

The background of the slide is a complex visualization of particle detector data. It features a dark grey background with a grid of faint, light grey lines. Overlaid on this are numerous bright cyan and magenta lines that radiate from two central orange dots. These lines represent the paths of particles or the reconstruction of an event. The lines are of varying thickness and extend across the entire frame, creating a sense of dynamic energy and scientific complexity.

Long-Lived Particles at the LHC and Beyond

Juliette Alimena (DESY)

German Women in Physics Conference

September 20, 2025



A Bit About Me



- I'm an **experimental particle physicist**
 - I work on high-energy physics
 - I work mostly on the **CMS experiment at the LHC**
 - Also on the FCC and the CODEX-b experiment
- DESY staff member
- I'm interested in **searches** for new phenomena, particularly **long-lived particles**
- *Really happy to be here! Hope you're having fun and learning a lot :)*
- Interrupt me at any time and **ask questions!**

My Biography

Bachelors degree from **University of Pennsylvania (1)**

- Sept. 2004 - May 2008

PhD in physics from **Brown University (2)**

- Sept. 2008 - Nov. 2015
- Earned a Masters in Physics by 2010
- Thesis: “A Search for Delayed Muons in the CMS Experiment”, Nov. 2015

Postdoctoral researcher at the **Ohio State University (3)** (based at CERN (4))

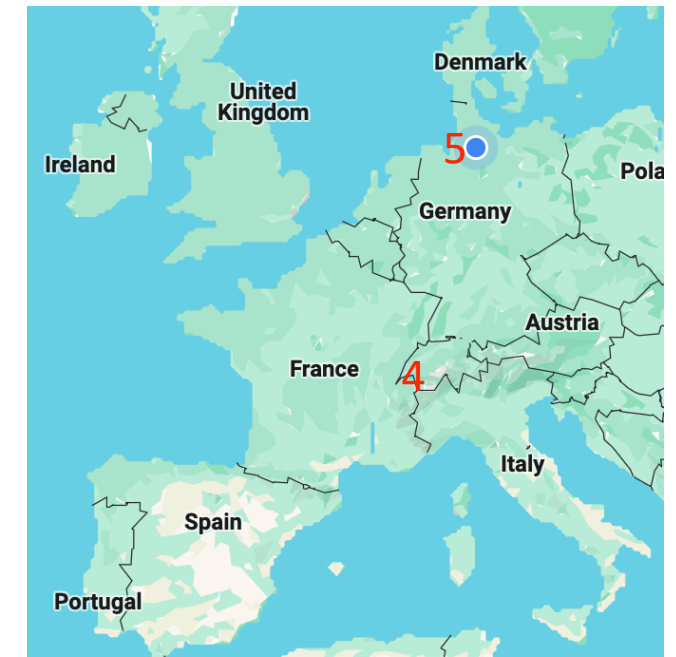
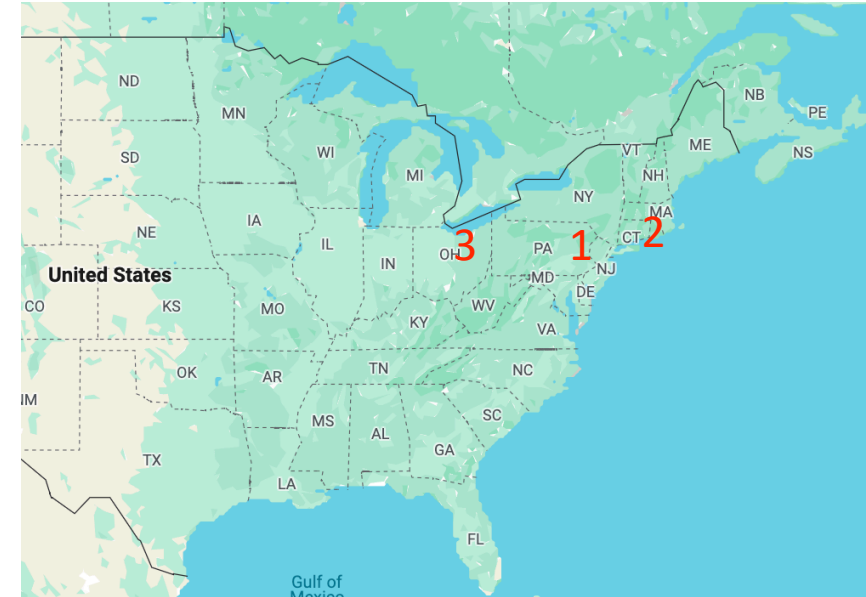
- Dec. 2015 - Sept. 2020

Research fellow at **CERN (4)**

- Oct. 2020 - Oct. 2022

Staff (tenure-track) at **DESY (5)**

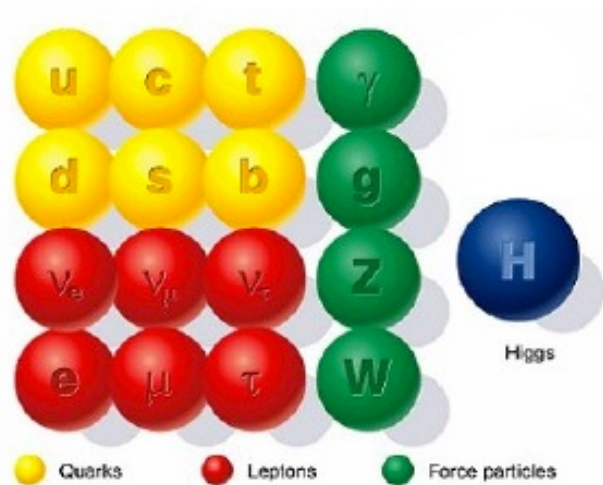
- As of Nov. 1, 2022



What is everything made of?

The Standard Model (SM)

Highly successful theory of
fundamental particle interactions

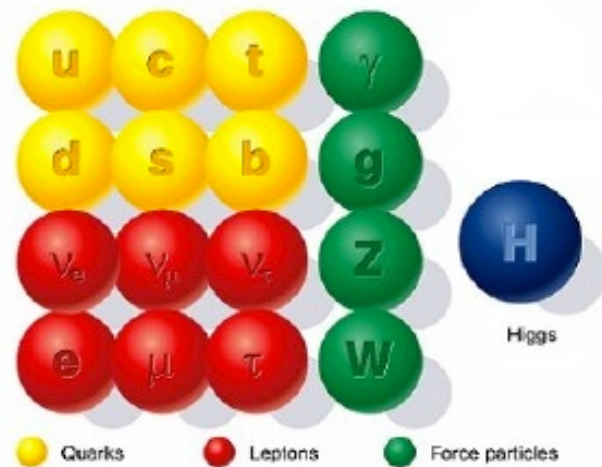


Standard particles

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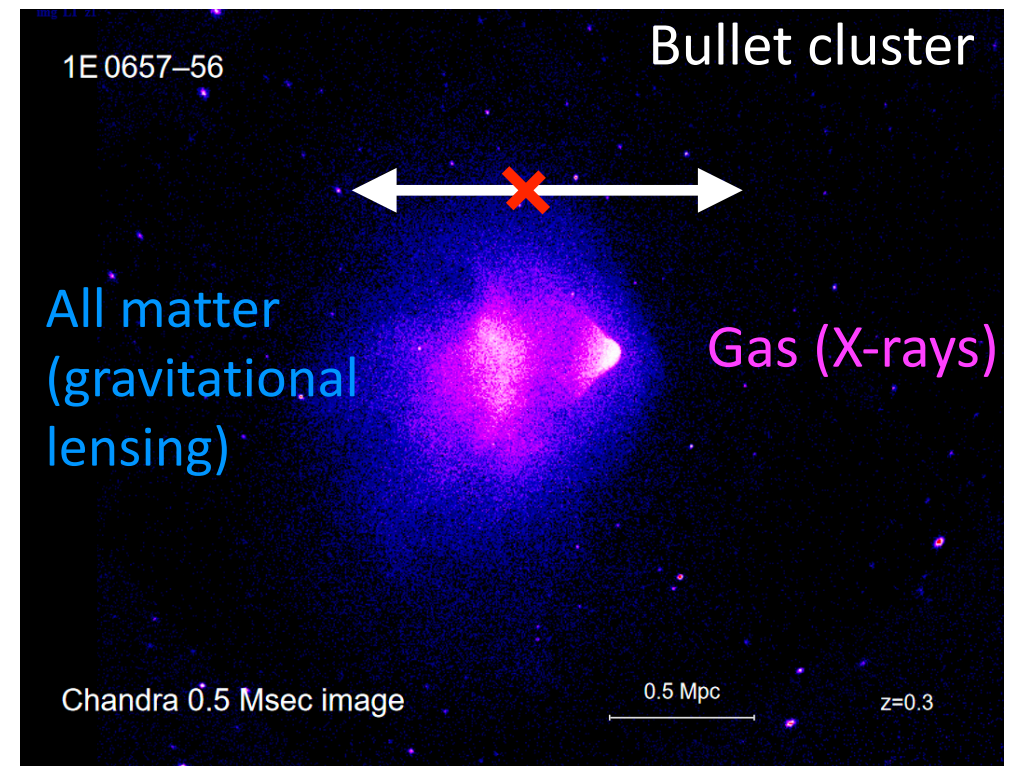
Highly successful theory of fundamental particle interactions



Standard particles

However, there are still many outstanding questions, e.g.:

What is dark matter?

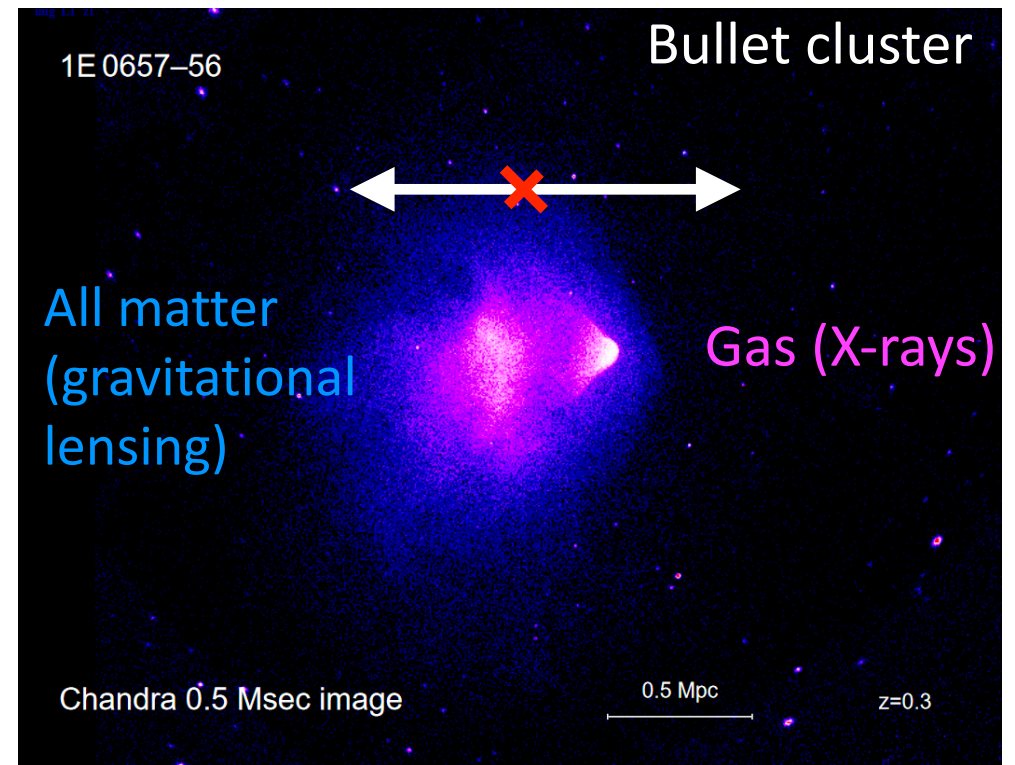
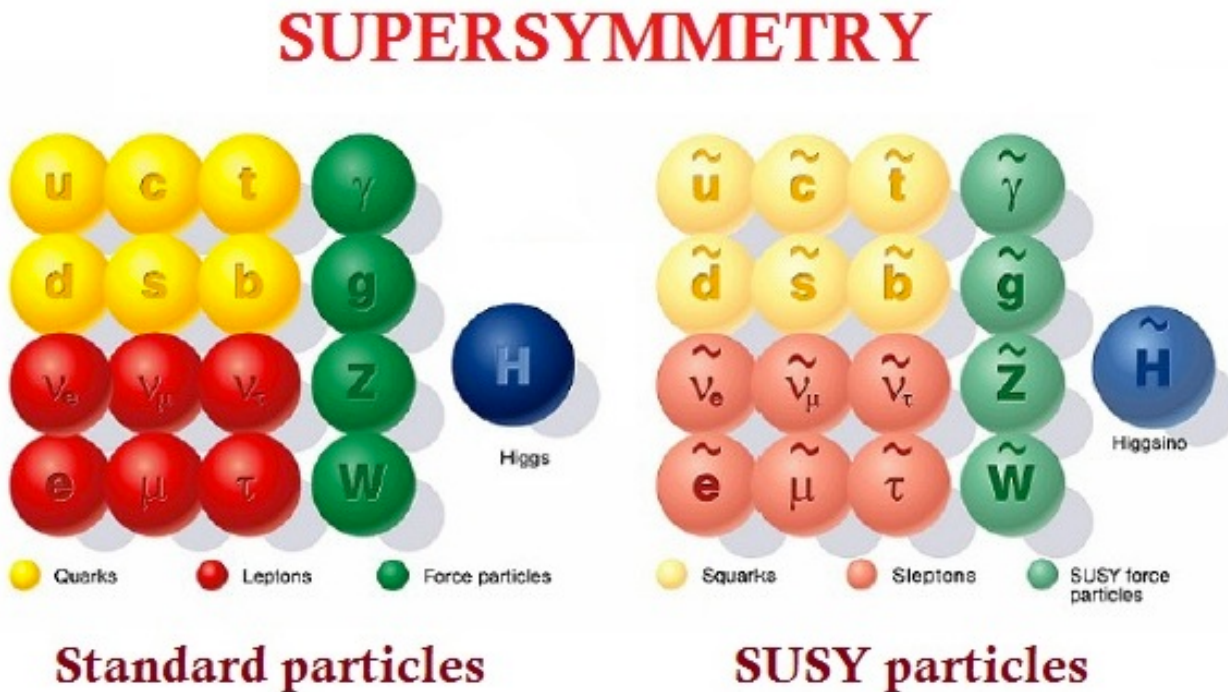


What is everything made of?

Many theories beyond the SM (BSM):

However, there are still many outstanding questions, e.g.:

What is dark matter?



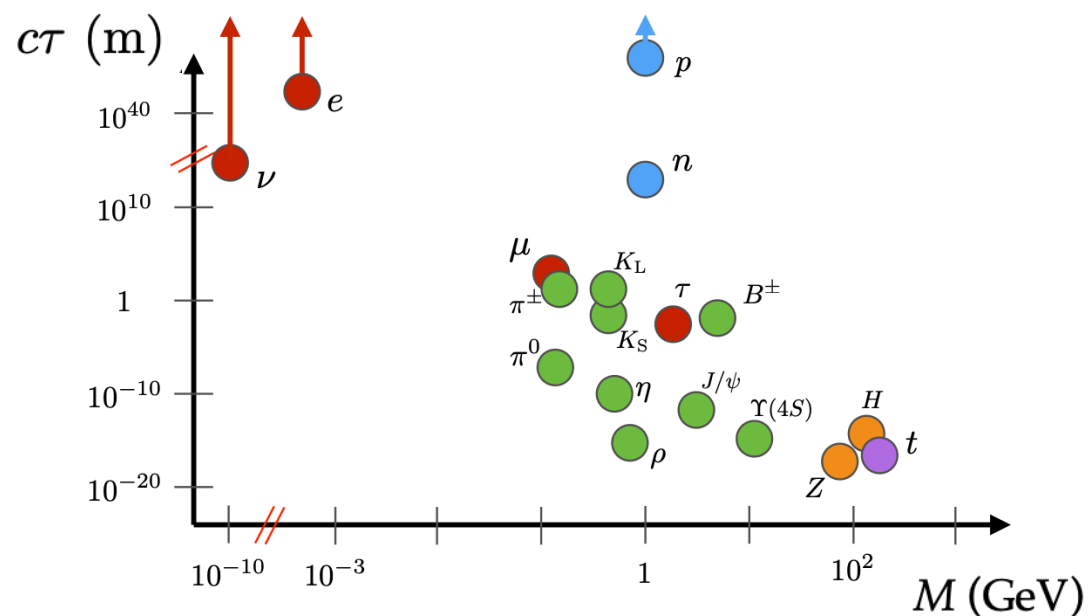
But no significant sign of new phenomena at the LHC yet!



**Are we looking in the
wrong place?**

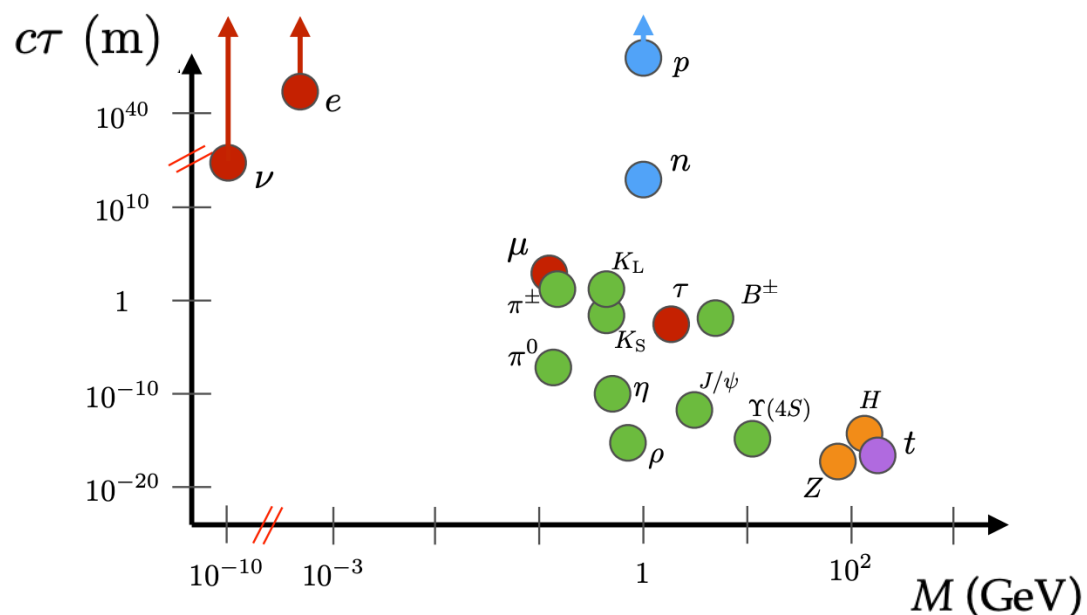
Long-Lived Particles (LLPs)

Standard model particles span a
wide range of lifetimes (τ)



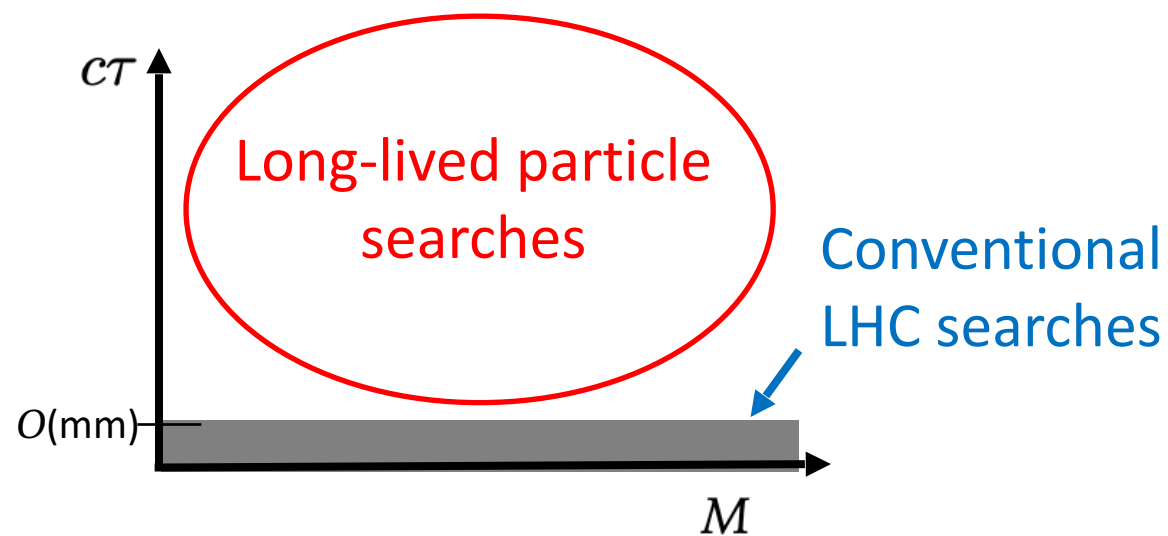
Long-Lived Particles (LLPs)

Standard model particles span a wide range of lifetimes (τ)



We expect **new phenomena** to have a wide range of lifetimes as well

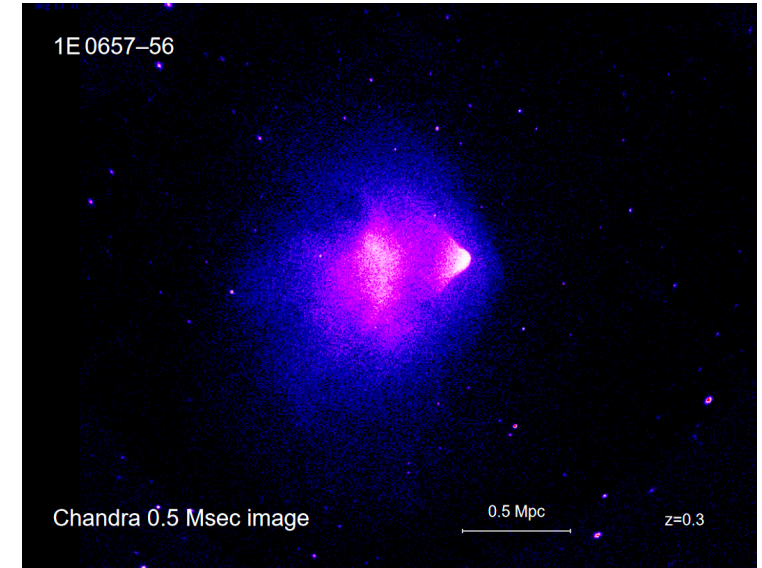
But **conventional searches** for new phenomena at the LHC are for **promptly** decaying particles



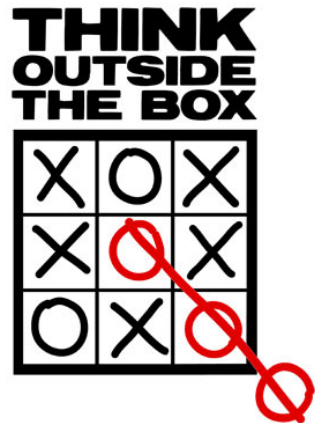
We also need to look for new particles with long lifetimes!

Why Search for New LLPs?

- **LLPs appear in many BSM scenarios**
 - Supersymmetry, dark photons, inelastic dark matter, axion-like particles, exotic Higgs bosons, etc.
- **Can provide a dark matter candidate**
- **Why not?**
 - No sign of new phenomena at the LHC yet! → **Need to look everywhere**
 - A new massive, long-lived particle would be a clear sign of new phenomena



Great discovery potential!



What's a New LLP?

- From an experimentalist's point of view, it's a particle beyond the standard model that:
 - decays a reconstructable distance from the primary collision
 - or
 - is quasi-stable on the scale of the detector

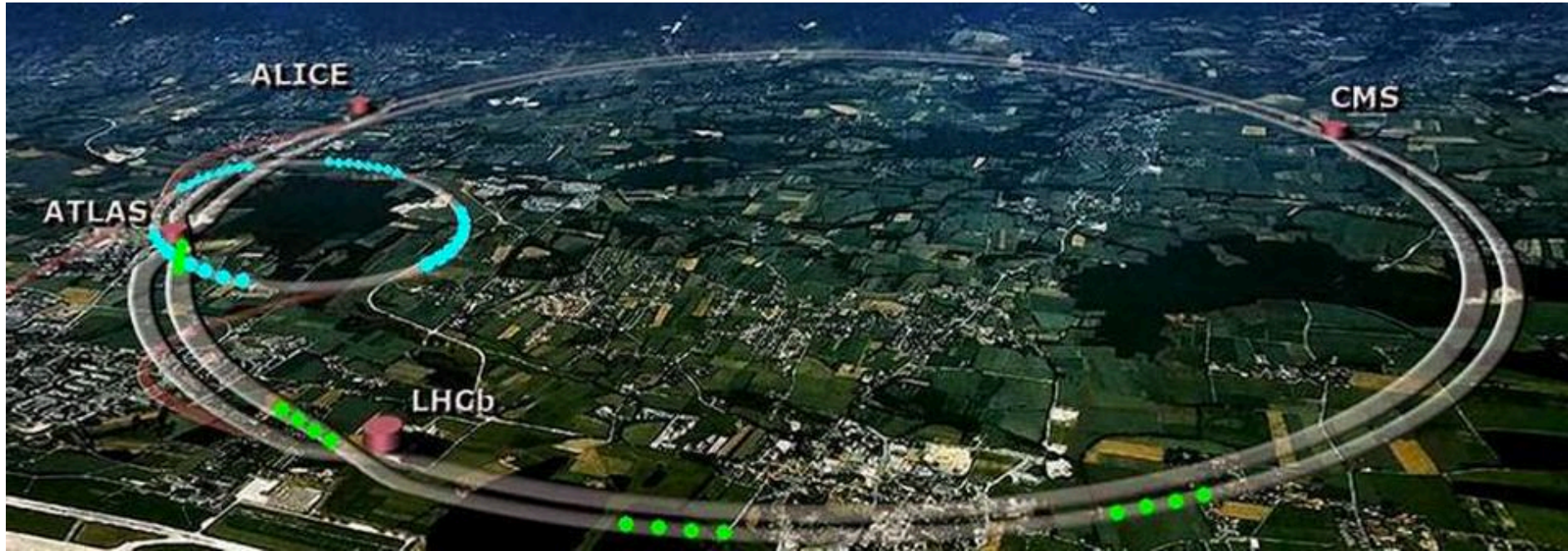
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 - be **charged**, neutral or have color
 - be light or heavy
 - travel fast or slow
 - decay to anything

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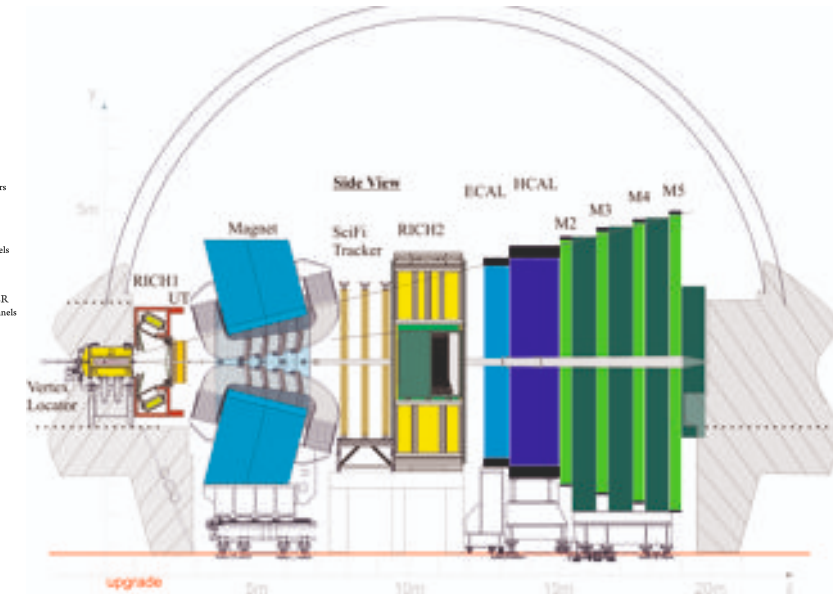
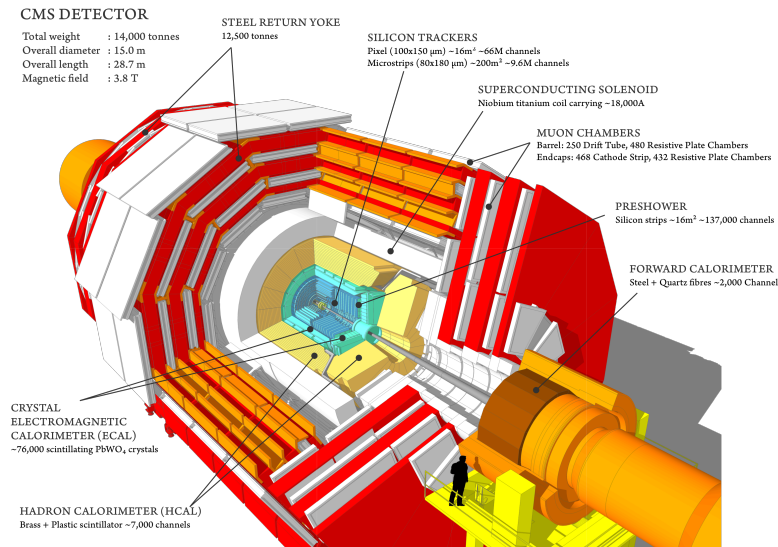
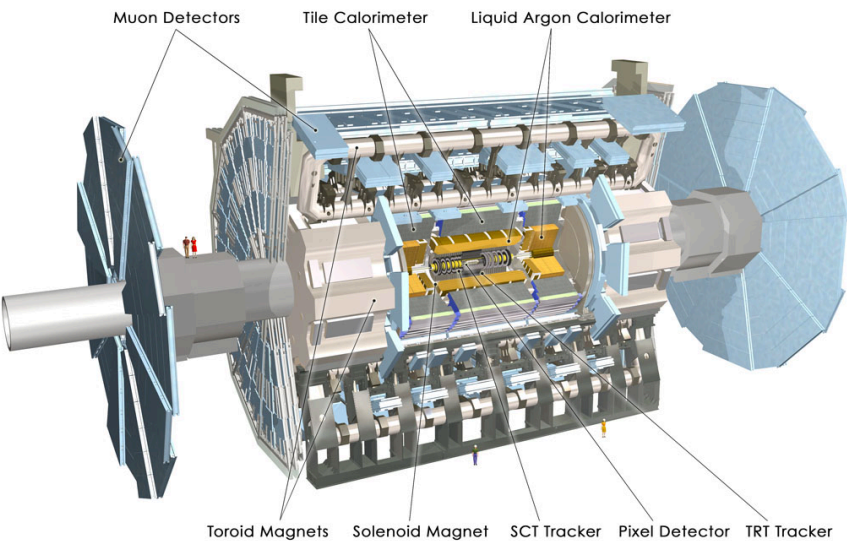
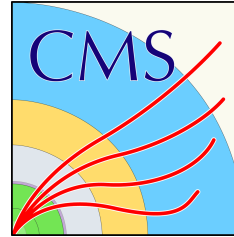
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 - decays a reconstructable distance from the primary collision
 - or
 - is quasi-stable on the scale of the detector
- They can:
 - be **charged**, neutral or have color
 - be light or heavy
 - travel fast or slow
 - decay to anything
- They often require dedicated searches or dedicated experiments

The Large Hadron Collider

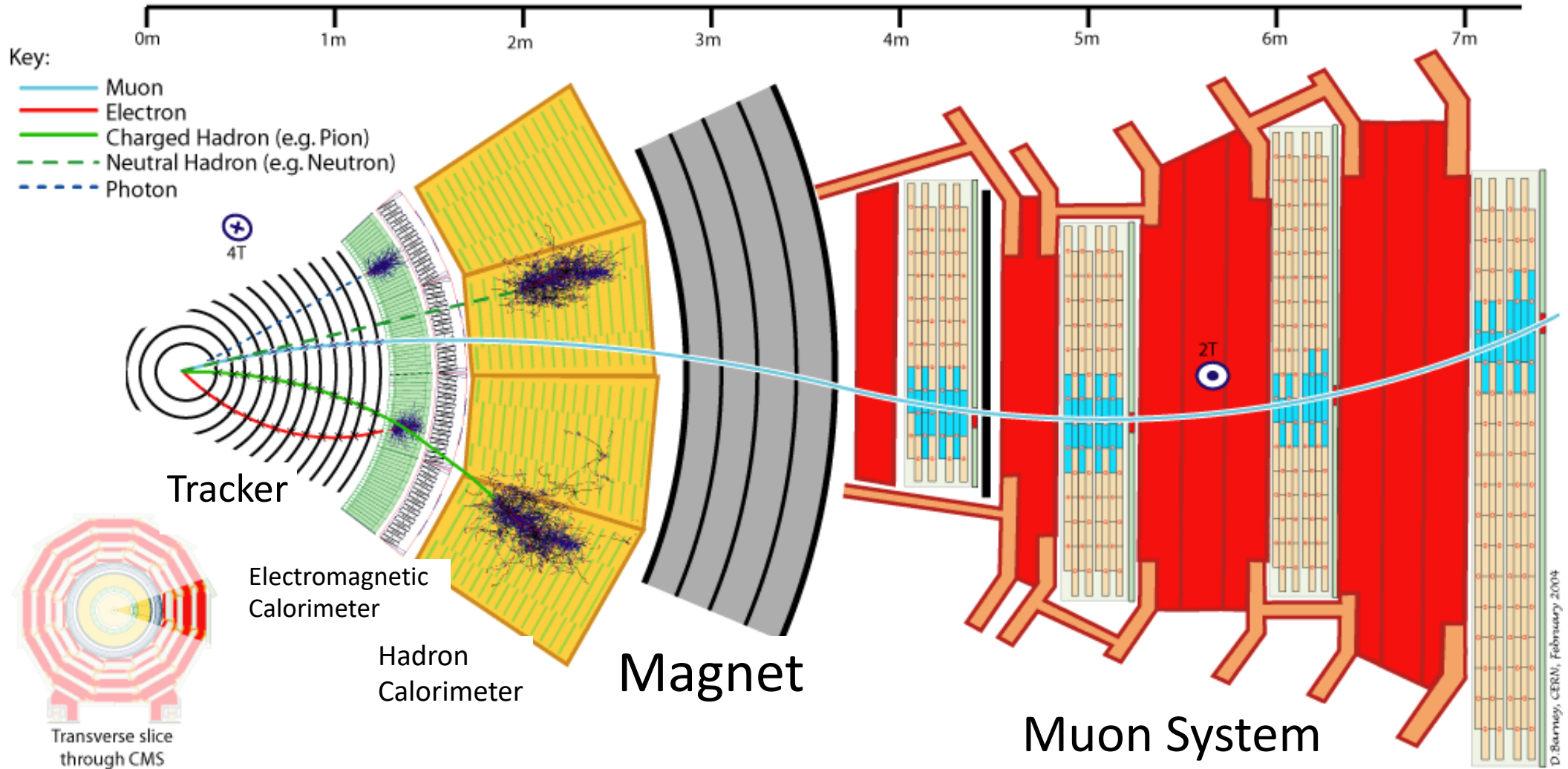


- ~15 years of successful operation of the LHC!
- Superb operation efficiency for the experiments
 - Usually $> 90\%$ efficient for both CMS and ATLAS (data taking + data quality)

General-Purpose LHC Experiments

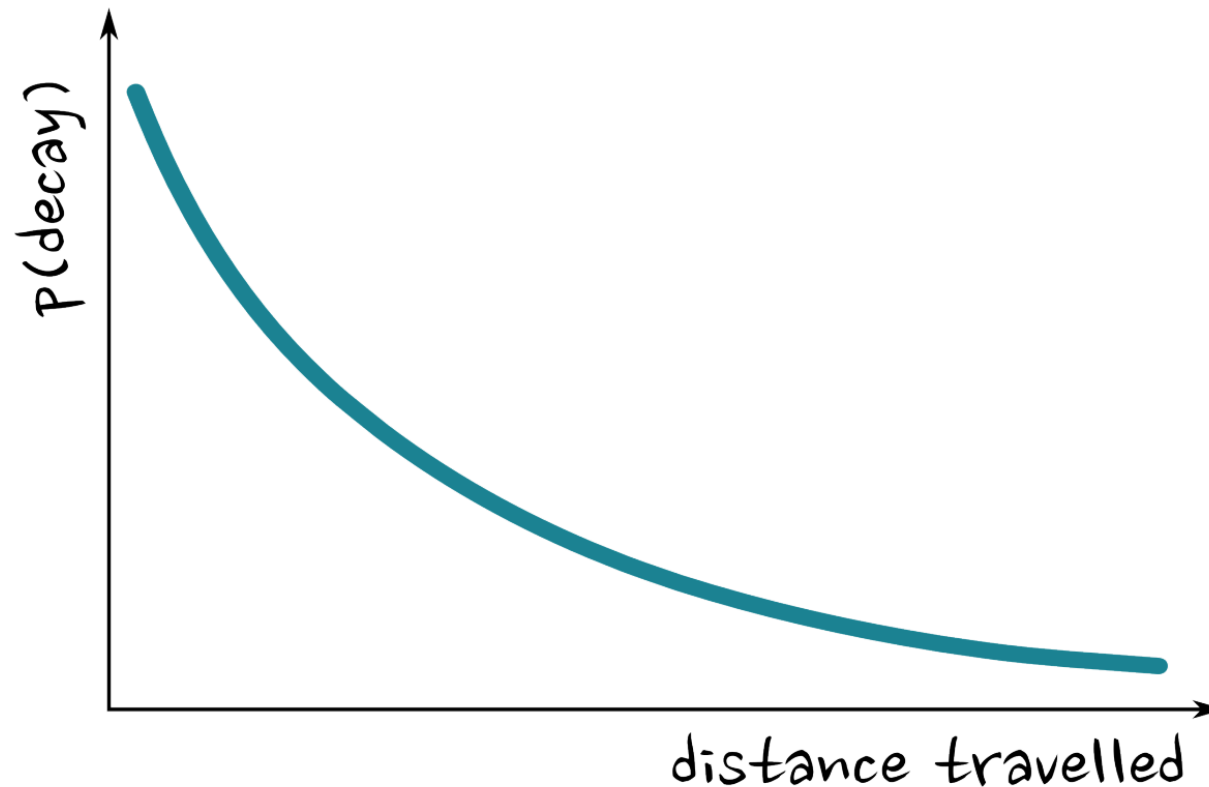


Anatomy of a General-Purpose Detector



Long Lifetimes

Any given particle's lifetime is sampled from an exponential

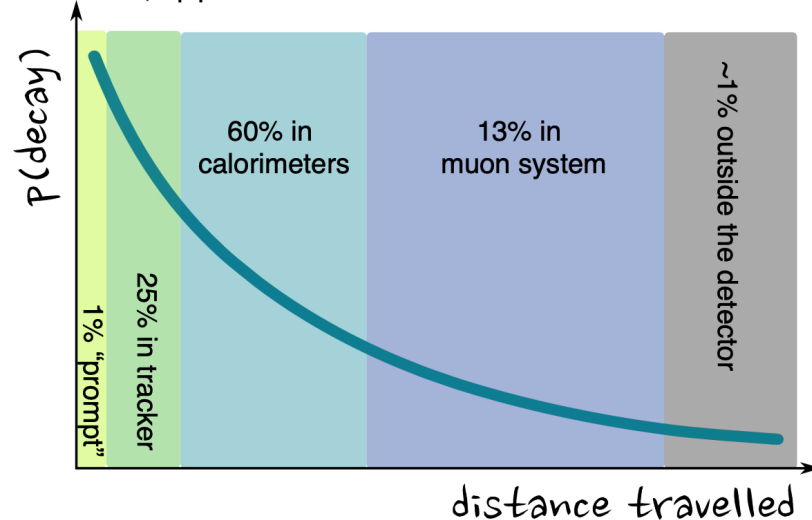


Long Lifetimes and the Detector

Any given particle's lifetime is sampled from an exponential

Even particles with a **short proper lifetime**
can decay far from the interaction:

e.g. for $c\tau = 5$ cm, $\langle\beta\gamma\rangle \sim 30$

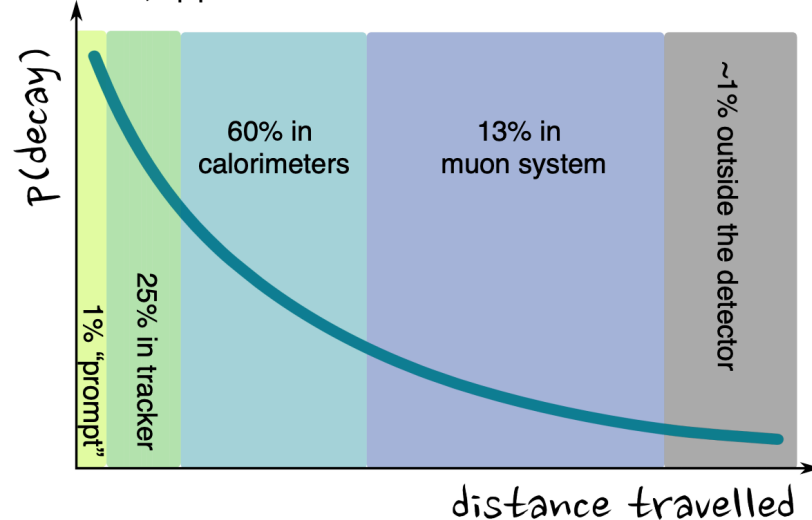


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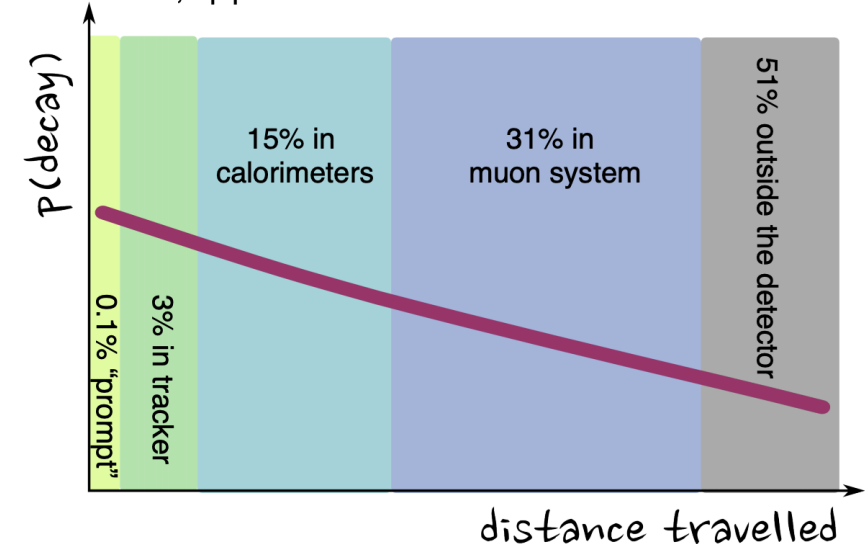
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But if we want to consider particles with **longer lifetimes**, we could benefit from a **different search strategy**:

e.g. for $c\tau = 50$ cm, $\langle\beta\gamma\rangle \sim 30$

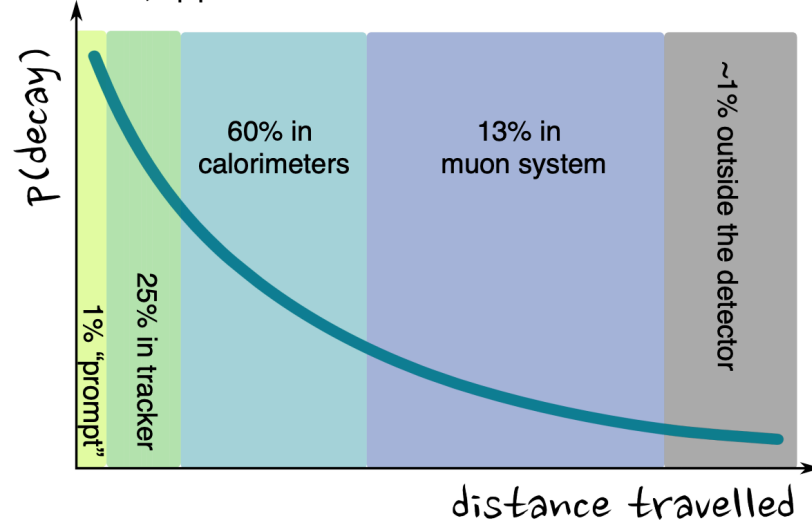


Variety of LLP Searches

Any given particle's lifetime is sampled from an exponential

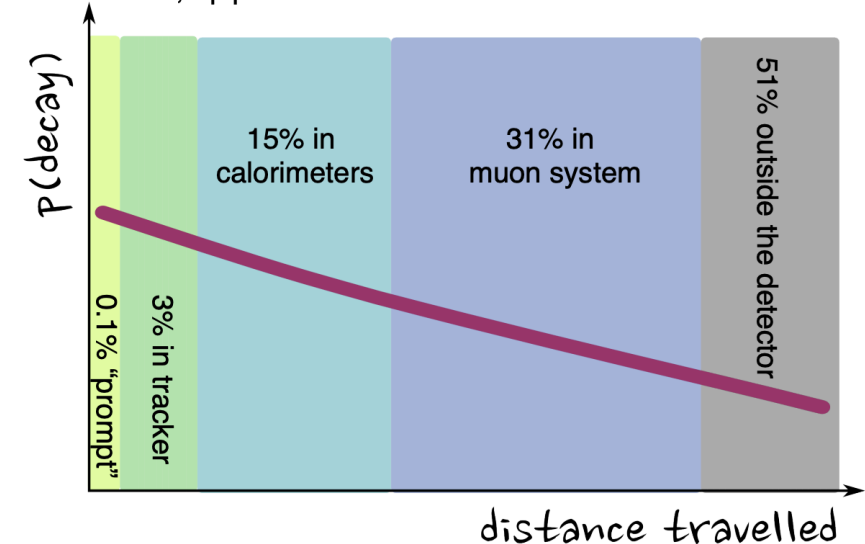
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Lifetime, mass, decay products, boost, etc. dramatically affect the detector signature, and thus we use all subdetectors

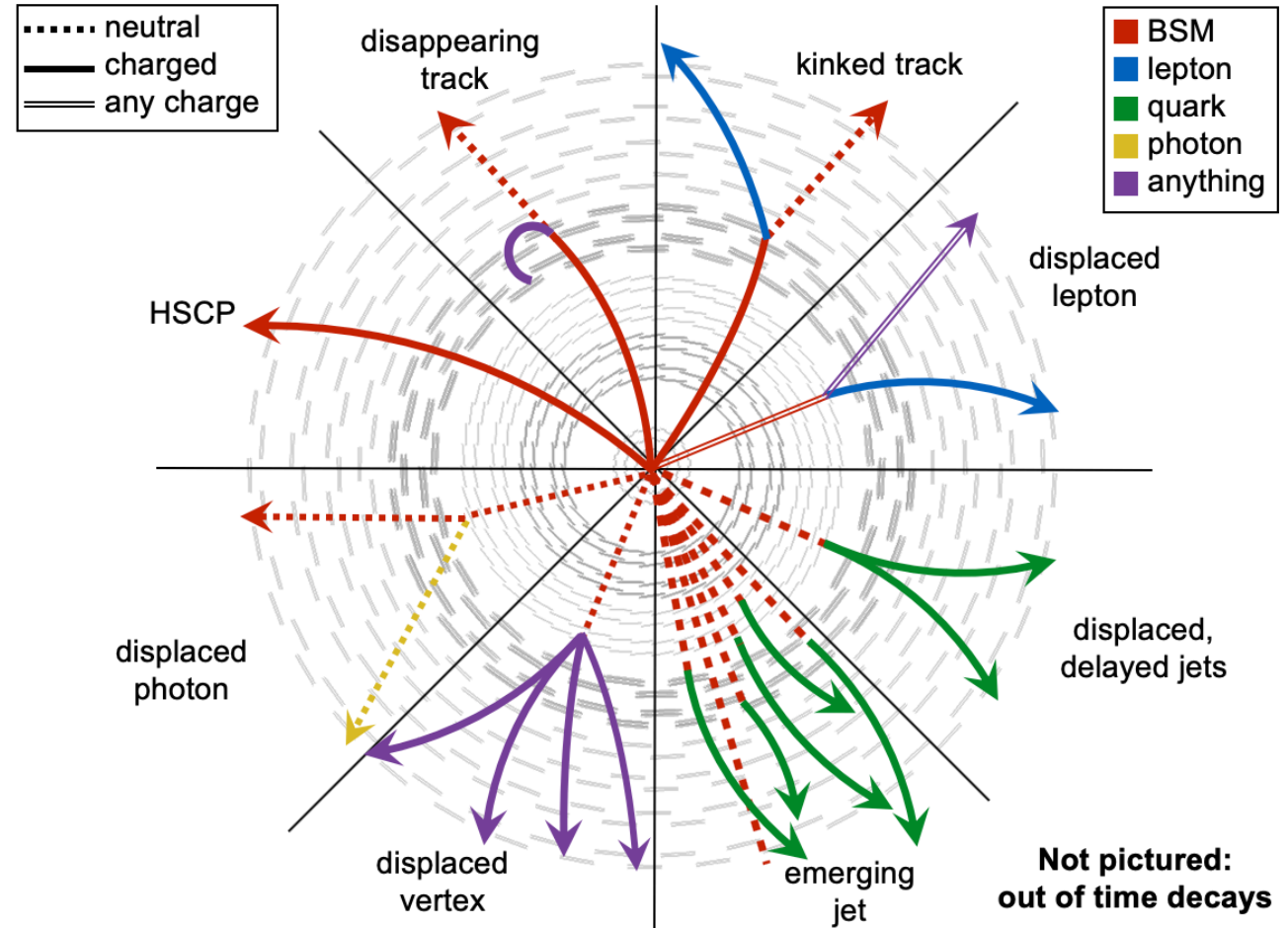
Long-Lived Particle Searches

Can search for LLPs that decay:

- Within the detector
- Outside of the detector

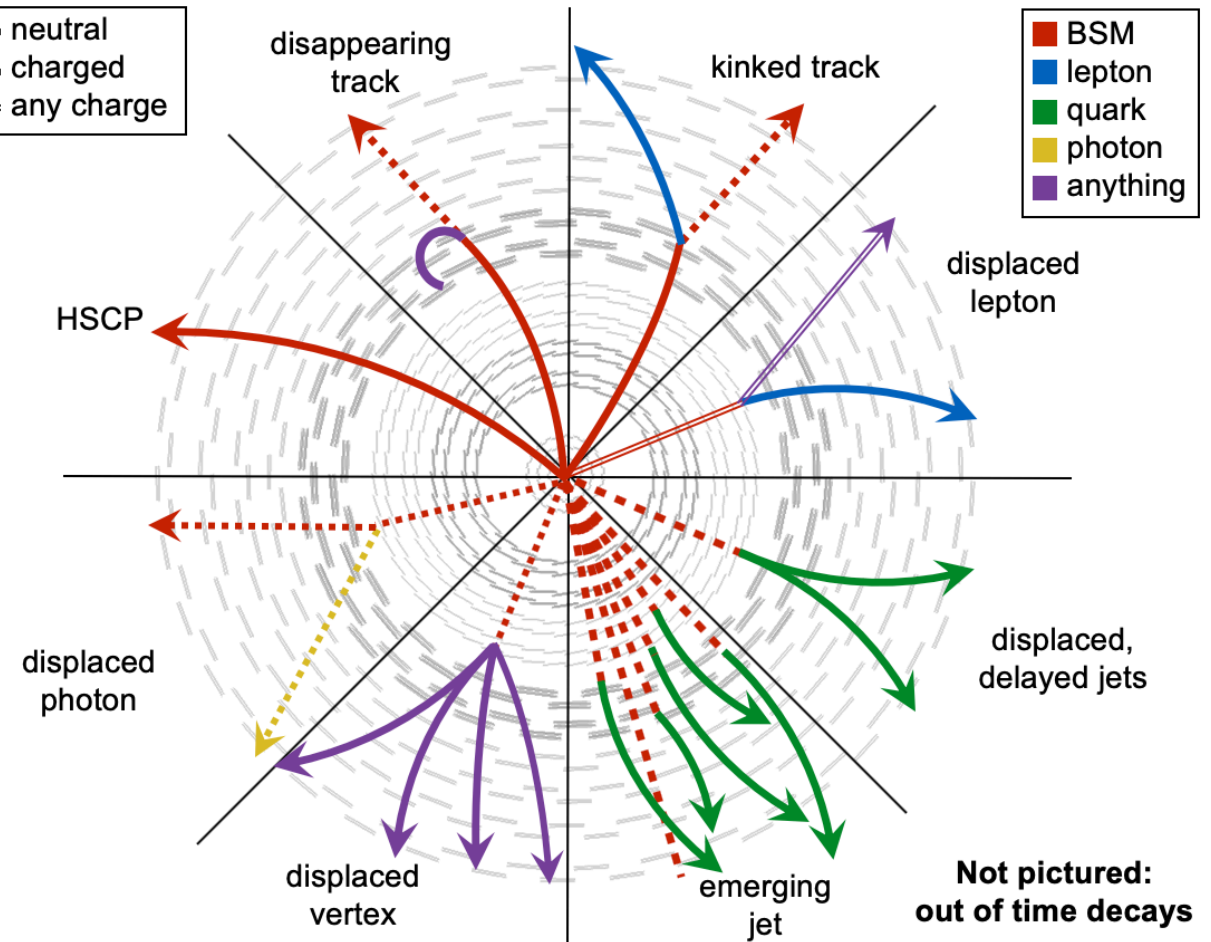
Can search for:

- The LLP itself
- Its displaced decay products
- Both



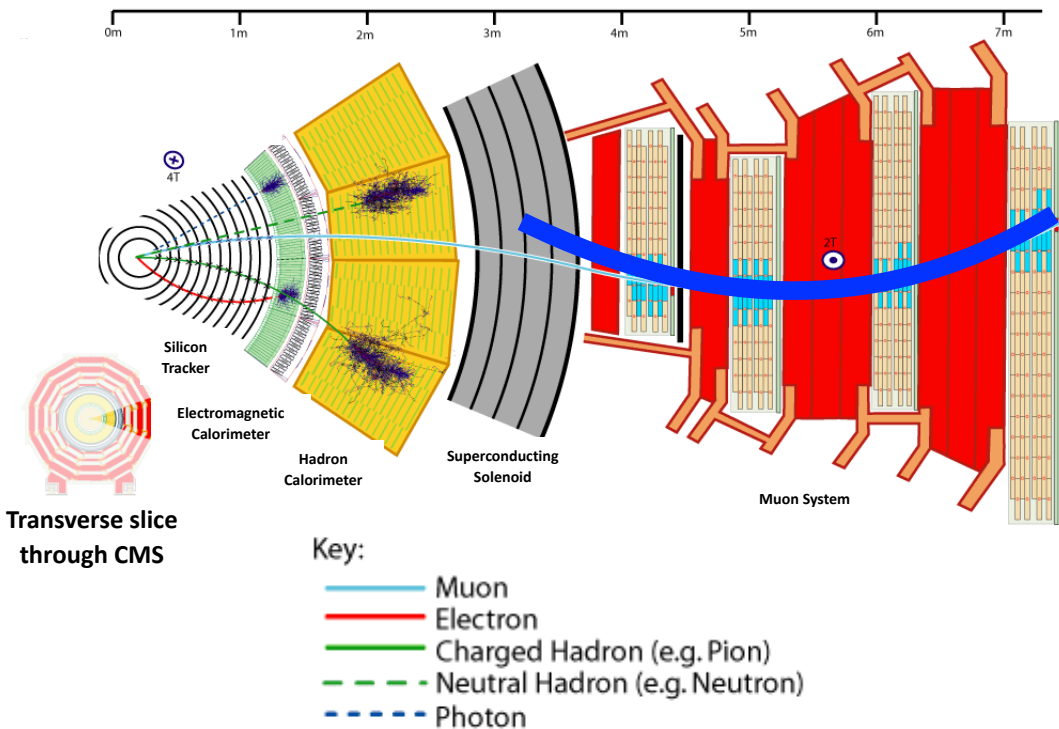
Long-Lived Particle Searches

- **Wide variety of:**
 - Charges
 - Final states
 - Decay locations
 - Lifetimes
- Design **signature-driven** searches
- Often interpret results with a **benchmark model**, but can expand to a **variety of scenarios**



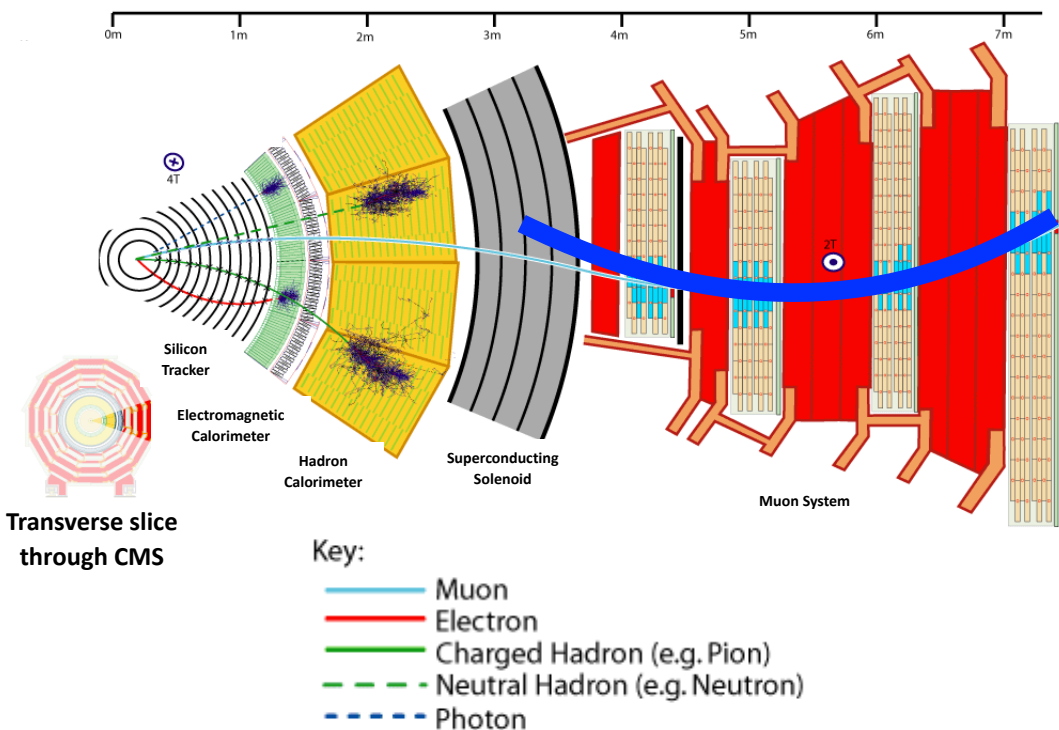
Challenges of LLP Searches

Unique object reconstruction and discriminating variables

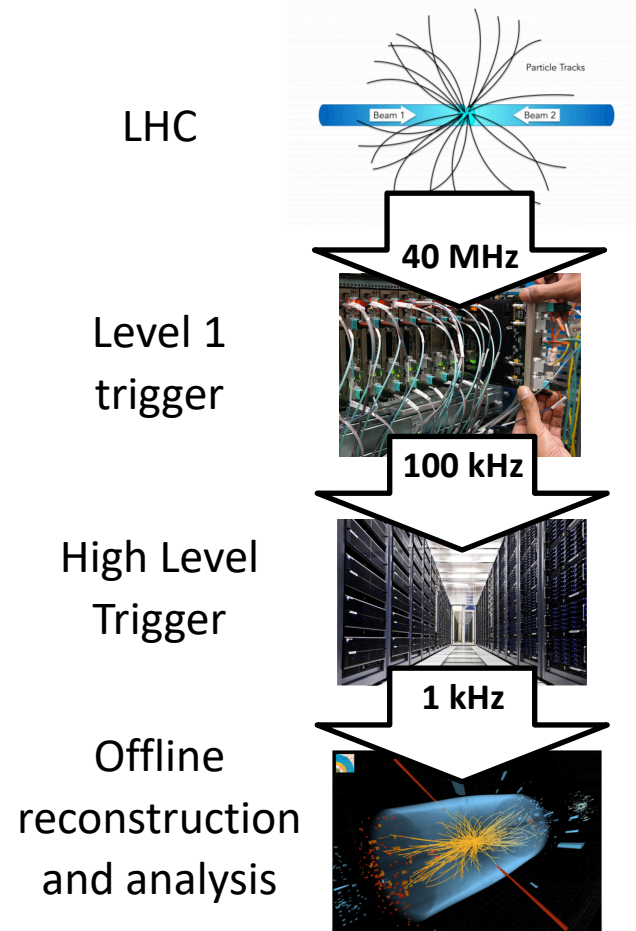


Challenges of LLP Searches

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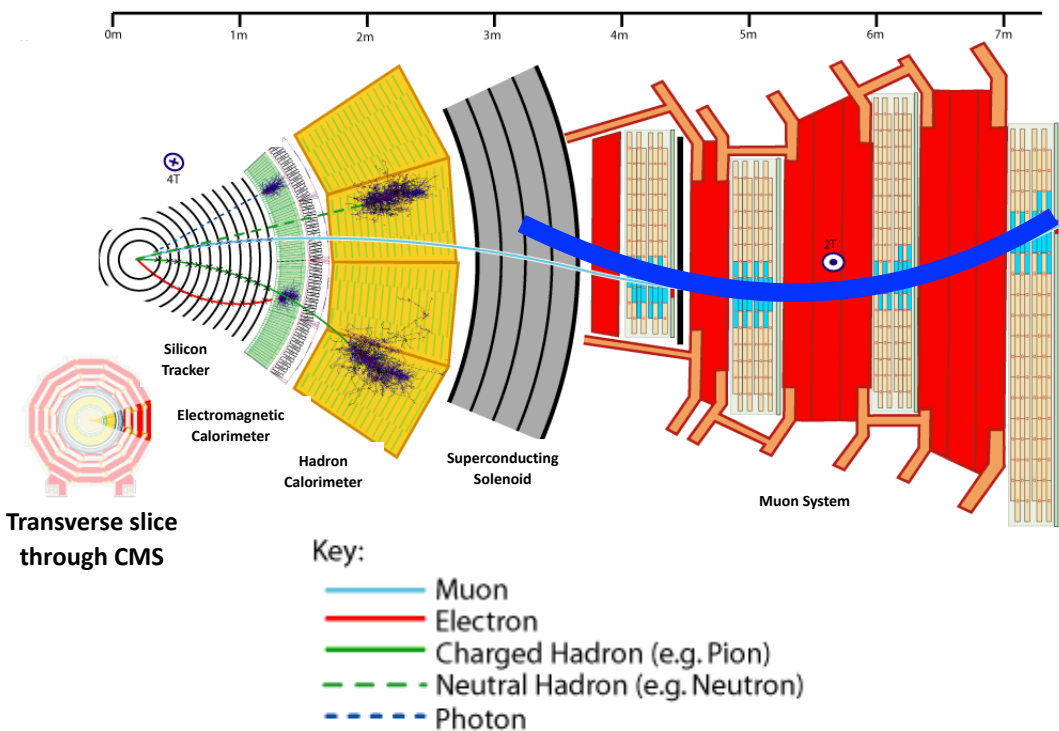


Dedicated triggers

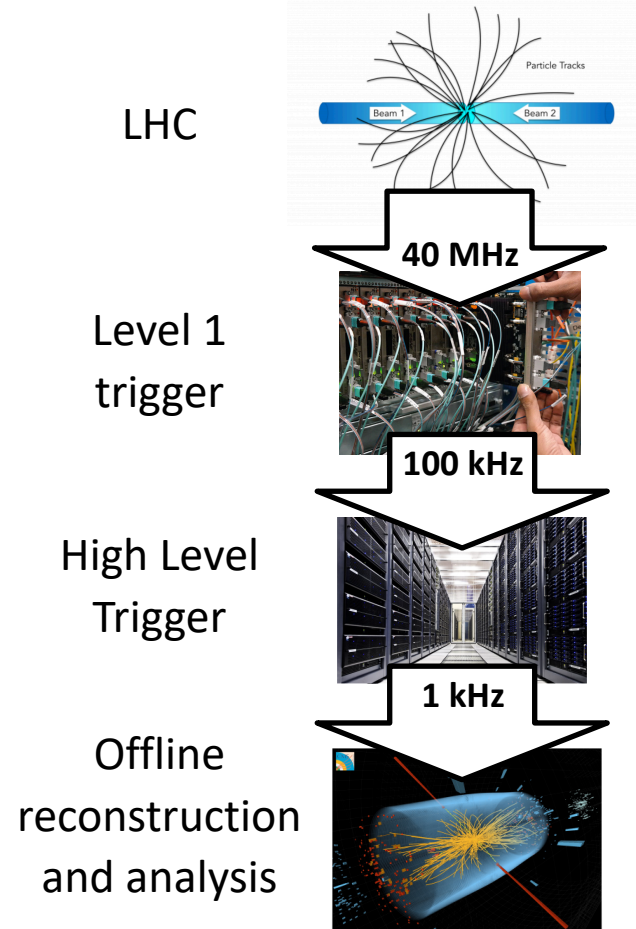


Challenges of LLP Searches

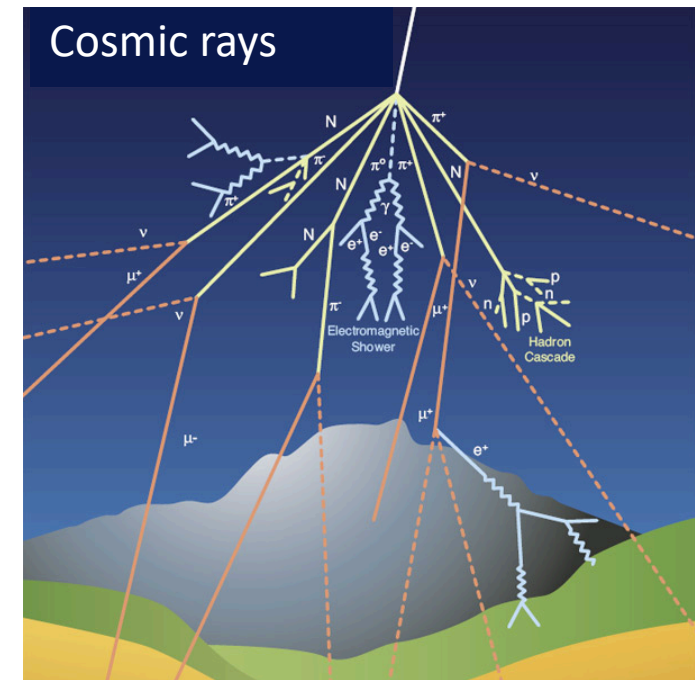
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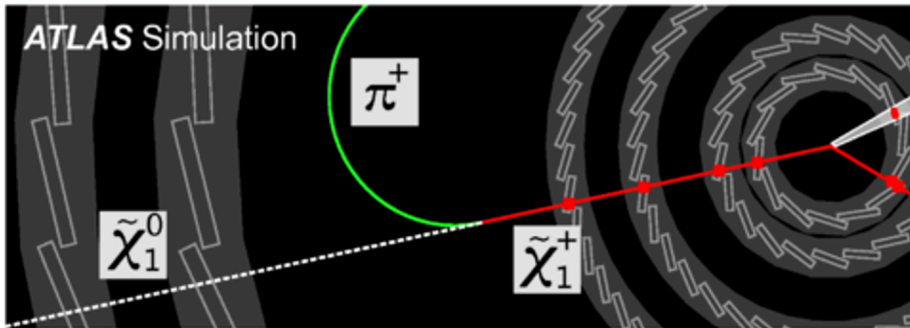


Atypical backgrounds

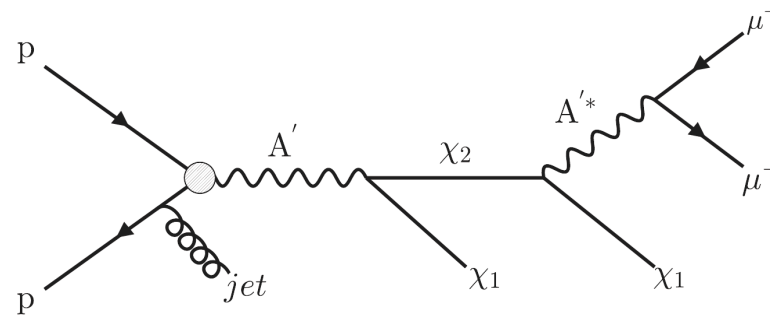


Recent LLP Searches

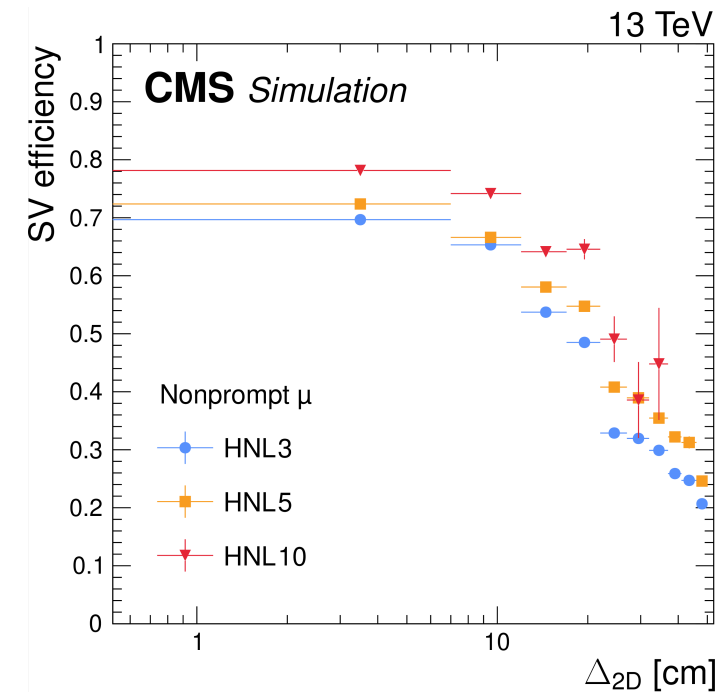
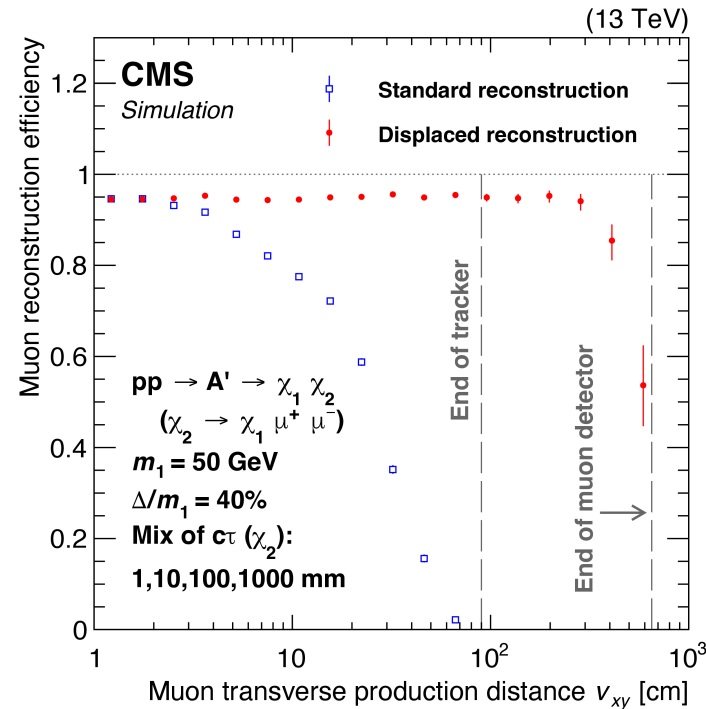
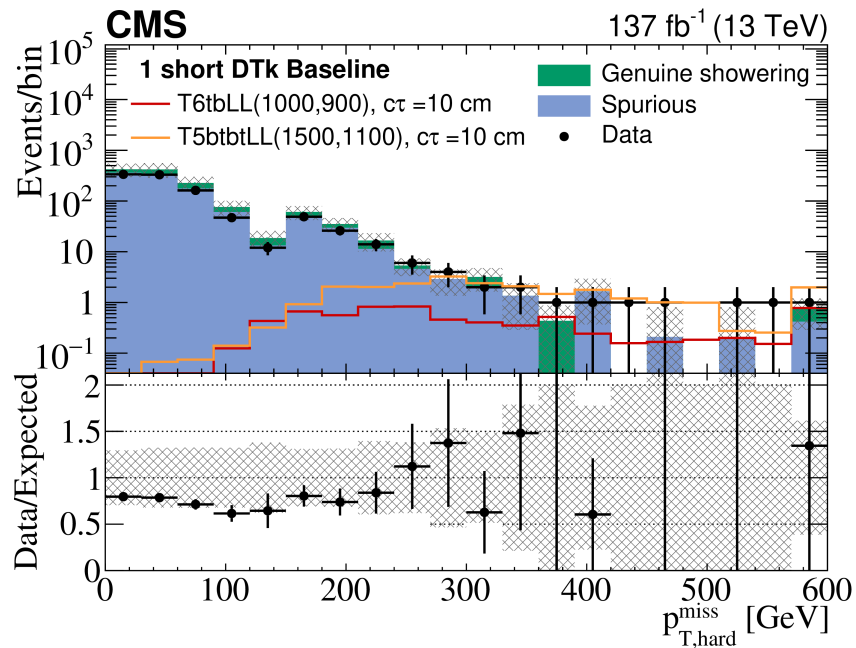
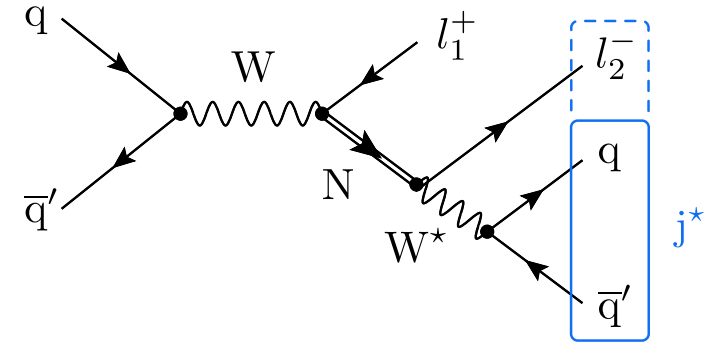
Disappearing tracks



Inelastic dark matter

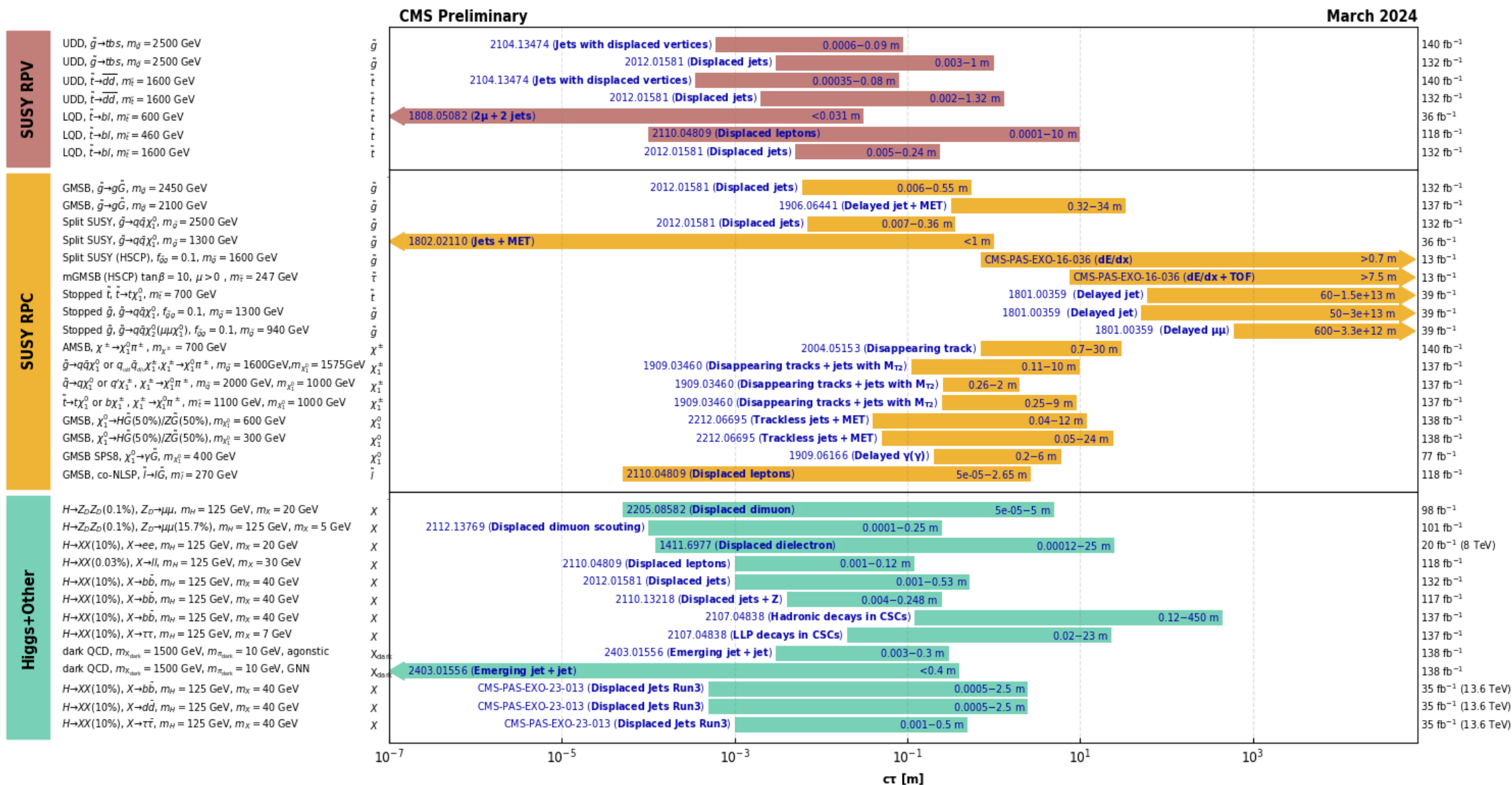


Heavy neutral leptons decaying to displaced jets



Wide range of signatures, models, and lifetimes explored at the LHC

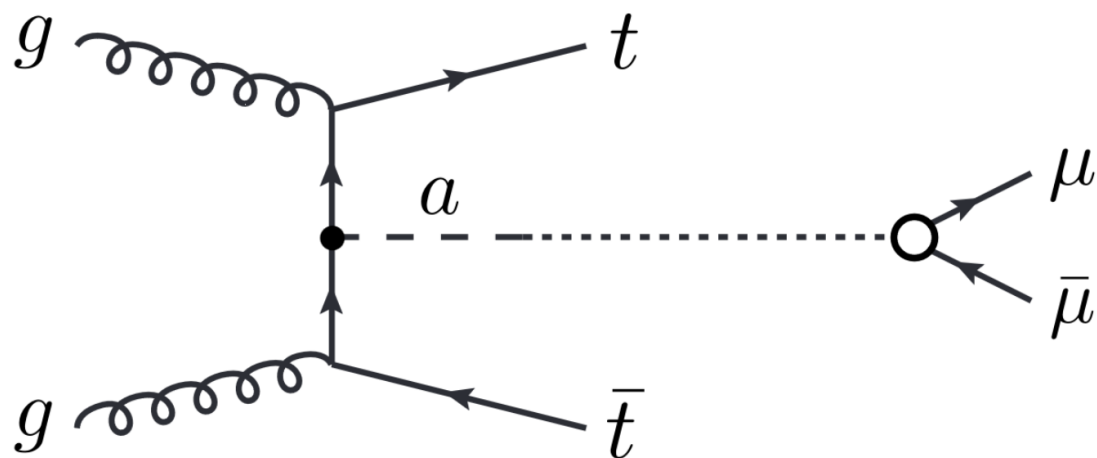
Overview of CMS long-lived particle searches



What am I working on now?

- One example of my ongoing work:

Search for displaced dimuons produced in association with $t\bar{t}$ with the CMS experiment



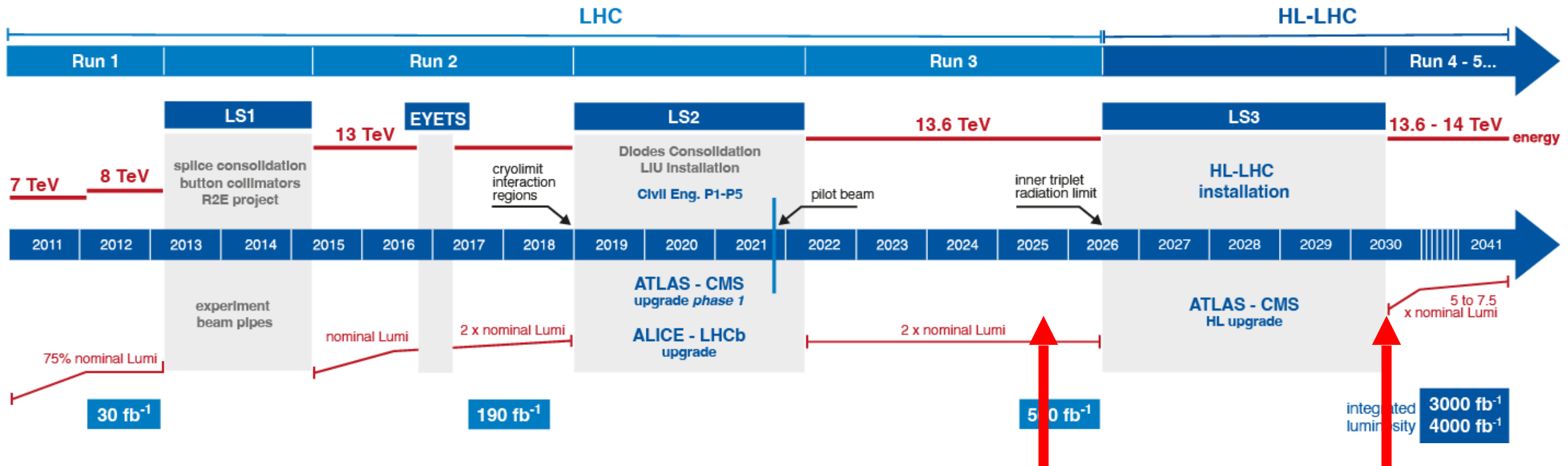
Working with Lovisa Rygaard (PhD student): see her talk for more details!



What's Next?



LHC / HL-LHC Plan



We are here,
in Run 3

High-Luminosity LHC
taking data in ~2030

High-Luminosity LHC

HL-LHC

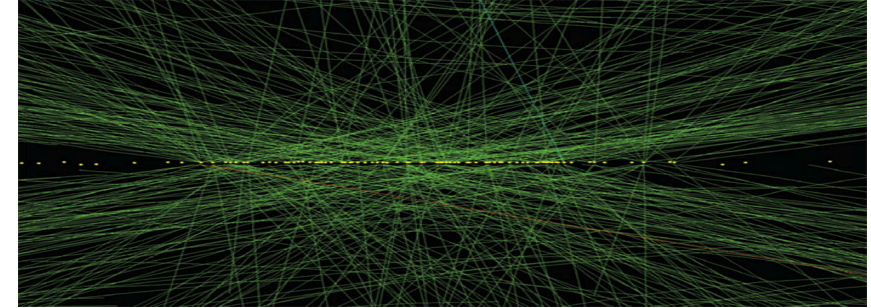
- 14 TeV center-of-mass energy
- > 10 times more data by the end
- Expect **up to 200 interactions** per proton-proton collision,

unprecedented amount of radiation

CMS Detector

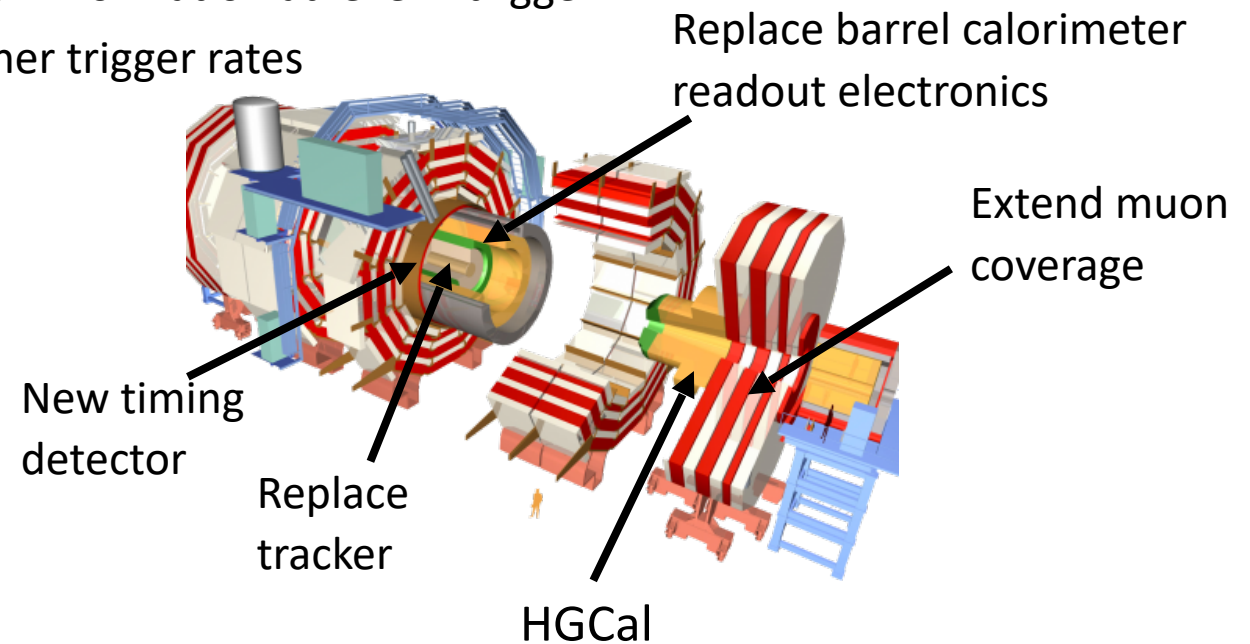
- Higher geometrical coverage, with high resolution for all subdetectors
- New subdetectors, including a **completely new** silicon high-granularity endcap calorimeter (HGCa), and a **completely new** MIP timing detector

High pileup: about 200 additional proton collisions per bunch crossing



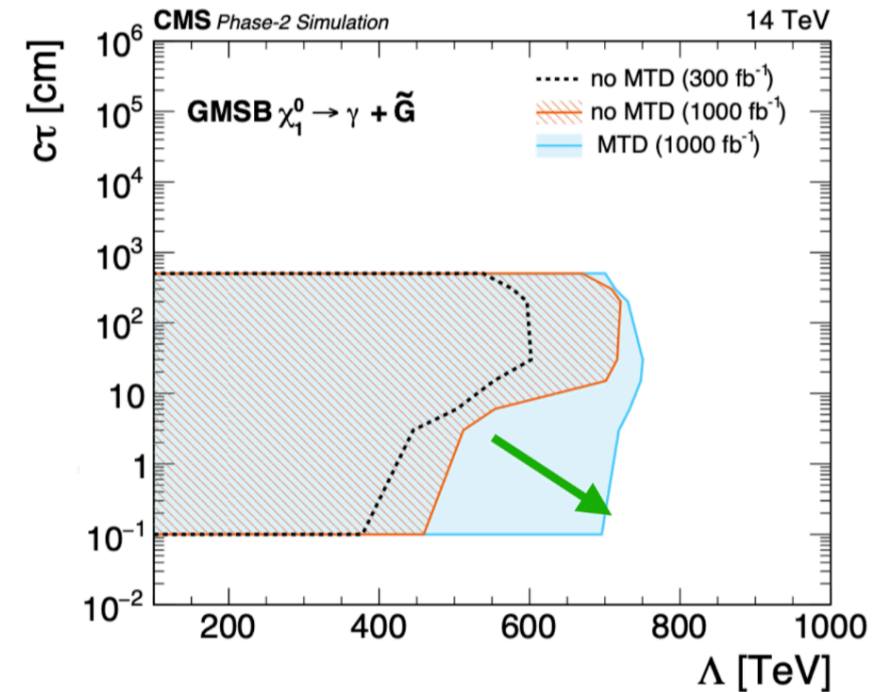
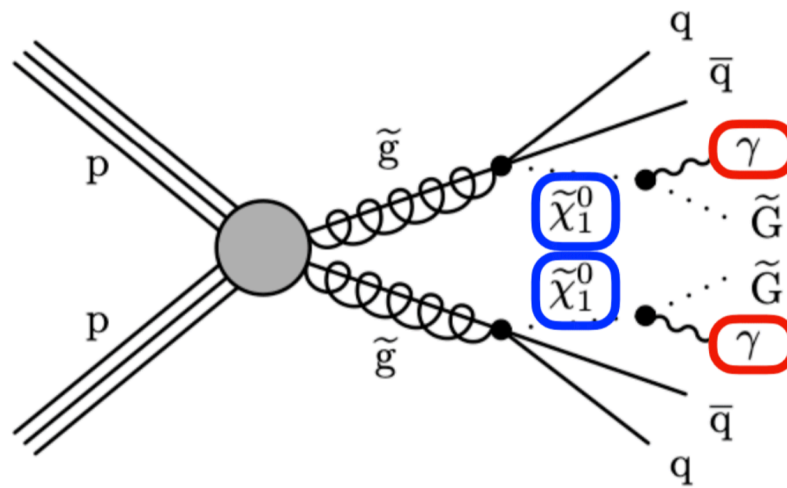
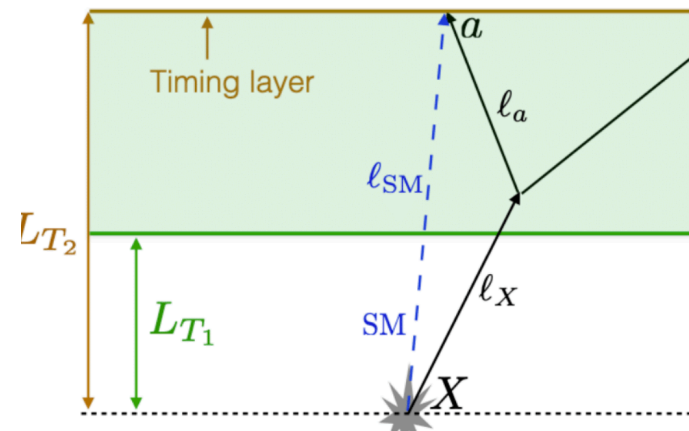
Track information at level 1 trigger

Higher trigger rates



LLPs & The MIP Timing Detector

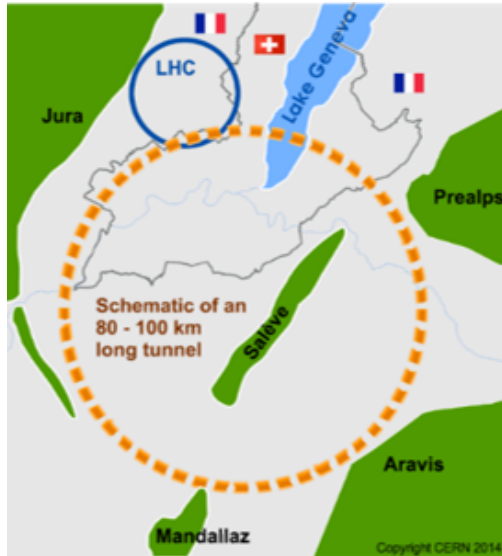
- How we can take advantage of this new CMS subdetector for LLPs:
- Look for delayed photons!
- Using the MTD really improves the sensitivity, especially for $0.1 < c\tau < 10$ cm



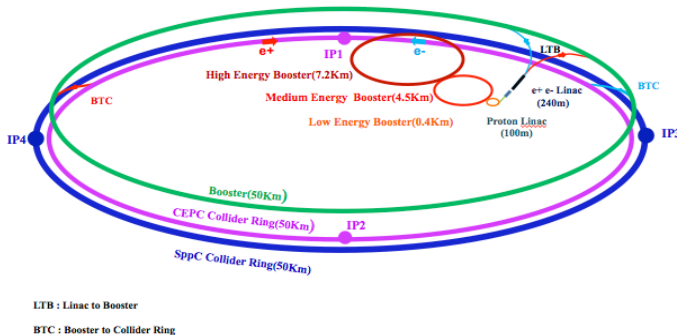
And After the HL-LHC?

Circular:

FCC (CERN)



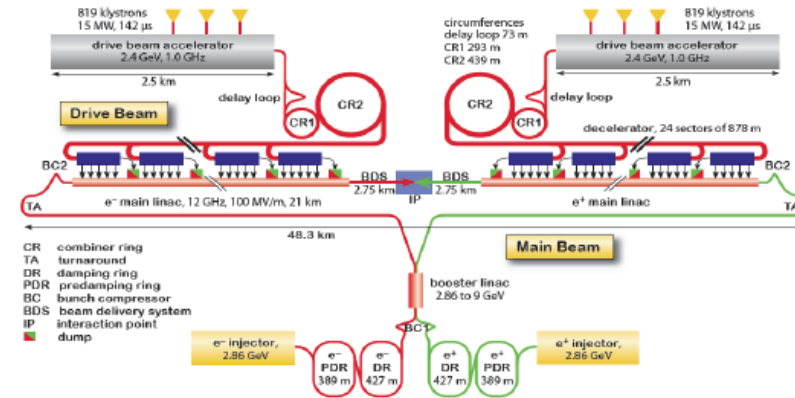
CEPC (China)



Linear:

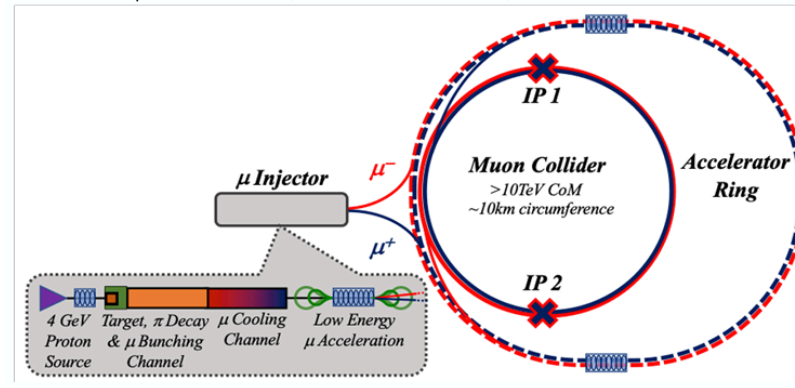
CLIC (CERN)

Overview of the CLIC layout at $V_s = 3$ TeV



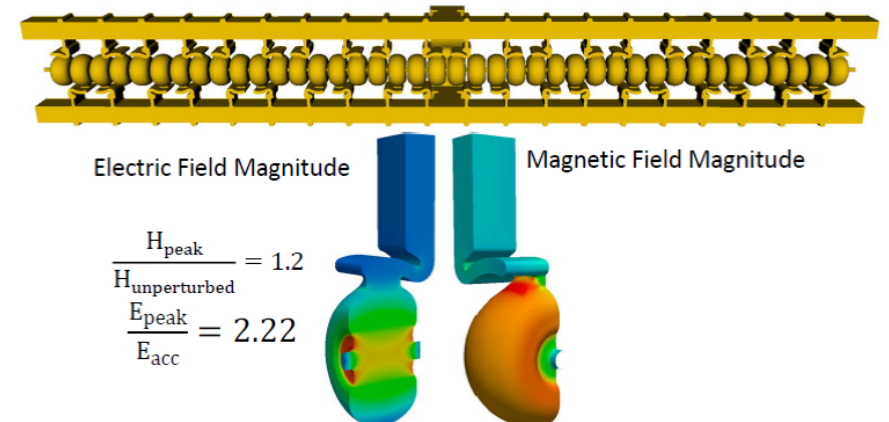
Muon Collider (CERN)

needs proton driver, thus CERN ideal, also for demonstrator



CCC (USA)

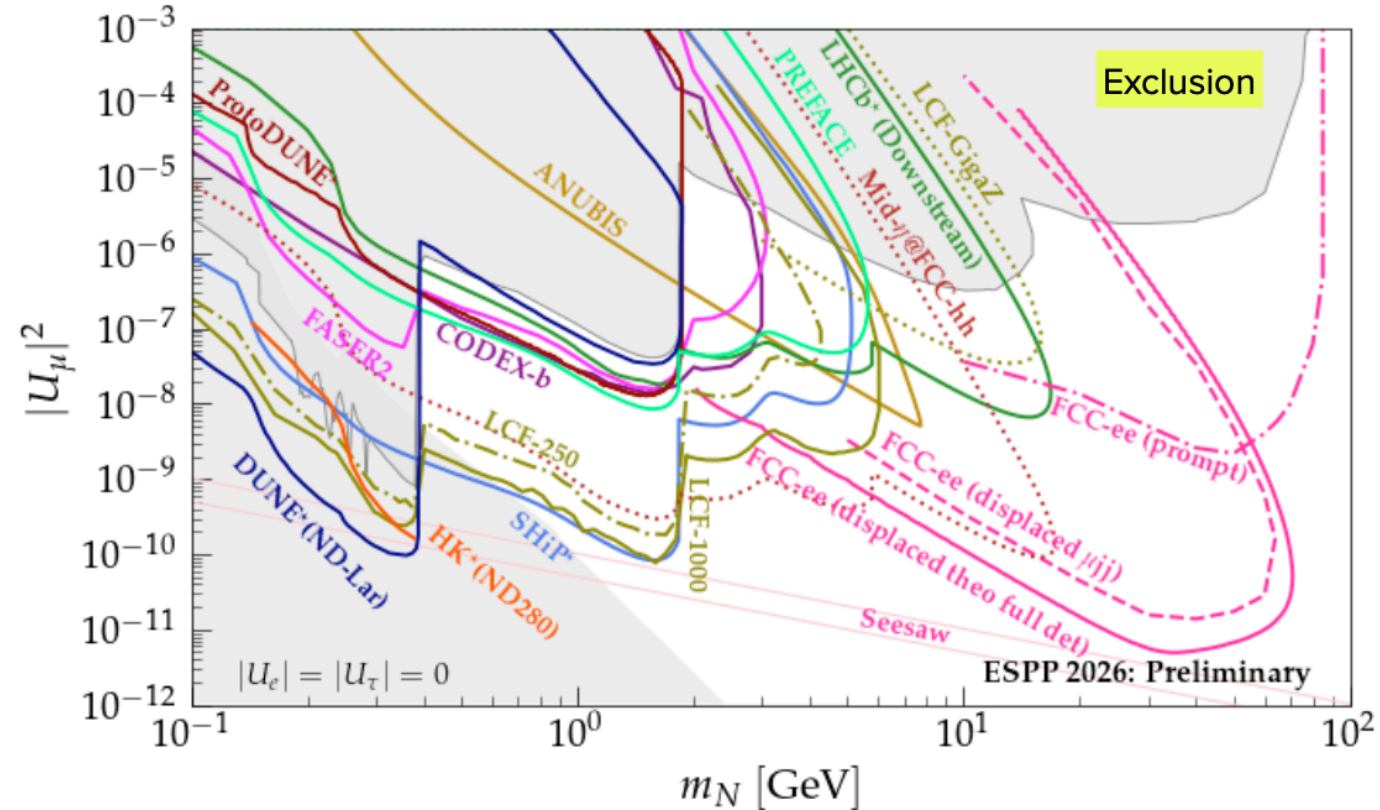
Vacuum Space for Distributed Coupling Linac



- We would like another particle collider!
- At the very least, some collider where we **make a lot of Higgs bosons!**
- Different stages of technical maturity
- All in the multi-Giga €/\$/CHF range

LLPs at Future Colliders

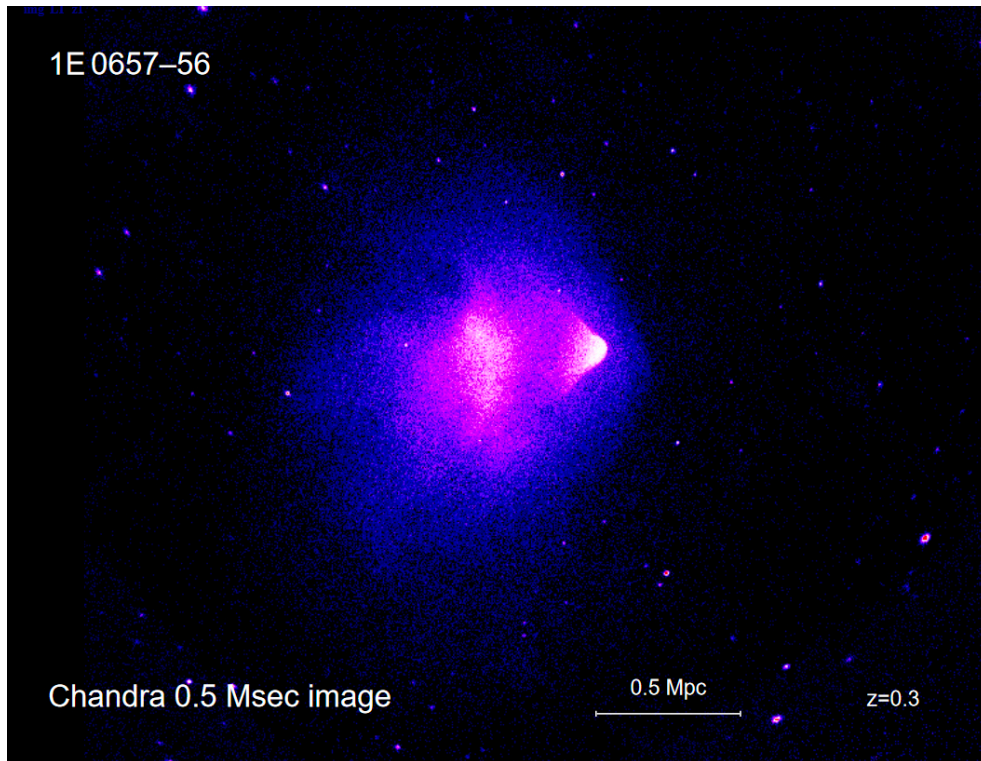
- One example of projections:
heavy neutral leptons
 - Can be long-lived
- **Significant part of the allowed parameter space under 100 GeV within the discovery reach of SHiP and FCC-ee at the Z-pole**



So... what were we trying to do again?

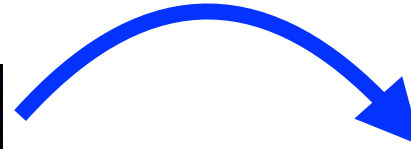
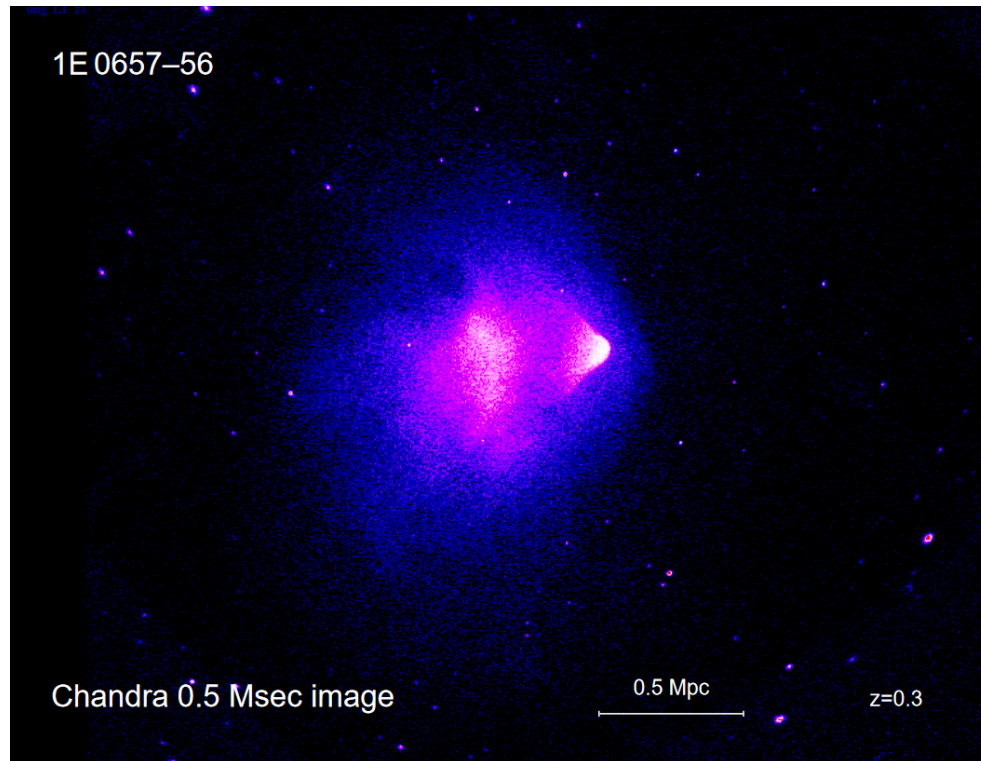
Fundamental scientific questions:

- Does the Higgs boson exist?
- What is the nature of dark matter?
- ...



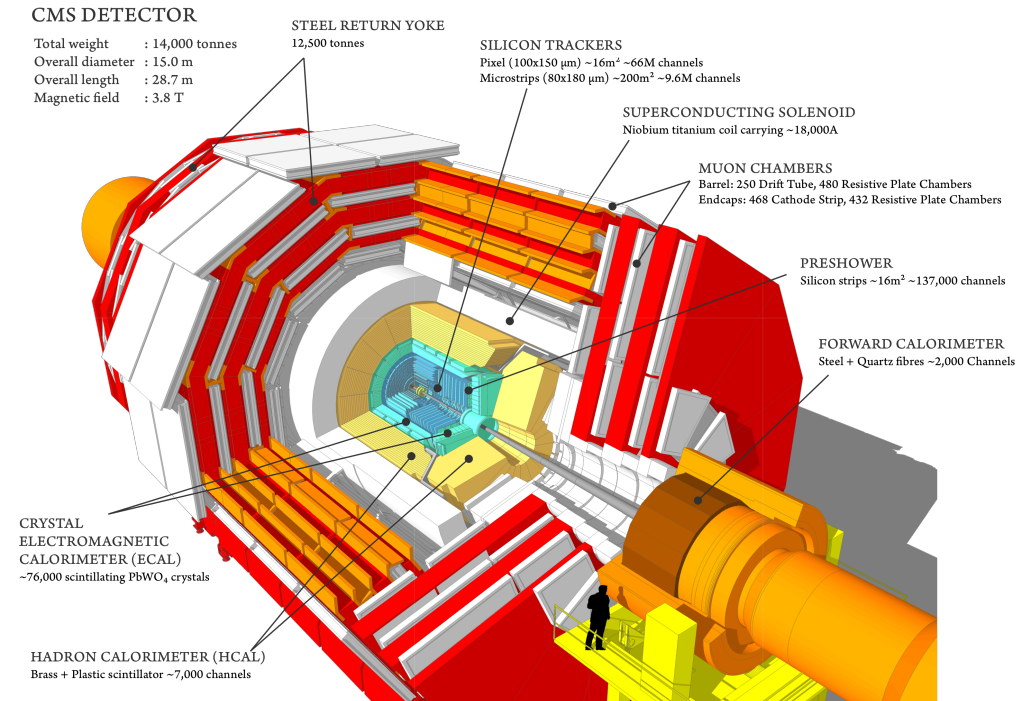
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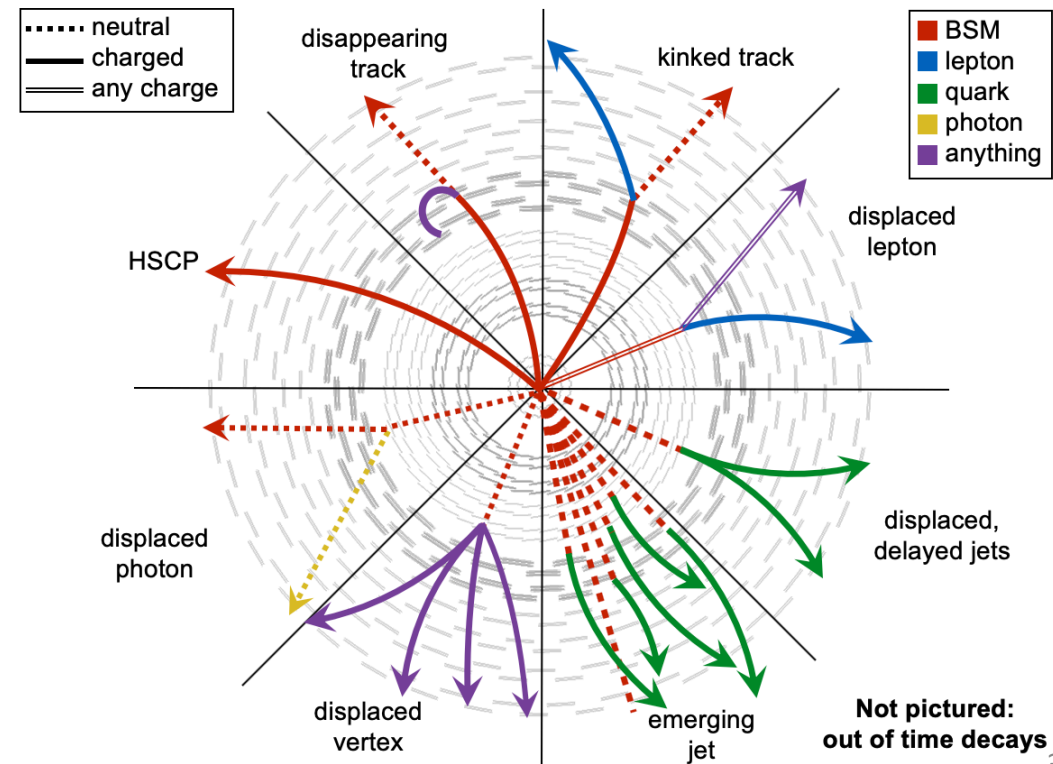
Build high energy colliders

- LHC and HL-LHC:
 - ATLAS, CMS, LHCb



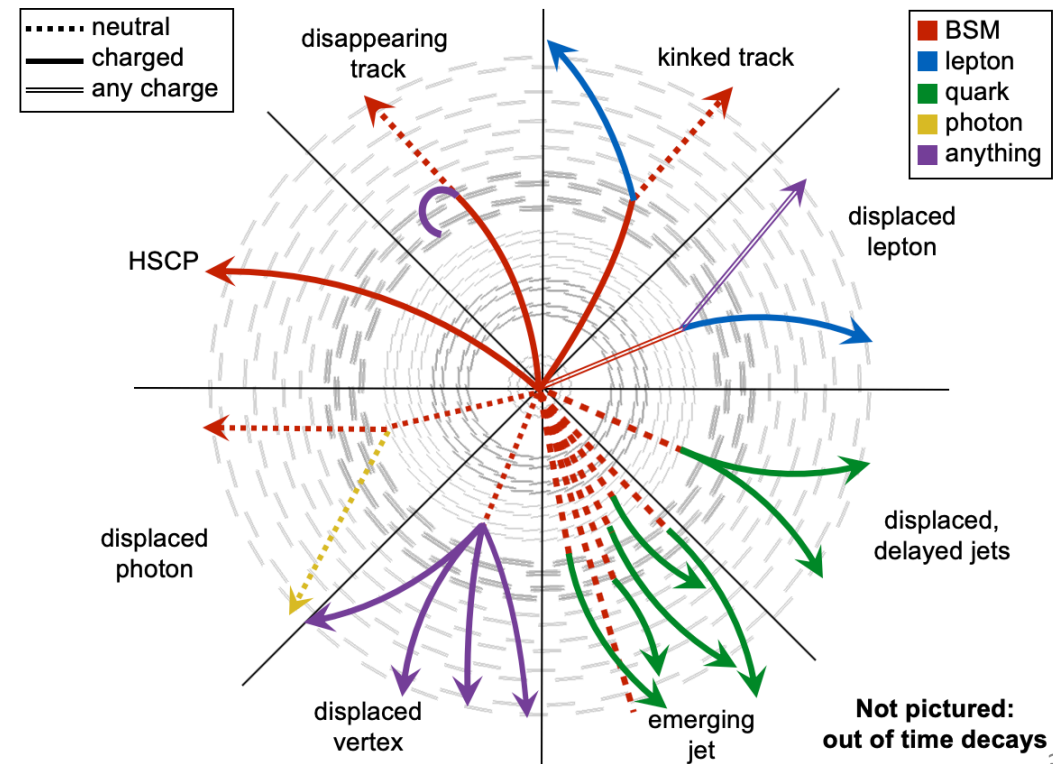
Exploit these colliders and detectors to the max

- Realize detectors **can do much more** than what they were initially designed for!
- **Look for new particles in ways not thought of** when the LHC was built!



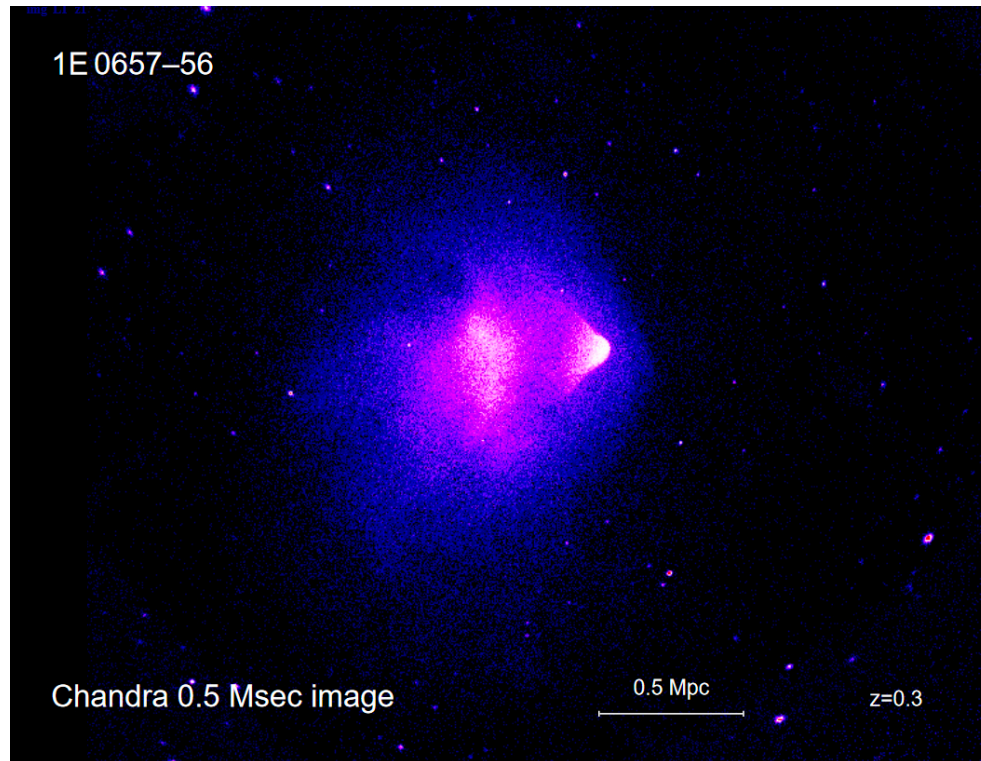
Exploit these colliders and detectors to the max

- **Challenging...** but lots of space for **creativity!**



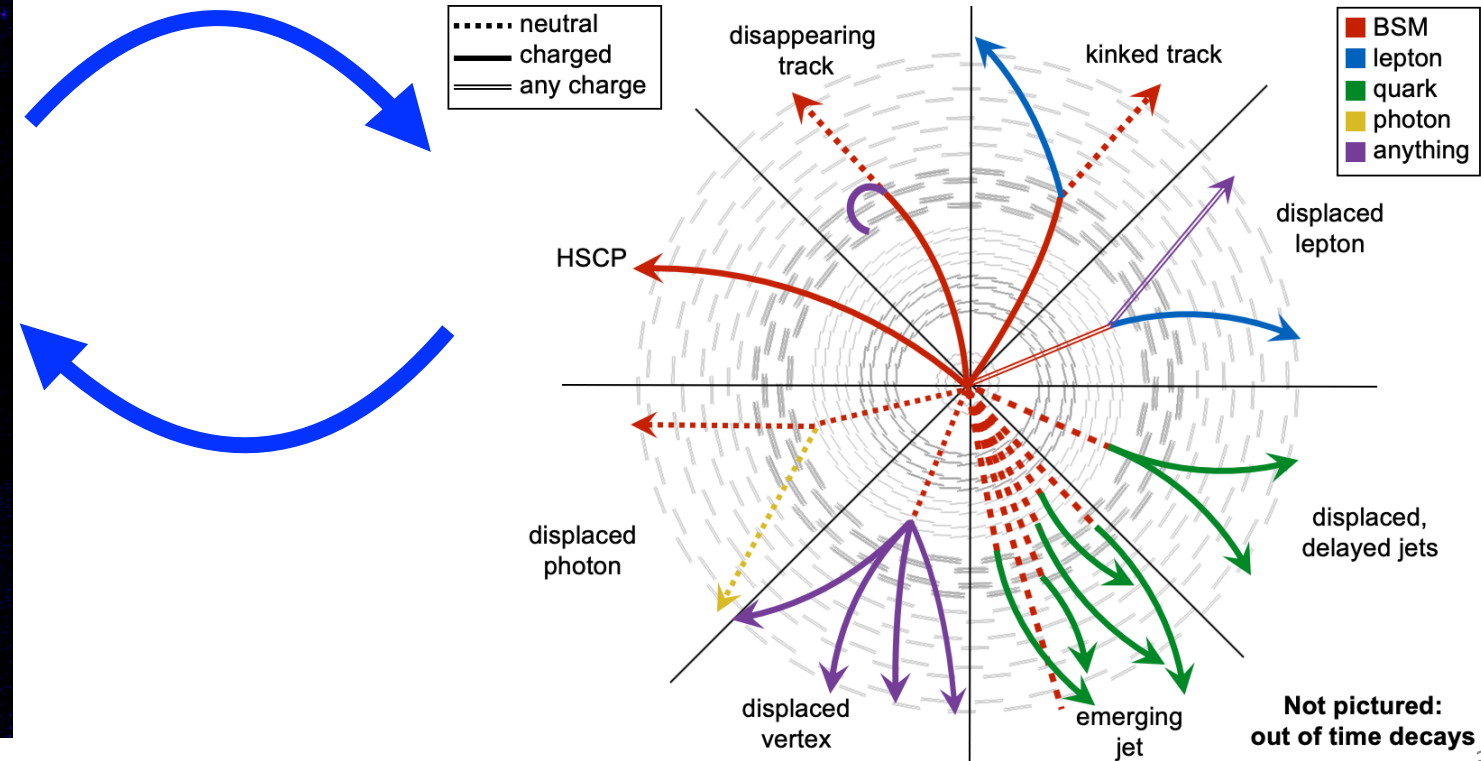
Again to address fundamental scientific questions:

- Does the Higgs boson exist?
- **What is the nature of dark matter?**
- ...



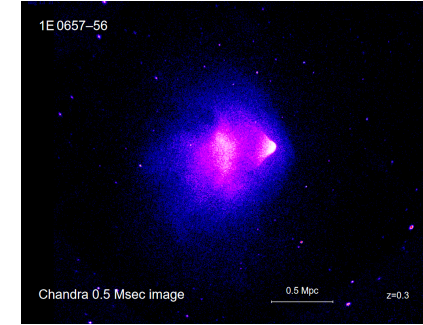
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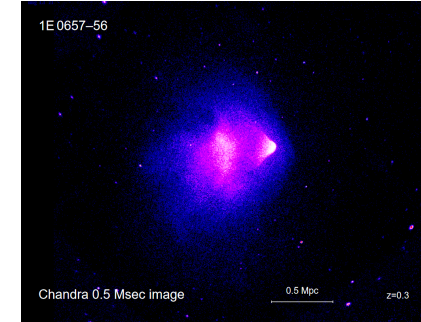
Take Home Points

- Lots of reasons to **search for new physics at the LHC**: unexplained observed phenomena like dark matter, neutrino masses, the hierarchy problem, etc.



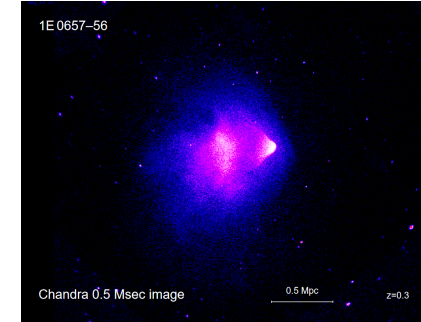
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- Performing a variety of searches for new particles at the LHC



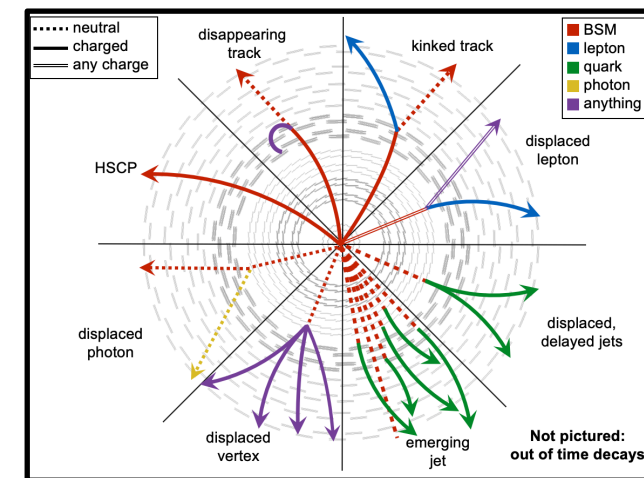
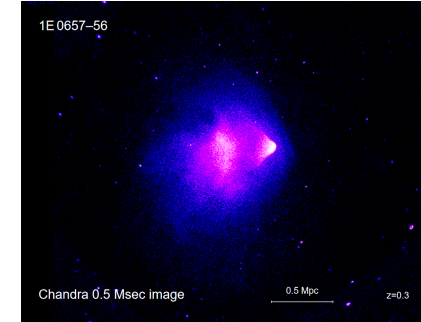
Take Home Points

- Lots of reasons to **search for new physics at the LHC**: unexplained observed phenomena like dark matter, neutrino masses, the hierarchy problem, etc.
- Performing a variety of searches for new particles at the LHC
- **But maybe we're searching in the wrong place**



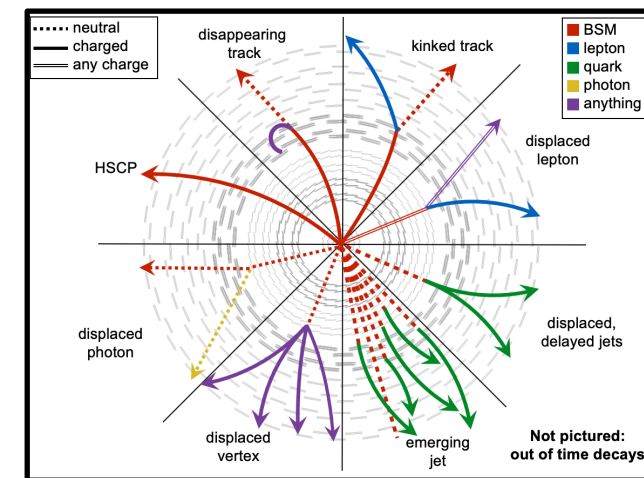
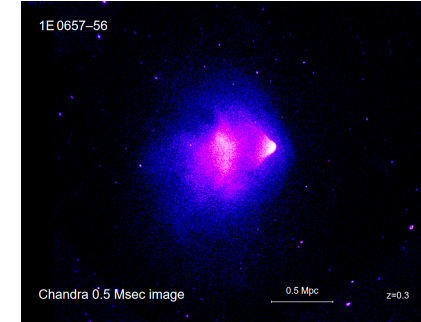
Take Home Points

- Lots of reasons to **search for new physics at the LHC**: unexplained observed phenomena like dark matter, neutrino masses, the hierarchy problem, etc.
- Performing a variety of searches for new particles at the LHC
- **But maybe we're searching in the wrong place**
- We should look for anything and everything that we're sensitive to, including **long-lived particles**



Take Home Points

- Lots of reasons to **search for new physics at the LHC**: unexplained observed phenomena like dark matter, neutrino masses, the hierarchy problem, etc.
- Performing a variety of searches for new particles at the LHC
- **But maybe we're searching in the wrong place**
- We should look for anything and everything that we're sensitive to, including **long-lived particles**
- **Exciting time for searches at the LHC, HL-LHC, and beyond!**



Interested in joining us?

- One option: The Quantum Universe Cluster of Excellence (U Hamburg + DESY) was recently renewed
- [Quantum Universe Attract. Workshop](#)
 - 23–25 Nov 2025
- Talk to me, [Henriette Ullmann](#), [Katharina Behr](#), and others!

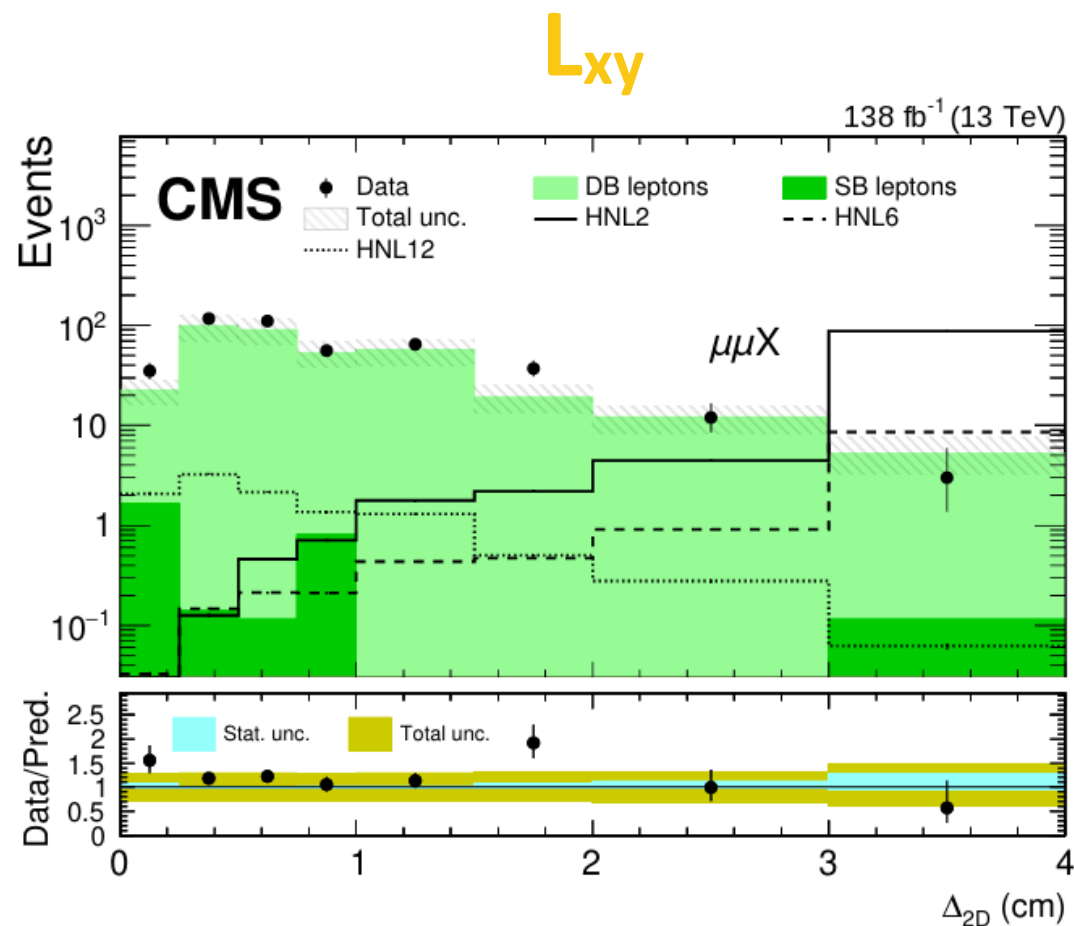
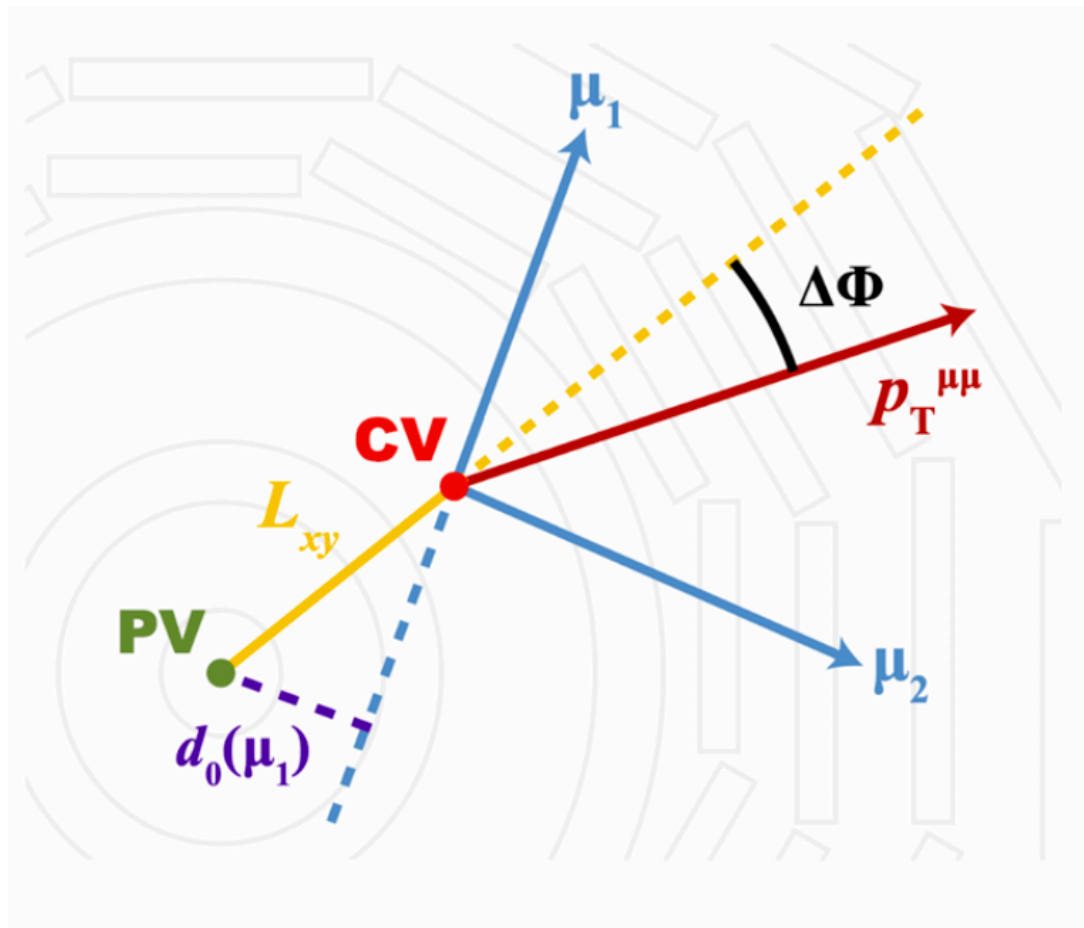


Maybe **YOU** will be the next
to discover something!

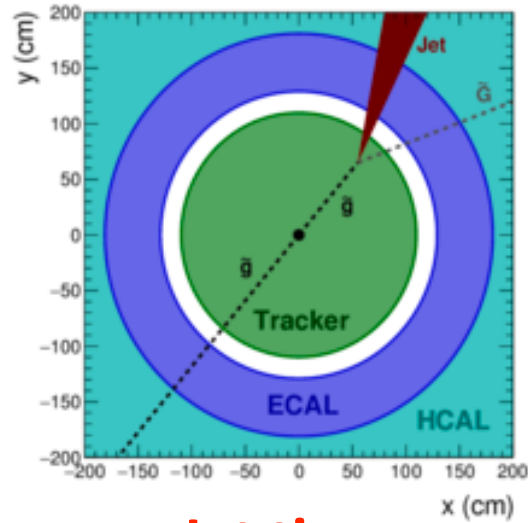


Backup

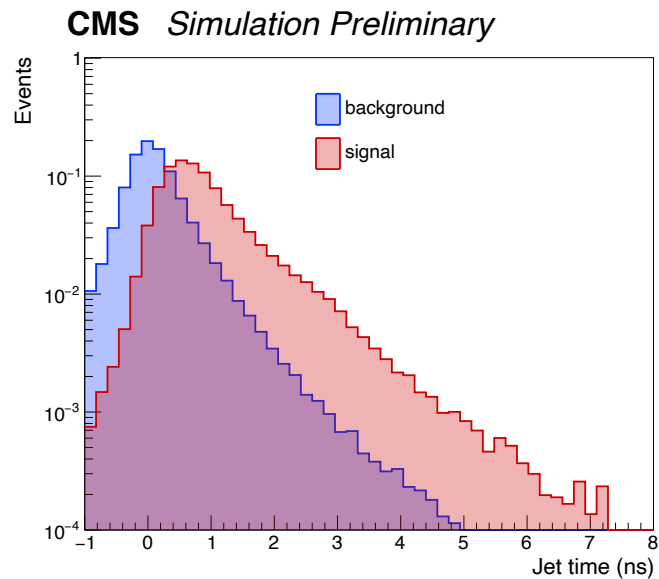
Example LLP Discriminating Variables: Displacement



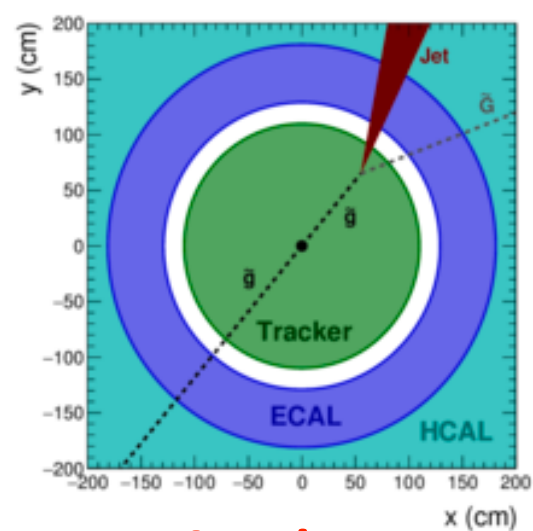
Example LLP Discriminating Variables: Delayed Time of Arrival



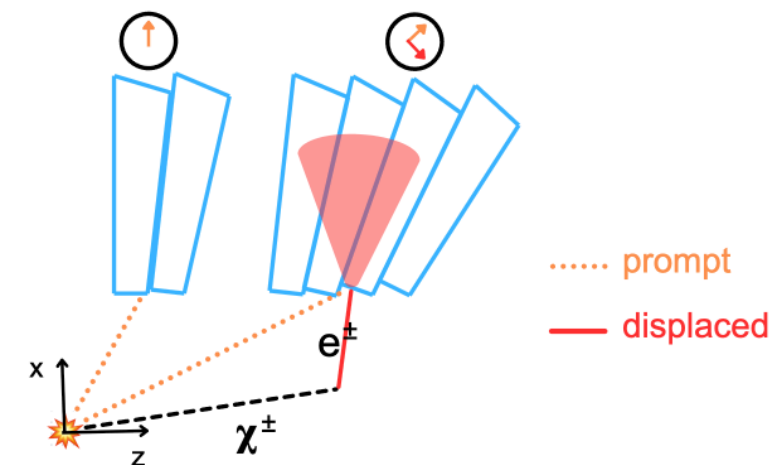
Jet time



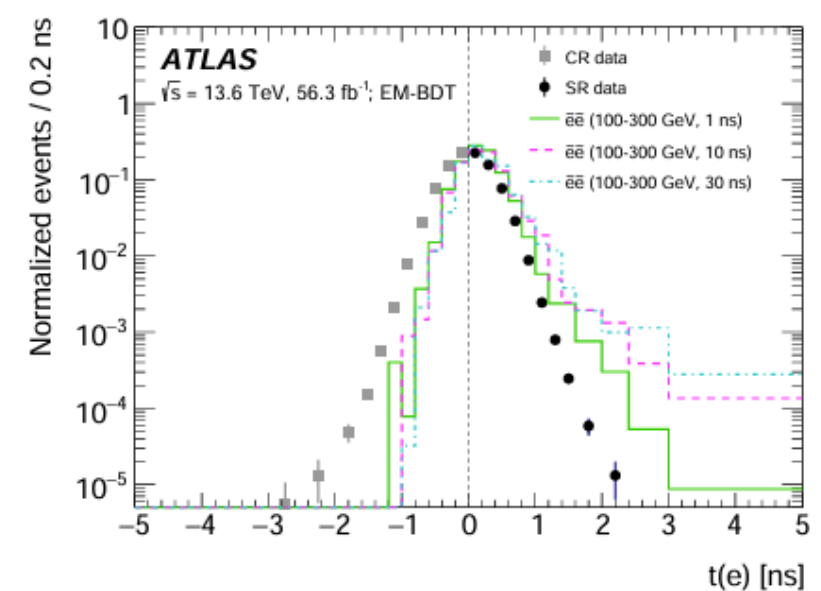
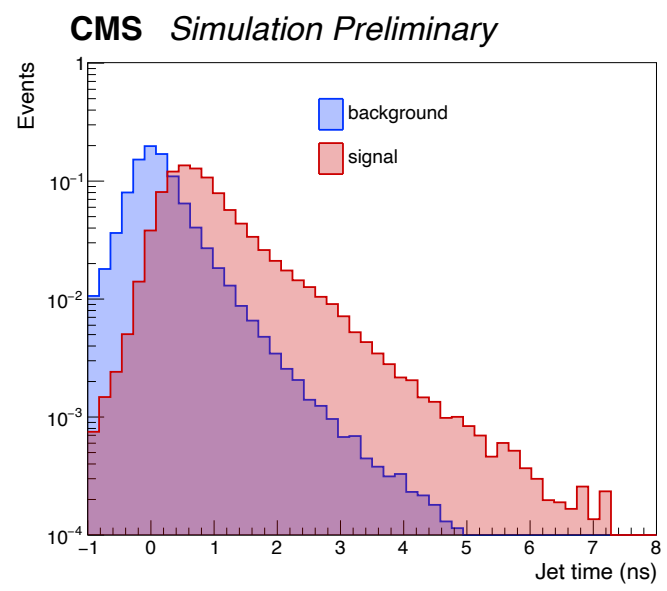
Example LLP Discriminating Variables: Delayed Time of Arrival



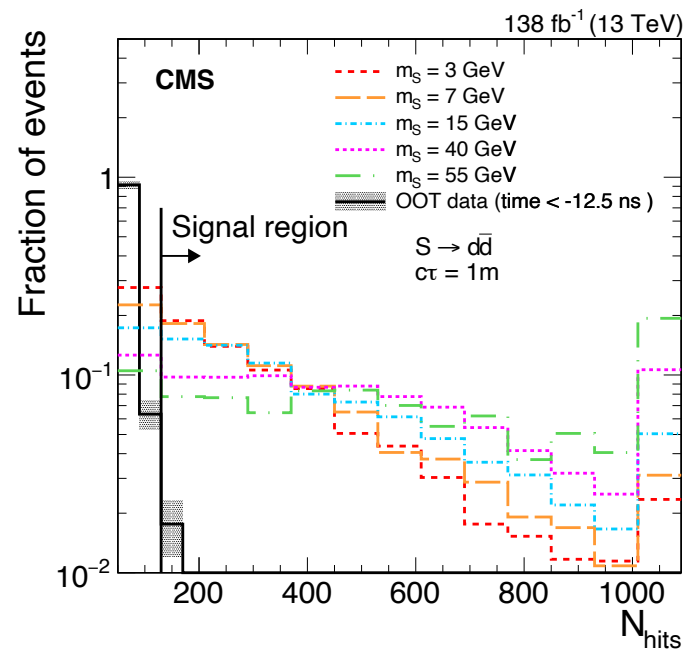
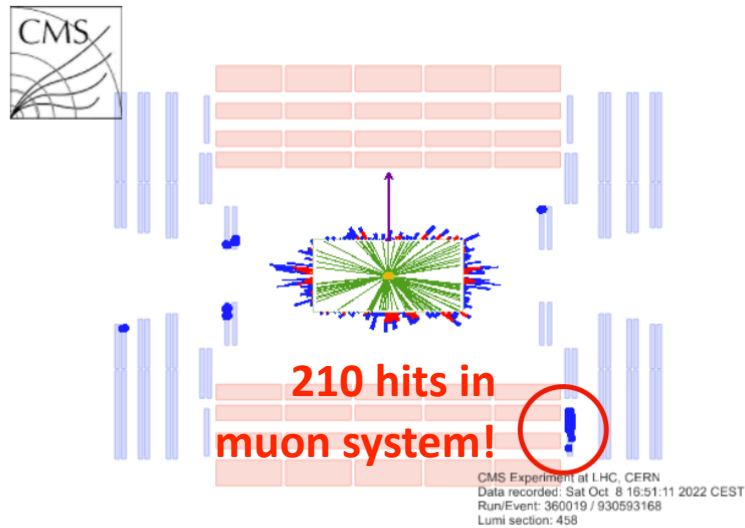
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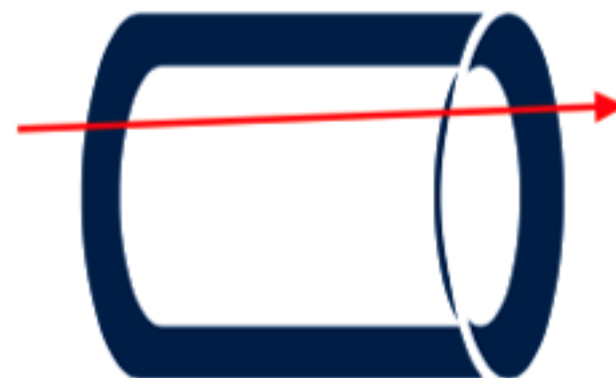
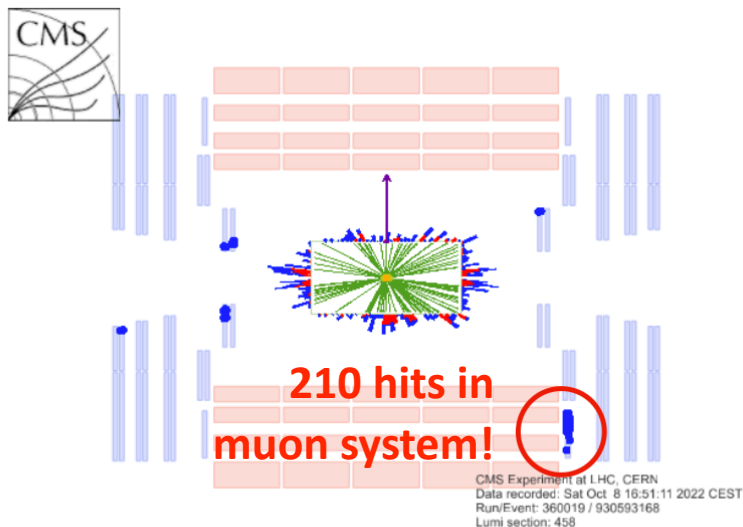
Electron time



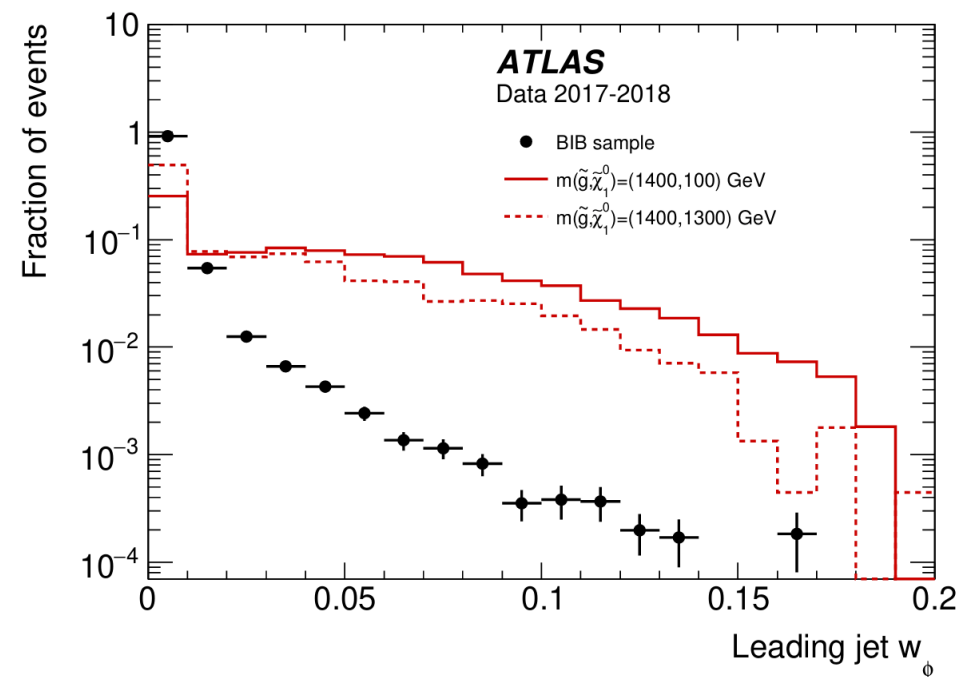
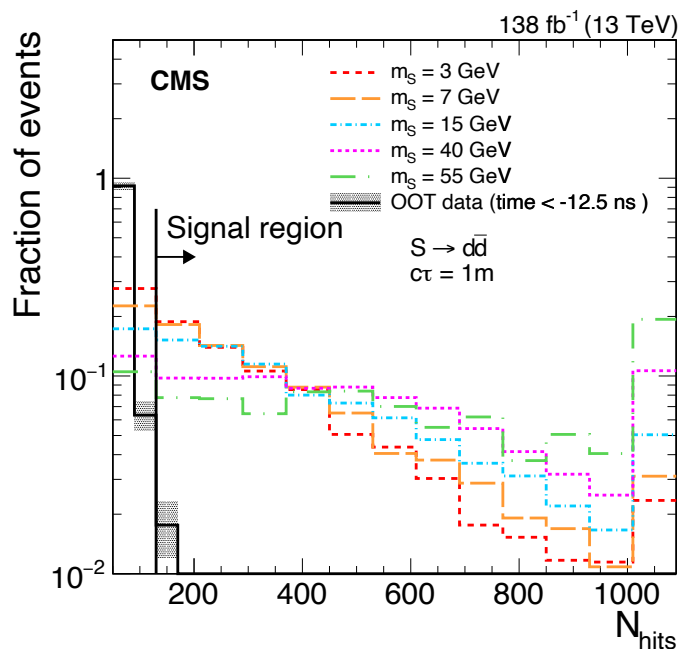
Example LLP Discriminating Variables: More Exotic



Example LLP Discriminating Variables: More Exotic



Jets from beam-induced background tend to be narrow in ϕ



LLP Triggers

- Long-lived particles could leave unique signatures that **may not captured by standard triggers**
- **Dedicated triggers** targeting different LLP signatures enable increased sensitivity to wide variety of signal models
- At CMS, during Run 3, variety of such triggers were **introduced and/or improved** compared to Run 2
- The performance of these triggers in 2022-2024 data and their **powerful complementarity** is the crux of this new preliminary result: [PAS-EXO-23-016](#)

