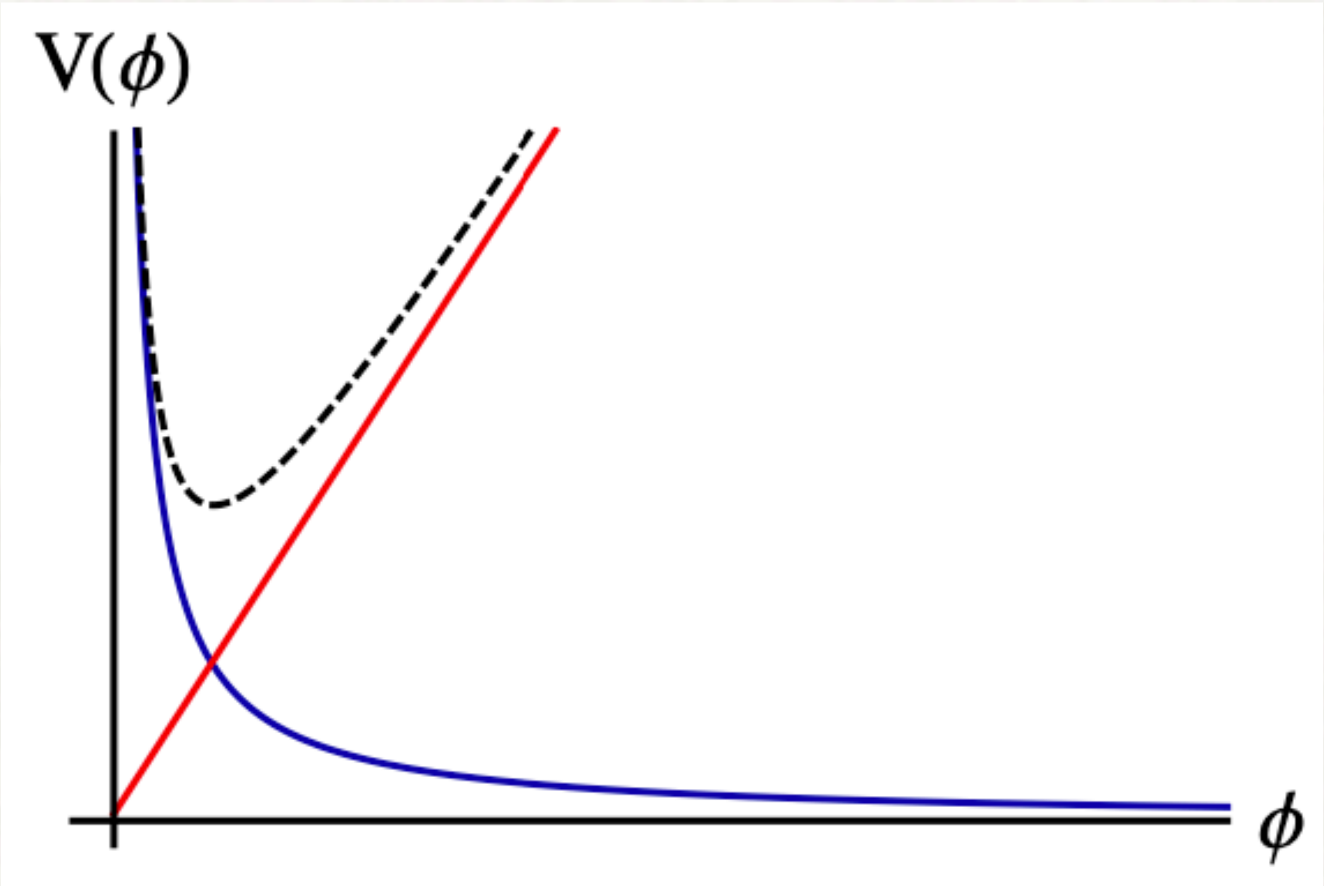
Problem: light scalars mediate long range 5th forces ⇒ not observed ($F_5 \sim F_N e^{-mr}$)

➡ screening mechanisms: make the 5th force undetectable

Low density



High density



Chameleon mechanism

$$V(s) = \frac{\Lambda^5}{s} + \frac{\rho s}{M}$$

- in regions of high density the scalar obtains a high mass ⇒ F_5 small

NB: main findings apply to other screening mechanisms

Why to look for DE at colliders

1. **Interaction between DE and SM** arises naturally in many models
   - DE must "feel" density of SM matter to become screened

   ➡ DE can be produced at colliders

Brax, Rep. Prog. Phys., 81 (2018) 016902
Burrage, Sakstein, JCAP11 (2016) 045

2. **Dark degeneracy**
   - modified gravity ↔ dark energy $G^{\mu\nu} \sim T^{\mu\nu}$
   - particle physics can help to break the degeneracy?

Kunz PRD 80 (2009) 123001
Kunz, Sapone PRL 98 (2007) 121301

3. **Complementarity**
   - landscape of models is enormous - need multiple approaches
   - colliders can probe different parts of parameter space

Brax, et al, PRD 94, 084054 (2016)
ATLAS, JHEP 05 (2019) 142

4. **Duality scalar DE ↔ Higgs portal**
   - constrain DE models through Higgs measurements

Burrage, et al, JCAP 11 (2018) 036

5. **New signatures !**

Toy model

$$\mathcal{L} \supset \frac{1}{2}\mu_h^2 H^2 - \frac{\lambda}{4} H^4$$ → **Higgs potential**

$$-\frac{\Lambda^5}{s} + \frac{v^2 \mu_h^2 s}{M}$$ → **DE potential**

a bit more complicated than Higgs,
but Higgs-like potential (symmetron)
gives same signatures

$$-\lambda_\psi H \bar{\psi}\psi$$ → **Yukawa coulping**

$$+\frac{\Lambda^5 H^2}{M^2 s} - \mu_h^2 \frac{s H^2}{M} - \mu_h^2 \frac{s^2 H^2}{M^2}$$ → **Higgs-DE interaction = Higgs portal**

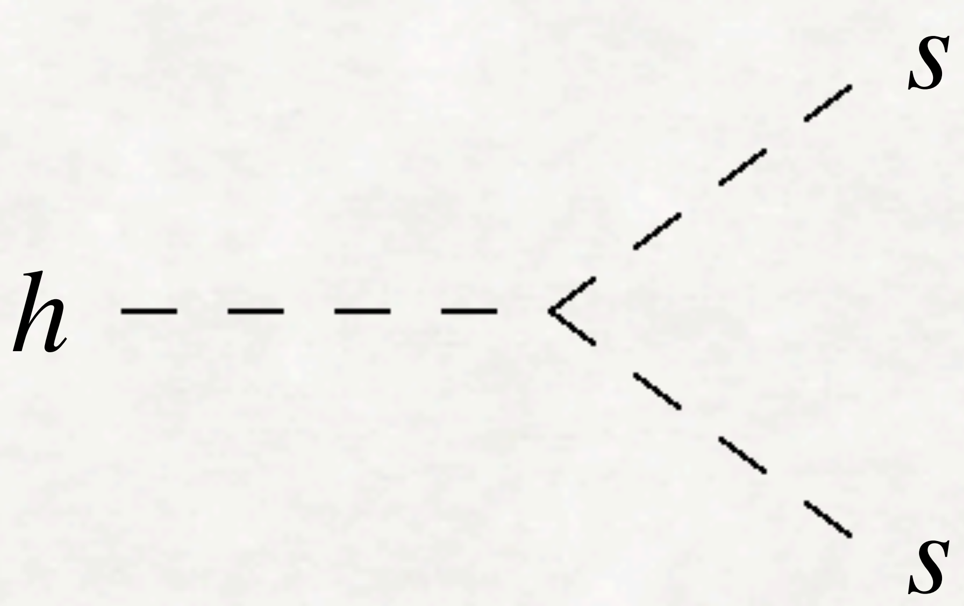
$$+\text{kin. terms}$$

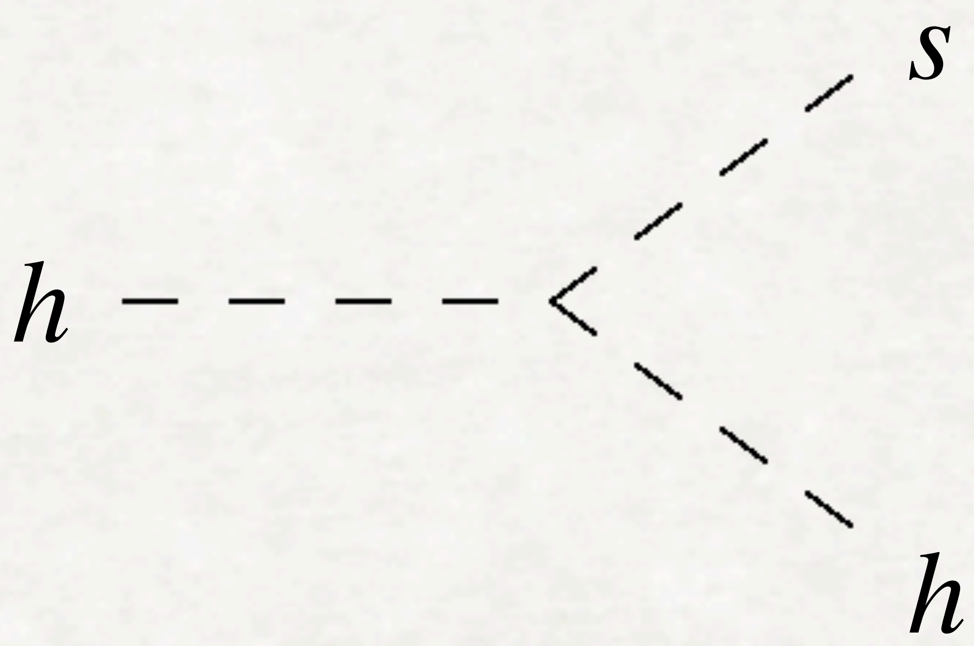
1. Light scalar $m_s \ll m_H$ ⇒ Higgs static
2. Higgs portal + Yukawa interaction

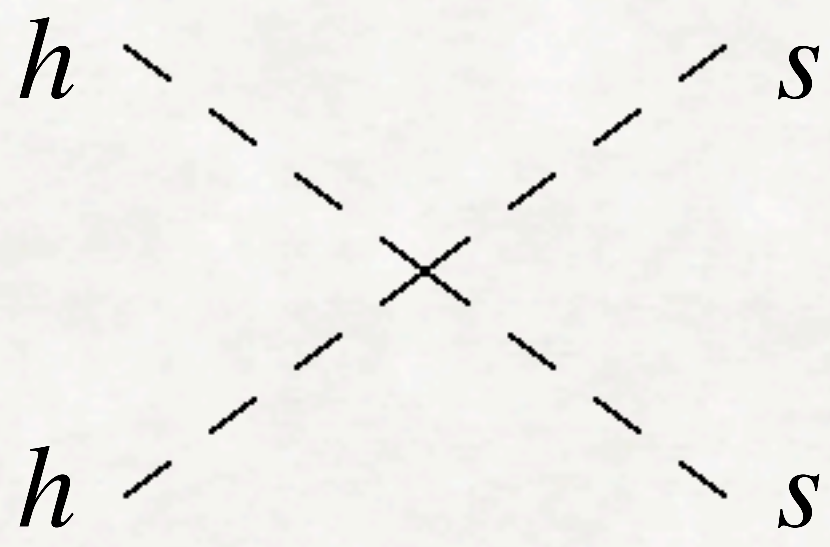
→ DE scalar mass depends on density

$$m_s \sim \rho_\psi = m_\psi \langle \bar{\psi}\psi \rangle$$

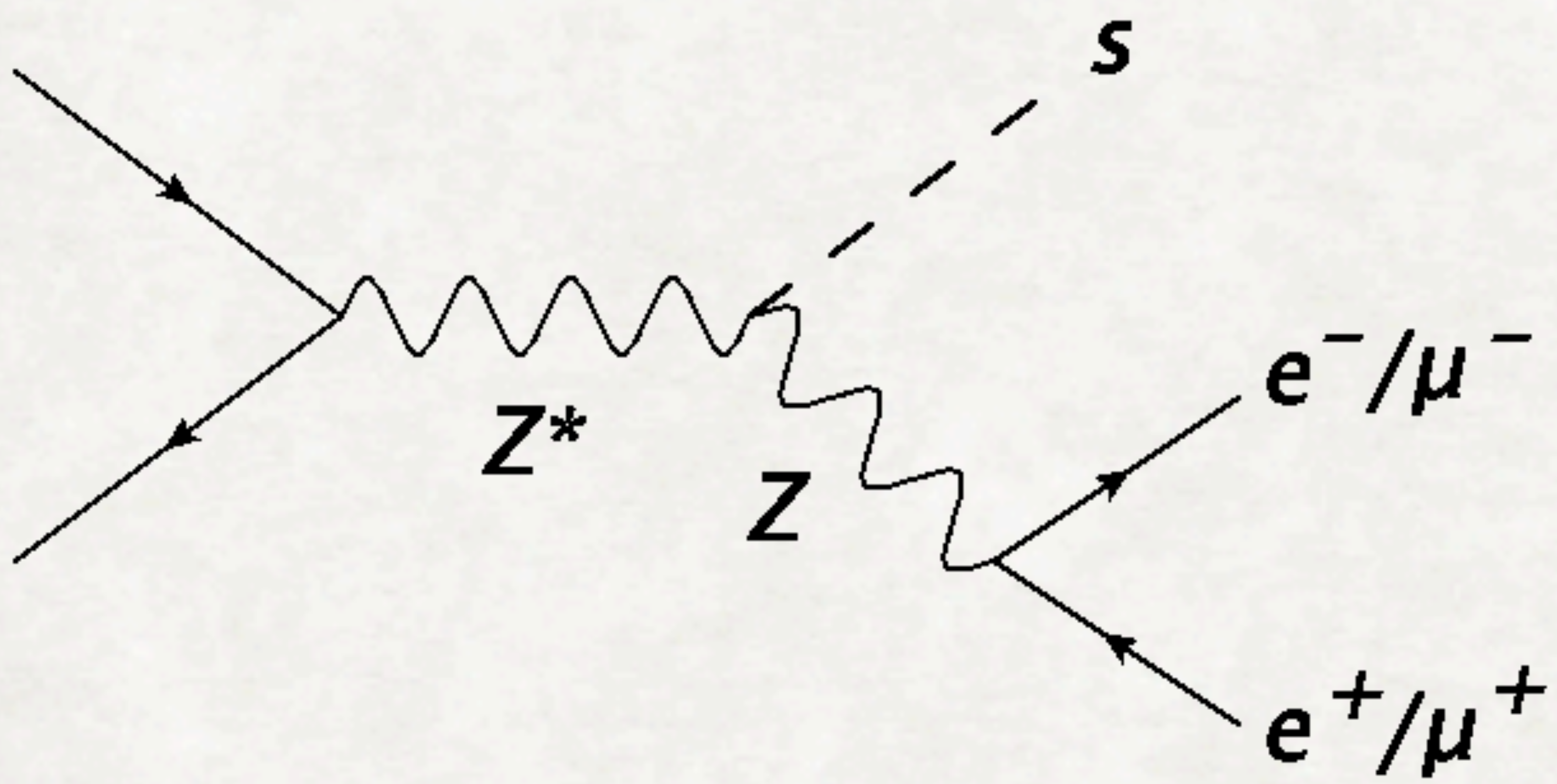
Interactions







- Trilinear and quartic couplings with SM Higgs
  - Higgs to invisible (when s is long lived)
  - Changes of Higgs couplings due to mixing with s
- s inherits Higgs couplings due to mixing



We focus on "DE-Strahlung"

✓ large cross-section $\sigma = 15.7 \left(\frac{2v}{M}\right)^2$ pb

✓ easy to trigger via leptons

Constraints from Higgs measurements

$$\mu = \frac{[\sigma(h) \times \mathrm{BR}]^{\mathrm{BSM}}}{[\sigma(h) \times \mathrm{BR}]^{\mathrm{SM}}} = \cos^2\theta \left(1 + \frac{\Gamma(h \to ss)}{\Gamma(h)\cos^2\theta}\right)^{-1}$$ with $$\sin\theta \simeq \frac{2v}{M}$$

Constraints from Higgs to invisible BR ~ 10% ➡ $M \gtrsim 3\ \mathrm{TeV}$

For the DE-Strahlung process this gives $\sigma \simeq 400\ \mathrm{fb}$

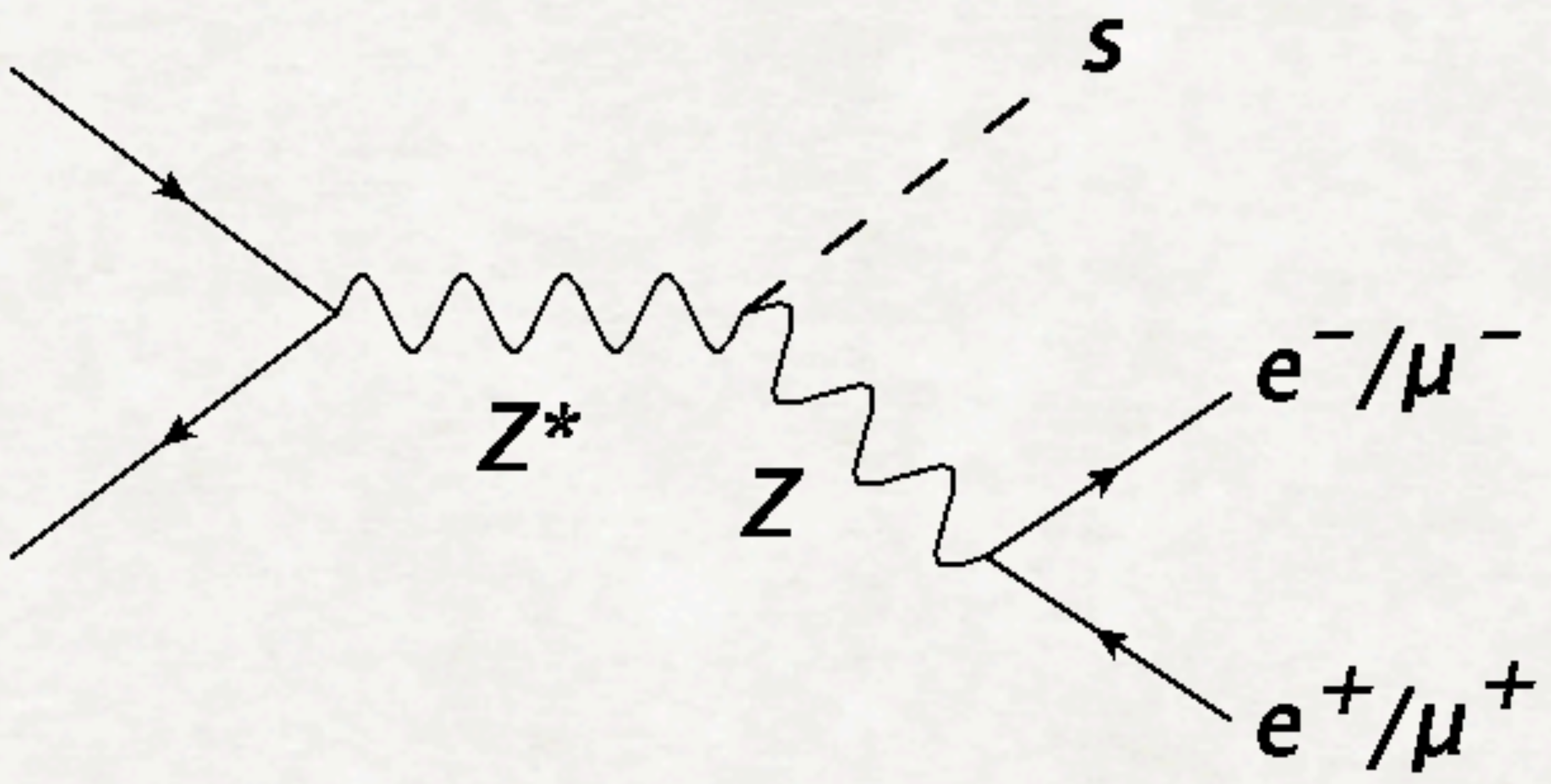
Mass and signatures

$$m_{s,\mathrm{eff}}^2 = 0.2 \left(\frac{\mathrm{TeV}}{M}\right)^{\frac{3}{2}} \left(\frac{10^{-3}\mathrm{eV}}{\Lambda}\right)^{\frac{5}{2}} \left(\frac{\rho_\psi}{\mathrm{g}\cdot\mathrm{cm}^{-3}}\right)^{\frac{3}{2}} \mathrm{GeV}^2$$

For example: $M = 3\ \mathrm{TeV}, \Lambda = 1.5 \cdot 10^{-3}\mathrm{eV}$

- in air: $m_s \approx 800\ \mathrm{keV} \Rightarrow$ only $s \to \gamma\gamma$
- in silicon tracker: $m_s \approx 4\ \mathrm{MeV} \Rightarrow s \to e^+e^-$
- in calorimeter: $m_s \approx 500\ \mathrm{MeV} \Rightarrow s \to \pi\pi$

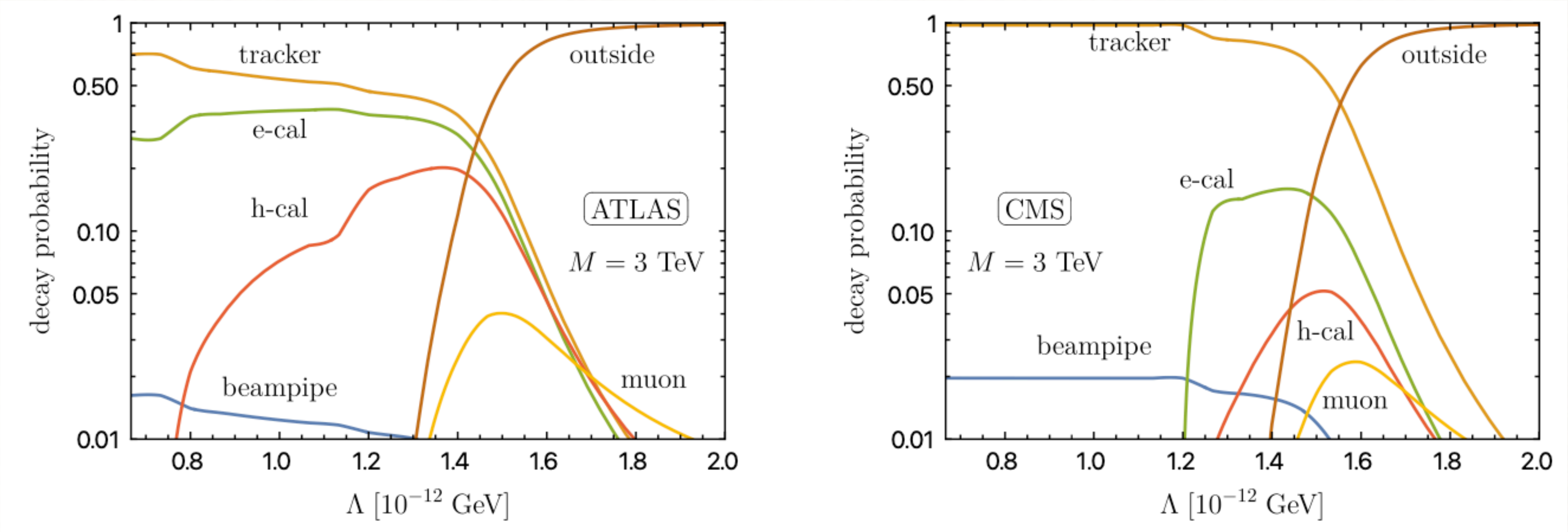
DE scalar travels through the detector, aquires a density dependent mass and decays to the heaviest accessible particles.



Displaced decays to photons/electrons/muons/jets in different subdetectors

ATLAS vs CMS

- Toy detector = cylindrical shells of uniform density
- Density calculated by averaging different detector components



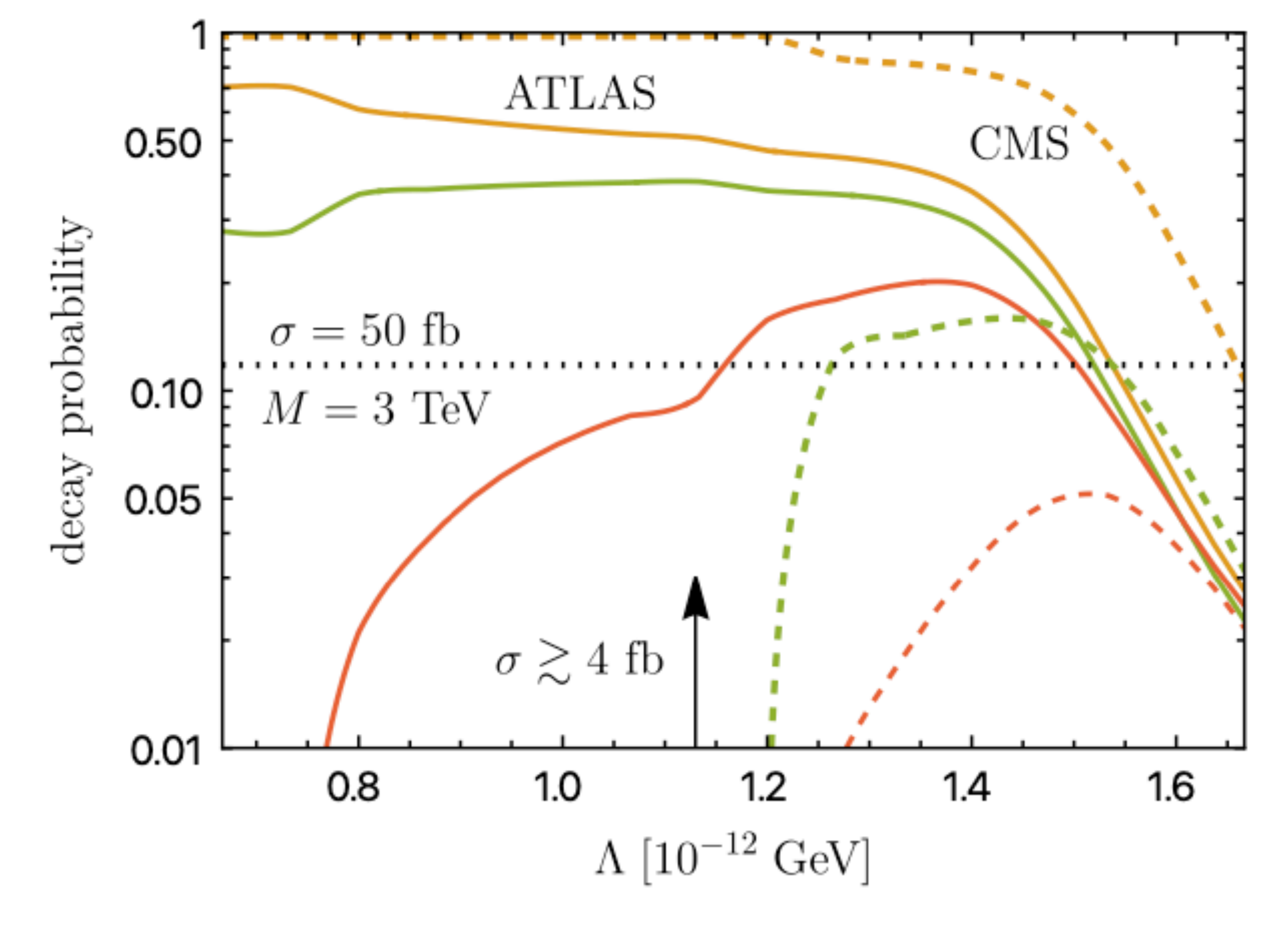
- Very different phenomenology due the different detector geometry & materials (esp. CMS ECal)
- CMS generally more compact and dense than ATLAS

ATLAS vs CMS

In contrast to other dark sector models, such models predict (for the same theory parameters)

- displaced decays in different detector components
- decays to different particles (due to different mass)

- High enough cross-sections for detection
- Combined analysis in ATLAS & CMS needed for discovery & for efficiently probing the parameter space



Outlook

- Investigation of other screening mechanisms

- Development of UFO model & investigation of other potential signatures

- More realistic detector simulation

- Once the above are at hand - a realistic experimental analysis would be possible - hopefully this will be followed up in ATLAS & CMS

- NB: this type of signature seems to appear generally in Higgs portal models with very light scalars!

Burrage, Millington in preparation

We showed with a toy model that Higgs portal couplings to very light scalars produce signatures which have not been explored in ATLAS/CMS

Light scalars acquire mass ~ environment density

Decay length / Branching ratios different on ATLAS/CMS

Striking difference with other dark sector models

Preliminary analysis shows good discovery potential

More detailed analysis under way - hopefully to be followed up by experimental searches!