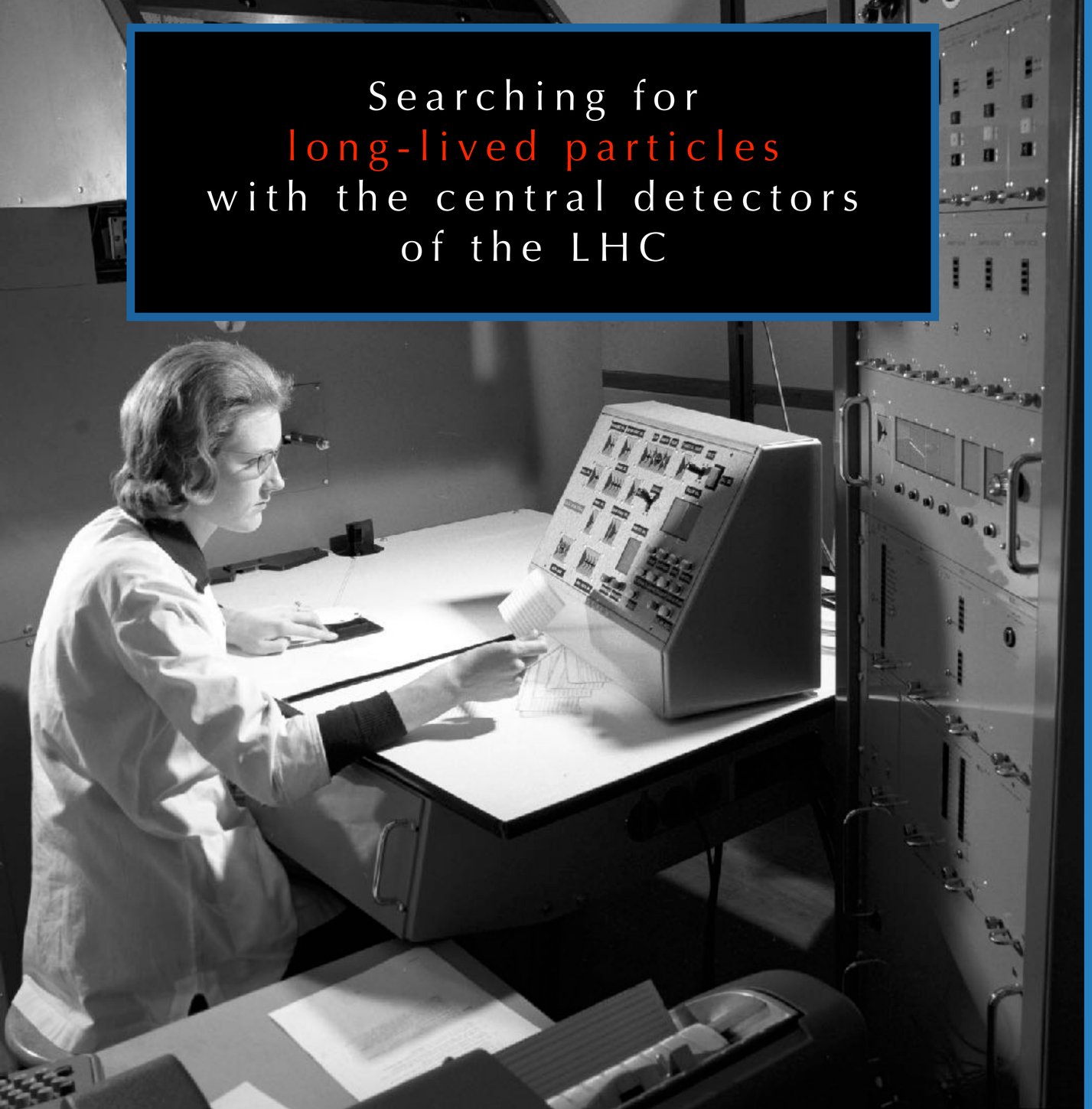
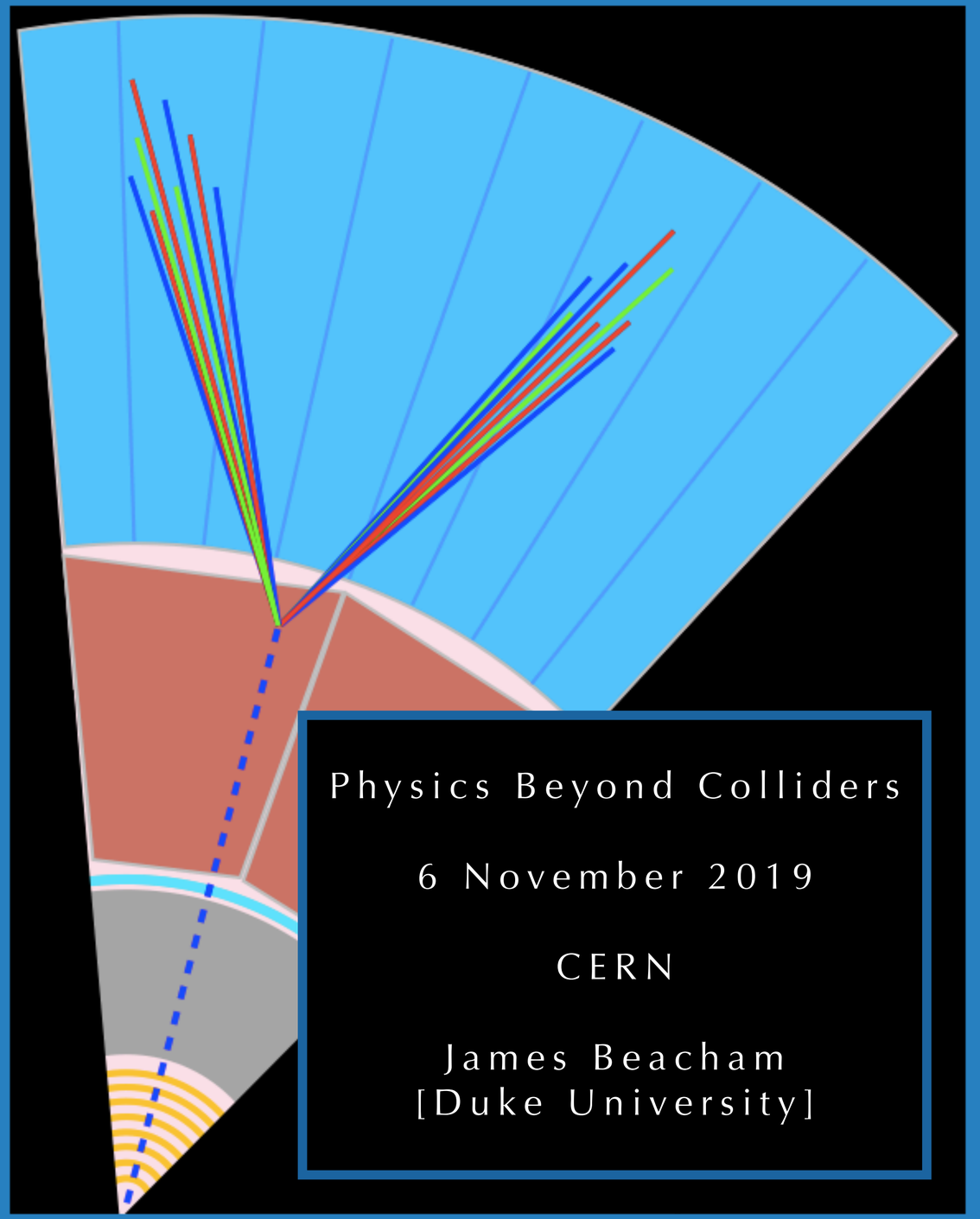
Searching for long-lived particles with the central detectors of the LHC





Physics Beyond Colliders

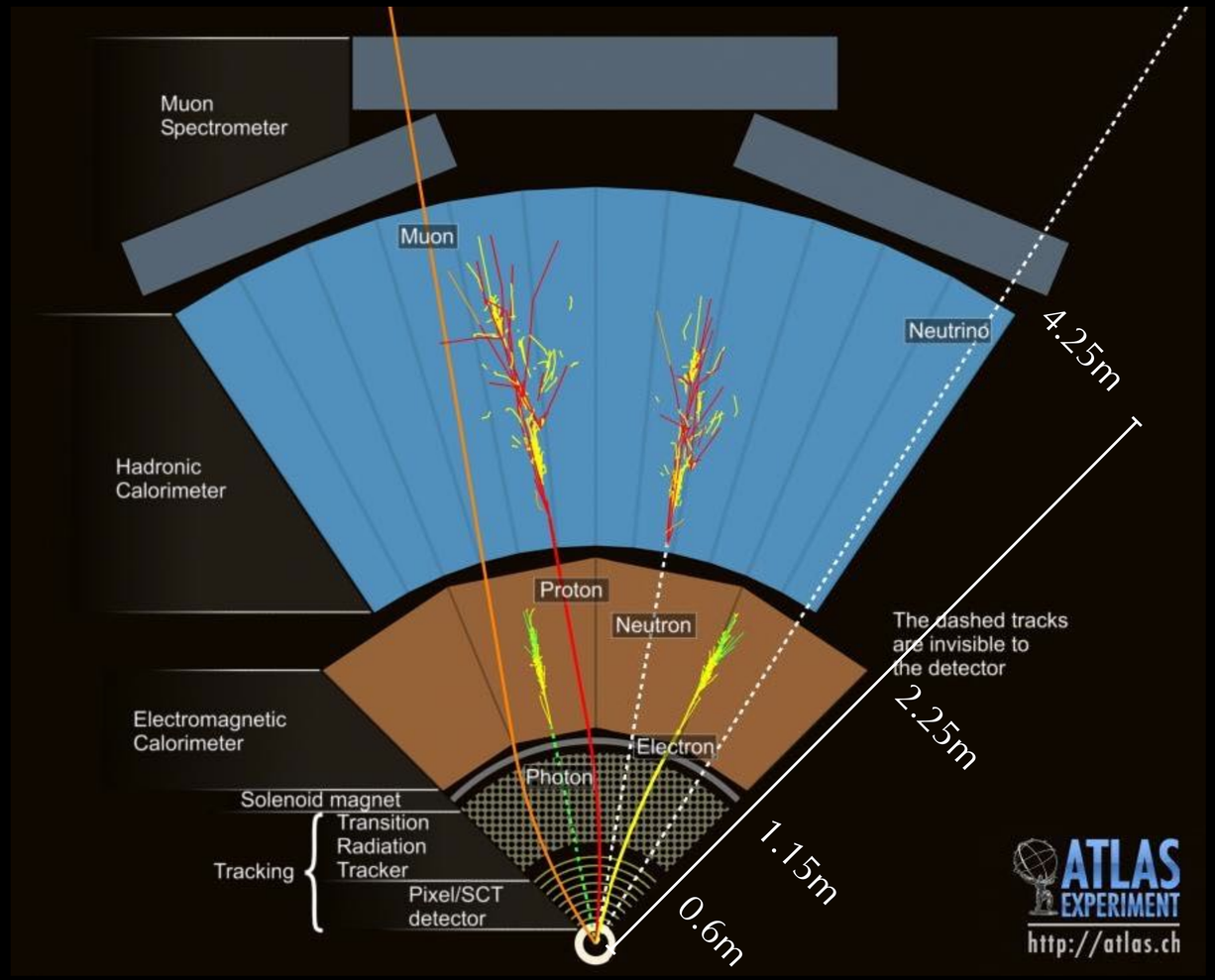
6 November 2019

CERN

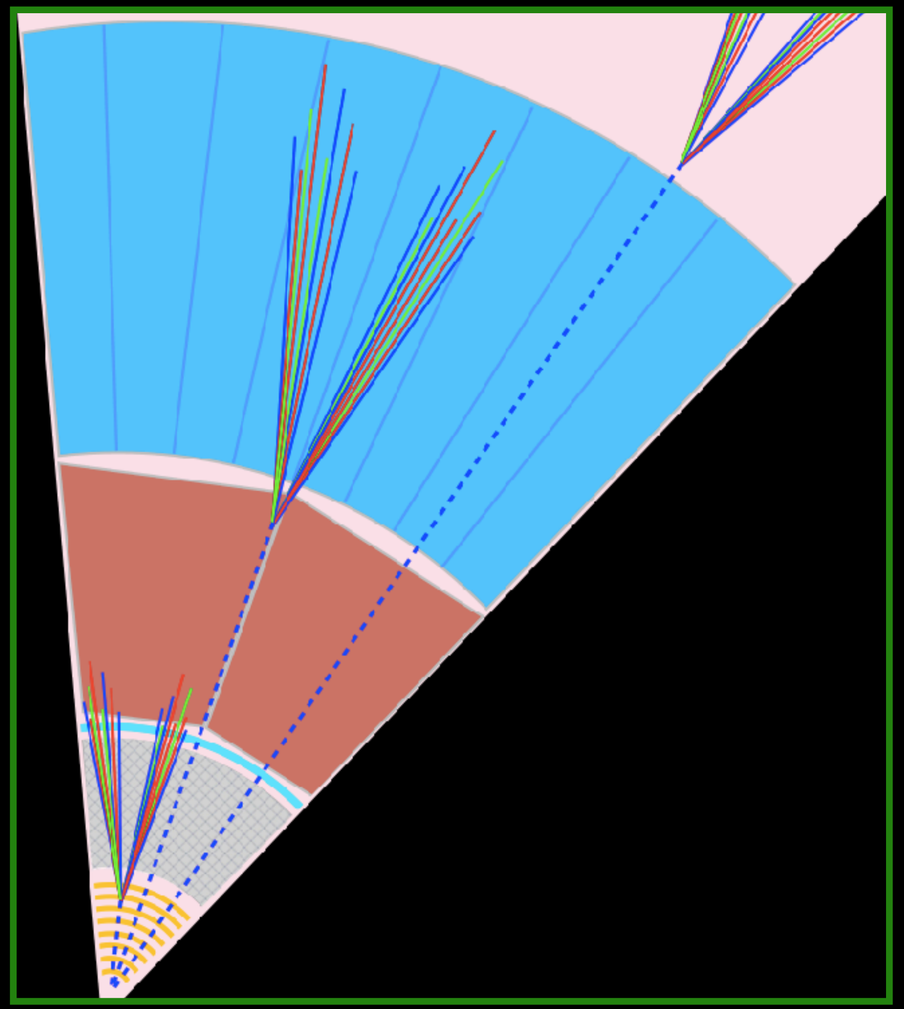
James Beacham
[Duke University]

Physics beyond colliders ... at colliders

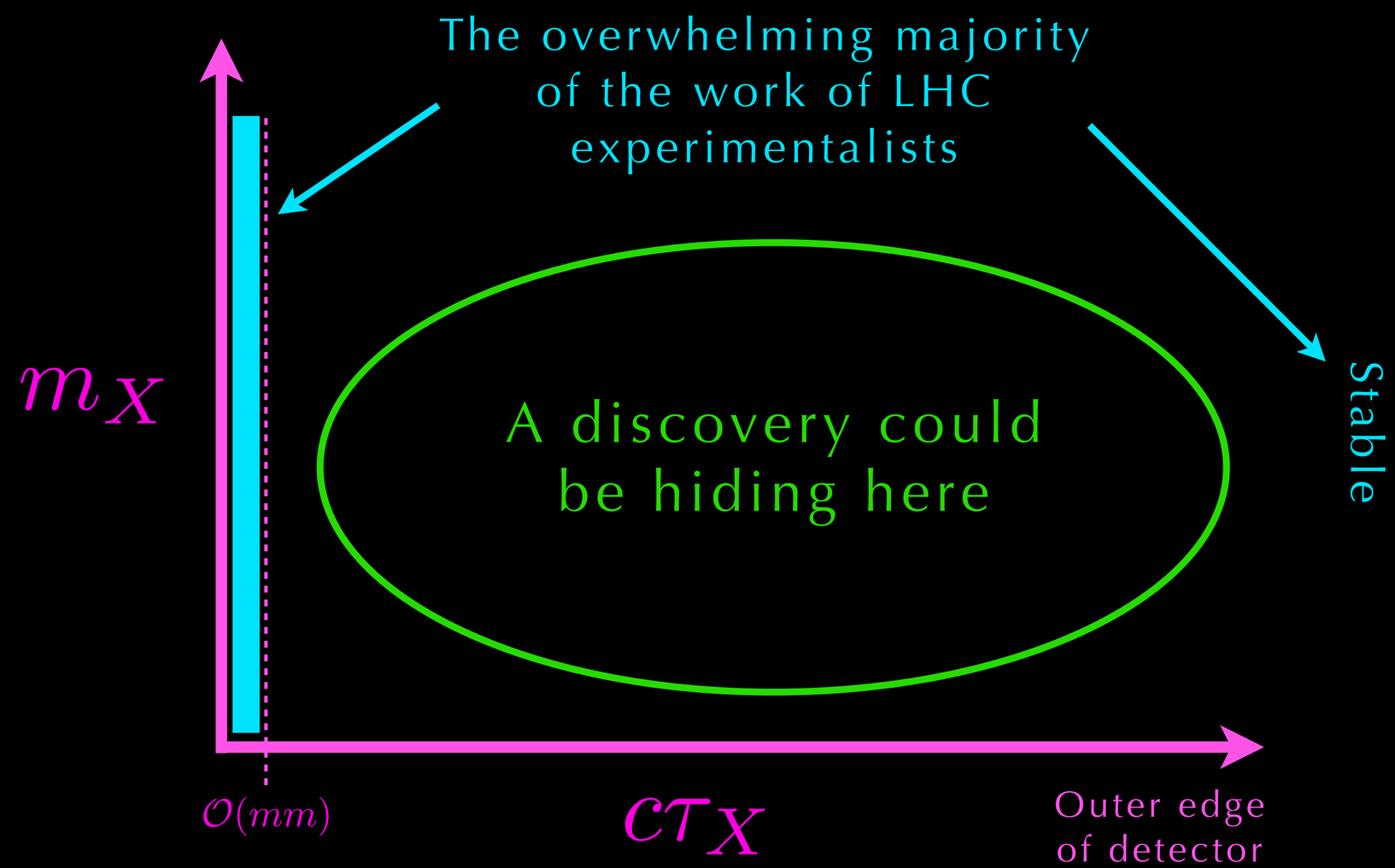
95% of our analysis effort at ATLAS and CMS is dedicated to understanding five prompt, isolated objects



The first "physics beyond colliders" occurs when the BSM particle starts drifting into the detector before decaying



The lifetime frontier



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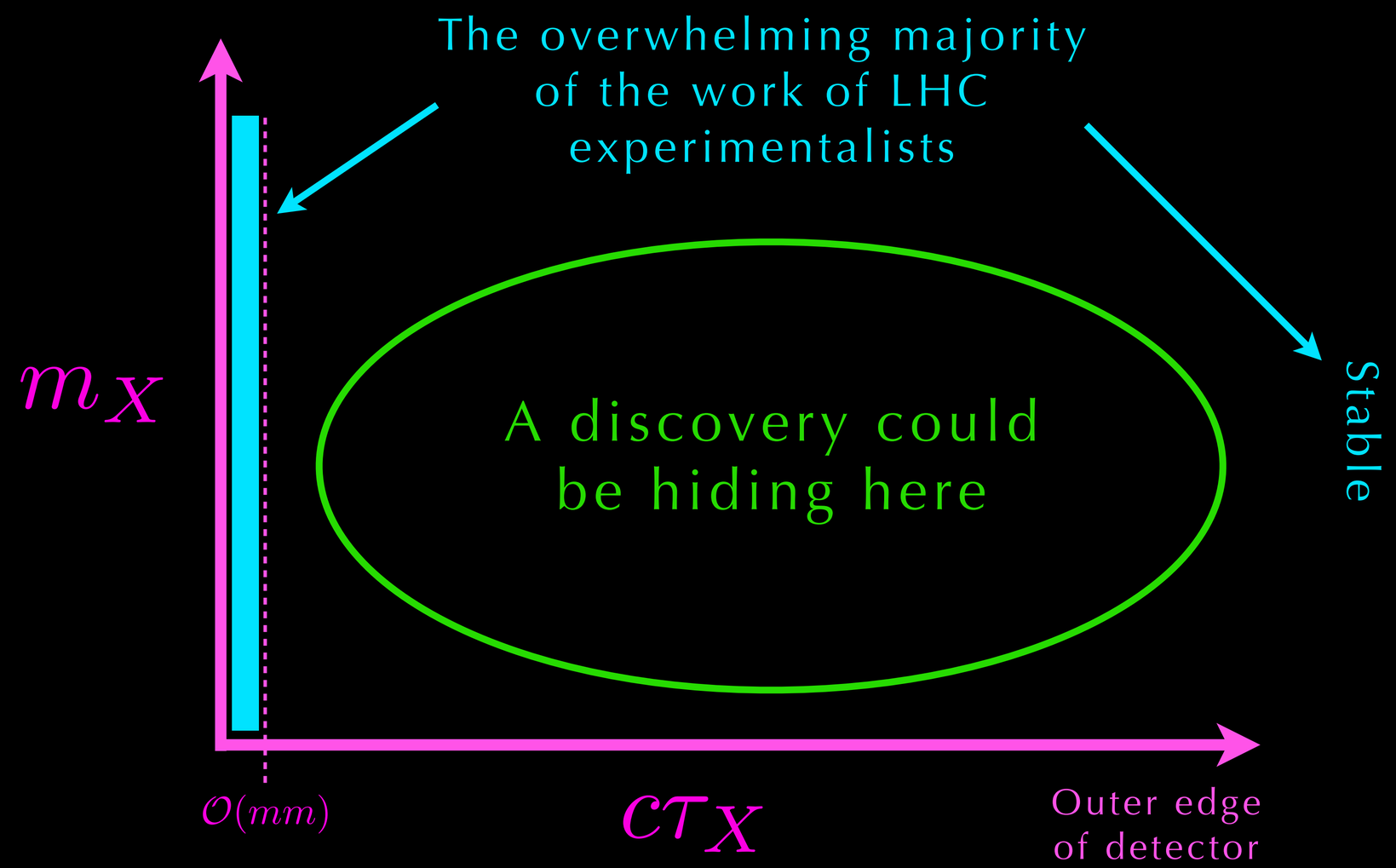
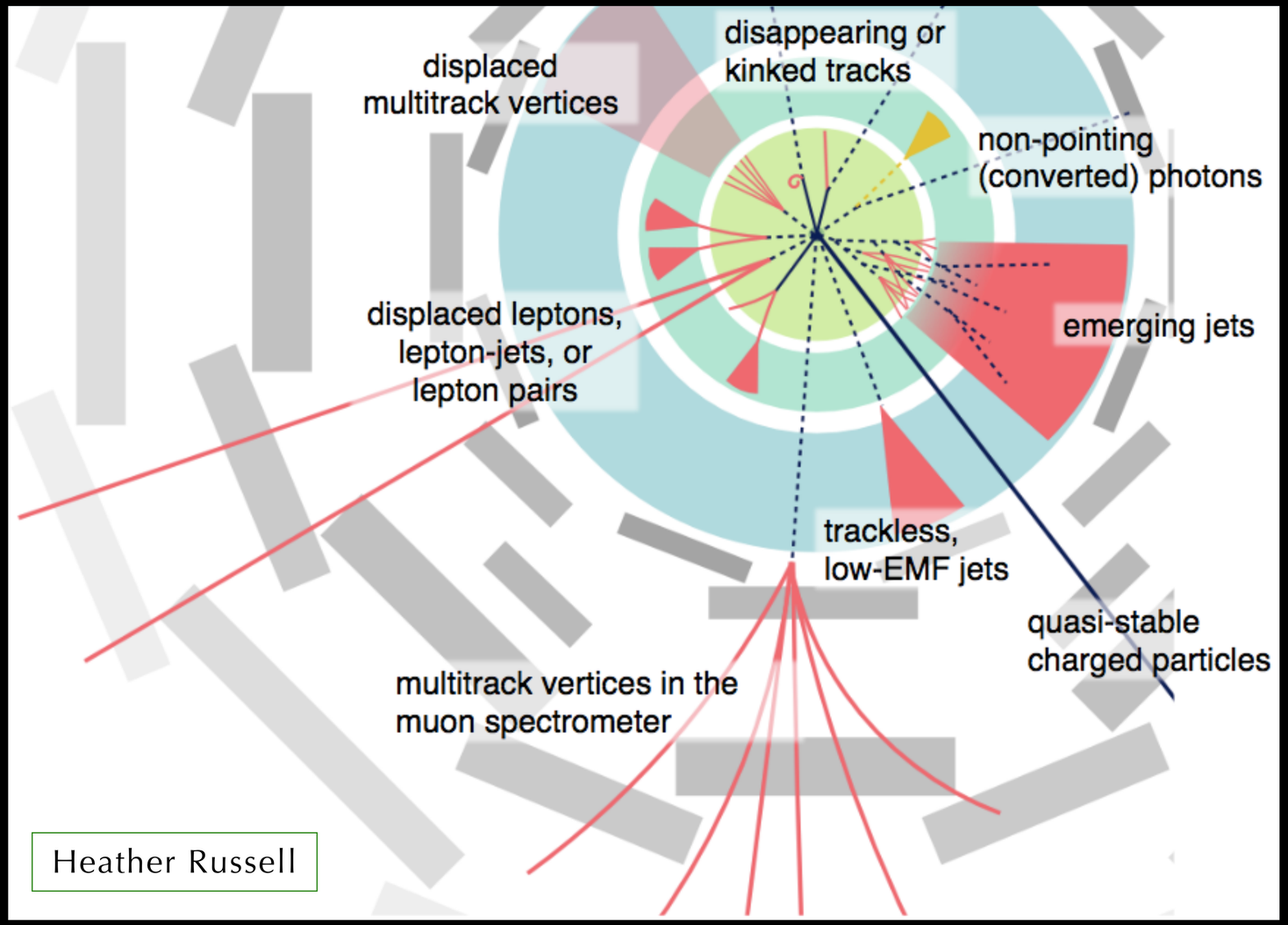


Large majority of ATLAS, LHCb, and CMS searches and analysis strategies assume the new particle decays promptly

Particle lifetimes in the SM span a very wide range and long lifetimes can generically appear in BSM theories

Obliges us to perform dedicated searches for long-lived BSM particles

Long-lived particles in the central LHC detectors



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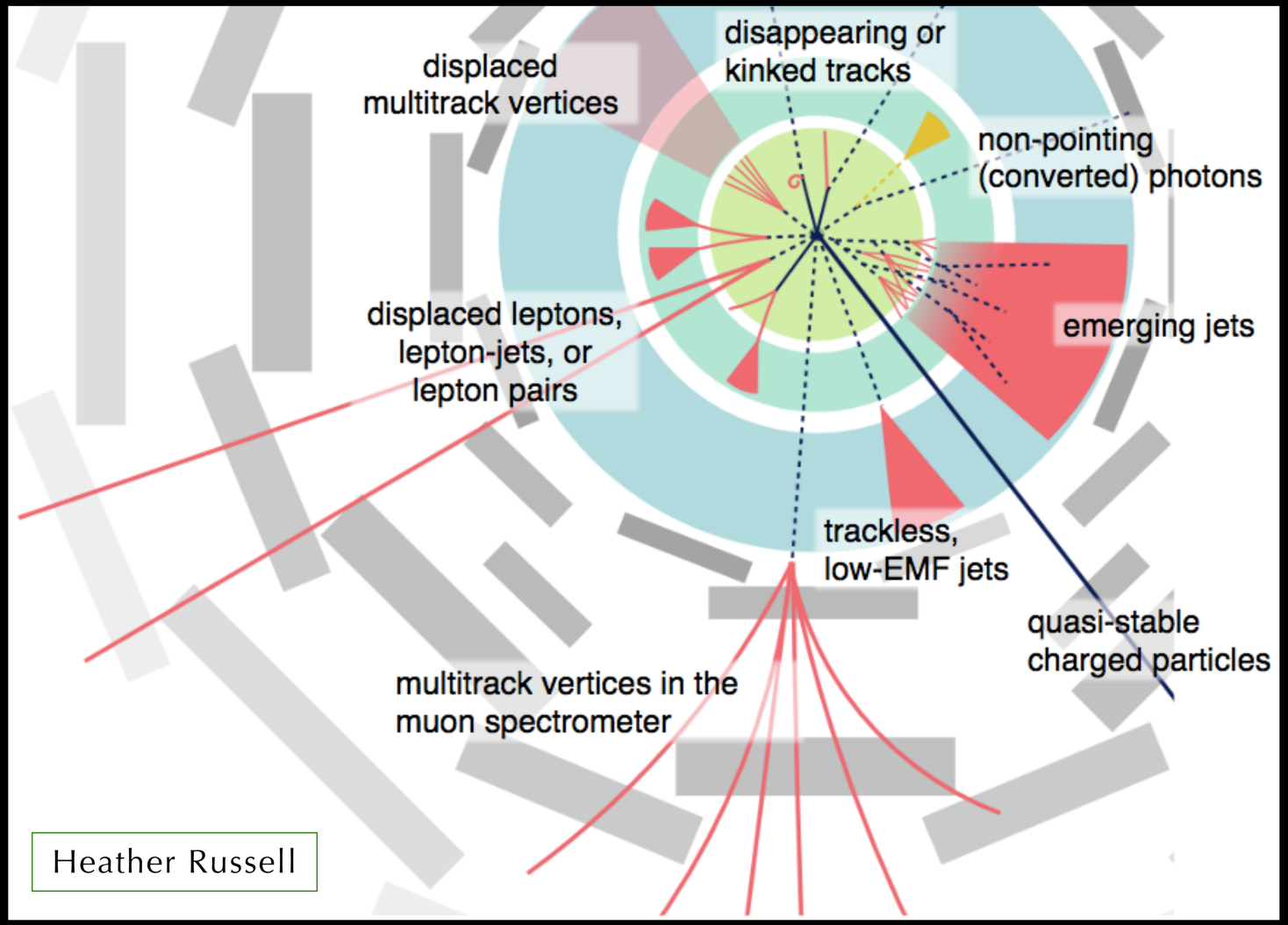
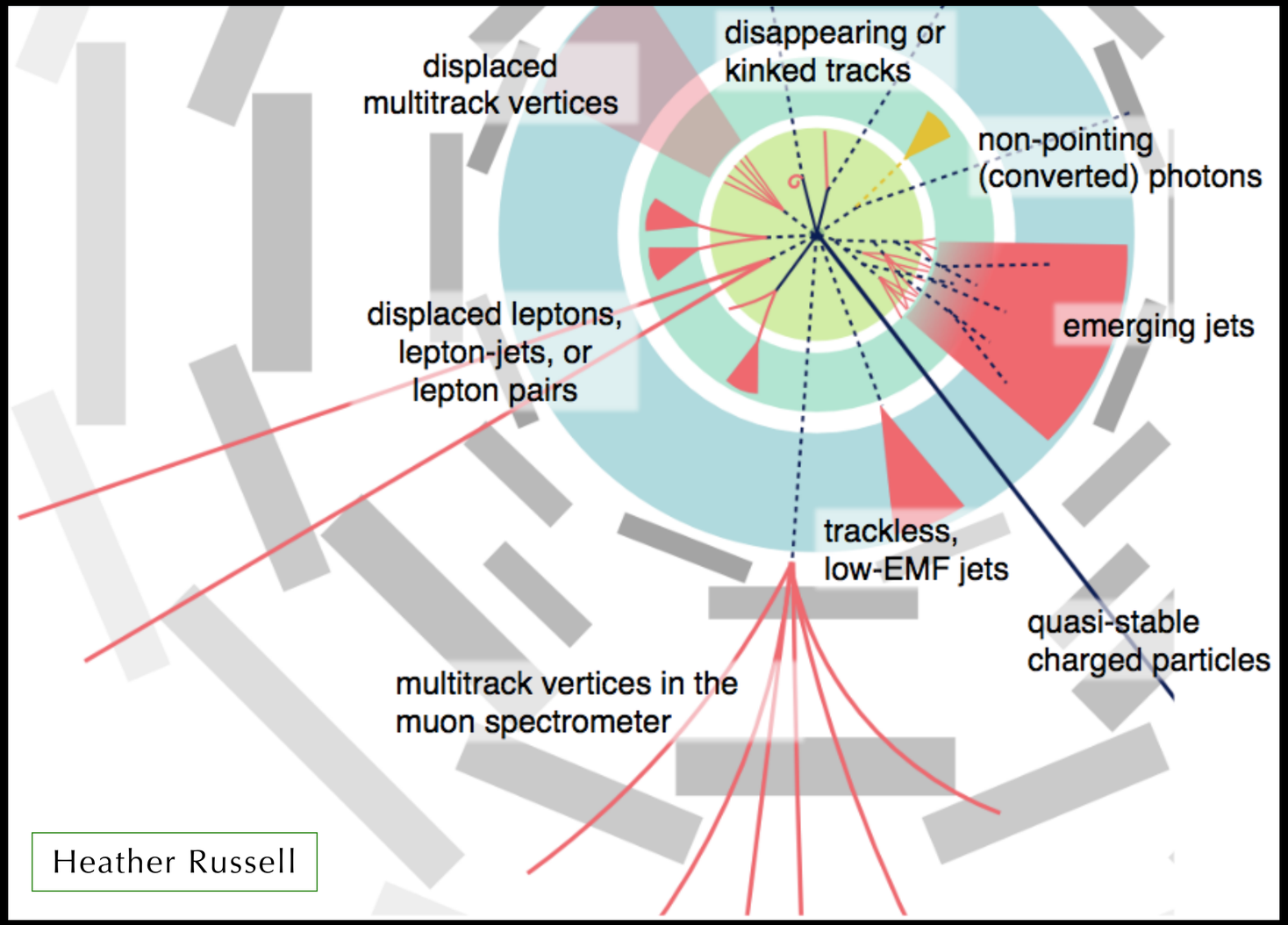


For our purposes, LLP = BSM particle with a non-negligible lifetime that gives up most of its energy or decays to SM somewhere in the detector acceptance of LHCb, CMS, ATLAS, MilliQan, MoEDAL, FASER, CODEX-b, MATHUSLA, AL3X, ANUBIS, etc.

Long-lived particles in the central LHC detectors



We've been doing these searches since day one of the LHC (and at LEP, & Tevatron), but until ~2016, they were always considered fringe, and they still make up less than 10% of our "exotic" searches

Public results with the central LHC detectors

CMS Exotica LLP

CMS SUSY RPV

LHCb Public Results

ATLAS Exotics

ATLAS SUSY

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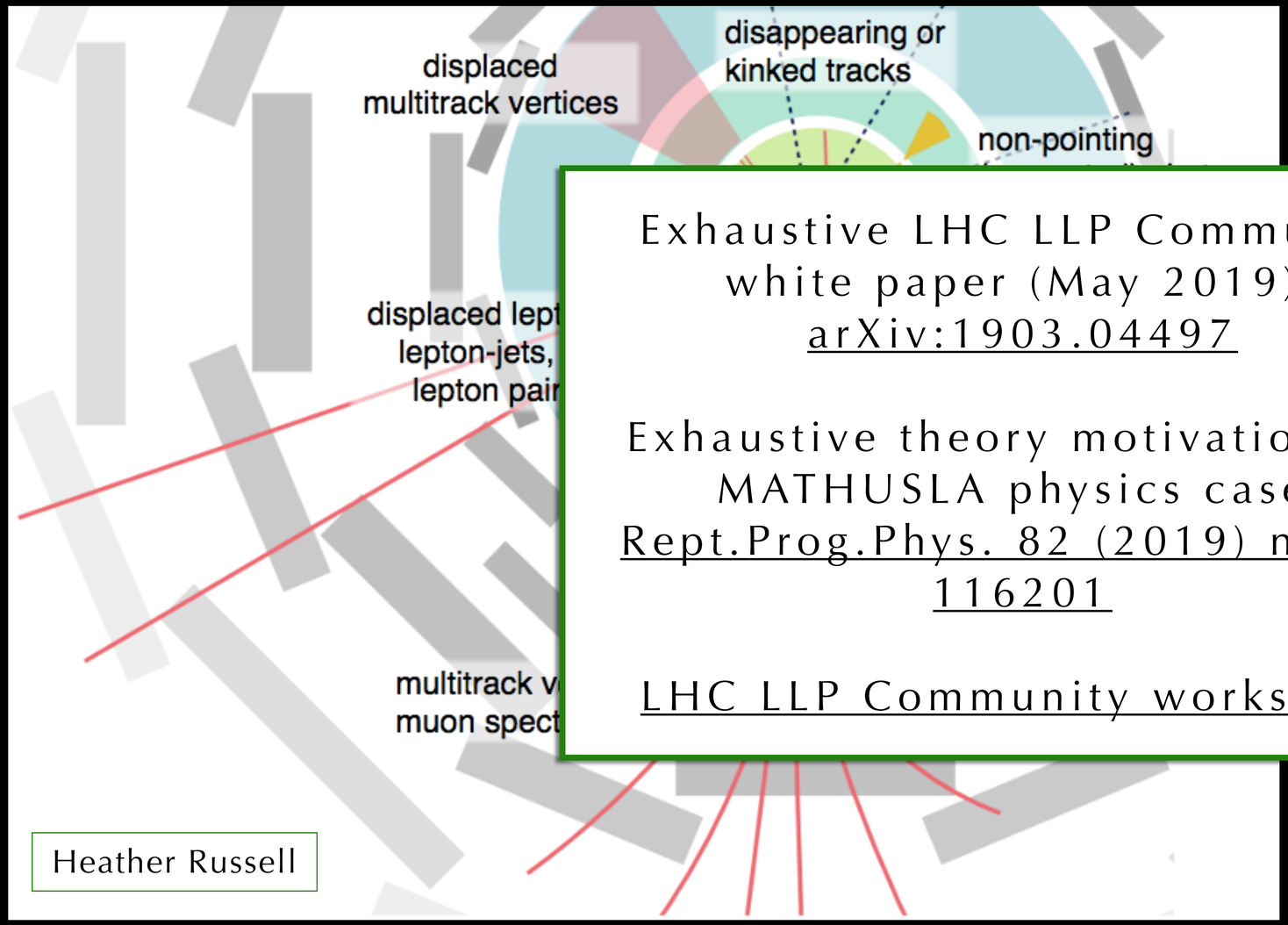

Exhaustive LHC LLP Community white paper (May 2019): arXiv:1903.04497

Exhaustive theory motivations in MATHUSLA physics case: Rept.Prog.Phys. 82 (2019) no.11, 116201

LHC LLP Community workshops

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results with the central LHC detectors

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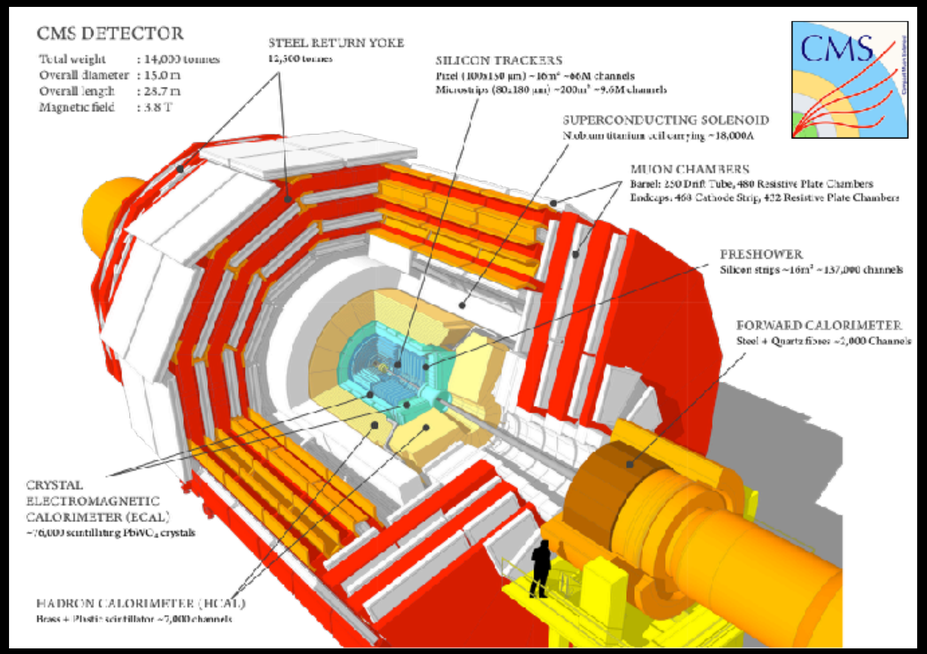
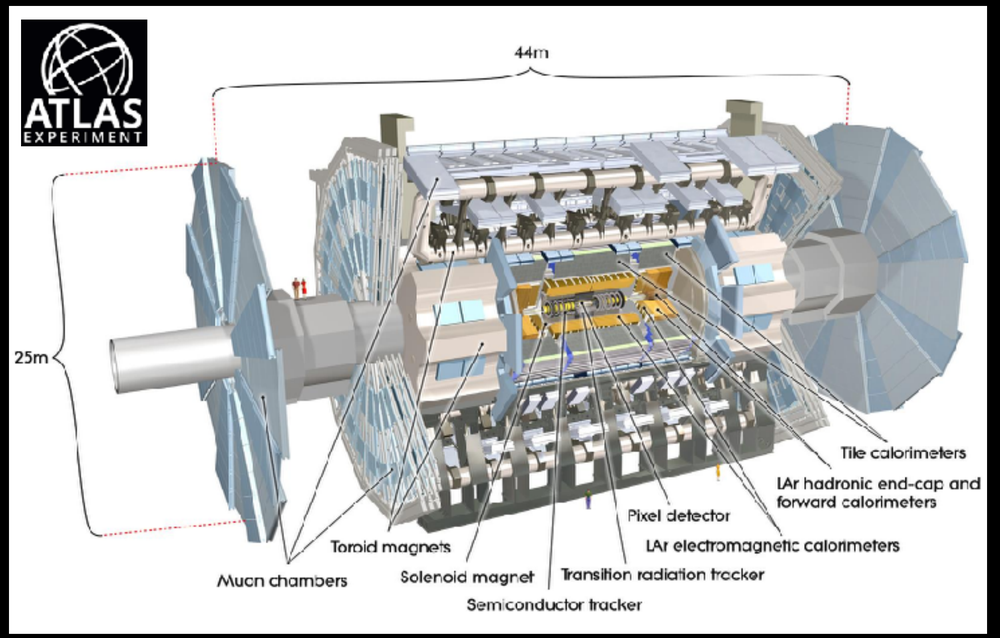
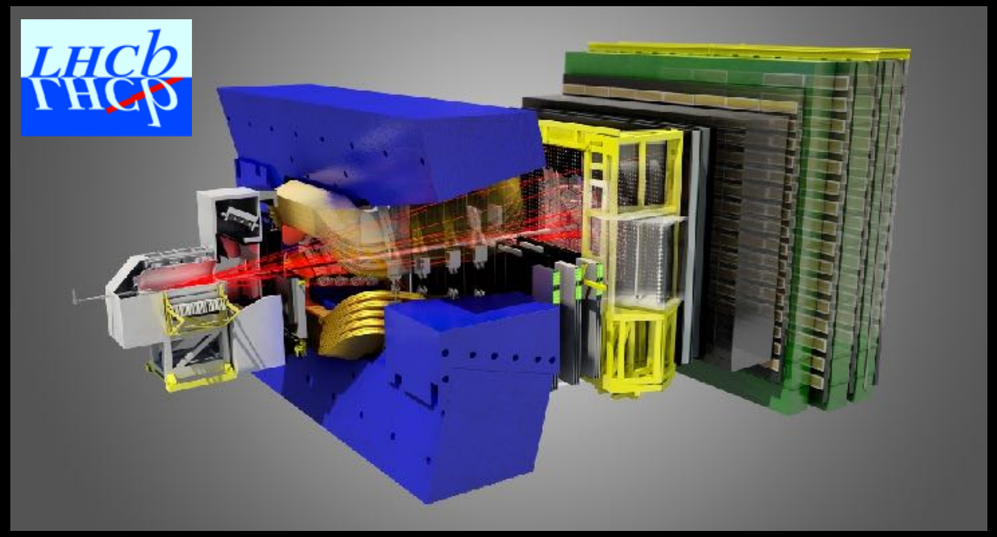
Long-lived particles at ATLAS, CMS, and LHCb







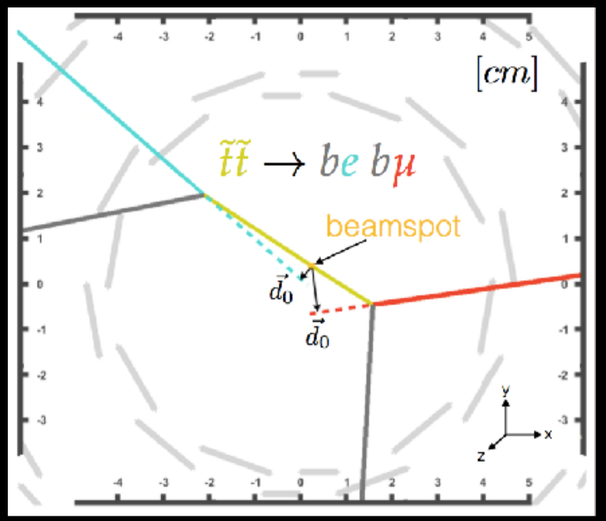
Searches are often SM-background-free but can be subject to very atypical background sources (like cosmic ray muons, beam halo, cavern backgrounds, etc.) that are challenging to estimate and irrelevant to most prompt searches

A few examples of signatures we search for (omitting disappearing tracks, quasi-stable charged particles, stopped particles, quirks, SUEPs, others, for time)

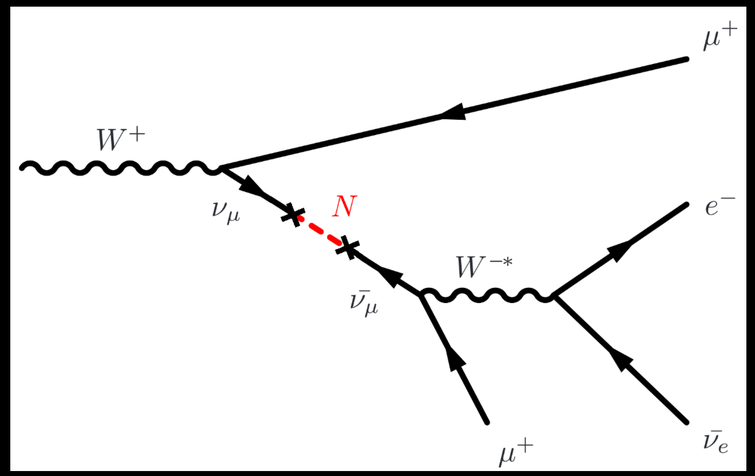
Neutral LLPs decaying to leptons

Identifying displaced charged particles requires the capacity to find tracks with large impact parameters

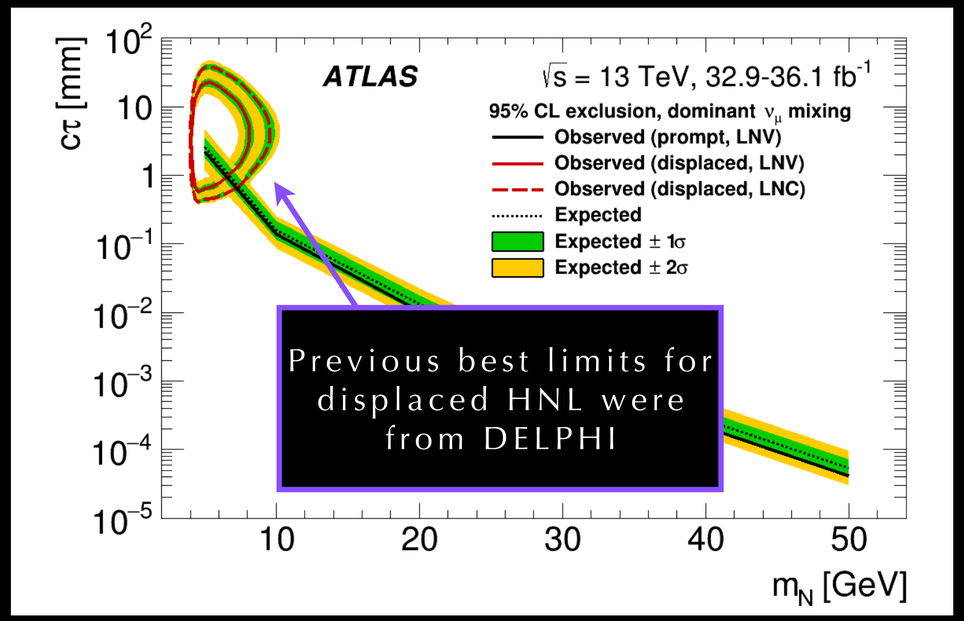
- If LLP decay occurs in the inner tracker, can use large-d0 tracking
  - CMS has good tracking for such cases by default
  - ATLAS runs special re-tracking [ATLAS large radius tracking note] and re-vertexing on a subset of events
- Both approaches require customized triggering strategies
- Can lead to various signatures involving one displaced lepton, a pair of separately displaced leptons, or a combination of prompt and displaced

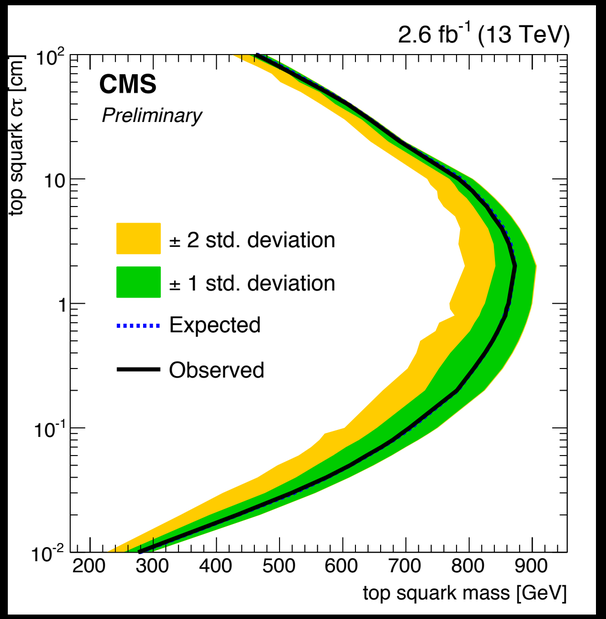


CMS-EXO-16-022



ATLAS (May 2019)
arXiv:1905.09787
submitted to JHEP





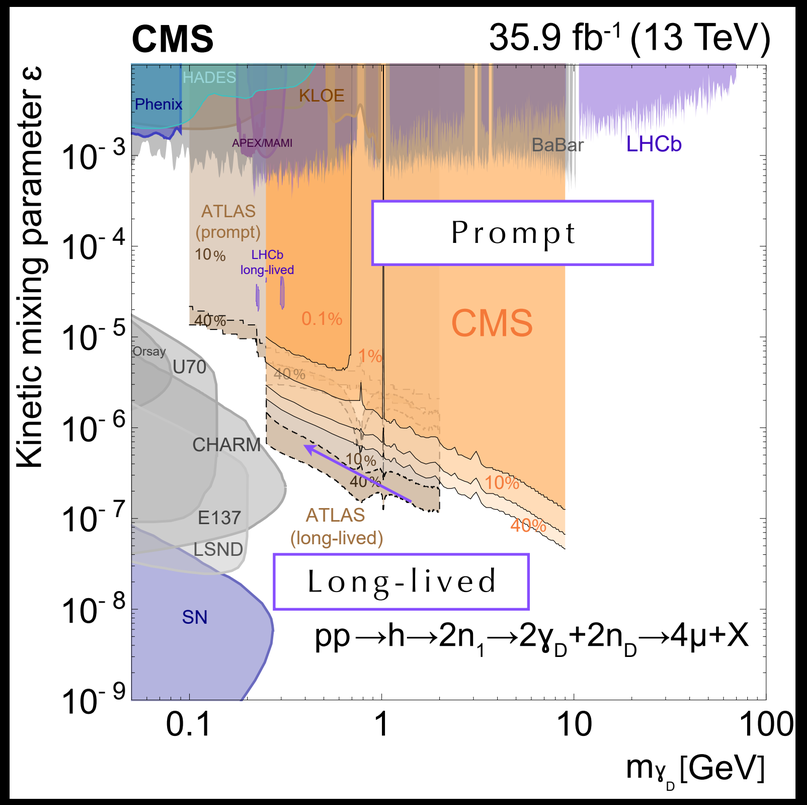
Neutral LLPs decaying to lepton-jets

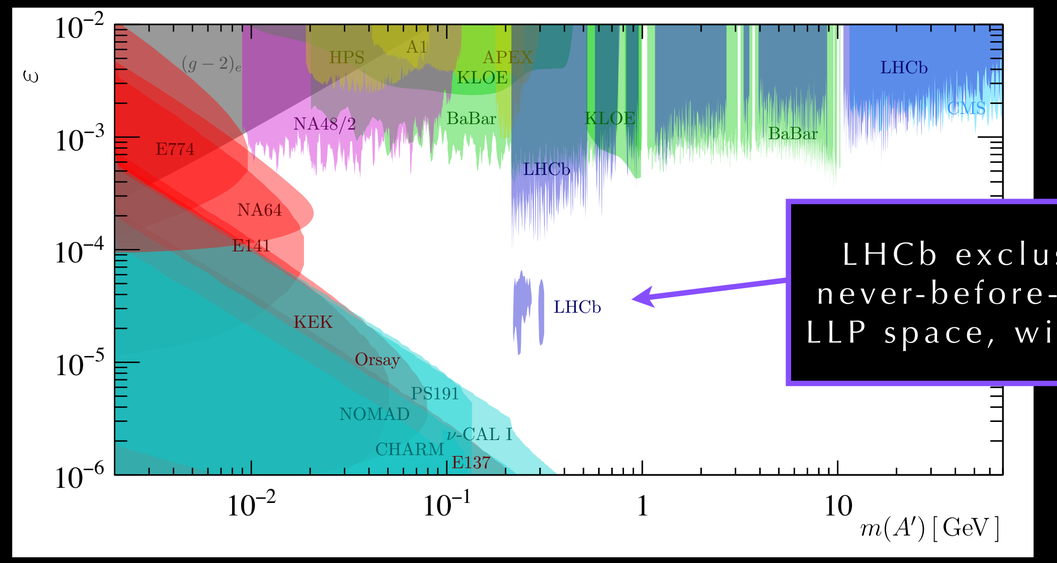
Lepton-jet = highly-collimated grouping of leptons from a low-mass (O(GeV)), boosted BSM particle like a dark photon / Z_{dark}

- Confounds standard lepton isolation criteria

PLB 796 (2019) 131

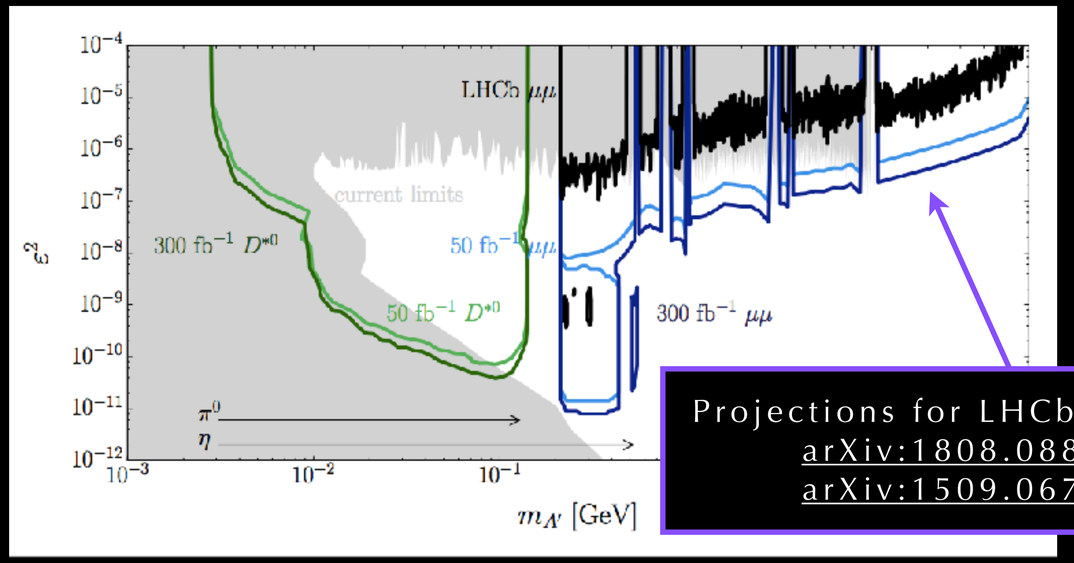
ATLAS-CONF-2016-042





LHCb exclusion in never-before-covered LLP space, with 5.5/fb

LHCb (Oct. 2019): arXiv:1910.06926



Projections for LHCb upgrade
arXiv:1808.08865
arXiv:1509.06765

LHCb: PRL 120, 061801

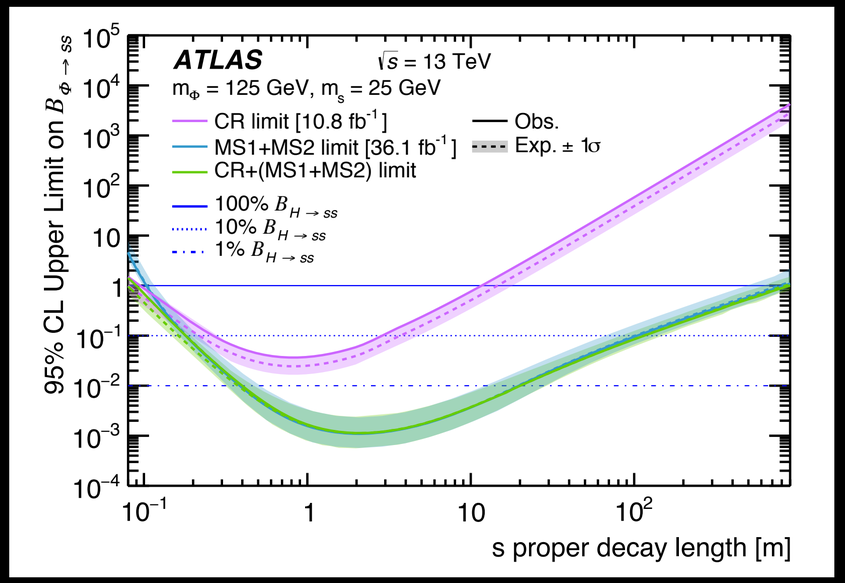
Neutral LLPs decaying to hadronic jets

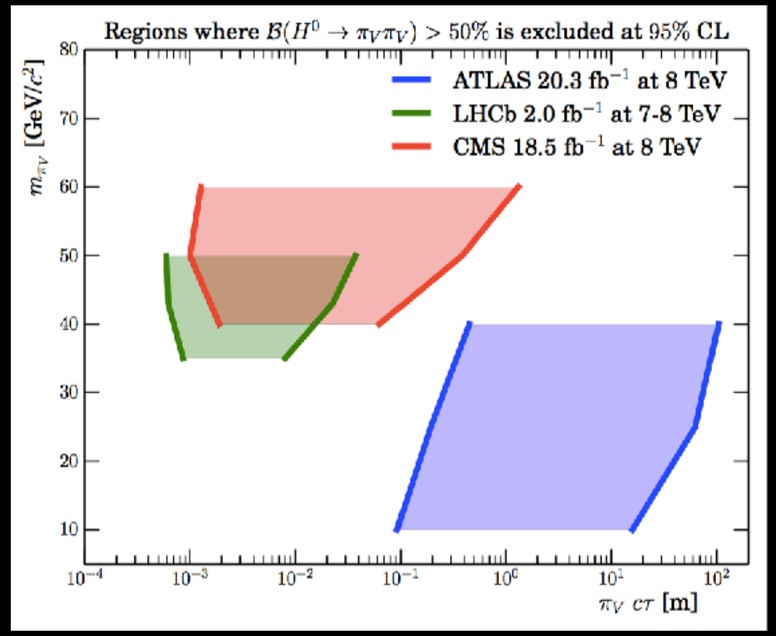
Hadronic LLP decays in different parts of the detectors require different search strategies

- Inner tracker —> Look for displaced multi-track vertices
- Calorimeters —> Look for large E_{Had} / E_{EM}
- Outer muon system —> Look for MS vertex

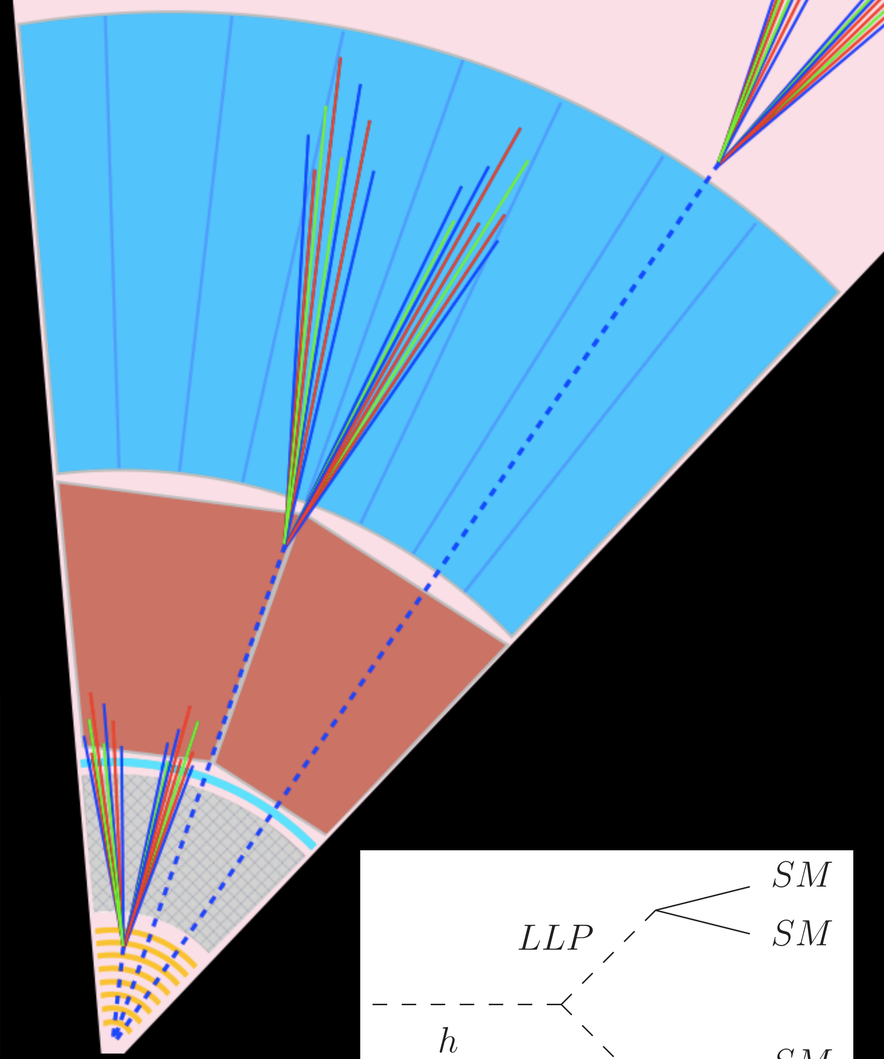
ATLAS, CMS, and LHCb use slightly different and complementary methods to isolate such potential signals

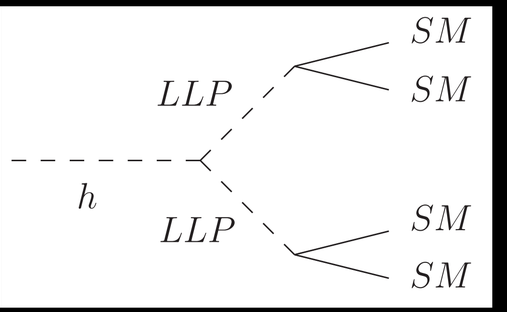
ATLAS CalRatio: EPJC 79 (2019) no.6, 481





LHCb: EPJC 77 (2017) 812



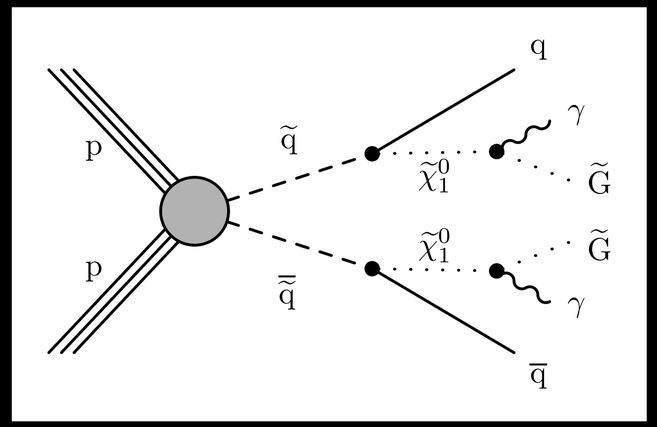


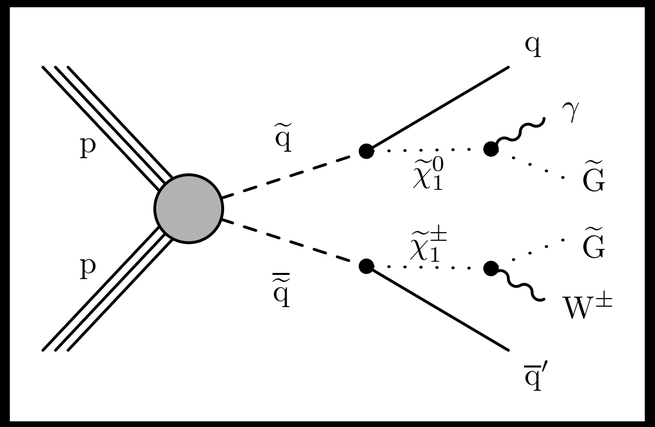
One benchmark scenario:
h125 —> 2xLLP —> jets

Delayed or non-pointing photons

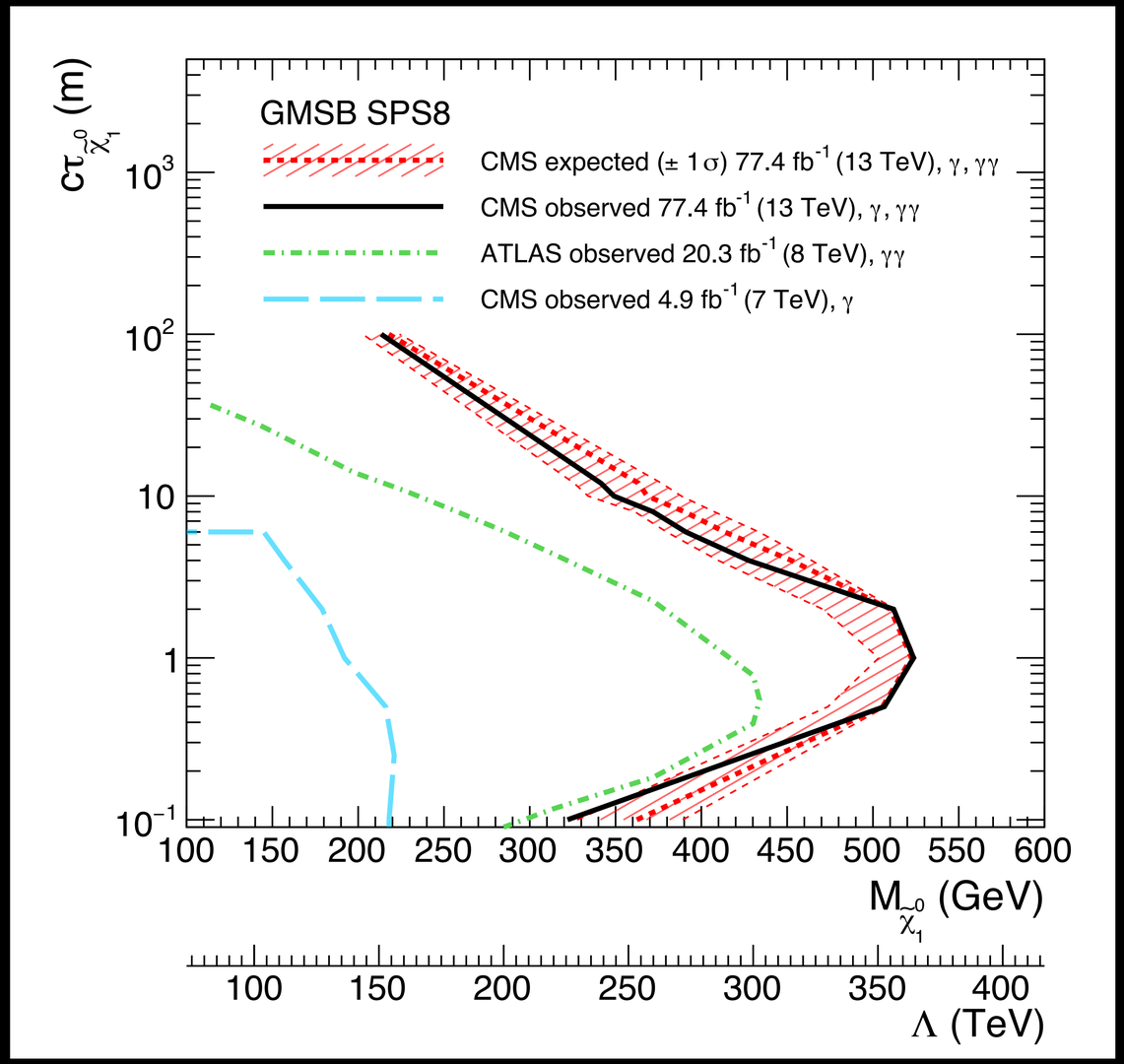
Single photons or pairs of photons that enter the electromagnetic calorimeter (Ecal) at non-normal angles

- Benchmark gauge-mediated SUSY-breaking scenario with long-lived neutralino
- Combination of standard photon and dedicated triggers looking for Ecal deposits with an elliptical shape
- Brand new result from CMS with 77.4/fb at 13 TeV; most recent ATLAS result from 8 TeV





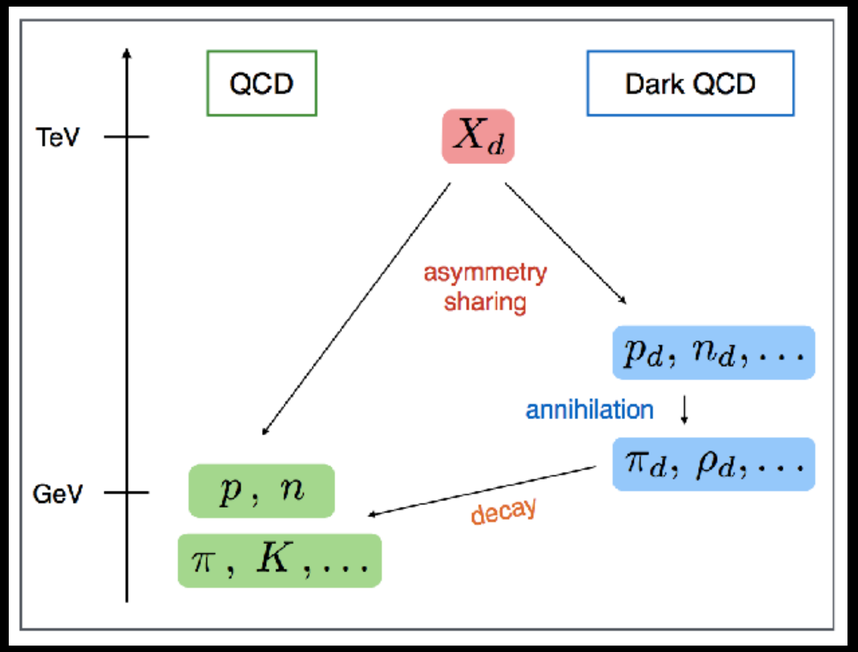
ATLAS, 8 TeV
PRD 90, 112005 (2014)



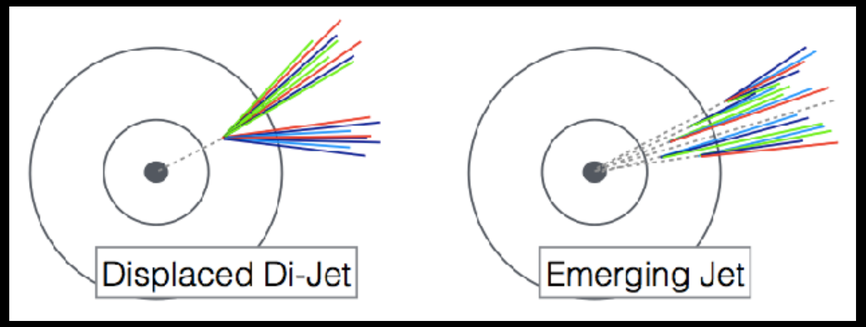
CMS (September 2019)
arXiv:1909.06166
submitted to PRD

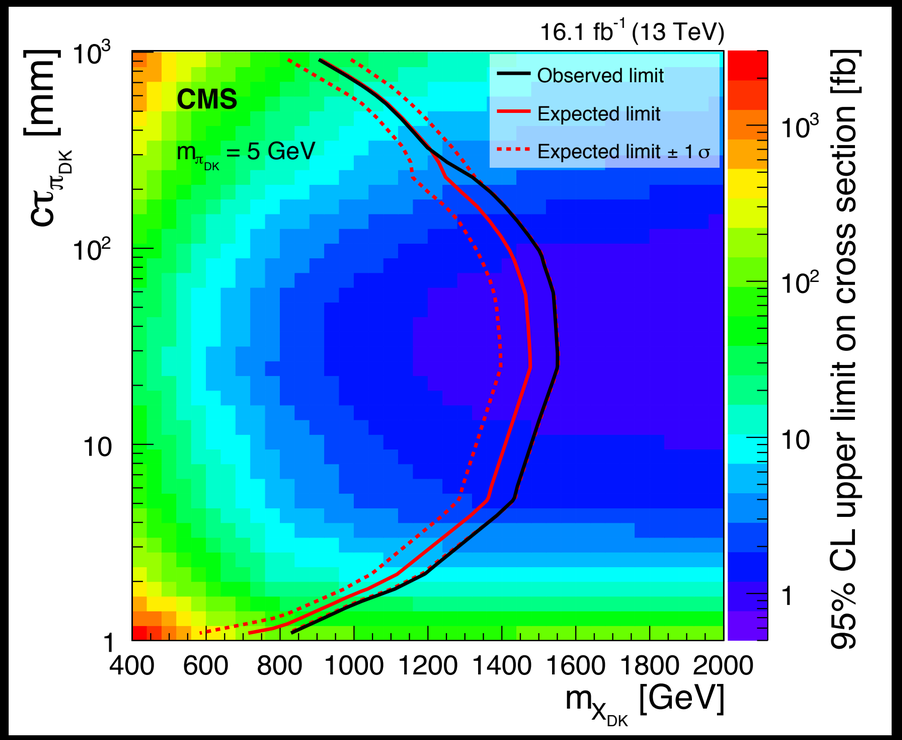
High-multiplicity neutral LLPs decaying hadronically: Emerging jets

JHEP (2015) 2015: 59



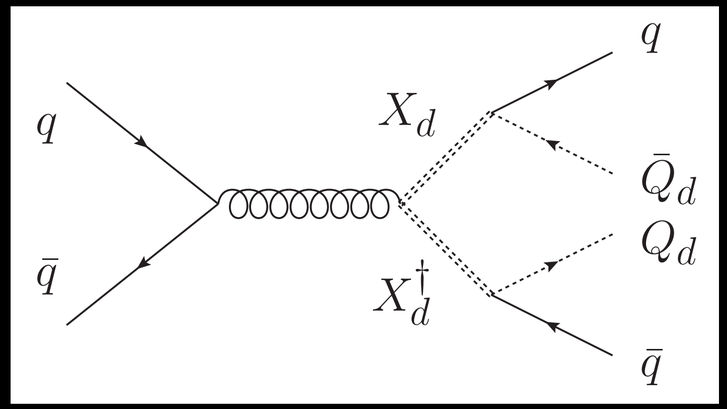
Dark quarks hadronize first in the hidden sector and, e.g., long-lived dark pions then decay to the visible sector via multiple displaced vertices of varying displacements within the same jet object





JHEP 02 (2019) 179

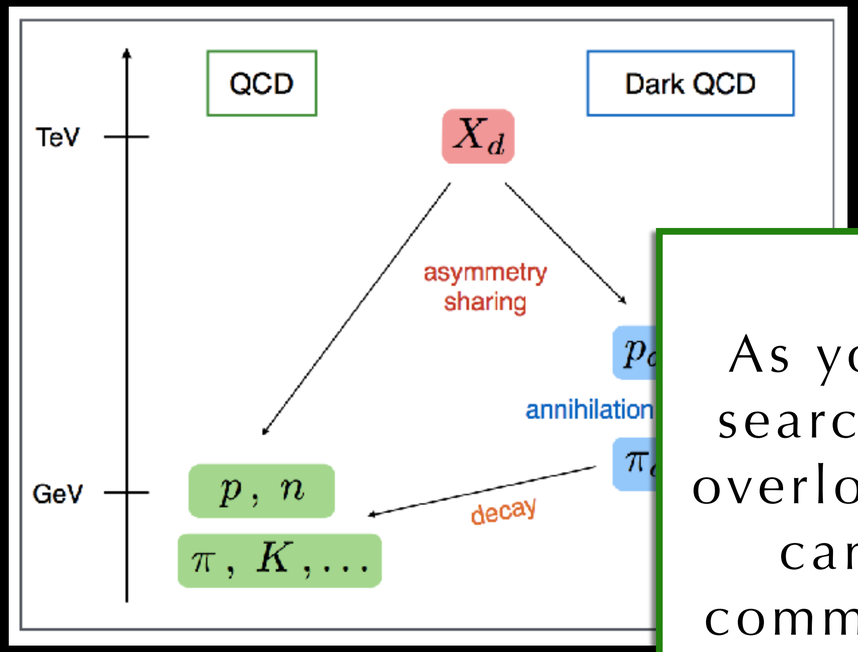
Thus, this is **neither prompt jets nor a pair of displaced jets** pointing to the same displaced vertex, but **emerging jets**



First results for this dark QCD model at the LHC from CMS — ATLAS search in progress

High-multiplicity neutral LLPs decaying hadronically: Emerging jets

JHEP (2015) 2015: 59



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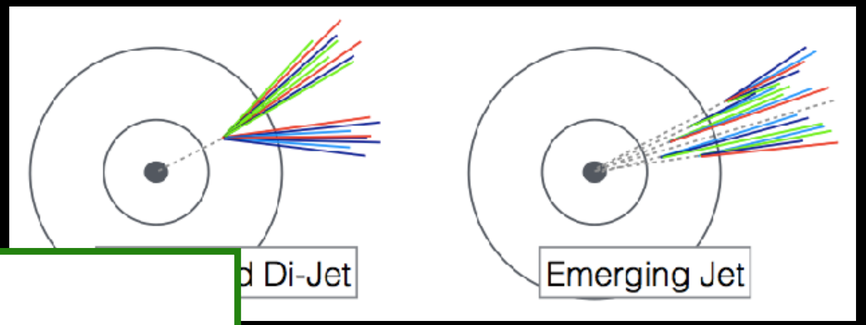
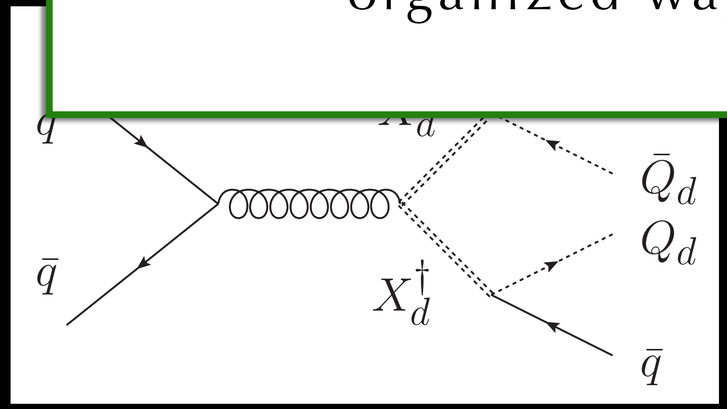
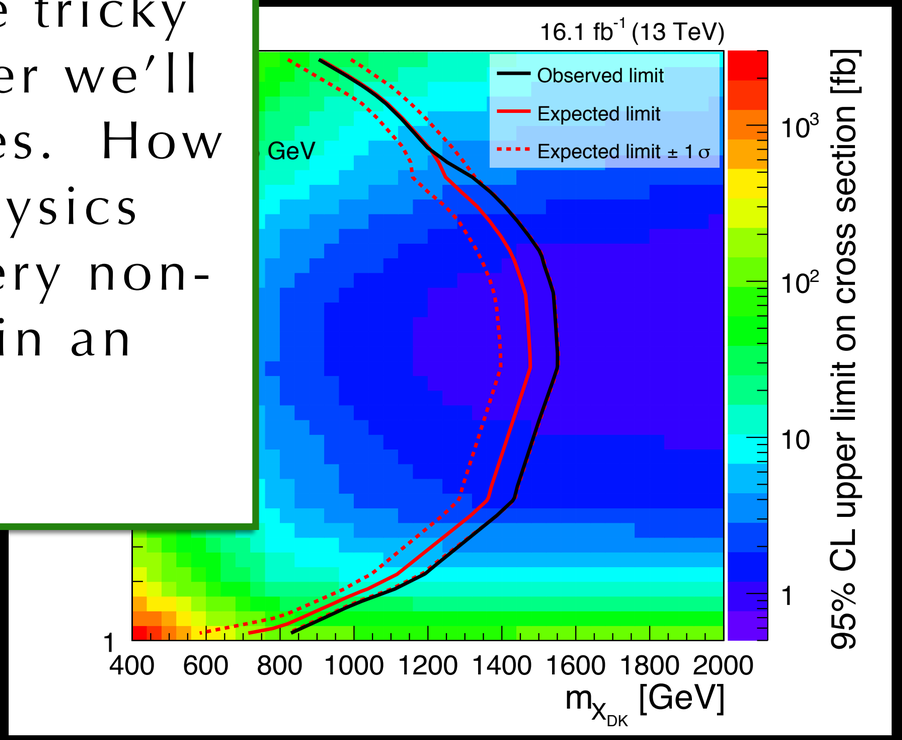


As you can see, these are tricky searches. There's a danger we'll overlook discovery avenues. How can we as a particle physics community think about very non-standard LLP searches in an organized way?

Thus, this is **neither prompt jets nor a pair of displaced jets** pointing to the same displaced vertex, but **emerging jets**





JHEP 02 (2019) 179

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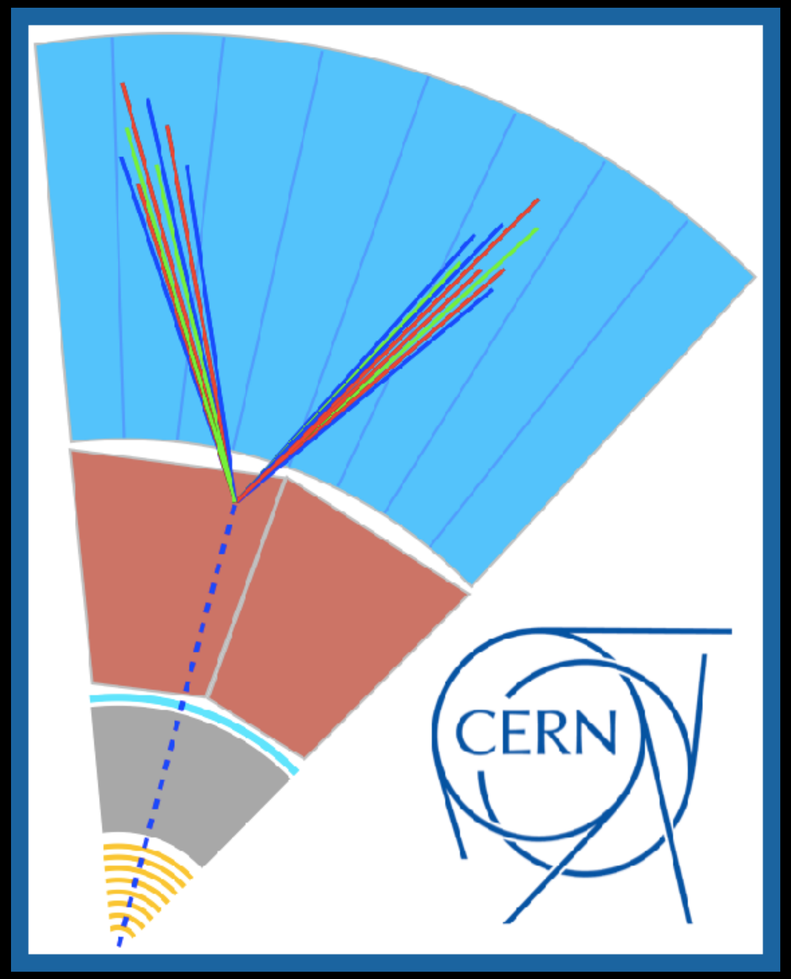


LHC Long-Lived Particle Community

...in collaboration with the theory/pheno community and MoEDAL, MilliQan, MATHUSLA, FASER, CODEX-b, AL3X, etc.

Formed to address one question:
How do we best ensure that we don't miss BSM LLP signatures for the remainder of the LHC program?

Workshops — two per year

LHC LLP white paper:
March 2019 — arXiv:1903.04497
To appear in J. Phys. G

Join the CERN egroup: lhc-llp

cern.ch/longlivedparticles

The LHC LLP Community white paper

arXiv:1903.04497 (to appear in J. Phys. G)

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

April 23, 2019

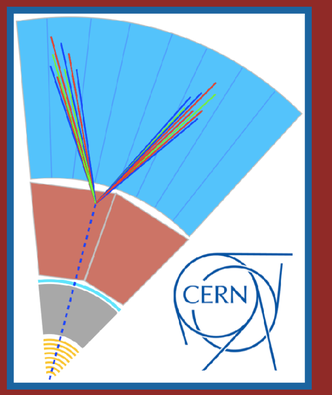
Particles beyond the Standard Model (SM) can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at experiments such as the Large Hadron Collider (LHC) at CERN, these long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision. Such LLP signatures are distinct from those of promptly decaying particles that are targeted by the majority of searches for new physics at the LHC, often requiring customized techniques to identify, for example, significantly displaced decay vertices, tracks with atypical properties, and short track segments. Given their non-standard nature, a comprehensive overview of LLP signatures at the LHC is beneficial to ensure that possible avenues of the discovery of new physics are not overlooked. Here we report on the joint work of a community of theorists and experimentalists with the ATLAS, CMS, and LHCb experiments — as well as those working on dedicated experiments such as MoEDAL, milliQan, MATHUSLA, CODEX-b, and FASER — to survey the current state of LLP searches at the LHC, and to chart a path for the development of LLP searches into the future, both in the upcoming Run 3 and at the High-Luminosity LHC. The work is organized around the current and future potential capabilities of LHC experiments to generally discover new LLPs, and takes a signature-based approach to surveying classes of models that give rise to LLPs rather than emphasizing any particular theory motivation. We develop a set of simplified models; assess the coverage of current searches; document known, often unexpected backgrounds; explore the capabilities of proposed detector upgrades; provide recommendations for the presentation of search results; and look towards the newest frontiers, namely high-multiplicity "dark showers", highlighting opportunities for expanding the LHC reach for these signals.

Editors:

Juliette Alimena[1] (Experimental Coverage, Backgrounds, Upgrades), James Beacham[2] (Document Editor, Simplified Models), Martino Borsato[3] (Backgrounds, Upgrades), Yangyang Cheng[4] (Upgrades), Xabier Cid Vidal[5] (Experimental Coverage), Giovanna Cottin[6] (Simplified Models, Reinterpretations), Albert De Roeck[7] (Experimental Coverage), Nishita Desai[8] (Reinterpretations), David Curtin[9] (Simplified Models), Jared A. Evans[10] (Simplified Models, Experimental Coverage), Simon Knapen[11] (Dark Showers), Sabine Kraml[12] (Reinterpretations), Andre Lessa[13] (Reinterpretations), Zhen Liu[14] (Simplified Models, Backgrounds, Reinterpretations), Sascha Mehlhase[15] (Backgrounds), Michael J. Ramsey-Musolf[16,126] (Simplified Models), Heather Russell[17] (Experimental Coverage), Jessie Shelton[18] (Simplified Models, Dark Showers), Brian Shuve[19,20] (Document Editor, Simplified Models, Simplified Models Library), Monica Verducci[21] (Upgrades), Jose Zurita[22,23] (Experimental Coverage)

A comprehensive document — a combination review paper, set of recommendations, accounting of open discovery possibilities, record of accumulated knowledge, and speculation for the future — that (paired with the MATHUSLA physics case document arXiv:1806.07396 / Rept.Prog.Phys. 82 (2019) no.11, 116201) serves as a definitive guide to LLP searches at the LHC

LHC Long-Lived Particle Community



Upcoming workshop

Searching for long-lived particles at the LHC: Sixth workshop of the LHC LLP Community

27-29 November 2019
University of Ghent

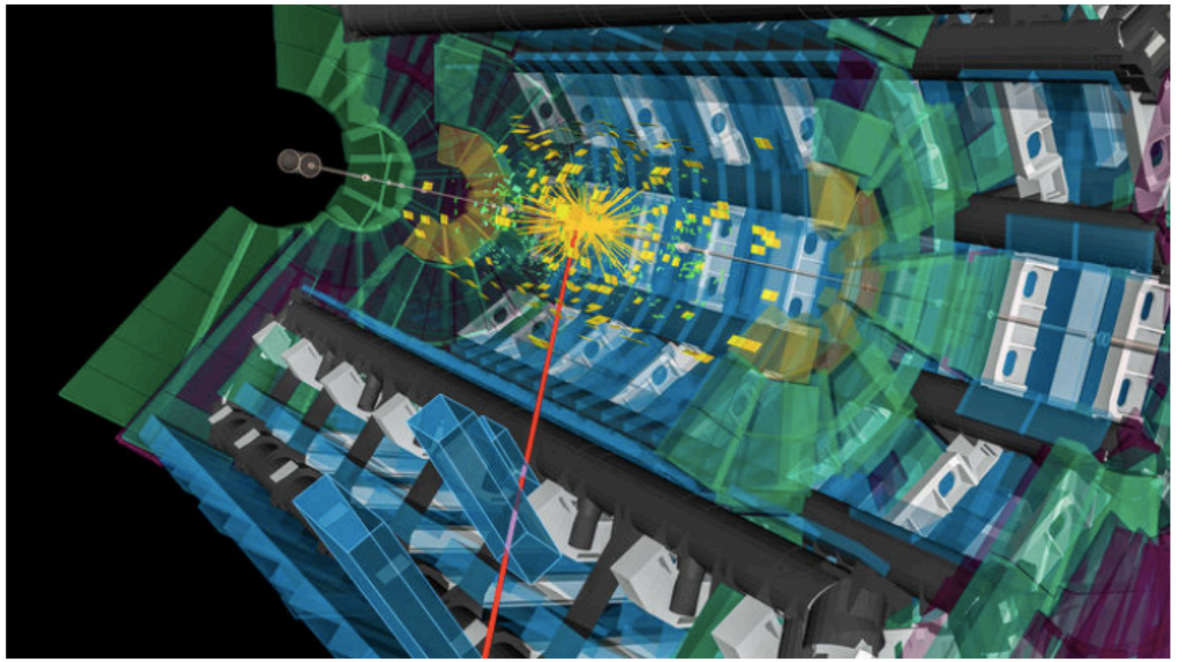
https://indico.cern.ch/e/LHC_LLP_November_2019

Join the CERN egroup: lhc-llp

Article in Science News

22 May 2019

Science



In a simulated event, the track of a decay particle called a muon (red), displaced slightly from the center of particle collisions, could be a sign of new physics. ATLAS EXPERIMENT © 2019 CERN

Atom smasher could be making new particles that are hiding in plain sight

By **Adrian Cho** | May. 22, 2019 , 12:20 PM

Are new particles materializing right under physicists' noses and going unnoticed? The world's great atom smasher, the Large Hadron Collider (LHC), could be making long-lived particles that slip through its detectors, some researchers say. Next week, they will gather at the LHC's home, CERN, the European particle physics laboratory near Geneva, Switzerland, to discuss how to capture them. They argue the LHC's next run should emphasize such searches, and some are calling for new detectors that could sniff out the fugitive particles.

LLPs at the HL-LHC

The central detectors will be getting significant upgrades for the HL era

- Many effects on LLP searches

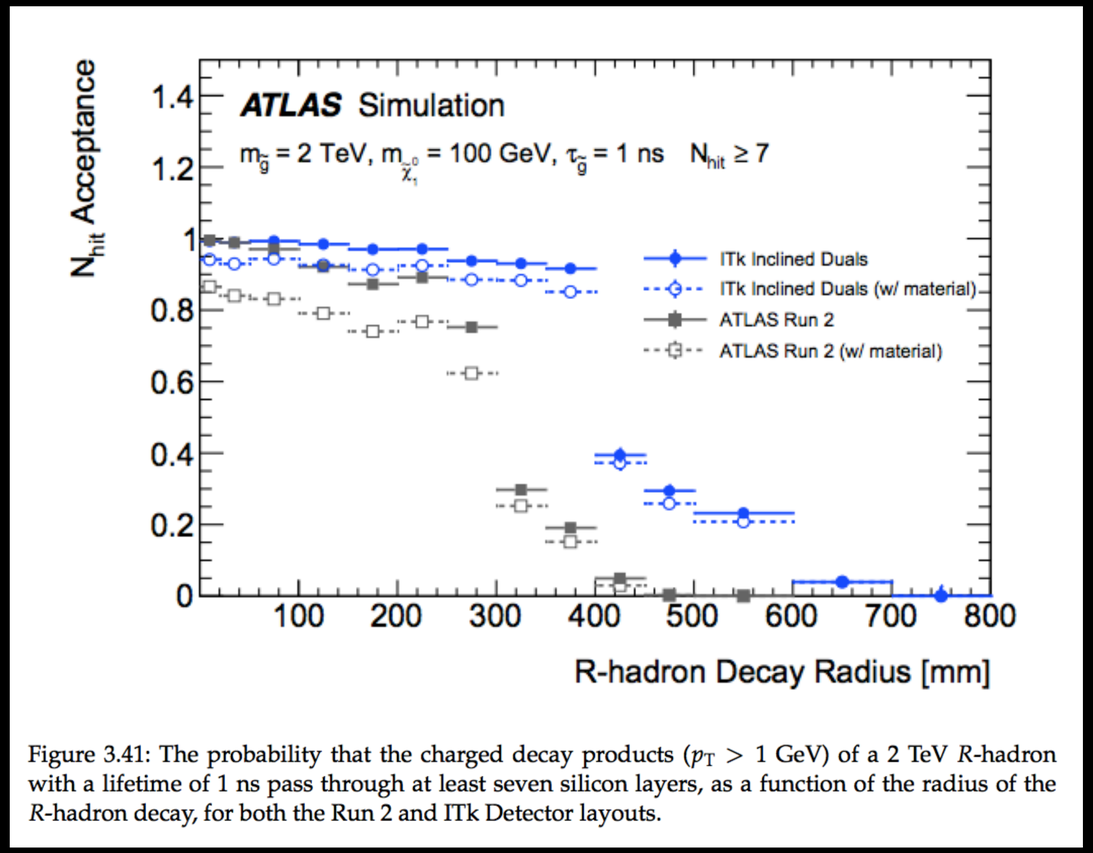
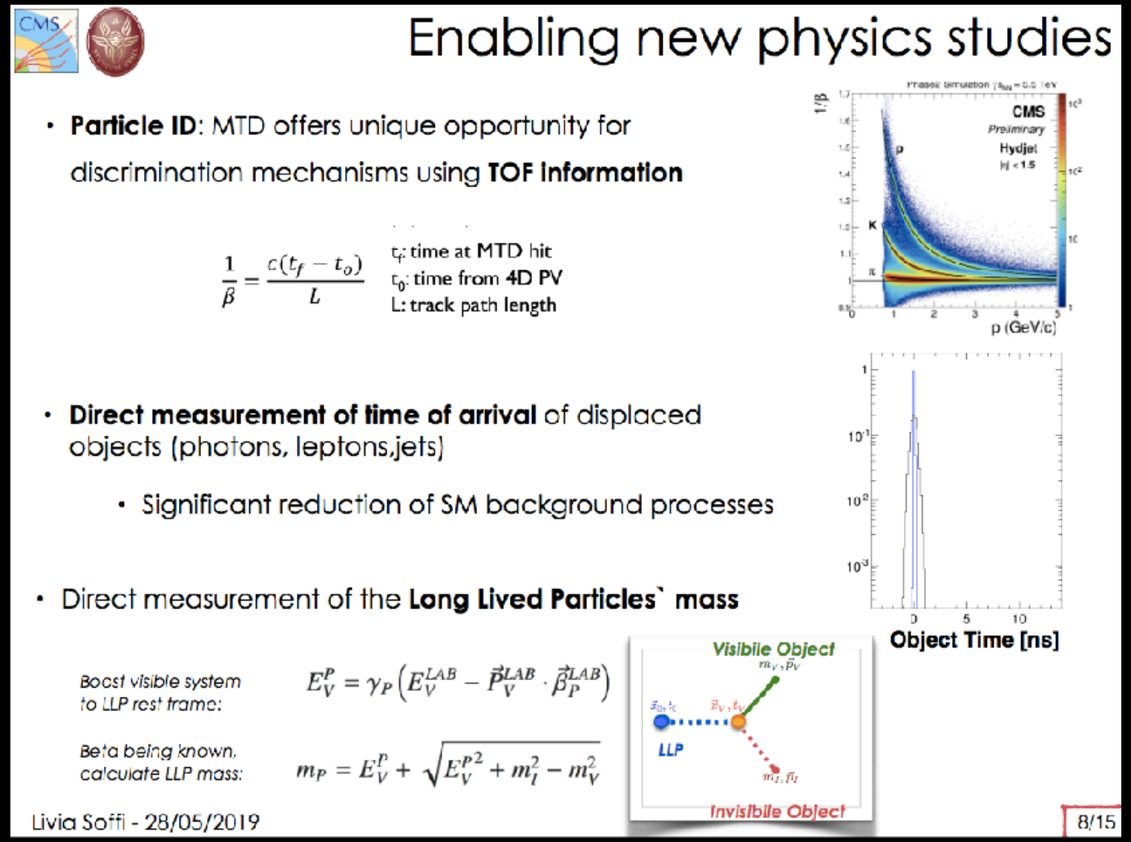


Figure 3.41: The probability that the charged decay products ($p_T > 1$ GeV) of a 2 TeV R-hadron with a lifetime of 1 ns pass through at least seven silicon layers, as a function of the radius of the R-hadron decay, for both the Run 2 and ITk Detector layouts.

Example: ATLAS Inner Tracker will be completely replaced, giving better sensitivity to, e.g., long-lived R-hadrons [ATLAS ITk Pixel TDR]



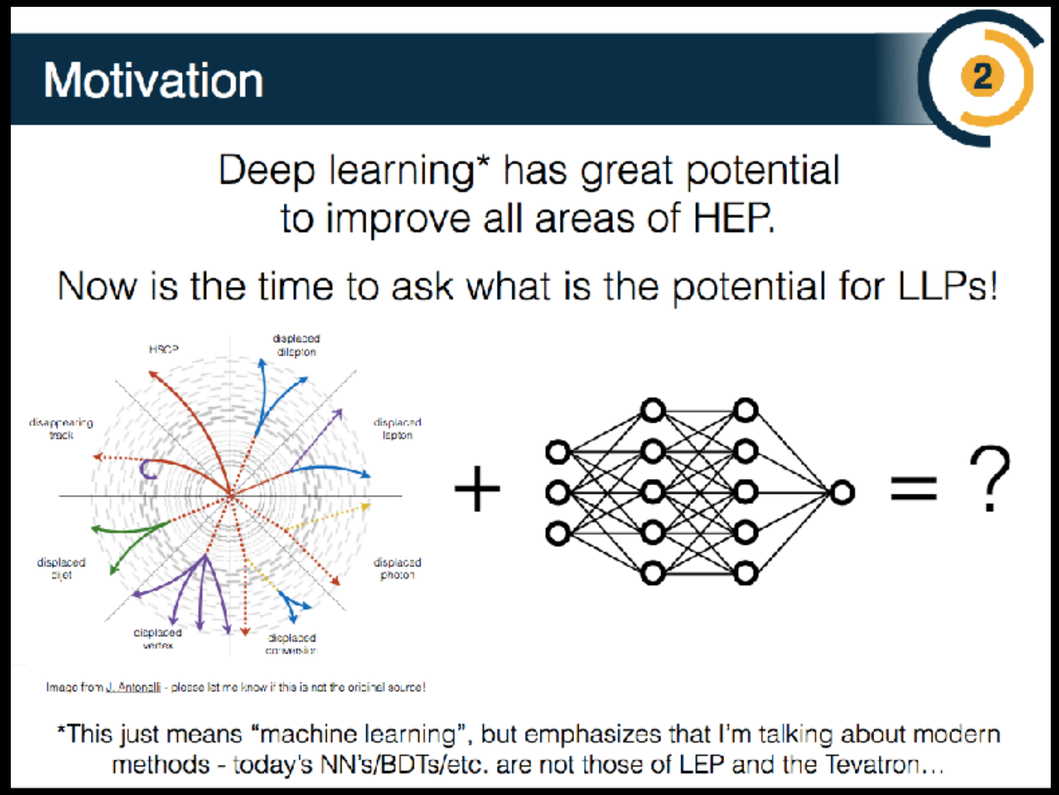
New CMS timing layer a hot topic in LLPs; using this extra piece of information shows promise to provide strong gains for many LLP analyses [L. Soffi talk; TDR; Z. Liu talk]

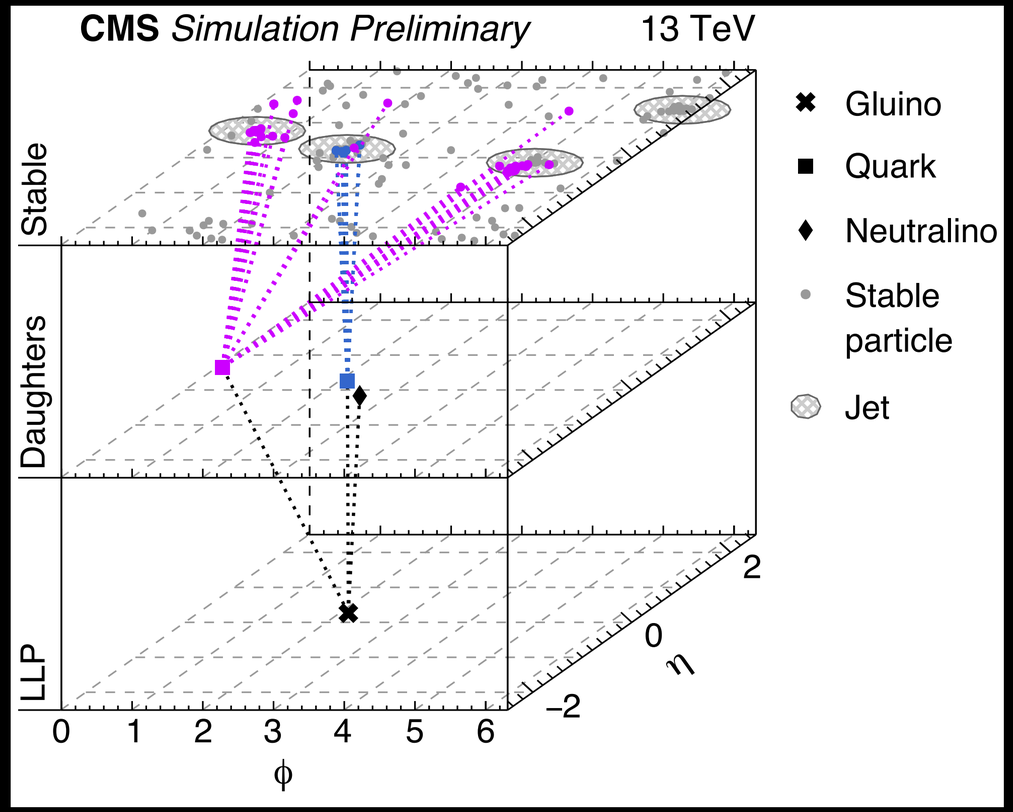
From the May 2019 LHC LLP workshop: Machine learning for LLPs

Hosted a working group to ask how we can leverage the power of deep learning techniques for our challenging LLP searches

- Surveyed known applications of ML in public LLP searches at the LHC
- Brainstormed an ML4LLP challenge using CMS Open Data (for background) and Delphes (for signal models) to guide work
- Work ongoing

B. Nachman intro talk





Brand new CMS result (Nov. 2019) on using a deep neural network-based tagger to search for new LLPs decaying to jets

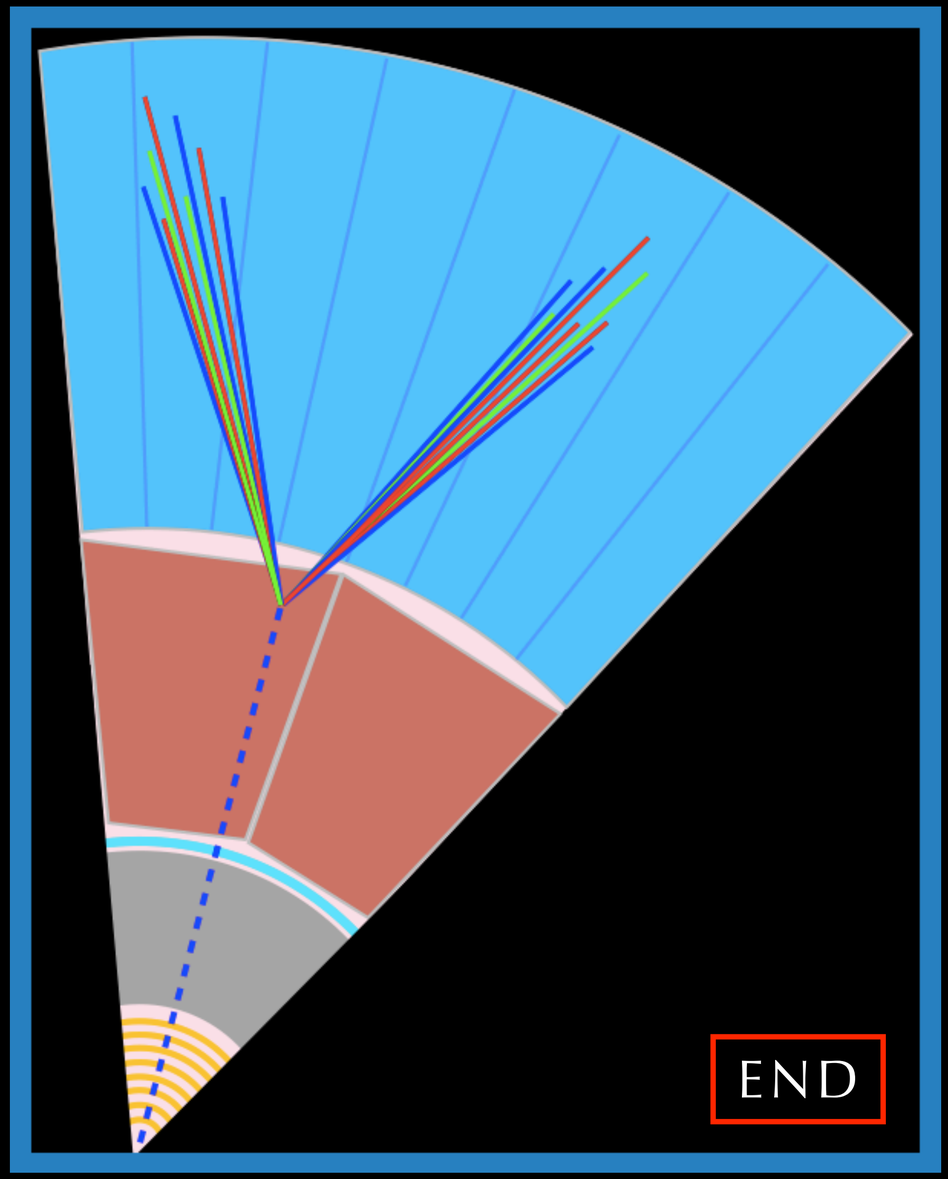
Conclusions

The future of particle physics is experimental

Successful establishment of a wide range of results consistent with SM expectations requires us to shift from theory-driven to signature-driven search strategies

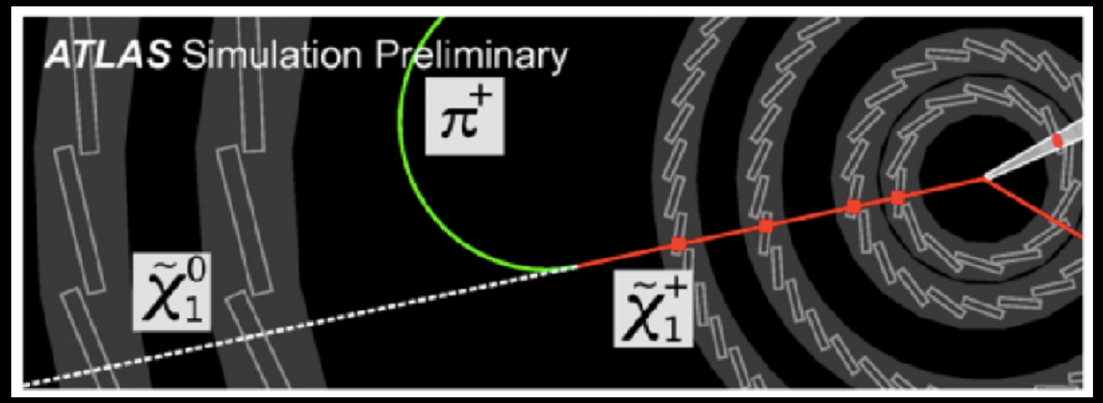
Our duty is to explore the unknown; this means stretching our current detectors at the LHC to the limits of their discovery potential at 13/14 TeV, irrespective of theory model or motivation

Long-lived particle signatures, previously regarded as fringe efforts, are taking their place within the central set of BSM searches at the LHC and beyond



Reserve slides

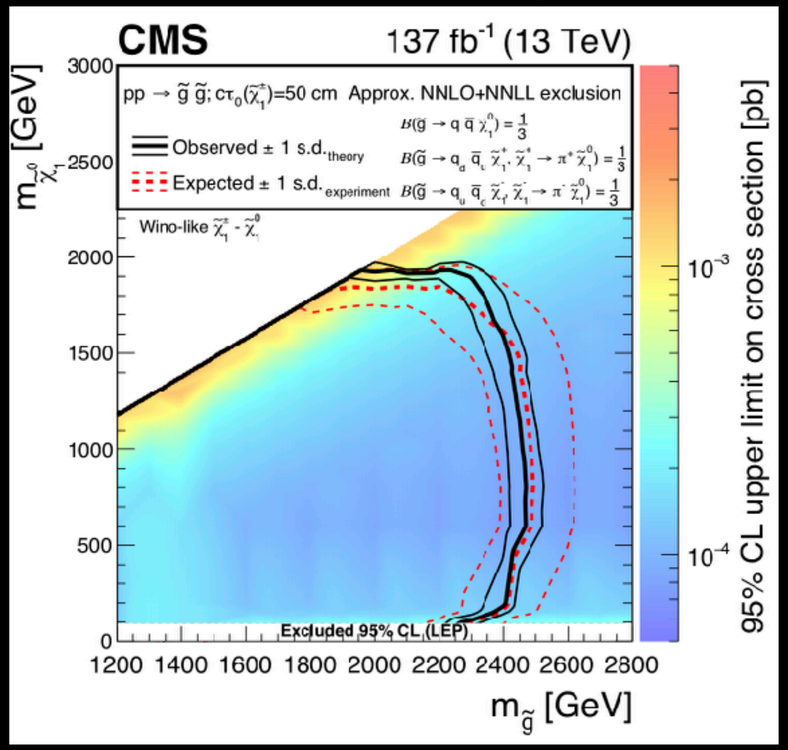
Disappearing tracks



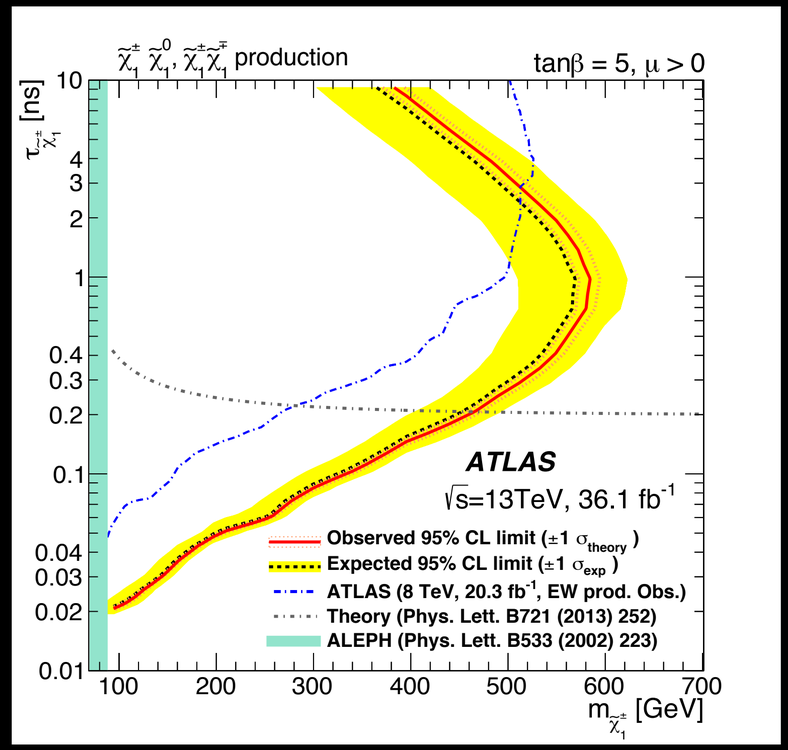
When a charged BSM particle decays to a neutral BSM particle of similar mass and a low-p_T SM particle, track can disappear

- Neutral particle escapes detector —> MET triggers
- Use non-standard tracking to identify track stubs

CMS (Sept. 2019): arXiv:1909.03460
Submitted to EPJC



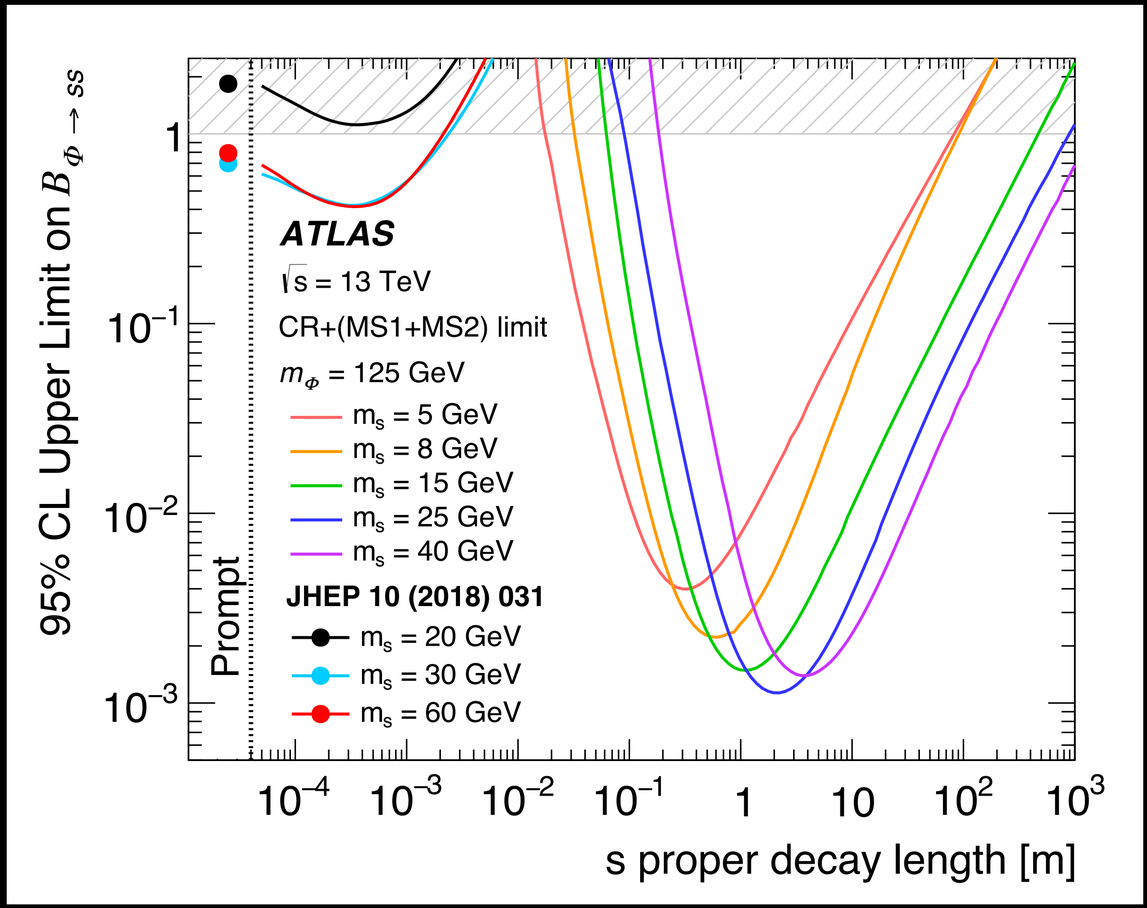
ATLAS: JHEP 06 (2018) 022



Comparing prompt and long-lived searches

Very short-lived vs. longer-lived LLPs decaying to jets

- Recent ATLAS search for {W,Z}/h125 —> *aa* —> 4b for a promptly decaying *a*, where an additional limit was set on a scenario with an *a* with a non-zero lifetime [JHEP 10 (2018) 031]



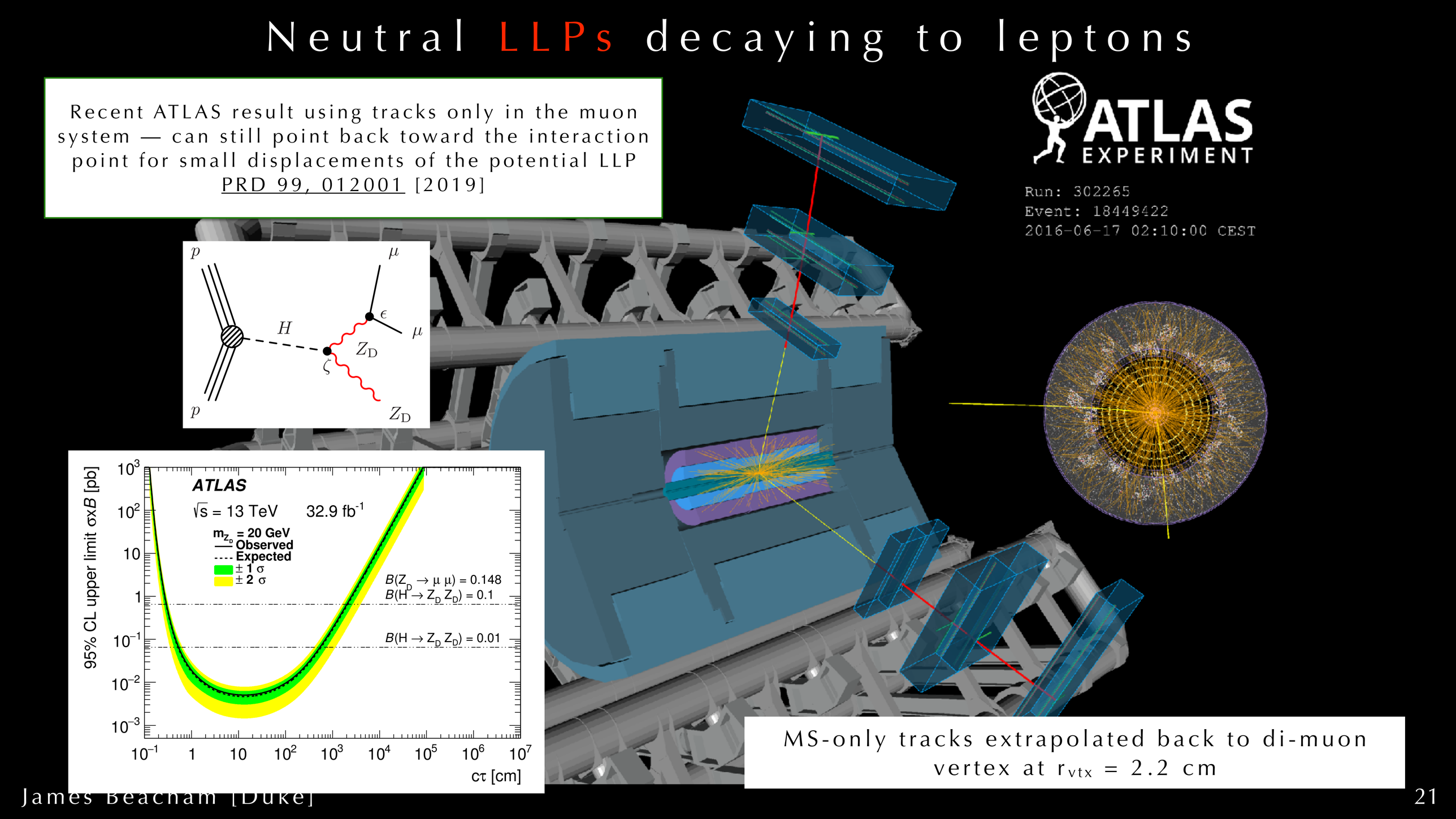
- Compared to ATLAS searches for h125 —> 2xLLP —> jets appearing in the calorimeters and muon systems, clearly shows gaps in coverage
- Essentially required generating some additional simulated samples and calculating a limit, a large gain for just a little extra work

ATLAS re-interpretation of a few SUSY RPV-meets-RPC searches: ATLAS-CONF-2018-003

CMS did something similar in the context of a SUSY search for jets + missing energy: JHEP 05 (2018) 025

Neutral LLPs decaying to leptons

Recent ATLAS result using tracks only in the muon system — can still point back toward the interaction point for small displacements of the potential LLP
PRD 99, 012001 [2019]



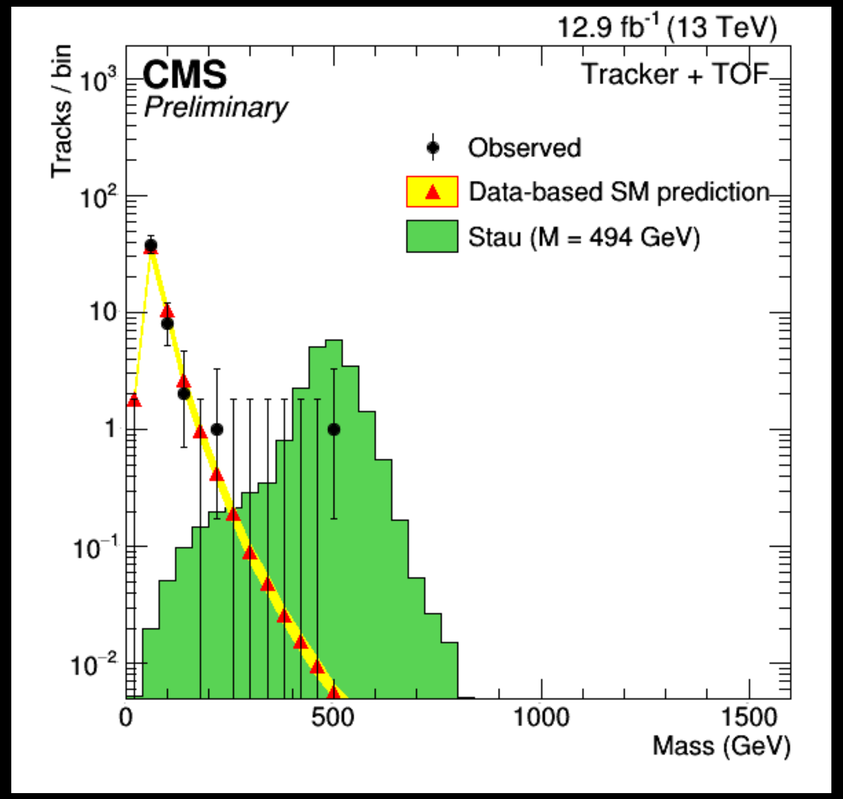
MS-only tracks extrapolated back to di-muon vertex at r_{vtx} = 2.2 cm

Quasi-stable charged particles

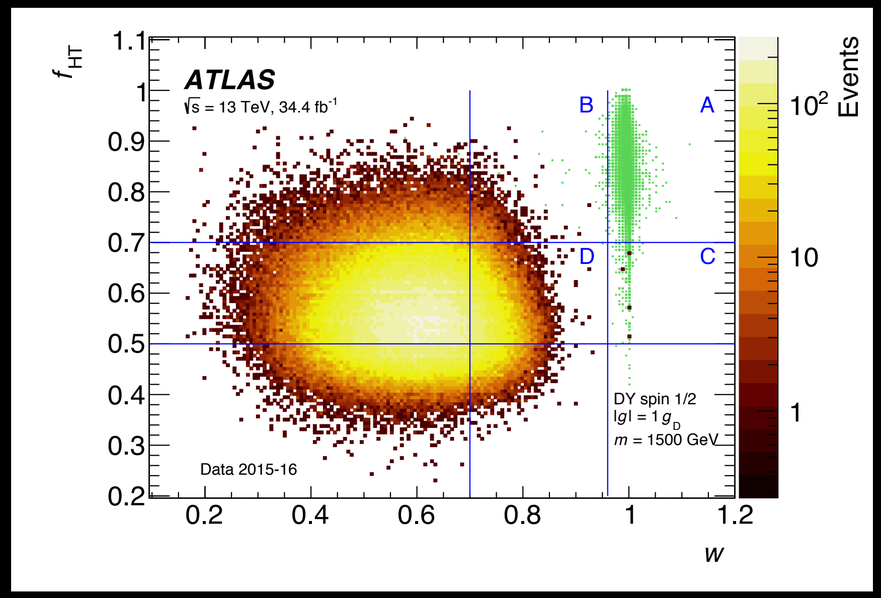
They propagate through the detector like muons, but leave behind a very non-muon-like signature

Can move much at speeds much slower than the speed of light or leave high ionization

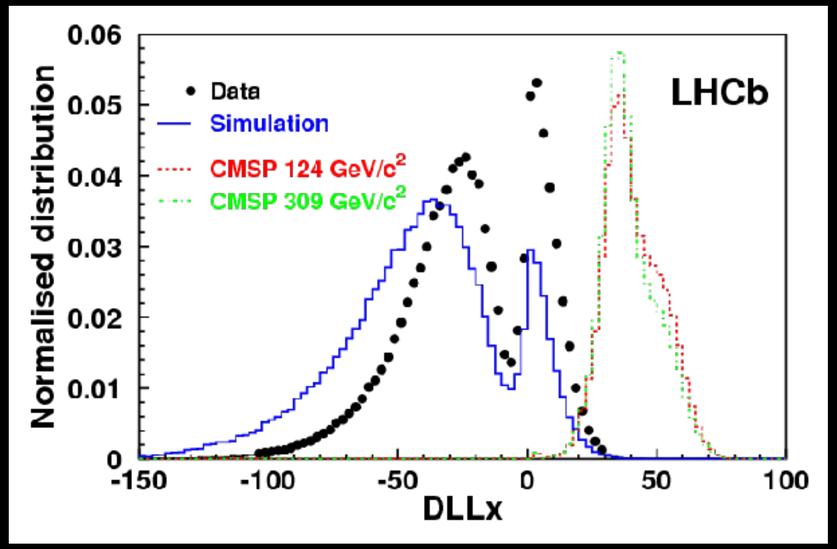
ID them via atypical ways that the charged particle interacts with the detector material



CMS [EXO-16-036] — exploiting time of flight discrimination using muon system and increased energy loss in silicon tracker



ATLAS [arXiv:1905.10130] search for high electric charge objects such as monopoles

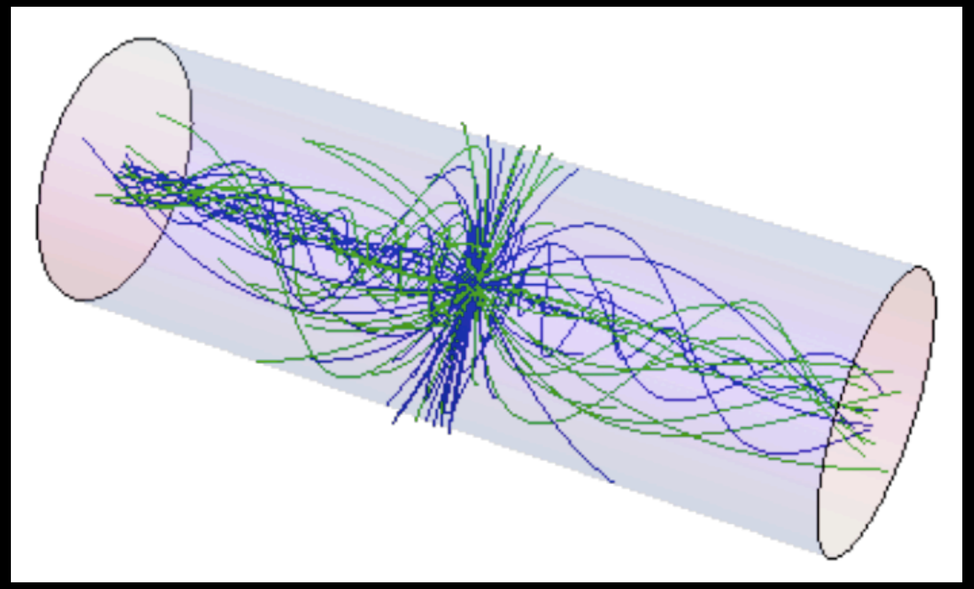


LHCb [EPJC (2015) 75: 595] — utilizing an estimator of the absence of Cherenkov radiation in RICH detectors

Uncovered LLP realms

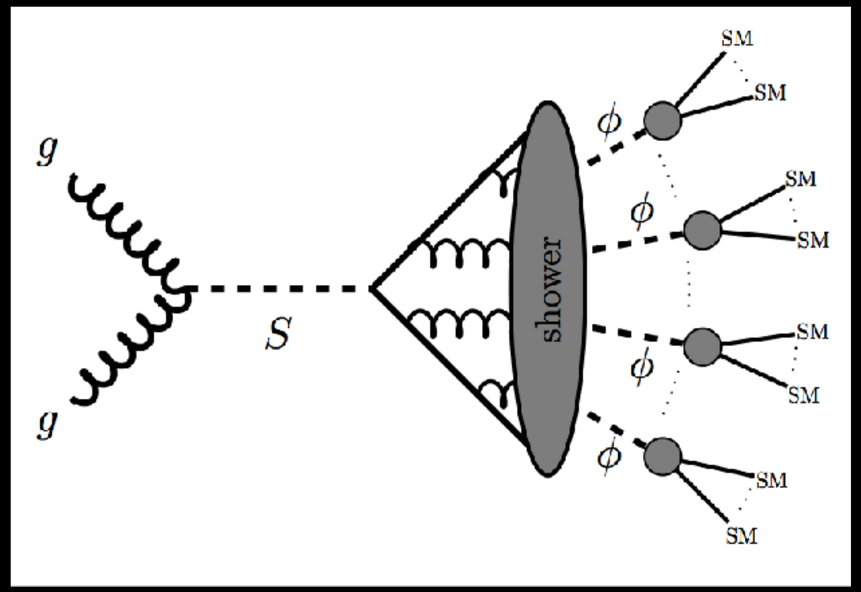
What about the other end of the dark QCD spectrum?

- Very strongly coupled hidden sector yielding a soft radiation pattern in the detector
- Soft, unclustered energy patterns, or SUEPs: JHEP (2017) 2017: 76



Cylinder is edge of ECal, with ~100 very soft electrons and muons swarming around

Hidden valley scenario with confining dynamics — here a strongly coupled regime with a high-mass mediator decaying eventually to a large multiplicity of low-energy SM states



Could a high multiplicity soft muon trigger be useful here?

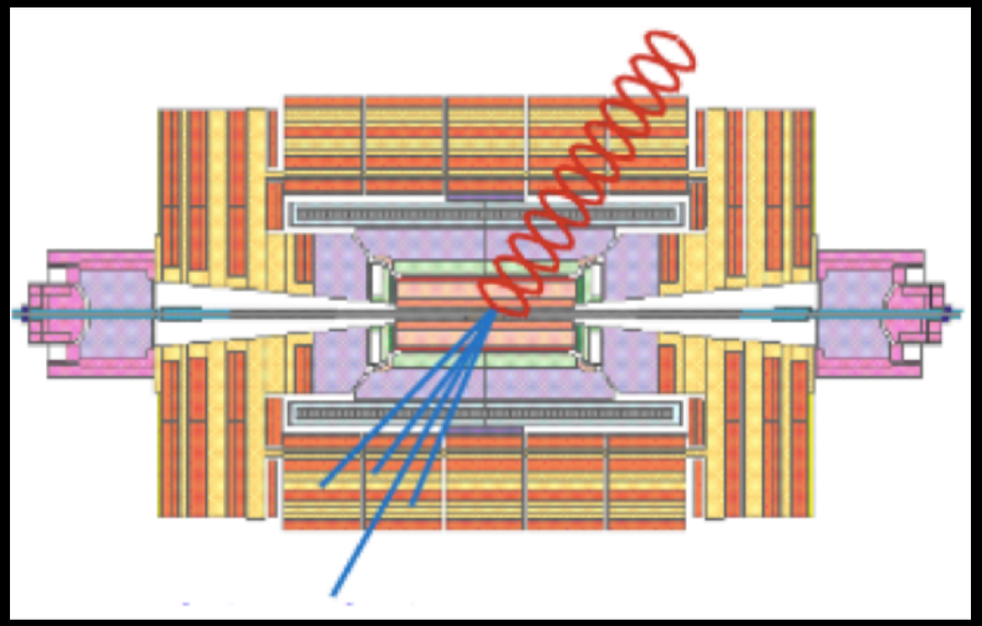
Uncovered LLP realms

Non-standard tracks from quirks

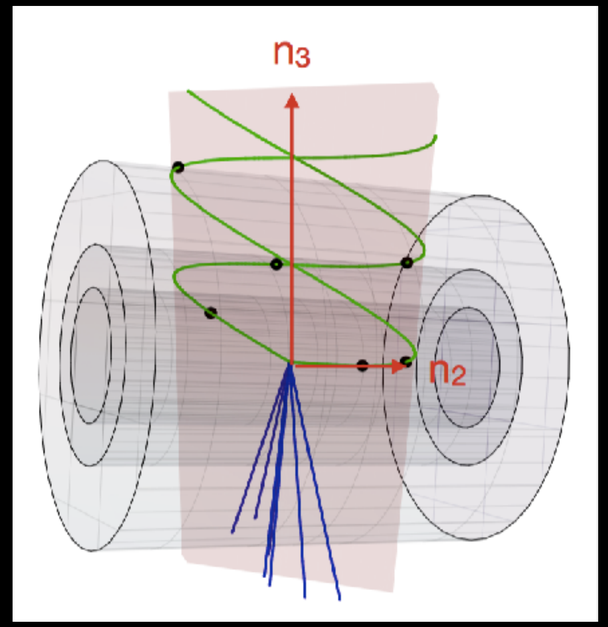
- Quirks: Particles charged under new confining gauge group but with masses much greater than the confinement scale —> distinct quirk/antiquirk pairs never form —> they oscillate until they annihilate

PRD 96, 115015

- As such, they leave a wild, oscillating-pair signature in the detector



Talk by Knapen at Trieste LHC LLP Workshop



- This is hard, both because standard tracking isn't useful here and because it's difficult to model in Geant4 — only existing search is at D0

- S. Knapen, et al, proposed a model-independent method of looking for patterns of hits that lay in a plane in the detectors — promising avenue for discovery