OFF THE BEATEN TRACK

LONG-LIVED PARTICLES AT THE LHC

TOVA HOLMES

NUCLEAR AND PARTICLE PHYSICS SEMINAR

UPPSALA UNIVERSITY

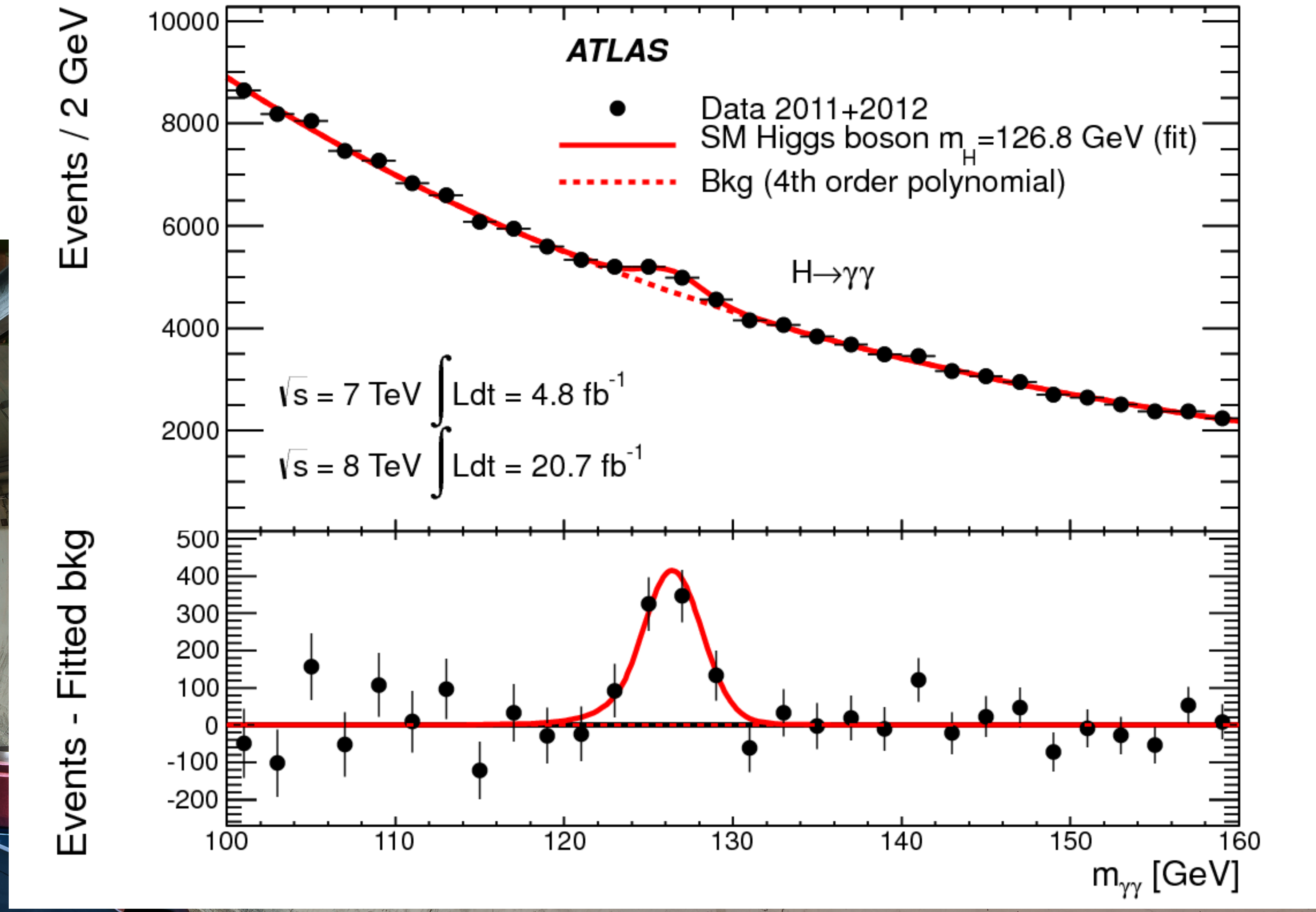
OCTOBER 22, 2020

my goal:

find new fundamental particles


CERN

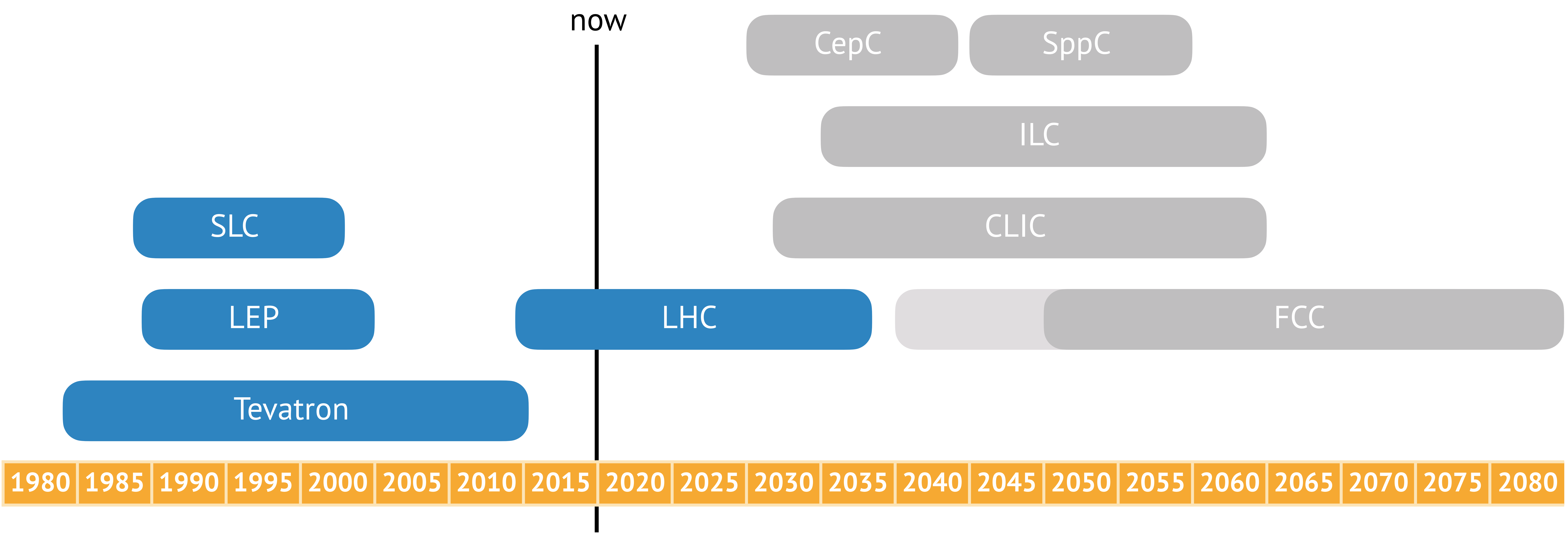
Higgs discovery, 2012



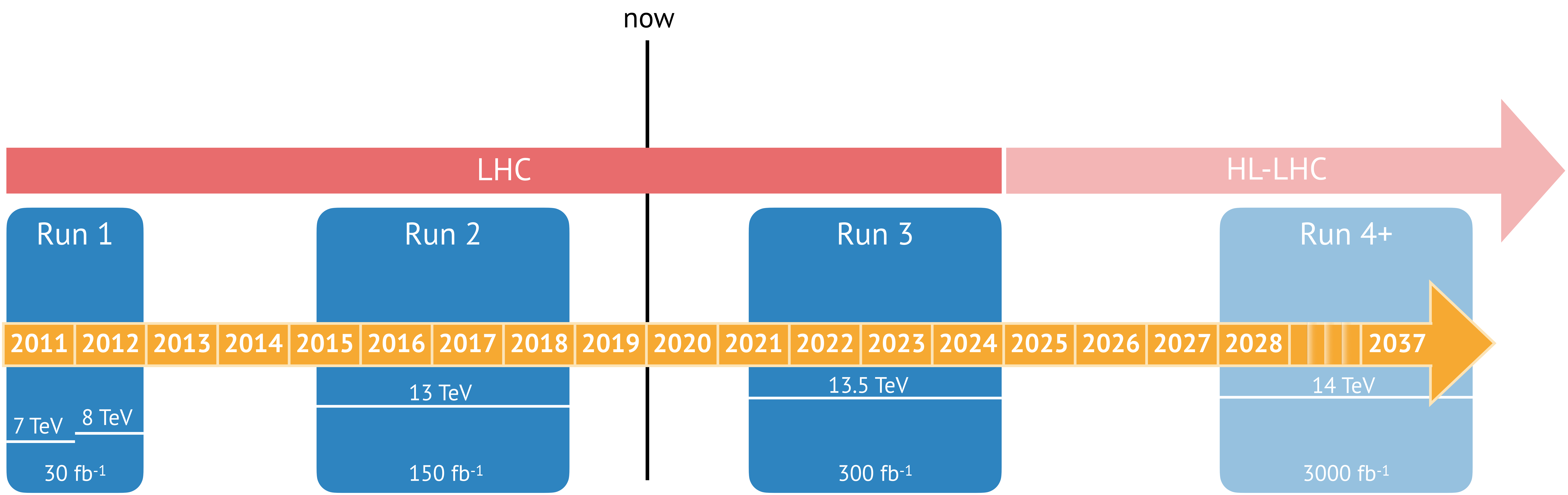
Most recent machine to accomplish that goal: the Large Hadron Collider

CERN

The Energy Frontier

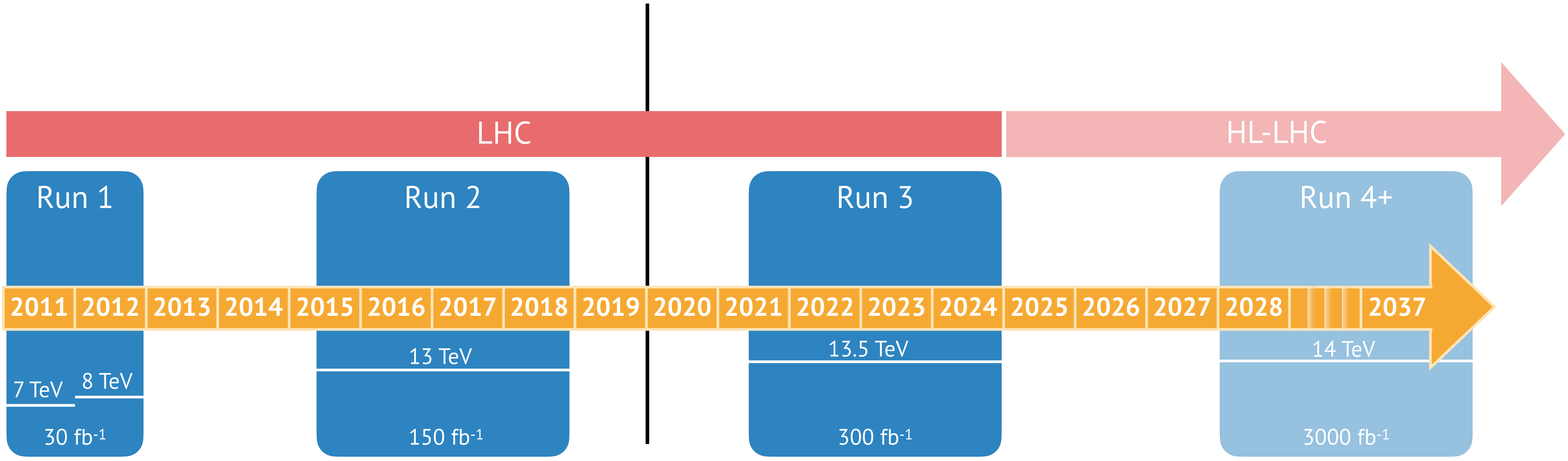


The LHC


now
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4+
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2037
7 TeV
8 TeV
13 TeV
13.5 TeV
14 TeV
30 fb-1
150 fb-1
300 fb-1
3000 fb-1

The LHC

Run 1 → Run 2	Run 2 → Run 3	Run 3 → Run 4+
Luminosity x5 Energy +60%	Luminosity x1 Energy +4%	Luminosity x10 Energy +4%

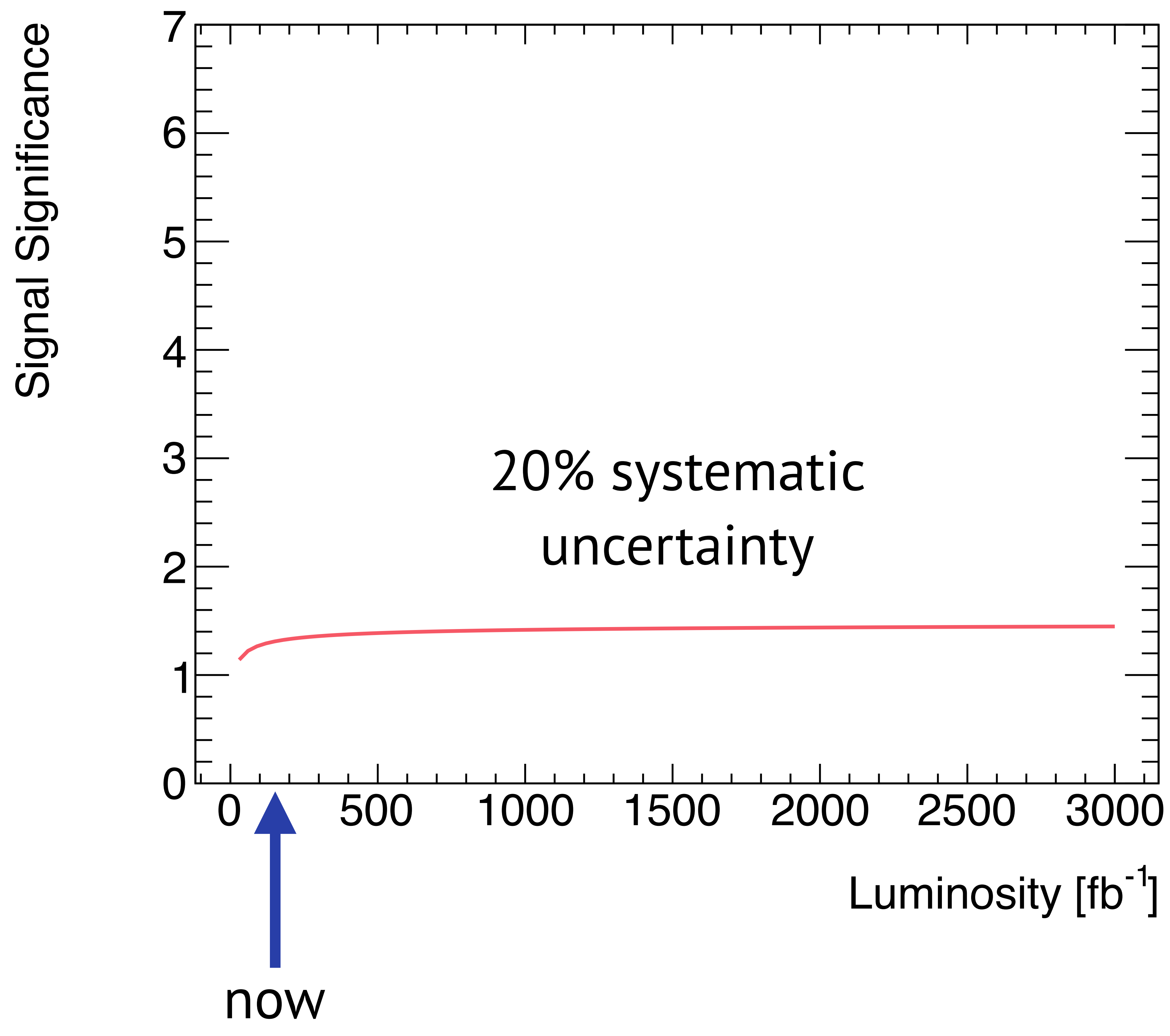


The Worst Case

$$S \sim \frac{n_{sig}}{\sigma_{bkg}}$$

if σ_{bkg} is **driven by systematics** that are a fixed fraction of the total background

σ_{bkg} ∝ luminosity, and more data doesn't give more sensitivity

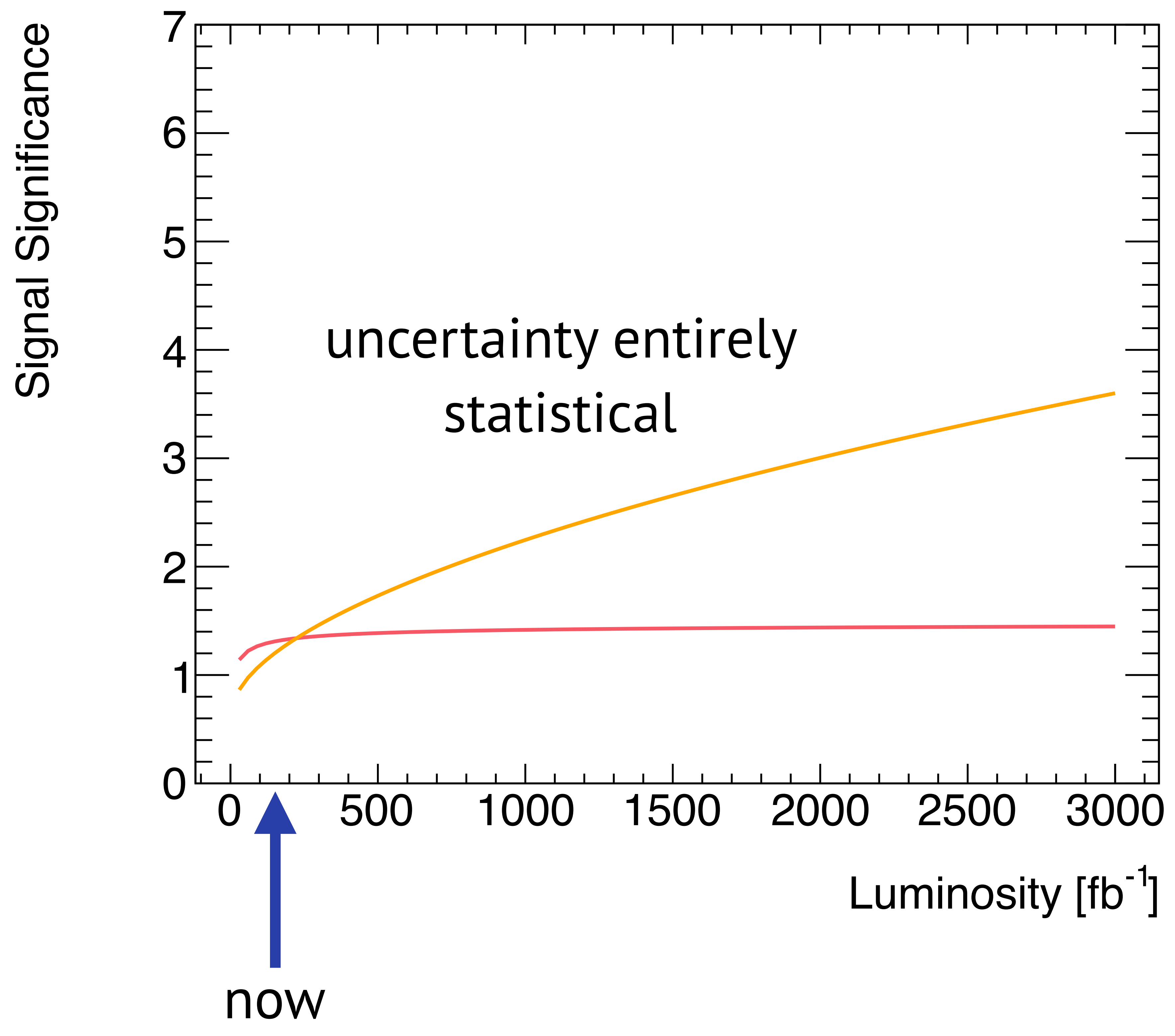


The Medium Case

$$S \sim \frac{n_{sig}}{\sigma_{bkg}}$$

if σ_{bkg} is **driven by statistical uncertainty**

σ_{bkg} ∝ √(luminosity), and sensitivity increases as roughly the square root of luminosity

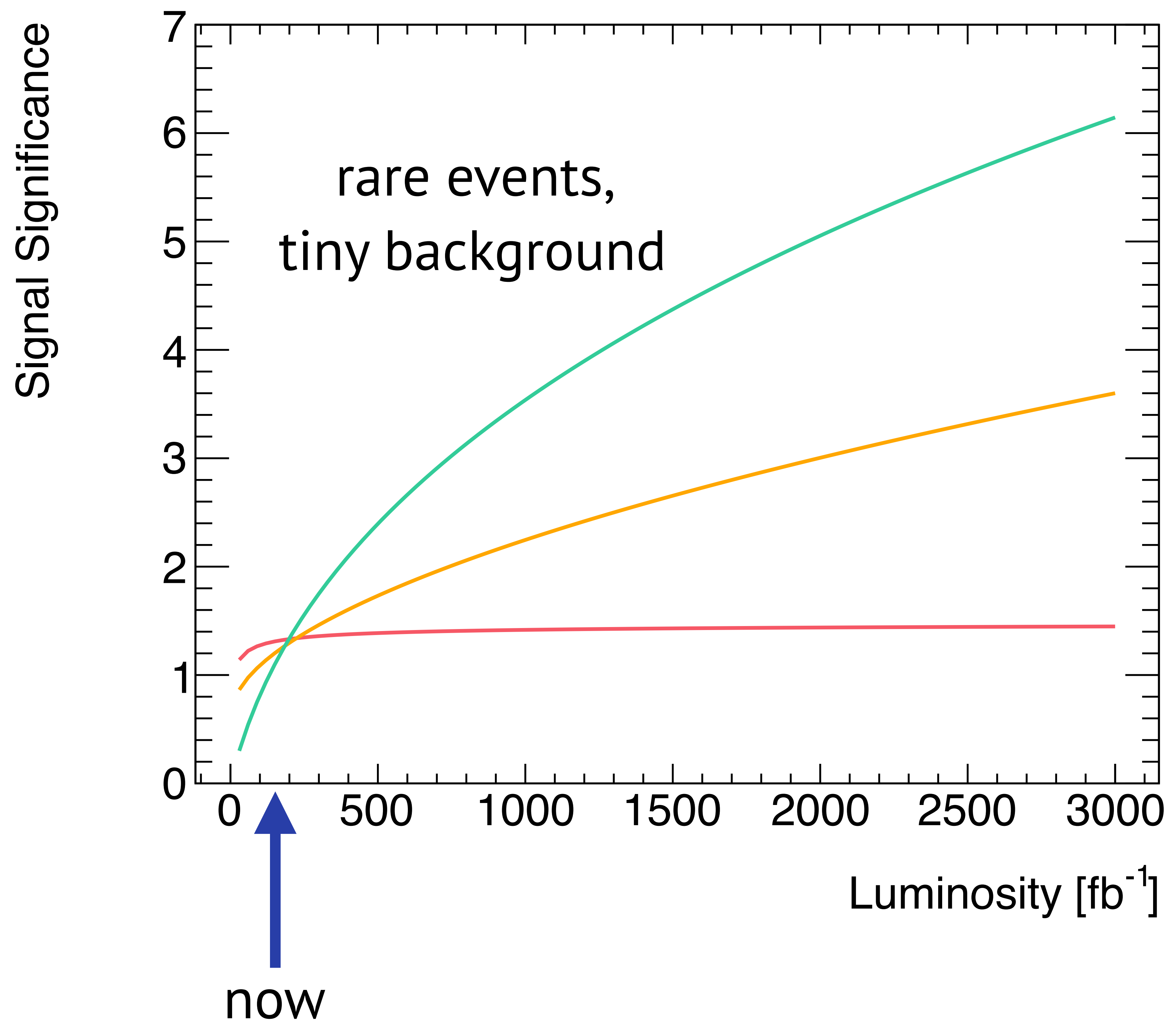


The Best Case

$$S \sim \frac{n_{sig}}{\sigma_{bkg}}$$

if the **standard model background is tiny**

then it's only a question of producing and reconstructing your signal, and **sensitivity is proportional to luminosity**



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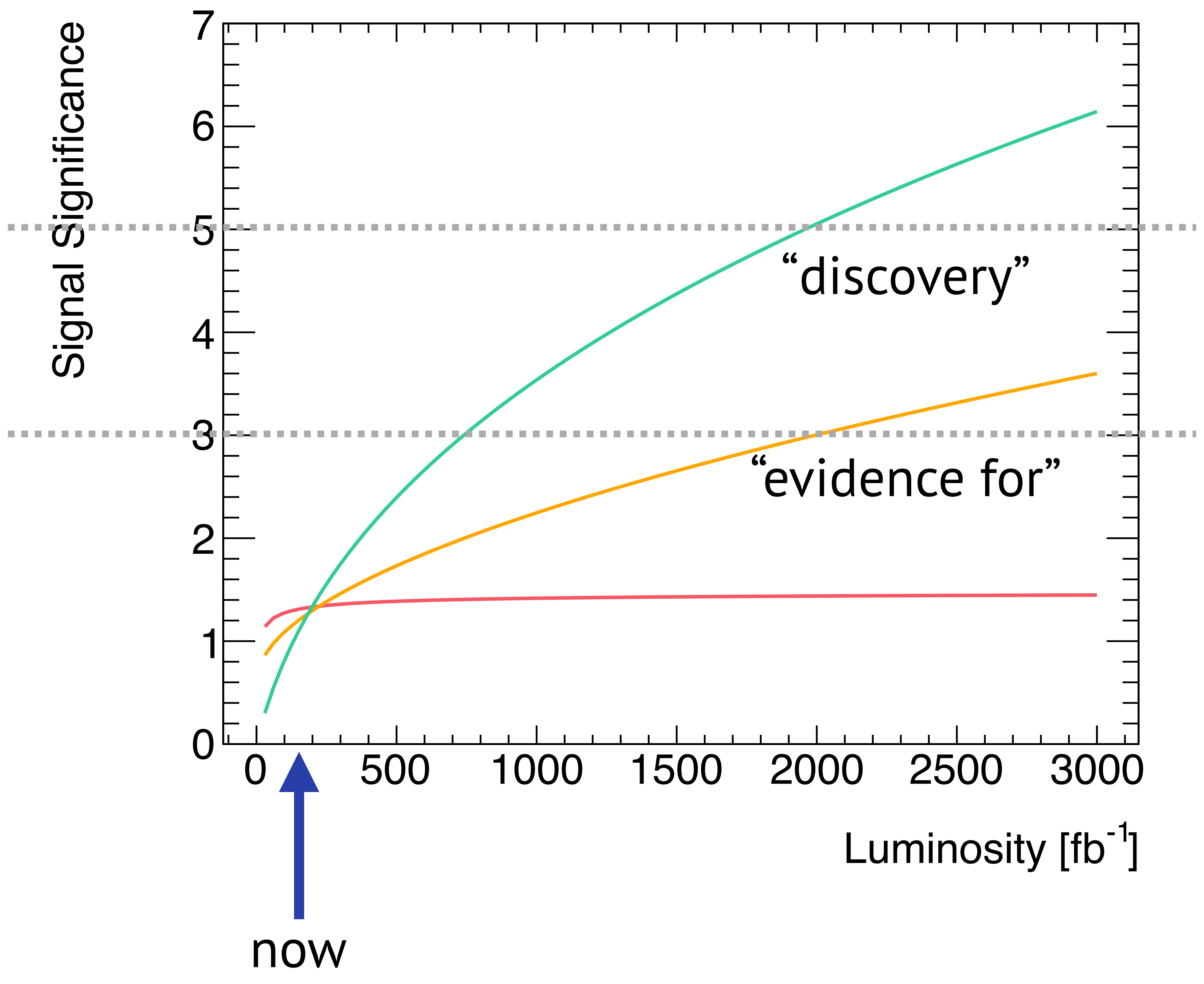
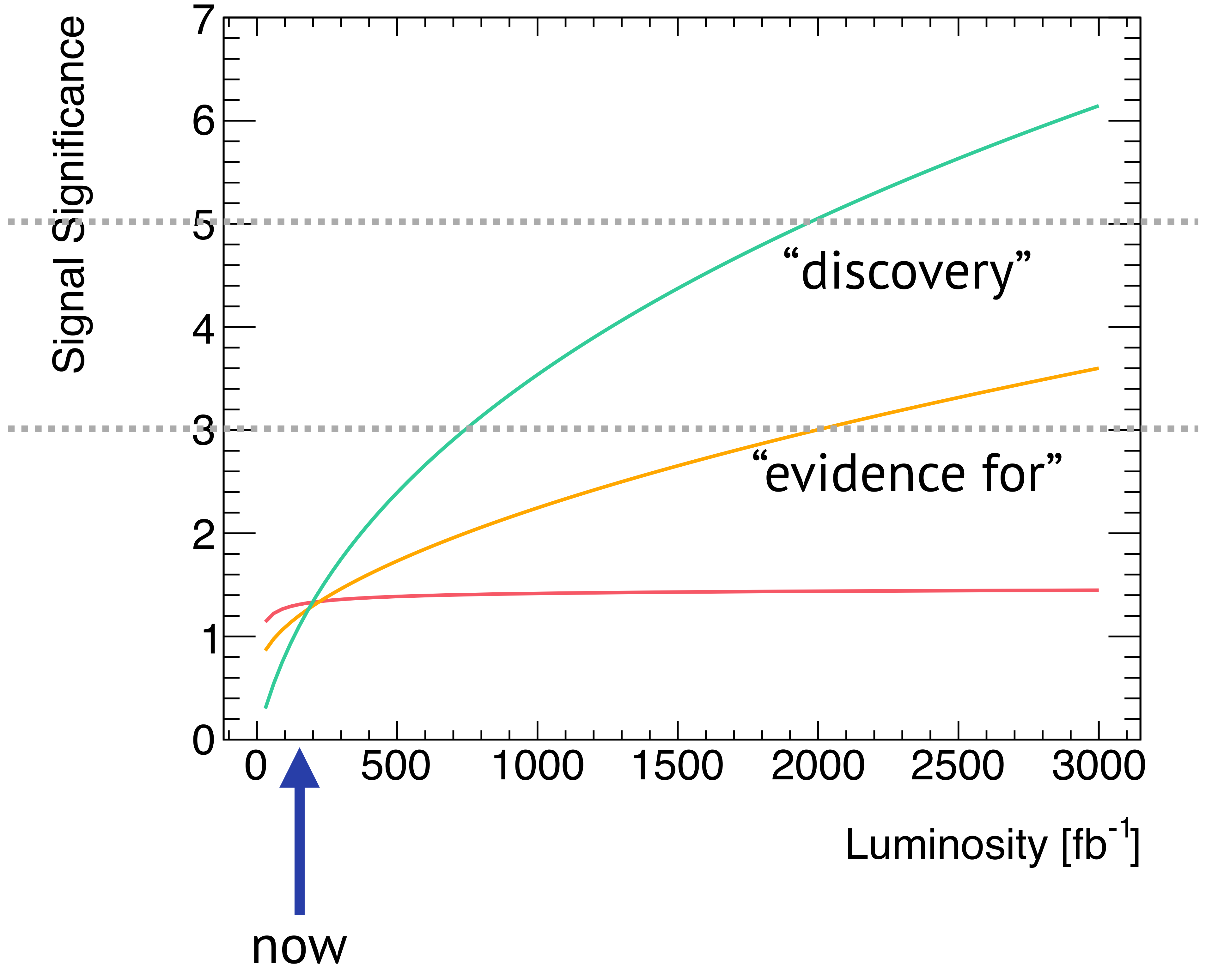


The Best Case

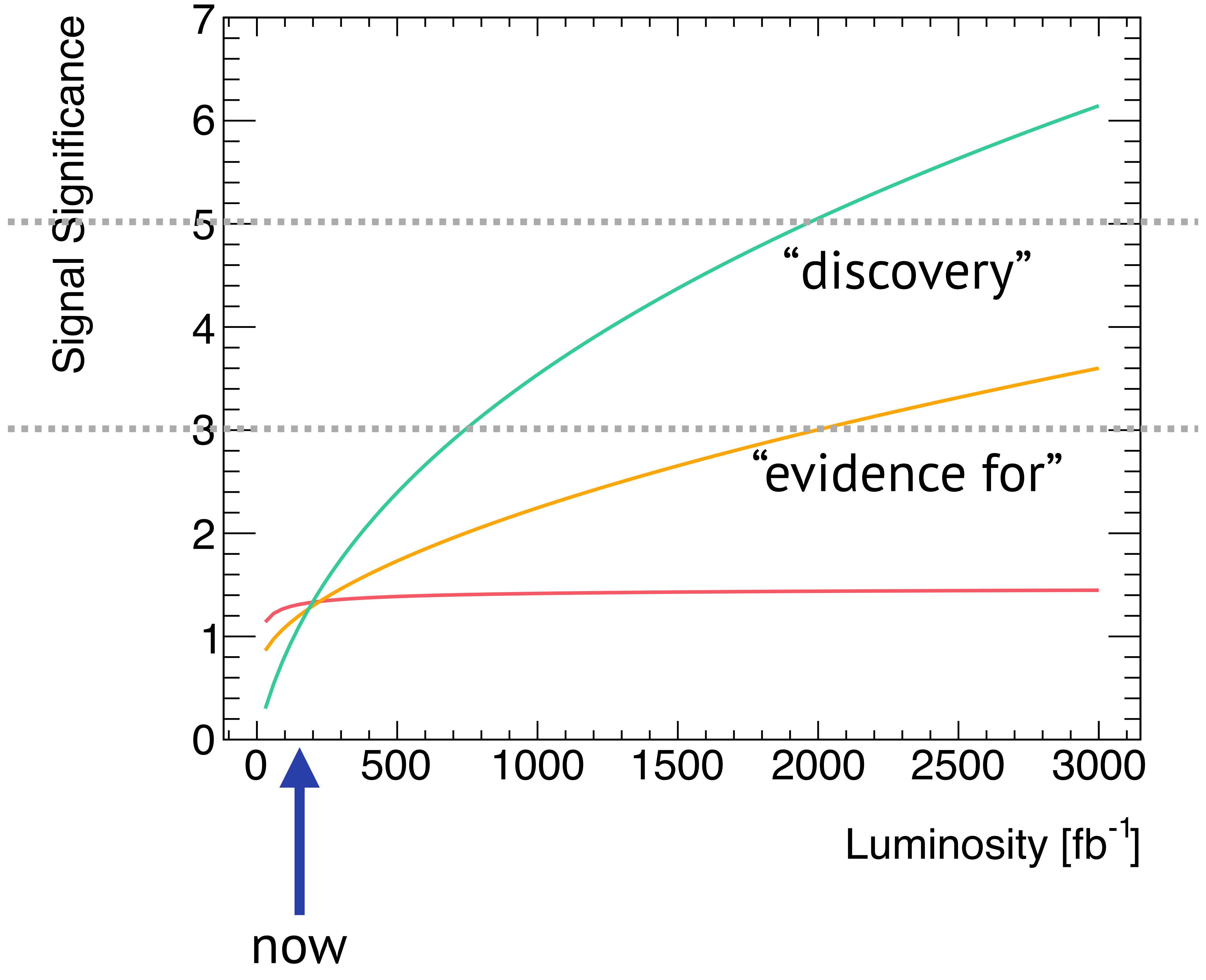
As we move forward with the LHC the physics that continues to be most exciting is rare stuff with small backgrounds



The Best Case

As we move forward with the LHC
the phy
exci

OR
stuff that's really hard to reconstruct
→ effectively "rare"

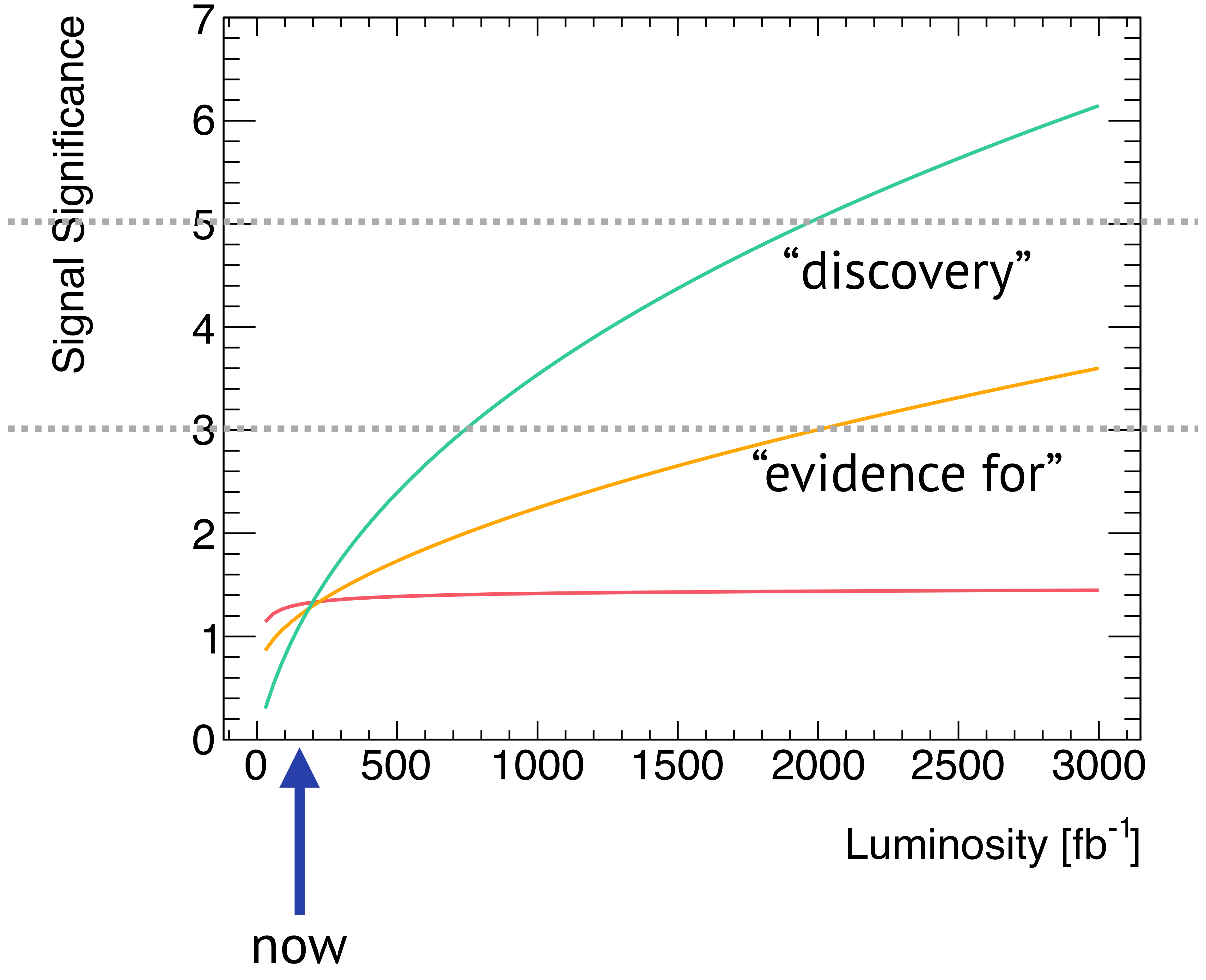


The Best Case

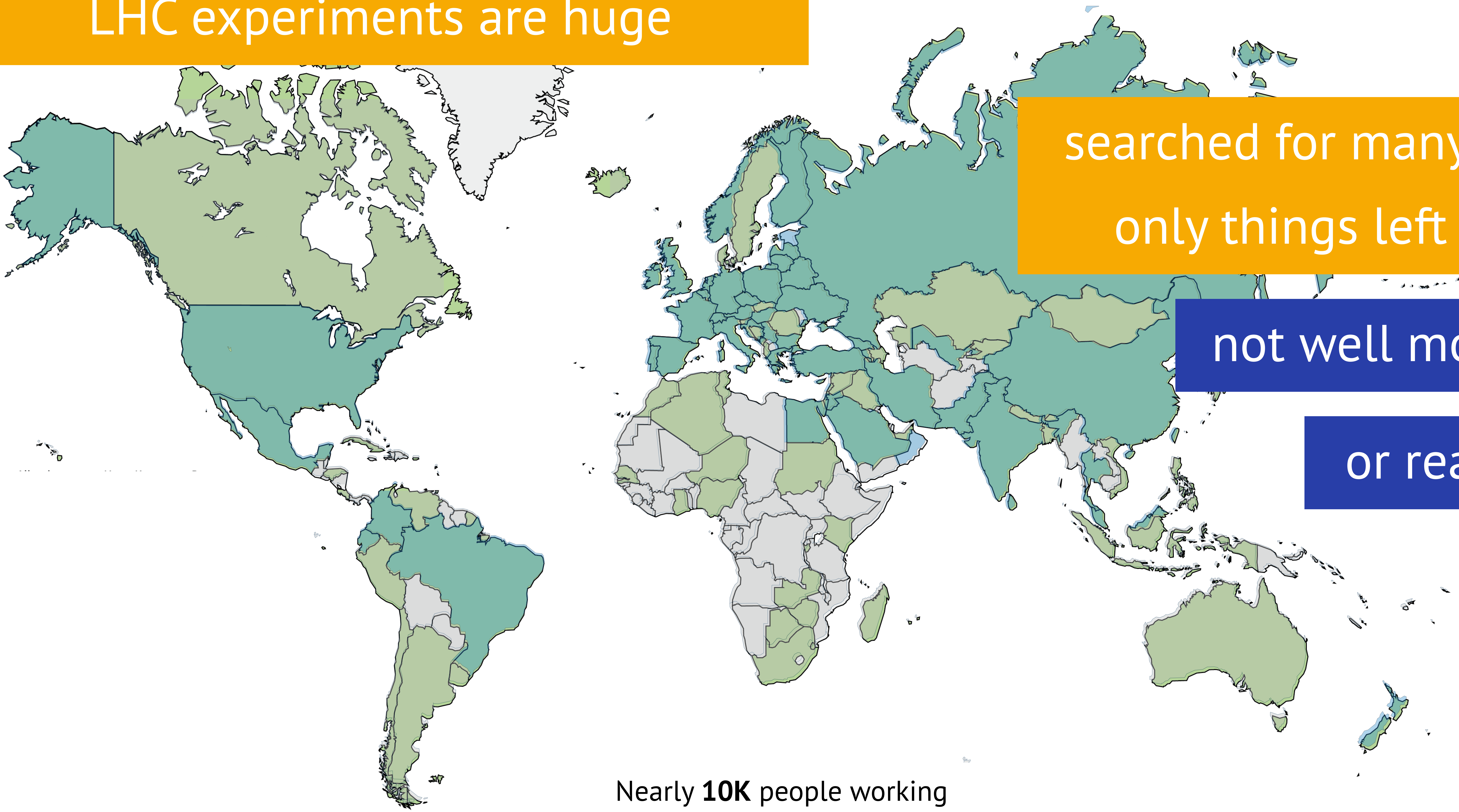
As we move forward with the LHC
the phy
exci

OR
stuff that's really hard to
truct
ely "rare"

OR
stuff we haven't
looked for at all yet



LHC experiments are huge

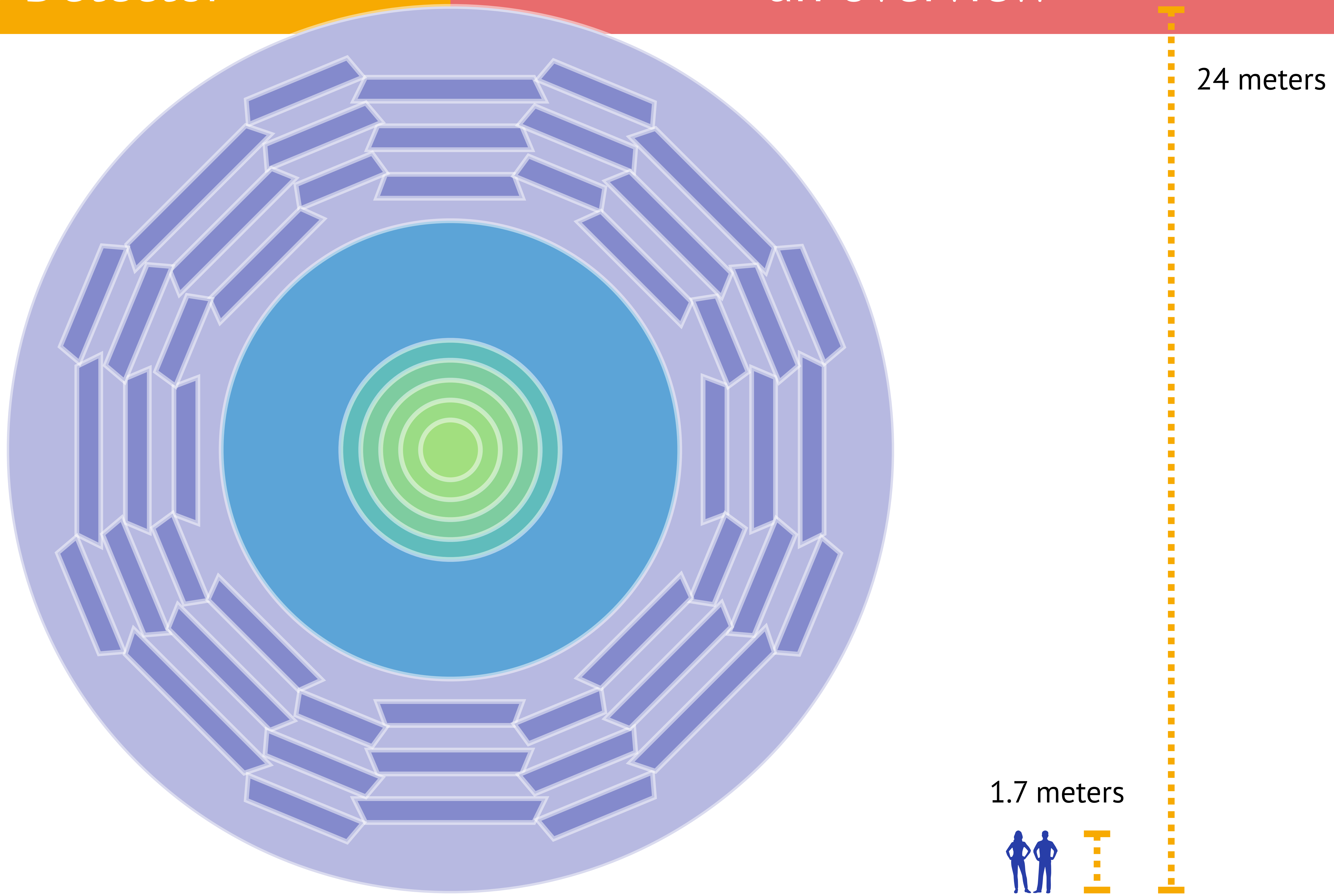


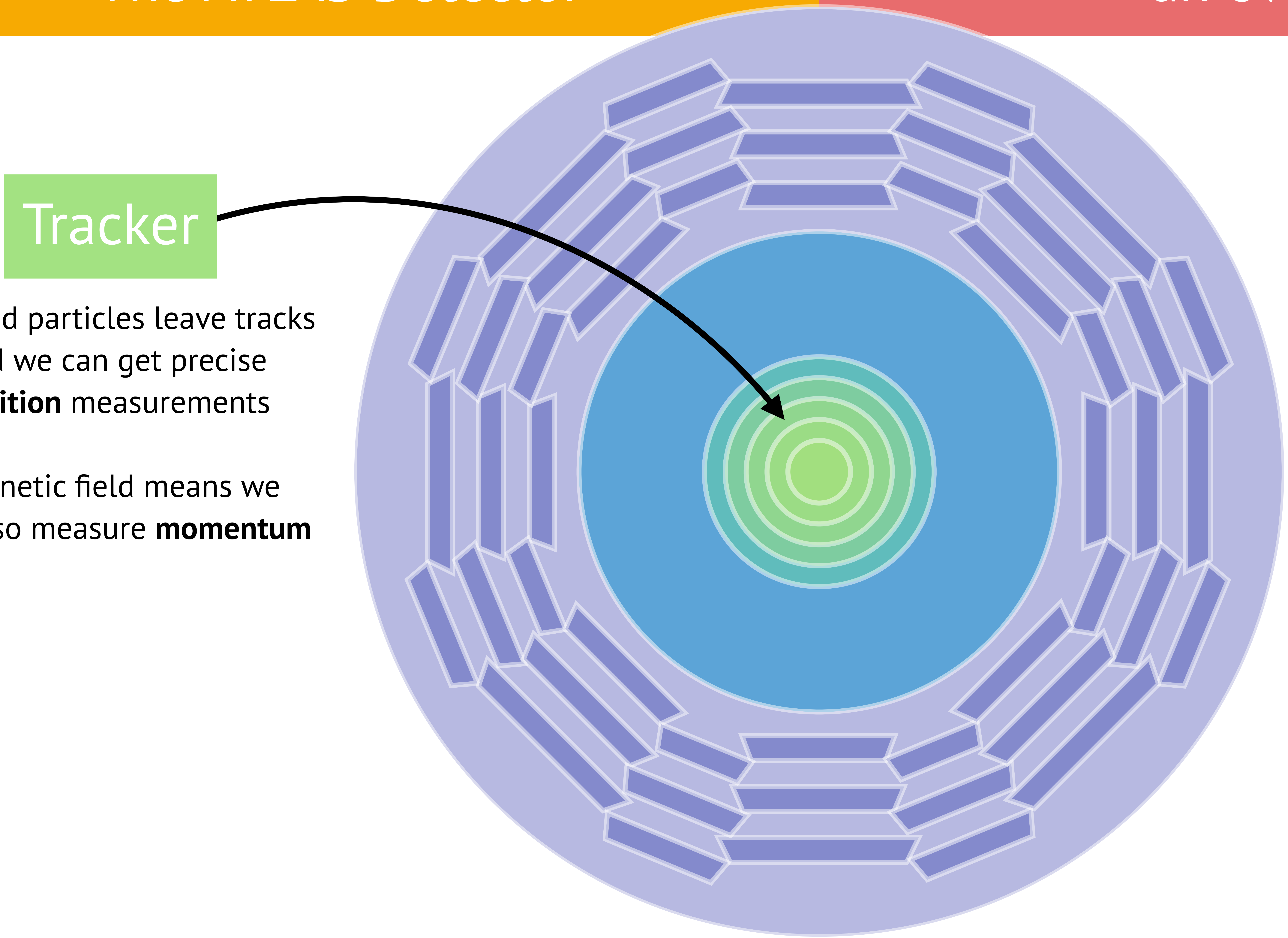
Nearly **10K** people working
on ATLAS and CMS

searched for many things
only things left are...

not well motivated

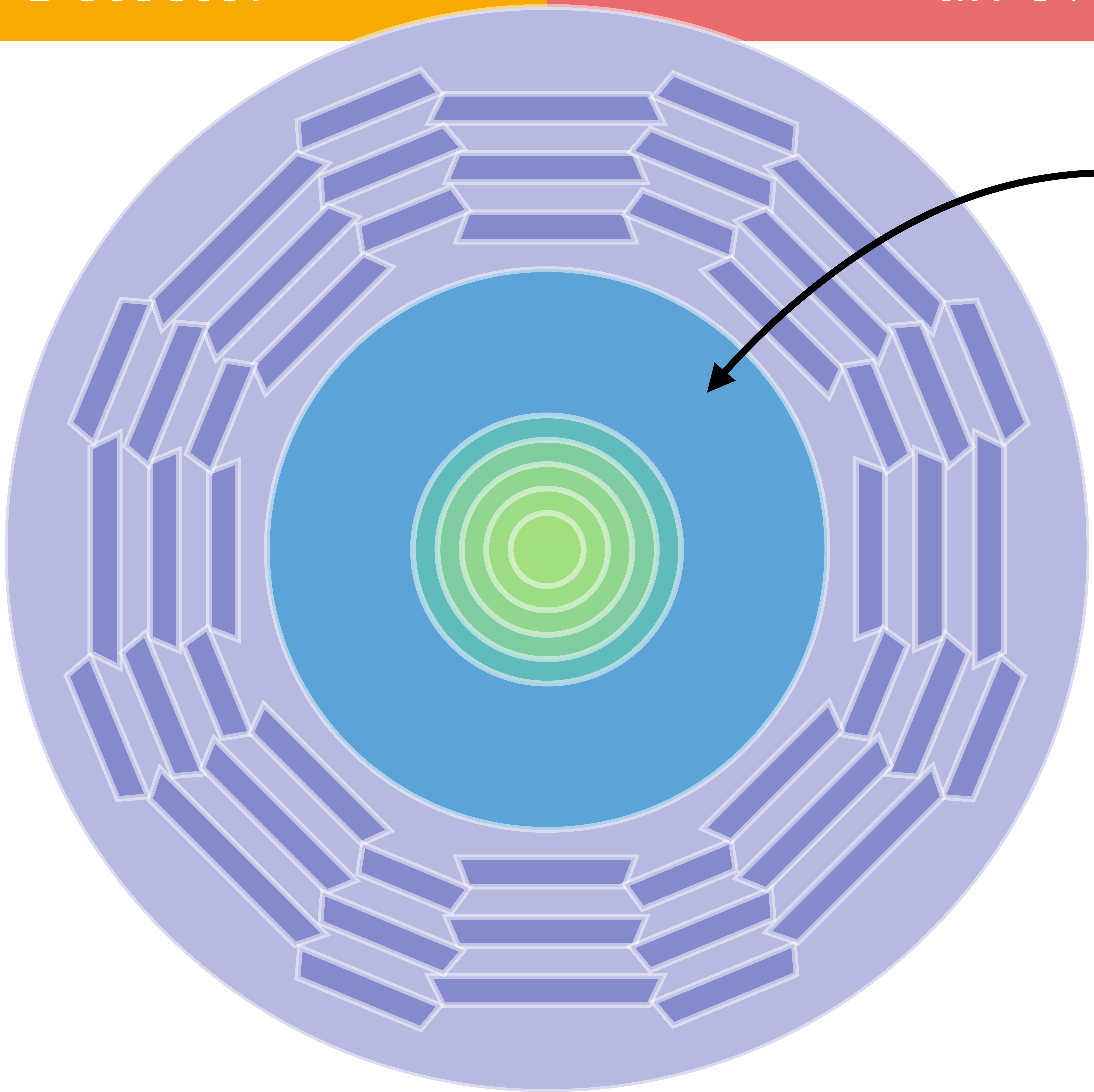
or really hard


24 meters
1.7 meters



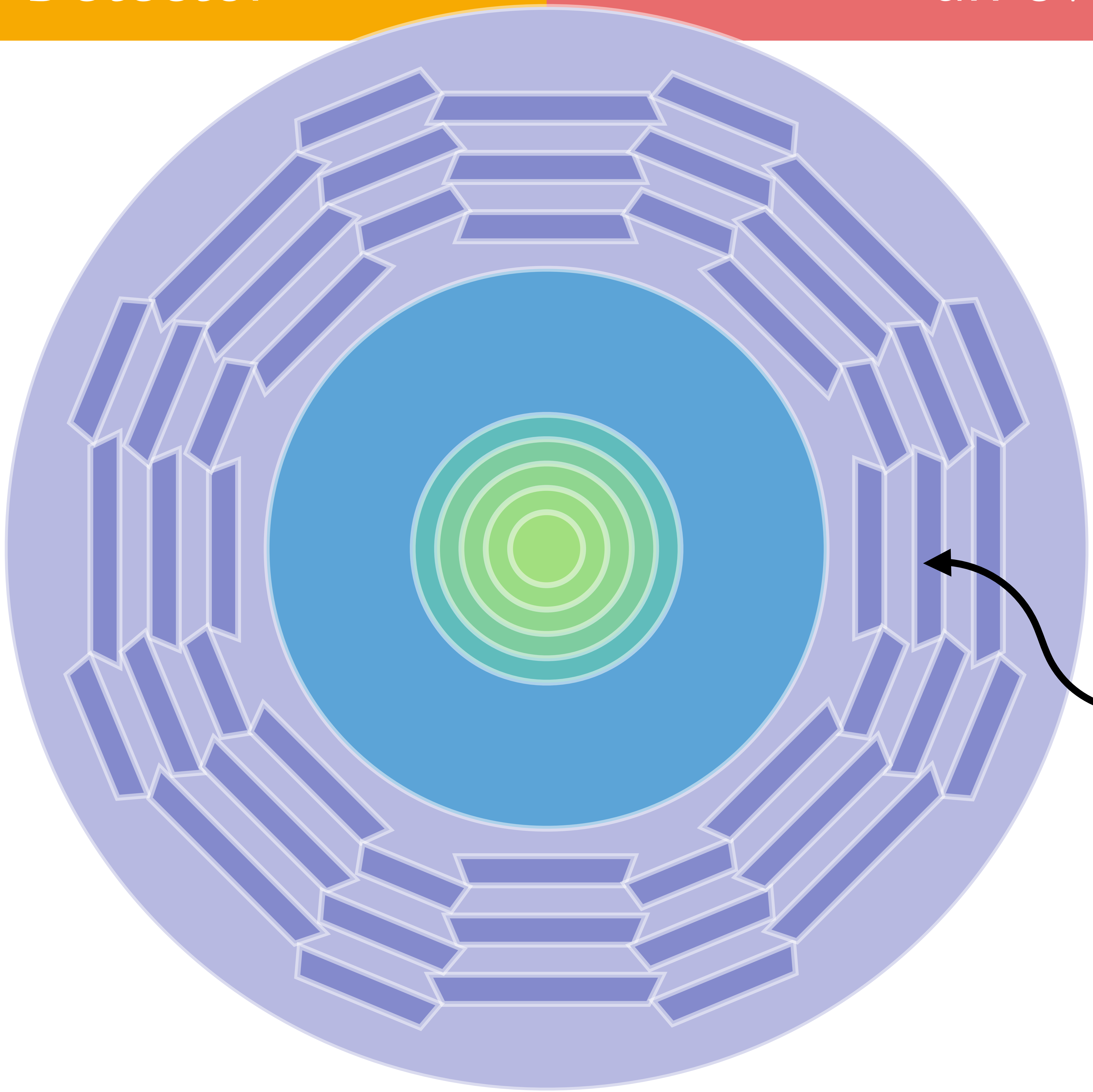
Charged particles leave tracks and we can get precise **position** measurements

Magnetic field means we can also measure **momentum**



Calorimeter

Stops particles and measures the **energy** deposited



Muon System

Muons aren't stopped by the calorimeter

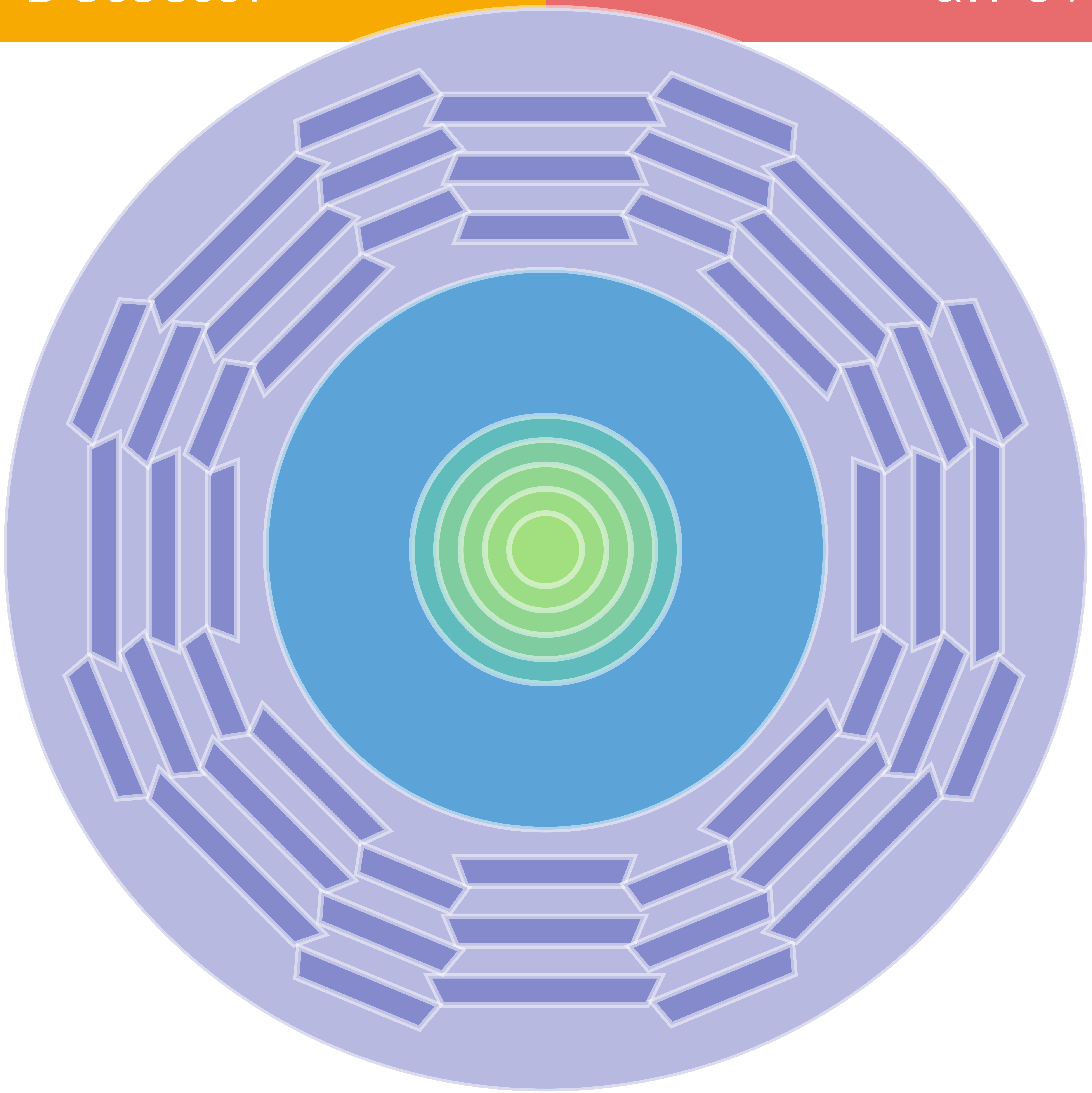
Muon system provides signatures similar to the tracker, but with **very little background**

The ATLAS Detector — an overview

Tracker

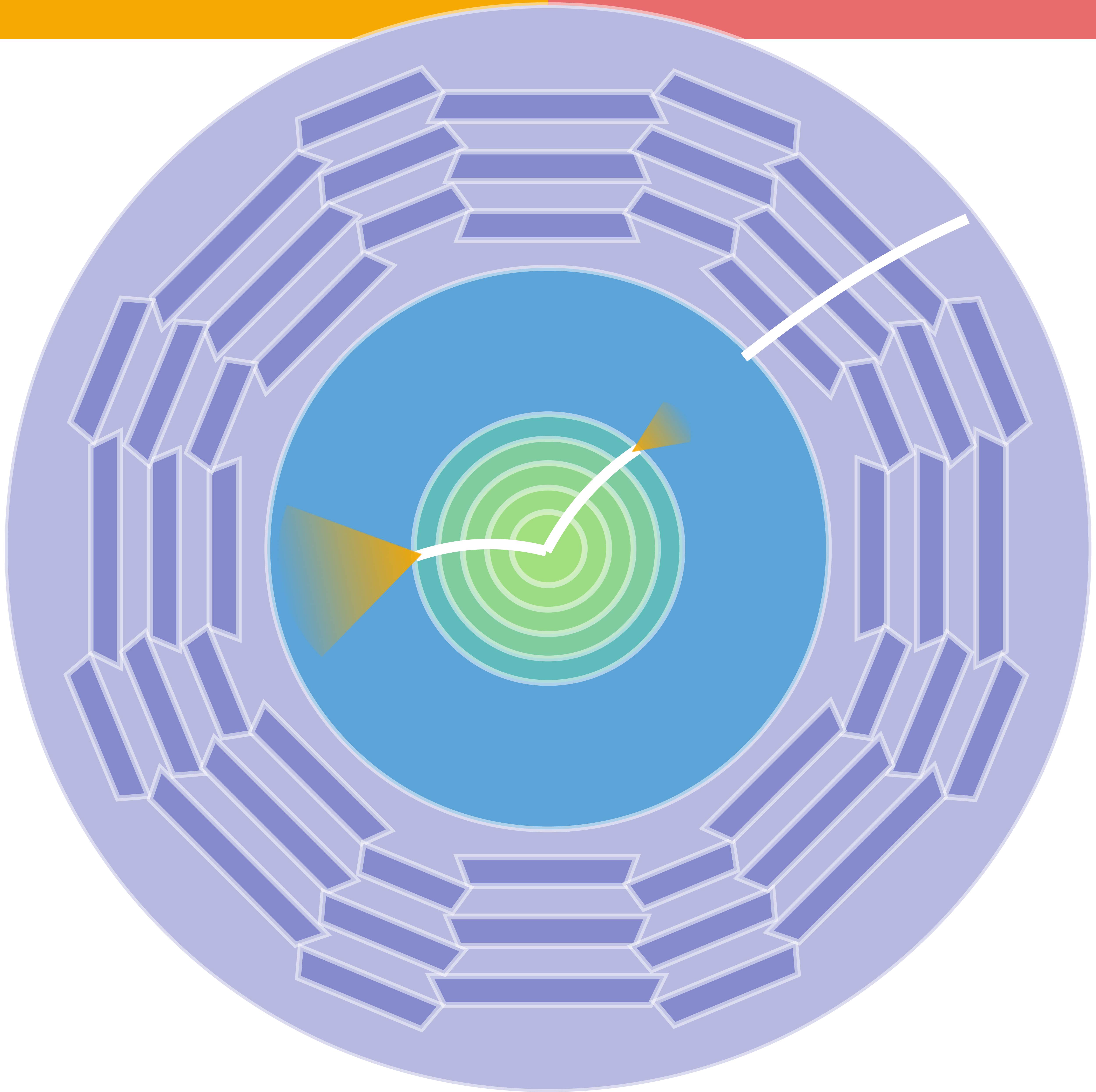
Calorimeter

Muon System



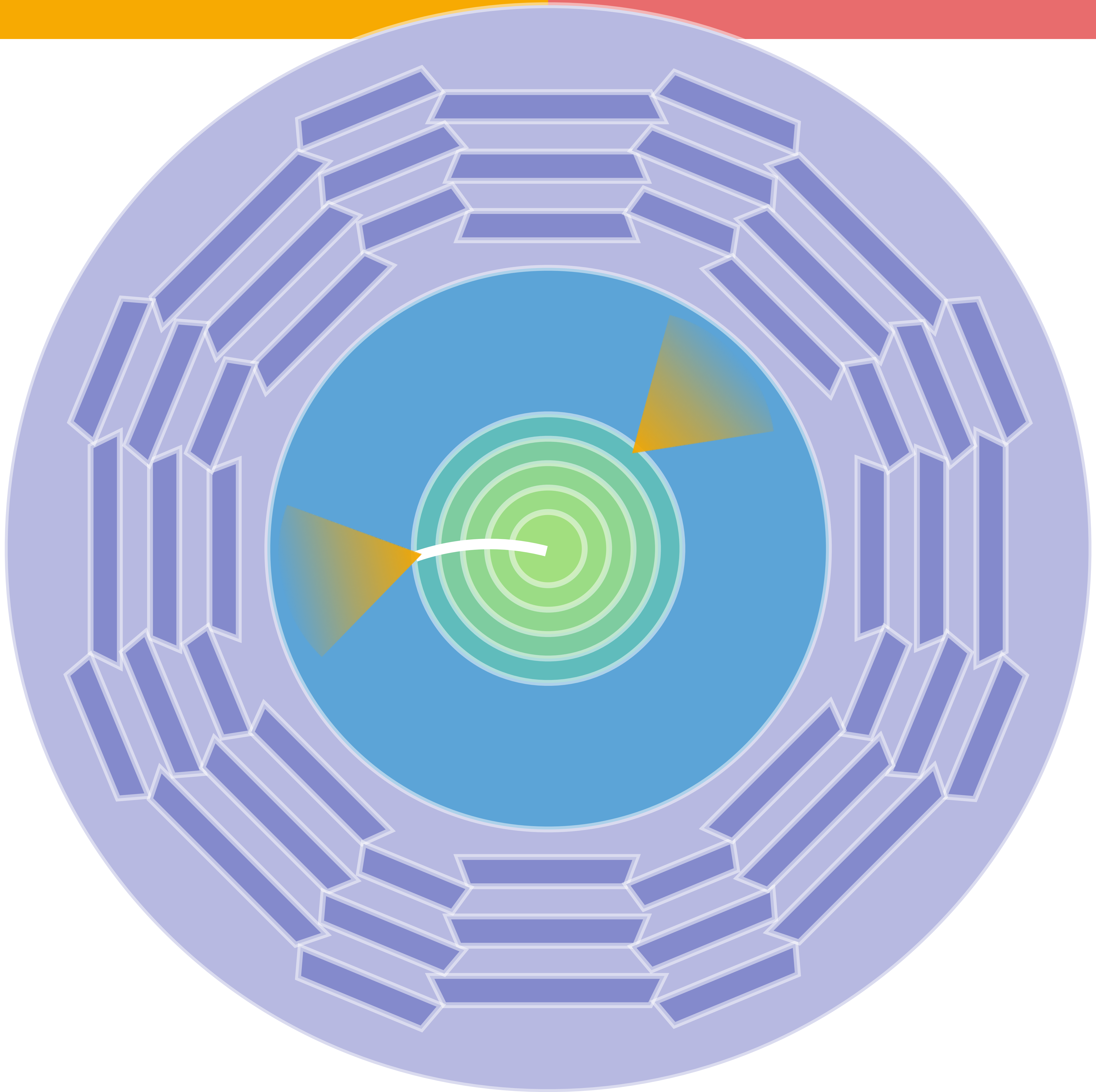
Layers of complimentary
particle detection

Designed so we can
identify a particle
traveling through all of them

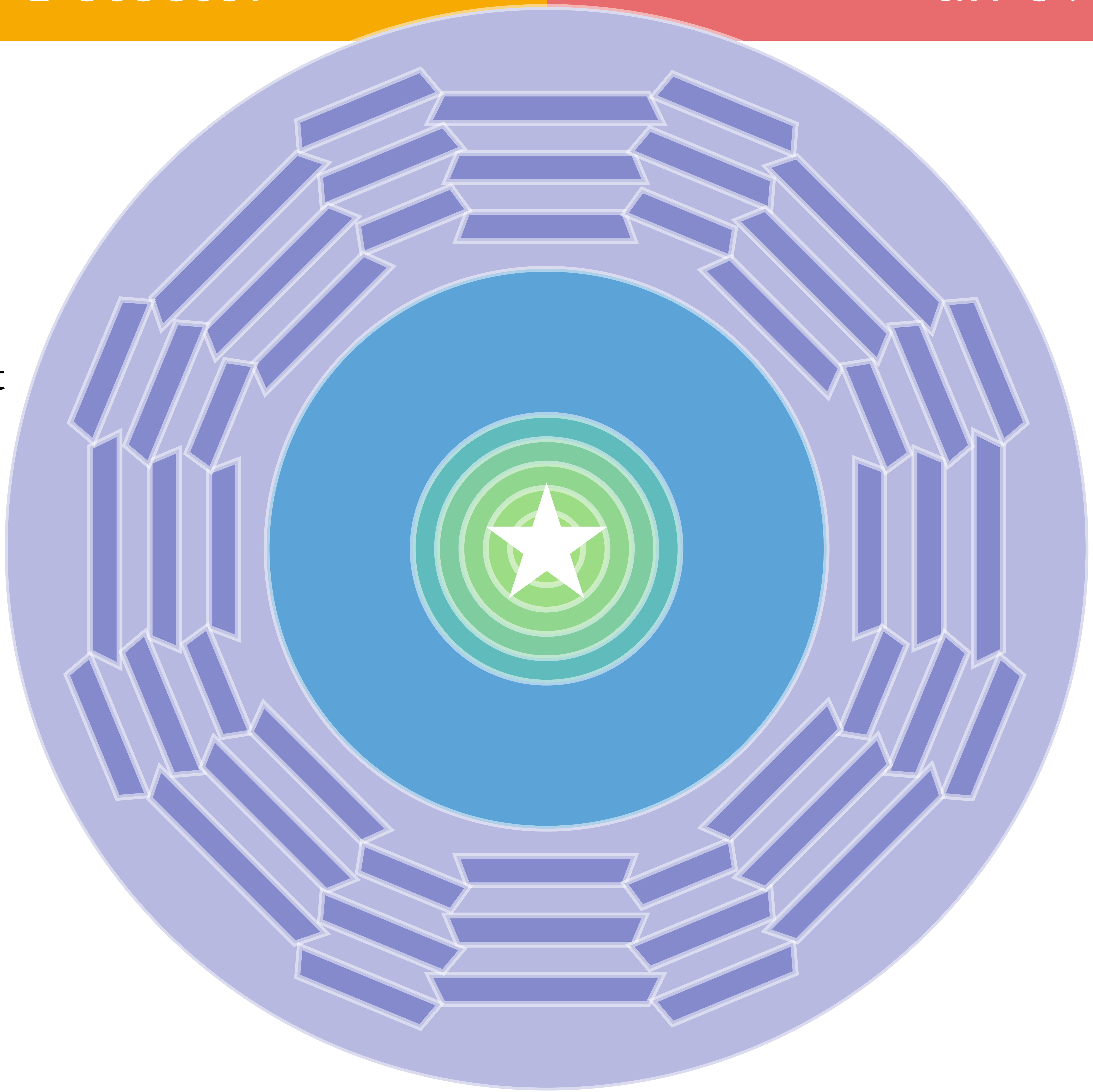


So we can tell an **electron** from a **muon**

same inner detector tracks
electron leaves a large deposit in the calorimeter
muon comes with a track in the muon system



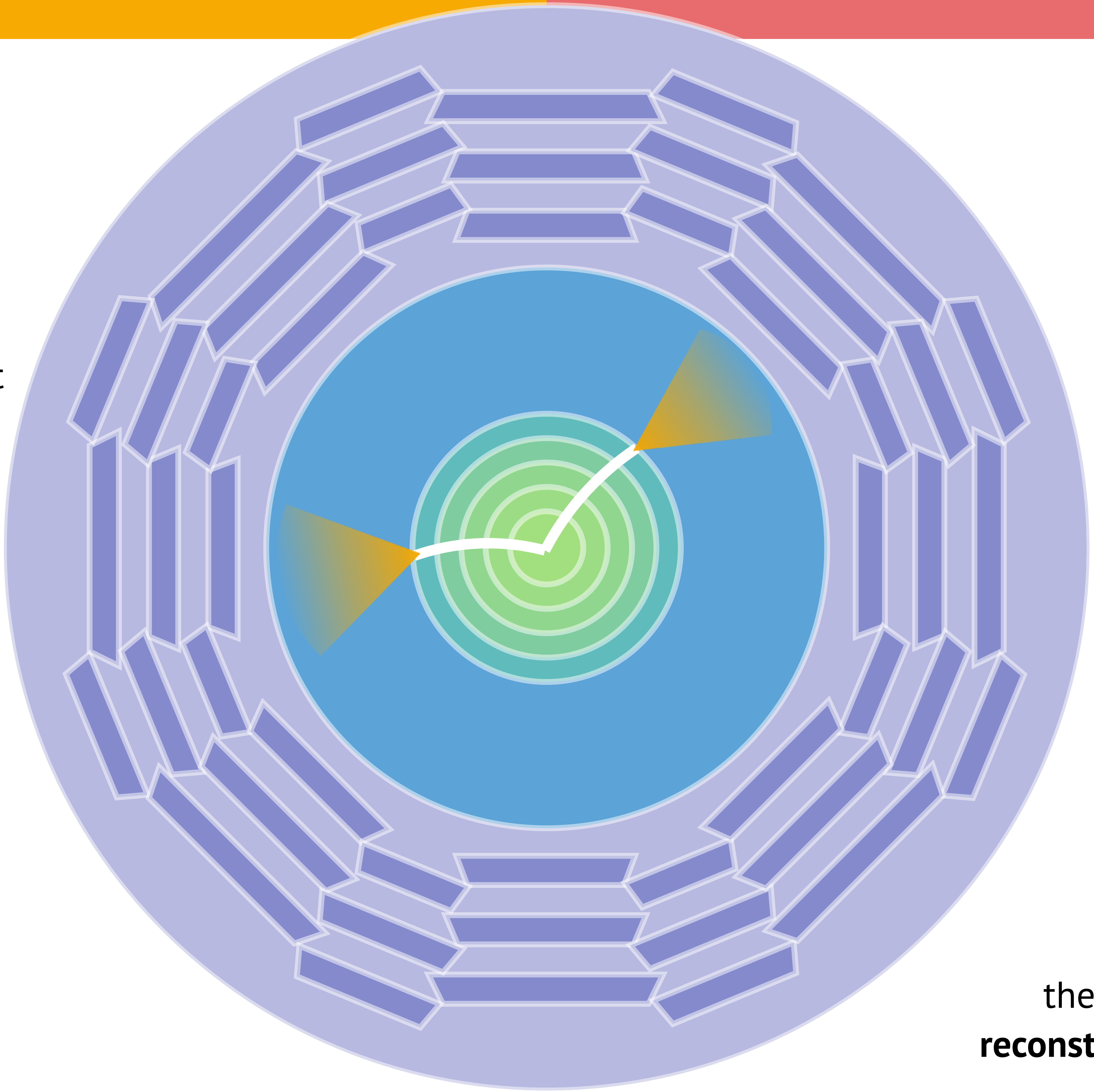
An **electron** and a **photon** look the same in the calorimeter, but only the electron leaves a track in the **tracker**



Success of particle ID is dependent on two assumptions

your particles **start at the center** of the detector and travel out

the particles you detect are **standard model** particles



Success of particle ID is dependent on two assumptions

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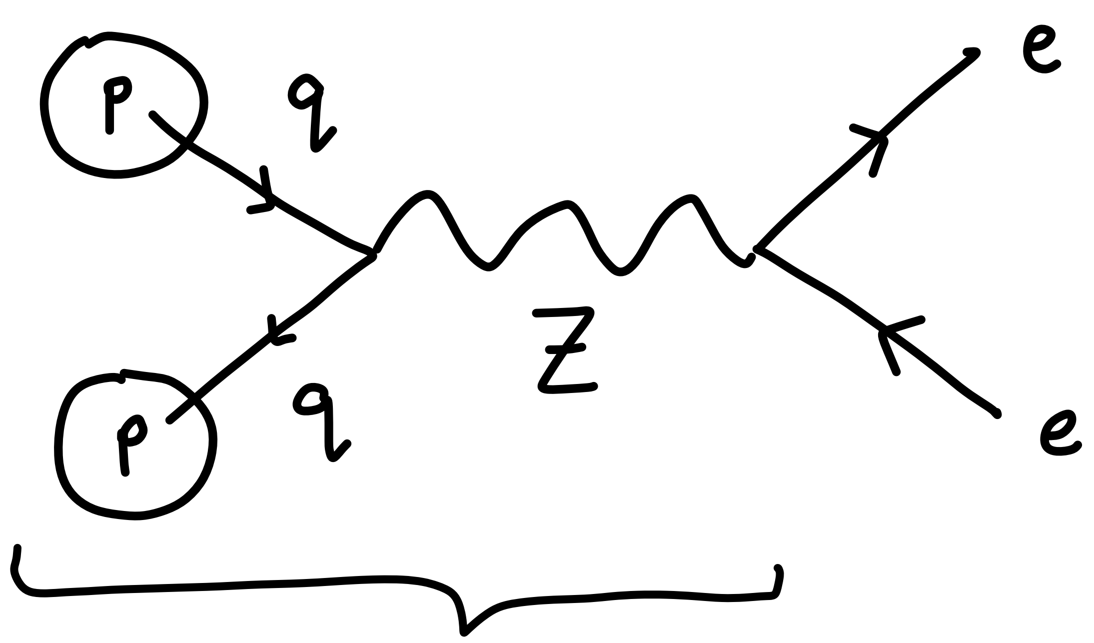
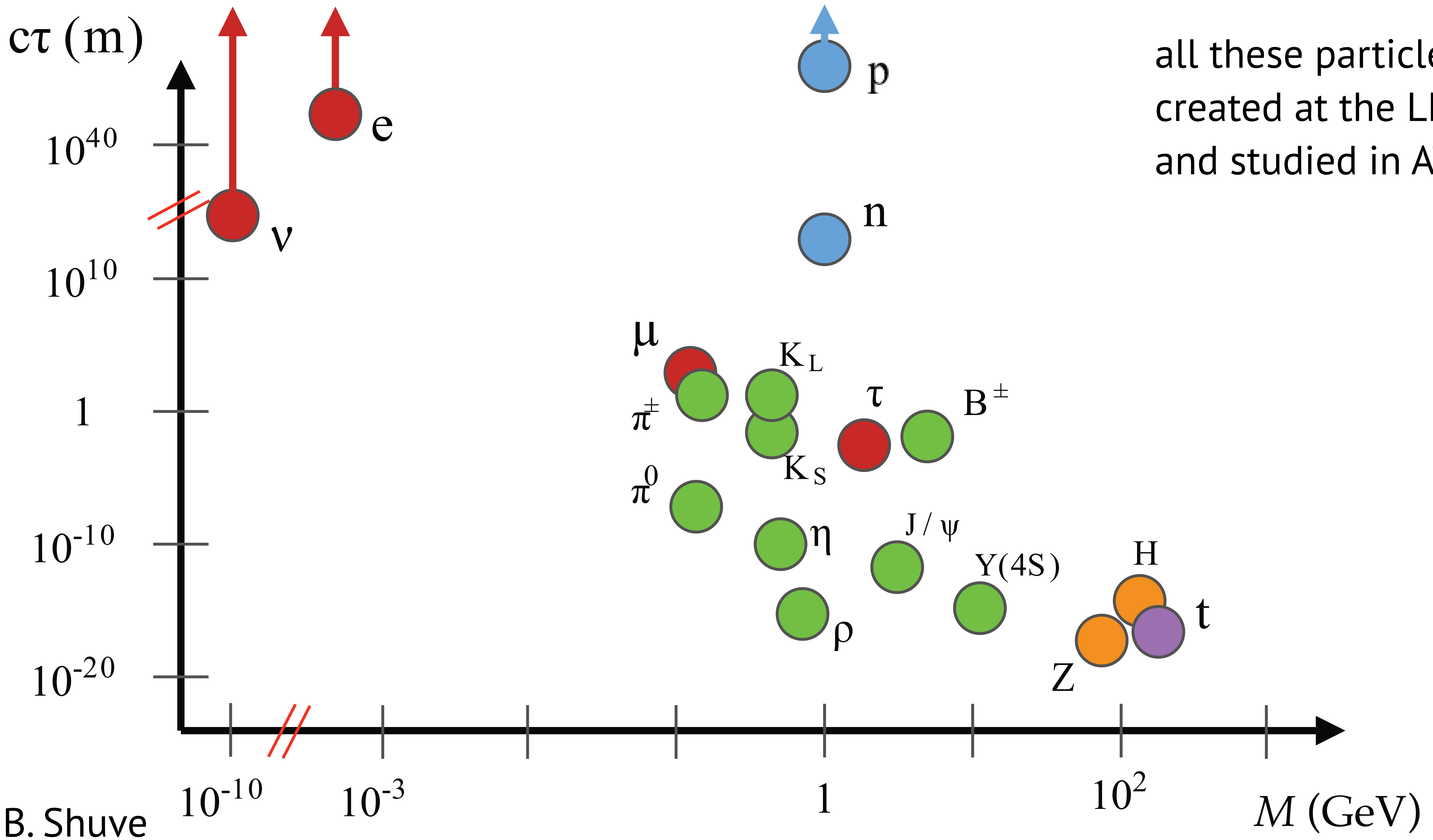
Typically true!



all this happens in ~ 10^{-25} seconds

detector only ever sees the **electrons** from the Z decay **reconstruct** the Z from their properties

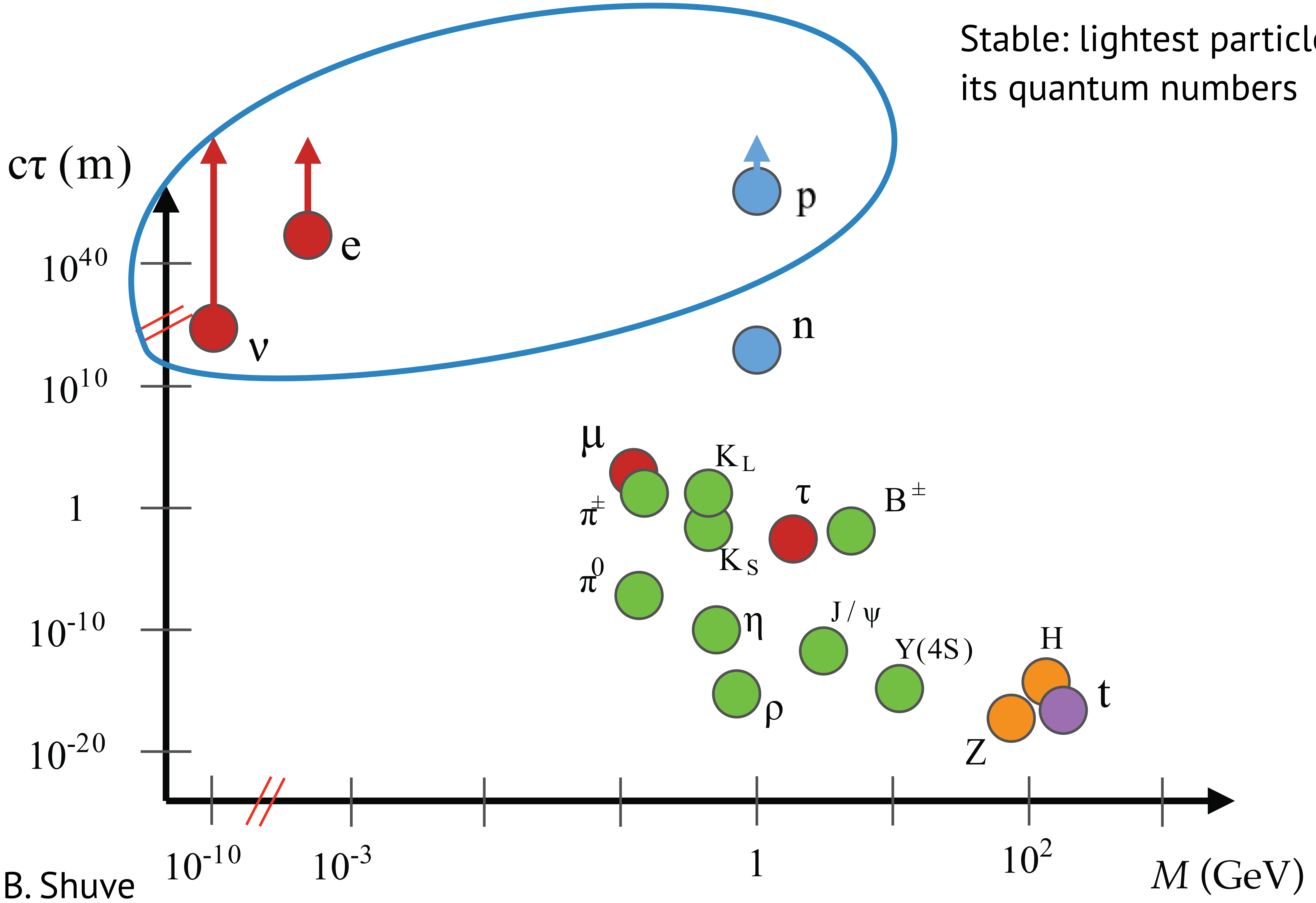
The standard model is full of "long-lived particles"



all these particles are created at the LHC and studied in ATLAS

B. Shuve

The standard model is full of "long-lived particles"



Stable: lightest particle with its quantum numbers

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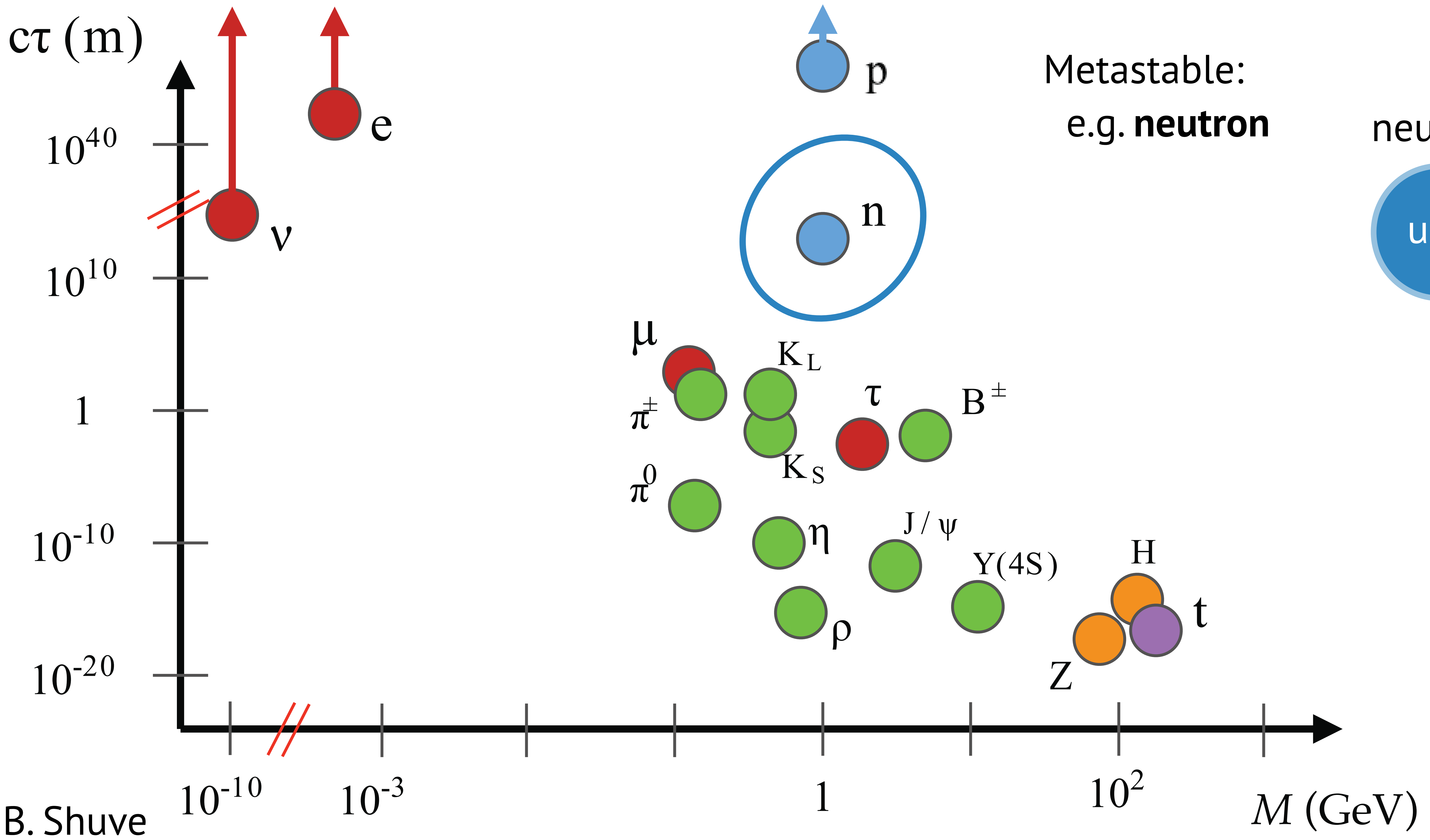
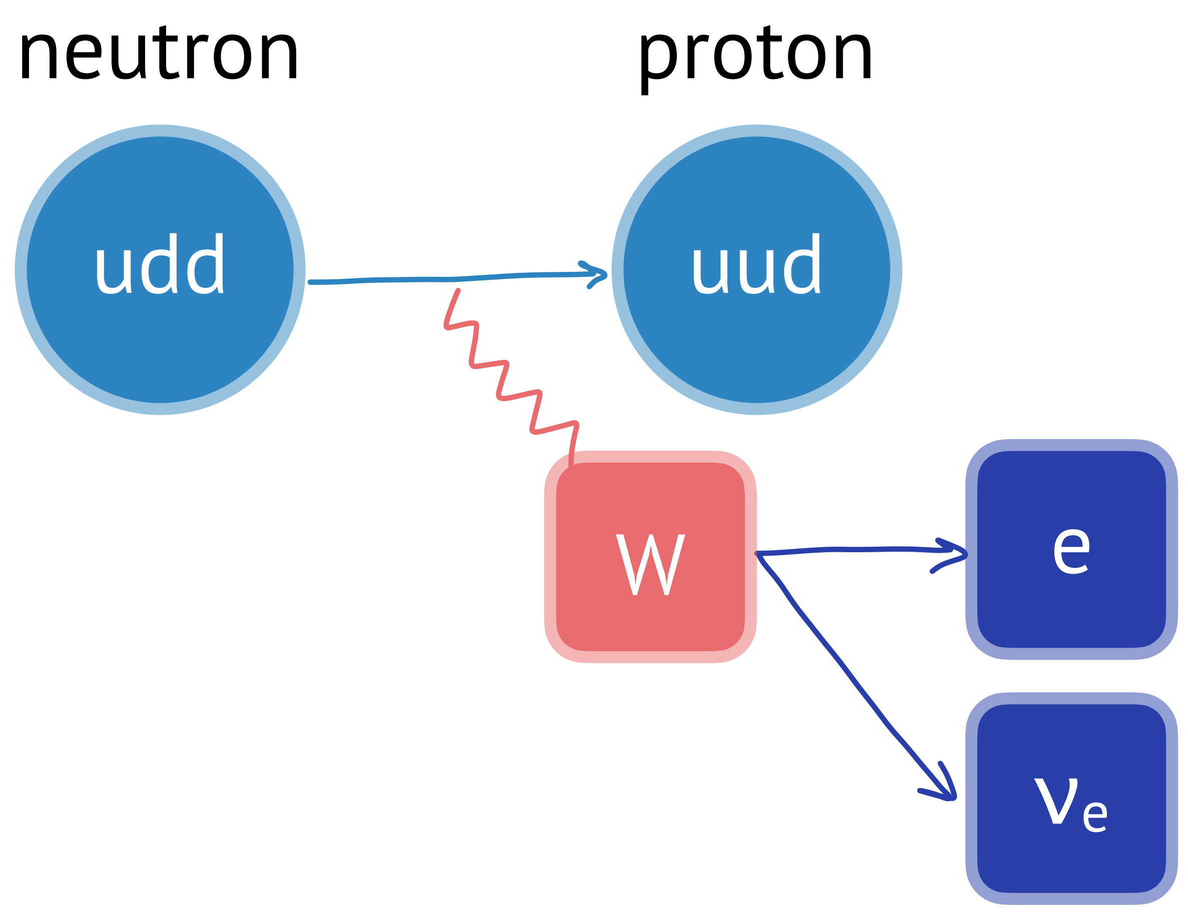


B. Shuve

Stable: lightest particle with its quantum numbers

Metastable:
e.g. **neutron**



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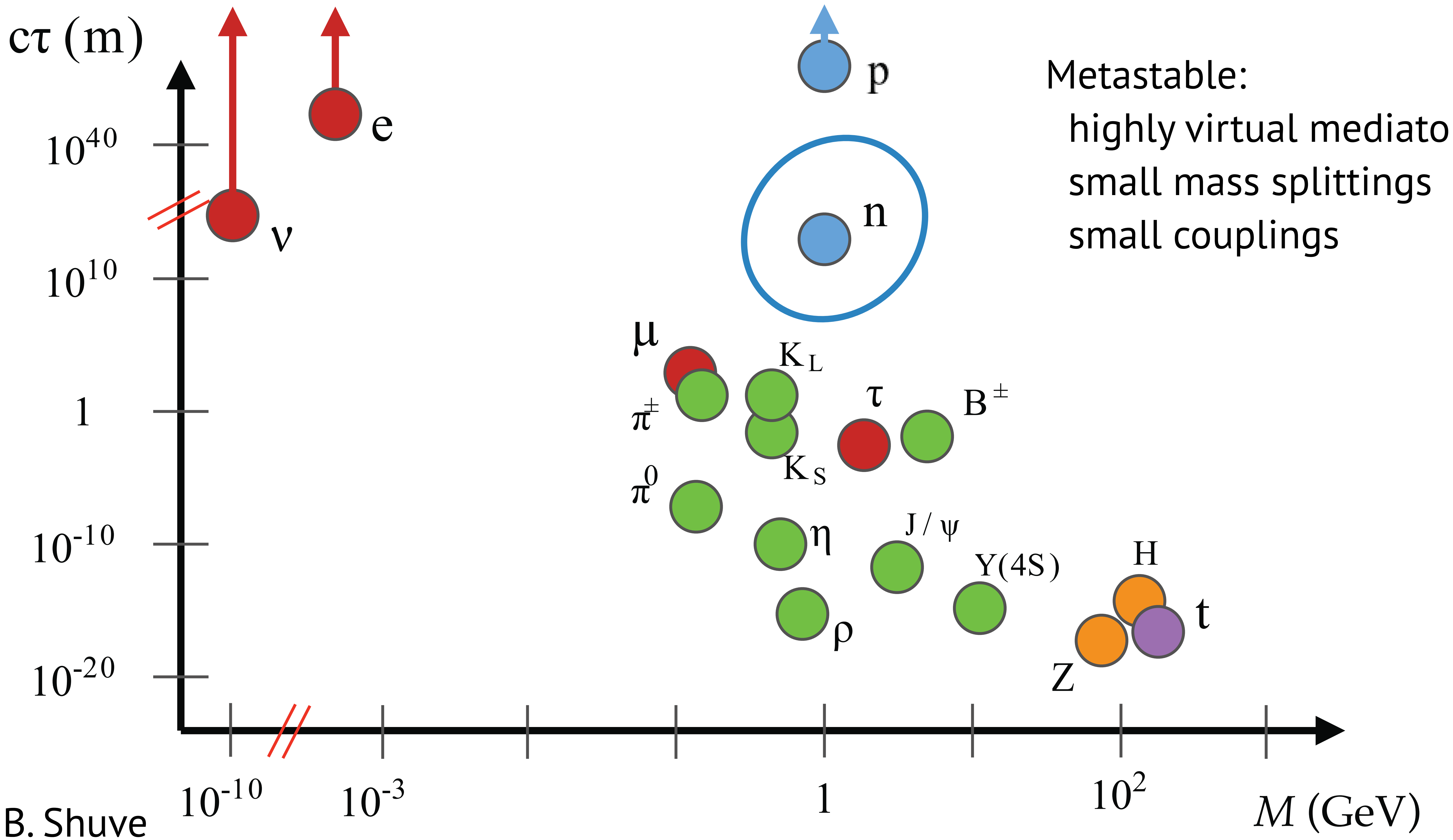

B. Shuve

Stable: lightest particle with its quantum numbers

Metastable:
- highly virtual mediators
- small mass splittings
- small couplings

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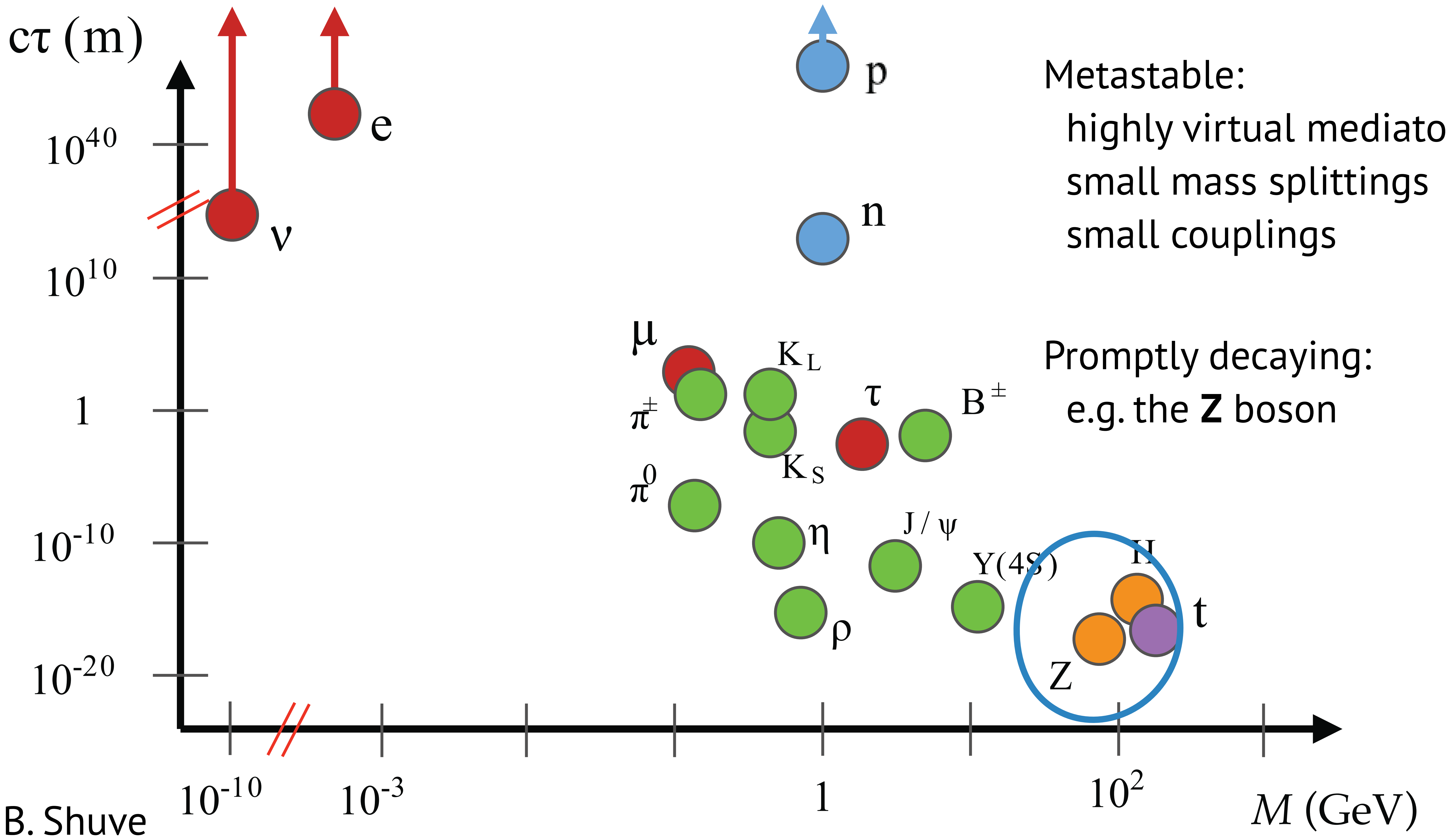

B. Shuve

Stable: lightest particle with its quantum numbers

Metastable:
- highly virtual mediators
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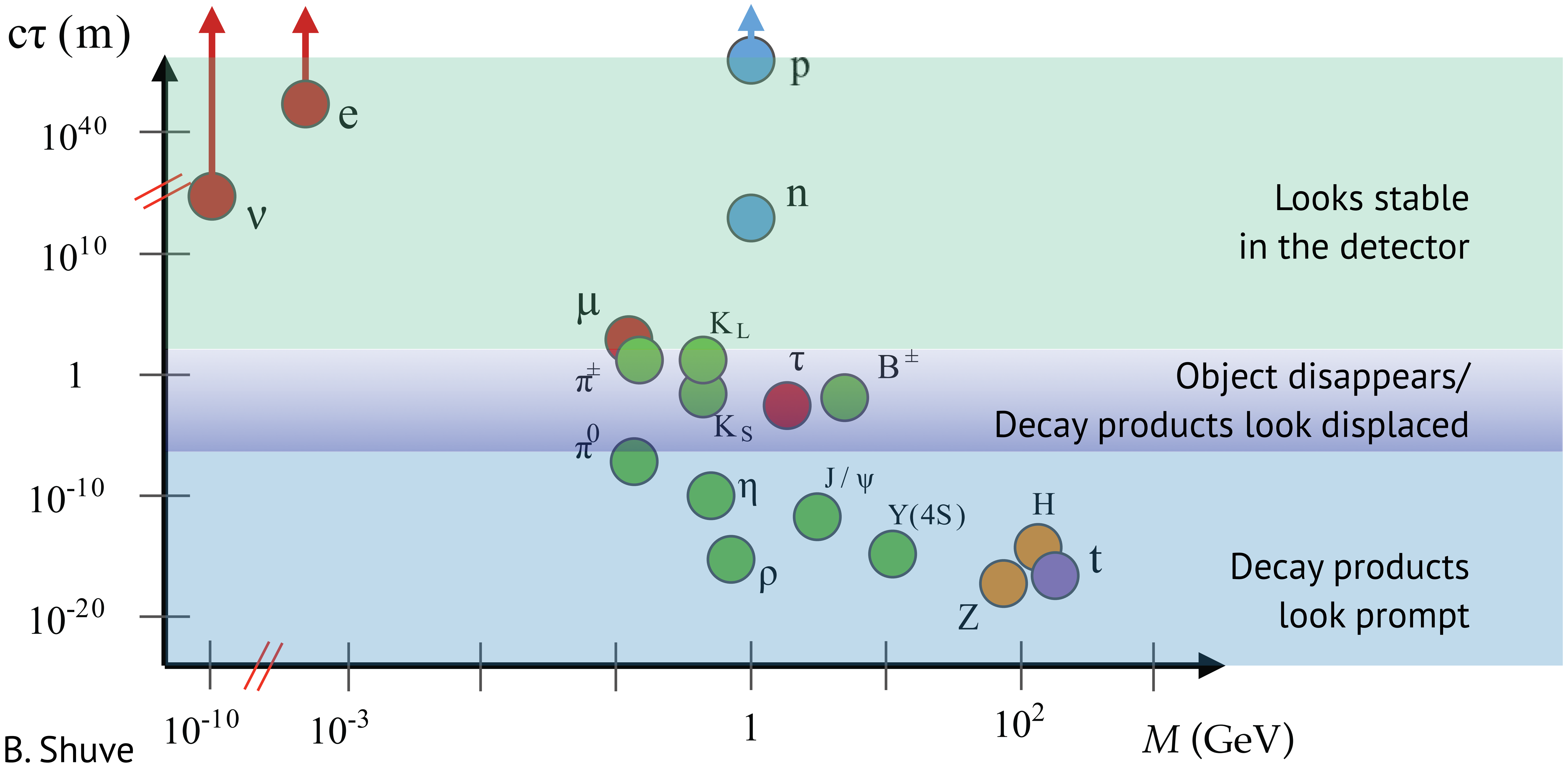
- small couplings

Promptly decaying:
- e.g. the **Z** boson

From the experimental point of view...

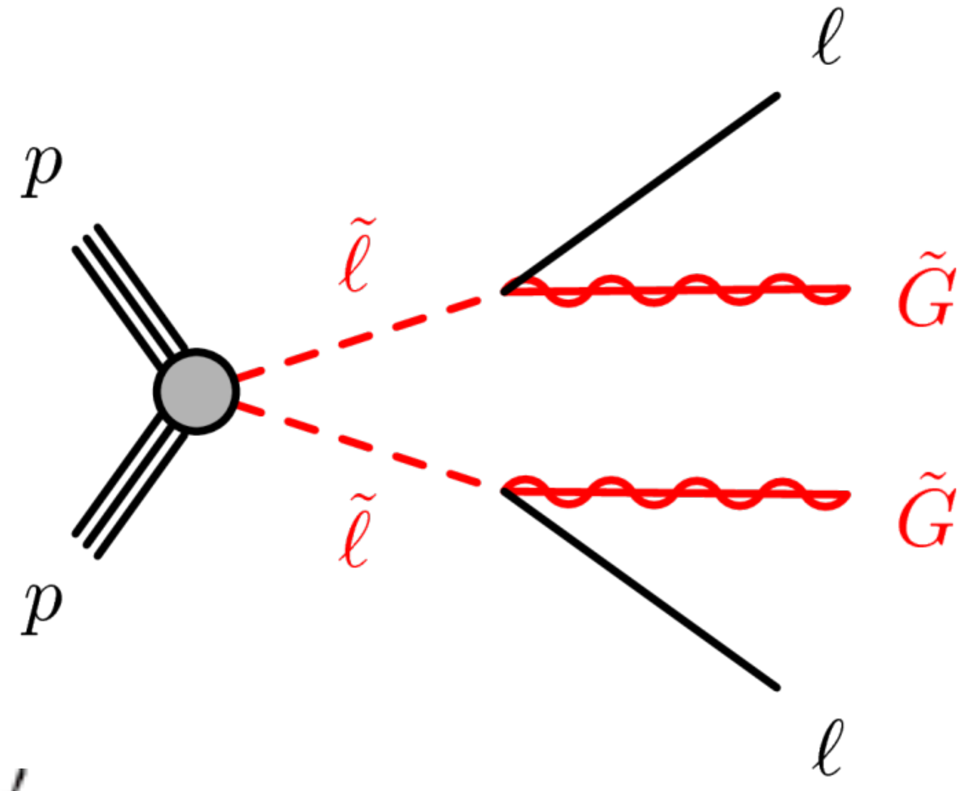


B. Shuve

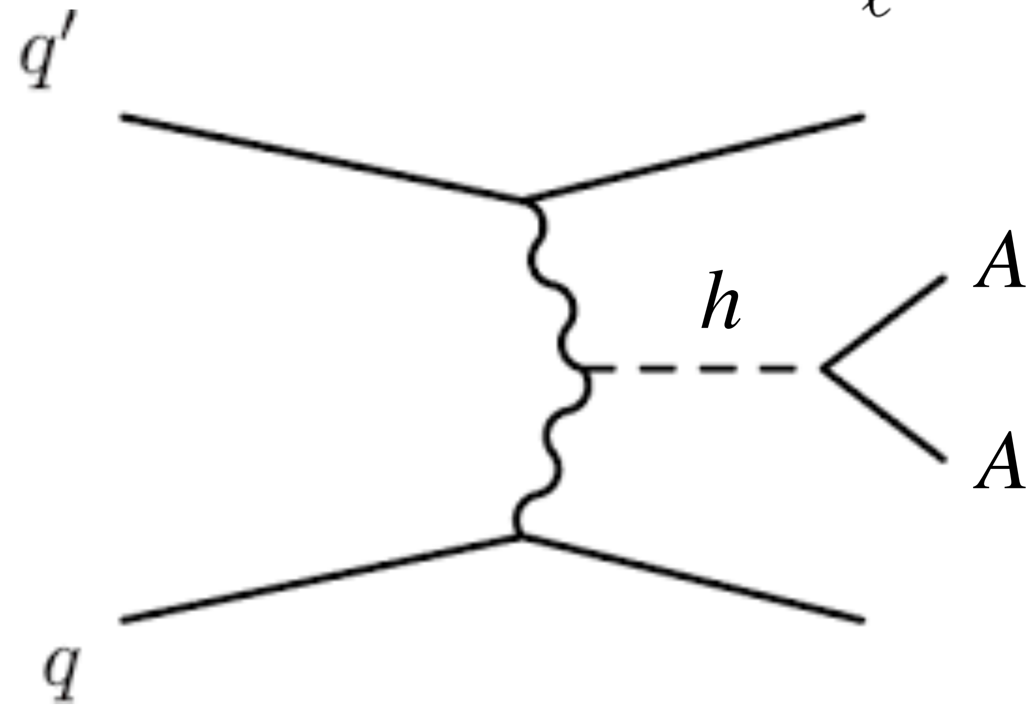
No reason to think there are only Standard Model long-lived particles…

Beyond-the-Standard-Model particles can be long-lived for the same reasons (small mass splittings, small couplings, virtual mediators)

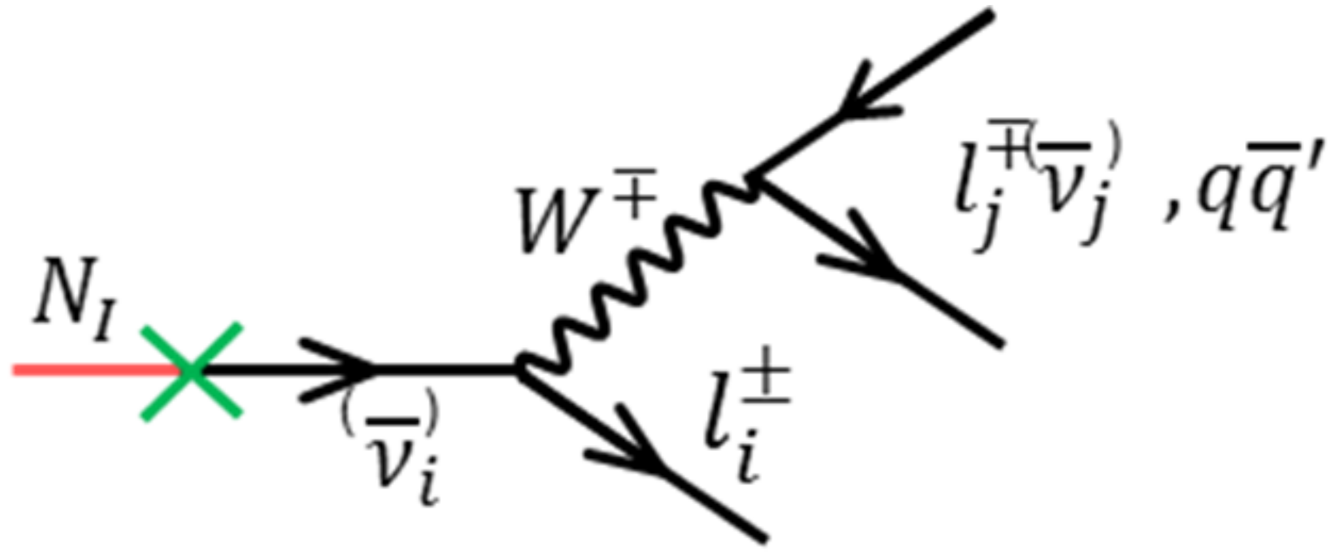
In Supersymmetry…



From hidden sectors…



Right-handed neutrinos…



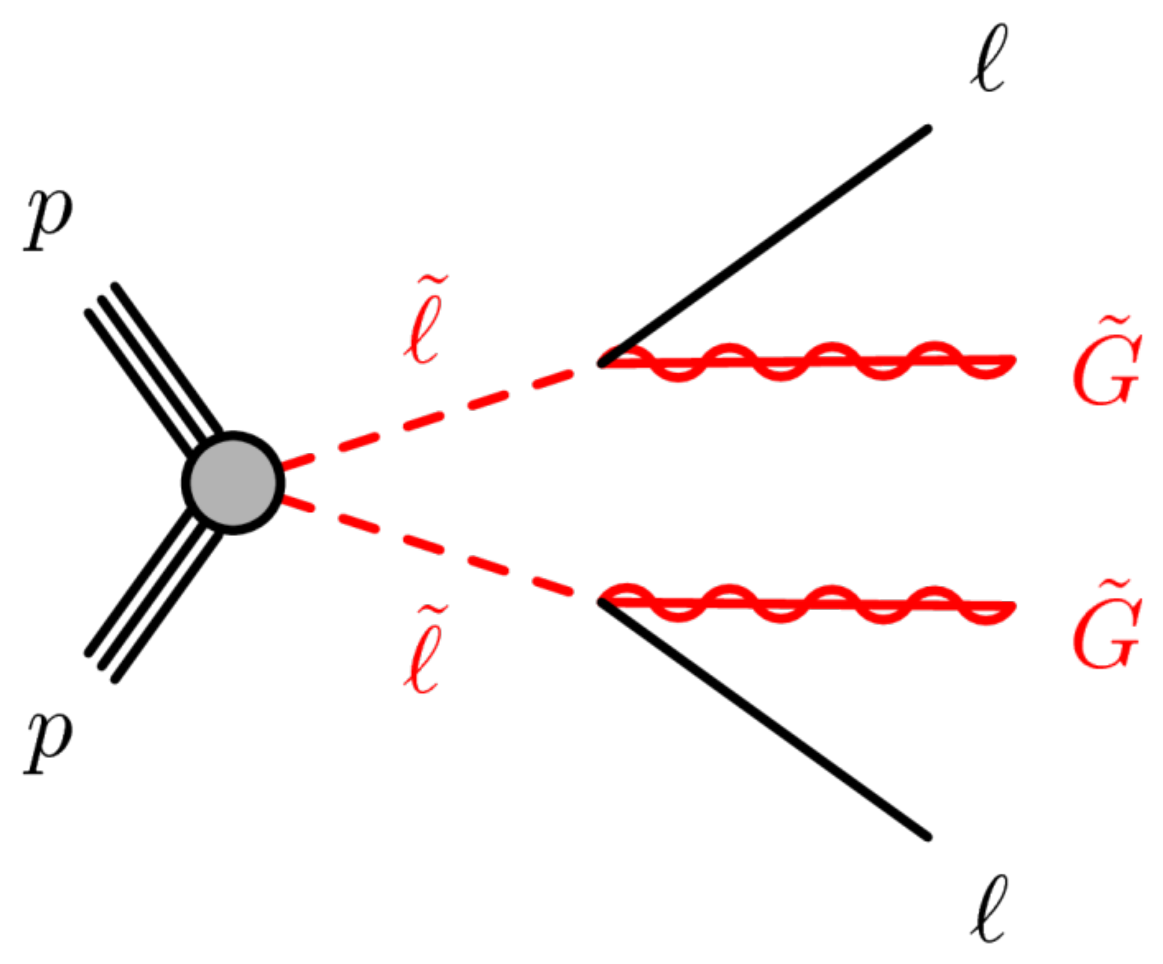
Any **dark matter candidate** has to be metastable or stable!

No reason to think there are only Standard Model long-lived particles…

Beyond-the-Standard-Model particles can be long-lived for the same reasons (small mass splittings, small couplings, virtual mediators)

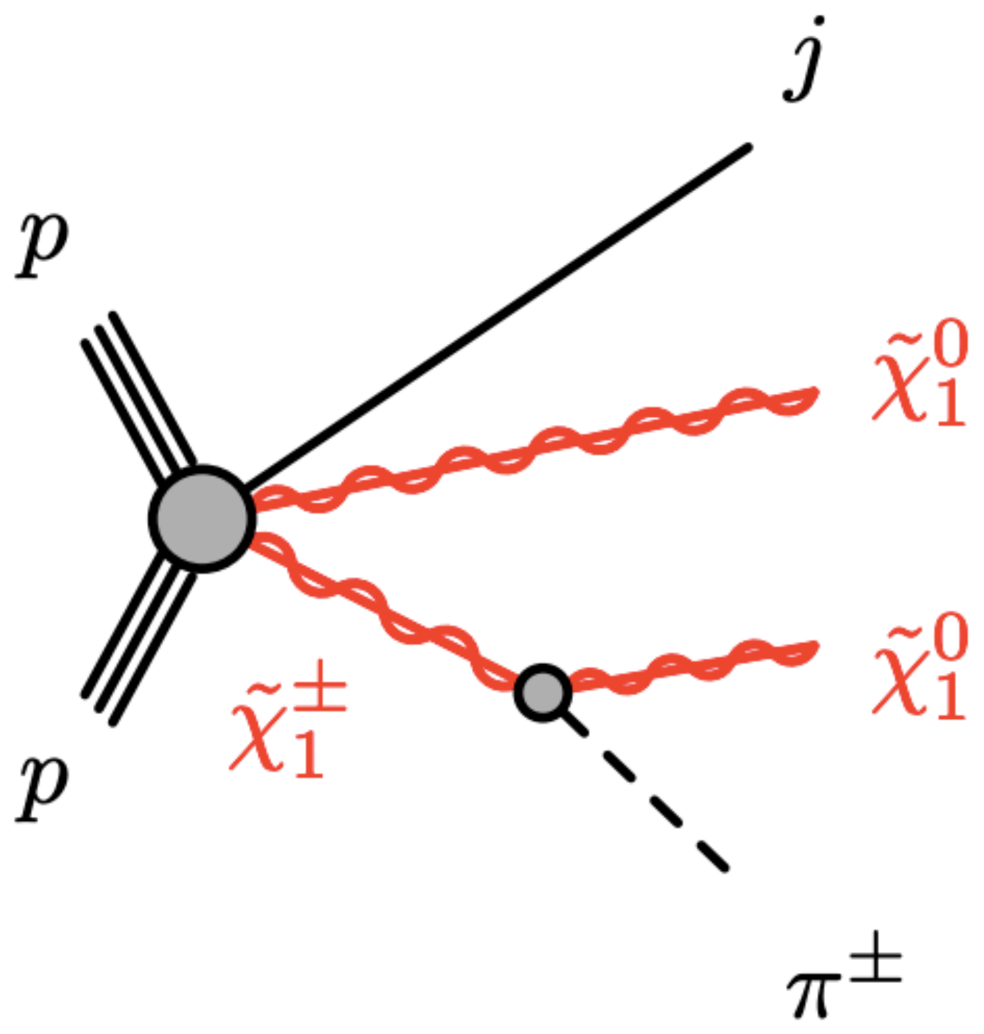
Happens in all kinds of theories of new physics, but I'll focus on one: **SUPERSYMMETRY**

Tiny Couplings



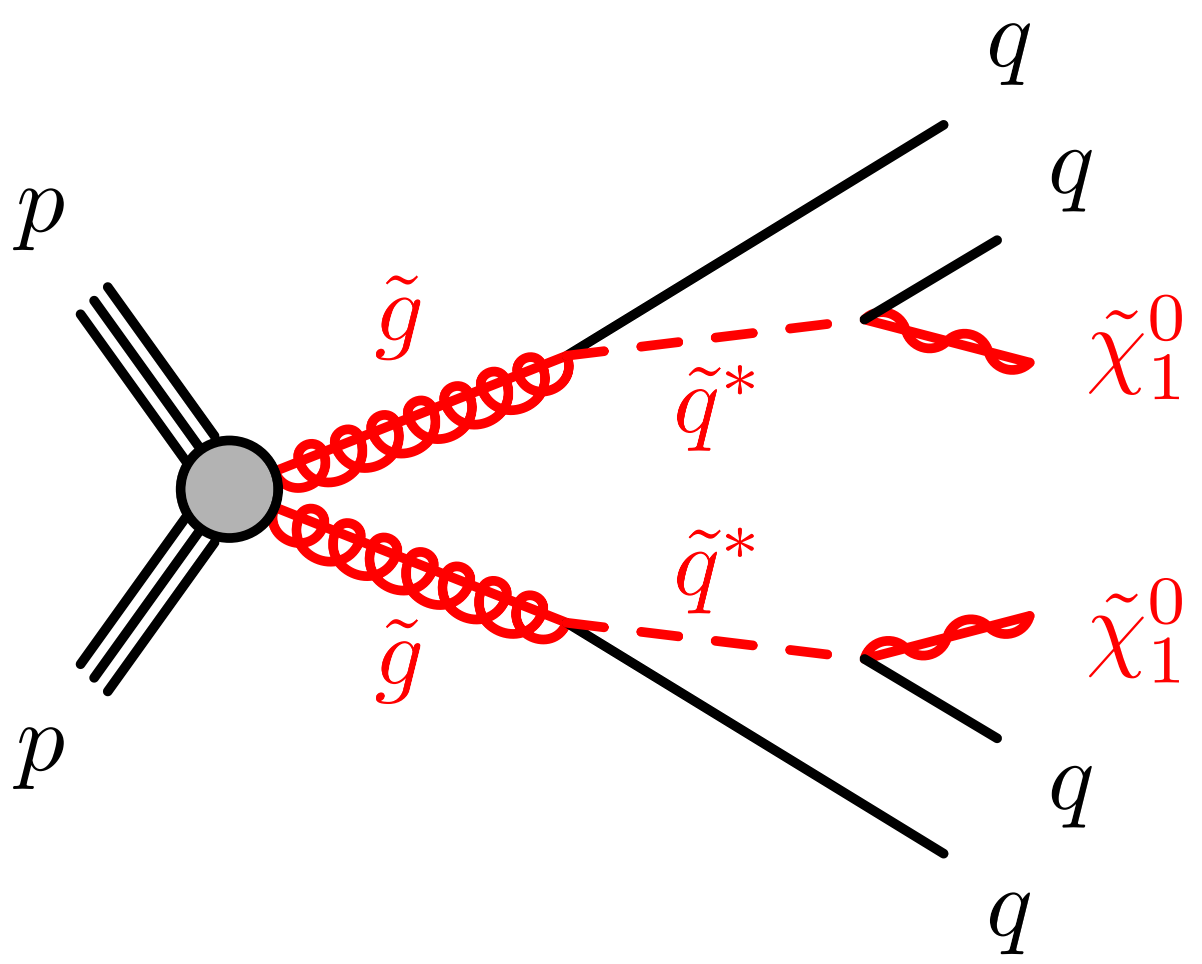
Gauge Mediated Symmetry Breaking

Small Mass Splittings



Anomaly Mediated Symmetry Breaking

Virtual Mediators



Split Supersymmetry

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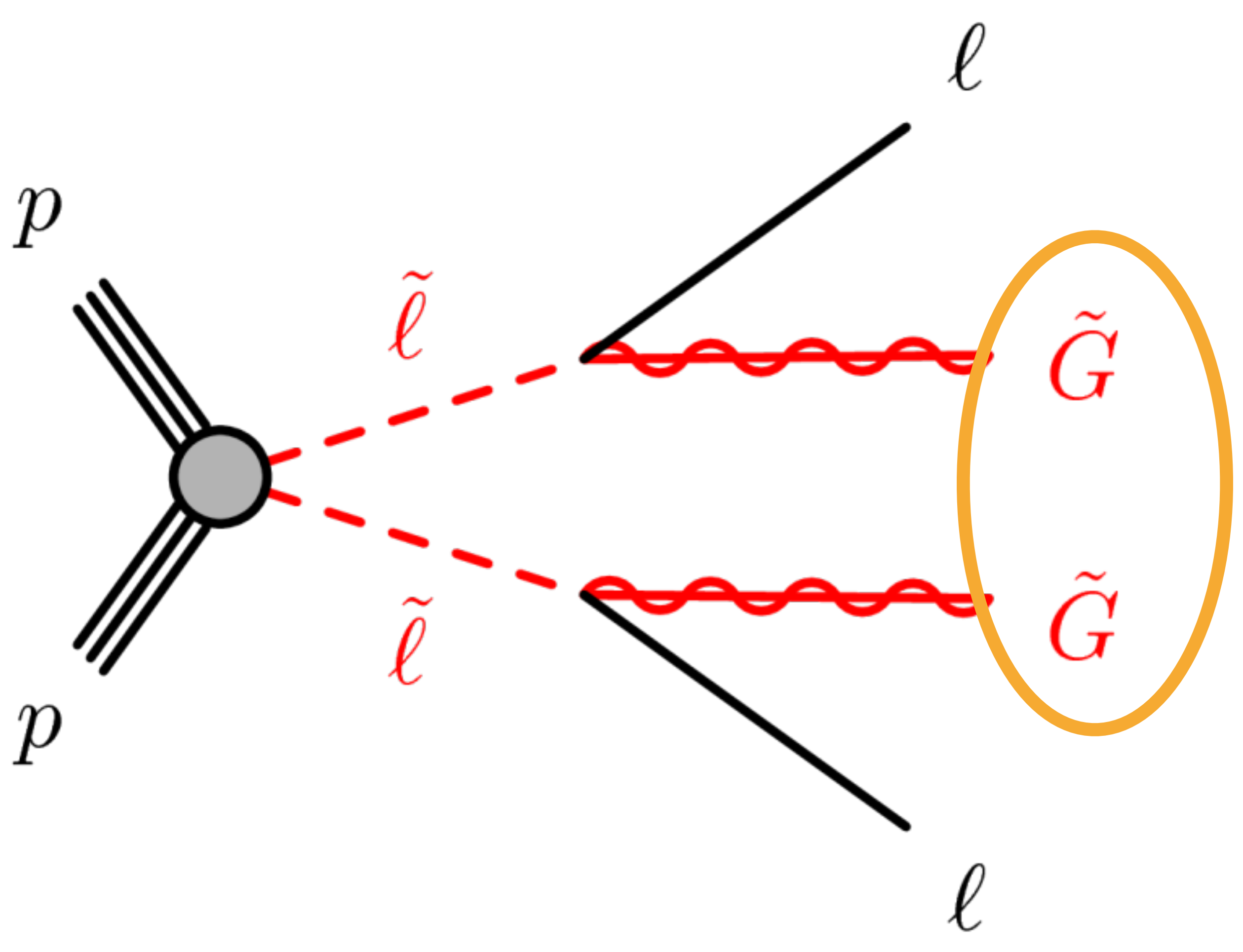

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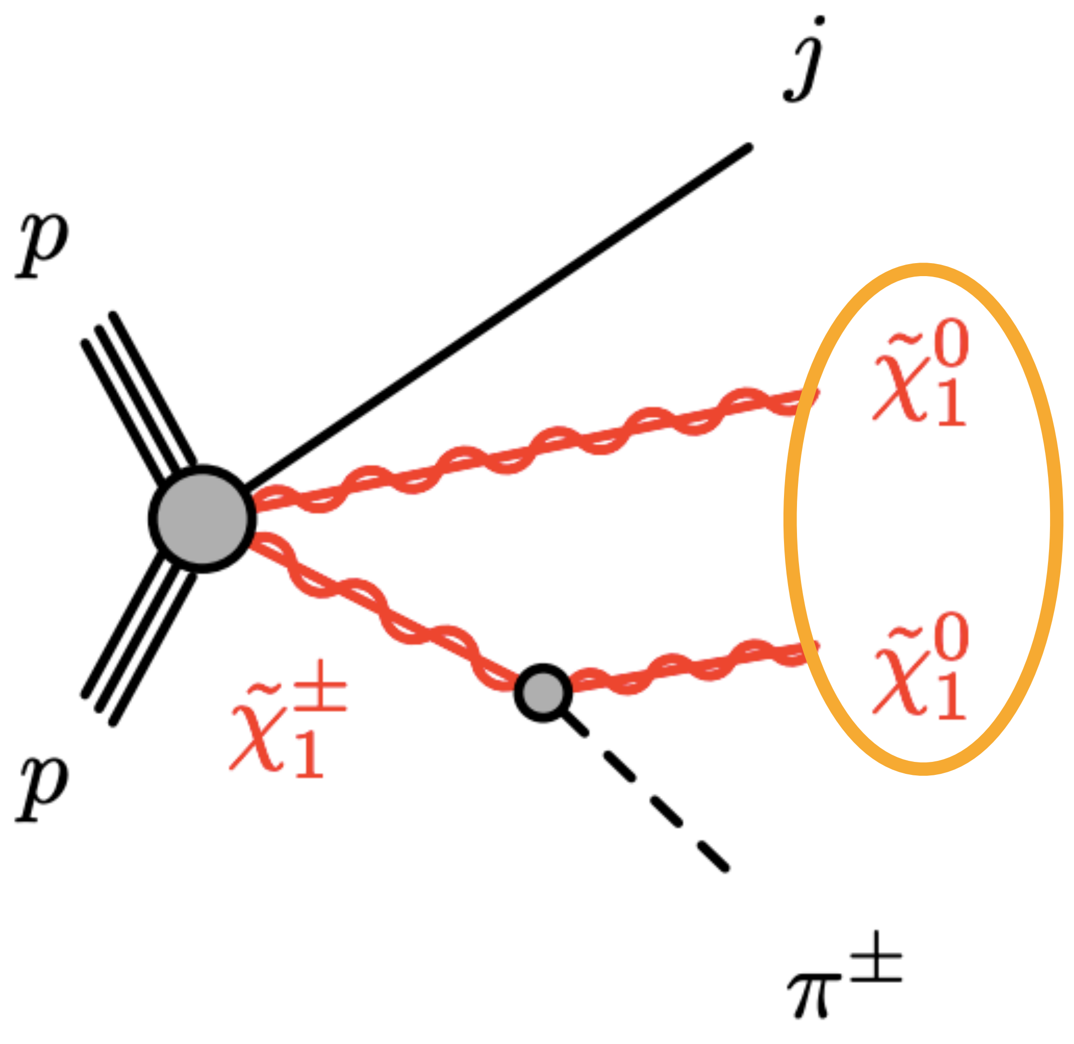

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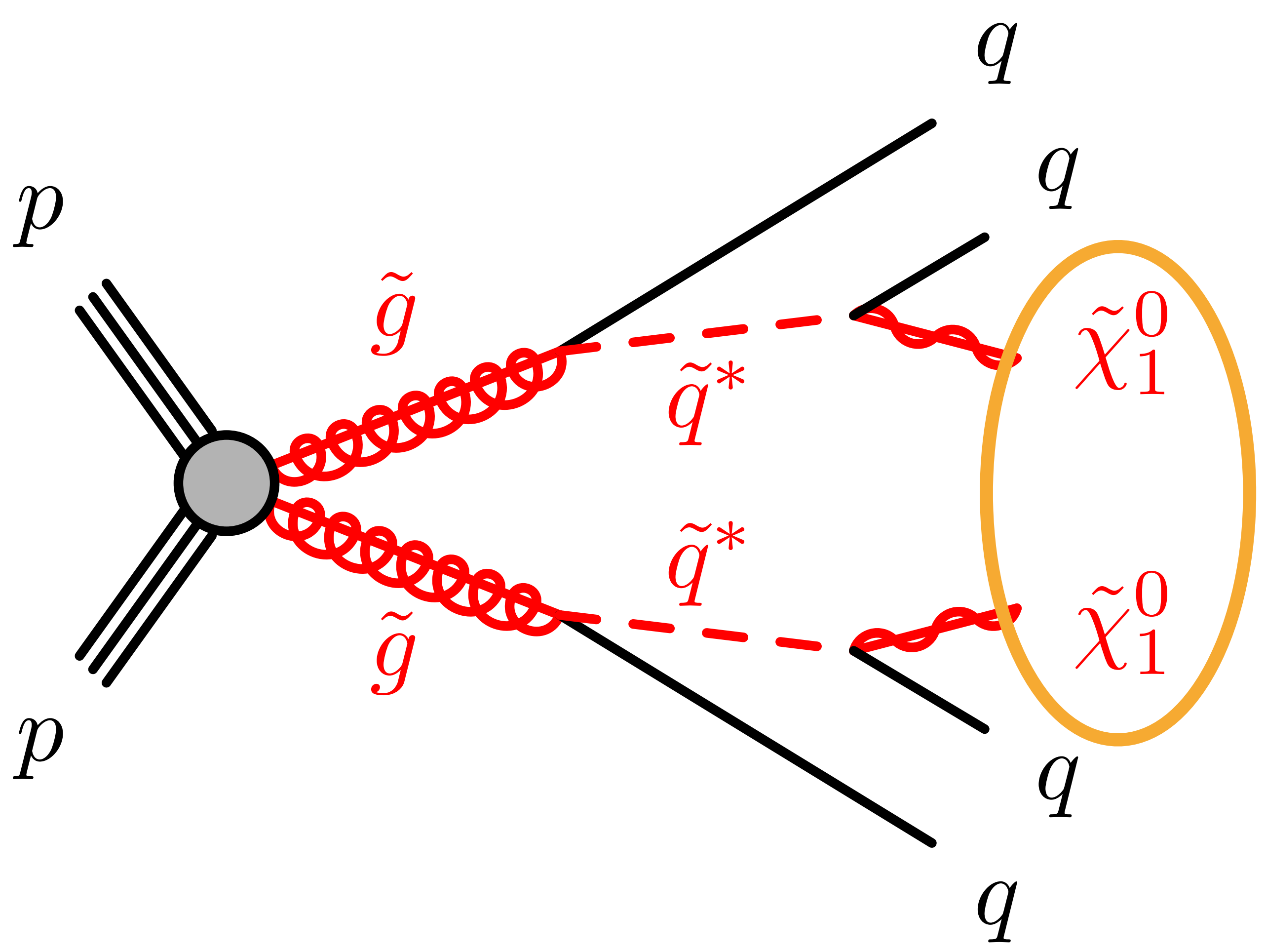

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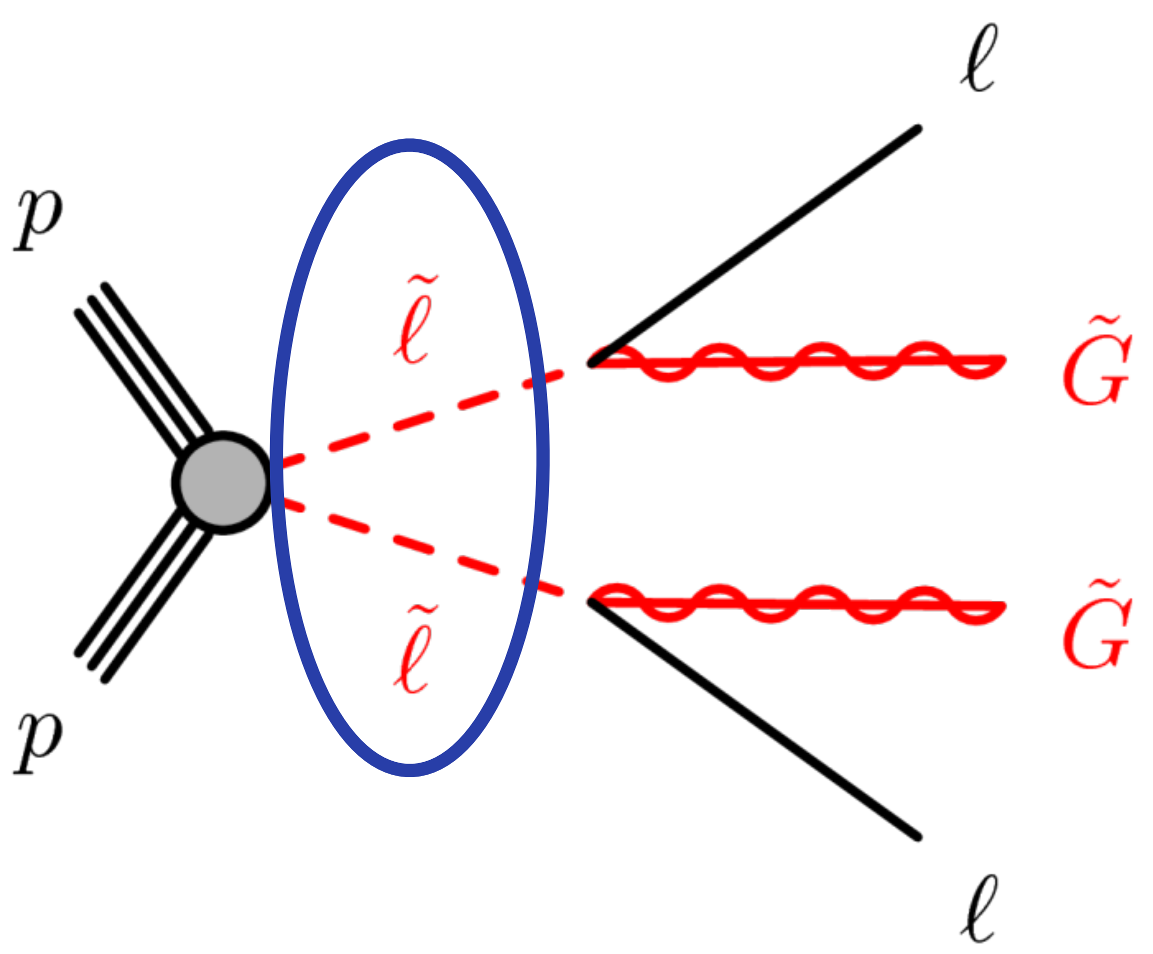

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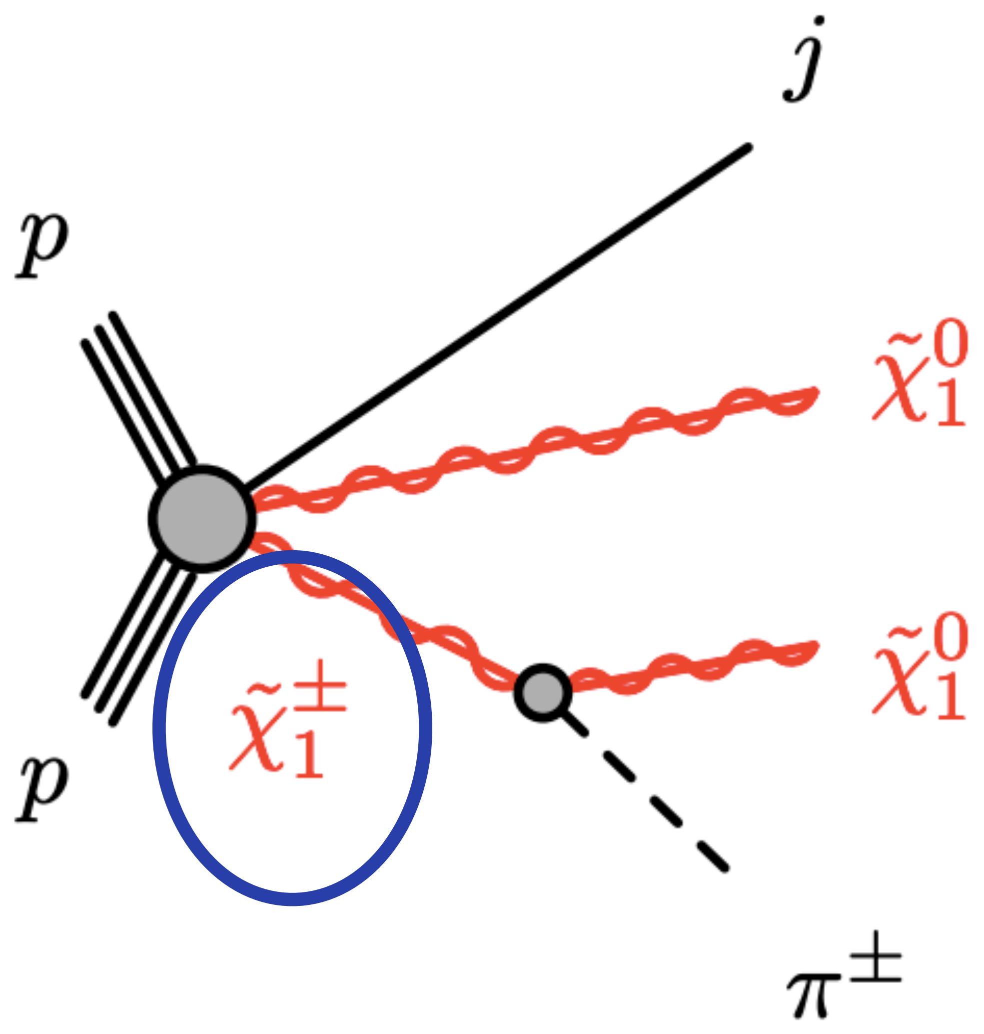

Anomaly Mediated Symmetry Breaking

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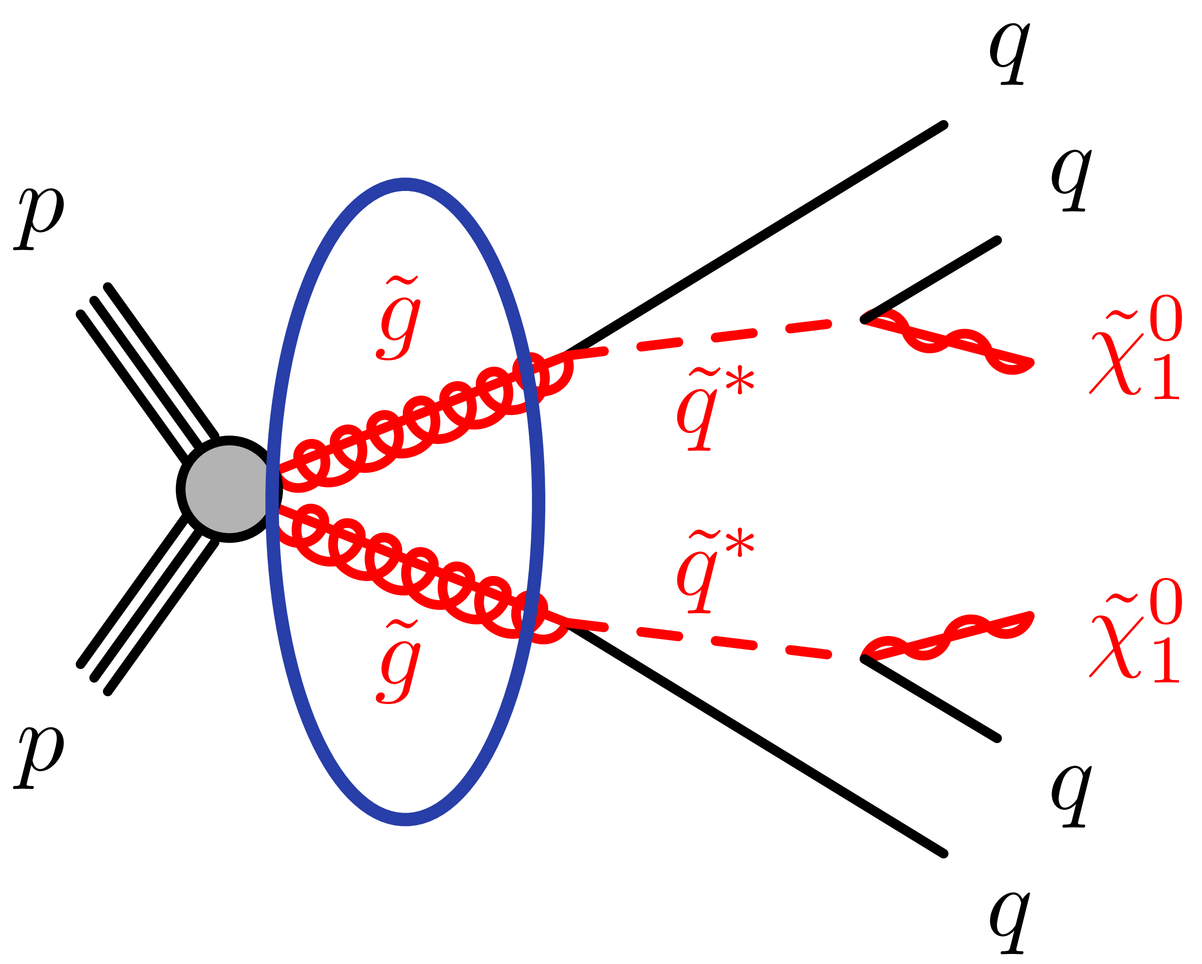


Split Supersymmetry

Happens in all kinds of theories of new physics, but I'll focus on one: **SUPERSYMMETRY**

Why we love SUSY	Why we don't love SUSY
Gives a solution to the **hierarchy** problem	
Gives a **dark matter** candidate	
Is a particularly **elegant** mathematical concept	
Gives rise to many different particles with complex and ~unpredictable mass spectra (keeps us employed for decades)	

Happens in all kinds of theories of new physics, but I’ll focus on one: **SUPERSYMMETRY**

Why we love SUSY

Why we don’t love SUSY

We thought it would be easier to find

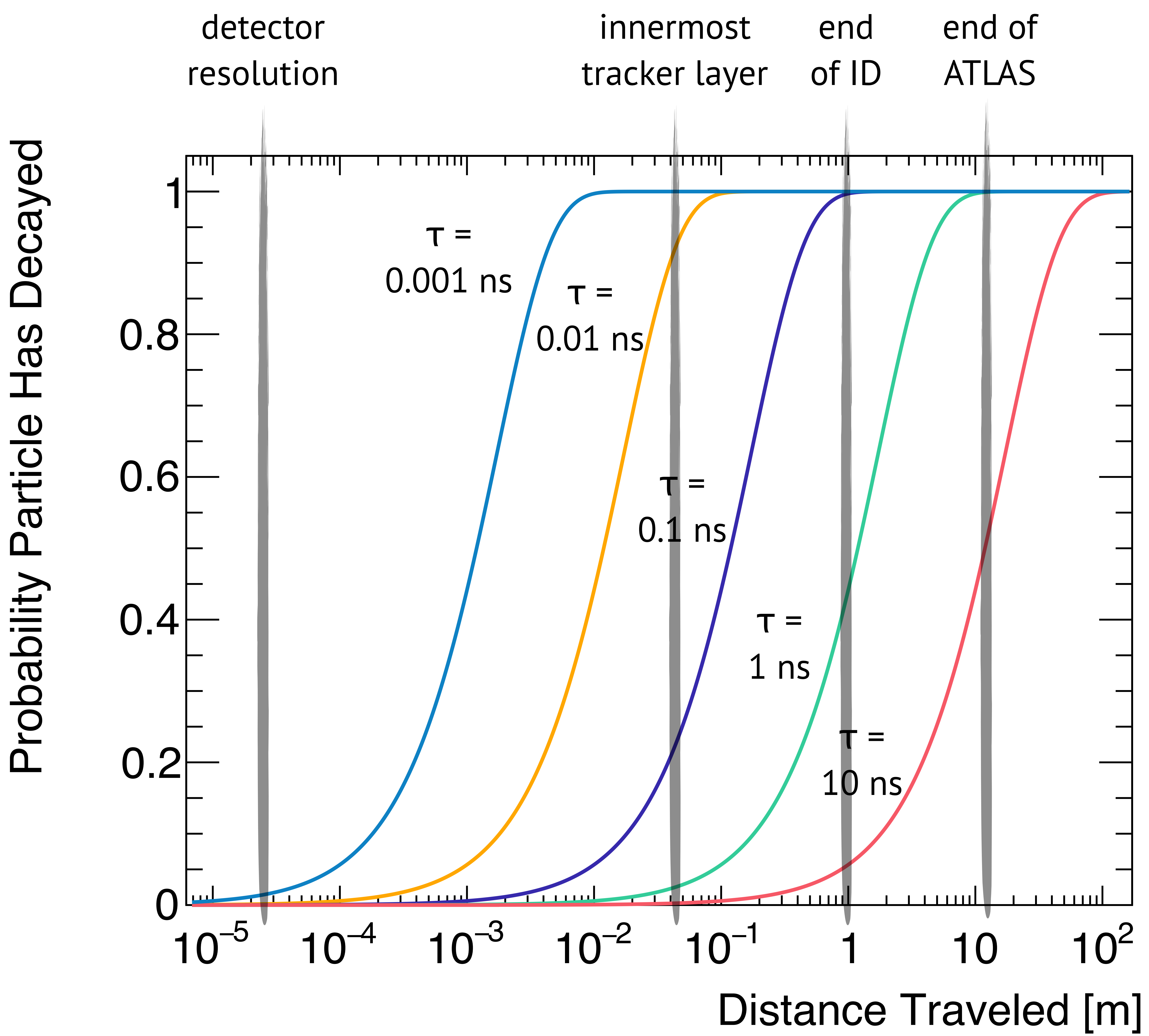
What makes lifetime hard?

Varying lifetime creates completely different **signatures** in our detector

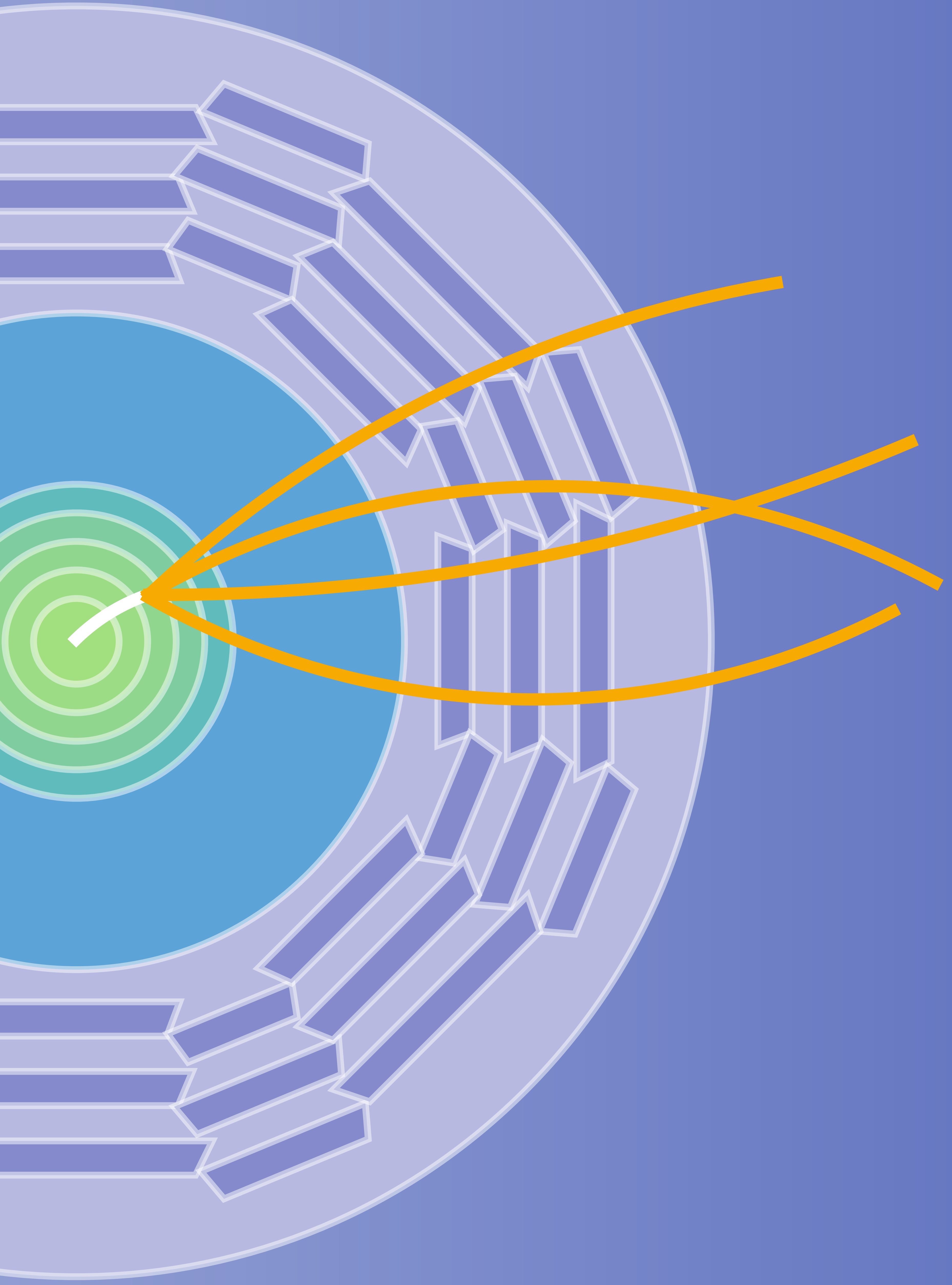
Many of those variations include signatures we **didn't design detectors** to reconstruct

Must have **dedicated** searches for each signature – adds a **new dimension** to the types of searches we need to cover all scenarios!

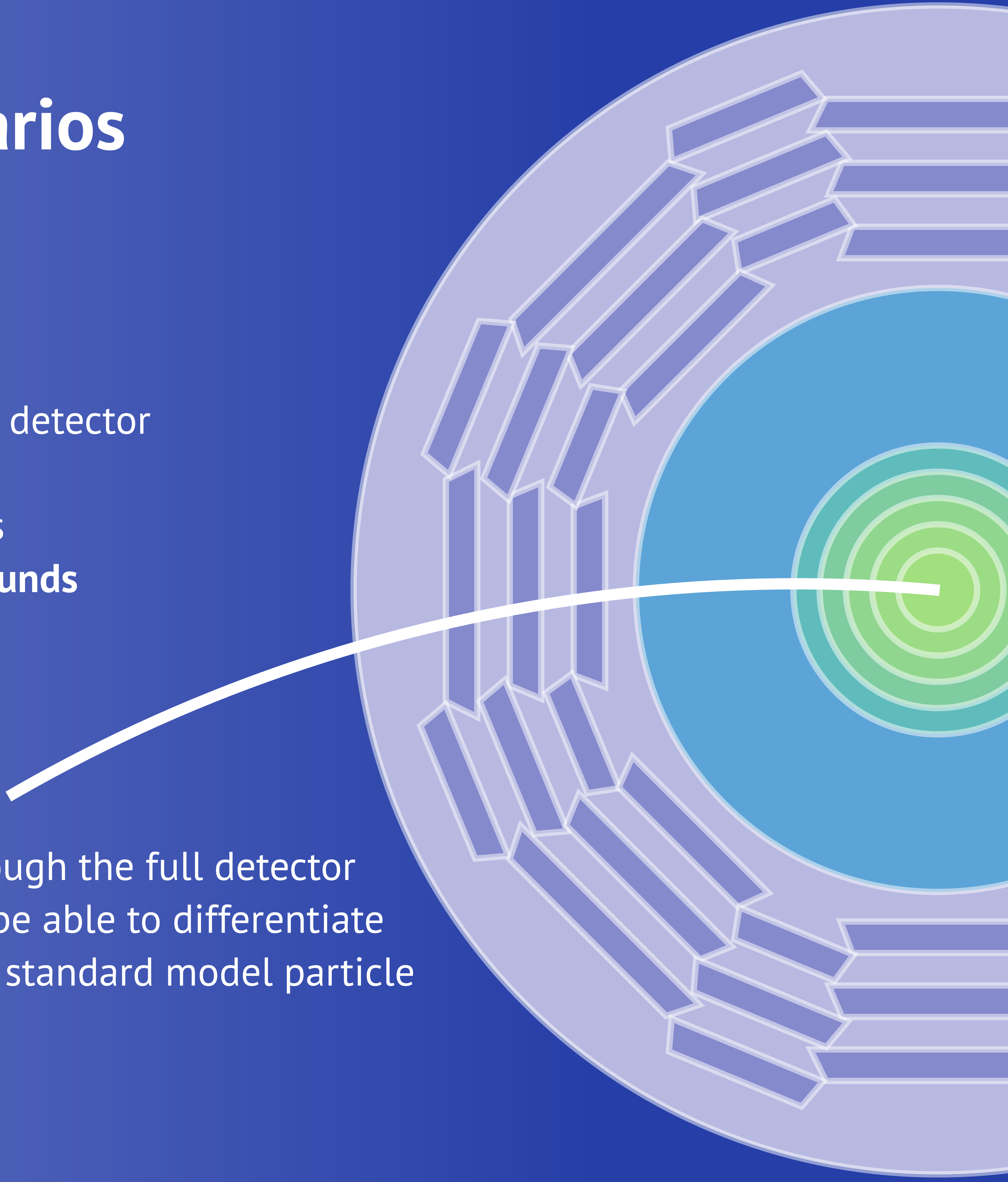
200 GeV particle
energy: 500 GeV



Two main scenarios

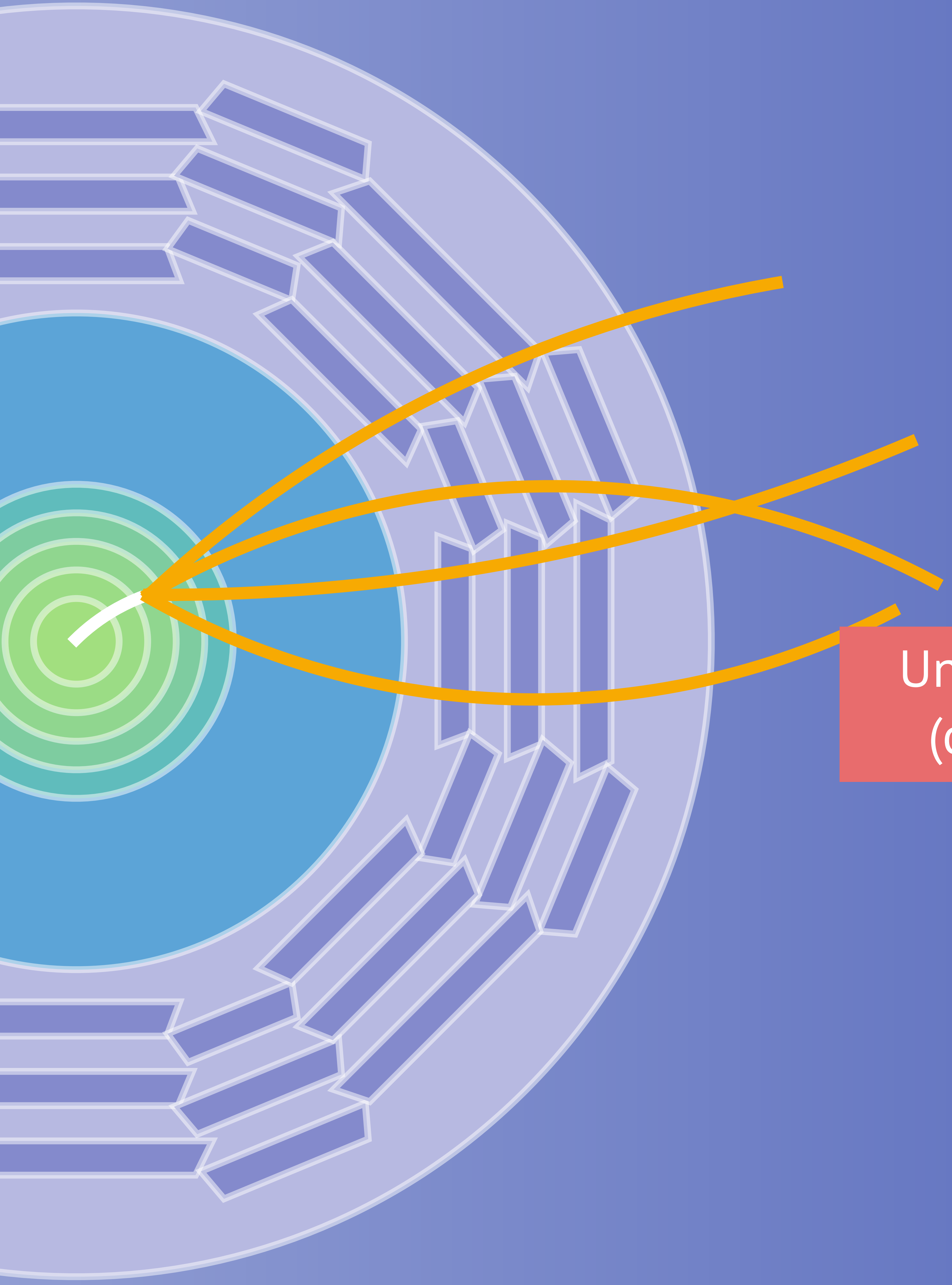


Metastable:
Decays somewhere inside the detector
– need different **algorithms** depending on where it decays
– deal with different **backgrounds**



Stable:
Passes through the full detector
– need to be able to differentiate this from a standard model particle

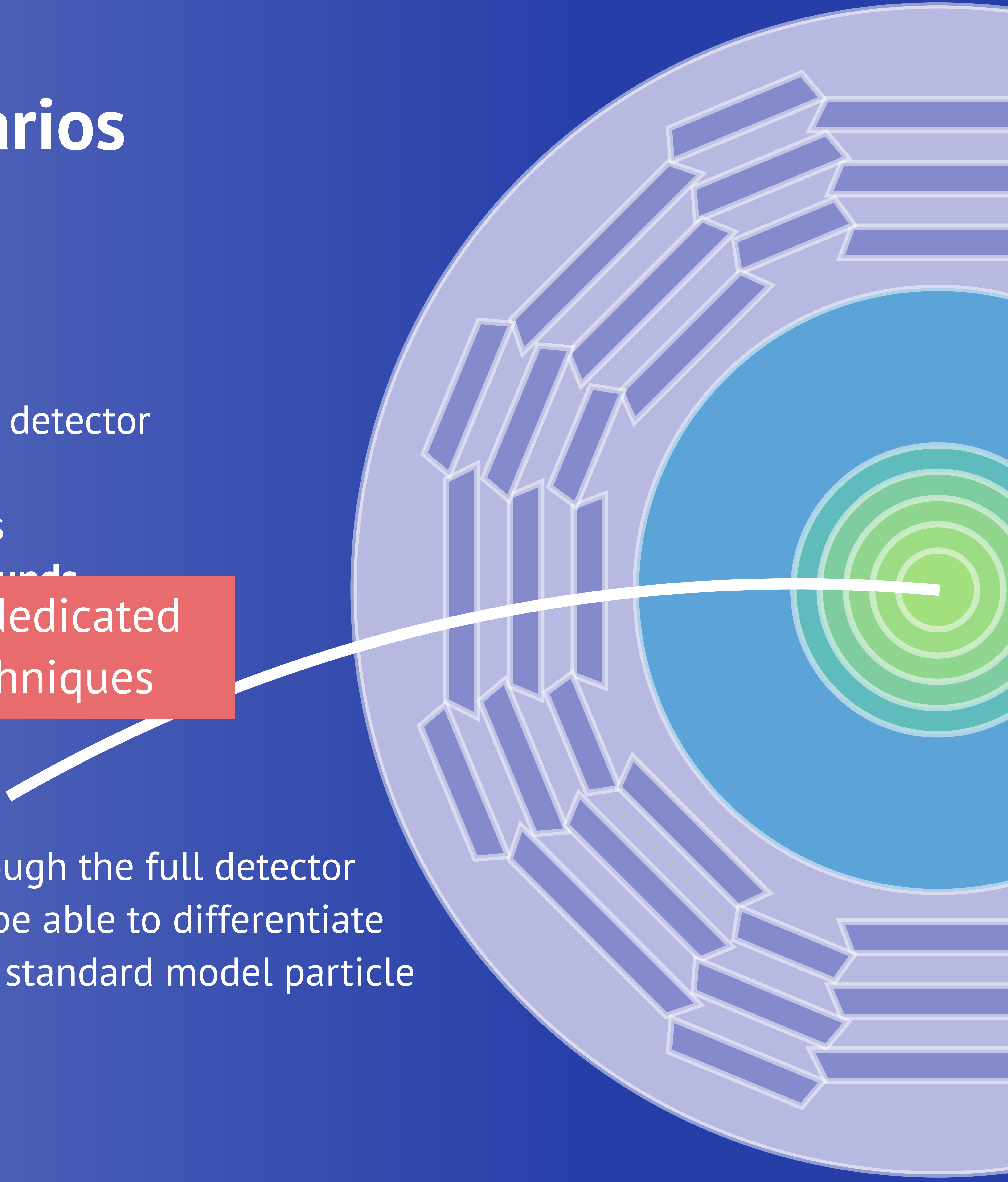
Two main scenarios



Metastable:
Decays somewhere inside the detector
– need different **algorithms** depending on where it decays
– deal with different **backgrounds**

Unusual signatures require dedicated (often time consuming) techniques

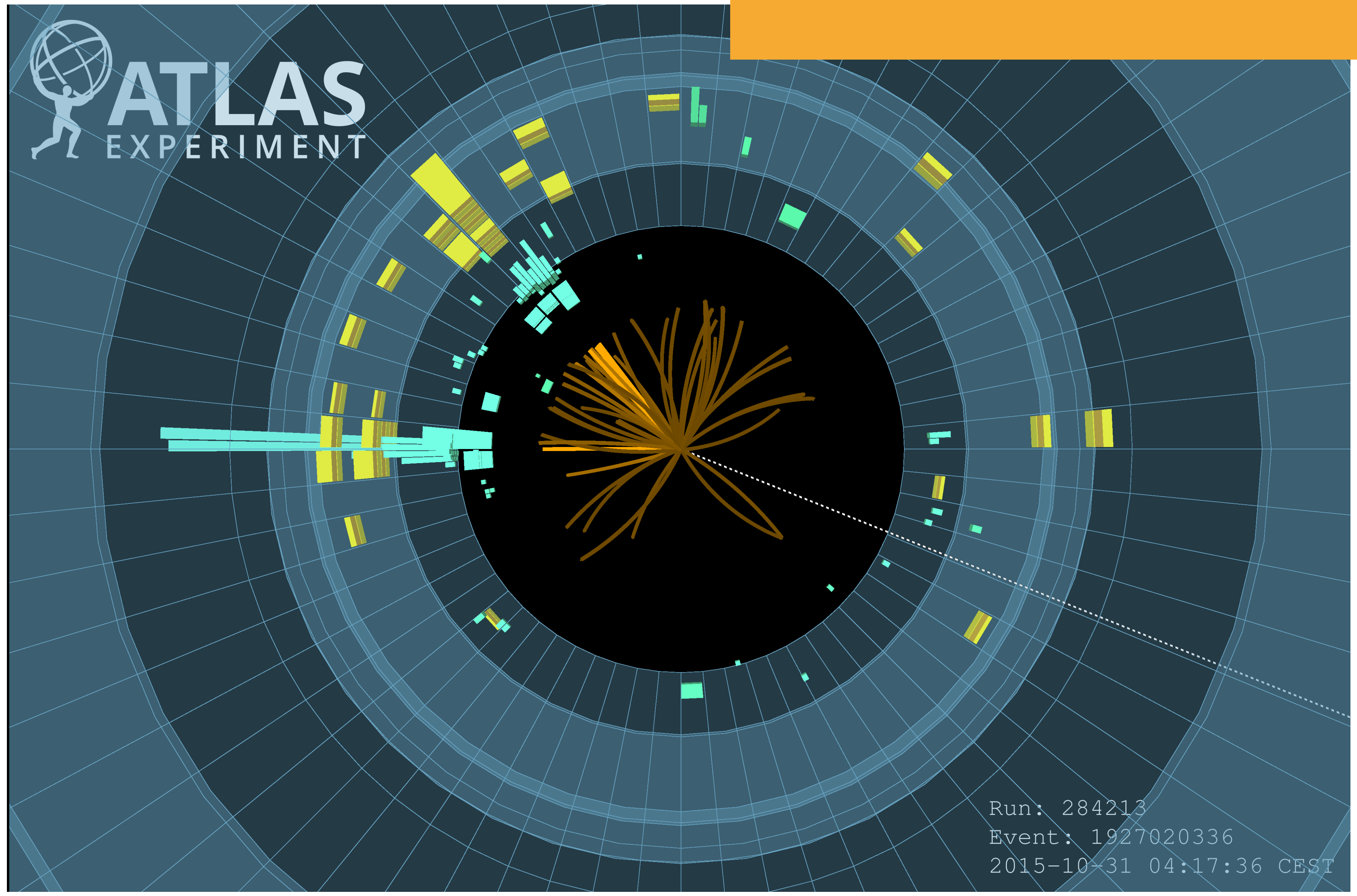
Stable:
Passes through the full detector
– need to be able to differentiate this from a standard model particle



Problem:

By the time you can do this special reconstruction, ATLAS has already thrown away more than 99.99% of collisions

The ATLAS Trigger



ATLAS public event displays

Final decision on what to keep is made in around 250 ms

How do we decide if this event is worth keeping?

(image of an event with analysis-level “offline” reconstruction)

Level 1 trigger decisions are made with rough **calorimeter** and **muon** information

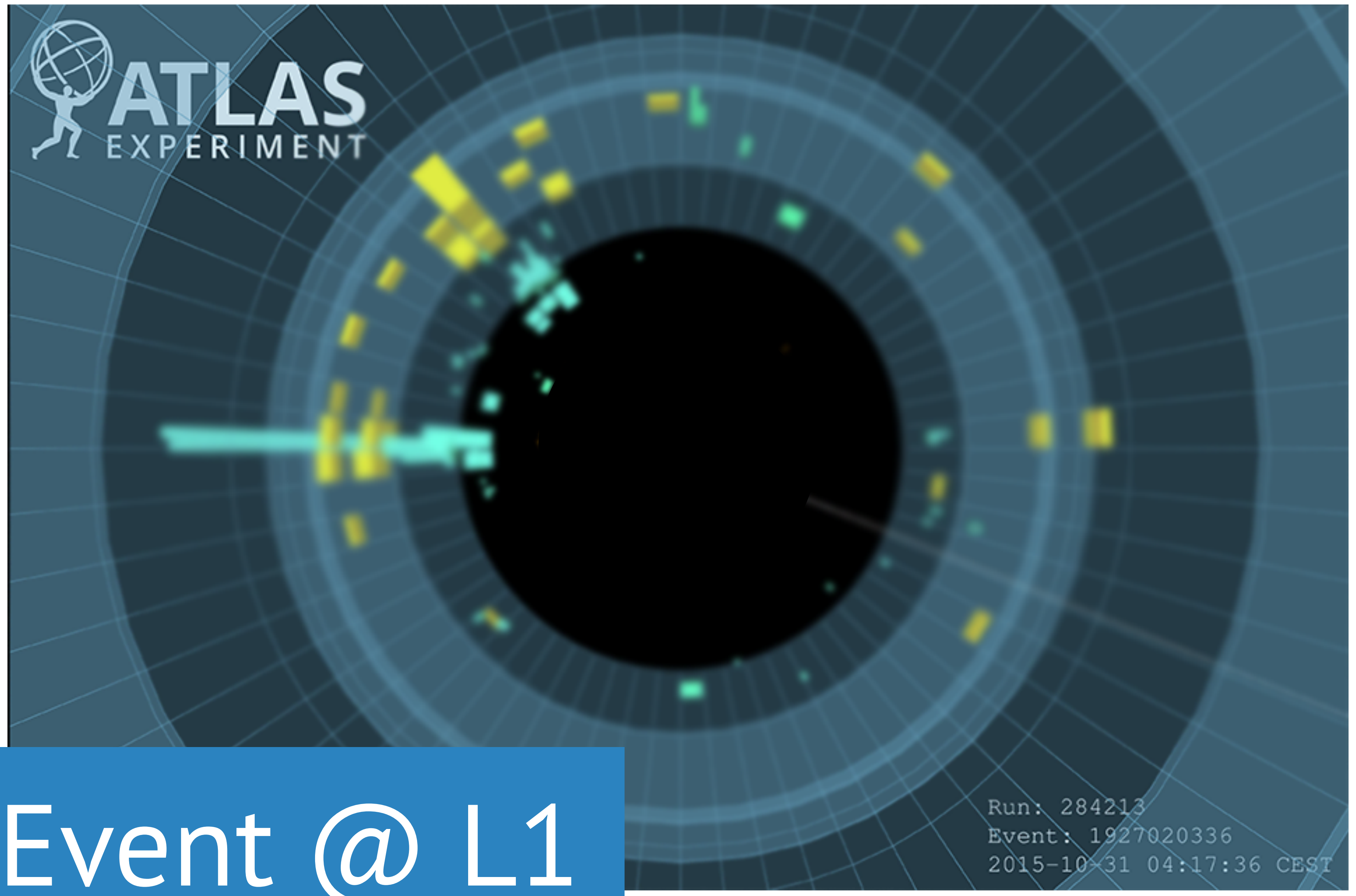
40 MHz → 100 kHz

hardware

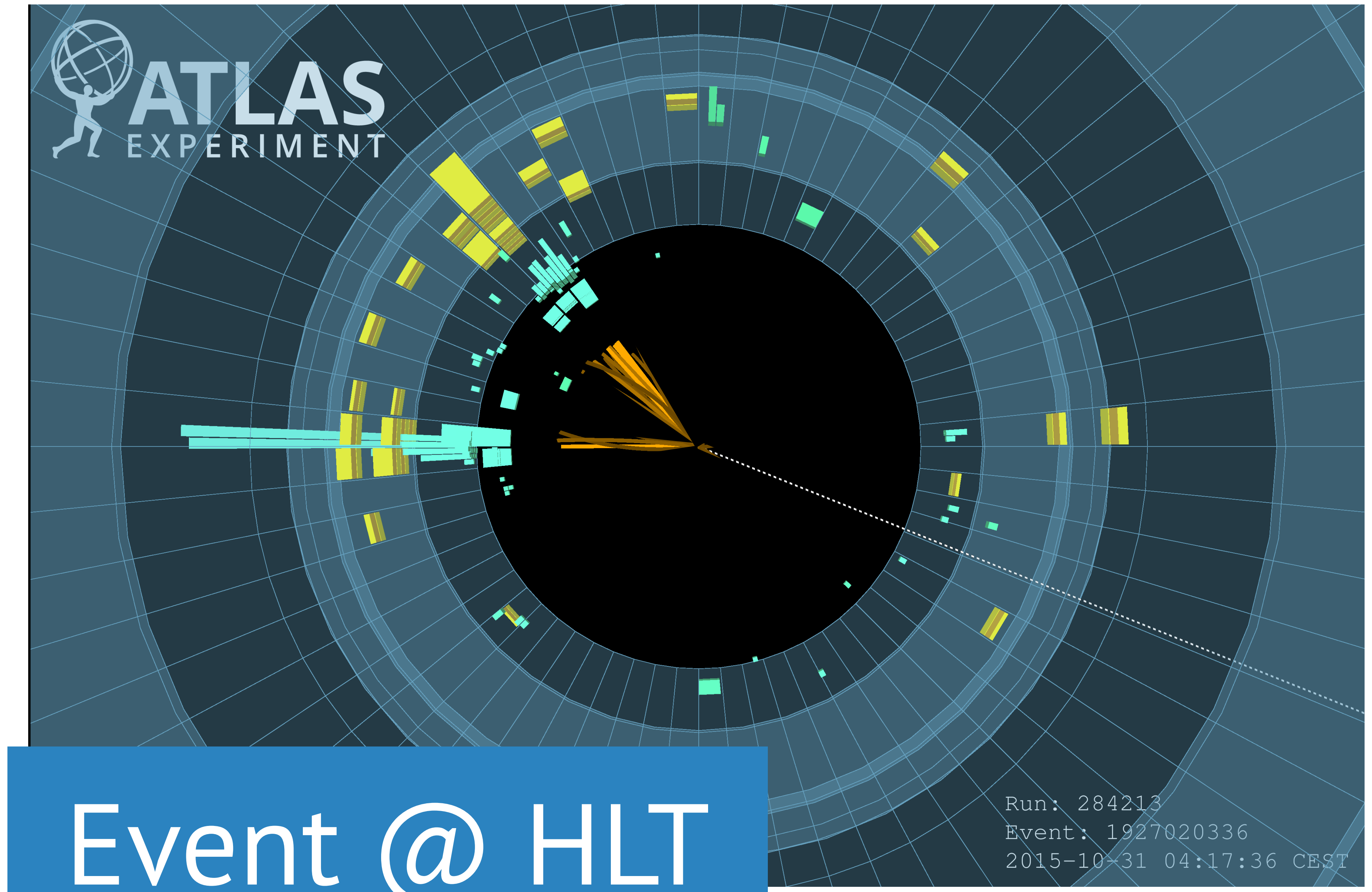
High Level Trigger uses **full precision** information in **small regions**

100 kHz → 1 kHz

software



Event @ L1



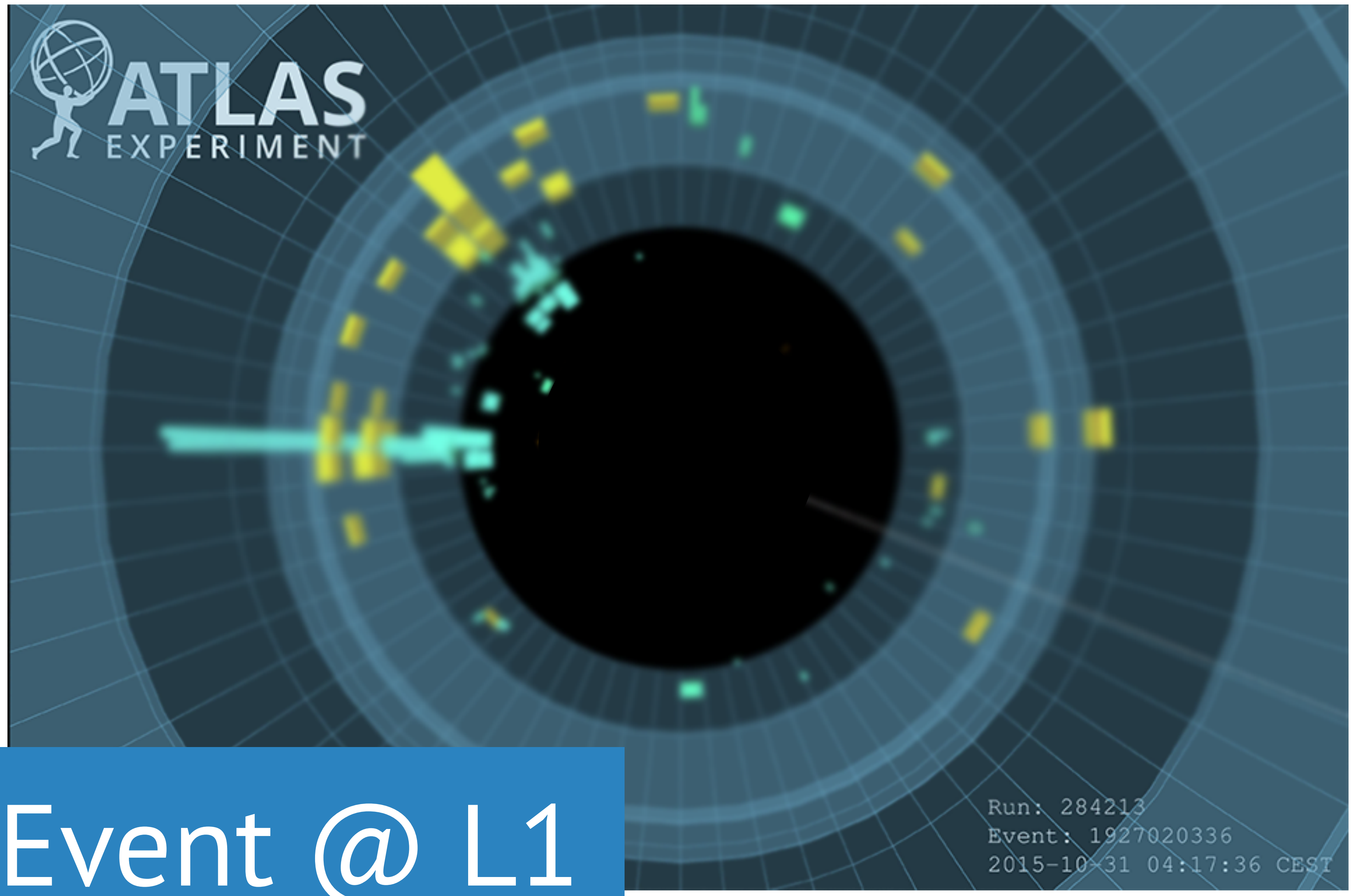
Event @ HLT

Level 1 trigger decisions are made with rough **calorimeter** and **muon** inform

High Level Trigger uses **full pre**
information in **small regio**

tracking:
best measurement of
particle lifetime

only available in
small slices



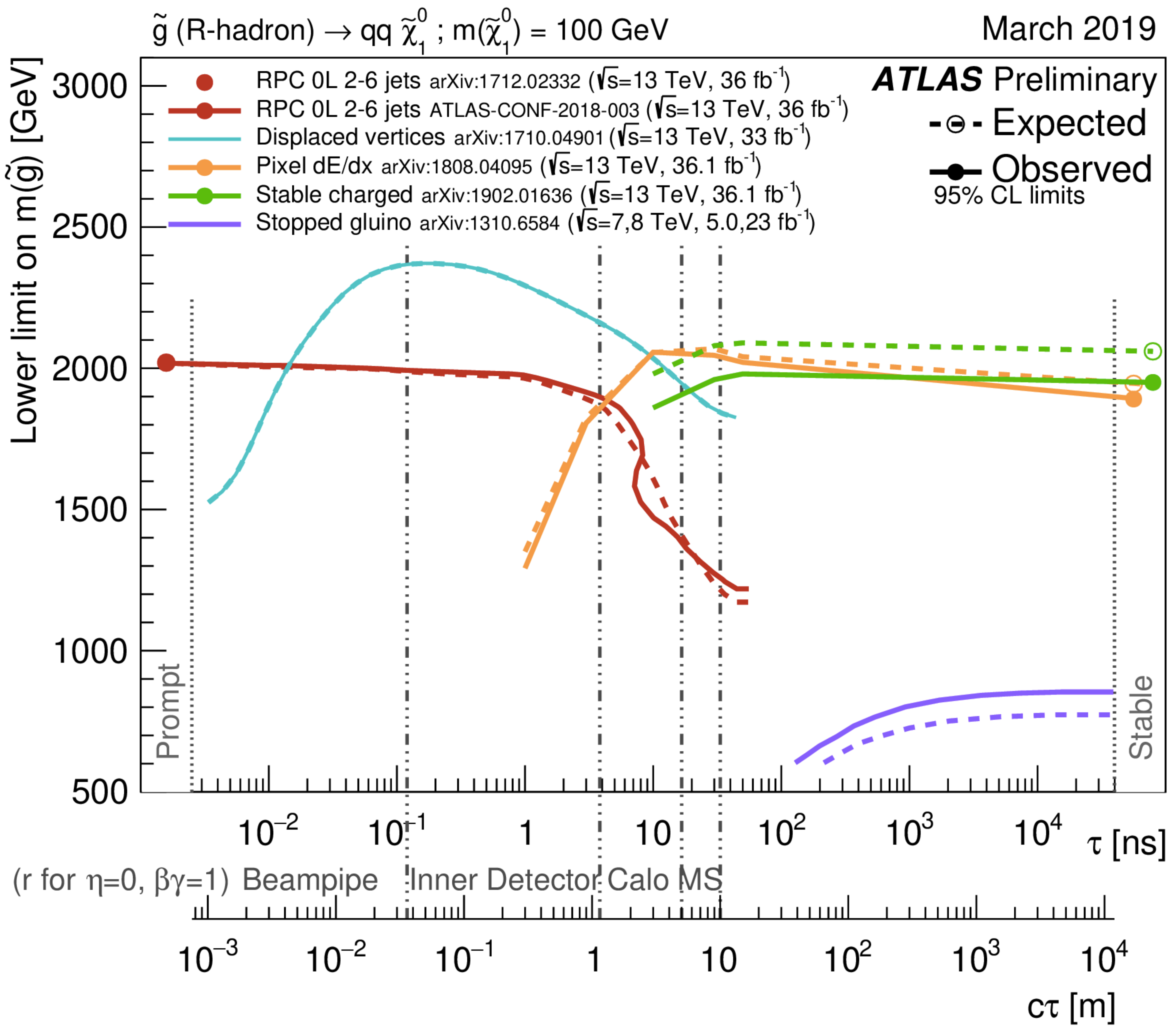
Event @ L1

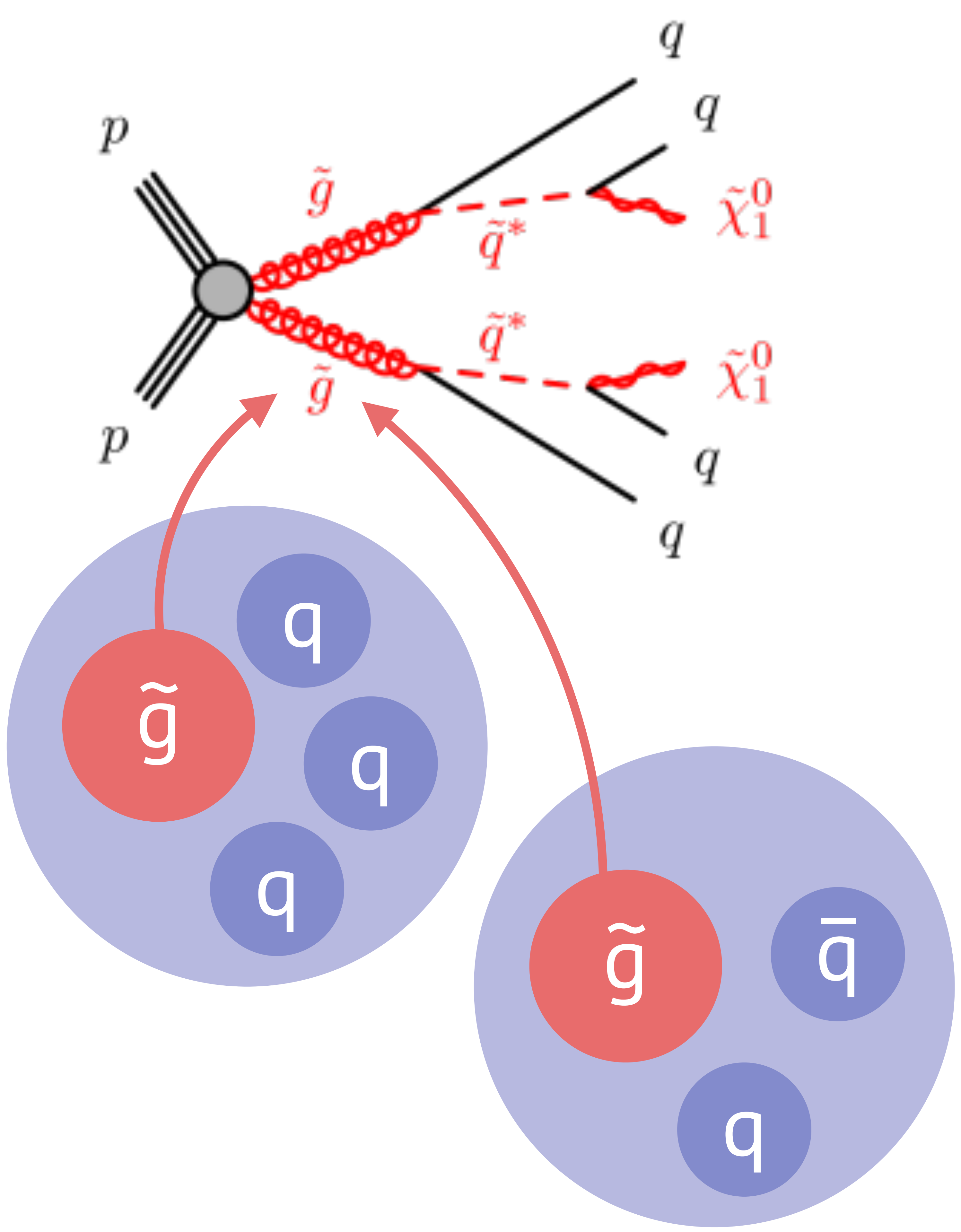
Event @ HLT

ATLAS searches for long-lived particles

an example of success
R-hadrons

hadron formed with a metastable SUSY particle





LLP Summary Plots

ATLAS searches for long-lived particles

an example of success
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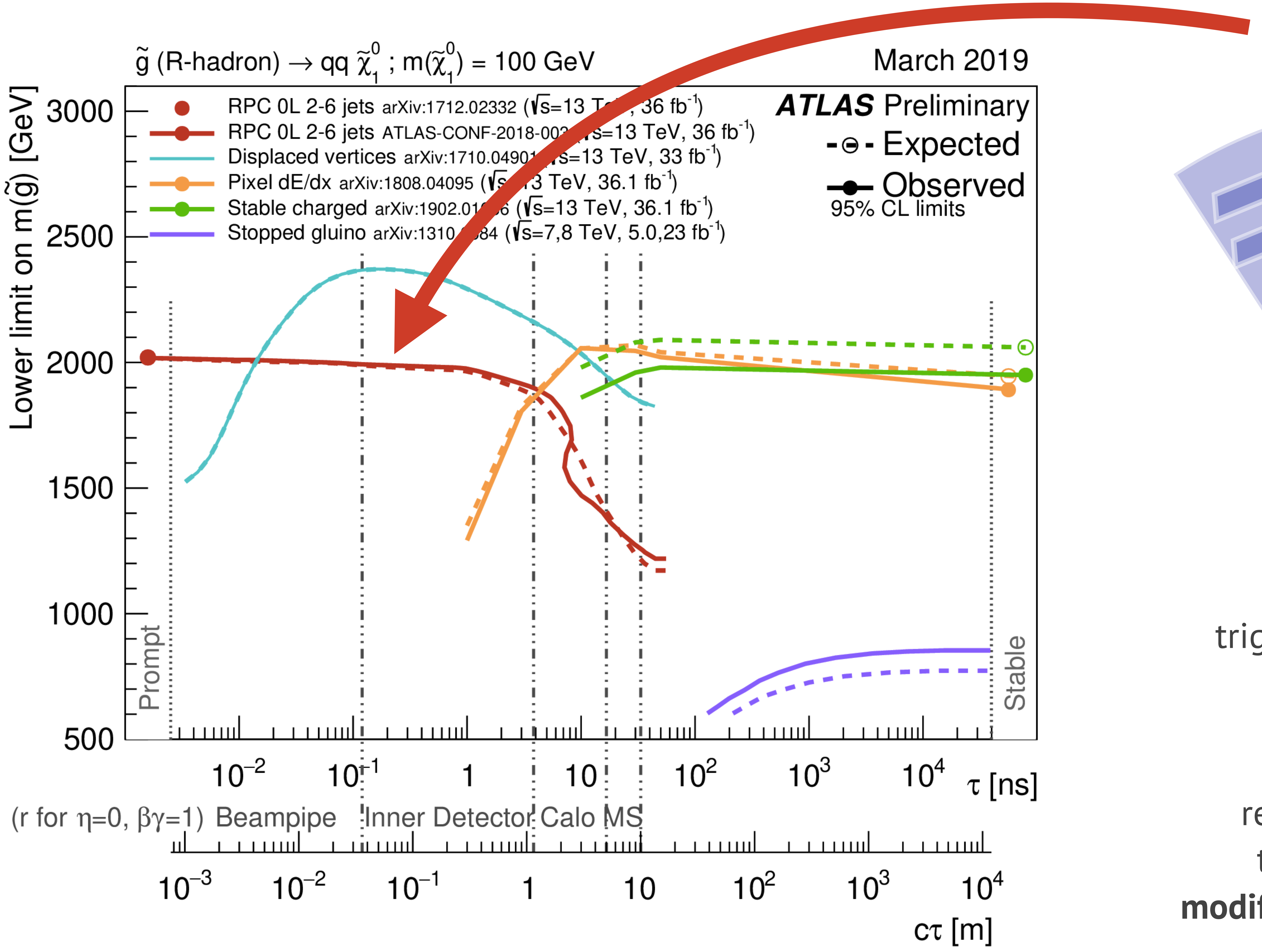
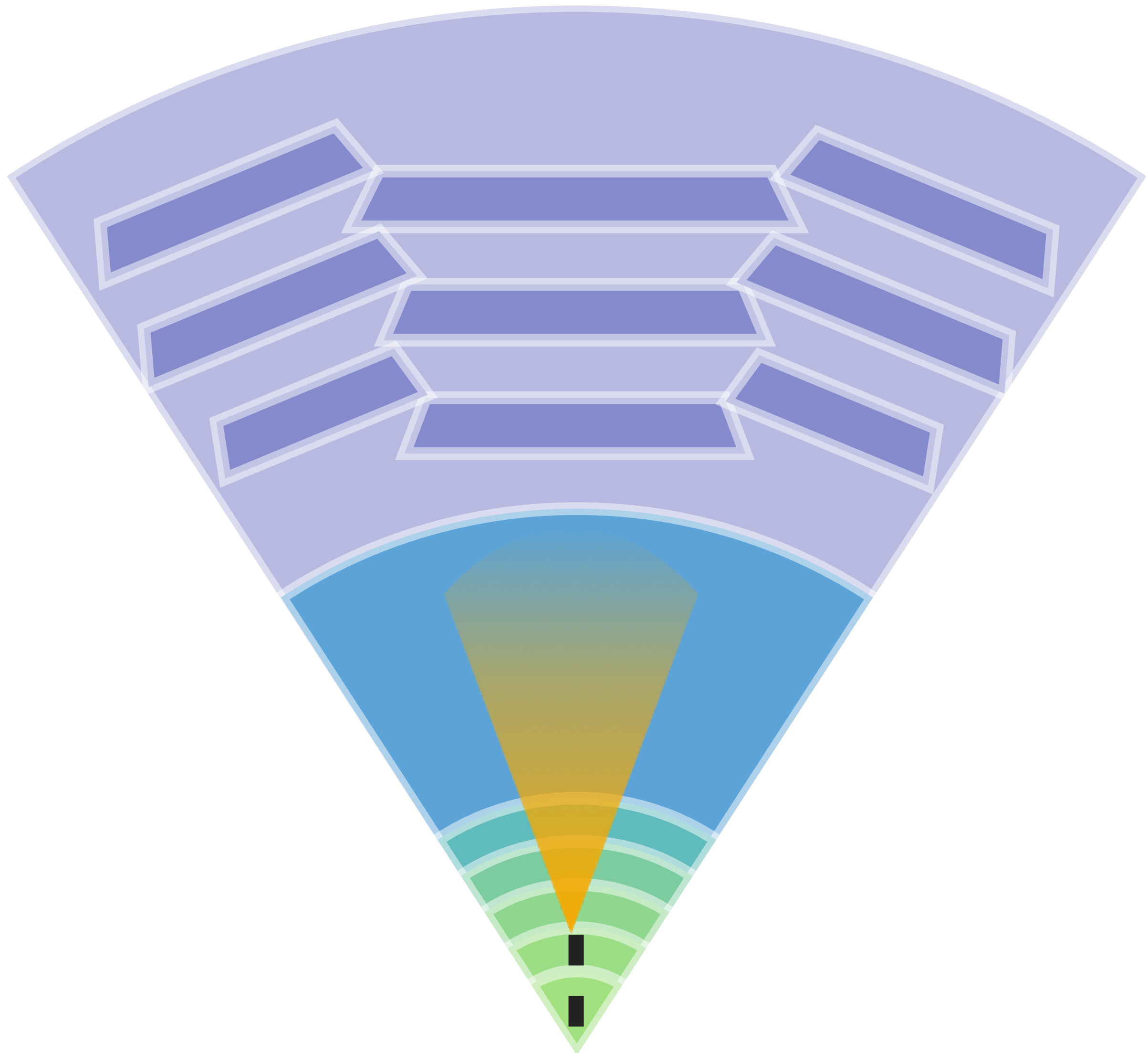


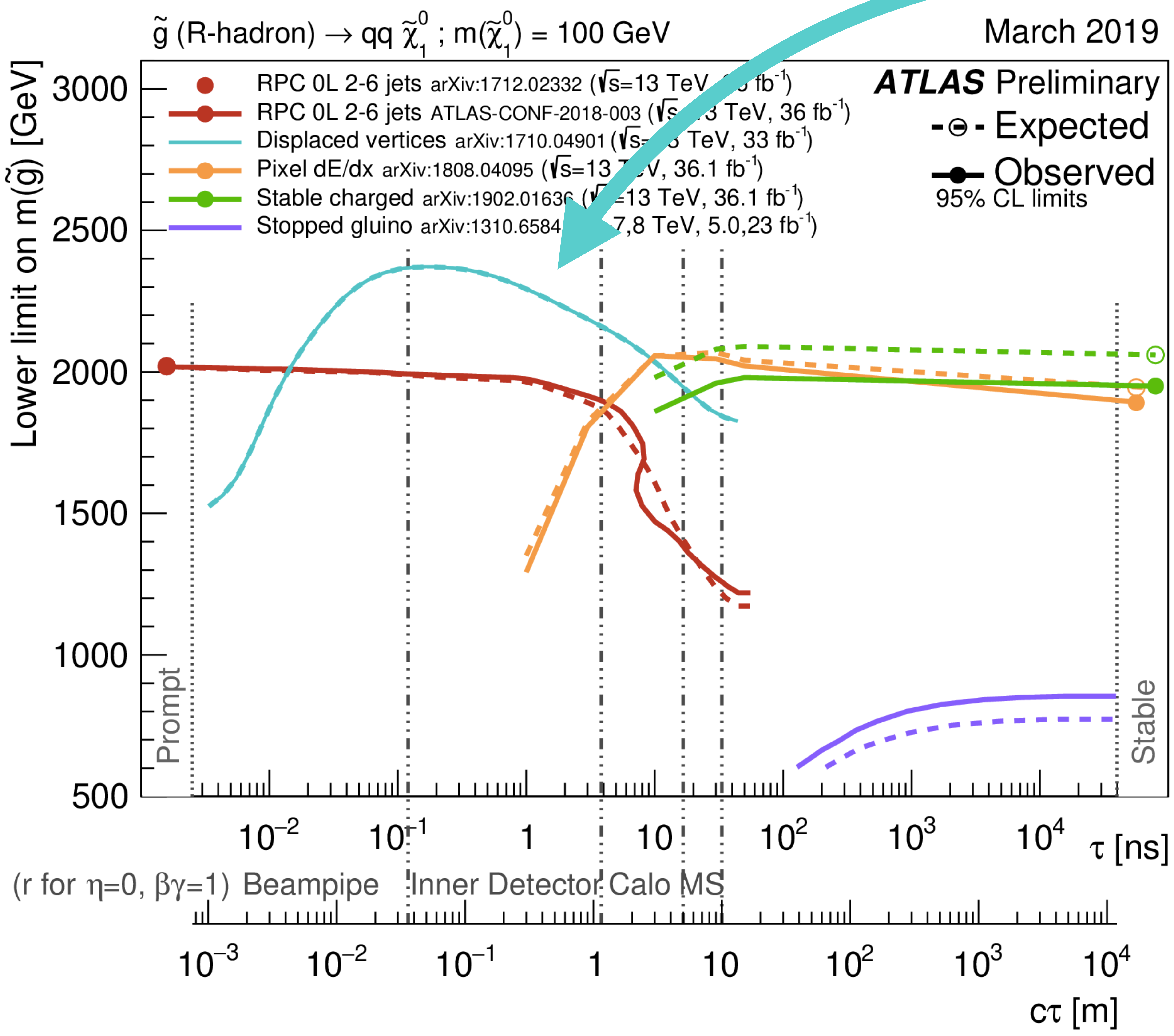


triggers on missing energy
from neutralino

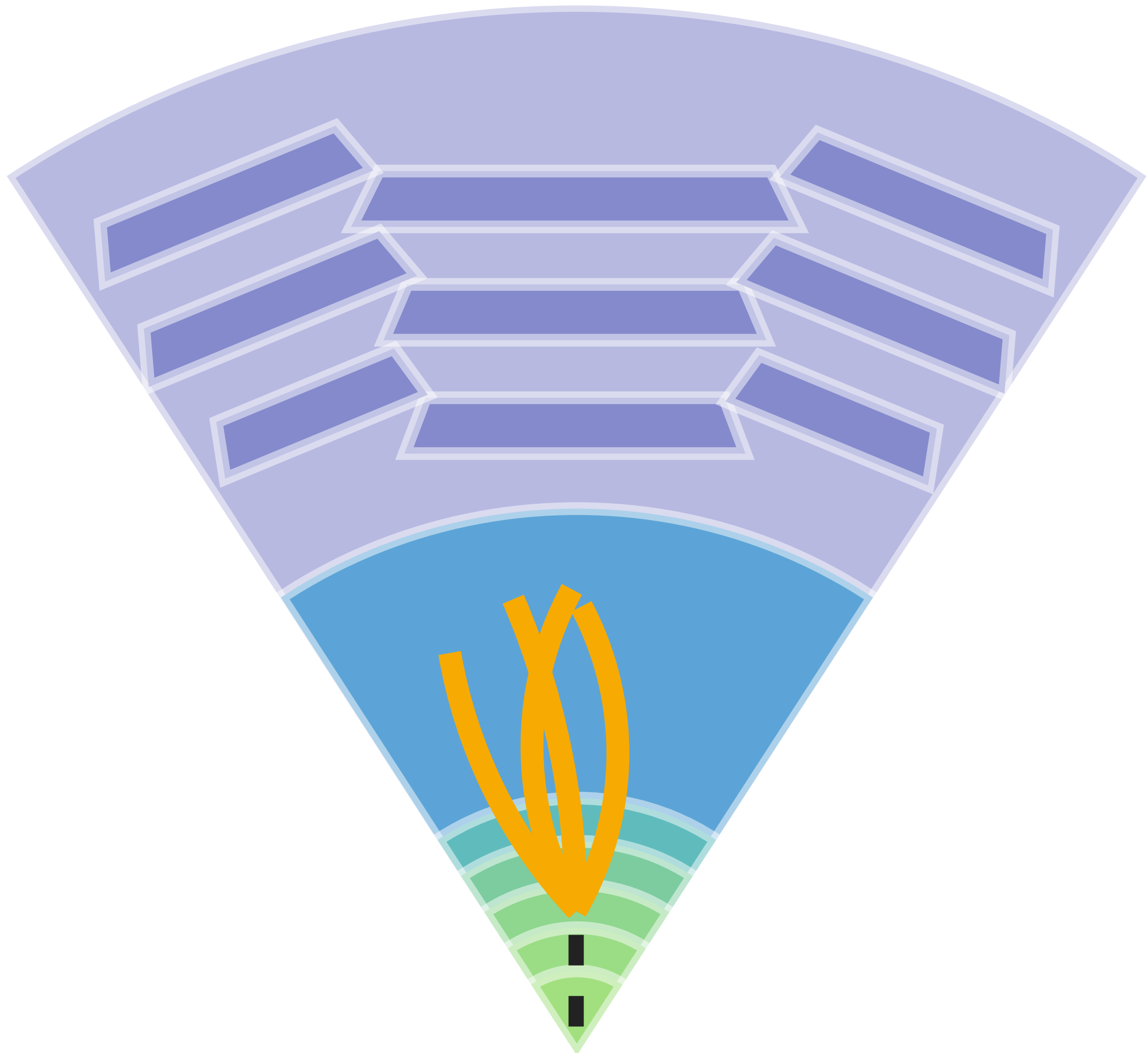
original search
required decay products
to have prompt tracks
modified to increase acceptance

ATLAS searches for long-lived particles

an example of success
R-hadrons



Displaced Vertices

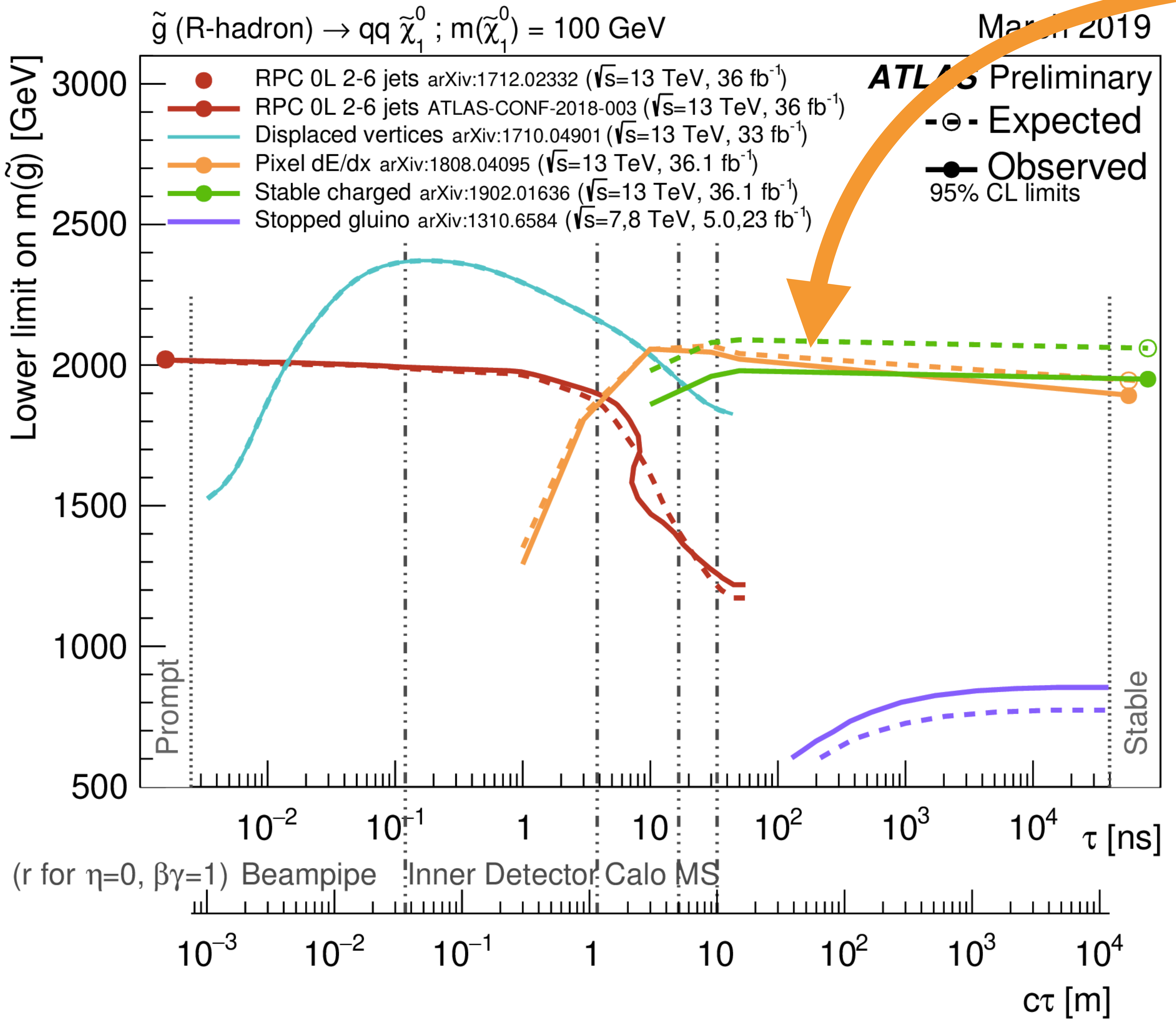


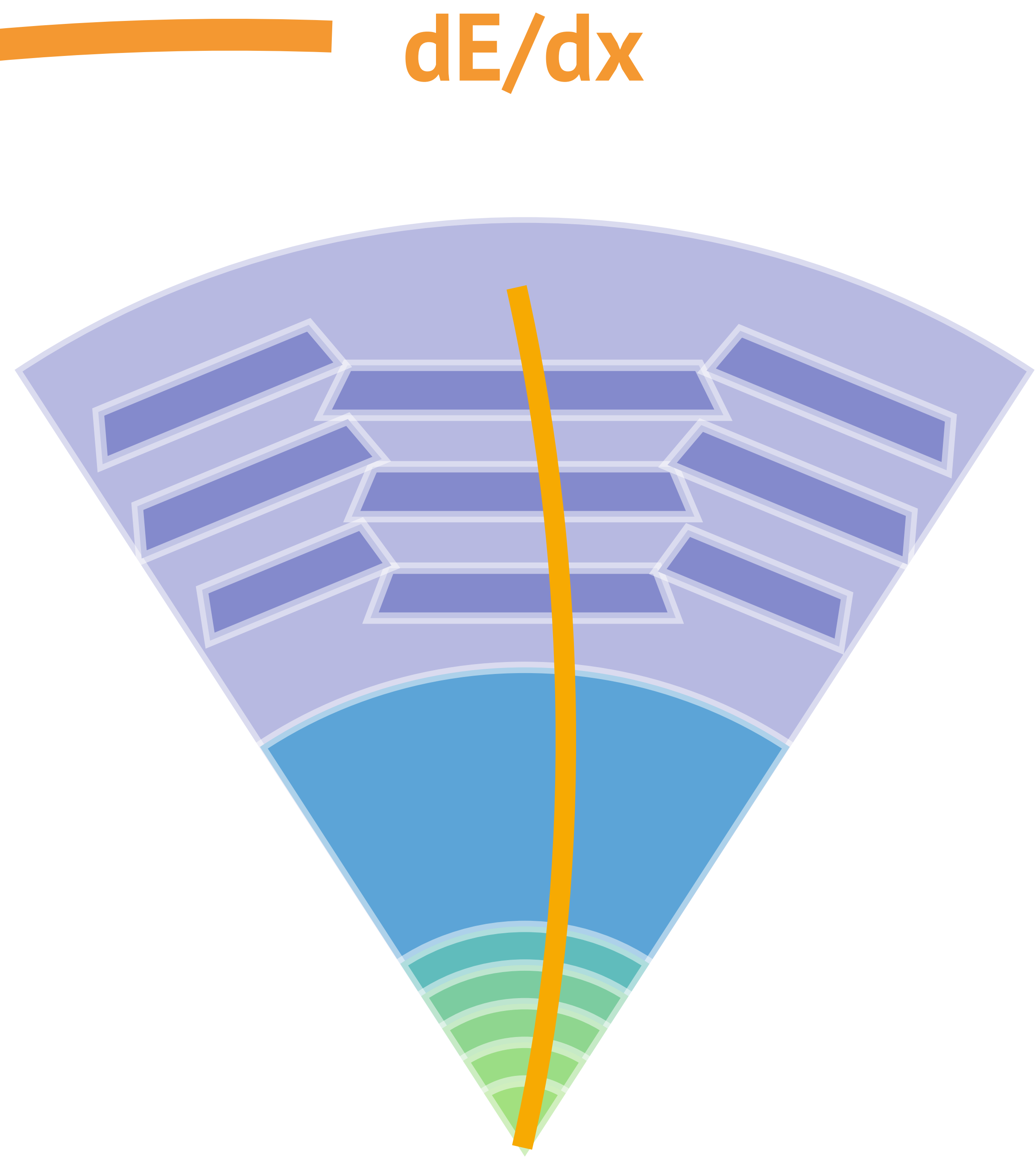
triggers on missing energy from neutralino

reconstructs displaced vertices with dedicated tracking algorithms

ATLAS searches for long-lived particles

an example of success
R-hadrons

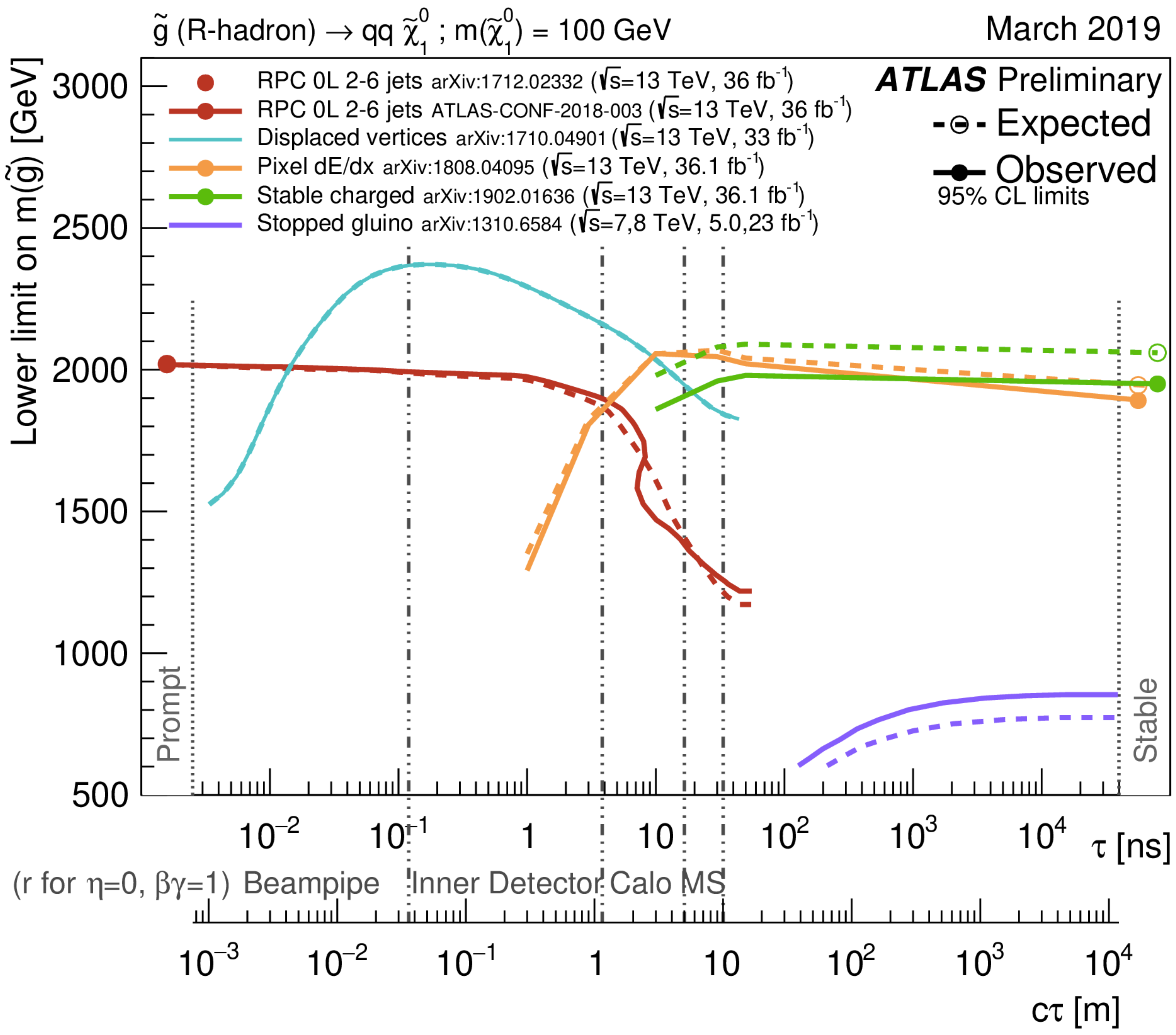




triggers on missing energy from neutralino (works less well when stable)

calculate energy deposition in silicon sensors to find high-mass particles

ATLAS searches for long-lived particles



Many different dedicated searches for R-hadrons
Together they cover the full lifetime range

Each signature has different strategy, specialized techniques

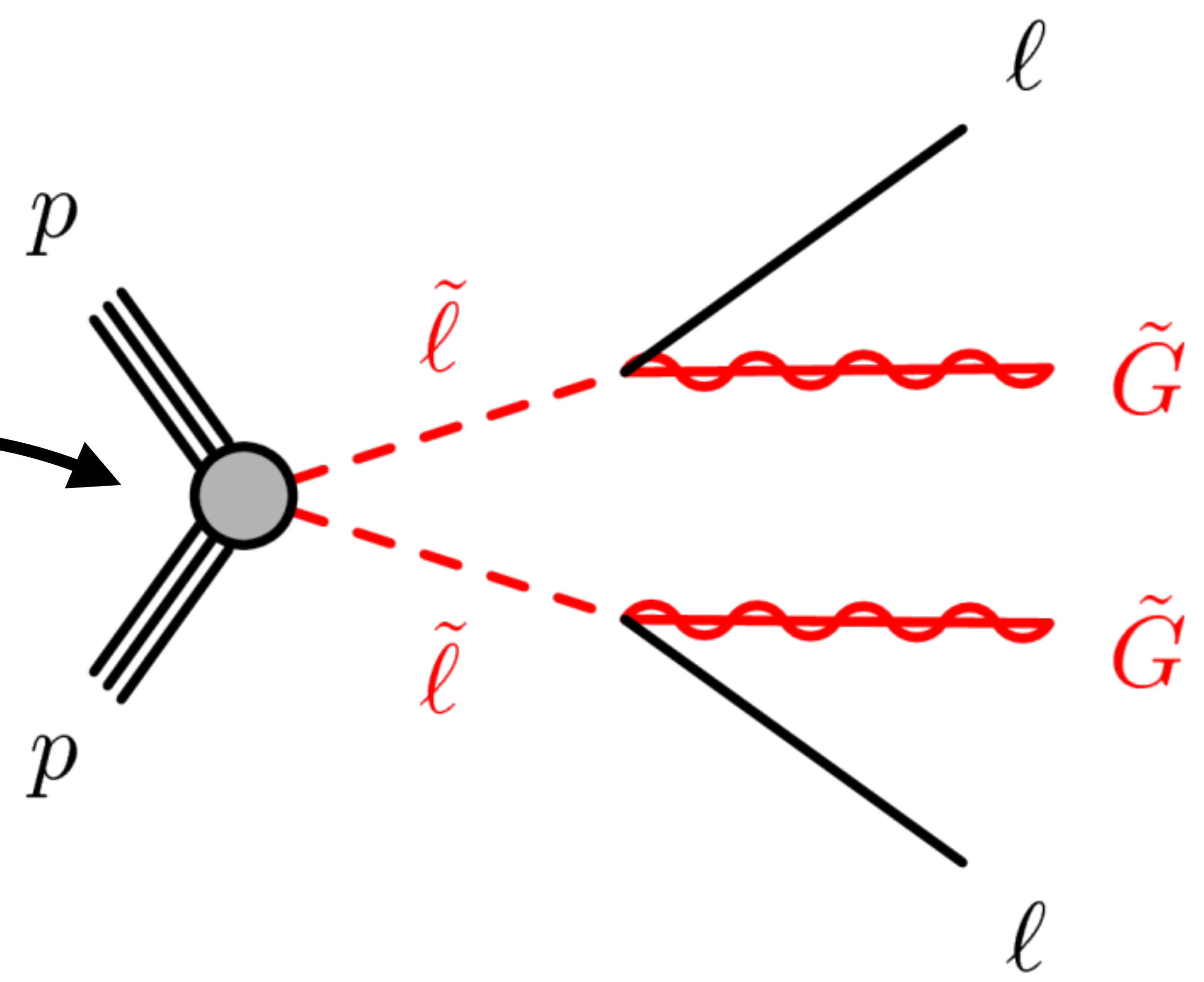
- modified track requirements
- specialized track and vertex reconstruction
- dE/dx calculation

None use a trigger related to long lifetimes

But in this case, we've done great

Uncovered territory

Still models that hadn't been looked at, like
For intermediate lifetimes, tightest limit from OPAL (15 years ago, a fraction of the LHC energy)



One we don't have limits is because it's so **rare**

If they exist, the LHC would have produced in Run 2:

500 GeV gluinos: 4.7 million
500 GeV sleptons: 94

In order to pick out these events, in the sea of LHC data, you have to be really looking for them!

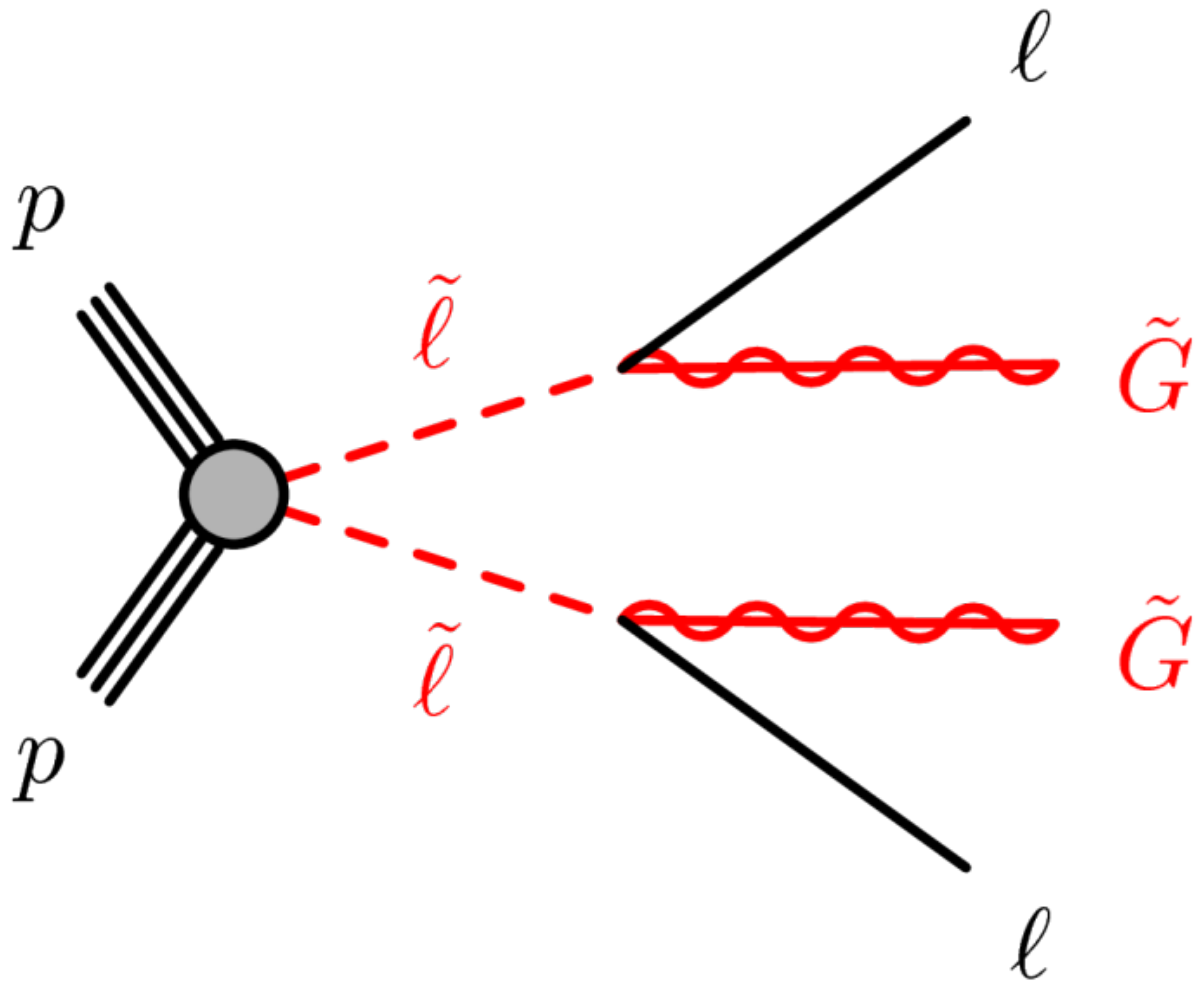
Previously we'd only been able to rule out these particles at **< 90 GeV**

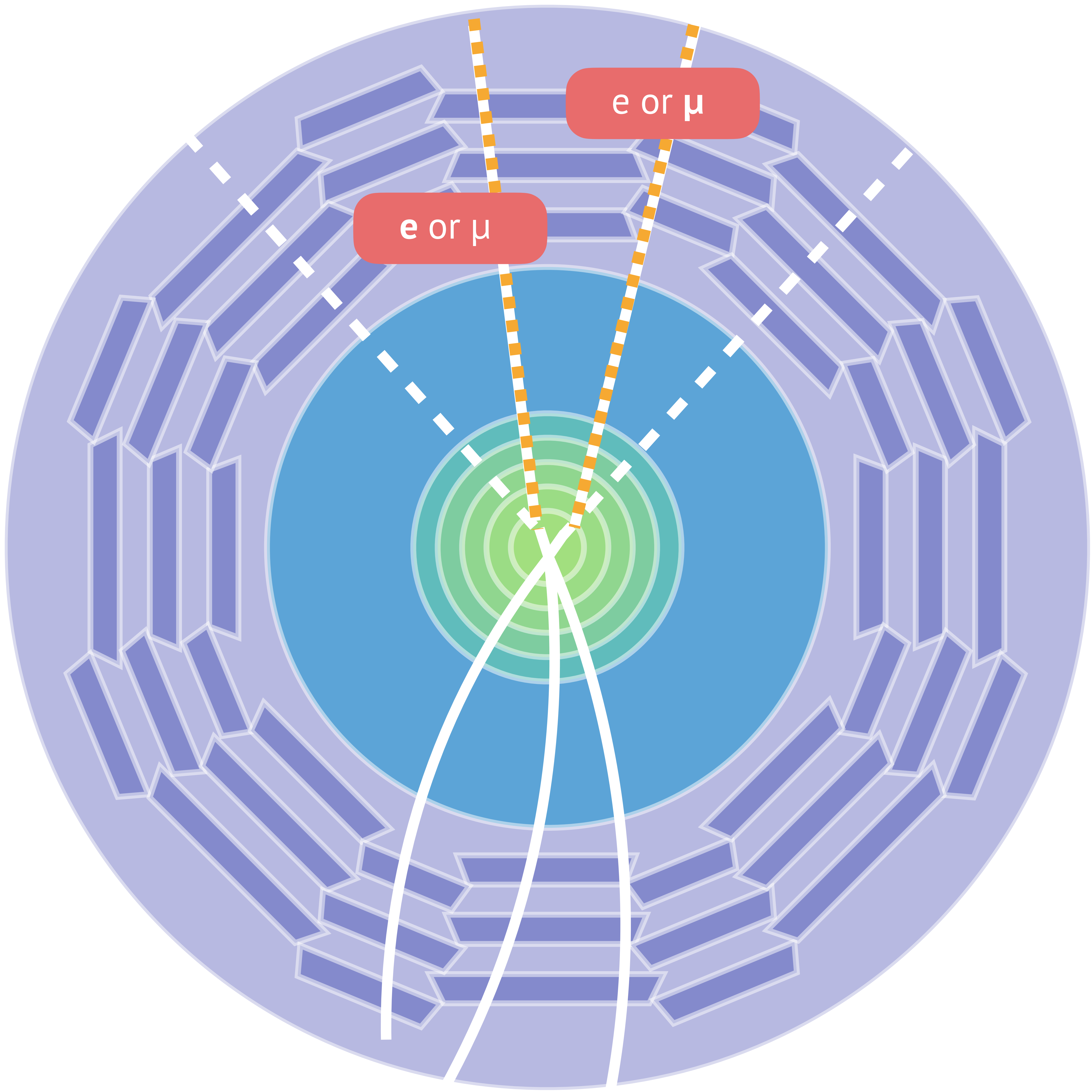
Required a **dedicated search** to go further

OPAL paper, ATLAS Slepton & Chargino Production

what I’ve been working on

Displaced leptons – and nothing else!



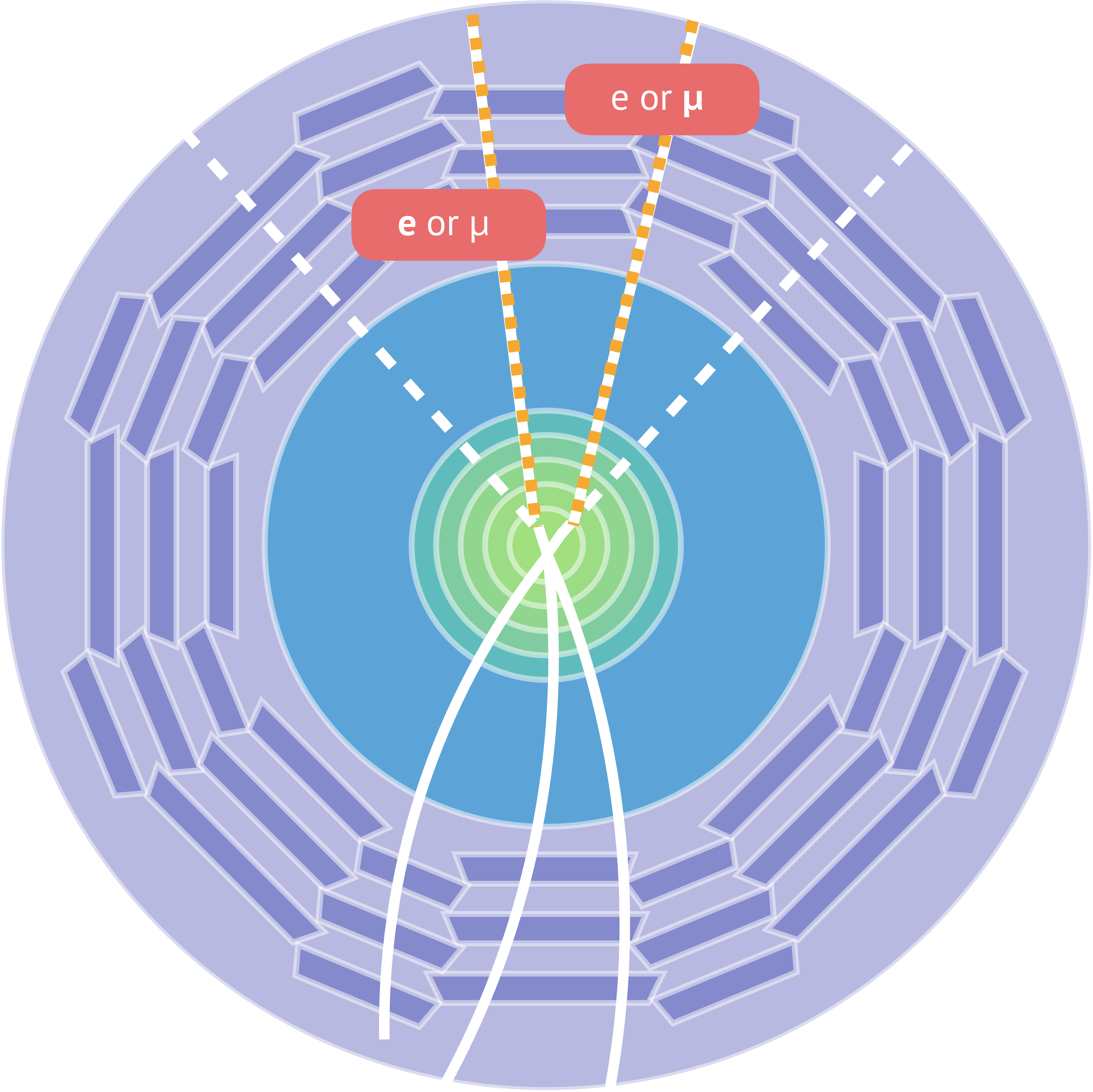


hasn't been done for a reason: **it's hard**

Very displaced leptons means **standard reconstruction algorithms** fail

- Which may sound like it isn't a big deal, but in these huge experiments, those algorithms were made by **thousands** of people working to perfect them

- Not easy to re-do as a tiny team!



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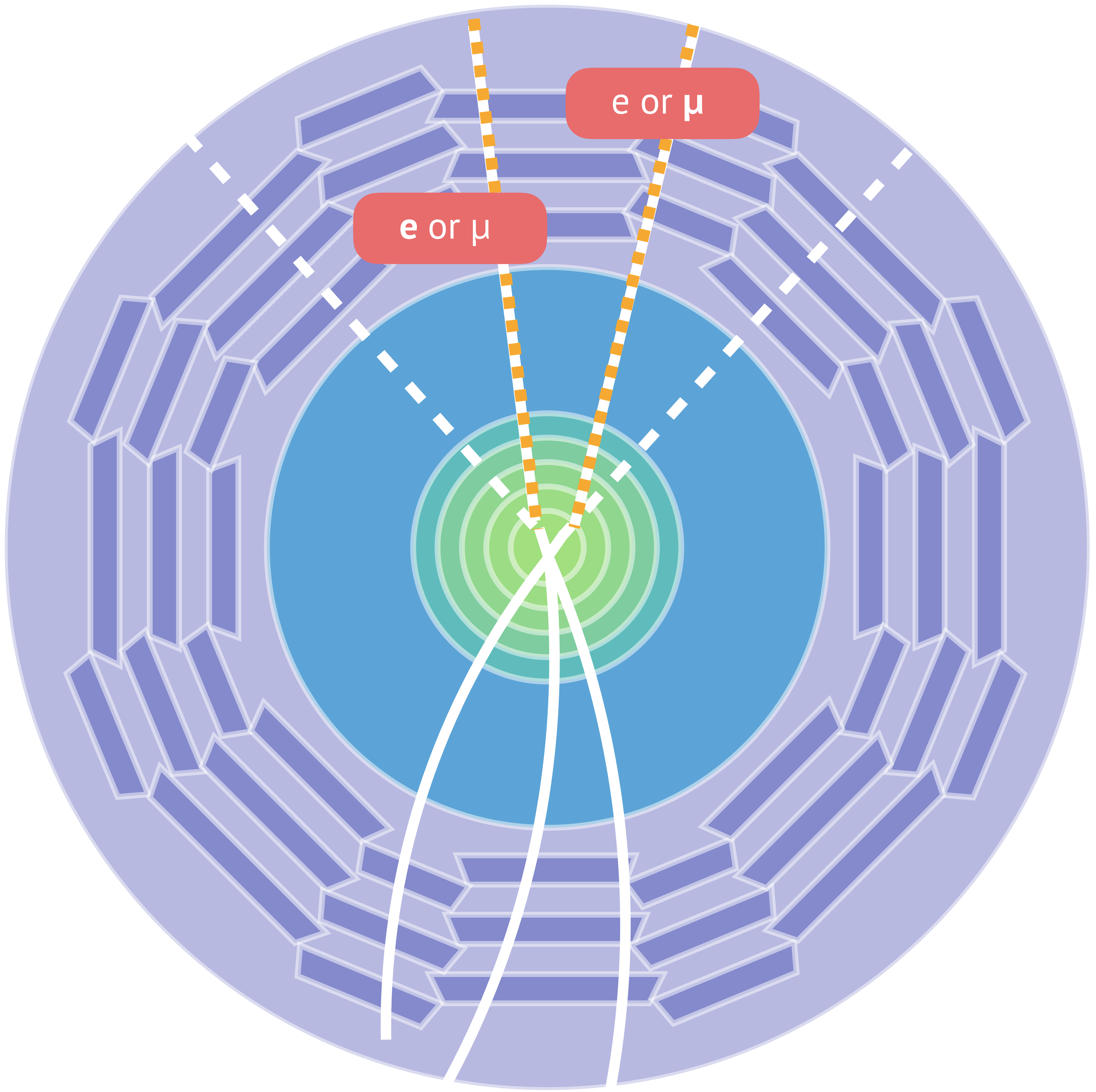
Very displaced leptons means **standard reconstruction algorithms** fail

Which may sound like it isn’t a big deal, but in these huge experiments, those algorithms were made by **thousands** of people working to perfect them

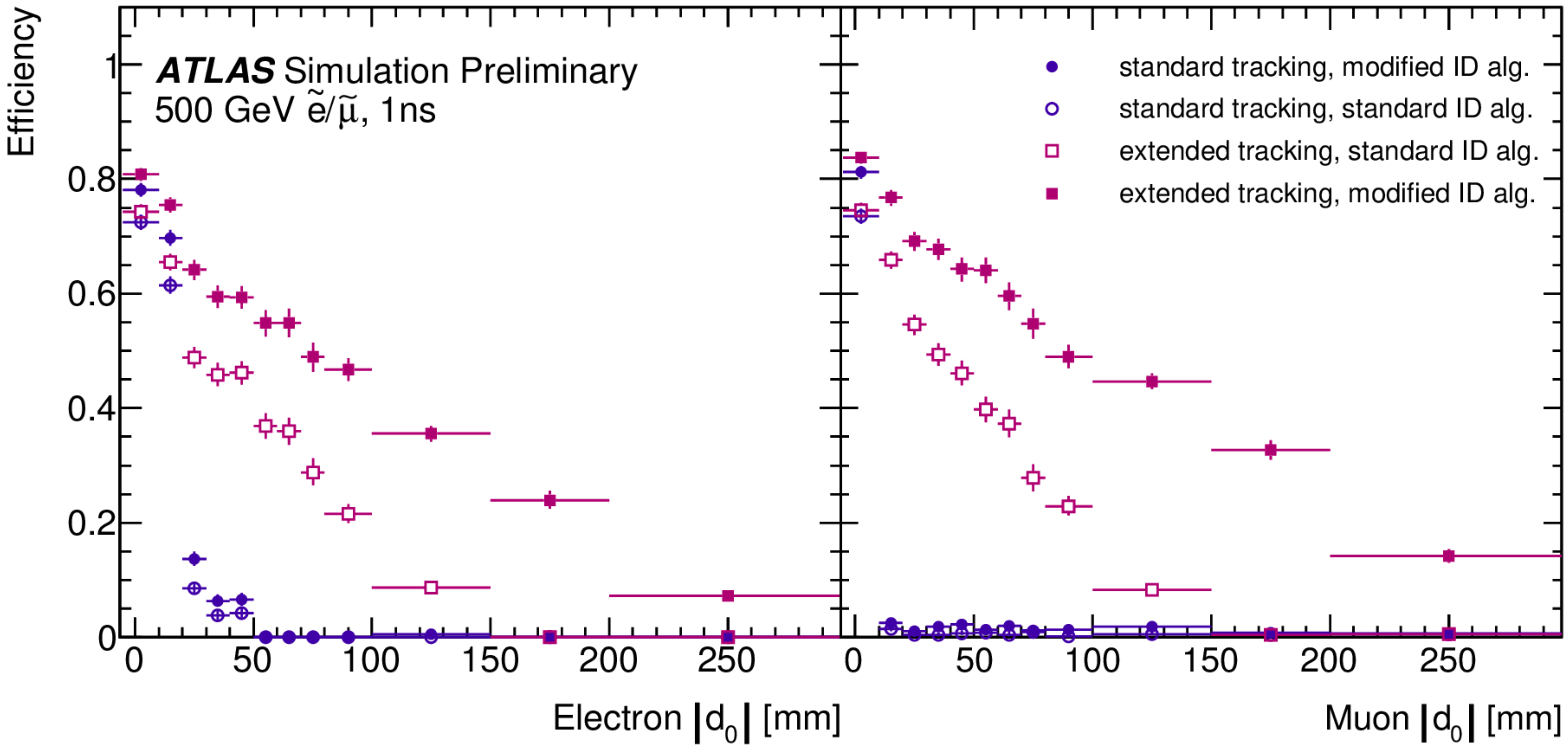
Not easy to re-do as a tiny team!

First step: Record the data!
Need **special triggers** for displaced objects
→ no tracking information so much harder to pick out from backgrounds



hasn't been done for a reason: **it's hard**

Next step: make sure you can **reconstruct** your signal
Able to get good efficiency out to high values of displacement



ATLAS CONF

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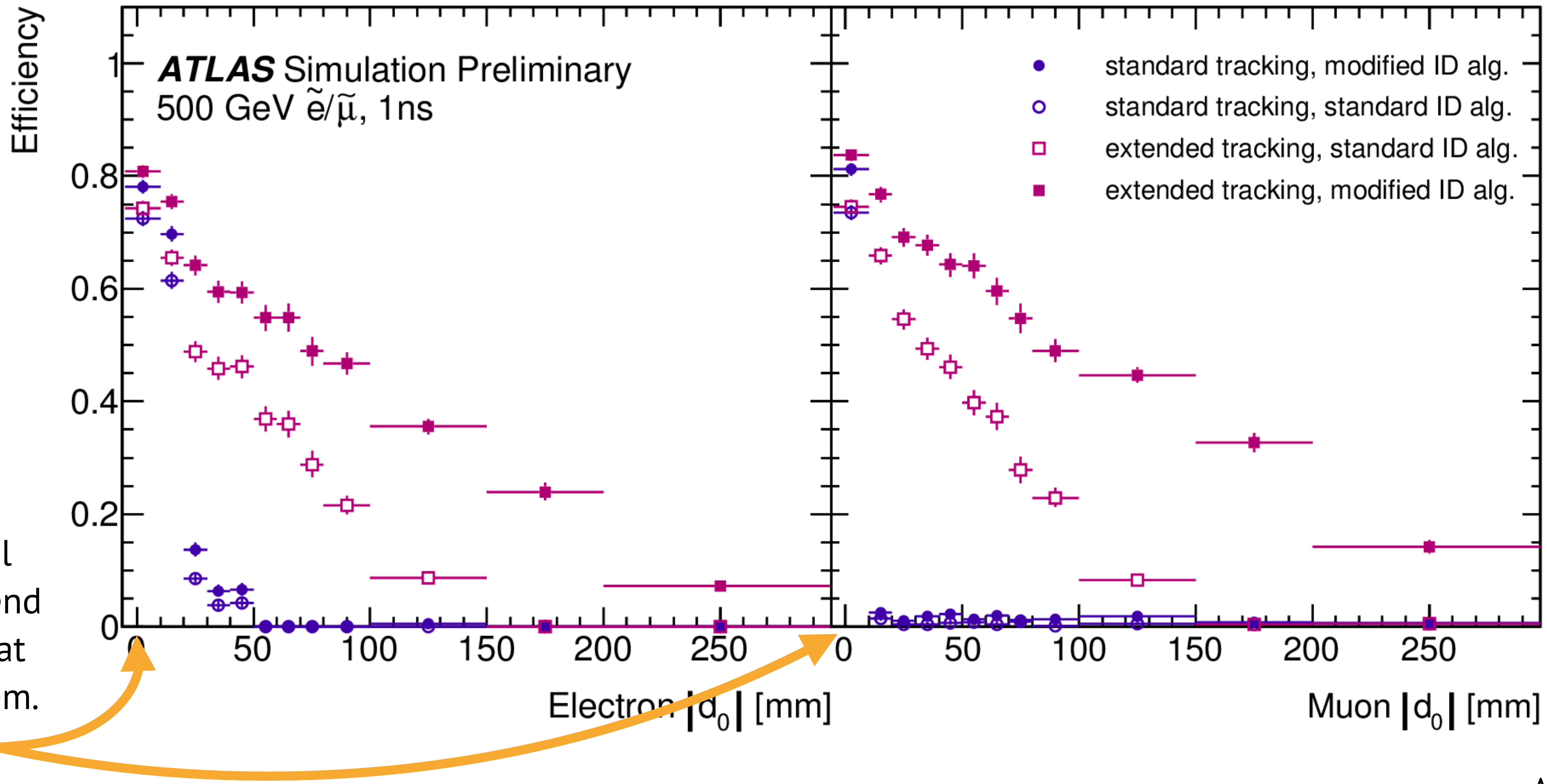

3rd step: **Isolate** the signal
Almost all SM processes end up in the first bin. We cut at $|d_0| > 3$ mm to remove them.

ATLAS CONF

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Next step: make sure you can **reconstruct** your signal
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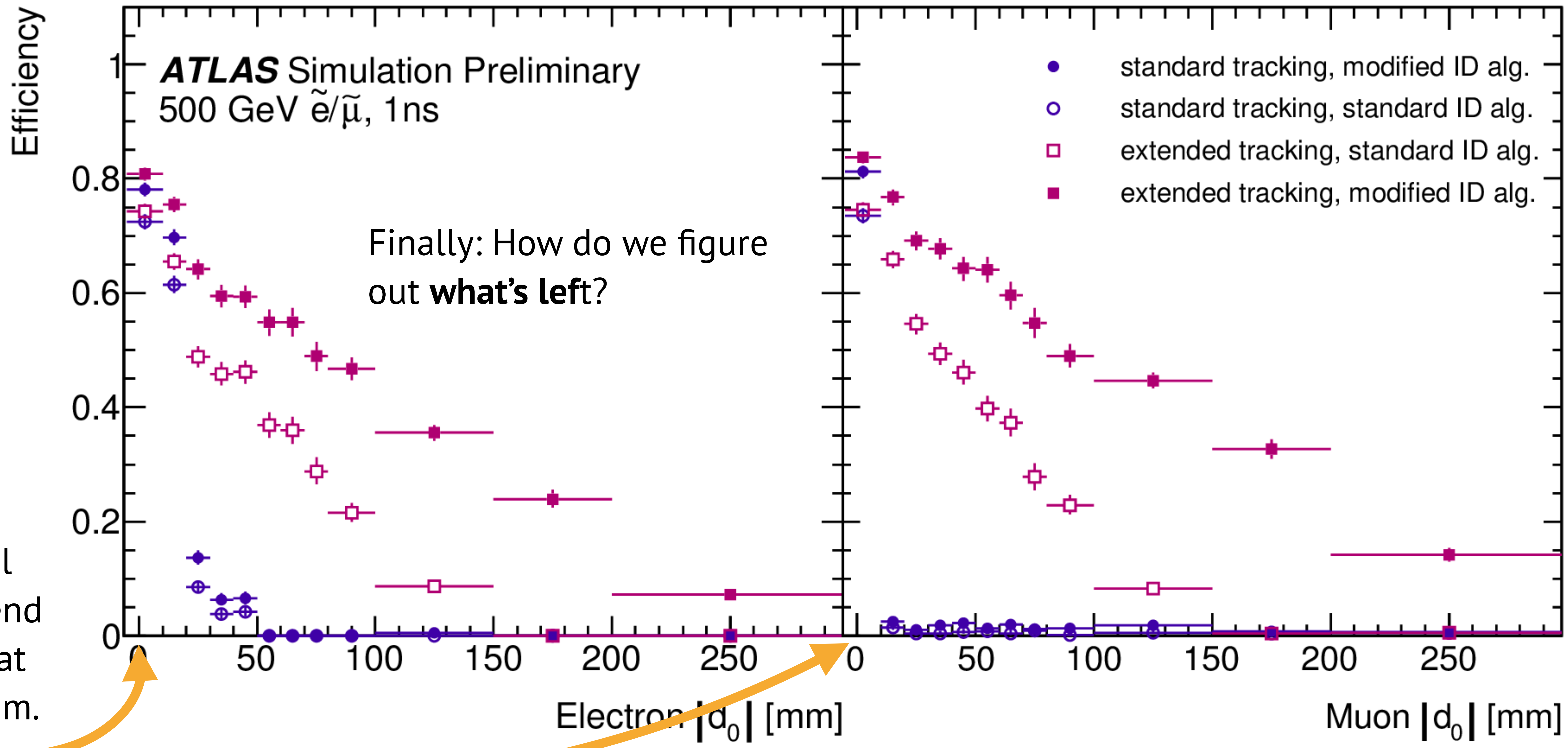


Finally: How do we figure out **what's left**?

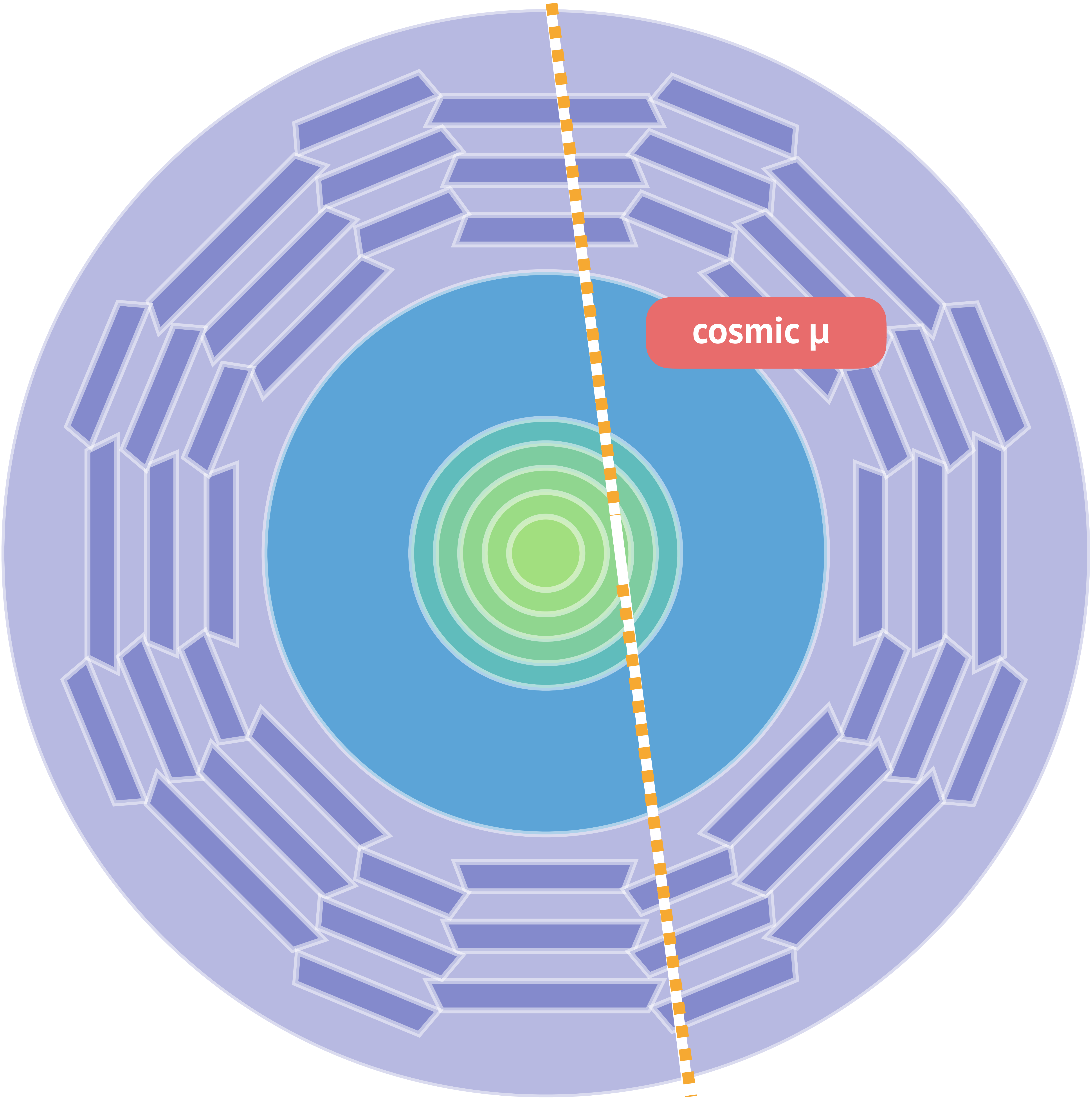
3rd step: **Isolate** the signal
Almost all SM processes end up in the first bin. We cut at $|d_0| > 3$ mm to remove them.

ATLAS CONF

hasn’t been done for a reason: **it’s hard**

When you have a search with tiny backgrounds, it can be more **complicated** than you expect

Dominant background for μμ
cosmics



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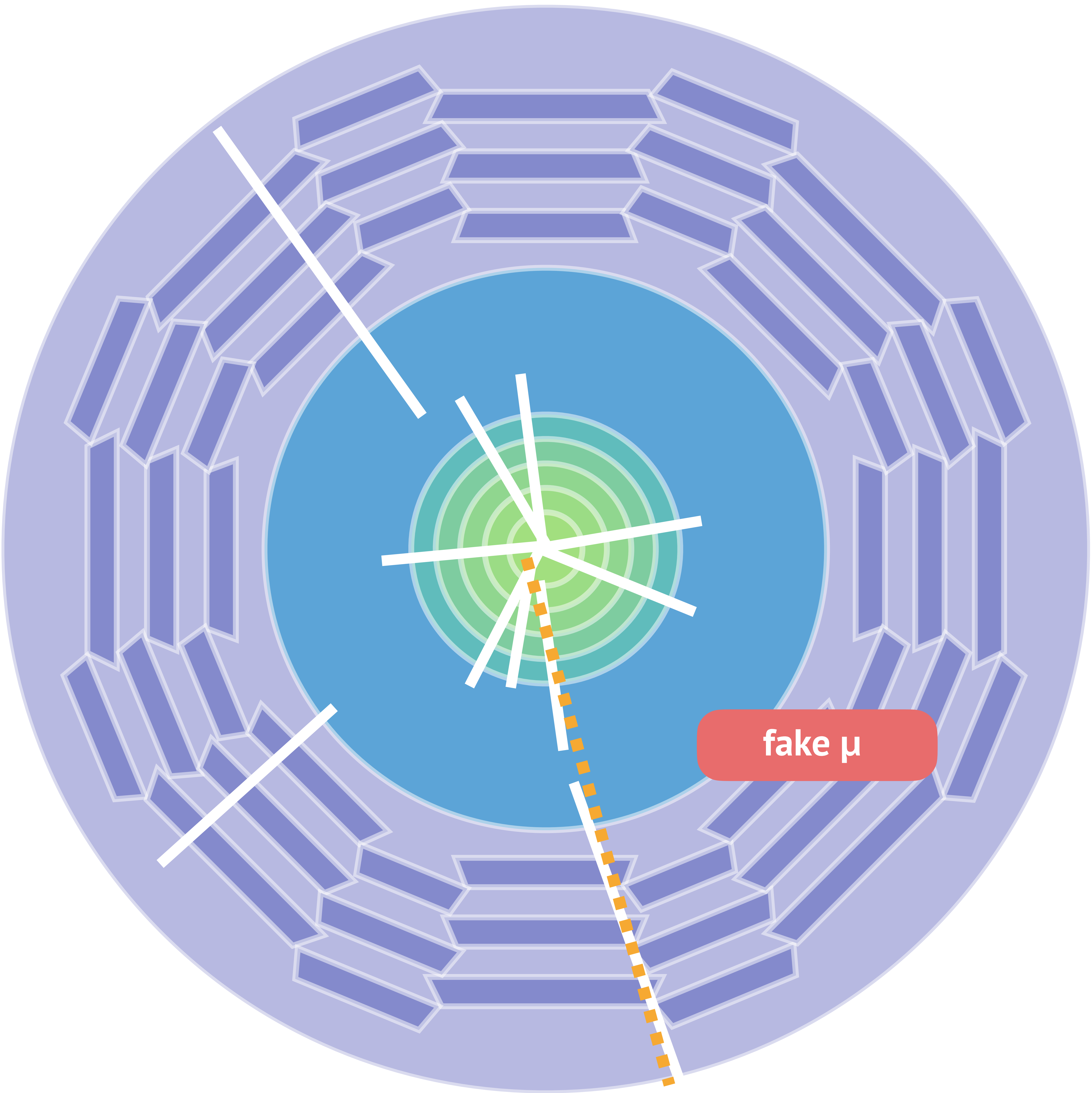
When you have a search with tiny backgrounds, it can be more **complicated** than you expect

Dominant background for μμ

~~cosmics~~
fake muons

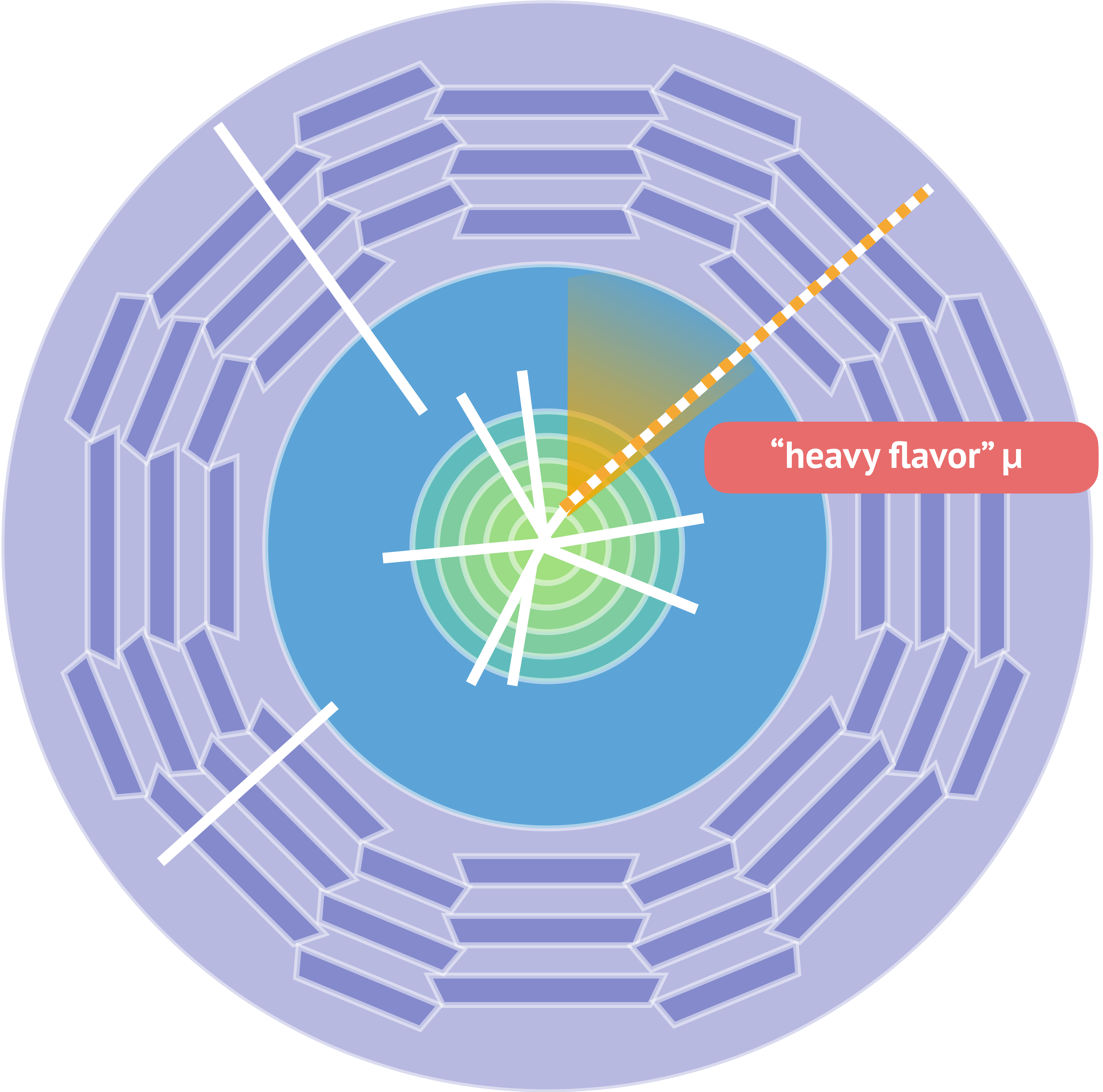


hasn't been done for a reason: **it's hard**

When you have a search with tiny backgrounds, it can be more **complicated** than you expect

Dominant background for μμ

~~**cosmics**~~
~~**fake muons**~~
rare standard model processes



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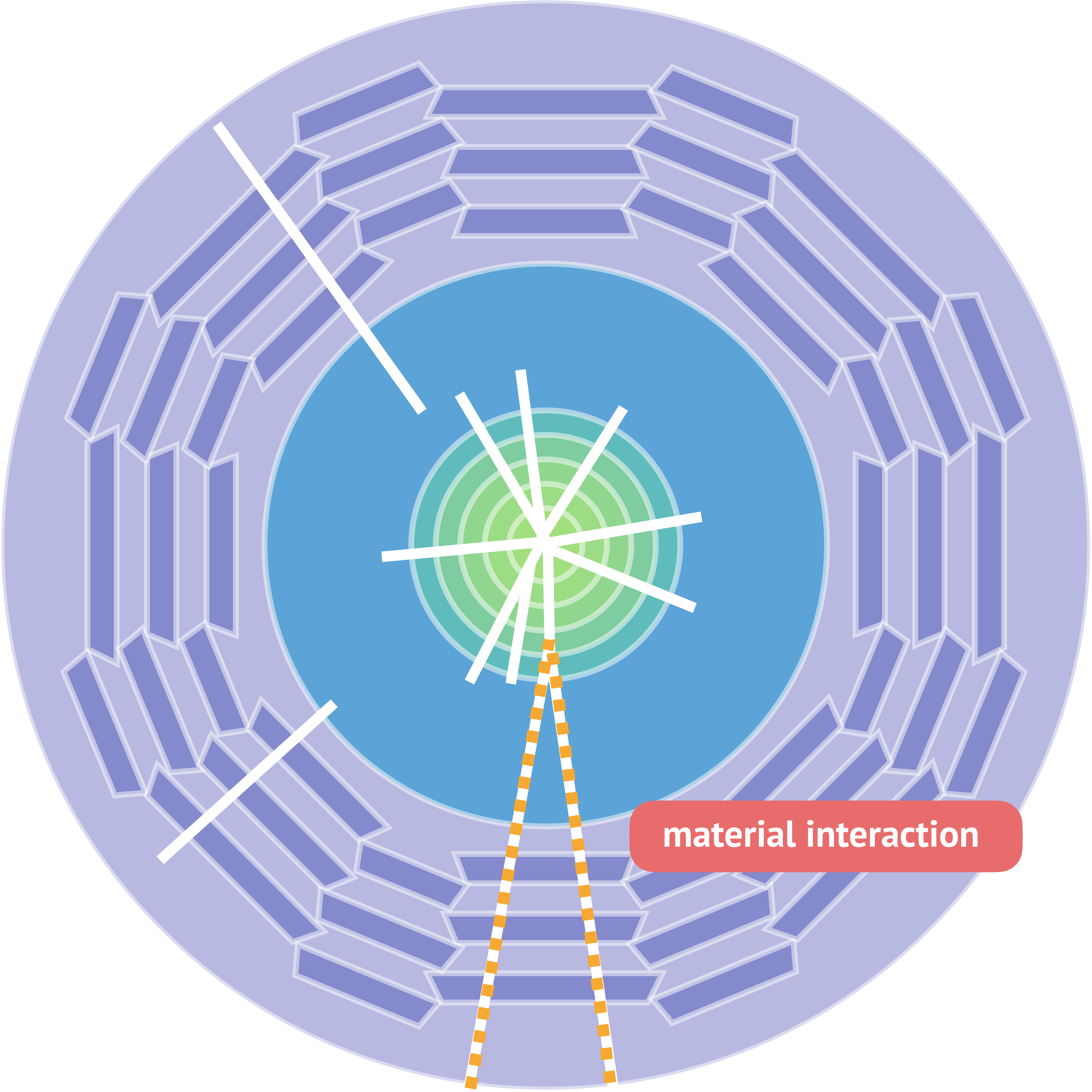
When you have a search with tiny backgrounds, it can be more **complicated** than you expect

Dominant background for μμ

- **~~cosmics~~**
- **~~fake muons~~**
- **~~rare standard model processes~~**
- **material interactions**



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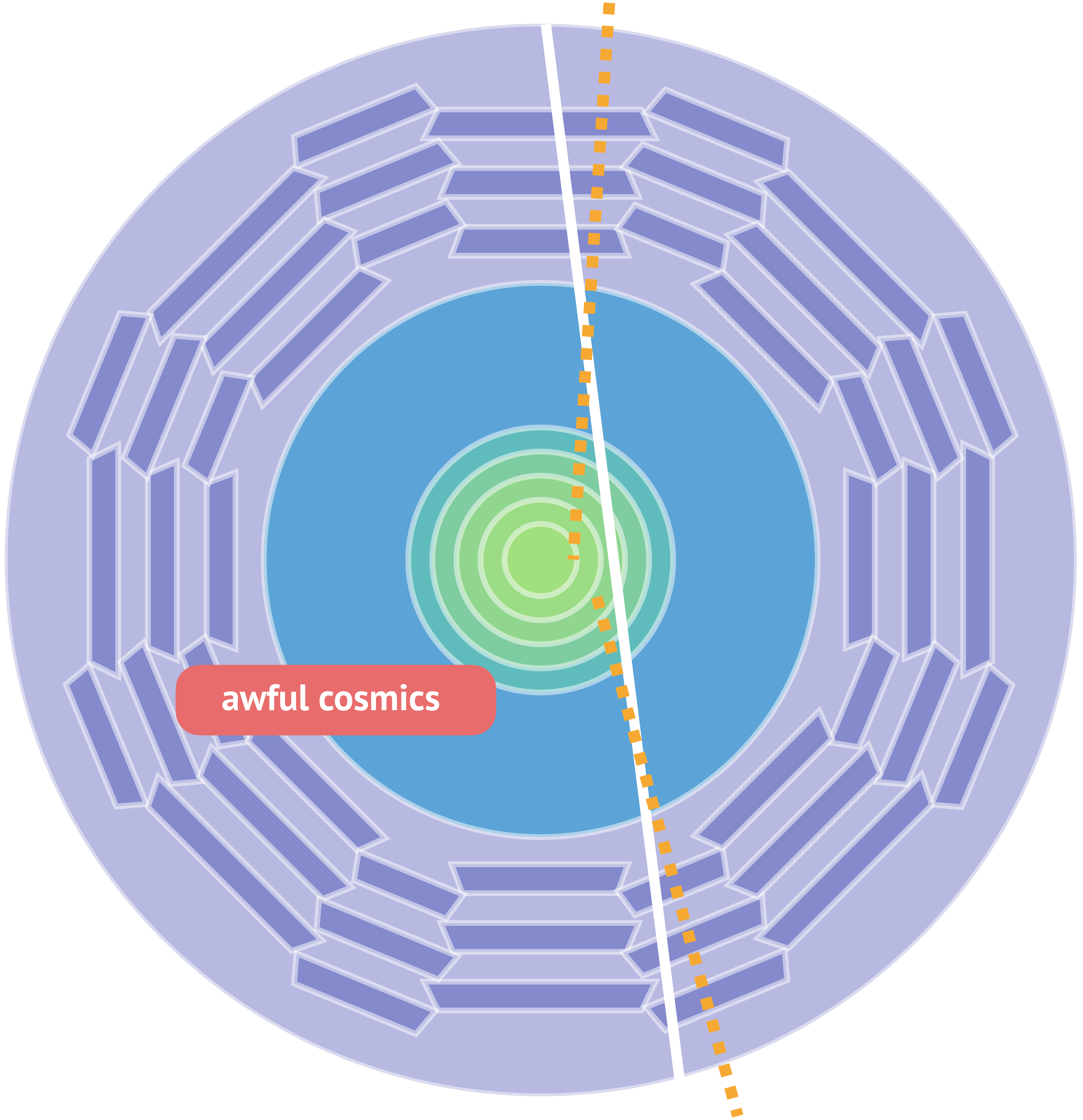
When you have a search with tiny backgrounds, it can be more **complicated** than you expect

Dominant background for μμ

- ~~**cosmics**~~
- ~~**fake muons**~~
- ~~**rare standard model processes**~~
- ~~**material interactions**~~
- **massive reconstruction failures**

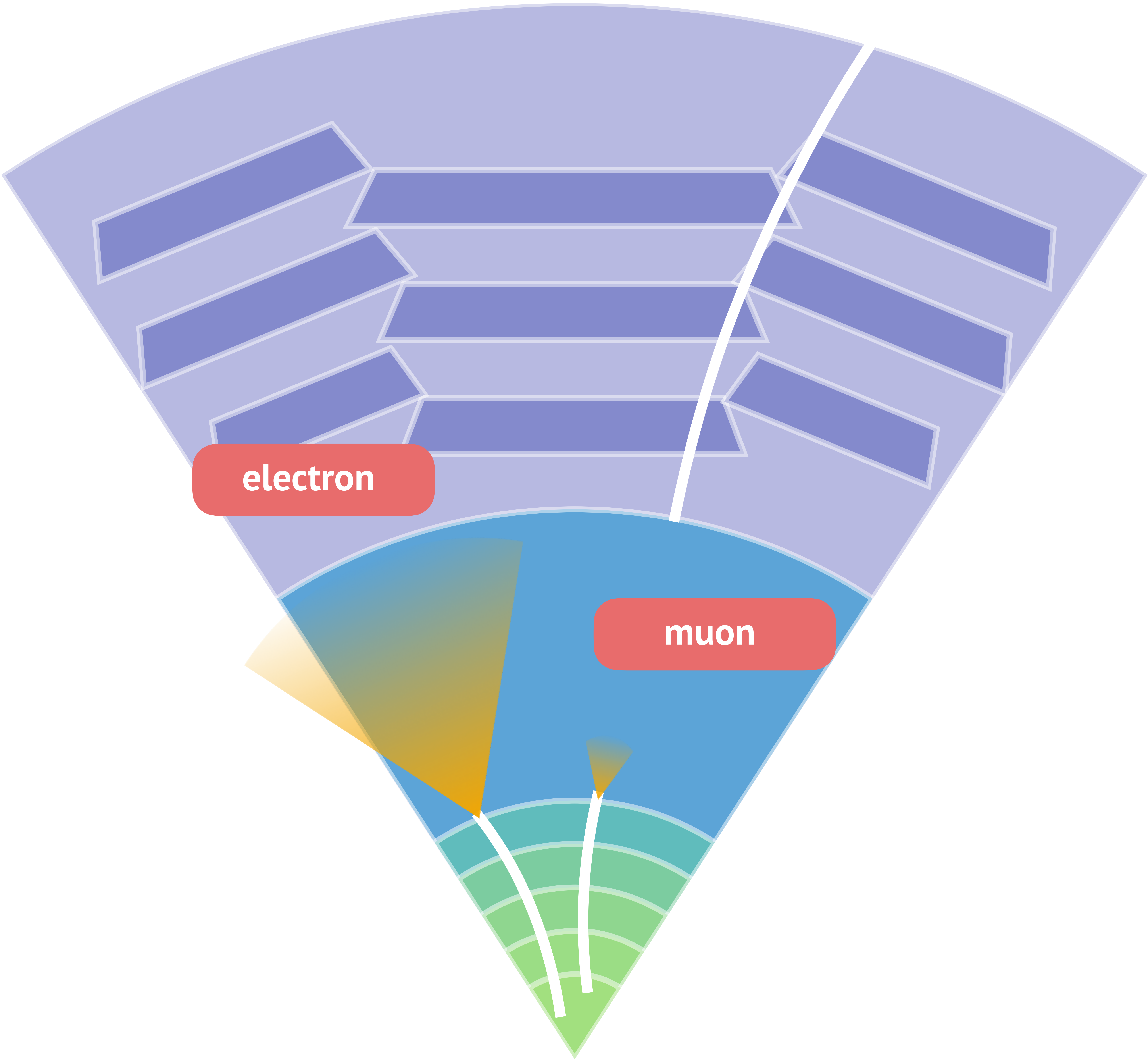


estimating backgrounds

This is the kind of logic you go through in each channel - ee, μμ, eμ

Figure out what backgrounds really contribute
- μμ: mismeasured **cosmic** muons
- ee: photons associated with **fake** tracks
- eμ: **fake** leptons and **heavy flavor**

Figure out how to estimate these backgrounds
- **Can't use simulation!**



estimating backgrounds

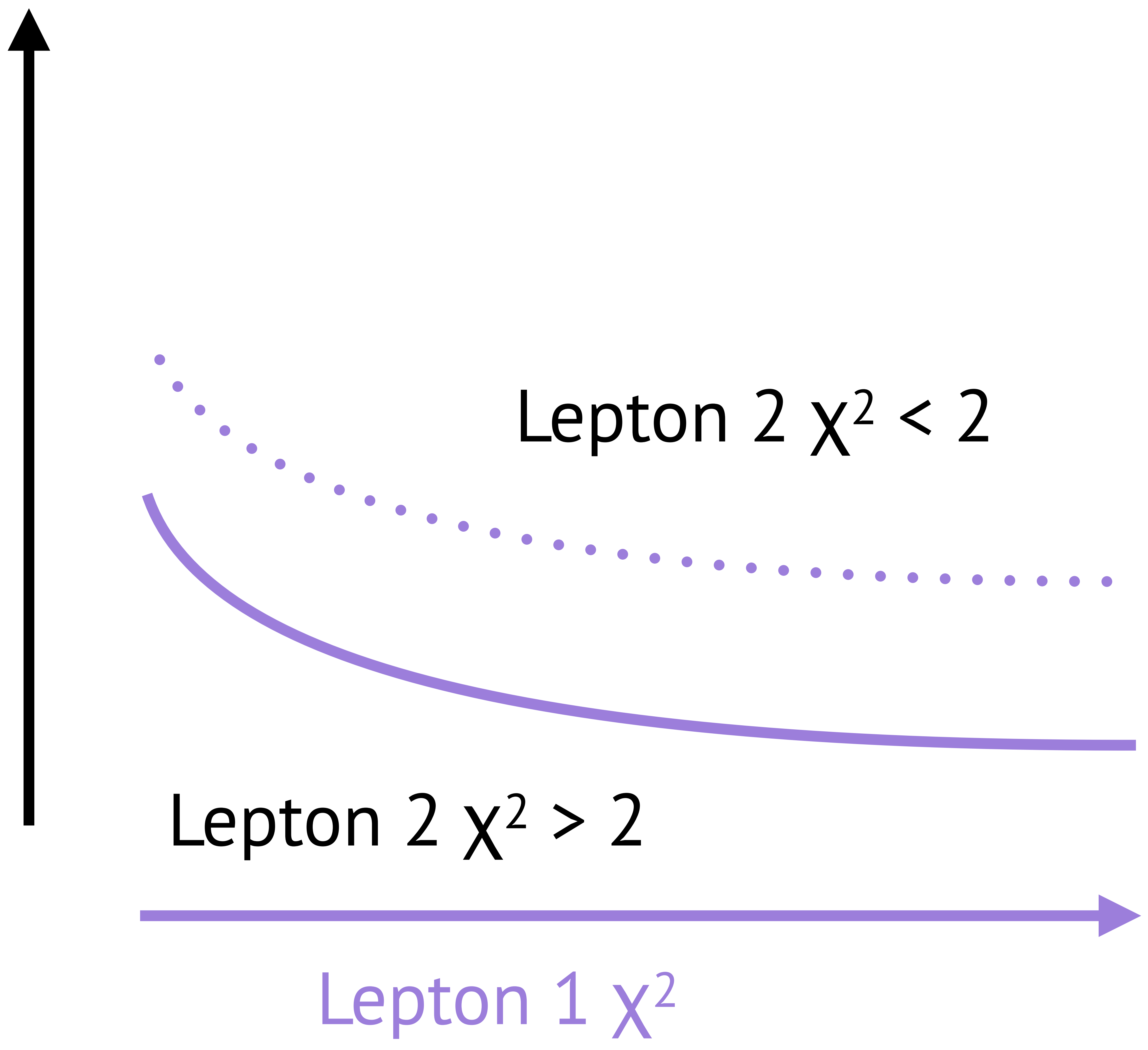
Data-driven approaches designed to model each background:

fakes and heavy flavor:

take advantage of the **uncorrelated** nature of the two leptons in the event

cut on the **quality** of one – it doesn't affect the **shape** of the other distribution

$$\text{both pass} = \frac{(1^{st}\text{ fails, }2^{nd}\text{ passes}) * (2^{nd}\text{ fails, }1^{st}\text{ passes})}{\text{both fail}}$$



estimating backgrounds

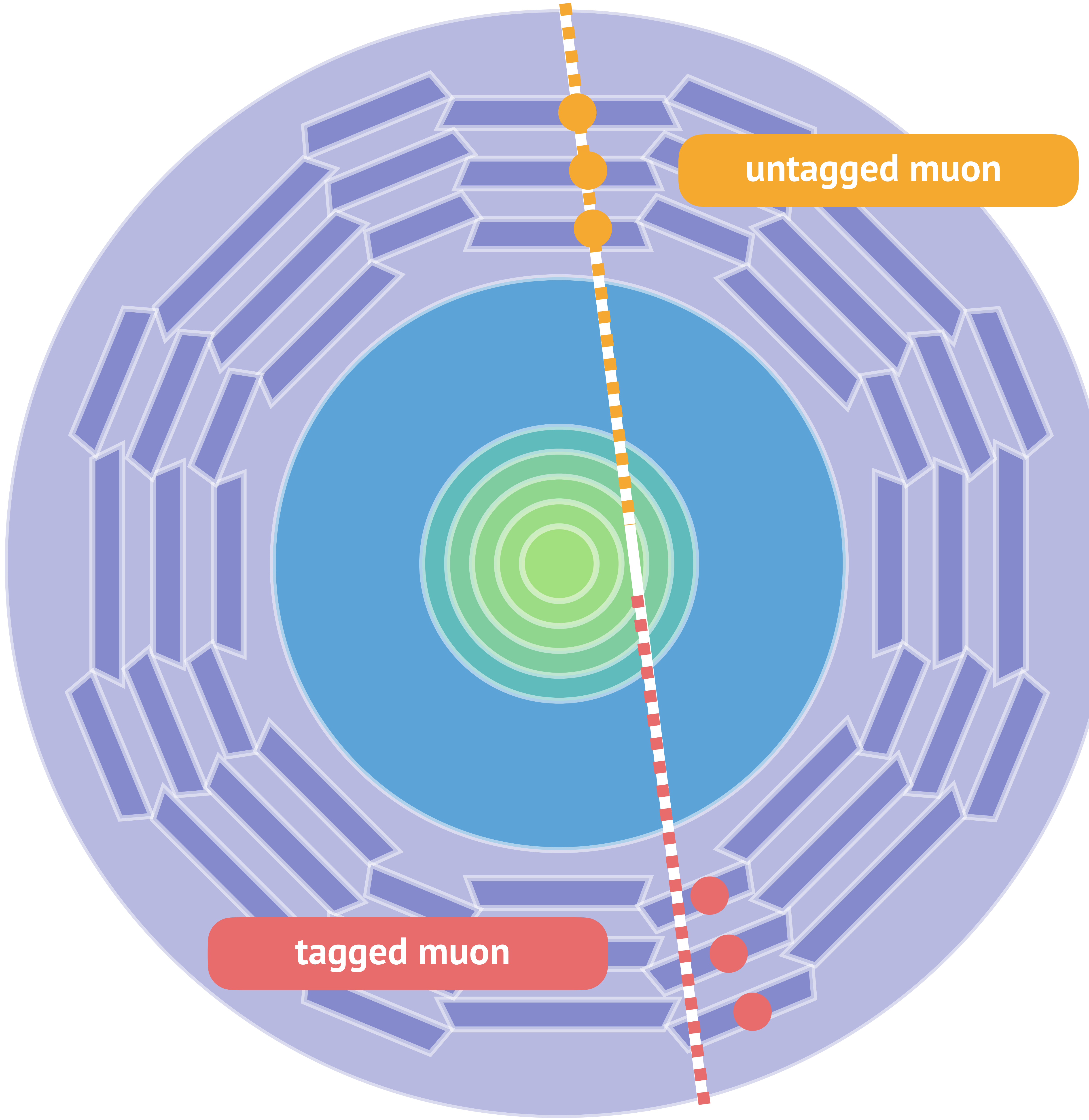
Cosmic estimate follows a similar strategy, but is less intuitive

Reliable ID tracks, but timing means often **missing information in the MS**

Combined muon has correct measurement, but can't find MS activity to tag

- **mismeasured** muon is **tagged**
- well measured muon isn't

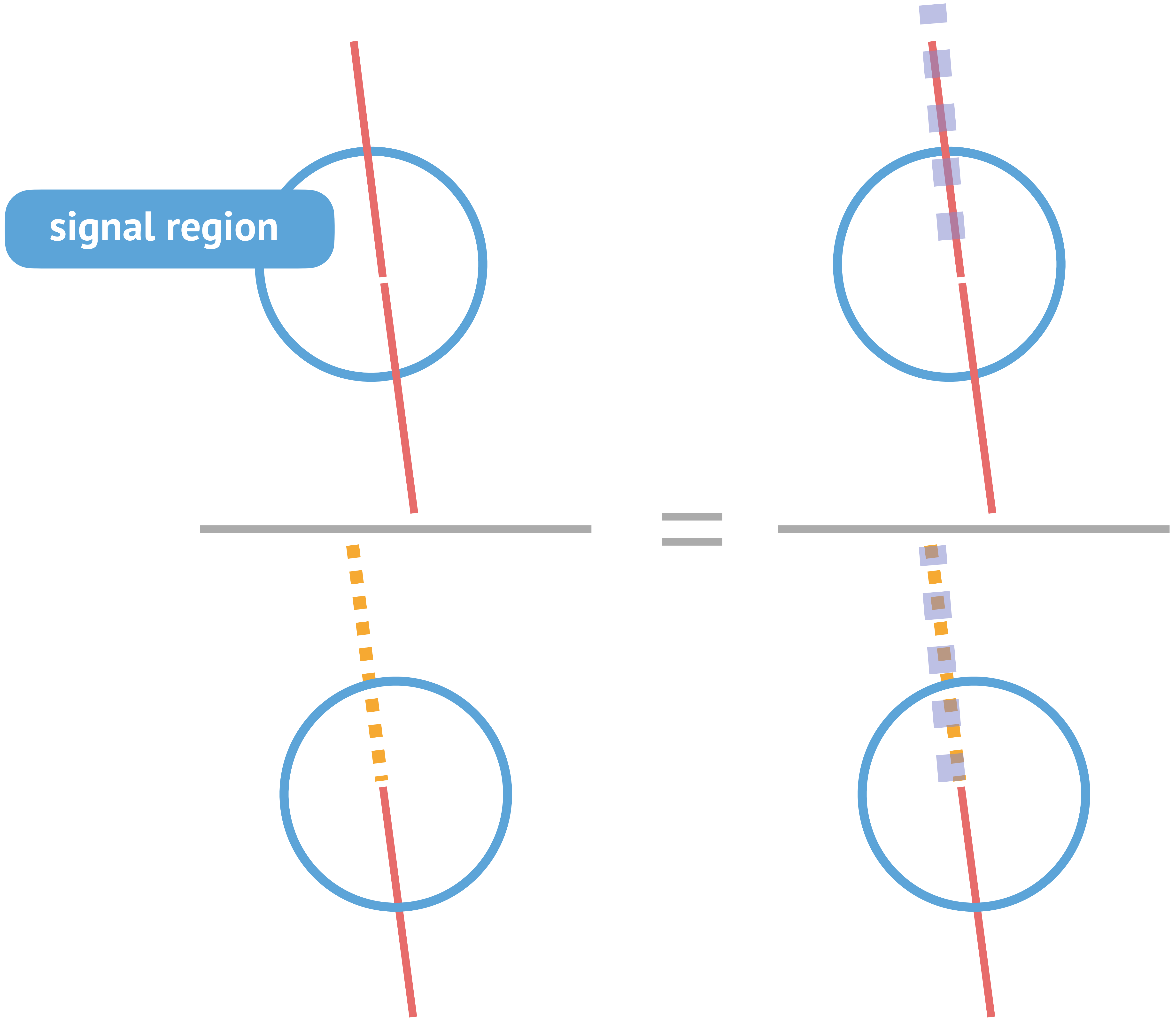
Quality of muon is independent of probability to be tagged (given the same muon quality on the opposite side)



estimating backgrounds

Measure ratio of “good quality” to “poor quality” muons in events with one cosmic tag

Apply that ratio to events with an untagged poor quality muon to estimate the background



cosmic-tagged

good quality muon

(used in signal region)

poor quality muon

(missing measurements)

The last steps…

Able to reduce our backgrounds to **fractions of a event**, estimate all backgrounds
And finally, can look in our **signal regions**

Region	SR-ee	SR-$\mu\mu$	SR-$e\mu$
Fake + Heavy-Flavor	0.46 ± 0.10	–	$0.007^{+0.019}_{-0.007}$
Cosmics	–	$0.11^{+0.20}_{-0.11}$	–
Expected Background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$

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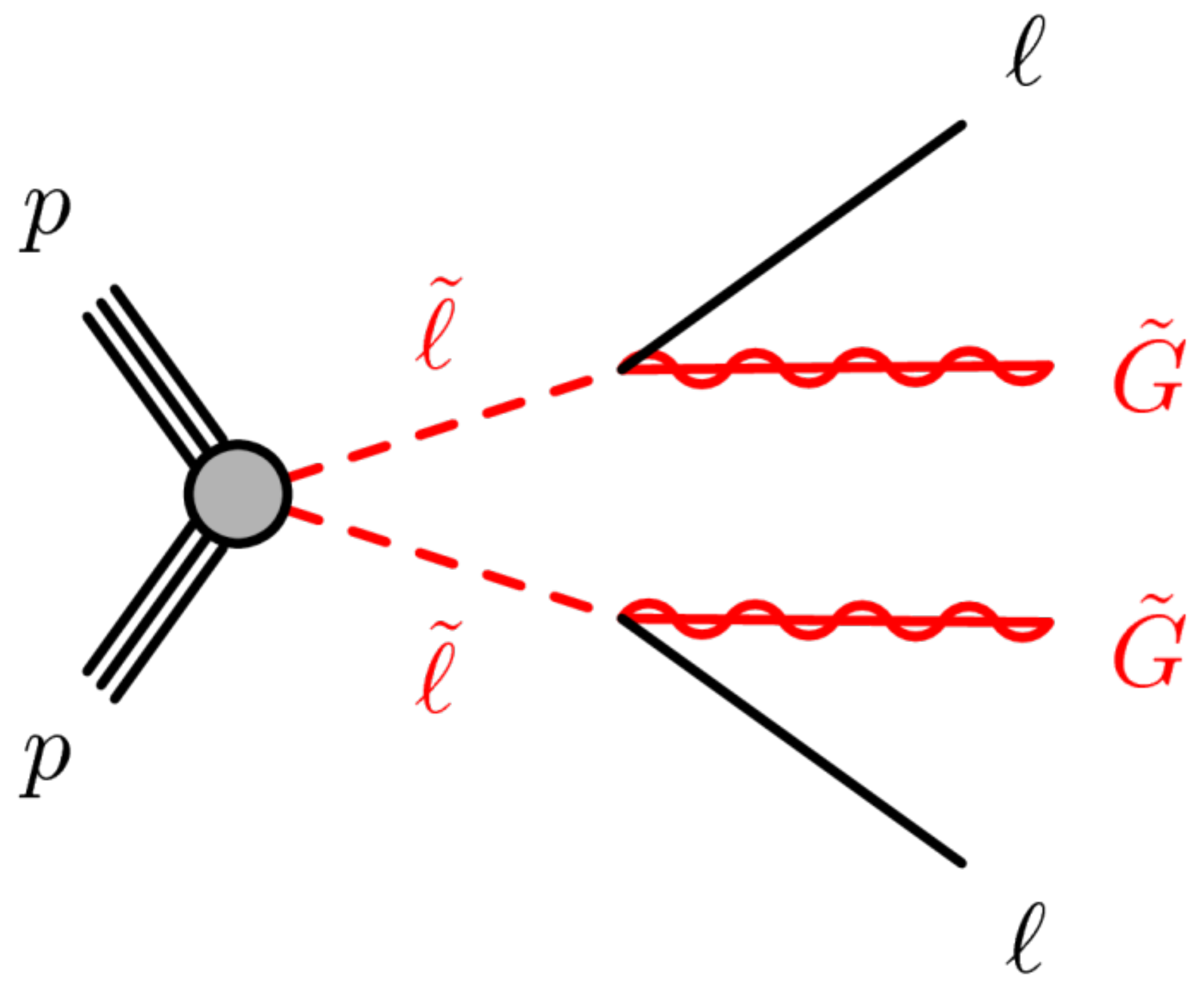
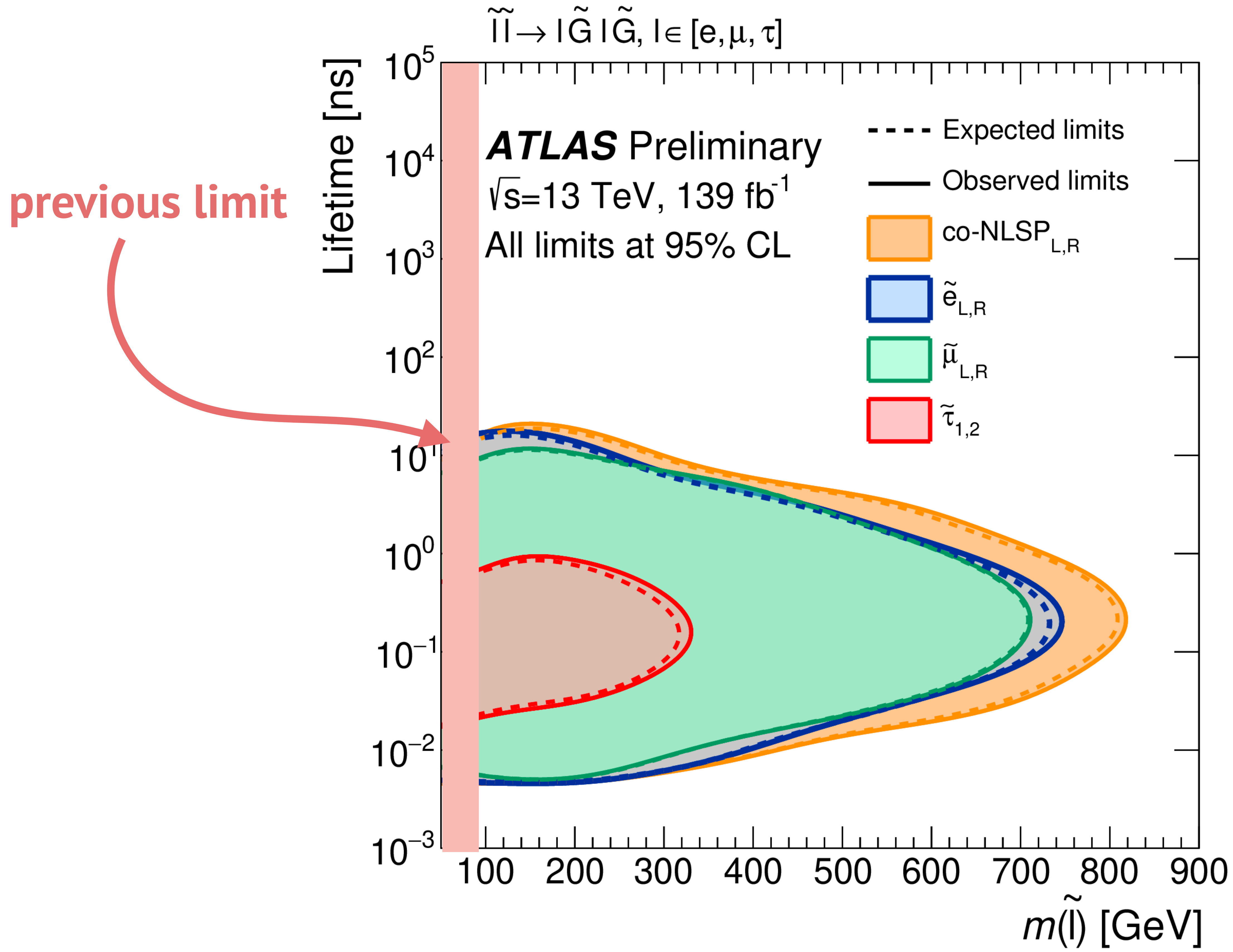
Cosmics	–	$0.11^{+0.20}_{-0.11}$	–
Expected Background	0.46 ± 0.10	$0.11^{+0.20}_{-0.11}$	$0.007^{+0.019}_{-0.007}$
Observed events	0	0	0

And see... **nothing!**

The last steps...

Able to reduce our backgrounds to **fractions of a event**, estimate all backgrounds
And finally, can look in our **signal regions**

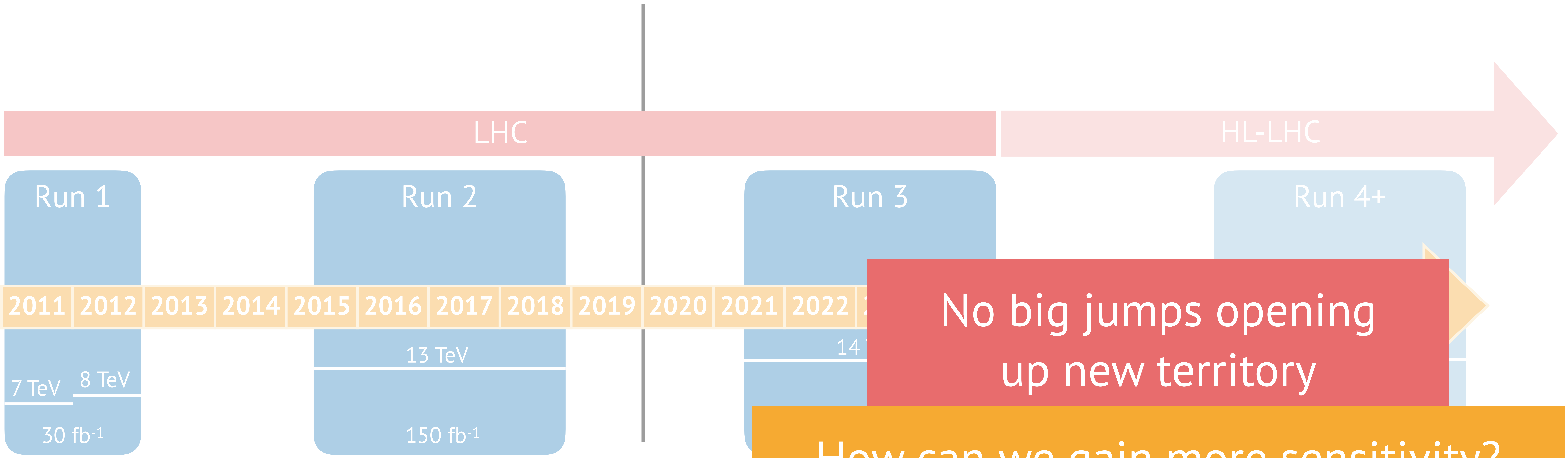




ATLAS CONF

Run 2 → Run 3

Luminosity x1
Energy +8%



No big jumps opening up new territory

How can we gain more sensitivity?

To improve long-lived searches

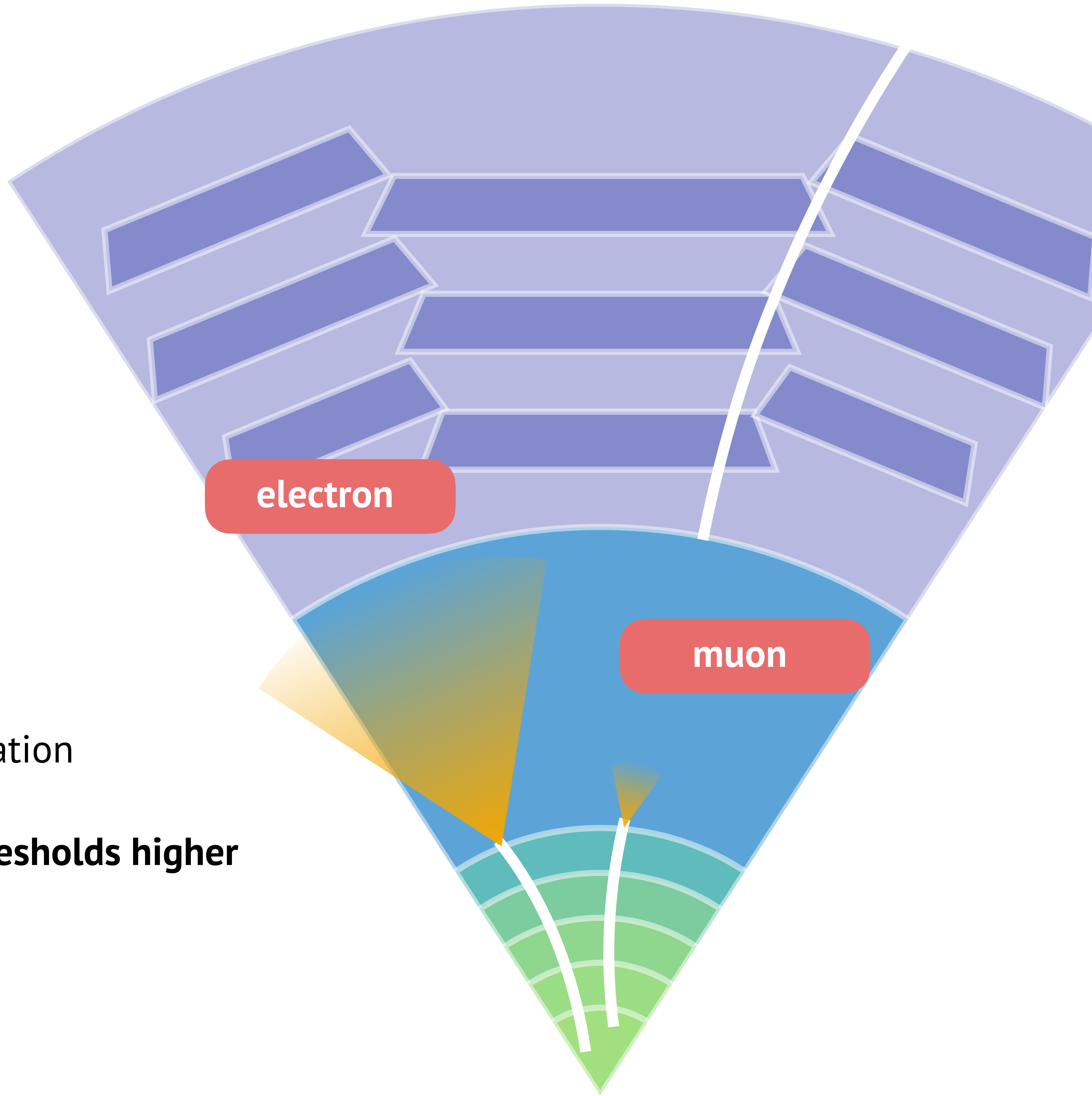
must improve the **Trigger**

For our displaced lepton search…

For some parameter space that we haven't yet excluded trigger acceptance is **as low as 3%**!

When you can't use tracks, throw away **half of your lepton** information

Can't reject backgrounds as well ➞ have to make your **energy thresholds higher**



To improve long-lived searches

must improve the **Trigger**

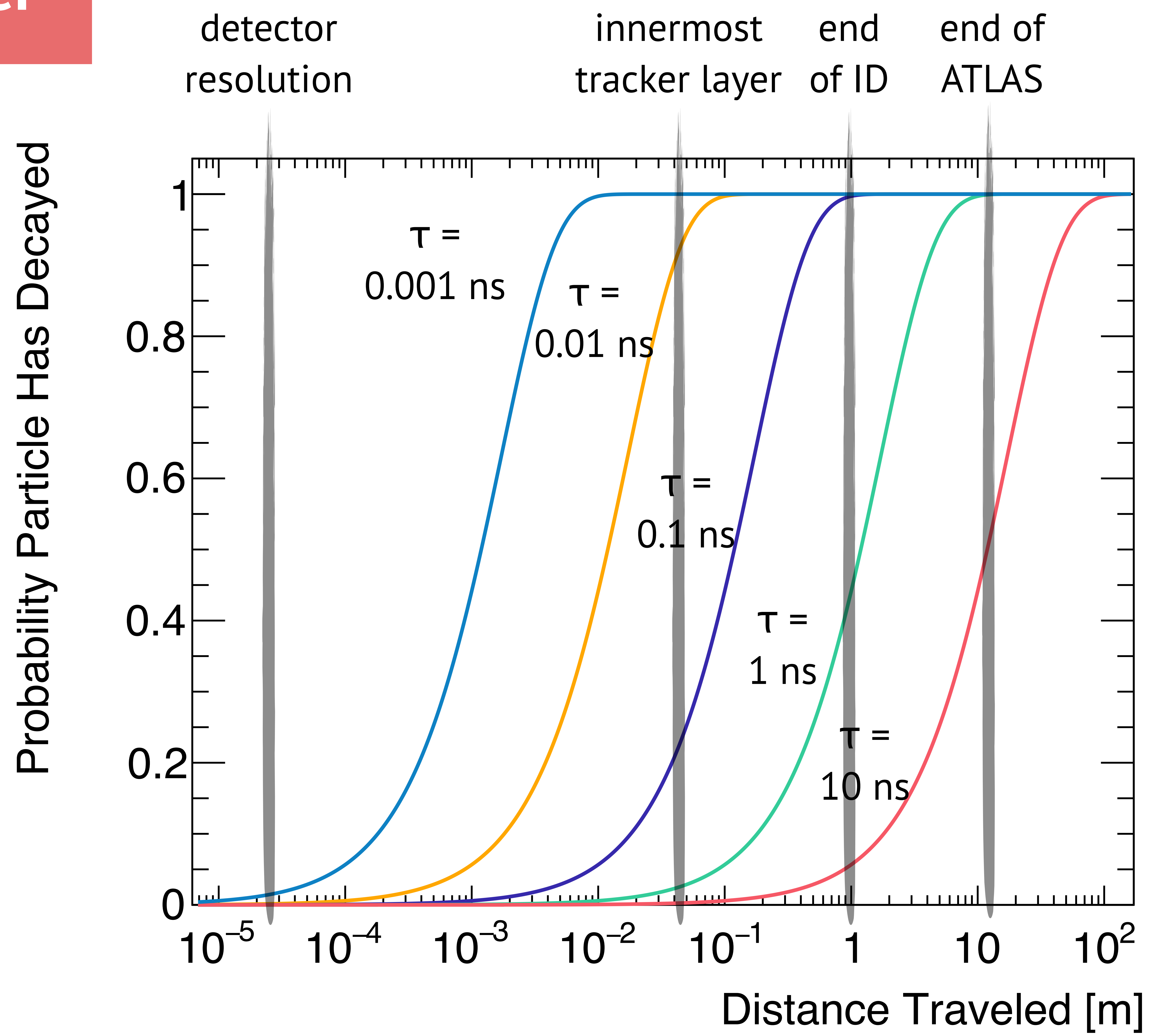
what can we do for Run 3…

No big changes to the detector
→ can only make **software** changes

Working on developing smart strategies to **quickly** produce approximations of these long-lived particle track signatures

- what **rough information** can we add that makes a big difference?

200 GeV particle
energy: 500 GeV



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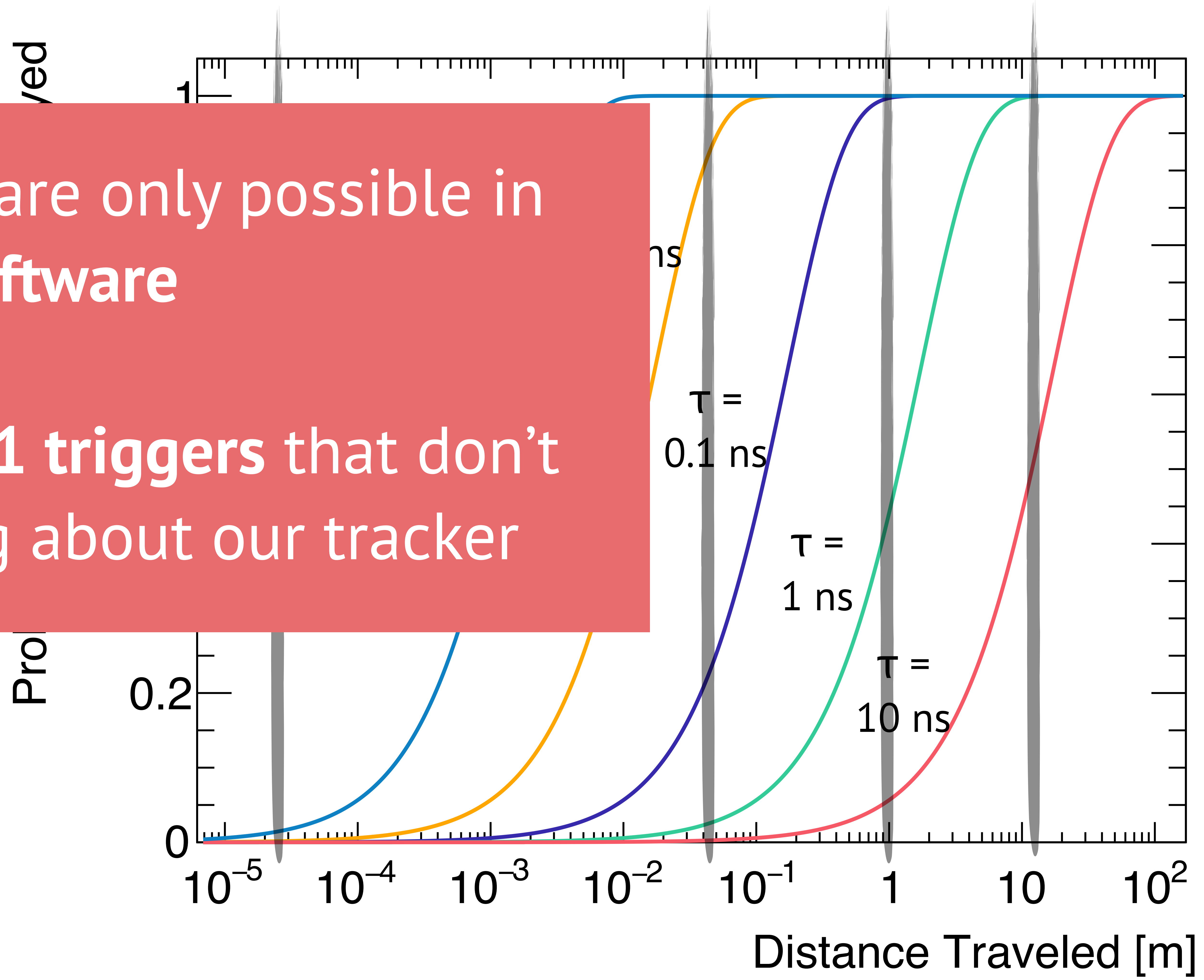


what can we do f… Run 3…

these changes are only possible in **software**

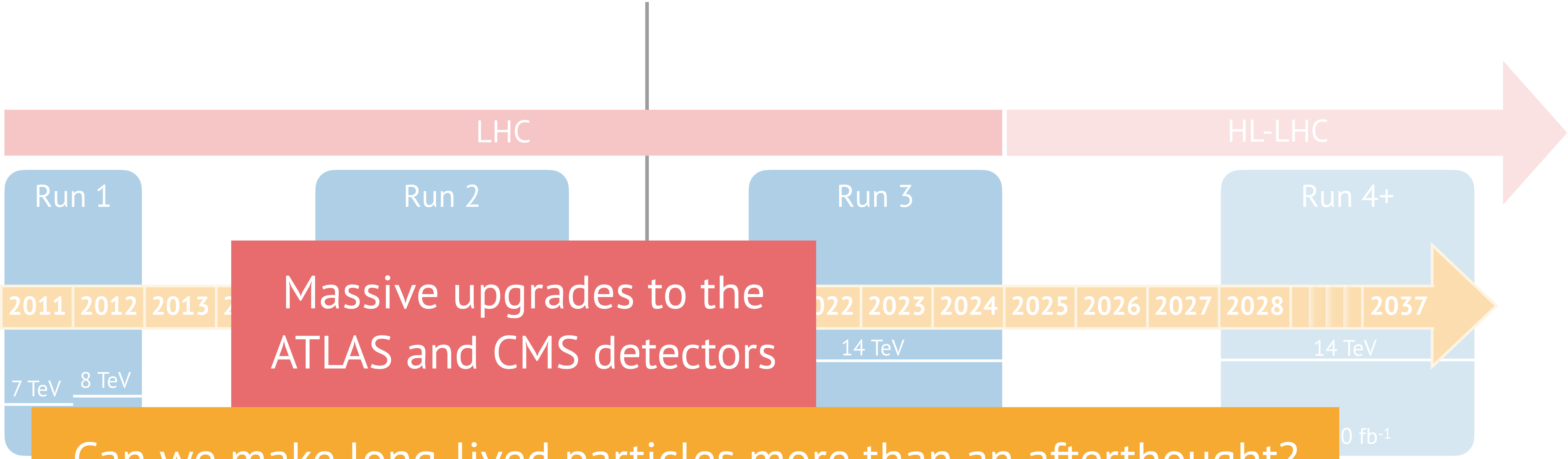
still need **level 1 triggers** that don't know anything about our tracker

No big changes to the dete…
→ can only make **software** …

Working on developing sma… **quickly** produce approximat… long-lived particle track signatures
- what **rough information** can we add that makes a big difference?

Run 3 ⟶ Run 4+

Luminosity x10
Energy +0%



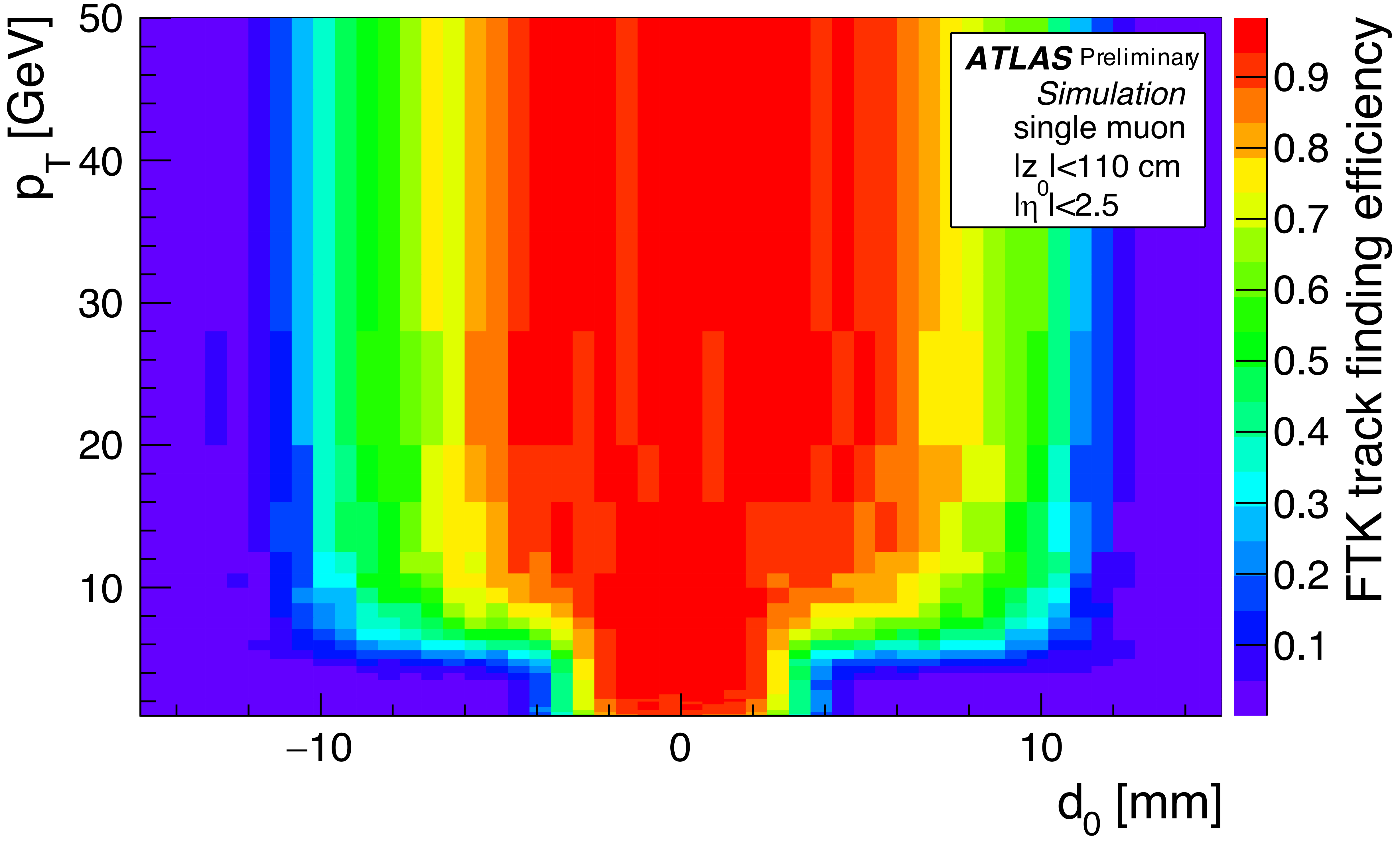
Massive upgrades to the ATLAS and CMS detectors

Can we make long-lived particles more than an afterthought?

Both ATLAS and CMS are working on a hardware-based tracker

CMS: **L1Track**
ATLAS: **HTT**

Example of tracking efficiency for a hardware tracker



And on ATLAS, I worked on demonstrating that these trackers could help us find long-lived particles

For some signatures, this hardware tracker configuration resulted in **up to 7x trigger acceptance**

But it's not just trackers…

the tricky thing about long-lived particles is how diverse their signatures are

Tracker

Displaced tracking
Anomalous charge deposits
Trackless signatures

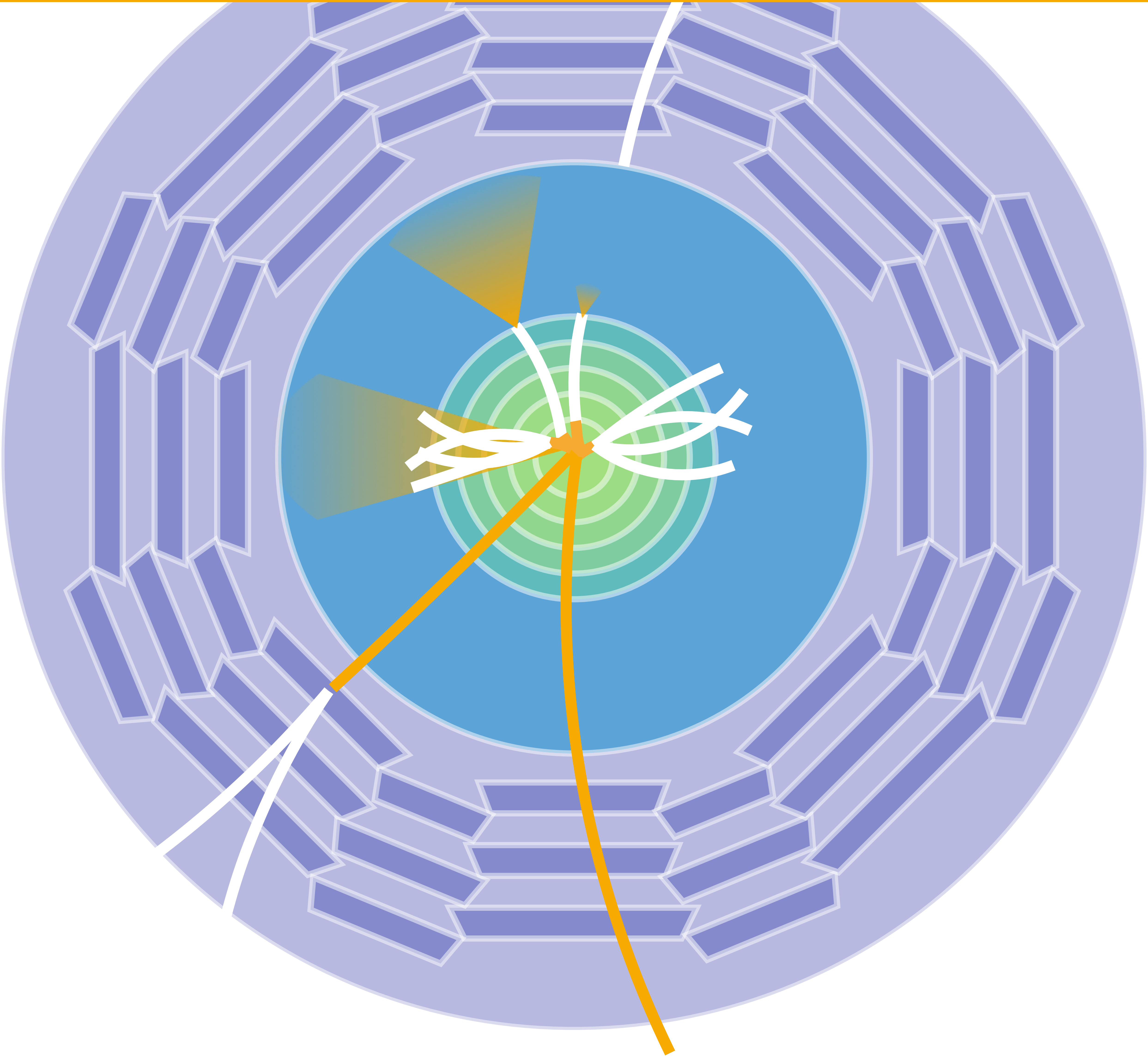
Calorimeter

Timing information to find slow particles, to allow us to trace particle trajectories in 4D (including time!) and reduce backgrounds

Fine-grained pointing information to look for displaced decays

Muon System

Displaced tracking
Timing information to find slow moving heavy particles



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Fine-grained pointing inf to look for displaced deca

Muon System

Displaced tracking
Timing information to find slow moving heavy particles

To have the best chance of finding new physics, we have to plan for all the shapes it can take

In conclusion...

As we move forward with LHC physics, **rare and hard to reconstruct** processes are the most interesting place to look

Long-lived particles are often both of these things

Still lots of room to find well-motivated new physics, if we just **expand our imagination** (and algorithms) beyond the LHC beamspot

If we act now, can open up **new sensitivity** in the next generation of detectors!


THANK YOU!