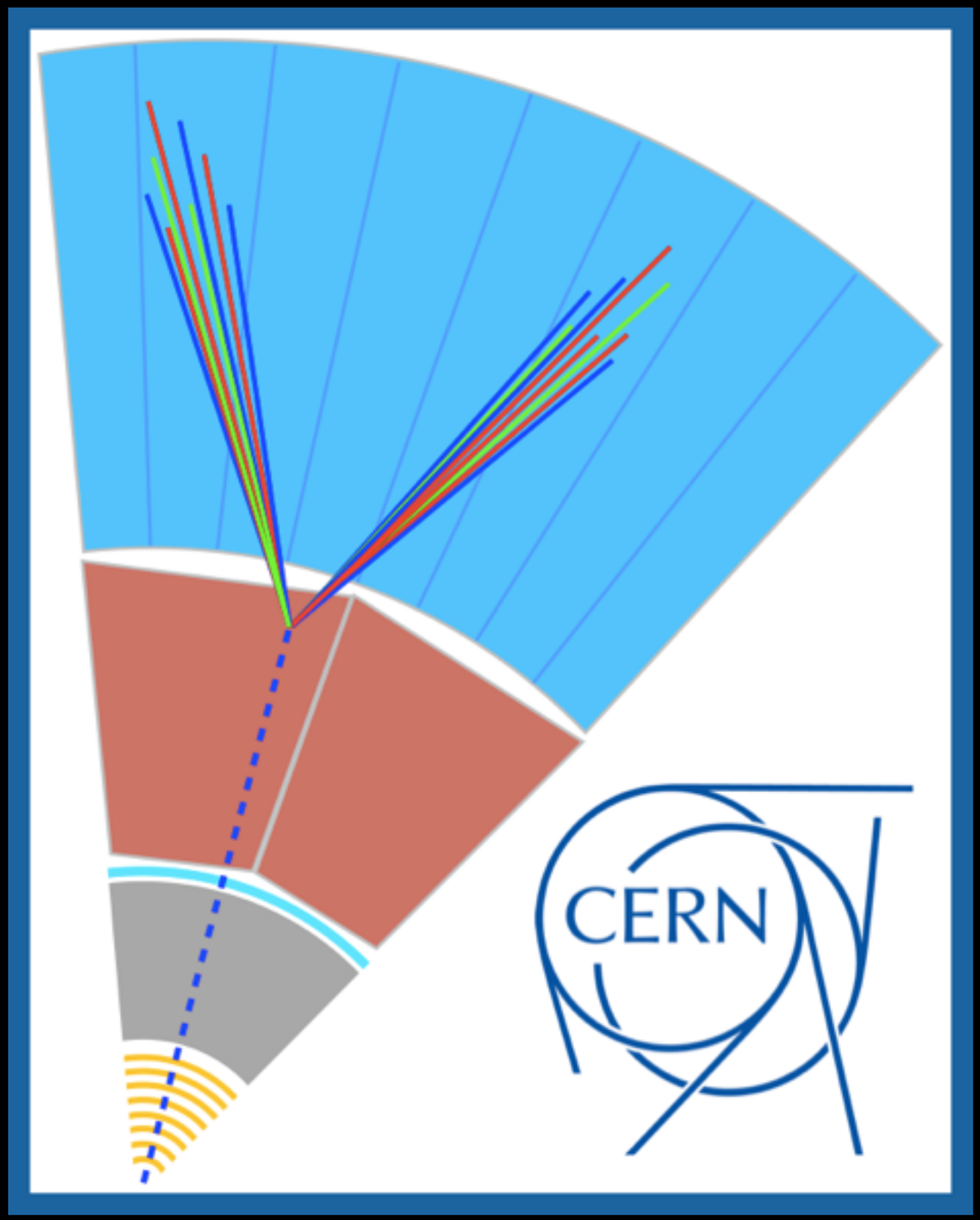


Searches for long-lived particles at the LHC

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 and their origin
- ❑ what is the role of *H*(125) ?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → 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_LV_L cross-section at high $M(V_LV_L)$? 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

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 ?

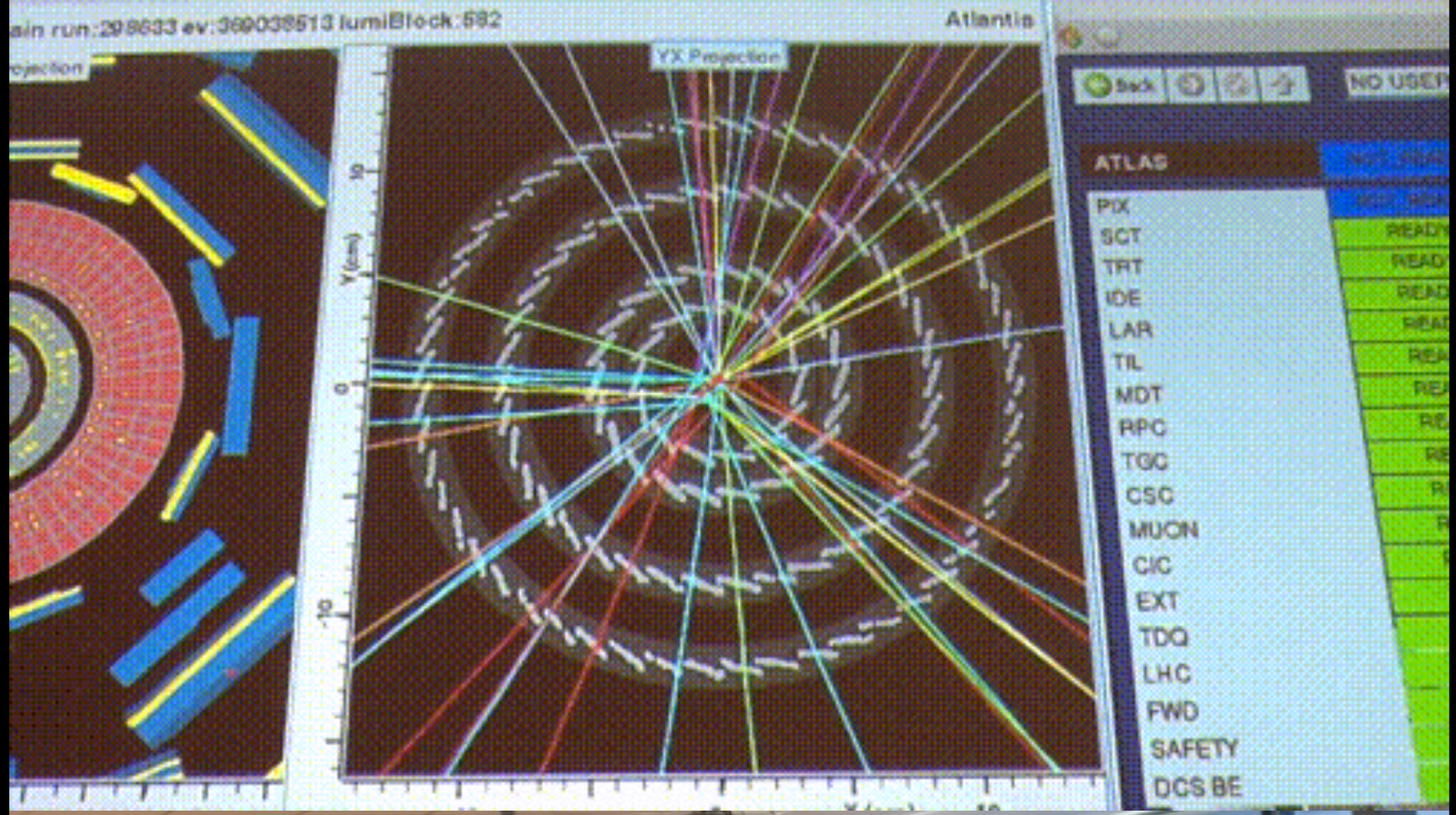
Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ *ν* masses and and their origin
- ❑ what is the role of *H*(125) ?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → 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

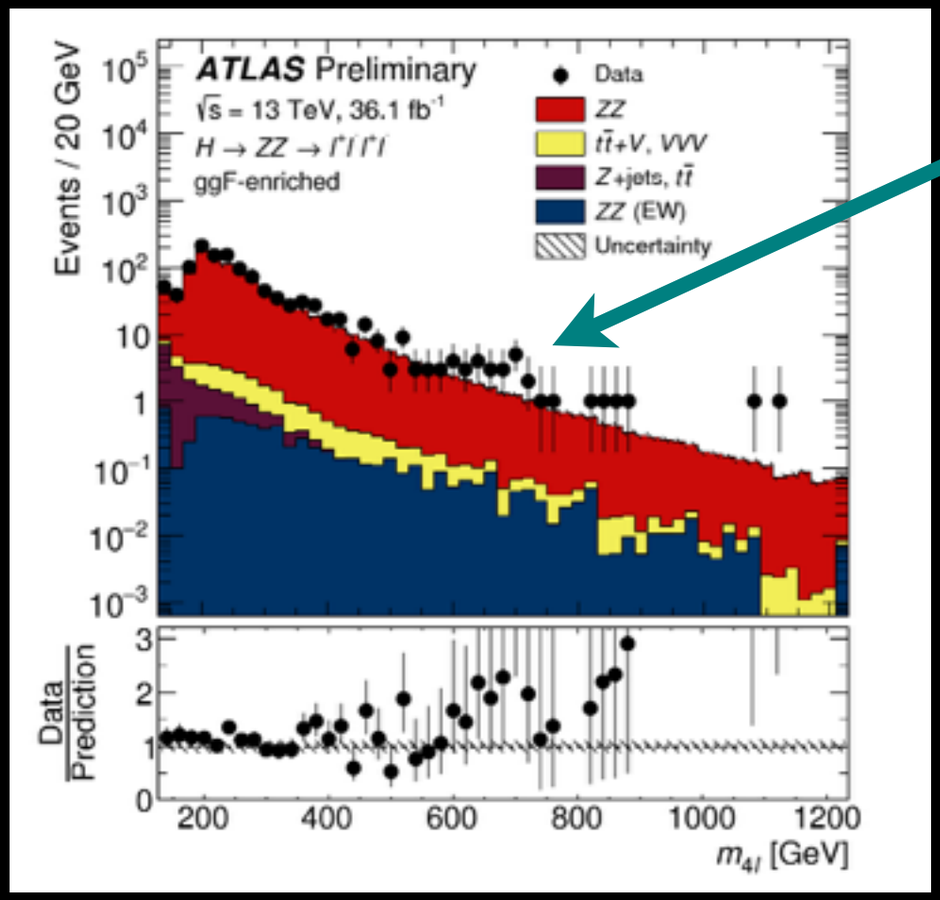
I. Shipsey


Atlantis
YX Projection
Y (cm)
10
0
-10
ATLAS
PIX
SCT
TRT
IDE
LAR
TIL
MDT
RPC
TGC
CSC
MUON
CIC
EXT
TDQ
LHC
FWD
SAFETY
DCS BE

June 2015

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



?

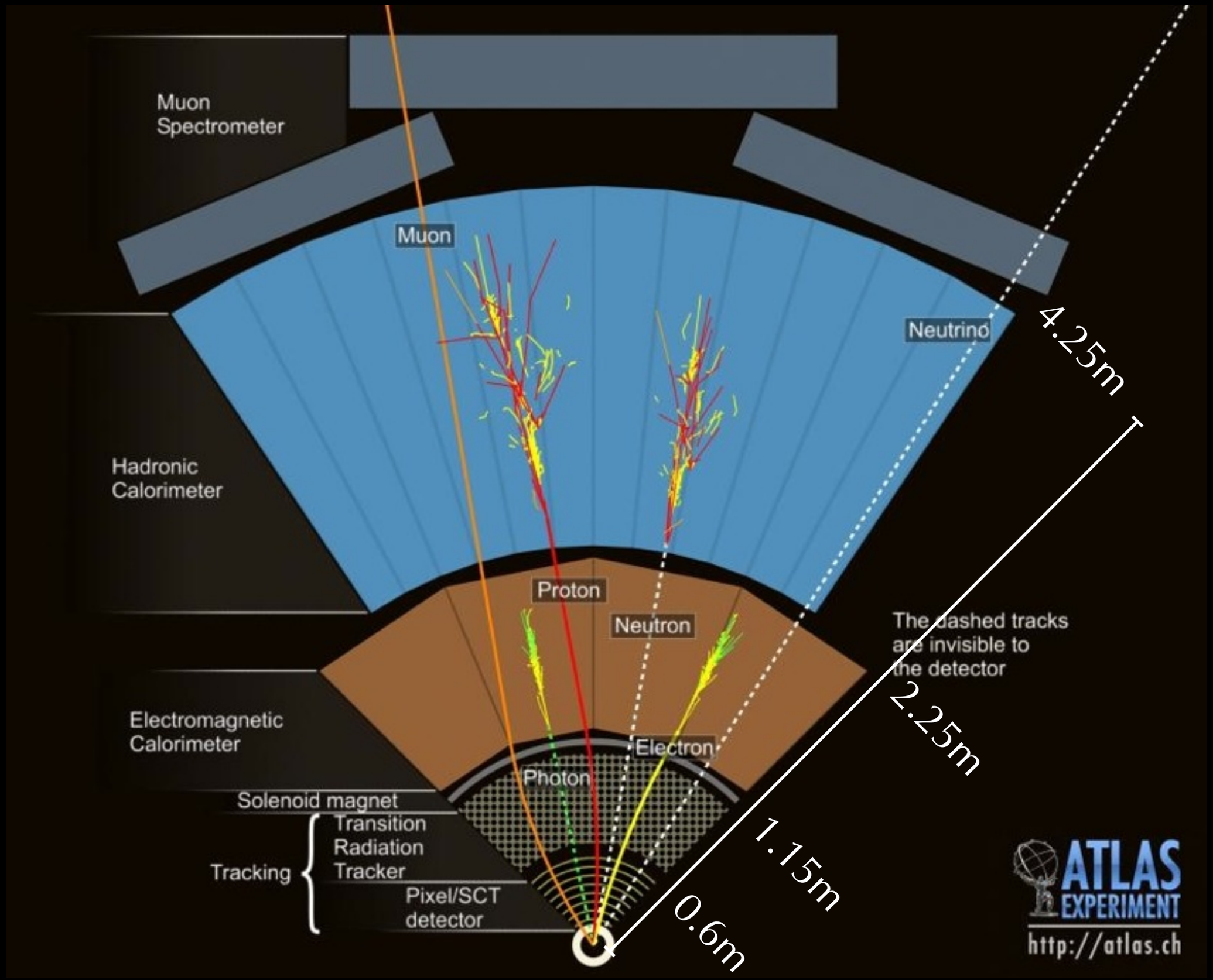
There are no more guarantees and no ace-in-the-hole motivations.

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

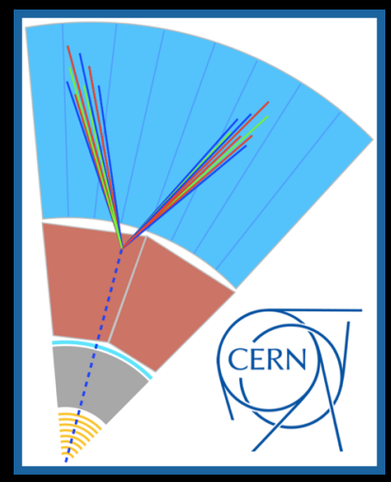
We would certainly love some old-school theoretical guidance, but we don't really have it (WIMP miracle in tension, lack of plain vanilla SUSY, etc.)

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

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



New physics X at the LHC



The overwhelming majority of the work of LHC experimentalists

A relatively few intrepid explorers doing inventive things with long-lived particle signatures

Stable

m_X

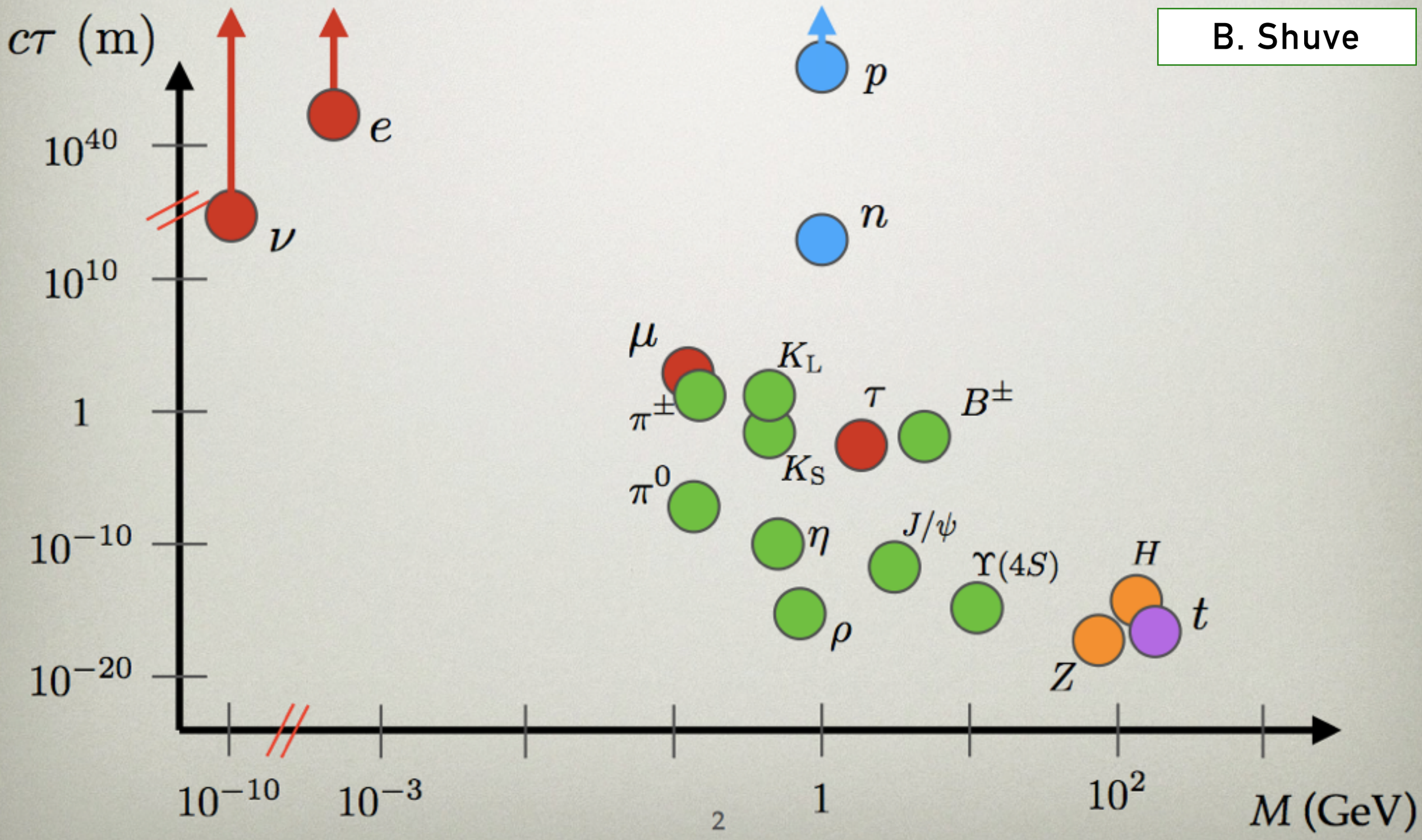
$\mathcal{O}(mm)$

$c\tau_X$

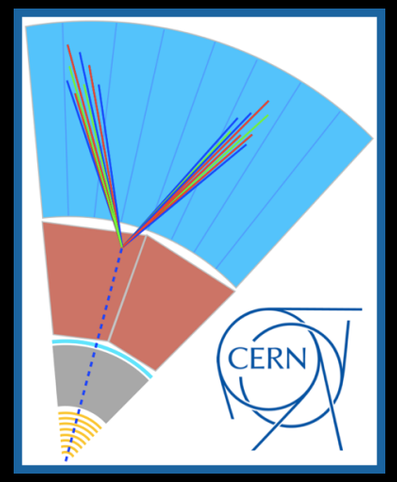
Outer edge of detector

The lifetime frontier

B. Shuve

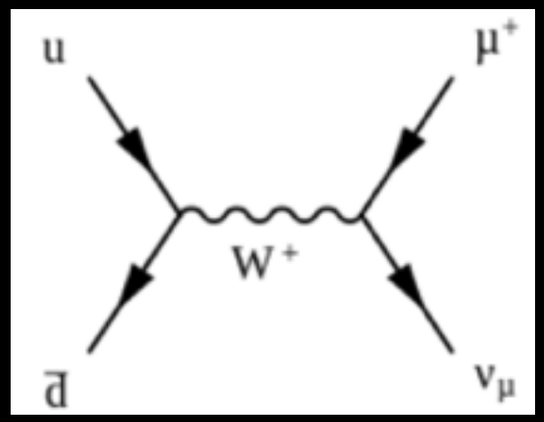


LLPs — SM and BSM



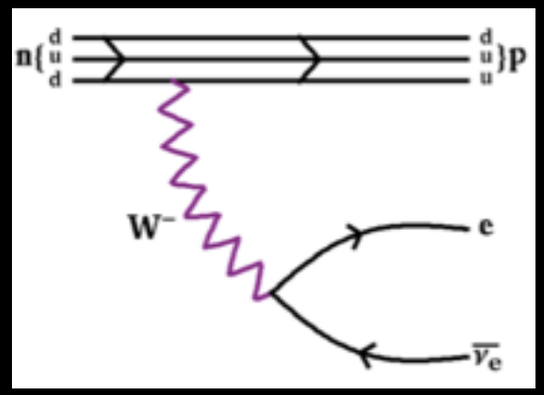
Long lifetimes typically arise in the SM when approximate symmetries make the particle stable

Small symmetry-breaking parameters can suppress the decay rate



Charged pion

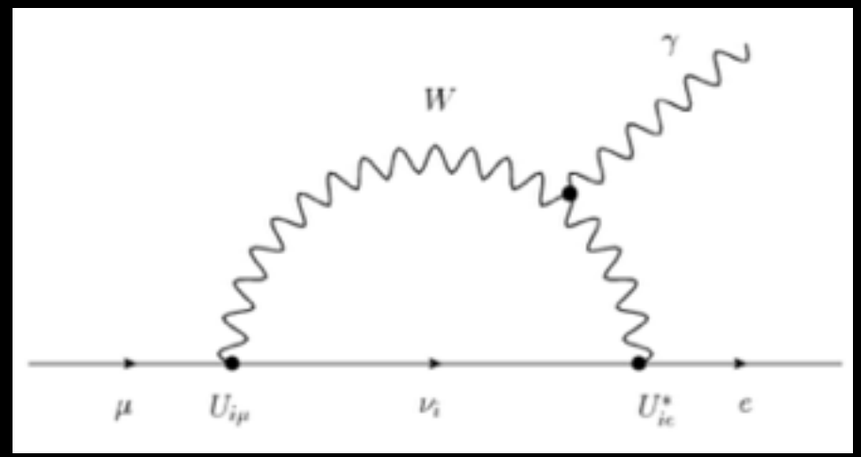
Decay highly off-shell



Neutron

Isospin: p and n nearly degenerate

Decay highly off-shell



FCNC

Lepton flavor violated only by extremely small neutrino Yukawas

BR(μ—>ey)~10^{-54}

Same principles apply to BSM LLPs, which can generically appear

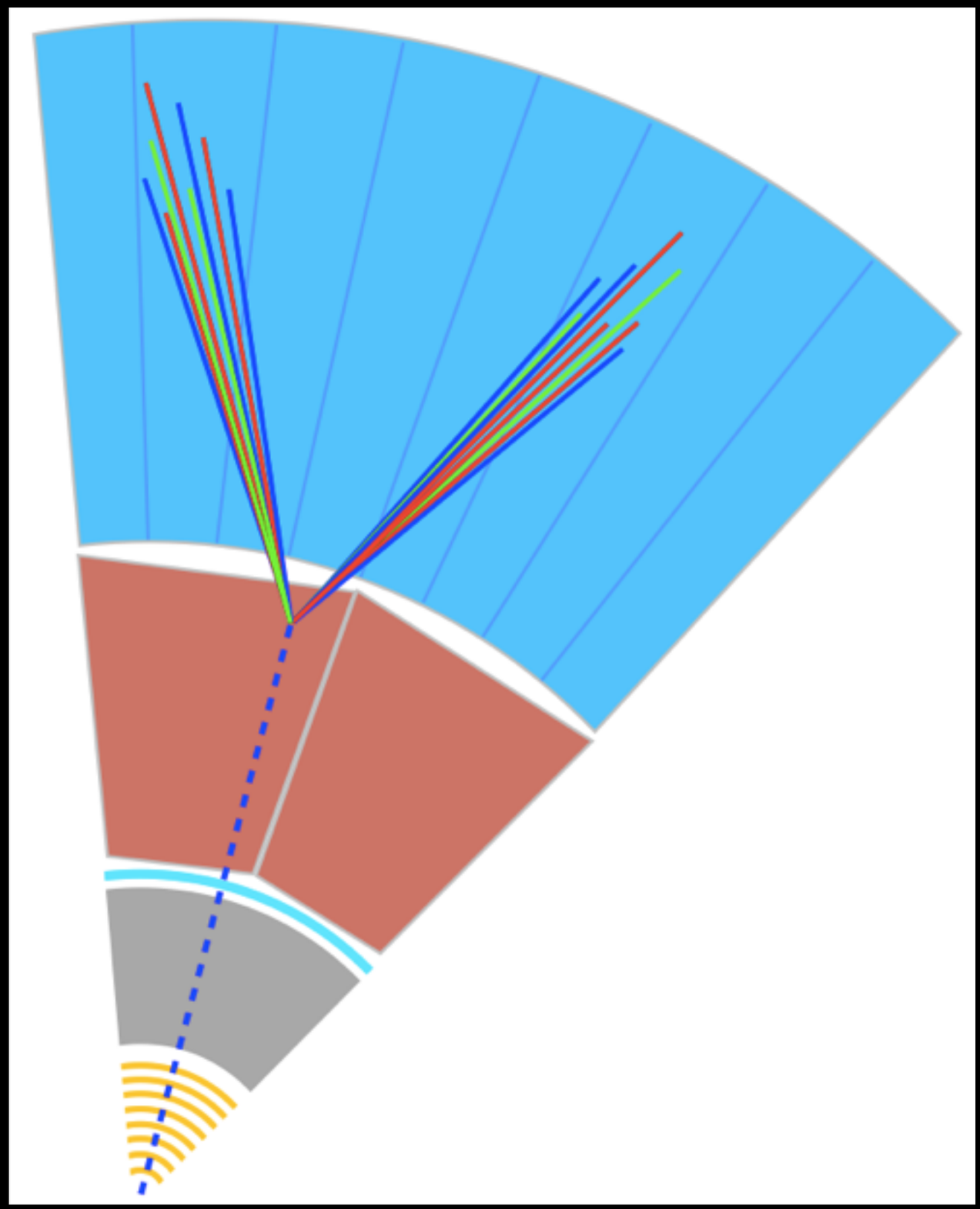
- Lifetime is usually best treated as a free parameter
- A few canonical example BSM classes that yield LLPs

Talks by Strassler, Knapen, Shuve, others

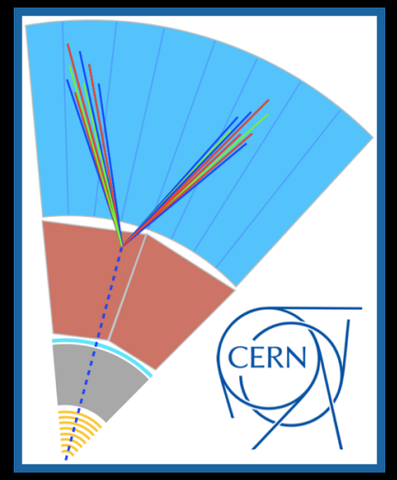
The lifetime frontier at the LHC

Long-lived particle searches are experimentally driven

Luckily it's easy to get LLPs in our usual BSM frameworks — a few examples here

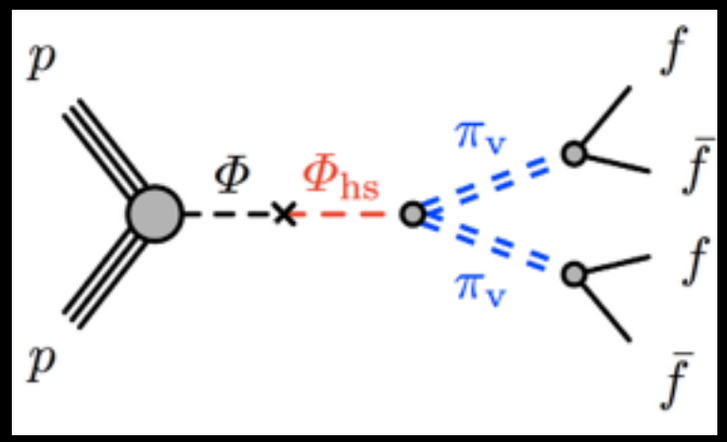


BSM example: Hidden sector portals

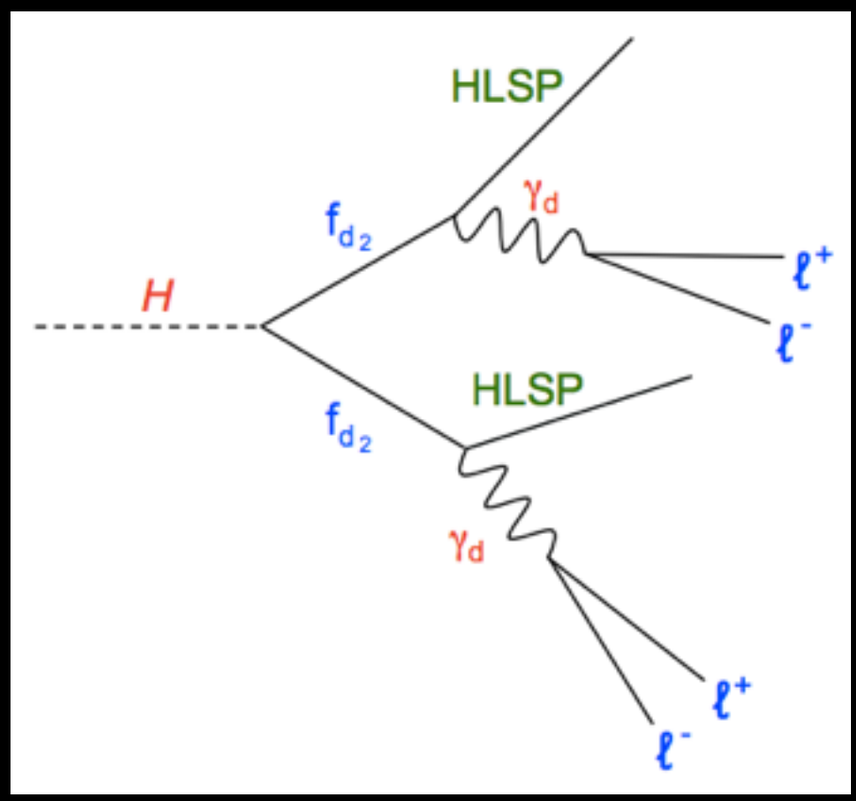


Higgs portal

- Small width of h125 —> easy to get BSM physics
- A wide range of LLP signatures can arise



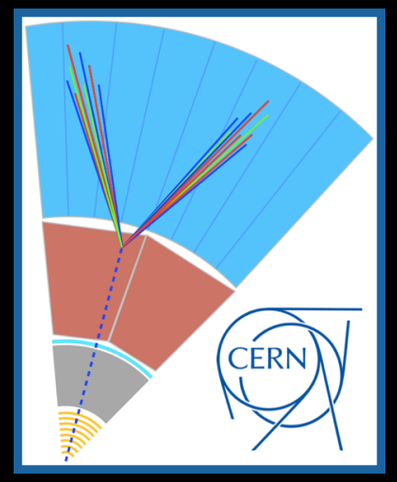
Higgs mixing with hidden sector scalar



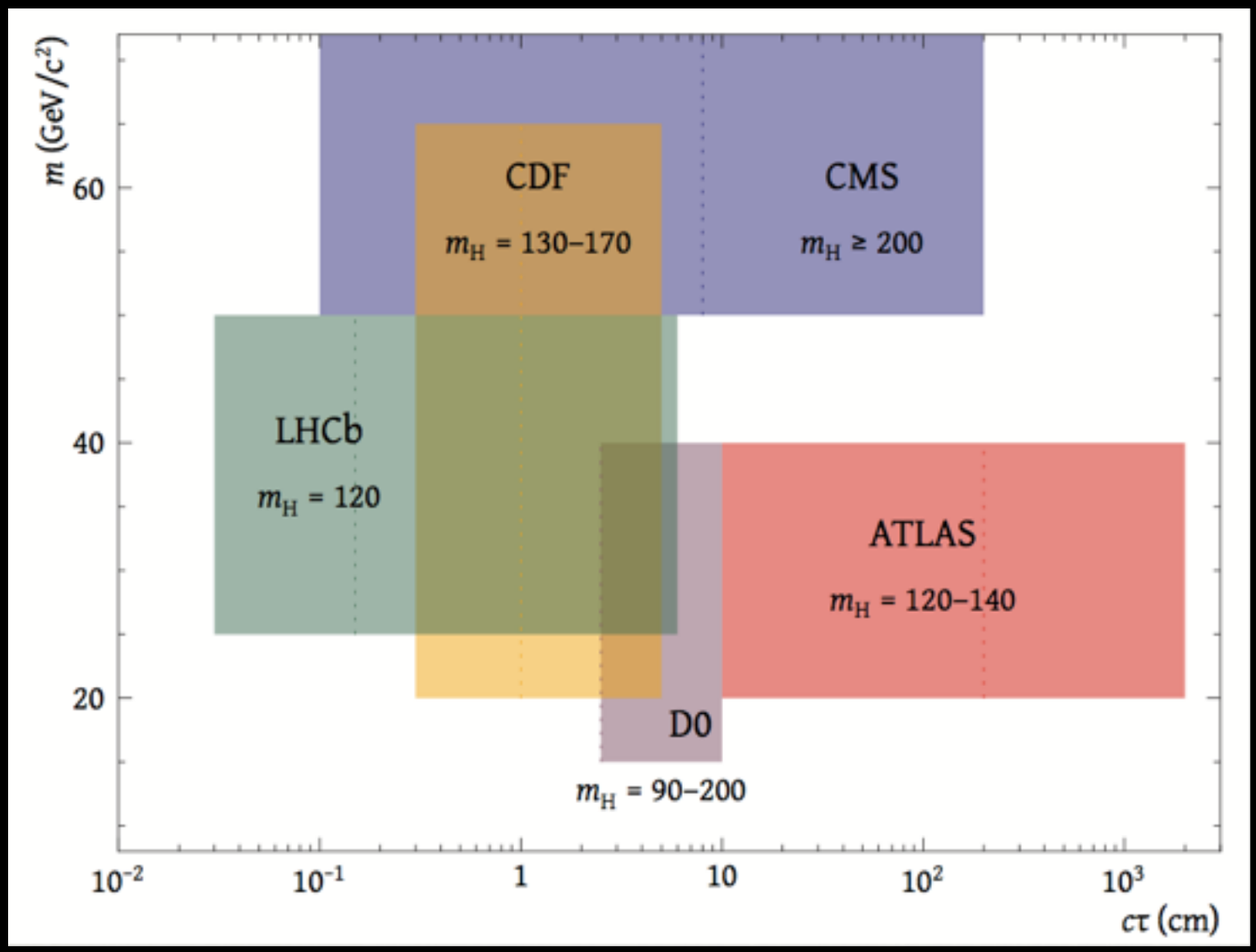
Higgs decaying to dark sector fermions which decay to dark photons and lepton-jets

- Can use Higgs VBF and associated production modes for triggering on additional prompt objects

BSM example: Hidden sector portals

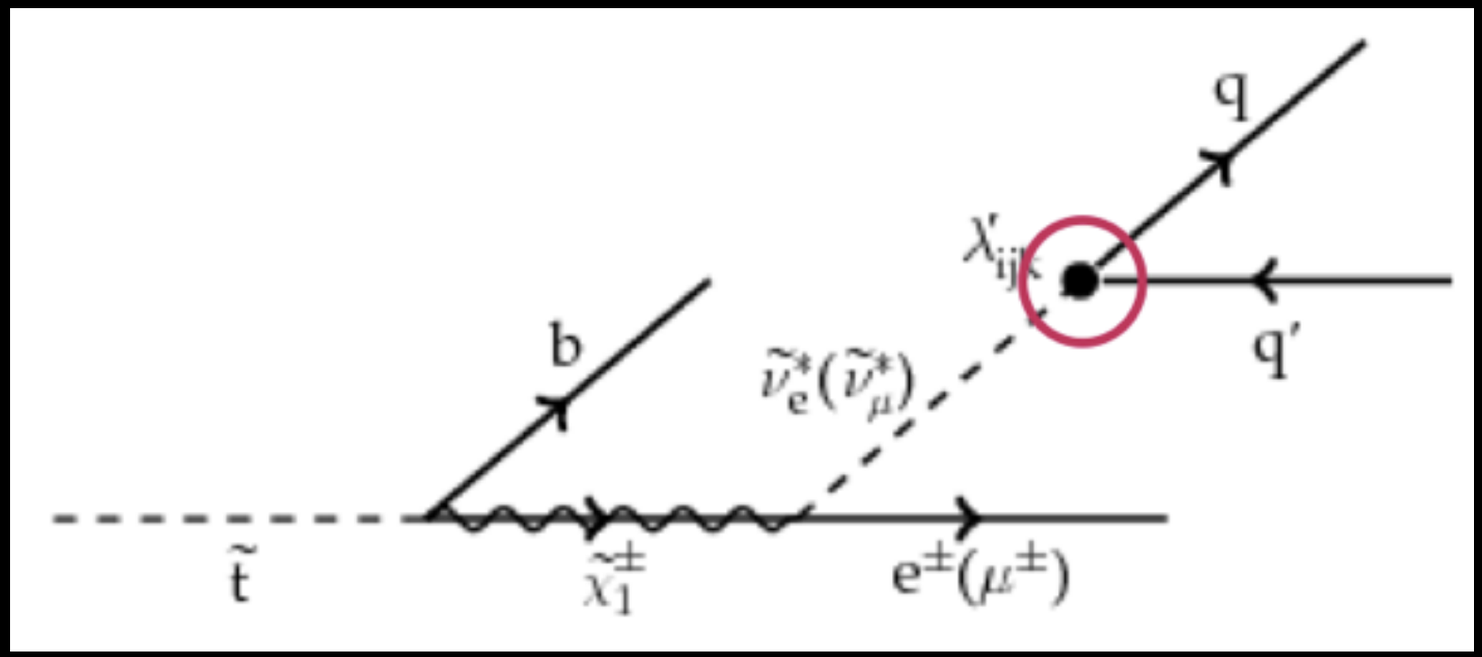


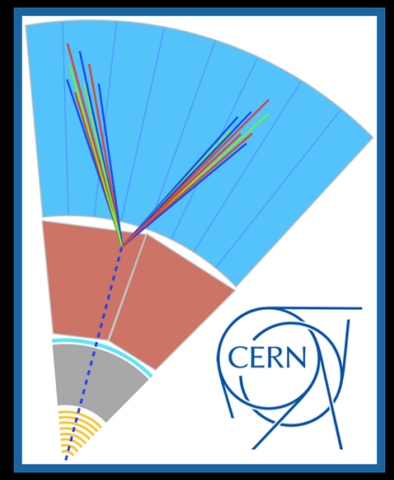
Higgs portal is also good for comparison among experiments



Pieter David thesis, LHCb, 2016

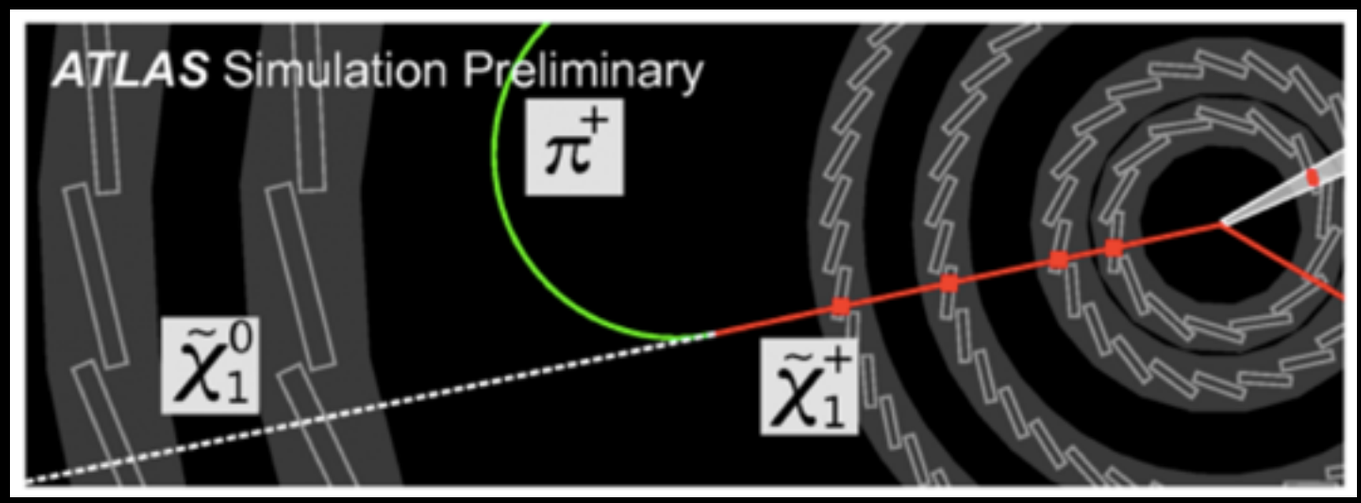
BSM example: RPV SUSY



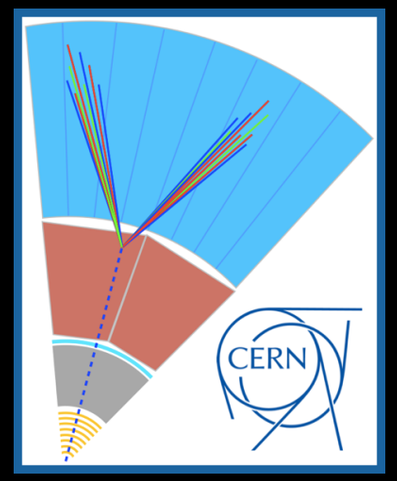


$|\lambda| < 10^{-8}$

Electroweak symmetry gives degeneracy of NLSP and LSP masses if little mixing between Higgsino / gauginos



Experiment-focused approach



LLPs can be a generic feature of BSM ideas

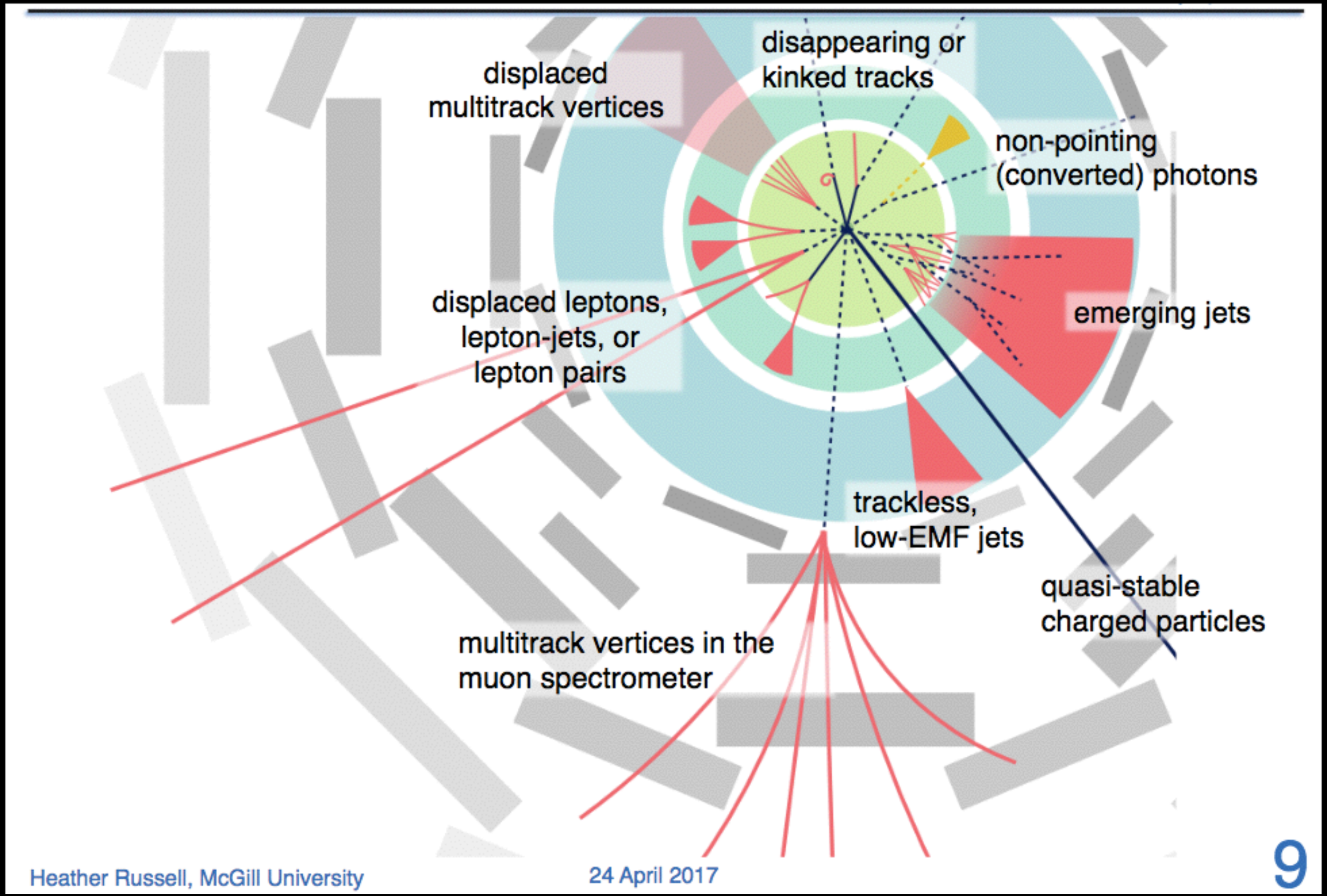
- Lifetime is usually best treated as a free parameter
- No clear old-school preferential motivations w.r.t. production and decay modes

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.

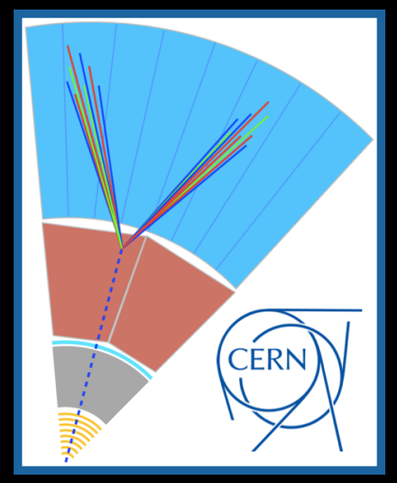
This is the fun part.

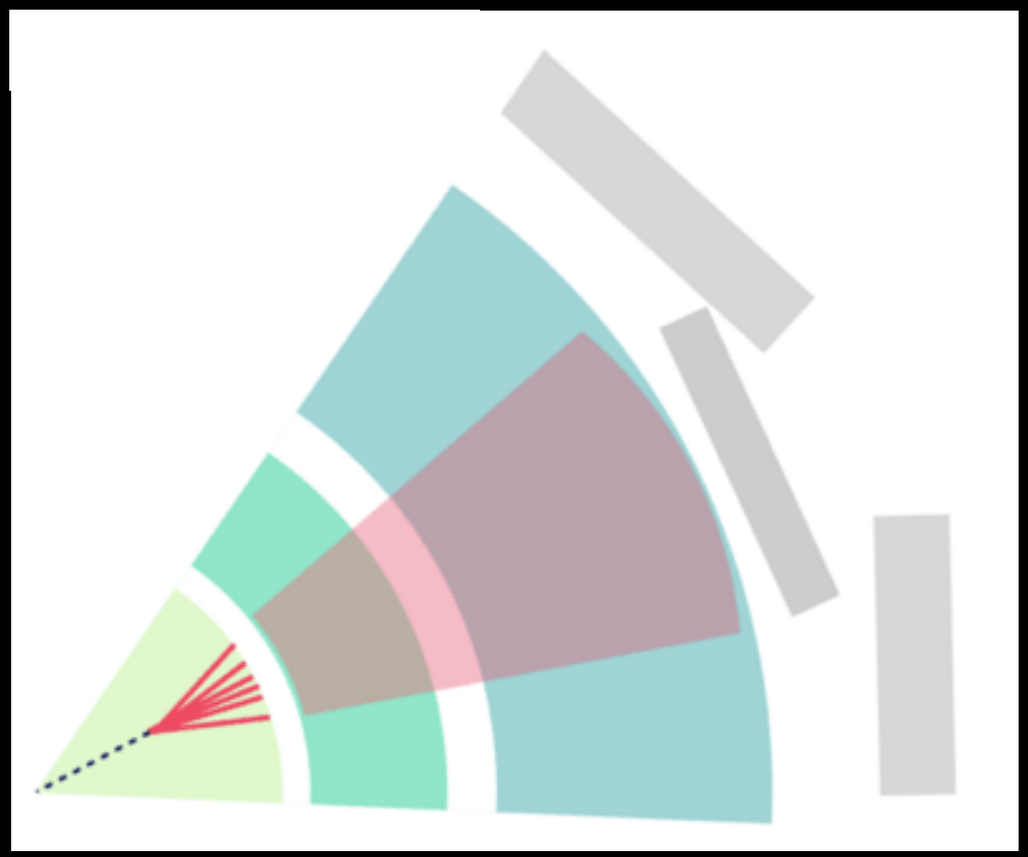
Challenges of LHC LLP searches



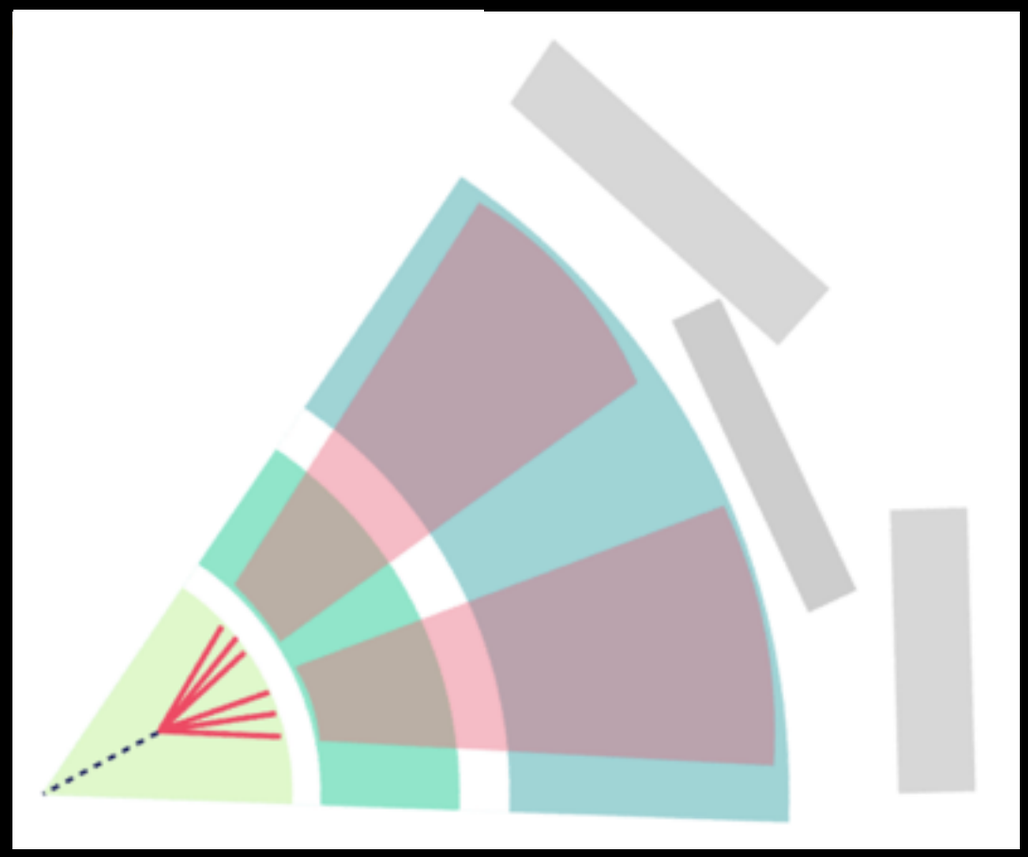
Displaced hadronic jets

The LLP can decay to jets in the inner tracker





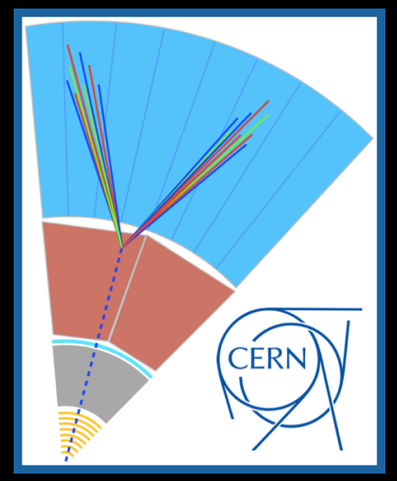
ATLAS approach — single multi-track vertex



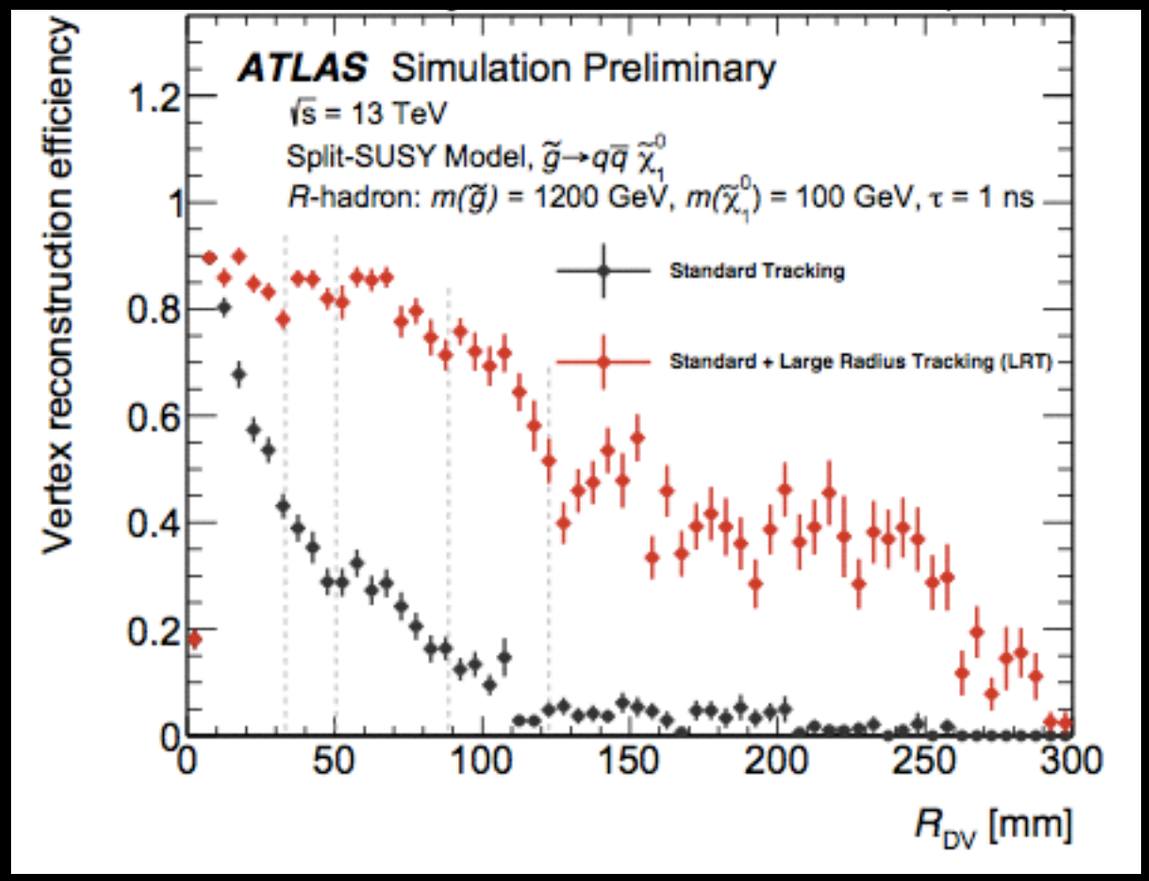
CMS and LHCb — displaced vertices with jet pairs downstream

Displaced hadronic jets

The LLP can decay to jets in the inner tracker

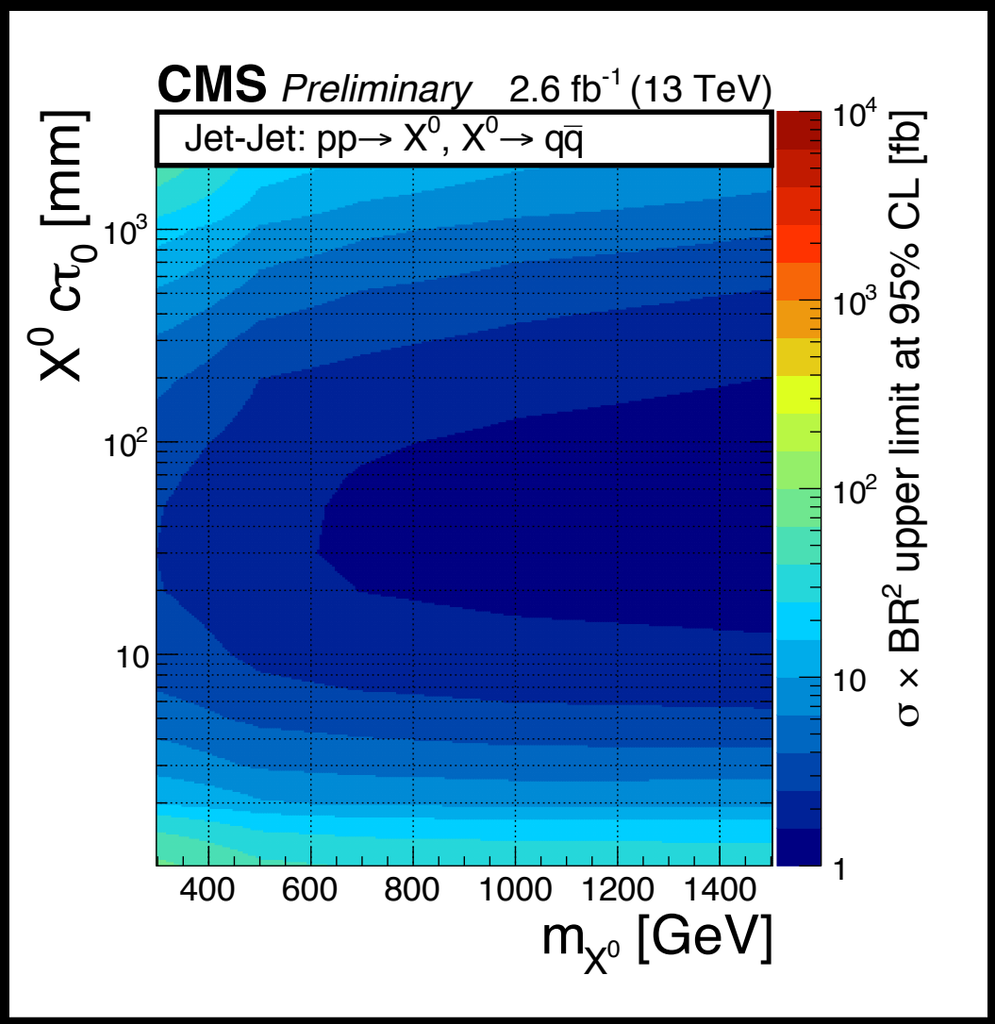


Phys. Rev. D 92, 072004 (2015)



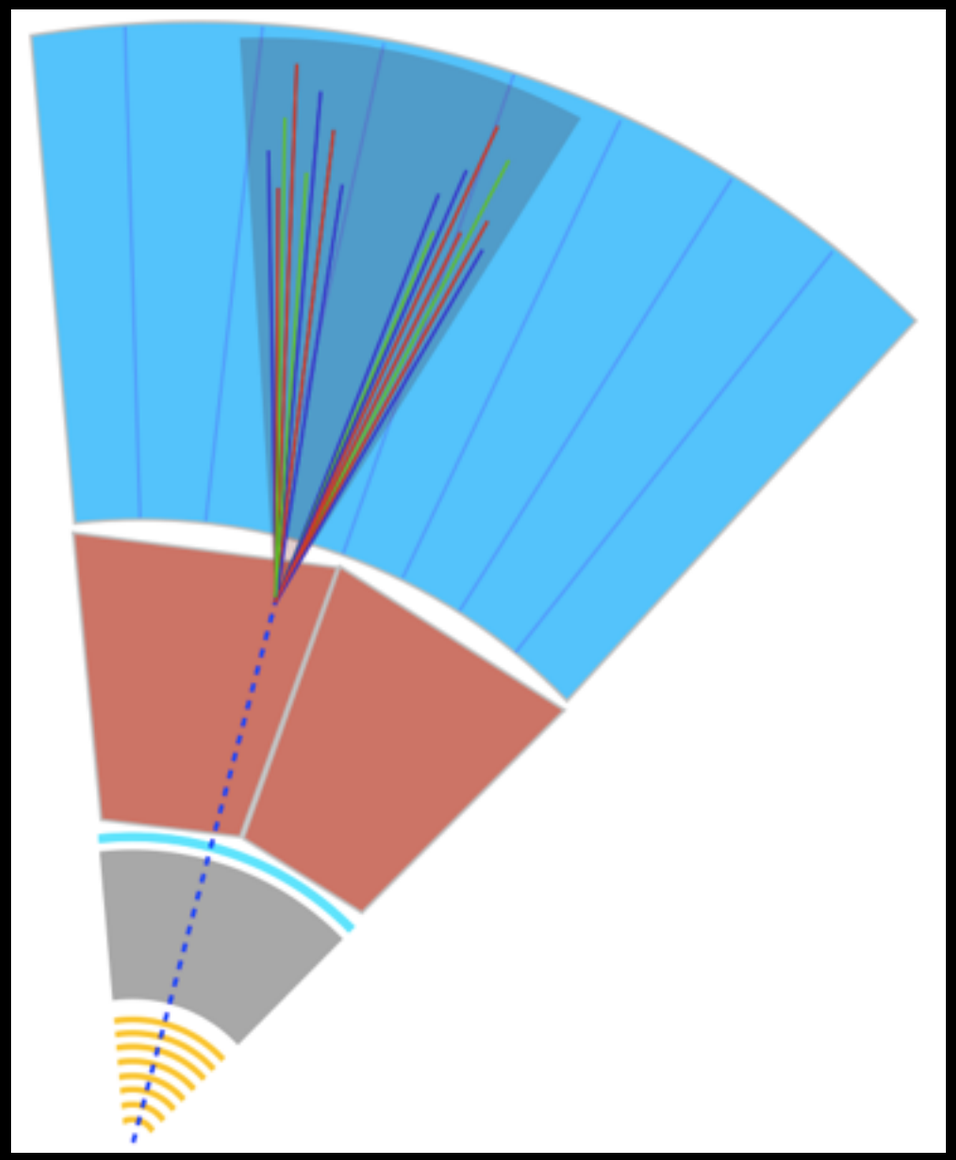
Trigger on MET

CMS-PAS-EXO-16-003

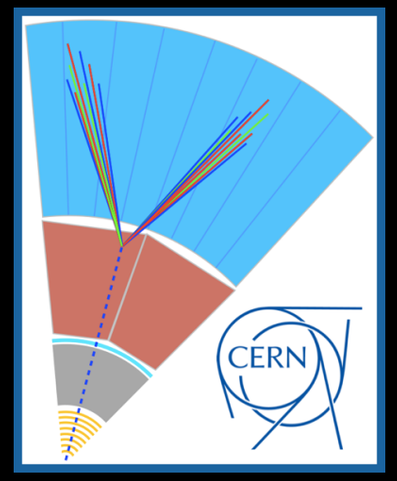


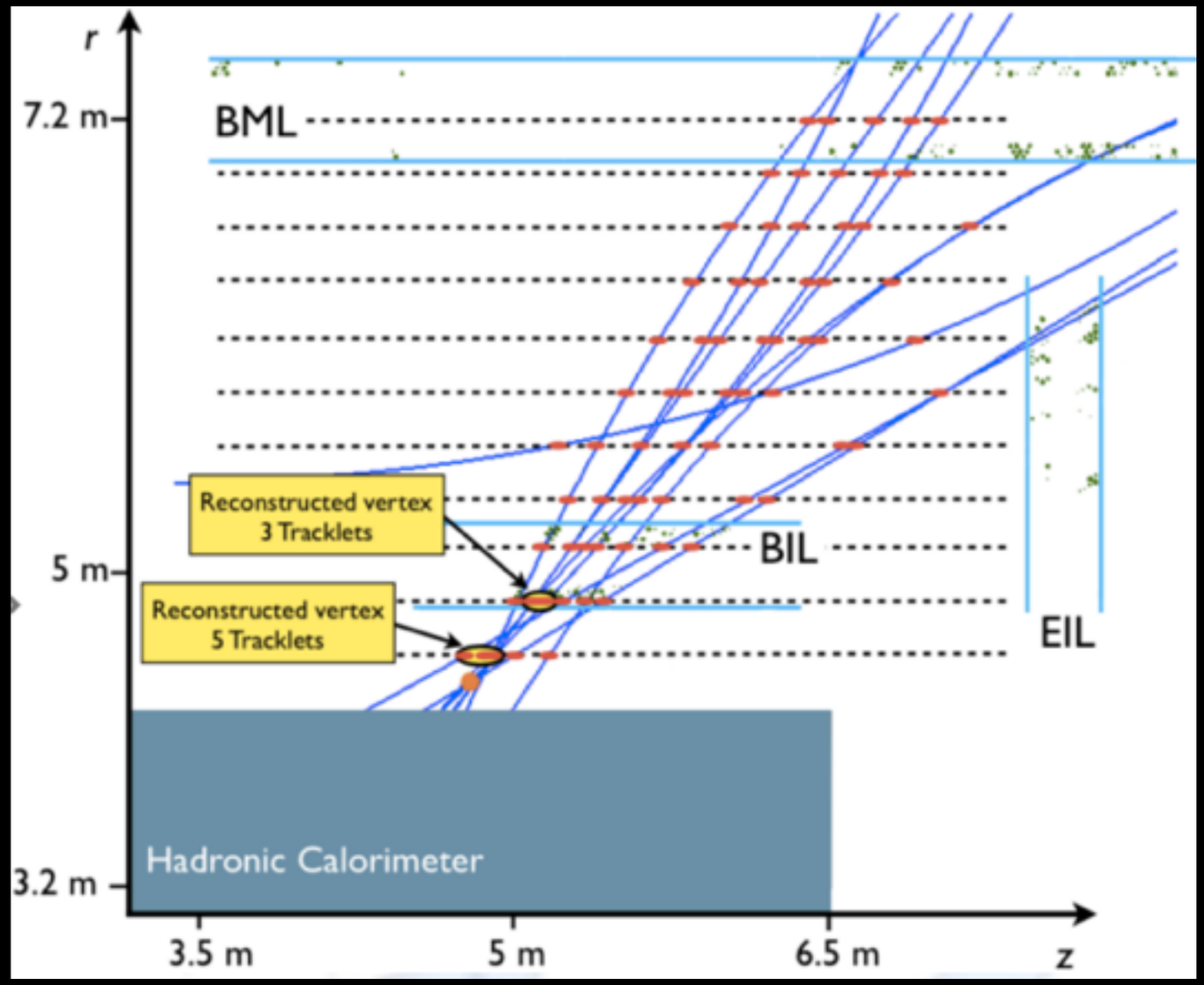
Specialized HT trigger with track veto

Displaced hadronic jets



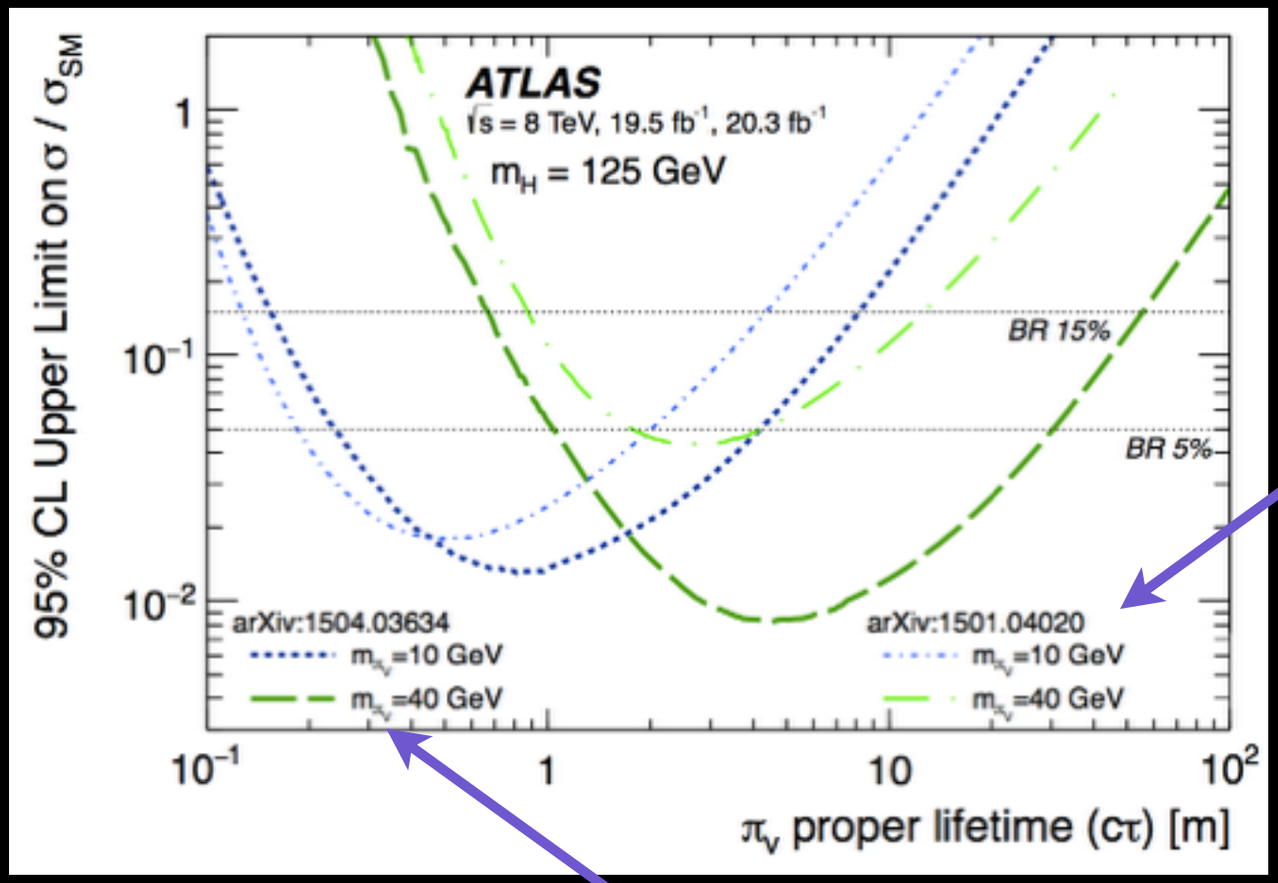
Or the LLP can decay in or just before the calorimeter...

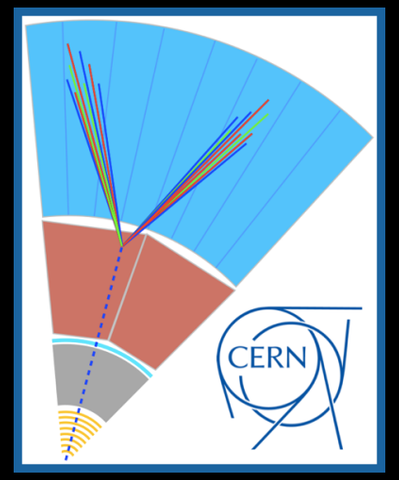




...or only in the MS

Displaced hadronic jets

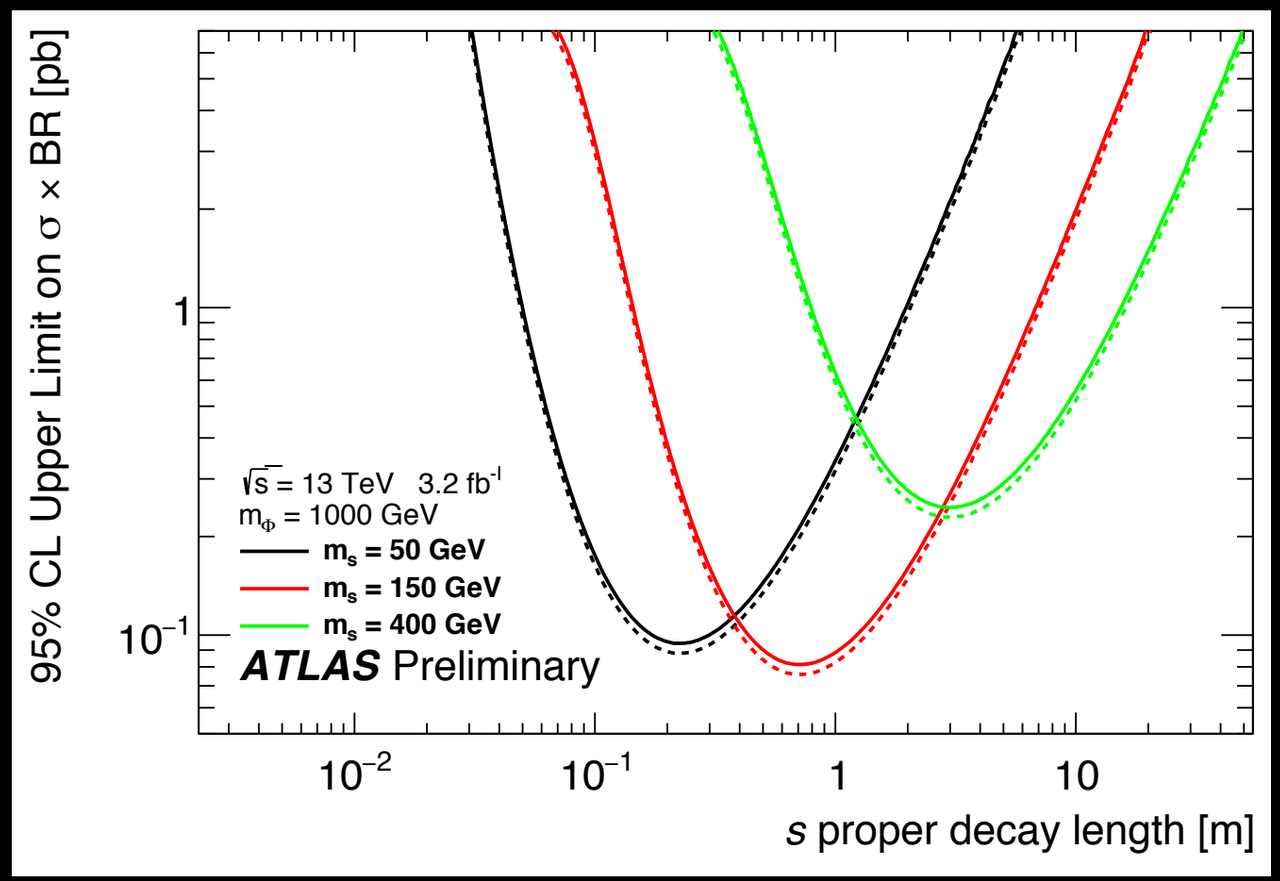




CalRatio

ID/MS

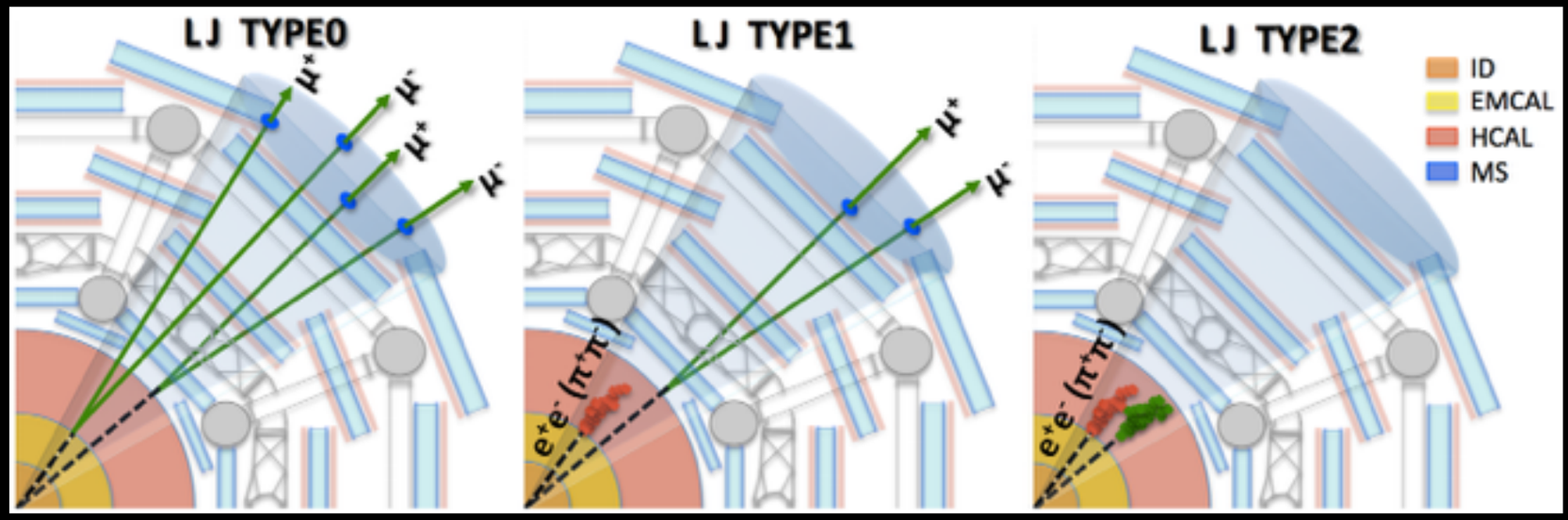
ATLAS-CONF-2016-103

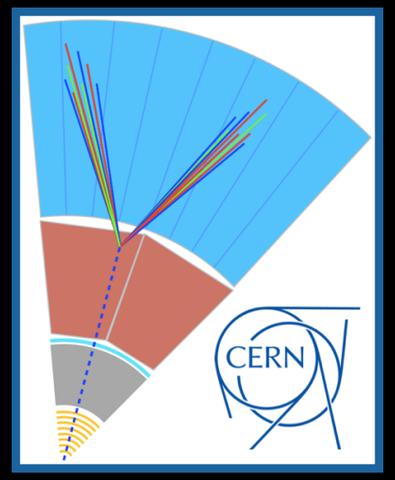


What about for lower LLP masses, for $m_{LLP} / m_X < 5\%$?

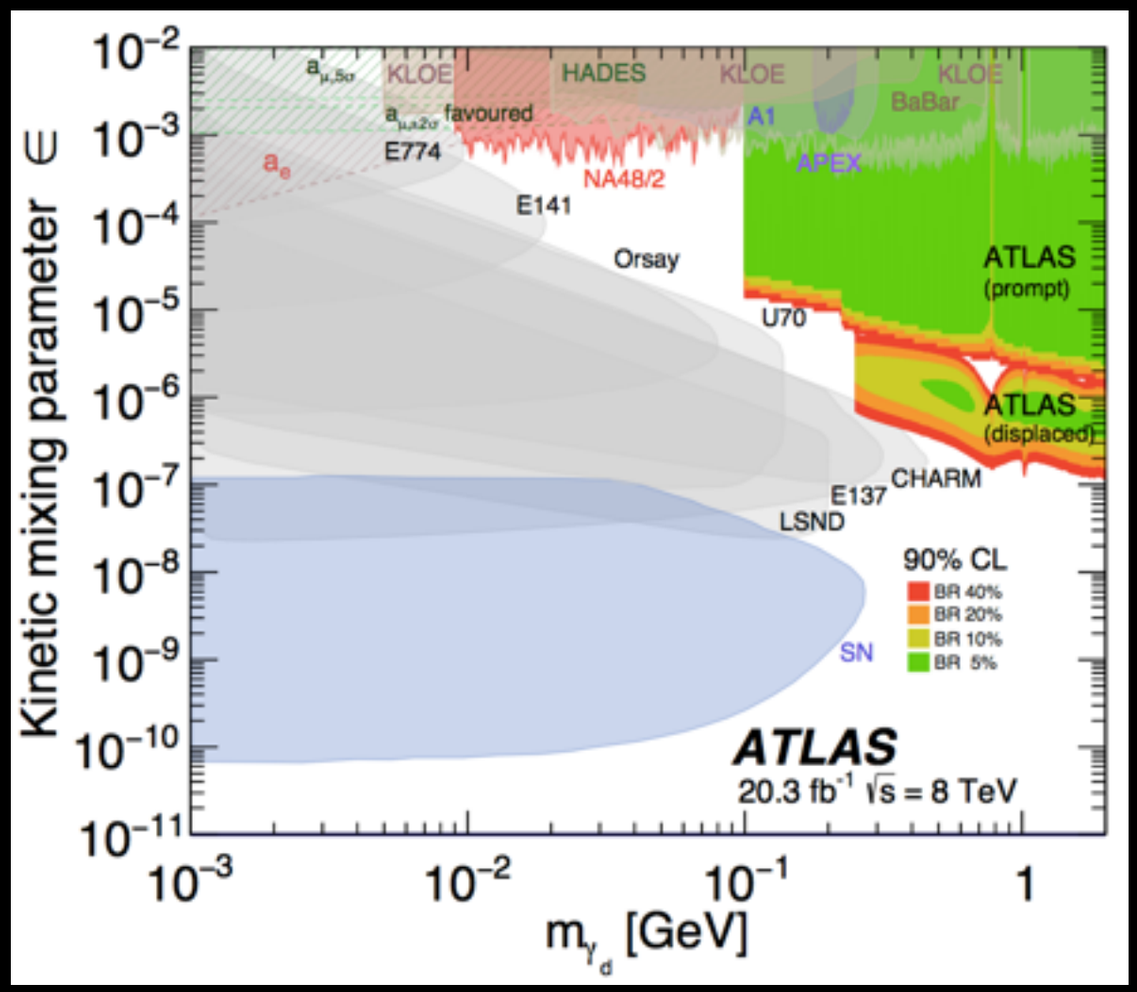
CalRatio for higher-mass scalars

Displaced lepton-jets

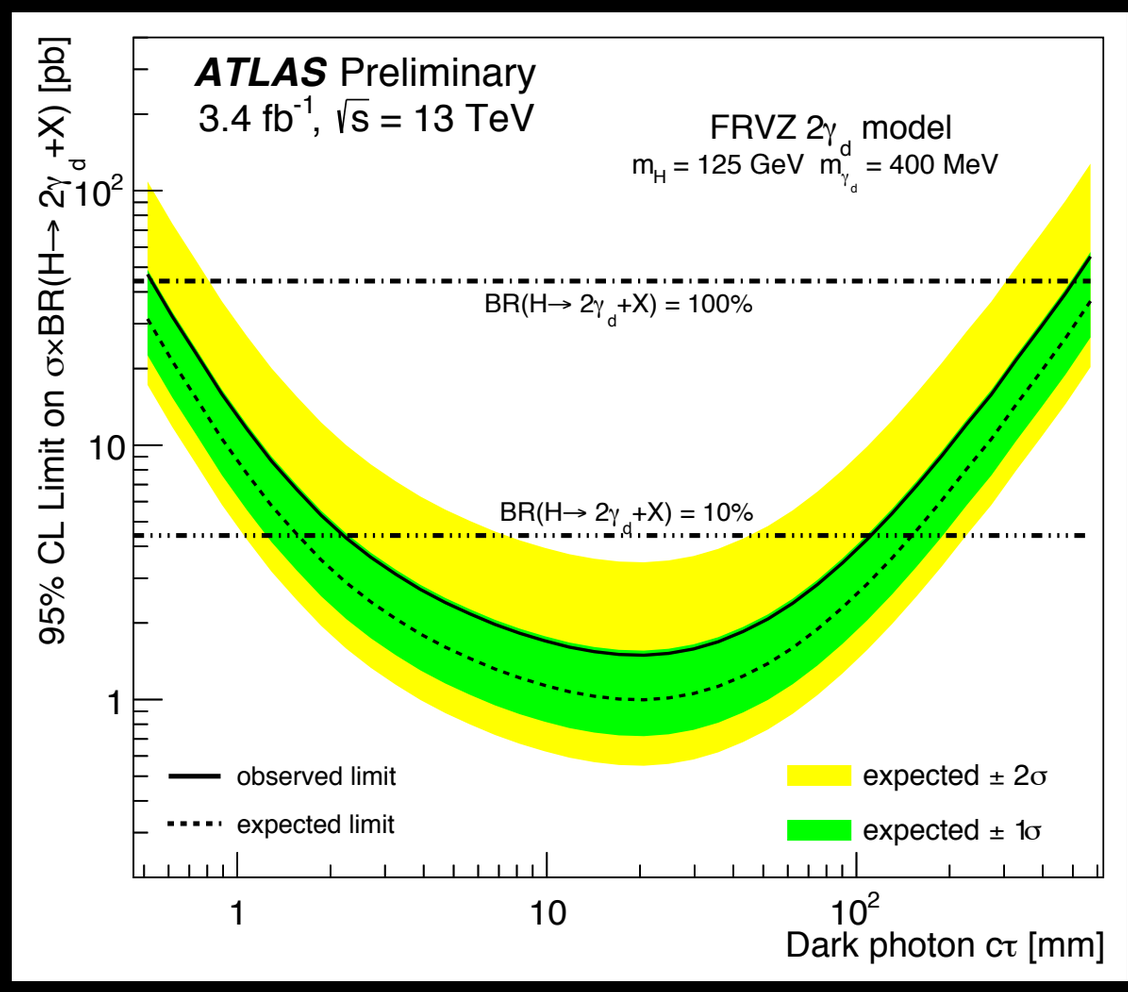




JHEP 1602 (2016) 062



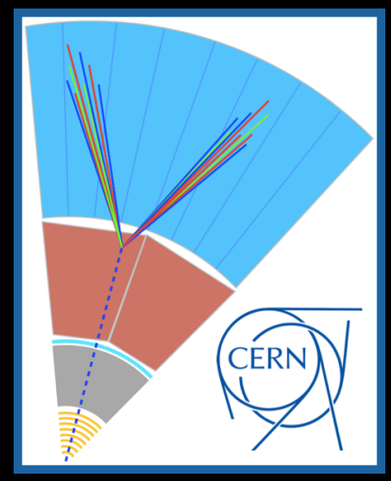
ATLAS-CONF-2016-042



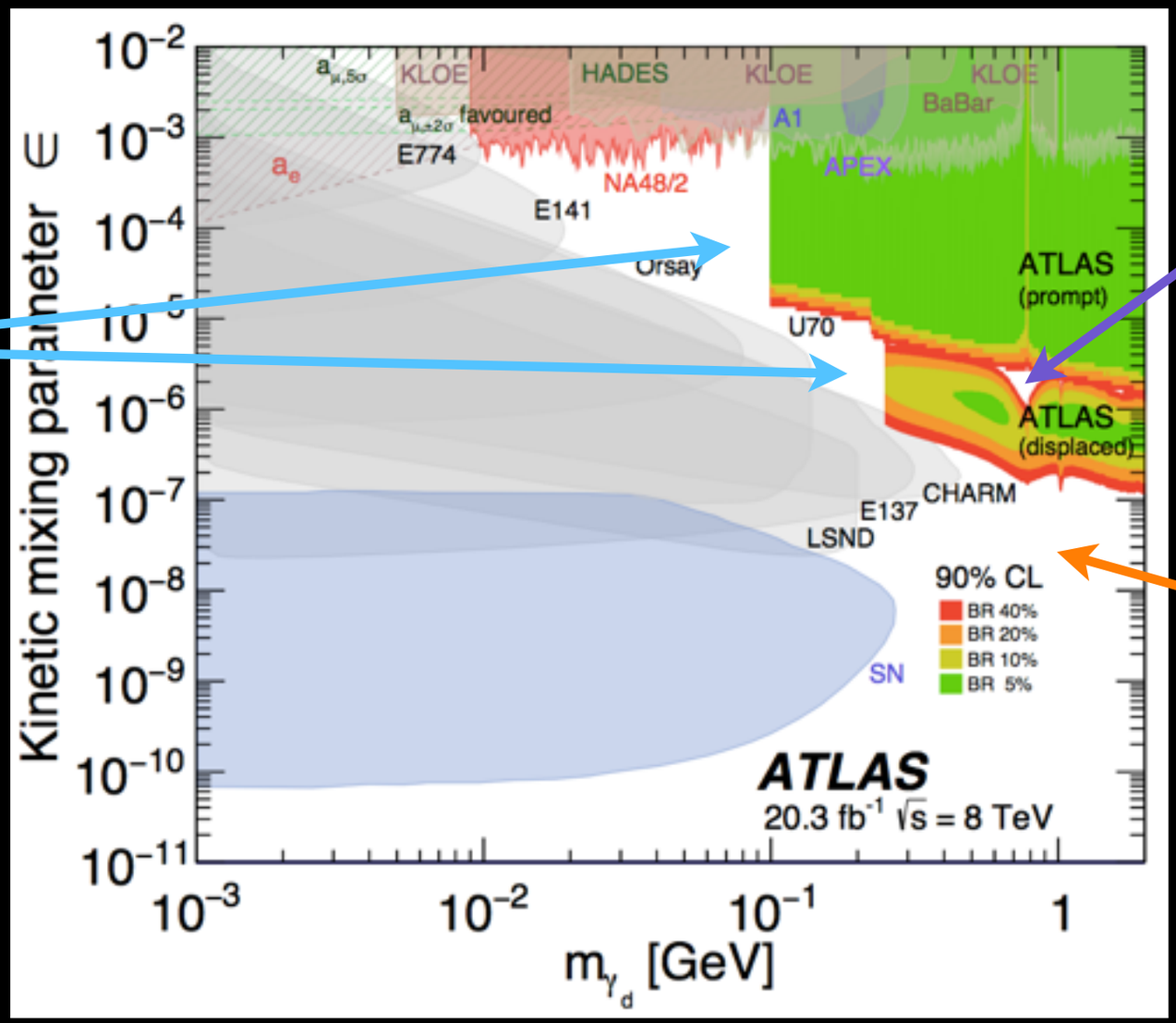
Improving displaced lepton-jets

Displaced lepton-jets

- Clearly apparent gaps where a discovery could be hiding
- Run 2 improvements already made (single LJ trigger, etc.)
- A minimal, flexible model can elucidate gaps



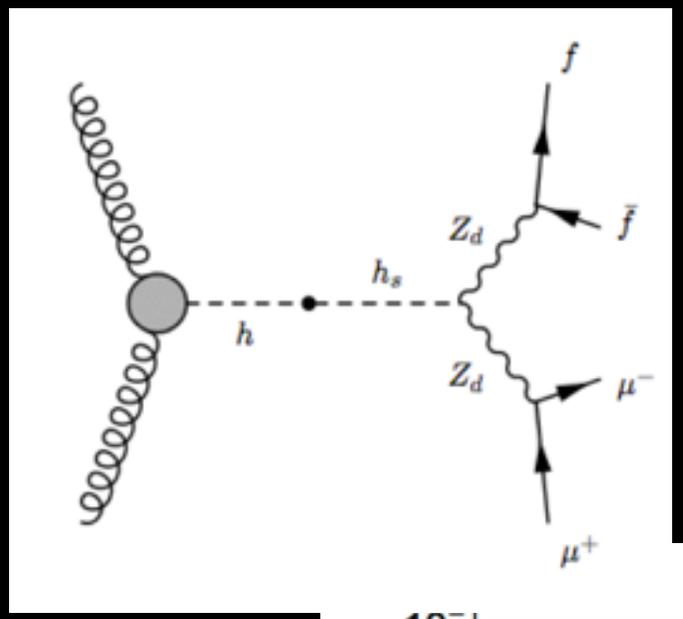
Low-mass: New triggers for non-standard LAr deposits



Mass-gap: Pion-jets

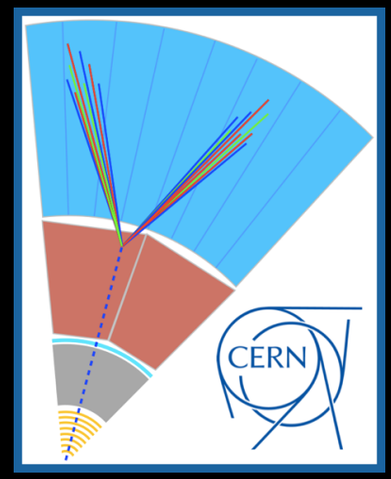
Very-displaced region: Need to trigger on single LLP decays

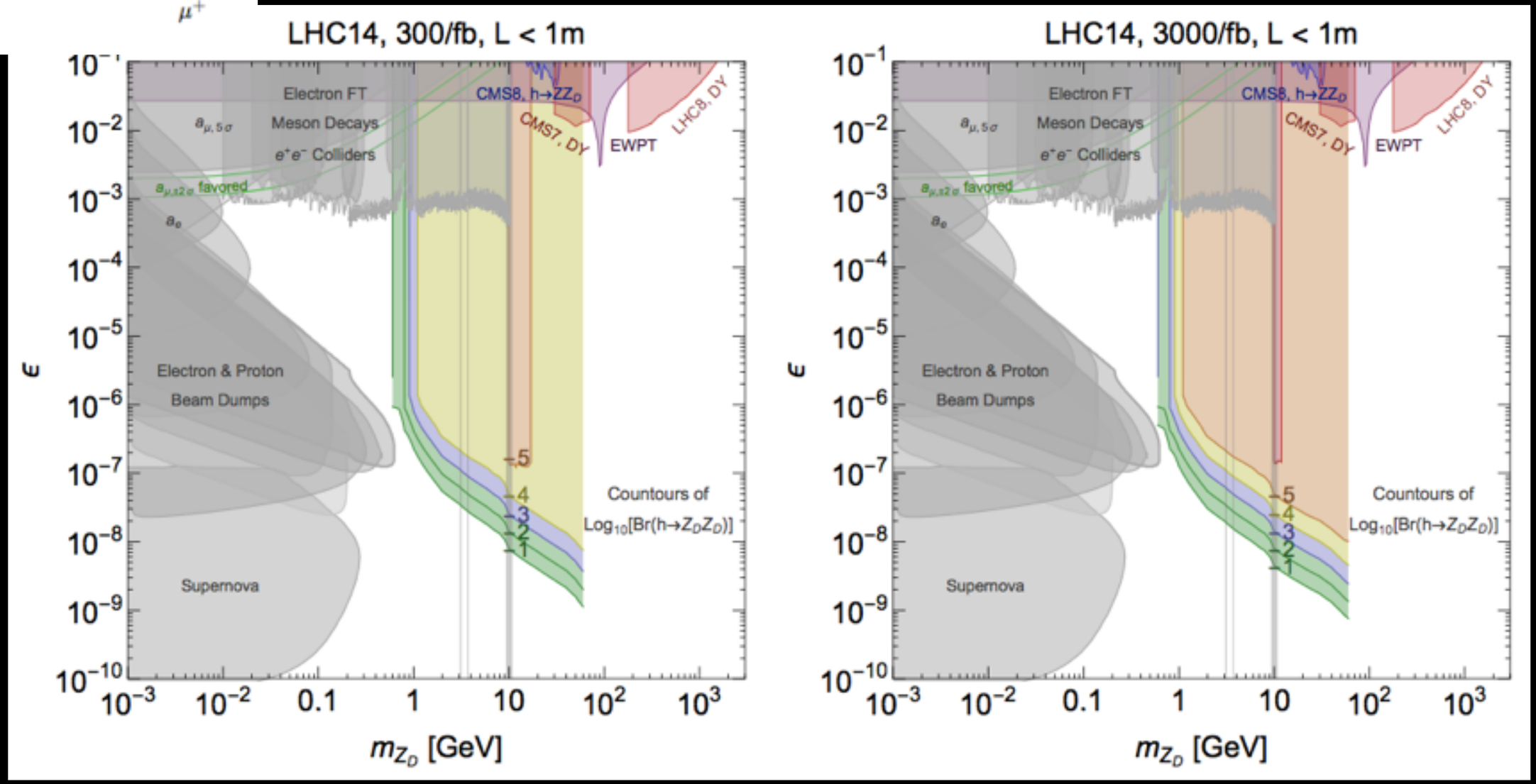
Coming soon: Displaced leptons



Higgs mixing with dark Higgs and subsequent decay to long-lived Z_{dark} pairs

Search underway now in ATLAS using MS-only muons

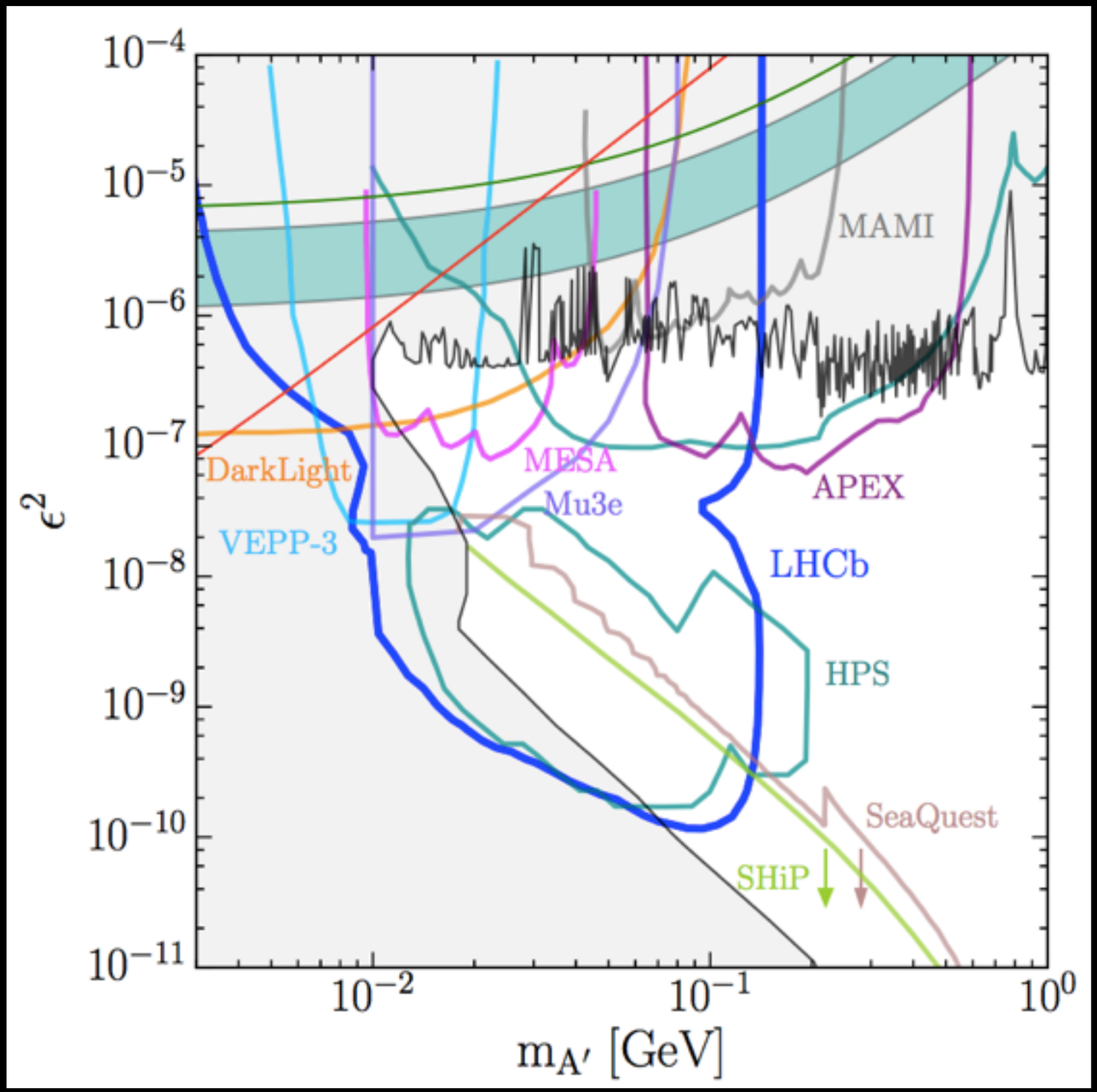




arXiv:1412.0018

On the horizon: Dark photons at LHCb Run 3

arXiv:1509.06765



Hidden gauge boson from charm meson decays

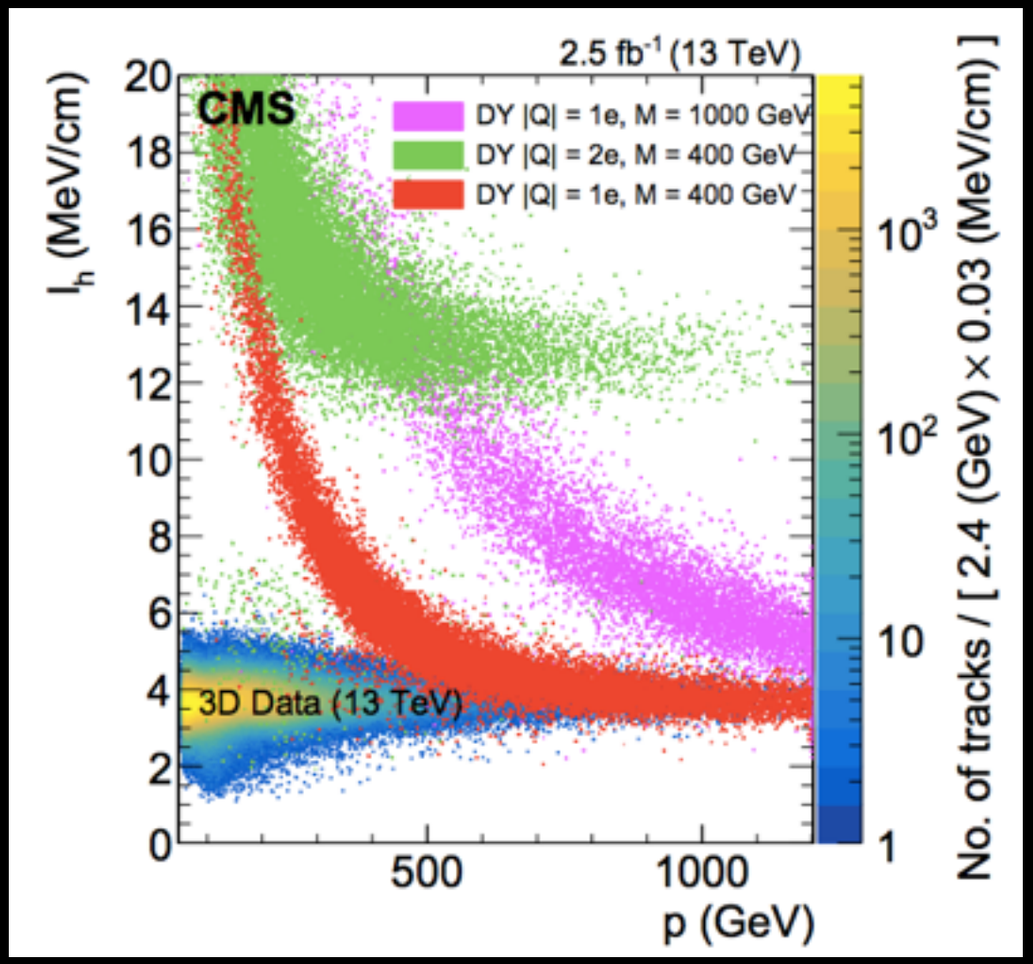
$D^{*0} \rightarrow D^0 \gamma$

Rate in LHCb ~ 700 kHz —> ~5 trillion events in LHC Run 3

Closes (some of) the gap between APEX/HPS resonance search and vertexing searches

What we do: Charged LLPs

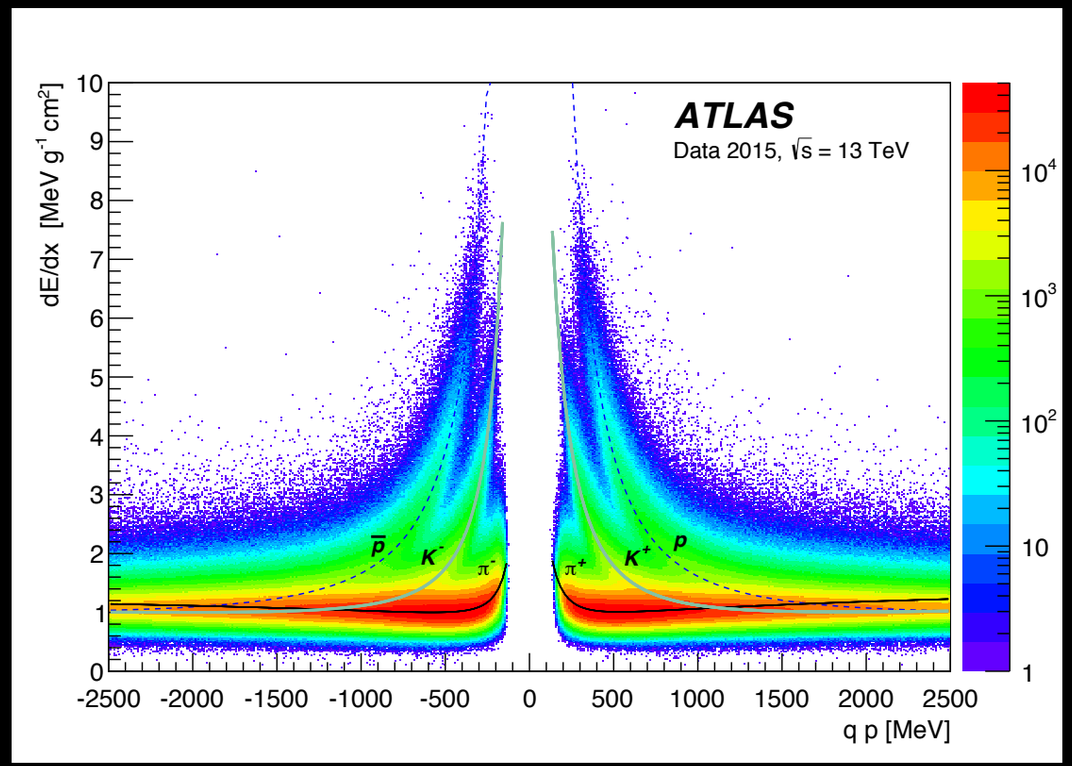
Phys. Rev. D 94, 112004 (2016)



Estimator of dE/dx in pixels and silicon tracker

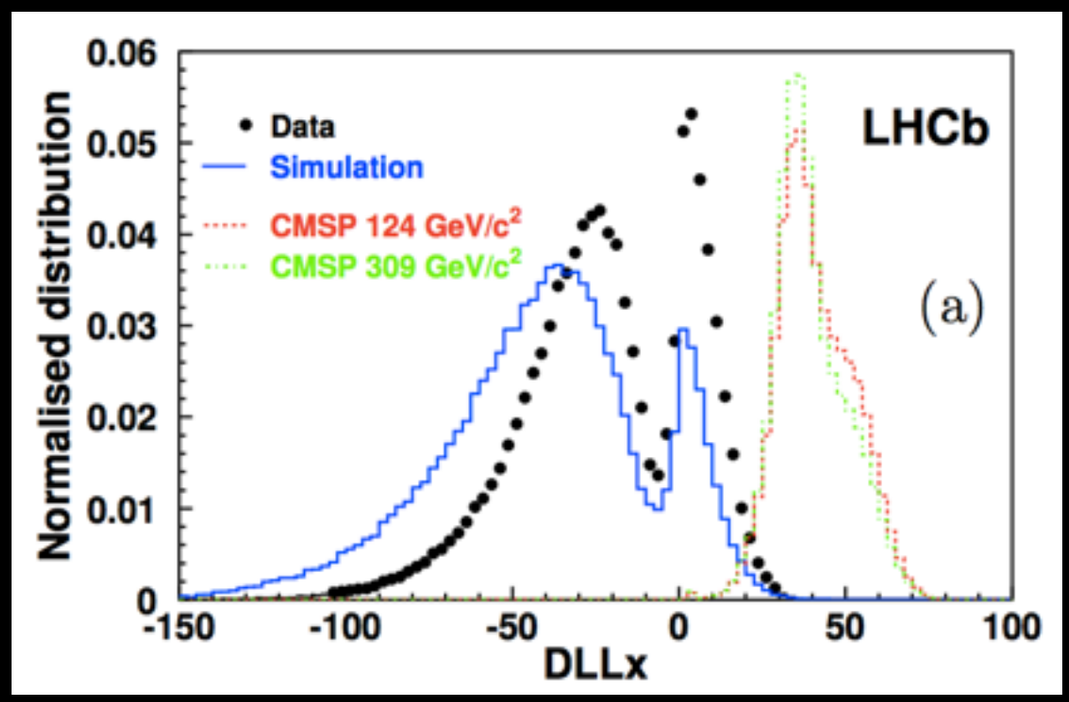
How to get to lower masses?

Phys. Rev. D 93, 112015 (2016)

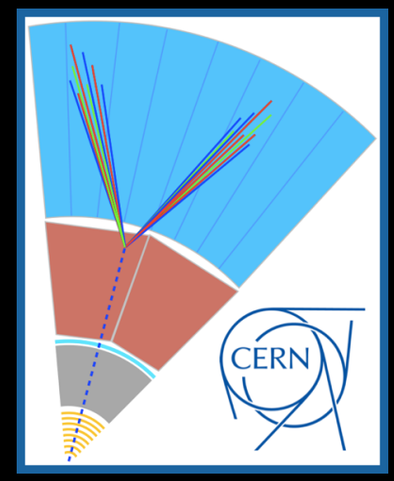


Measure of lack of Cherenkov radiation

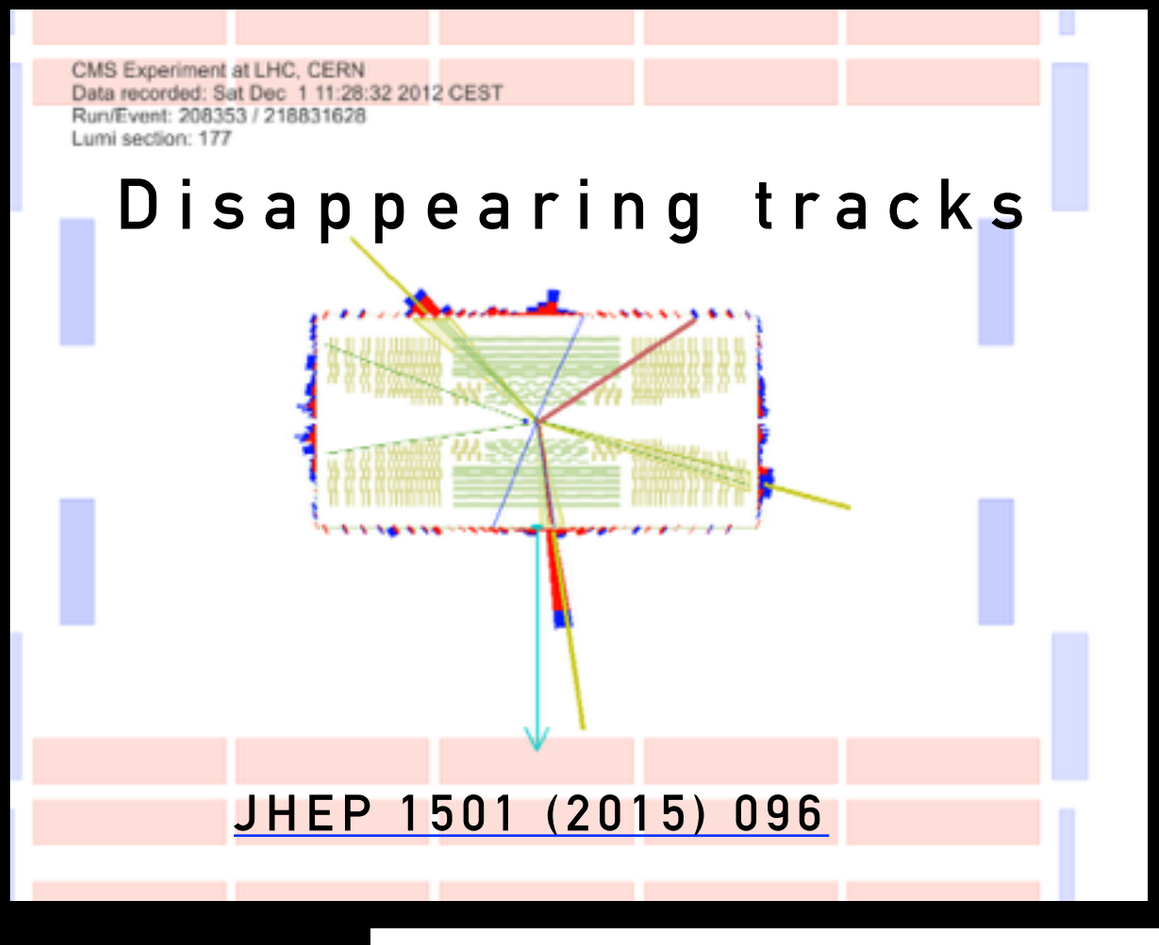
Eur.Phys.J. C75 (2015) no.12, 595



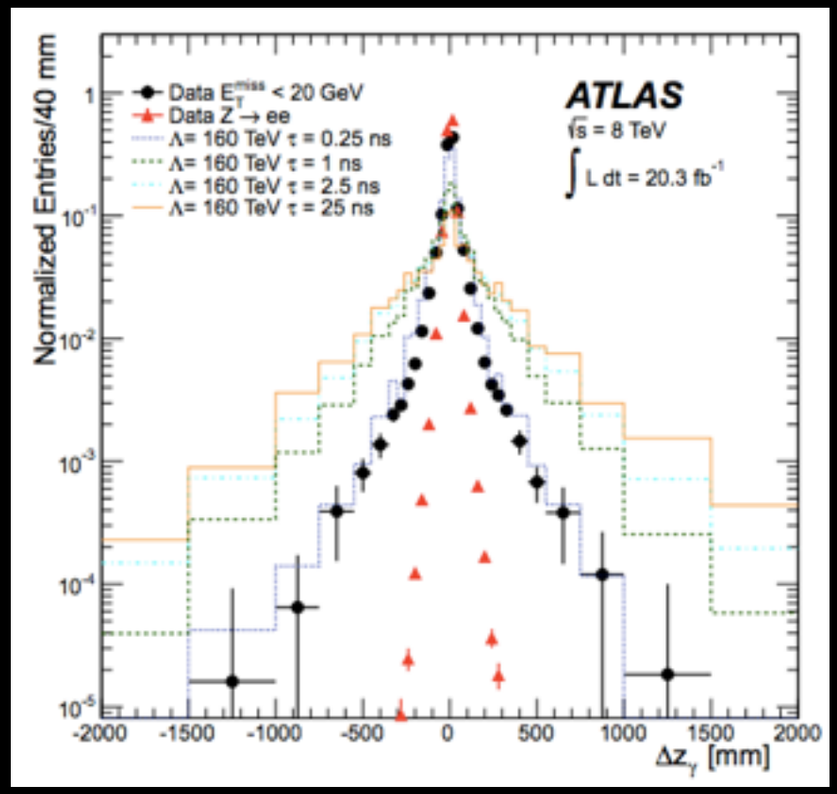
Other great searches not covered here



Disappearing tracks

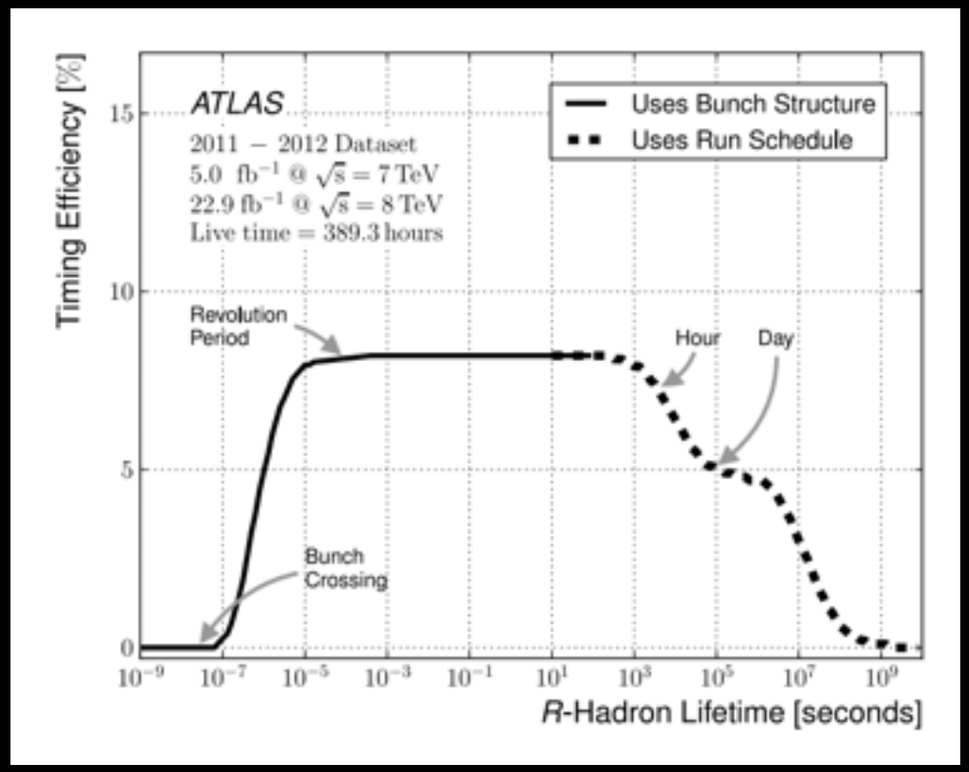


JHEP 1501 (2015) 096



Non-pointing photons

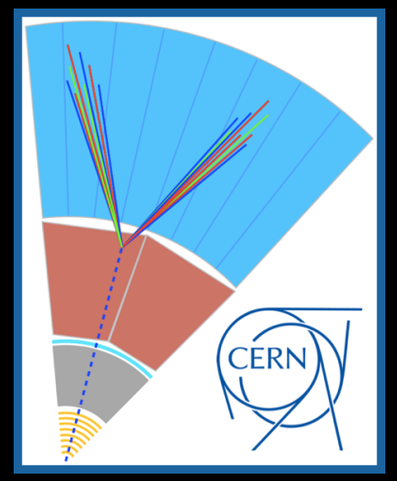
Phys. Rev. D 90, 112005 (2014)



Stable/stopped particles

Phys. Rev. D 88, 112003 (2013)

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

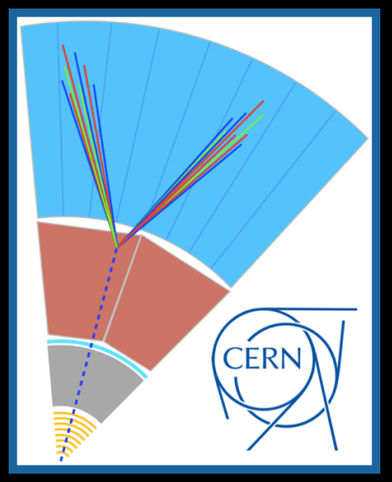
There's a danger in spending a large amount of time and effort to make incremental improvement in an existing search when the existing search may be a bit too narrow in scope already

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

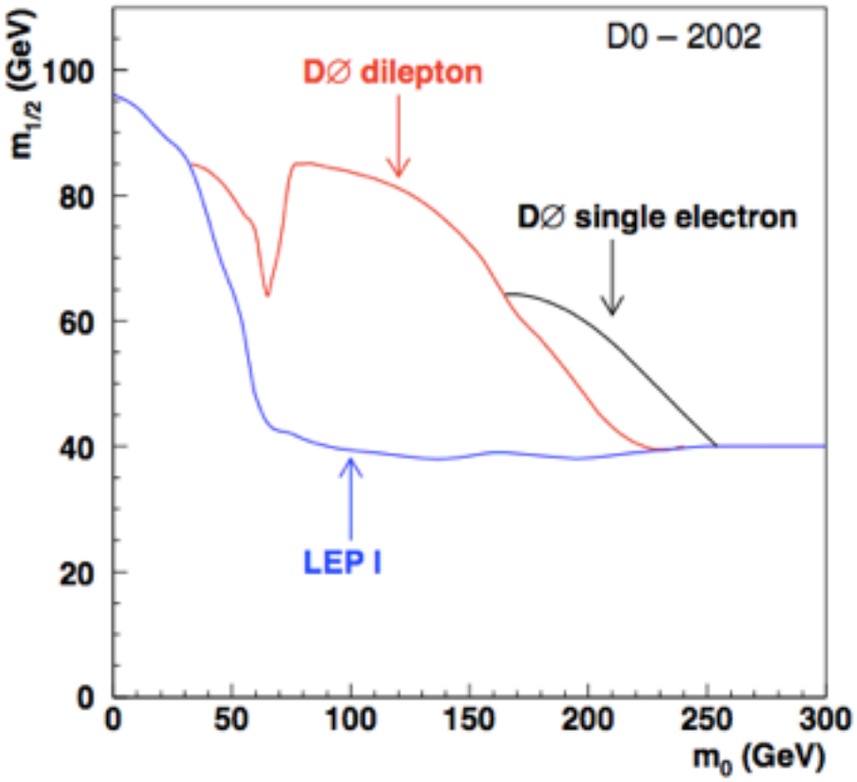
How do we best ensure that we don't miss
BSM LLP signatures for the remainder
of the LHC program?

How do we know we're not missing a discovery?

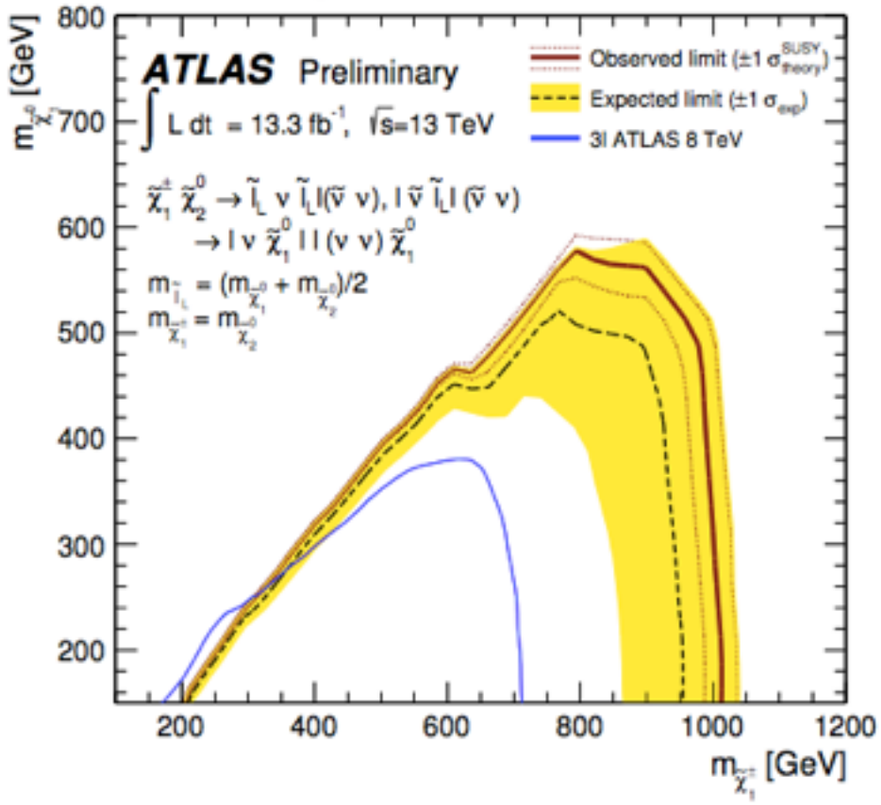
We don't. But we can avoid being too narrow in scope.



Complete Model:



Simplified Model:

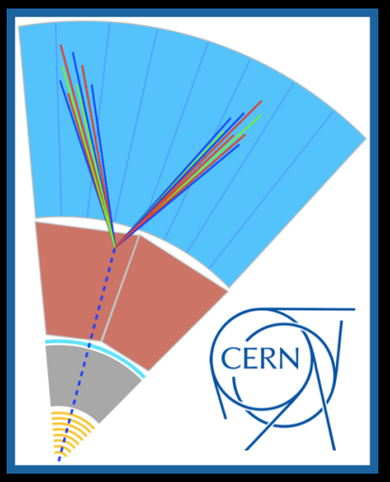


- What does this search actually constrain? Needs a translator!
- What if I don't care about mSUGRA?
- What if my sleptons are above LEP limit?

Evans (UIUC) | LLP Simplified Models | April 24, 2017

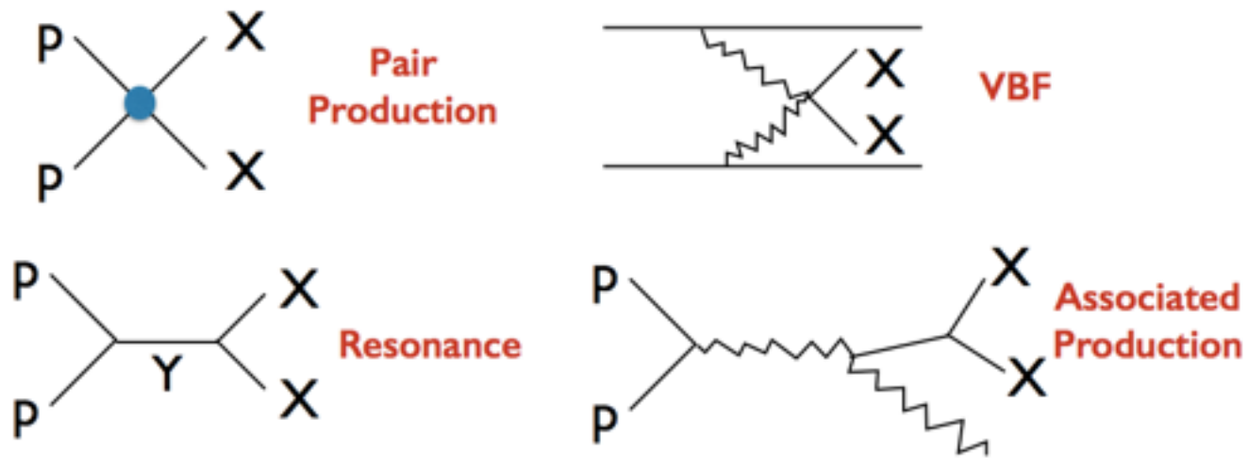
Simplified models could inform our search strategies and elucidate uncovered signatures and areas of parameter space

Simplified models



LLP Production Modes

(See Simplified Models summary)



A = invis, j, top, W, Z, L, h (oof…) … maybe even γ?

Notes by D. Curtin

Group of theorists and experimentalists recently completed a proposal of a minimal set of simplified models

Organized around LLP production and decay modes, always focused on what's experimentally important

LLP Decay Modes

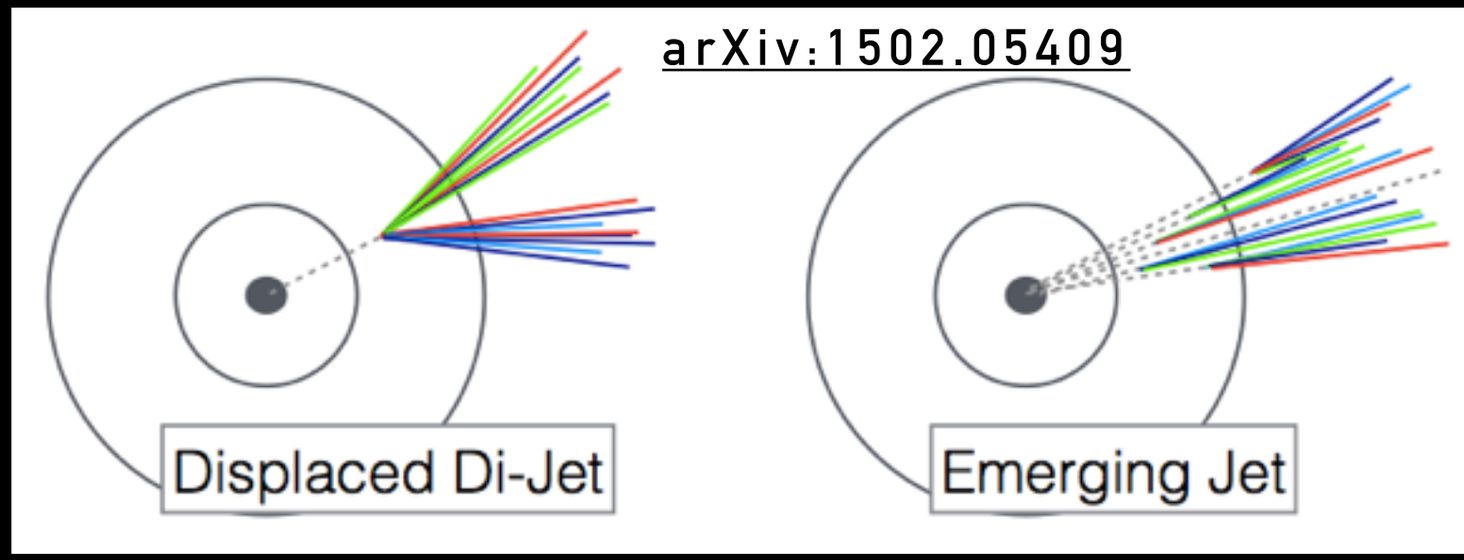
Many possibilities, but keep it simple for now while ensuring coverage:

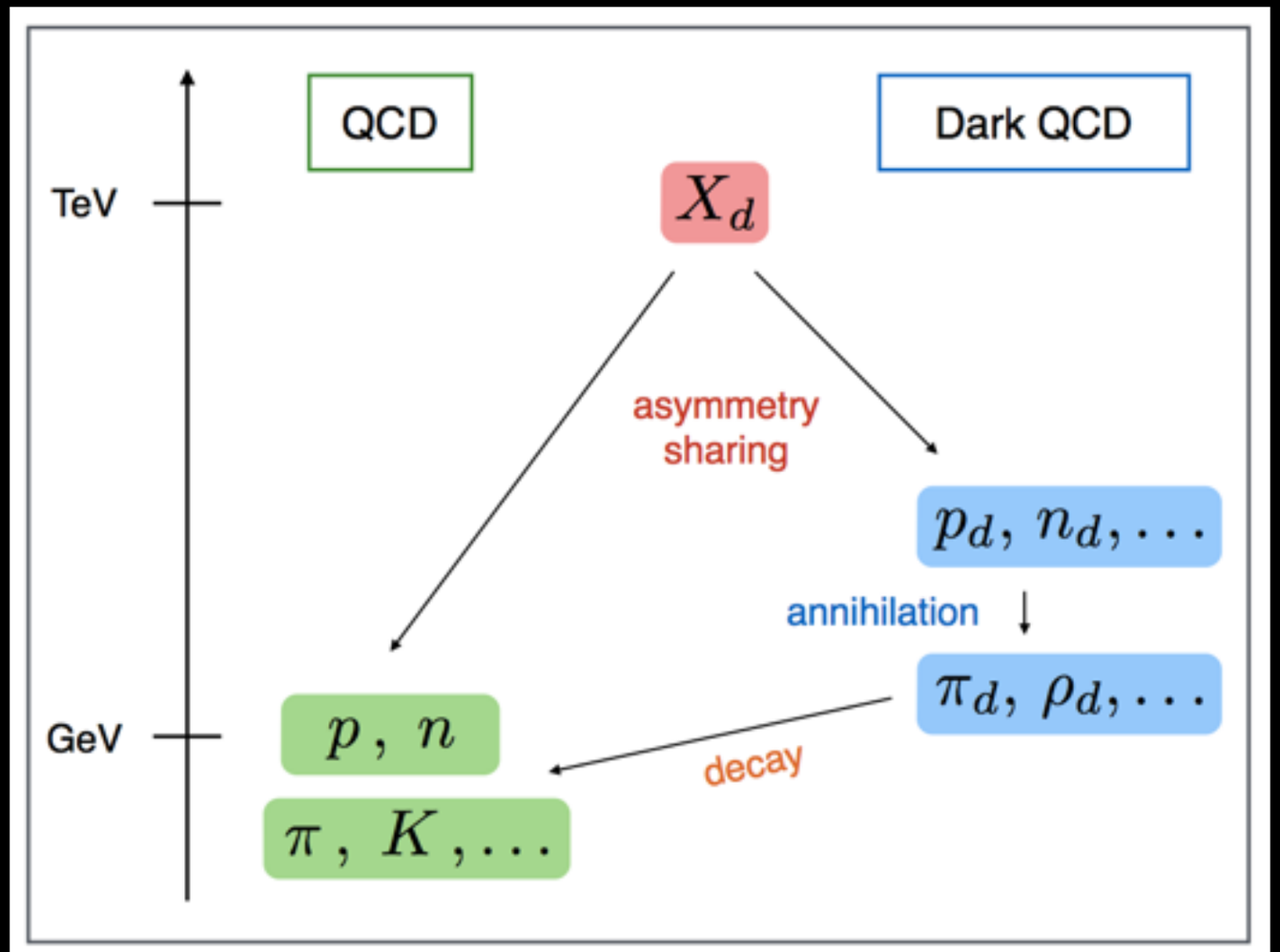
X → μμ, ee, ττ, jj, γγ
for simplicity either gauge- or Yukawa-ordered

X → μ, e, τ, j, γ + invis
(GMSB-like)

Frontiers/uncovered realms: Emerging jets

Why should beyond-the-Standard Model physics be simple, like a U(1) symmetry? What about dark QCD?

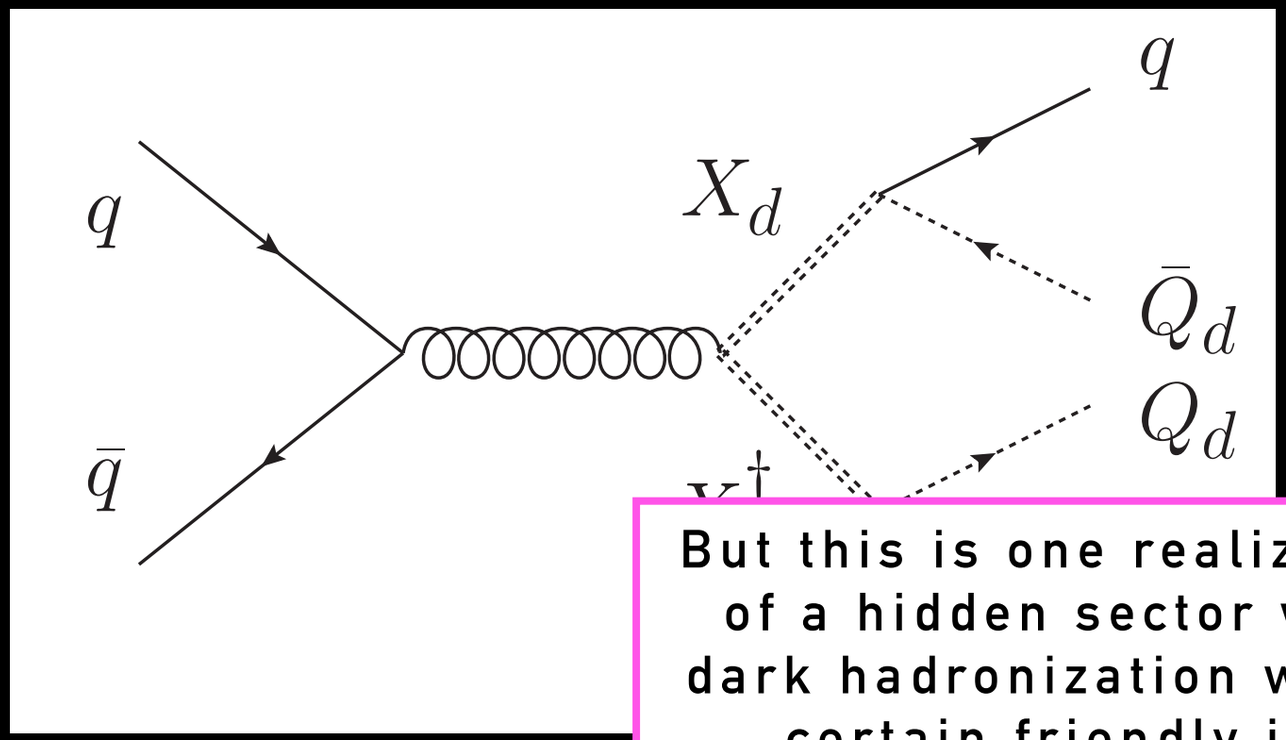


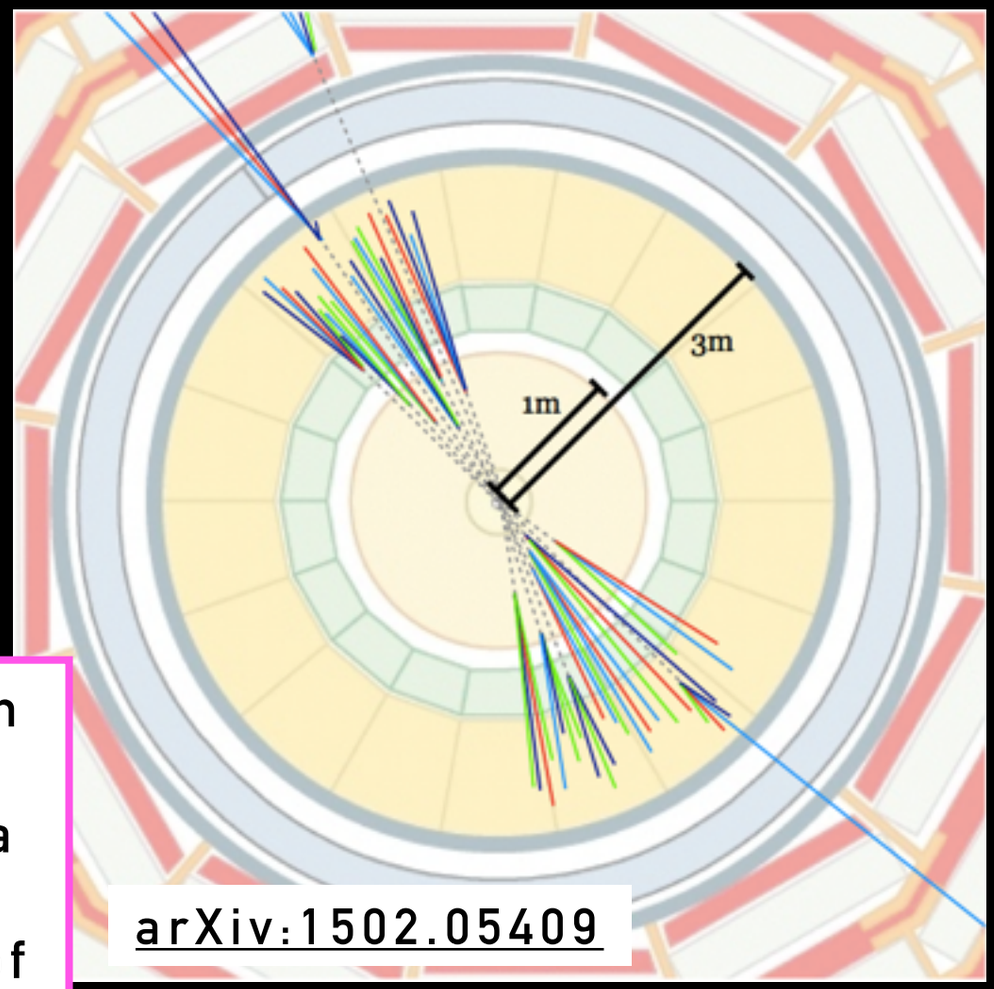


A novel LHC signature where dark or hidden sector quarks decay to the visible sector via multiple displaced vertices of varying displacements within the same jet object. Pair-produced dark quarks then give rise to neither prompt jets nor a pair of displaced jets pointing to the same displaced vertex, but to emerging jets.

Frontiers/uncovered realms: Emerging jets

Dark QCD-like sectors





arXiv:1502.05409

But this is one realization of a hidden sector with dark hadronization with a certain friendly jet multiplicity and choices of mediator, dark vector meson, dark pion masses, dark confinement scale. How to design a comprehensive approach?

Dark QCD —> dark quar ifetimes —> jets w/multiple displaced vertices / trac

Analysis strategy could + 2 dark-QCD / emerging jets

Need non-standard tracking for large-d0 tracks + secondary vertex finding routines

Searches underway in ATLAS and CMS; hopefully public results soon-ish!

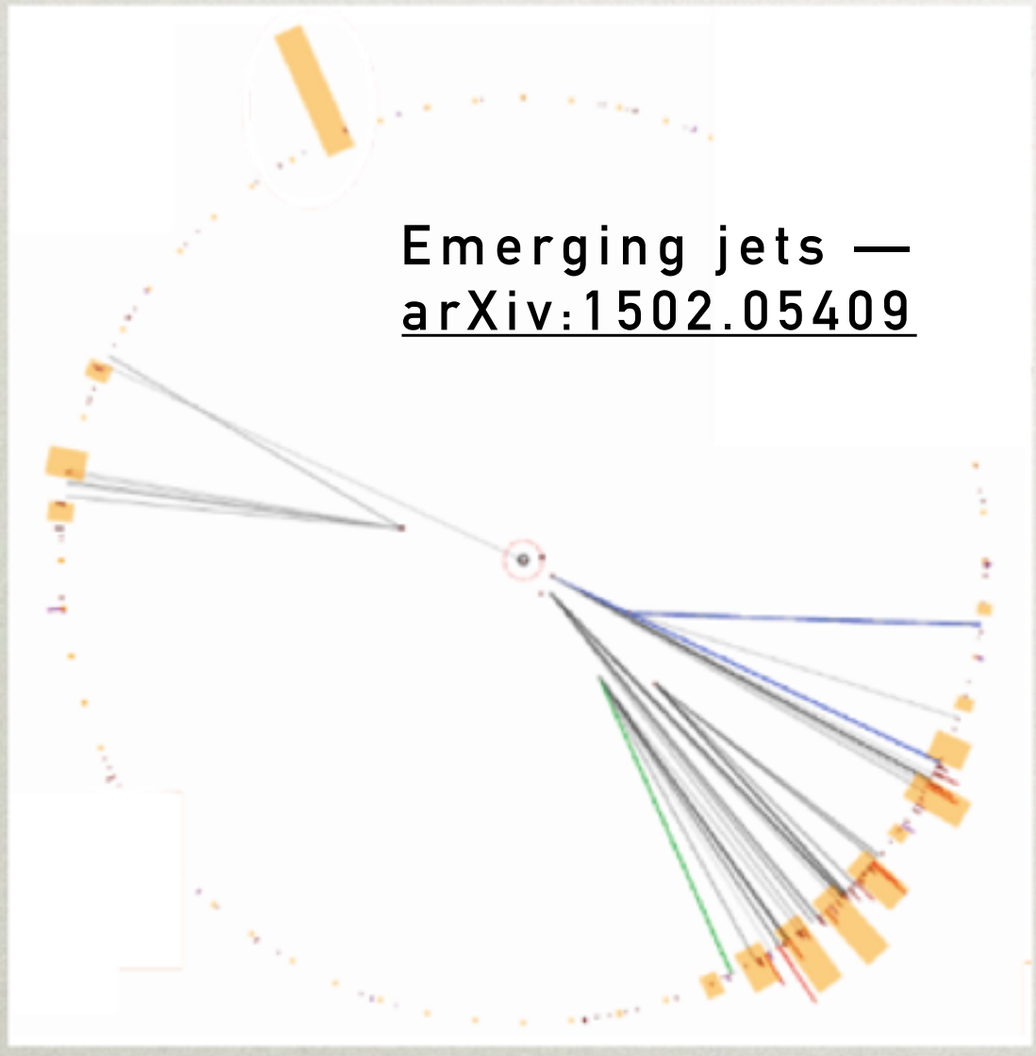
Frontiers/uncovered realms

Dark QCD-like sectors

- Emerging jets vs. SUEP (soft, unclustered energy patterns)
- How to interpolate between these two?
- Dark showers WG in LHC LLP Community — laying groundwork now

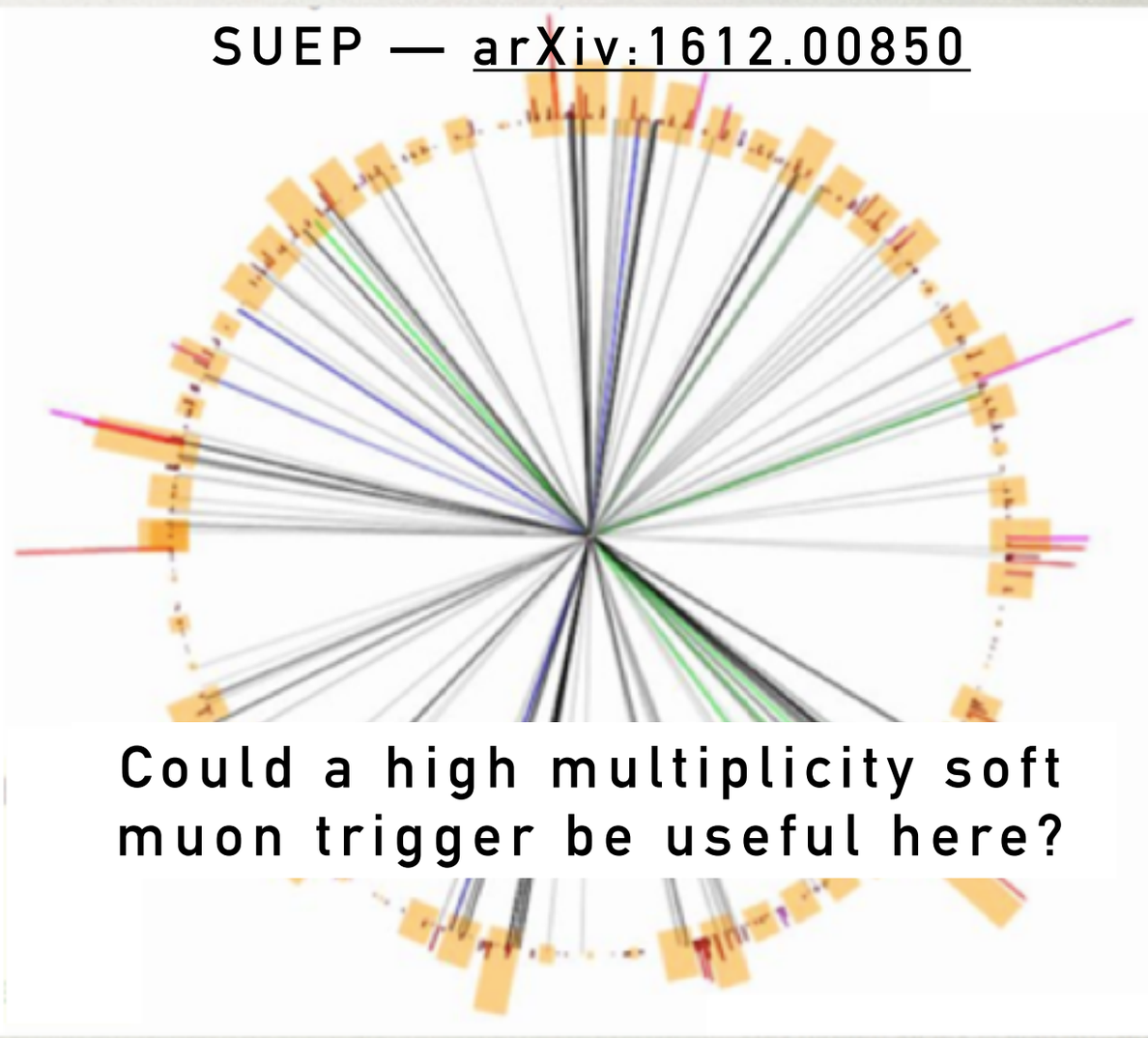
Schwaller, Stolarski, Weiler 2015

Emerging jets — arXiv:1502.05409



Knapen *et al.*, 2016

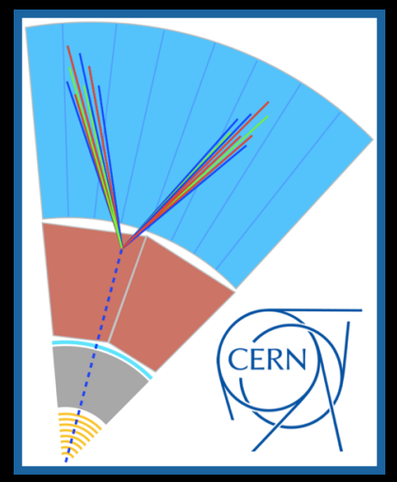
SUEP — arXiv:1612.00850



Could a high multiplicity soft muon trigger be useful here?

Images by M. Strassler

What triggers are missing?

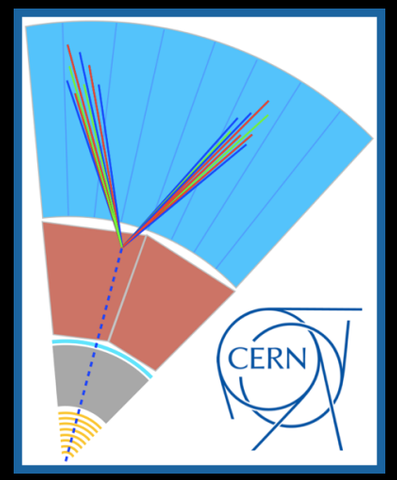


It turns out that ATLAS and CMS current HLT menus are actually pretty good for most LLP signatures

- ATLAS displaced vertex triggers in MS are effective, inclusive and versatile
- CMS triggers for displaced jets in inner tracker are as good as possible given current bandwidth limitations
- ATLAS CalRatio trigger (large HCal deposit, veto on EMCal) is also versatile and robust
  - ATLAS also ran a high-p_T EMCal-only trigger (RCalRatio) but hasn't been utilized fully for analysis
- For other LLP production modes, not clear there's even a need for hybrid prompt+displaced triggers
  - Just use prompt triggers and do offline DV searches!

But there are some opportunities for high-level triggers that still don't exist

What triggers are missing?



New triggers?

There is one new CMS high-level trigger that could be very useful:

Consider $X \to \tau\tau$

τ L1 thresholds are much lower than jets due to calo shape

two τ pT thresholds
20,12 GeV @ L1,
35,25 GeV @ HLT

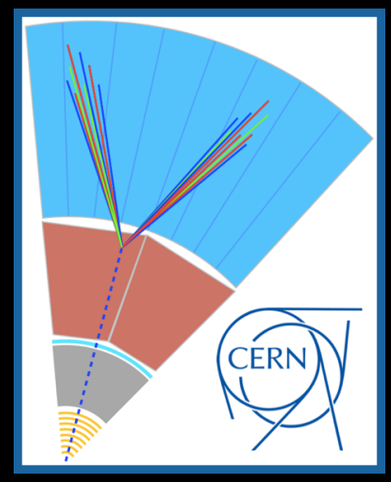
optimized for $h \to \tau\tau$
but inefficient for
$h \to XX,\ X \to \tau\tau$

New CMS trigger suggestion:
run displaced jet reconstruction on L1 τ seeds

Would be very sensitive to e.g. $h \to (X \to \tau\tau)(X \to bb)$ and many other models (light boosted X decaying hadronically, not just $\tau\tau$)… very physically motivated.

Notes by D. Curtin

What triggers are missing?



CMS displaced taus — hopefully underway now

High-multiplicity soft muon trigger for both ATLAS and CMS
- Could be very useful for SUEP

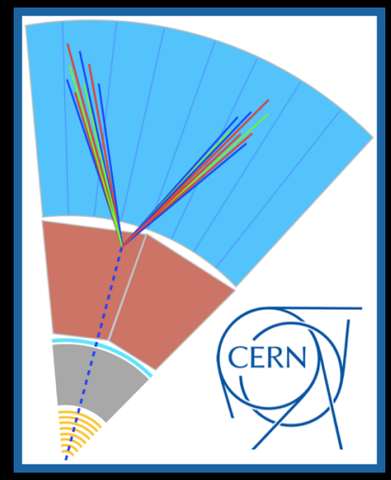
Inner detector hit-occupancy trigger (ATLAS)
- Instead of expensive large-d0 tracking in a dense environment, count hits not associated to tracks in a cone around some calorimeter deposit

Comprehensive studies of existing b-triggers
- How could judicious use of b-jet methods improve sensitivity to small-lifetime BSM LLPs?

What we could do better

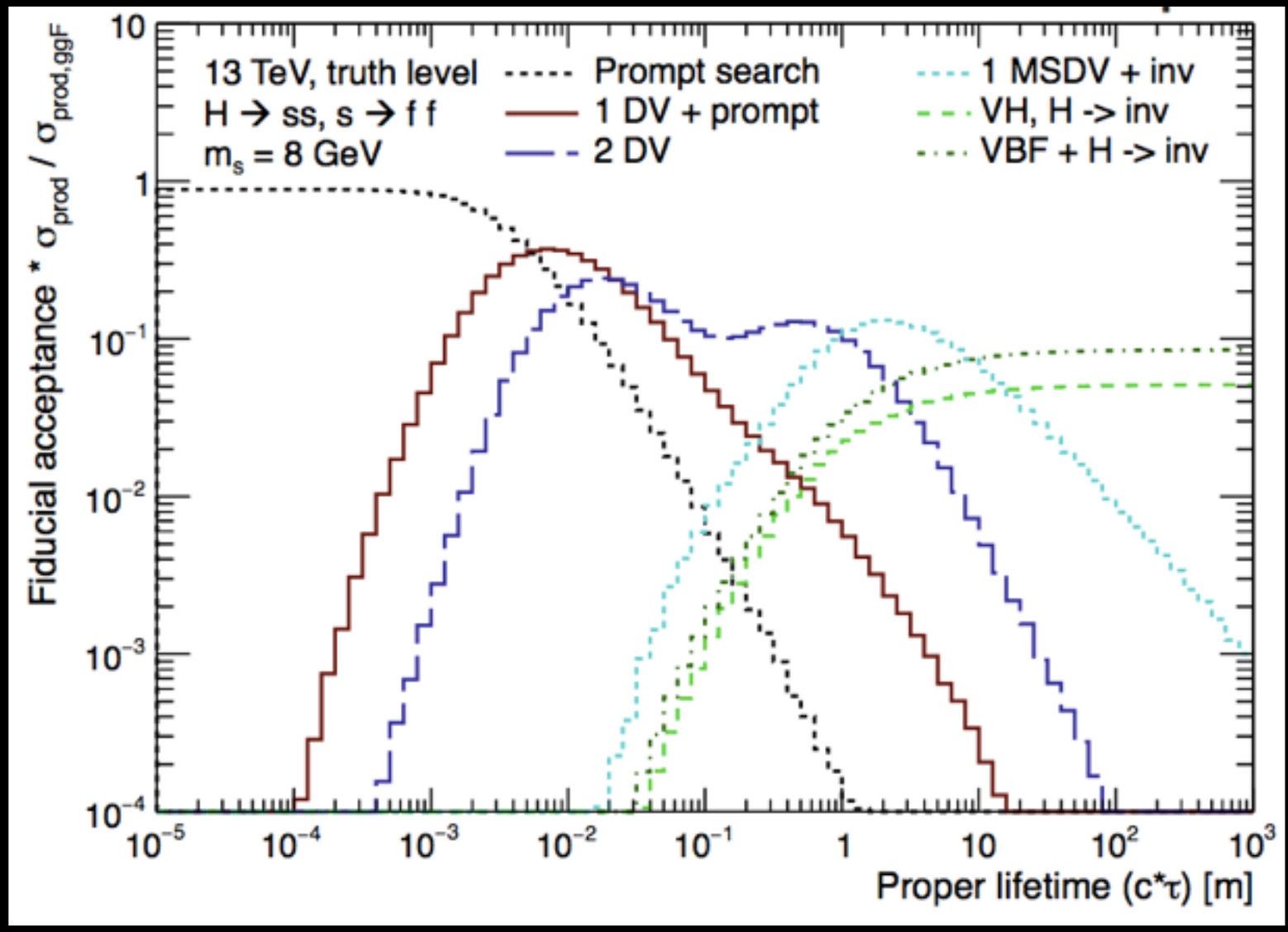
Where do our prompt and displaced searches overlap?

- 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?



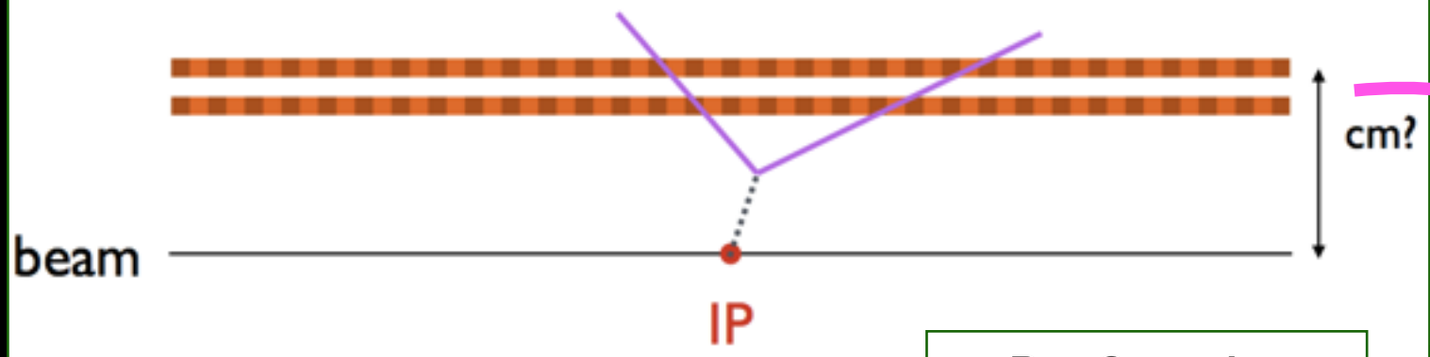
Probably our smaller-lifetime coverage isn't this good, but need to know the answer

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



Possible detector upgrades

What about triggering on very short decay lengths in tracker?

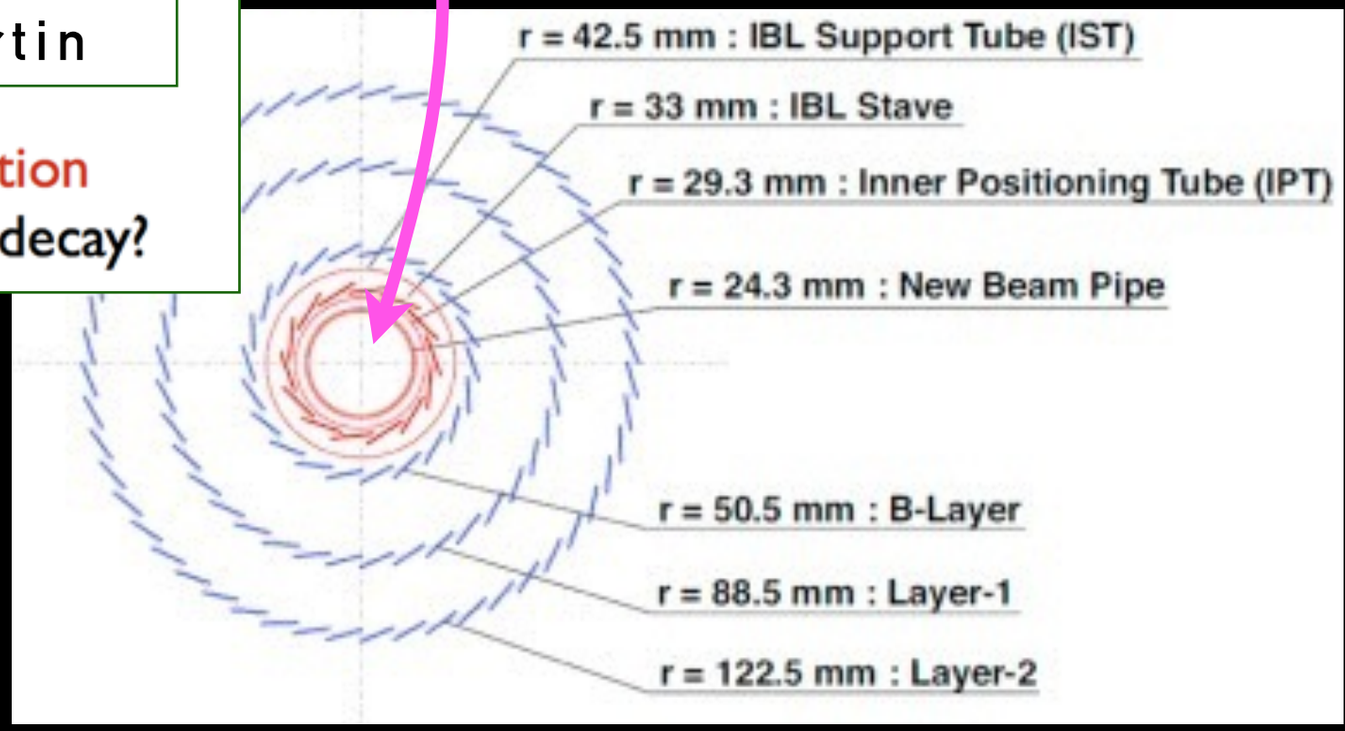


D. Curtin

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

Blue sky idea for ATLAS:

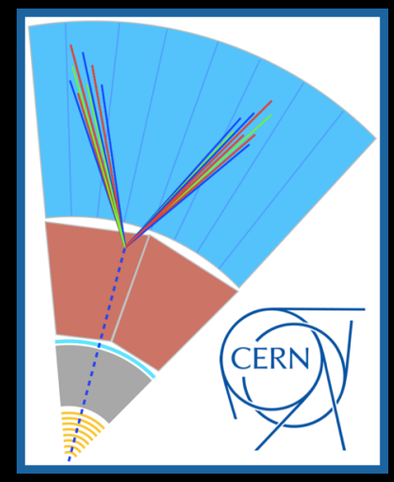
Simple high-resolution double-tracking layer inside the IBL



- 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?

LHC Long-Lived Particle Community



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

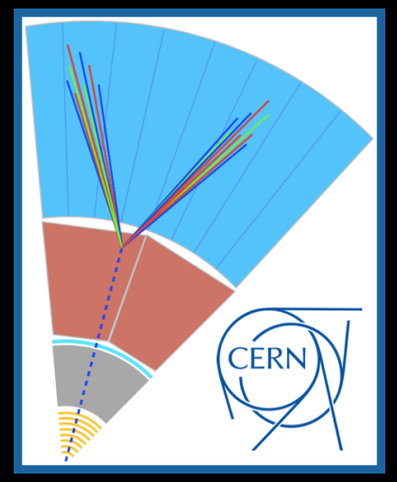
Overall goal is to address one question:

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

Currently producing a community white paper with recommendations resulting from our April 2017 workshop... https://indico.cern.ch/e/LHC_LLP_April_2017

...and you should join the effort!

LHC Long-Lived Particle Community



What areas of LLP searches need understanding or improvement?

- Simplified models
- Re-interpretation / presentation of results

- Backgrounds — wealth of wonderful and scary info here

- Triggers
  - B-triggers for small and intermediate lifetime LLPs
  - Studies for how to lower kinematic thresholds for soft, light LLPs

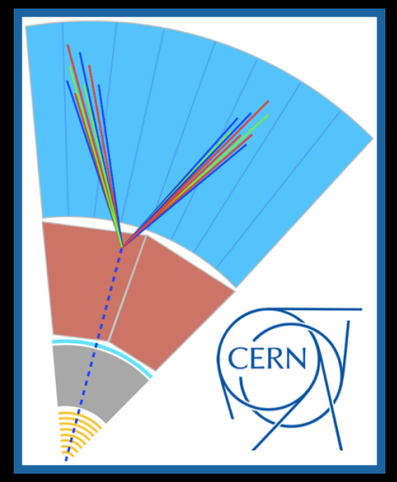
  - A few triggers that we don't have:
    - Displaced tau(s) for CMS (and ATLAS?)
    - High multiplicity soft muon triggers
    - FTK for tracklets for multiple signatures
    - ID hit occupancy triggers

- Dark QCD-like sectors

LHC LLP Community Workshop

https://indico.cern.ch/e/LHC_LLP_April_2017

CERN EGroup: lhc-llp



After the workshop (i.e., now)

- Spring and summer homework/projects
  - Perform and implement high-priority recommendations for triggers and trigger studies
  - Upgrade studies
  - Solidify recommendations for presentation of search results
  - Include high-priority, already-published analyses in the RECAST framework
  - Collect code library of simplified models
  - Write-up (chapter editors assigned)
- Autumn workshop in Trieste
  - 18-20 October 2017

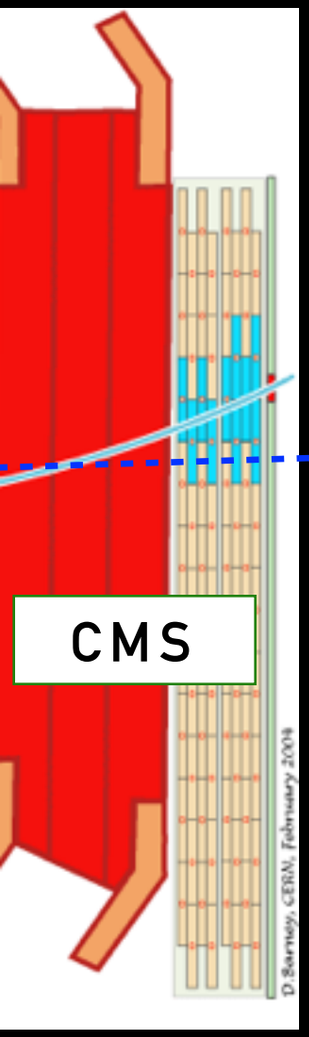
    https://indico.cern.ch/e/LHC_LLP_October_2017

Join us!

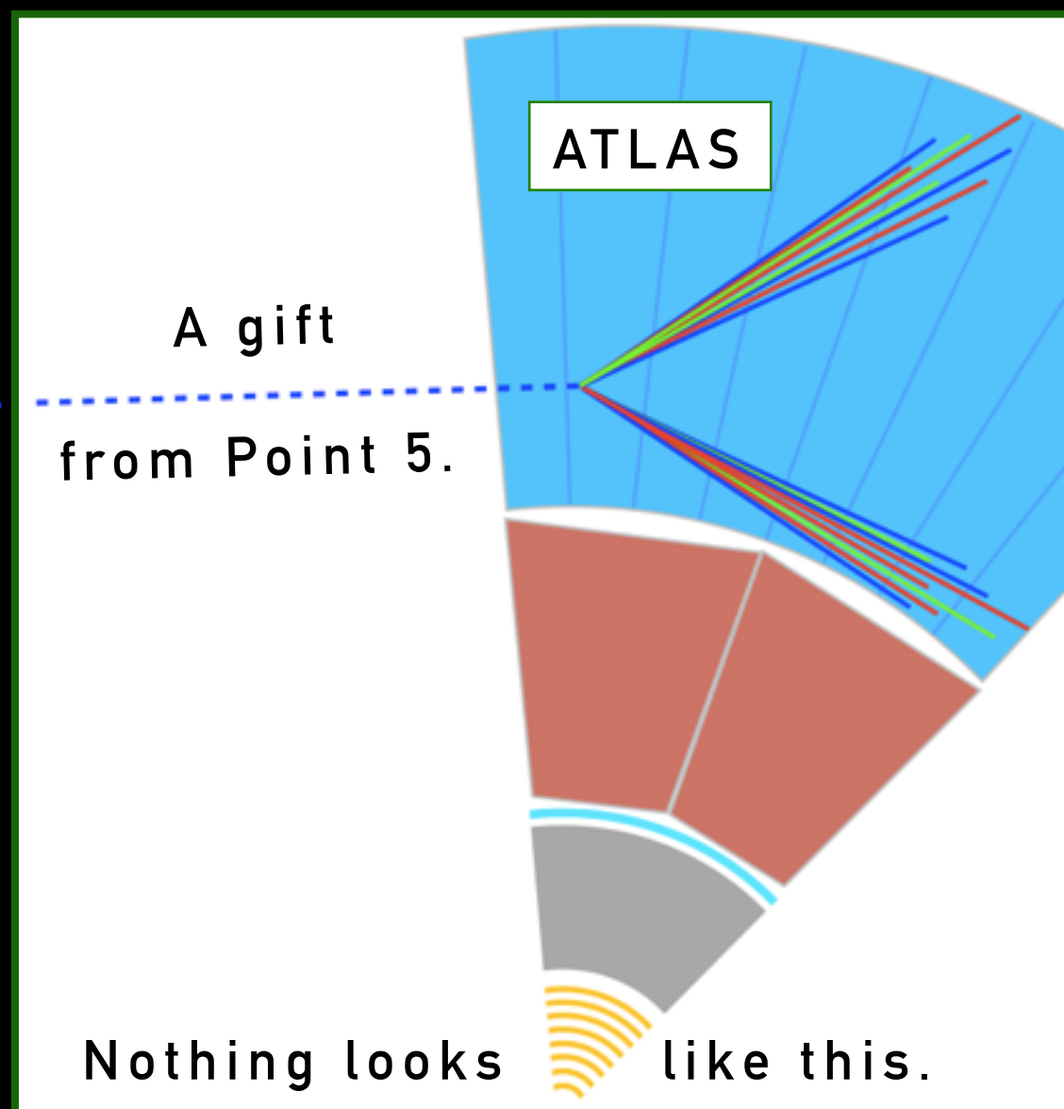
Long-shots and opportunities

What are we missing?

- What about nearly-trivial insanities?



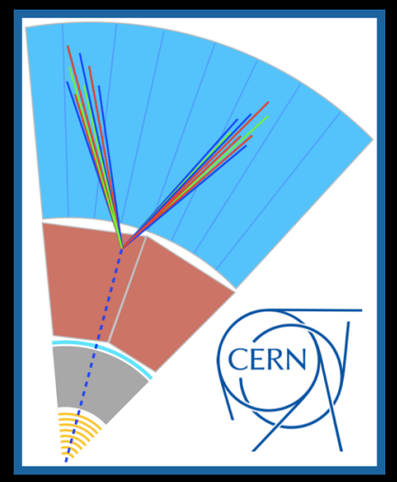
- ATLAS and CMS can each be used as a detector for LLPs produced in the other
- Solid angle coverage is vanishingly small, ~10^{-7}... <— insane
- ...but non-zero. And the signature is so rare that it would immediately show up in unfilled bunch crossings <— trivial
- A quizzical use of time? Why not 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.



- Side benefit, speaking of trivial: The result would trivially be featured in the popular science press; reaching the public in novel ways is of utmost importance in 2017

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 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 sophisicated 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!

END