Long-Lived Particles

— Searching for new physics at the Energy Frontier —

Matthias Danninger

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SFU
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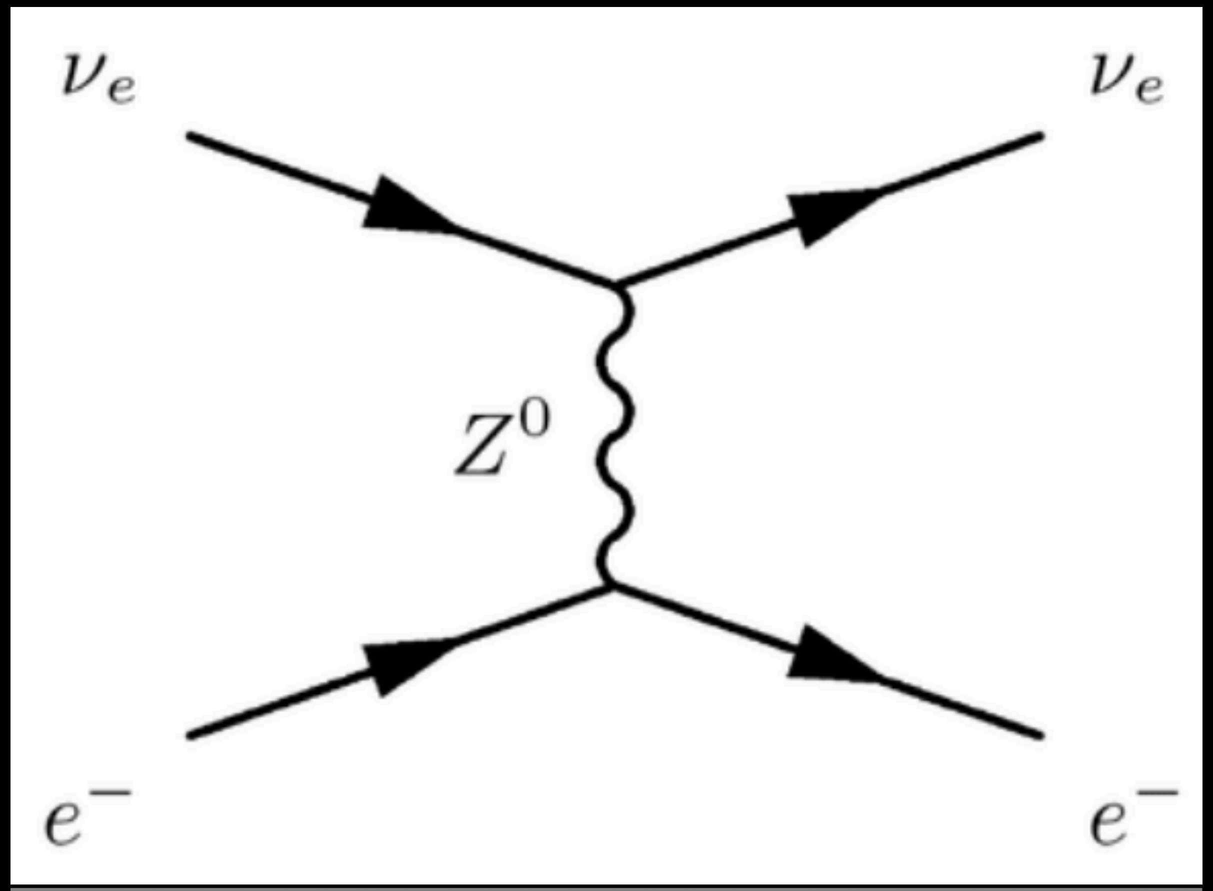
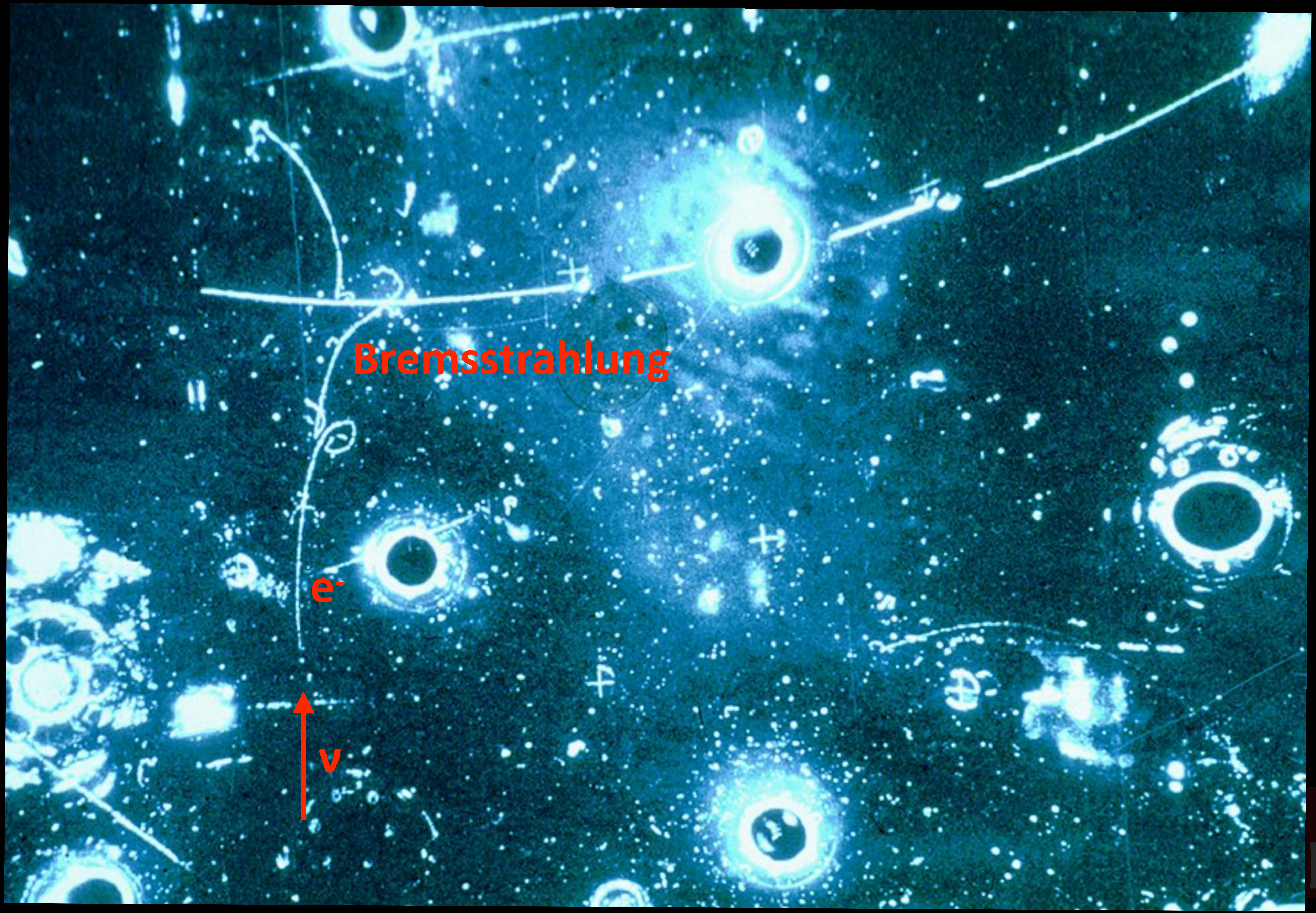
Particle Physics has come a long way!

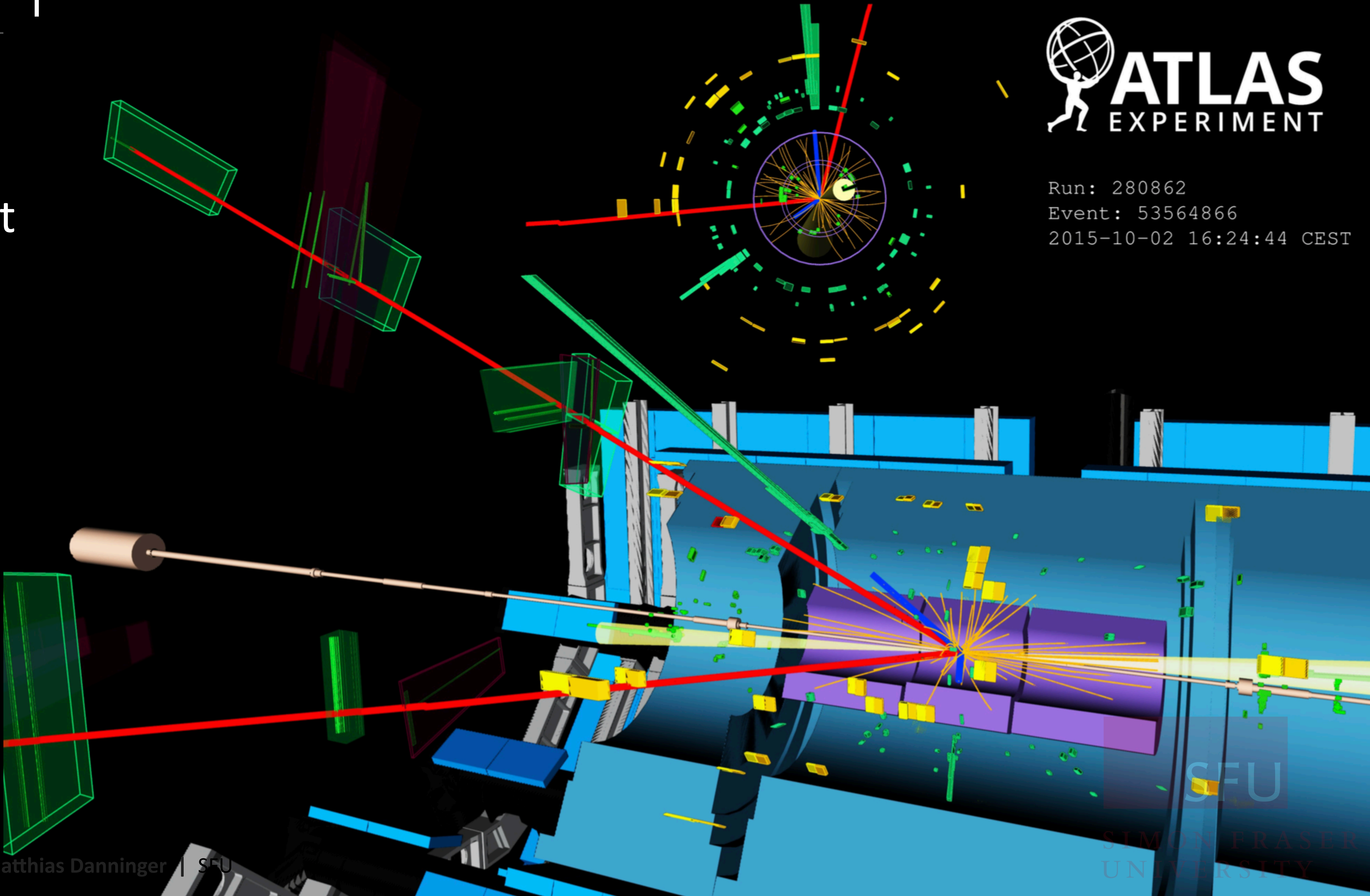




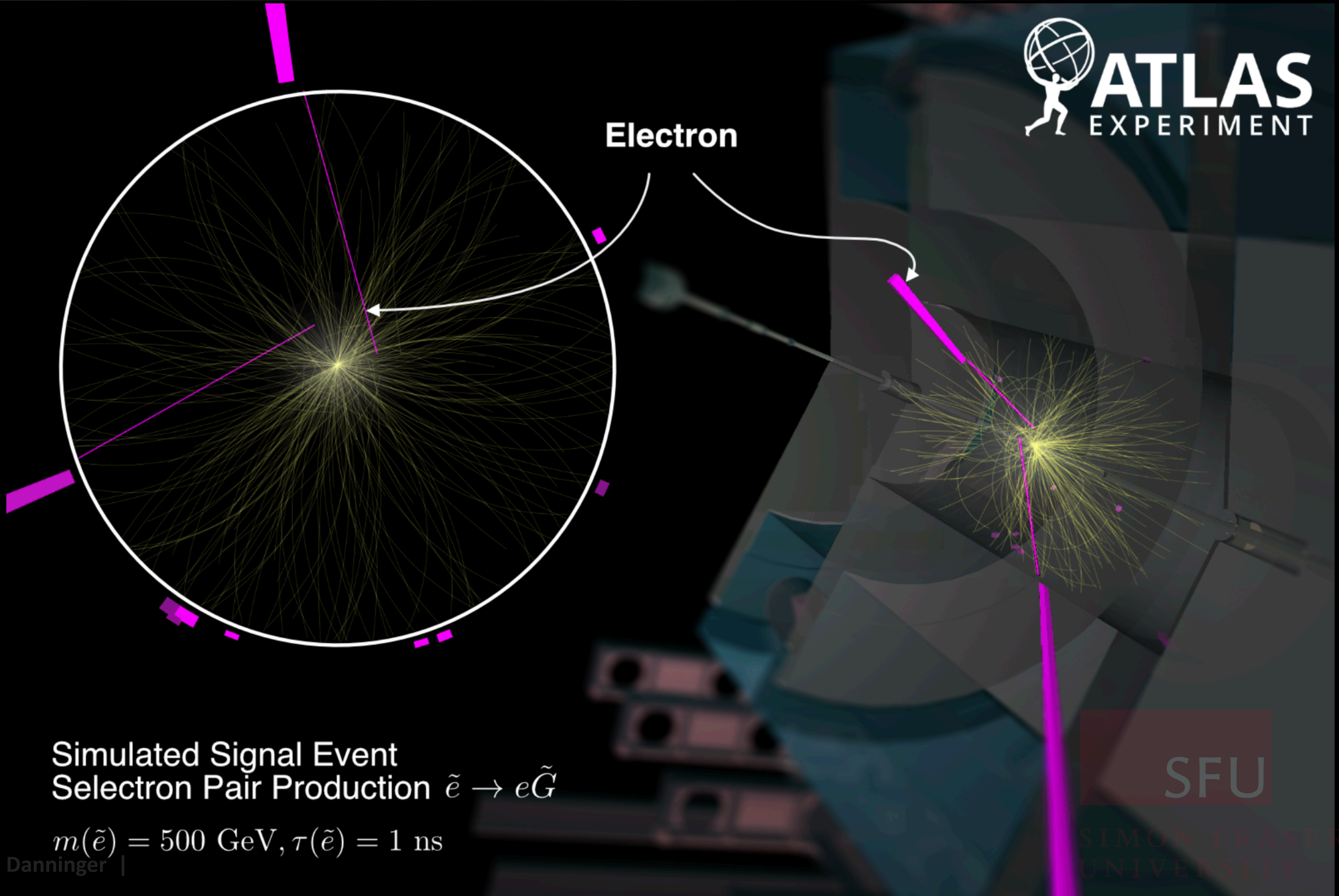
Event shows tracks produced in the 1200 litre Gargamelle bubble chamber that provided the first confirmation of a neutral current interaction (image: CERN)

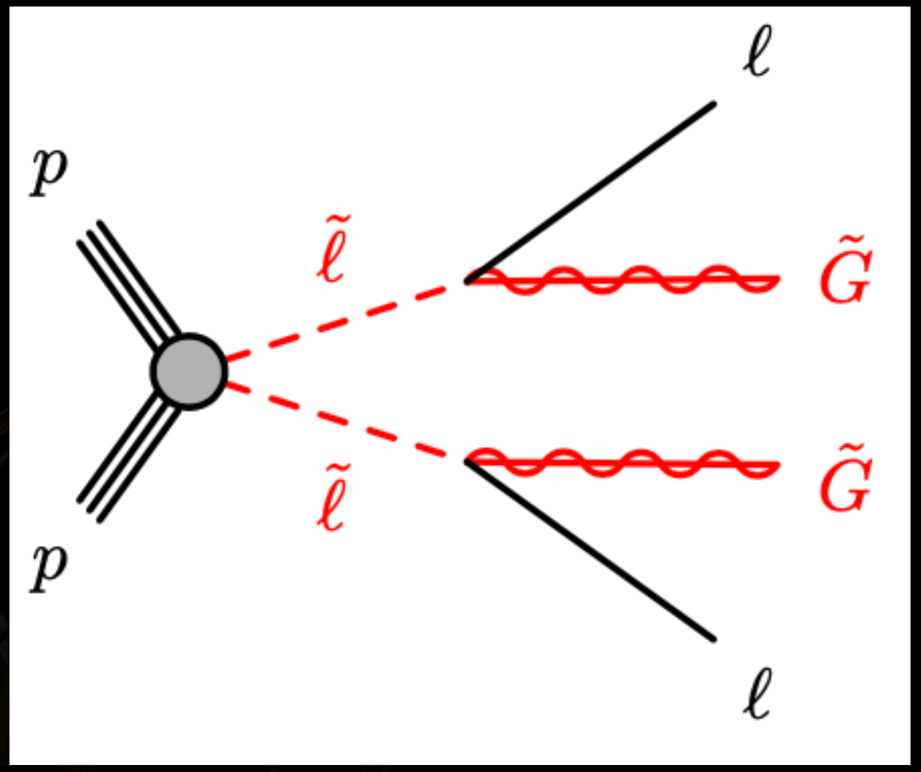
….. to produce and observe this!

H—>eeμμ
candidate event



….. but how can we observe this?

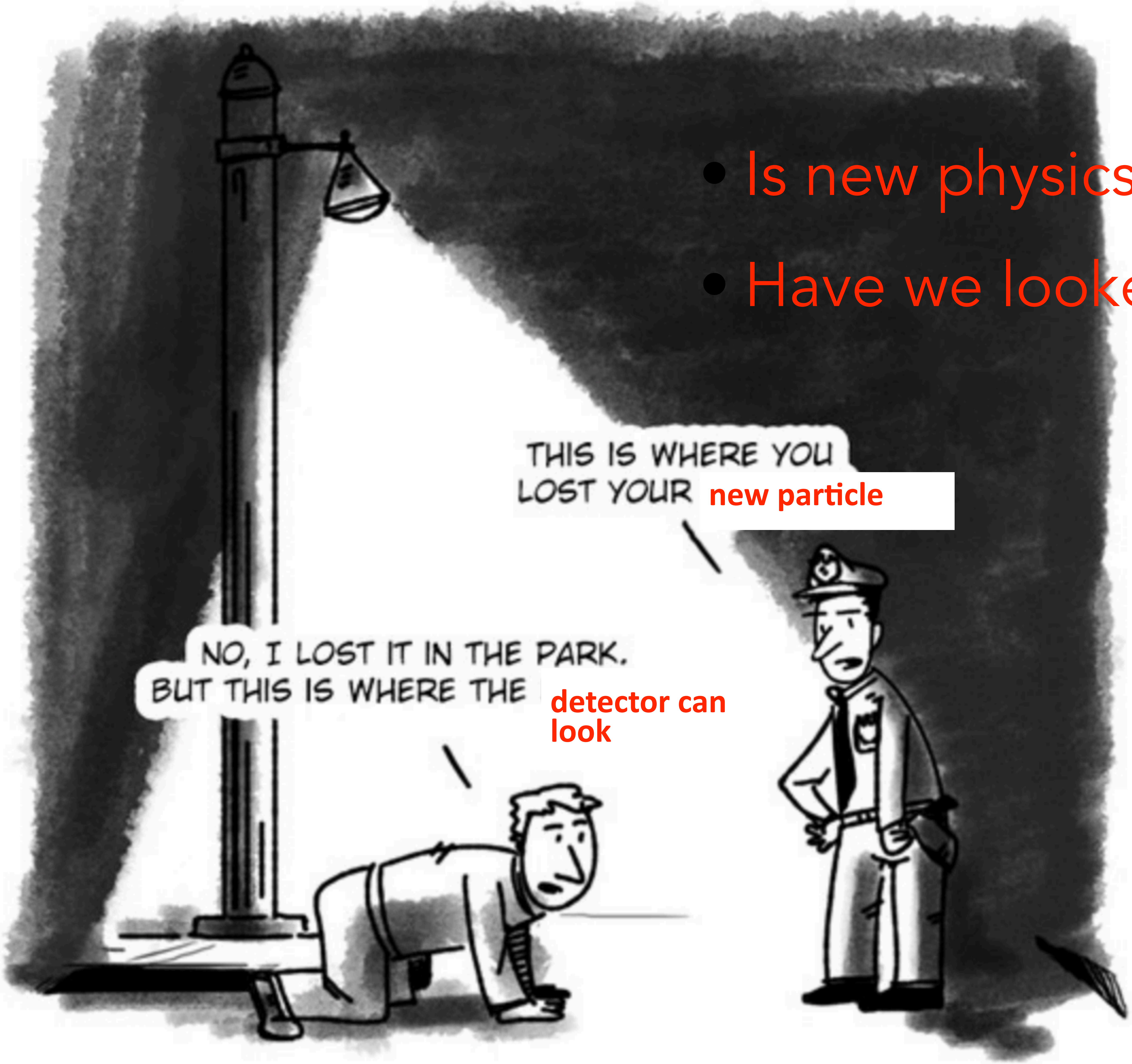




Simulated Signal Event
Selectron Pair Production $\tilde{e} \to e\tilde{G}$

$m(\tilde{e}) = 500\ \mathrm{GeV}, \tau(\tilde{e}) = 1\ \mathrm{ns}$

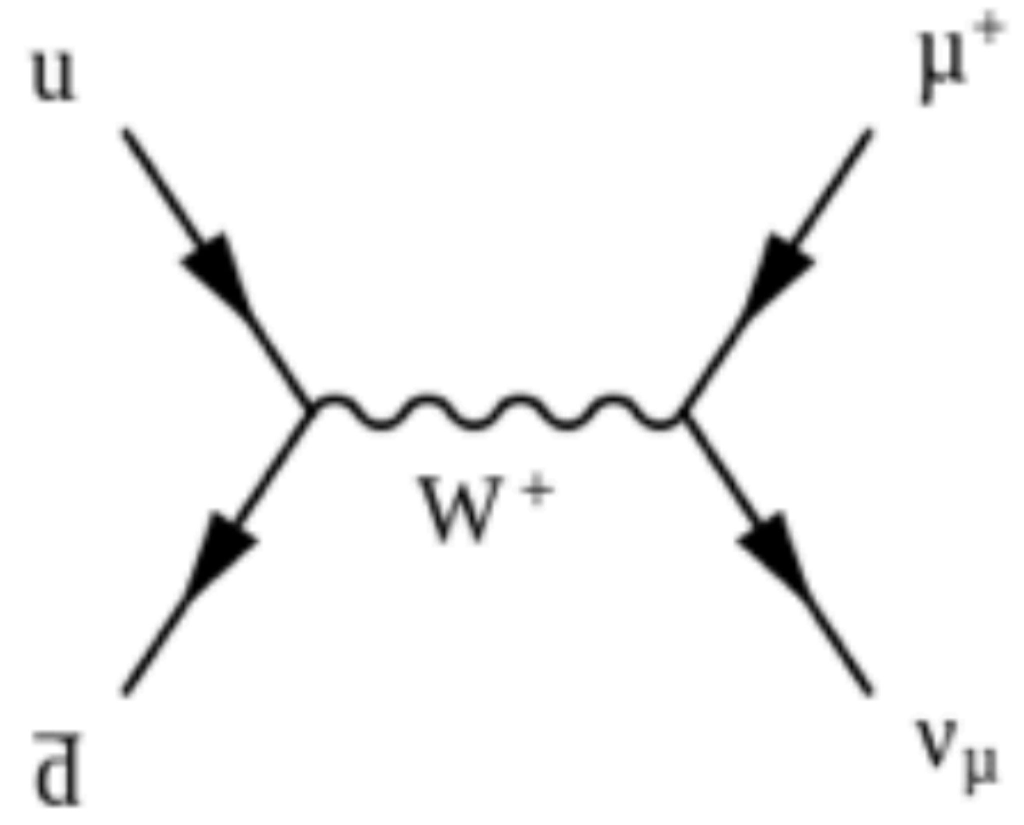
Long-lived particles & other unconventional signatures



- Is new physics out of reach for the LHC?
- Have we looked in the wrong place so far?

How to make Long-lived particles

- One simple Example: charged pion
    - Weak interaction
      (all others conserve quark flavour)
    - Decay is highly off-shell

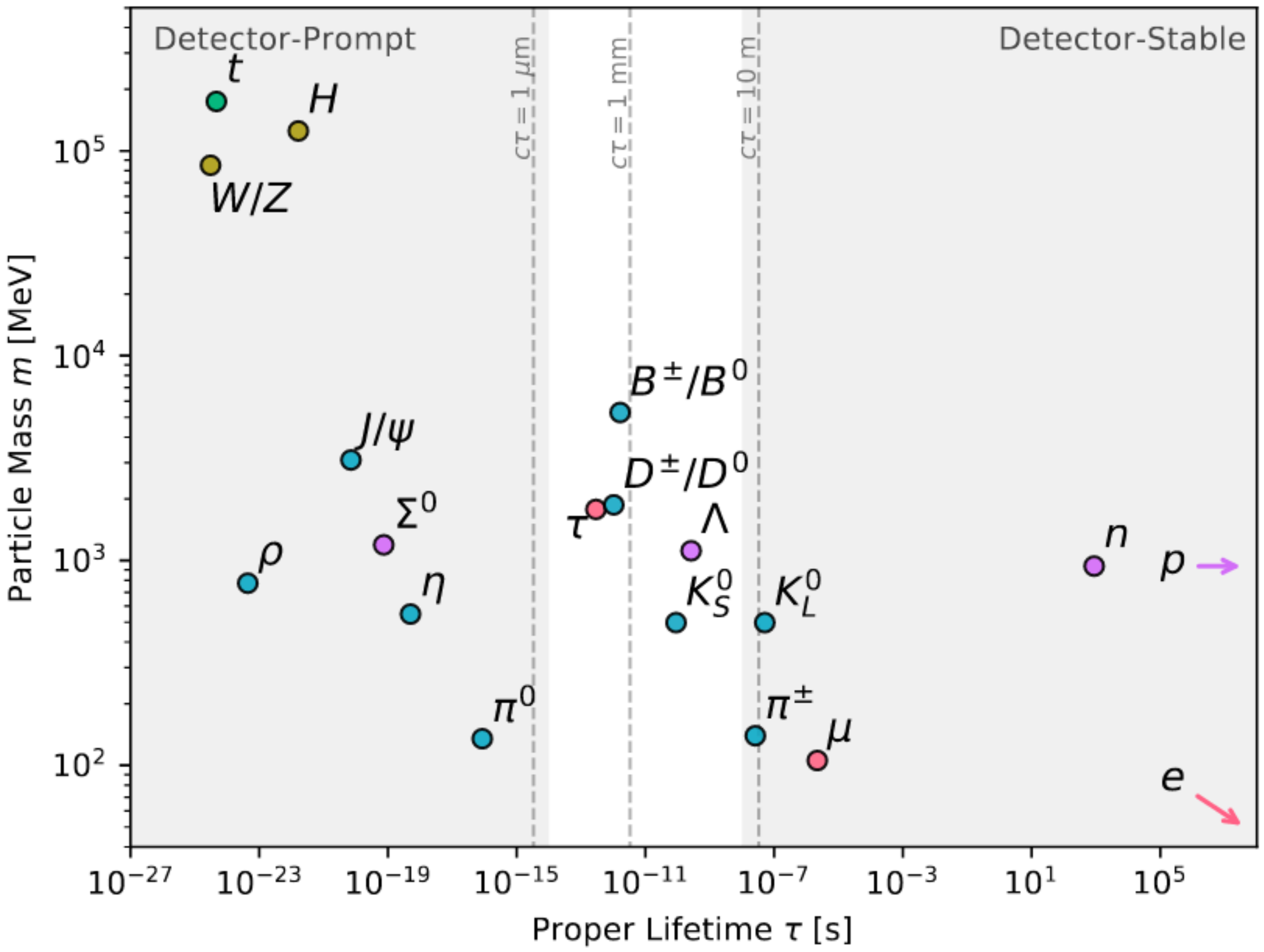


$$\Gamma \sim g_W^2 \left(\frac{m_\pi}{M_W}\right)^4 m_\pi$$

- Variety of mechanisms possible:
    - small couplings, approximate symmetries, heavy mediator, lack of phase space, etc..

Long-lived particles

1. Where is the new physics
2. Analogy to SM
3. Bottom-up Theoretical Motivation
   - Why not the same in BSM theories?
4. Top-Down Theoretical Motivation
   - LLPs can arise in almost any BSM theory!



Images from arxiv1810.12602

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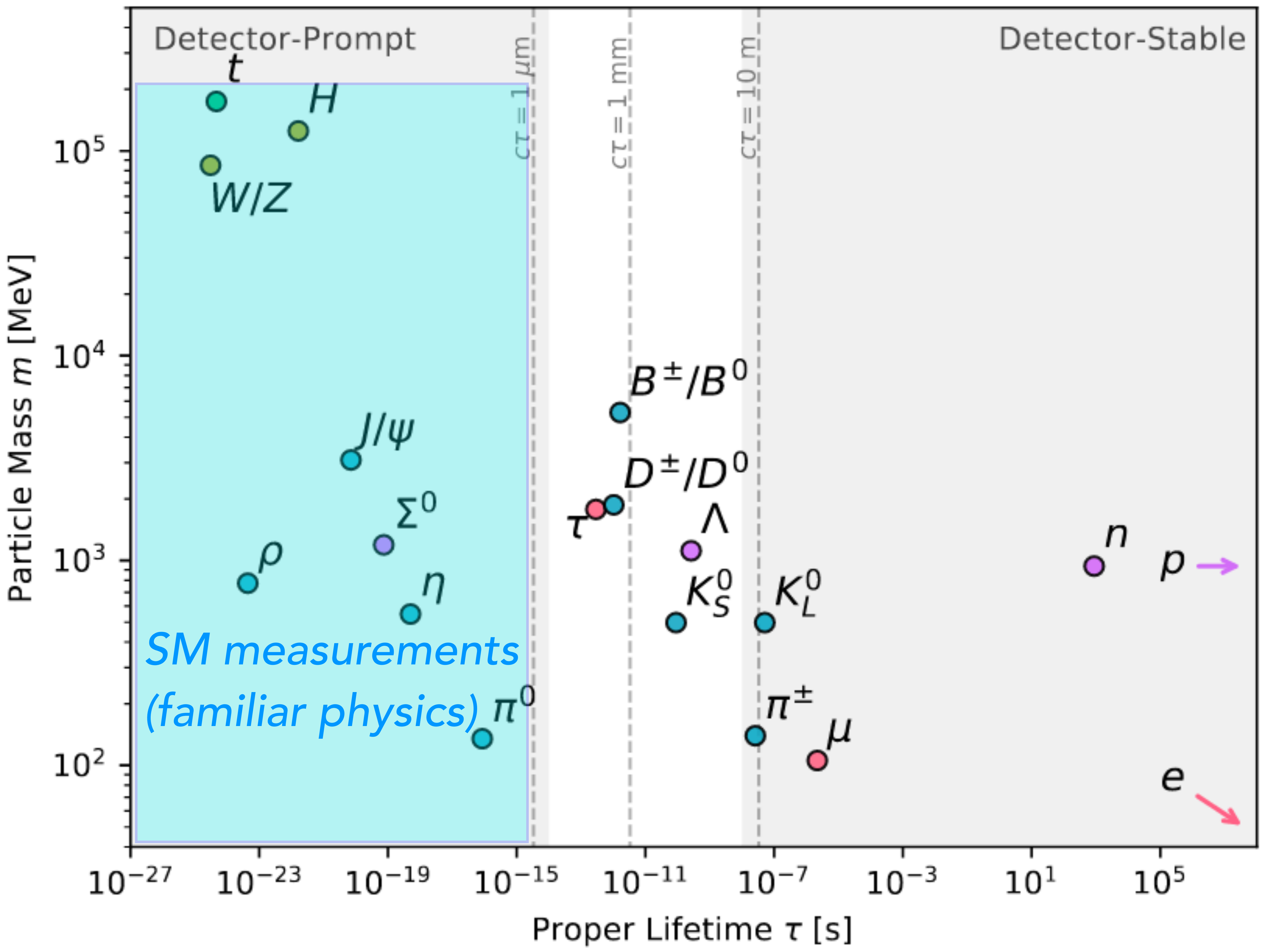

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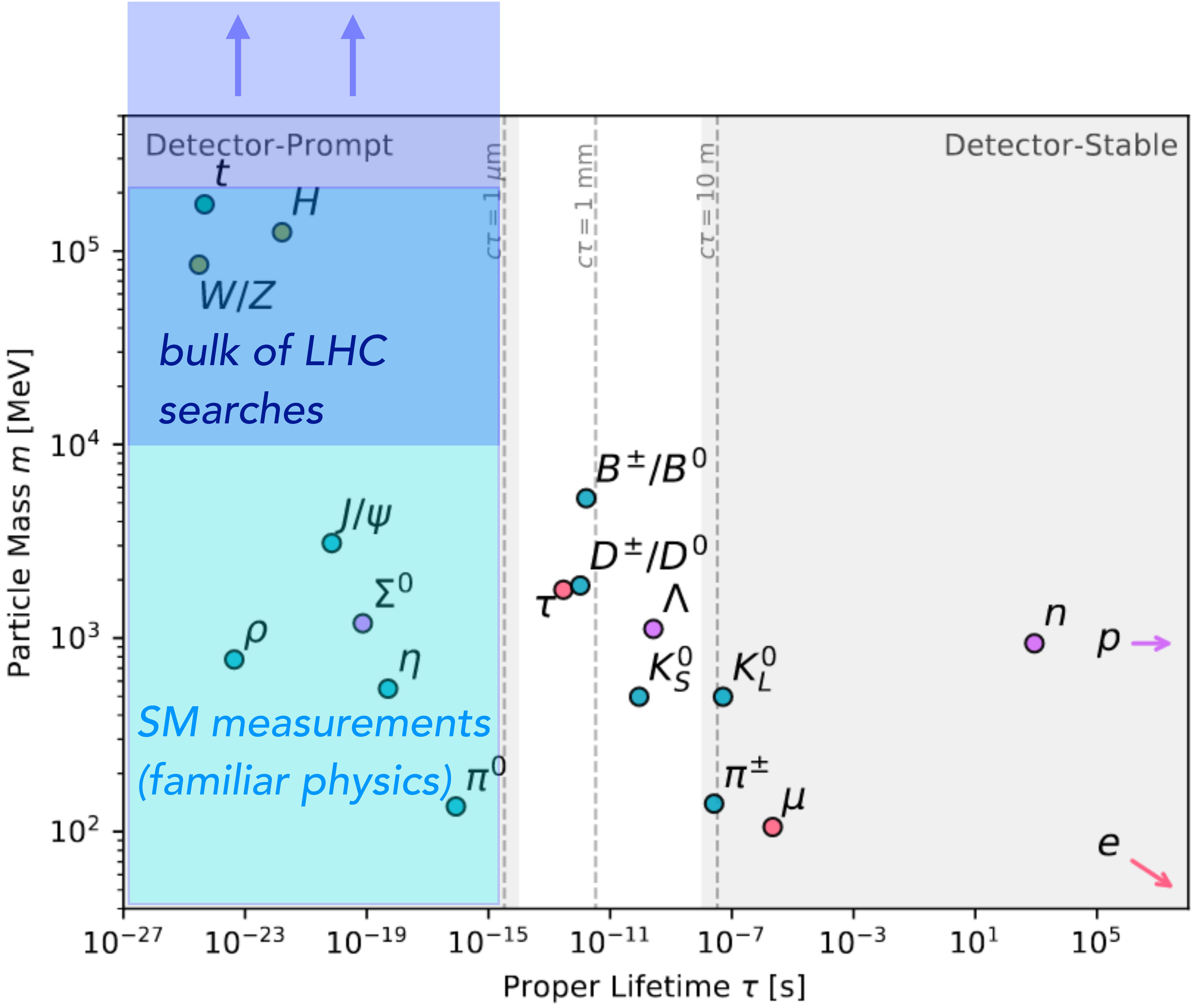

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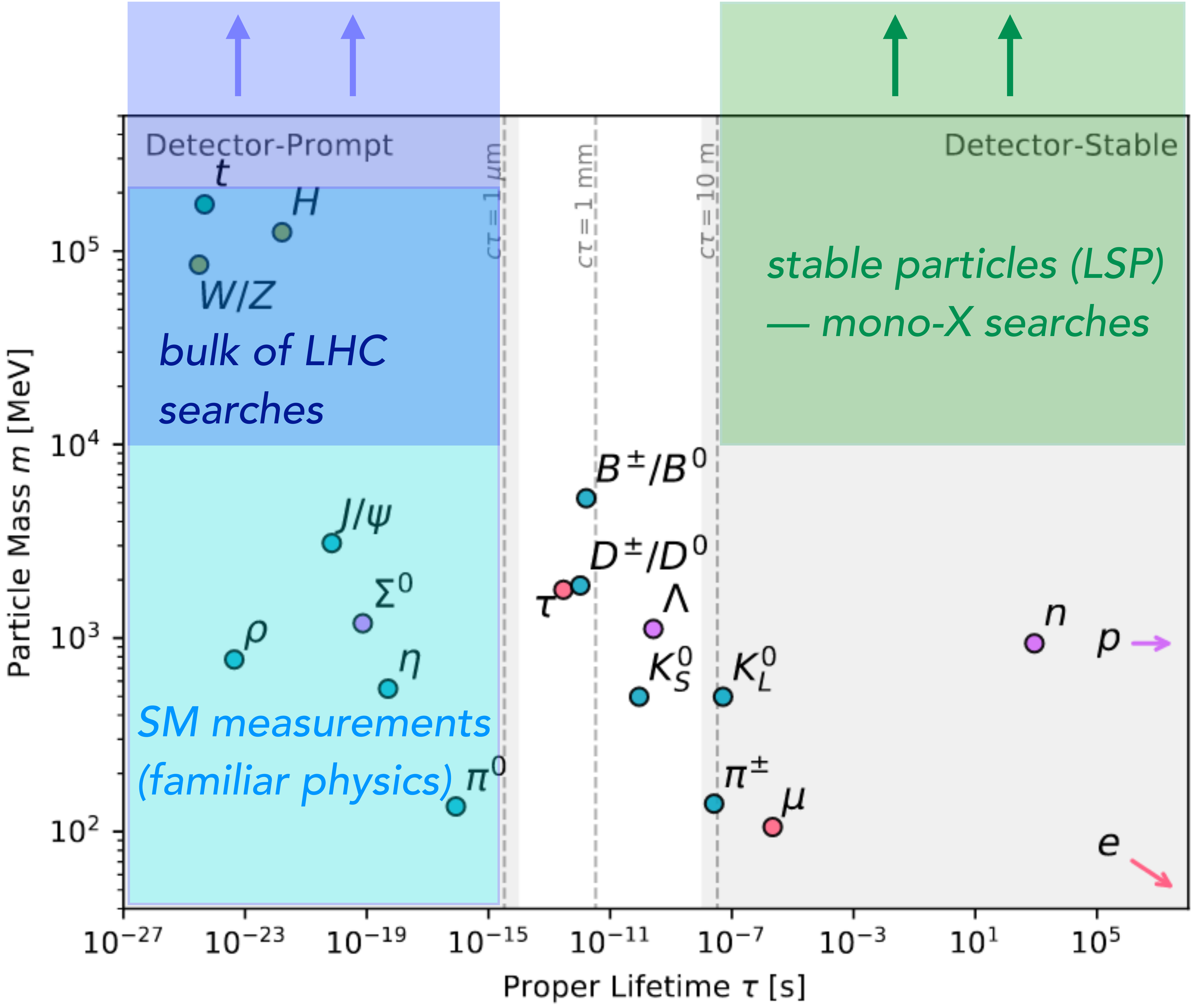

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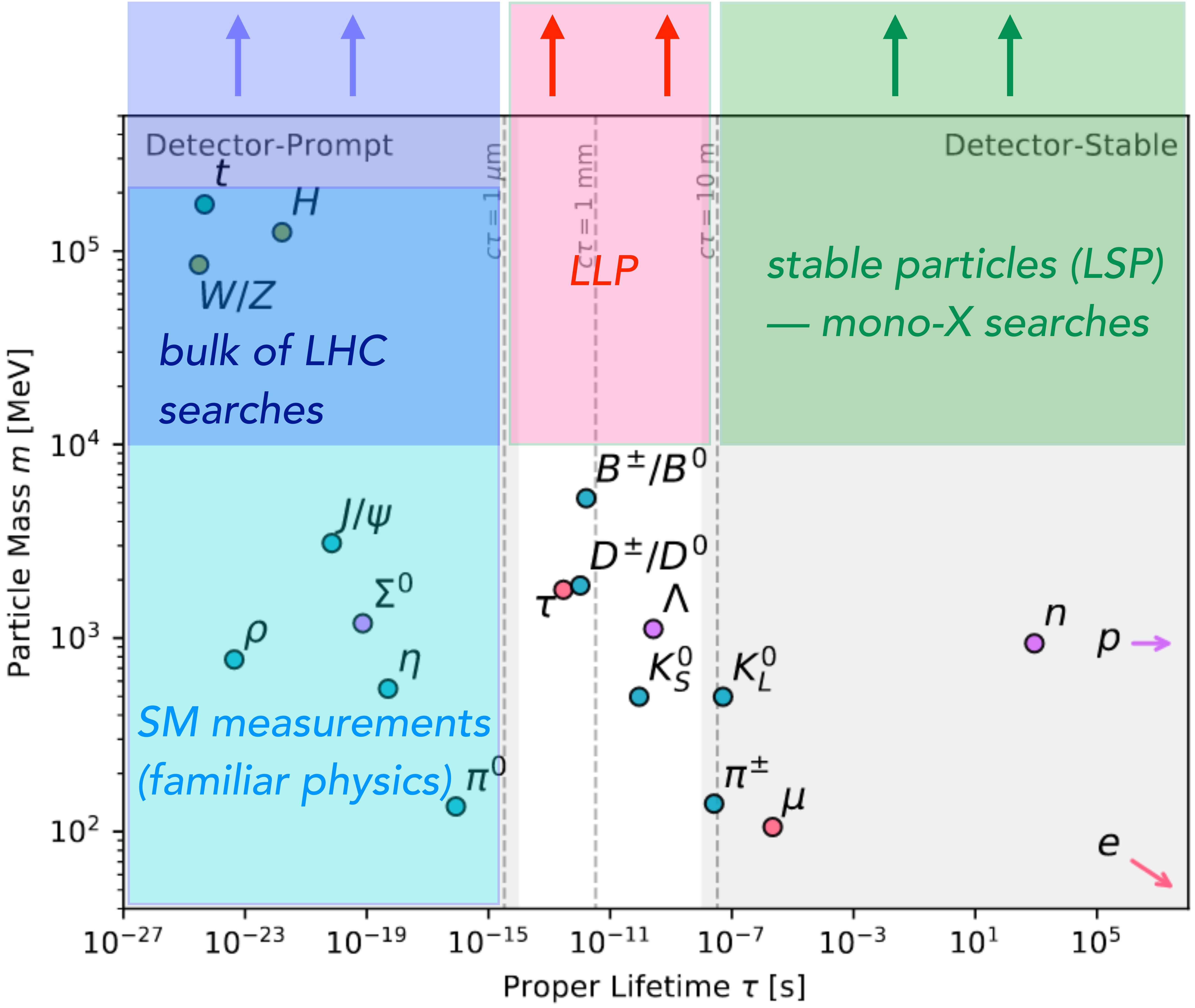

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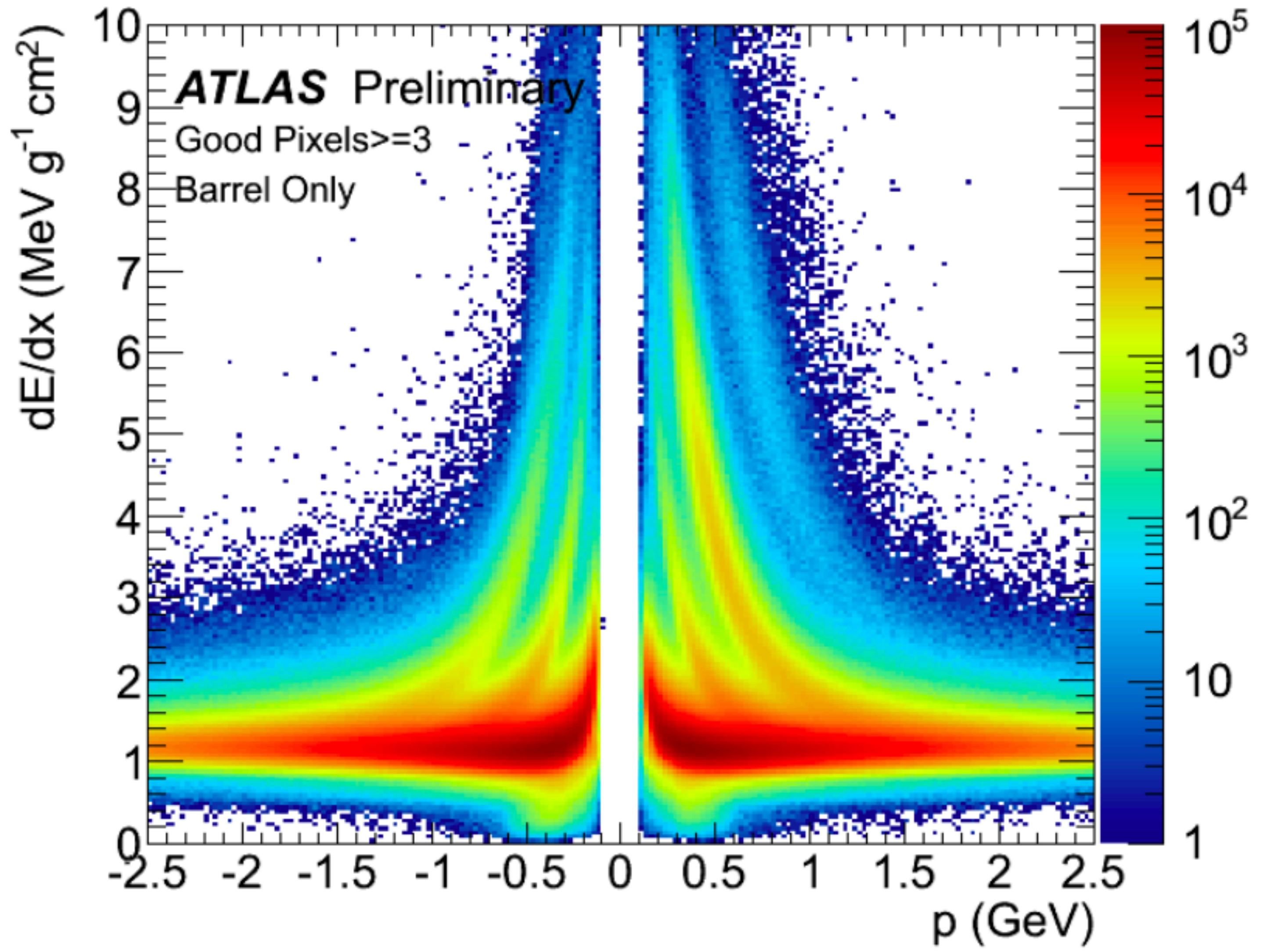
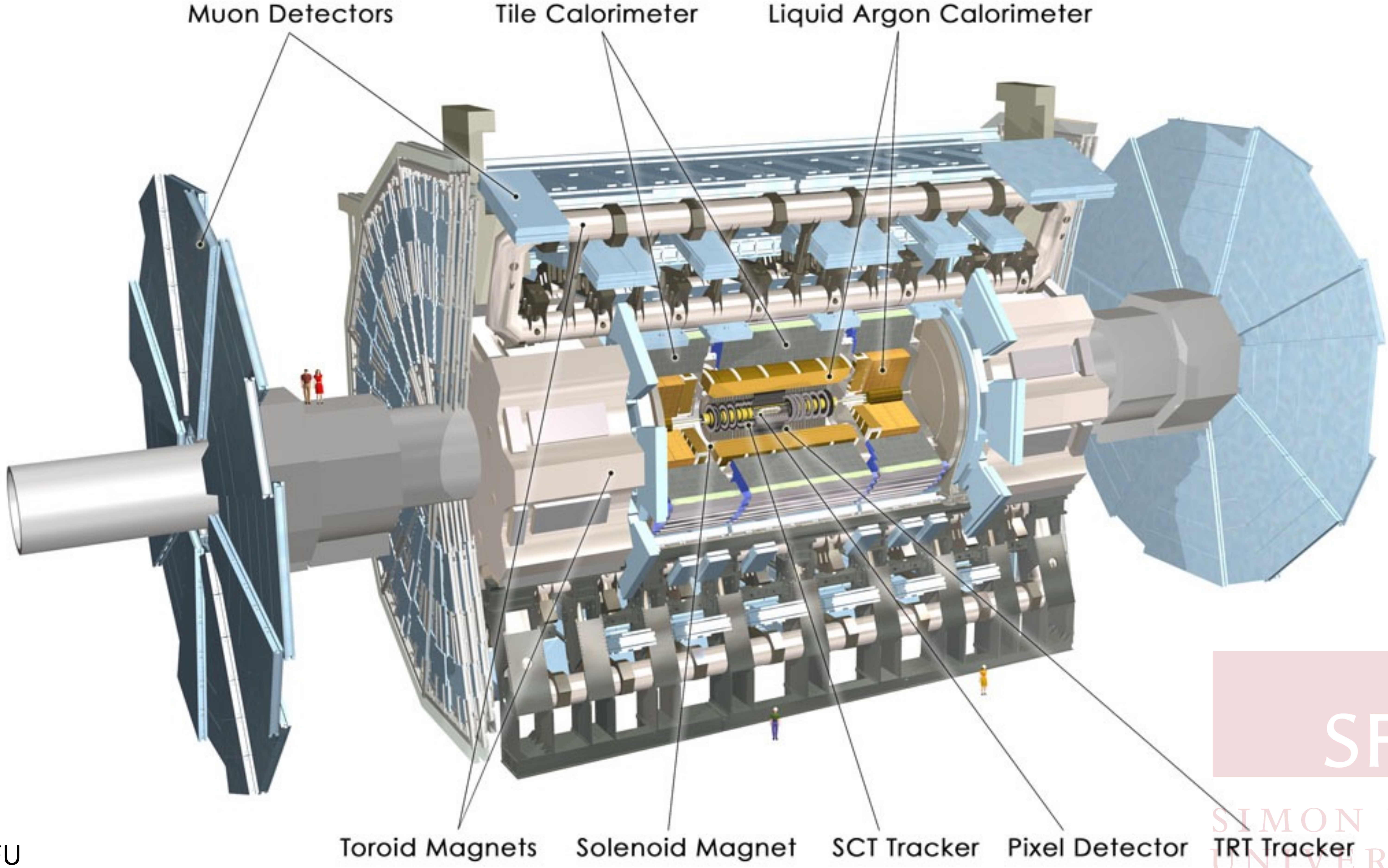
The (non-obvious) ATLAS experiment



Ionization loss: charge measured by:

- Pixel system
- Transition-Radiation Tracker (TRT)
- Monitored drift-tubes (MDT) in the muon system



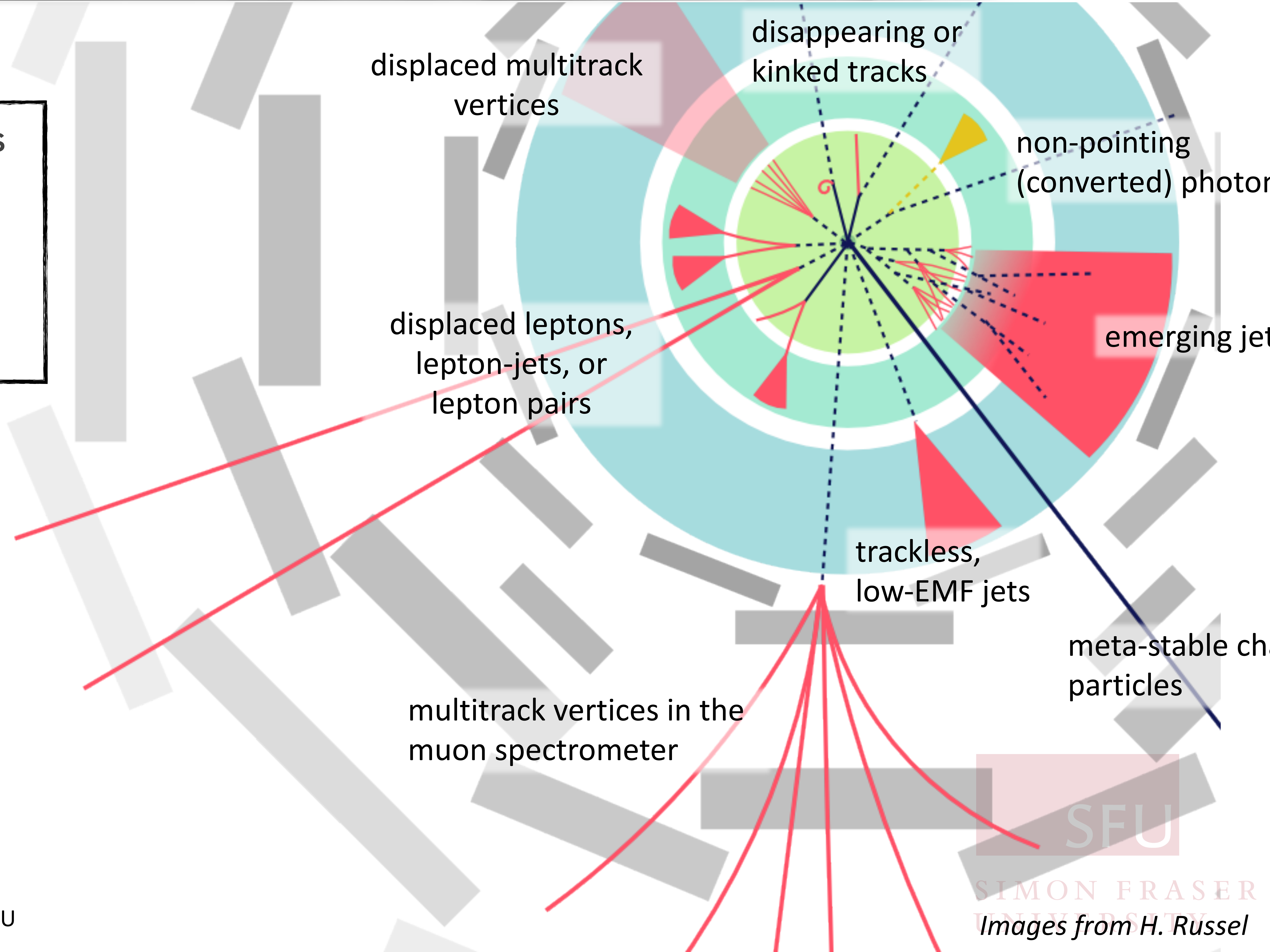
Time of flight: time of arrival by

- Electromagnetic (EM) and Hadronic Calorimeters
- Muon system

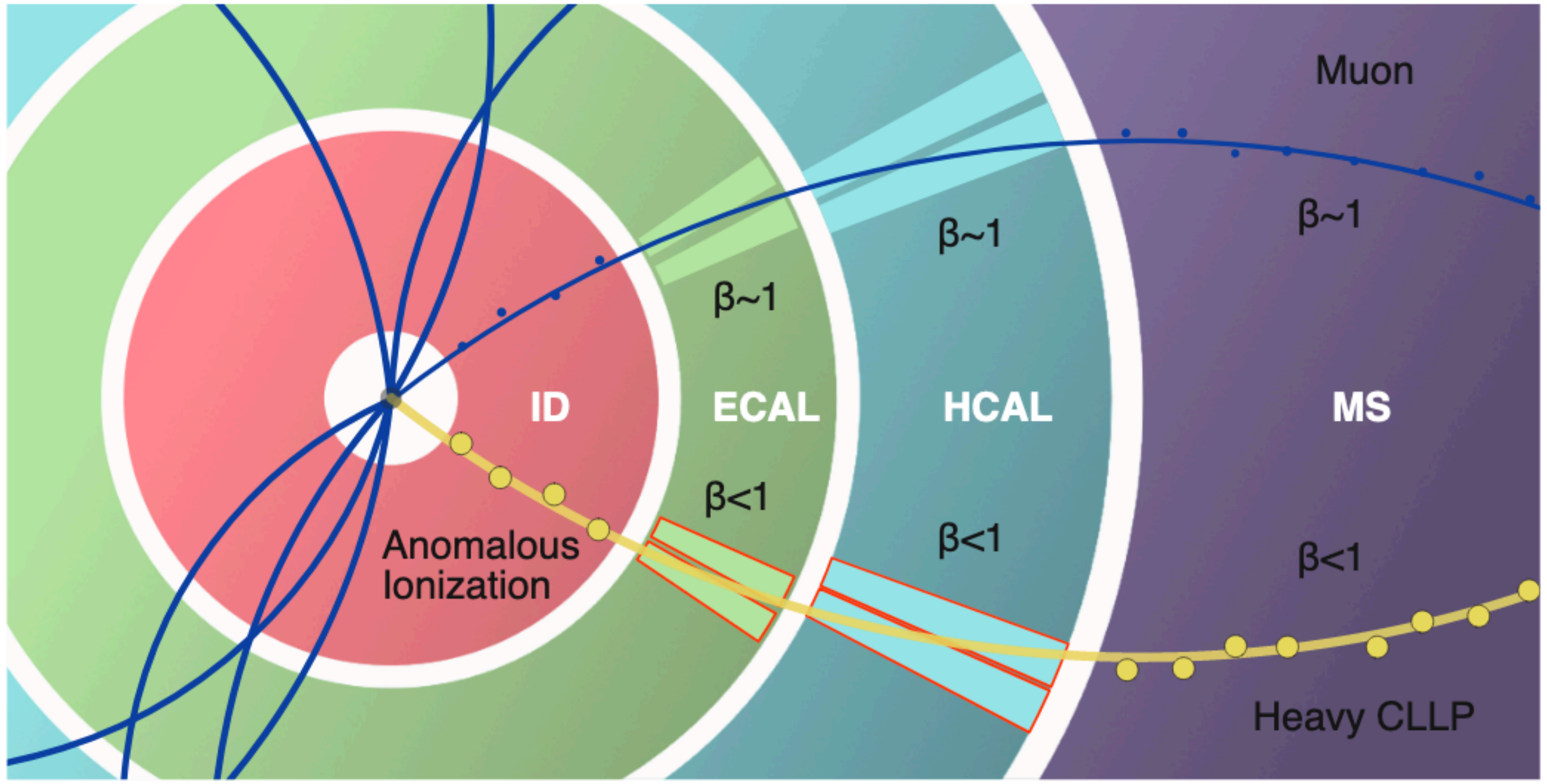
How does long-live physics look like?

Experimentally, long-lived particles are an interesting challenge

- LLPs use all parts of the detector in ways they were not necessarily designed to be used



Images from H. Russel



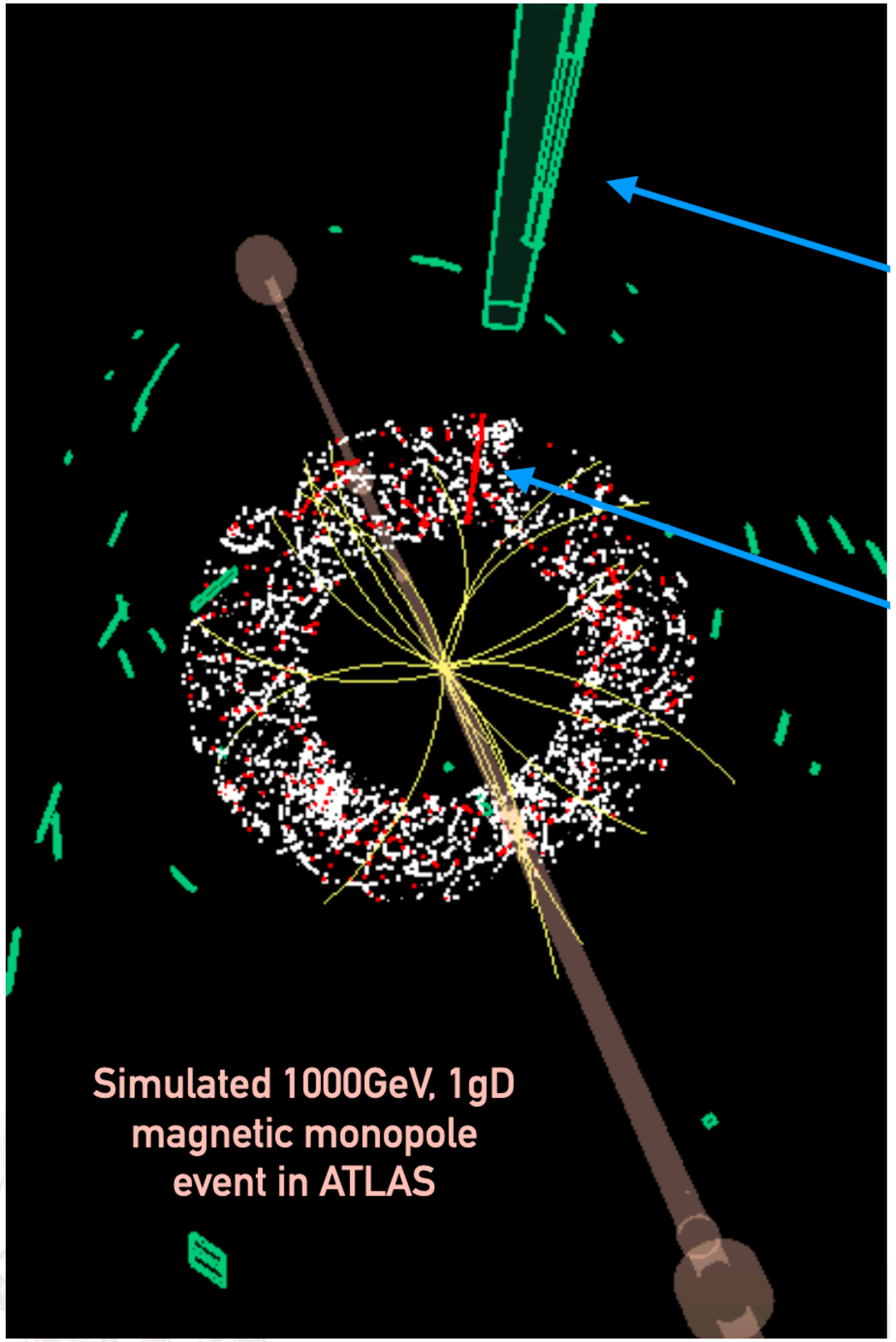
Direct Searches

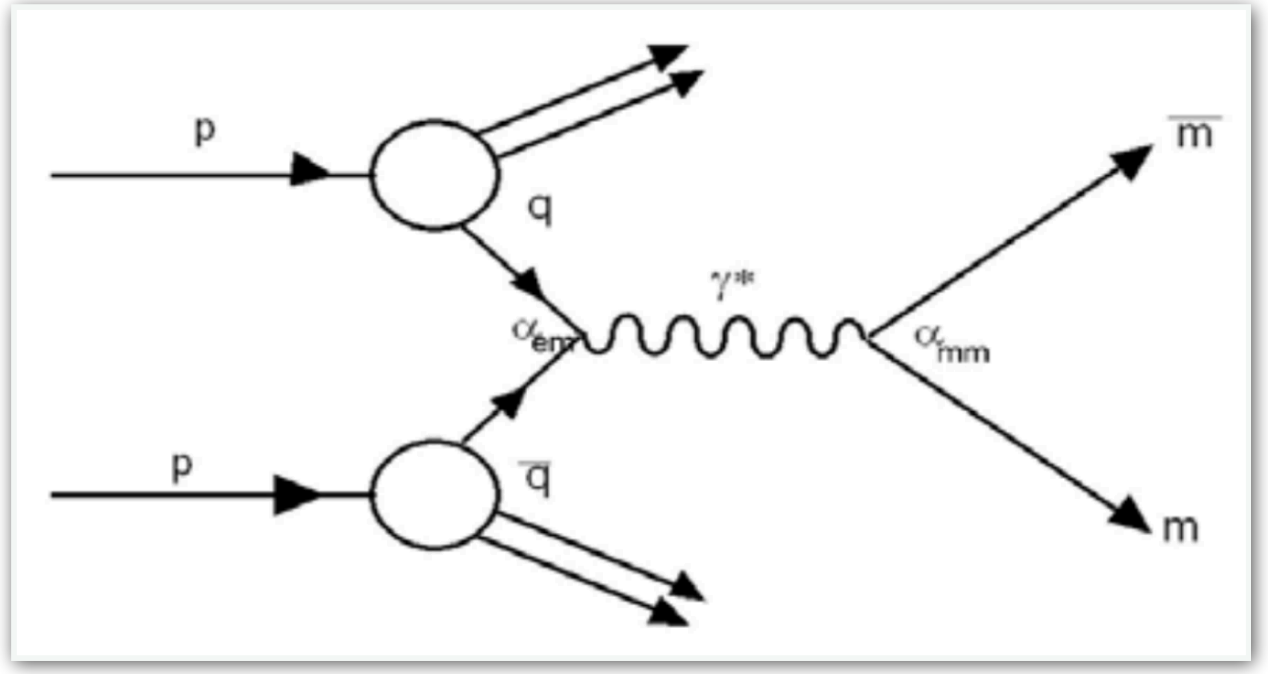
If LLP carries SM charge, we can look for its interactions with the detector directly

Images from arxiv1810.12602

Very Highly Ionizing Particles (HIPs)

PRL 124 (2020) 031802





$$q_m = N g_D e c,$$

$$g_D = 1/(2\alpha) = 68.5$$

- Analysis goals:
  - Test for Dirac's description of magnetic monopole
  - Search for High Electric Charge Objects (Q-balls, micro black hole remnants)
- Striking experimental signature in ATLAS:
  - ~5000x more ionization loss in detector than MIP

Very Highly Ionizing Particles (HIPs)

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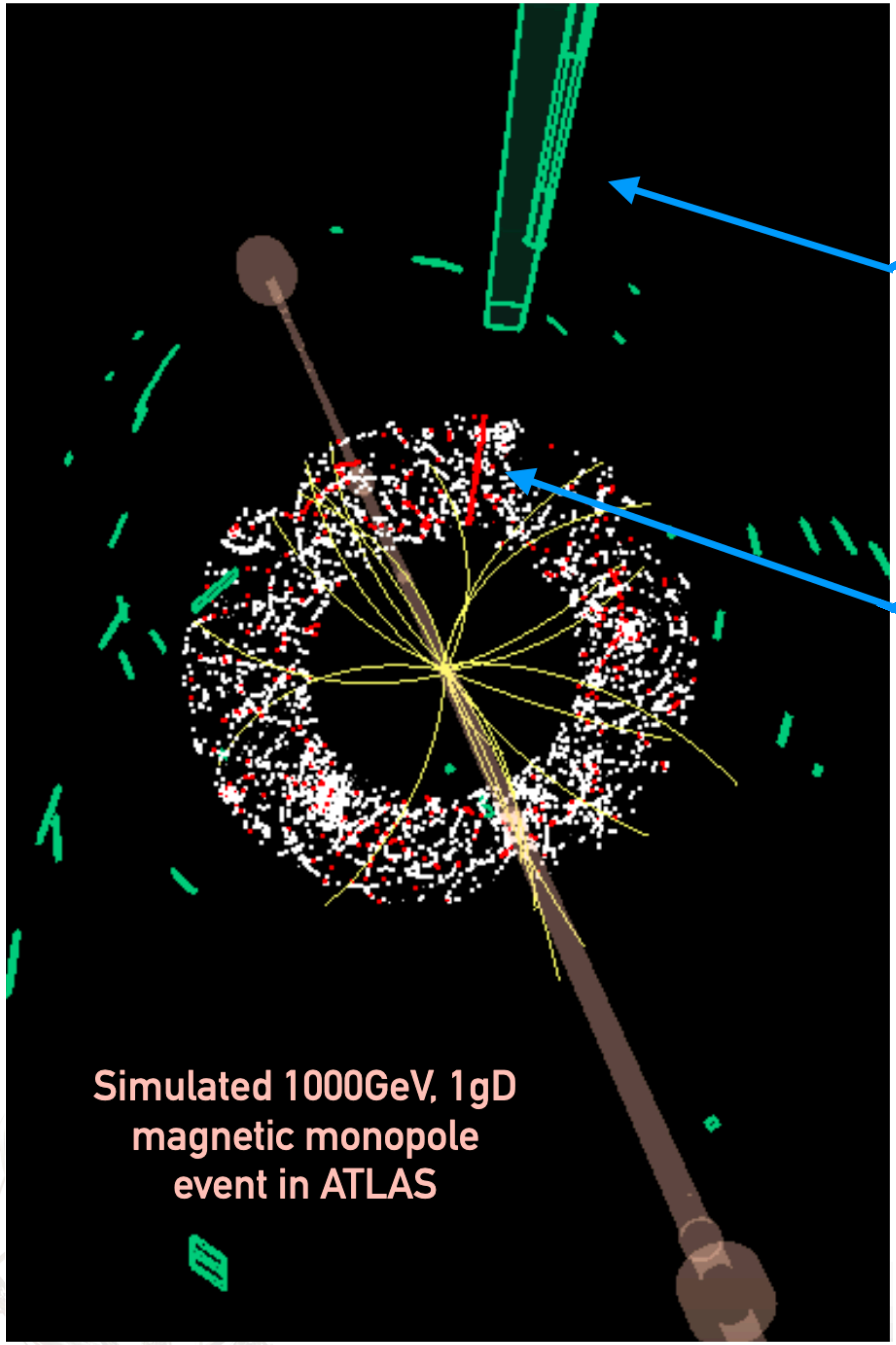
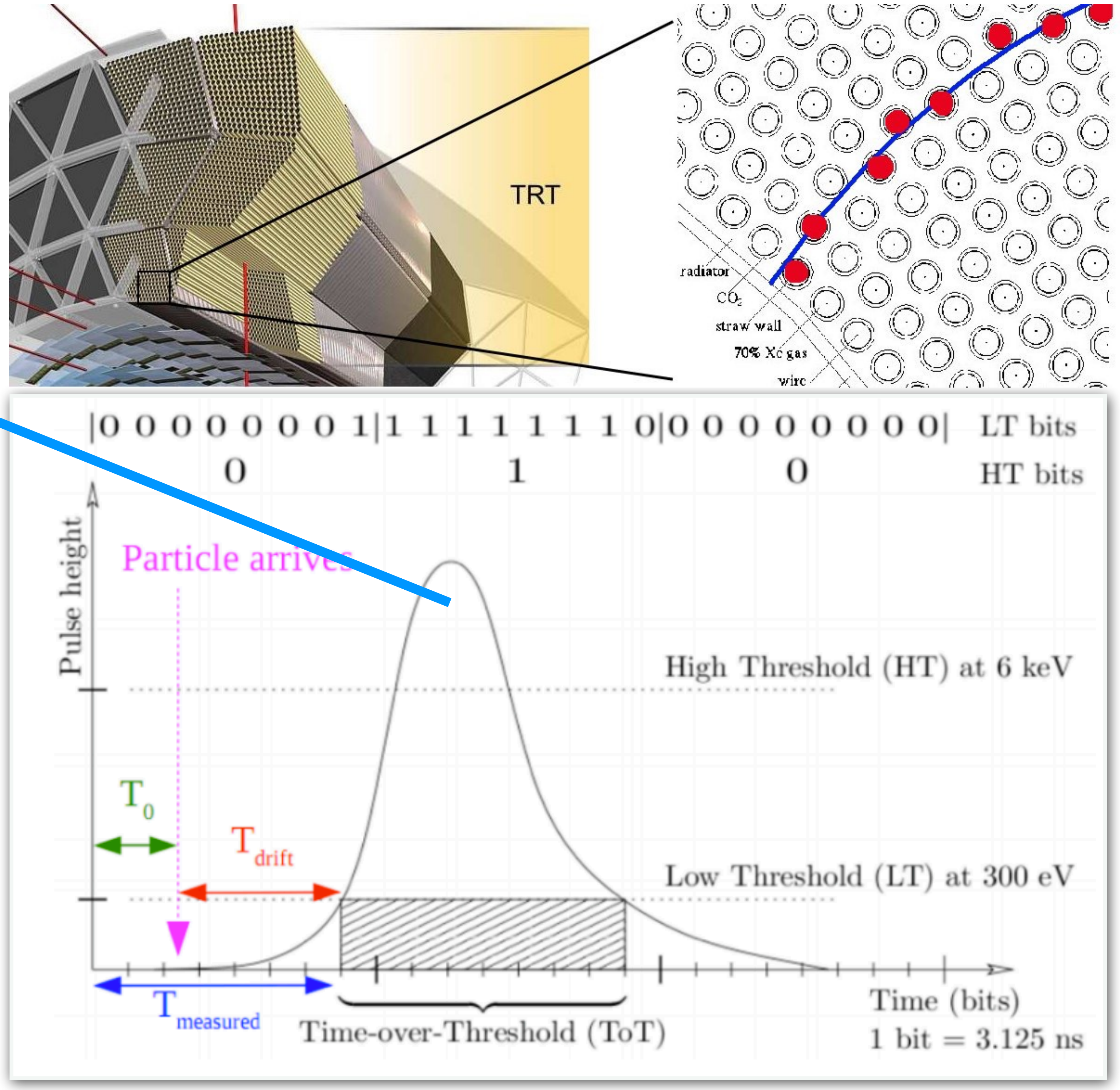


- Signal discriminating variables:
  - Concentrated high energy deposition in the LAr EM calorimeter (***w***)
  - TRT High Threshold hits (f_{HT})



- Drift tubes: ⌀4mm, up to 1440mm length
- ~298,000 straws
- resolution of 130 μm

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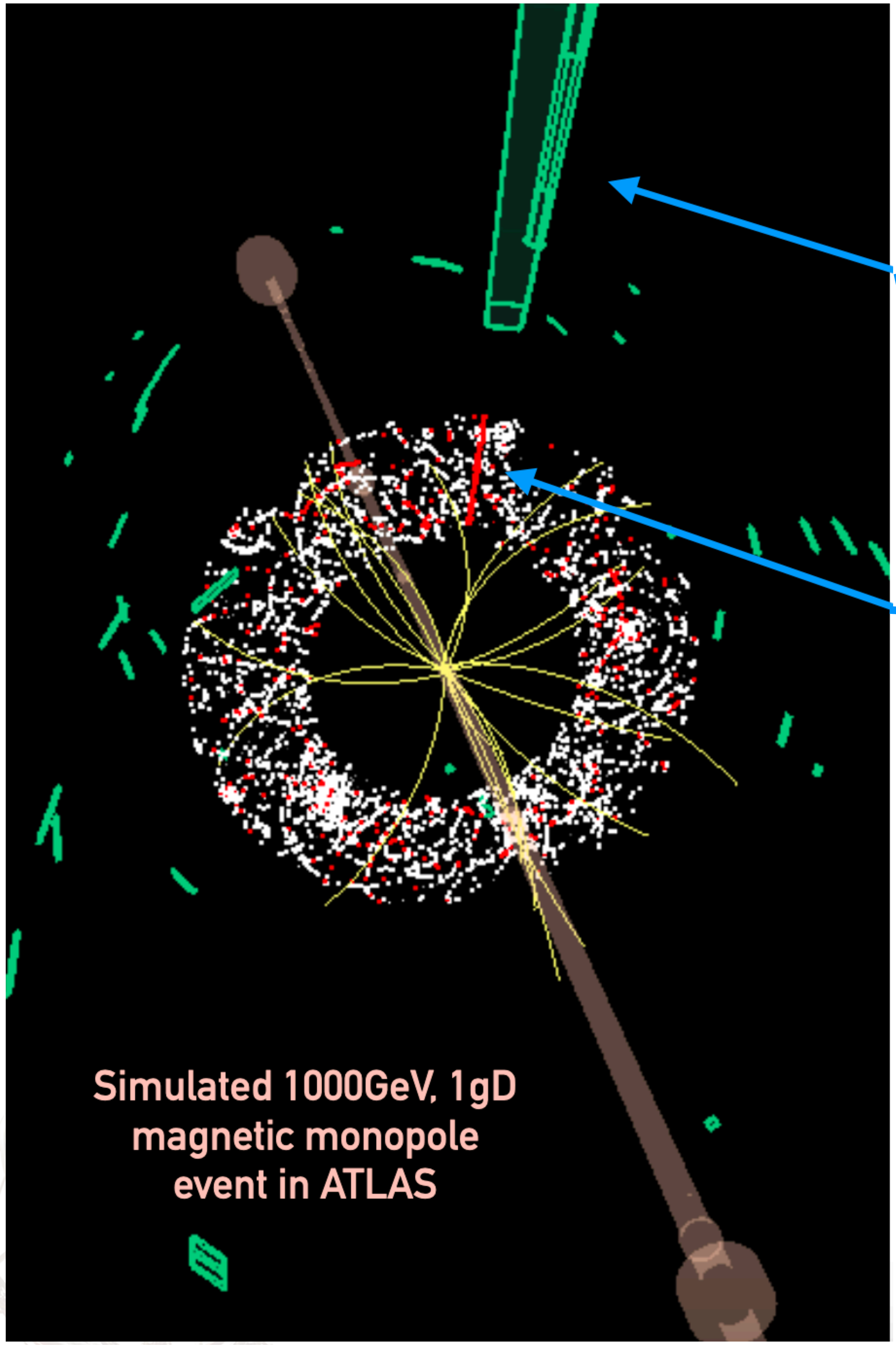
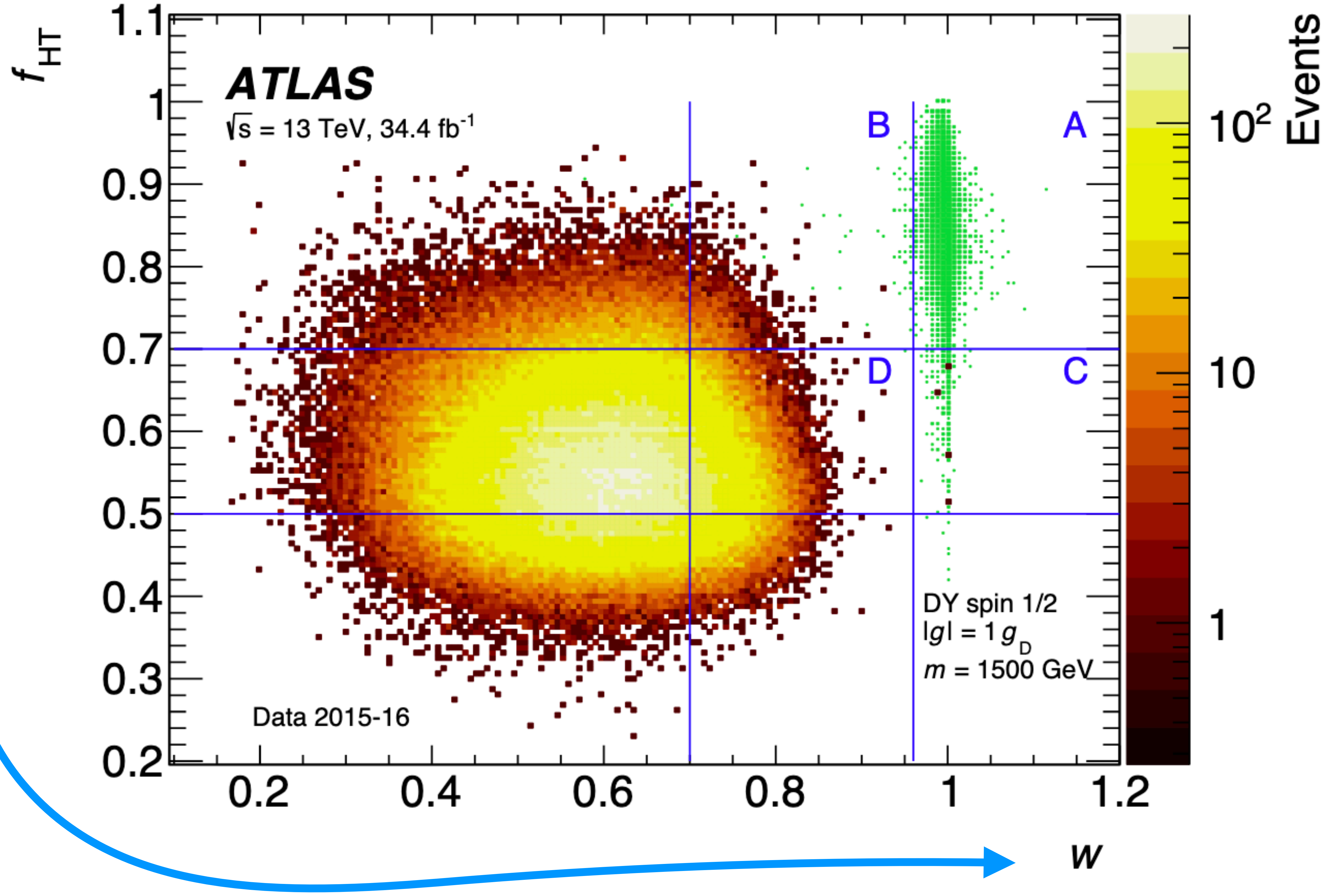
Very Highly Ionizing Particles (HIPs)

PRL 124 (2020) 031802



- Signal discriminating variables:
  - Concentrated high energy deposition in the LAr EM calorimeter (***w***)
  - TRT High Threshold hits (***f***$_{HT}$)
  - 0 events observed, expected $0.20 \pm 0.11\,(\mathrm{stat}) \pm 0.40\,(\mathrm{sys})$



$$N_A = N_B \times \frac{N_C}{N_D}$$

Very Highly Ionizing Particles (HIPs)

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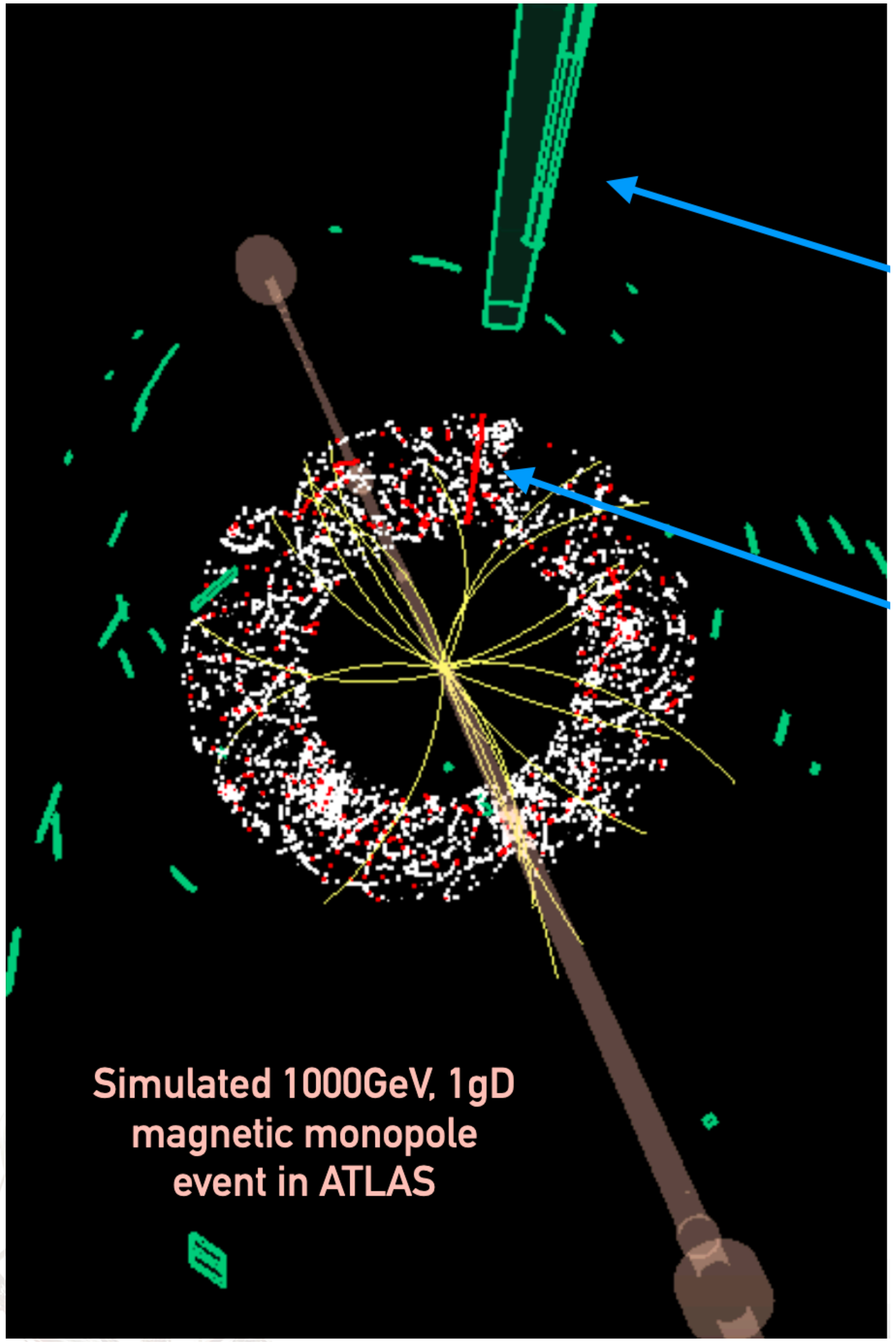
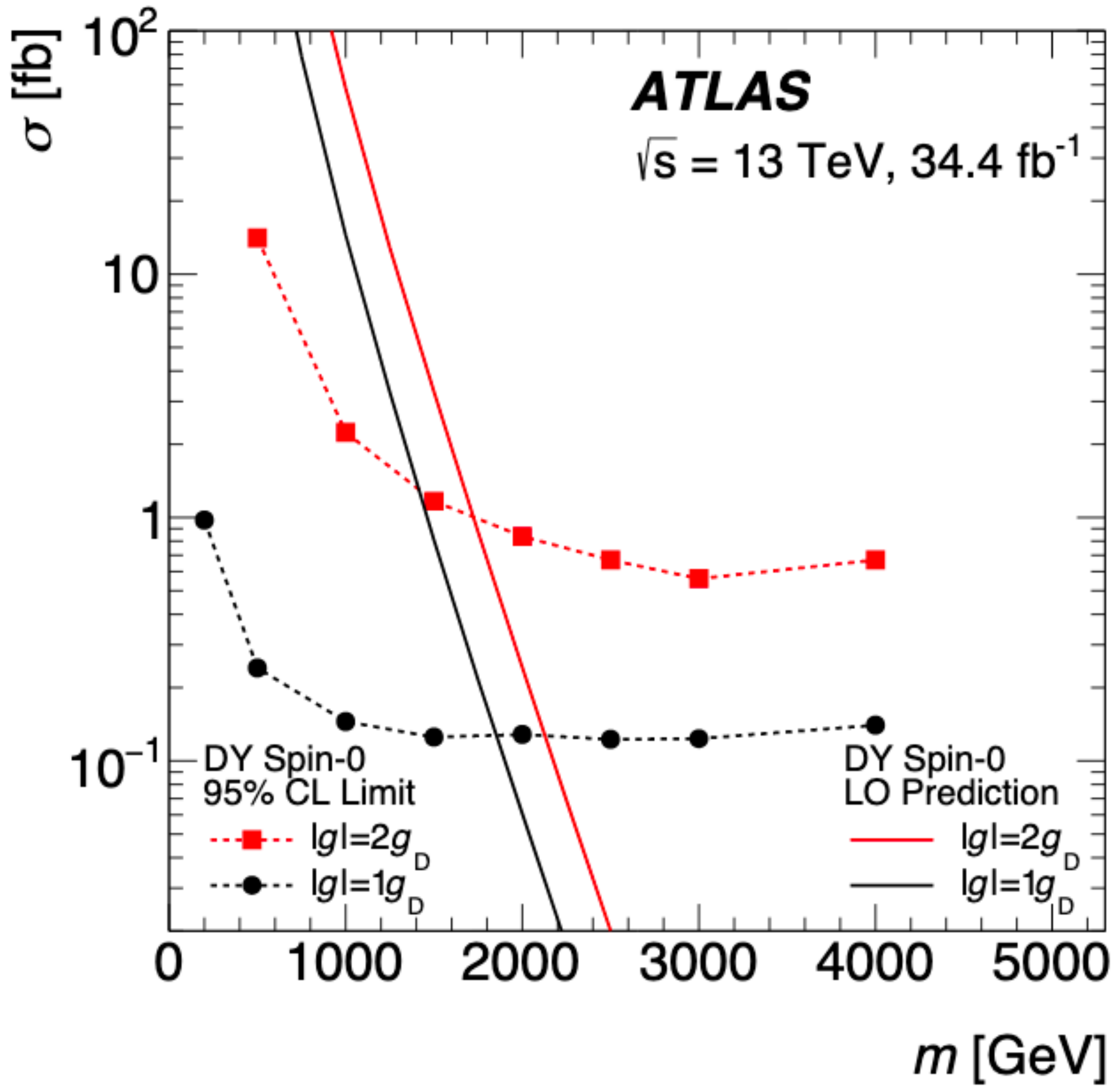
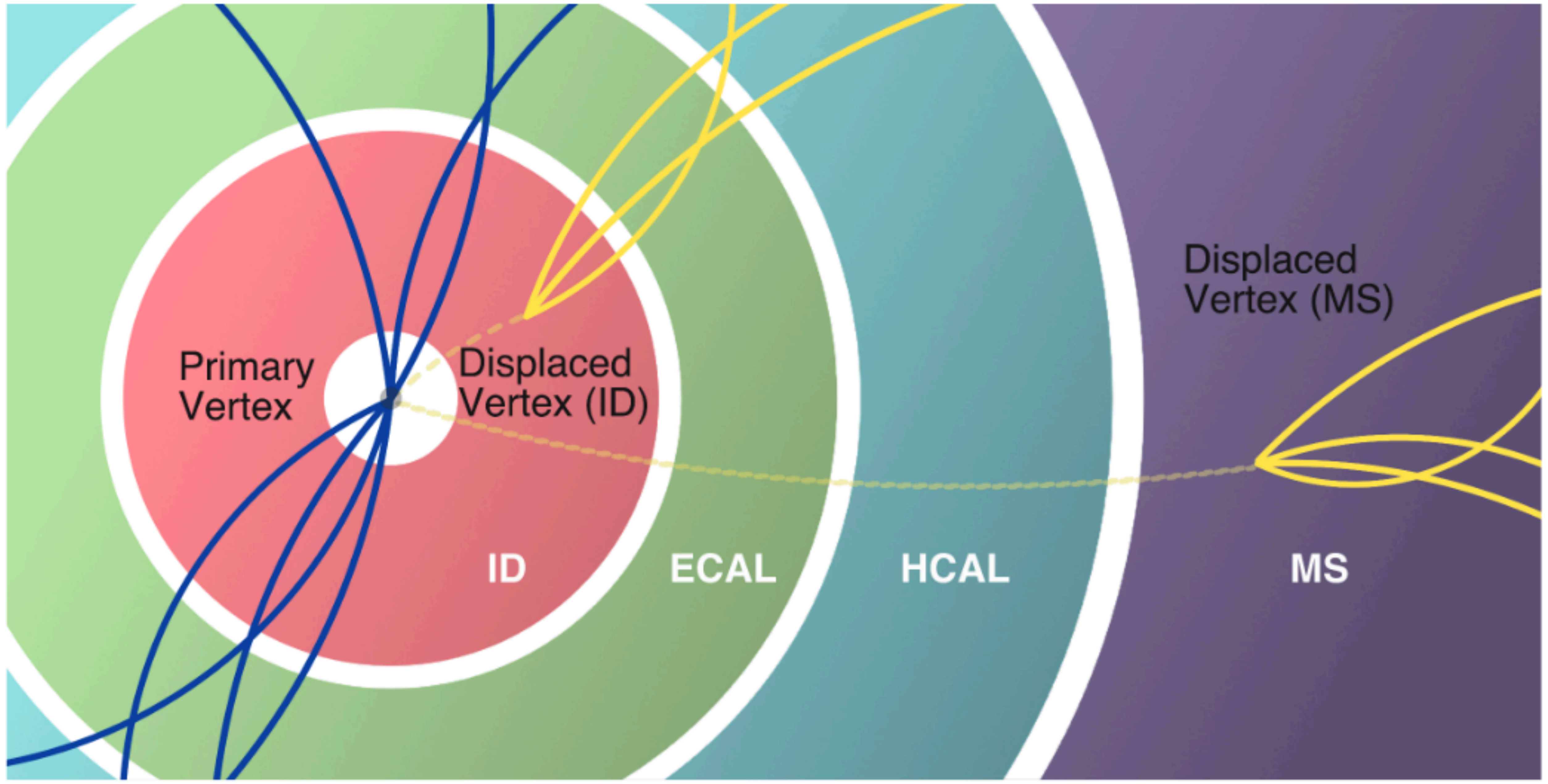


- $|g| = 1g_D$ scalar monopole excluded up to 1850 GeV.
- ~5x improvement to the ATLAS Run1 result.
- Sensitivity comparable to MoEDAL.





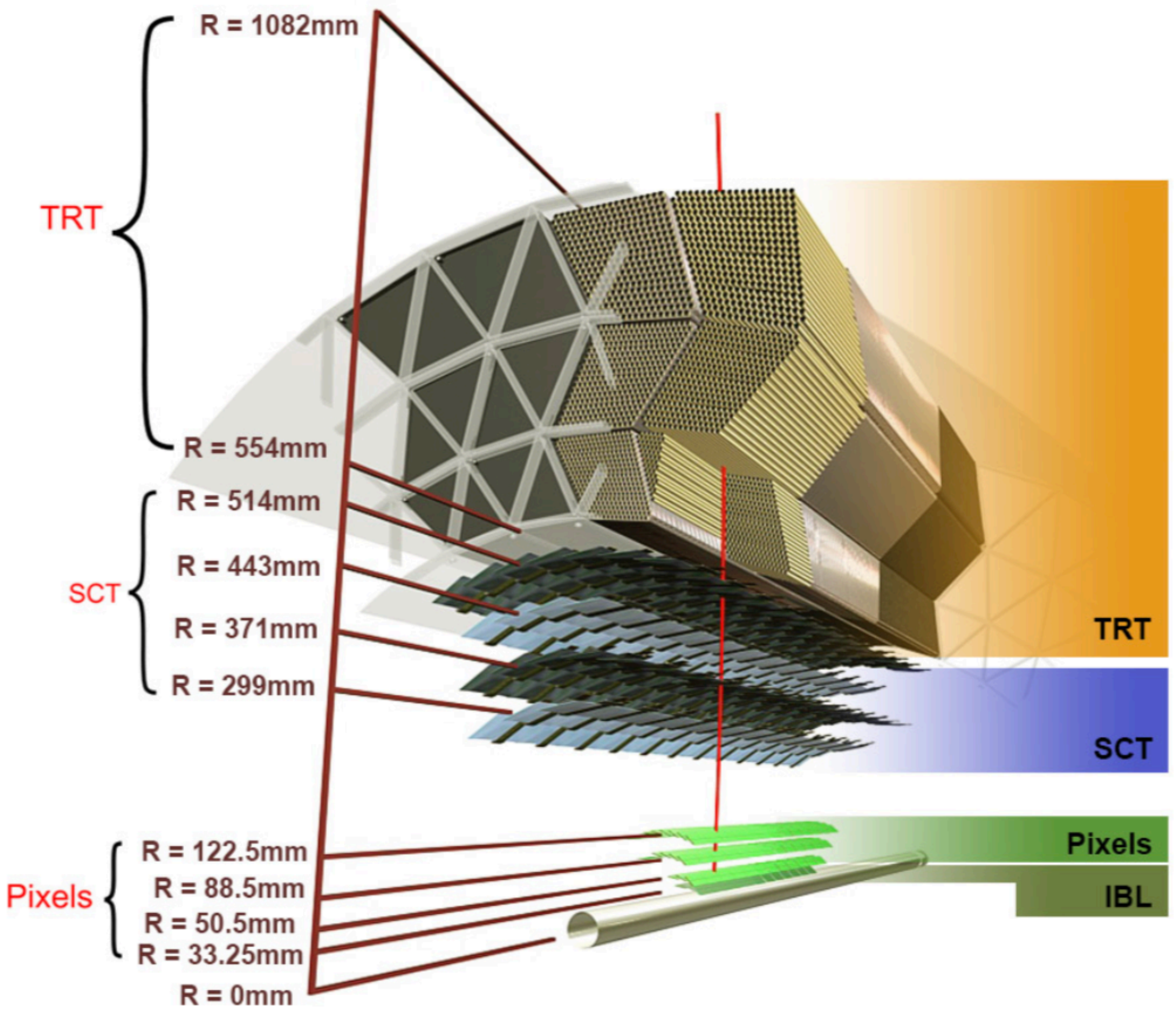
Indirect Searches

Looking for SM decay products of LLPs

Images from arxiv1810.12602

Indirect Searches for long-lived particles

ATLAS Inner Detector



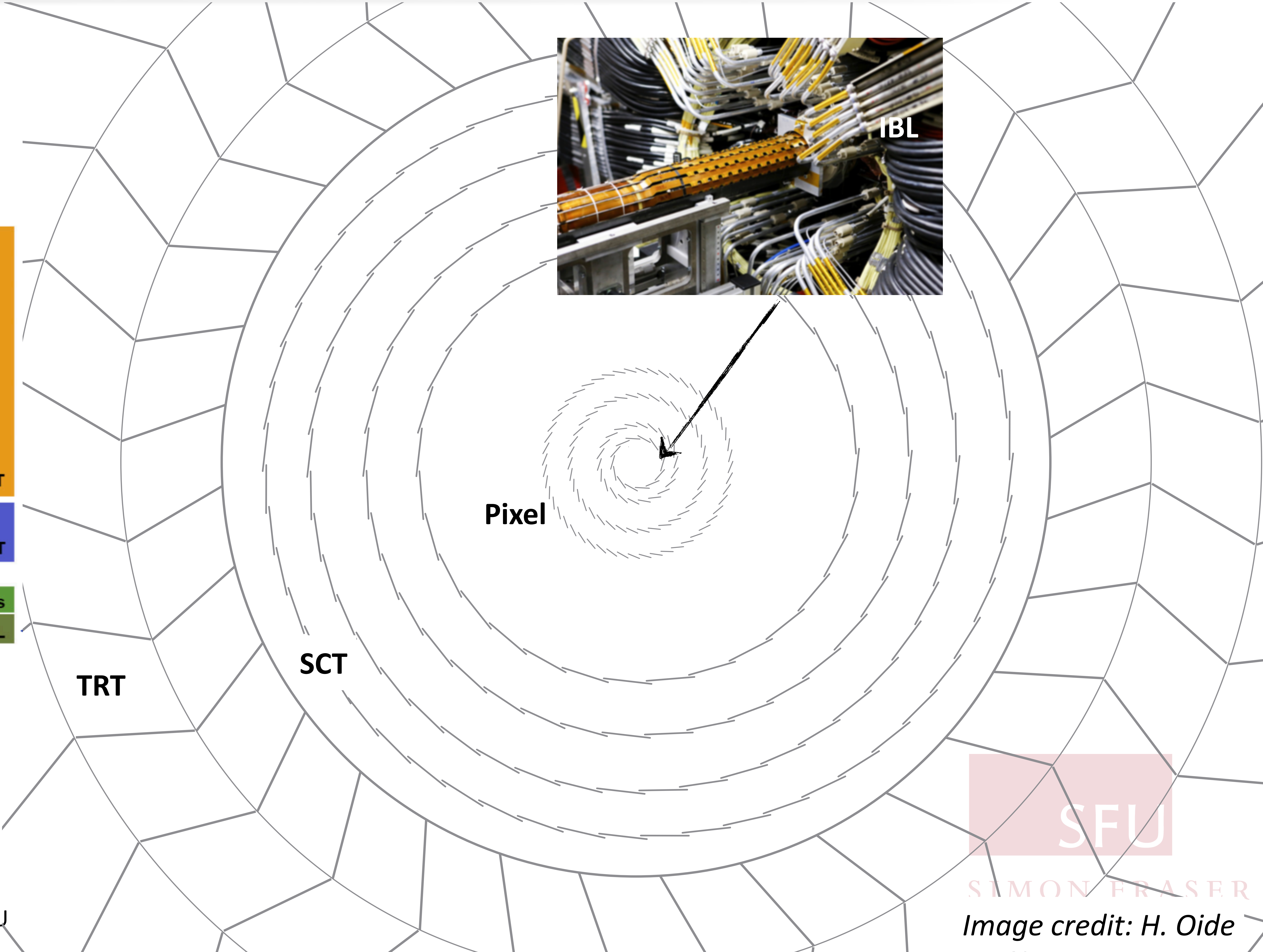
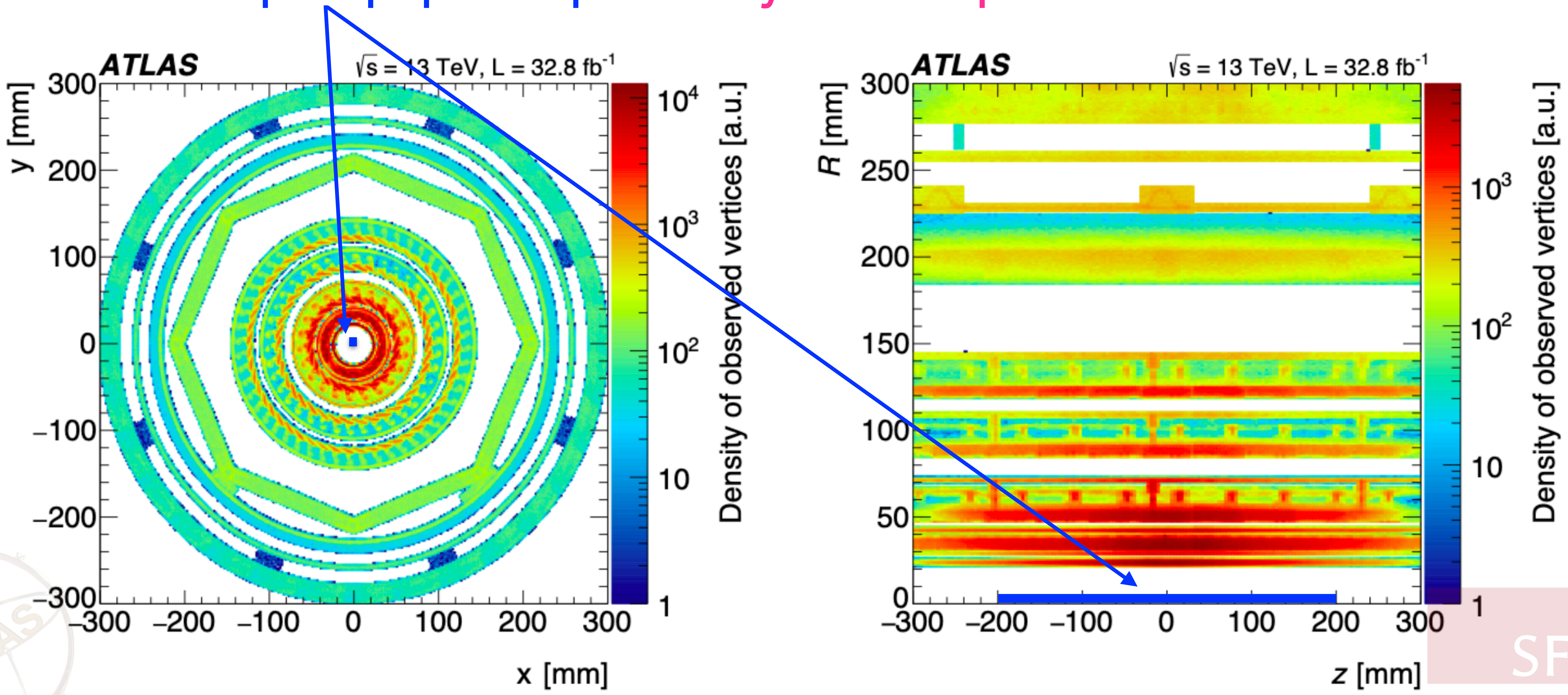


Image credit: H. Oide

Why LLP searches use non-standard reconstructions?

If you want to reconstruct a charged particle with Impact Parameters **(d_0,z_0)** outside the **prompt phase-space** —> **you need special reconstruction**



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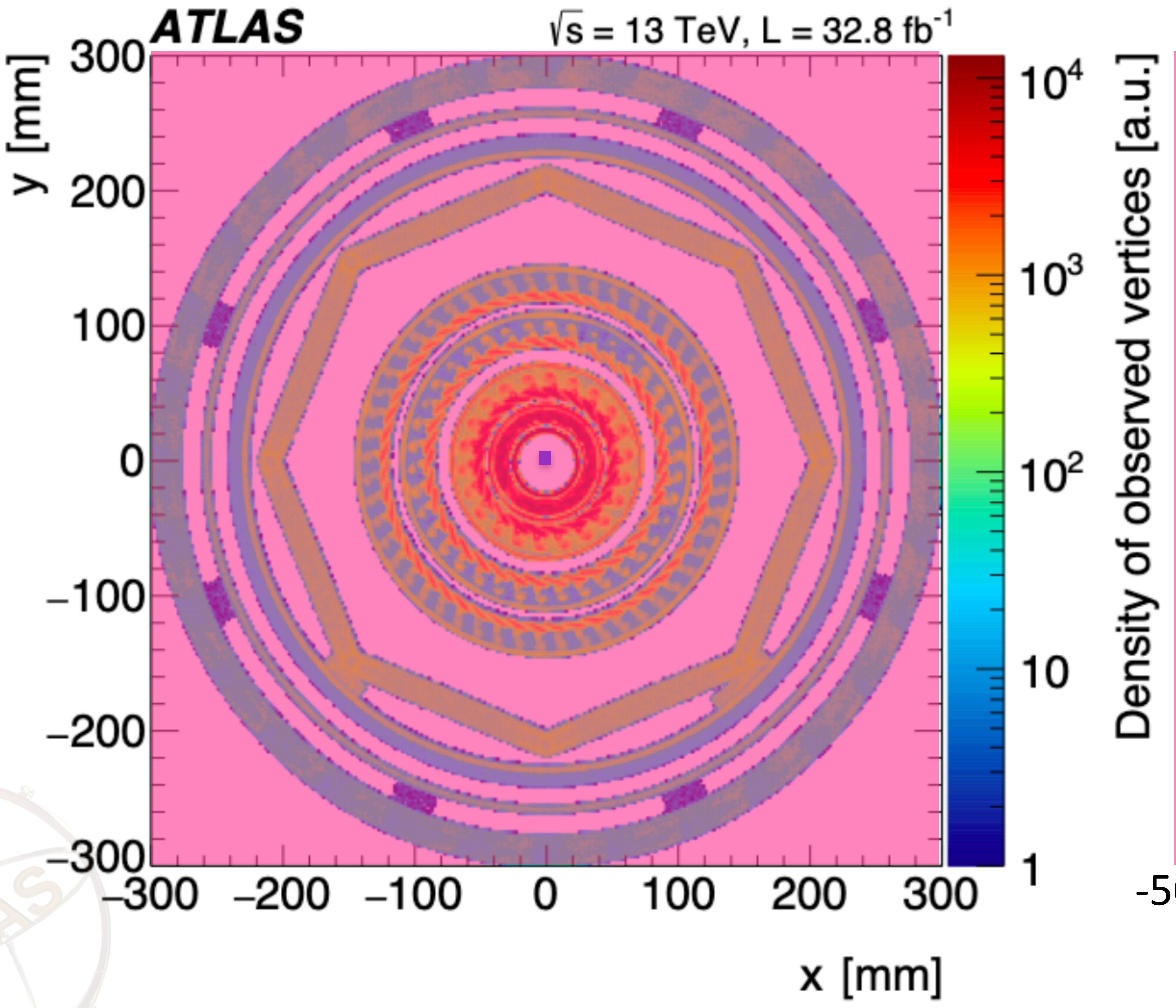
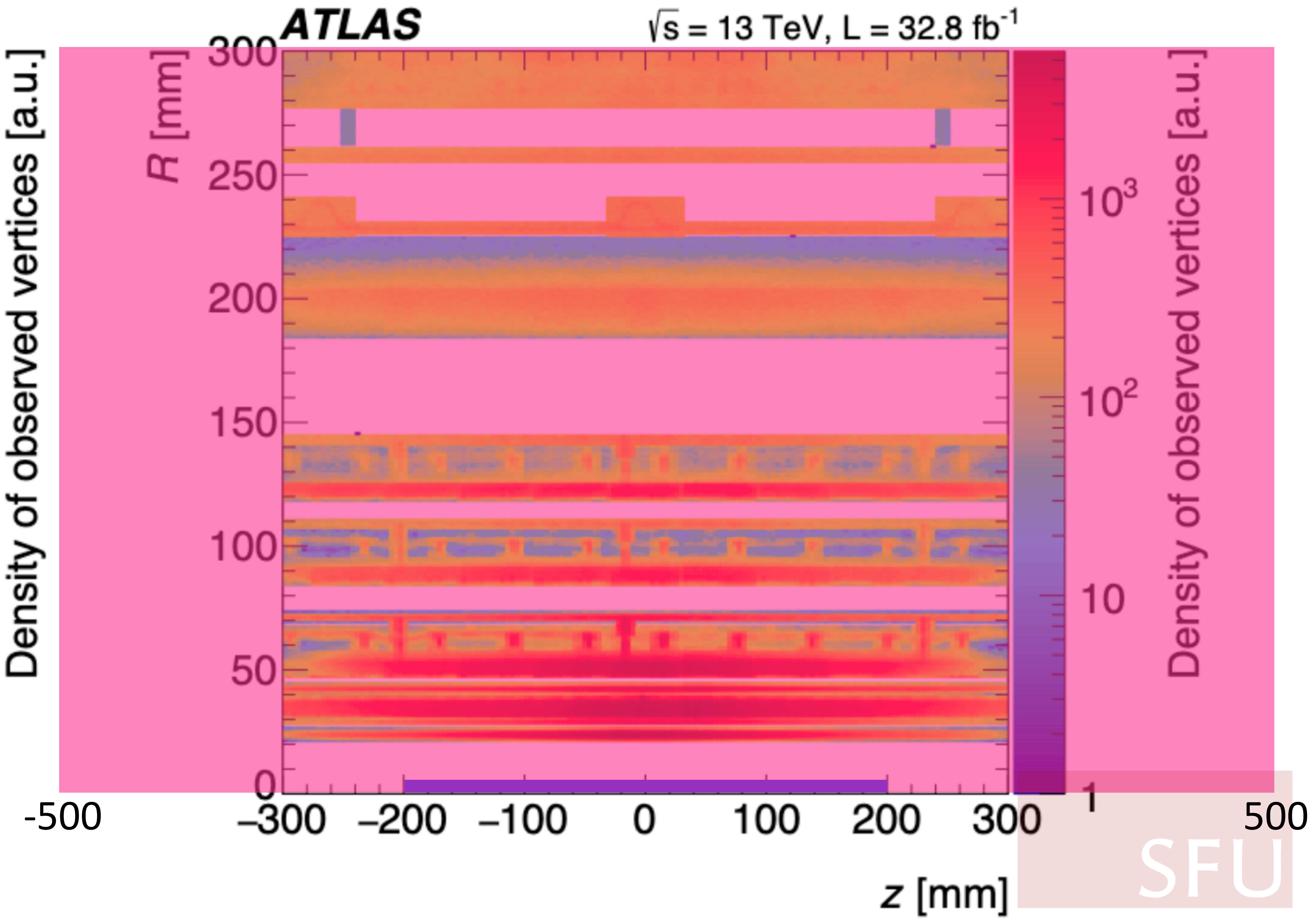
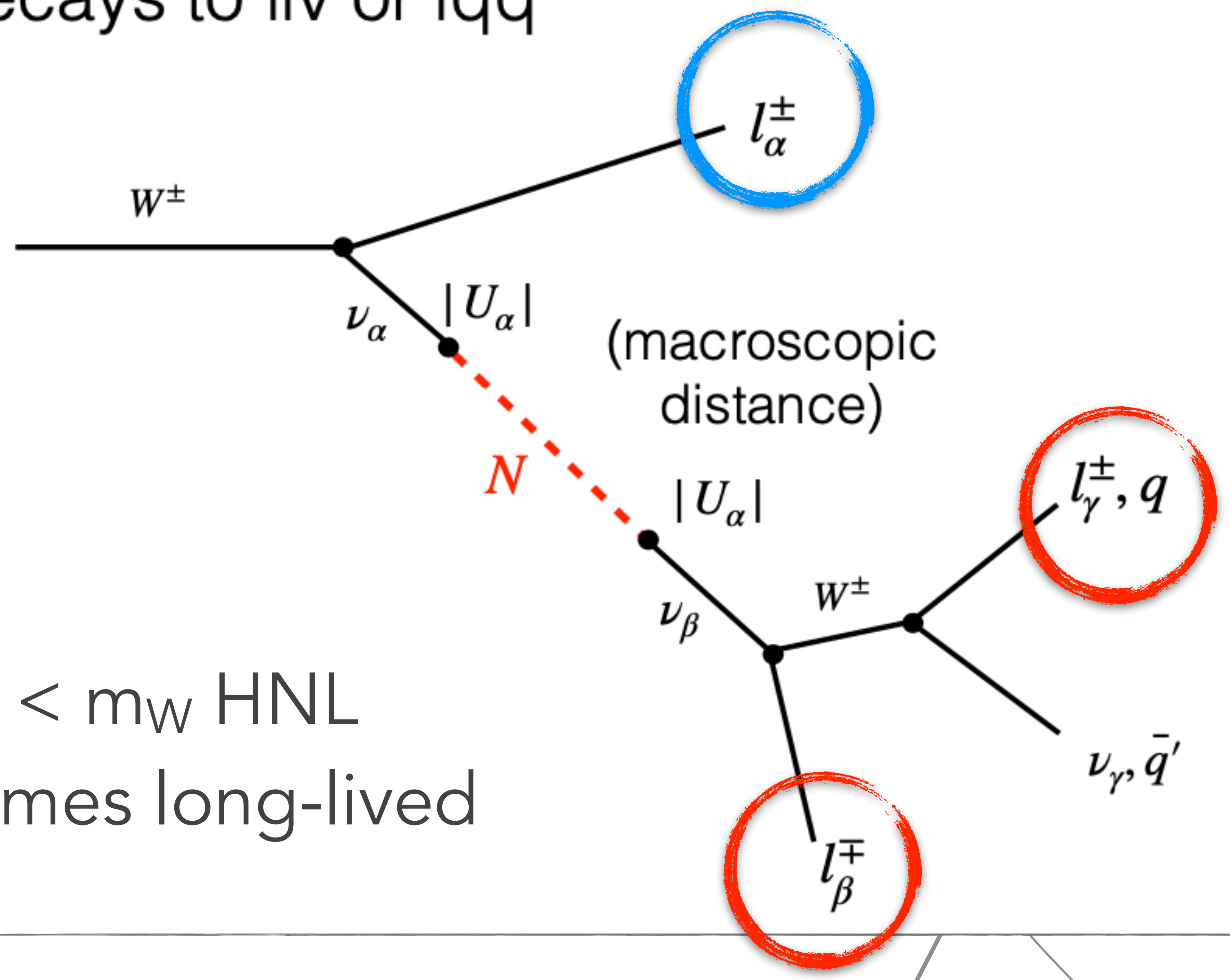




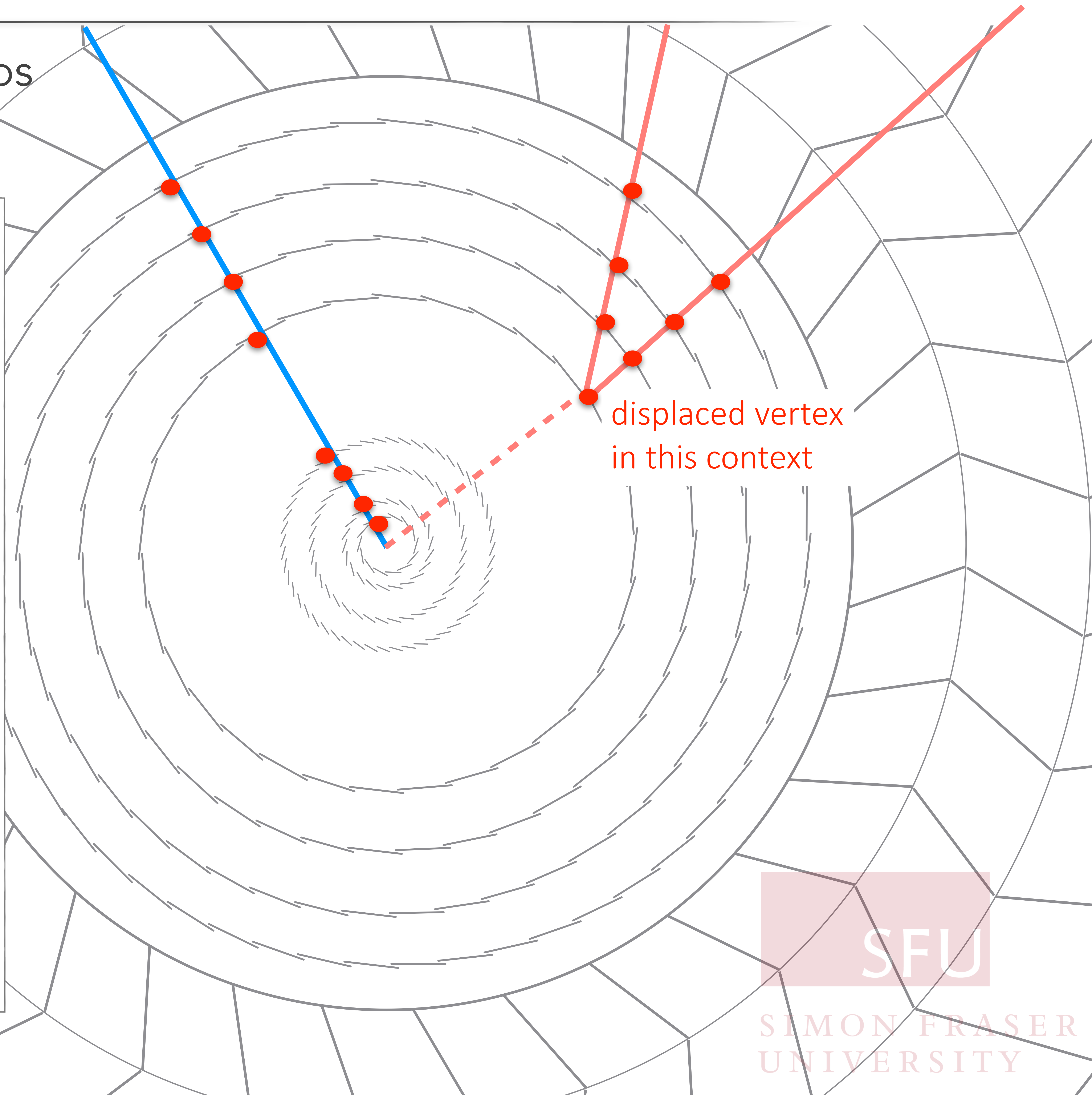
Heavy Neutral Leptons a.k.a Sterile Neutrinos

Electrically neutral particle, mixing with SM neutrinos
⇒ HNL can decay to SM particles

- Study **on-shell W boson decays** to prompt leptons
- HNL decays to llν or lqq'

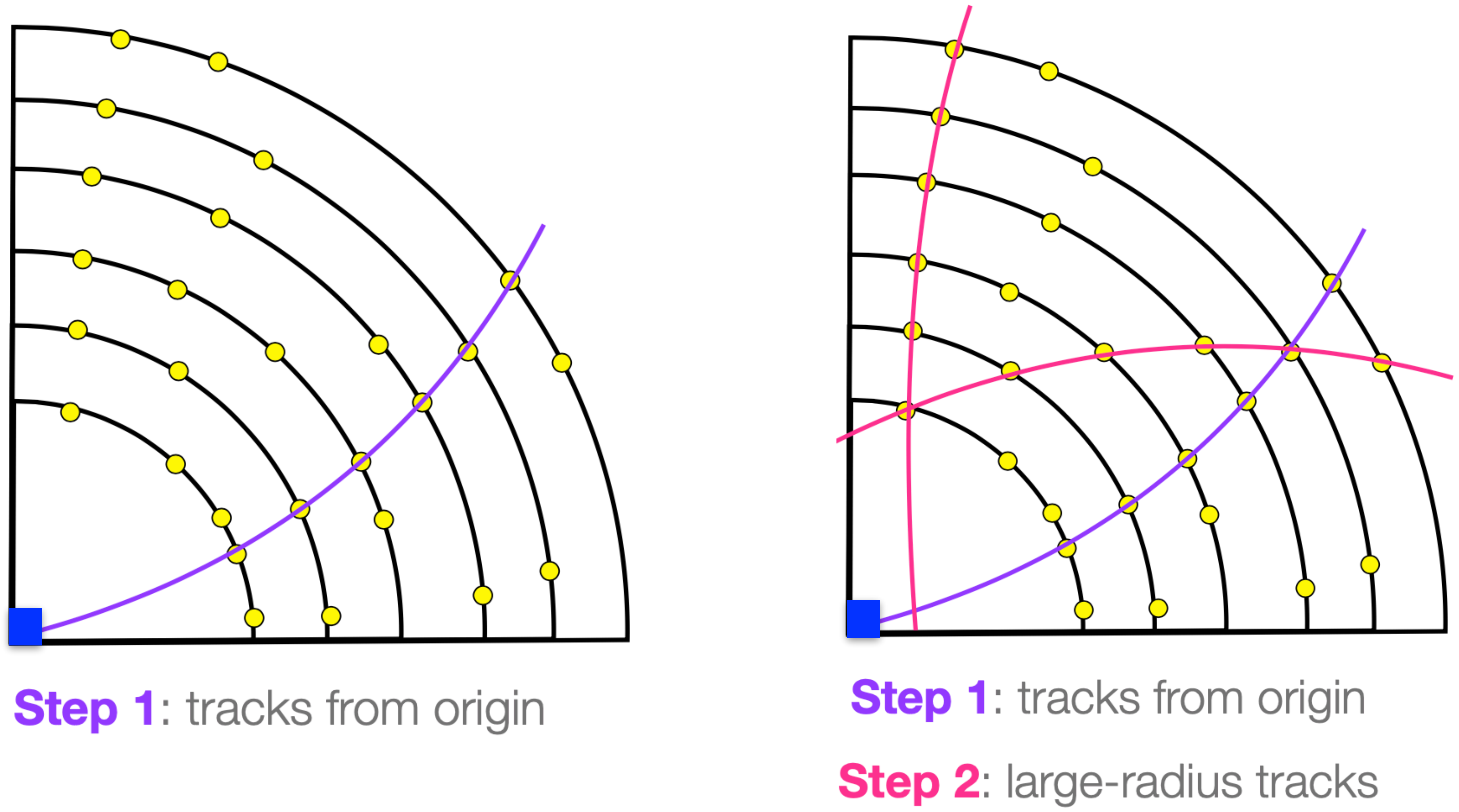


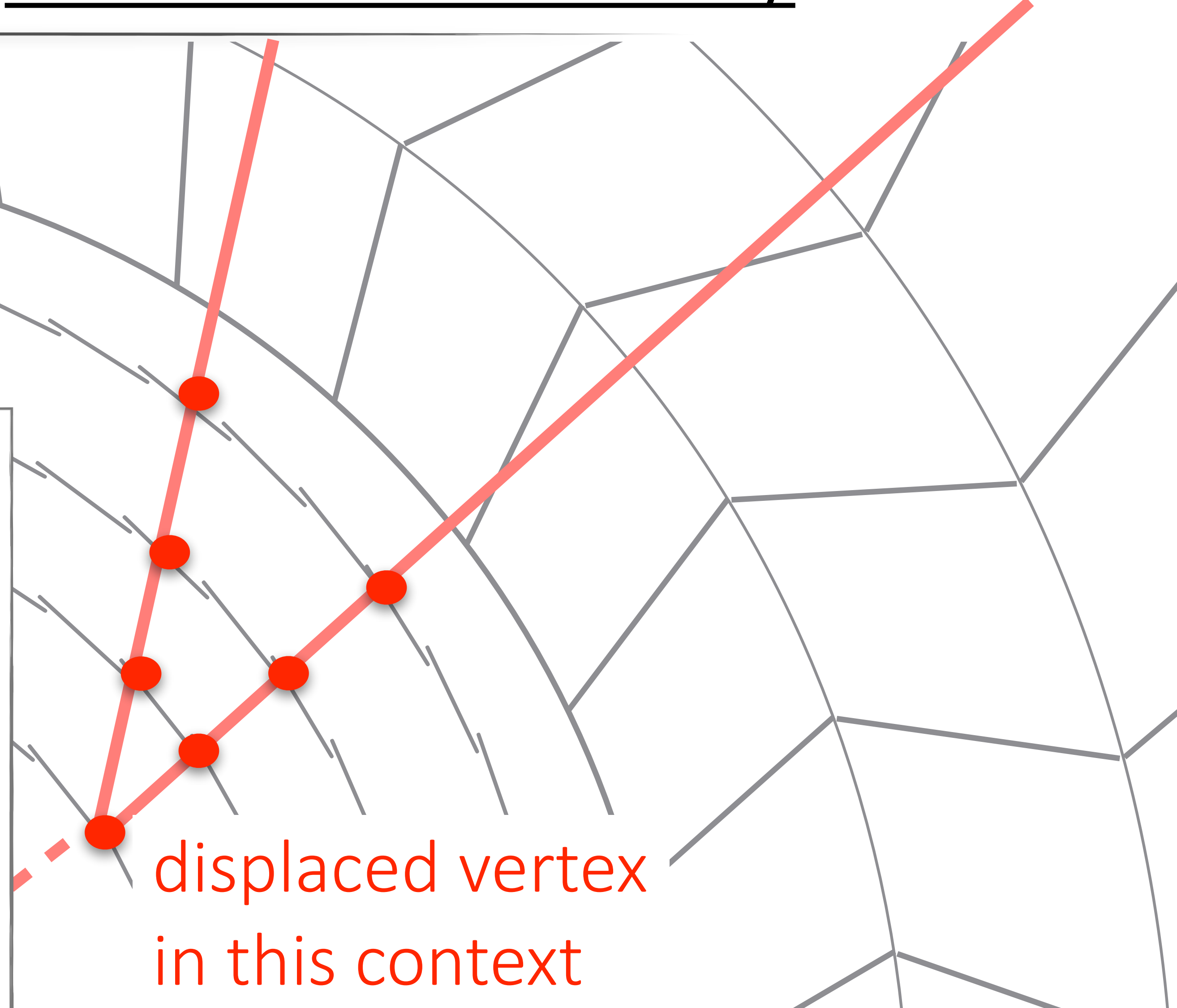
- $m_{HNL} < m_W$ HNL becomes long-lived



Large Radius Tracking

ATL-PHYS-PUB-2017-014/





- Default tracking on ATLAS turns off at $d_0 > 10$mm
- Computationally expensive; only available for 10% of data

Large Radius Tracking

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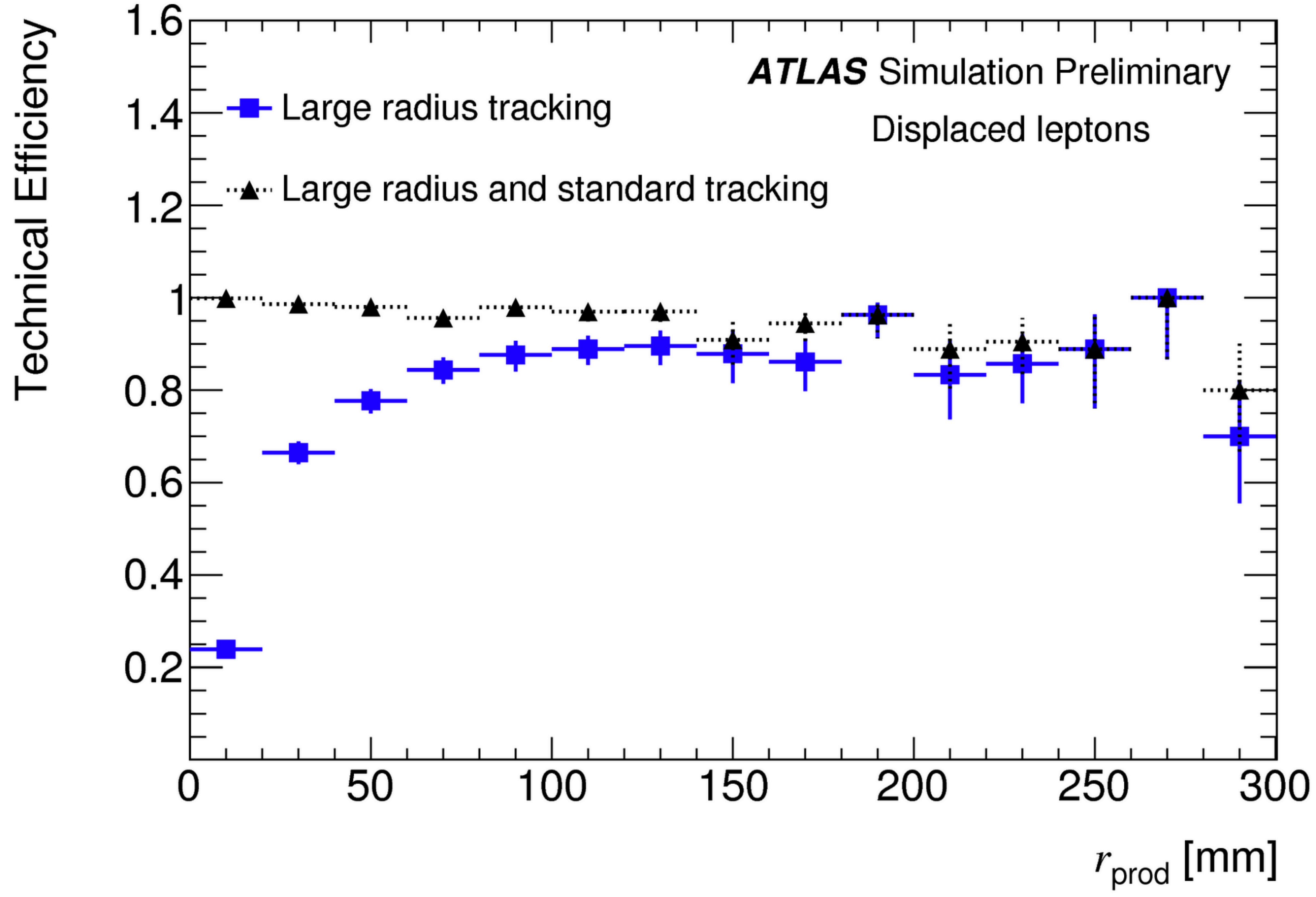

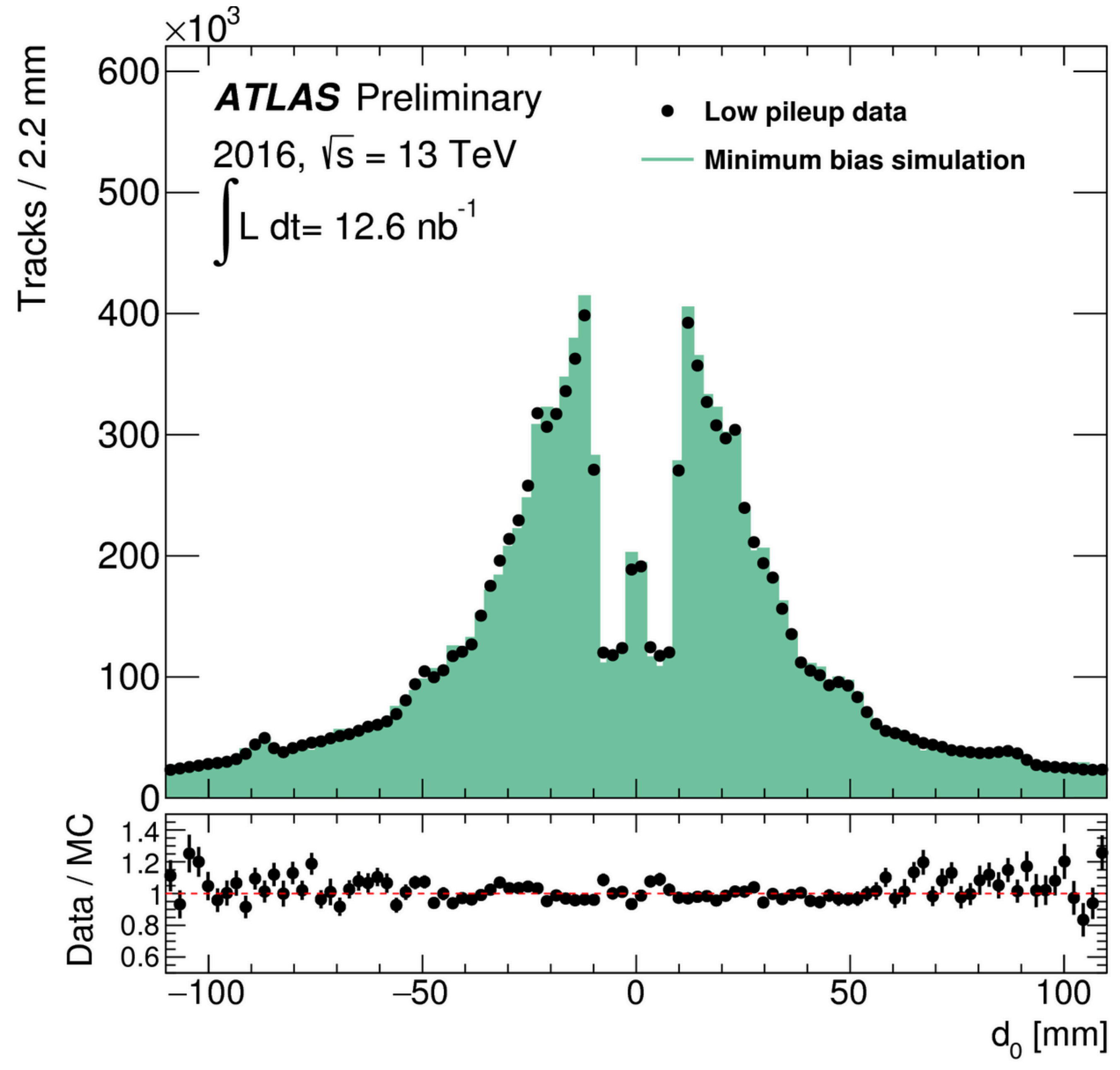

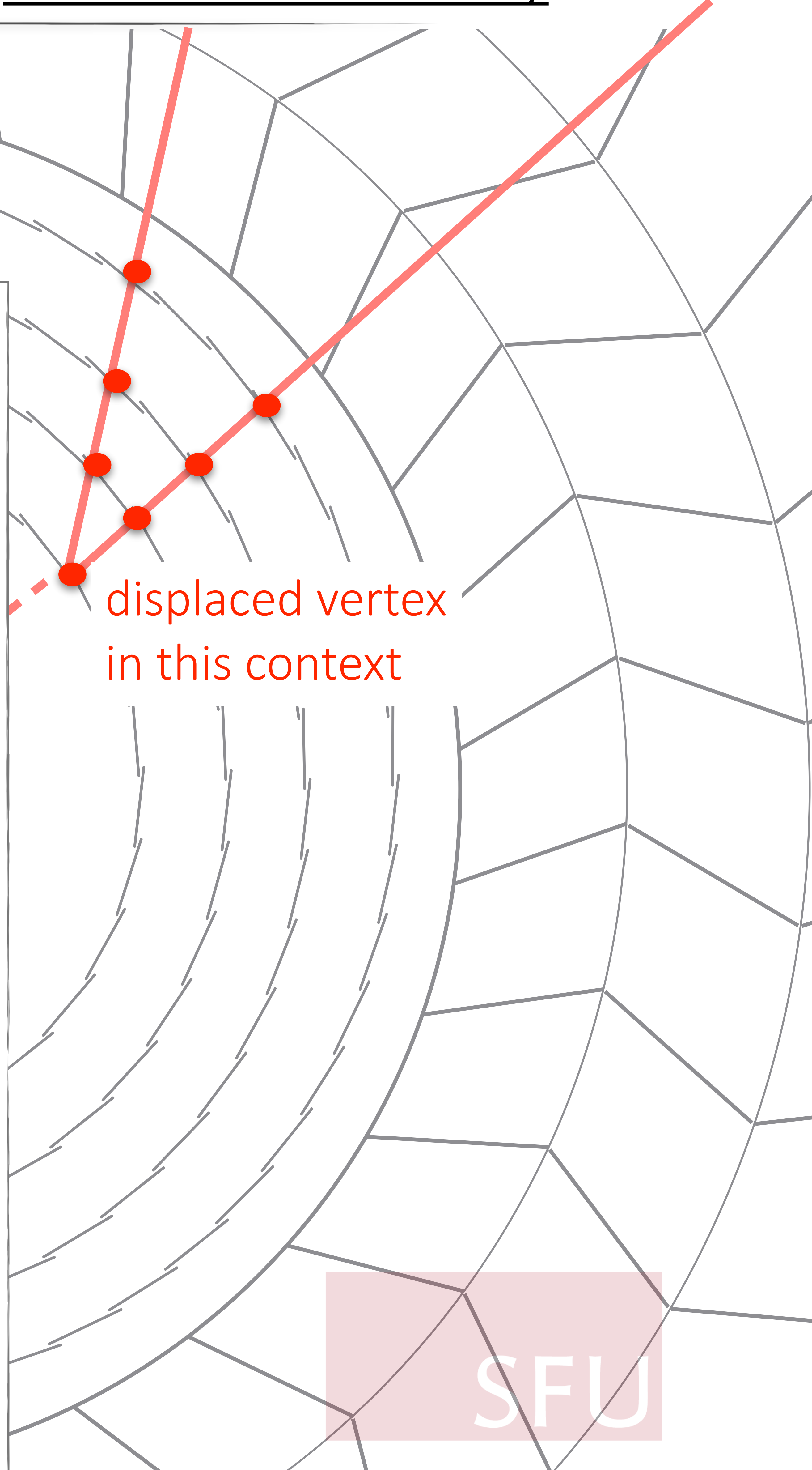

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Displaced Vertexing

ATL-PHYS-PUB-2019-013

We use these tracks (and standard tracks) to form displaced vertices

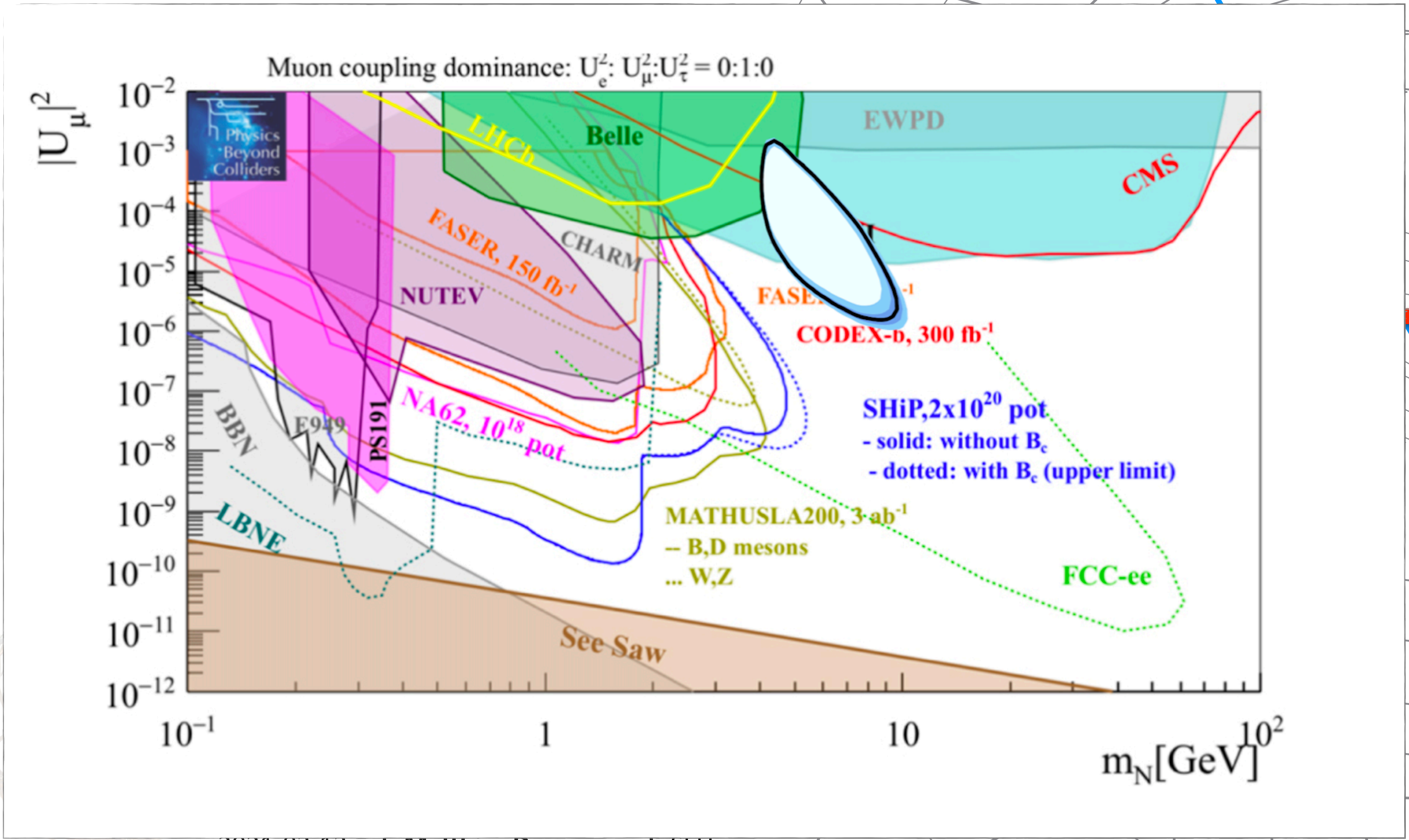
HNL search — Background estimated from same-sign 2-trk DVs

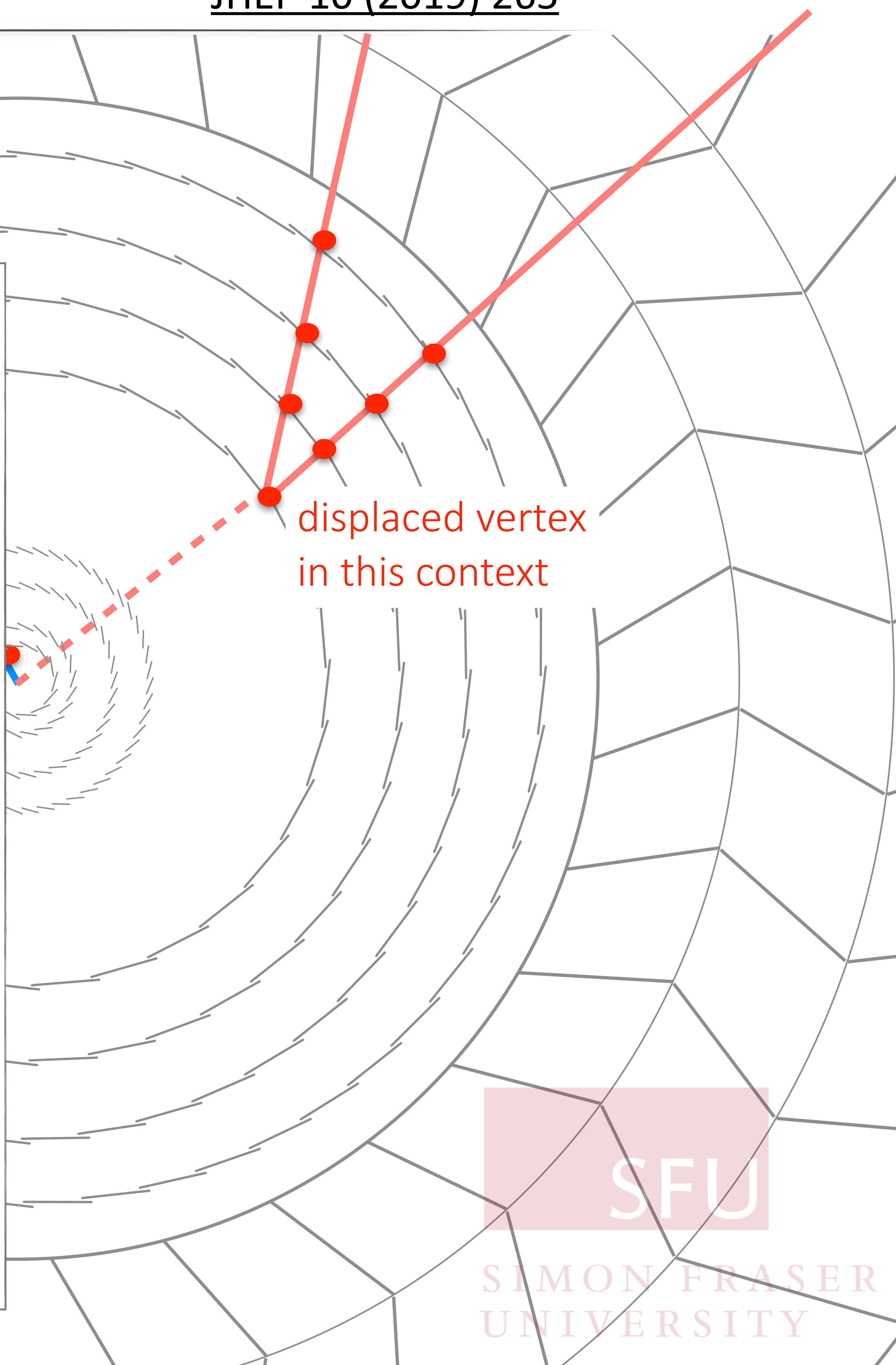
- Accidental tracks crossing events & Cosmics
- Less dominant are hadronic interactions in the material (leptons)

Heavy Neutral Leptons a.k.a Sterile Neutrinos

JHEP 10 (2019) 265

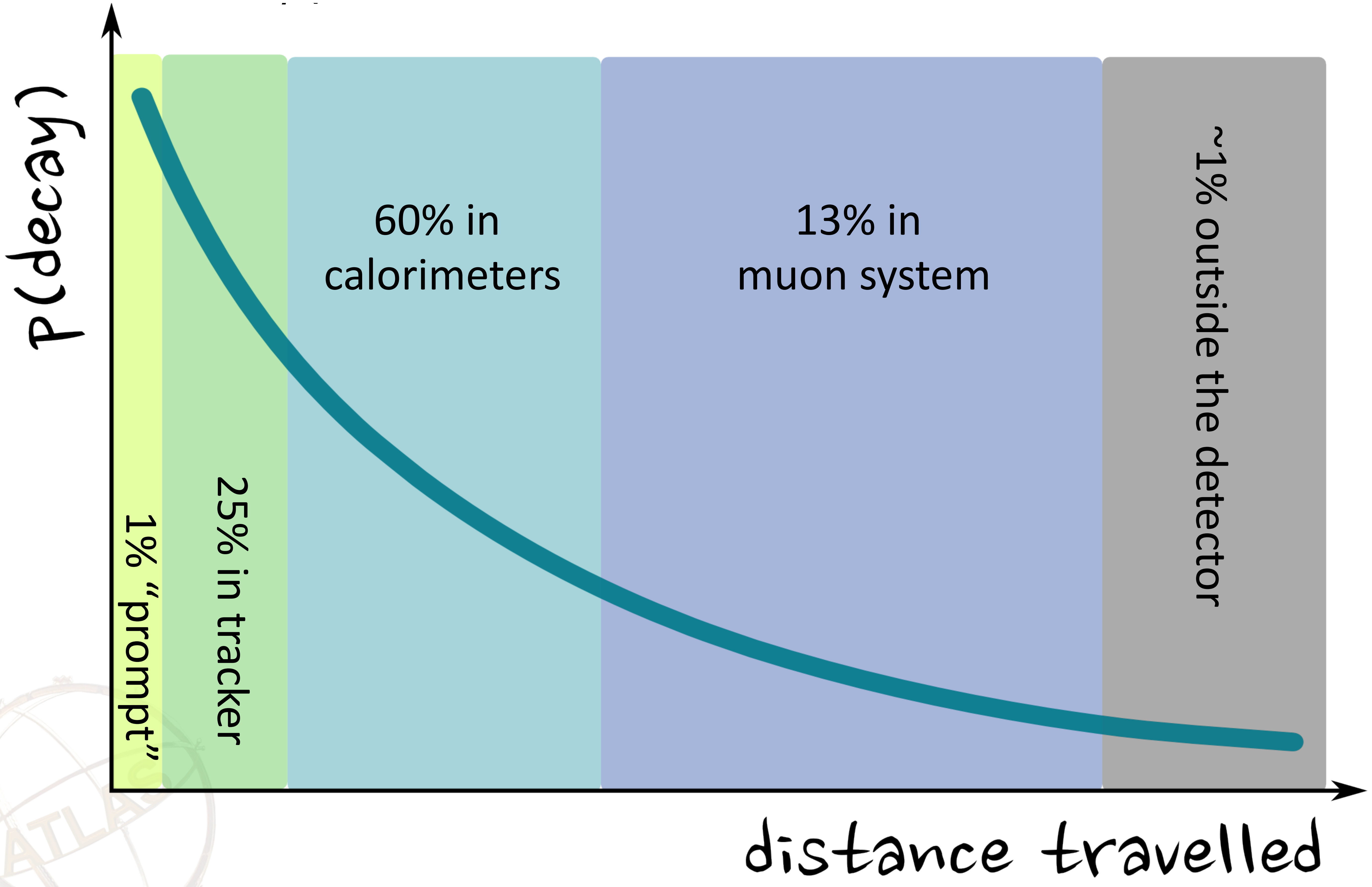
Unique sensitivity to HNL coupling strength in relatively low-mass region

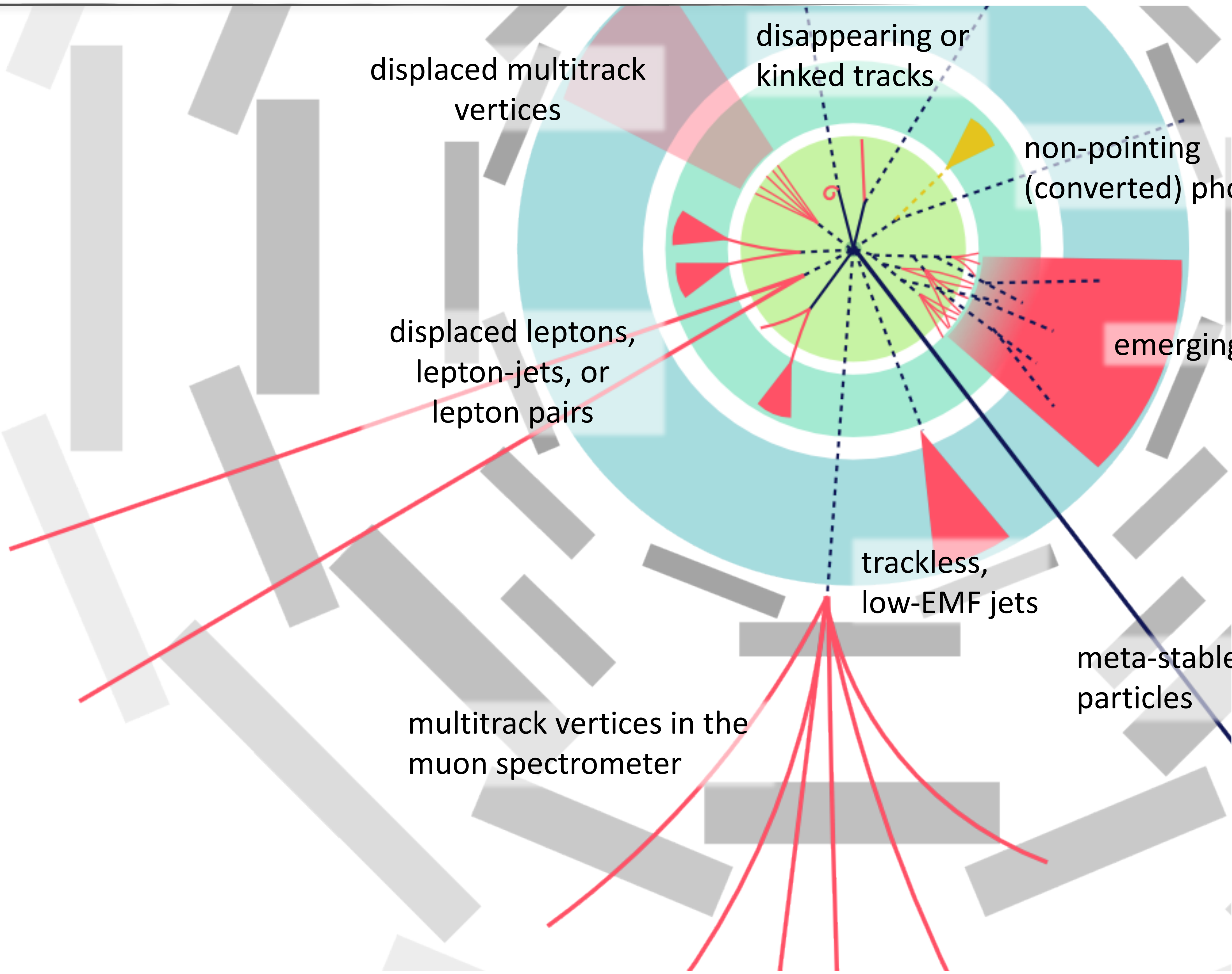




Different detector systems — Different LLPs

e.g. for $<c\tau>$ = 5 cm, $<\beta\gamma>$ ~ 30





Images from H. Russel

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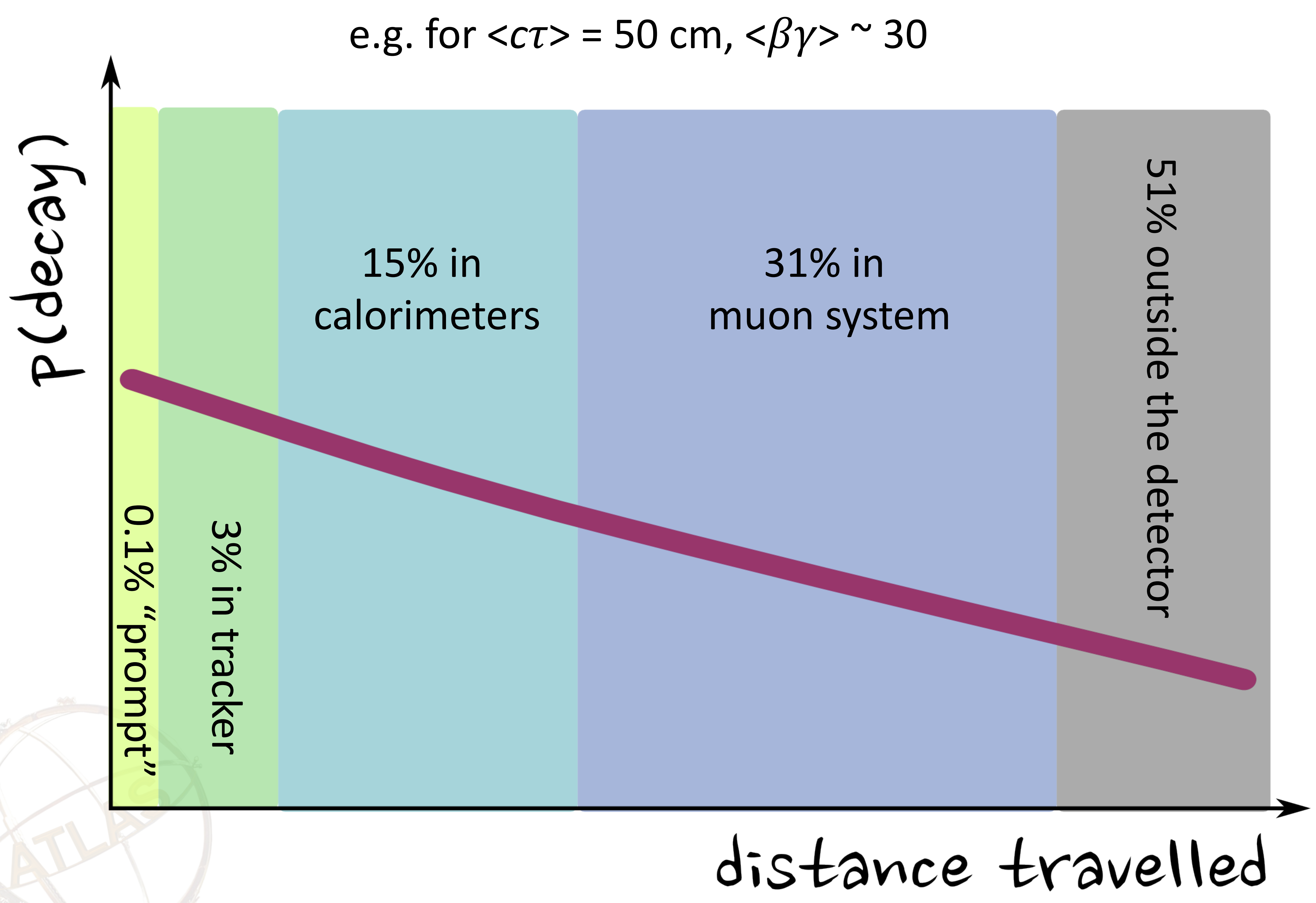
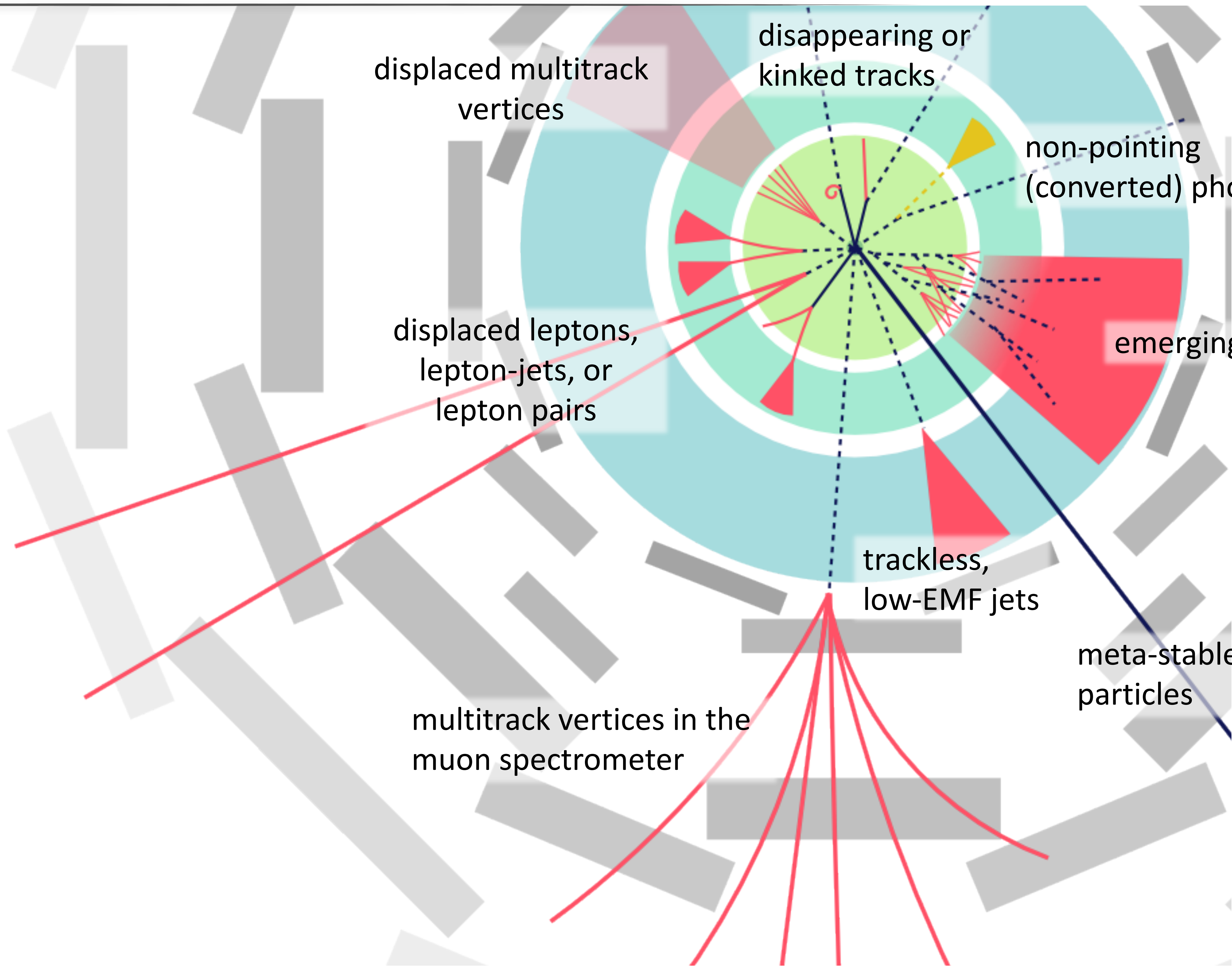
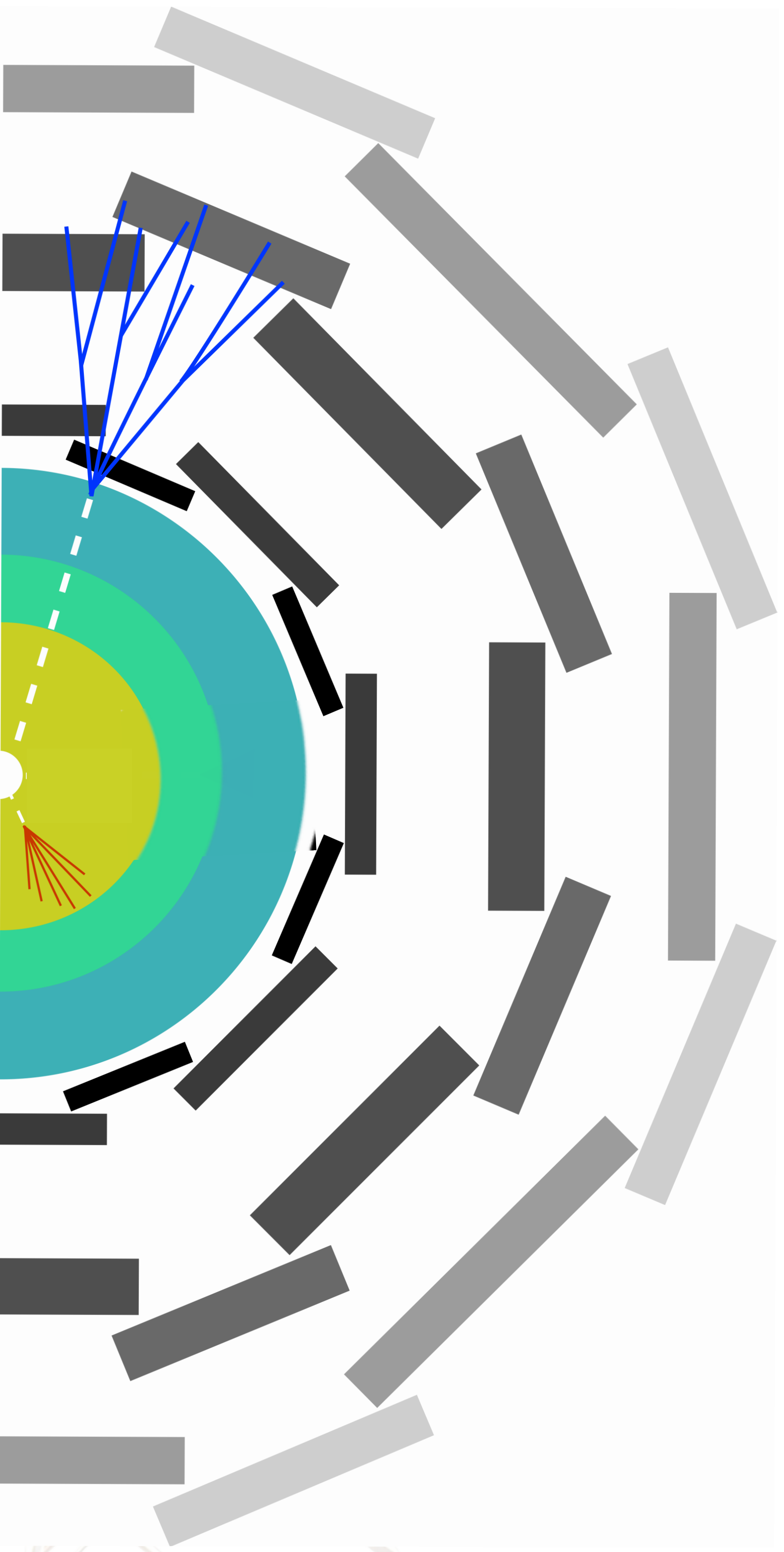
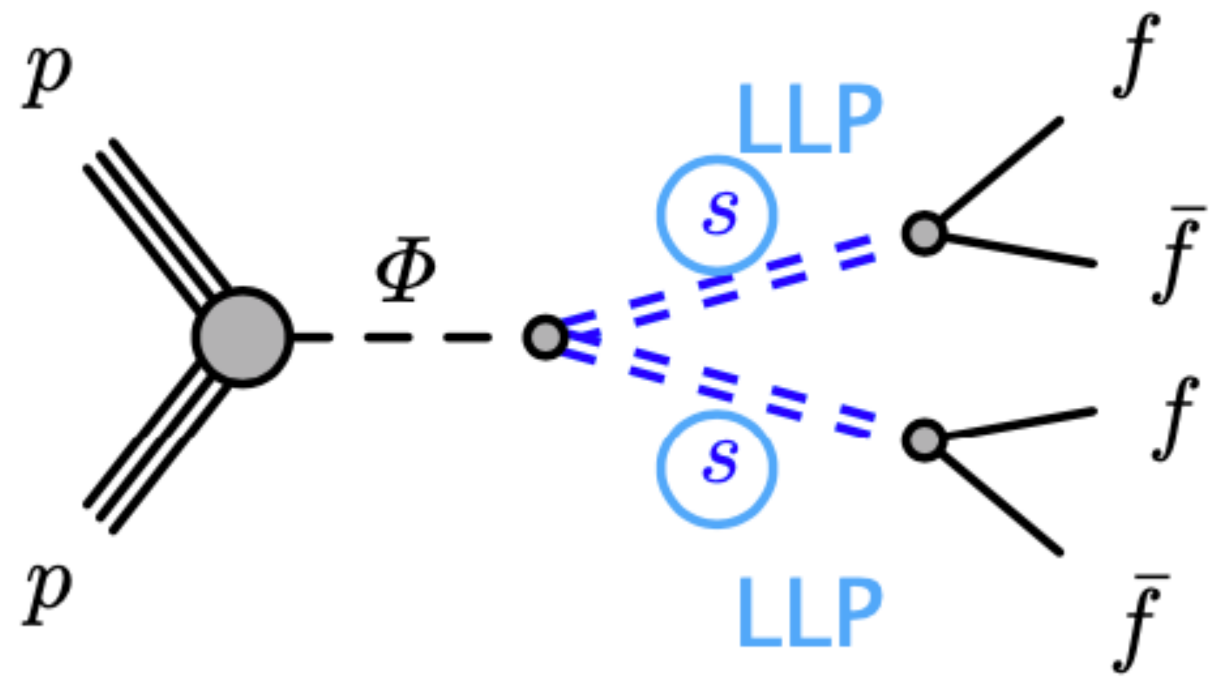


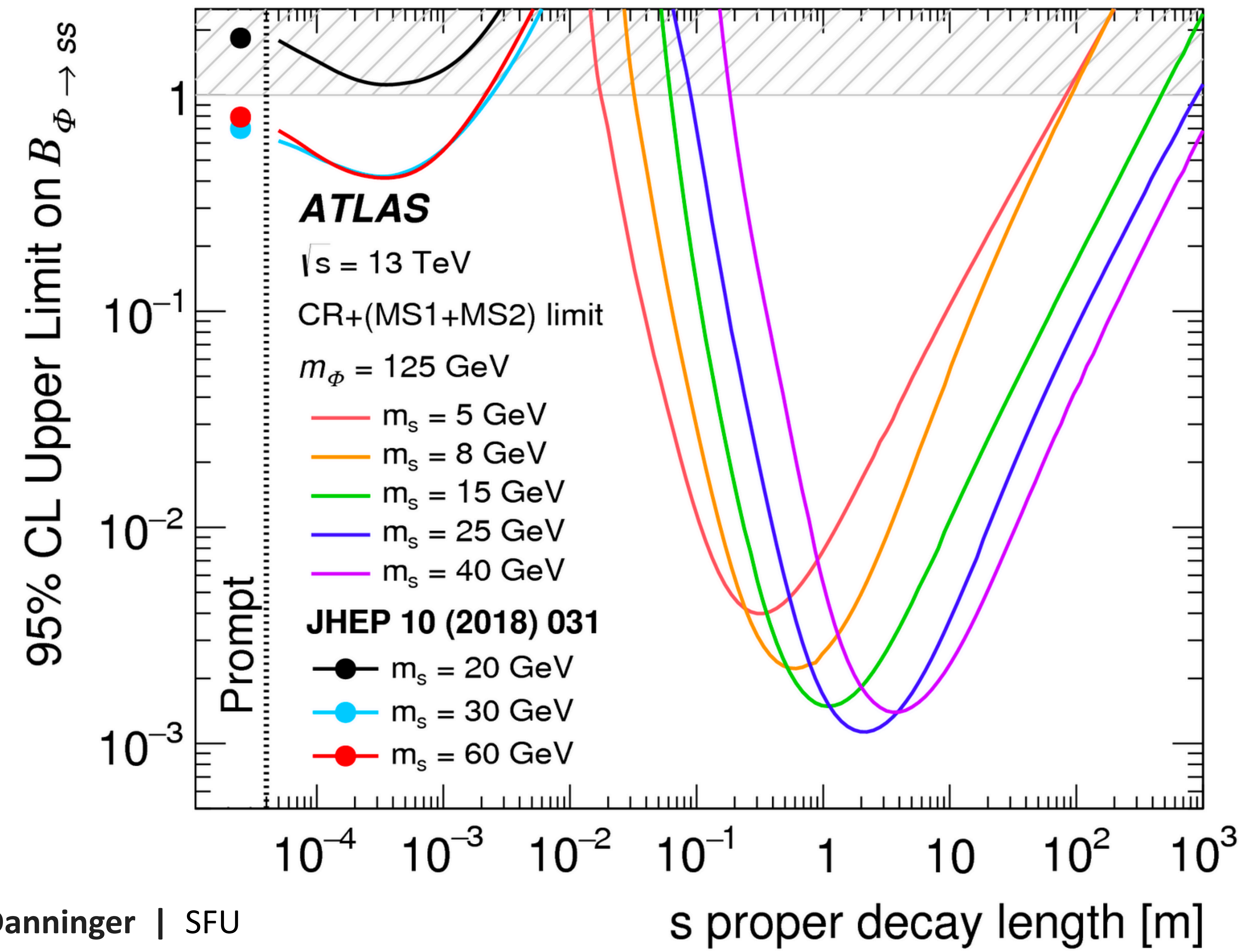


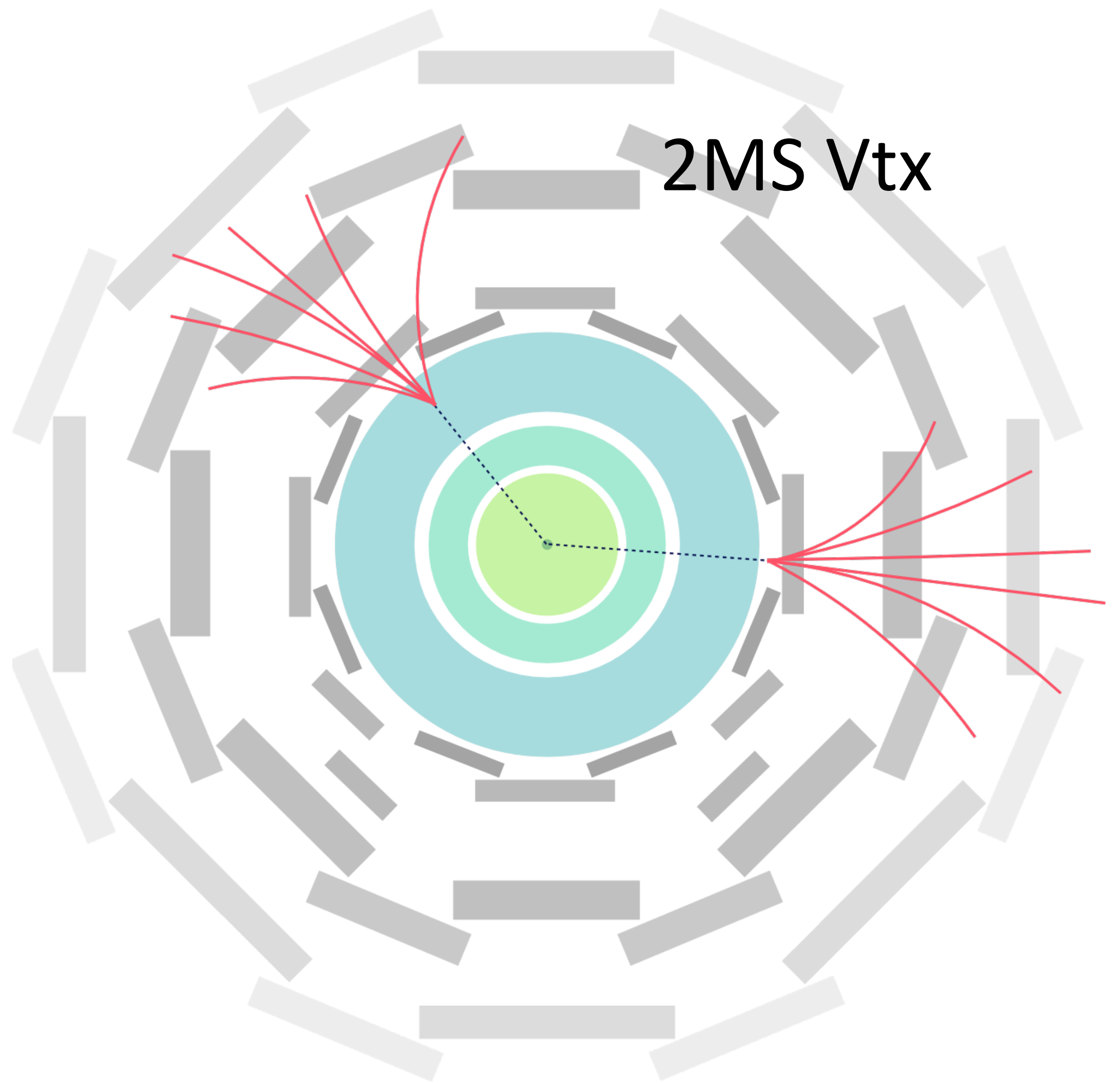
Images from H. Russel

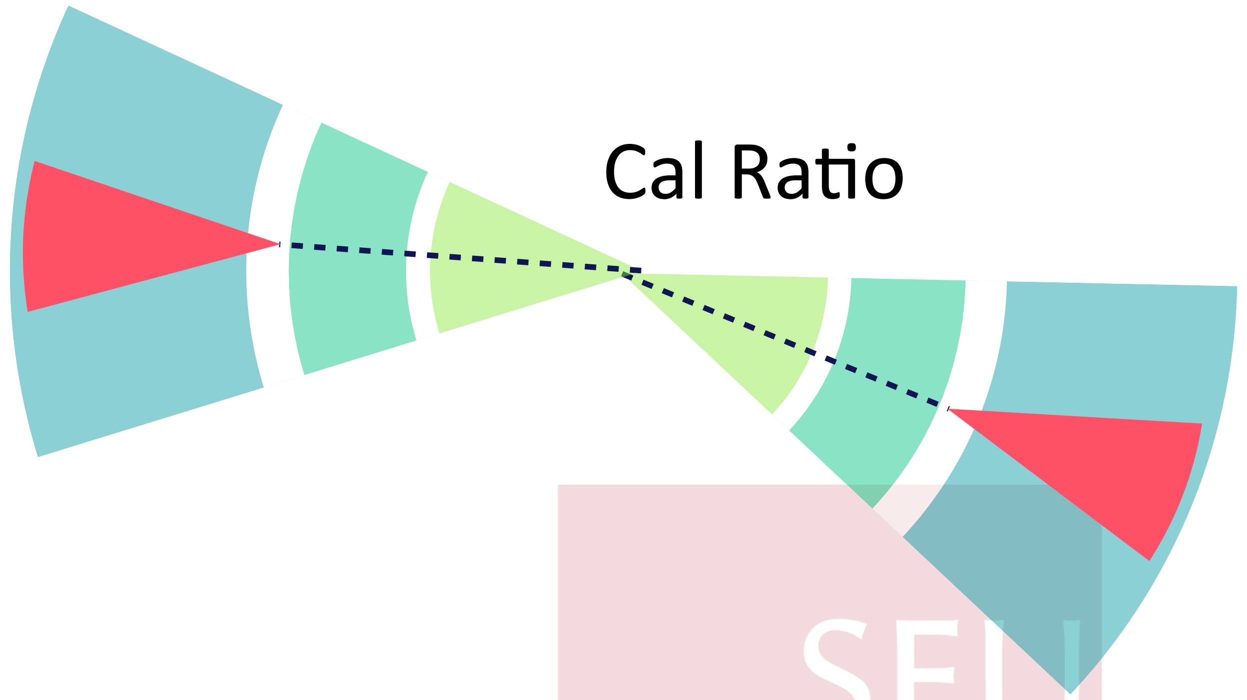
Is the Higgs the connection to the Hidden Sector?



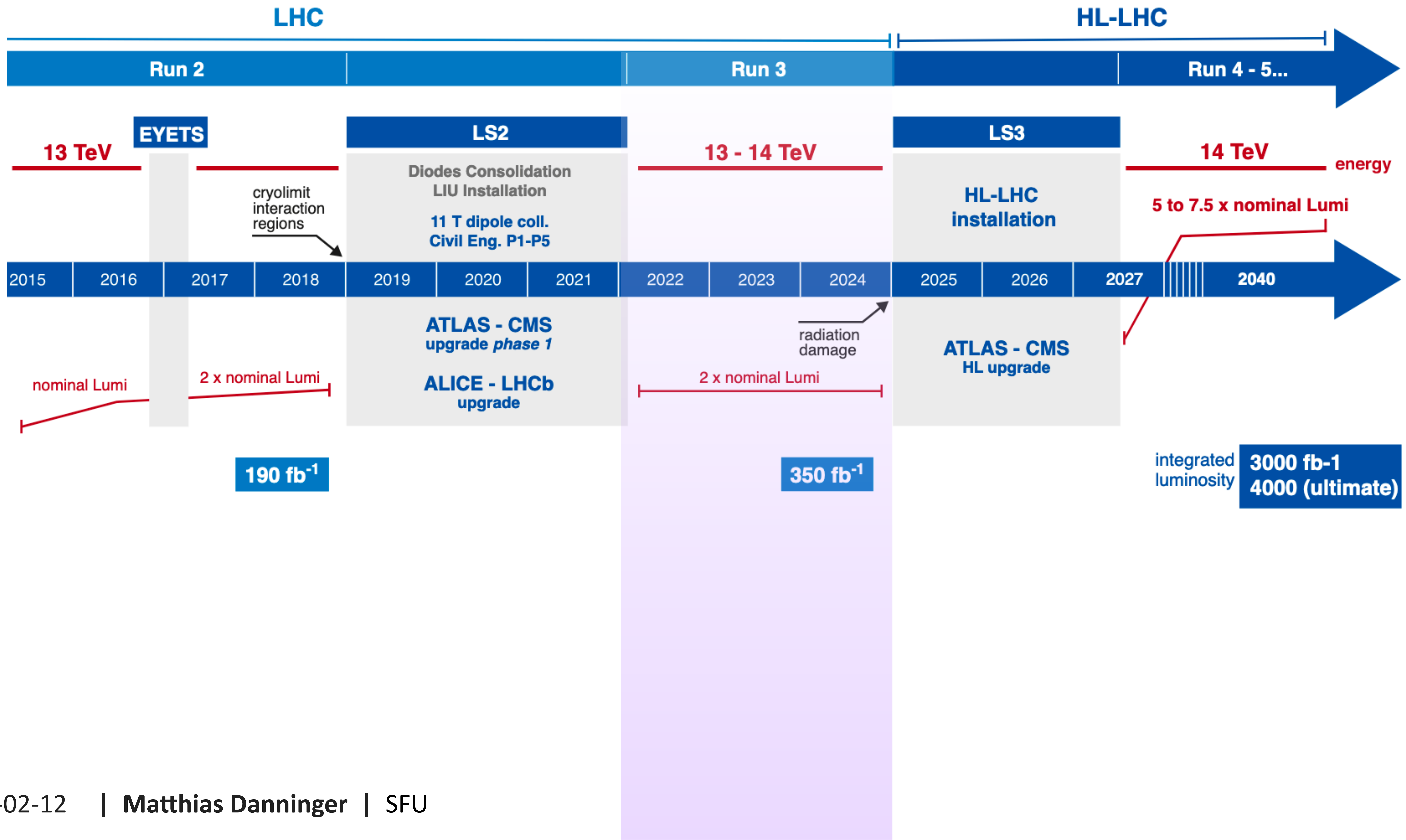








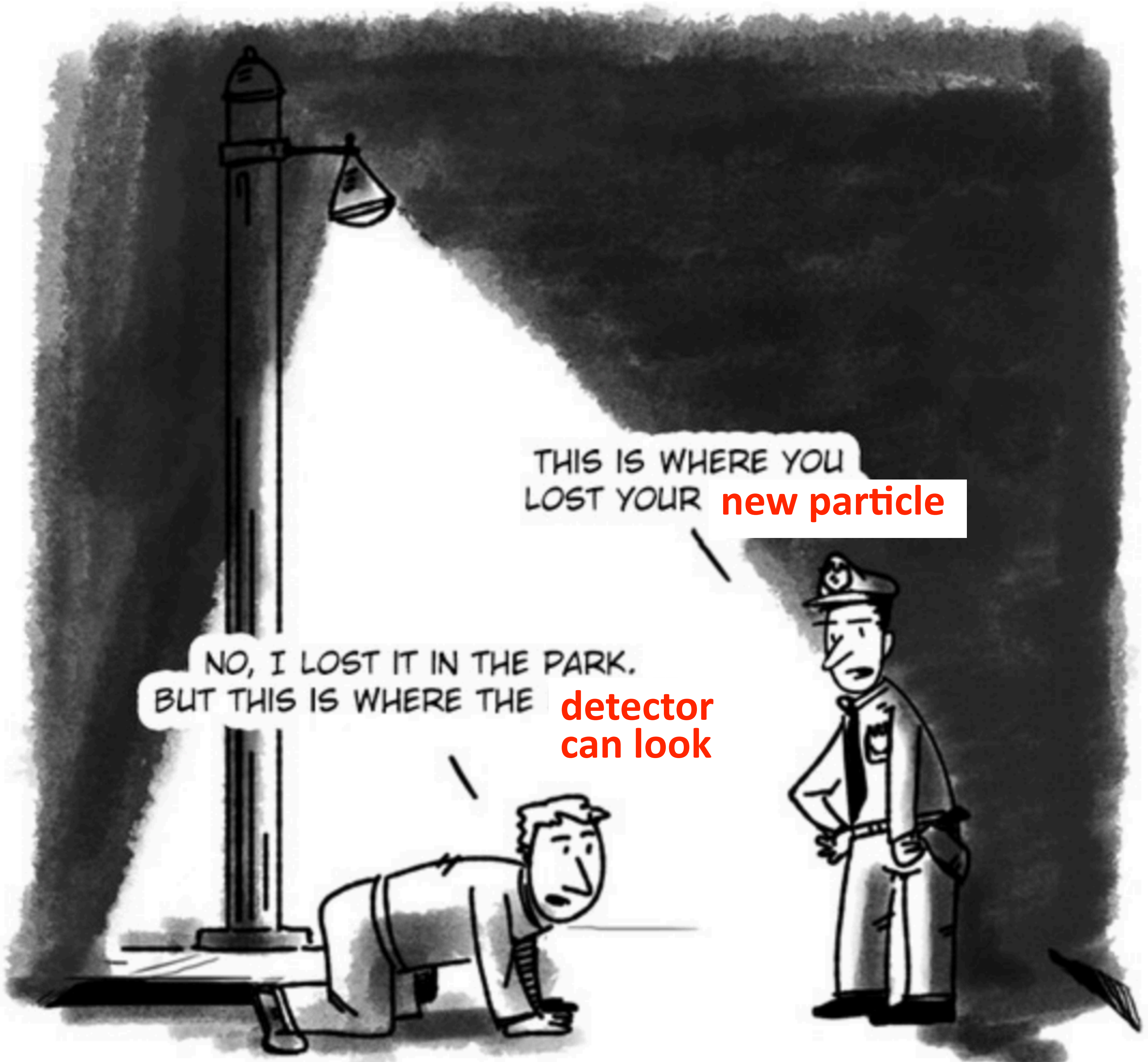
So, why do I get excited about LLP searches in LHC Run 3 with ATLAS?



Long-lived particles (LLP)

- Is new physics out of reach for the LHC?
- Have we looked in the wrong place so far?

- LLPs is one promising direction to expand our searches
- Not a very mature field yet @ LHC
  —> Still plenty of room for creativity
- Theoretically well motivated!



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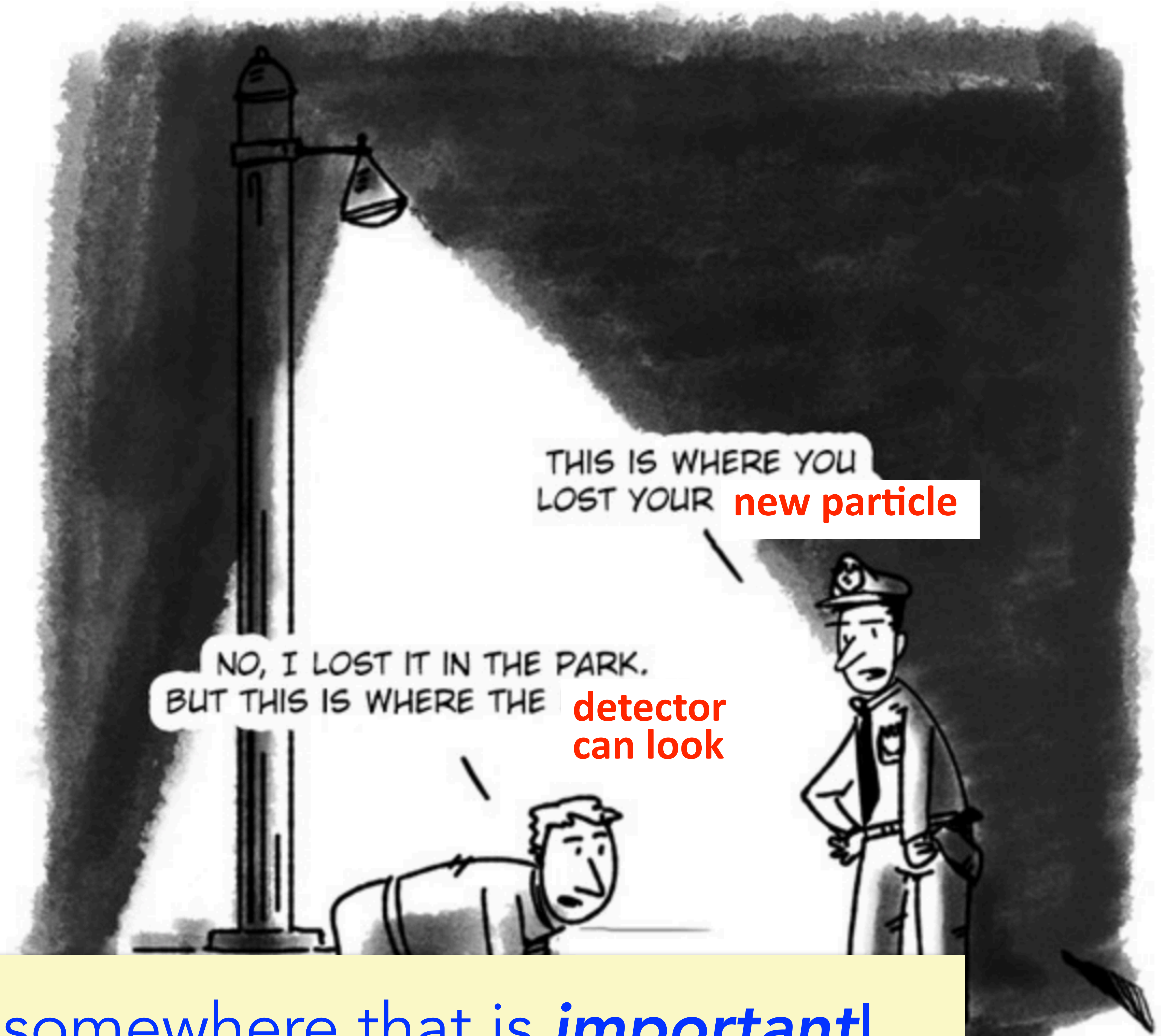

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Search somewhere that is ***important***!

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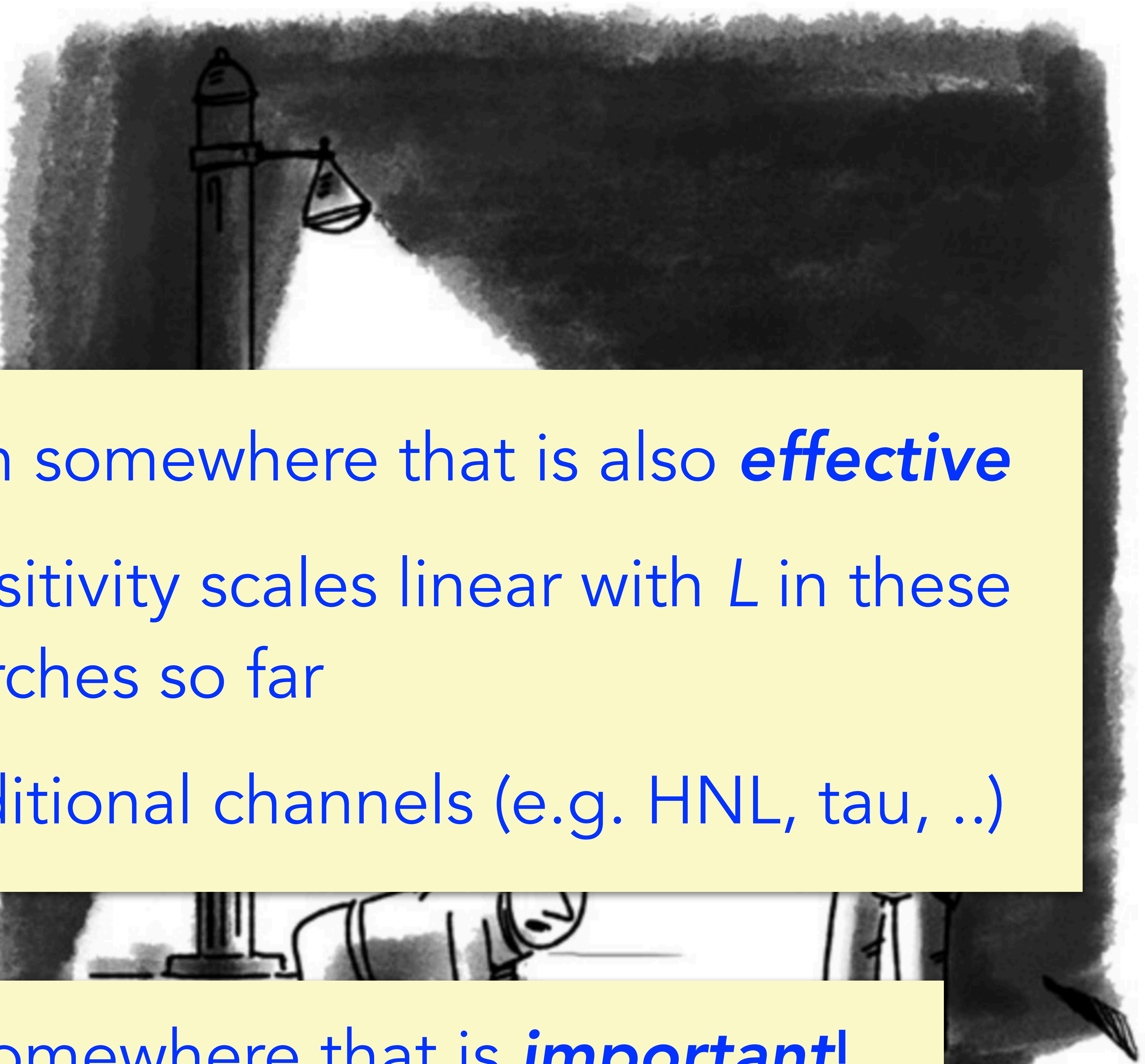

Search somewhere that is also ***effective***

- Sensitivity scales linear with *L* in these searches so far
- Additional channels (e.g. HNL, tau, ..)

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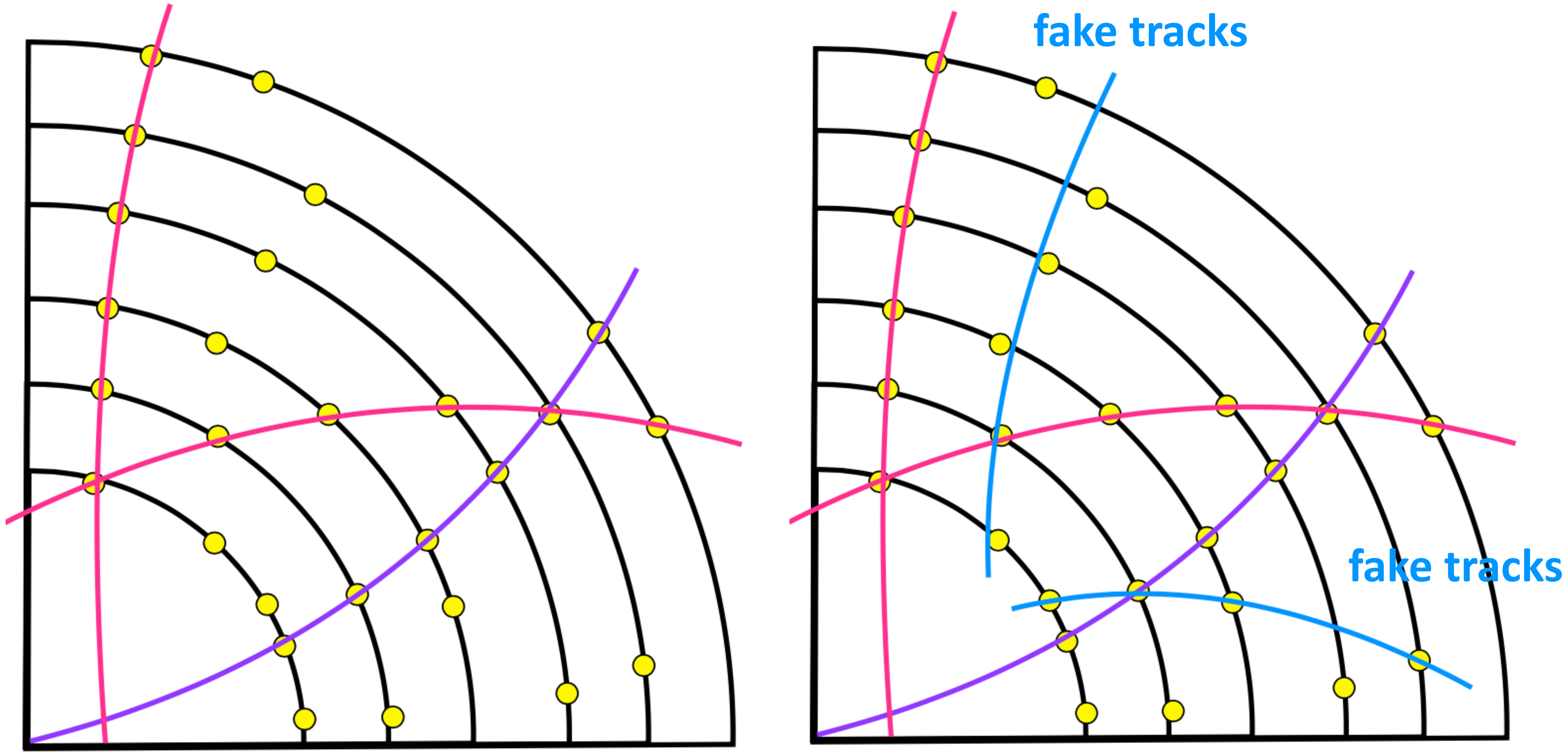
  —> Still plenty of room for creativity
- Theoretically well motivated!

Search somewhere that is ***important***!

Advances in detector performance



Step 1: tracks from origin

Step 2: large-radius tracks

Step 1: tracks from origin

Step 2: large-radius tracks

- Large-Radius Tracking so far very resource intensive and produces ~80% ***fake tracks***
- Only available on 10% of data in Run 2
- Improvements ahead of Run 3
  —> Significant speed up
  —> Significant fake reduction
- LLP becoming mainstream!!

Conclusions

- LLP searches are an exciting challenge in ATLAS (*no routine analysis!!*)
- We have enabled already a huge amount of new physics searches
- LLP searches still have huge potential to grow in ATLAS
- Exciting prospects for next LHC data taking run
  - We benefit from technical advances
  - New opportunities for discovery