

Searches for long-lived particles at the LHC

Second workshop
of the LHC LLP
Community

17-20 October 2017



The Abdus Salam
International Centre
for Theoretical Physics

Open questions before 4 July 2012

EWSB

- ☐ Does the Higgs boson exist?

Quarks and leptons:

- ☐ why 3 families ?
- ☐ masses and mixing
- ☐ *CP* violation in the lepton sector
- ☐ matter and antimatter asymmetry
- ☐ baryon and charged lepton number violation

Physics at the highest E-scales:

- ☐ how is gravity connected with the other forces ?
- ☐ do forces unify at high energy ?

Dark matter:

- ☐ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ☐ one type or more ?
- ☐ only gravitational or other interactions ?

Neutrinos:

- ☐ ν masses and their origin
- ☐ what is the role of $H(125)$?
- ☐ Majorana or Dirac ?
- ☐ *CP* violation
- ☐ additional species \rightarrow sterile ν ?

The two epochs of Universe's accelerated expansion:

- ☐ primordial: is inflation correct ?
which (scalar) fields? role of quantum gravity?
- ☐ today: dark energy (why is Λ so small?) or gravity modification ?

SEARCH2016 Oxford —
Meade/Papucci/Shipsey/Sundrum

I. Shipsey

Open questions after 4 July 2012

Higgs boson and EWSB

- ☐ m_H natural or fine-tuned ?
→ if natural: what new physics/symmetry?
- ☐ does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- ☐ elementary or composite Higgs ?
- ☐ is it alone or are there other Higgs bosons ?
- ☐ origin of couplings to fermions
- ☐ coupling to dark matter ?
- ☐ does it violate CP ?
- ☐ cosmological EW phase transition

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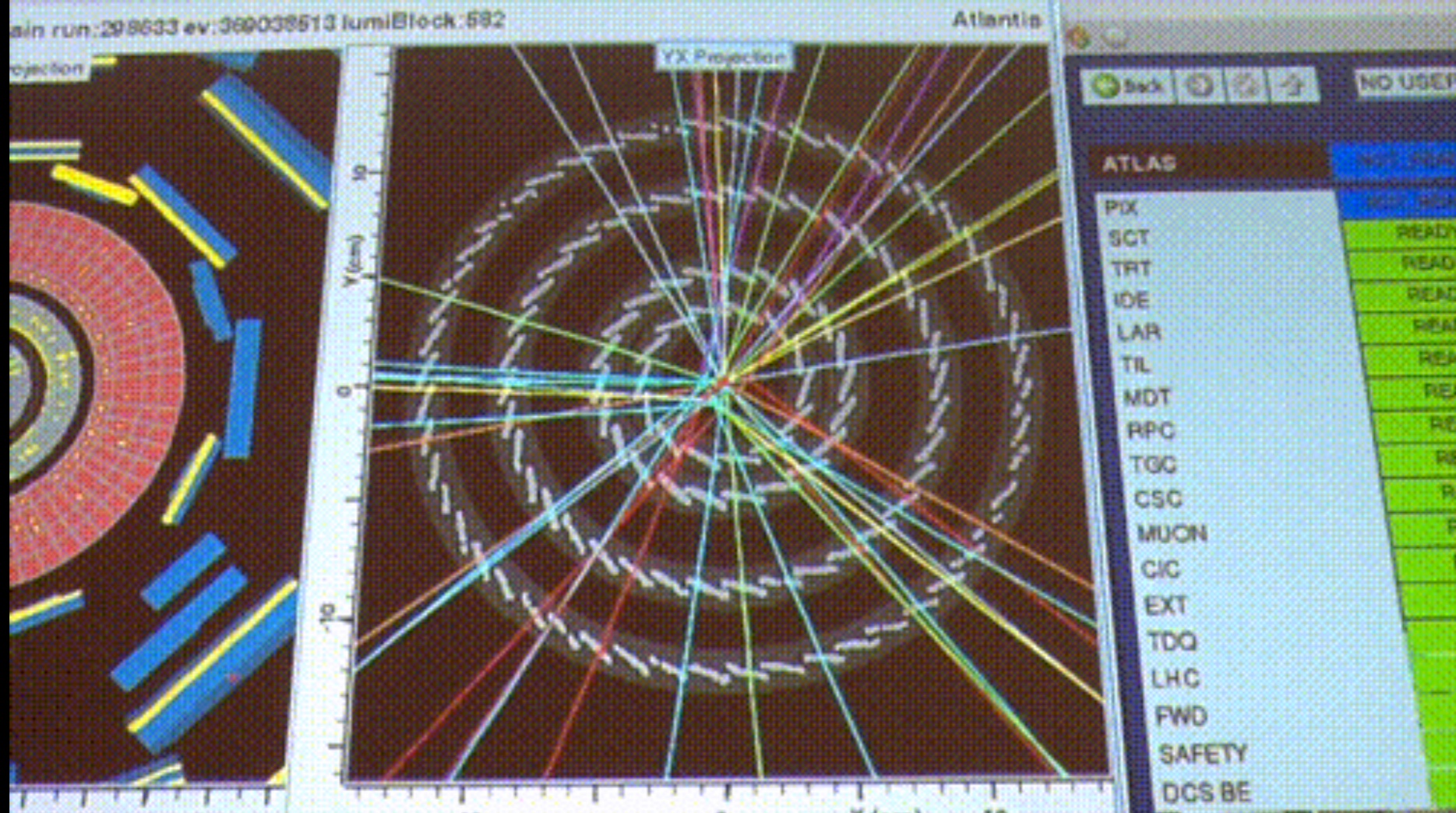
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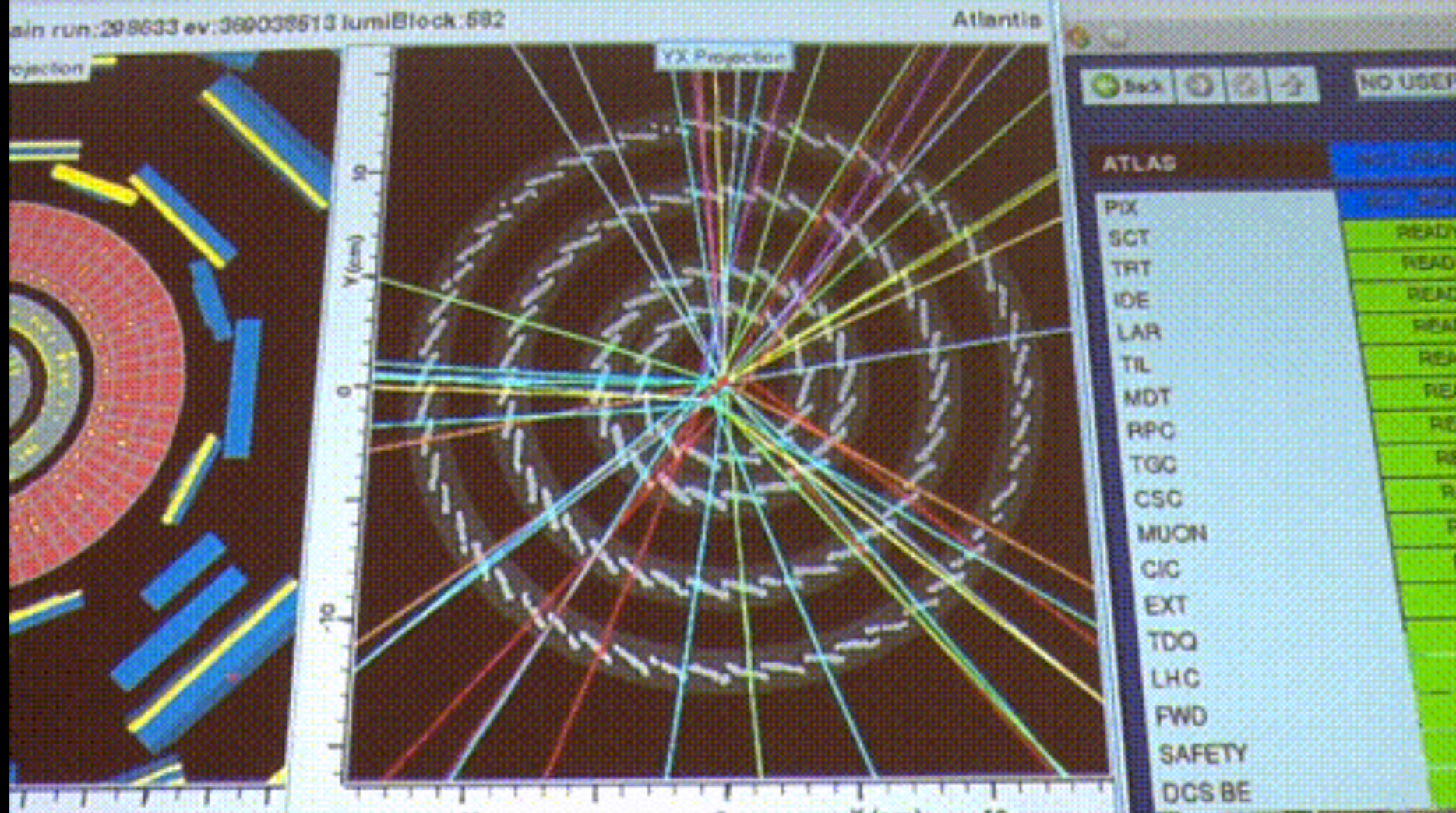
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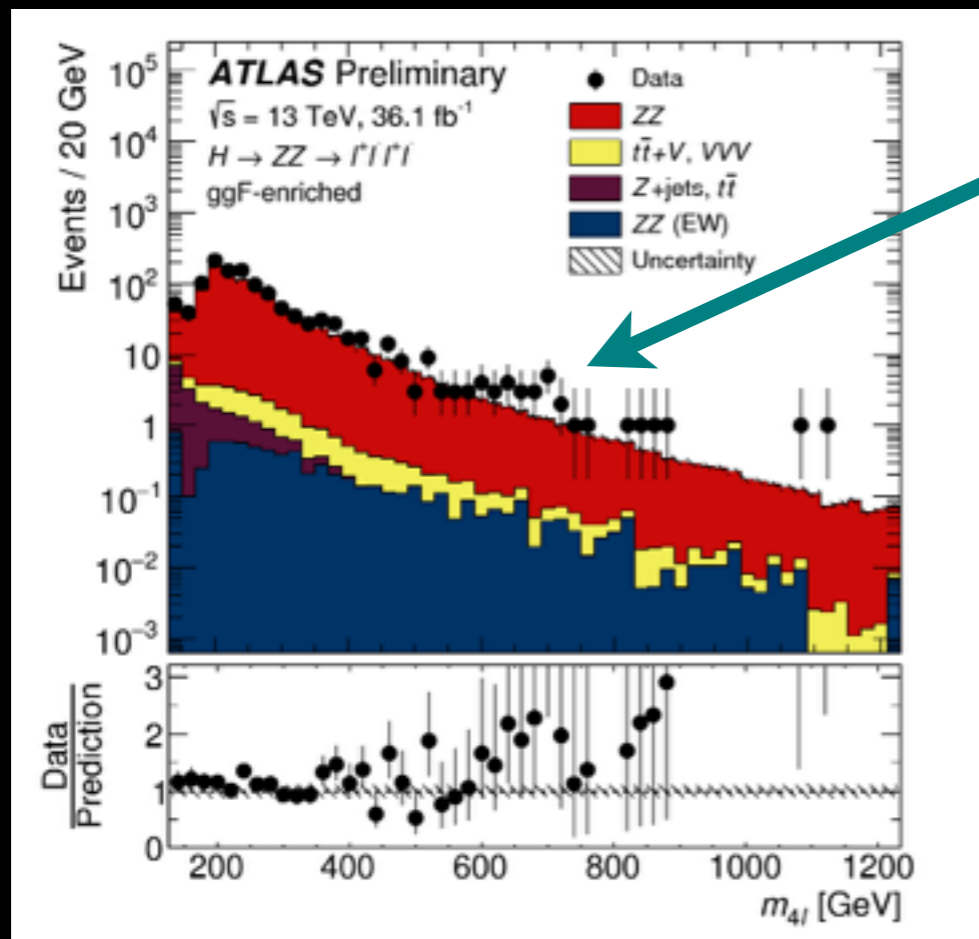
I. Shipsey





New physics at the LHC in 2017

Our first extensive look at 13 TeV yields impressive agreement with Standard Model expectations and no huge, immediate resonances or excesses



There are no more guarantees and no ace-in-the-hole motivations.

We must shift from theory-driven search strategies to signature-driven ones.

We would certainly love some old-school theoretical guidance, but we don't really have it (WIMP miracle in tension, lack of plain vanilla SUSY, etc.)

What do we have? Some of the most sophisticated devices ever built.
How do we extend their reach into new physics parameter space?

The paradigm is shifting — you are part of it

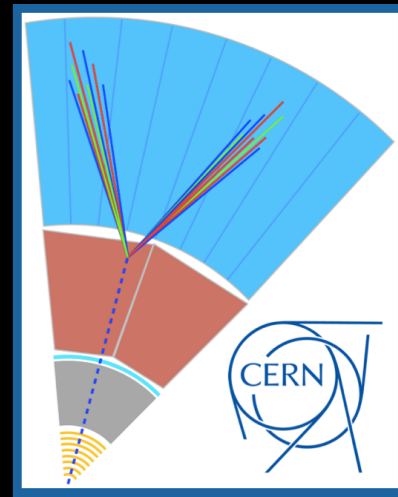


CERN hosts thousands of scientists, representing 22 member countries, all working to understand how the universe was created. CMS is one of seven detectors on site. Leslye Davis/The New York Times

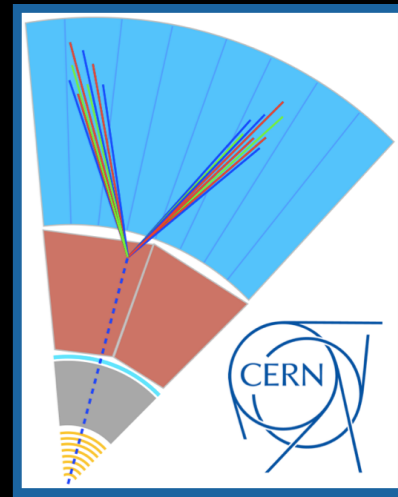
Yearning for New Physics at CERN, in a Post-Higgs Way

Physicists monitoring the Large Hadron Collider are seeking clues to a theory that will answer deeper questions about the cosmos. But the silence from the frontier has been ominous.

By DENNIS OVERBYE JUNE 19, 2017



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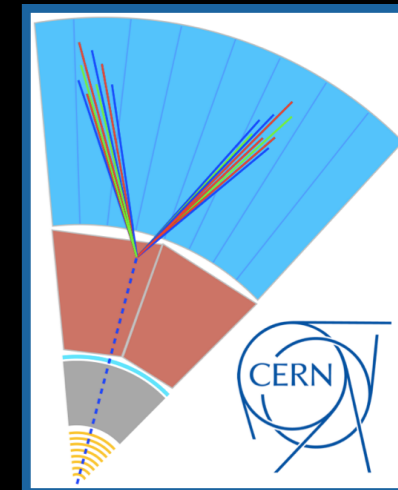
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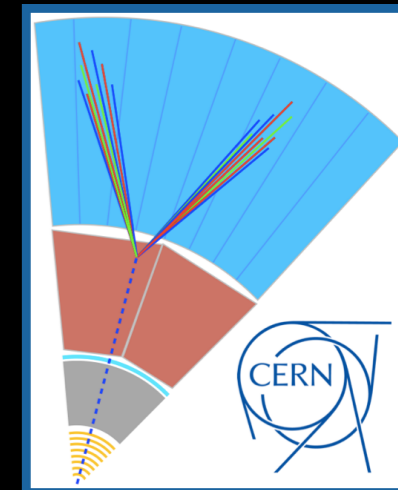
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Our job as physicists is to reduce, to negligible, the chance that we'll miss any possible new particles over the duration of the LHC's run. The first look at 13 TeV yielding a whole host of successful validations of the Standard Model prediction is **not** a bad thing at all. It's freedom. And for those of us who like to think in wild new ways, this is exciting.

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Dennis Overbye

In response to the message from James Beacham, 21/06/2017

To: James Beacham

Inbox

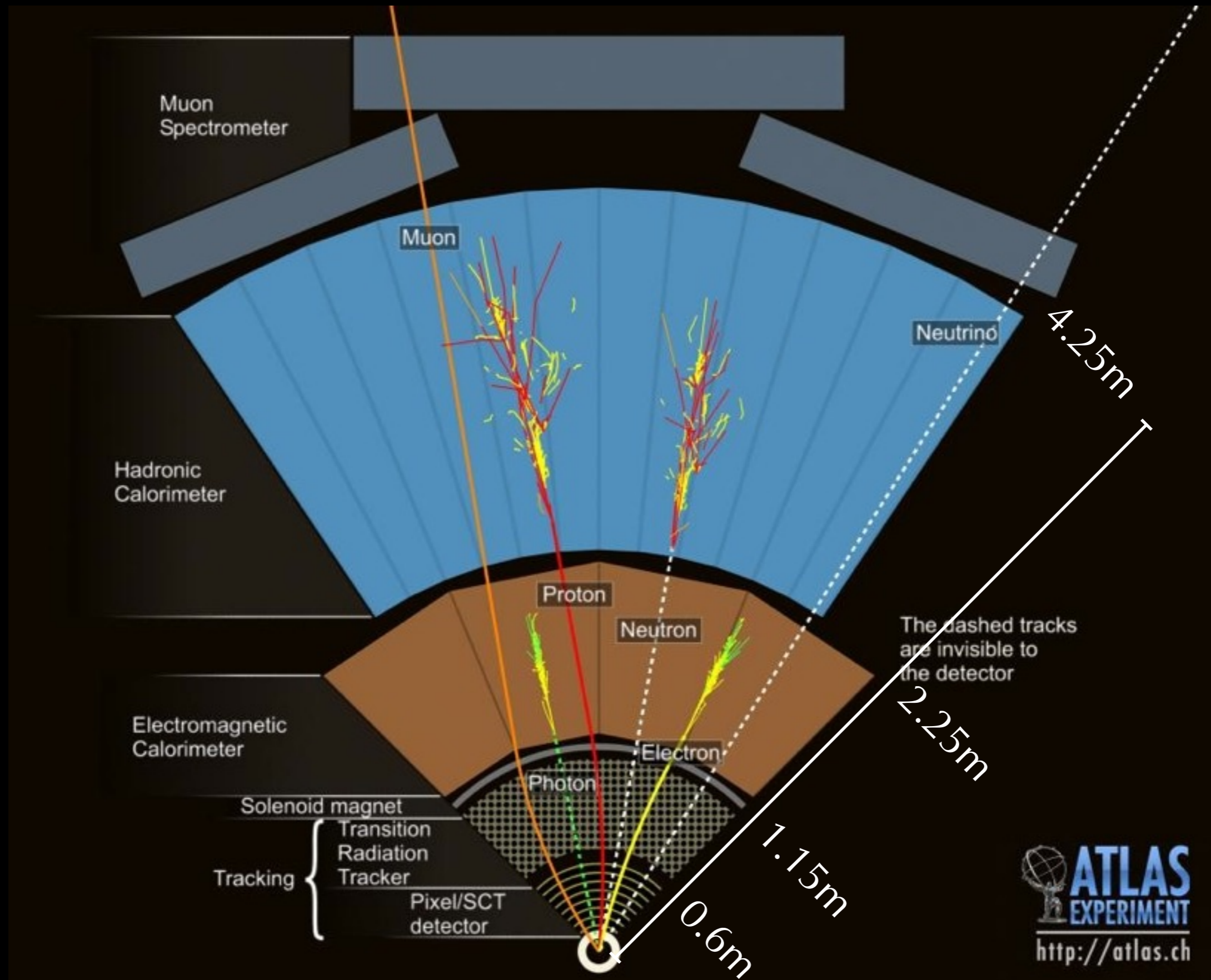
22 June 2017 02:33

Well said

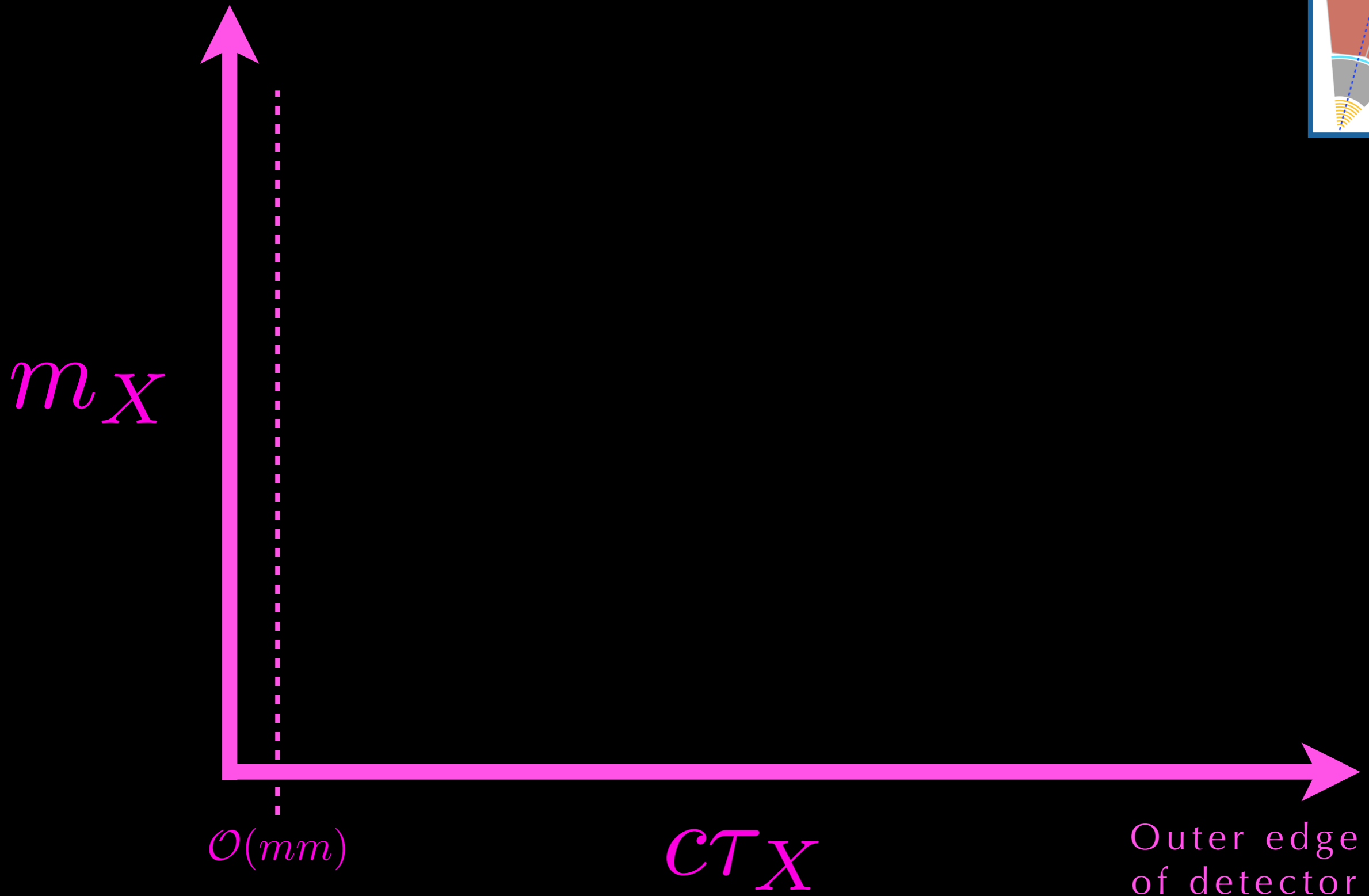
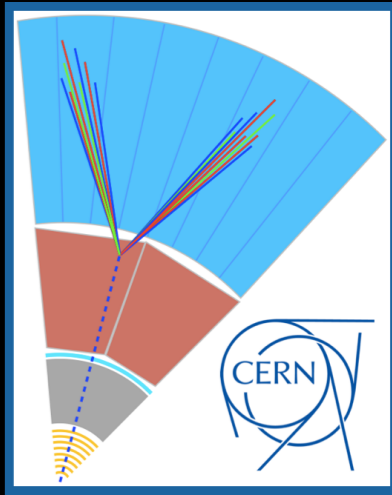
Lots of good ideas there but I have to get off my airplane now
Dennis

Sent from my iPhone

95% of our analysis effort is dedicated to understanding five prompt objects

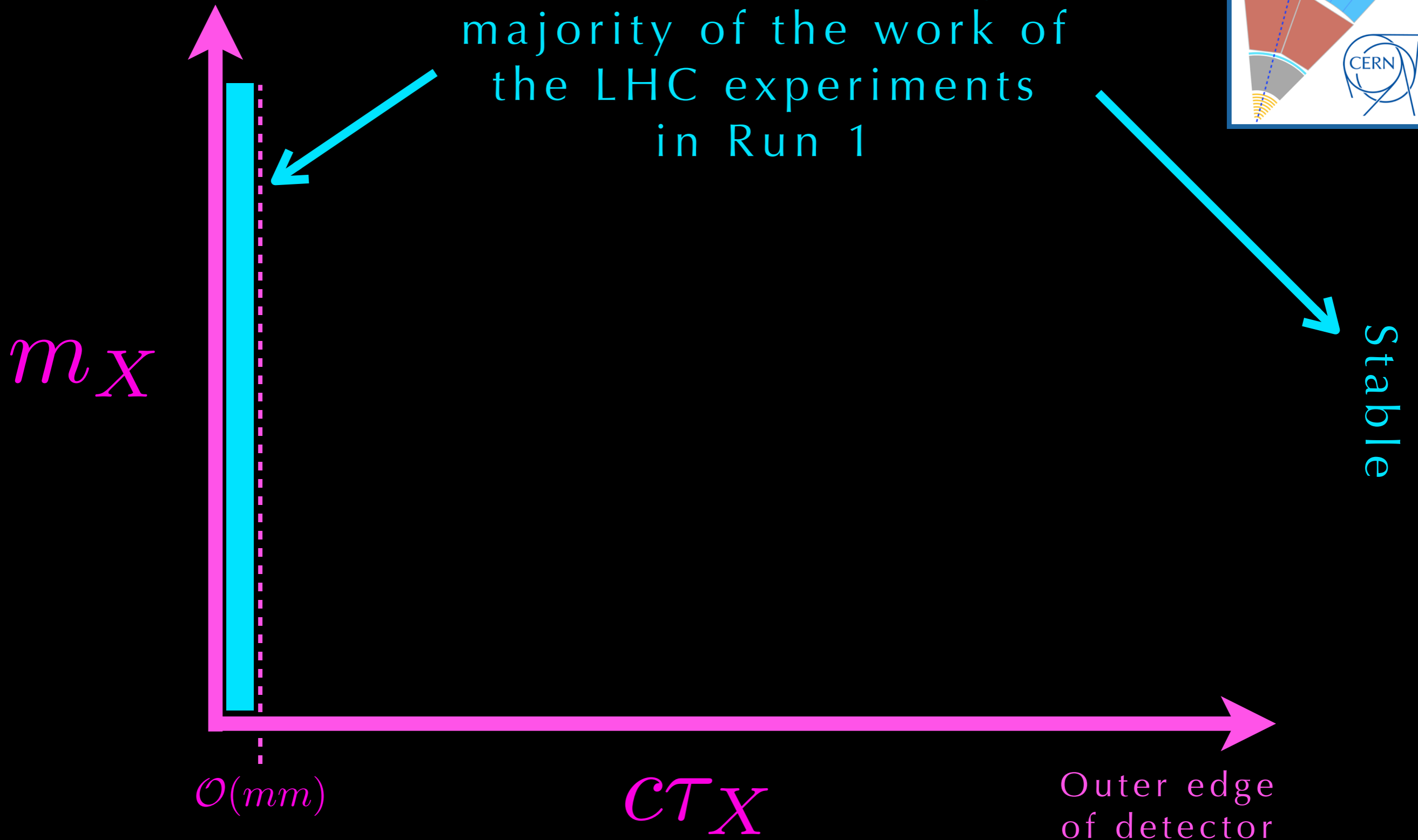
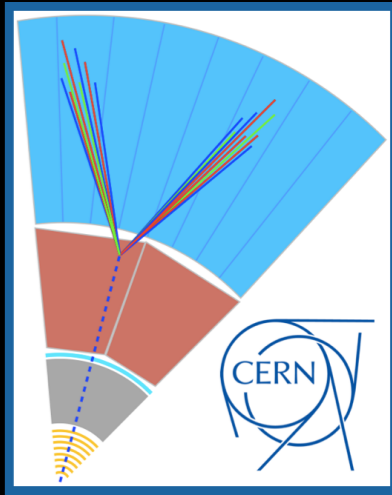


New physics X at the LHC



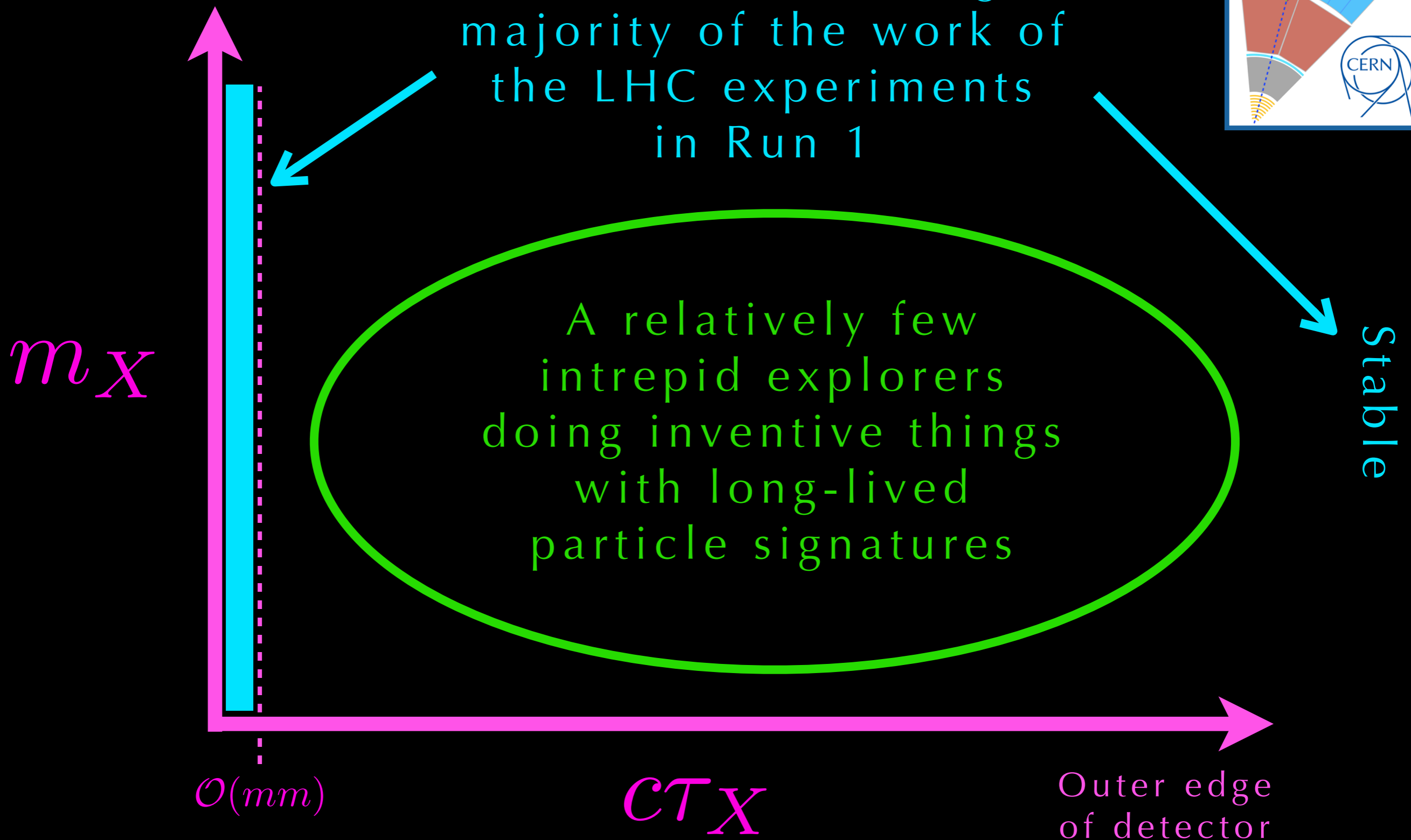
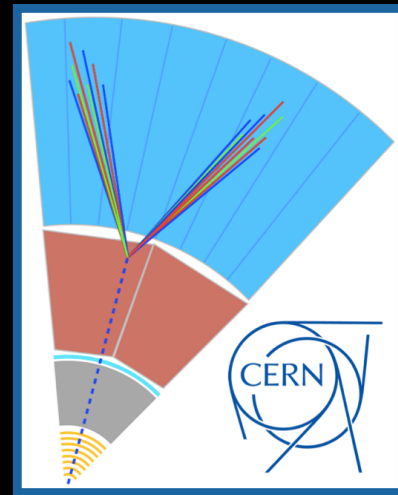
New physics X at the LHC

The overwhelming majority of the work of the LHC experiments in Run 1



New physics X at the LHC

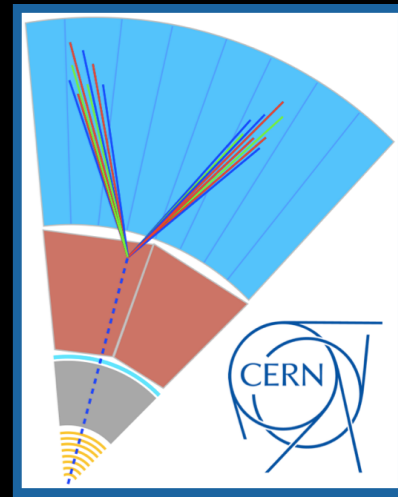
The overwhelming majority of the work of the LHC experiments in Run 1



Experiment-focused approach

LLPs can be a generic feature of BSM ideas

- Lifetime is usually best treated as a free parameter
- No clear old-school preferential motivations w.r.t. production and decay modes



This is **good news** for signature-minded experimentalists, because it means that particles can decay in various subsystems of the detector with impunity! This means a large number of intriguing, non-standard detector objects and often difficult triggering strategies.

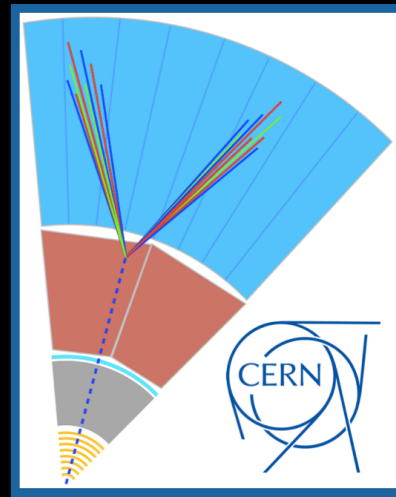
The **bad news** is that this this means a large number of challenging, non-standard detector objects and difficult triggering strategies. But “bad” in this case just means we need to think critically about the large space of production and decay modes and detector objects.

This is the fun part.

The LHC **LLP** Community

An experimental signature focused initiative

For our purposes, LLP = BSM particle that dies (gives up all its energy or decays to SM) somewhere in the detector acceptance of LHCb, CMS, ATLAS, MilliQan, Moedal, FASER, CODEXb, MATHUSLA, etc.



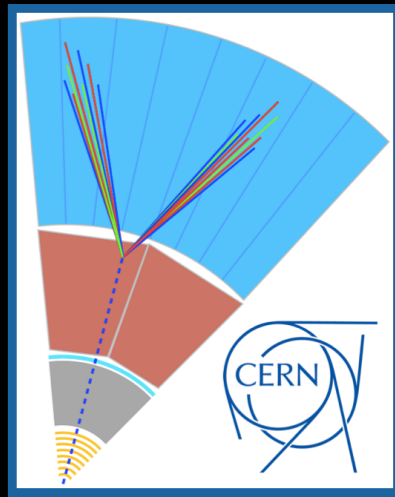
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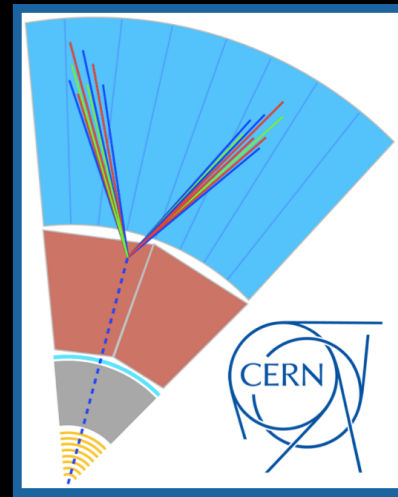
Neutral, stable particle = MET \rightarrow DM!

- Plenty of well-understood DM searches exploiting prompt objects \rightarrow not the explicit focus of this group (though, as always, used as motivation for simplified models)



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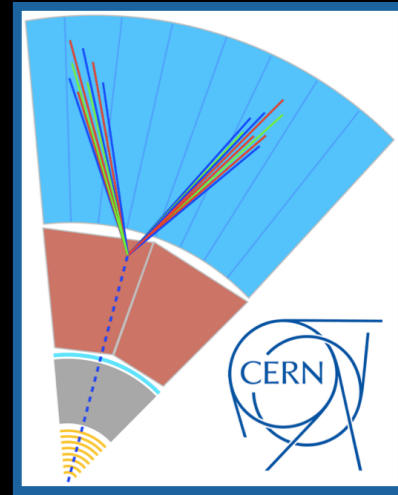
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Q: How do we know what detector objects could we be missing (or could do better at identifying) that could map back to generic BSM LLP motivations?

A: Ask the community.

The LHC LLP Community Initiative



...in collaboration with the theory/pheno community and MoEDAL, SHiP, milliQan, MATHUSLA, etc.

Continuing the work begun by several workshops

- “LLP Signatures” — UMass — Nov. 2015
- “Experimental Challenges” — KITP — May 2016
- LHC LLP Mini-Workshop — CERN — May 2016
- Searches for LLPs at the LHC: First Workshop of LHC LLP Community — CERN — April 2017

One question:

How do we best ensure that we don't miss BSM LLP signatures for the remainder of the LHC program?

Experimental signature based focus

Searches for long-lived particles at the Large Hadron Collider at CERN

September 24, 2017

Emmy Noether Bryn Mawr College, Pennsylvania, USA

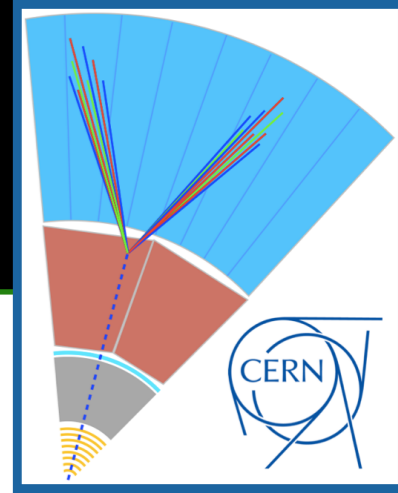
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Simplified model proposal organized around generic classes of LLP production and decay mode, always with an eye toward what the detectors might be able to do

Essentially done.

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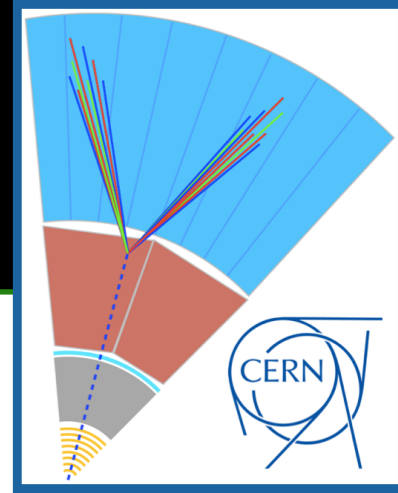
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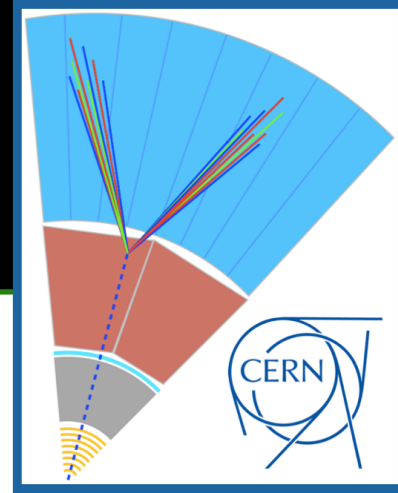
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Experimental coverage: How well do the existing searches cover the parameter space?

Advanced: On track for end-of-year.



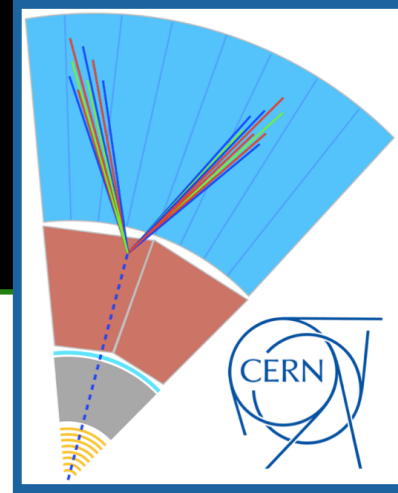
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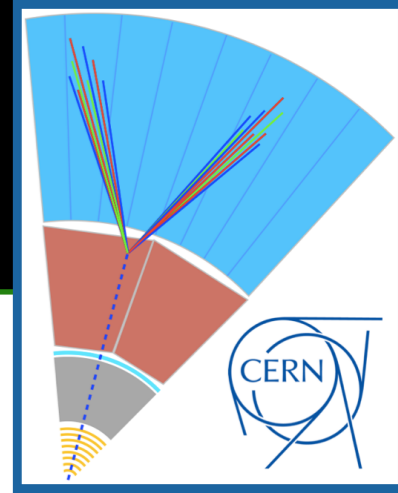
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What triggers are missing? What upgrade studies should be done to advocate for new detector components?

Long-term discussion, to be addressed here and in the future.



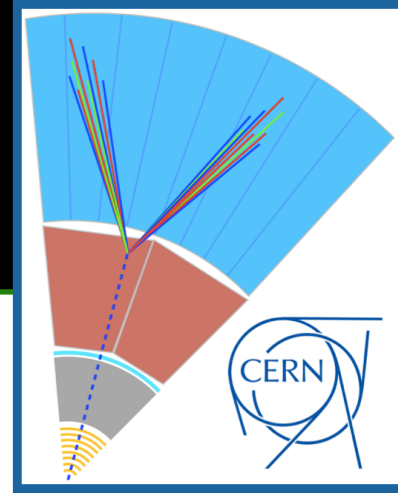
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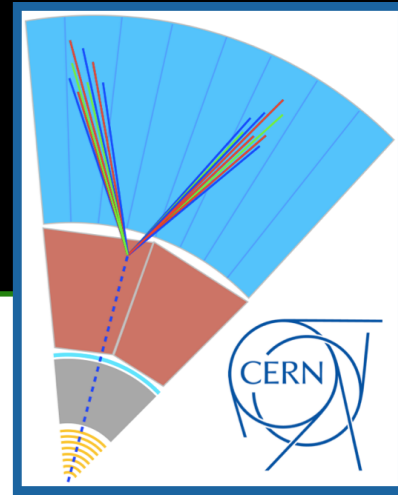
Experimental signature based focus

Searches for long-lived particles at the Large Hadron Collider at CERN

September 24, 2017

Emmy Noether Bryn Mawr College, Pennsylvania, USA

Contact editors: lhc-llp-admin@cern.ch



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How should we
present our results to
ensure optimal re-
interpretation and re-
cast-ability?

Advanced: On track
for end-of-year.



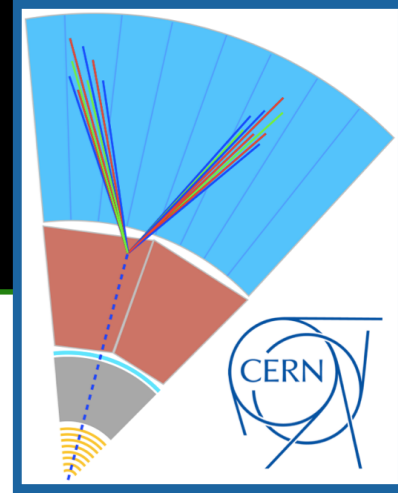
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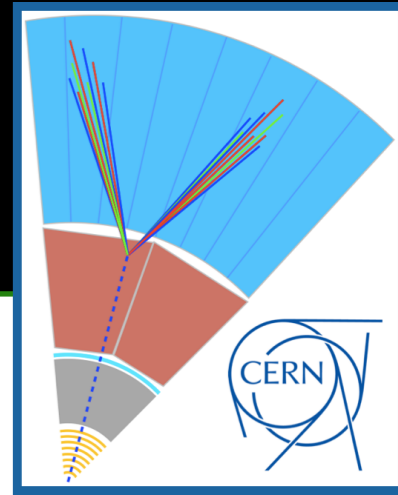
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QCD-like (more or less) dark sectors:
What kinds of experimental signatures are between emerging jets and SUEP?

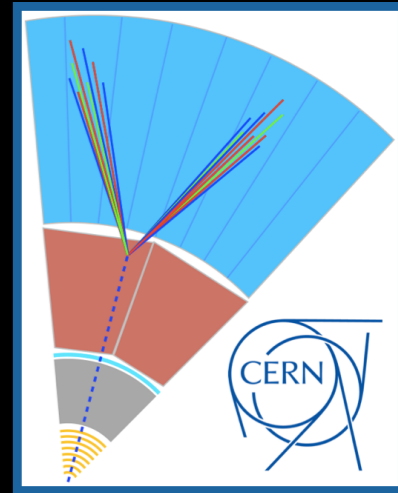
Longer-term work on uncharted territory; still examining how we know what we don't know.

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What we should answer as a result of this workshop



Simplified models

- Ready to go and be used by the experiments. What's missing?

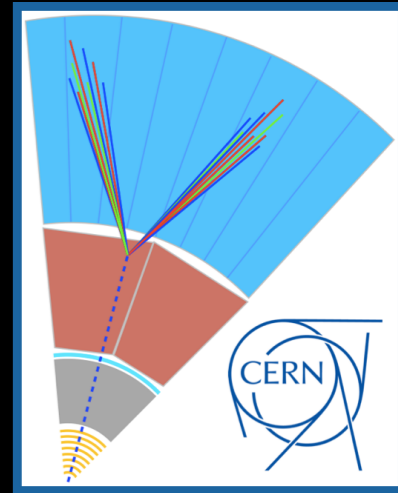
Experimental coverage

- What gaps in coverage exist that should motivate new, improved, and/or expanded searches?

Trigger & upgrades & beyond

- A few concrete, missing triggers in CMS and ATLAS were identified at the April workshop. What did we miss that we've identified since then? What studies have been performed to support possible detector upgrades that would improve sensitivity to LLP signatures? What about the prospects, challenges, and opportunities with a high luminosity or a high energy (~ 25 TeV) LHC? New, blue-sky ideas mandatory.
- Example: Full hermetic coverage for upgrade timing? CMS is prioritizing, ATLAS is not. We, here, can help arrive at a consensus
 - Studies still need to be done to demonstrate killer-app status — which ones?
 - Example: New detector components?

What we should answer as a result of this workshop



Recasting and re-interpretation

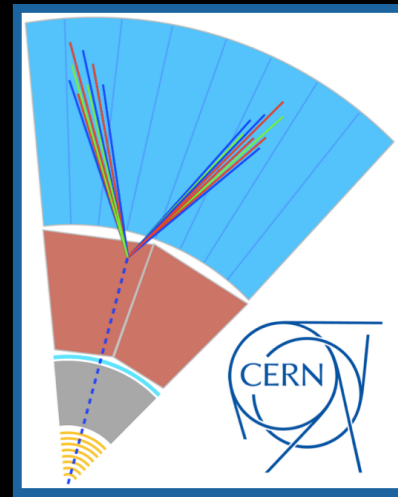
- Joint session with re-interpretations workshop at Fermilab, today!
- A set of coherent, comprehensive, and reasonable recommendations for the presentation of search results to ensure optimal re-cast-ability
- Demonstrate the mature utility and necessity of detector collaboration controlled frameworks like RECAST to work in conjunction with and in parallel to re-interpretation tools
- Very advanced chapter, with plenty to talk about tomorrow.

Dark showers

- Dark QCD! A lot we don't know. How do we know what we don't know?
- Pencil-like jet regime —> Emerging jets searches
- Soft radiation patterns —> SUEP- γ signatures
- How do we interpolate between these, w.r.t. theory/pheno (generators, event shape variables, etc.) and in the detector (how do we trigger on these and ID them)?
- A rich discussion is currently ongoing in this WG — you are encouraged to join and participate in the meetings and help us map this territory

Workshop goals

Converge toward the content of the white paper!

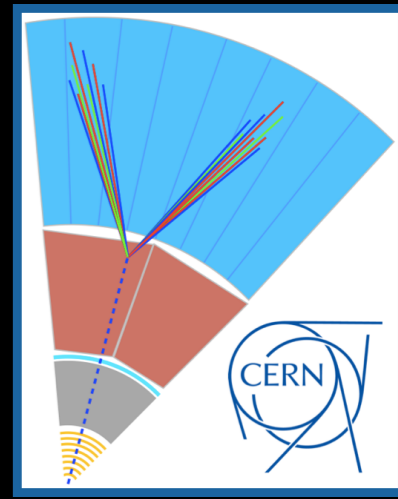


- 1) If you're not already working directly with one of the WGs / chapter groups, jump in! We need you! At lunch, meet up with any of the chapter editors and discuss ways to get involved.
- 2) For theorists: Find your new model to work on that might yield a detector signature we haven't yet thought of
- 3) For experimentalists: Find your next-year analysis project, and find your upgrade study to do ASAP!
- 4) Repeat: Upgrade studies! These are the sessions on Friday.
- 5) New ideas for now and our next workshop in the Spring, e.g., ...

What we could do better

Incremental improvements can be and are being made to all or most of these searches

- For Run 2, have had to adapt to increased pileup conditions, changing trigger thresholds, etc.
- This will be even more essential moving into the High-Luminosity era



But we should take a step back, as well, and look at the broader picture

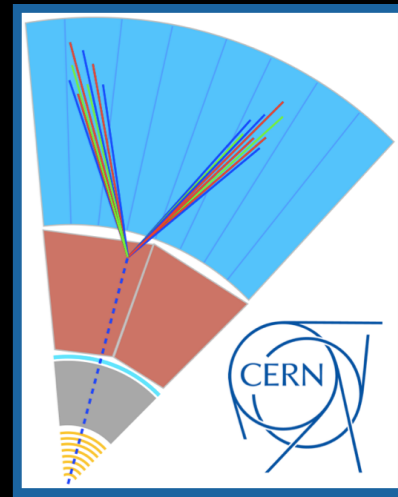
These searches often require non-standard analysis methods, triggers, backgrounds, that can consume a lot of time

There's a danger in spending a large amount of time and effort to make incremental improvement in an existing search when the existing search may be a bit too narrow in scope already

In the end we're trying to address one question:

How do we best ensure that we don't miss
BSM LLP signatures for the remainder
of the LHC program?

What we could do better

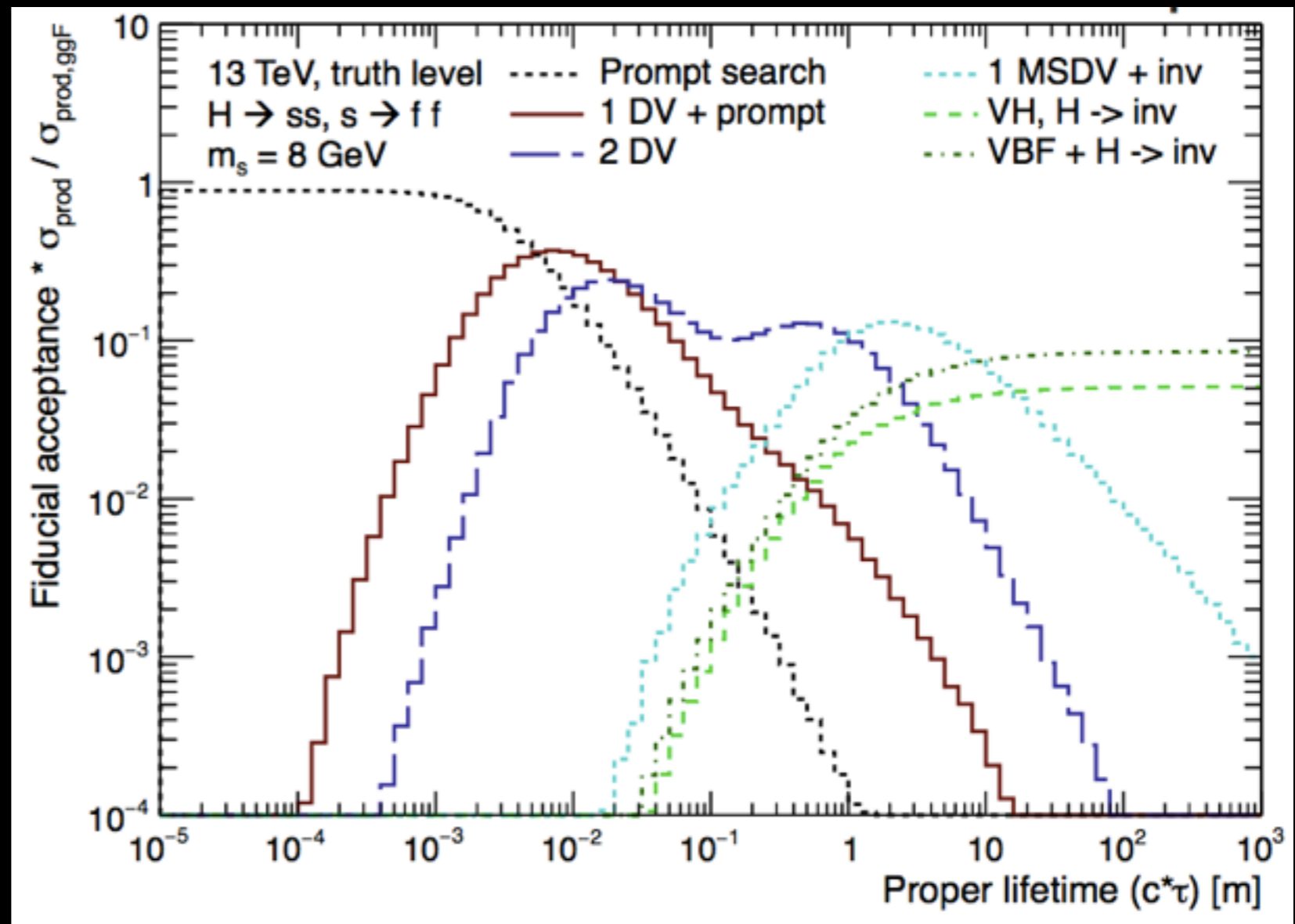


Where do our prompt and displaced searches overlap?

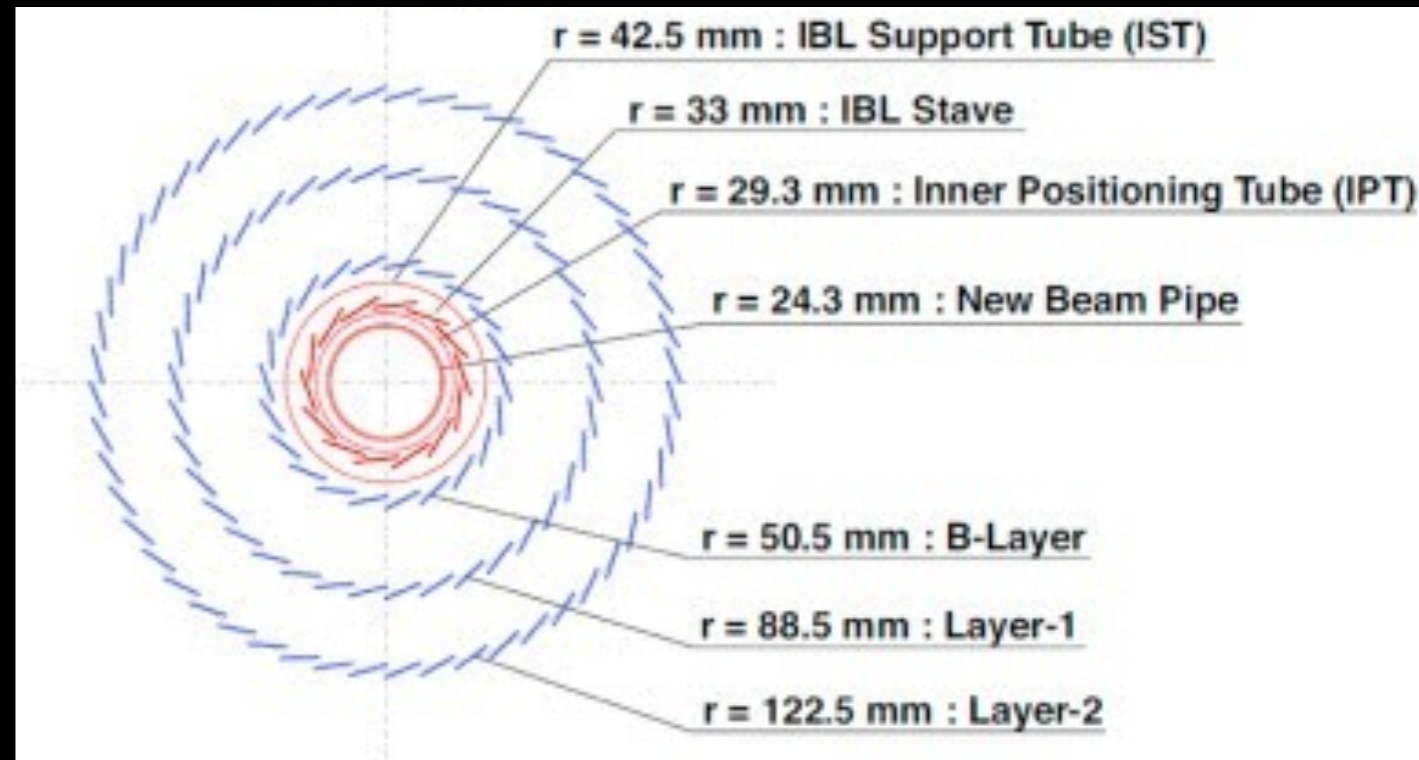
- Truth study by H. Russell for h125 decaying to fermions via a pair of 8 GeV LLPs
- How to compel prompt searches to run long-lived signal MC through their search and vice versa?

Probably our smaller-lifetime coverage isn't this good, but need to know the answer

Also need comprehensive studies of existing b-triggers for small-to-intermediate lifetime signatures, because...

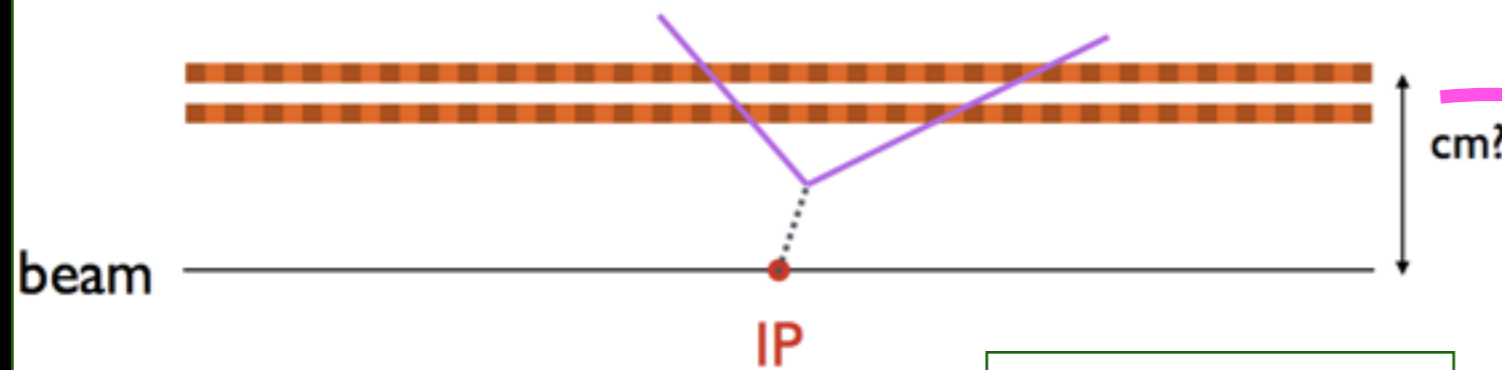


Possible detector upgrades



Possible detector upgrades

What about triggering on very short decay lengths in tracker?



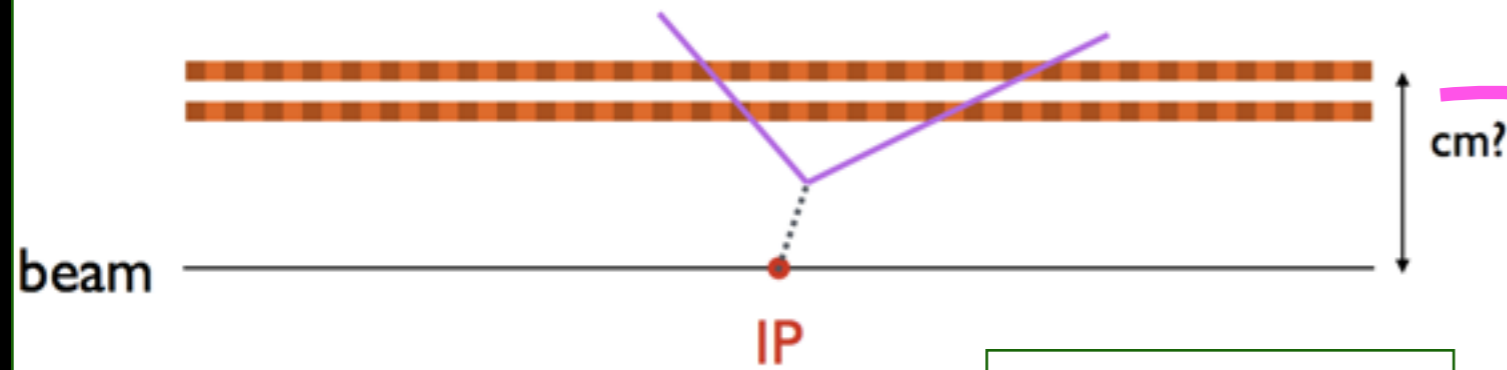
D. Curtin

Some sort of **tracklet-based DV reconstruction** in the double-layer to trigger on possible LLP decay?



Possible detector upgrades

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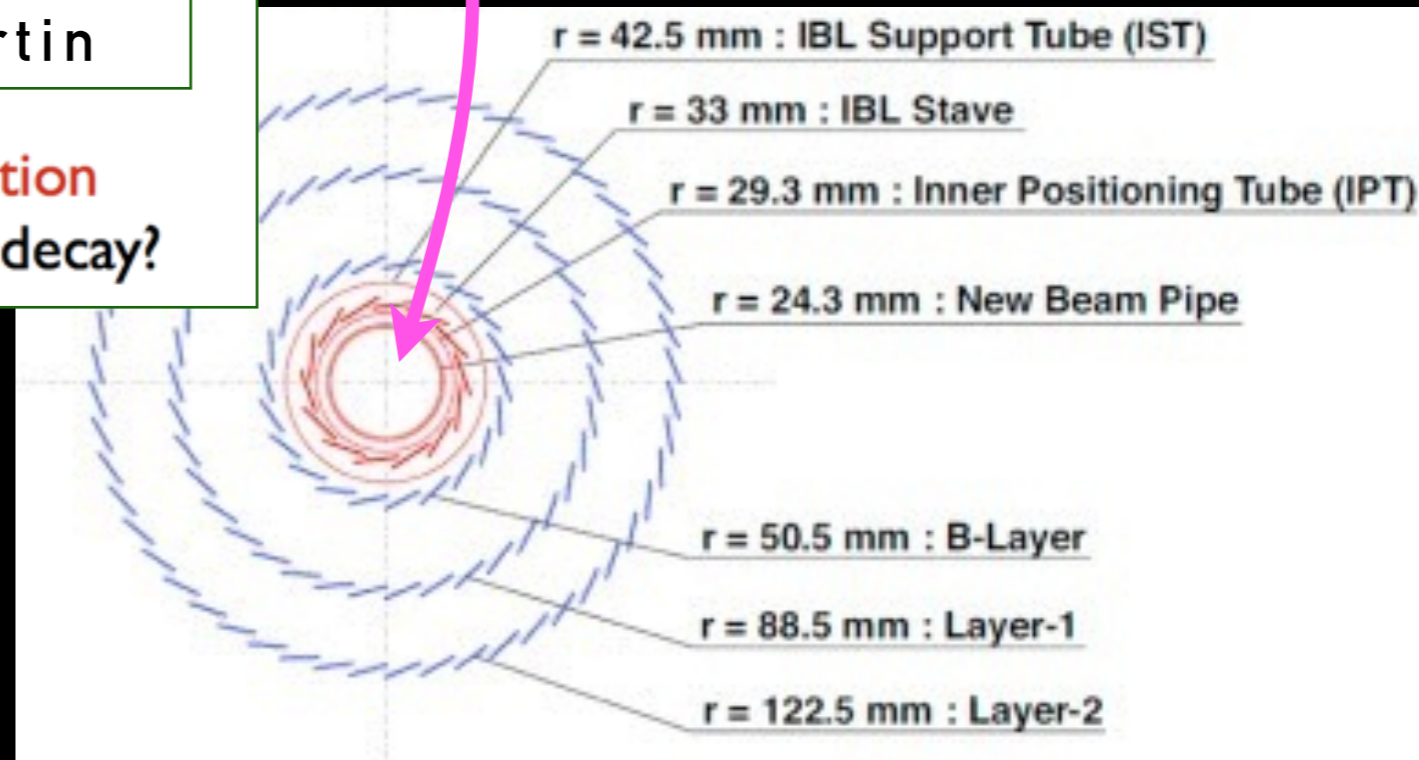


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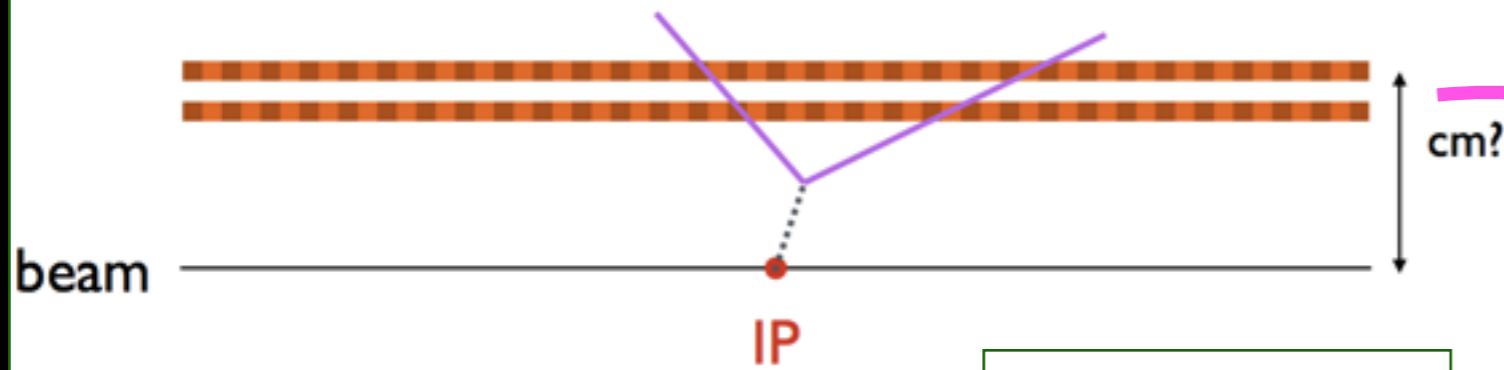
Blue sky idea for ATLAS:

Simple high-resolution double-tracking layer inside the IBL



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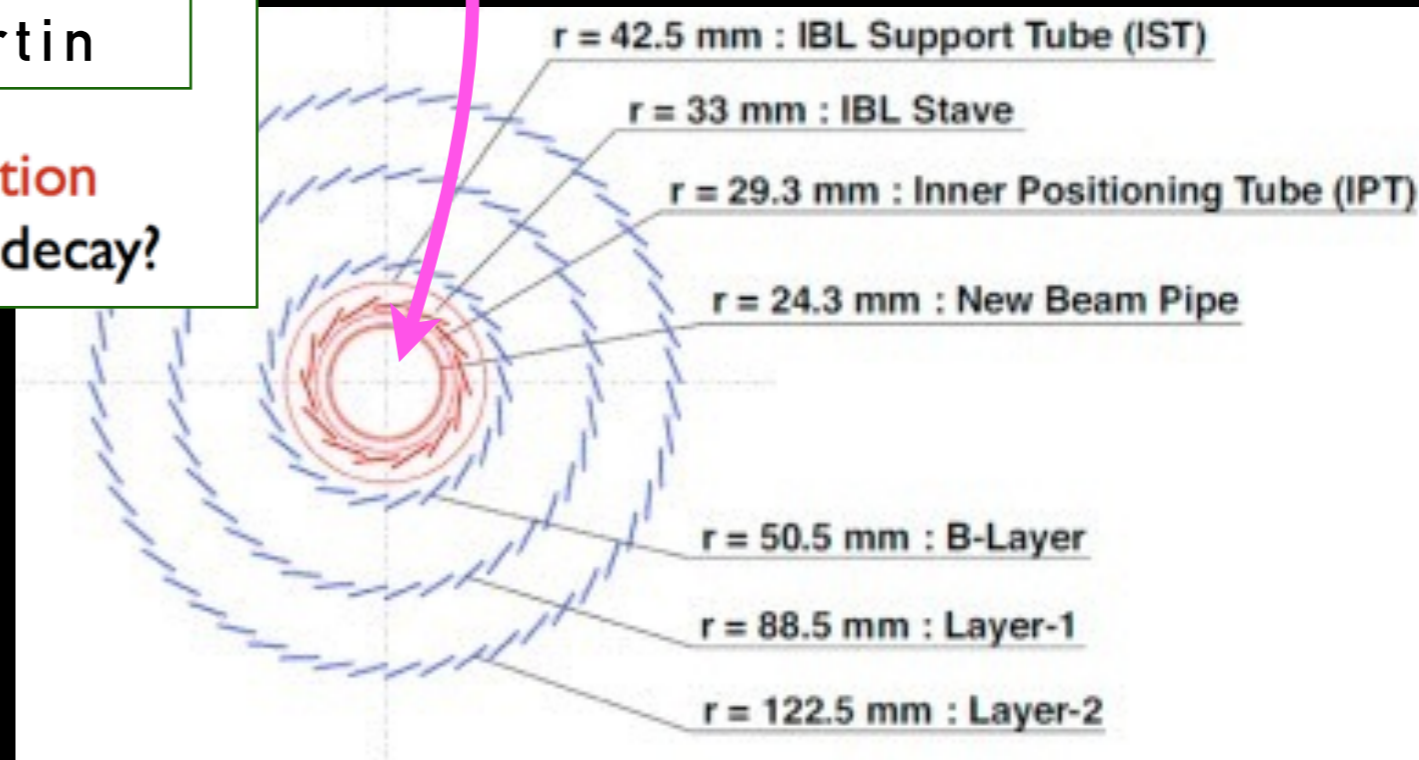
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- This would likely significantly improve our sensitivity to h125 decays to shorter-lifetime LLPs! But by how much?
- Would also help with very short lifetime charged LLPs

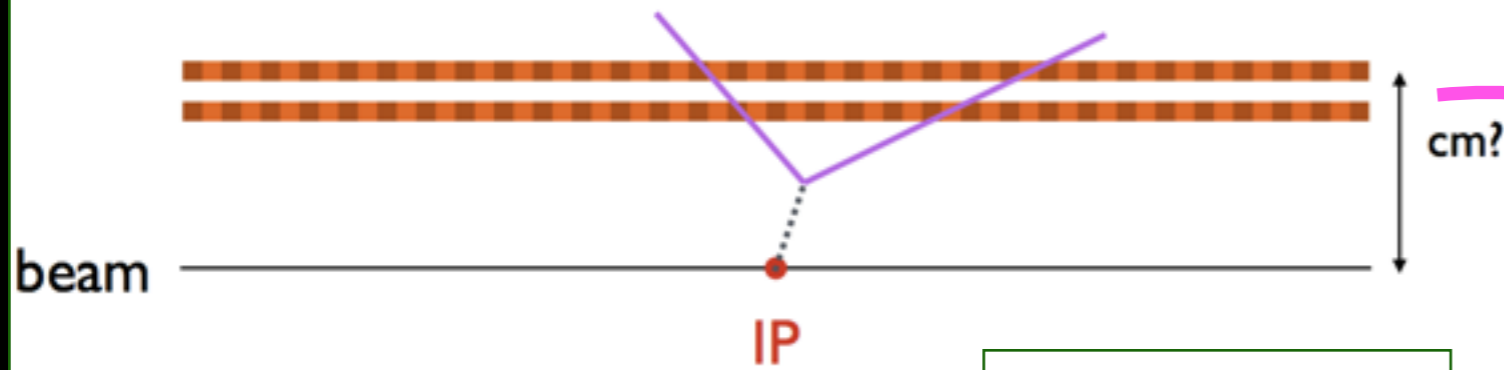
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Possible detector upgrades

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D. Curtin

Some sort of **tracklet-based DV reconstruction** in the double-layer to trigger on possible LLP decay?

- This would likely significantly improve our sensitivity to h125 decays to shorter-lifetime LLPs! But by how much?
- Would also help with very short lifetime charged LLPs
- Pileup would likely make it useless!
- Would probably be incinerated by the beam!
- What about a purposely temporary next-to-beam tracking layer that would only survive a certain integrated luminosity and die?

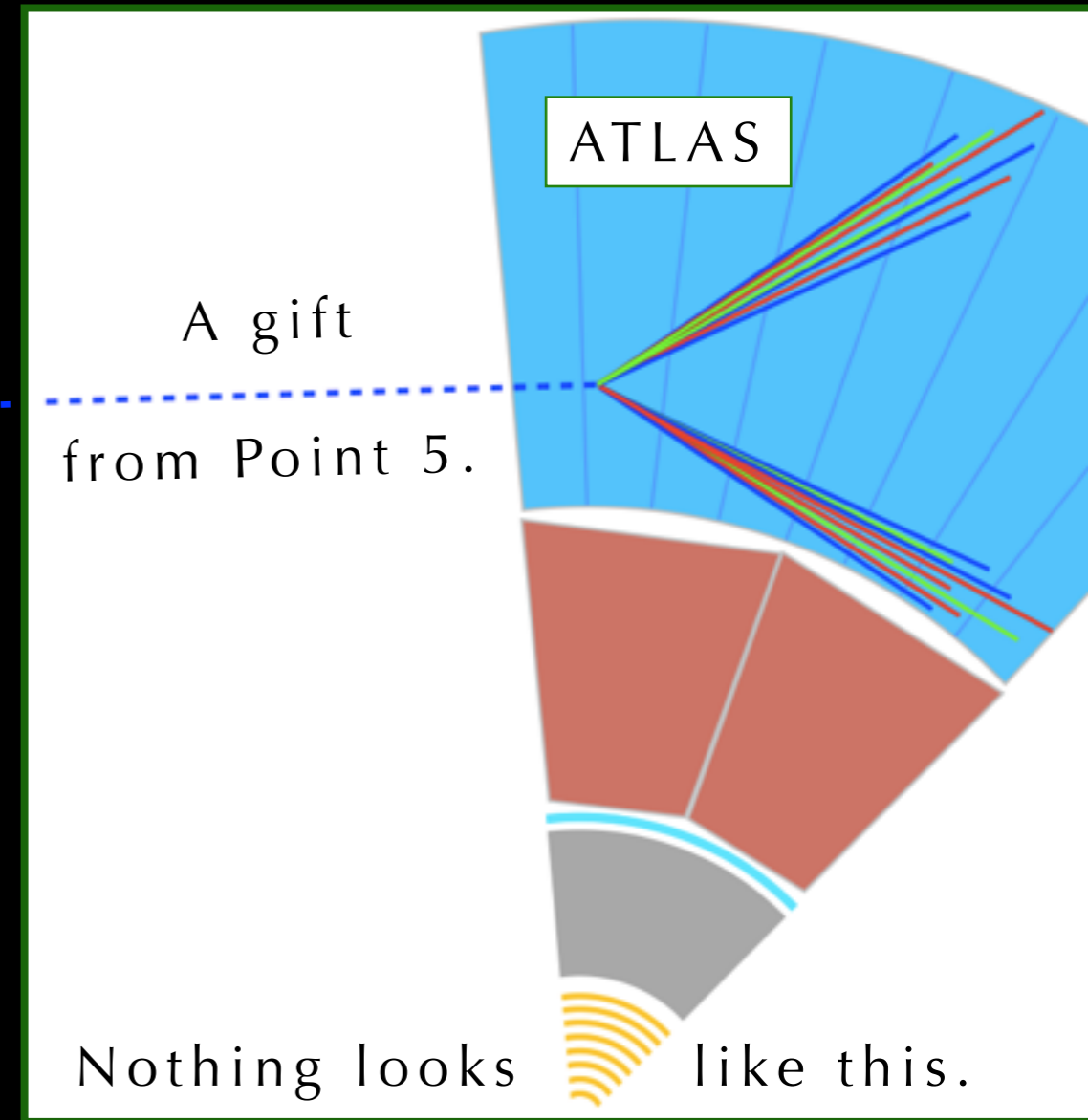
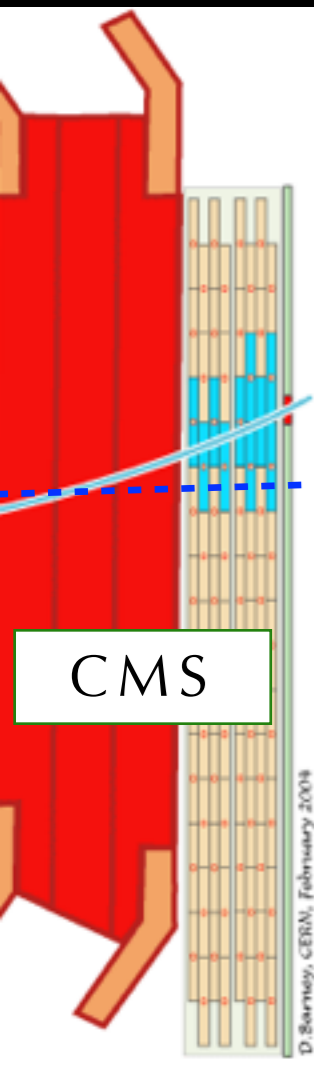
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Long-shots and opportunities

What are we missing?

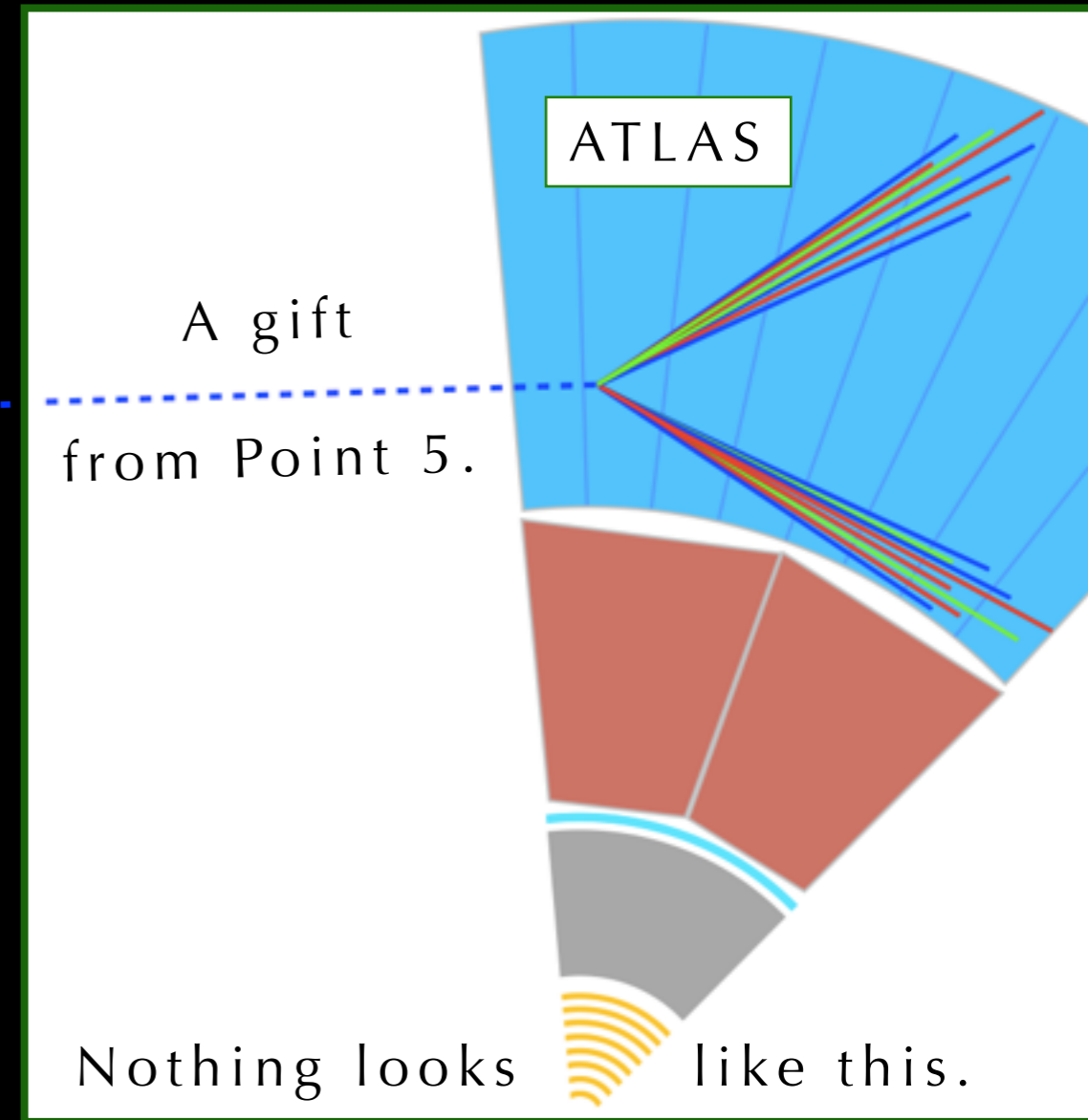
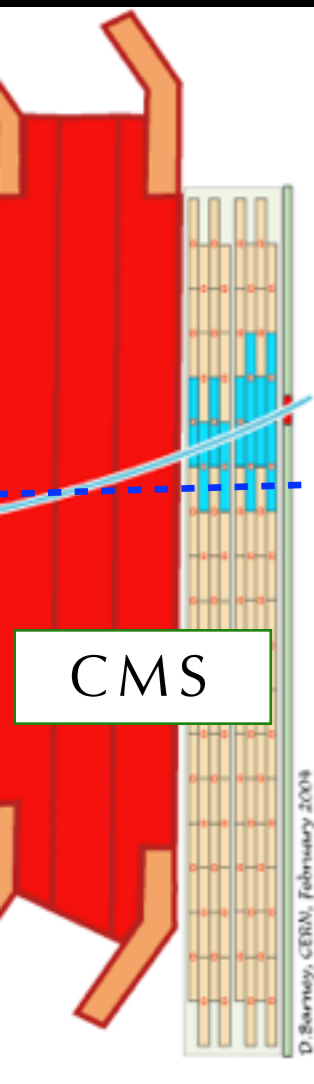


Long-shots and opportunities

What are we missing?

- What about nearly-trivial insanities?

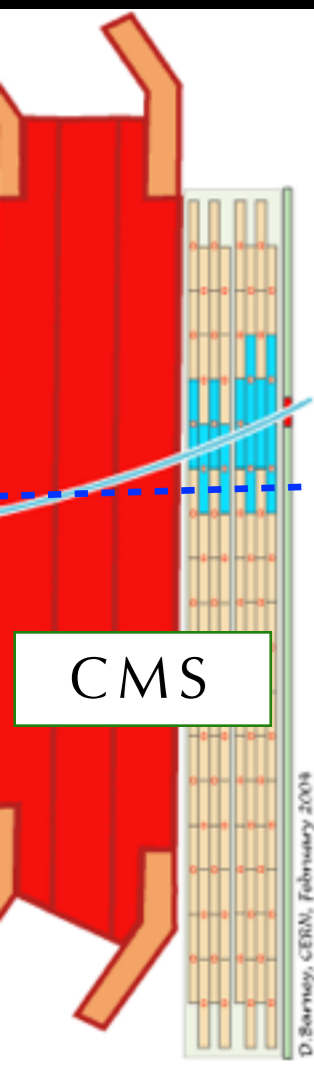
- ATLAS and CMS can each be used as a detector for LLPs produced in the other
- Solid angle coverage is vanishingly small, $\sim 10^{-7} \dots$ \leftarrow insane



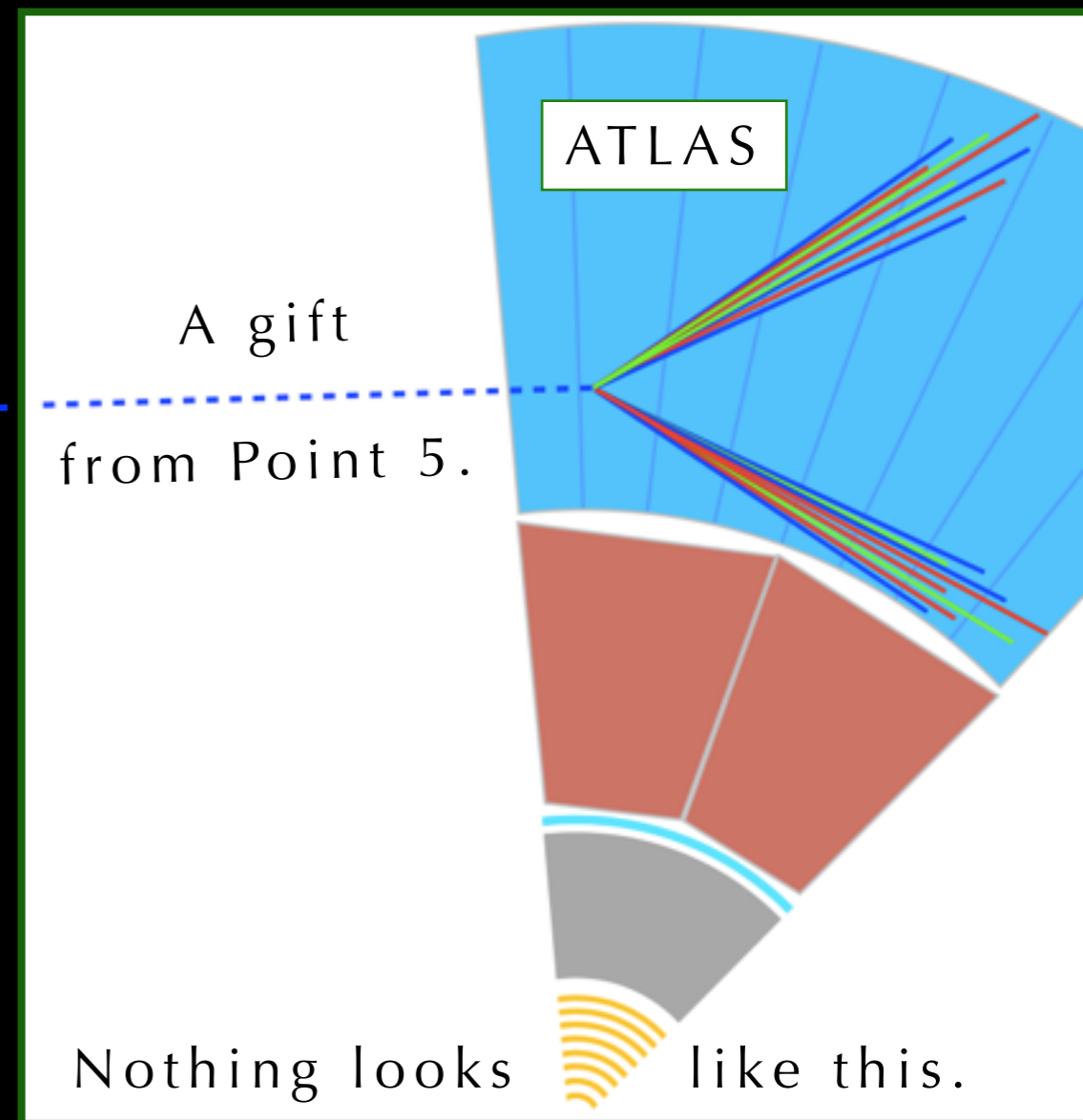
Long-shots and opportunities

What are we missing?

- What about nearly-**trivial insanities**?



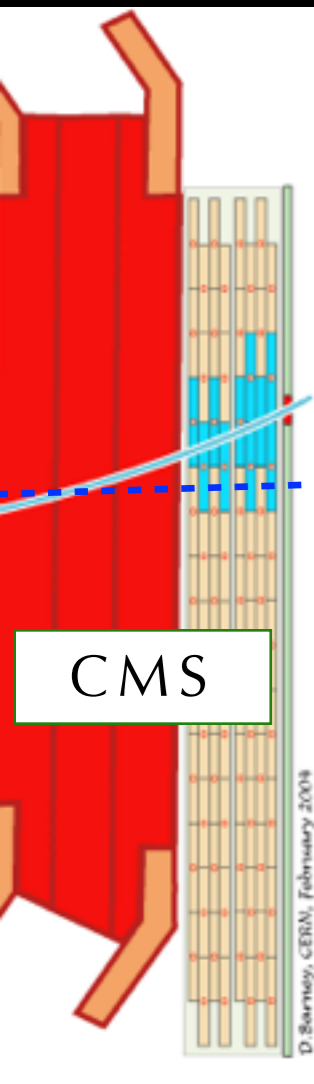
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- ...but non-zero. And the signature is so rare that it would immediately show up in unfilled bunch crossings \leftarrow **trivial**
- A quizzical use of time? Why not spend a month looking for this and getting a limit, as a proof of concept?
- Remember that the LHC is our only good source of Higgses, Ws, etc., for a very long time.



Long-shots and opportunities

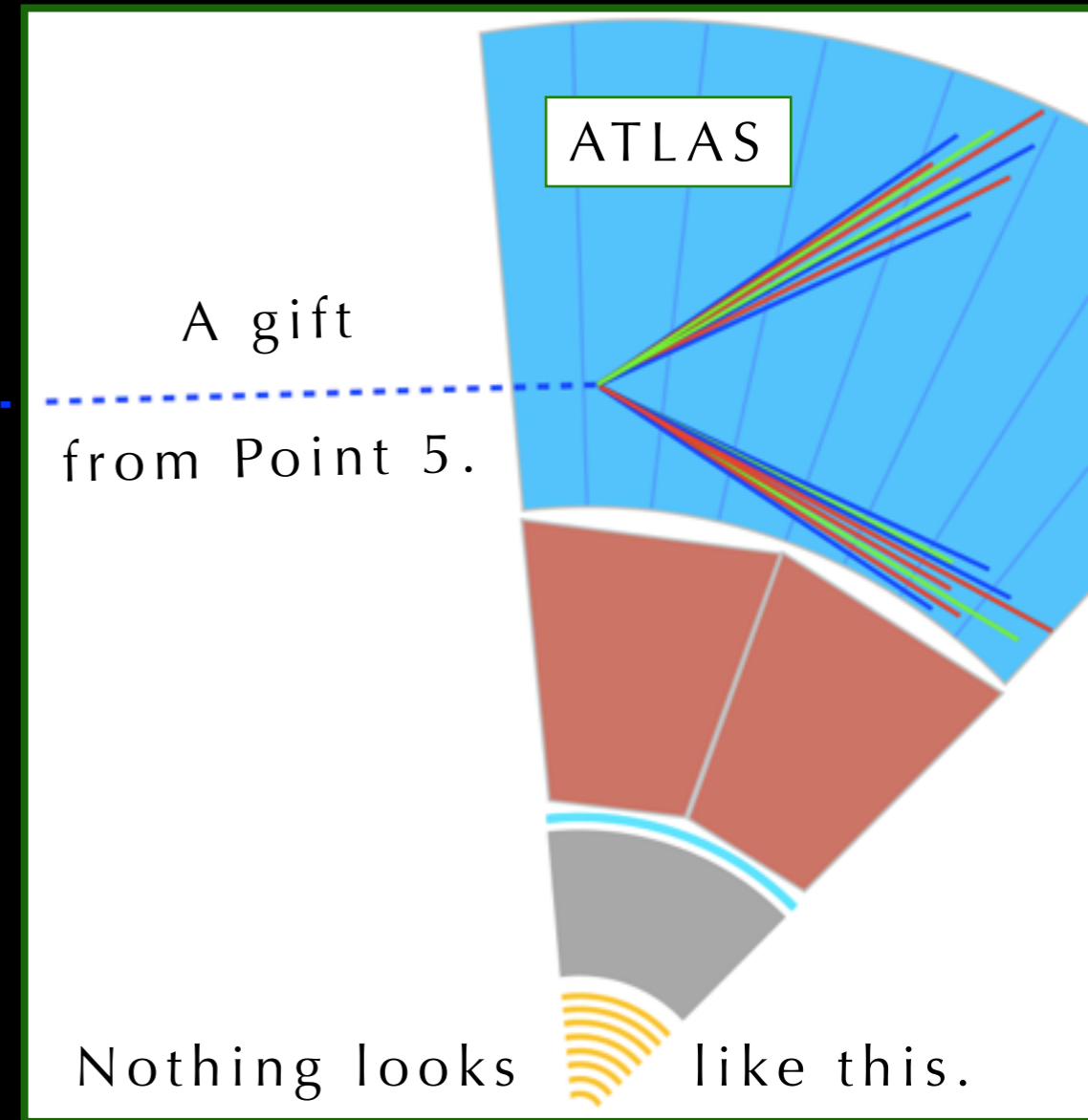
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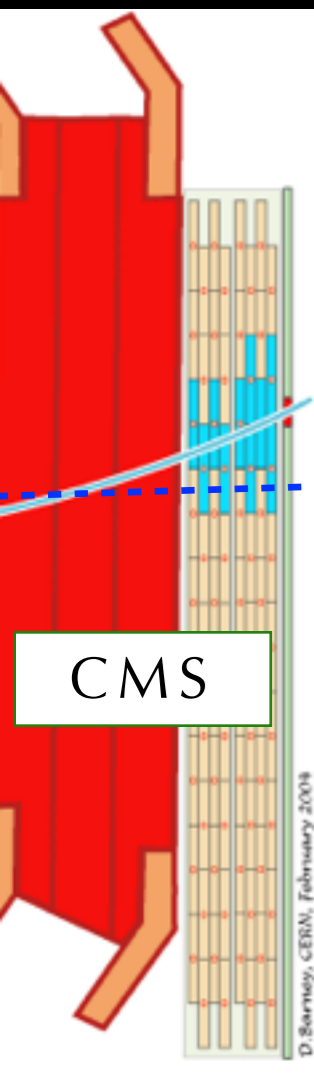
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Long-shots and opportunities

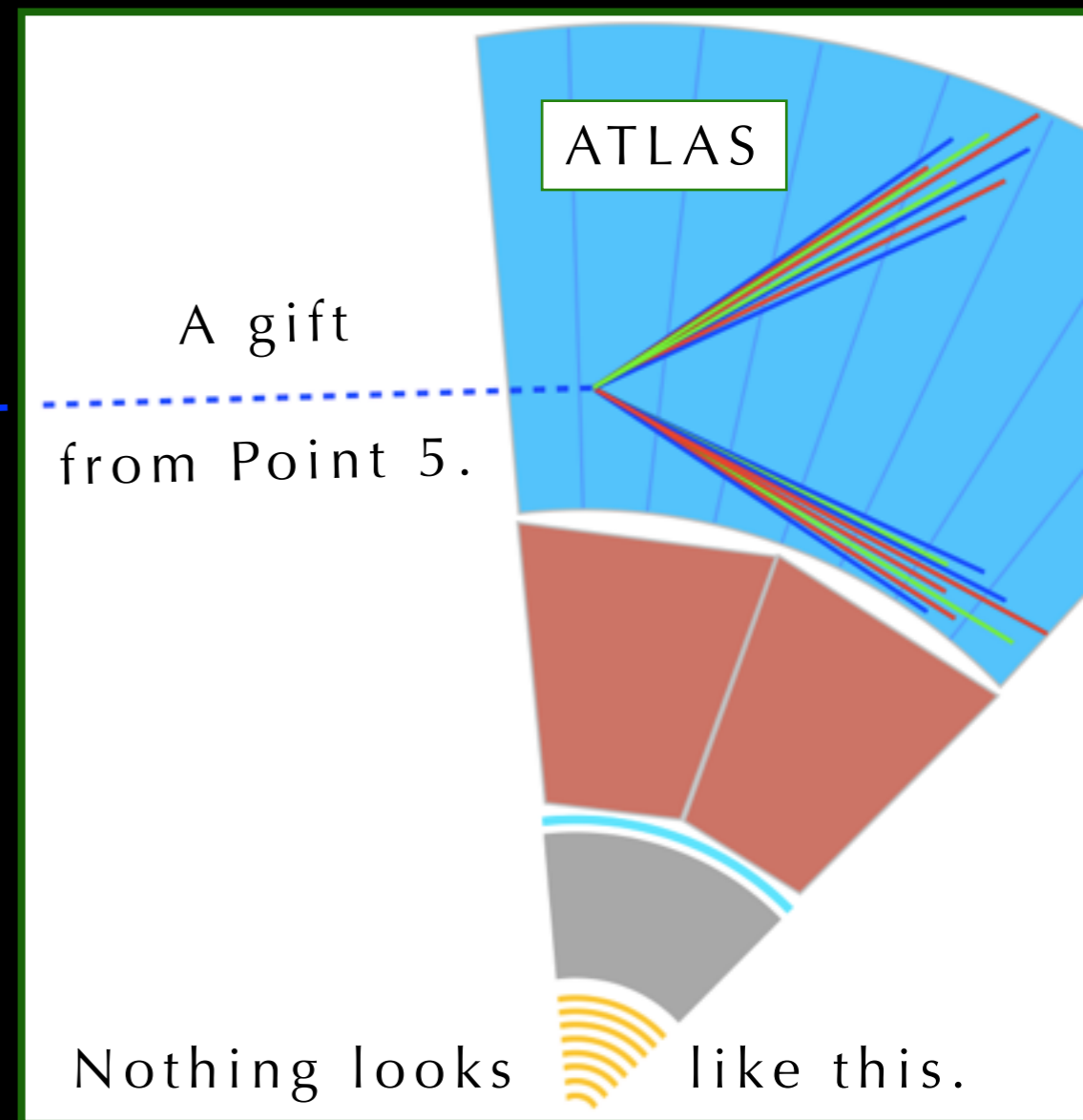
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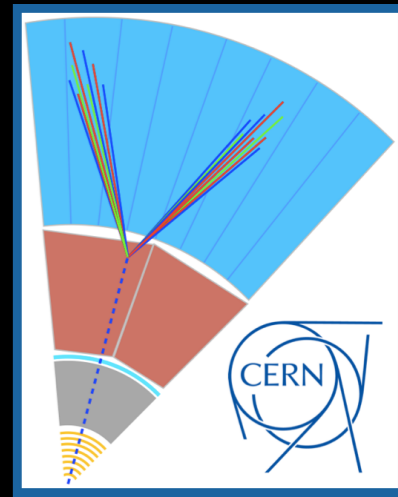
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Meade, Nussinov, Papucci, Volansky mentioned this in passing in 2009

The future is experimental

Our job as physicists is not to find SUSY or WIMP dark matter or sequential SM Z' or QBH or VLQs or...



After our first look at 13 TeV, our traditional motivation paradigms are fading or dead

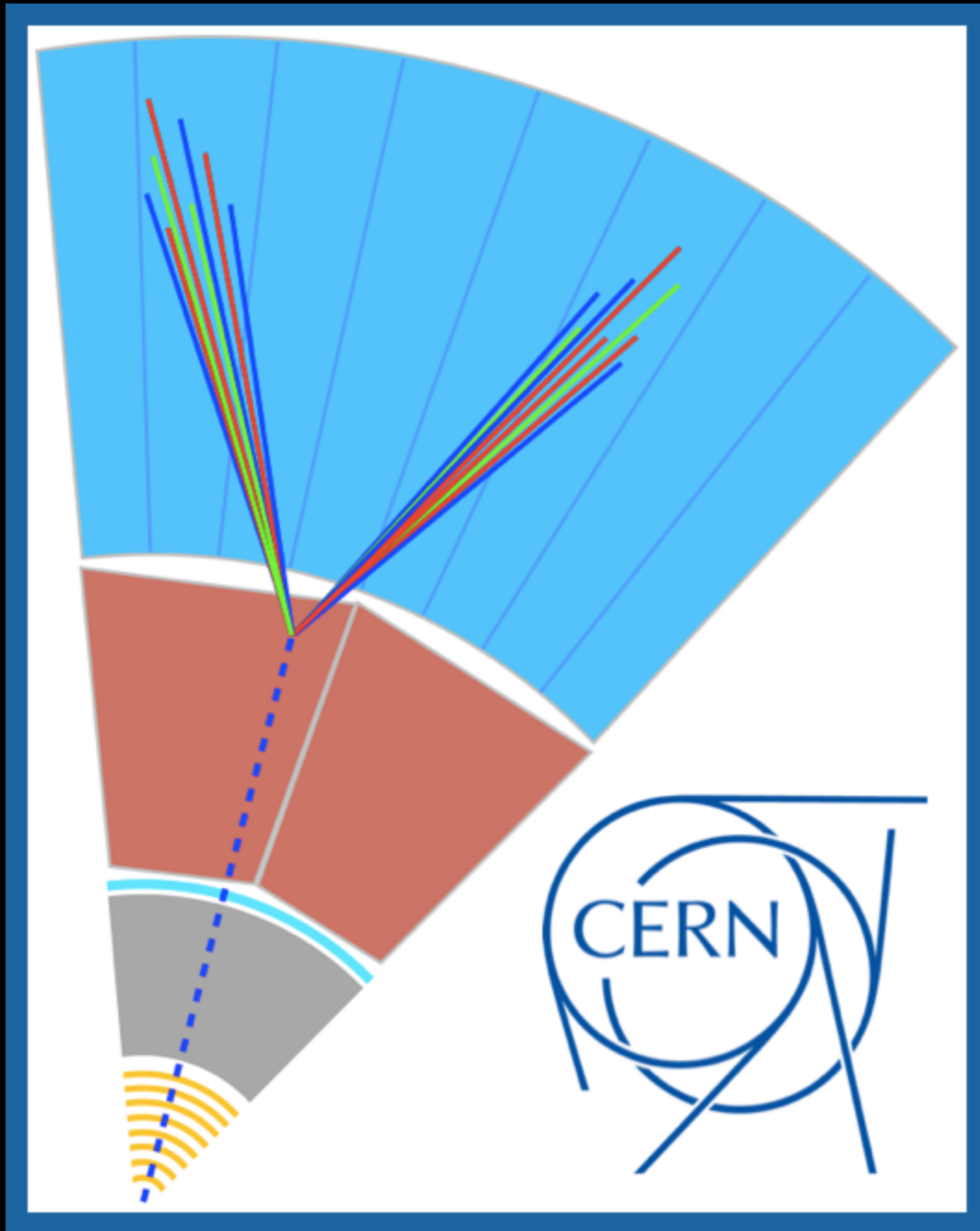
The Higgs discovery only answered one open question — does the SM Higgs exist? — and raised a bunch of others!

But these other questions are no longer accompanied by guaranteed discoveries

Scary: Where do we look?

Freedom: Everywhere! We have one of the most sophisticated devices ever built at our disposal, and our job is to push it to its limits, to map out all available experimental object space

This means bold new ideas involving LLPs. 2017 is the perfect time to be bold!



Workshop goal:
Map the future.
You're doing it
right now.