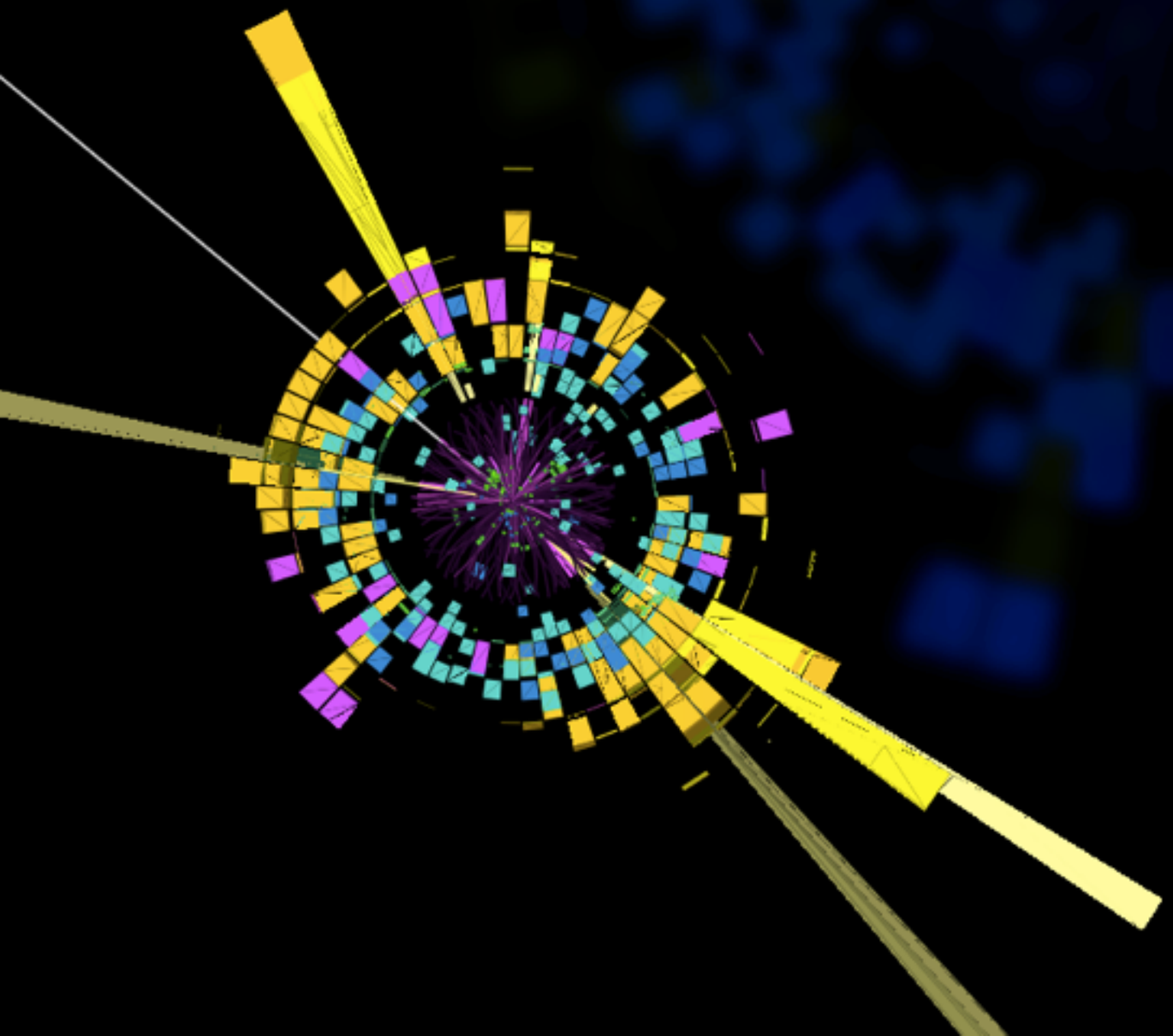


LONG LIVED PARTICLE SEARCHES IN ATLAS

Karri Folan DiPetrillo

Second LHC Long-lived Particle Workshop

18 October 2017

HARVARD UNIVERSITY

Thanks to the organizers
and ICTP!

Some thoughts on LLP Searches

We’re all here because

We think long-lived particles are well motivated

We’re all here because

We think long-lived particles are well motivated

Small Mass Splittings

Highly virtual couplings

Small couplings

But many ways to approach LLP searches

On a scale of

But many ways to approach LLP searches

On a scale of

model

lifetime

final state

mass

Theorist **Experimentalist**

But many ways to approach LLP searches

On a scale of

detector

trigger

reconstruction

person power

Theorist **Experimentalist**

Reality of LLP searches

Need to be cognizant of models that motivate searches, but….

Creatively utilizing resources that weren't designed to look for every kind of LLP

the *detector* impacts fiducial acceptance

developing *triggers* for LLPs
OR triggering on prompt objects in the same event

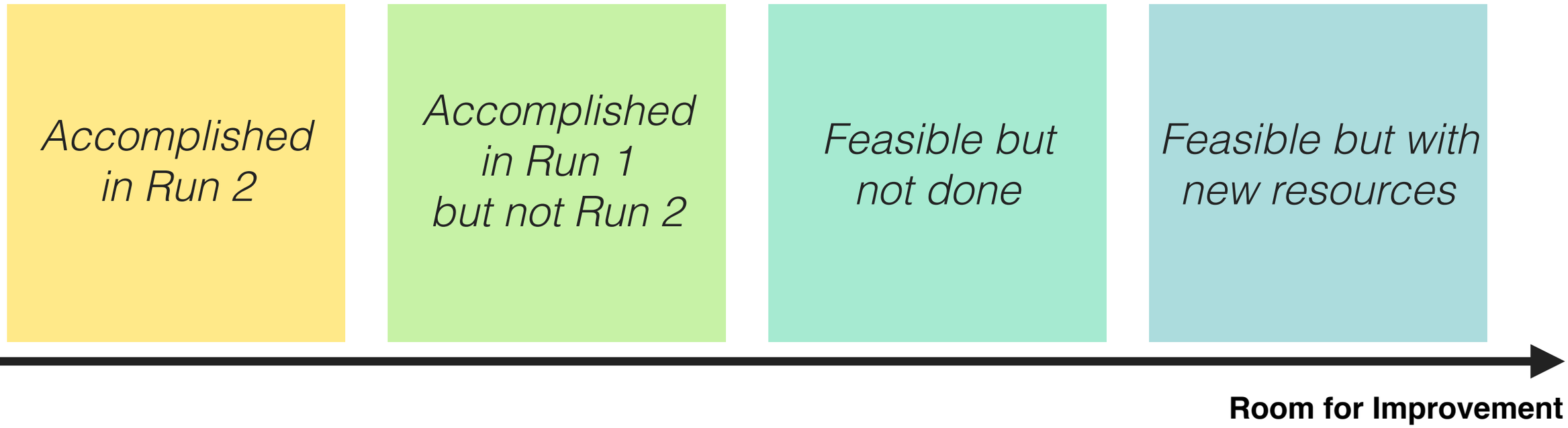
using special *reconstruction*

with *small groups of highly motivated people*

Framing this talk: experiment → theory

I'll break down ATLAS LLP searches in terms of what we can do with our experimental resources

highlighting what is

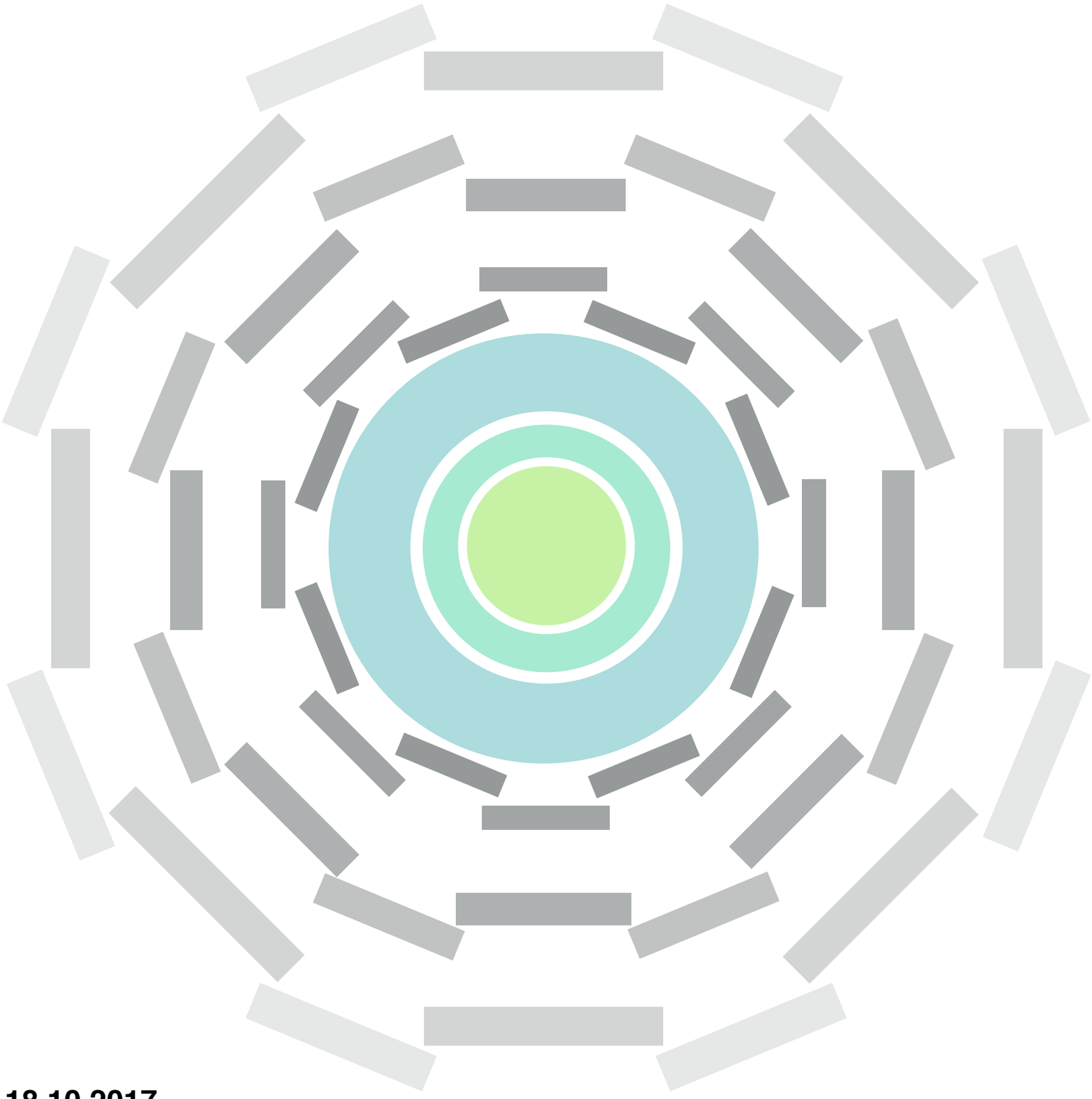


and then discuss the impact on physics coverage

The basics of ATLAS LLPs

The ATLAS Detector

Many thanks to Heather Russell for the ATLAS and LLP figures!



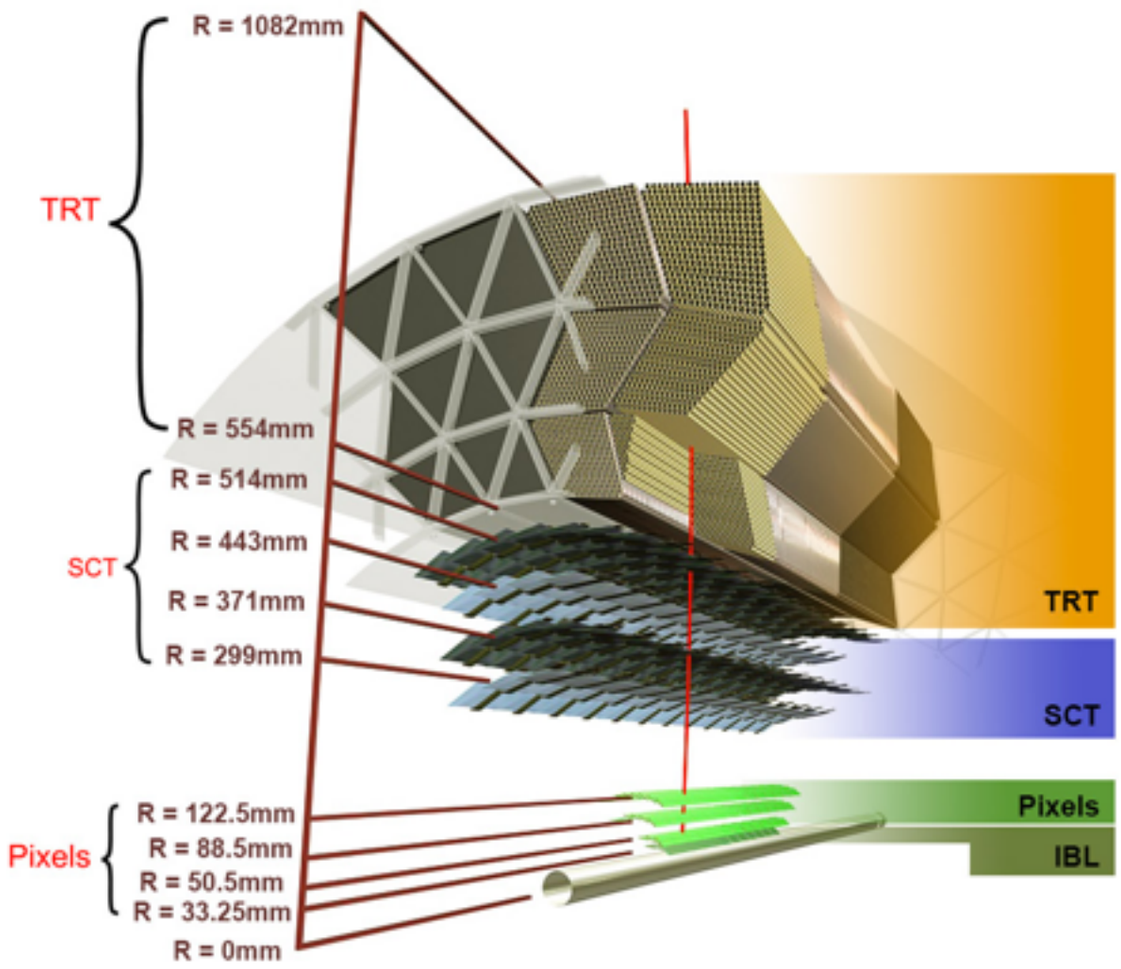
Inner Detector

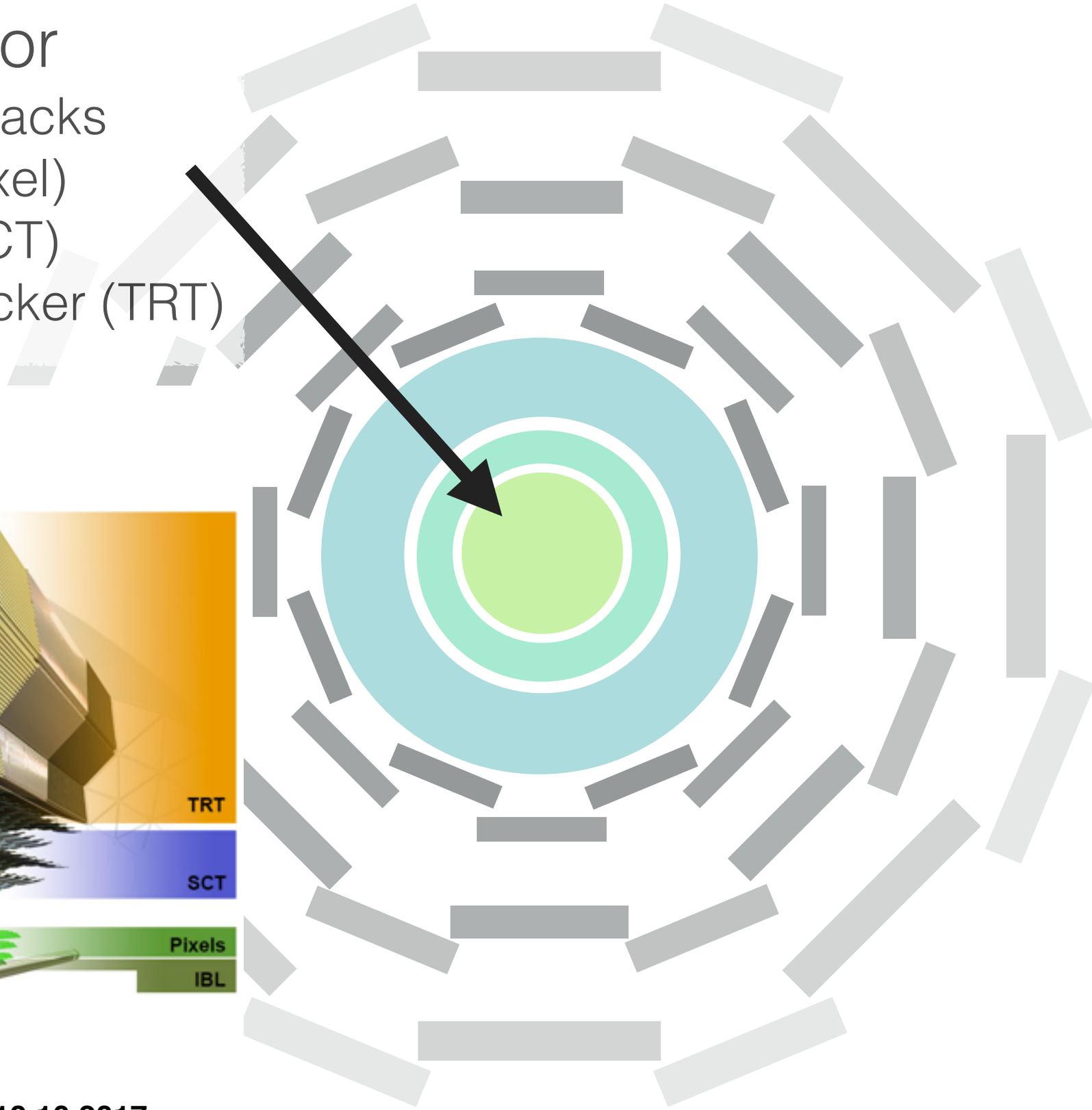
charged particle tracks

Silicon Pixels (Pixel)

Silicon Strips (SCT)

Transition Radiation Tracker (TRT)



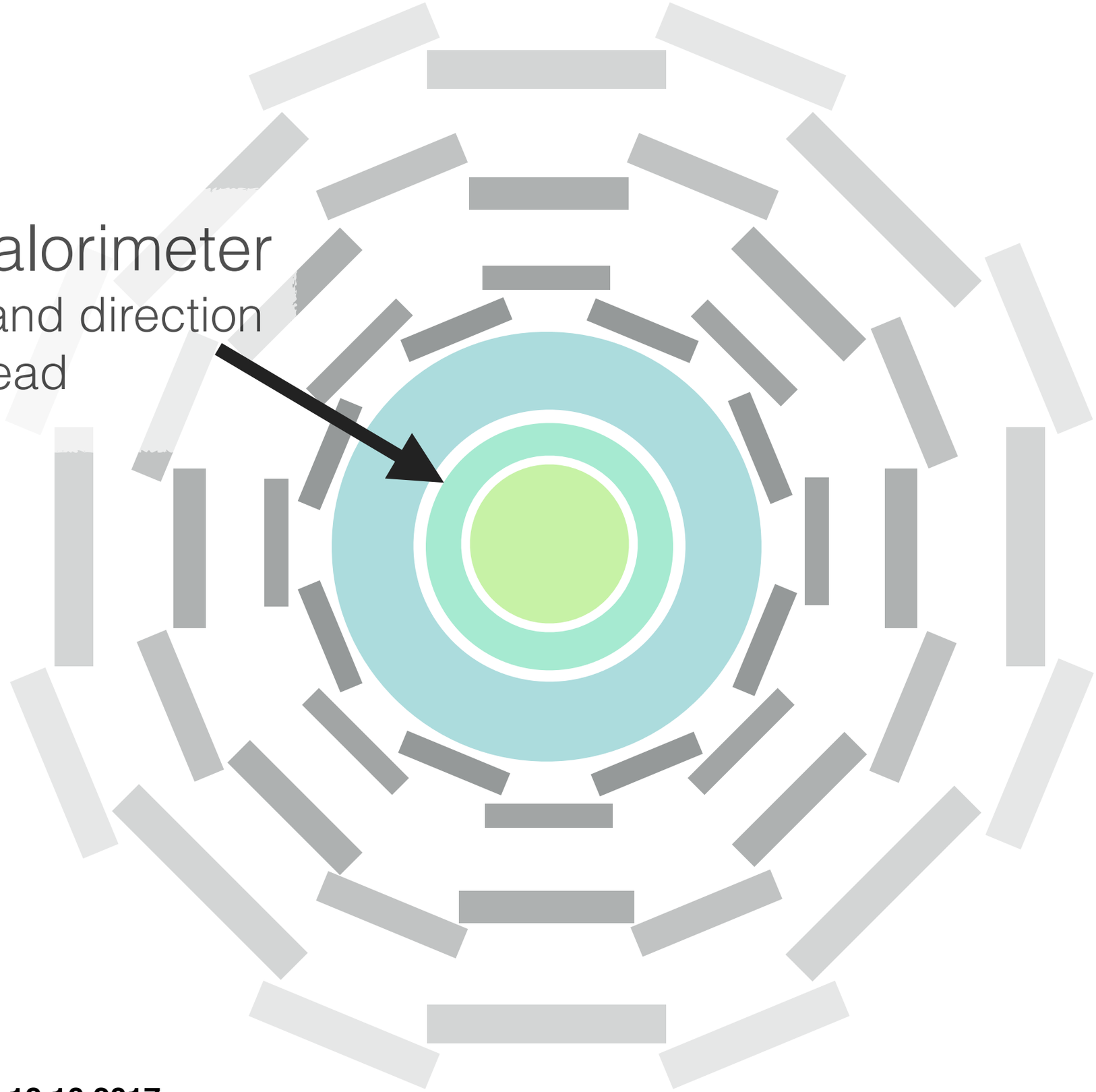


The ATLAS Detector

Electromagnetic Calorimeter

electron/photon energy and direction

Liquid Argon/Lead

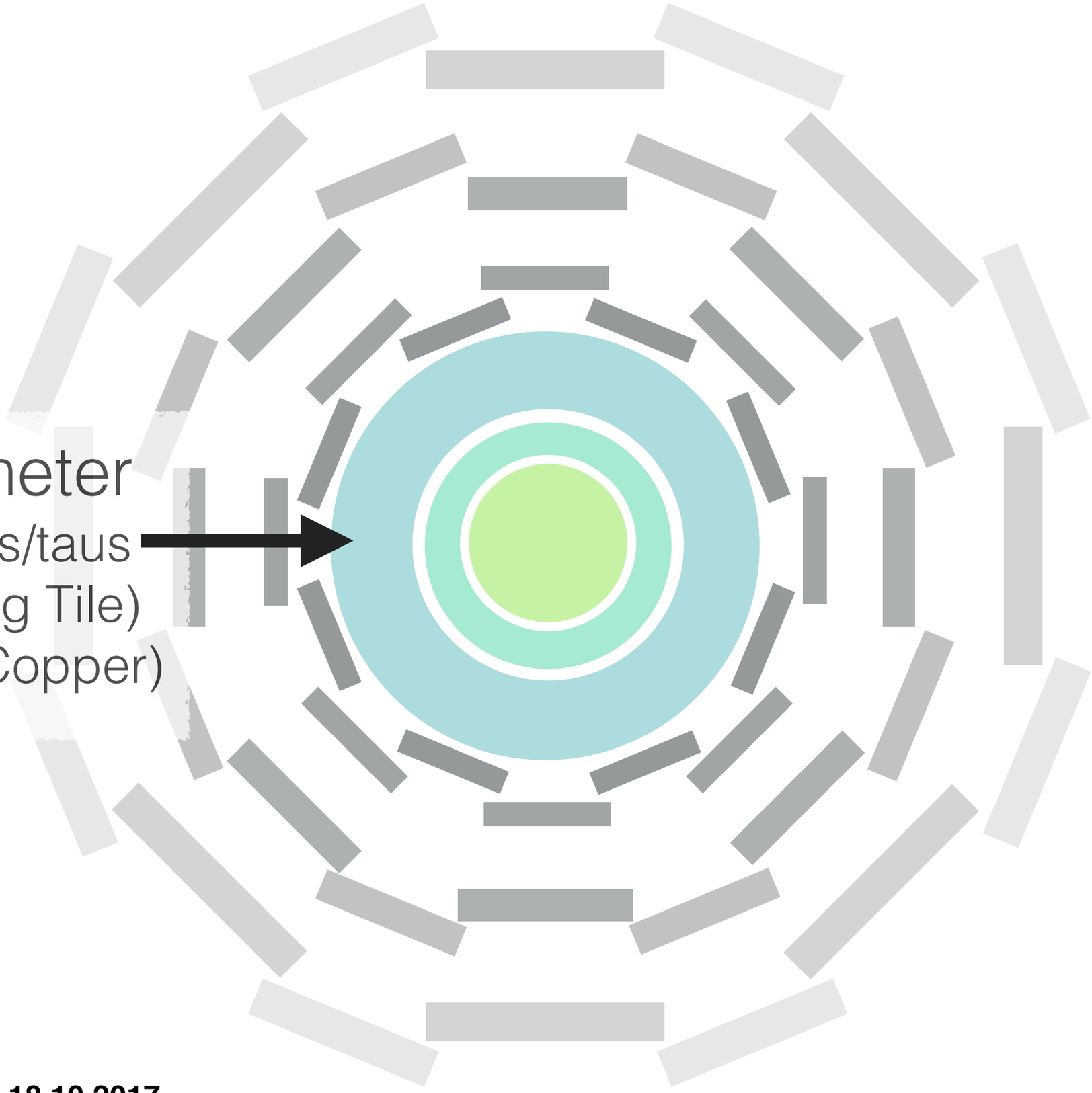


Hadronic Calorimeter

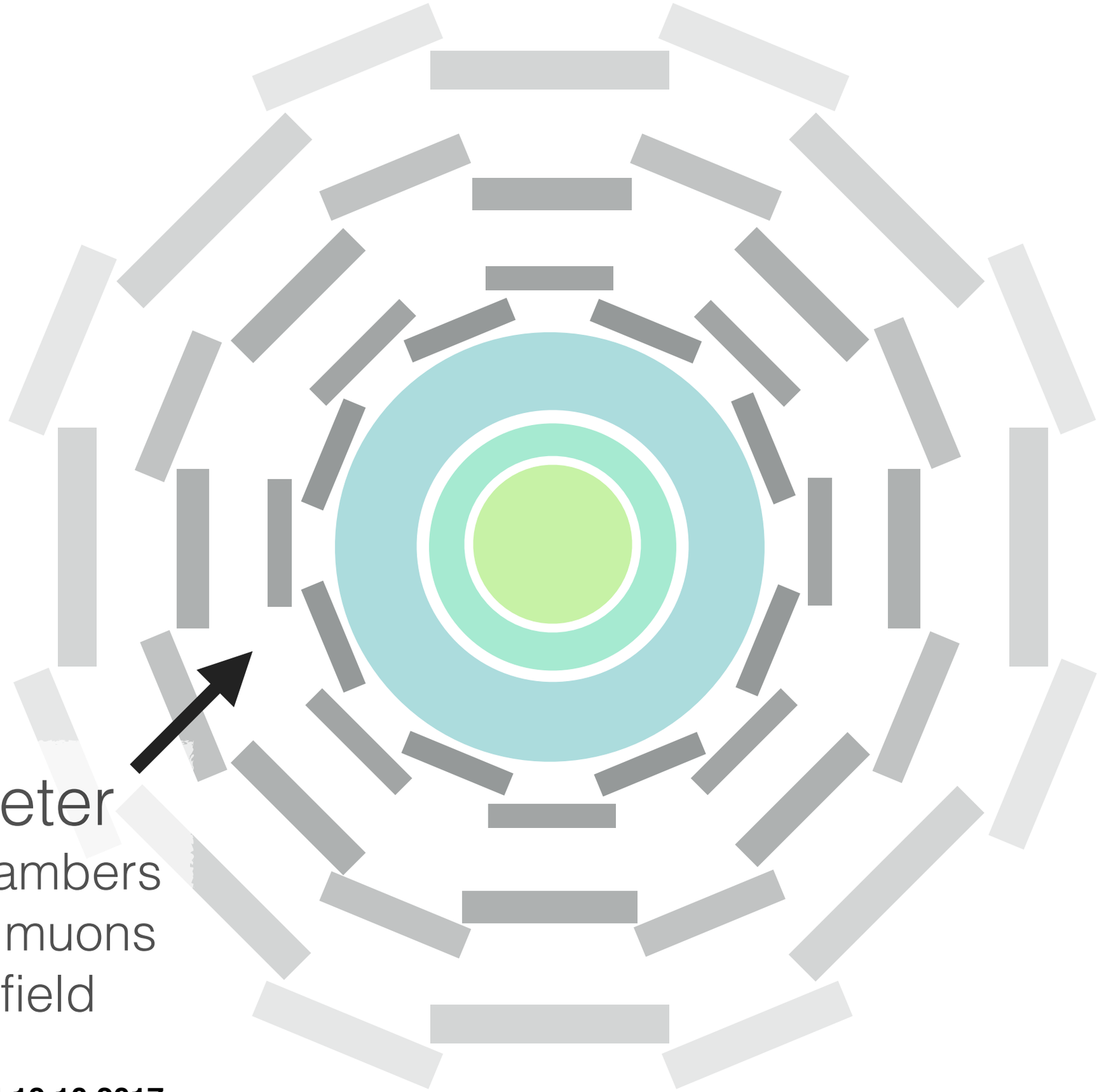
measuring hadrons/jets/taus

Barrel (Steel/Scintillating Tile)

Endcap (Liquid Argon/Copper)



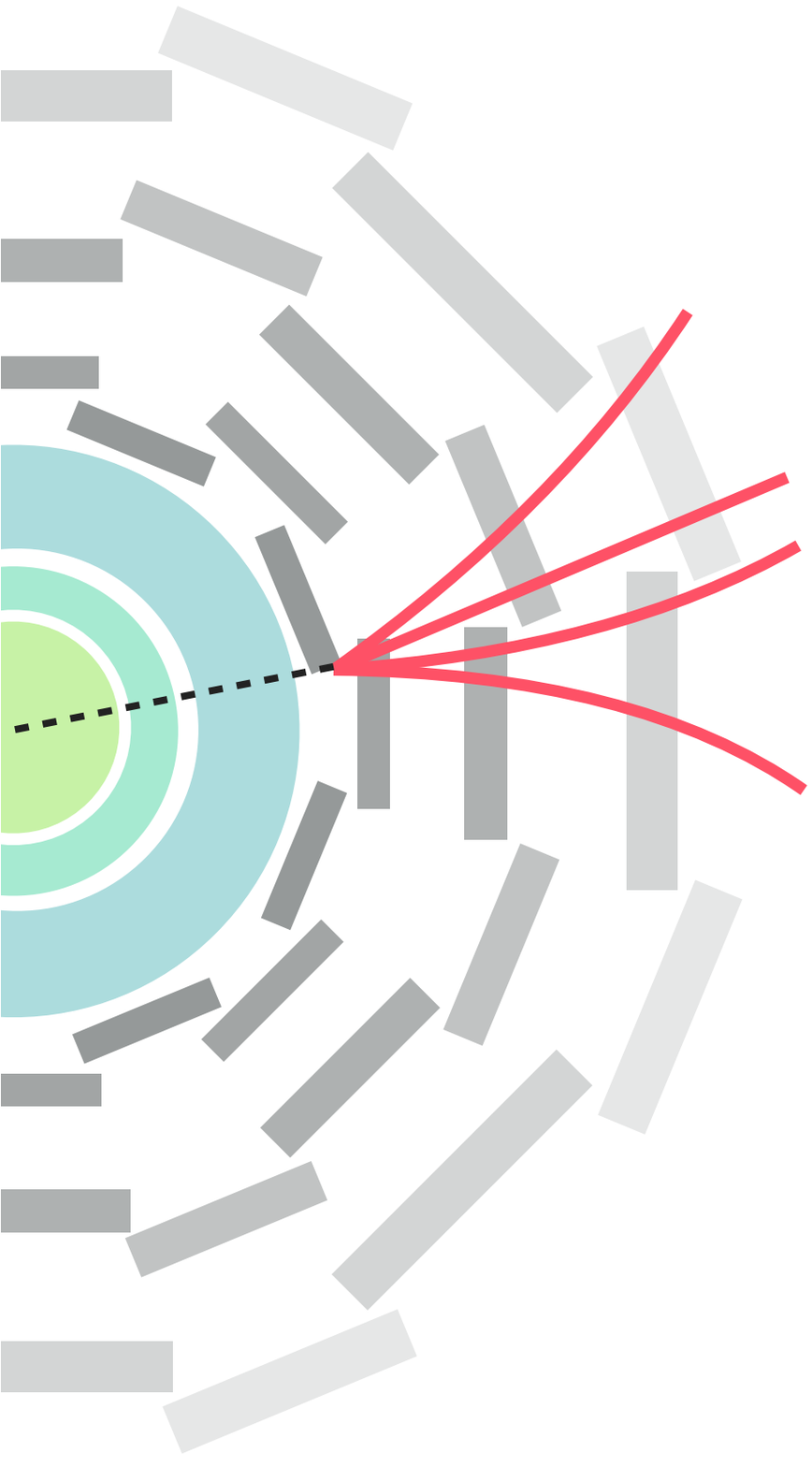
The ATLAS Detector



Muon Spectrometer

tracking and trigger chambers
to measure bending of muons
in toroidal magnetic field

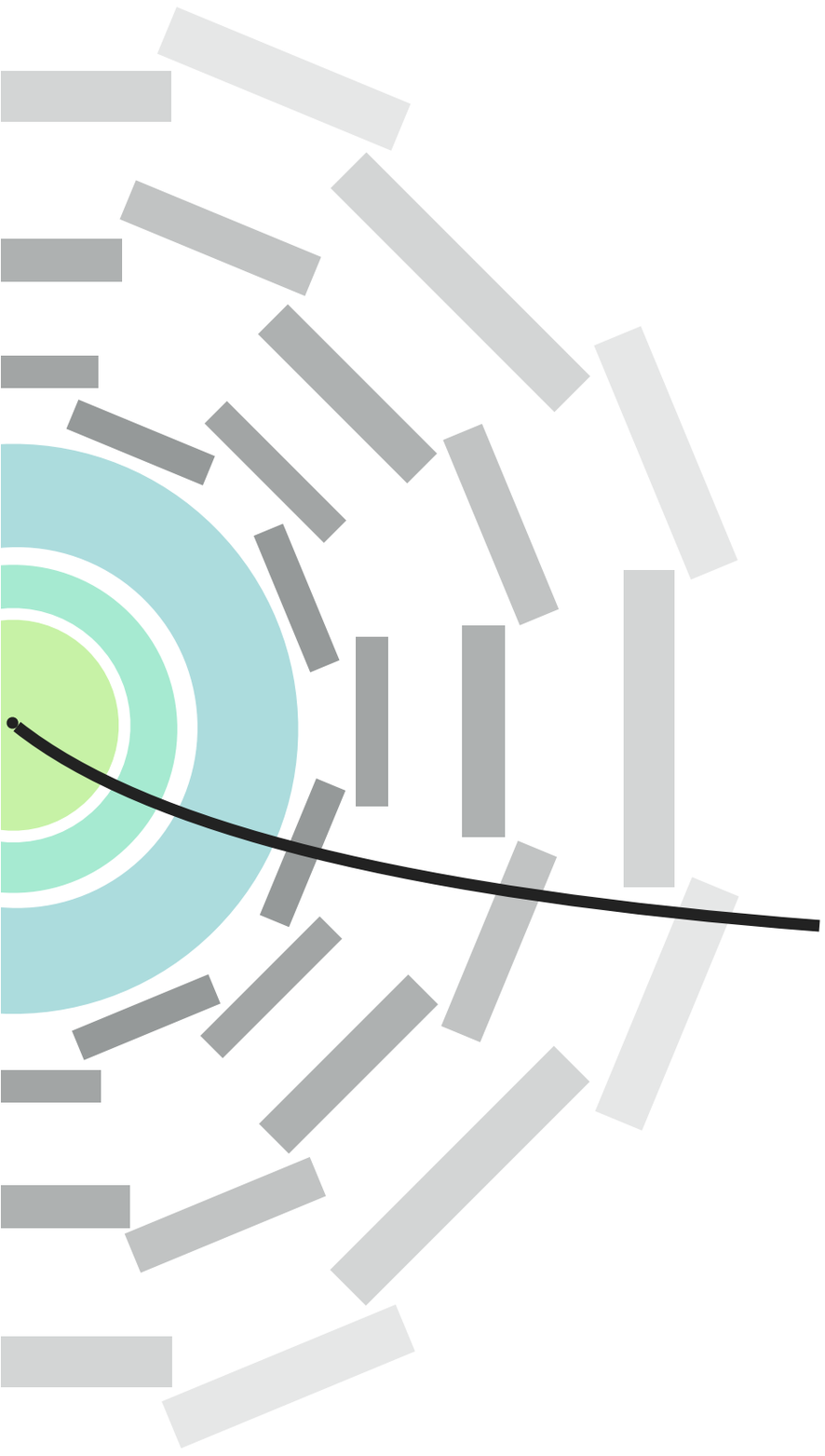
What do we mean by long-lived?



In ATLAS, an LLP can be

a particle that decays some reconstructable distance away from the p-p interaction point

What do we mean by long-lived?

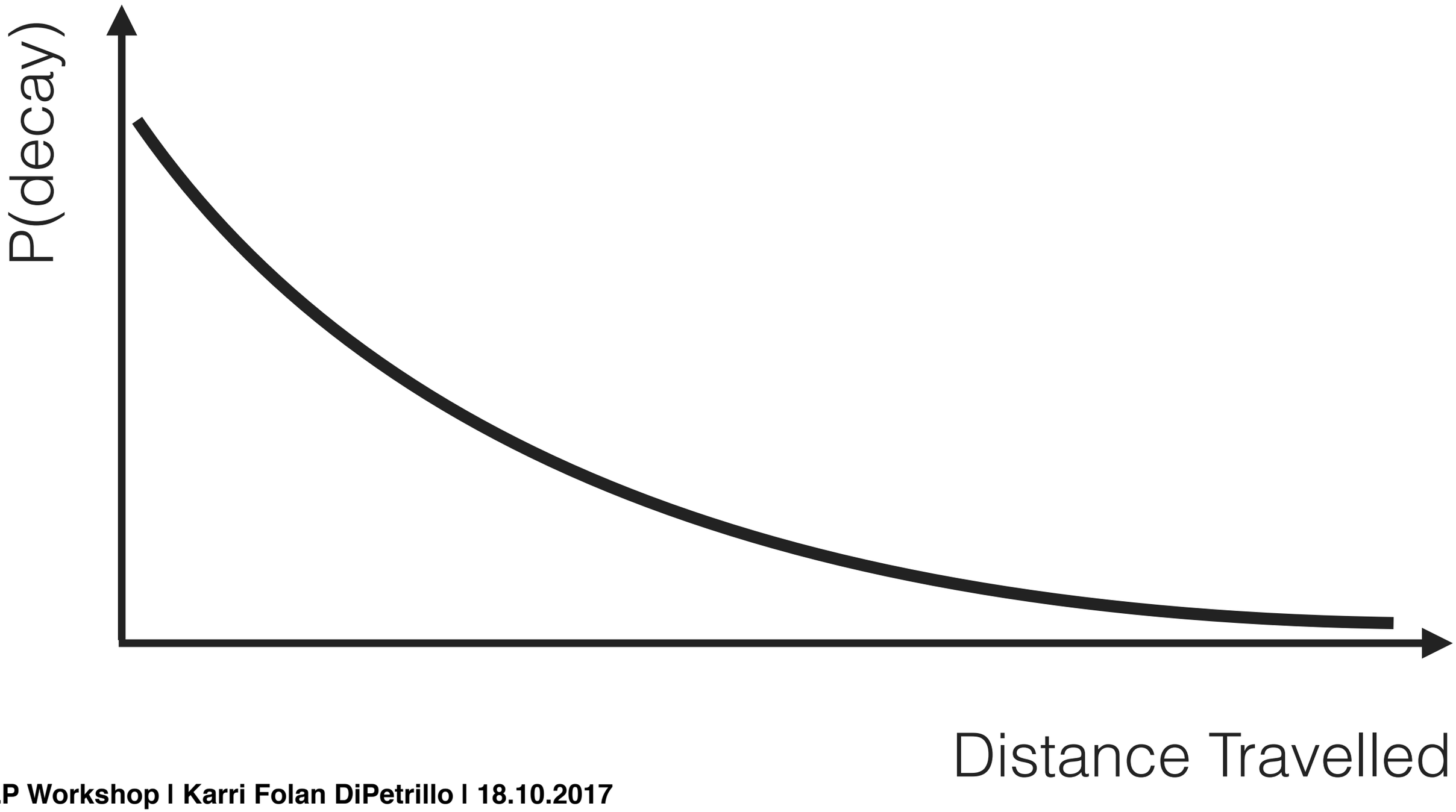


OR

charged and quasi-stable on the scale of our detector

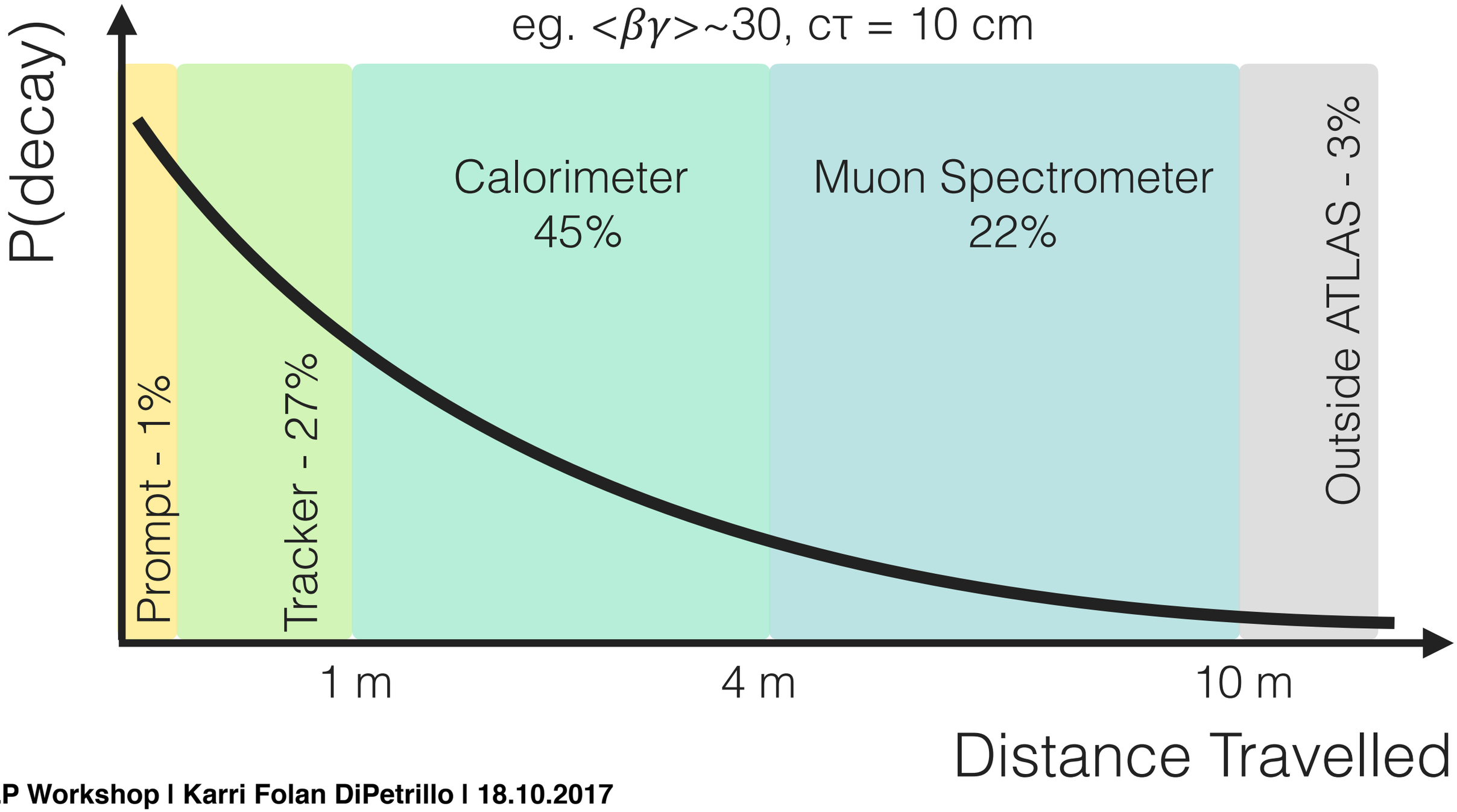
What lifetimes can we probe?

Any given particle's lifetime is sampled from an exponential

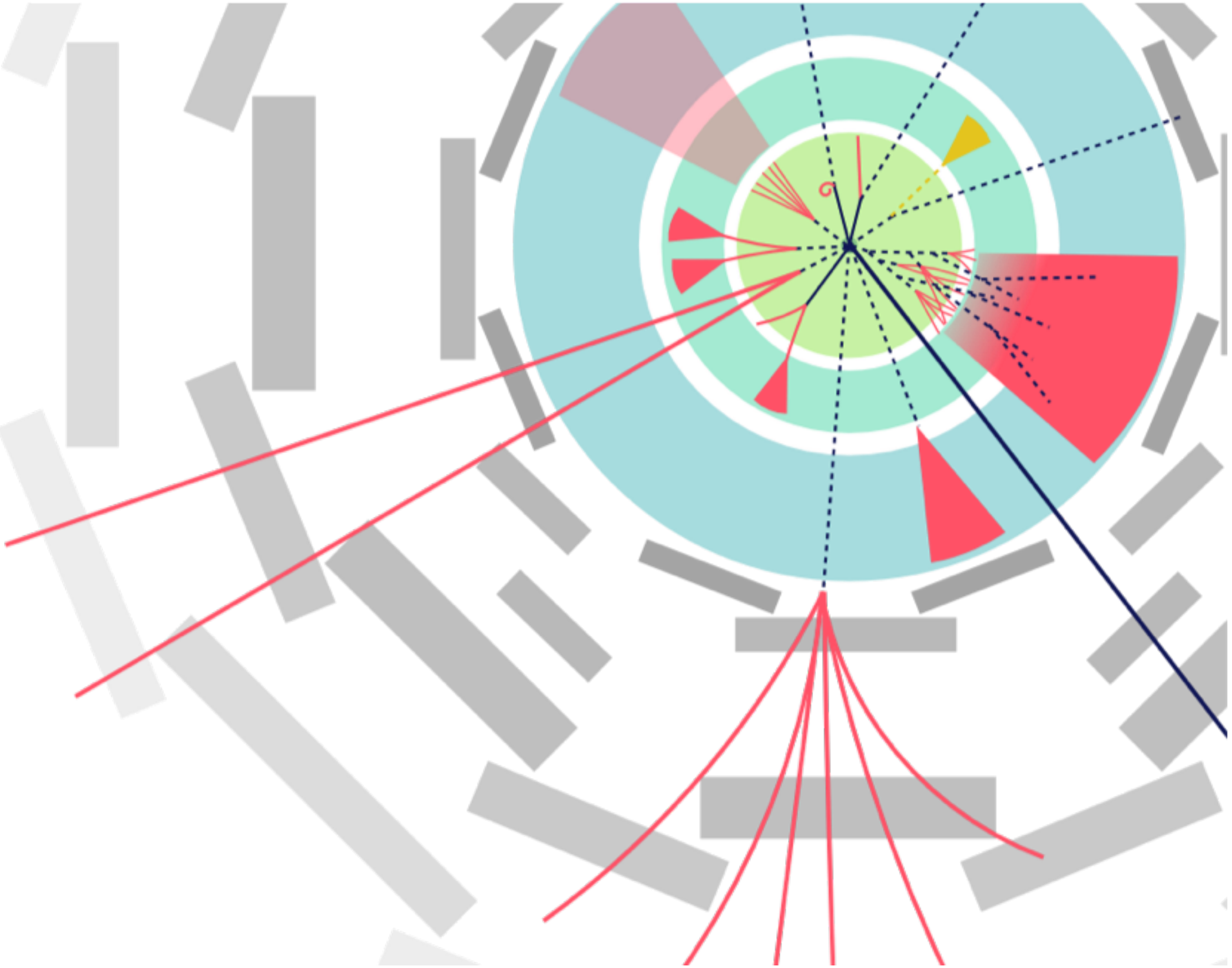


What lifetimes can we probe?

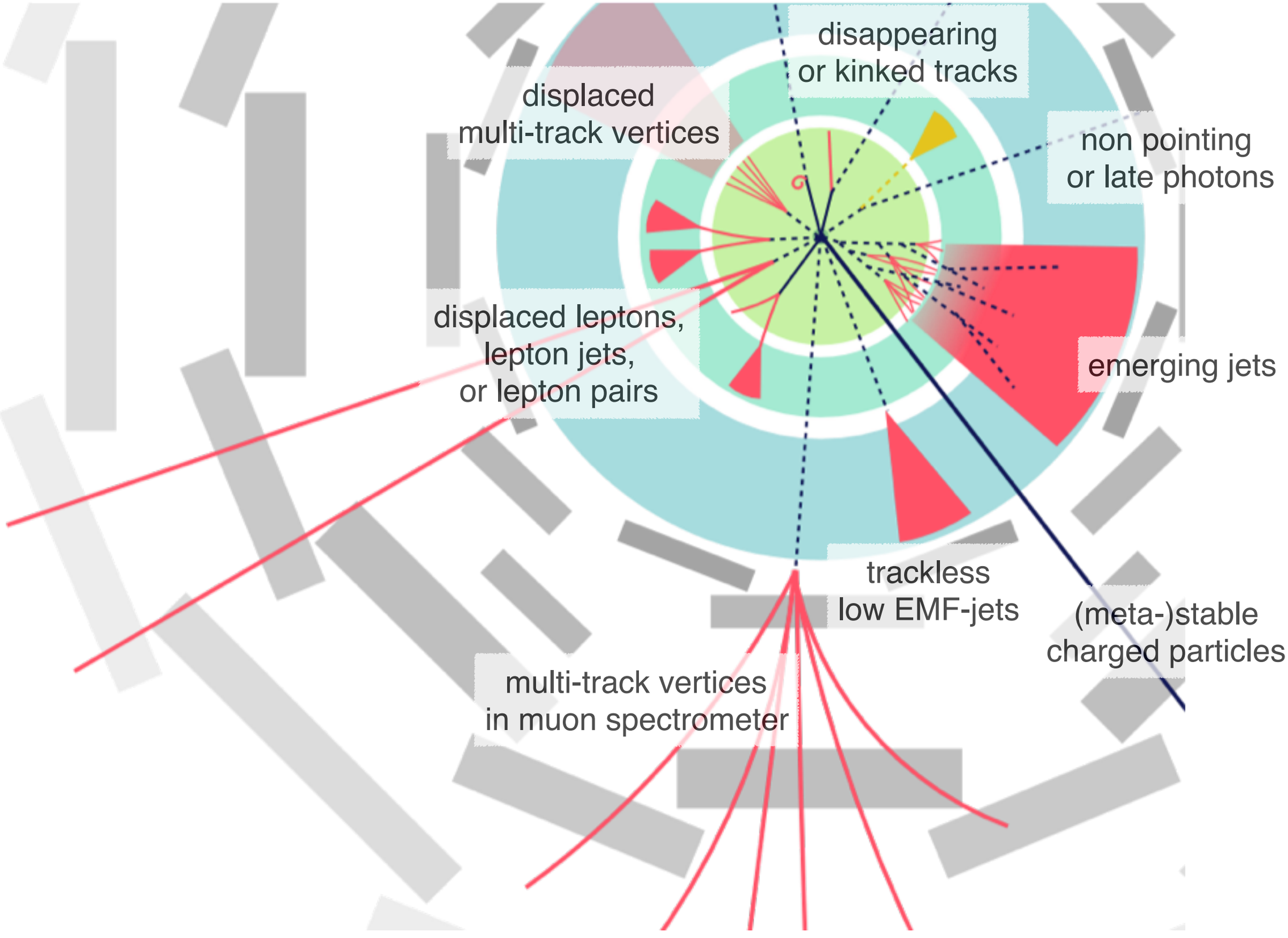
Sometimes we can target specific lifetimes using certain parts of the detector



What final states can we probe?



What final states can we probe?



How do we trigger on these objects?

ATLAS trigger basics

- L1: calorimeter & muon information
- HLT: e/μ/γ/τ/jets/MET
- limited tracking info at HLT
- typically d0 requirements on e/μ

Is there room for improvement?
Many HLT ideas limited by L1 constraints

15:20 **ATLAS Fast TracKer (FTK) -- Info, status, and prospects**
Speaker: Tova Ray Holmes (University of Chicago (US))

15:40 **ATLAS Fast TracKer (FTK) -- Overview of triggering constraints**
Speaker: Lesya Horyn (University of Chicago (US))

LLP Strategies

very hard

1. Design your own
displaced lepton jets:
"narrow scan" and
"cal ratio"

2. Be sneaky
displaced e: γ trigger
displaced μ: Muon
Spectrometer only trigger

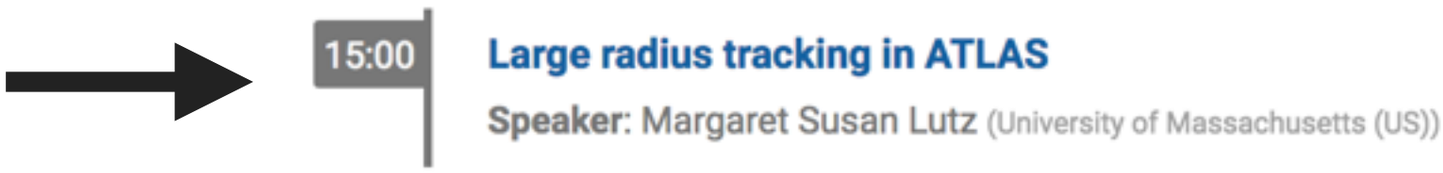
3. Be lucky
Inner Detector displaced
vertices: multi-jet/MET

very easy

How do we reconstruct these signatures?

Lots of work in non-standard reconstruction

- Pixel tracklets
- Large radius tracking
- Slow muons
- Secondary Vertex finding

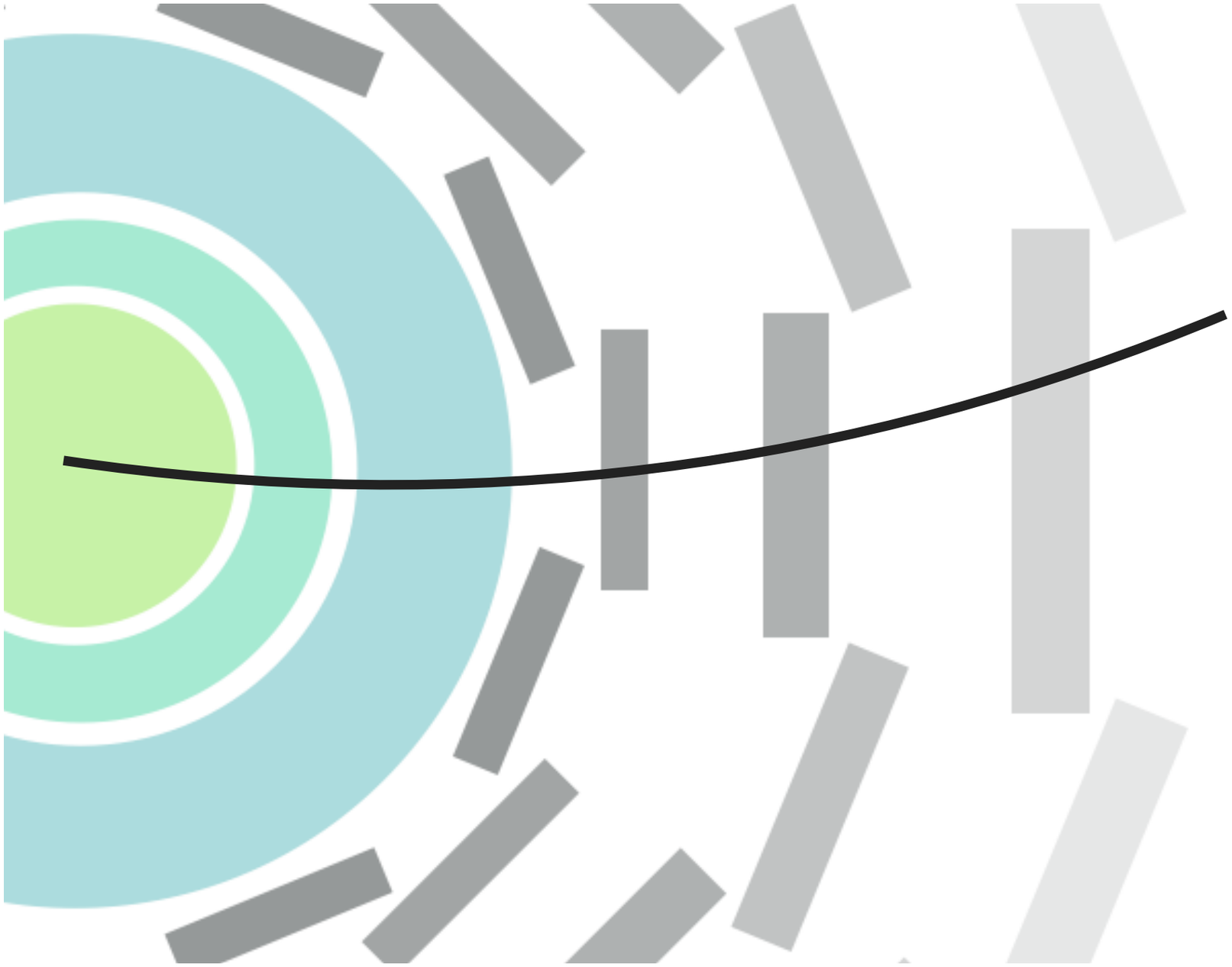


These methods are difficult, but essential

- computationally expensive
- require running on raw data
- filter out events using special data streams
- so we can run our non-standard reconstruction a single time

ATLAS LLP Searches

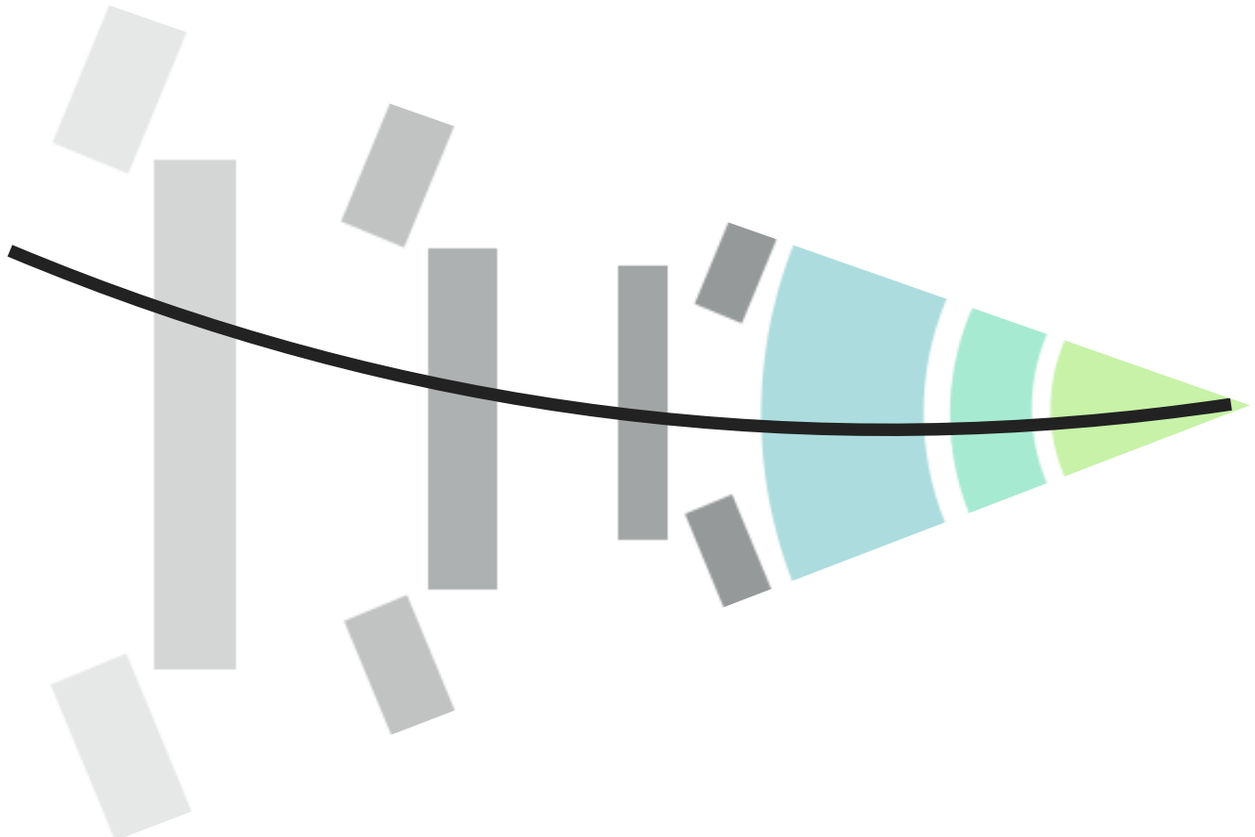
(Meta-)Stable Massive Charged Particles

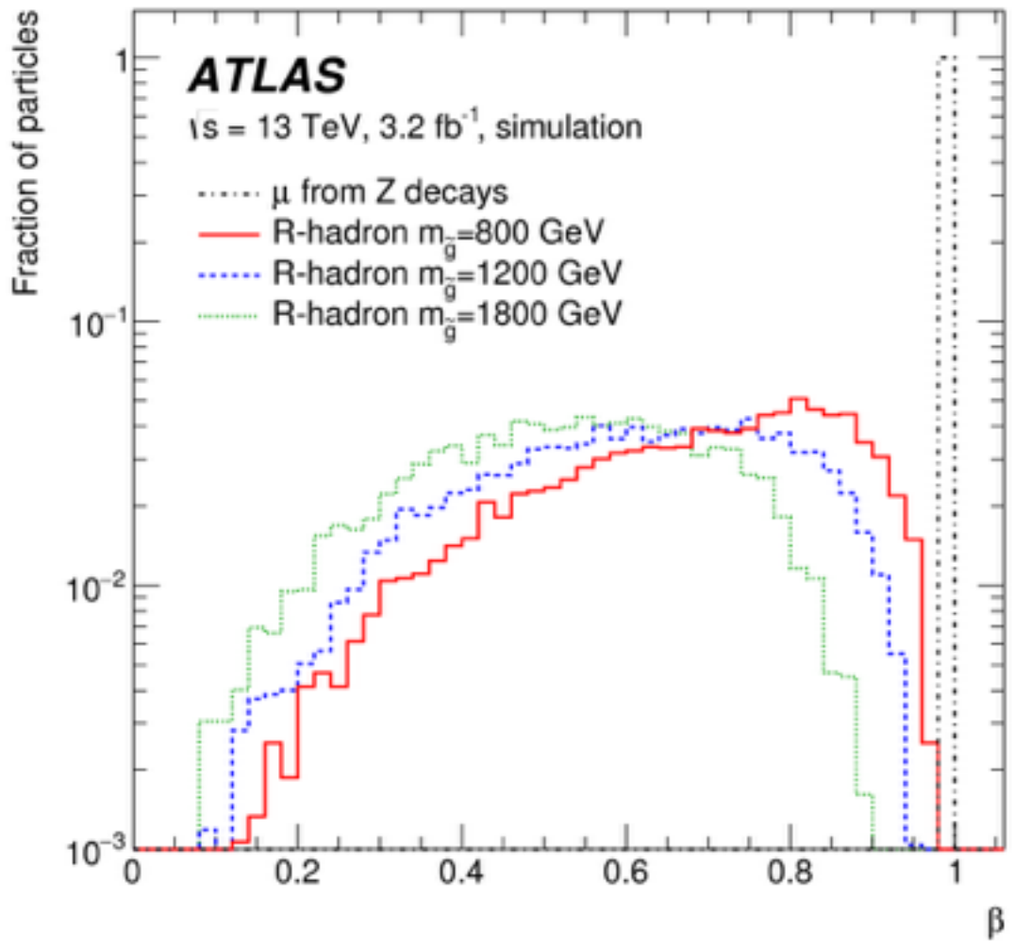


(Meta-)Stable Massive Particles

Charged particles with lifetimes ~ 0.4 ns or more

- interaction of charged particles w/ detector
- particles are ***s l o w*** and **highly ionizing**





What ATLAS can do

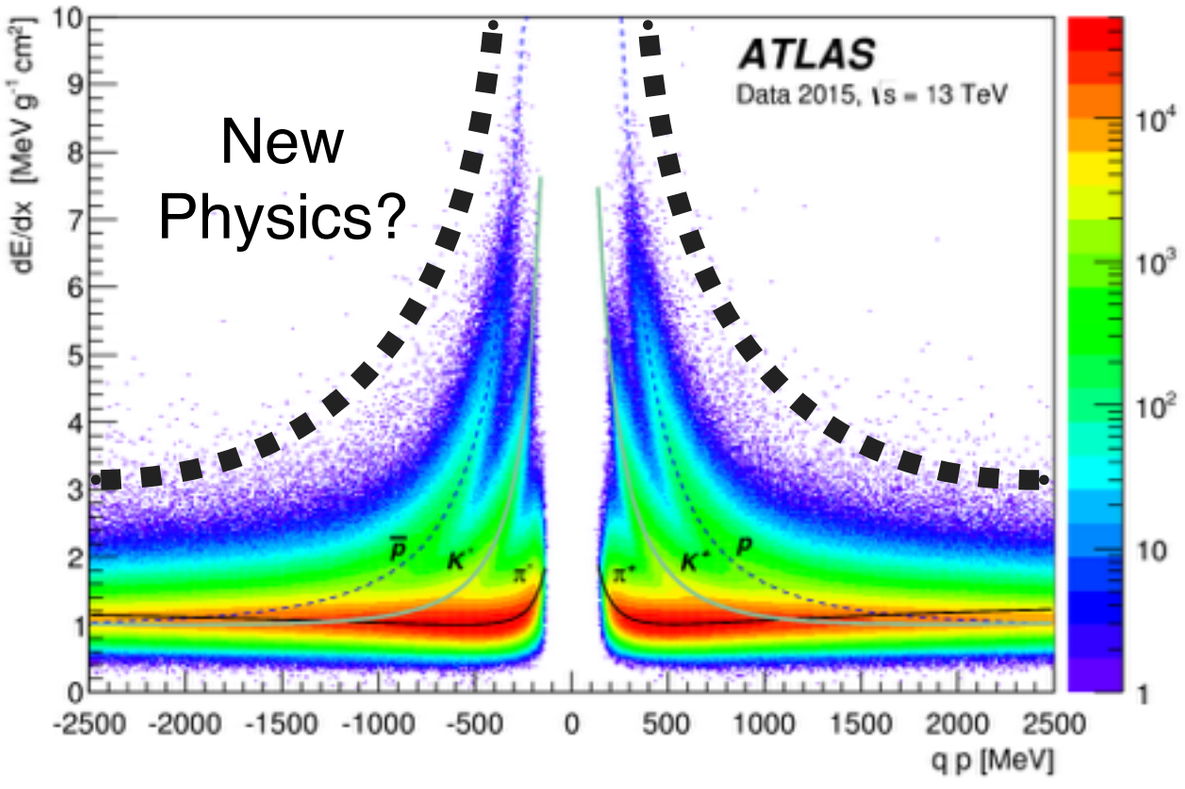
- Pixel Detector: specific ionization from clusters, dE/dx → $\beta\gamma$
- Calorimeters & Muon Spectrometer: timing, ToF → β

Pixel dE/dx

PRD 93 (2016) 112015
13 TeV 3.2 fb^{-1}

Measure $\beta\gamma$ from dE/dx with pixel clusters

- sensitive to $\beta\gamma$ between 0.3 and 1.5

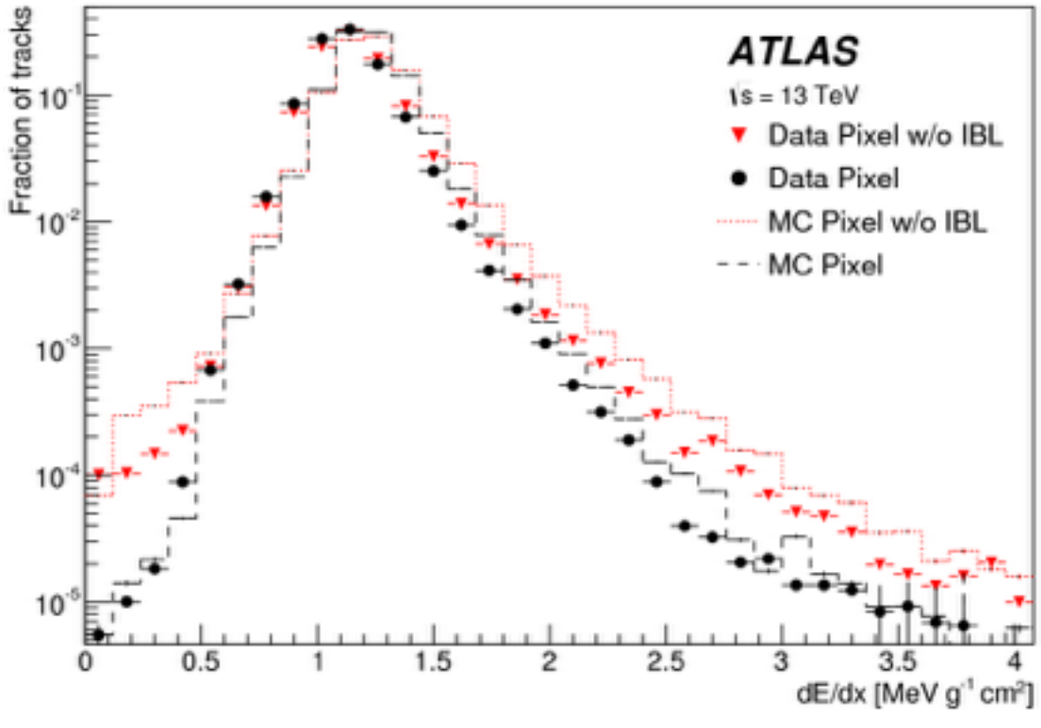


Can't trigger on inner detector tracks…

use MET trigger

Improvements in Run 2

- IBL reduces dE/dx Tails
- Better electron/muon rejection



Pixel + Tile Calorimeter

Make a mass estimate using

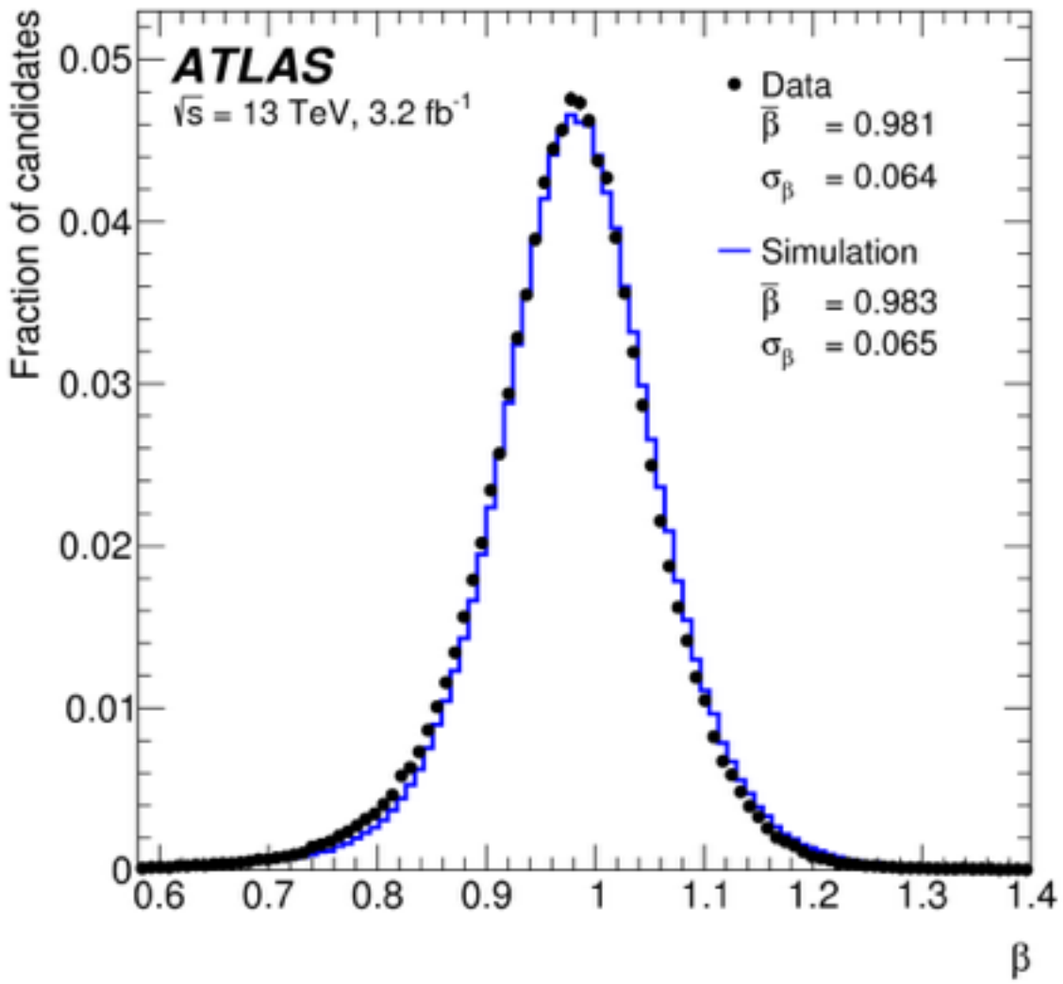
- Pixel dE/dx
- Tile time of flight

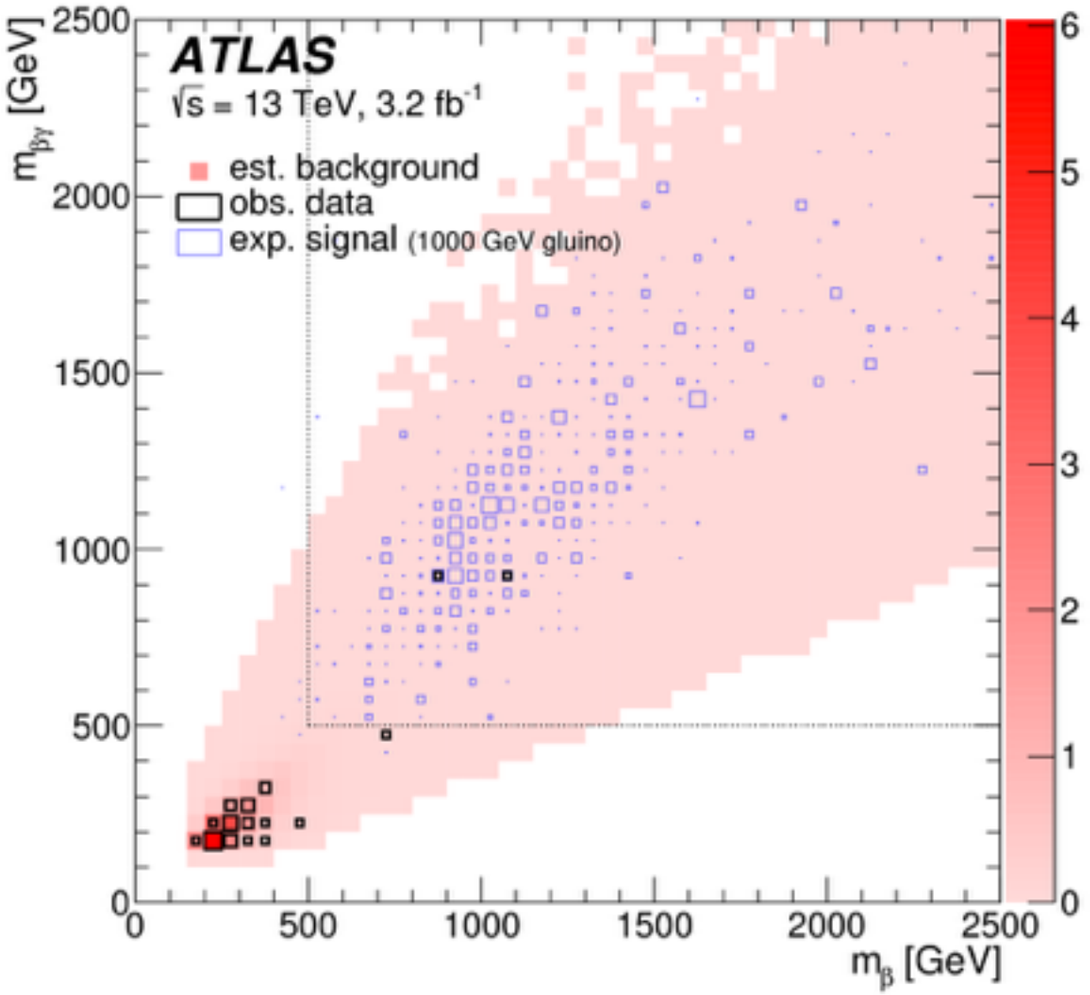
Tile cell timing resolution: 1.3-2.5 ns after calibration

β resolution: $\sigma(\beta)$~ 0.1

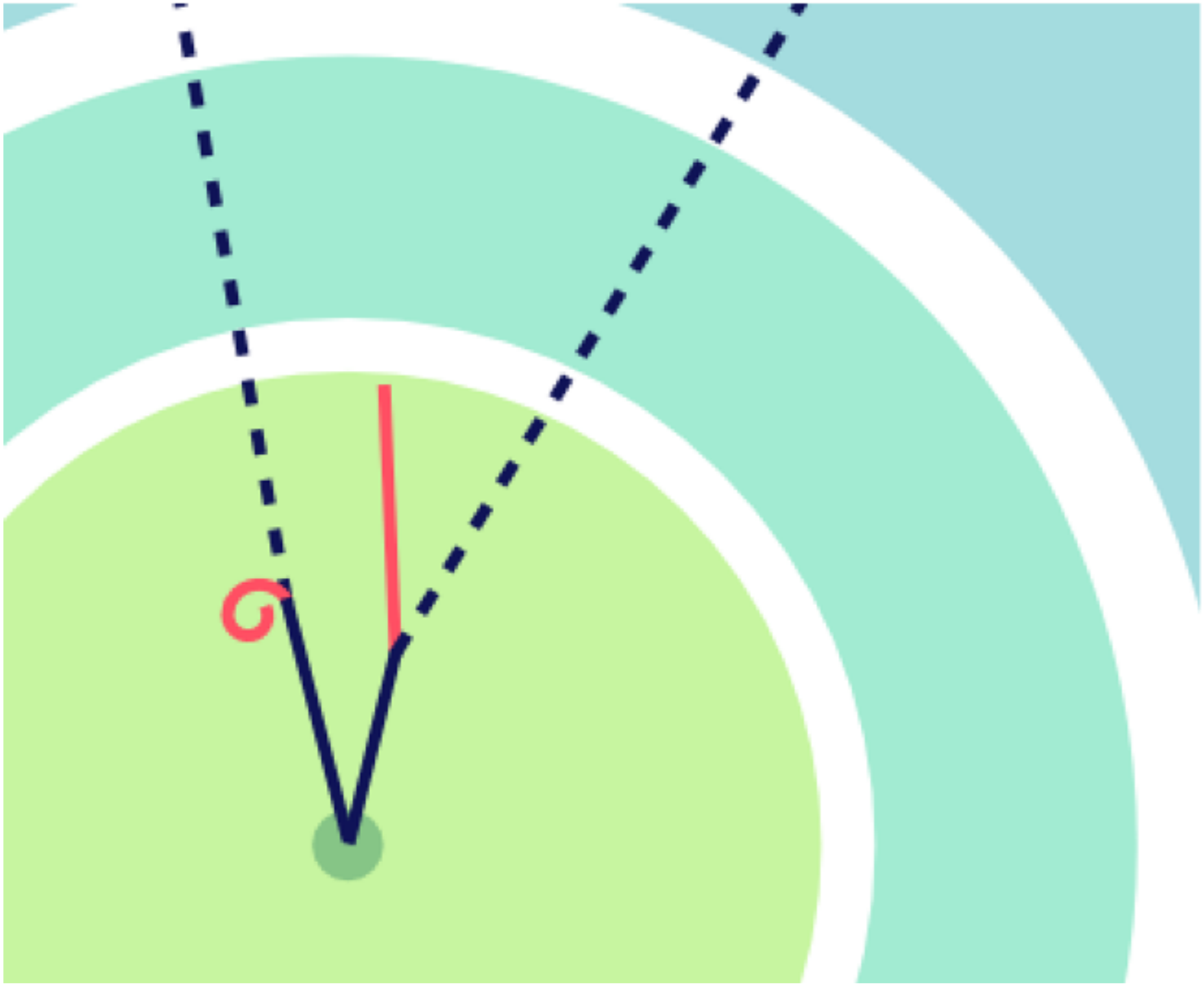
PLB 760 (2016) 647-665
13 TeV 3.2 fb^{-1}

JHEP 01 (2015) 068
8 TeV 19.1 fb^{-1}
ToF from Muon Spectrometer not yet used in Run 2!





Decays in the Inner Detector
Tracking Tricks

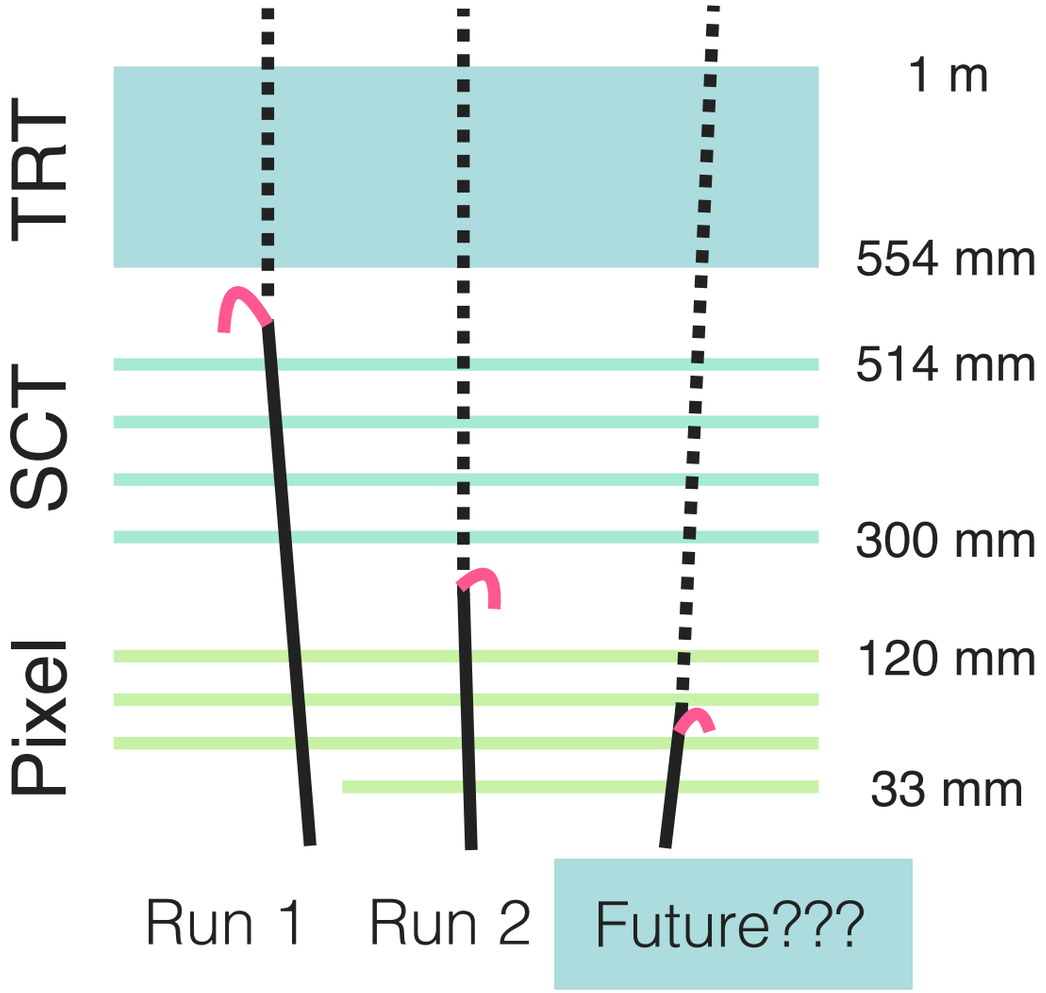


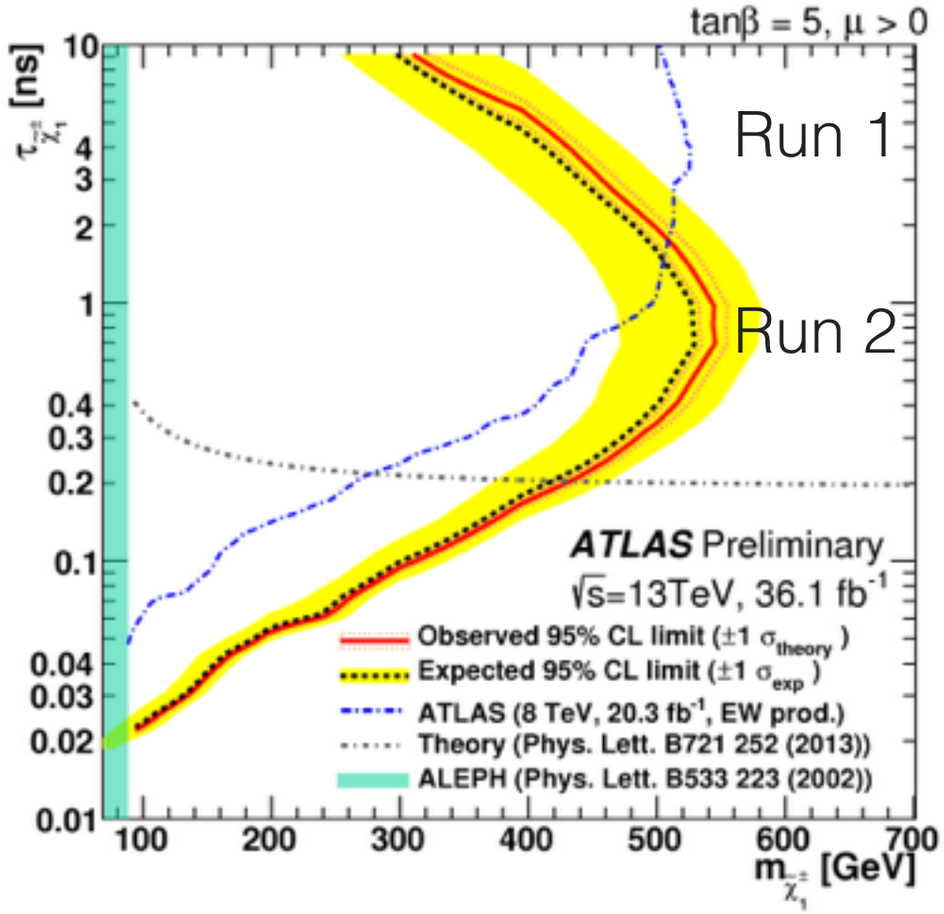
Disappearing Tracks

ATLAS-CONF-2017-017
13 TeV 36 fb^{-1}

Signature of small mass splittings

charged LLP → heavy neutral stable particle
+ undetected SM particle



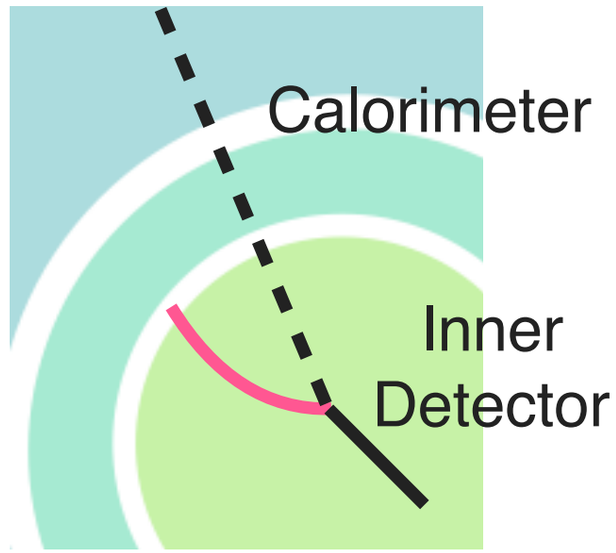


Triggering is difficult : use other objects in the event
(MET and 1 offline jet)

Kinked Tracks/Displaced Leptons

similar to displaced track scenarios, but the secondary charged particle can be reconstructed

charged LLP → neutral stable particle
+ *reconstructed* charged particle

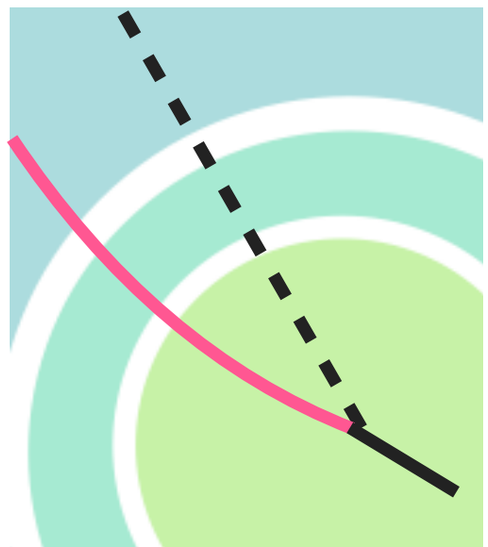


1. Kinked tracks

both tracks must have pT > 1 GeV
similar trigger difficulties as disappearing track

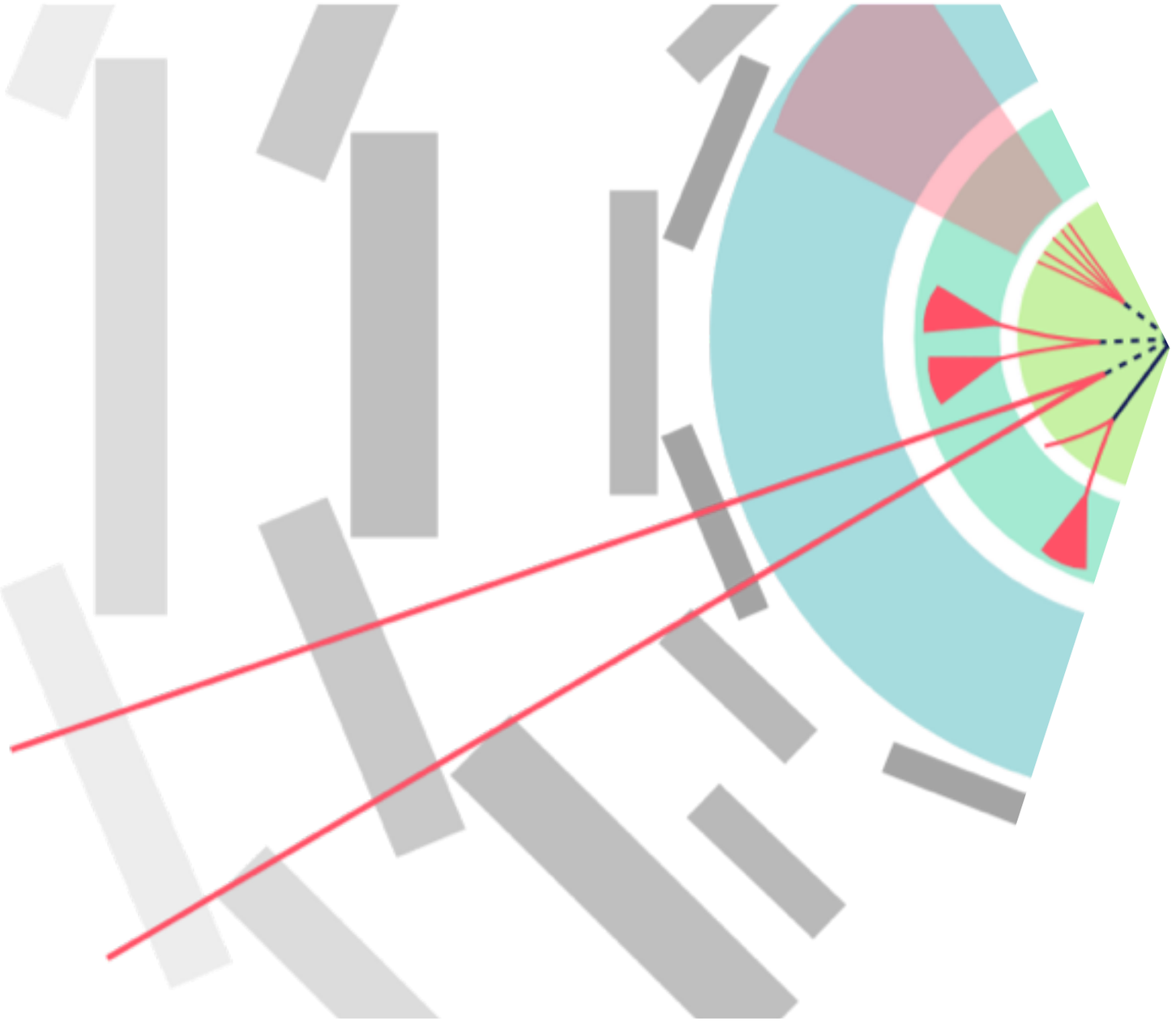
2. Displaced Leptons

at higher pT leptons can trigger the event
using charged LLP track likely unnecessary



We haven't done these searches!
but I think we could

Decays in the Inner Detector
Displaced Vertices



Displaced di-lepton vertices

Leptonic decays with inner detector displaced vertices

use large-d0 tracking and secondary vertex finding
to find displaced vertices in pixel barrel
require DV mass > 10 GeV and 2 leptons

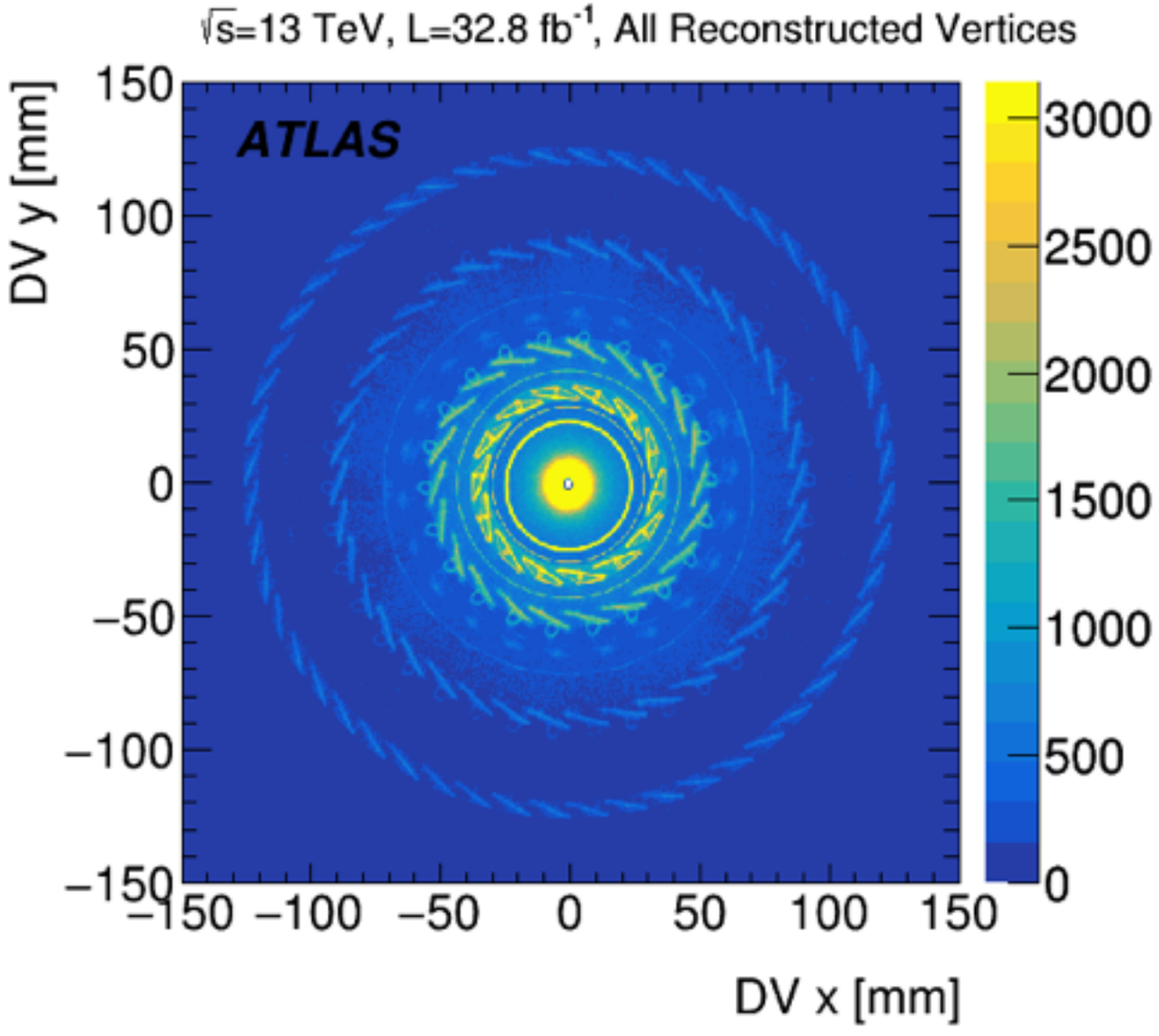
Use the leptons to trigger

γ trigger on displaced electrons
Muon Spectrometer only trigger for displaced muons

Non-standard Backgrounds

cosmics, random crossings,
material interactions

PRD 92 (2015) 072004
8 TeV 20.3 fb^{-1}



Multi-track displaced vertices

arXiv:1710.04901
13 TeV 33 fb^{-1}
Run 2: DV+MET

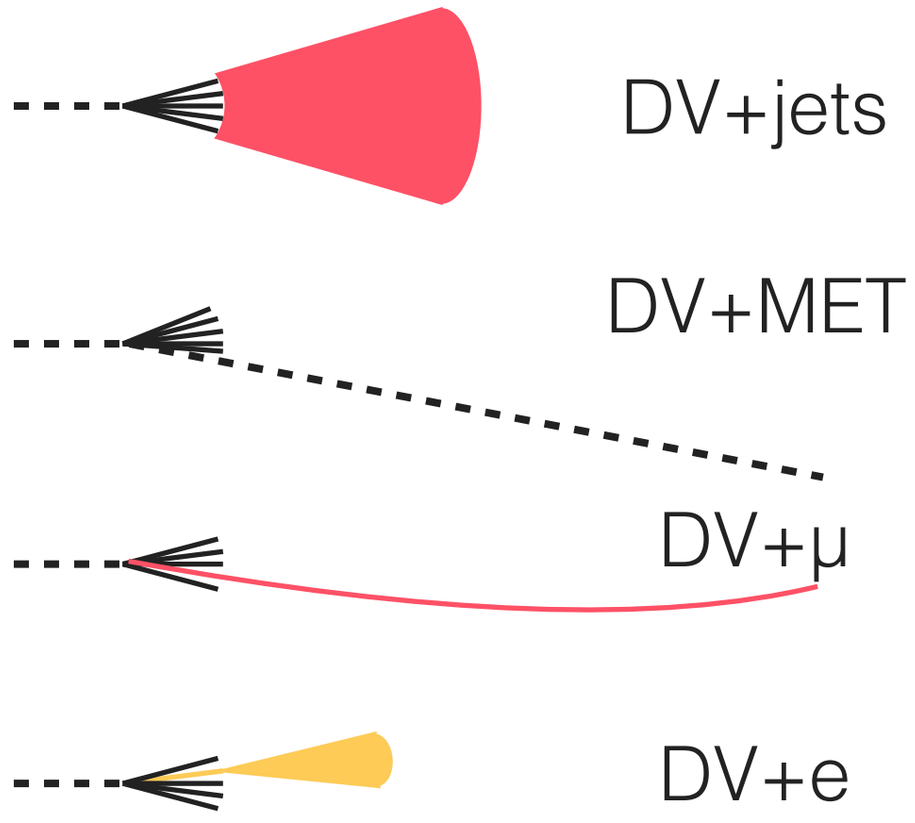
PRD 92 (2015) 072004
8 TeV 20.3 fb^{-1}
Run 1: DV+e/μ, DV+jets, DV+MET

Looking for displaced hadronic decays w/ a multi-track vertex signature

using large-d0 tracking & secondary vertex finding
require DV mass > 10 GeV and ≥ 5 tracks

Use other objects to trigger on the event

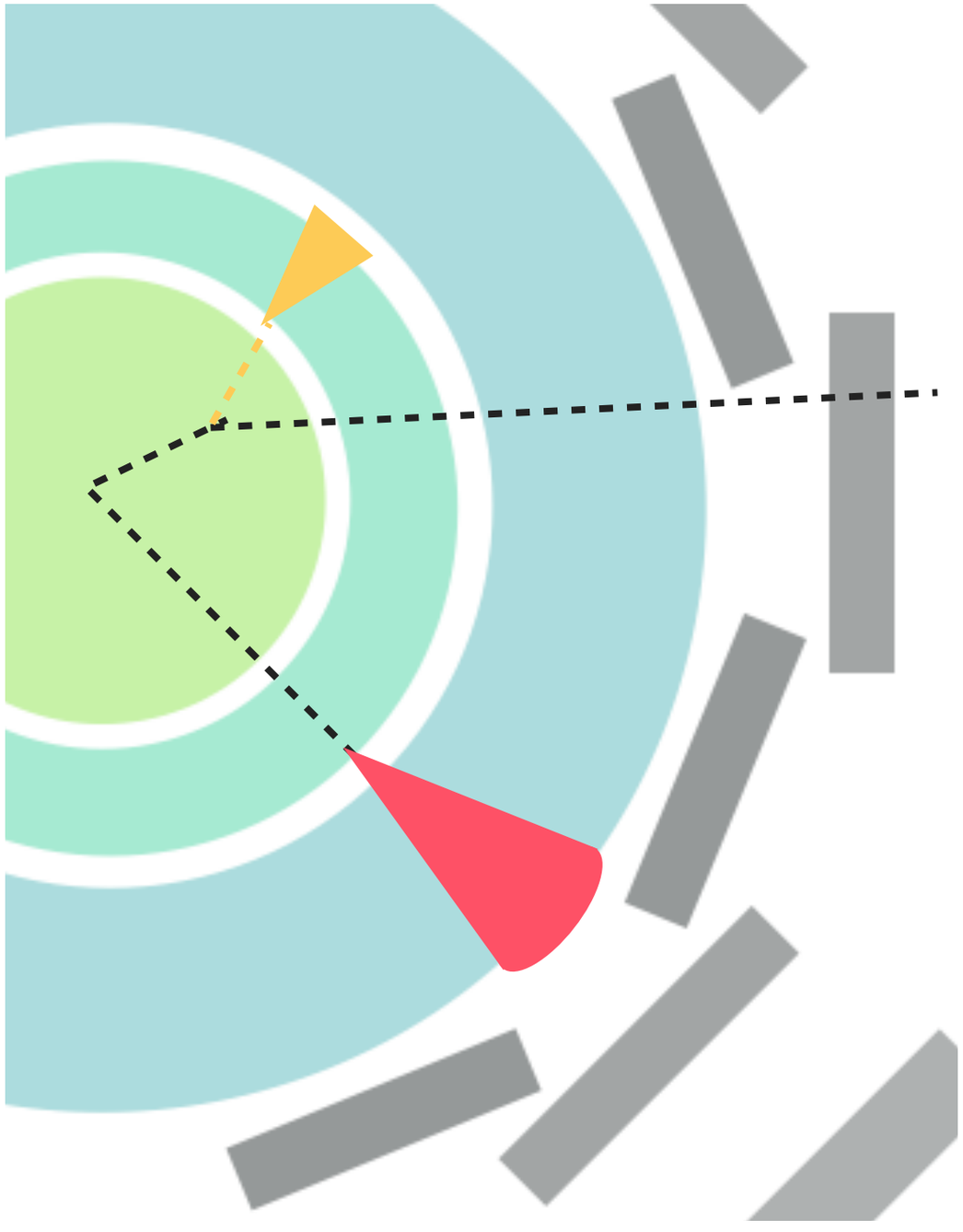
- standard MET & jet triggers
- muon spectrometer only trigger
- γ trigger for displaced e



Possible future improvements

- improve vertexing efficiency
- probe sensitivity to lower masses, fewer tracks
- probe shorter lifetimes, < 0.01 ns

Detecting Decays using the Calorimeter

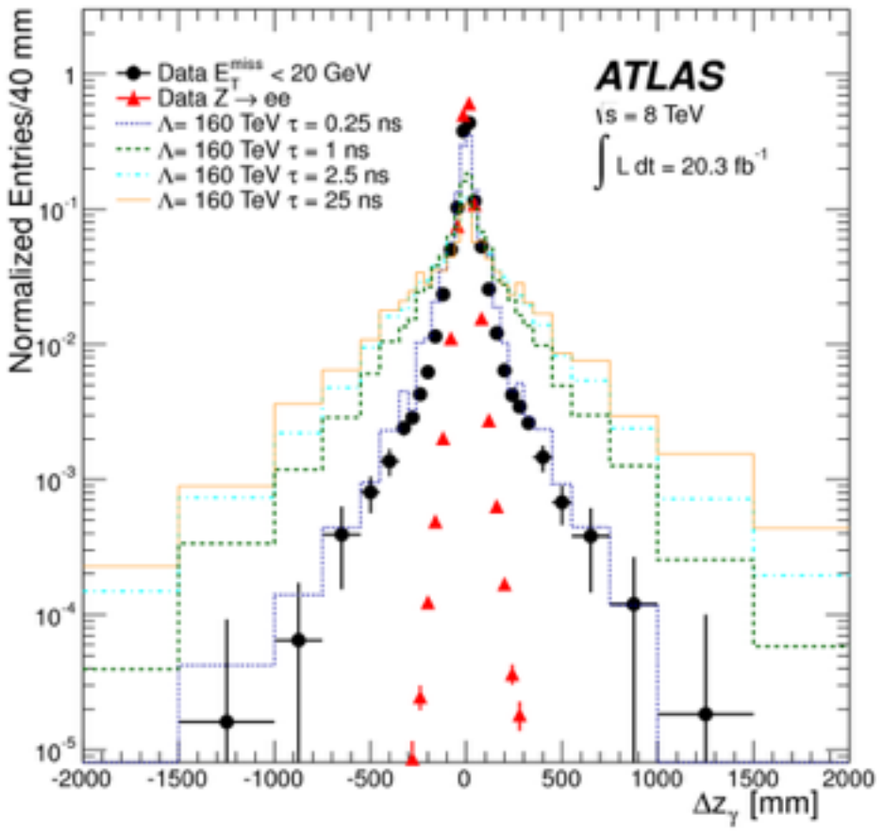


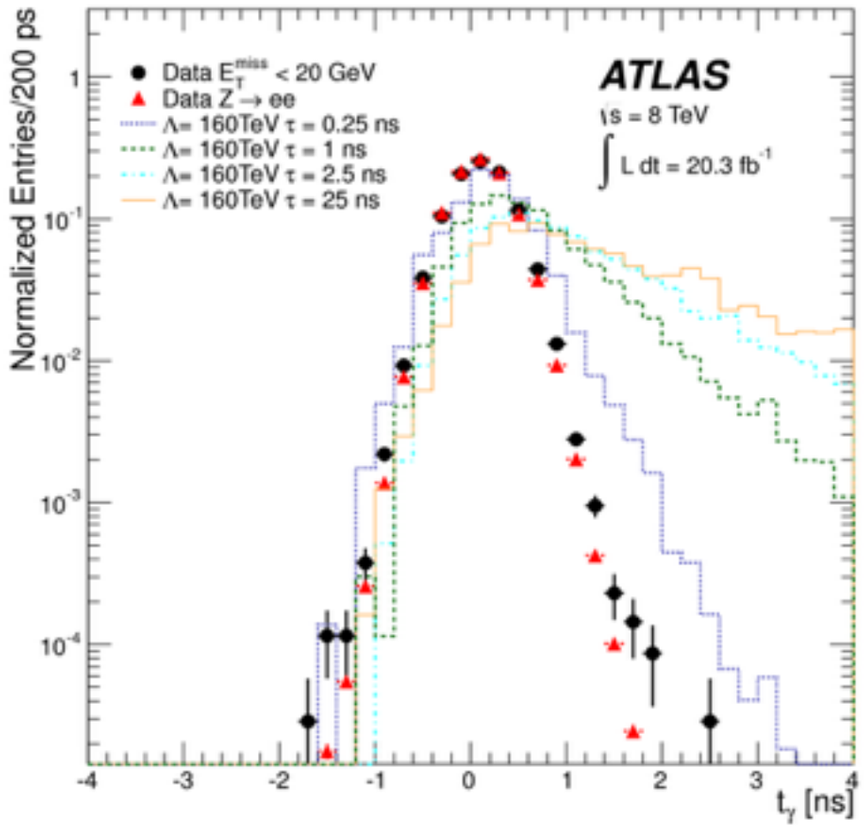
Non-Pointing/Delayed Photons

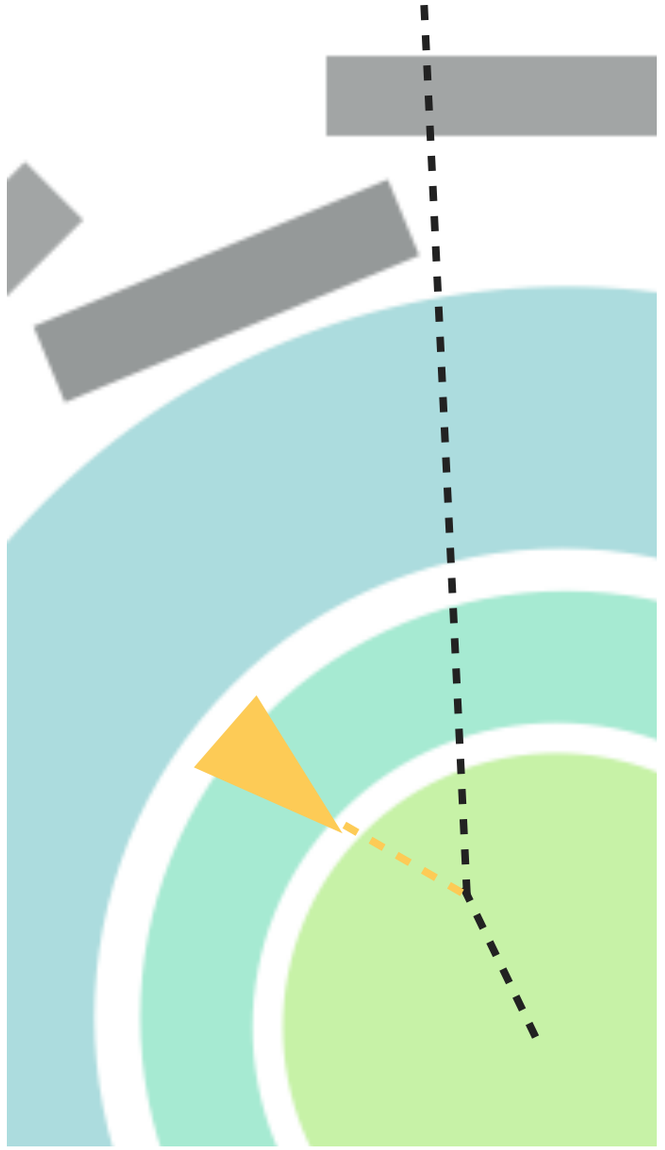
Targeted decay:

neutral LLP → photon + invisible particle
photon might not point back to the primary vertex
and/or arrive late compared to a prompt photon

PRD 90 (2014) 112005
8 TeV 20.3 fb^{-1}
Run 1: di-photon
+ MET Final State





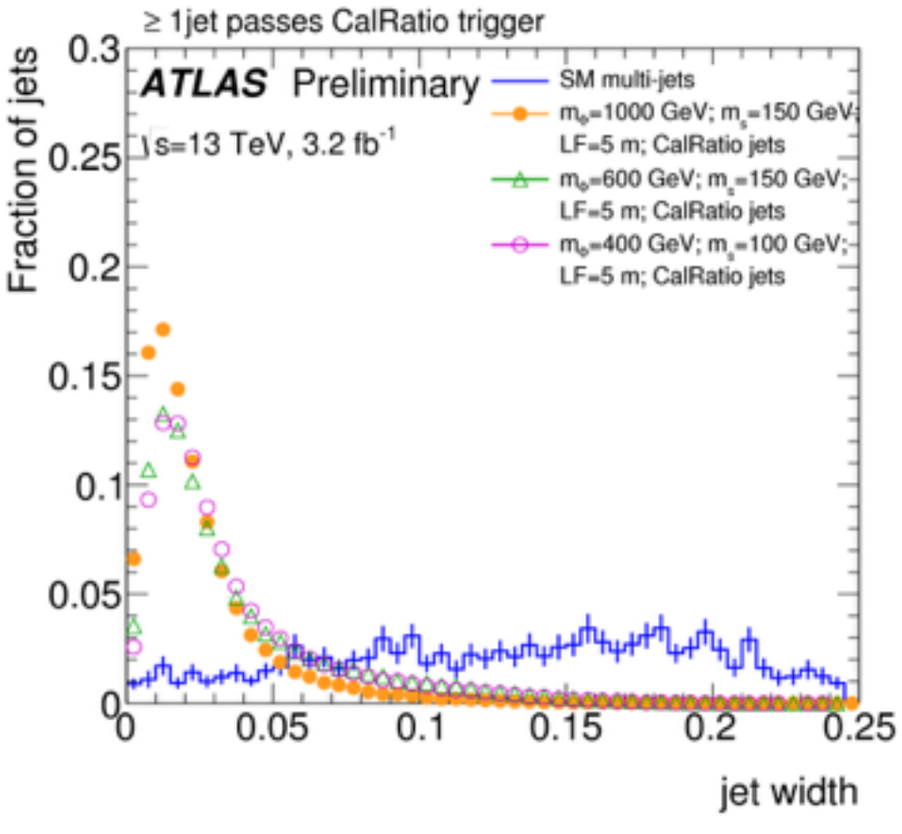


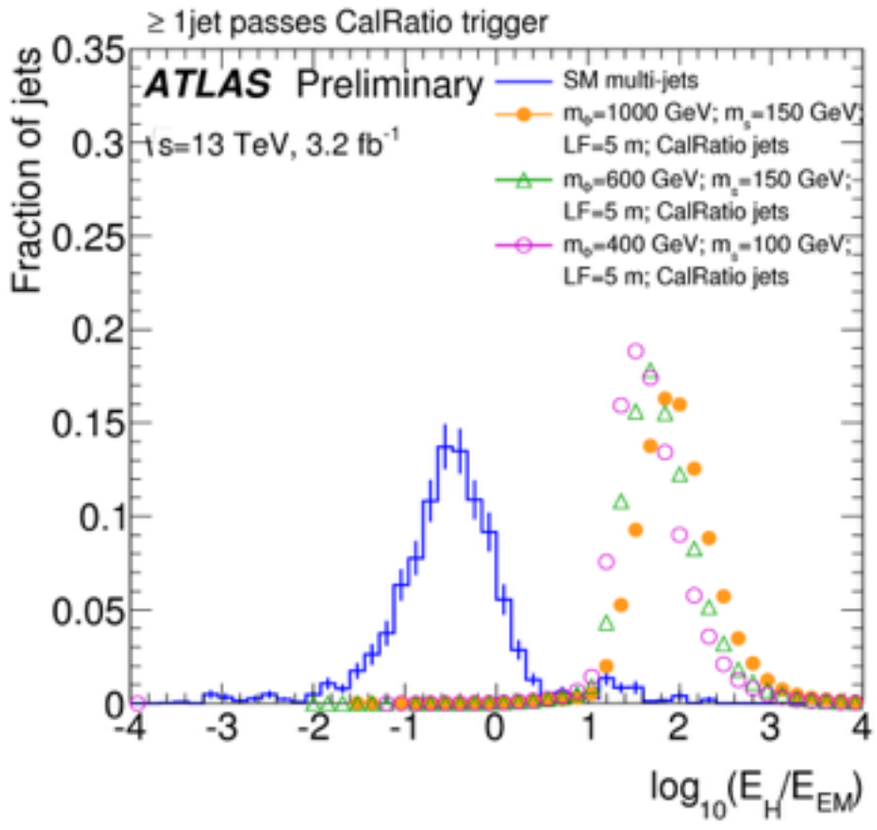
Reconstruction: LAr calorimeter can measure photon **pointing** & **ToF**

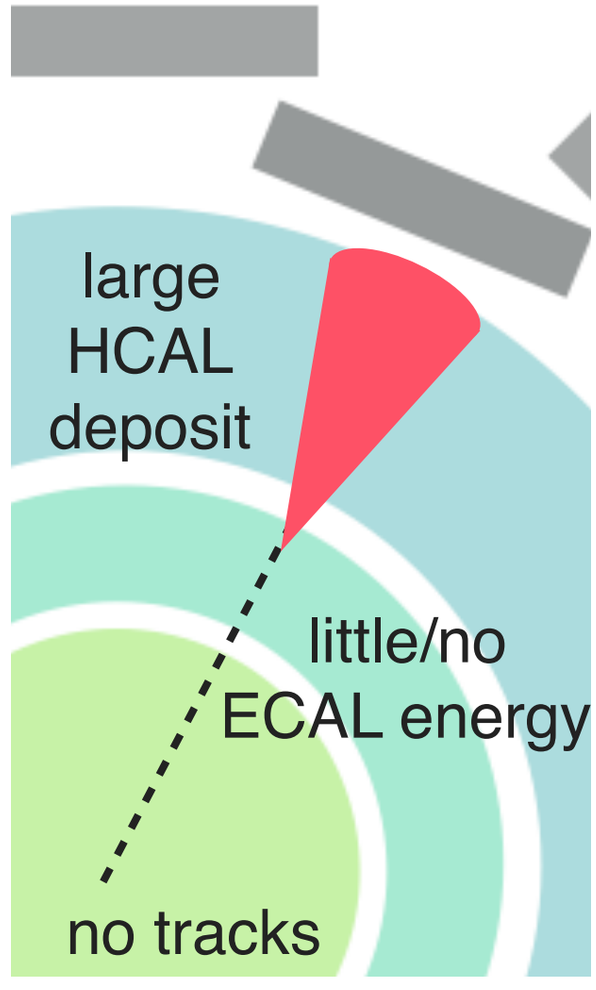
Displaced Jets - HCAL

Searching for long-lived particles decaying within the calorimeter

ATLAS-CONF-2016-103
13 TeV 3.2 fb^{-1}







Trigger: Low EMF trigger - L1Tau seed

Analysis improvements in Run 2

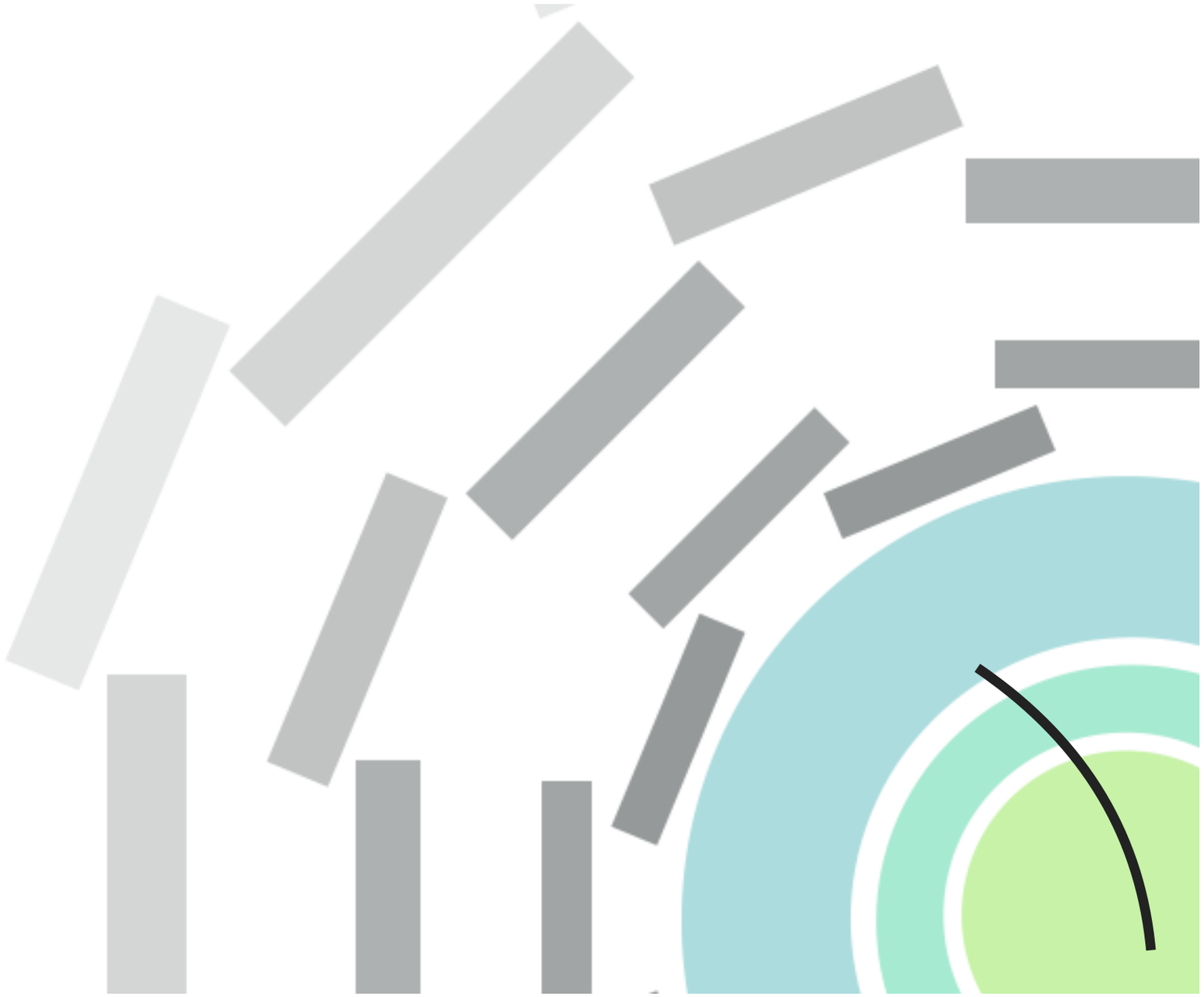
Boosted Decision Tree to select displaced jets

Backgrounds

SM multi-jet
cosmic muons
beam induced background

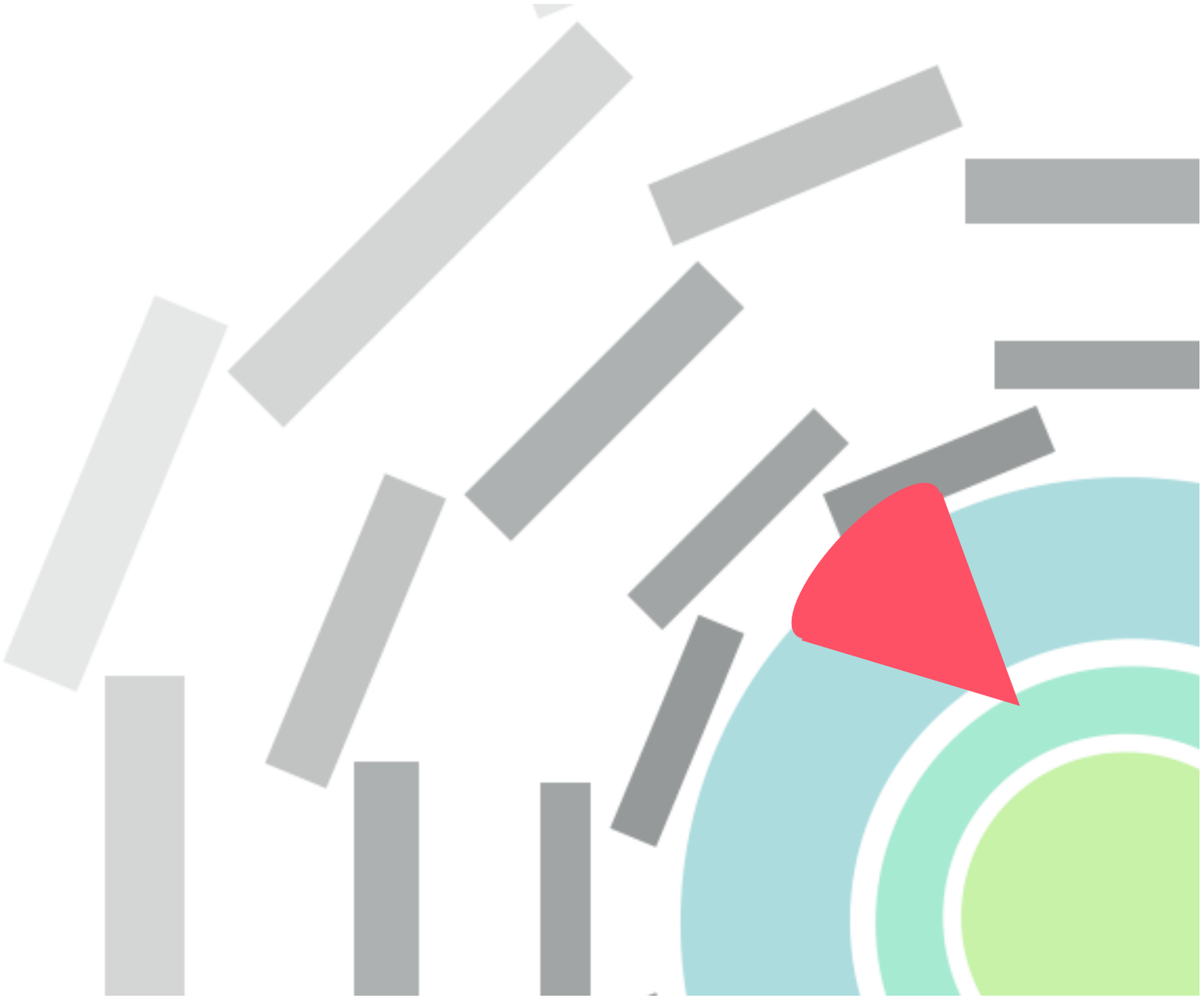
Stopped Particles

what happens when your particle moves so slowly it gets stopped by the calorimeter…



Stopped Particles

and decays later!



Stopped Particles

Looking for R-hadrons stopped by the calorimeter

probe lifetimes up to order hours/days/years
sensitive to very small β, neutral R-hadrons, and when charge flips prevent reconstruction

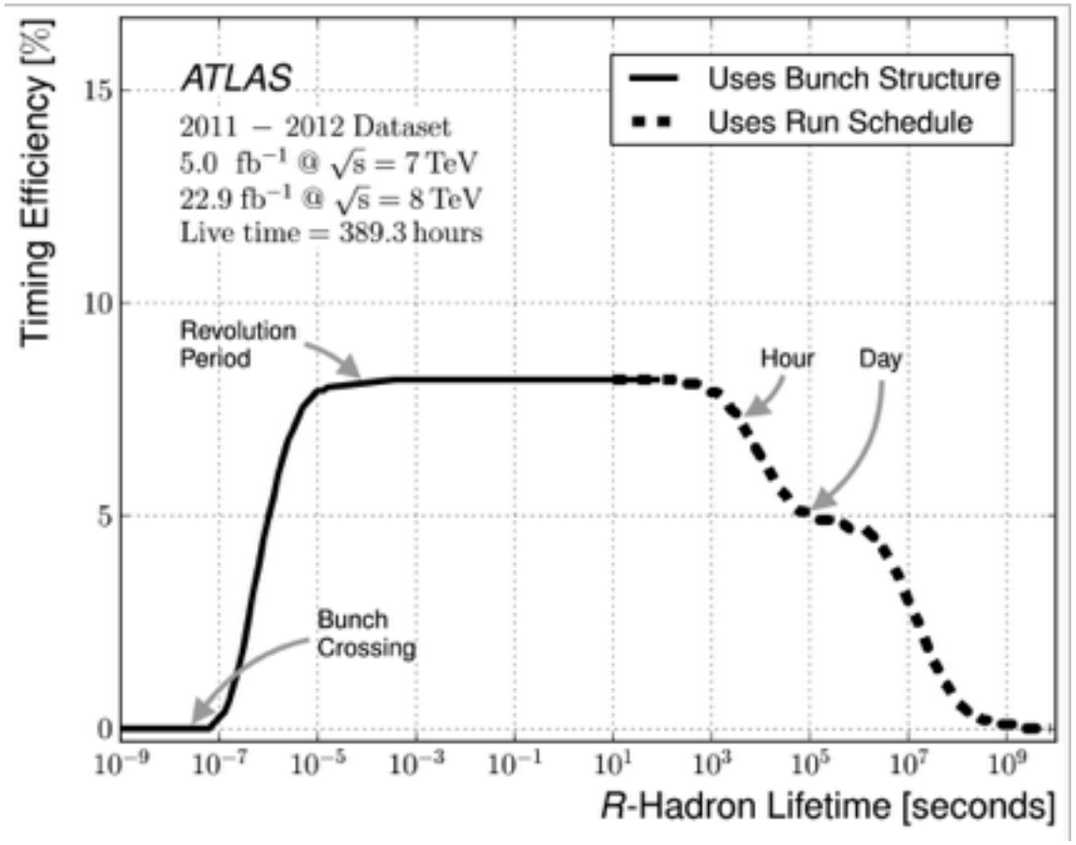
Trigger: empty bunch crossings

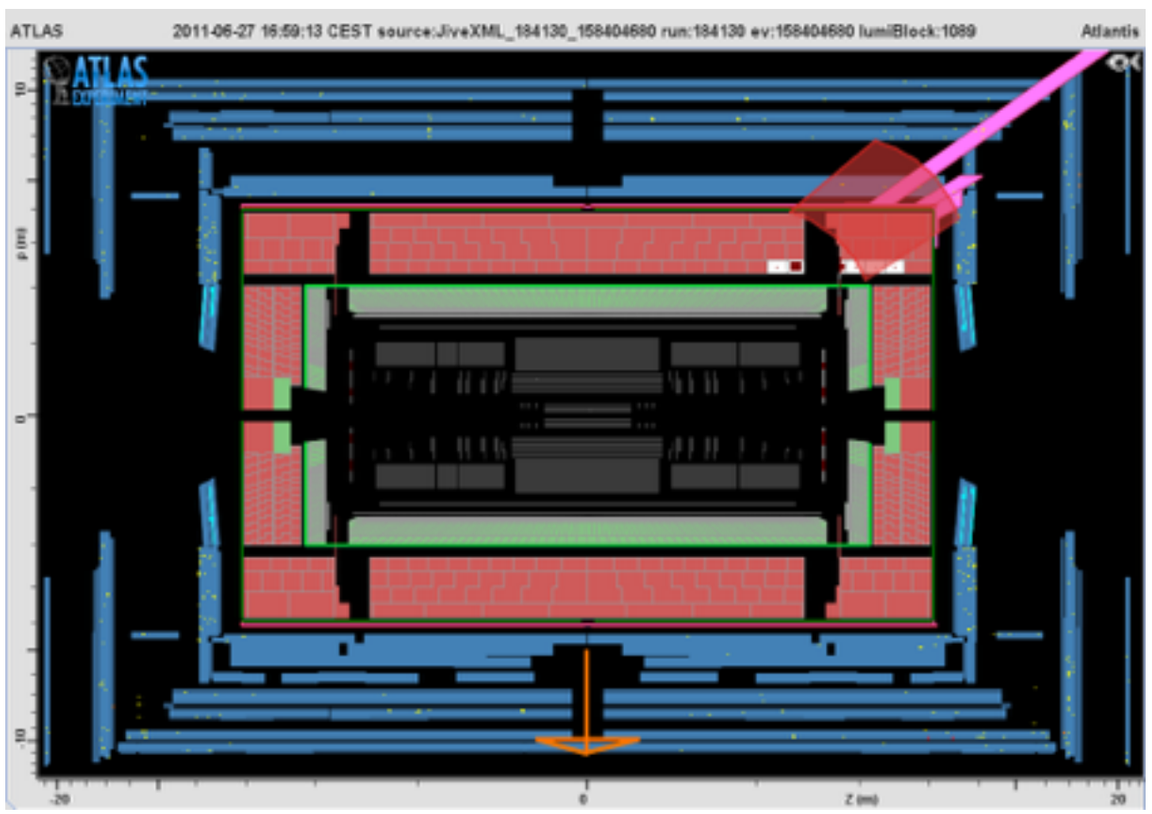
no bunches at the interaction point
require a low pT jet and Et-miss

Non-standard backgrounds:

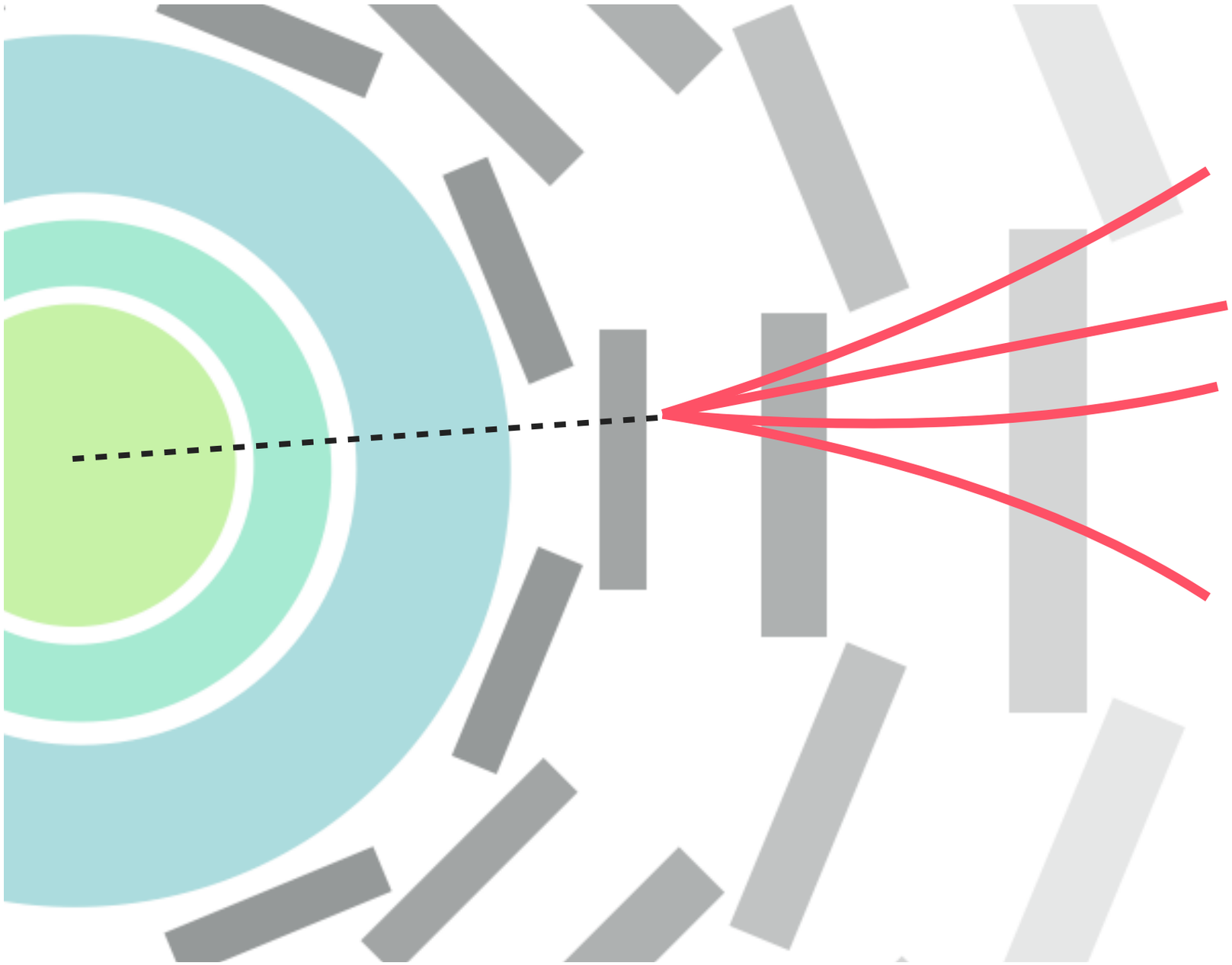
cosmic muons & beam-halo
veto on muon activity

PRD 88 (2013) 112003
8 TeV 27.9 fb^{-1}
not yet in Run 2!





Detecting Decays with the Muon Spectrometer



Displaced vertices in the muon system

PRD 92, 012010 (2015)
8 TeV 20.3 fb^{-1}

Run 1 Search for Displaced Hadronic Jets in MS and ID

Looking for displaced decays of hadronic jets

targets vertices between end of HCAL and start of 2nd MS station

Trigger: cluster of muon ROIs

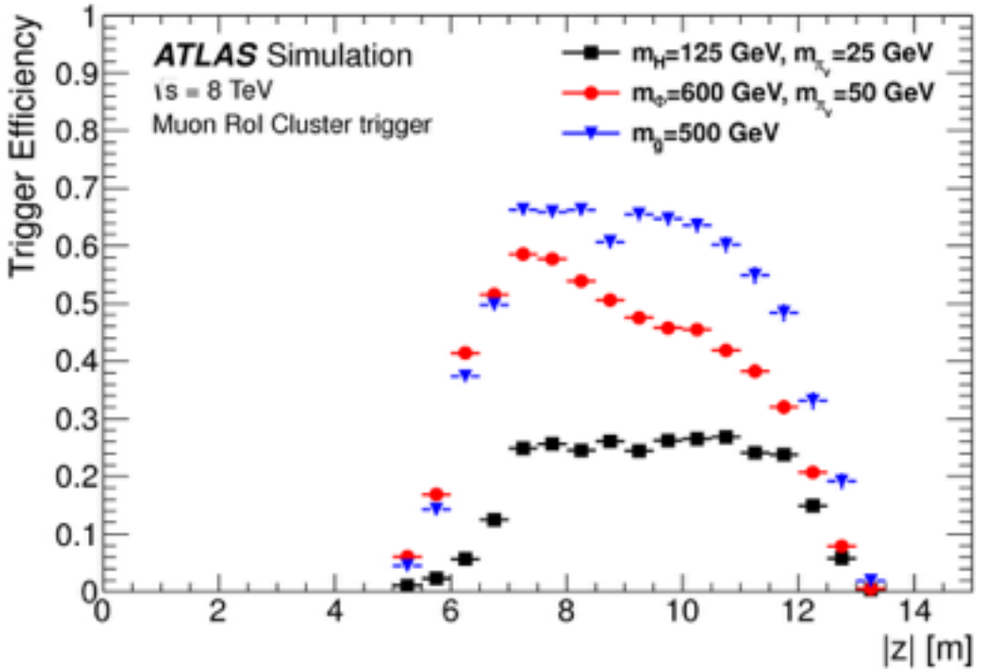
in a cone of $\Delta R < 0.4$
preceded by little ID & Calo activity

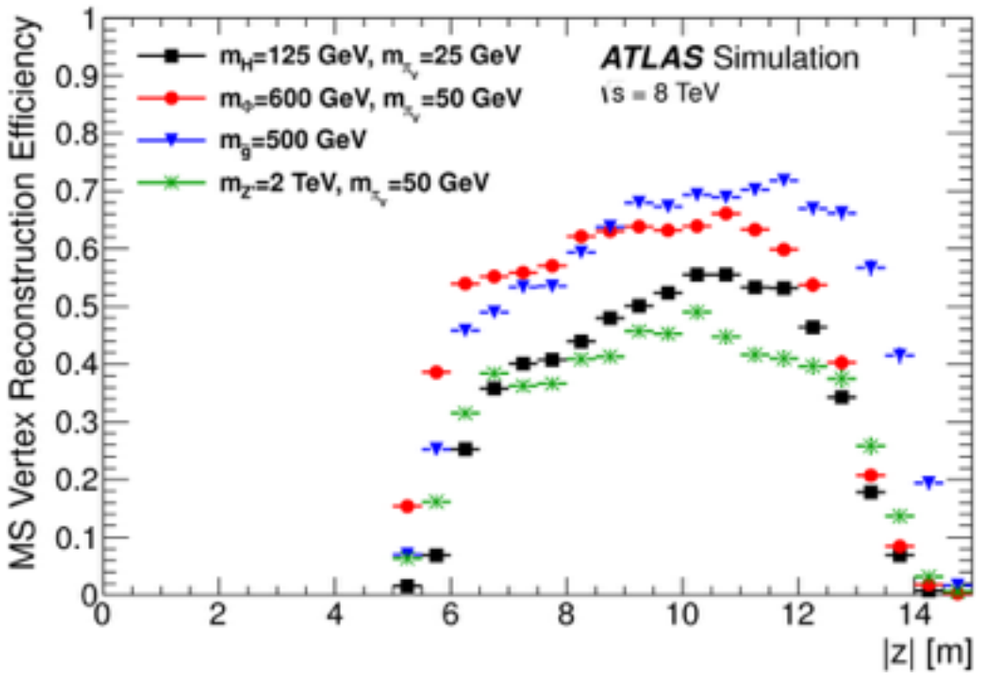
MS vertex reconstruction

muon segments → tracklets → vertices

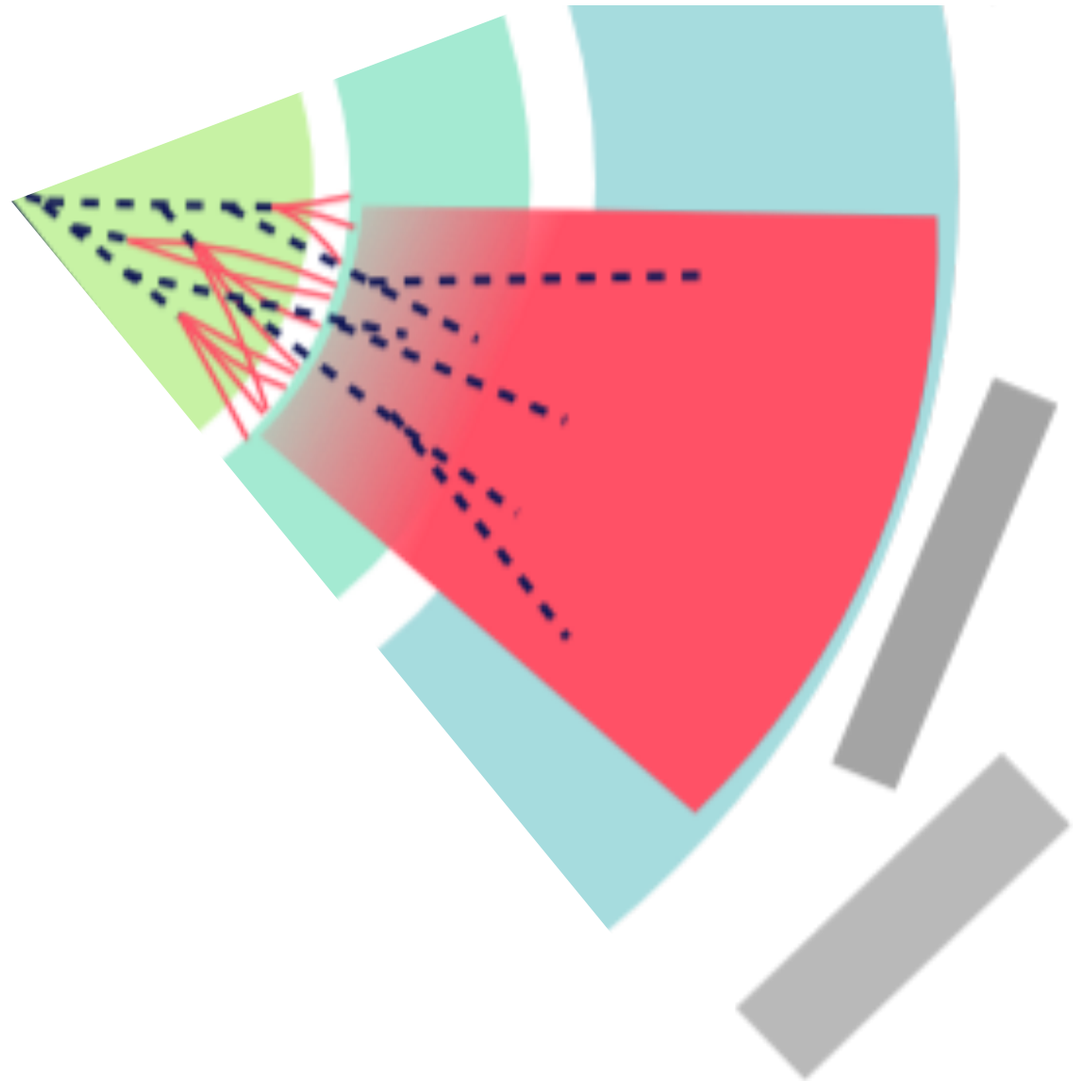
Backgrounds:

SM punch-through,
cosmics, and cavern background





Detecting Decays
with multiple subdetectors

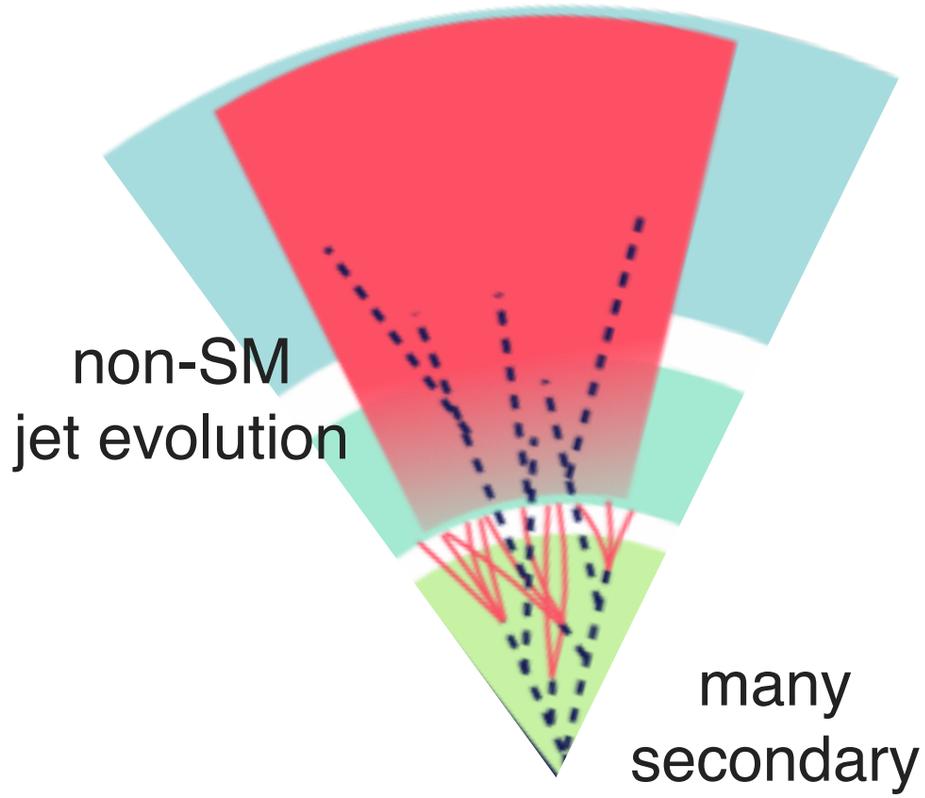


Emerging Jets

A new signature resulting from dark showers in QCD-like hidden sectors

Could get a handle on the event using high multiplicity of secondary vertices in the **Inner Detector** and non-standard jets in the **Calorimeter**

Jet slowly **emerges** as LLPs decay to SM particles

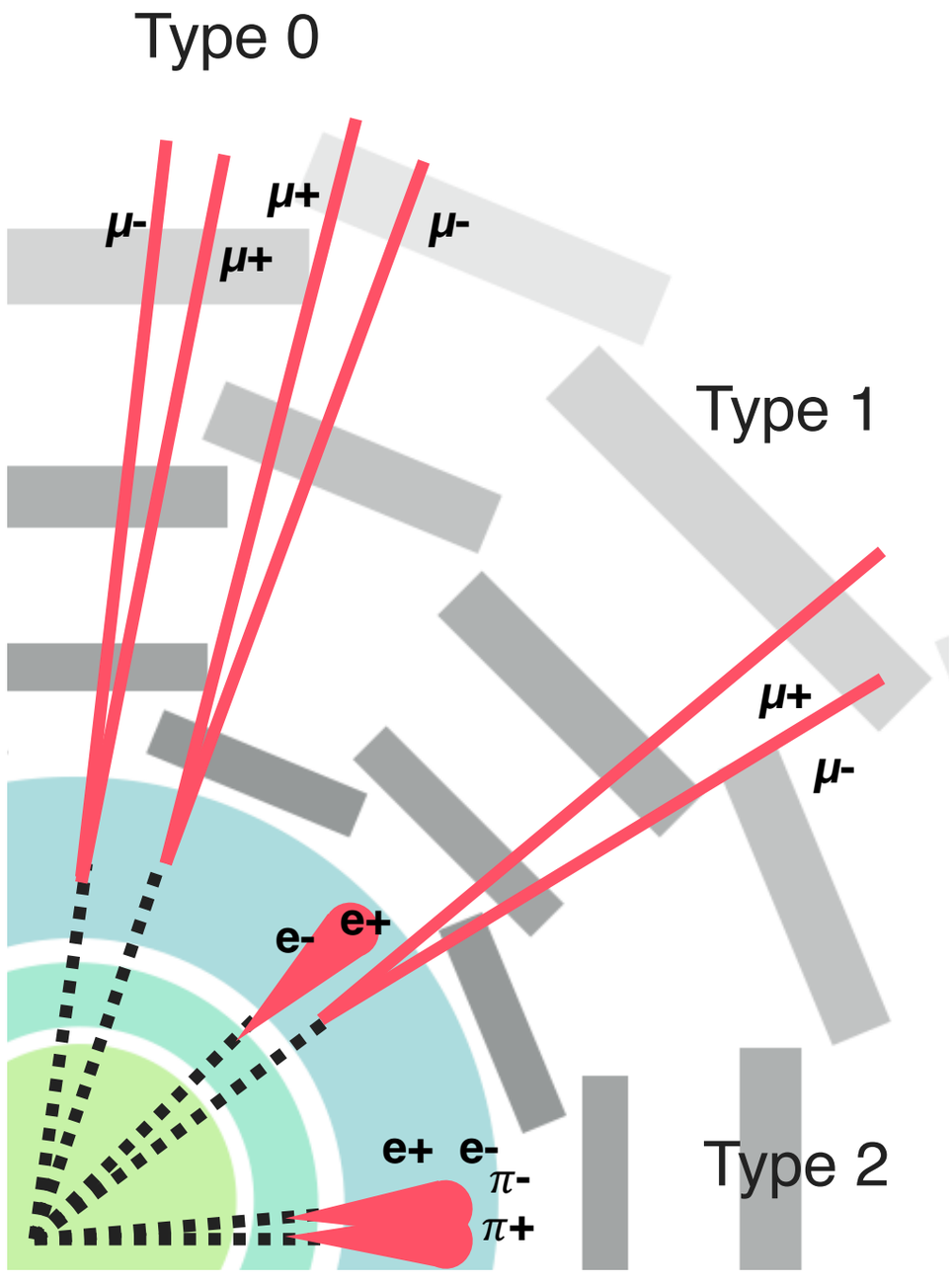


Displaced Lepton jets

Neutral long-lived particles decaying to collimated jets of leptons and mesons

requires combination of **Calorimeter** & **Muon** information

ATLAS-CONF-2016-042
13 TeV 3.4 fb^{-1}



Improved LLP Triggers

- MS only: cluster of muons w/ no nearby jets
- Narrow Scan: pairs of nearby muons, but only 1 seed at L1
- Cal Ratio: low EM fraction jets

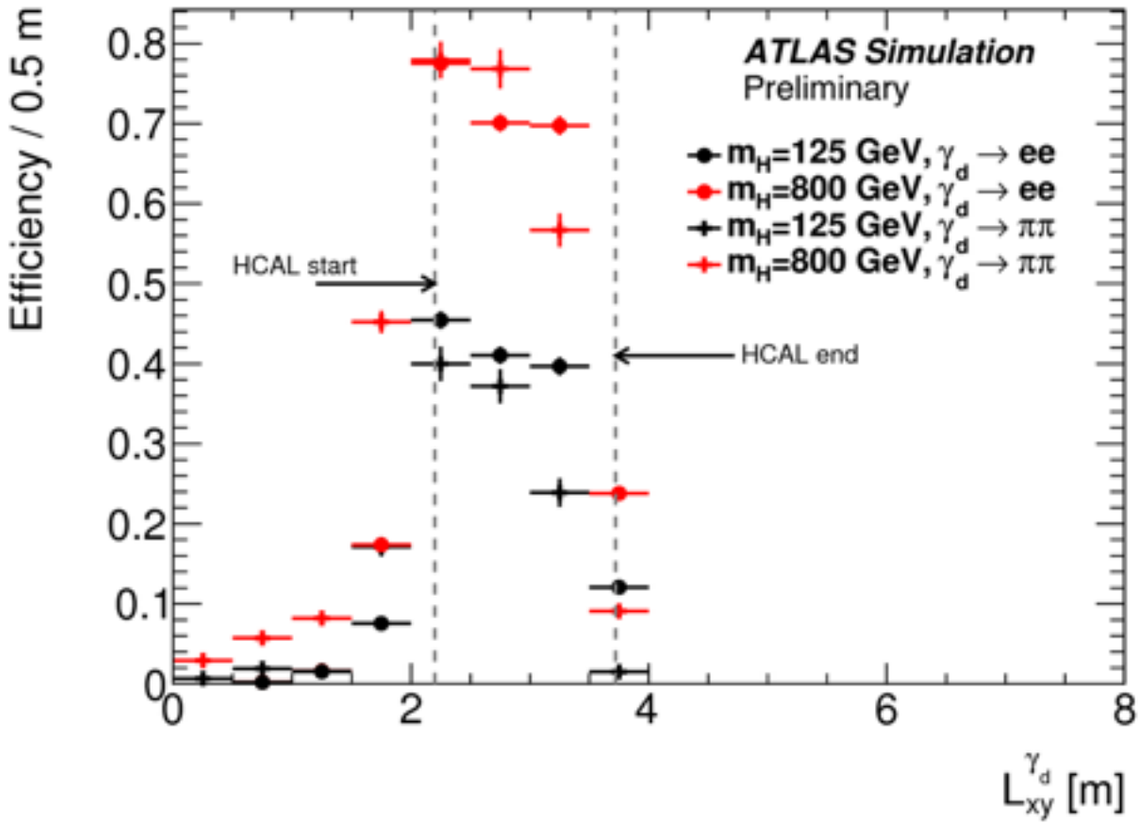
Displaced Lepton jets

Neutral long-lived particles decaying to collimated jets of leptons and mesons

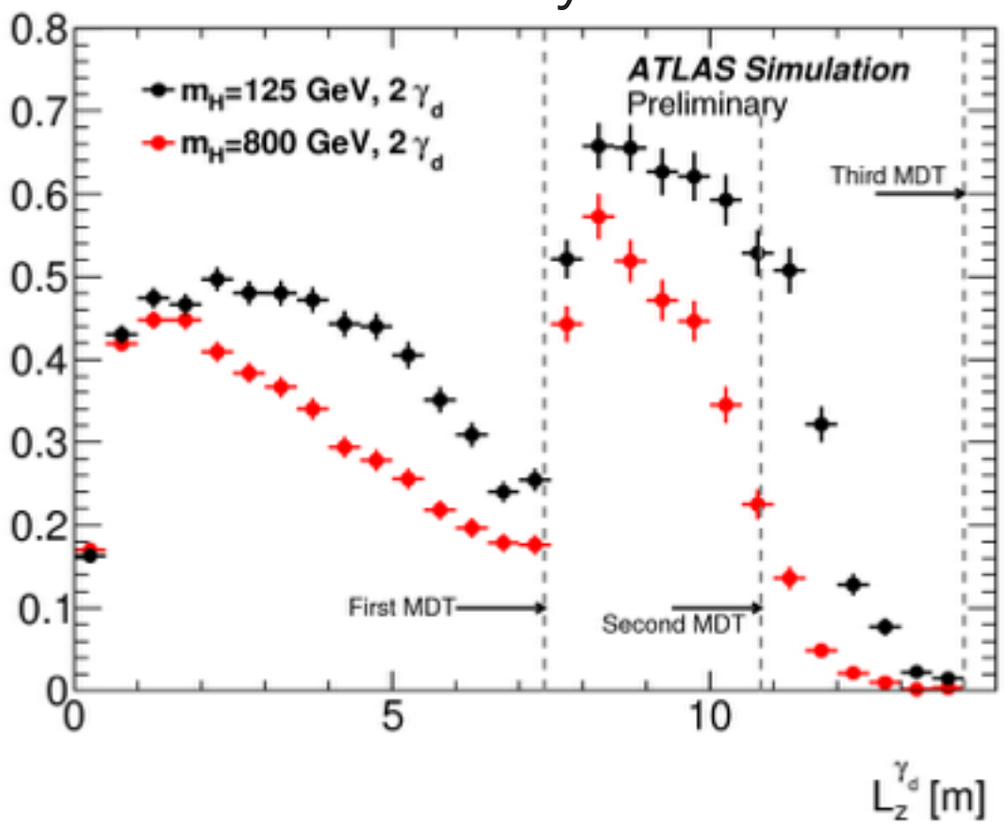
requires combination of **Calorimeter** & **Muon** information

ATLAS-CONF-2016-042
13 TeV 3.4 fb^{-1}

Type 2: LJ Reconstruction Efficiency

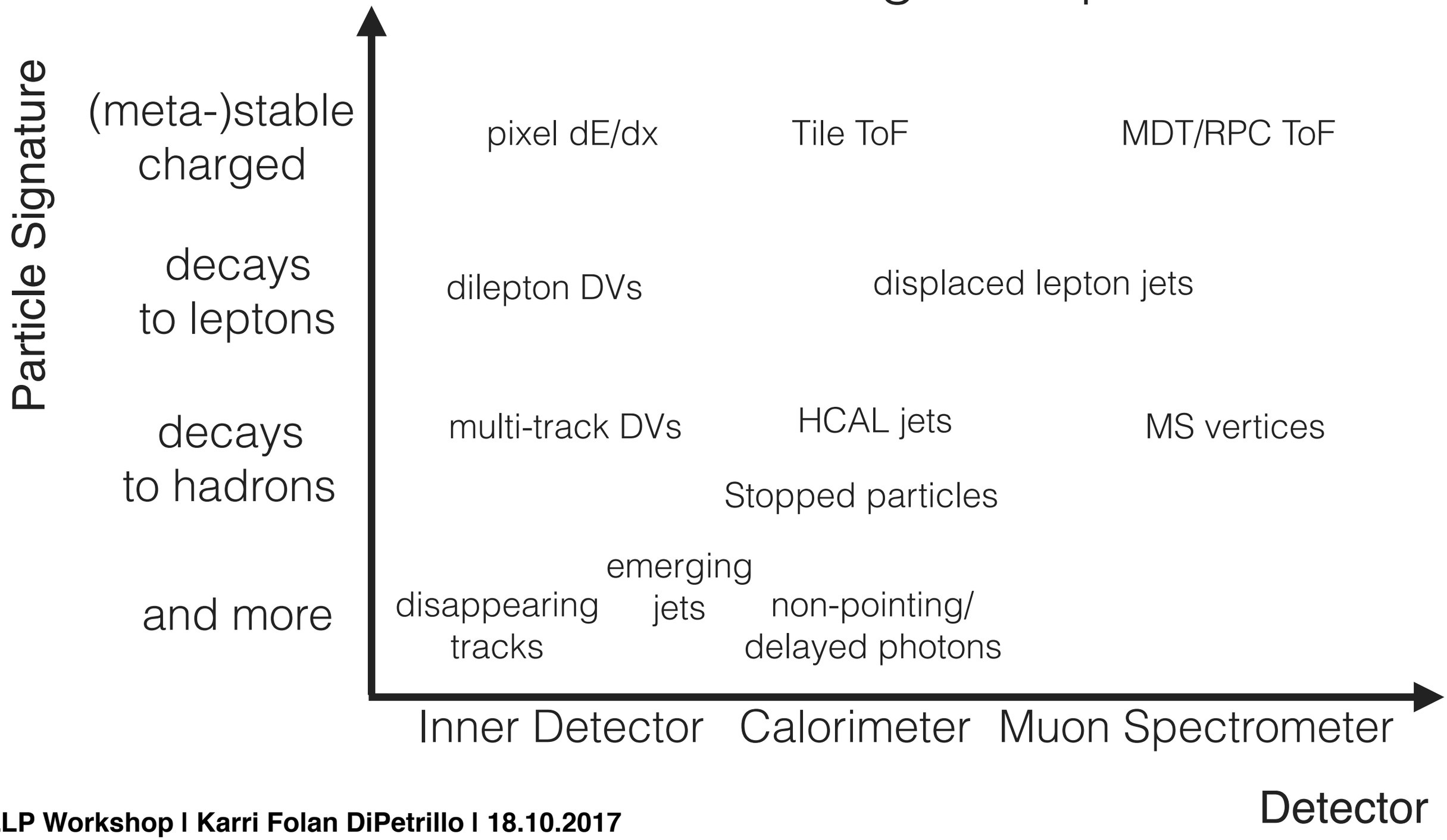


Run 2: Better Muon Reconstruction Efficiency for nearby muons



Experimental LLP “phase space”

Tried to show how ATLAS uses experimental resources to search for long-lived particles

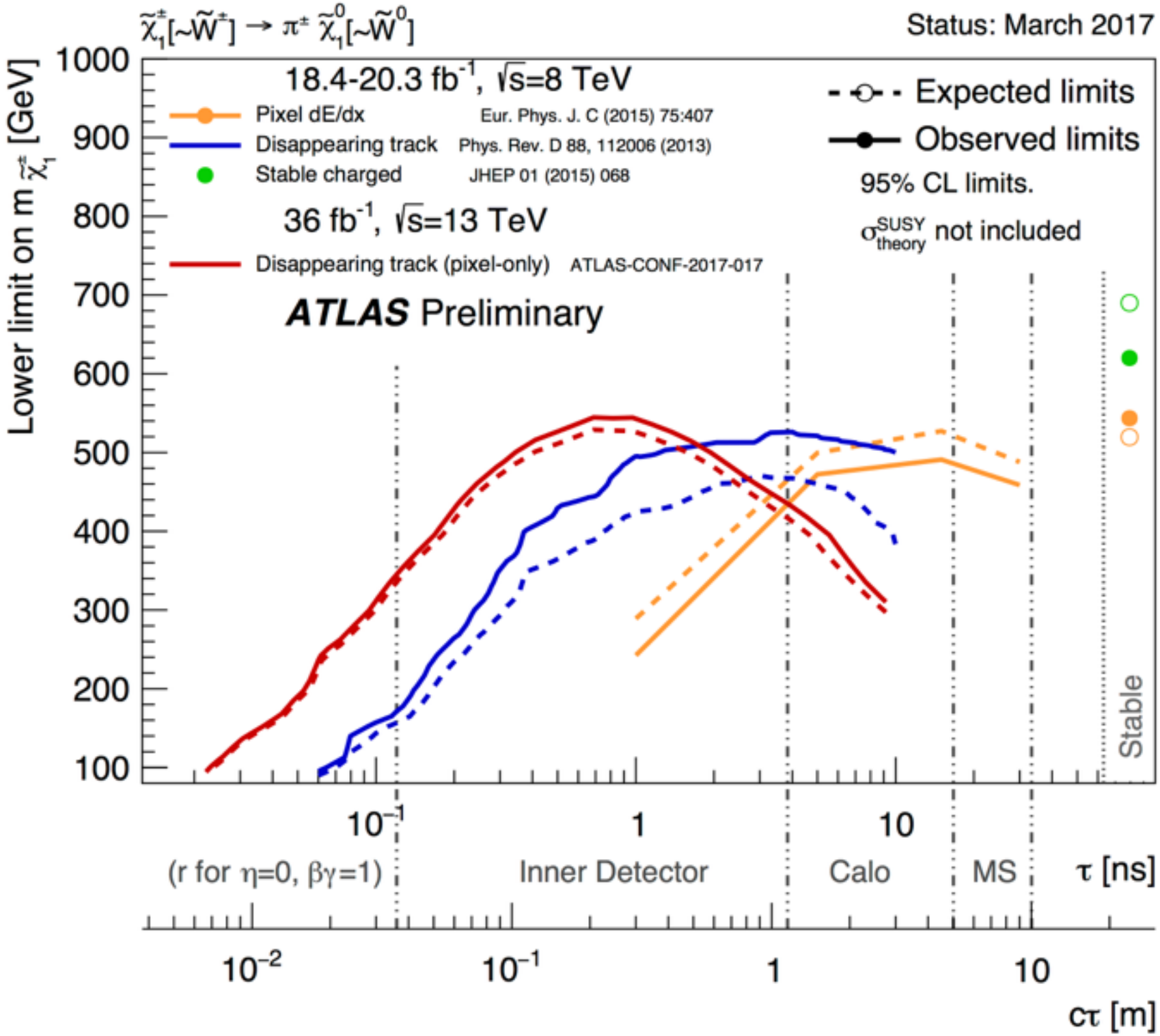


Theory LLP “phase space”

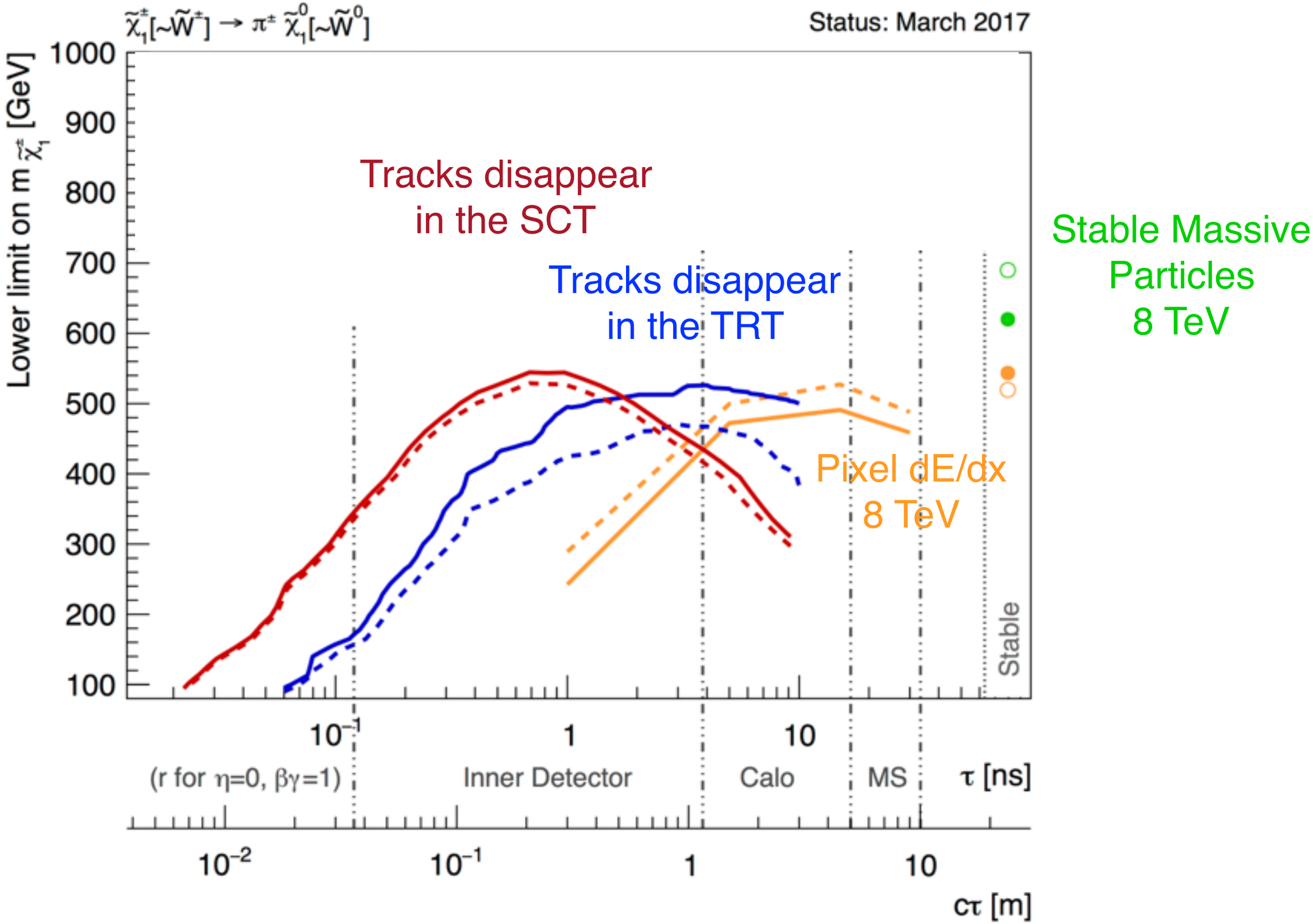
Now I’ll try to see how we do with your favorite models…

Physics Coverage

SUSY: charginos (small mass splittings)



SUSY: charginos (small mass splittings)



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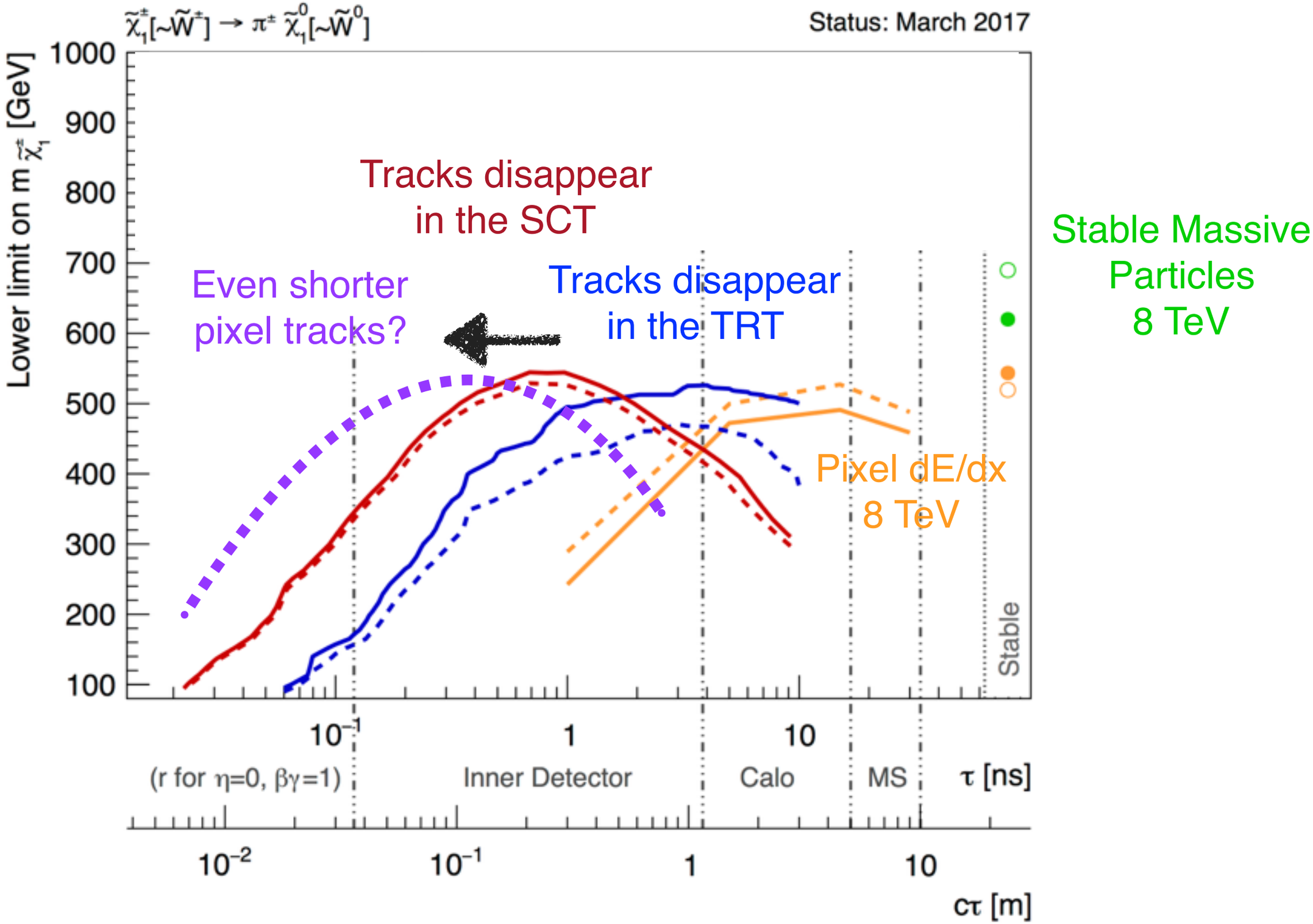
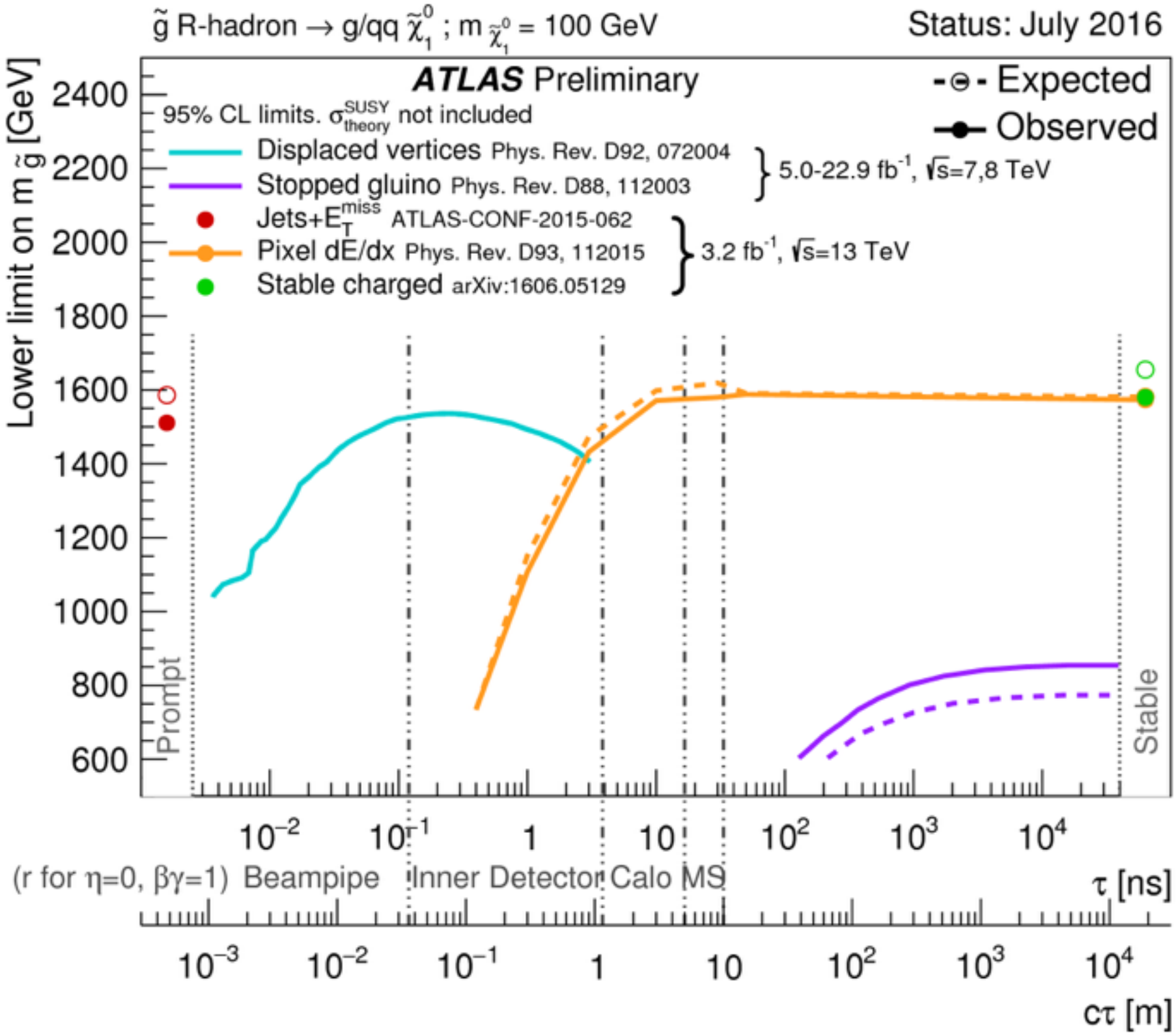
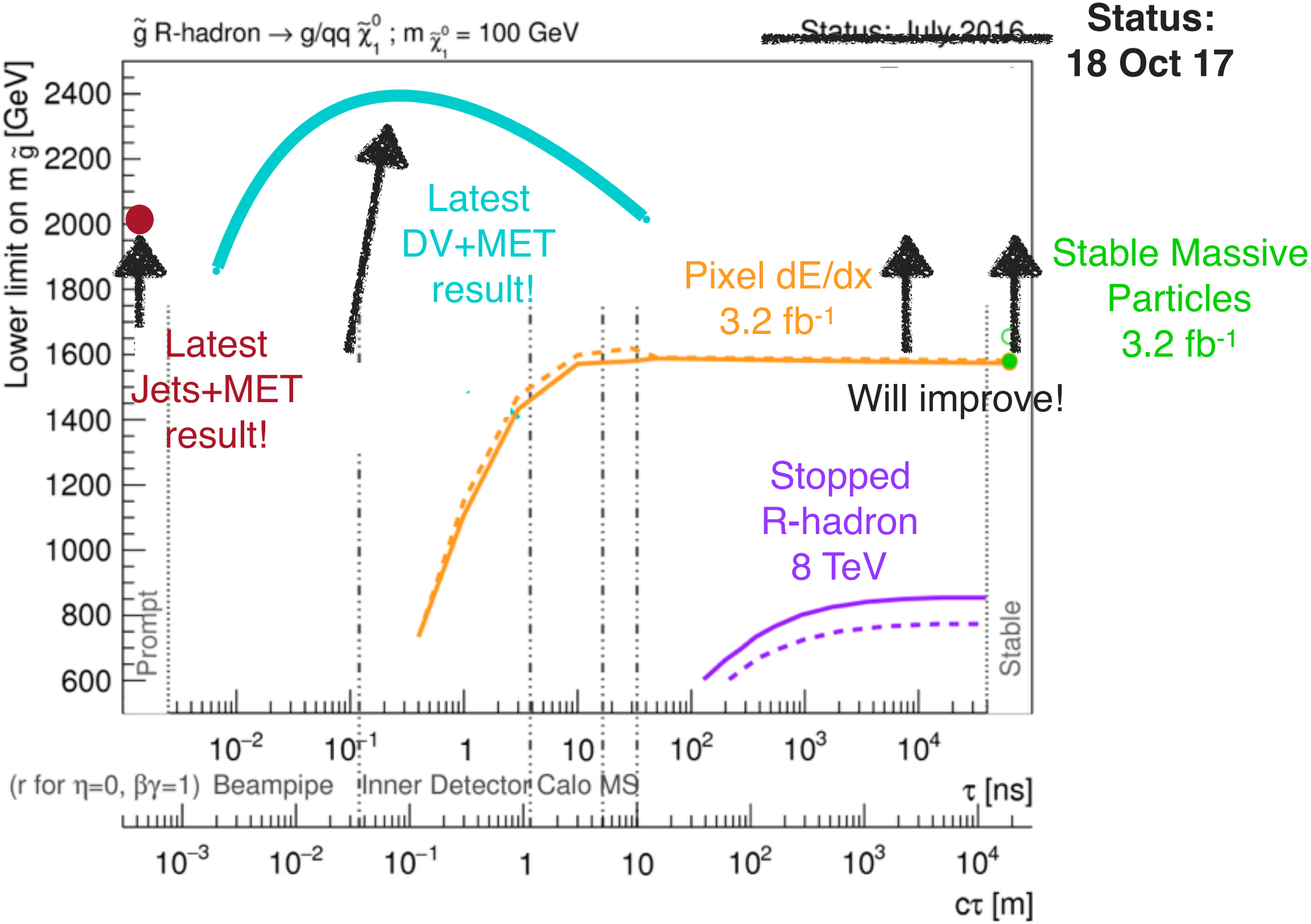


SUSY: gluino R-hadrons (heavy mediator)



SUSY: gluino R-hadrons (heavy mediator)



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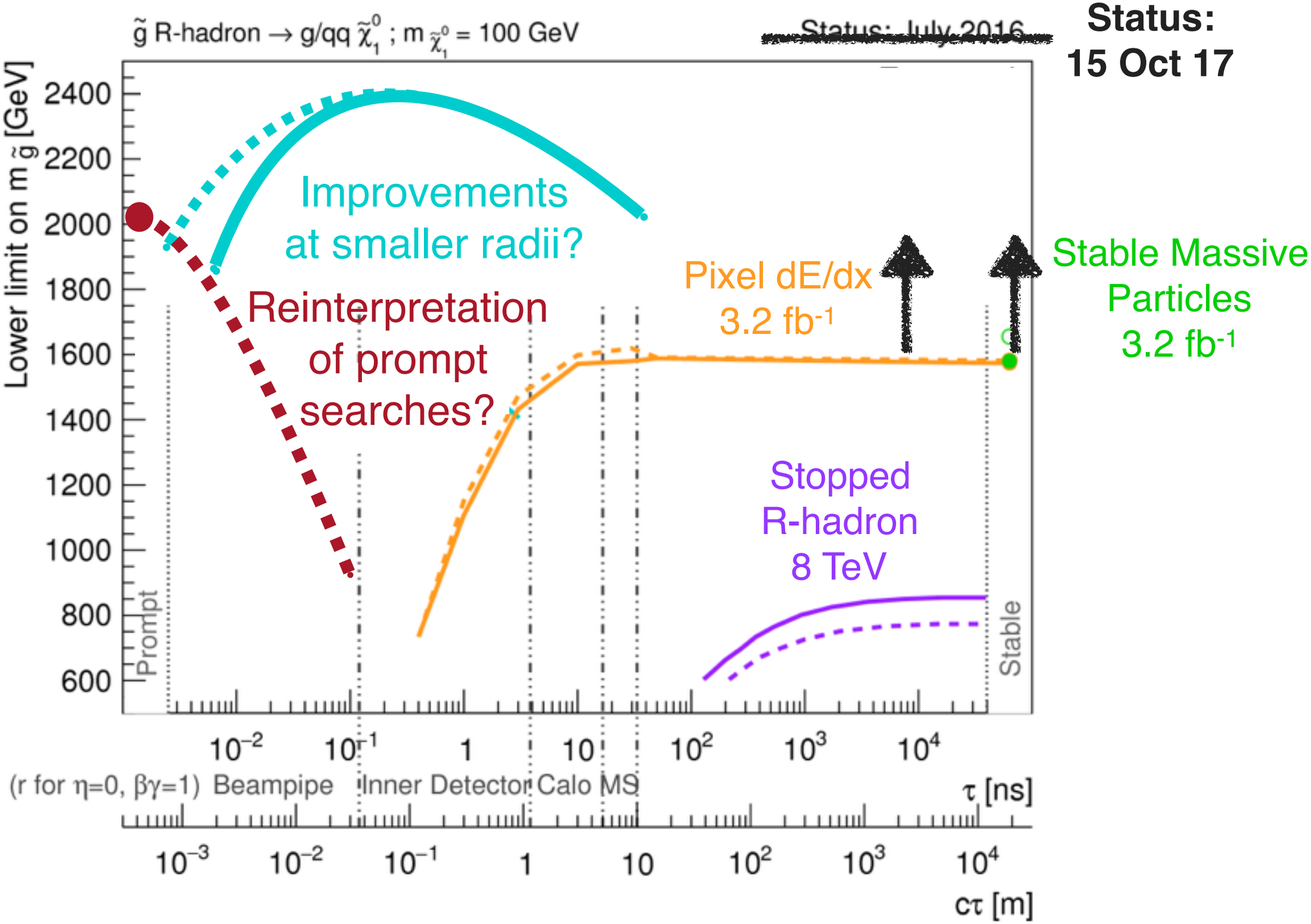
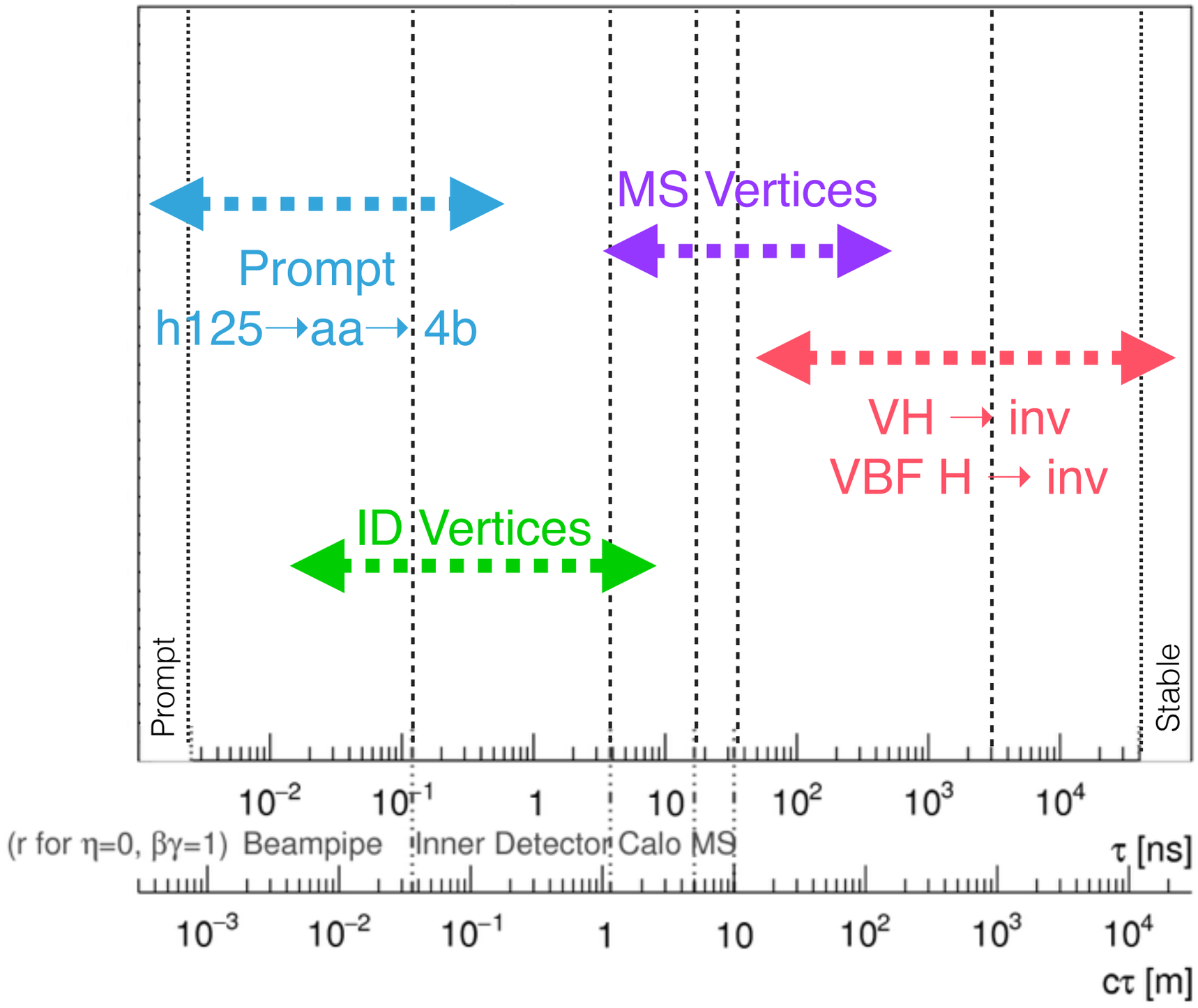


SM Higgs→ss, s→ff

Not an actual plot!!



A lot of room to play with

Do prompt b-tagged searches have sensitivity to LLPs at short displacement?

Do we have coverage for collimated/resolved signatures?

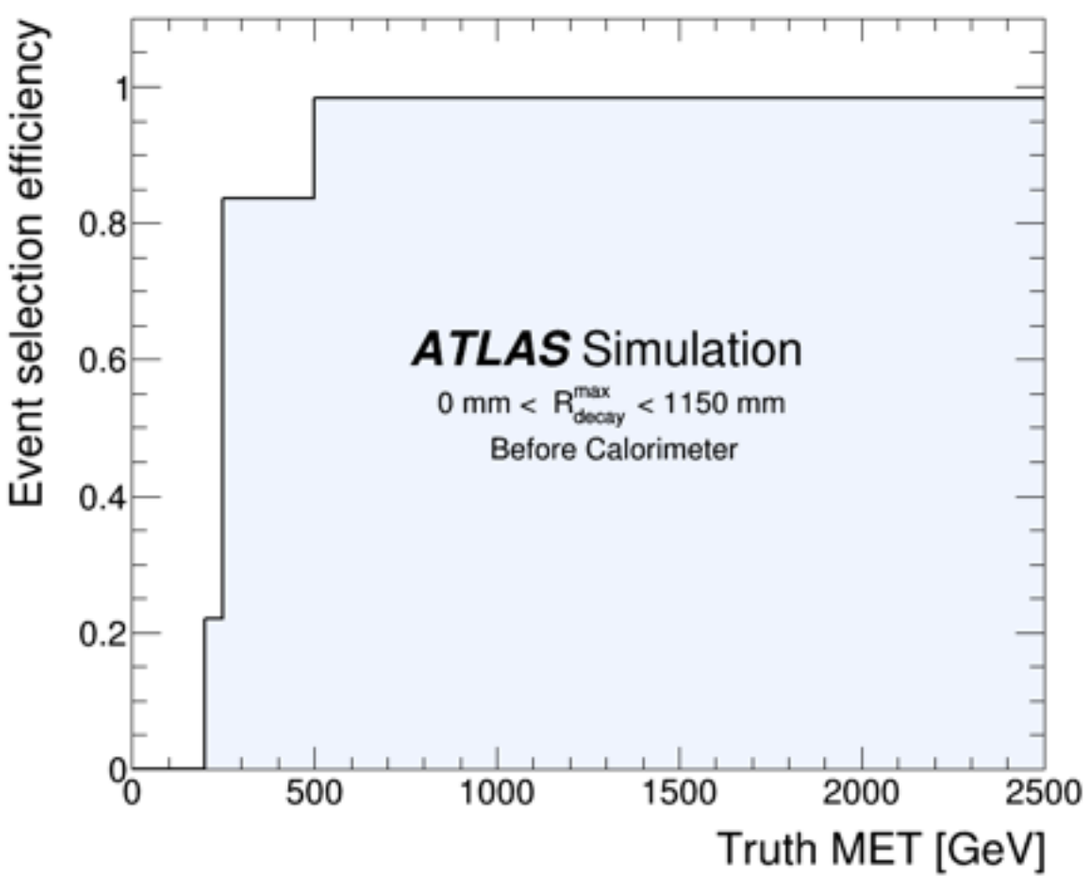
How does targeting different production modes help with triggering?

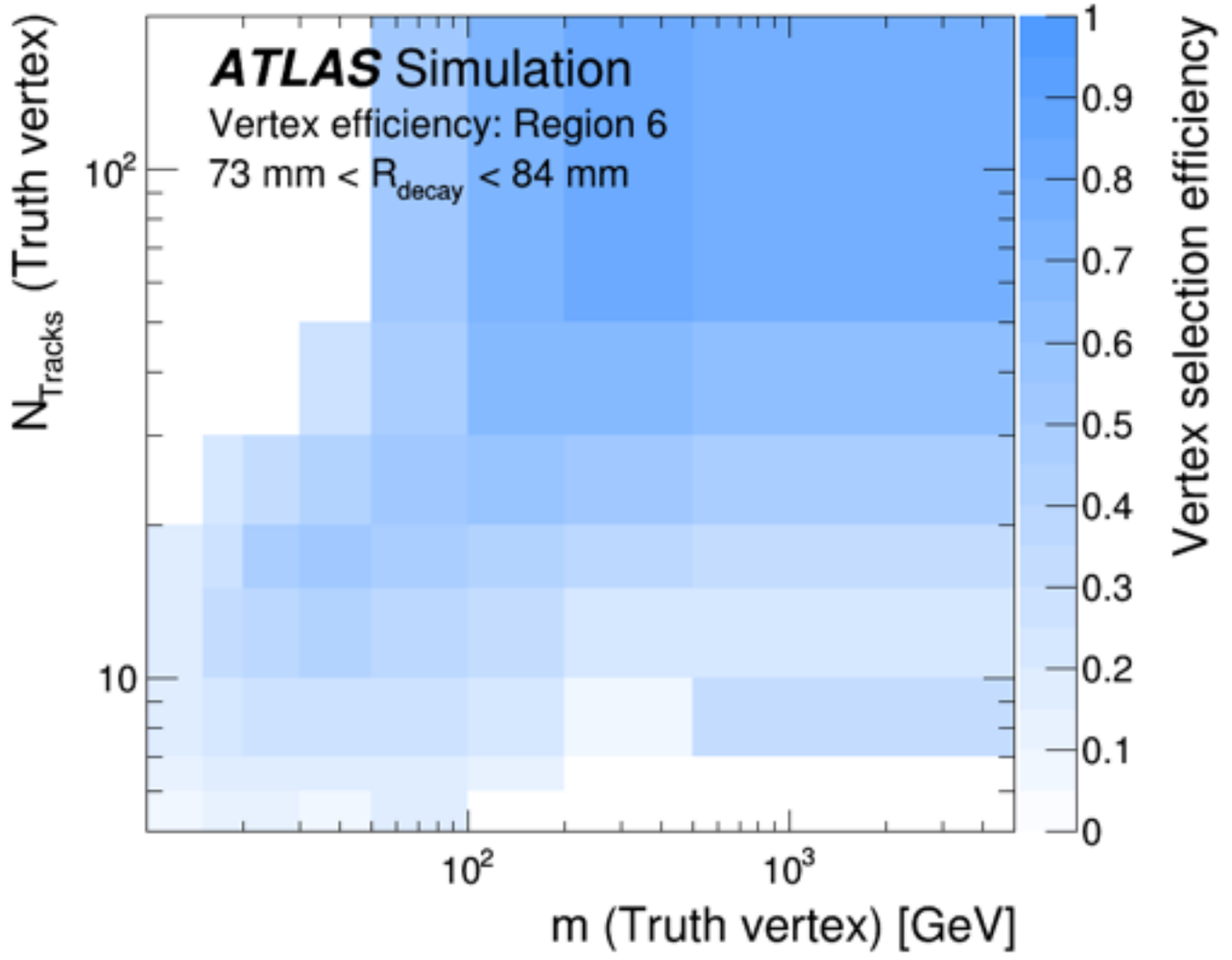
Material for Reinterpretation

If you're not satisfied w/ our interpretations… we're providing parametrized efficiencies as aux material

with prescriptions for easy use

DV+MET Event & Vertex Level Efficiencies





Conclusions

Summary

Overview of ATLAS LLP searches

Highlighted how we can make use of different parts of the detector

Discussed some of the specialized triggers and reconstruction methods used to search for LLPs

Showed how we measured up against some benchmark models

And how material is available for reinterpretation

Backups