Searching for Long-Lived Particles at the LHC and Beyond

Juliette Alimena (DESY)

Colloquium at Paul Scherrer Institut

October 3, 2024

Outline

The road ahead

Latest results

- From the LHC and beyond

Intro to Long-Lived Particles

- Why
- What
- How (basically)

The road ahead

Latest results

- From the LHC and beyond

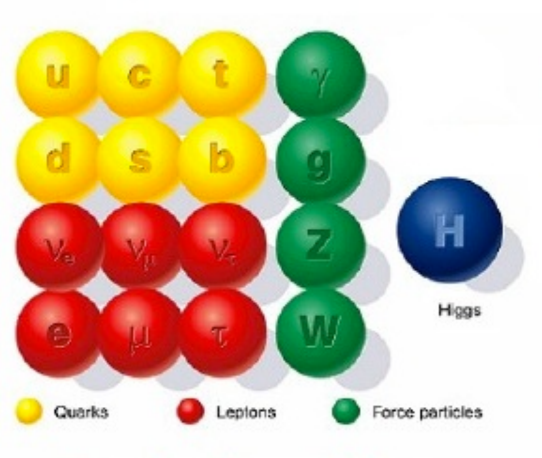
Intro to Long-Lived Particles

- Why
- What
- How (basically)

What is everything made of?

The Standard Model (SM)

Highly successful theory of
fundamental particle interactions

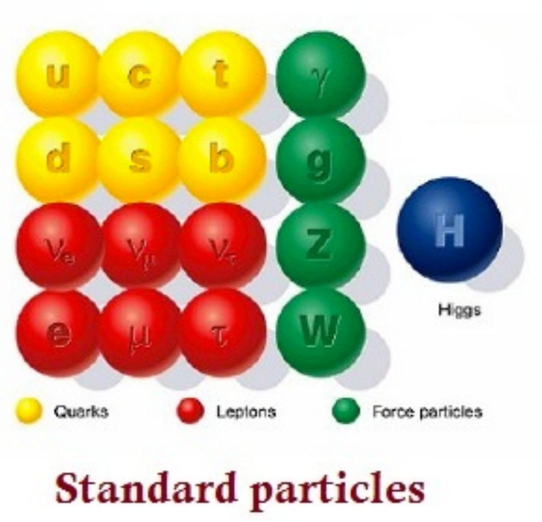


Standard particles

What is everything made of?

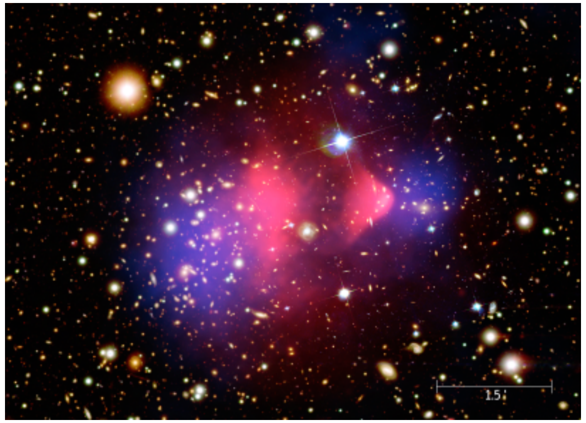
The Standard Model (SM)

Highly successful theory of fundamental particle interactions

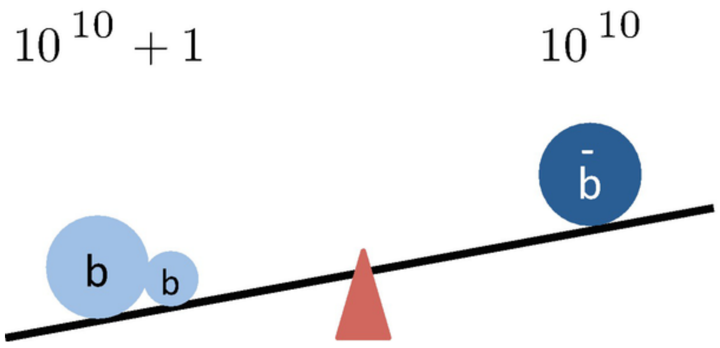


However, there are still many outstanding questions, e.g.:

Dark matter

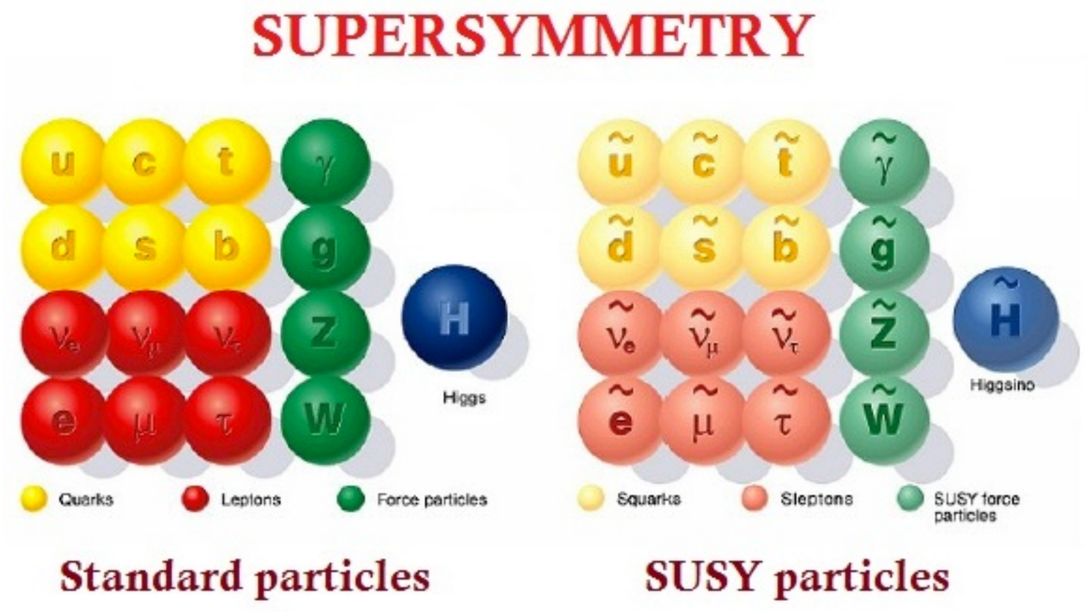


Matter-antimatter asymmetry



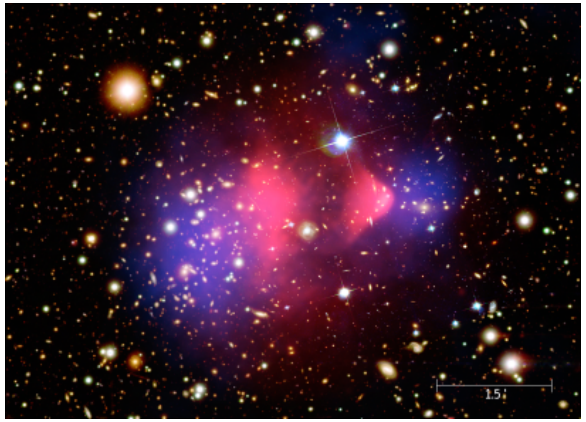
What is everything made of?

Many theories beyond the SM (BSM):

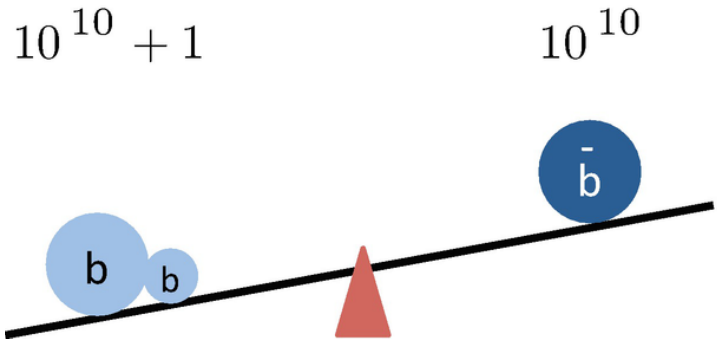


However, there are still many outstanding questions, e.g.:

Dark matter



Matter-antimatter asymmetry

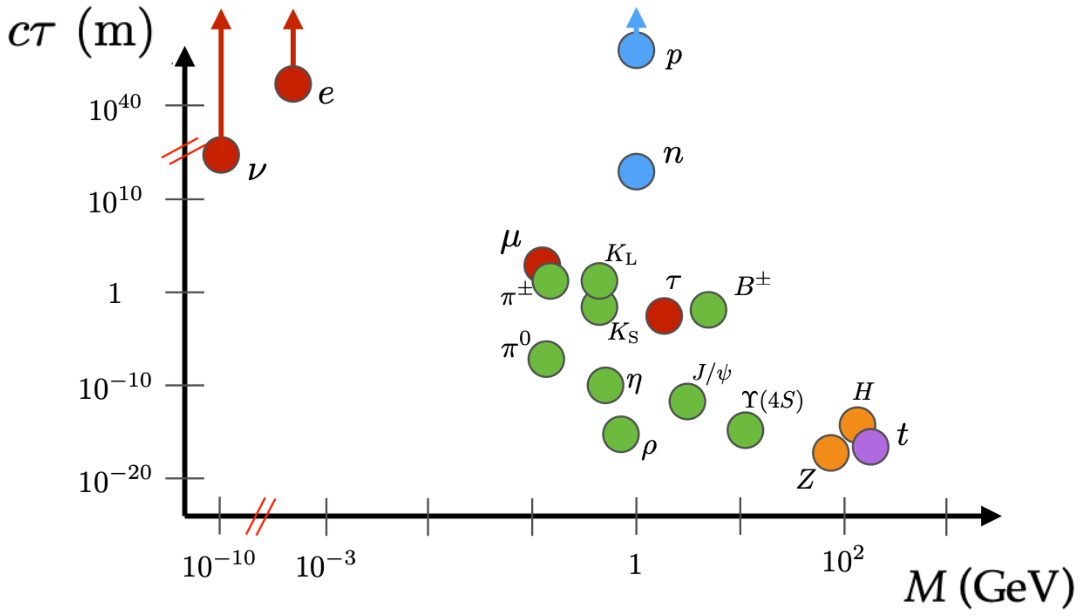


But no significant sign of new phenomena at the LHC yet!

Are we looking in the wrong place?

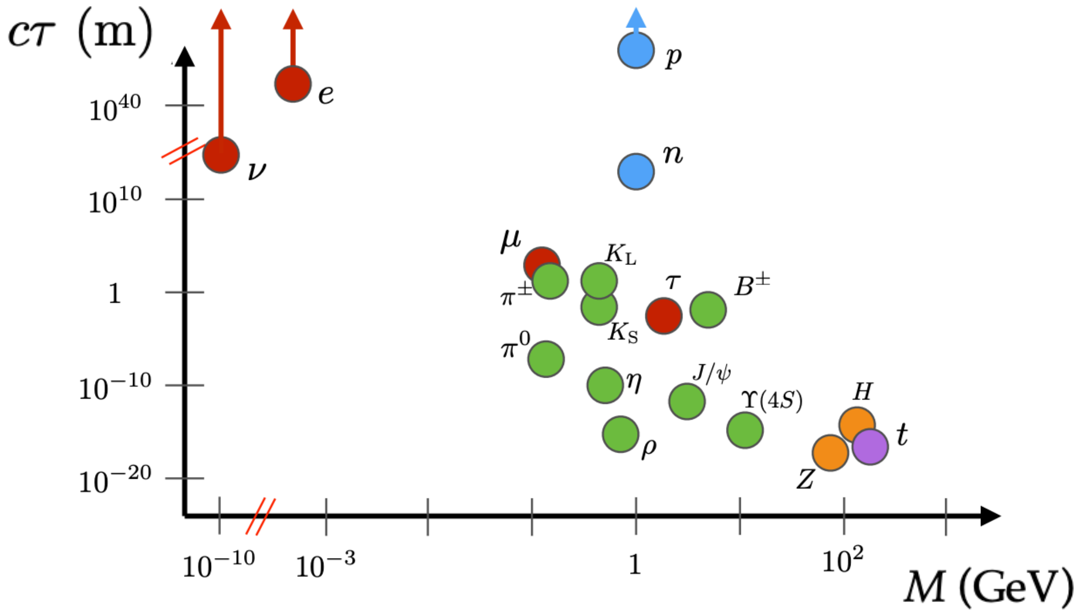
Long-Lived Particles (LLPs)

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



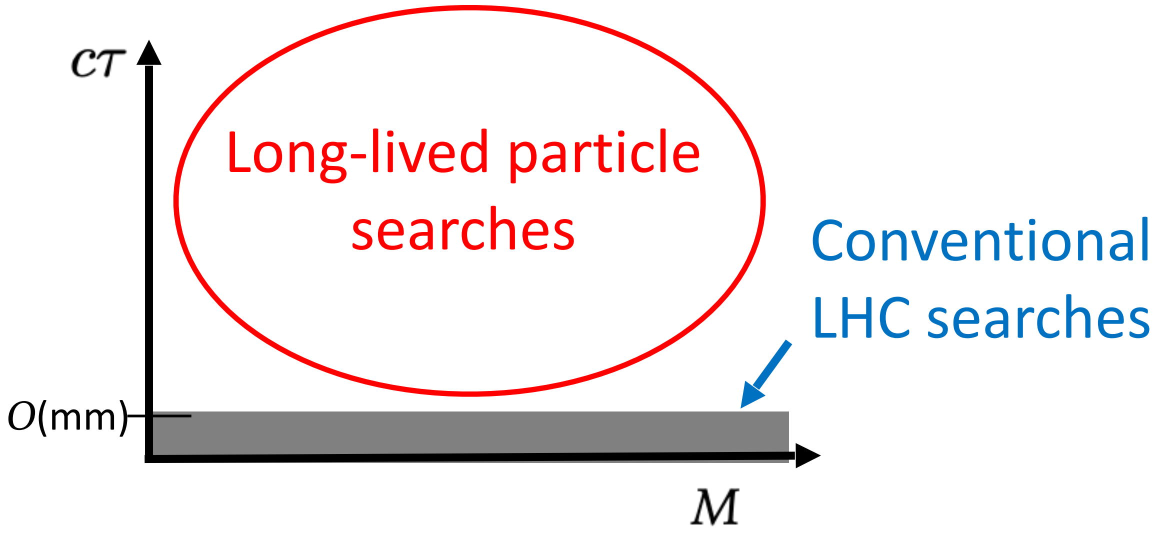
Long-Lived Particles (LLPs)

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!

… and we need it now! (LHC Run 3)

- No significant sign of new phenomena at the LHC yet
- BSM phenomena must either be rarely produced or beyond the reach of our detectors/reconstruction
- LHC already operates close to the maximum center-of-mass energy
- If we're going to find new phenomena at the LHC, it will be in uncovered regions of phase space
- **We need to search for unconventional signatures now!**

How You Get LLPs

- Mechanisms to produce BSM long-lived particles are the same ones as those that give us long-lived particles in the SM

- Three main ways:
  - Heavy (off-shell) mediator
  - Small couplings
  - Compressed spectra

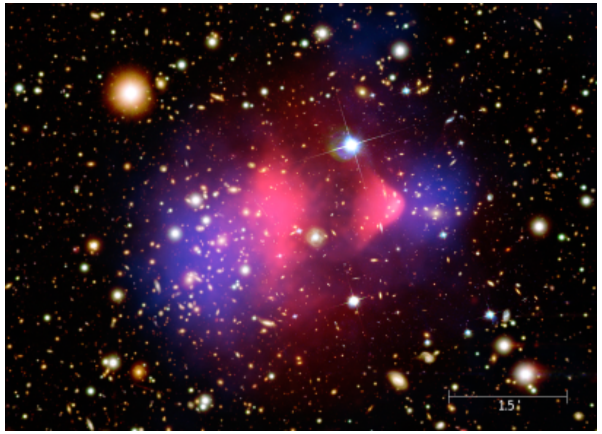
e.g. $\pi^\pm \to \mu^\pm \nu_\mu$ ($c\tau \sim 7.8$m)

$$\tau = \frac{8\pi}{f_\pi^2 G^2 m_\mu^2 m_\pi} \left(\frac{m_\pi^2}{m_\pi^2 - m_\mu^2} \right)^2$$

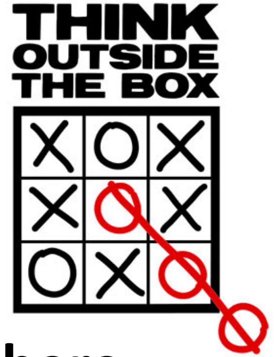
small coupling, heavy mediator

compressed spectra

Why Search for New LLPs?



- **LLPs appear in many BSM scenarios**
  - Nearly mass-degenerate states (compressed SUSY, AMSB, etc.)
  - Heavy virtual mediators (split-SUSY, heavy neutral leptons, etc.)
  - Small couplings (dark photons, freeze-in DM, RPV SUSY, etc.)
  - *The lifetime is a free parameter of the model, although it can be constrained by cosmology (Big Bang Nucleosynthesis)*



- **Can provide a dark matter candidate**
  - DM could be the LLP itself, or produced in association with the LLP
- **Why not?**
  - No significant 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

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

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

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

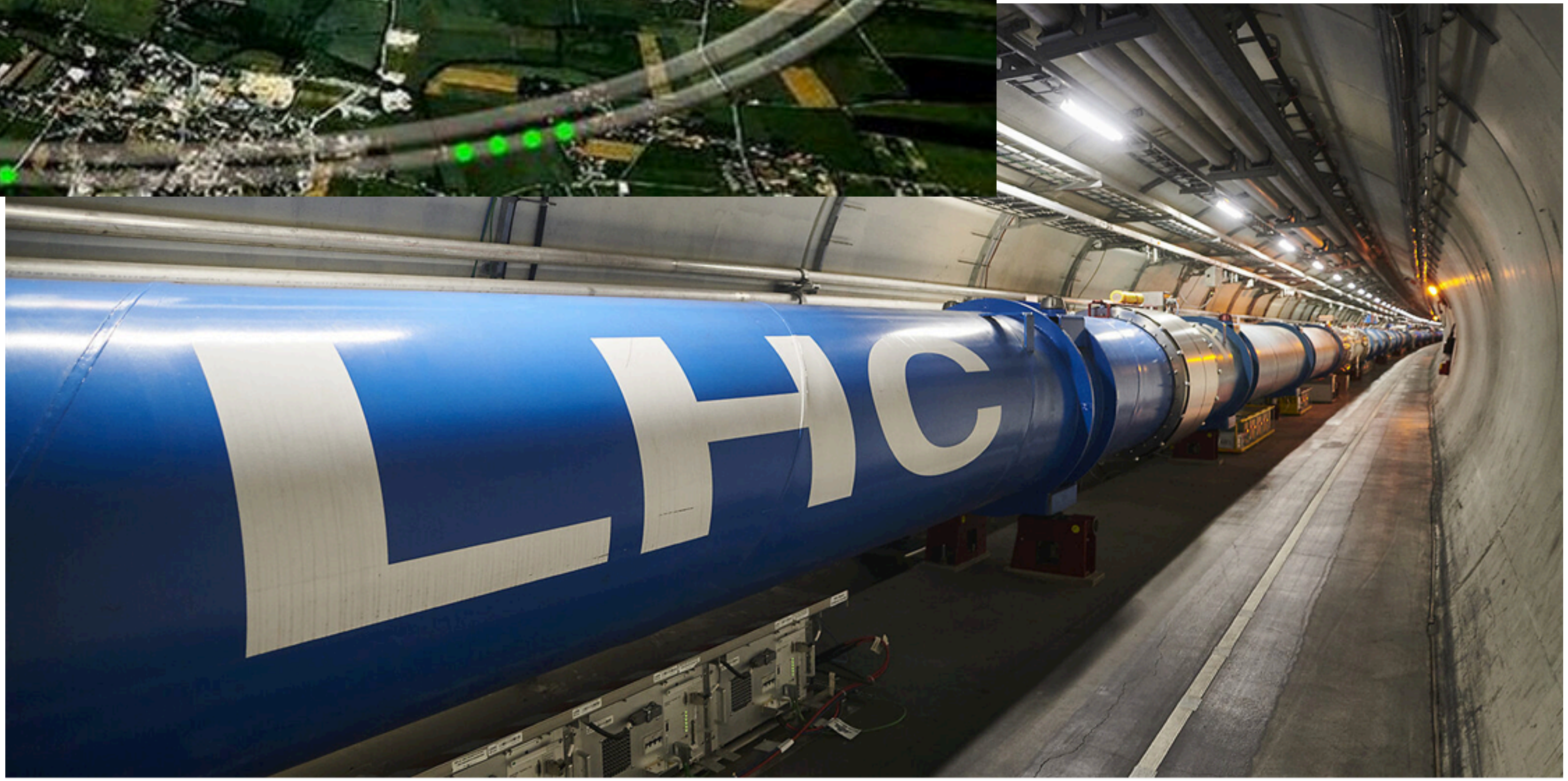
  or

  is quasi-stable on the scale of the detector

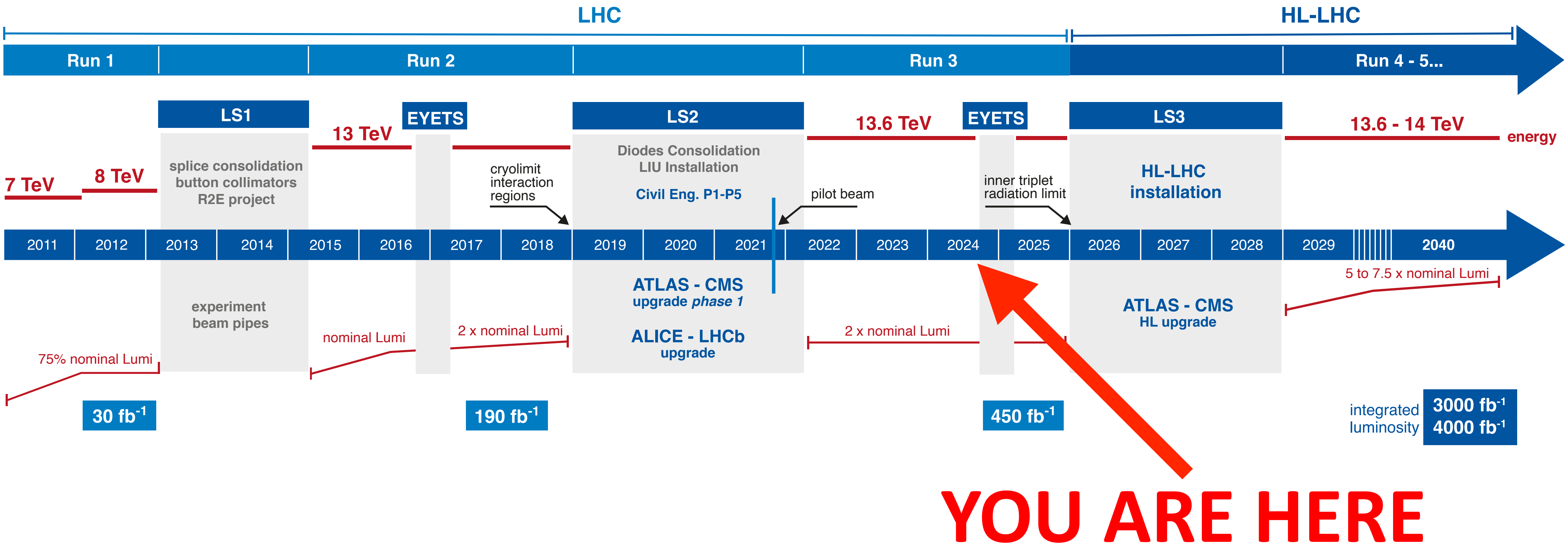
- They can:
  - be **charged,** neutral or have color
  - be light or heavy
  - travel fast or slow
  - decay to anything

- They often require dedicated searches or dedicated experiments

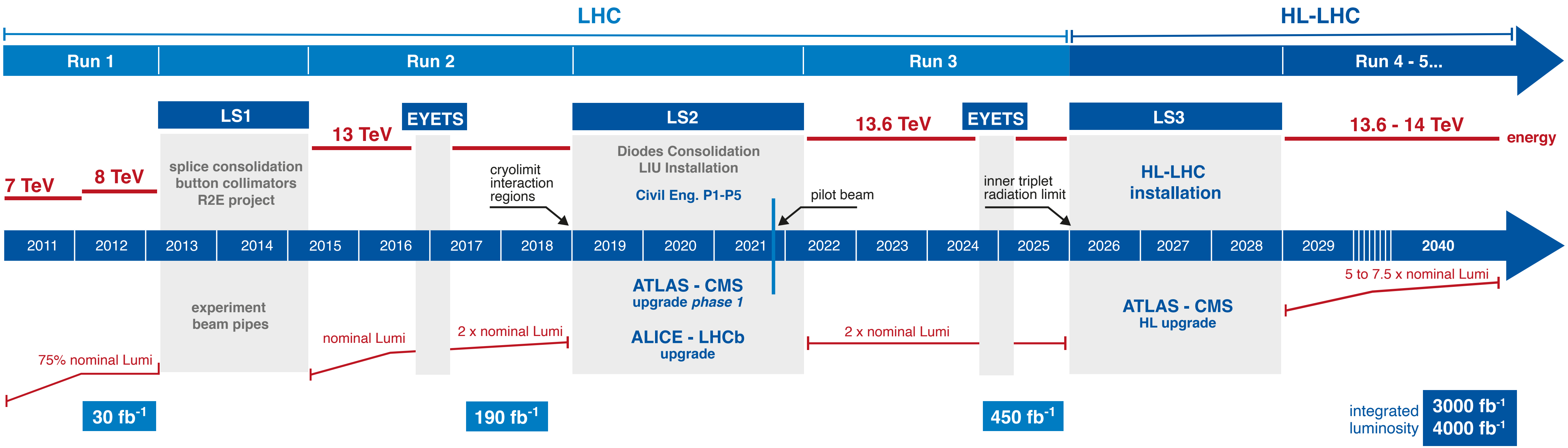
The Large Hadron Collider



LHC Timeline

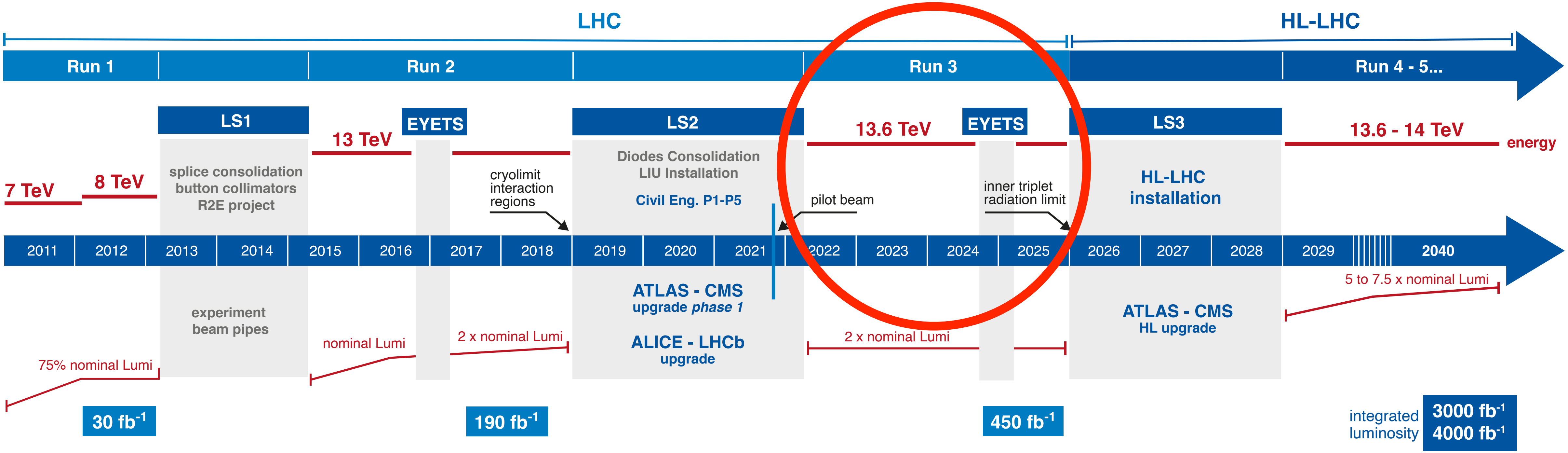


LHC Timeline



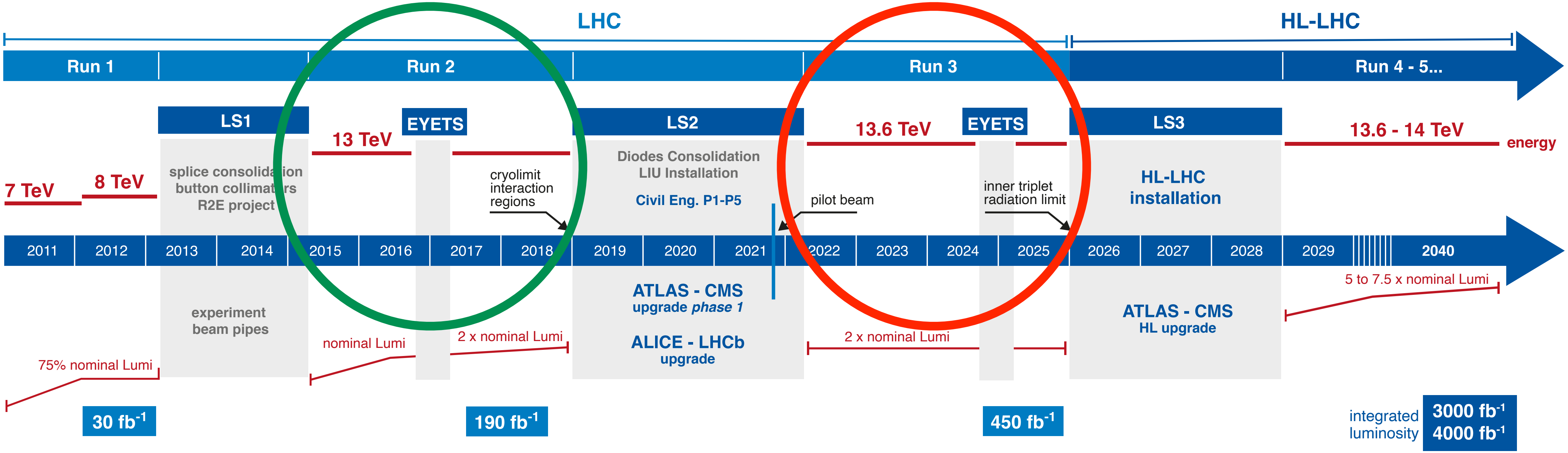
- **More than 10 years** of successful operation of the LHC!

LHC Timeline



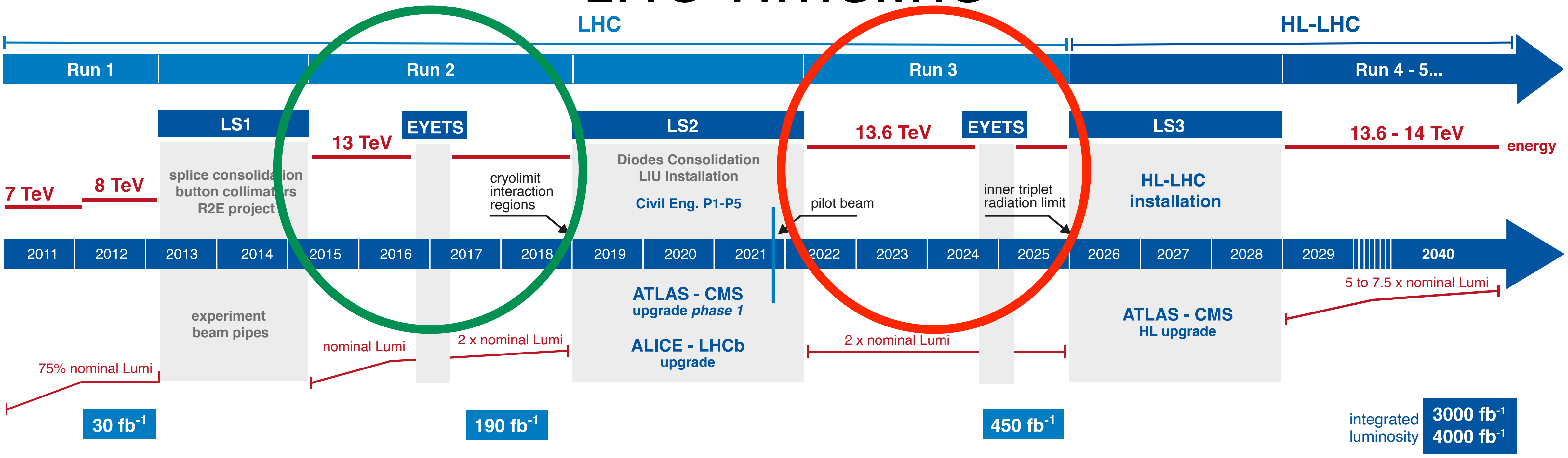
- **More than 10 years** of successful operation of the LHC!
- **Run 3** is well underway

LHC Timeline



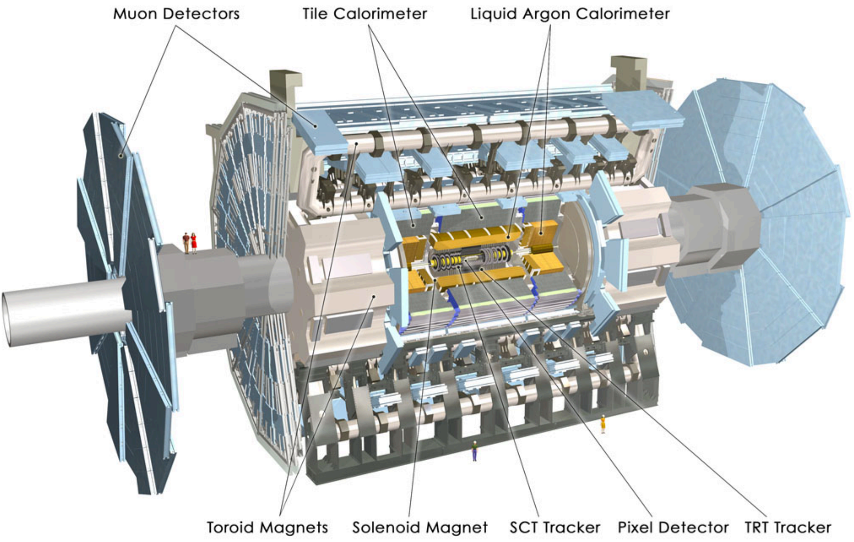
- **More than 10 years** of successful operation of the LHC!
- **Run 3** is well underway
- Still **publishing analyses** with the well-understood (and still top-notch!) **Run 2** data set, but beginning to add Run 3 data (more data! new tools! improved reach!)

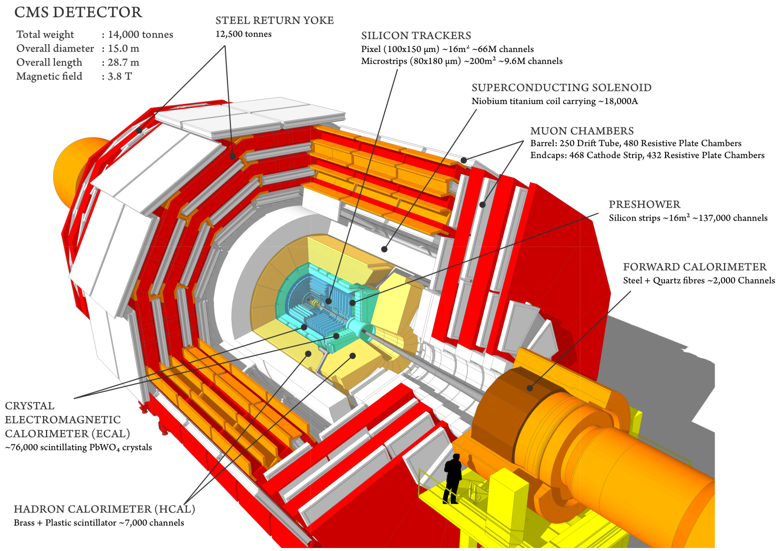
LHC Timeline

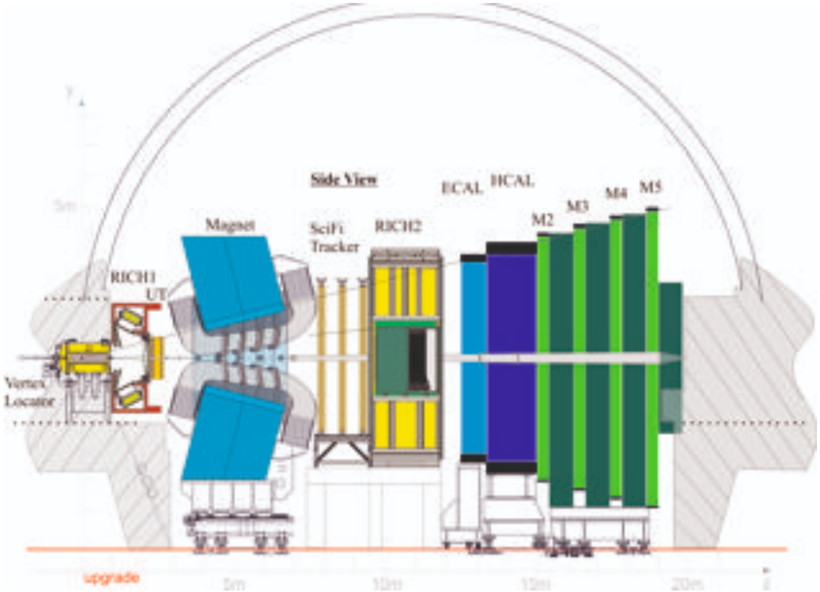


- **More than 10 years** of successful operation of the LHC!
- **Run 3** is well underway
- Still **publishing analyses** with the well-understood (and still top-notch!) **Run 2** data set, but beginning to add Run 3 data (more data! new tools! improved reach!)
- **Superb operation efficiency** for the experiments
    - Usually > 90% efficient for both CMS and ATLAS (data taking + data quality)

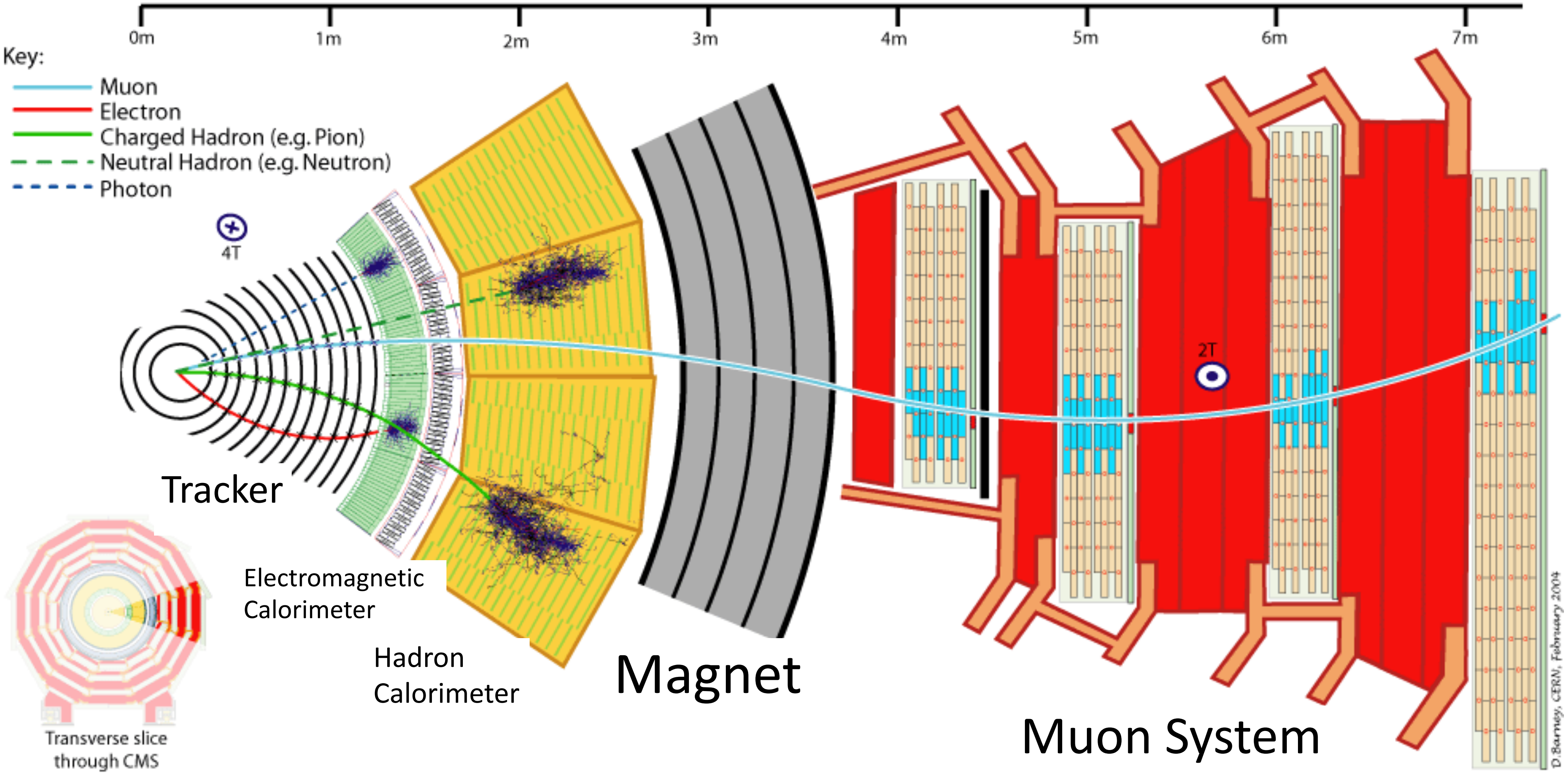
General-Purpose LHC Experiments







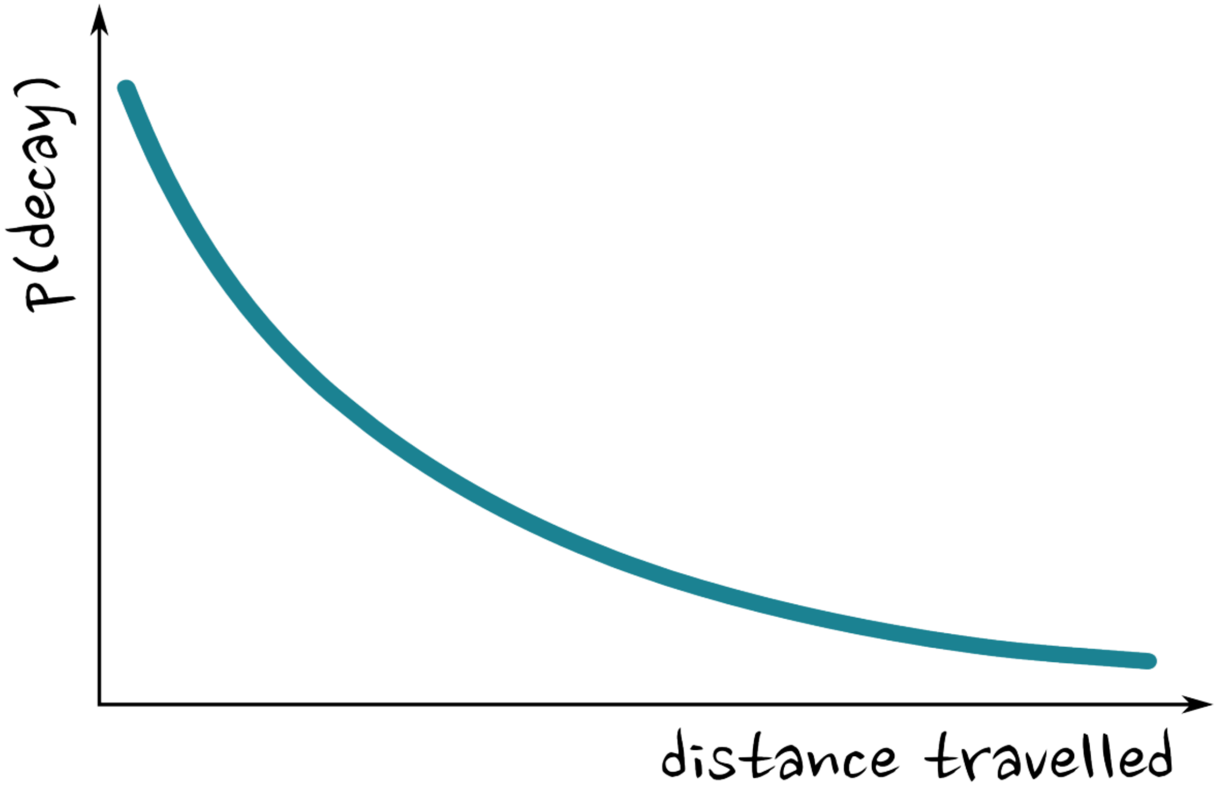
Anatomy of a General-Purpose Detector



Adapted from Heather Russell

Long Lifetimes

Any given particle's lifetime is sampled from an exponential



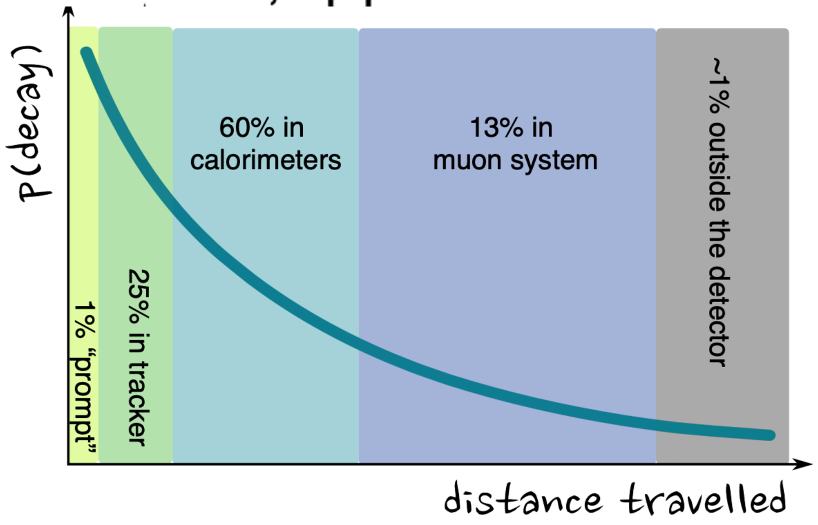
Adapted from Heather Russell

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 cτ = 5 cm, <βγ> ~ 30

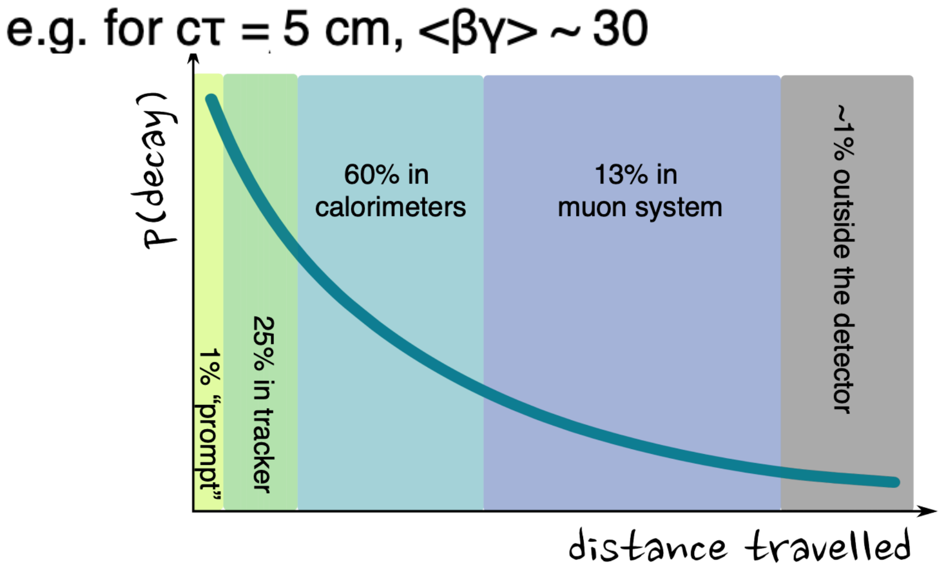


Adapted from Heather Russell

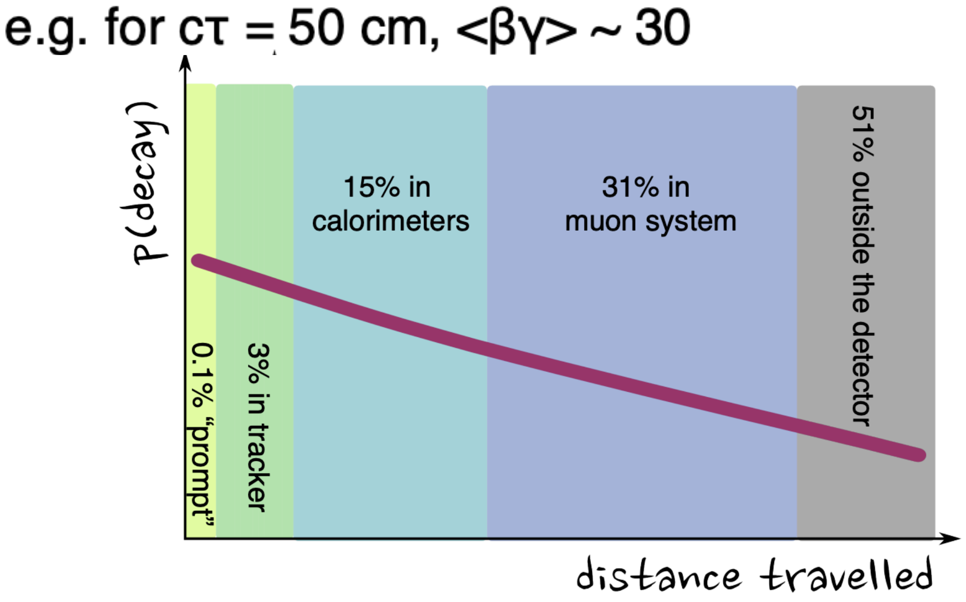
Long Lifetimes and the Detector

Any given particle's lifetime is sampled from an exponential

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



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



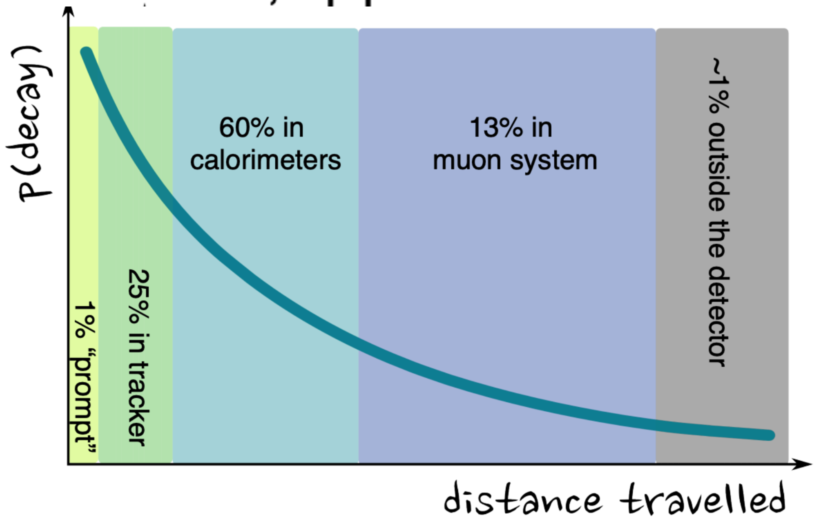
Adapted from Heather Russell

Variety of LLP Searches

Any given particle's lifetime is sampled from an exponential

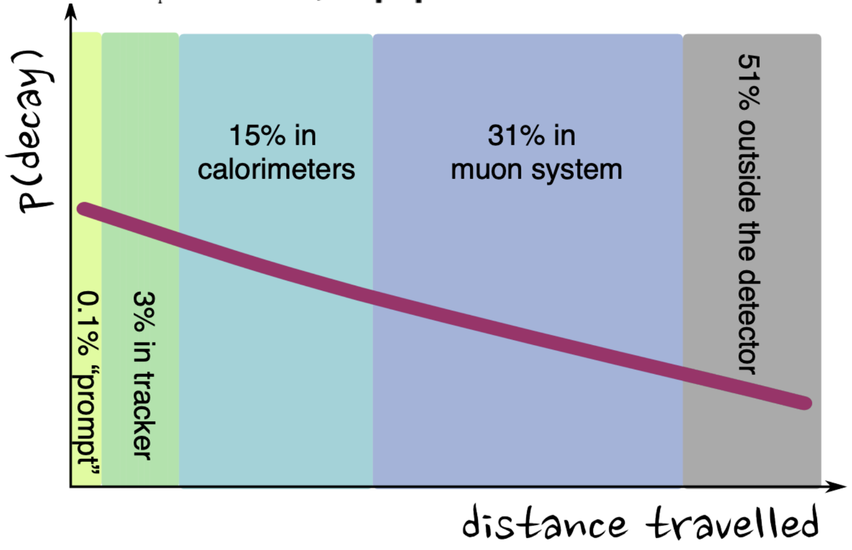
Even particles with a **short proper lifetime can decay far** from the interaction:

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



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

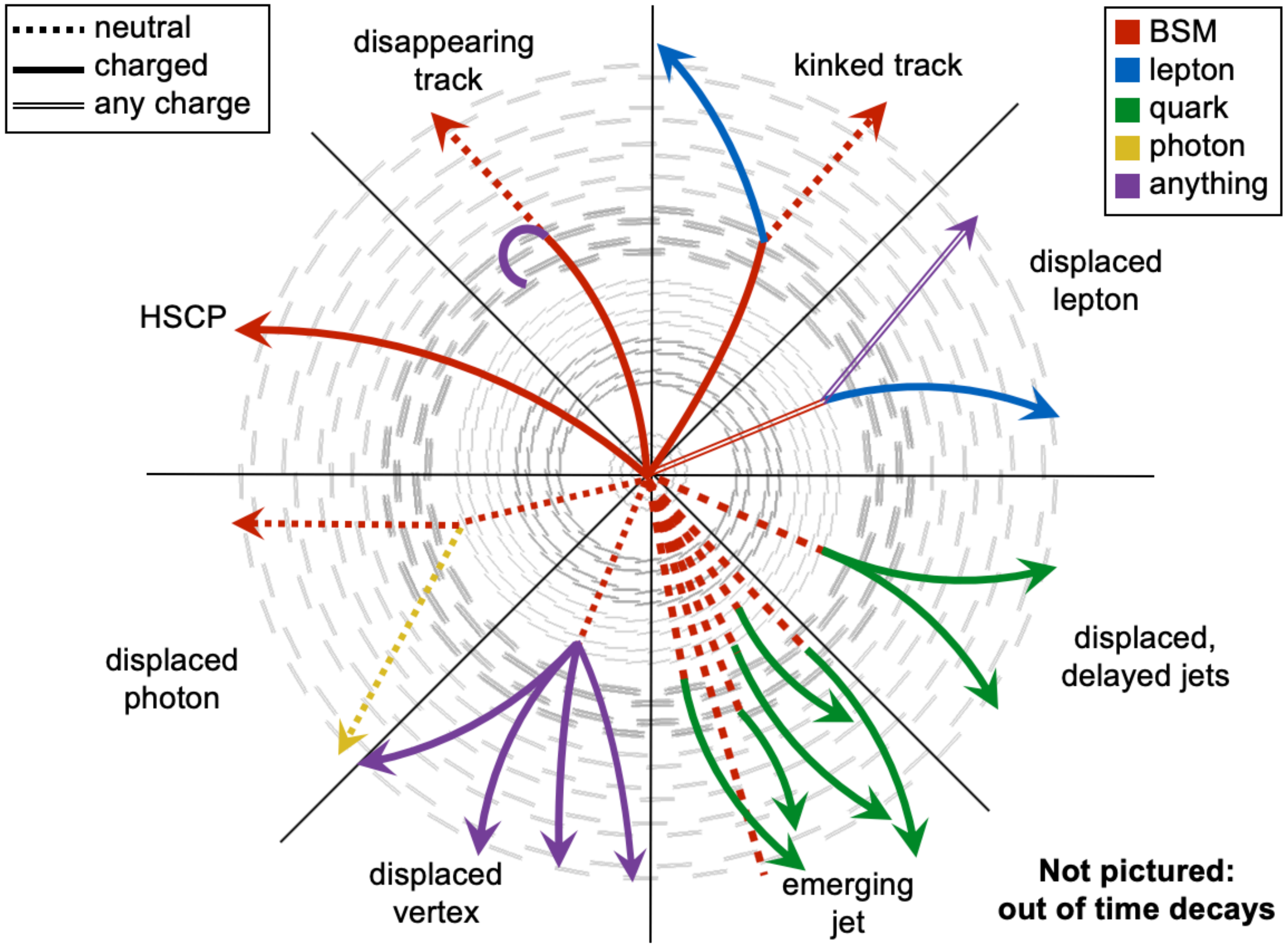
e.g. for $c\tau$ = 50 cm, $\langle\beta\gamma\rangle \sim 30$



Lifetime, mass, decay products, boost, etc. dramatically affect the detector signature, and thus we use all subdetectors… and also dedicated/auxiliary LLP detectors!

Long-Lived Particle Searches

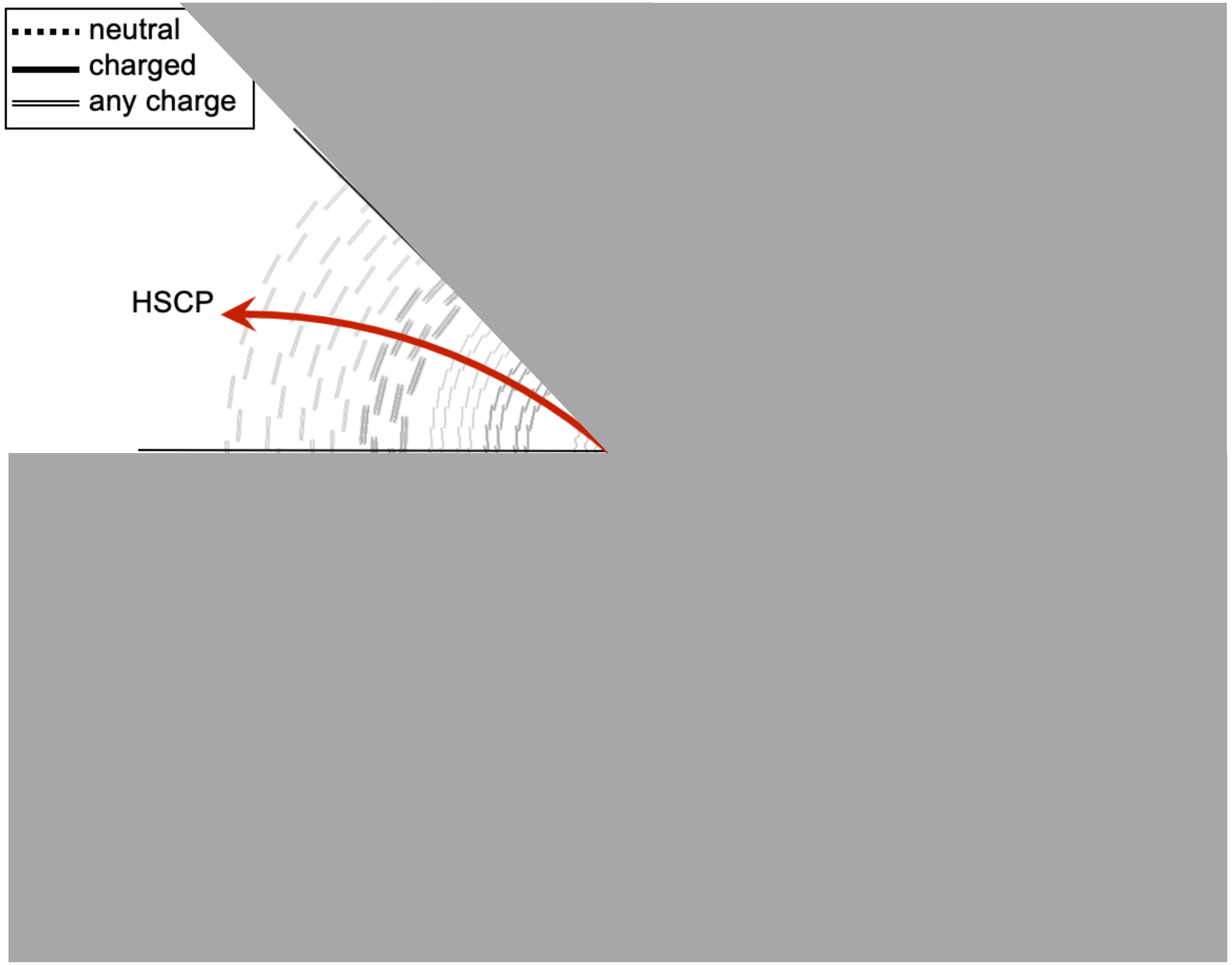
- **Wide variety** of:
  - Charges
  - Final states
  - Decay locations
  - Lifetimes
- Design **signature-driven** searches
- Often interpret results with a **benchmark model**, but can expand to a **variety of scenarios**



Long-Lived Particle Searches

Can search for LLPs that decay:

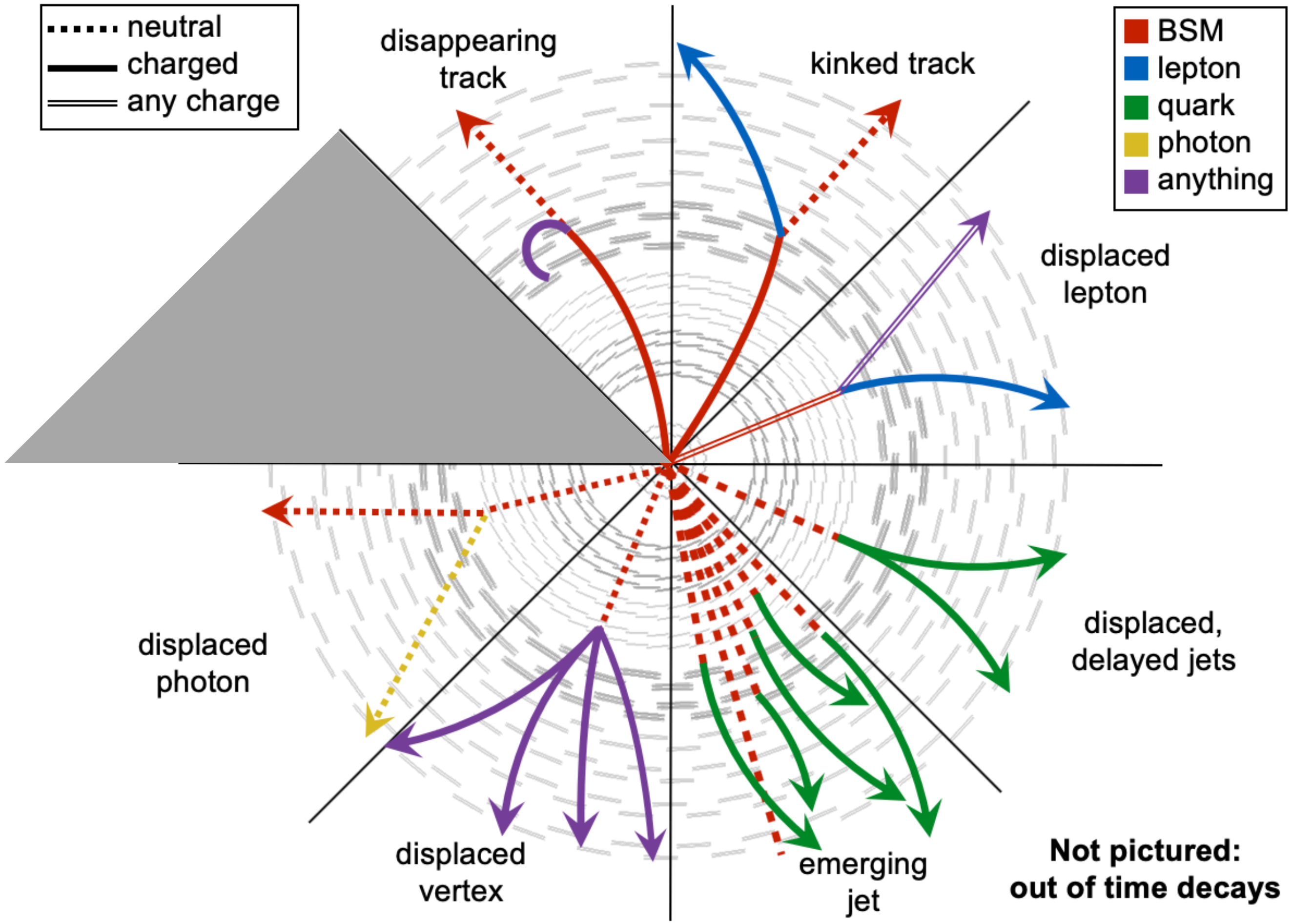
- **Outside of the detector**
-



Long-Lived Particle Searches

Can search for LLPs that decay:

- Outside of the detector
- **Within the detector**



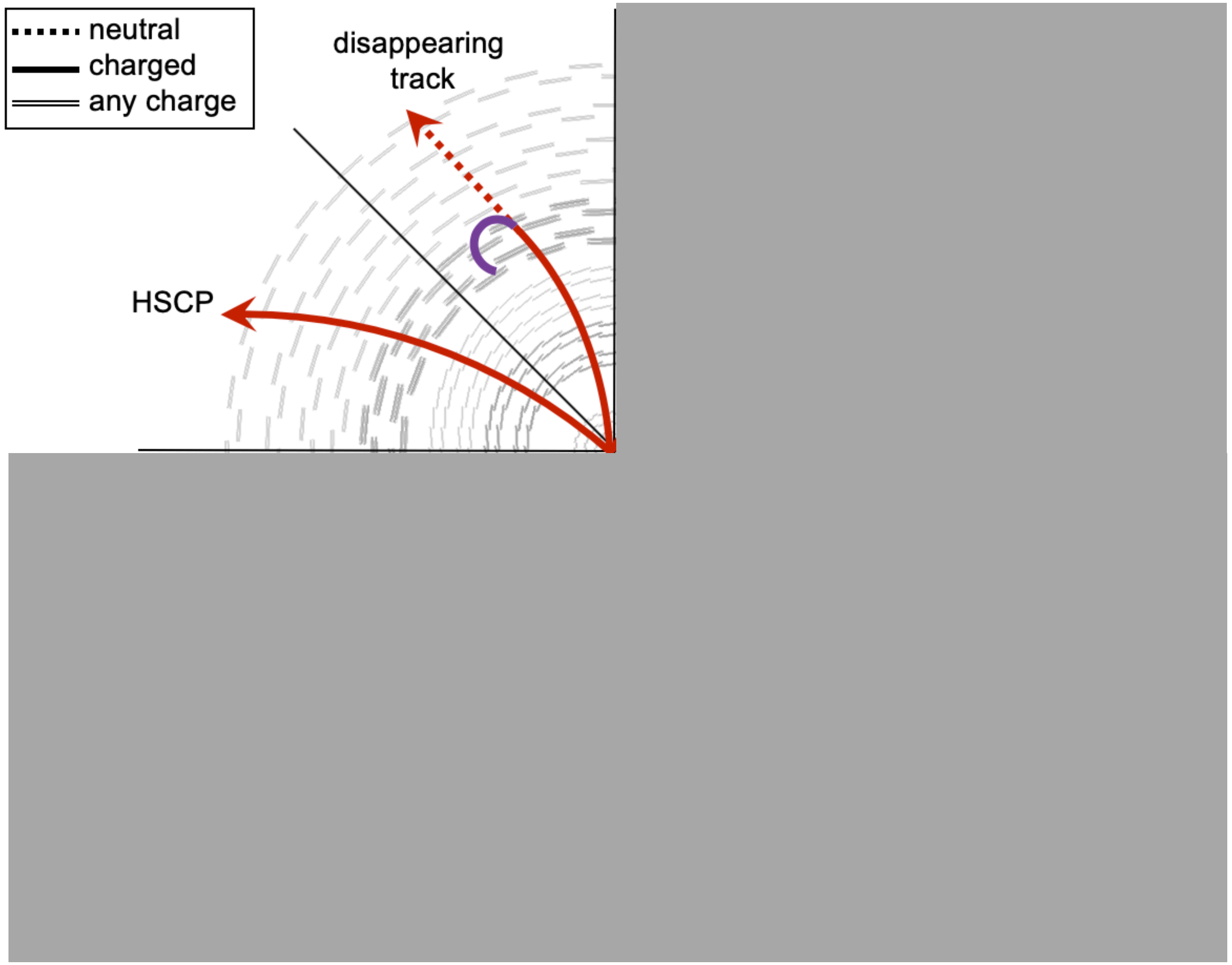
Long-Lived Particle Searches

Can search for LLPs that decay:

- Within the detector
- Outside of the detector

Can search for:

- **The LLP itself**
-



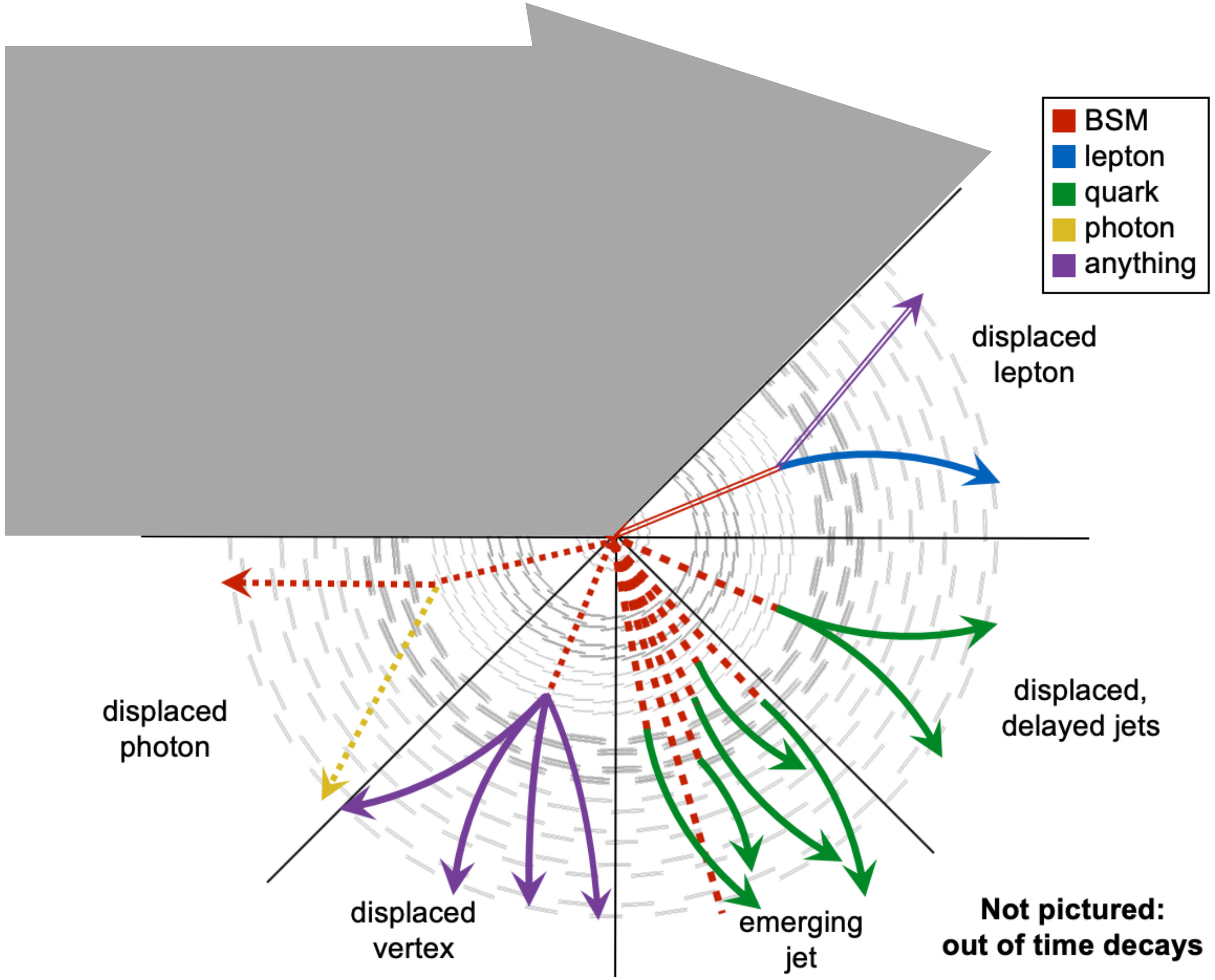
Long-Lived Particle Searches

Can search for LLPs that decay:

- Within the detector
- Outside of the detector

Can search for:

- The LLP itself
- **Its displaced decay products**
-



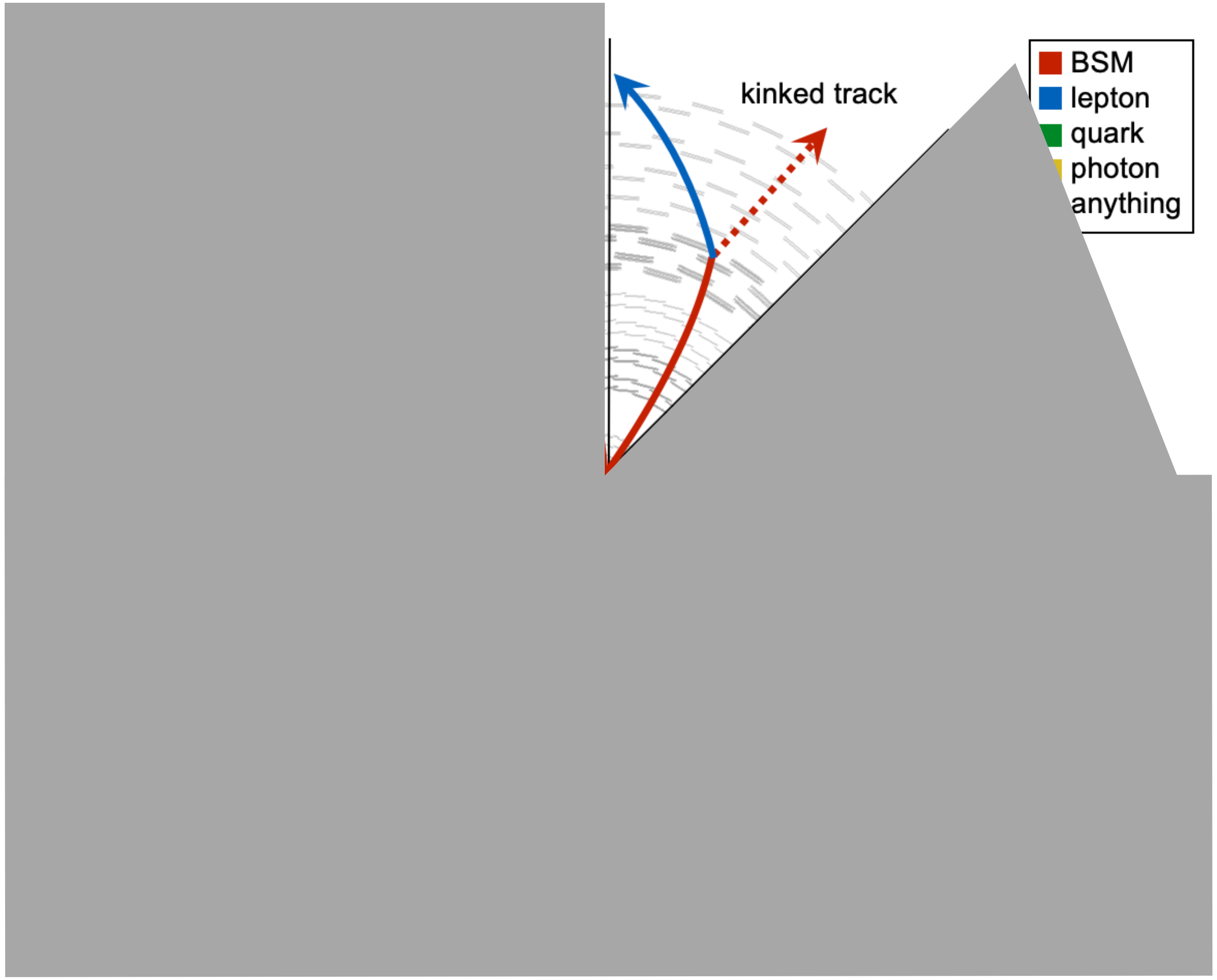
Long-Lived Particle Searches

Can search for LLPs that decay:

- Within the detector
- Outside of the detector

Can search for:

- The LLP itself
- Its displaced decay products
- **Both**



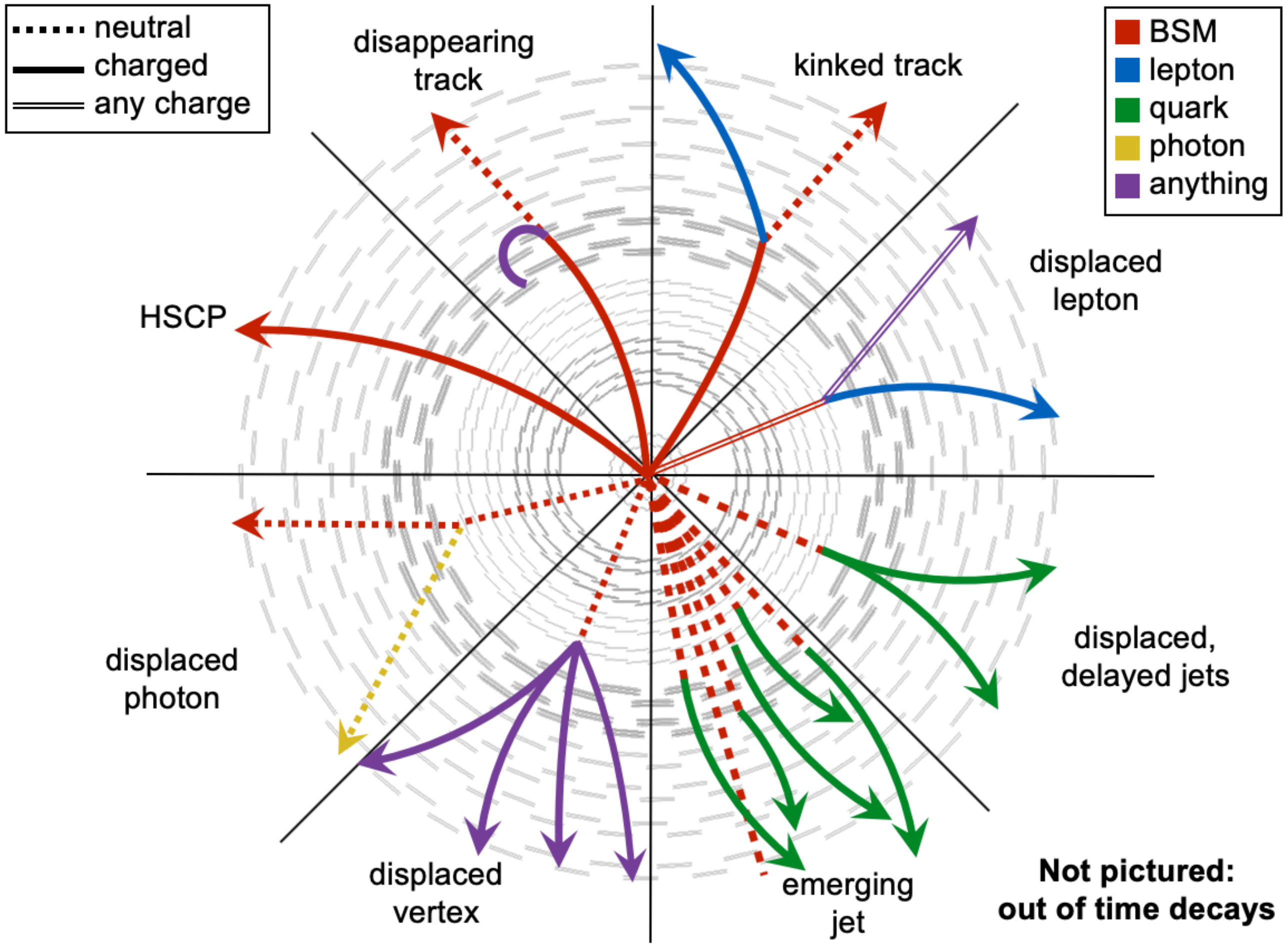
Long-Lived Particle Searches

Can search for LLPs that decay:

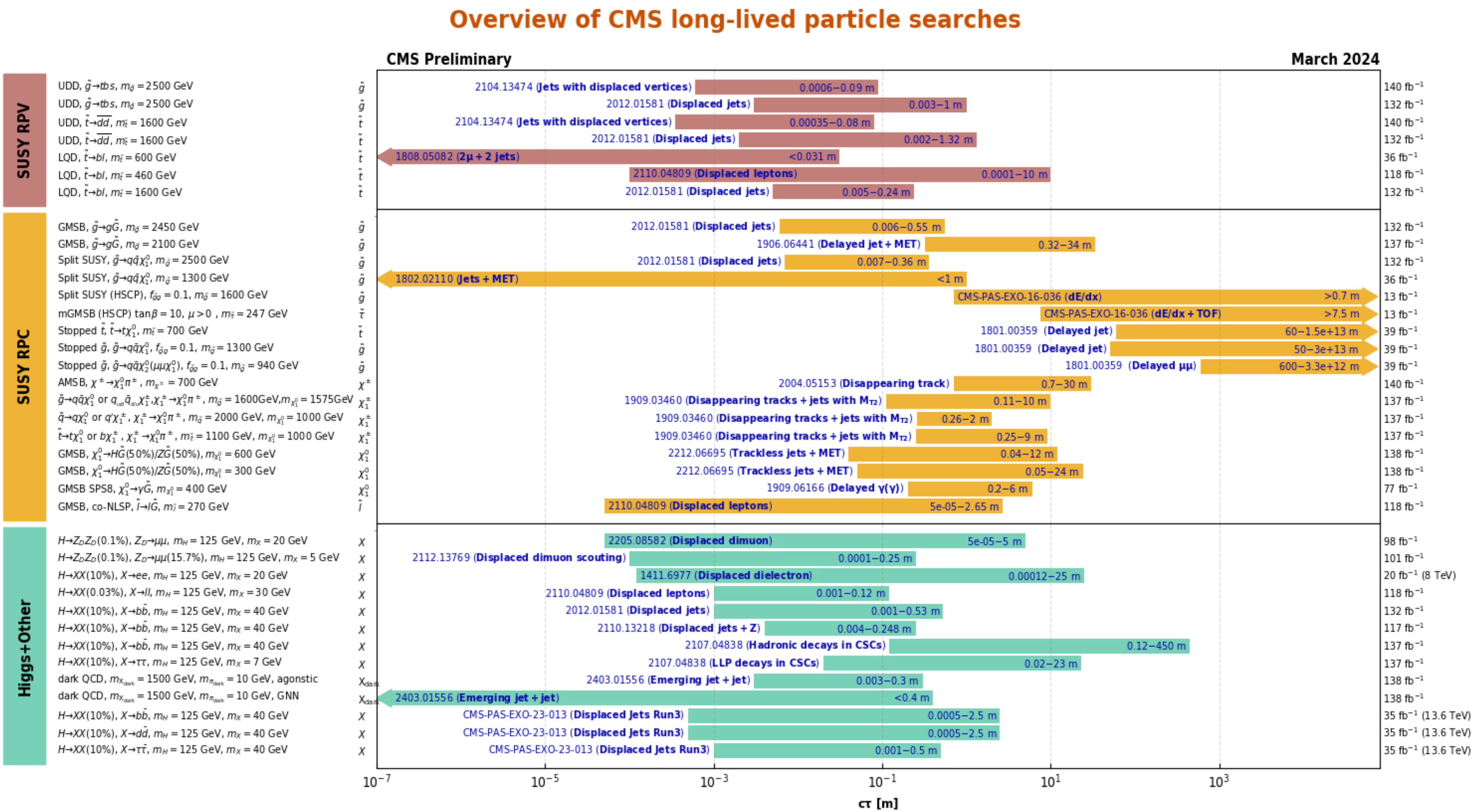
- Within the detector
- Outside of the detector

Can search for:

- The LLP itself
- Its displaced decay products
- Both



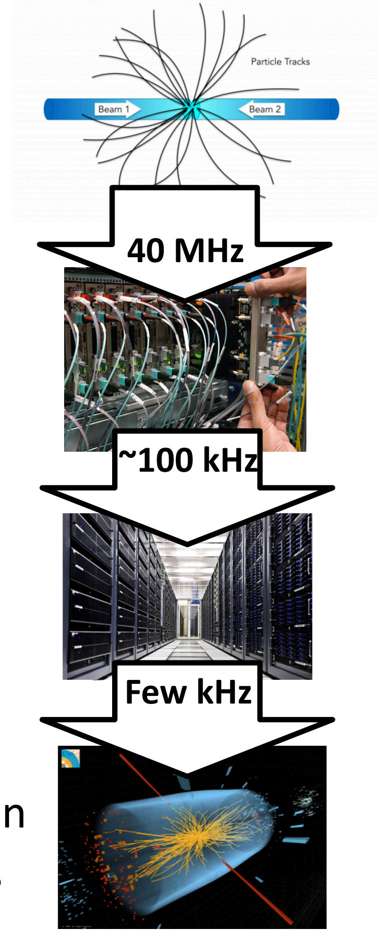
Wide range of signatures, models, and lifetimes explored at the LHC



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

LLP Challenges

Dedicated triggers



LHC

Level 1 trigger

High Level Trigger

Offline reconstruction and analysis

LLP Challenges

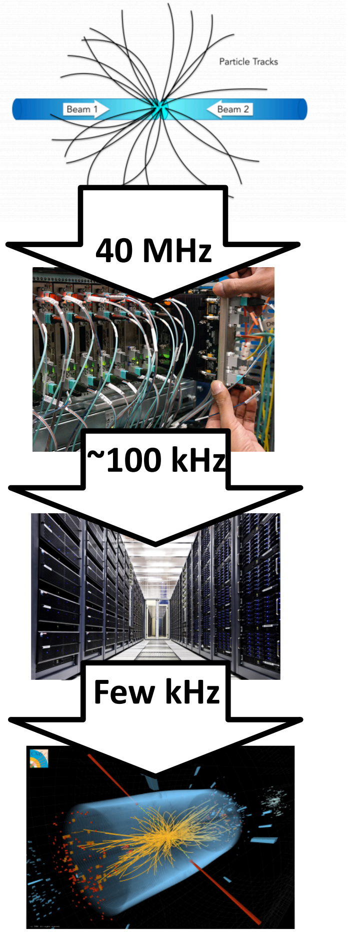
Dedicated triggers

LHC

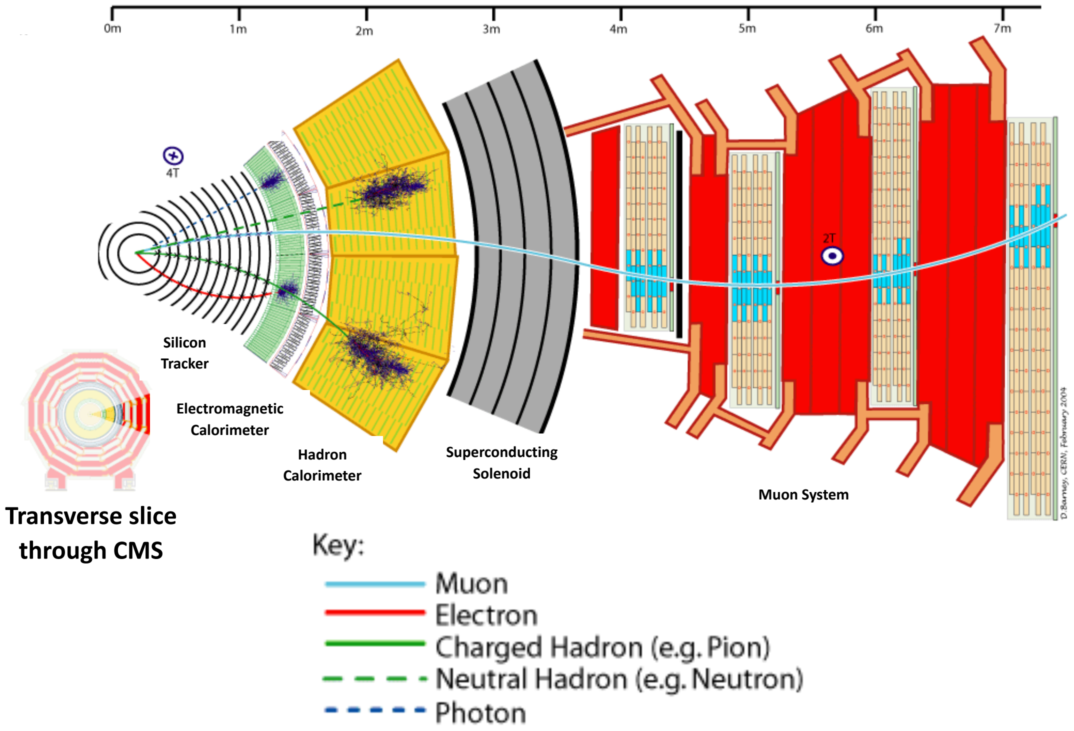
Level 1 trigger

High Level Trigger

Offline reconstruction and analysis



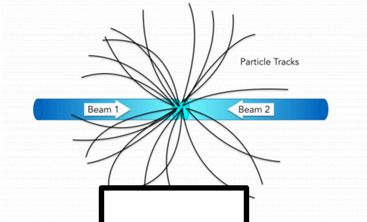
Unique object reconstruction and/or observables



LLP Challenges

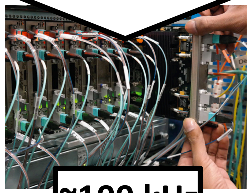
Dedicated triggers

LHC



40 MHz

Level 1 trigger

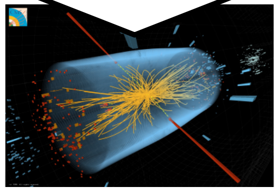


~100 kHz

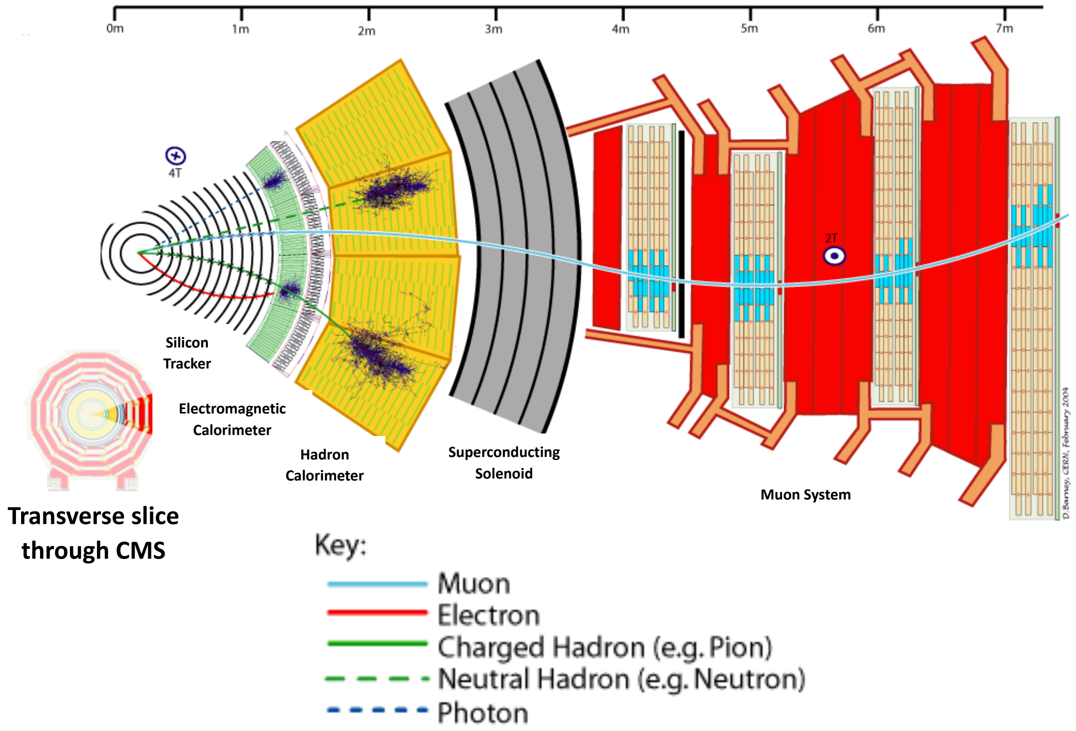
High Level Trigger

Few kHz

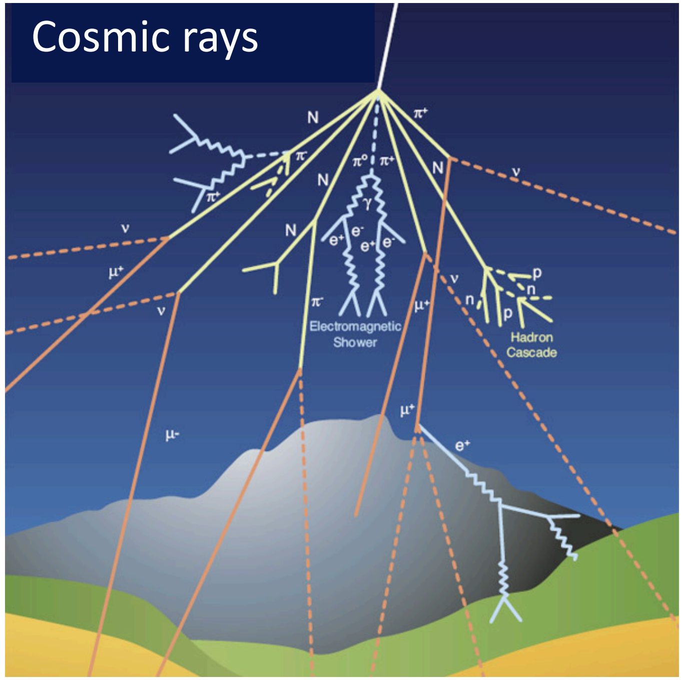
Offline reconstruction and analysis



Unique object reconstruction and/or observables



Atypical backgrounds



I'll now describe a recent LLP search with several of these ~~challenges~~ **opportunities for innovation**

The road ahead

3

Latest results

- From the LHC and beyond

2

Intro to Long-Lived Particles

- Why
- What
- How (basically)

1

Intro to L

Particles

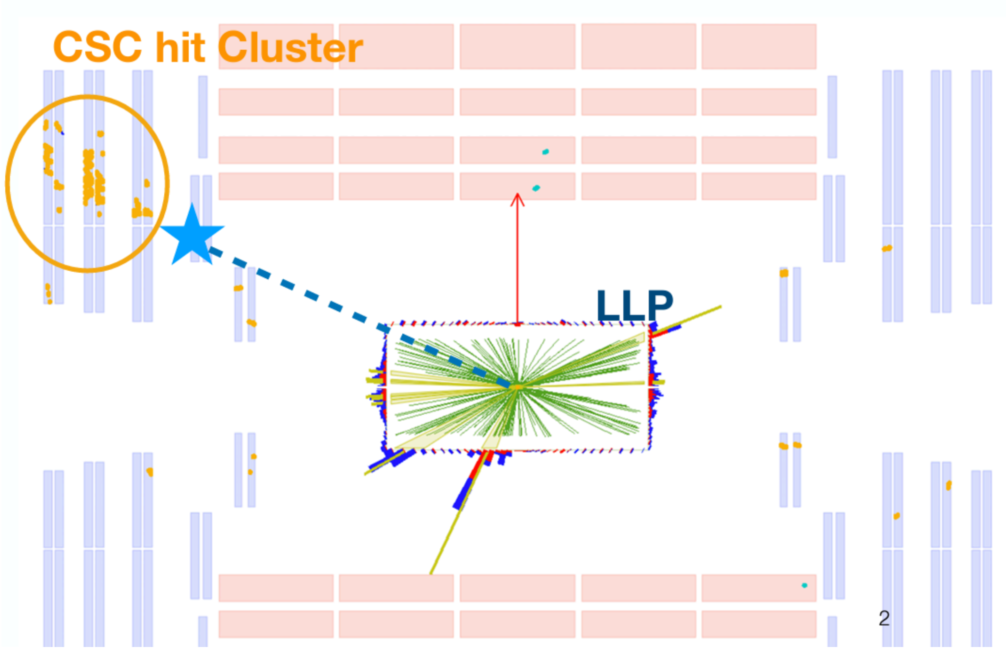
- Why
- What
- How (ba

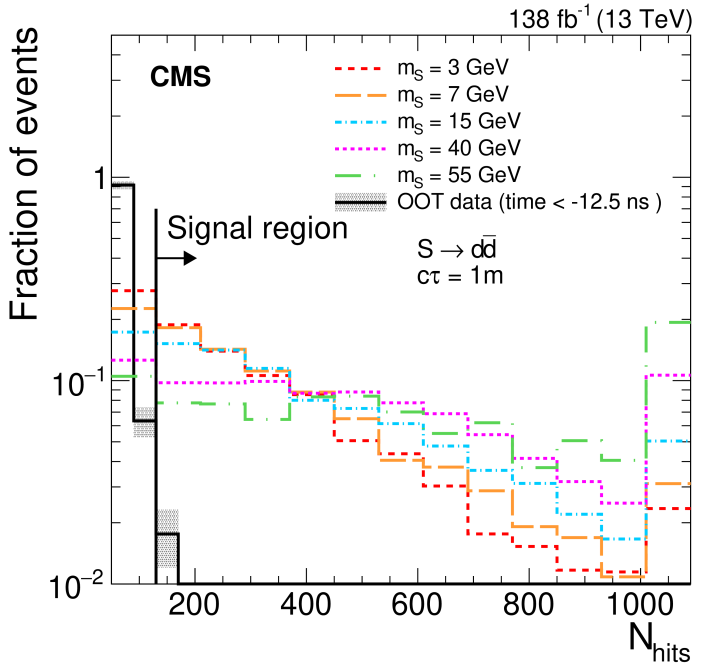
3

Muon Detector Showers (MDS)

- **Neutral LLPs with ctau> 1m** could decay **beyond the calorimeter** with:
  - No tracks, no jets, **high-multiplicity shower (hundreds of hits per cluster)** in the muon system
- Essentially, we *use the muon system as a sampling calorimeter*
- *Excellent background suppression from shielding material (background rejection of 1e6)*
- **Unique signature** due to the presence of steel in the CMS muon system
- Sensitive to hadronic, tau, photon, and electron decays

arXiv:2402.01898

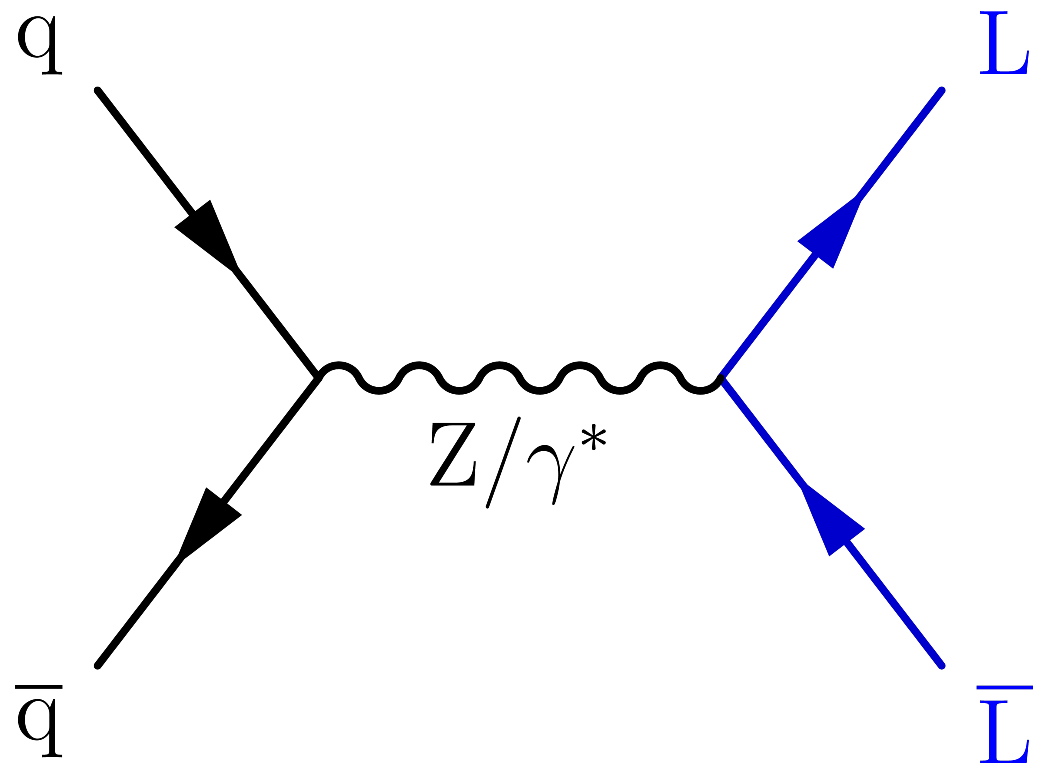




MDS Latest Result: Vector-Like Leptons

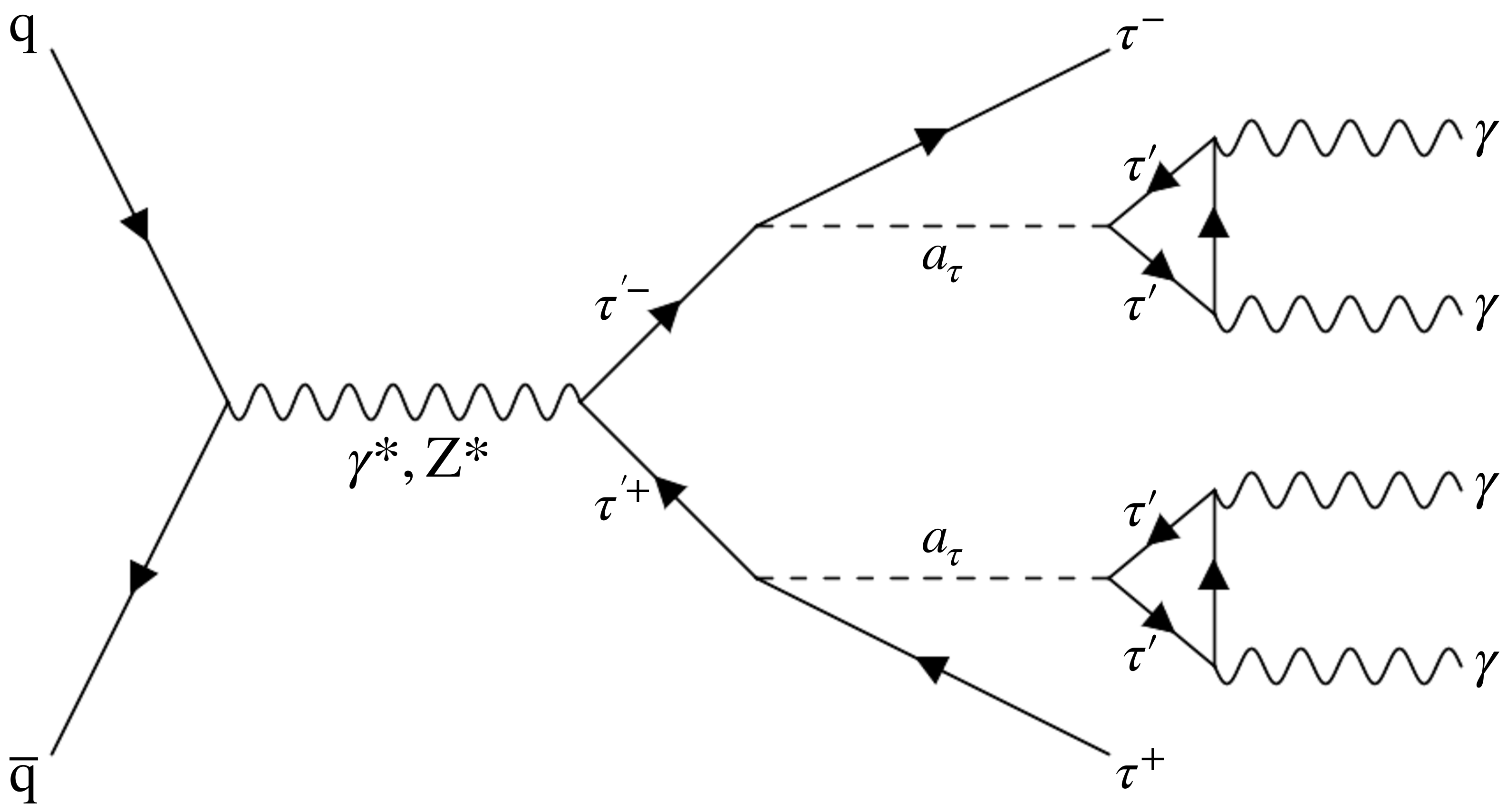
[CMS-EXO-23-015]

- In SM, fermions are **chiral**:
  - Left- and right-handed fermions experience different interactions
- However, BSM scenarios with additional chiral fermions: **largely excluded**
- **Therefore, if new elementary fermions exist, they must be of vector-like (non-chiral) nature**
- Vector-like fermions: **simple and well-motivated extension** of the SM
- **Vector-like leptons (VLLs)** produced via electroweak processes



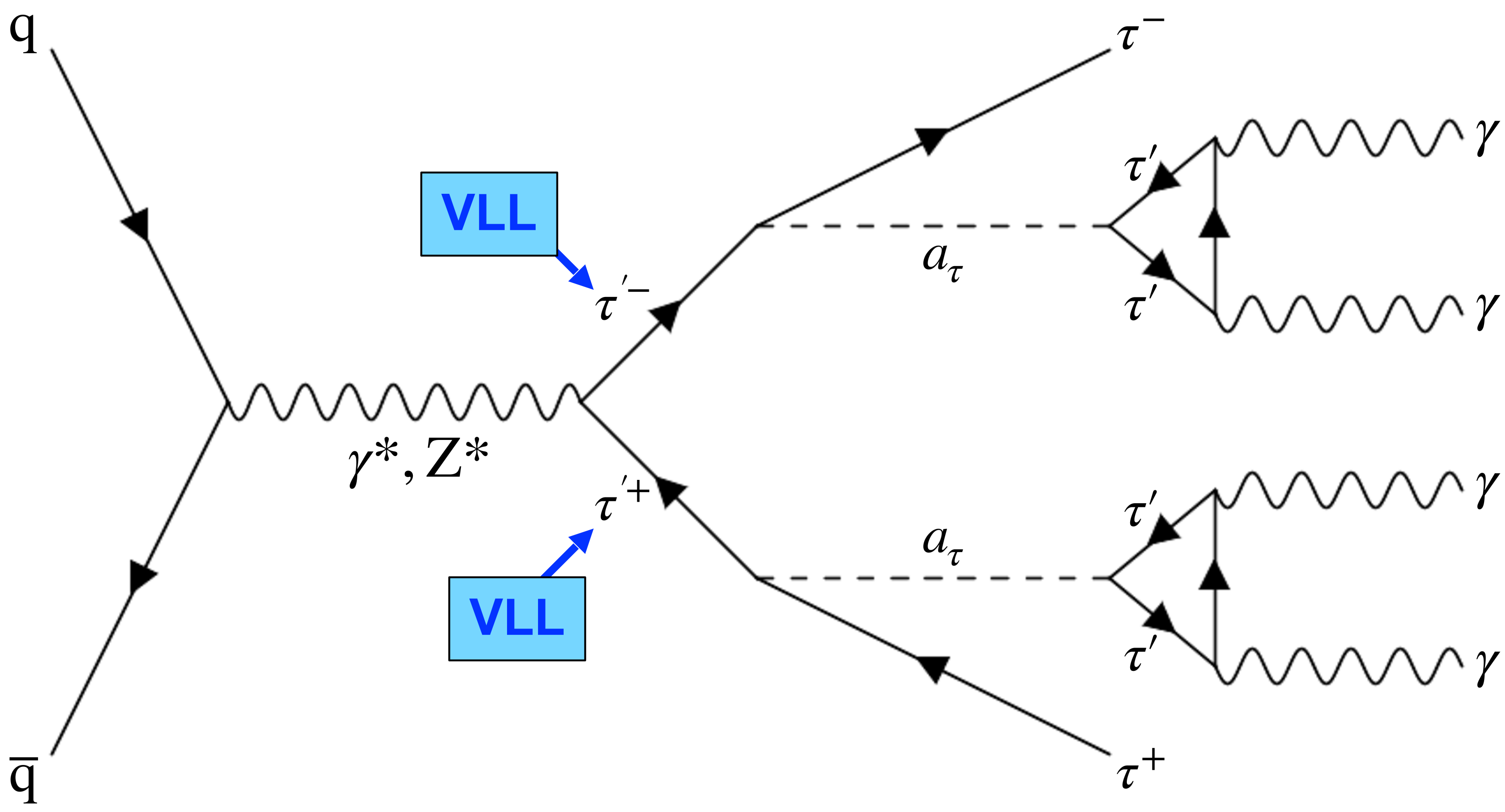
Vector-Like Leptons

CMS-EXO-23-015



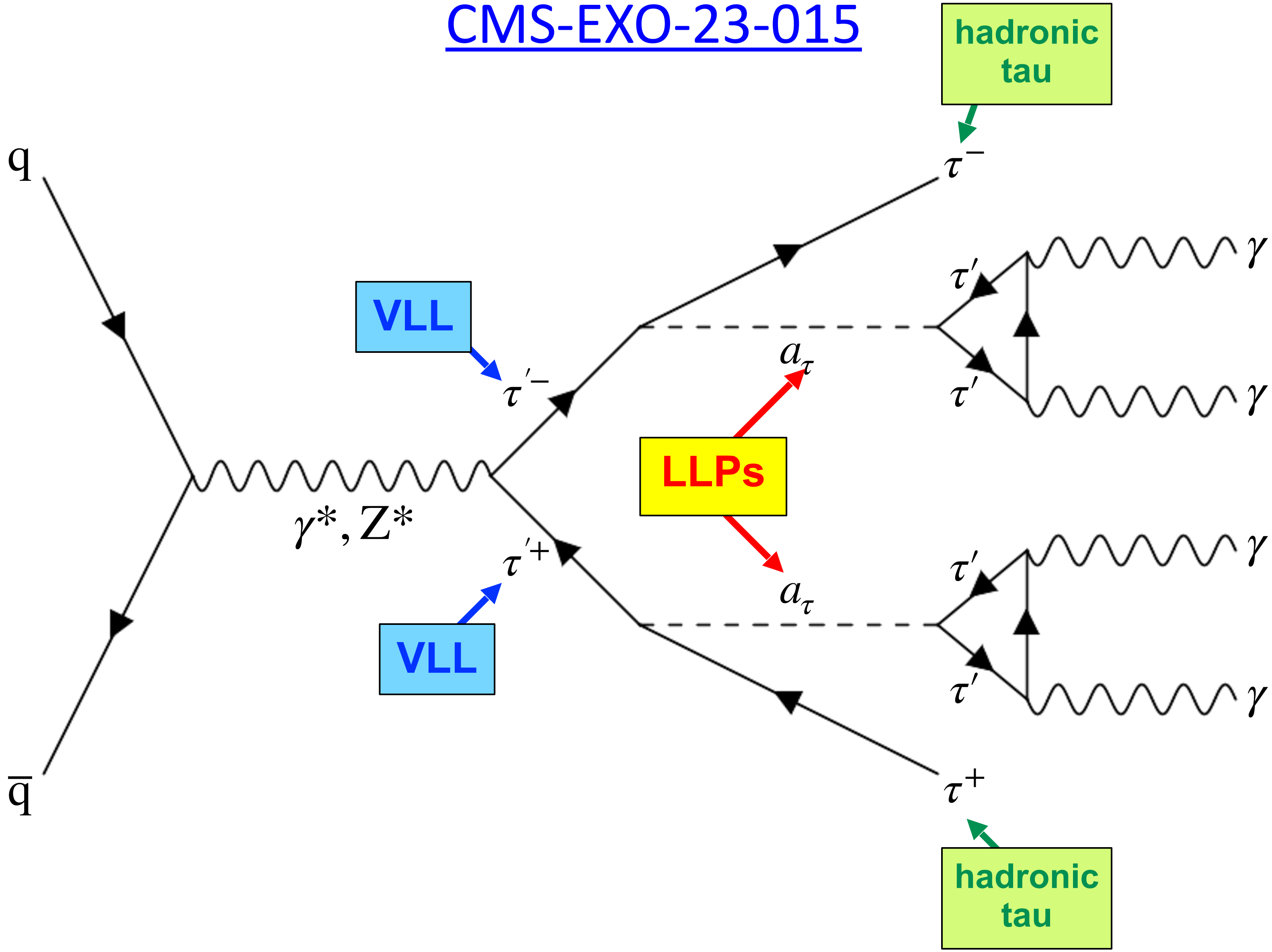
Vector-Like Leptons

CMS-EXO-23-015



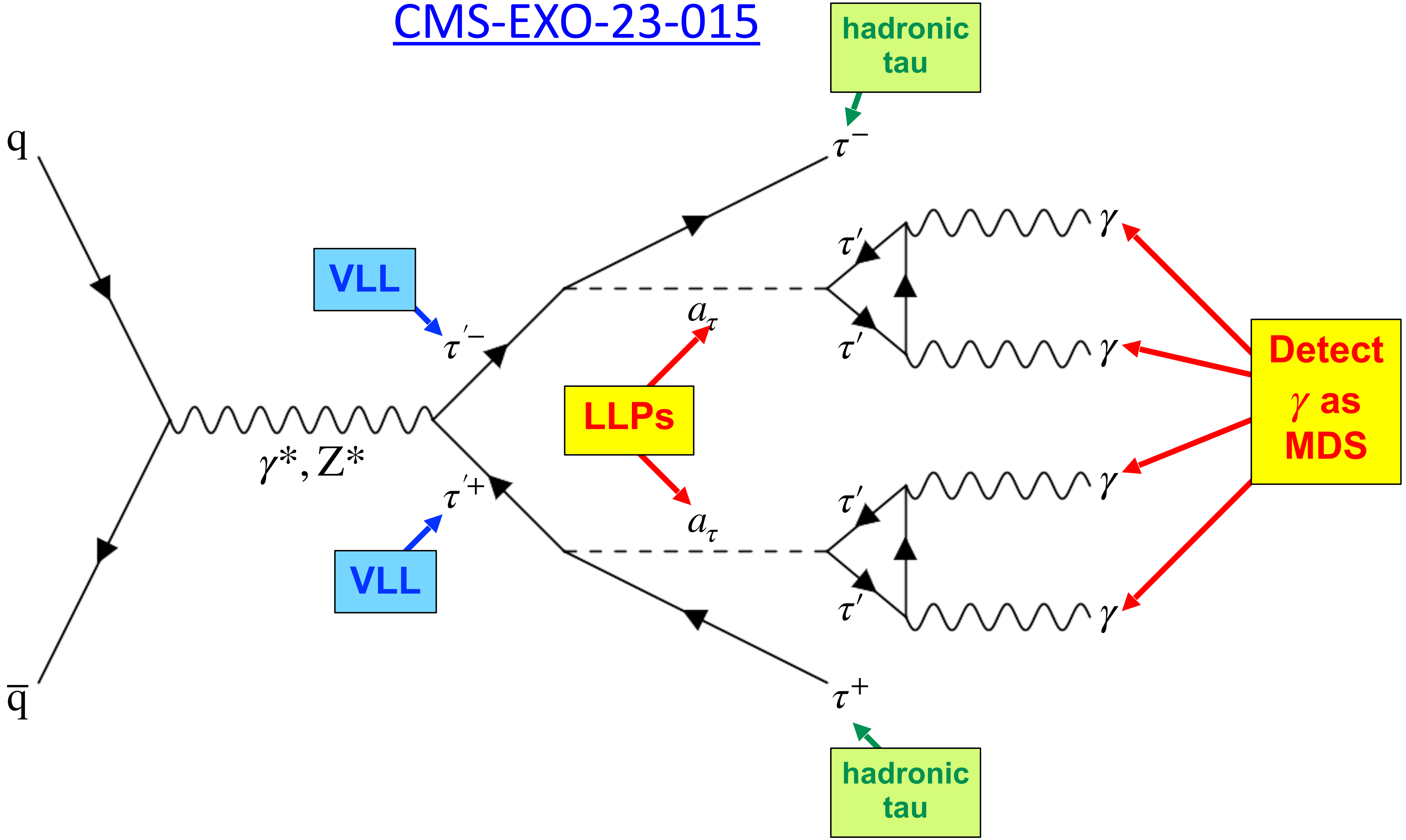
Vector-Like Leptons

[CMS-EXO-23-015]



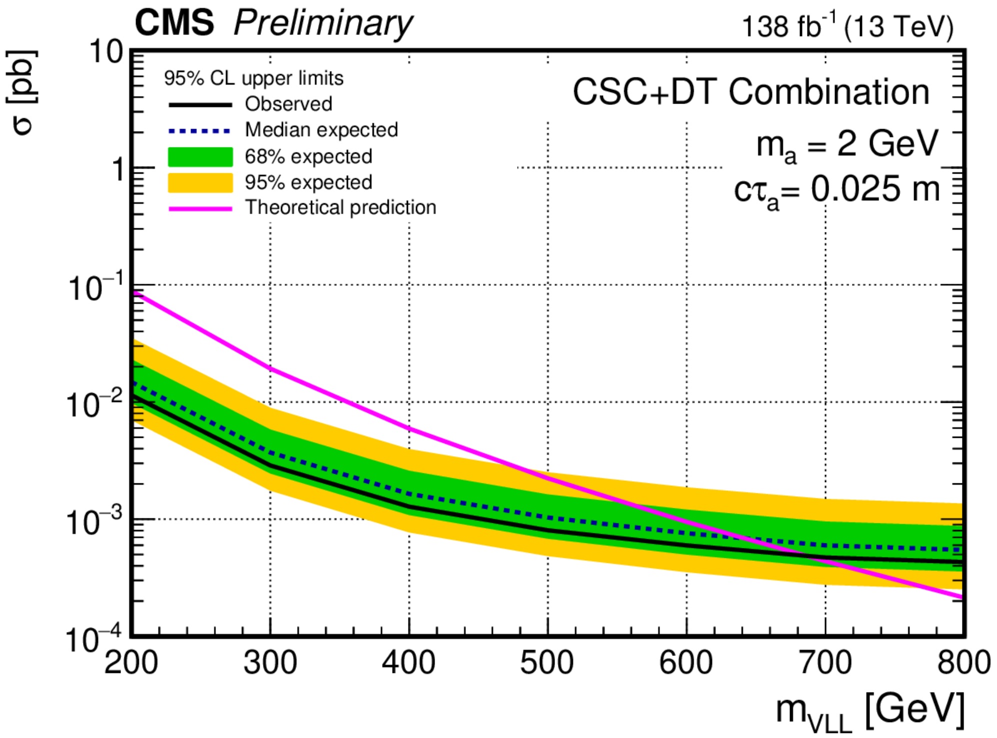
Vector-Like Leptons

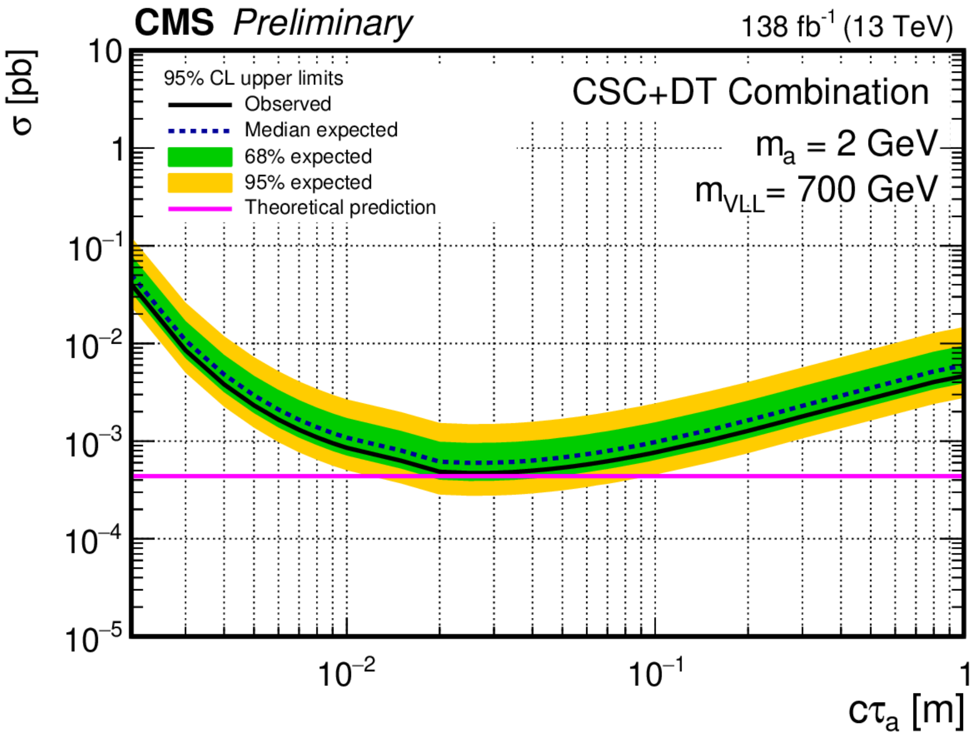
CMS-EXO-23-015



VLL Results

CMS-EXO-23-015





Exclude VLL masses:

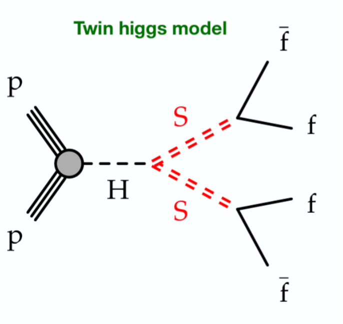
- < 690 GeV observed
- < 640 GeV expected

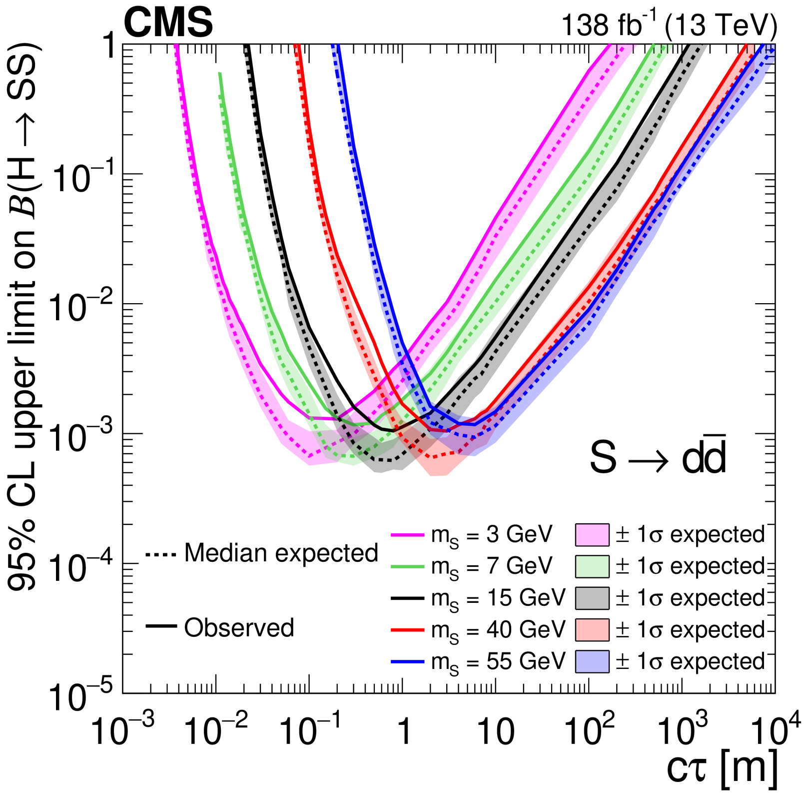
Other MDS Results

Higgs to LLPs

arXiv:2107.04838

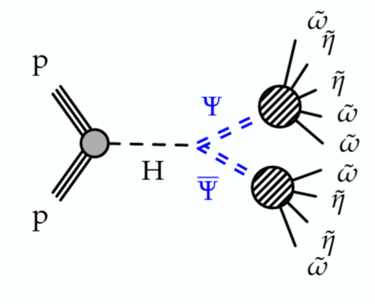
arXiv:2402.01898

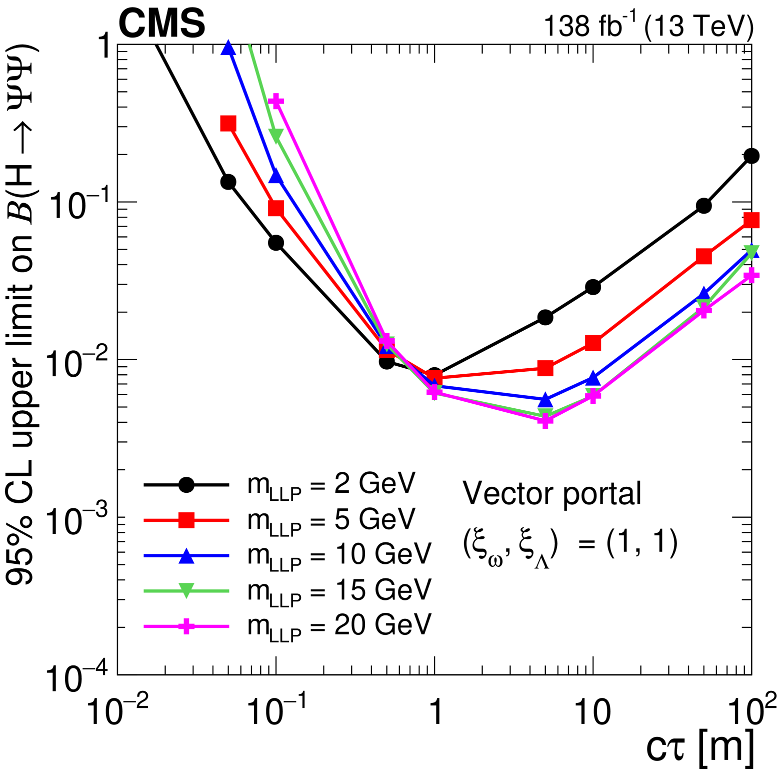




Dark Showers

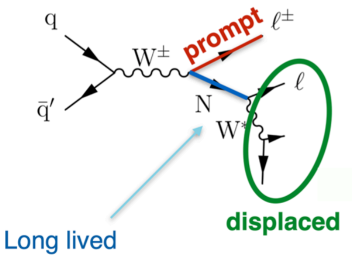
arXiv:2402.01898

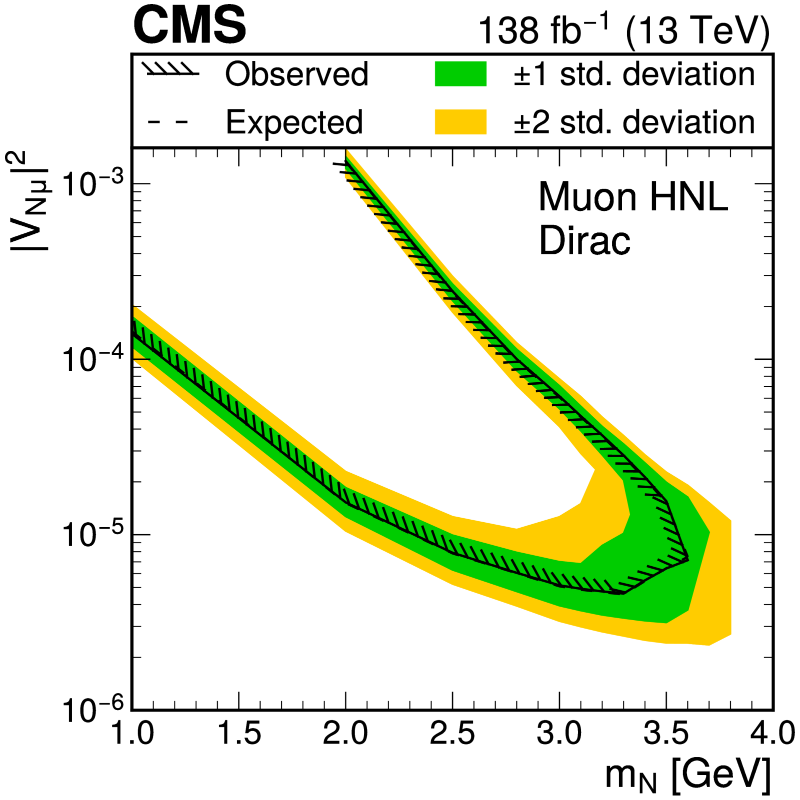




Heavy Neutral Leptons

arXiv:2402.18658



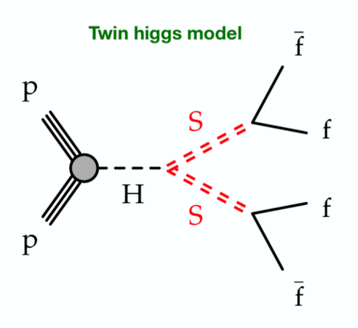


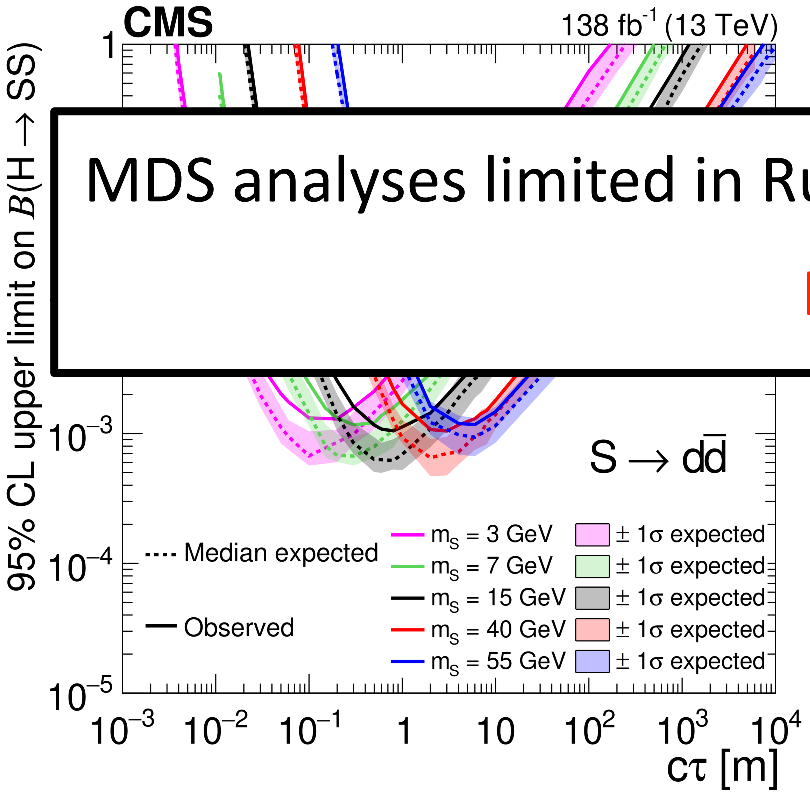
Other MDS Results

Higgs to LLPs

[arXiv:2107.04838](https://arxiv.org/abs/2107.04838)

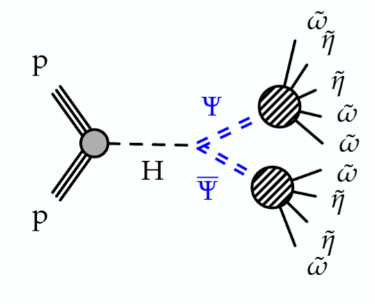
[arXiv:2402.01898](https://arxiv.org/abs/2402.01898)

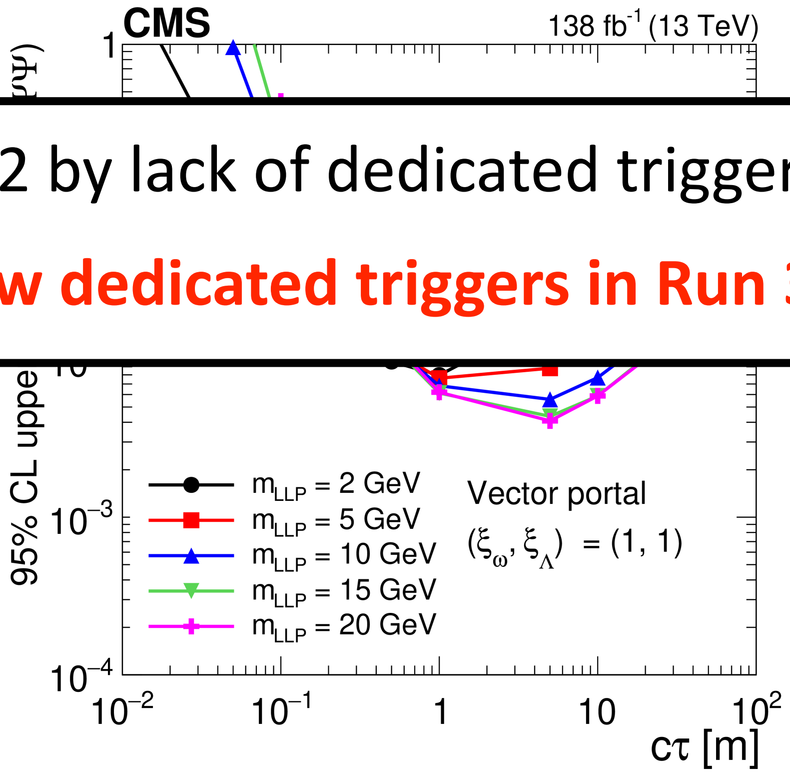




Dark Showers

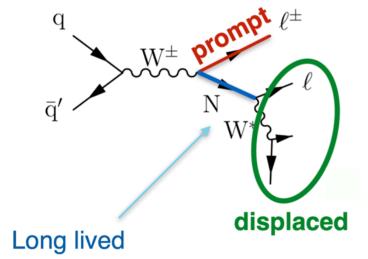
[arXiv:2402.01898](https://arxiv.org/abs/2402.01898)

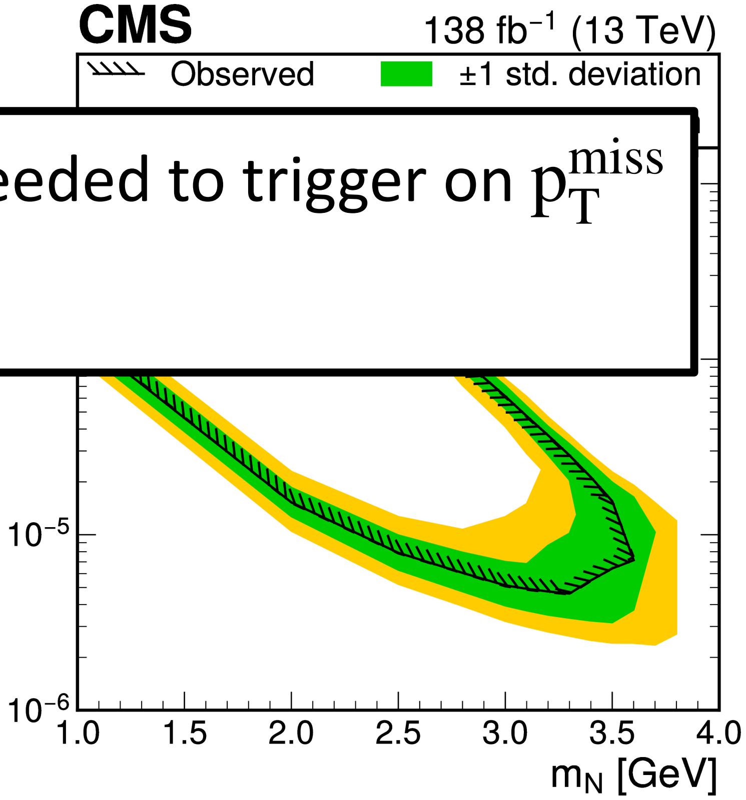




Heavy Neutral Leptons

[arXiv:2402.18658](https://arxiv.org/abs/2402.18658)





MDS analyses limited in Run 2 by lack of dedicated trigger: needed to trigger on p_T^{miss}

New dedicated triggers in Run 3!

The road ahead

Latest results

- From the LHC and beyond

Intro to Long-Lived Particles

- Why
- What
- How (basically)

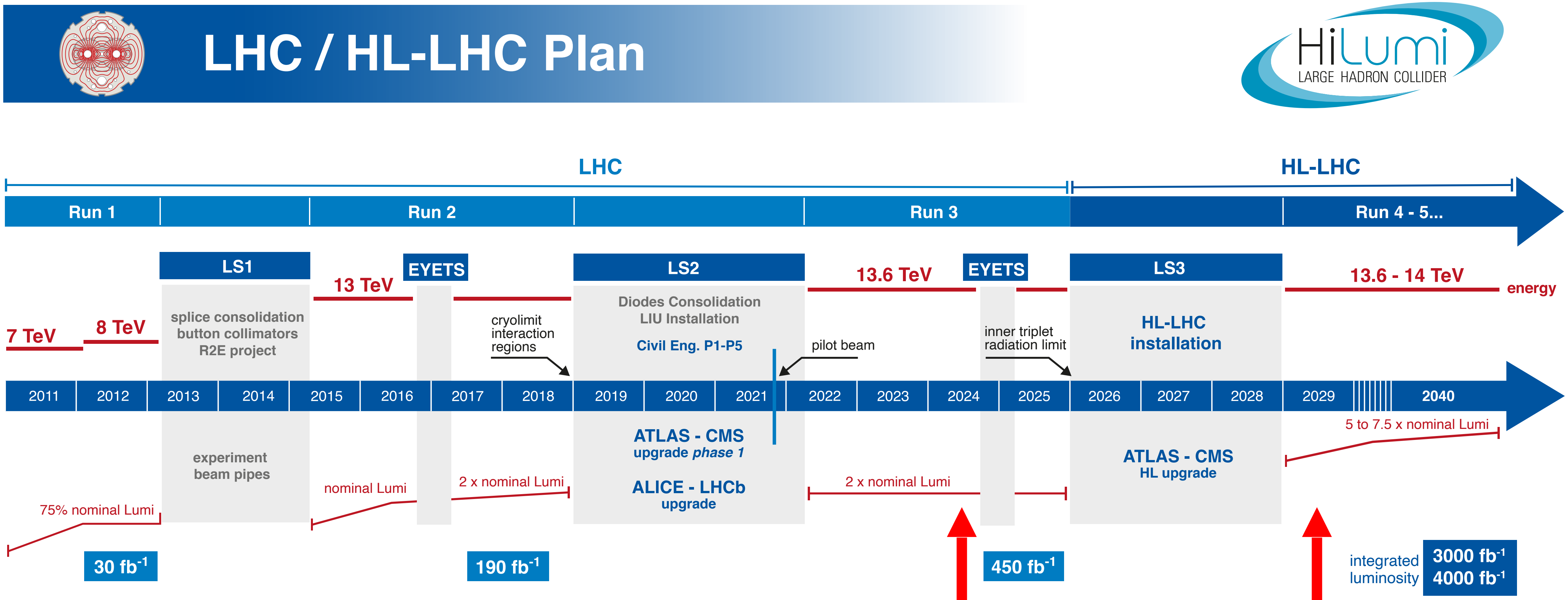
Intro to Lo

Particles

- Why
- What
- How (basi

3

What's Next?



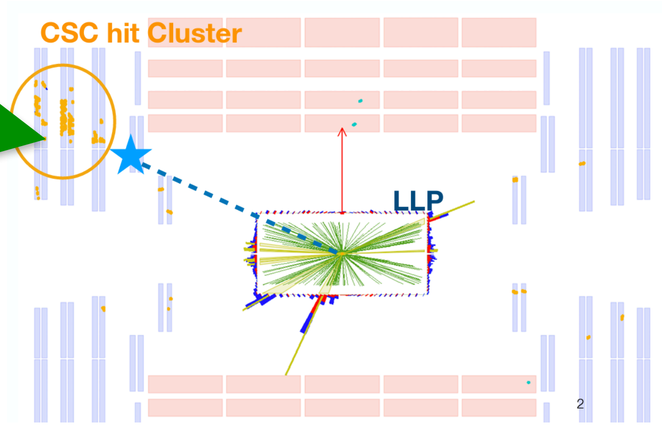
We are here, in Run 3

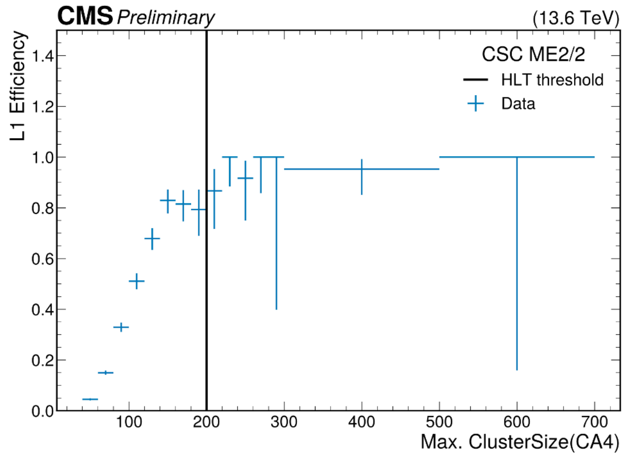
High-Luminosity LHC taking data in ~2029

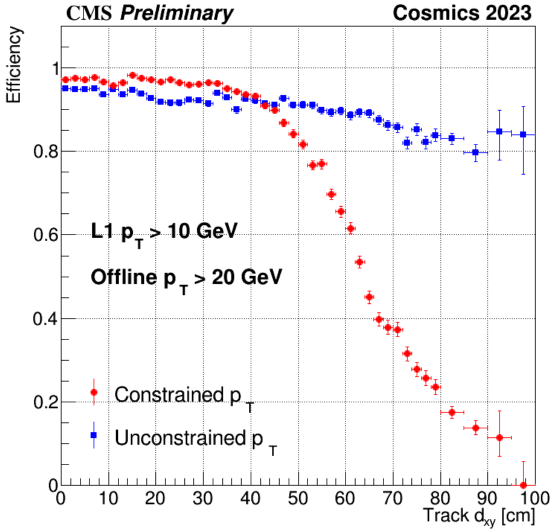
New LLP Triggers in CMS for Run 3

At both L1 (hardware) and HLT (software) levels

- New L1 & HLT triggers for **showers in the muon system**
- New triggers for **delayed jets:**
  - Using HCAL depth and timing (thanks to HCAL upgrade): L1 & HLT
  - Using ECAL timing: HLT
- New HLT triggers for **displaced taus**
- New L1 & HLT algorithms for **displaced muons**



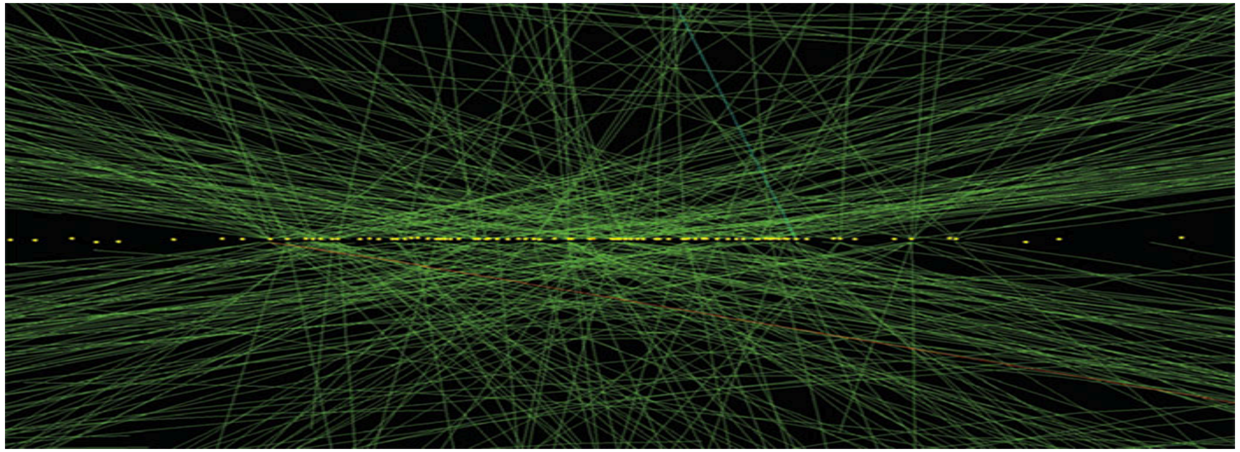




High-Luminosity LHC

- 14 TeV center-of-mass energy
- About 20 times more data by the end
- Expect up to 200 interactions per proton-proton collision, unprecedented amount of radiation
- Will have **substantial upgrades** to the ATLAS and CMS detectors:
  - To cope with the increased data rate and radiation
  - To improve and maximize the physics potential

High pileup: about 200 additional proton collisions per bunch crossing



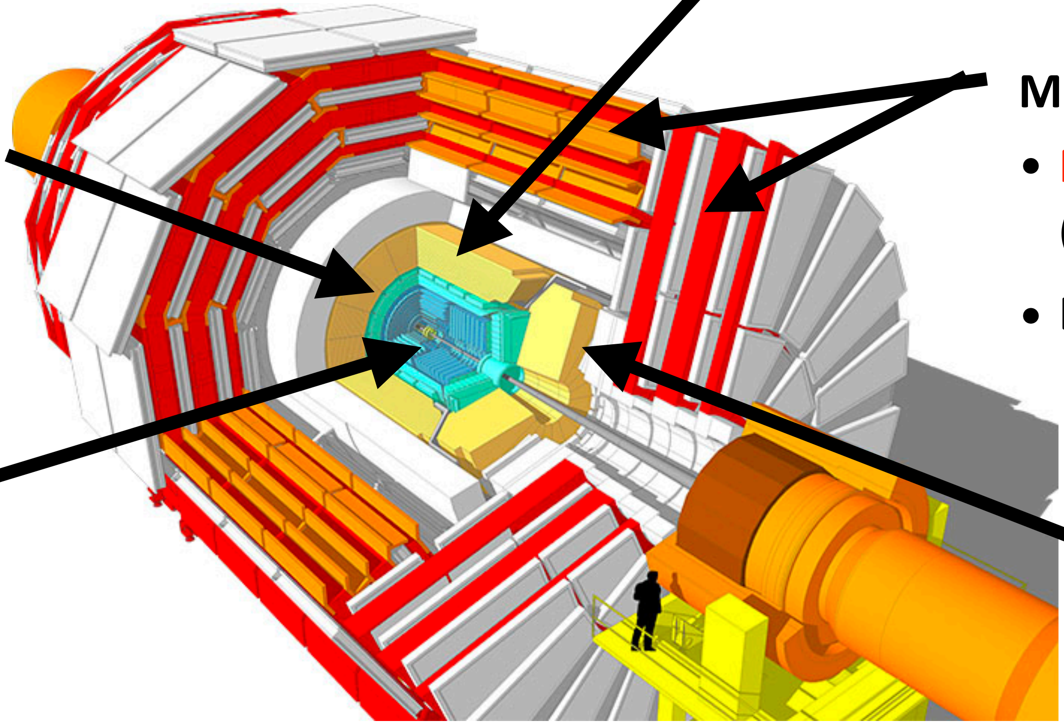
CMS Phase 2 Upgrade

Level 1 Trigger [TDR]
- New track trigger at 40 MHz
- 750 kHz L1 output
- 40 MHz data scouting (real time analysis)

DAQ & High Level Trigger (HLT) [TDR]
- Heterogeneous architecture
- 7.5 kHz HLT output

Barrel Calorimeter [TDR]
- ECAL crystal granularity readout at 40 MHz with precise timing for e/gamma at 30 GeV

New MIP timing detector (MTD) [TDR]
- 30 ps timing resolution



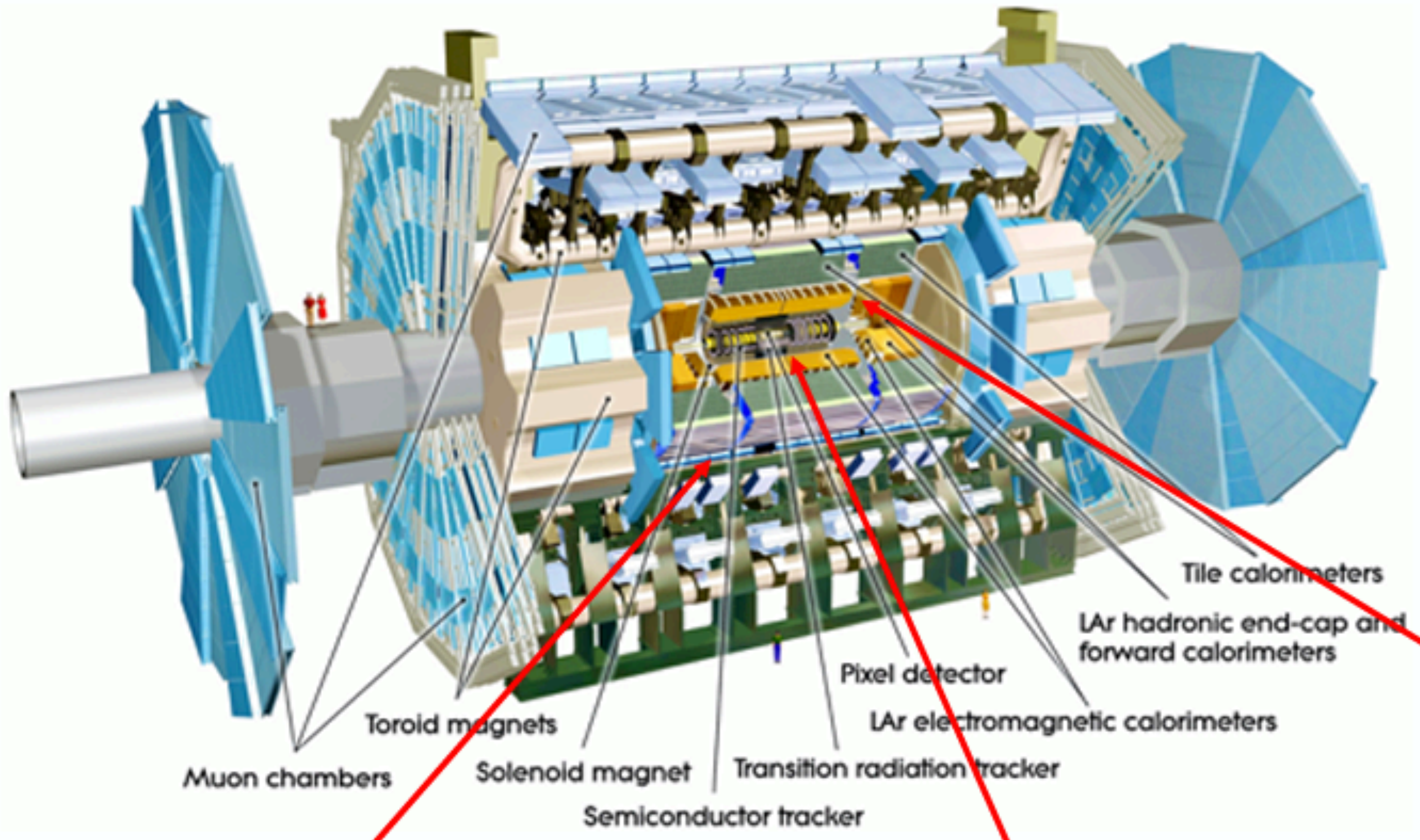
Muon System [TDR]
- New Gas Electron Multipliers (GEMs) & new iRPCs $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| \sim 3$

Replaced Tracker [TDR]
- Increased granularity
- Extended coverage to $|\eta| \sim 4$
- Designed for tracking in L1T

New High-Granularity Endcap Calorimeter (HGCAL) [TDR]
- Imaging calorimeter
- 3D showers and precise timing

From G. Unal

ATLAS Phase 2 Upgrade



Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz

Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter

Tile Calorimeter

Muon system

High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)

Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITk)

All silicon, up to $|\eta| = 4$

Additional small upgrades

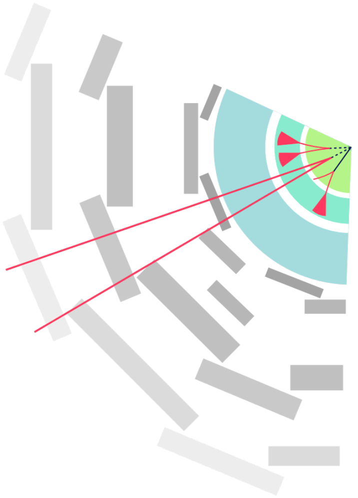
Luminosity detectors (1% precision goal)

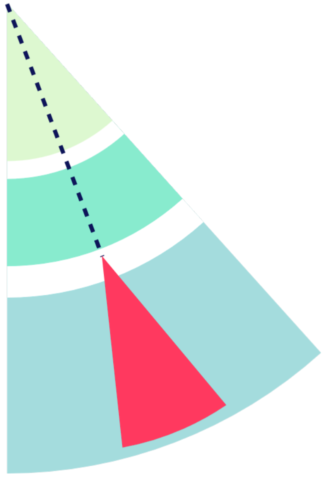
HL-ZDC

HL-LHC Upgrades and LLPs

A Few Highlights

- ATLAS and CMS: All-silicon **trackers with extended coverage** to $|\eta| \sim 4$
- CMS: **Tracking info in L1 trigger**
- ATLAS: **Improved pointing** by using HCAL info
- CMS: New **high-granularity silicon calorimeter** in endcap (3D imaging + timing)
- CMS: New single layer **MIP timing detector** in barrel and endcap
- ATLAS: New **High-Granularity Timing Detector** in multiple layers in the endcap (track-to-vertex association, identification improvements)

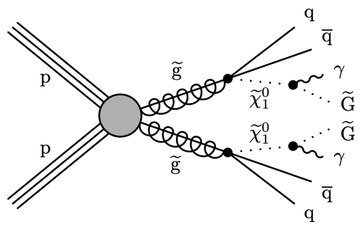


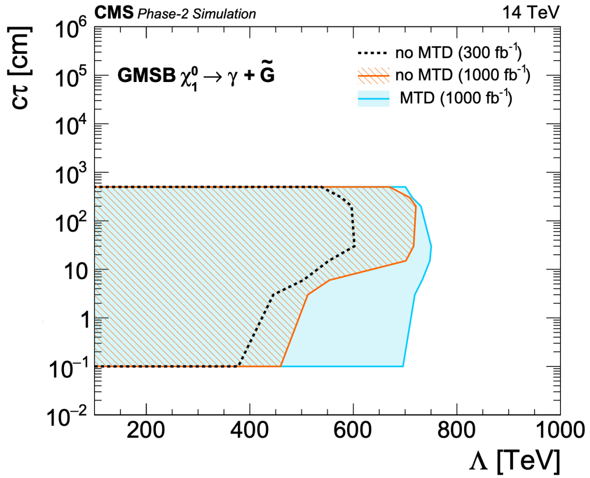


LLPs at the HL-LHC

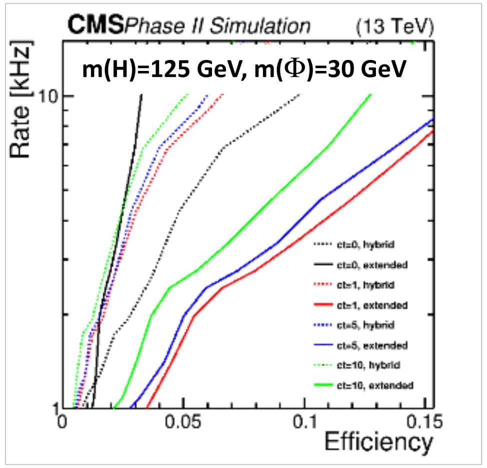
Lots of potential!

Delayed photons in timing detectors

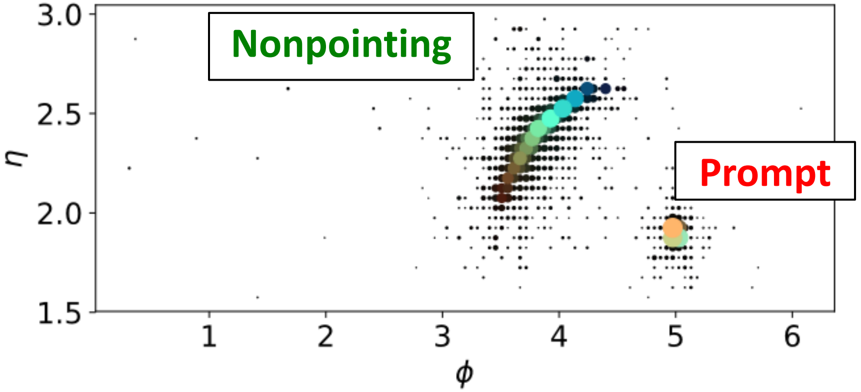


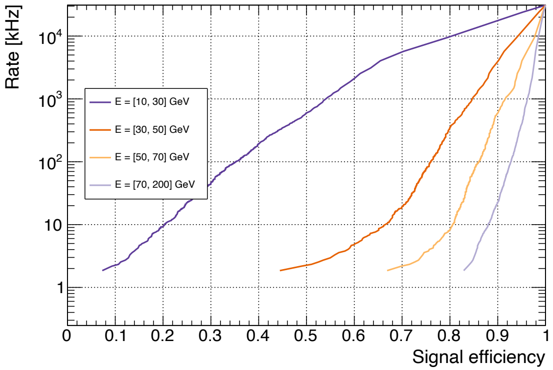


L1 track triggers for displaced jets

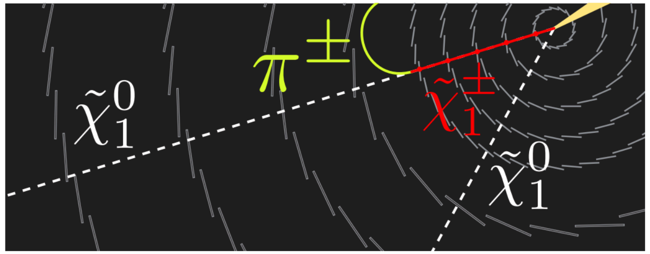


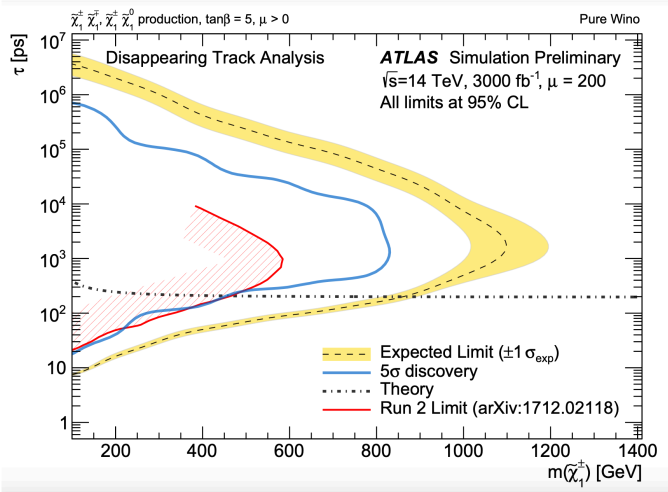
L1 ML trigger for nonpointing particles





Disappearing tracks



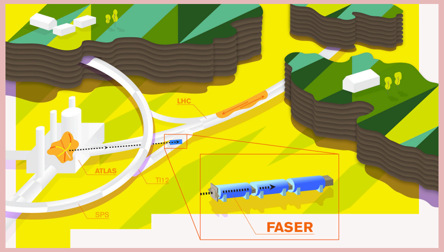


Just a sampling!

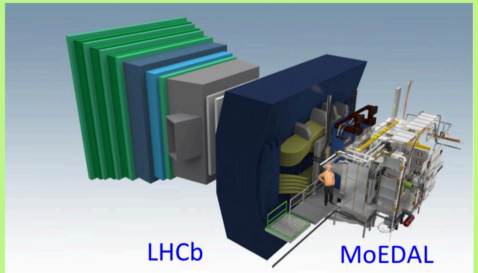
Some Dedicated LLP Experiments

- Besides the more general purpose LHC experiments, there are approved and proposed **experiments dedicated to looking for LLPs**
- Just a few examples:

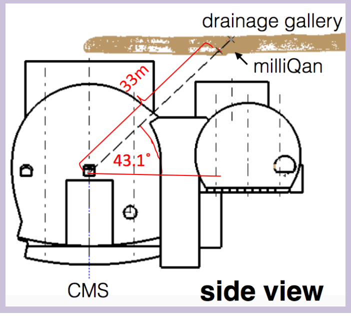
FASER: searches for long-lived dark photons and similar particles in the extreme forward direction

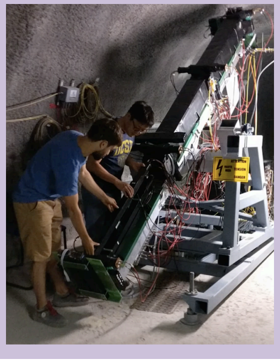


MoEDAL: searches for monopoles stopped in the beampipe with a SQUID precision magnet

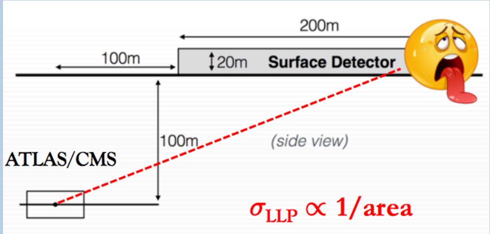


MilliQan: searches for millicharged particles with a detector pointed at the CMS interaction point





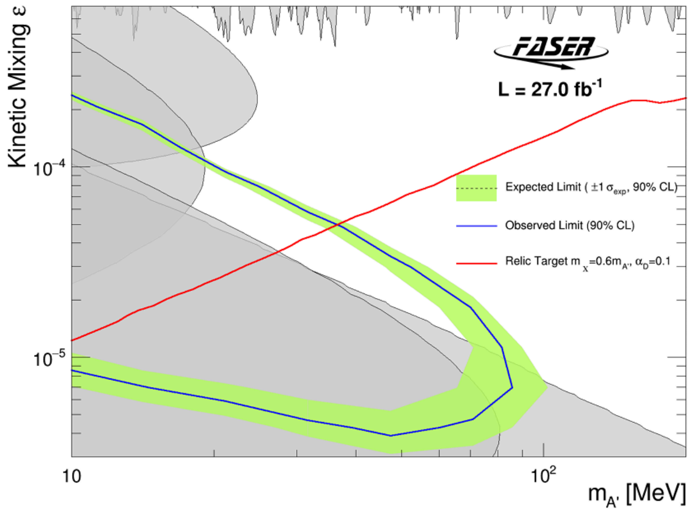
MATHUSLA: searches for (very) long-lived weakly interacting neutral particles with a large-volume, air-filled surface detector



Results from Dedicated LLP Experiments

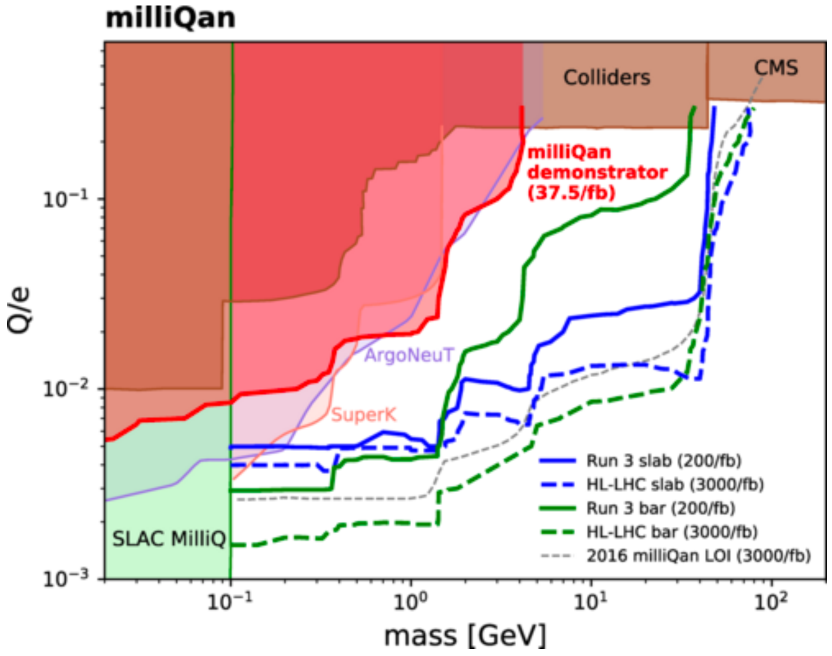
Dark photons: FASER

[PLB (2023) 138378]



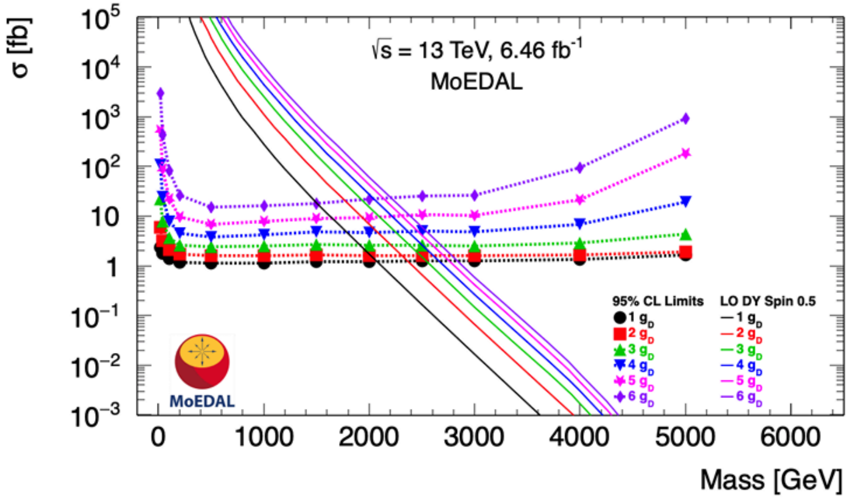
Millicharged particles: milliQan

[PRD 104 (2021) 032002]



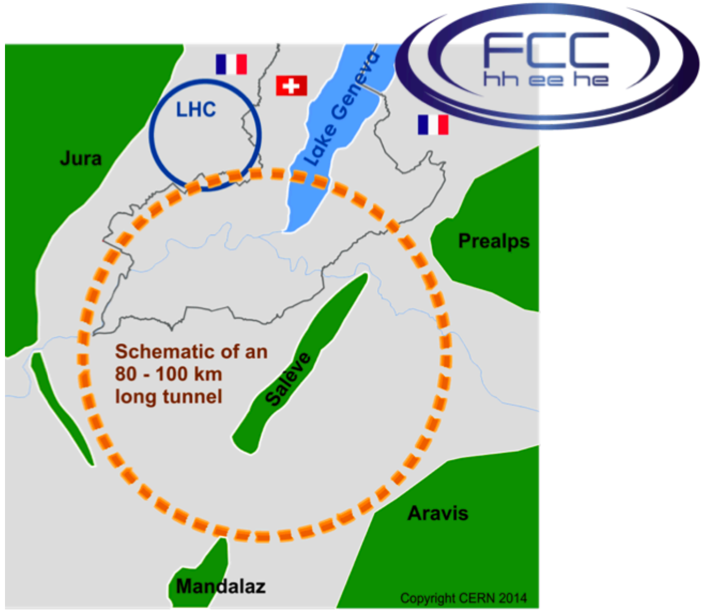
Monopoles and HECOs: MoEDAL

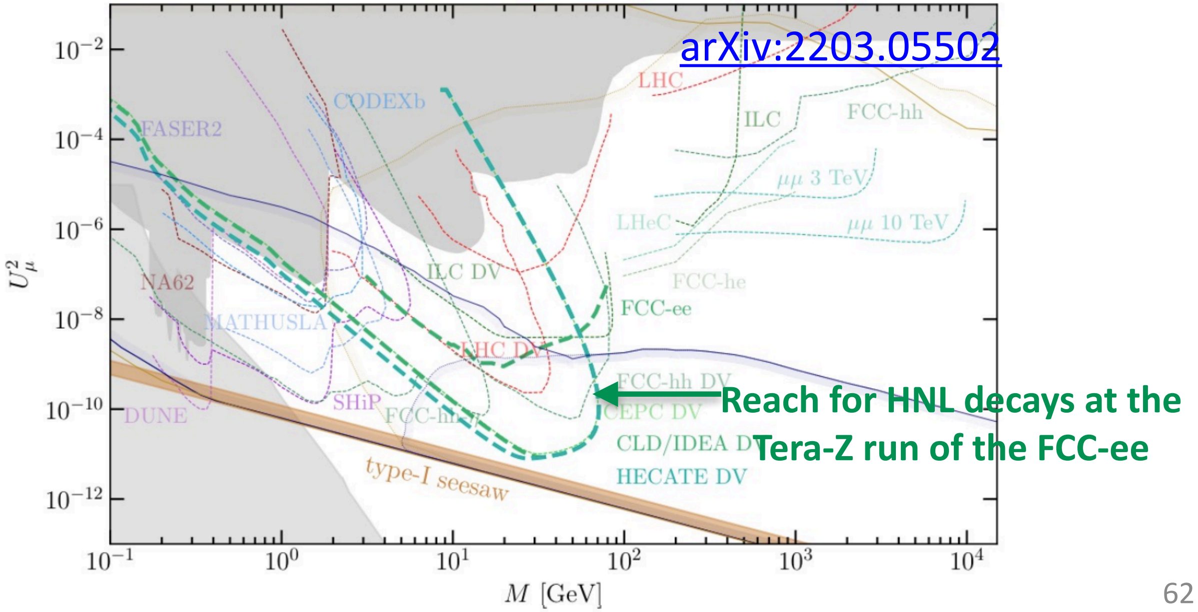
[arXiv:2311.06509]



Future Colliders and LLPs

- Past the HL-LHC, it's unclear what future collider project we will have
- But it's clear it will be a **Higgs factory**
  - Given both the European Strategy Report and Snowmass
- One option: Future Circular Collider (FCC) at CERN
  - One 100 km tunnel, two stages:
    - Stage 1: FCC-ee (Z, W, H , tt) as Higgs EW and top factory at high luminosities
    - Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options
- Studying future sensitivity of the FCC to LLPs
  - One example: **Heavy Neutral Leptons**





What Else?

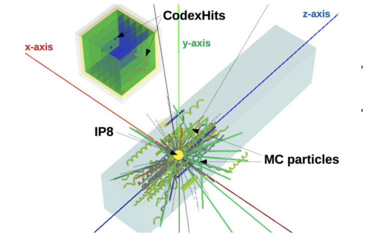
- The previous slides were **far from exhaustive** – **many other searches** for LLPs have been done or are in progress
- **<u>But here are some other things we can try:</u>**
  - Soft displaced objects
  - Displaced taus
  - Kinked tracks
  - Quirks
  - Data-taking strategies like **data scouting** and **data parking**
  - New triggers
  - **And many more!**

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 exotic particles at the LHC
- We have many theoretical models to guide experimentalists now, but there's no longer a big shiny beacon like there was before the Higgs boson discovery
- —> We should look for anything and everything that we're sensitive to, including long-lived particles
- Exciting time for searches at the LHC!
- Maybe **YOU** will be the next to discover something!

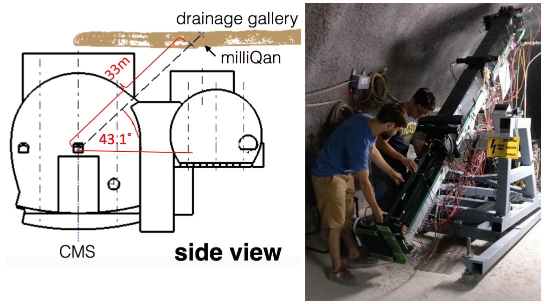
Backup

Approved and Proposed LLP Experiments



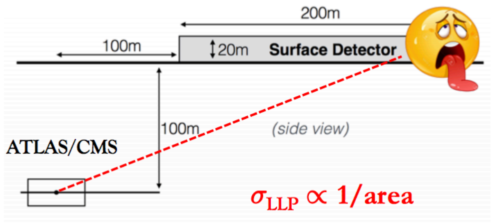
CODEX-b: searches for long-lived weakly interacting neutral particles with a new detector near LHCb

FASER: searches for long-lived dark photons and similar particles in extreme forward direction



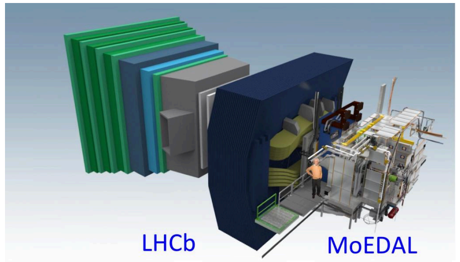
MilliQan: searches for millicharged particles with a detector pointed at the CMS interaction point

MAPP: searches for low-charged particles and long-lived neutrals that decay outside of LHCb



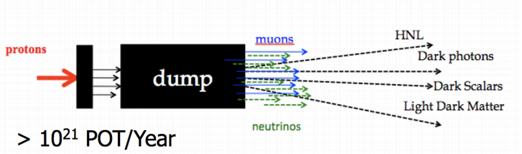
MATHUSLA: searches for (very) long-lived weakly interacting neutral particles with a large-volume, air-filled surface detector

MoEDAL: searches for monopoles stopped in the beampipe with a SQUID precision magnet



NA62: searches for vertices of long-lived neutral particles

SeaQuest: dark-sector searches

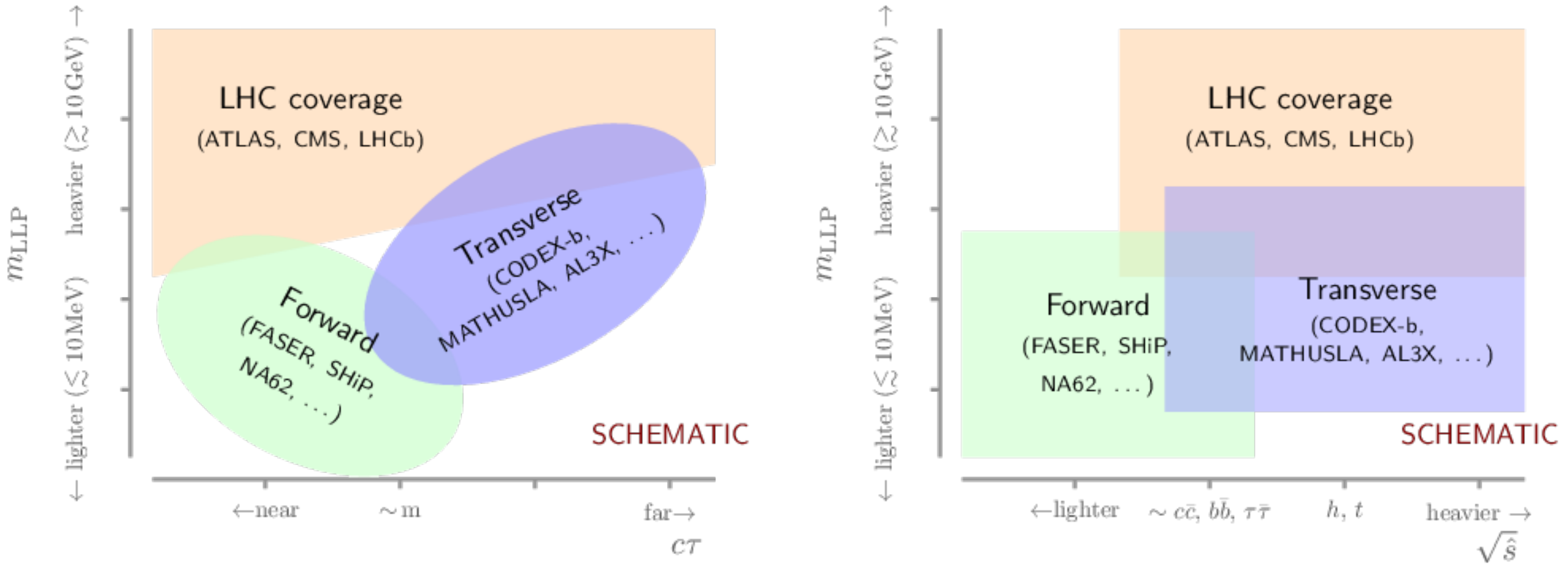


SHIP: searches for neutral hidden particles at the beam dump

And more!

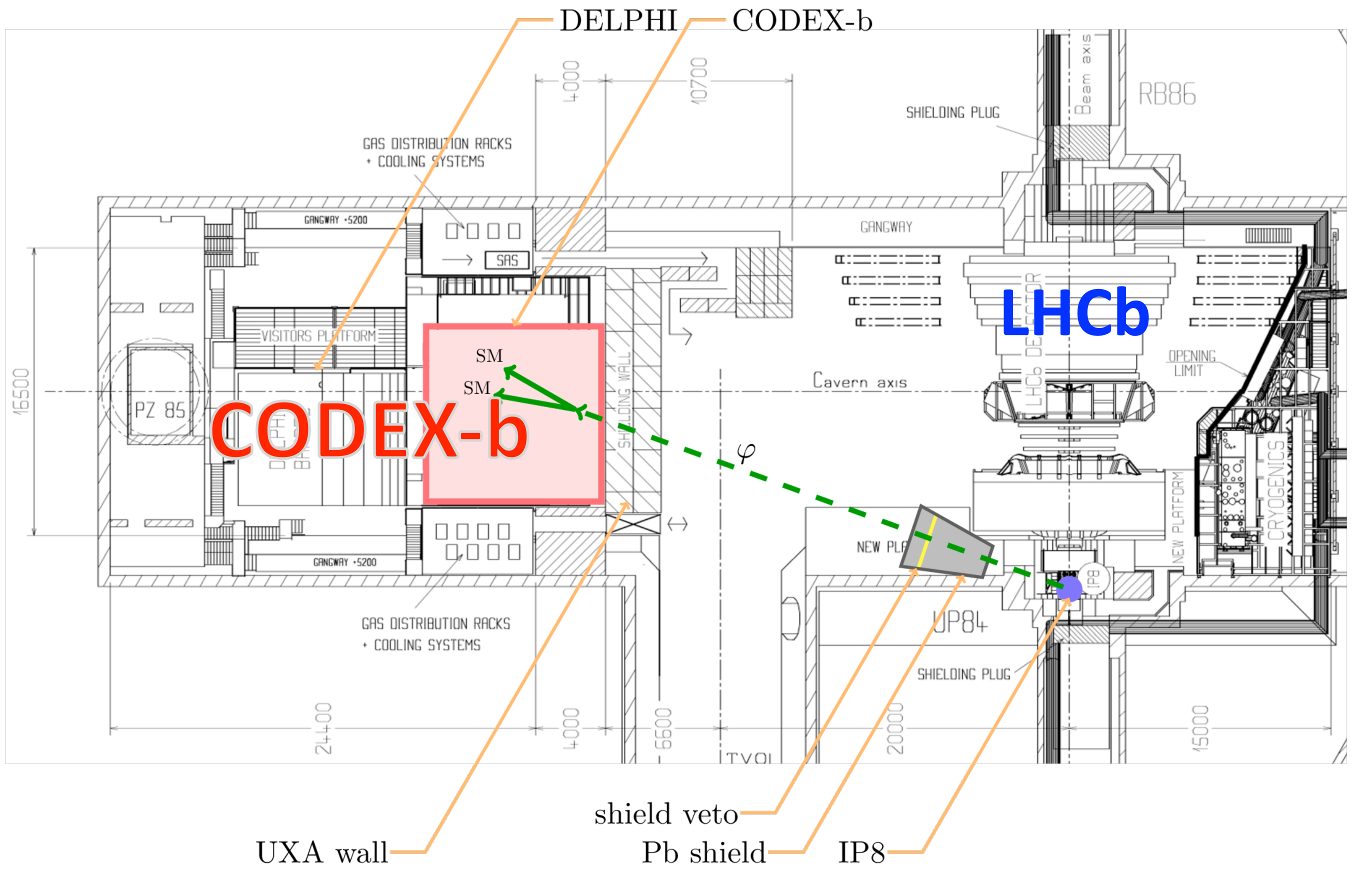
Transverse Detectors at the HL-LHC

Transverse, shielded detectors like CODEX-b are sensitive to **uncovered regions of LLP phase space**



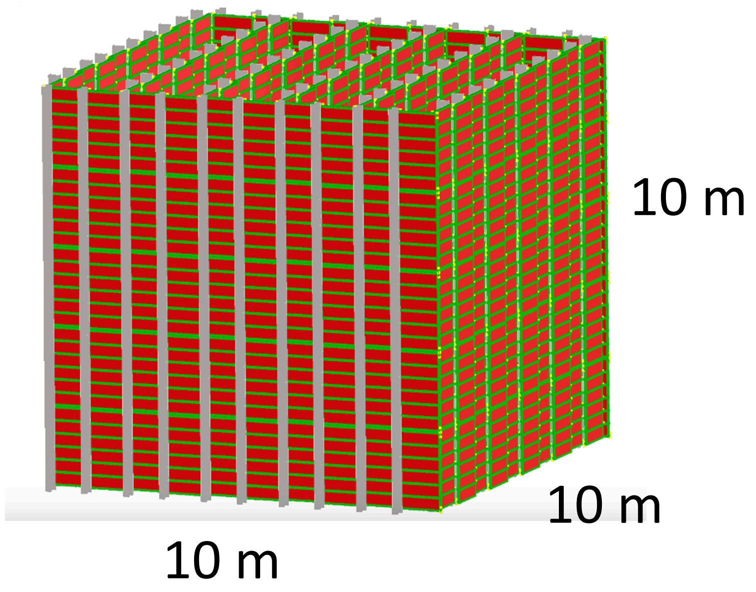
CODEX-b

COmpact Detector for EXotics at LHCb



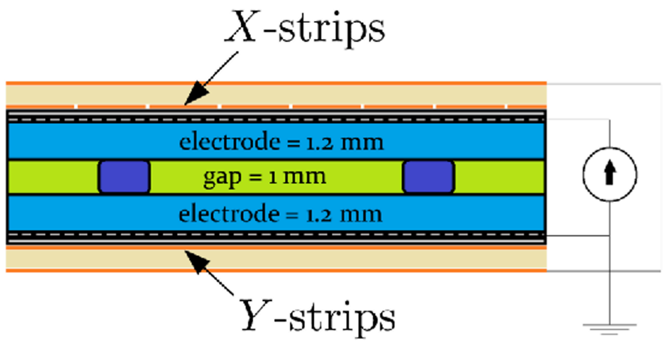
- **Tracking volume** off-axis to the beam, and aligned with LHCb
- Several locations about 25 m from LHCb being studied
- Active and passive shielding
- Integration with LHCb triggerless DAQ
- Aim for **0 background experiment**
- **Very competitive or world-best sensitivity in a wide range of scenarios**

CODEX-b Detector

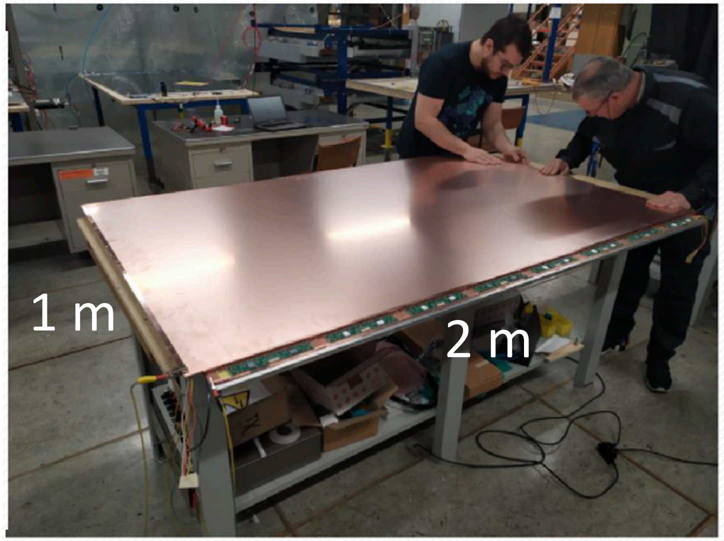


- 10m³ box of **Resistive Plate Chamber (RPC) tracking layers**
  - Well-known technology, same as for ATLAS Muon Upgrade (BIS78)
  - Medium size, **low cost**
- **Triplet of RPCs** form a panel:
  - ~1 mm spatial resolution in X-Y
  - ~100 ps timing resolution

RPC Singlet:



RPC Triplet:



VLL Event Selection and Backgrounds

CMS-EXO-23-015

Event selection:

- Trigger on missing transverse momentum
  - $p_T^{miss} > 120\,(200)$ GeV online (offline)
- Require ≥ 1 hadronic tau with $p_T > 30$ GeV
- Require ≥ 1 MDS

Backgrounds:

- Punch-through jets
- Muons that undergo bremsstrahlung
- Isolated hadrons from pileup, recoils, or underlying events
- Cosmic muon showers

VLL Event Selection and Backgrounds

[CMS-EXO-23-015]

Event selection:

- Trigger on missing transverse momentum
  - $p_T^{miss} > 120\,(200)$ GeV online (offline)
- Require ≥ 1 hadronic tau with $p_T > 30$ GeV
- Require ≥ 1 MDS

Backgrounds:

- Punch-through jets
- Muons that undergo bremsstrahlung

Suppress by rejecting clusters near jet or muon

- Isolated hadrons from pileup, recoils, or underlying events

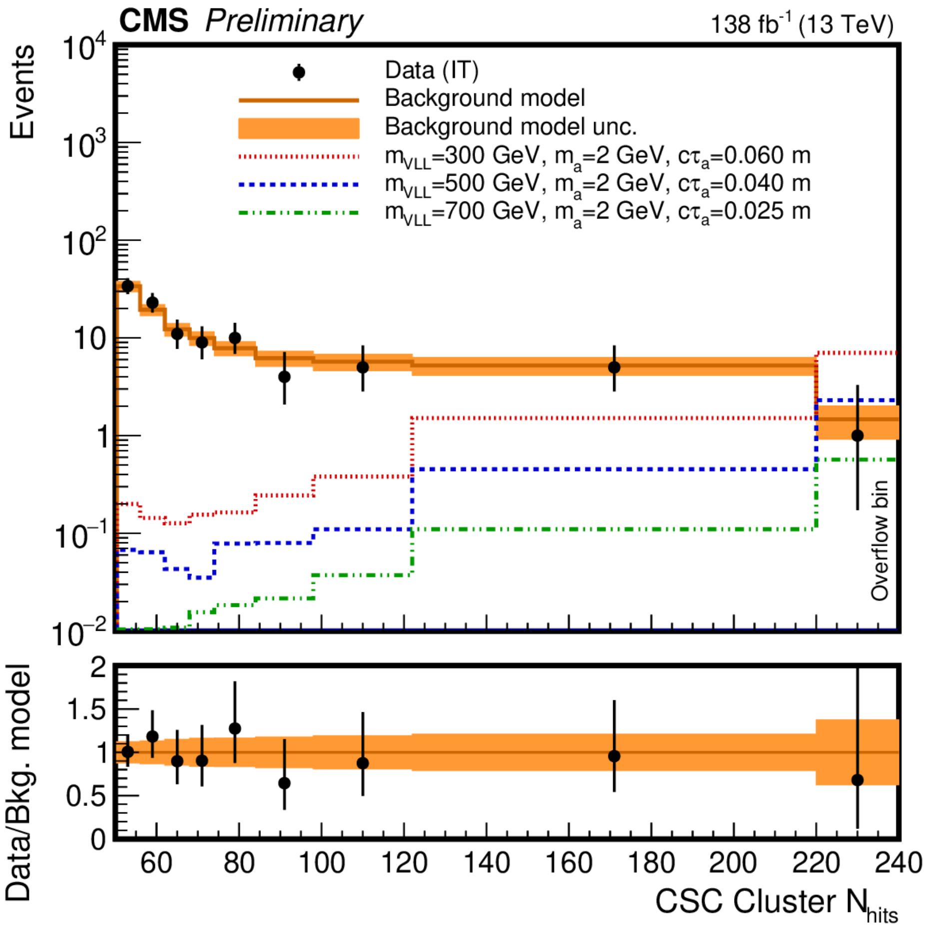
Suppress by requiring clusters to be in time with the bunch crossing

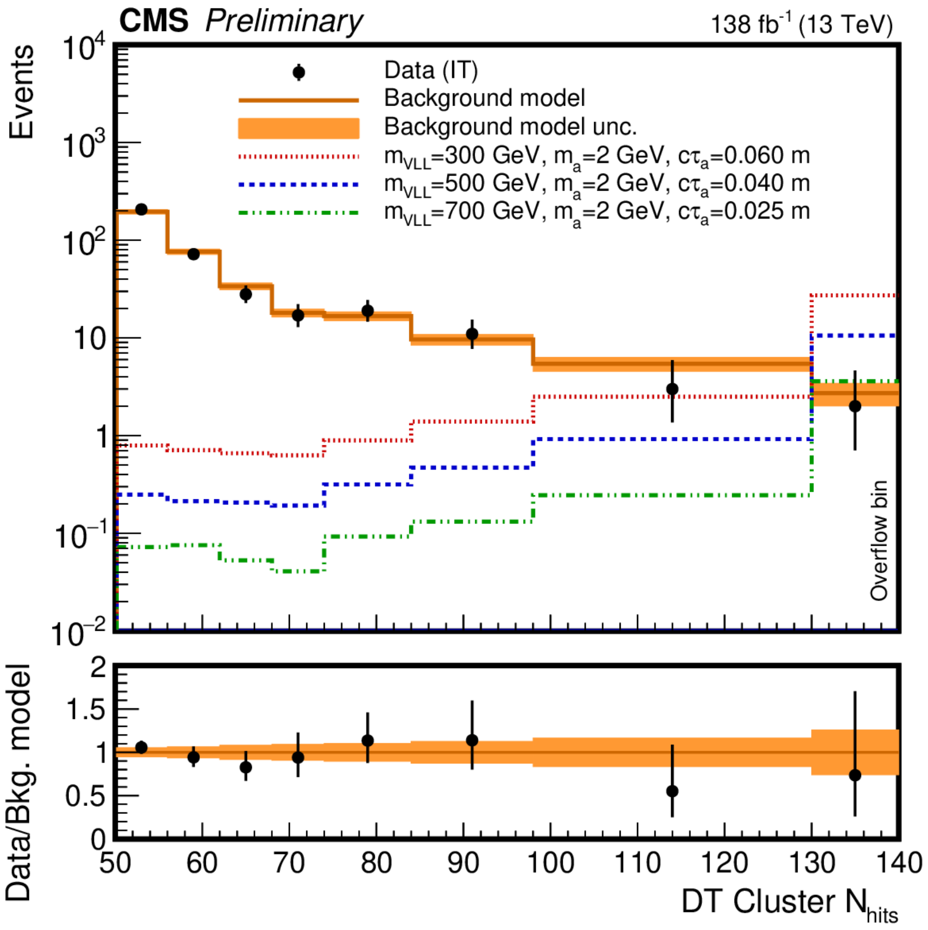
- Cosmic muon showers

Suppress by rejecting clusters with significant number of hits within $\Delta\phi < \pi/4$

VLL Results

CMS-EXO-23-015

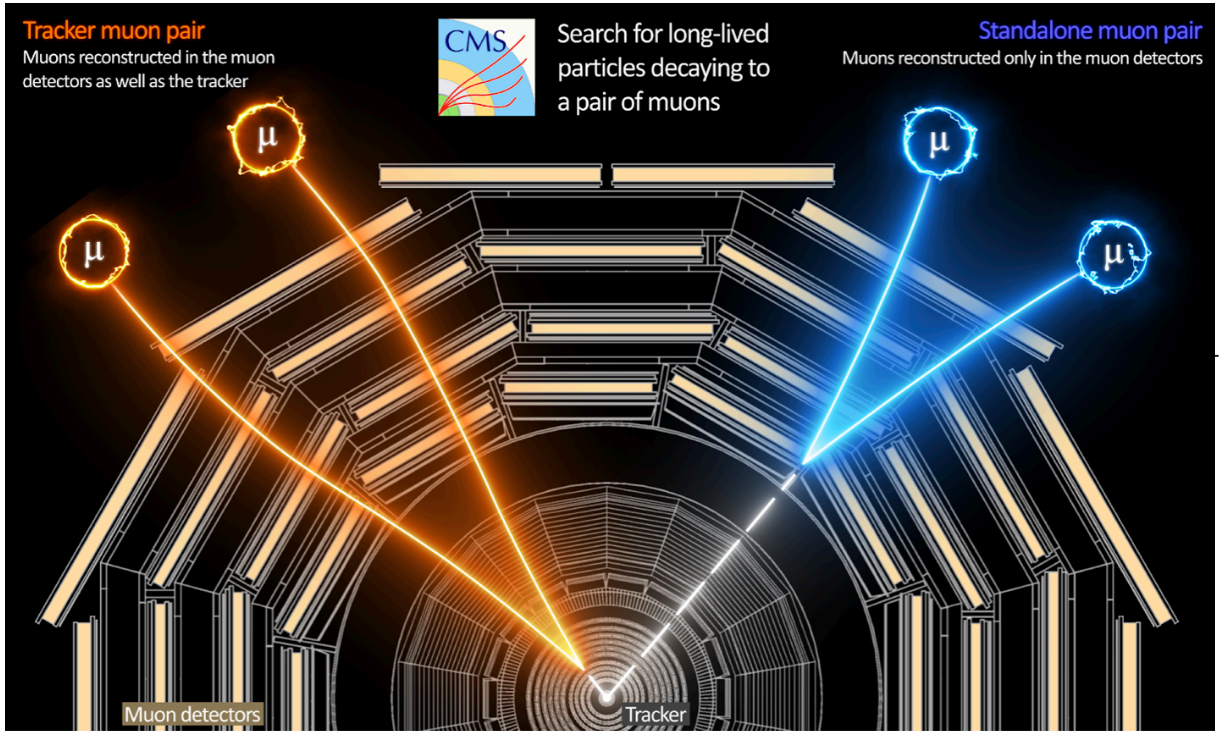




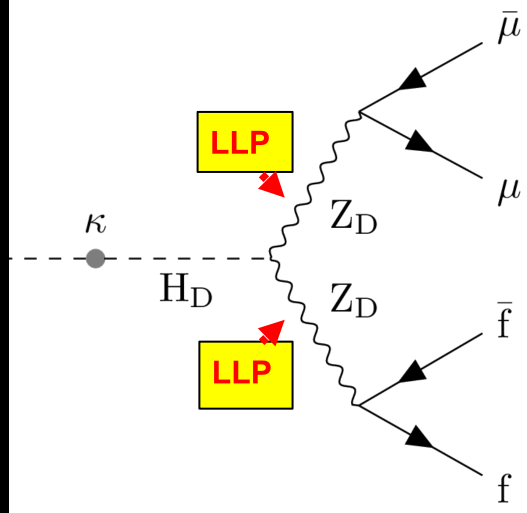
First CMS Run 3 Search: Displaced Dimuons

arXiv:2402.14491

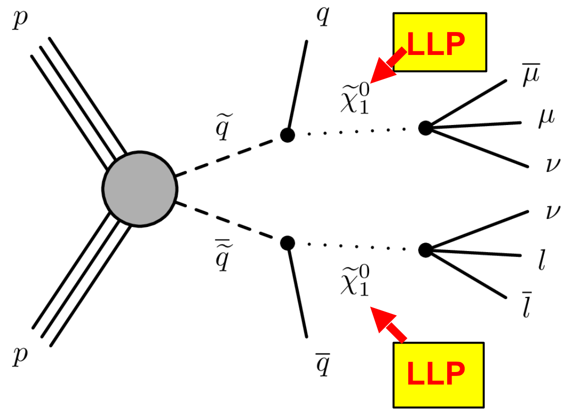
- **Generic, inclusive search** for long-lived particles decaying into pairs of oppositely-charged muons (displaced dimuons) within the tracker and beyond
- Uses 36.7 fb^{-1} of 13.6 TeV data taken in 2022



Hidden Abelian Higgs Model (HAHM)



RPV SUSY Model

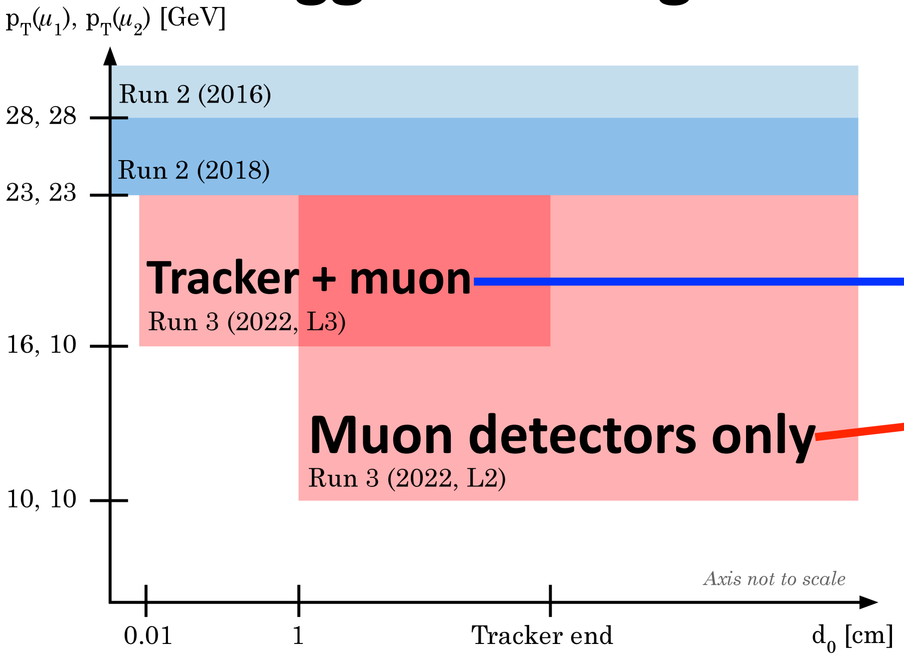


[arXiv:2402.14491](https://arxiv.org/abs/2402.14491)

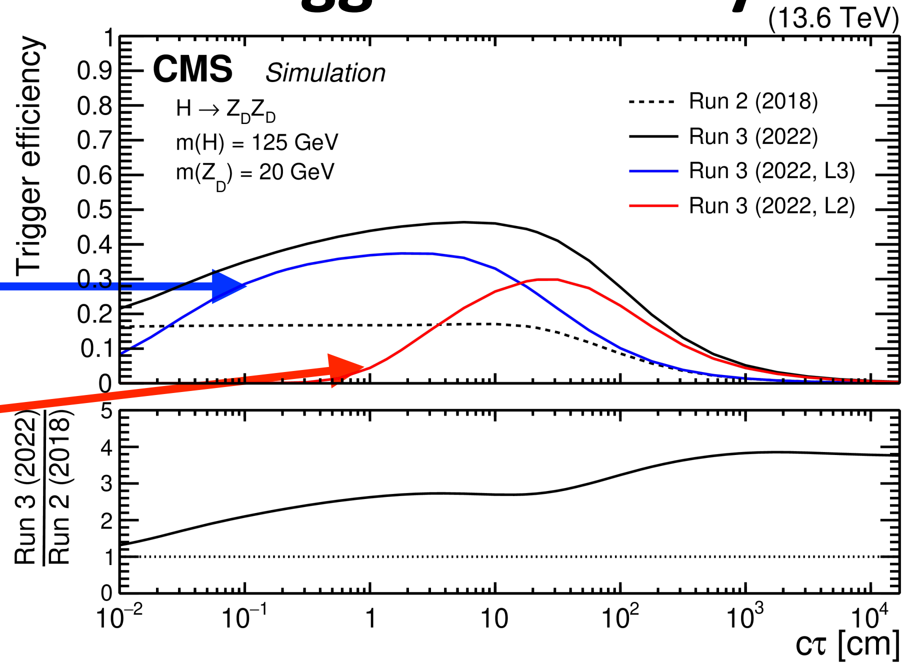
Displaced Dimuons: Triggers

- **Generic, inclusive search** for long-lived particles decaying into pairs of oppositely-charged muons (displaced dimuons) within the tracker and beyond
- Uses 36.7 fb^{-1} of 13.6 TeV data taken in 2022
- Improved triggers → **Substantial increase in acceptance x trigger efficiency** compared to Run 2
- Improve signal efficiency at low mass and large displacements up to a factor of 4

Trigger Coverage



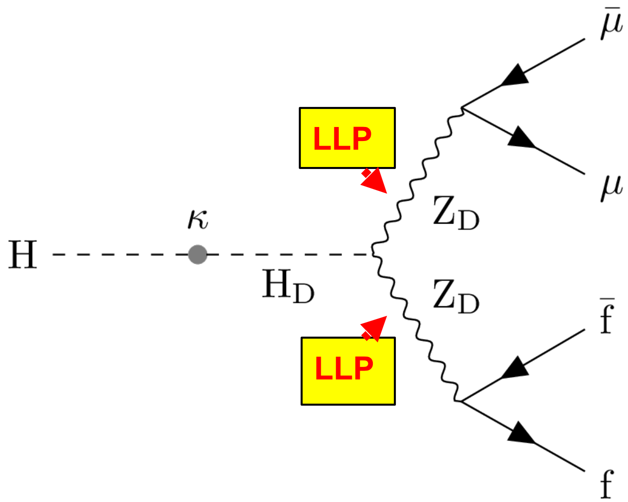
Trigger Efficiency



Displaced Dimuons: Sensitivity

arXiv:2402.14491

- **Generic, inclusive search** for long-lived particles decaying into pairs of oppositely-charged muons (displaced dimuons) within the tracker and beyond
- Uses 36.7 fb^{-1} of 13.6 TeV data taken in 2022
- Improved triggers → **Substantial increase in acceptance x trigger efficiency** compared to Run 2
- Improve signal efficiency at low mass and large displacements up to a factor of 4
- ***With partial Run 3 data, comparable or better sensitivity than Run 2 (only 38% of the data!)***



HAHM Model