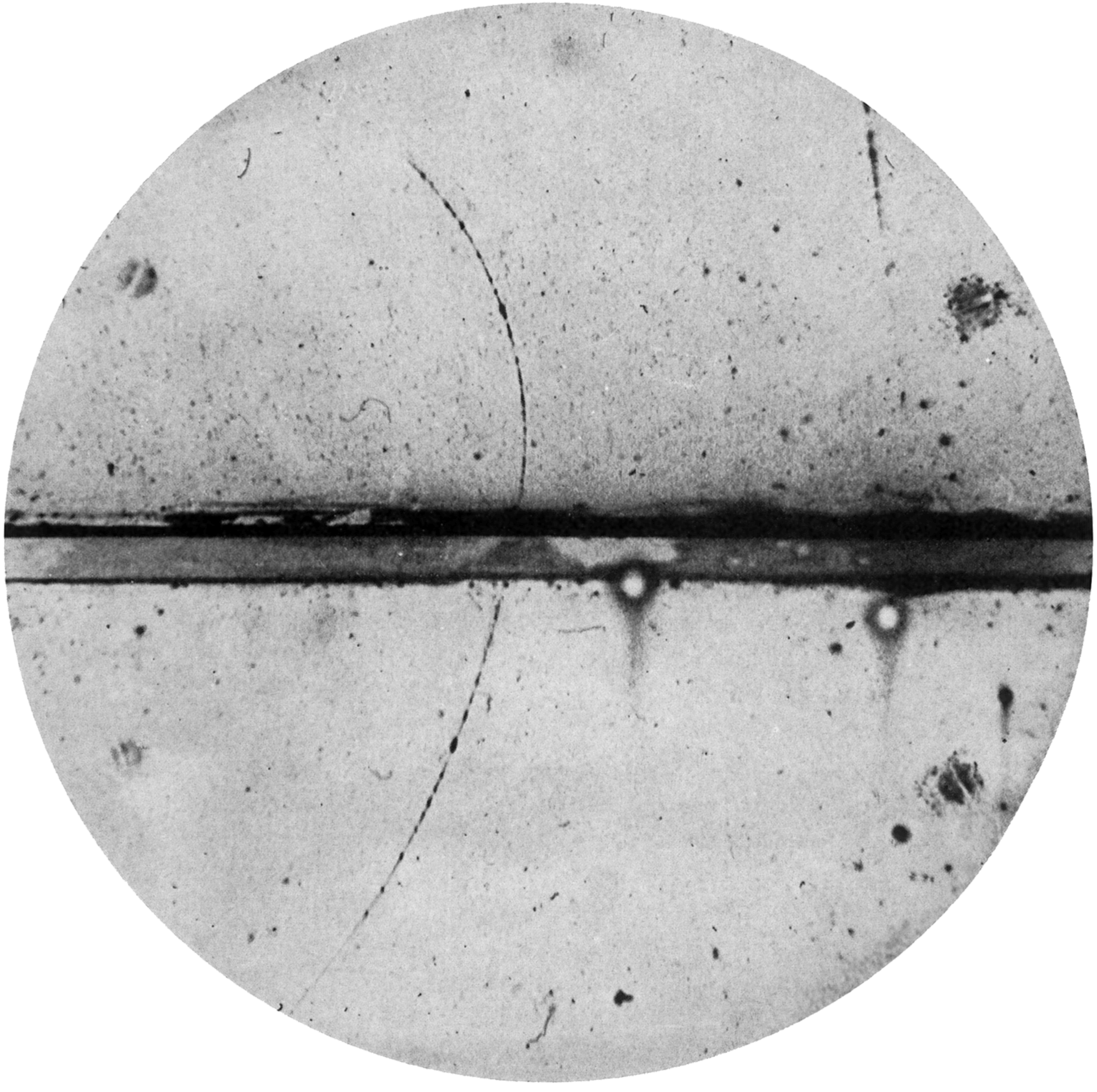
Particle Physics at the Large Hadron Collider

Karri Folan DiPetrillo

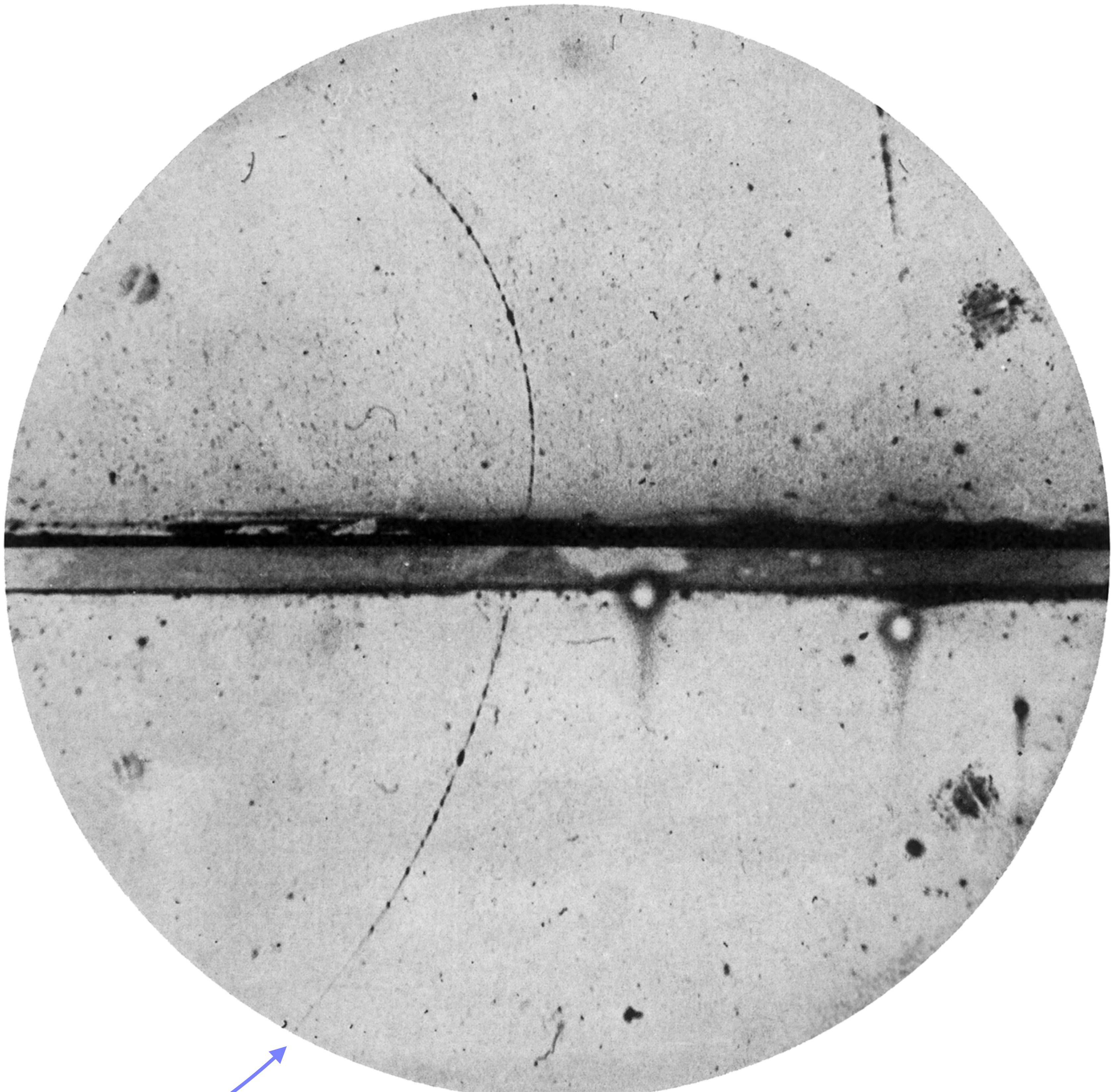
Summer Intern Lecture Series

2 July 2024

Can you guess any of these discoveries?



1932



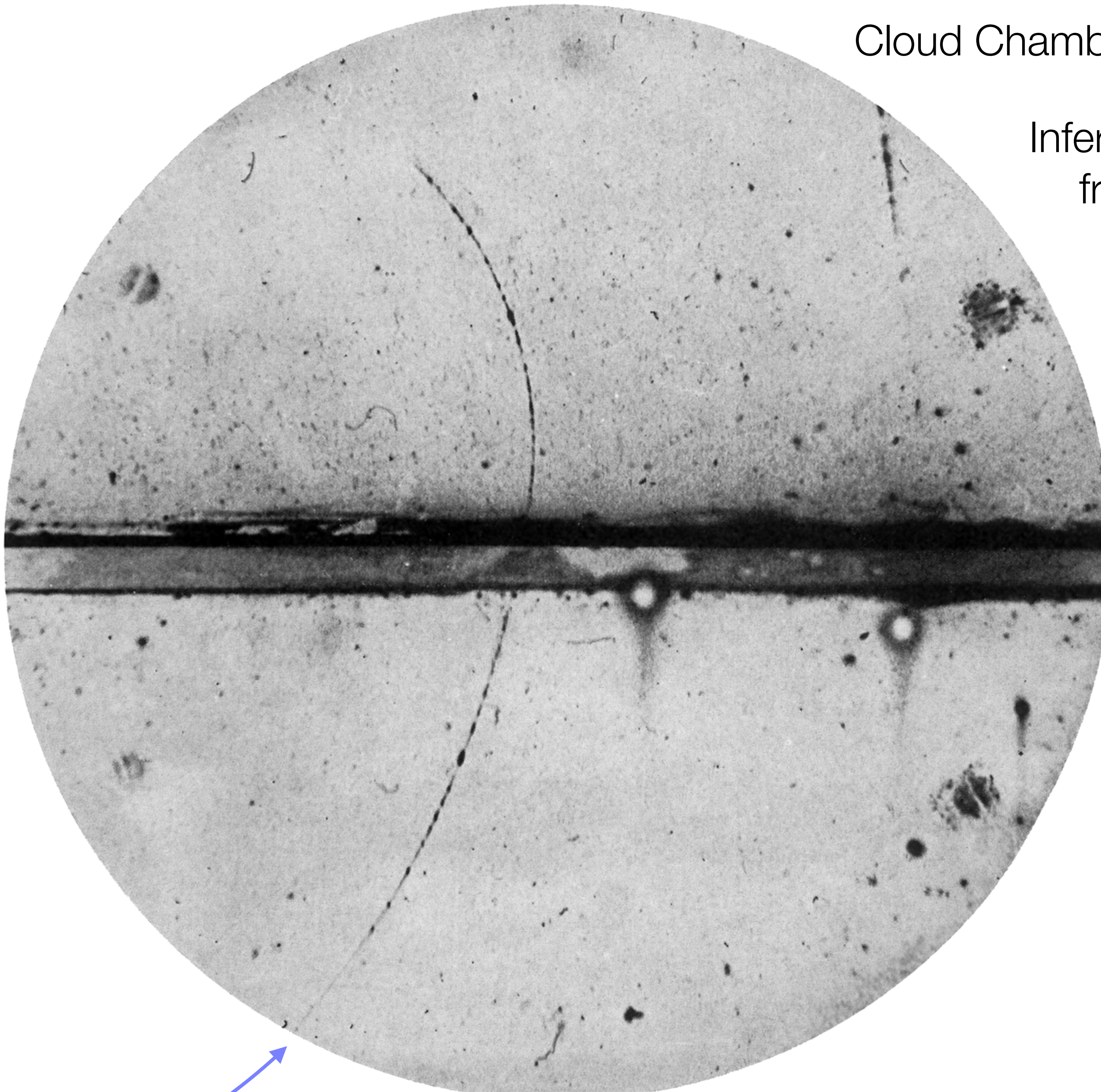
Positron, e^+
Evidence for anti-matter

1932

Cosmic ray event

Cloud Chamber + magnetic field

Infer charge & mass
from curvature



Positron, e^+
Evidence for anti-matter

1932

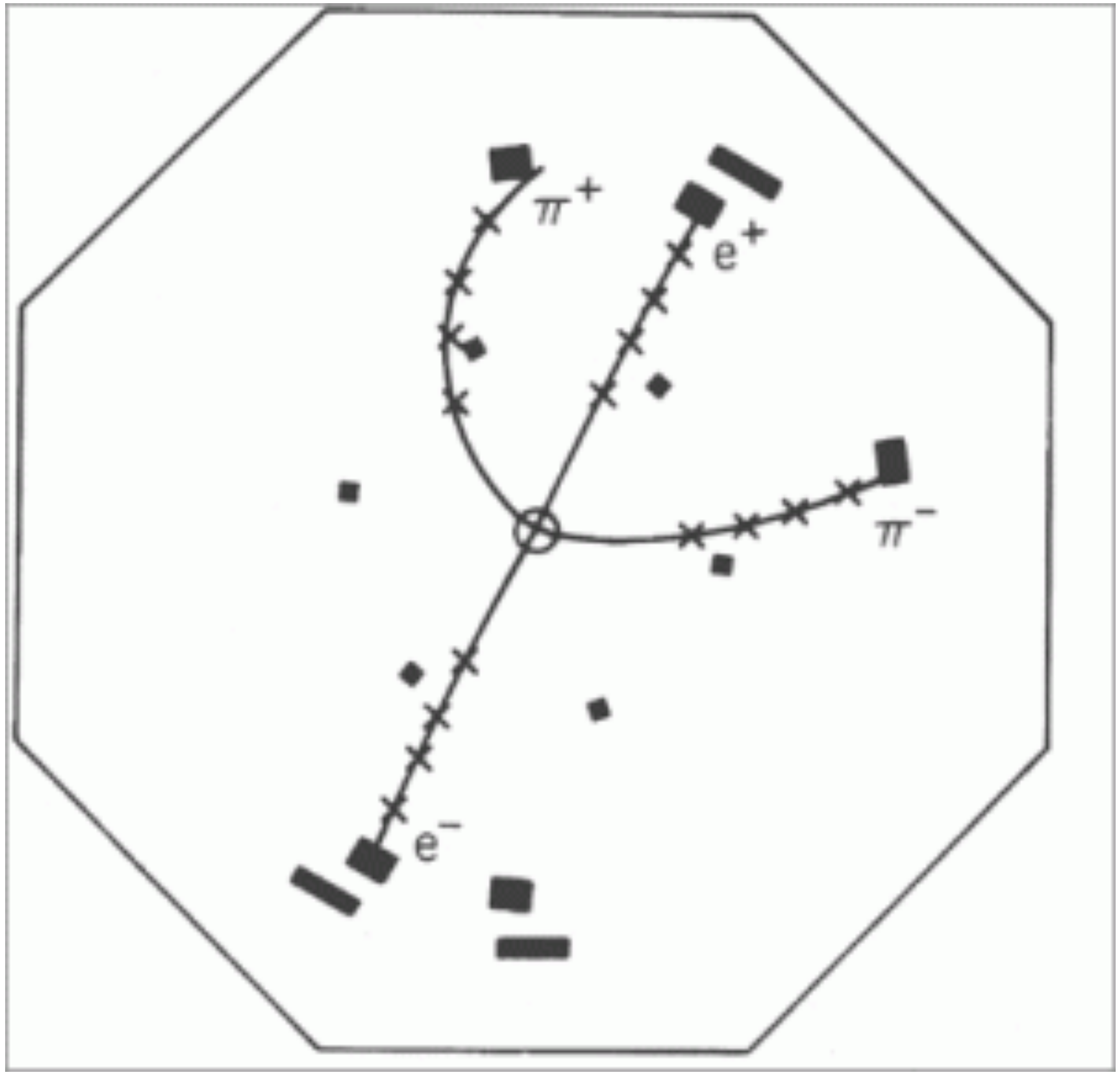
1947

1947

Cosmic ray event - Nuclear emulsion

Infer particle properties from ionization, mean angle scattering, and/or decay products

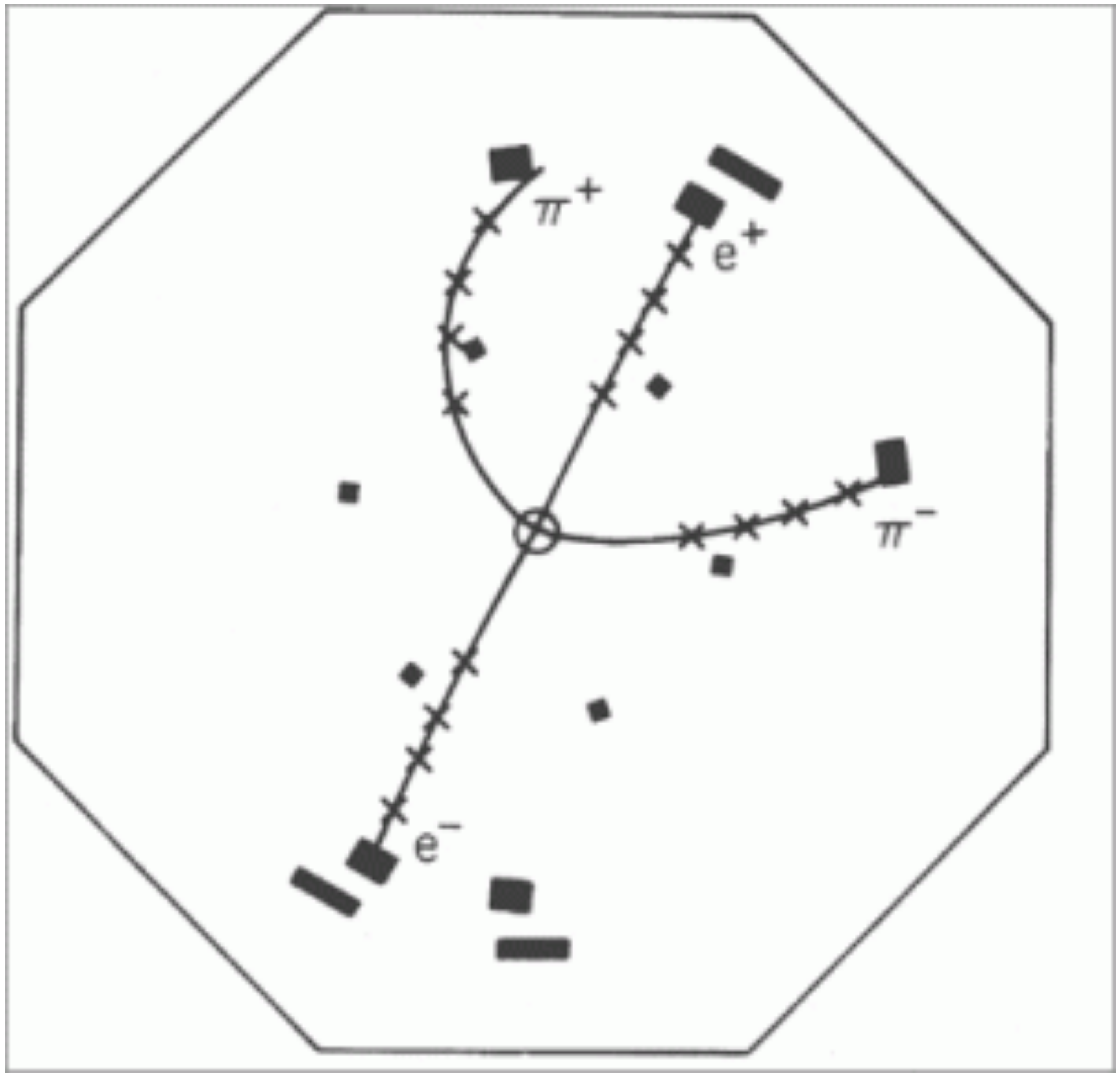
1947



1974

Ψ'→ ππ J/Ψ

Charm mesons

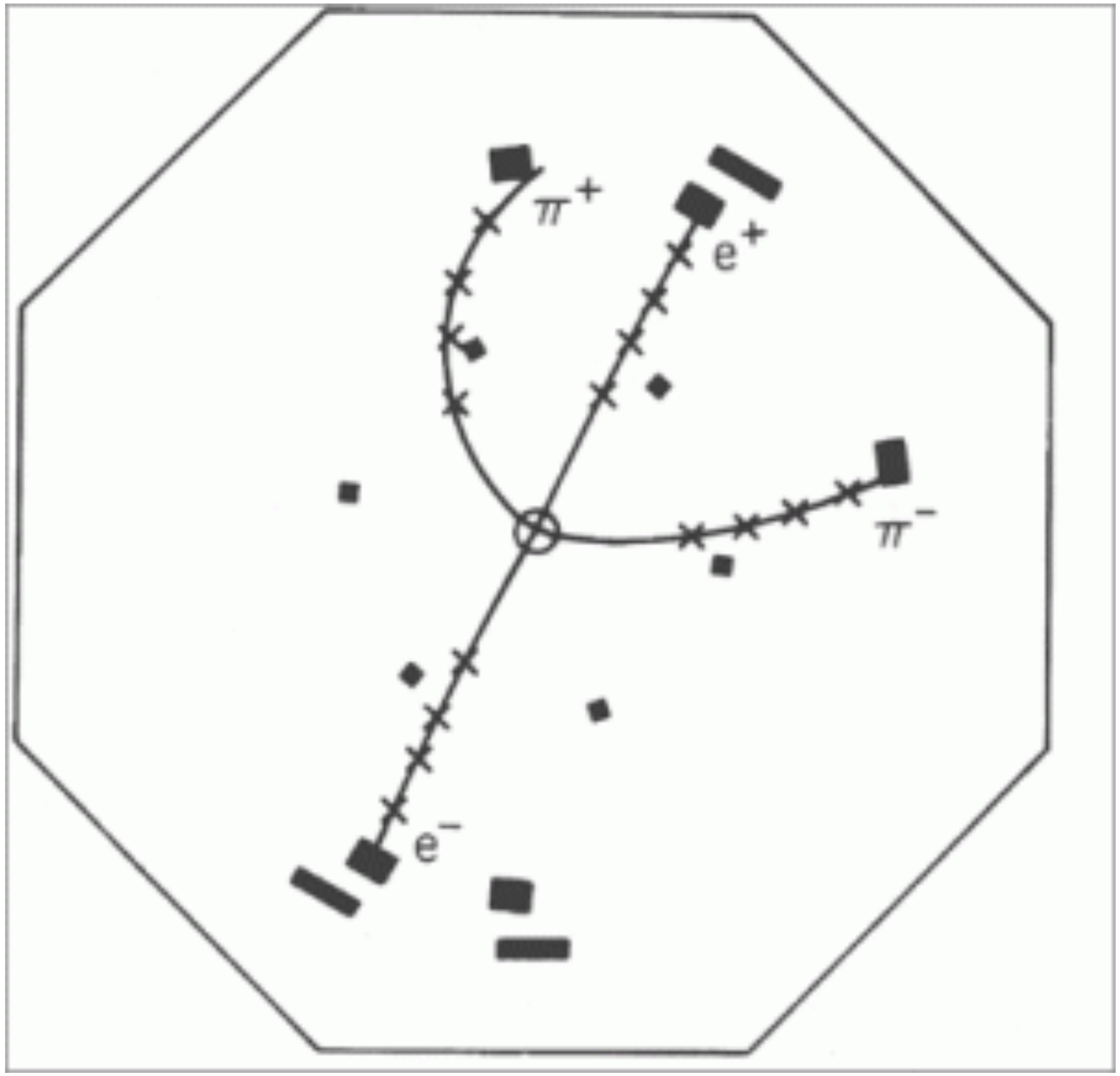


1974

$\Psi' \to \pi\pi\ J/\Psi$

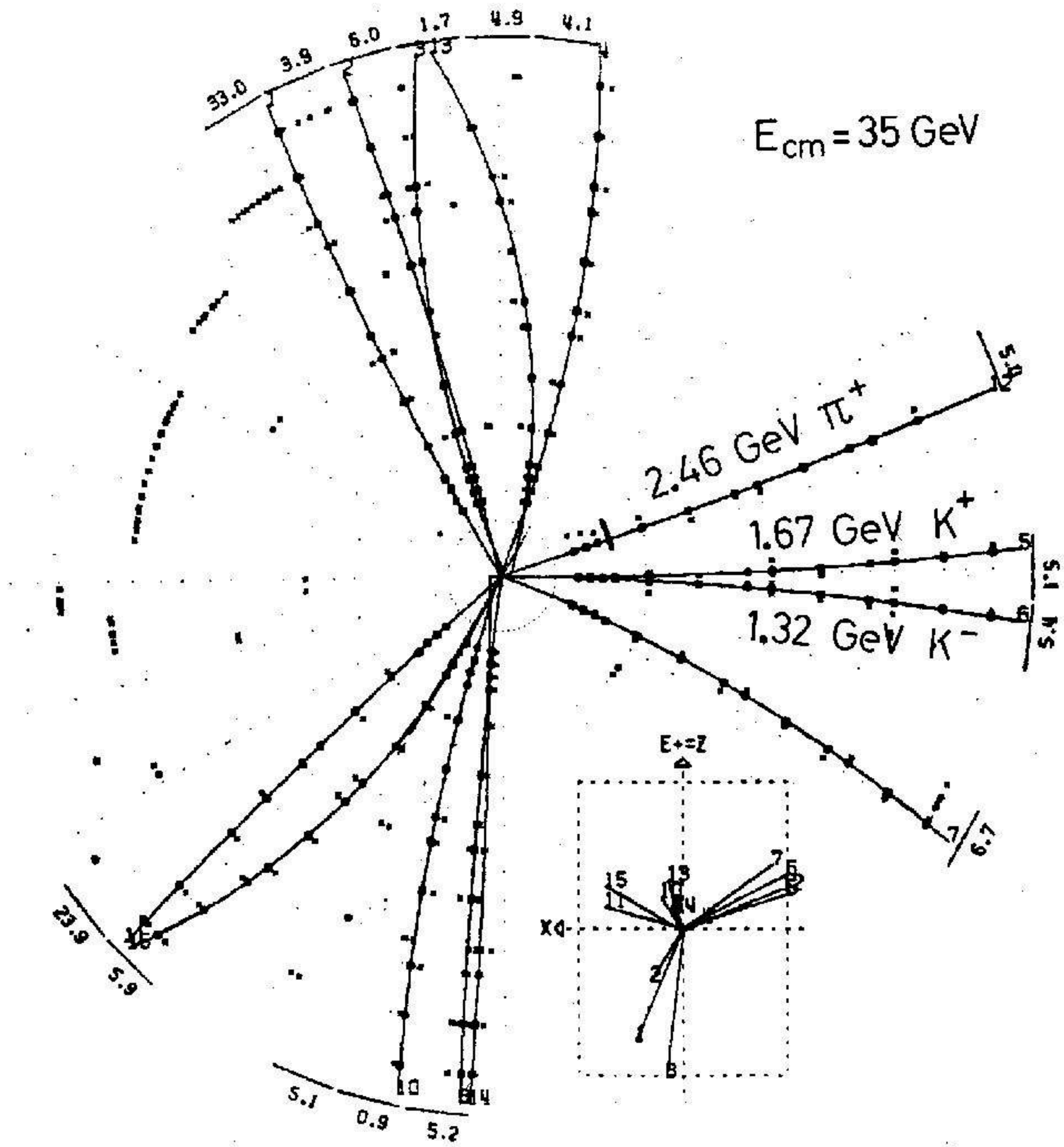
Charm mesons

E_{CM}= 3.695 GeV
e^+e collision
@ SPEAR



Mark 1
Cylindrical
Spark Chamber

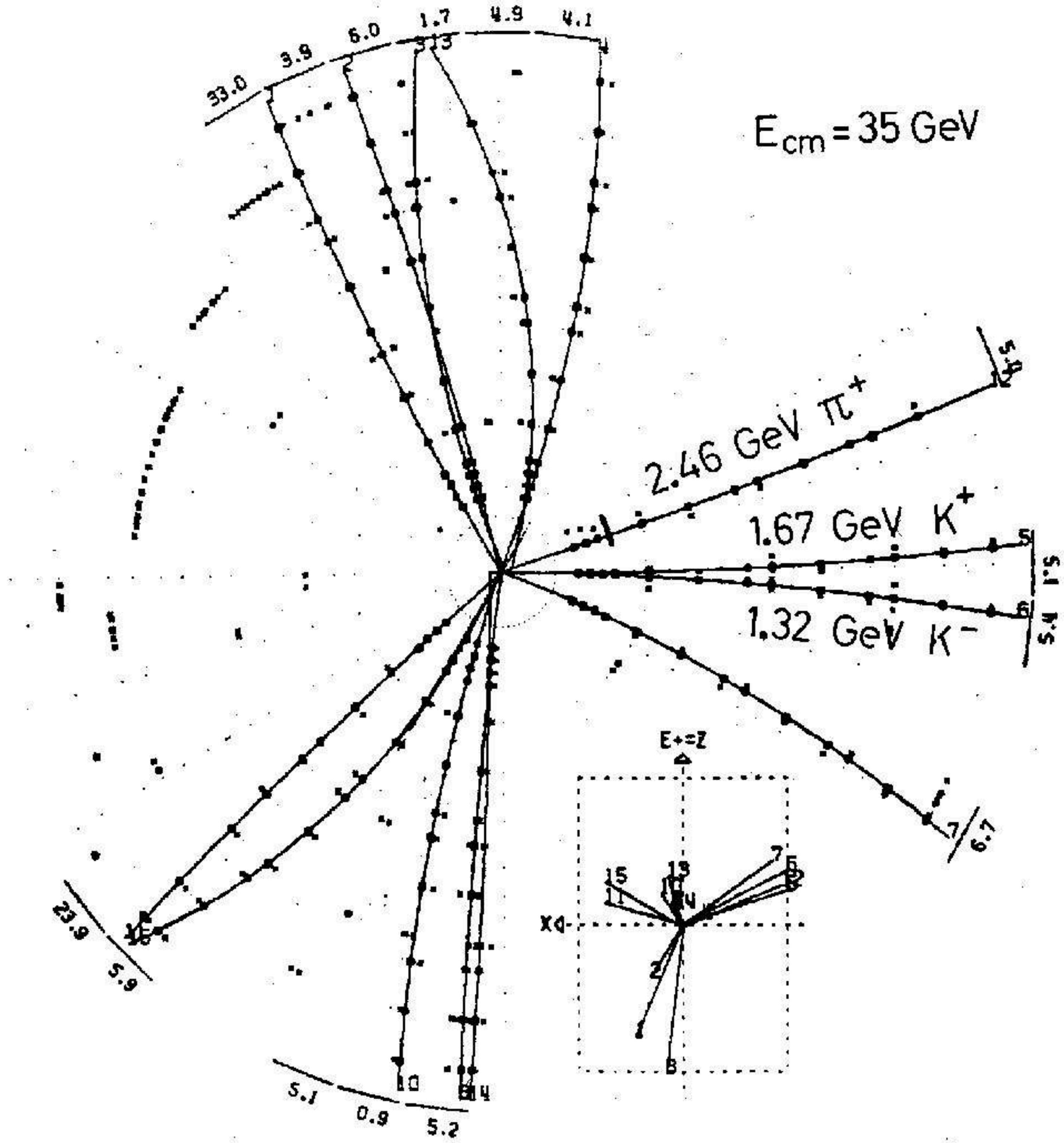
1974



33.0
3.9
6.0
1.7
4.9
4.1
Ecm = 35 GeV
2.46 GeV π+
1.67 GeV K+
1.32 GeV K−
6.7
23.9
5.9
5.1
0.9
5.2
E+=Z
X

1979

Three jet event
quark anti-quark + gluon

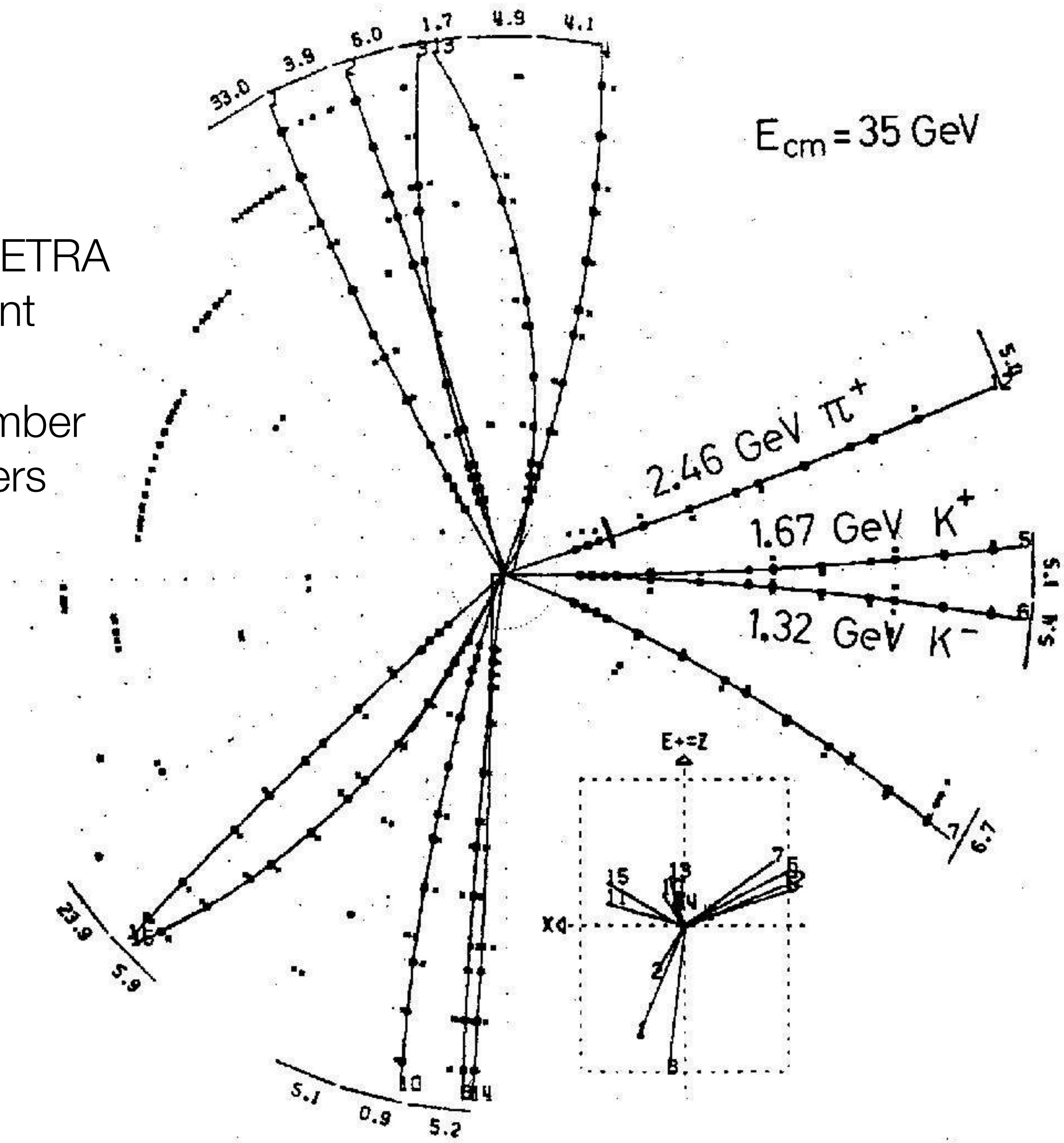


1979

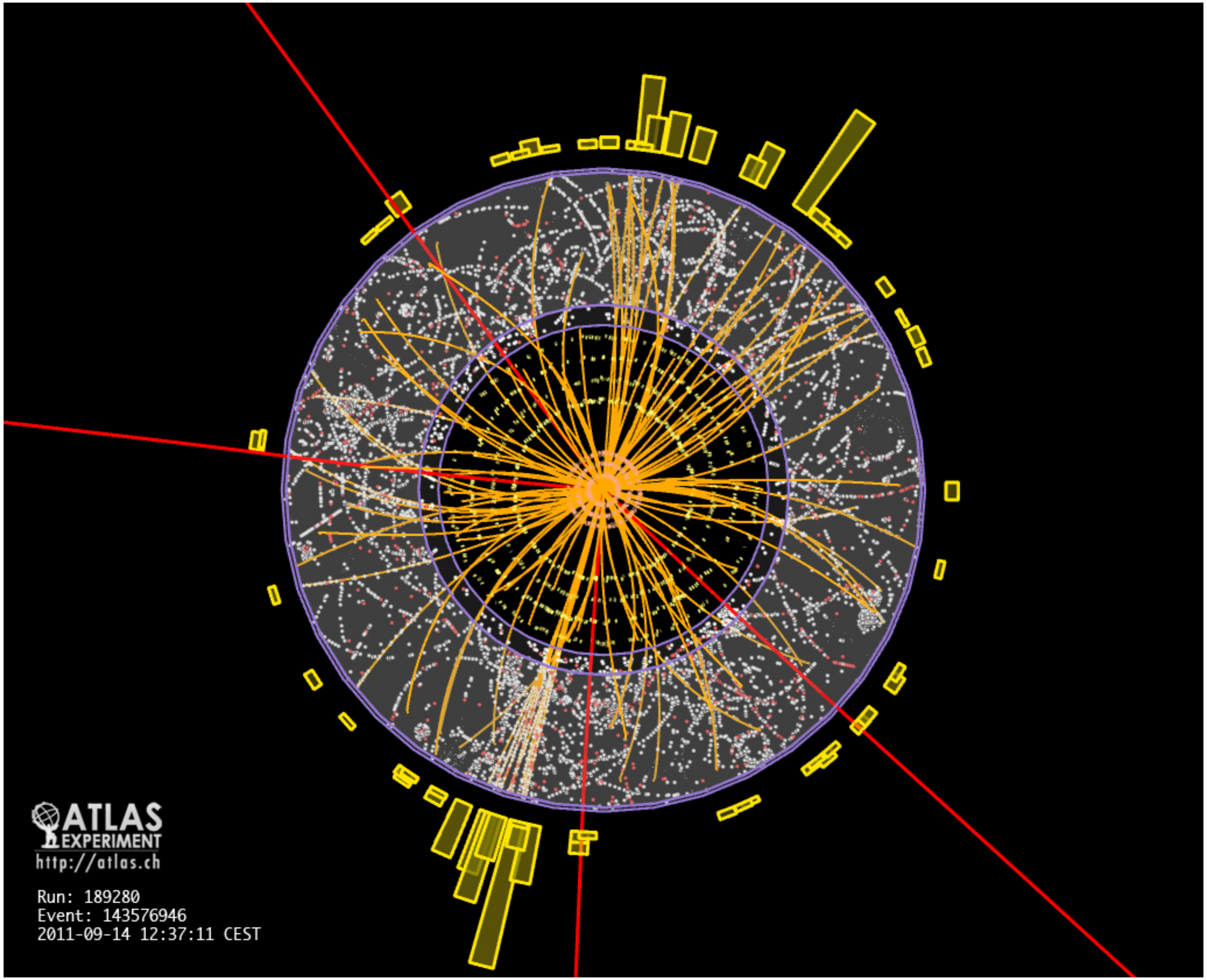
Three jet event
quark anti-quark + gluon

e+ e- annihilation @ PETRA
TASSO experiment

Cylindrical drift chamber
15 concentric layers
2340 cells

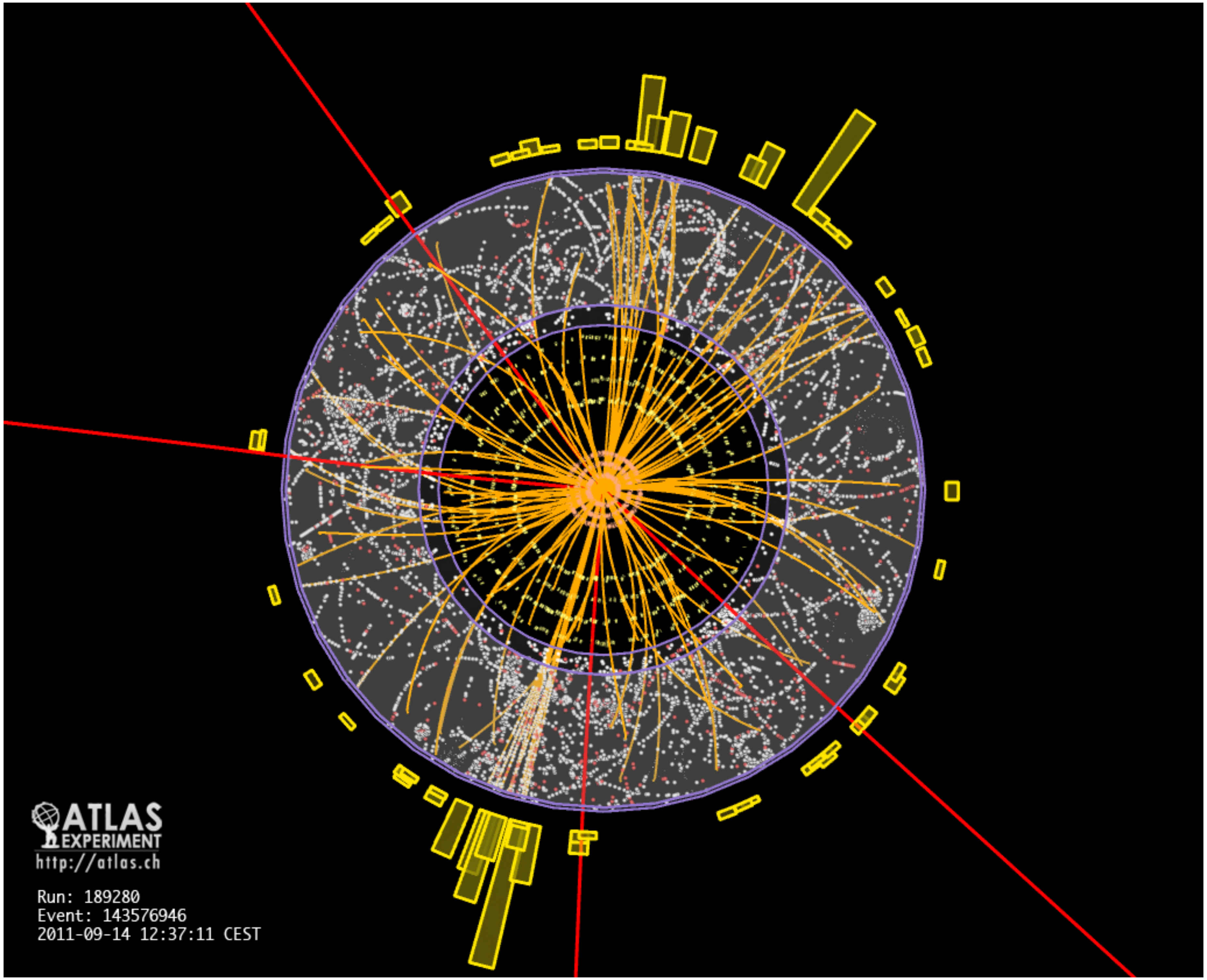


1979


ATLAS
EXPERIMENT
http://atlas.ch
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST

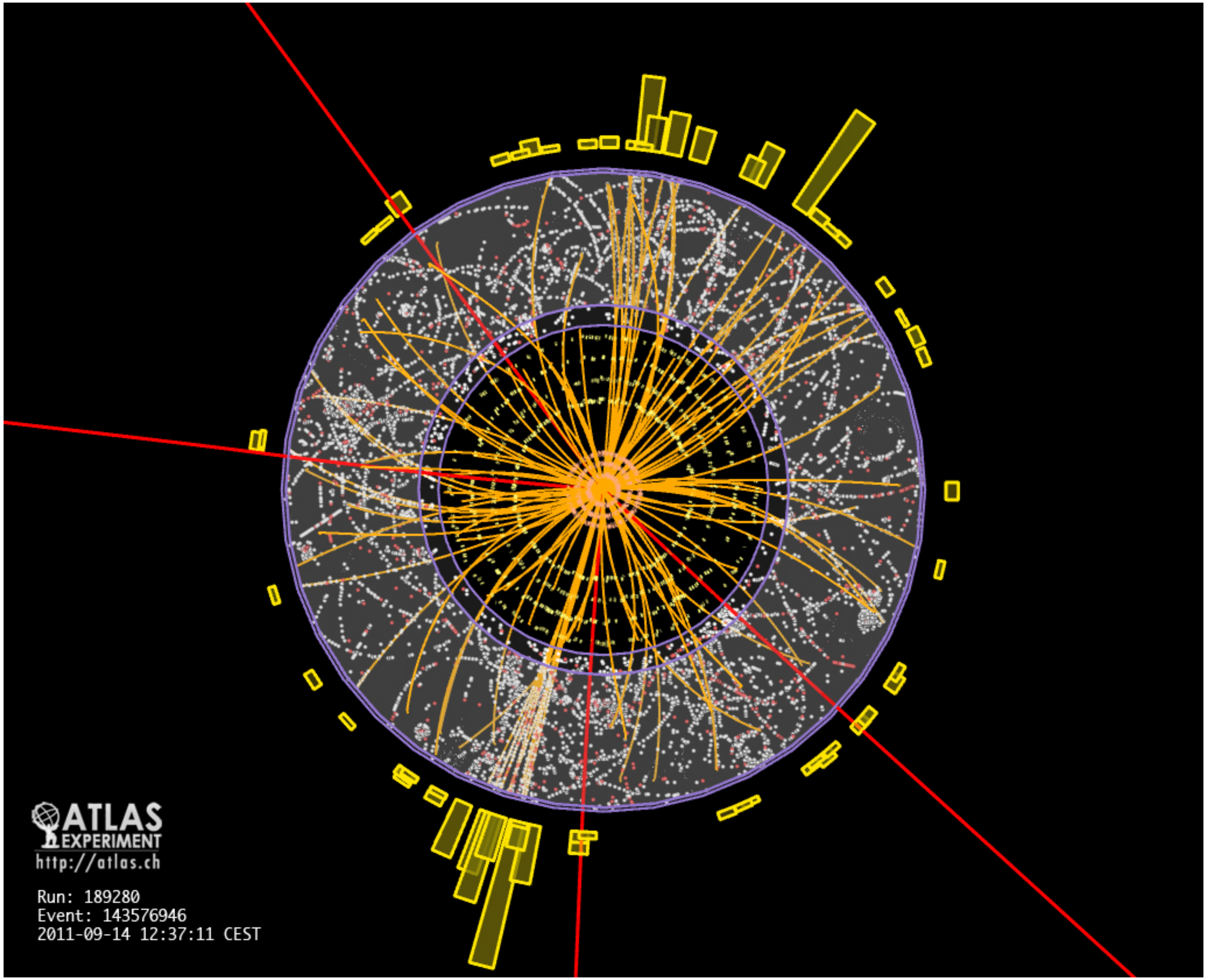
2012

Higgs Boson, h→4μ candidate



2012

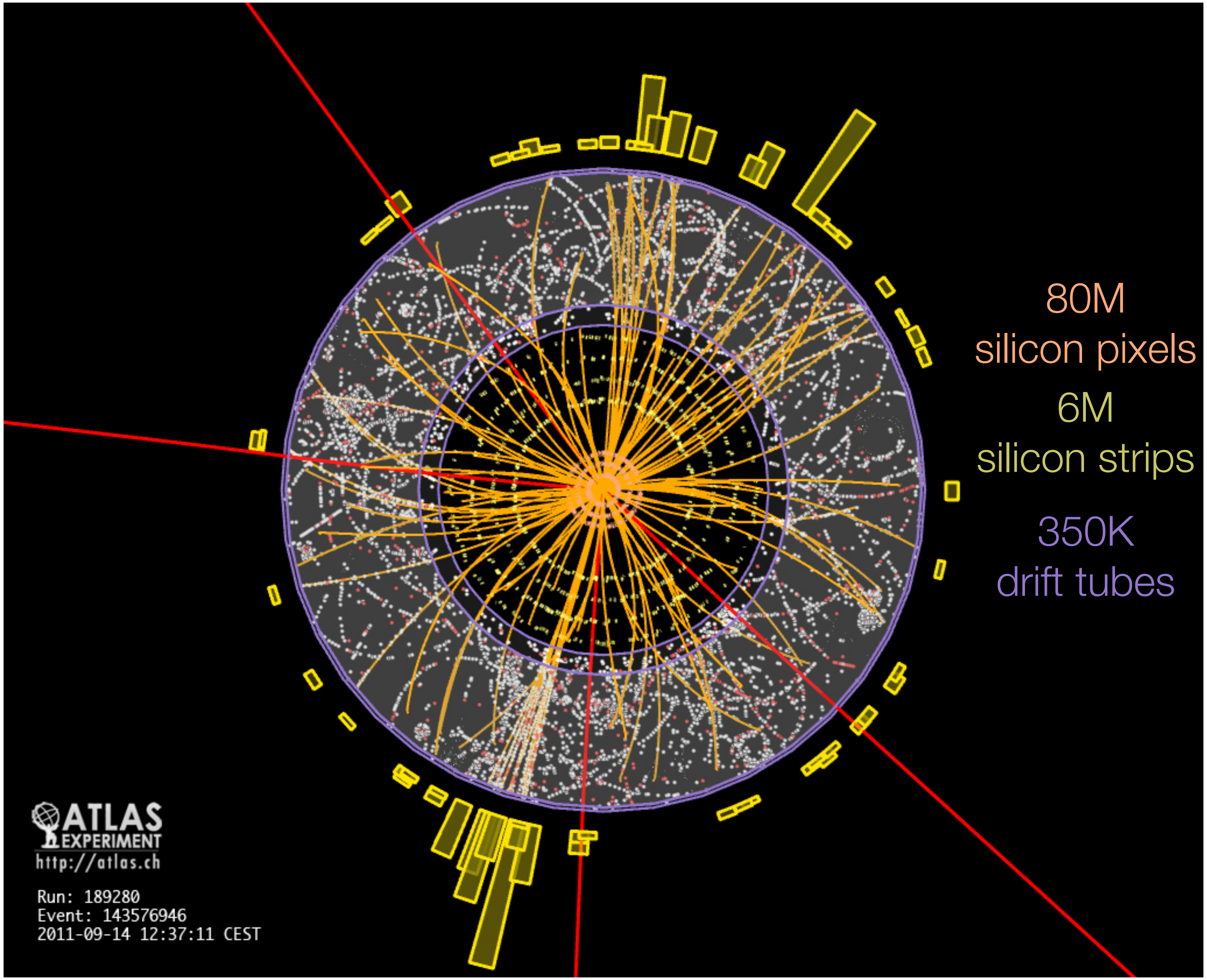
Higgs Boson, h→4μ candidate



$\sqrt{s}$=7 TeV proton-proton collision @ Large Hadron Collider
ATLAS Experiment

2012

Higgs Boson, h→4μ candidate



80M
silicon pixels
6M
silicon strips
350K
drift tubes

$\sqrt{s}$=7 TeV proton-proton collision @ Large Hadron Collider
ATLAS Experiment

2012

Themes to keep in mind

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Particle trajectories (tracks) = key to discovery

Directly detect new charged particles or their decay products

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Directly detect new charged particles or their decay products

Different sources of new particles

Observing matter around us → produced in high energy collisions

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Particle trajectories (tracks) = key to discovery

Directly detect new charged particles or their decay products

Different sources of new particles

Observing matter around us → produced in high energy collisions

Increasing demands on detectors

Need to disentangle more particles, faster

This talk

Particle Physics at the Large Hadron Collider (LHC)

Why physicists use colliders

What questions we’re trying to answer

How the ATLAS/CMS experiments work

How to do an example analysis

Useful references

CERN Summer Student Lecture Series [2019]

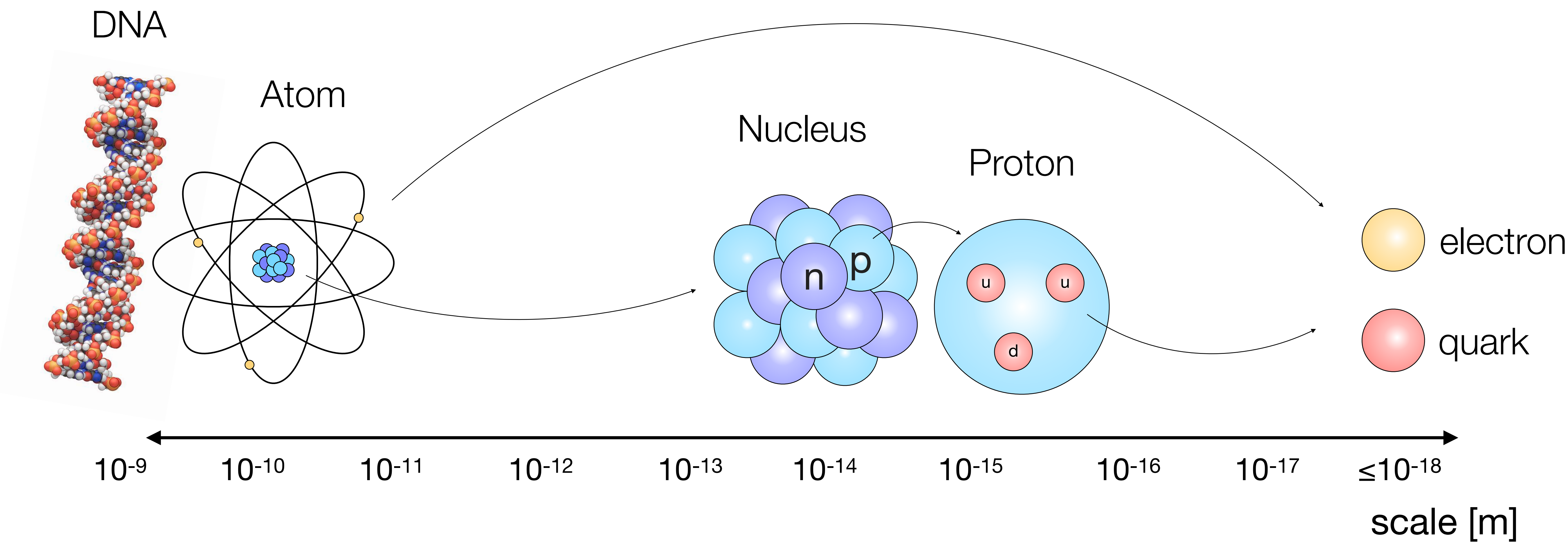
At the Leading Edge Chapter 1 [ask for pdf]

Lecture Proceedings [1,2]

Why colliders

Particle physics

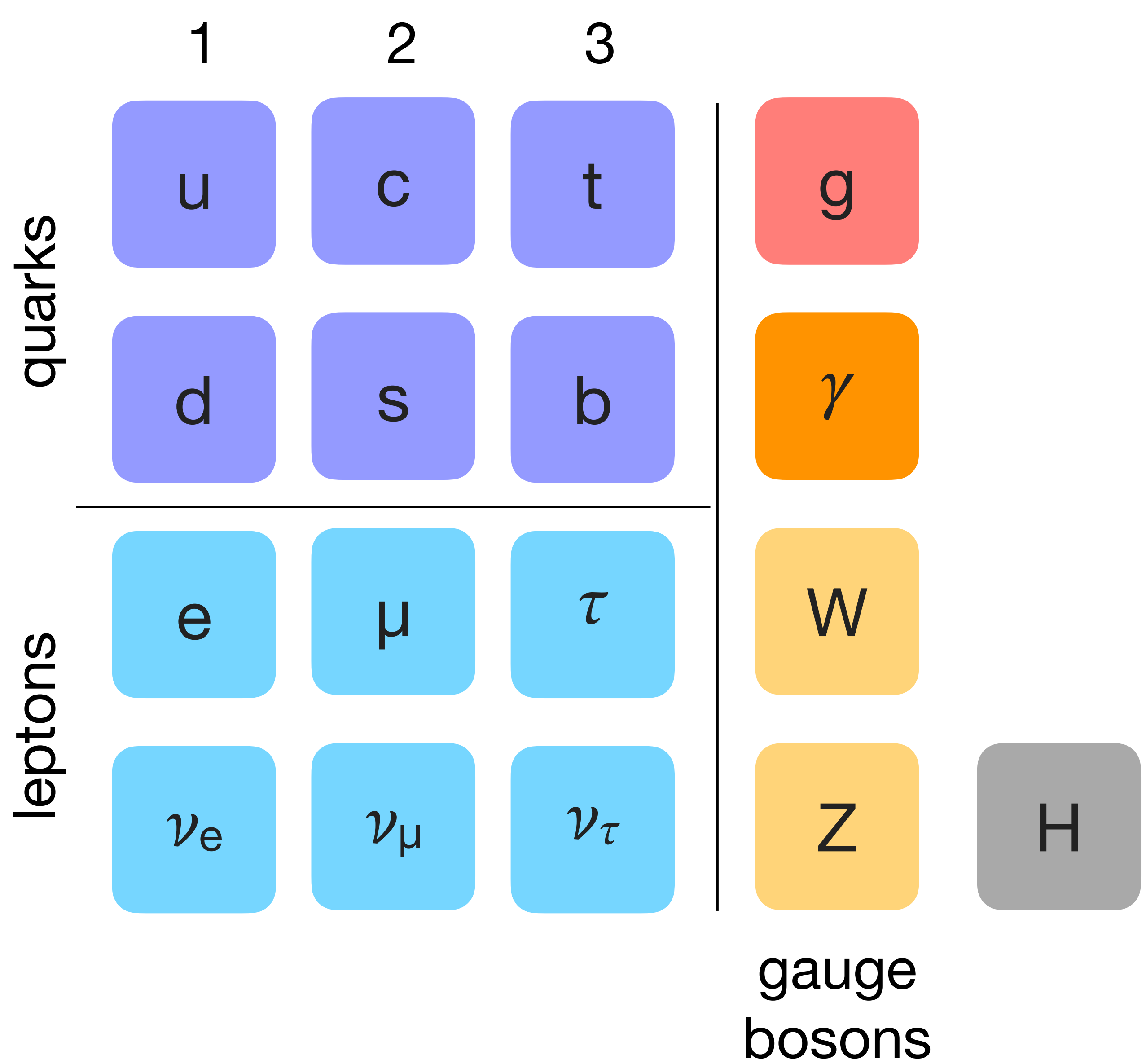
Interested in the smallest, irreducible, pieces of matter…
fundamental particles



And the forces that govern these particles

Best known description

The Standard Model



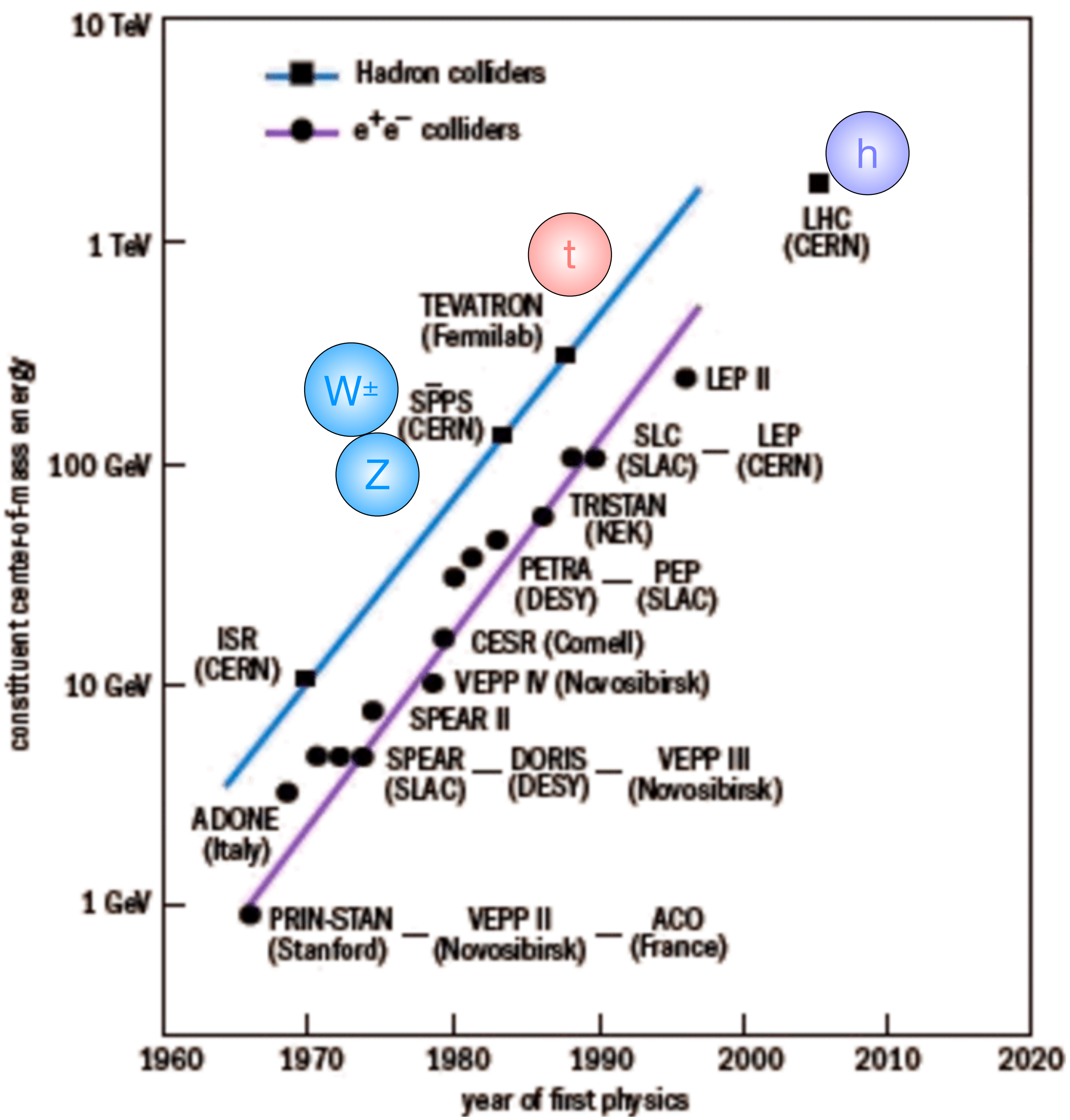
17 fundamental particles

12 matter particles

4 force carriers

1 scalar boson

High Energy Colliders



Powerful tool used to establish and test the Standard Model

1985: W and Z @SppS

1995: Top Quark @Tevatron

2012: Higgs Boson @LHC

How: controlled experiments that unambiguously probe

smaller scales: E=hc/λ

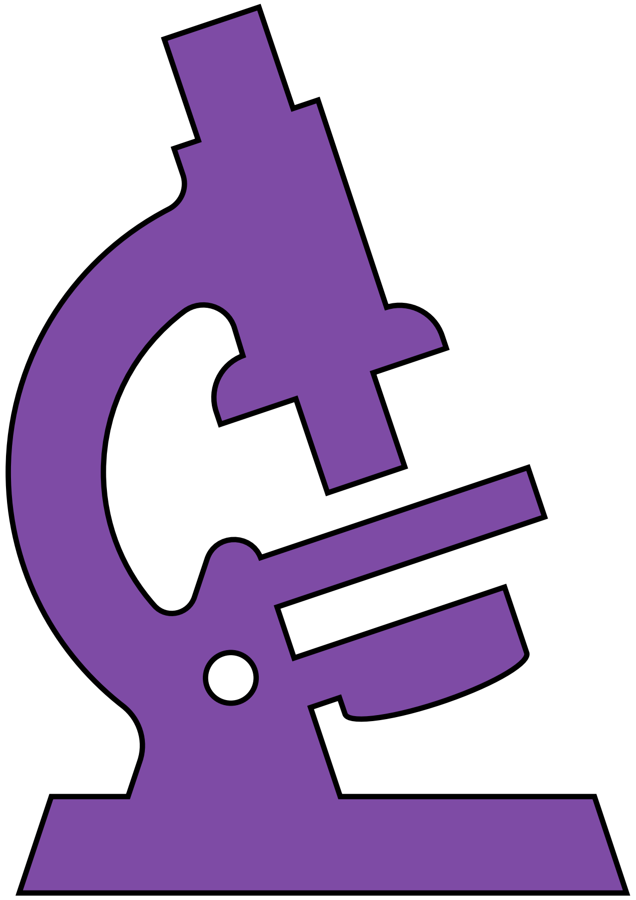
higher masses: $E=mc^2$

Colliders as a Microscope

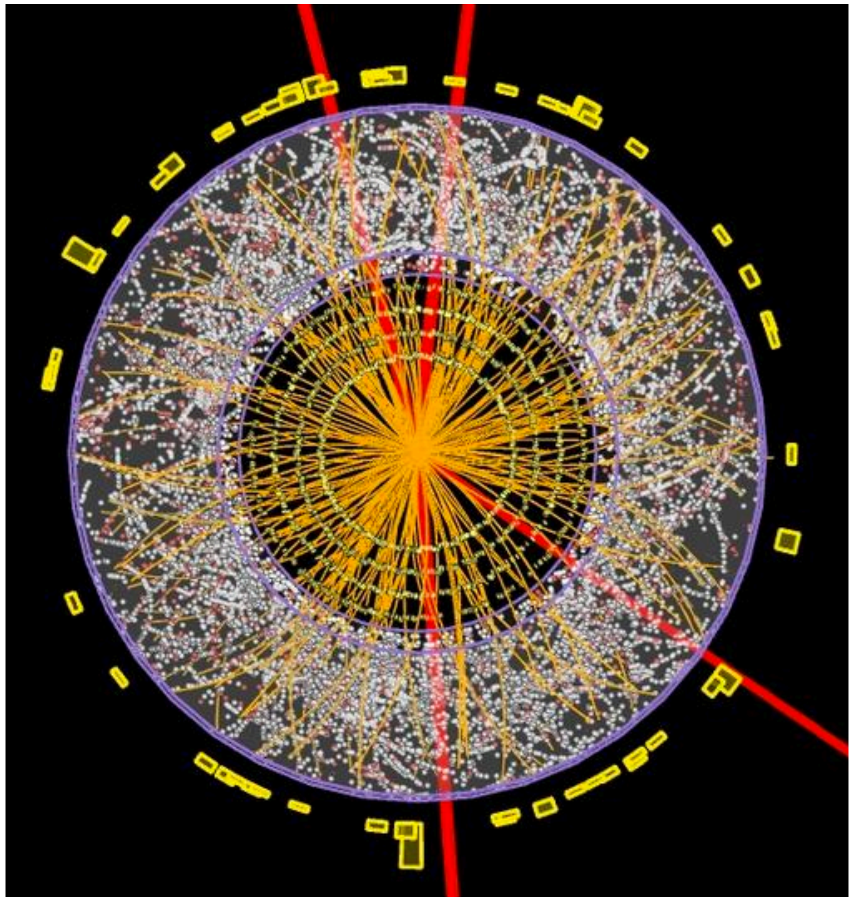
Quantum Mechanics tells us particles ~ waves

A particle with energy **E** has wavelength **λ**=**hc**/**E**

- **c** = the speed of light
- **h** = Planck intrinsic angular momentum (spin)



Visible light ~ 5×10^{-7} m



LHC collision ~ 10^{-19} m

A sense of scale

eV = energy an electron gains over 1 volt

Proton mass is 10^{-24} grams
E = 10^9 electron-volt (GeV)
$\lambda = 10^{-15}$ m

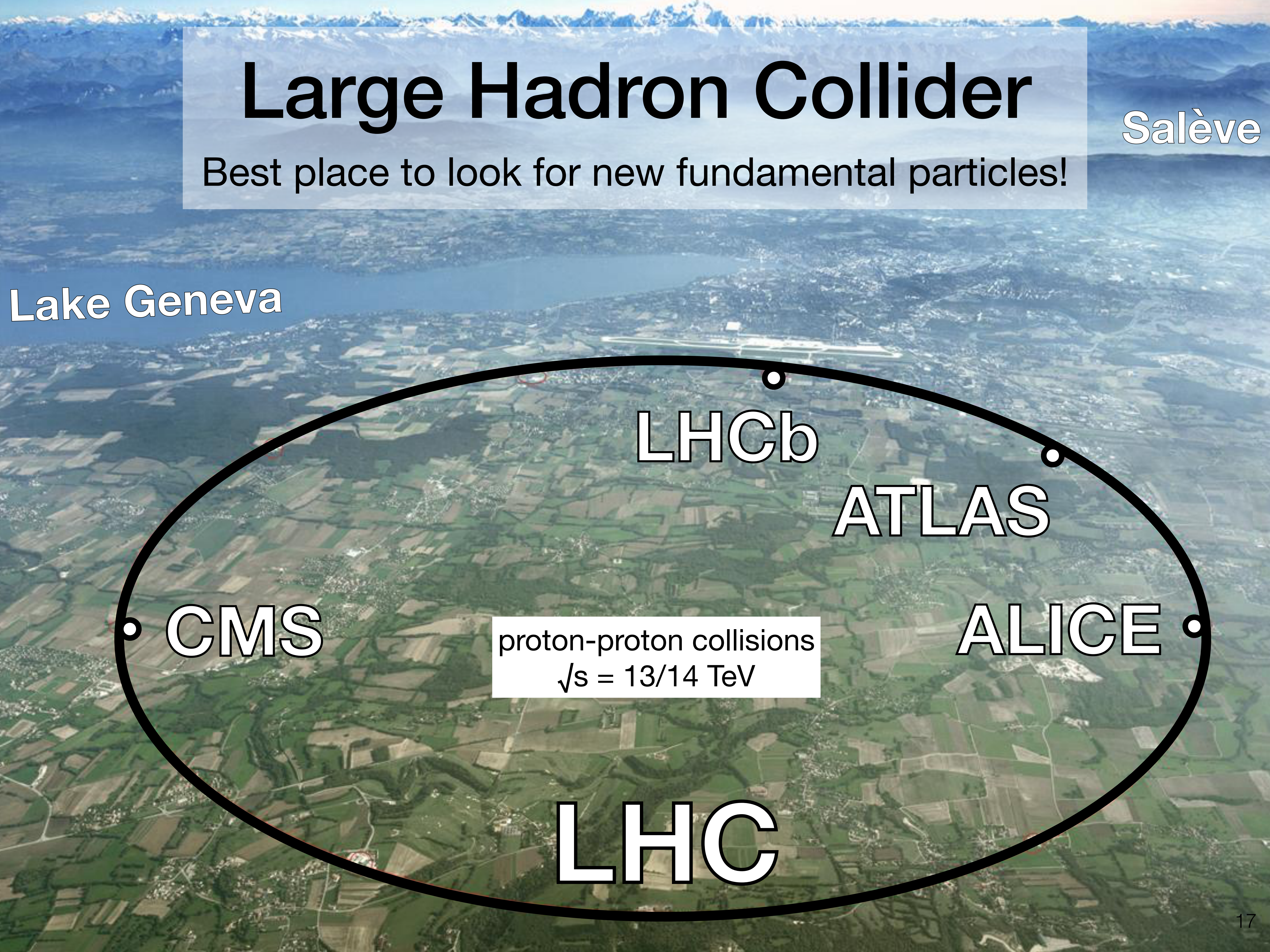
To accelerate an electron to 1 GeV…
need a stack of AA batteries that goes more than halfway around the world

The Large Hadron Collider accelerates protons to 6500 GeV!

Requires powerful accelerating gradients
and magnetic fields!

Large Hadron Collider

Best place to look for new fundamental particles!



Large Hadron Collider

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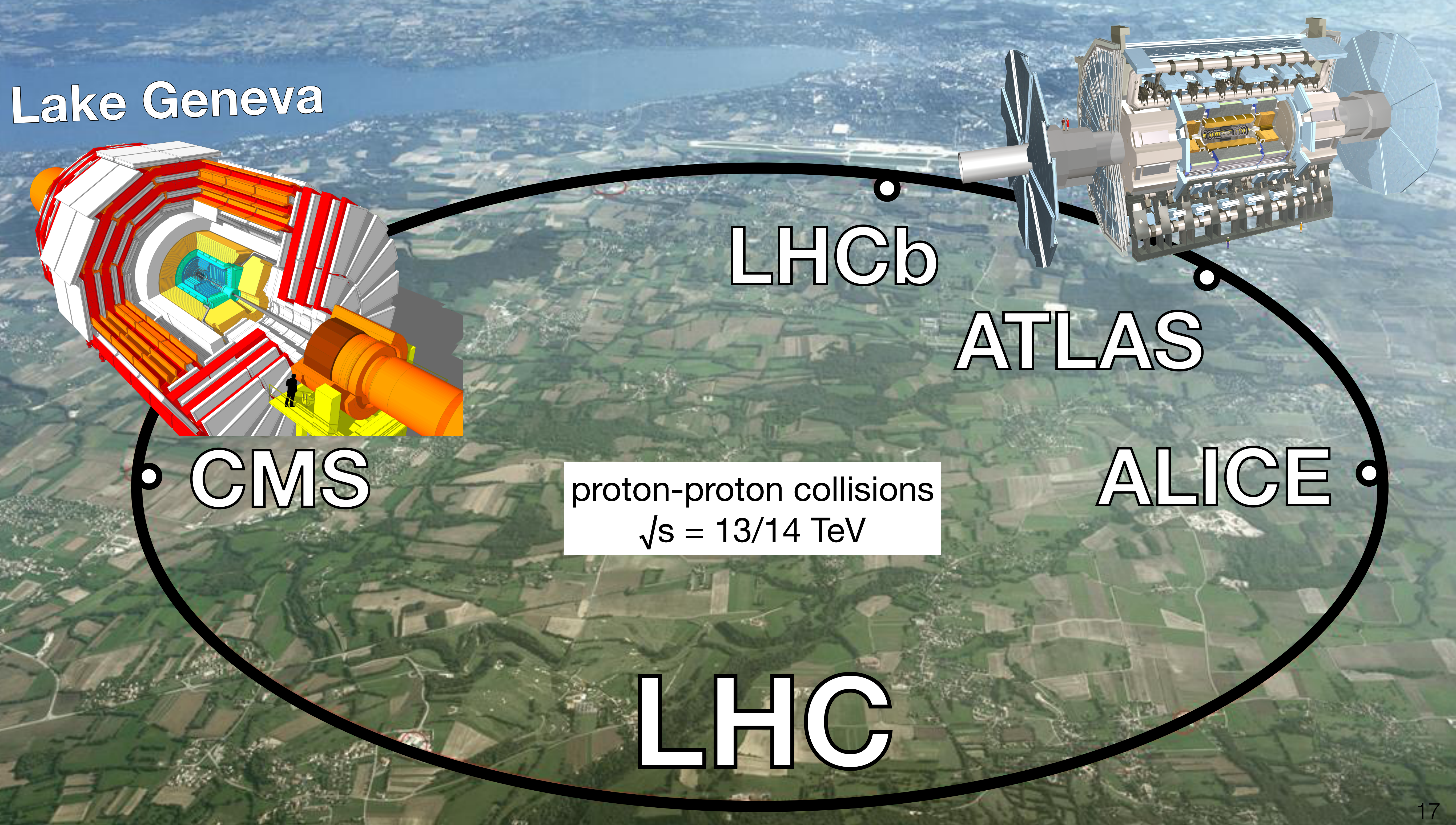
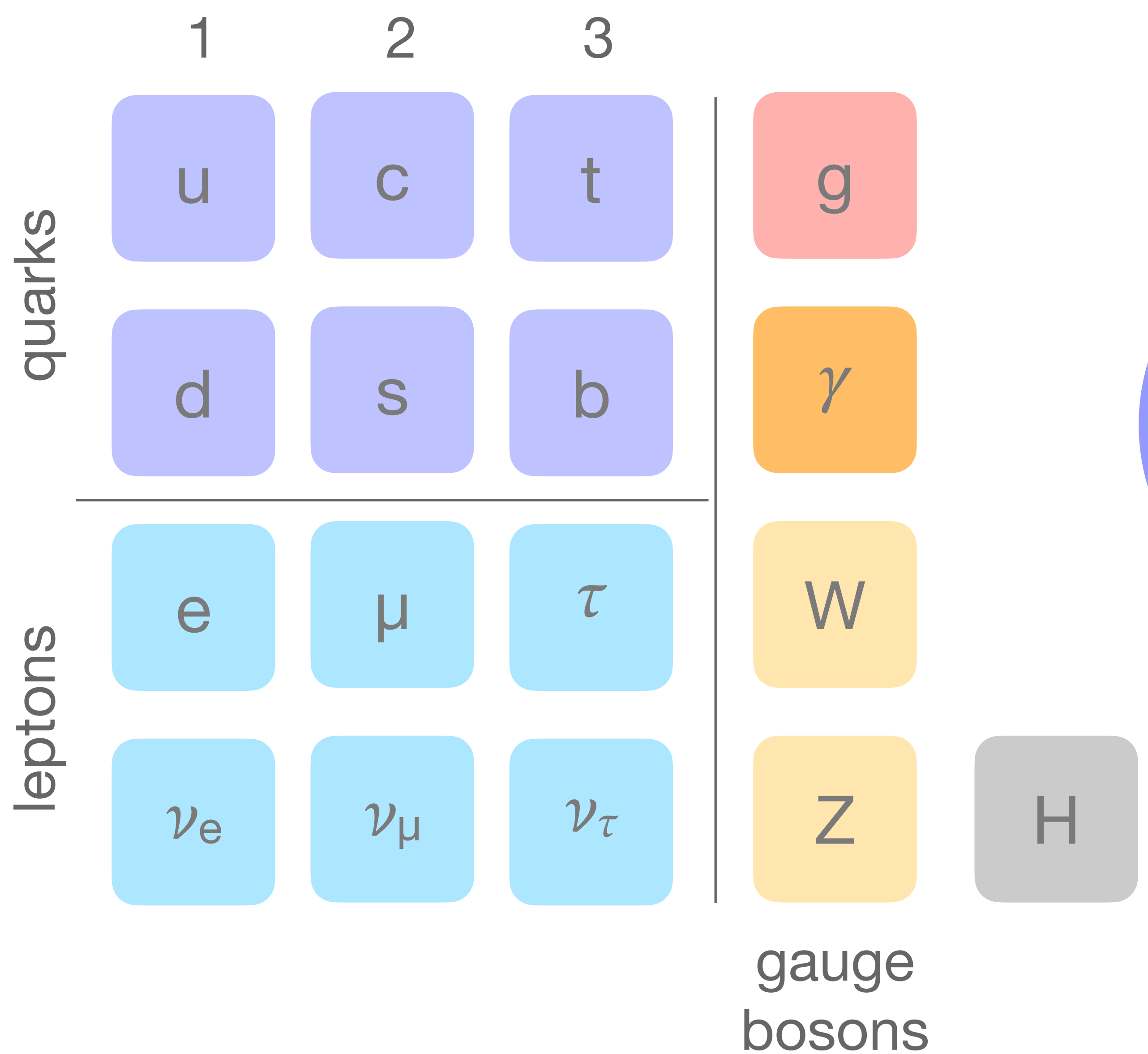
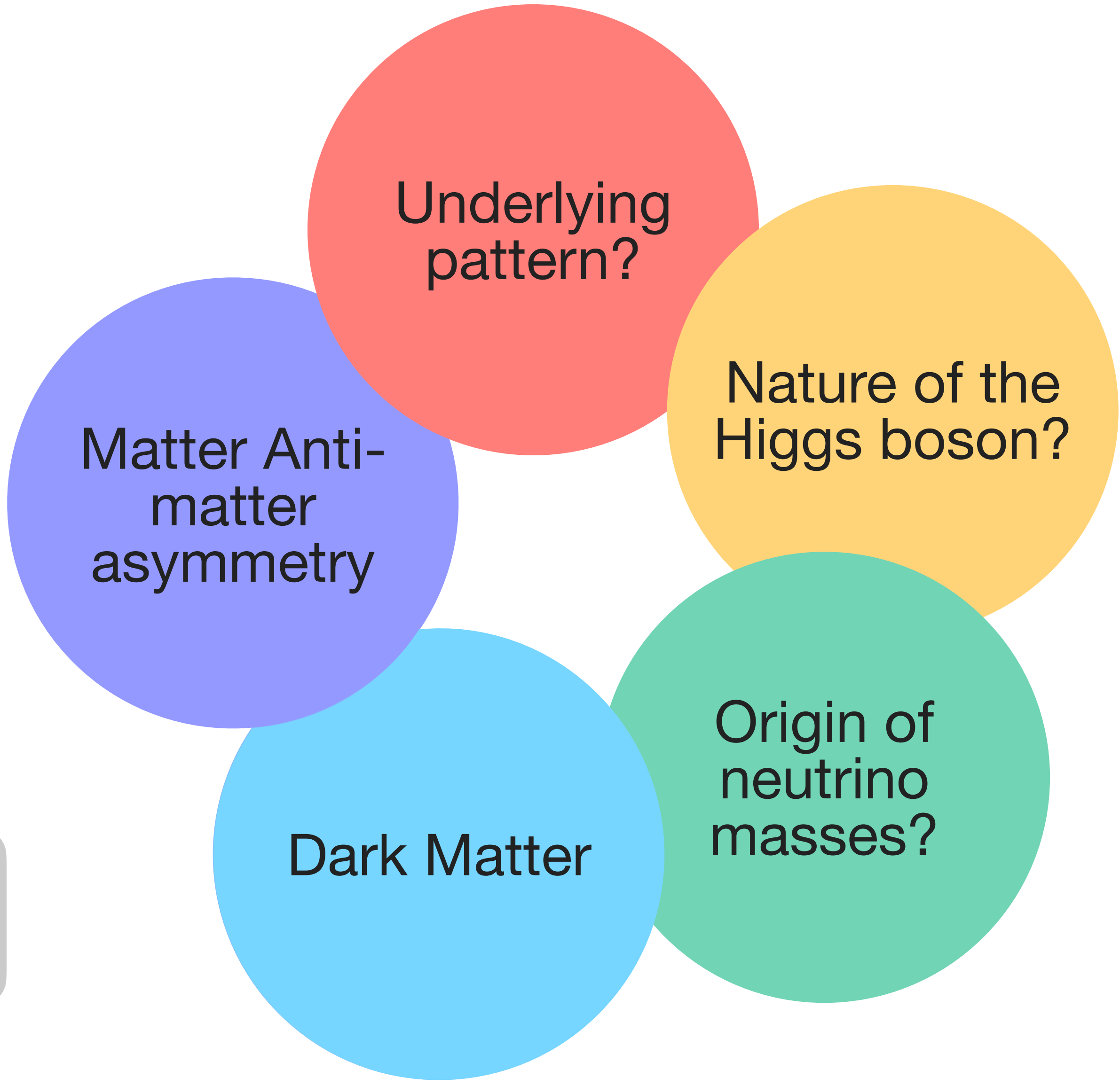


What we’re looking for

Many Open Questions

1. Several pieces we don't understand
2. Not a complete picture of universe





Let's take the Higgs as an example

The strong force

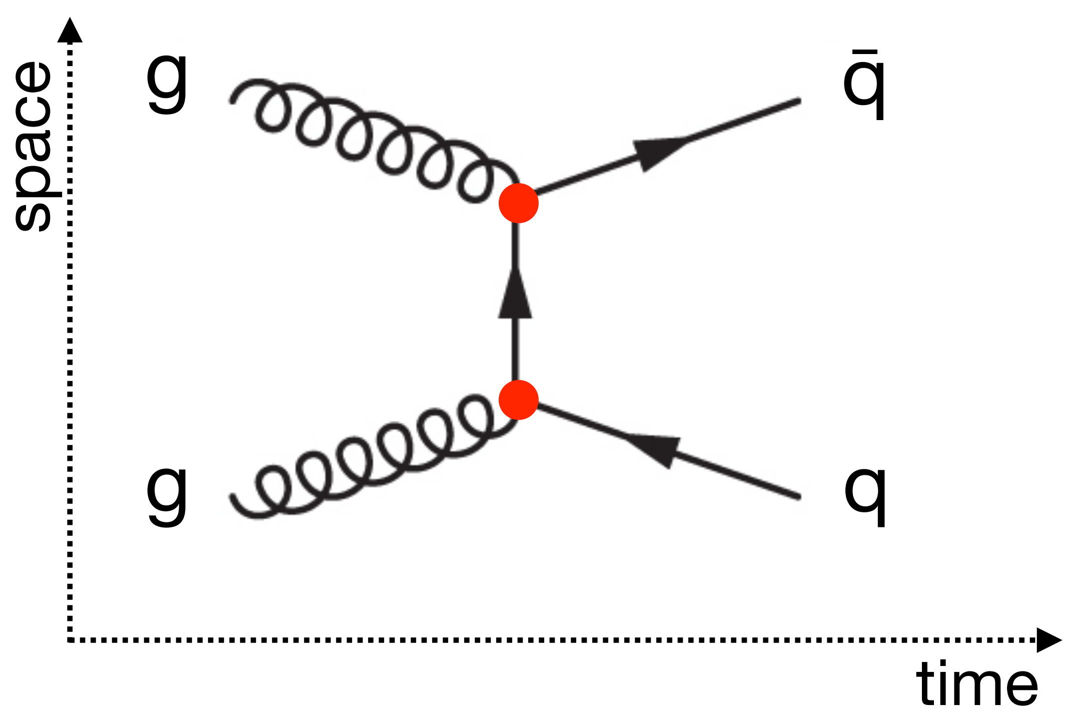
Strong force: interaction structure +
a single coupling

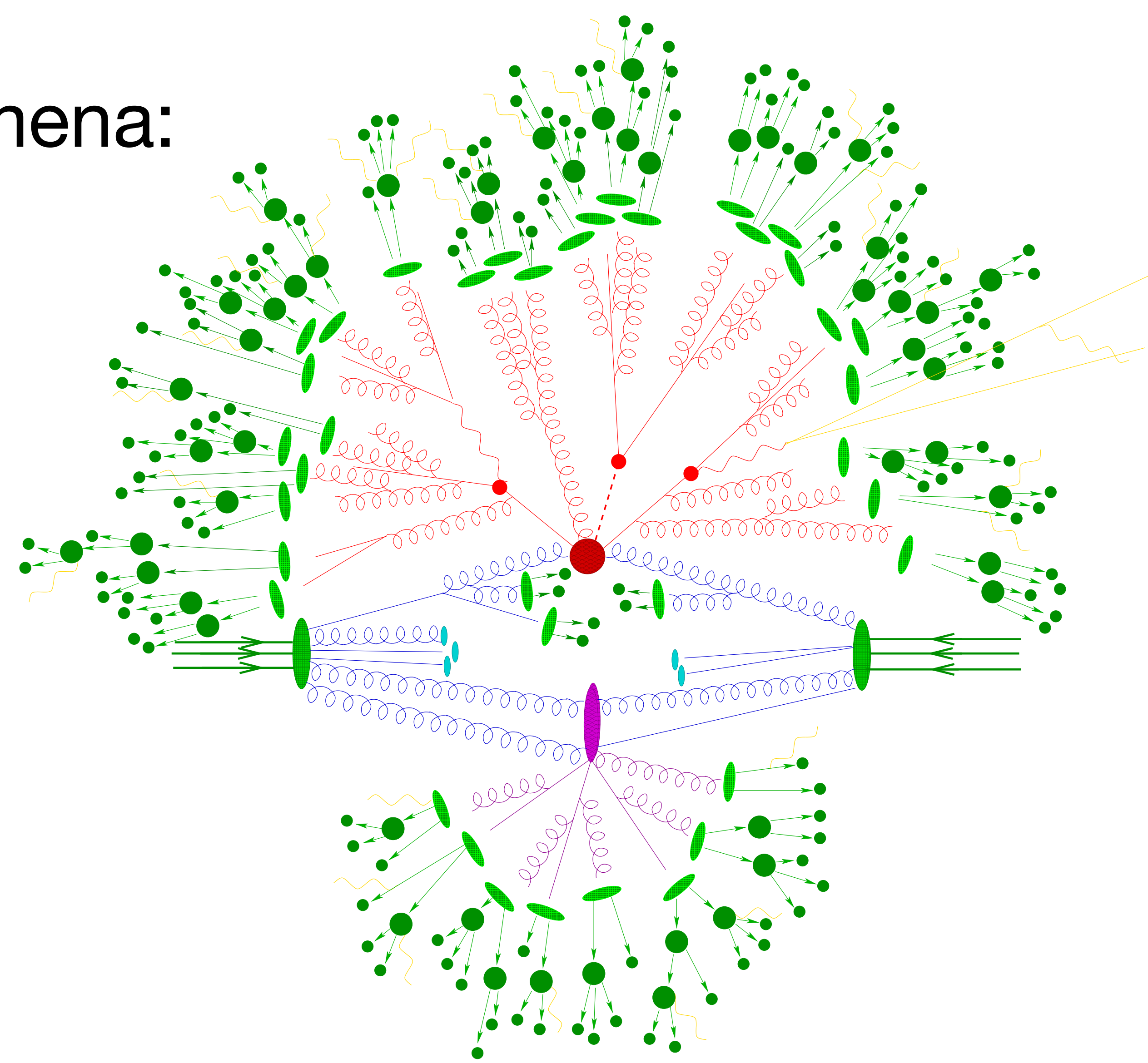
Predicts VAST range of phenomena:

proton, neutron masses

'excited' states

gluon force carrier



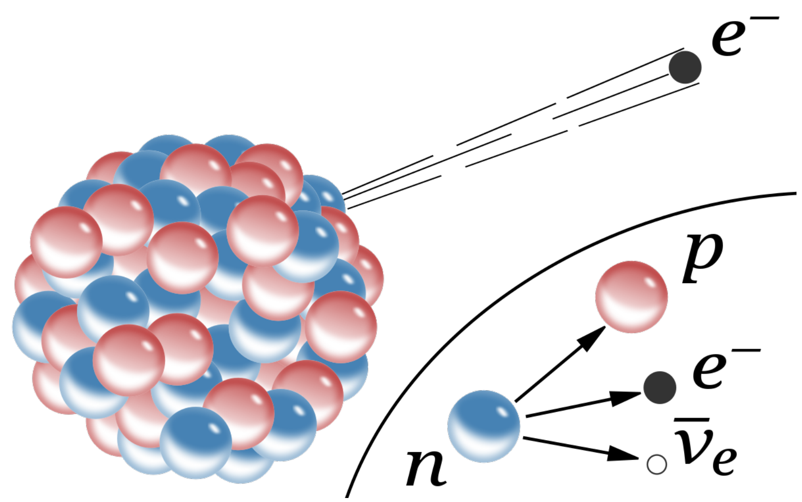


LHC collision

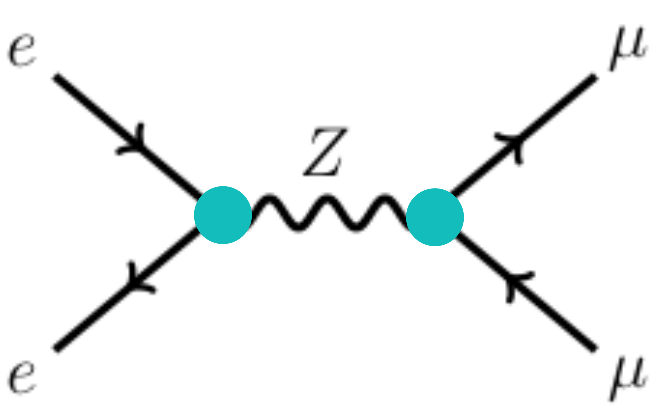
The weak force

Similarly, weak interactions explained by a single coupling!

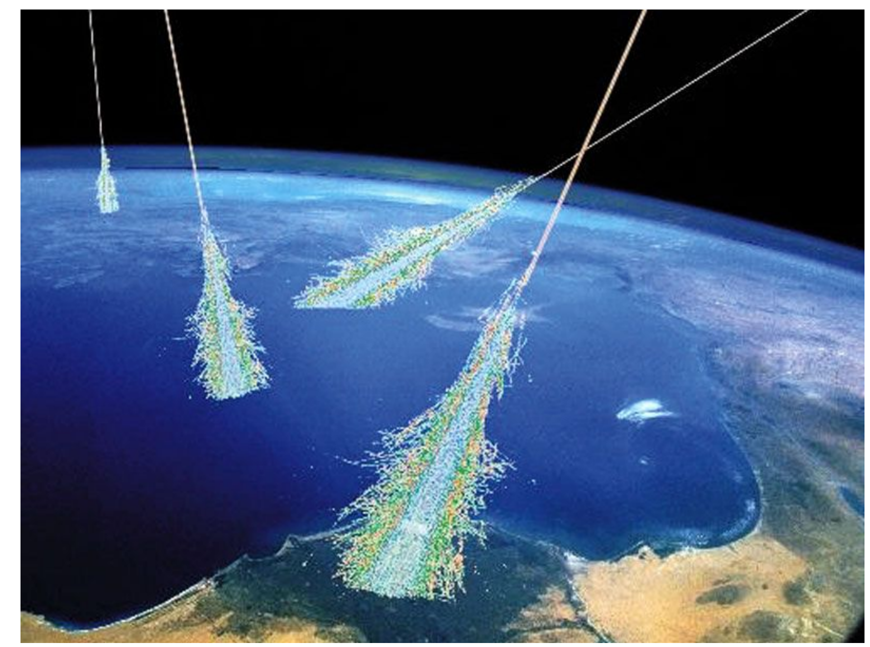
Radioactive decay

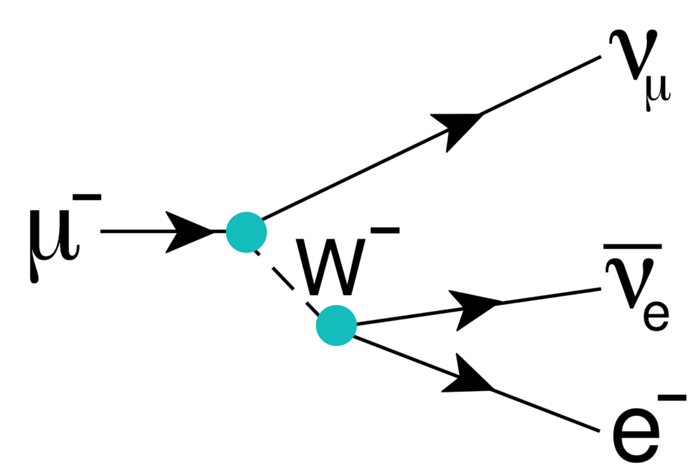


Z boson production at particle colliders



Muon decay in cosmic rays

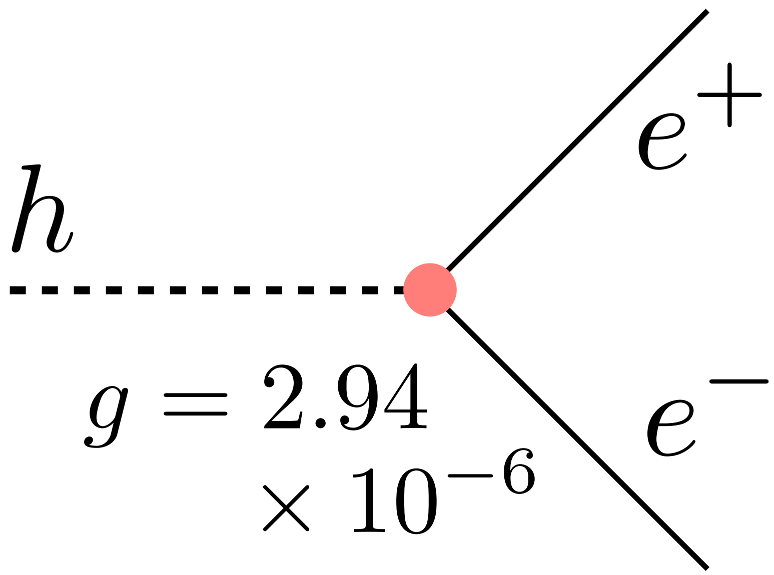




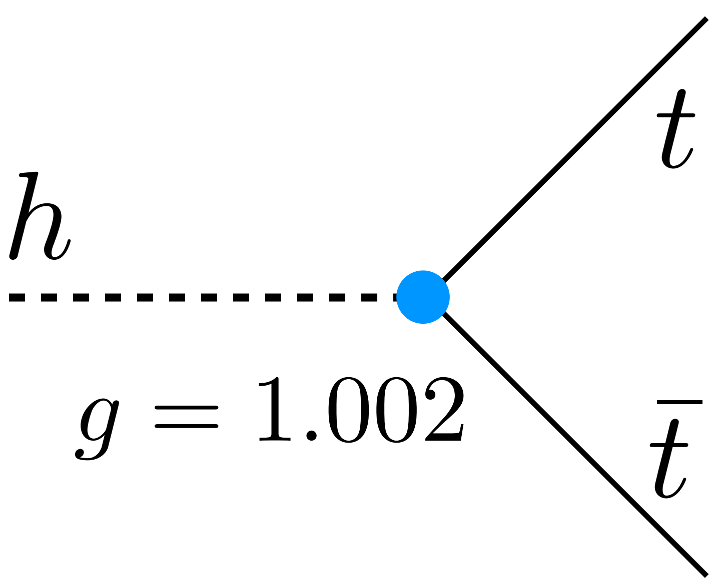
The Higgs is VERY different

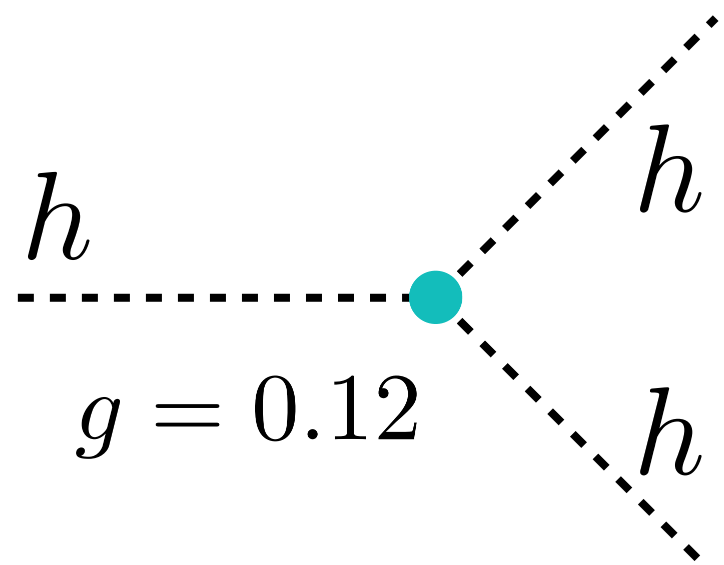
The Higgs field: couples to ALL massive particles.

Electron mass originates from a Higgs-electron coupling



Each particle has a different mass, which means a DIFFERENT coupling for EVERY SINGLE PARTICLE!





Why so many new couplings?

Measure them!

Beyond the Higgs?

Many questions revolve around the Higgs
— newest & least-understood part of the Standard Model

Why are there so many different masses and couplings,
and with such different sizes?

Is there only one Higgs boson?

Is the Higgs a fundamental particle or a composite, like the proton?

Is the Higgs also responsible for neutrino masses?

Does the Higgs respect the known symmetries of nature?

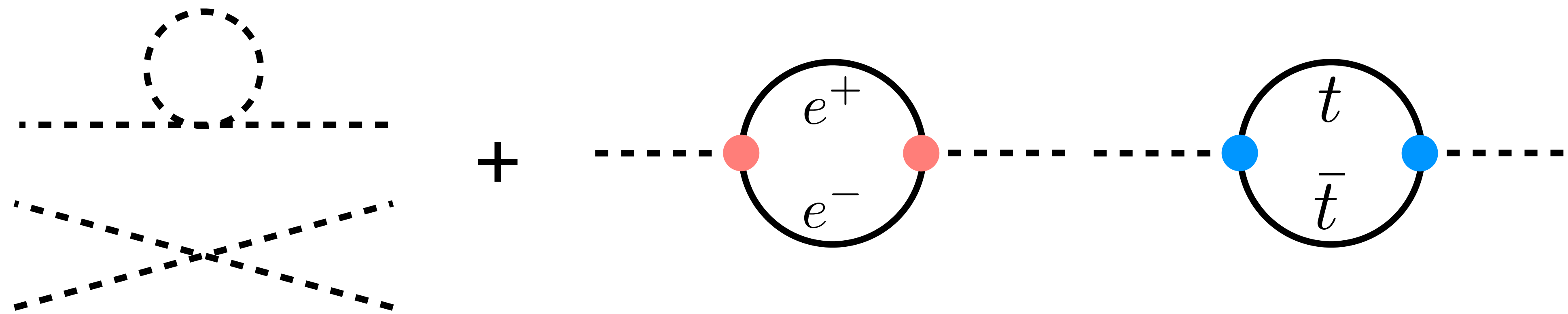
How does dark matter fit into this picture??

Why is the higgs mass 125 GeV?

Example: the hierarchy puzzle

Try to calculate Higgs mass. Find two contributions:

Higgs mass =

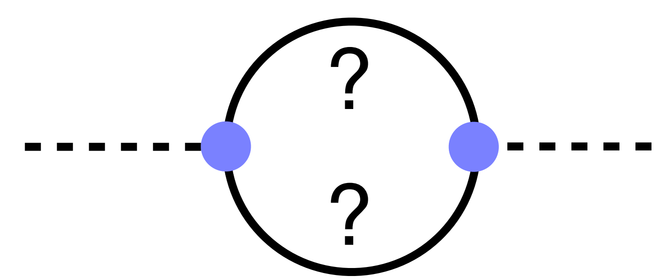


measured!125 GeV

a few terms ~ 100 GeV

contributions proportional from each massive particle

undiscovered particles too!



E.g. a 10^{16} GeV graviton wants to "pull up" the Higgs mass to 10^{16} GeV, but we observe it as 125 GeV. Why??

A new symmetry?

Suggests a new *mechanism* to keeps Higgs light

Supersymmetry is one possible answer

Idea: every SM particle gets a copy, with equal and opposite contribution to Higgs mass

Where are the super-partners?

How can we find them?

Expect their masses to be just above the Higgs

How the LHC can help

Highest energy particle collider in the world!

The only place in the world where we can

Study the Higgs boson

Search for Supersymmetric Particles

We can also

Look for other new particles (dark matter)

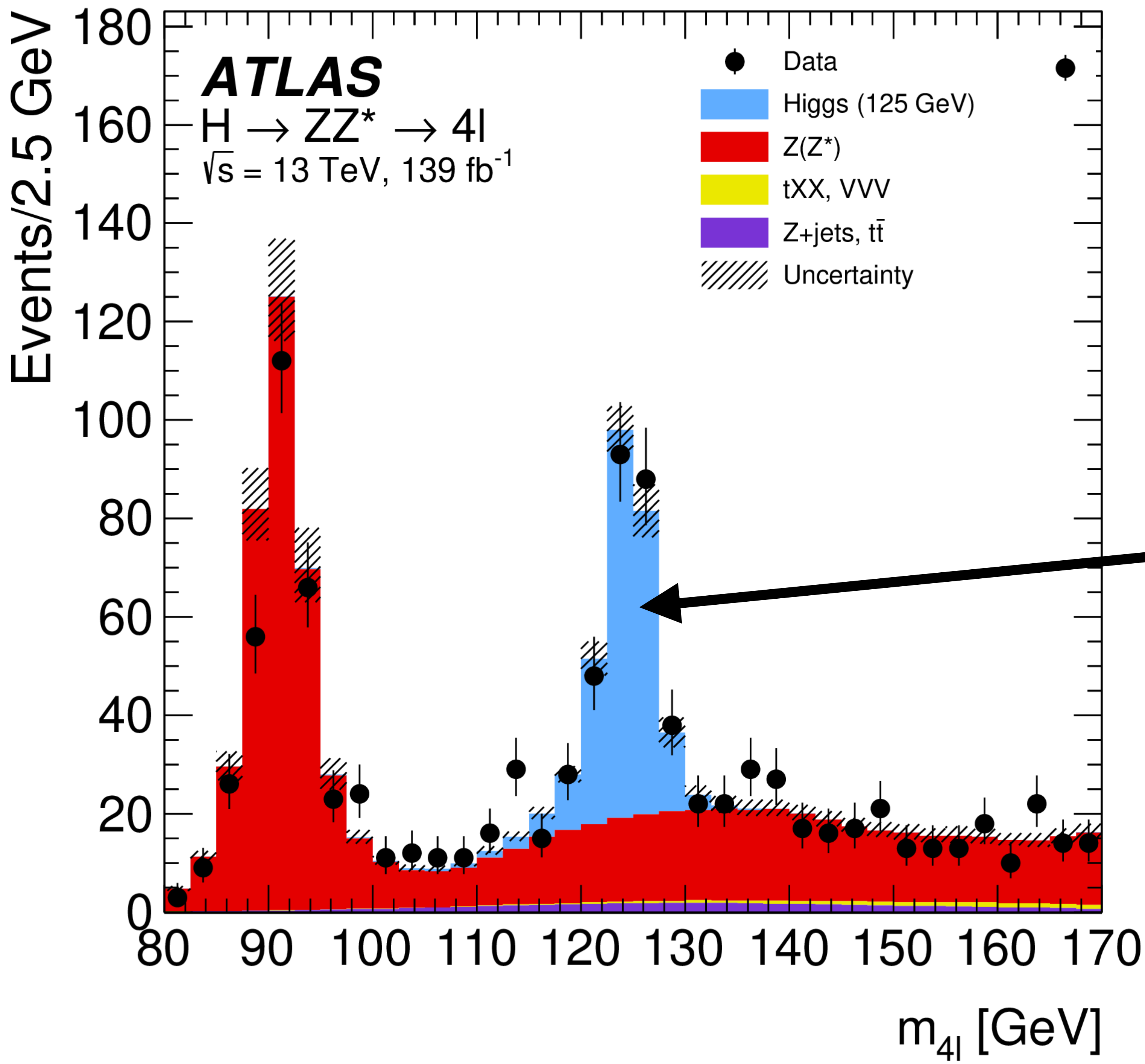
Study the Standard Model with unprecedented precision

How to do Physics at the LHC

The Easy Way…

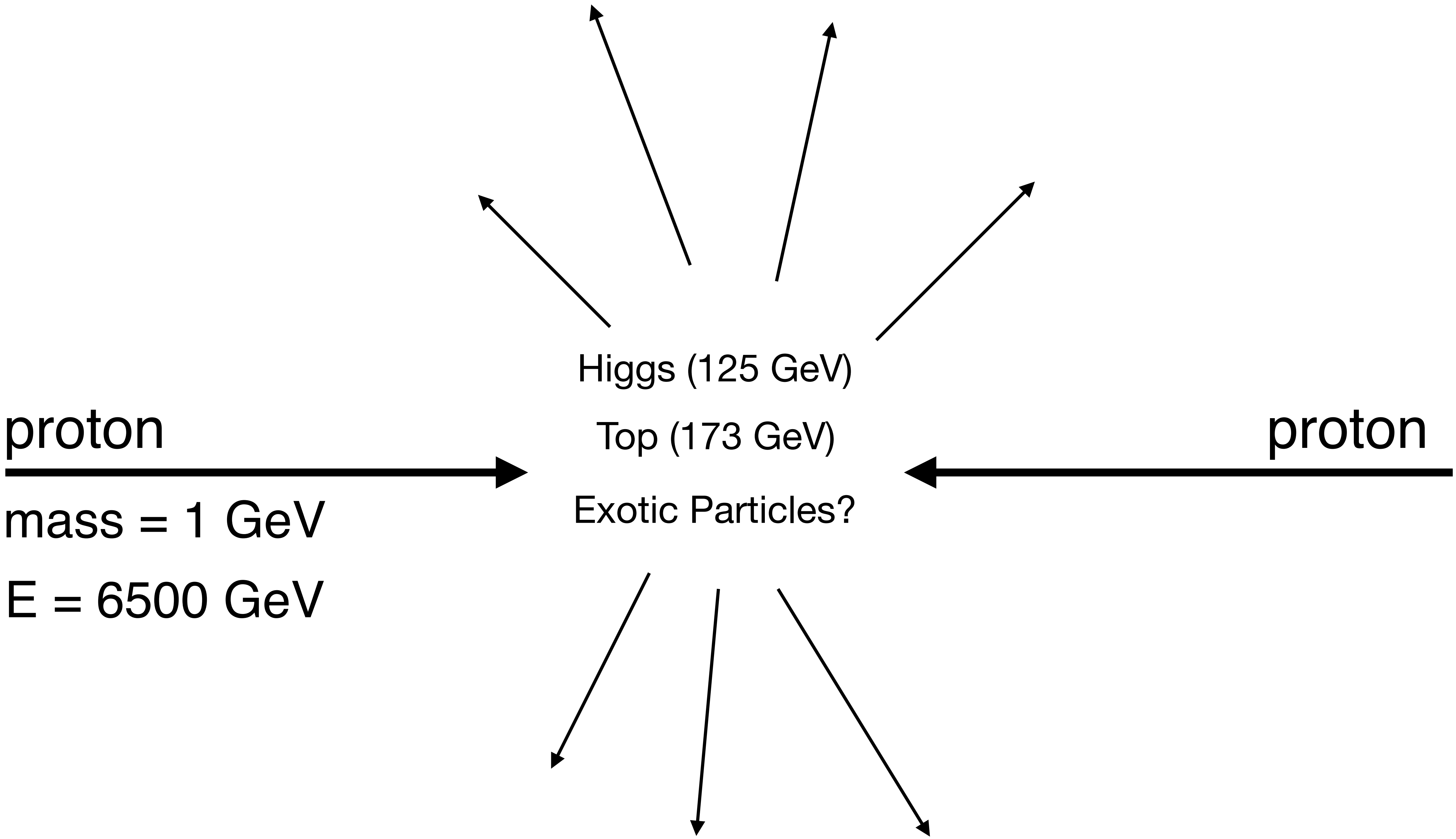
Example: How to find a Higgs

arXiv:2004.03969



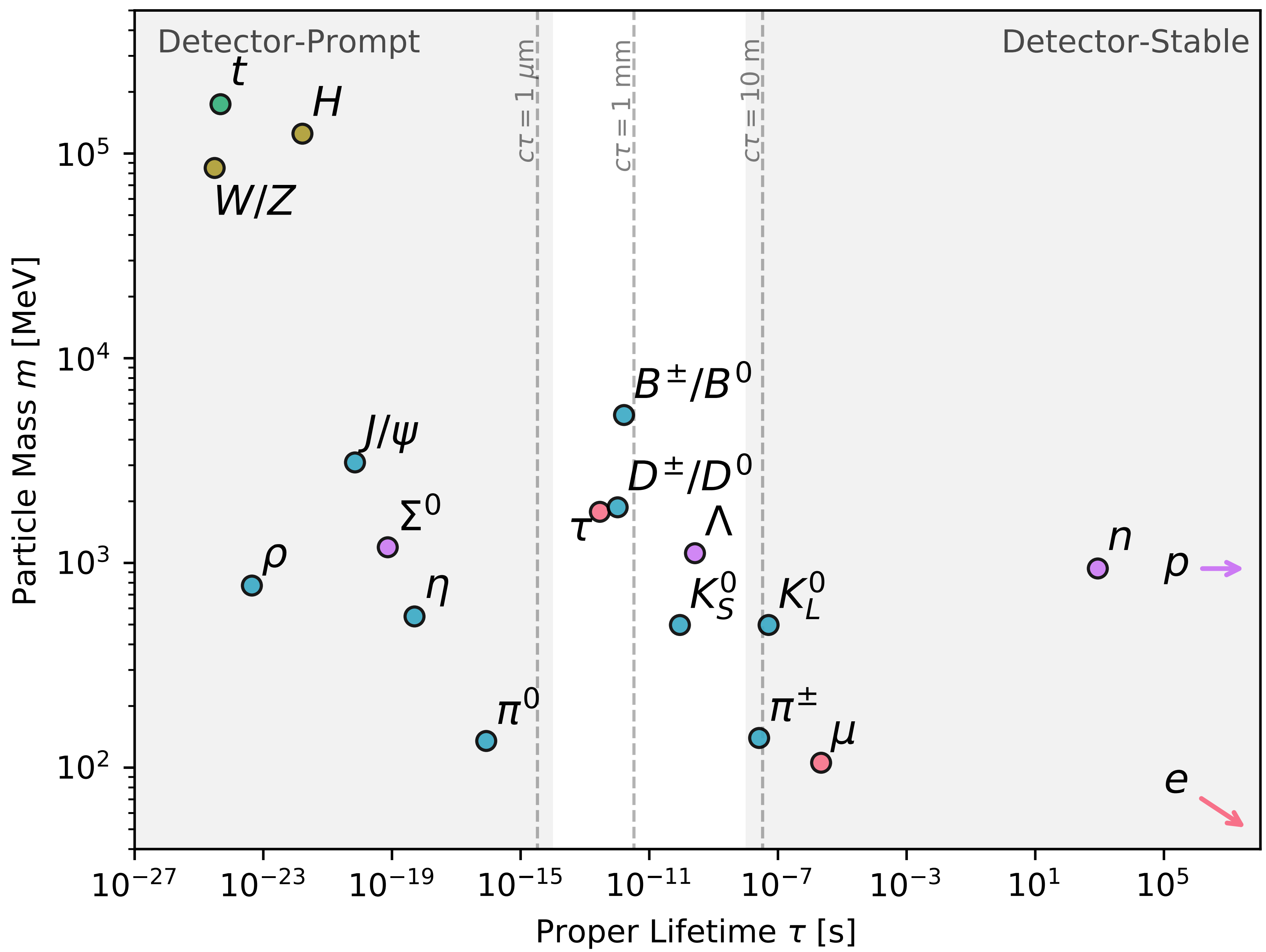
The Higgs!

Making heavier particles

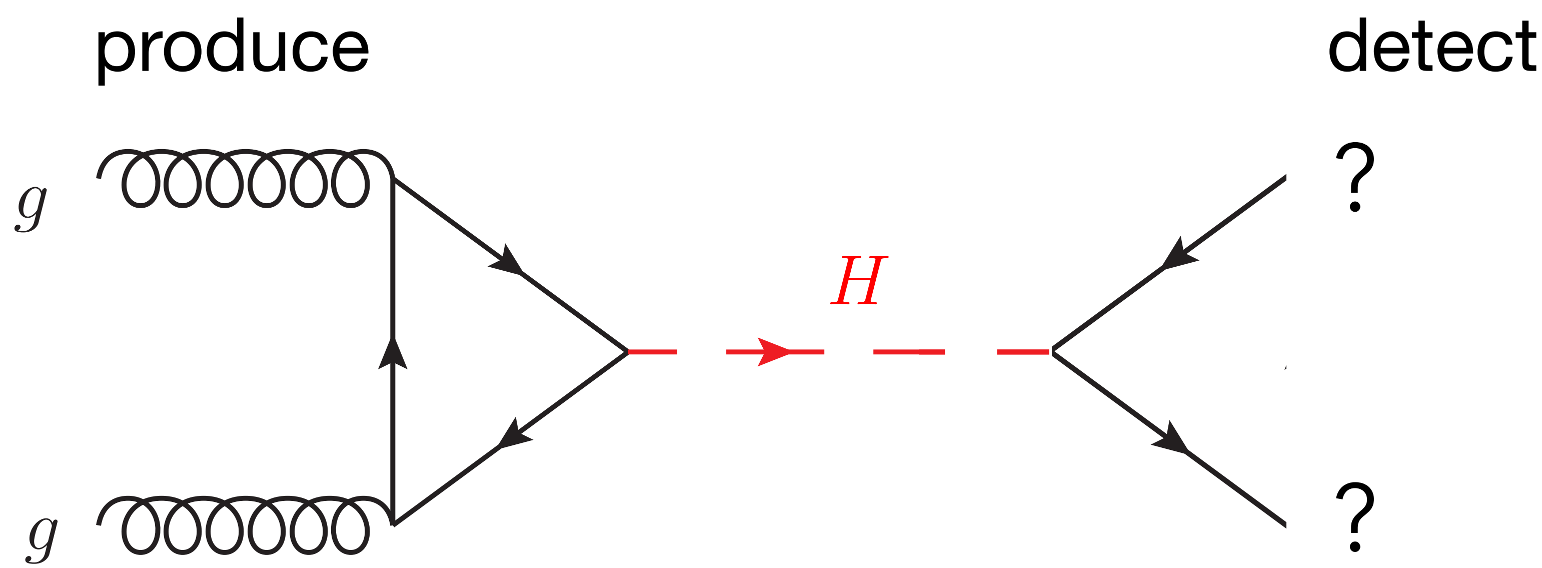


We don't see the Higgs, it decays…

Three categories of particles, based on lifetime

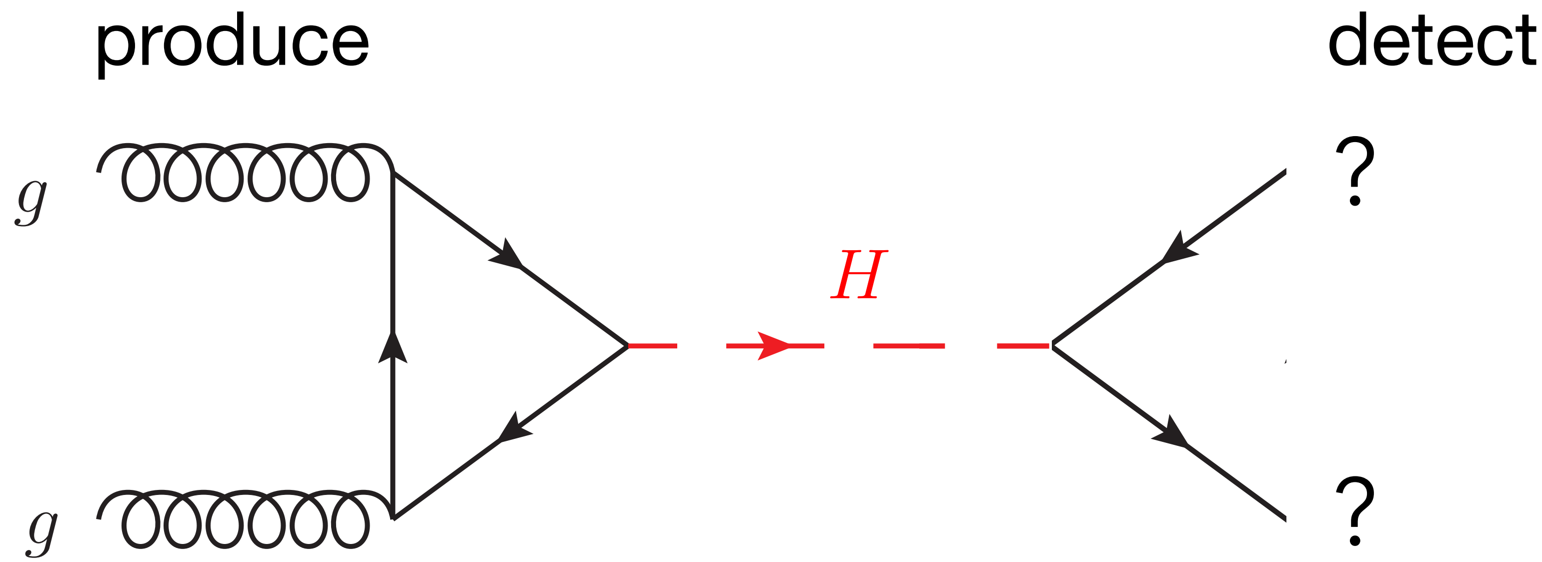


How does the Higgs decay?



- We produce ~90% of Higgs events via gluon fusion
- $H \to \gamma\gamma$ and $H \to ZZ$ have small rate but are very “clean”
- $H \to bb$ is large, but more difficult due to large backgrounds

How does the Higgs decay?



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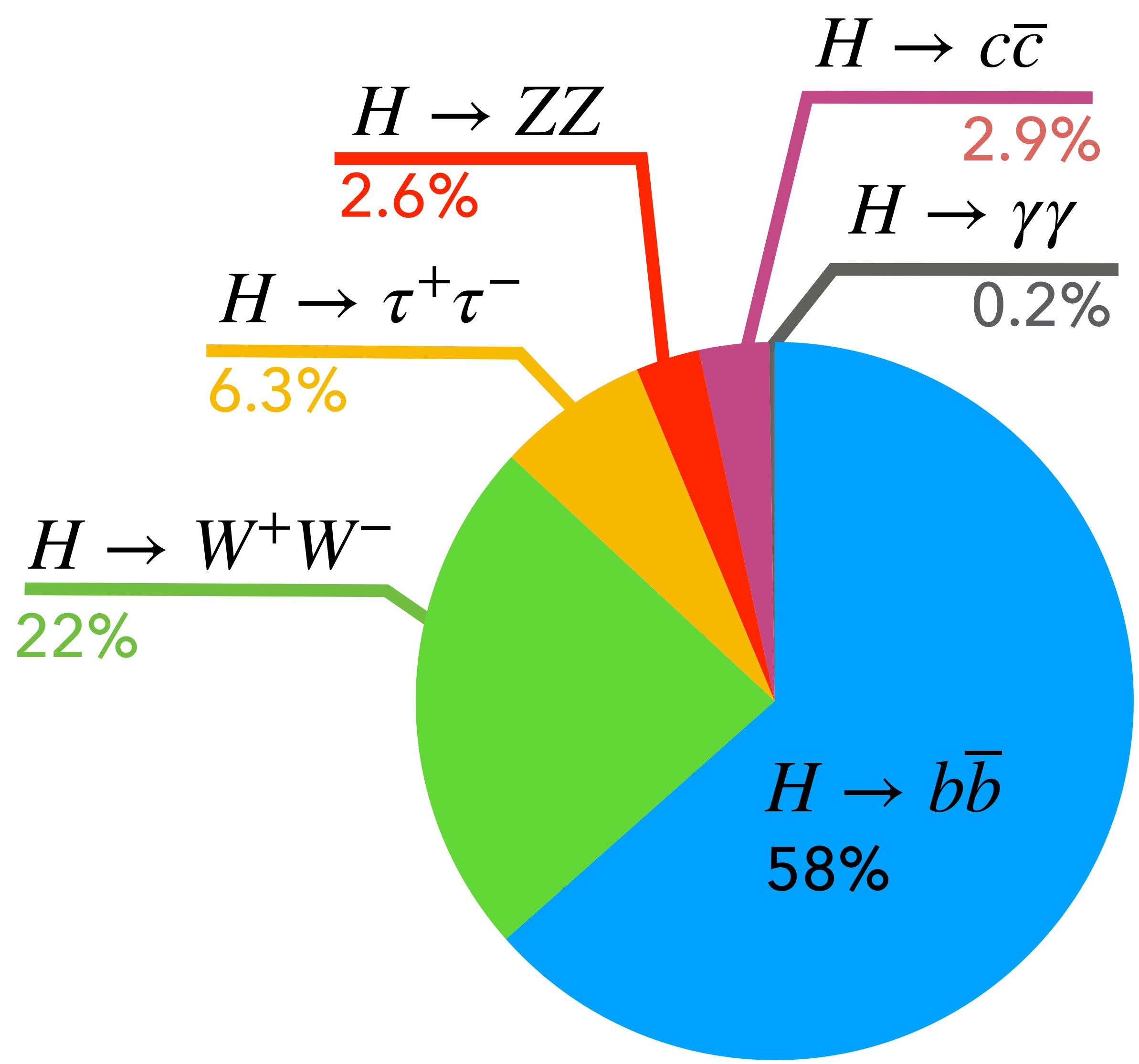
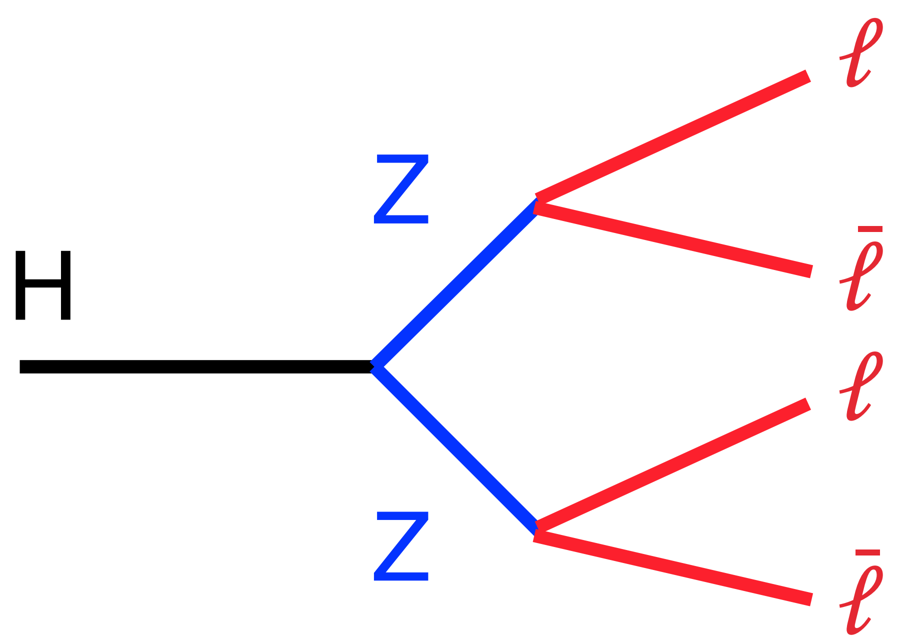
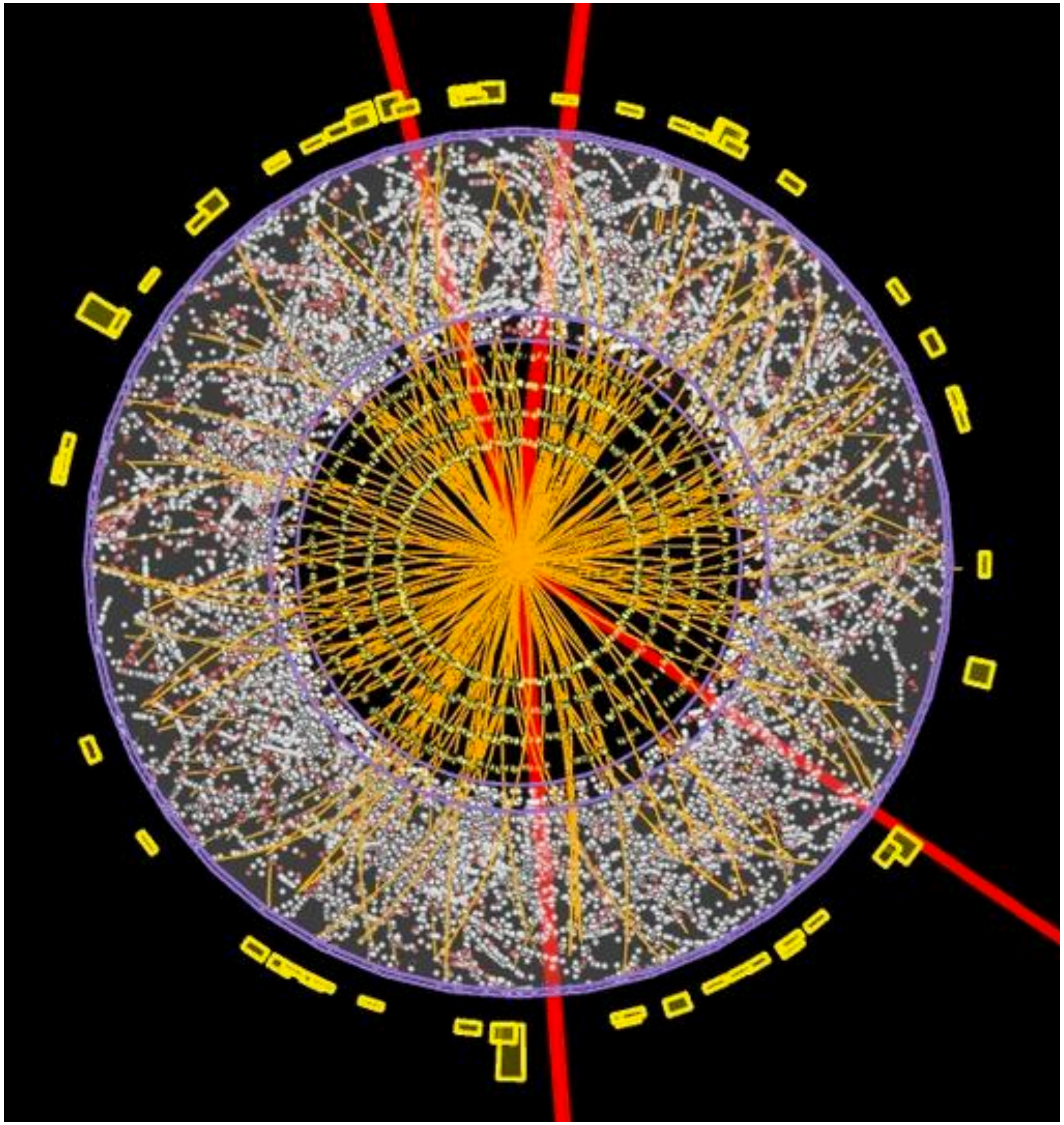


What we see in the detector

We never see the Higgs
Just it's decay products

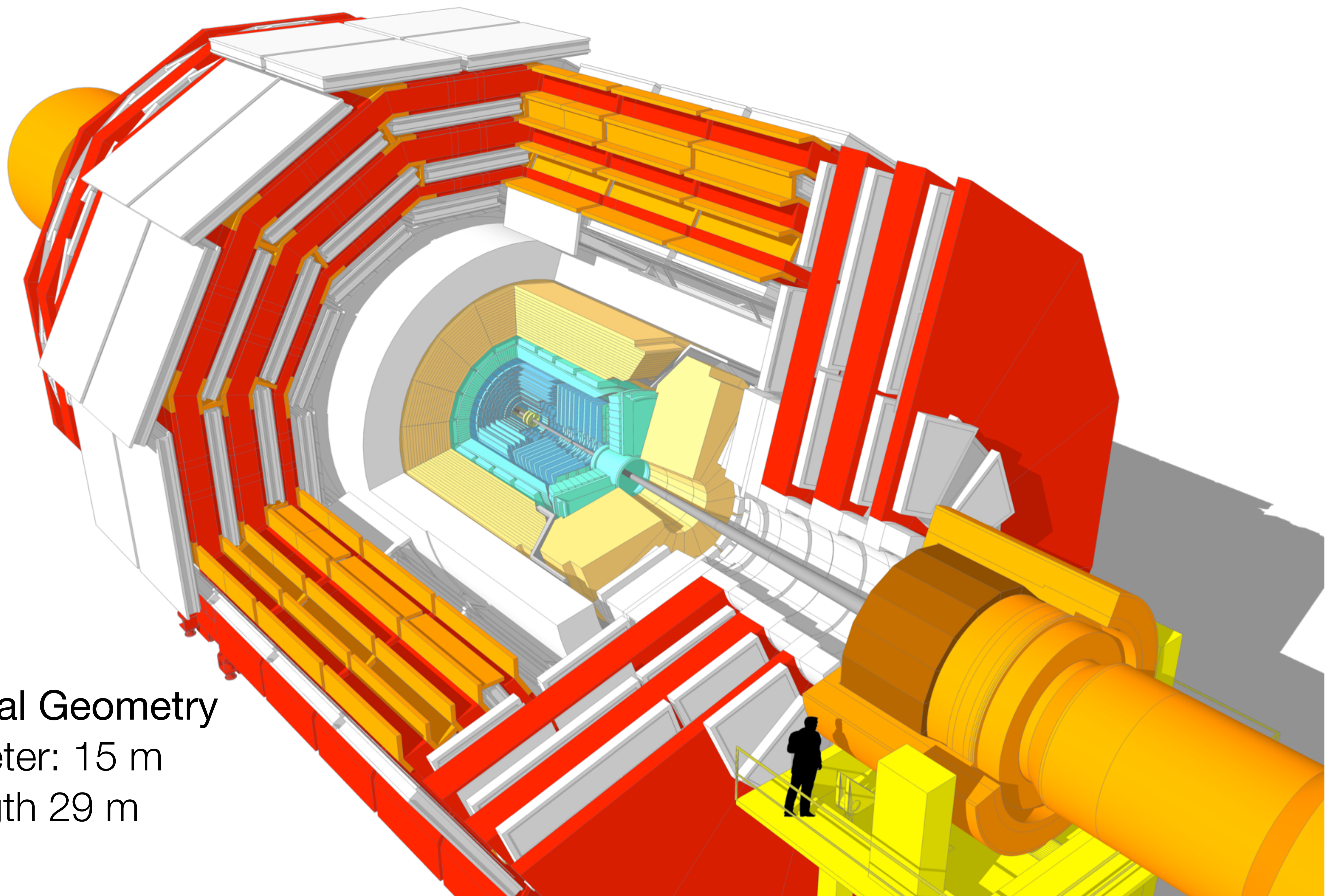


Our goal: identify & measure
all detector stable particles



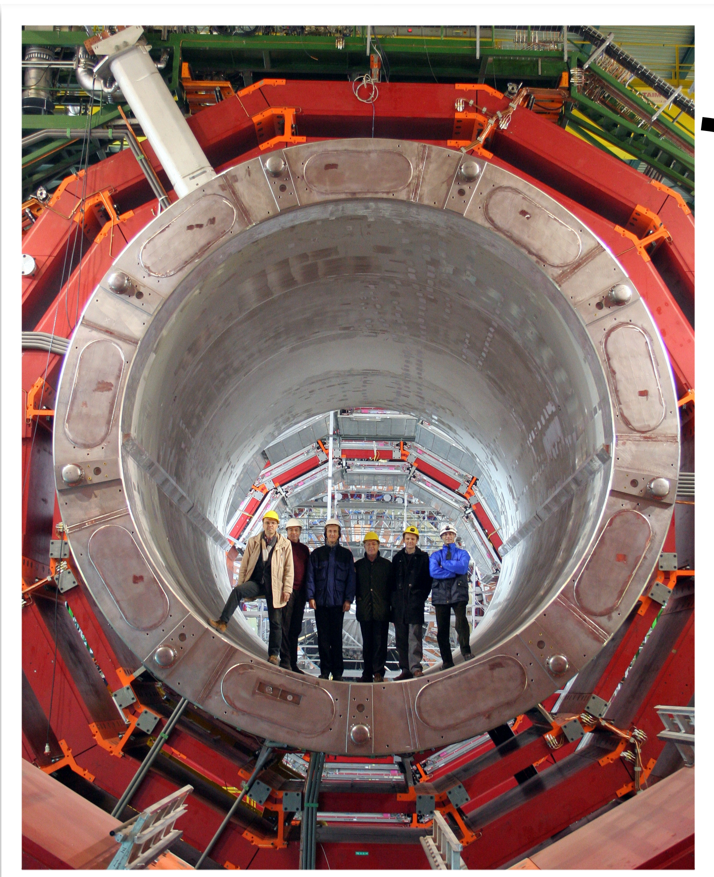
CMS design

Detector goal: detect all stable Standard Model Particles

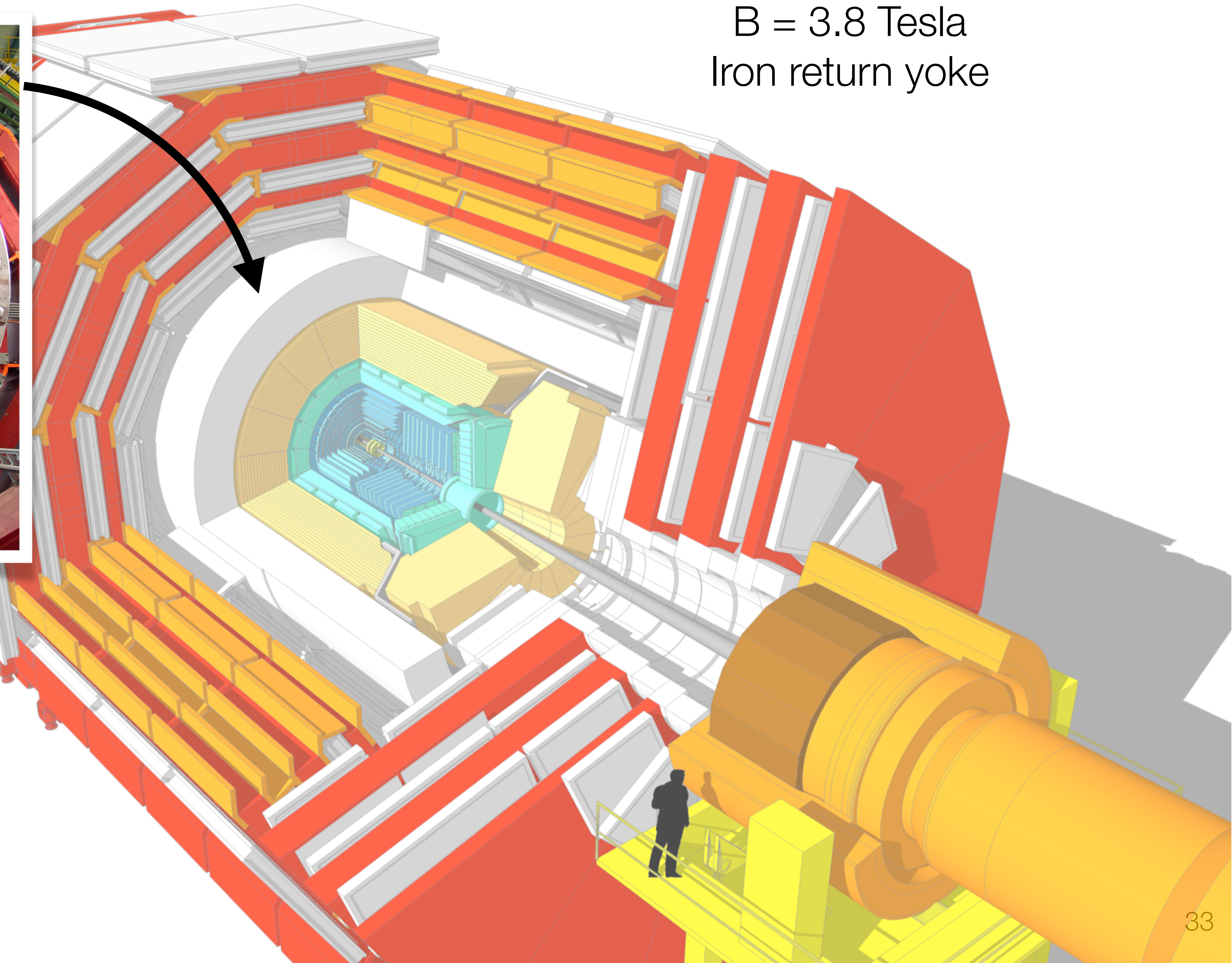


Cylindrical Geometry
Diameter: 15 m
Length 29 m

CMS design



Superconducting Solenoid
Largest in the world
B = 3.8 Tesla
Iron return yoke



Bends charged particles

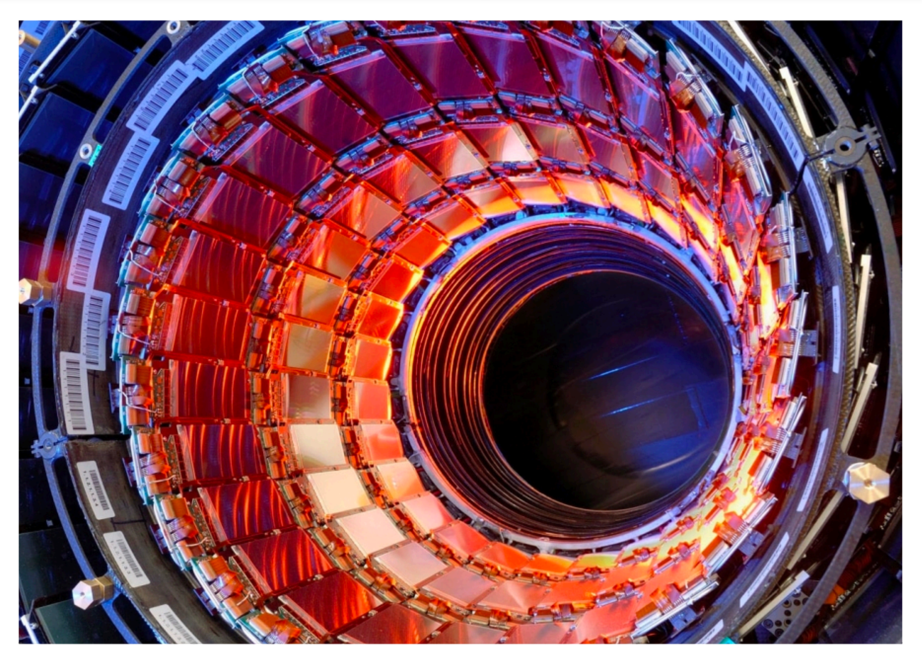
$$R = \frac{p}{q \cdot B}$$

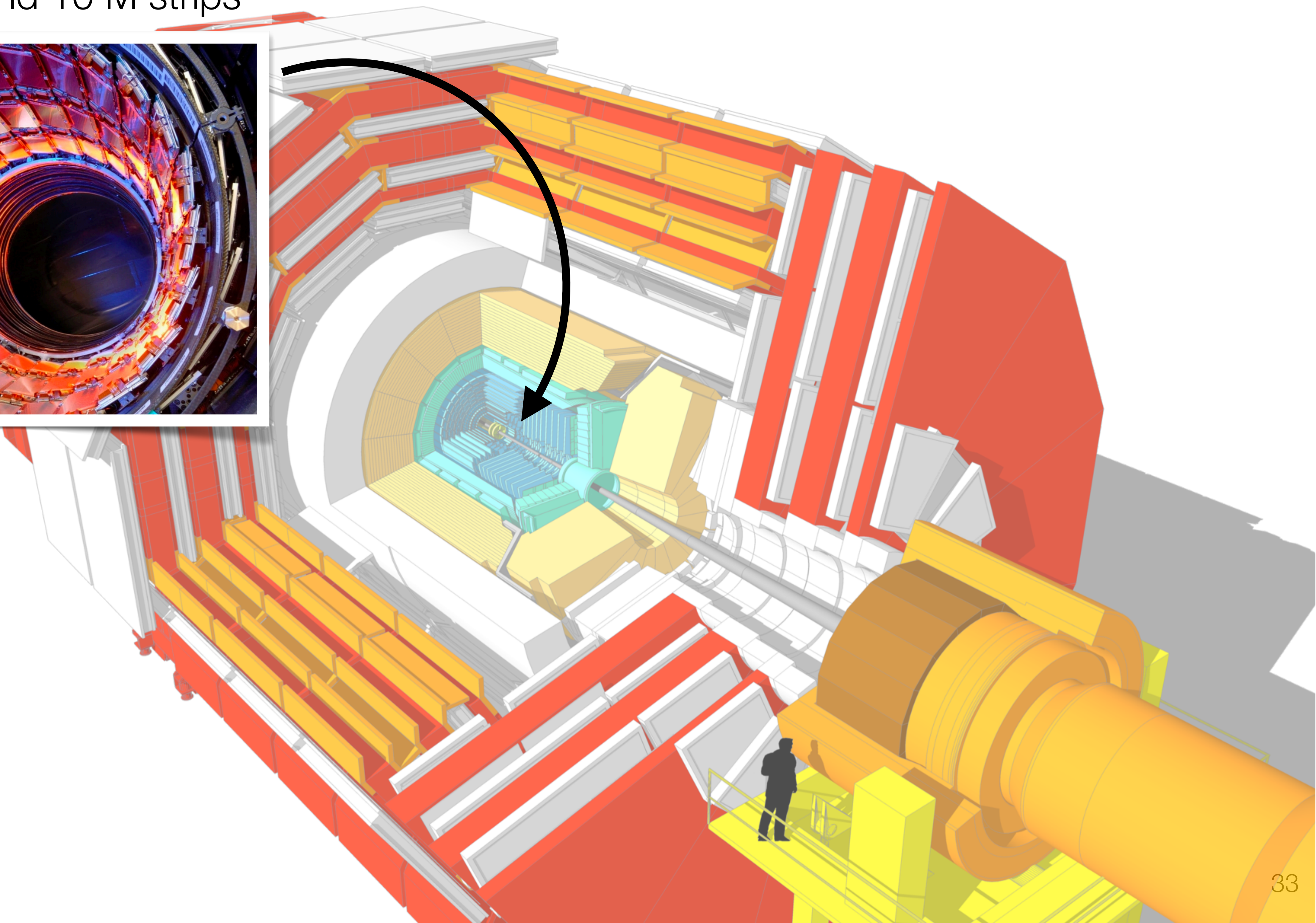
CMS design

Silicon Tracker

Trajectories of charged particles

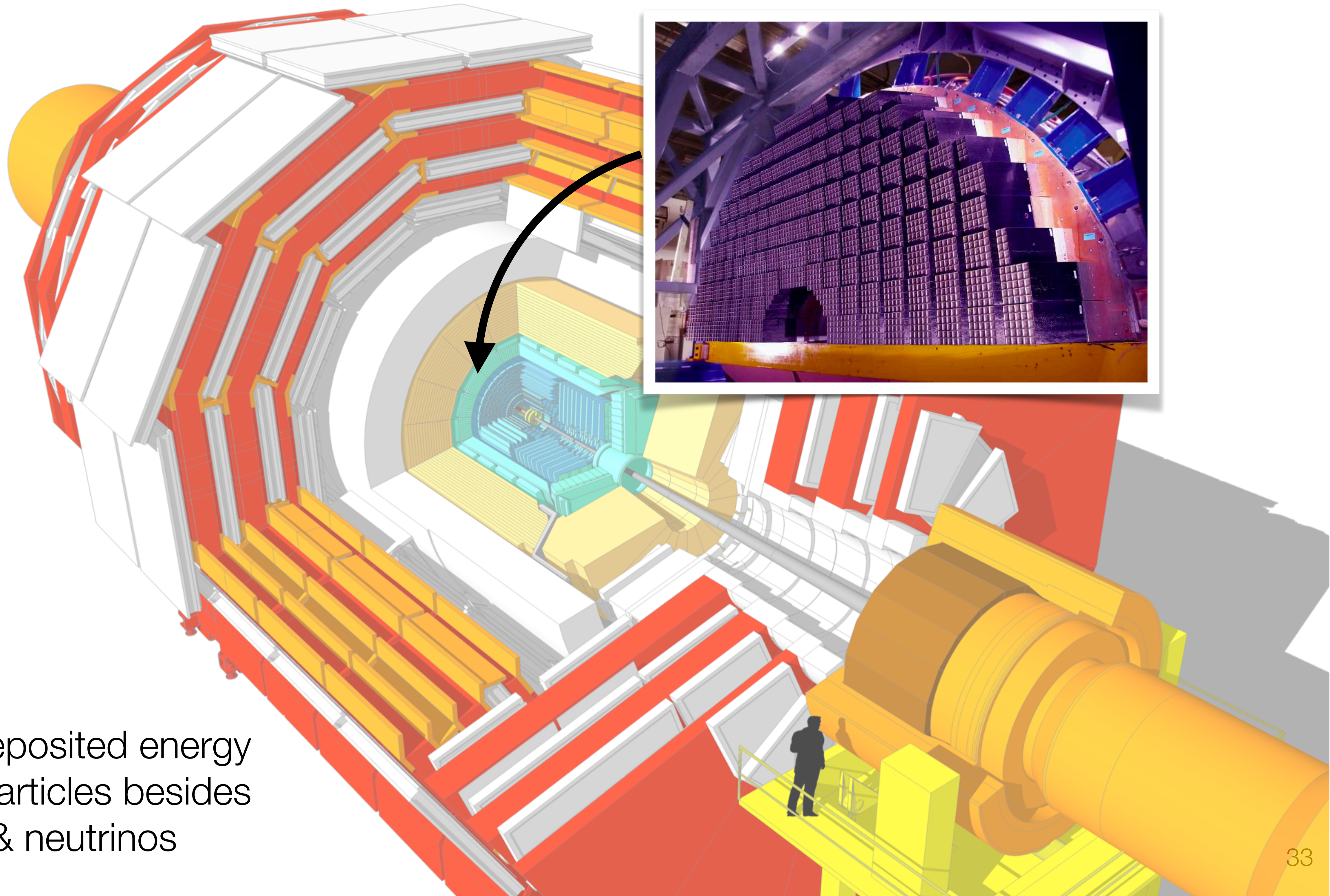
124 M pixels and 10 M strips





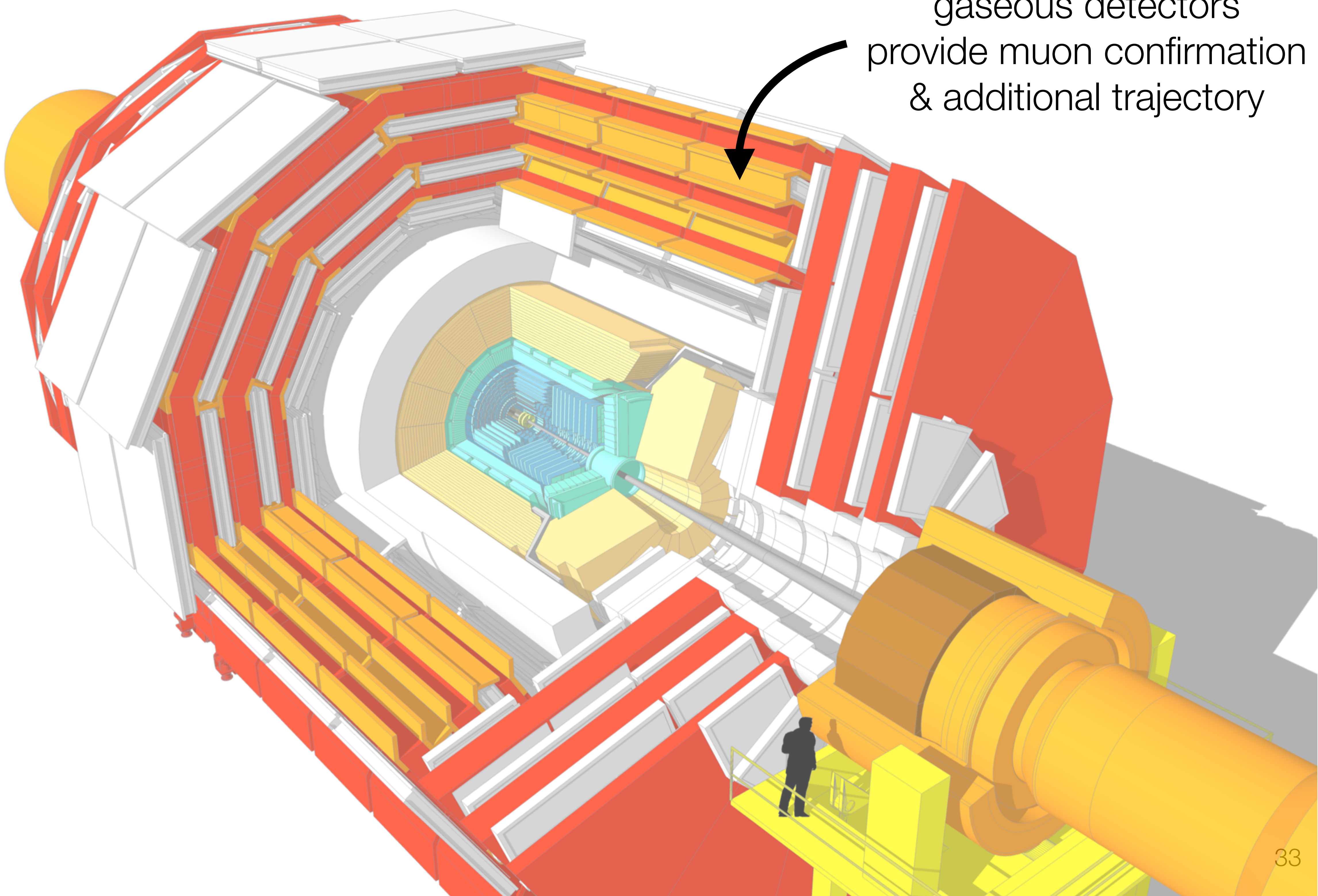
CMS design

Electromagnetic and
Hadronic Calorimeters



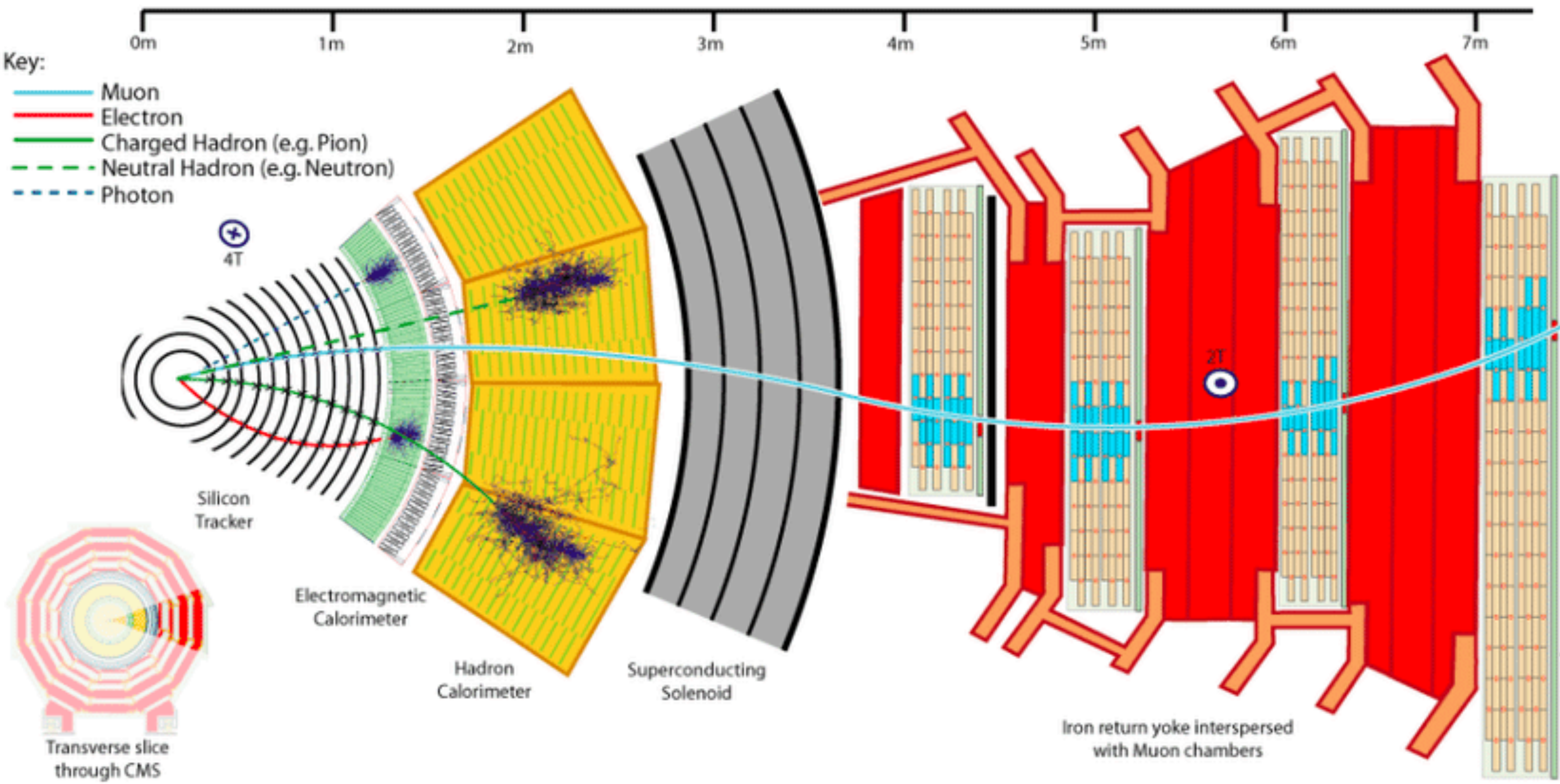
Measures deposited energy
& stops all particles besides
muons & neutrinos

CMS design



Muon Spectrometer
gaseous detectors
provide muon confirmation
& additional trajectory

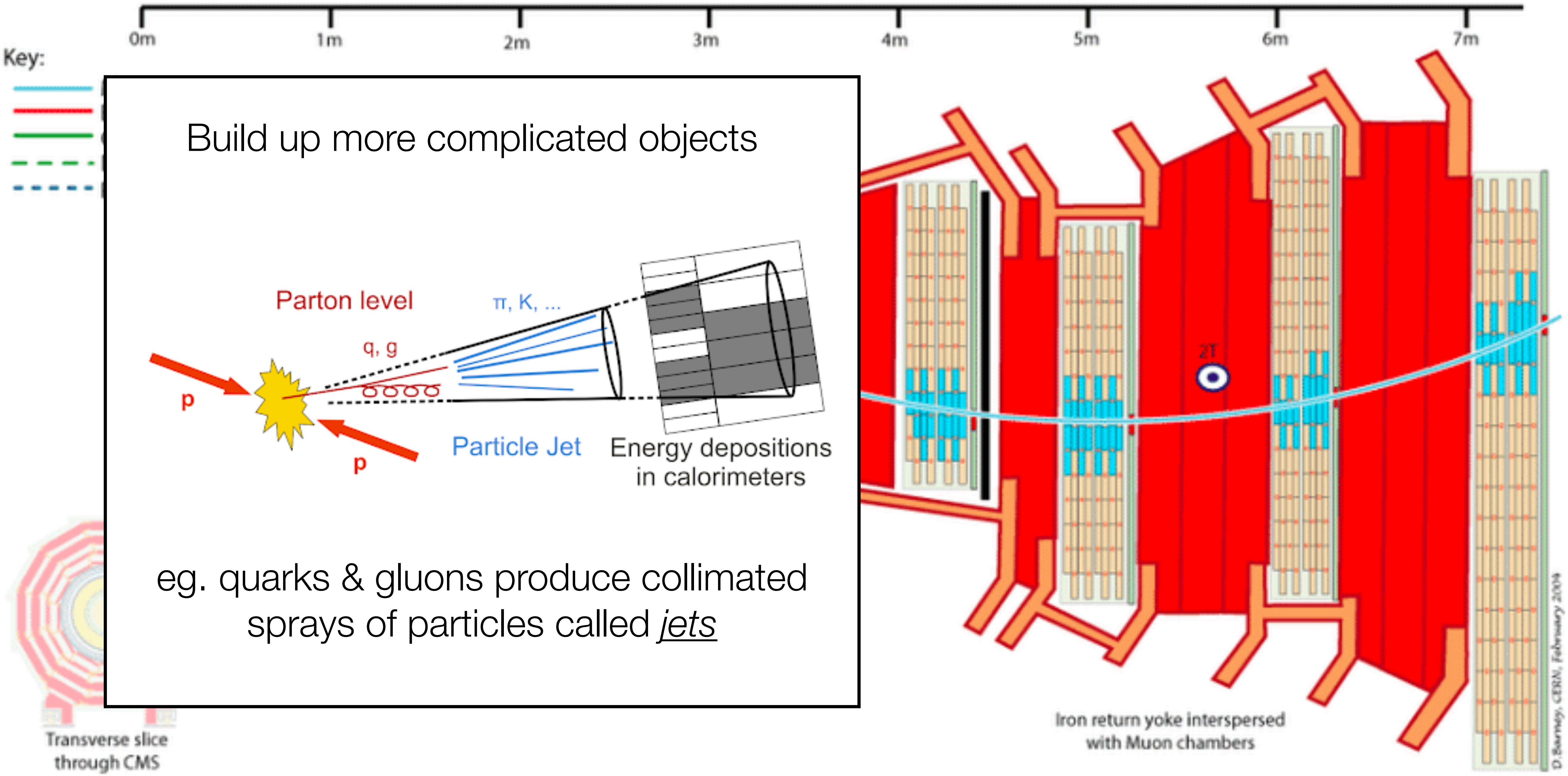
Particle Identification



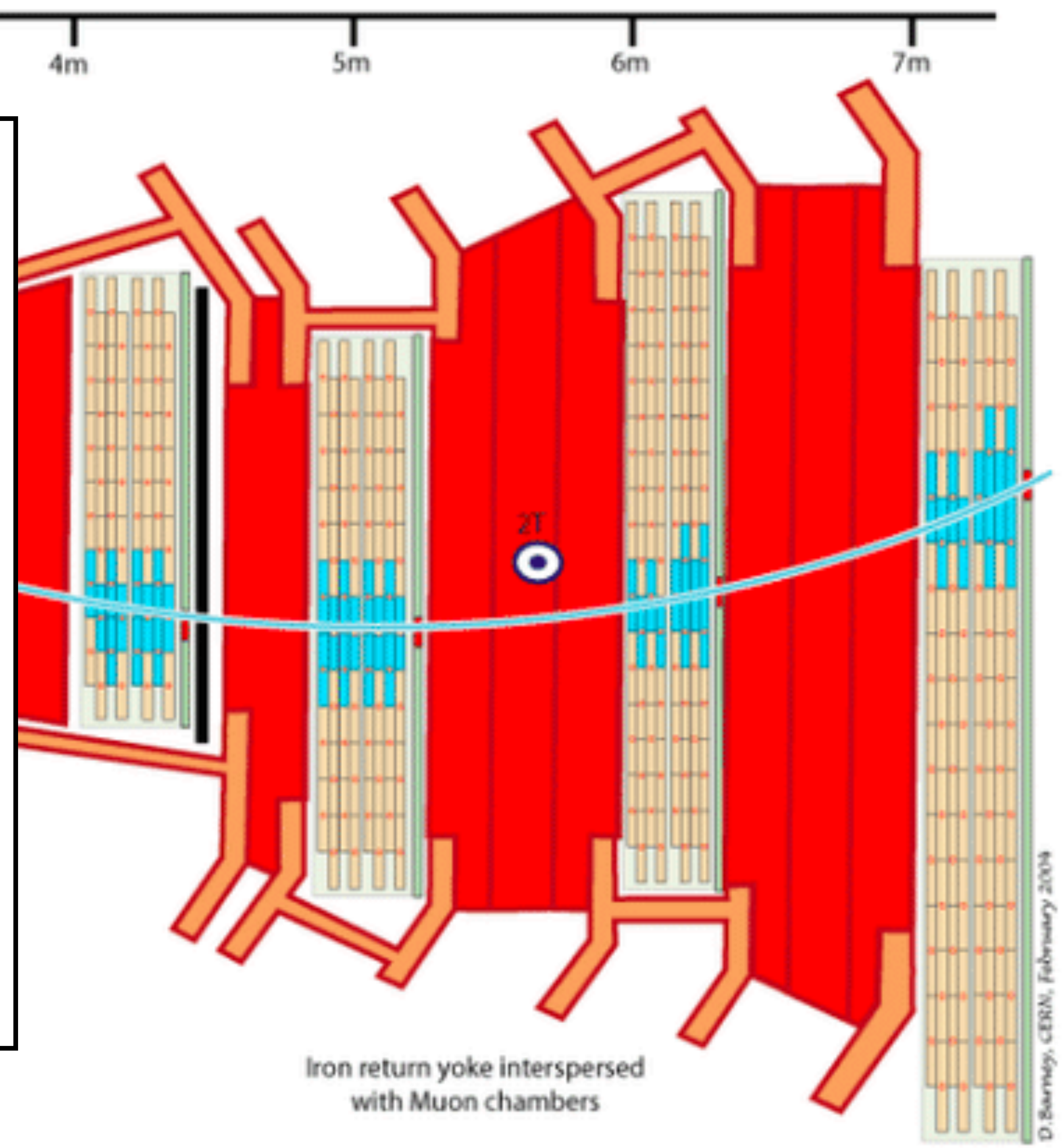
Particle Identification

Build up more complicated objects

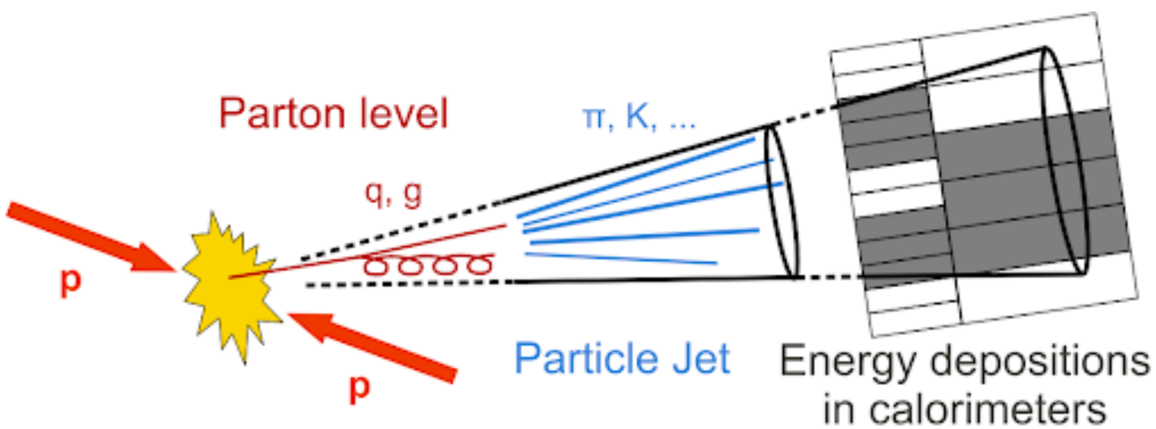
eg. quarks & gluons produce collimated sprays of particles called <u>*jets*</u>



Particle Identification



Build up more complicated objects



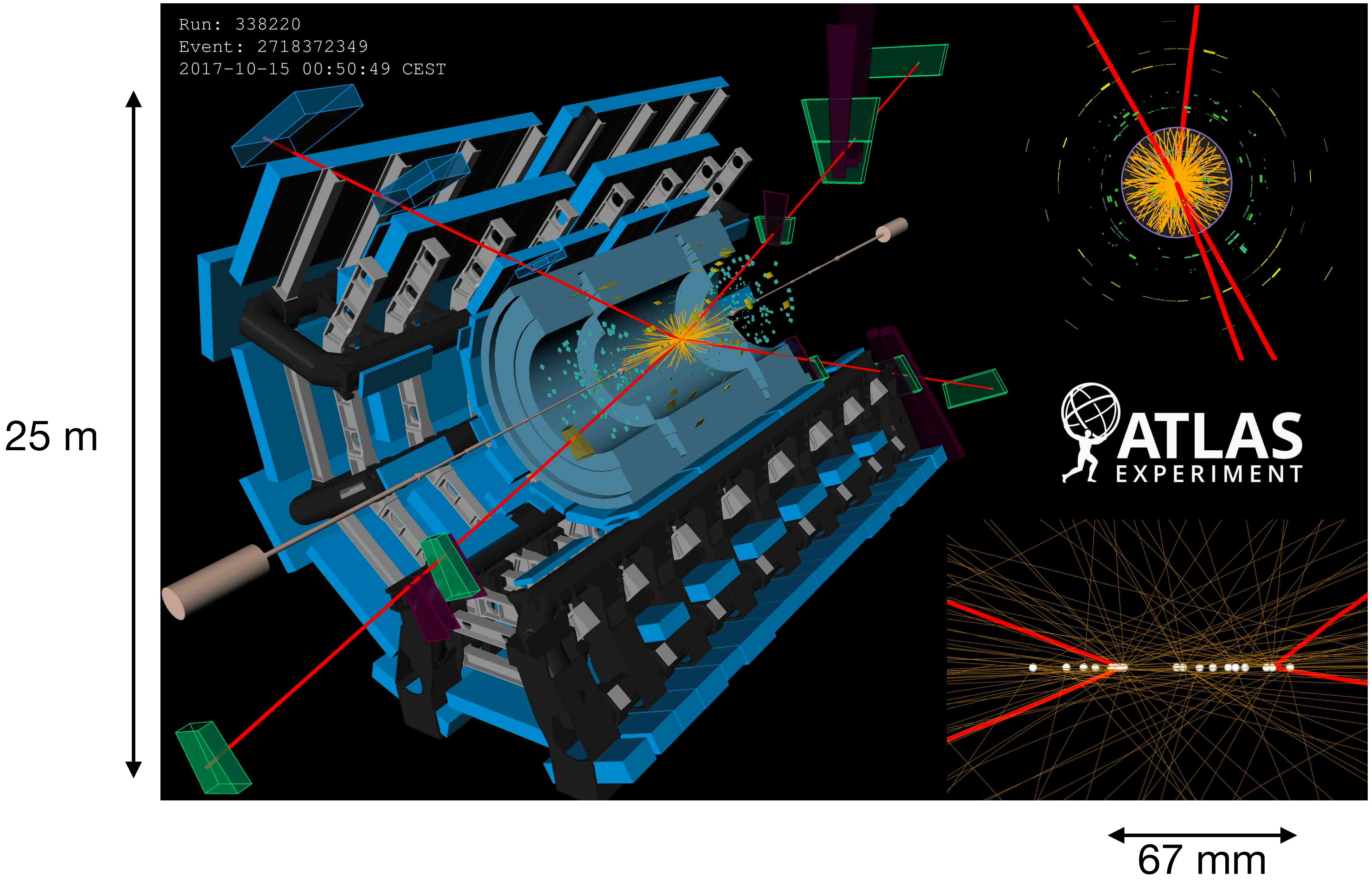
eg. quarks & gluons produce collimated sprays of particles called <u>*jets*</u>

And infer the presence of non-interacting particles (neutrinos/dark matter) as missing transverse momentum, p_T^{miss}

Disentangling collisions

We take advantage of the full detector's precision

Require particles point back to the collision of interest (within ~100 μm)



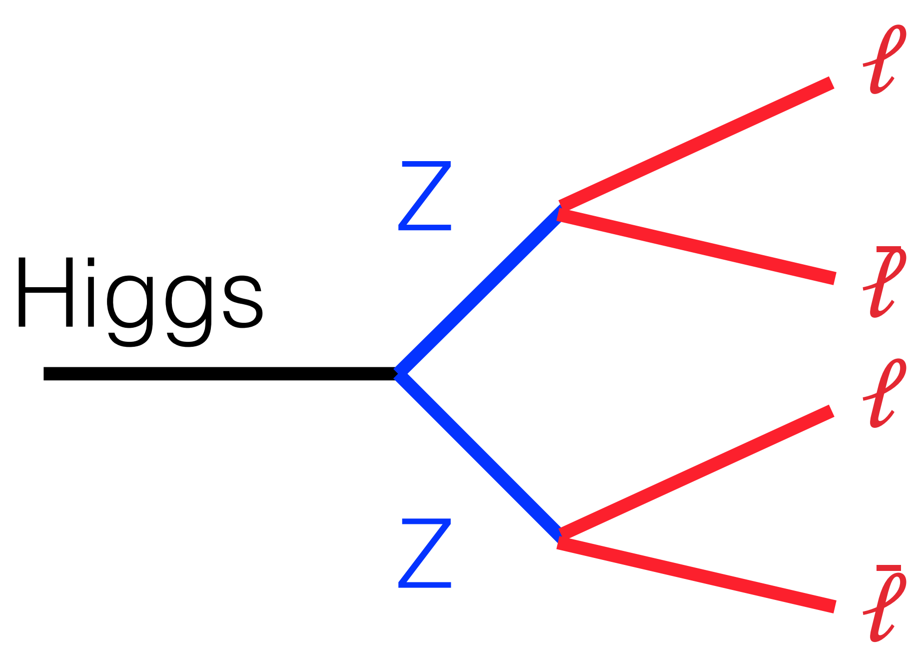
Then we make a Higgs

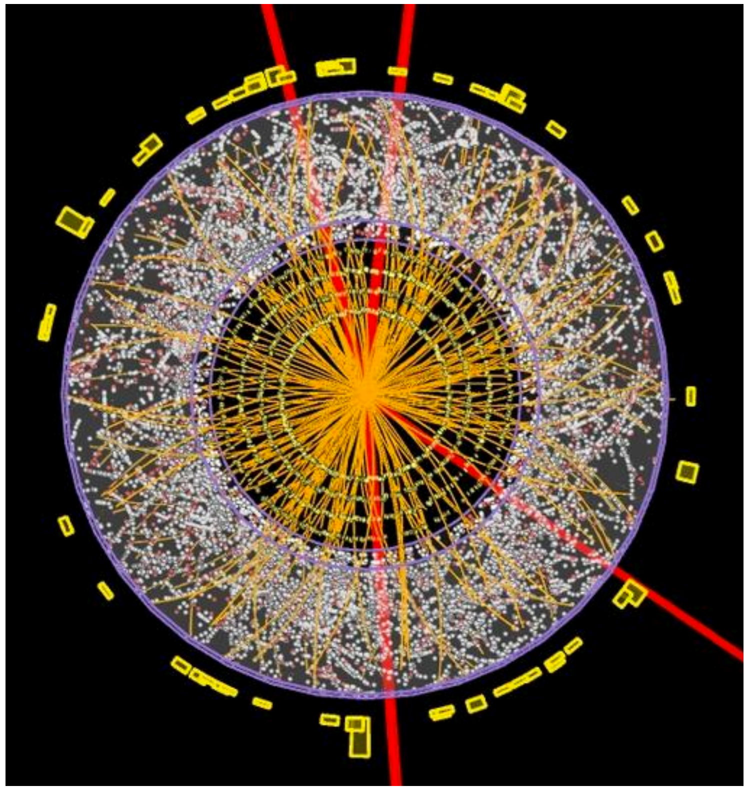
Select events with 4 leptons (e or μ)

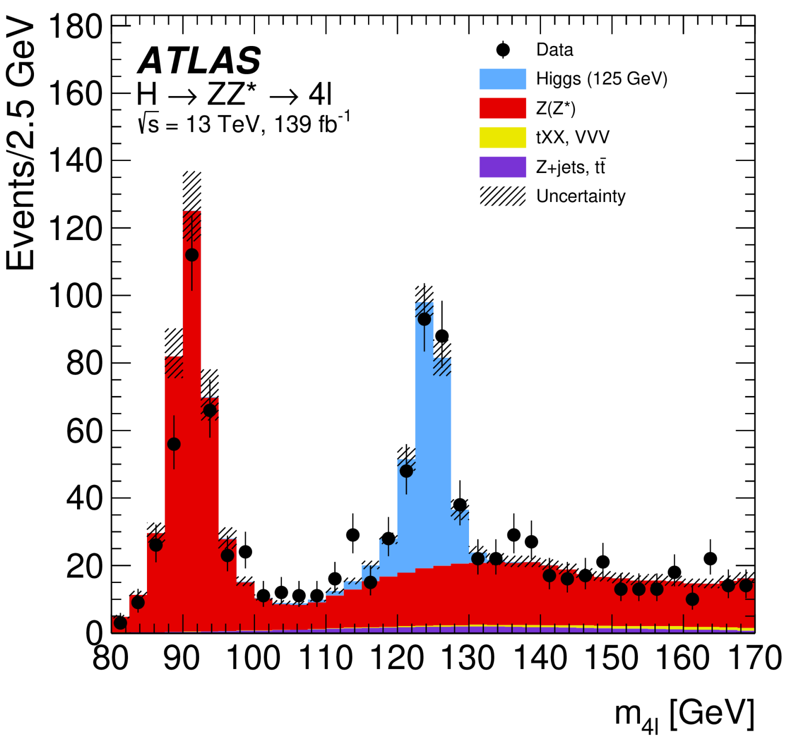
Identify pairs of leptons from Z bosons

Compute the Higgs mass using lepton momentum vectors

Fill histogram → see a bump!





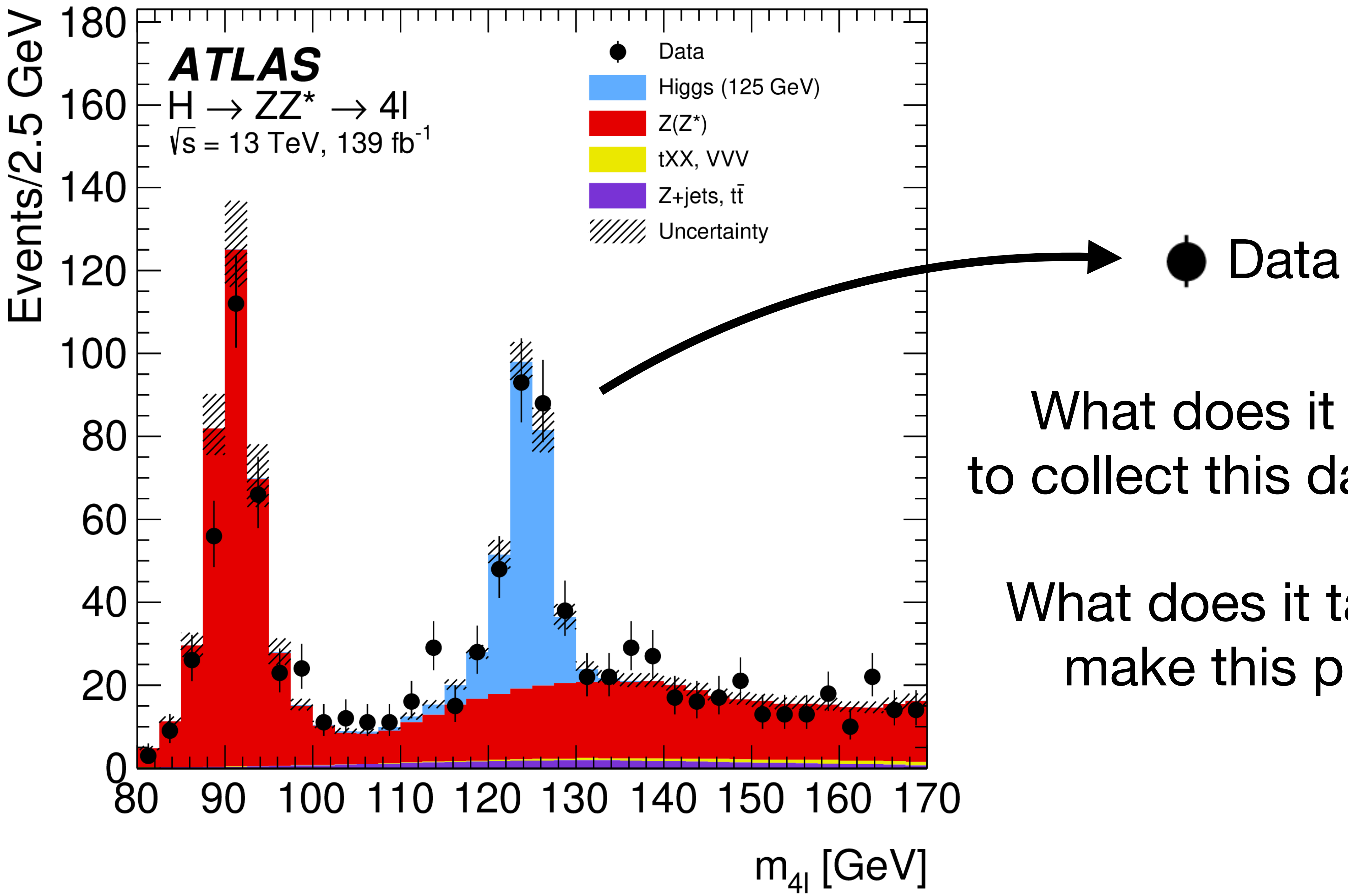


Challenge #1

The Detector

Example: How to find a Higgs

arXiv:2004.03969



What does it take to collect this dataset?

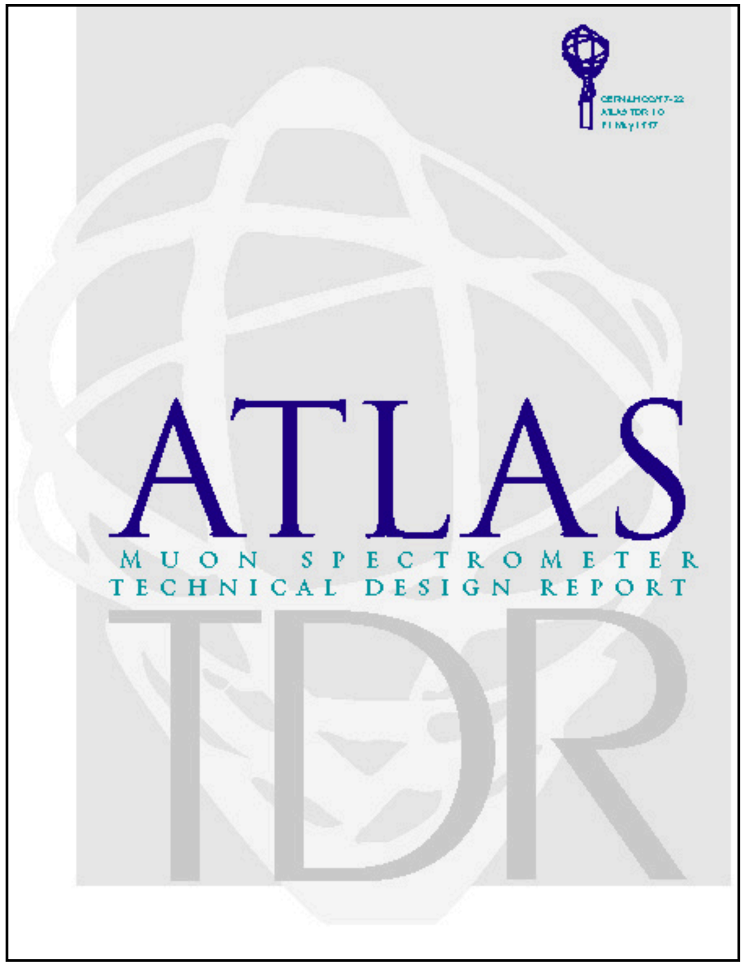
What does it take to make this plot?

It’s hard work to make a detector

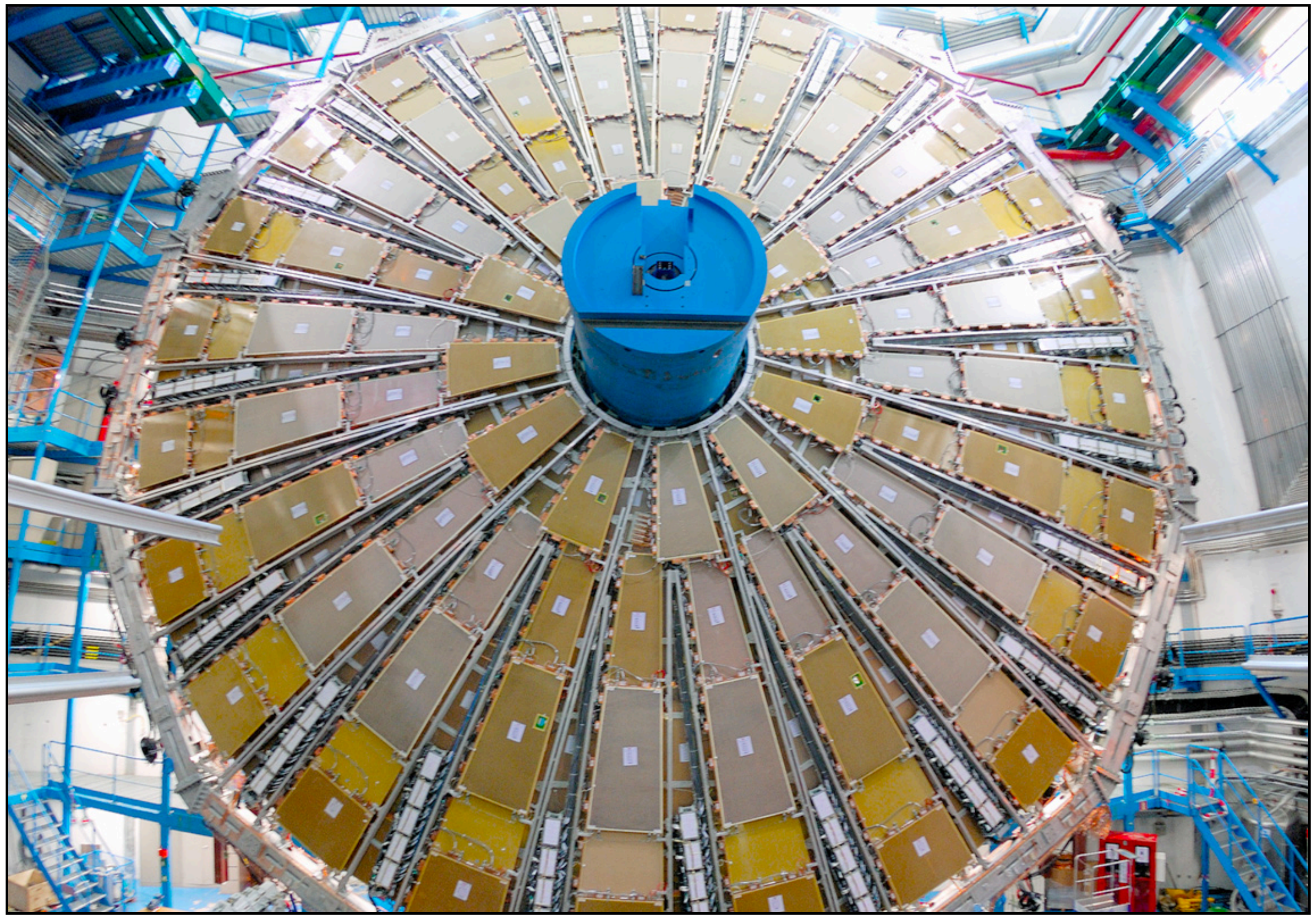
~complete design — installation

1997 → 2008

hundreds? of people to build ATLAS Muon Spectrometer



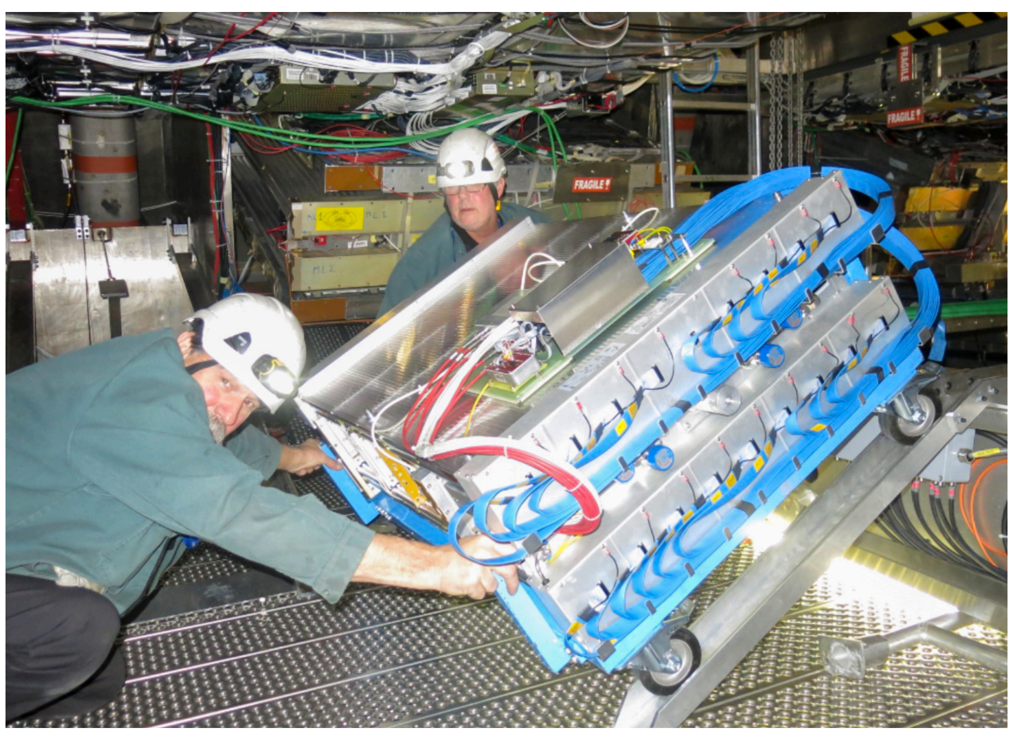
20 m

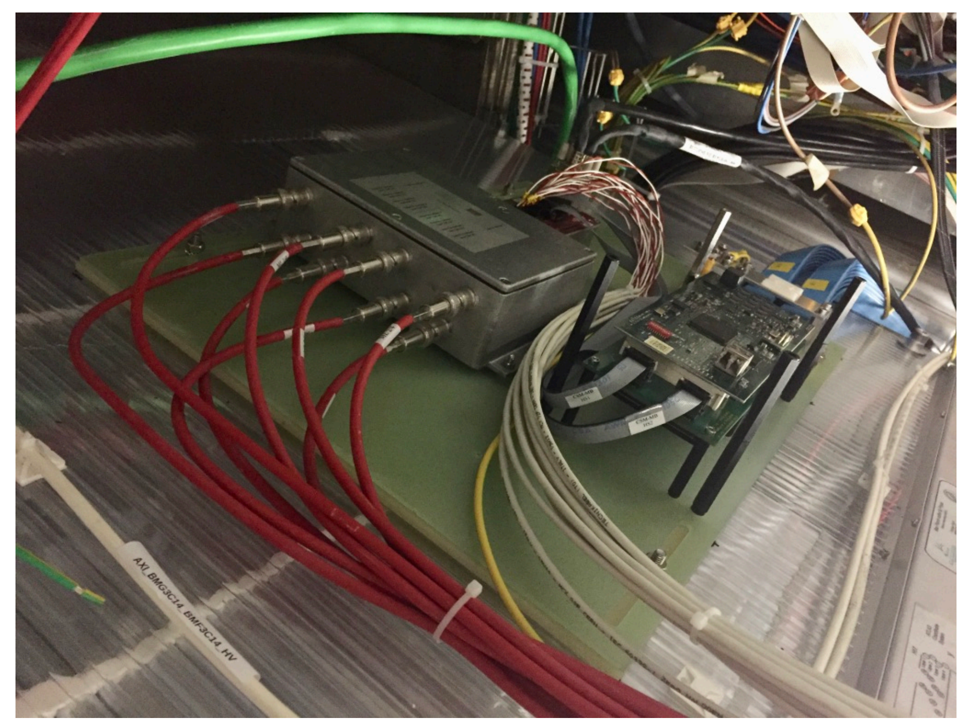


Even installing one chamber is hard

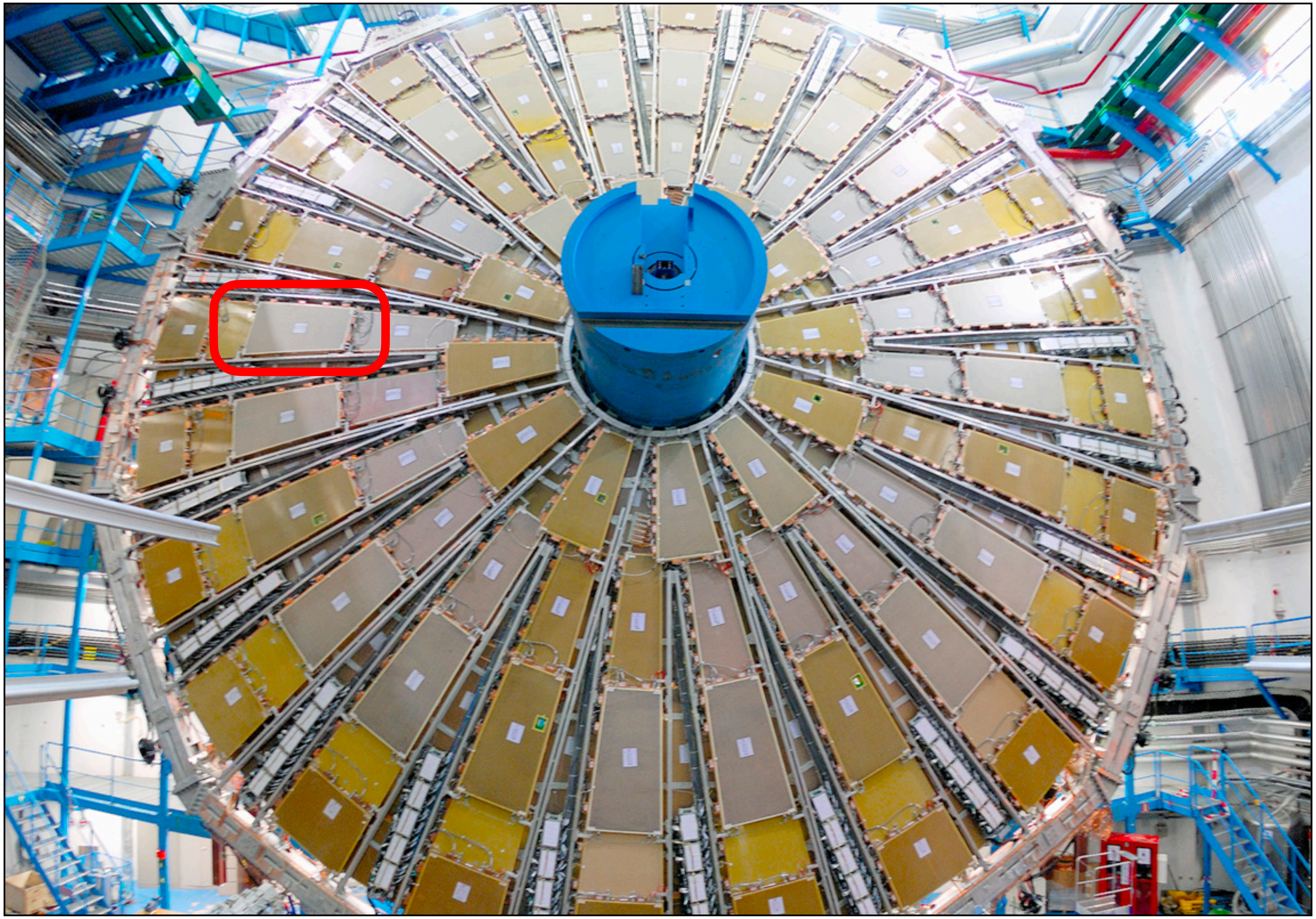
It probably takes 2 weeks per chamber
to go from the surface inside ATLAS/CMS
to be fully connected and turned ON

if nothing breaks…



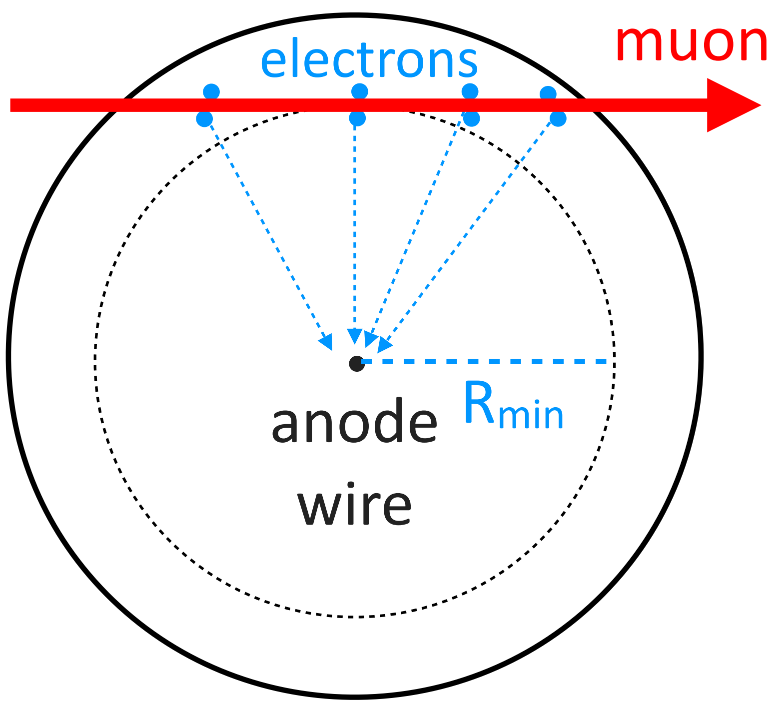


There are thousands of chambers

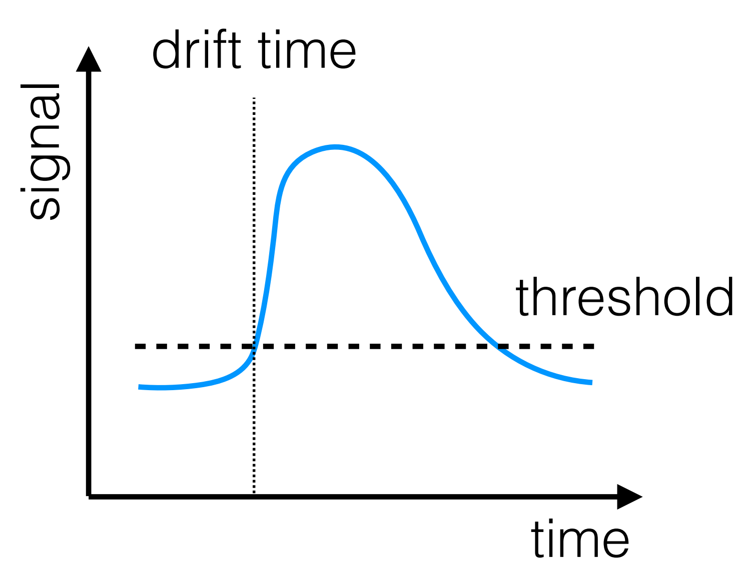


How a detector works

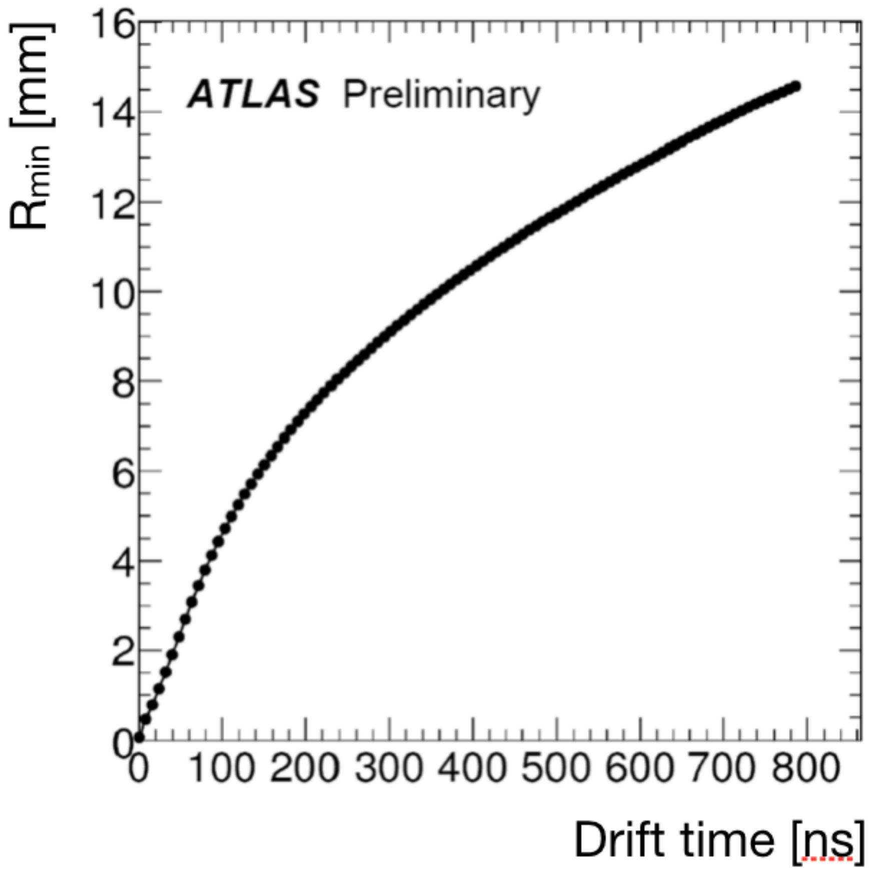
Muon chambers are made up of drift tubes
a single drift tube → position measurement



cathode tube
3 cm diameter



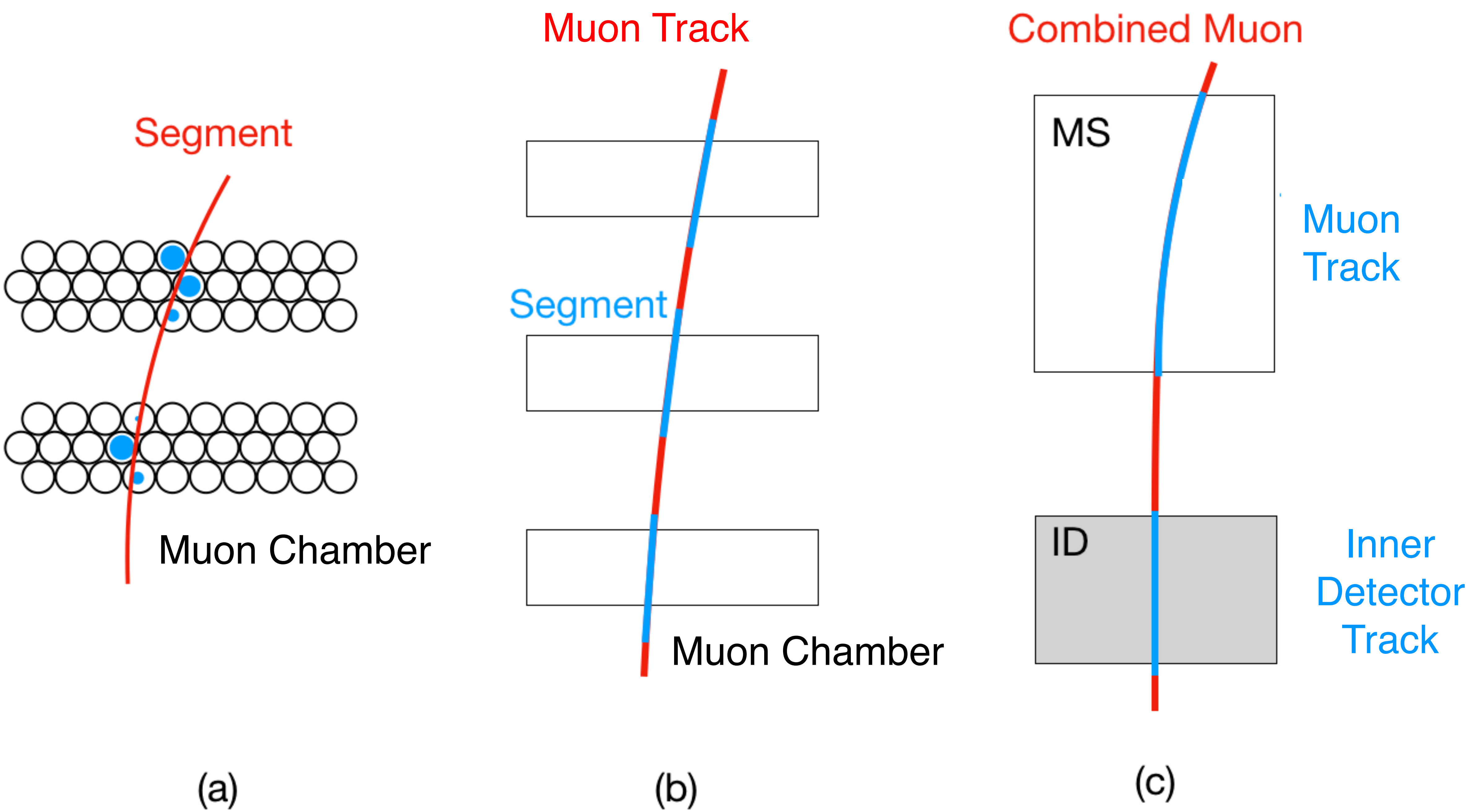
after some electronics
signal shaping



ATLAS has 300,000 muon drift tubes
The entire ATLAS detector has 100 million electronic channels!

Reconstructing particles

Then we take our signals and reconstruct them into muons



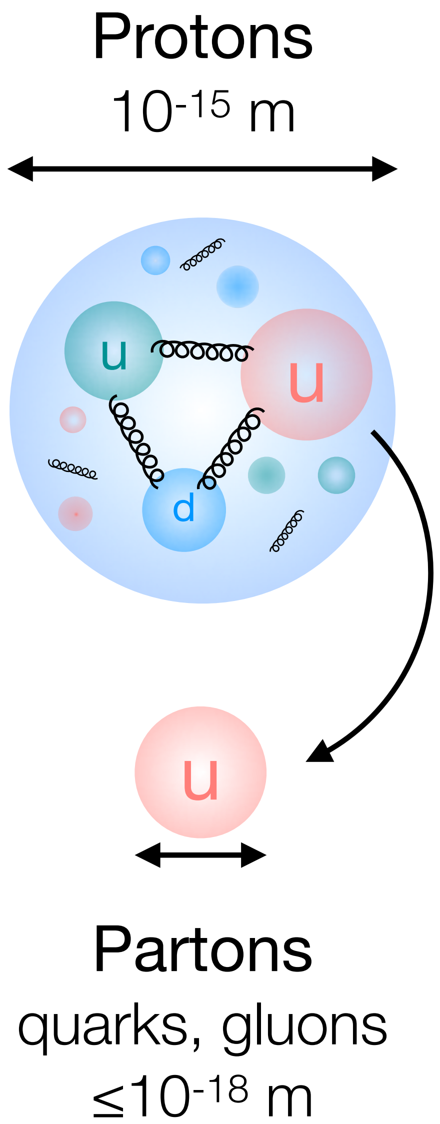
Challenge #2

The Event Rate

Colliding quarks and gluons

LHC 13 TeV energy probes distance scales of ~10^{-19} m

Means LHC is actually colliding quarks & gluons



Quarks & gluons only carry a fraction of the proton's momentum

Means most collisions are low momentum and not so interesting

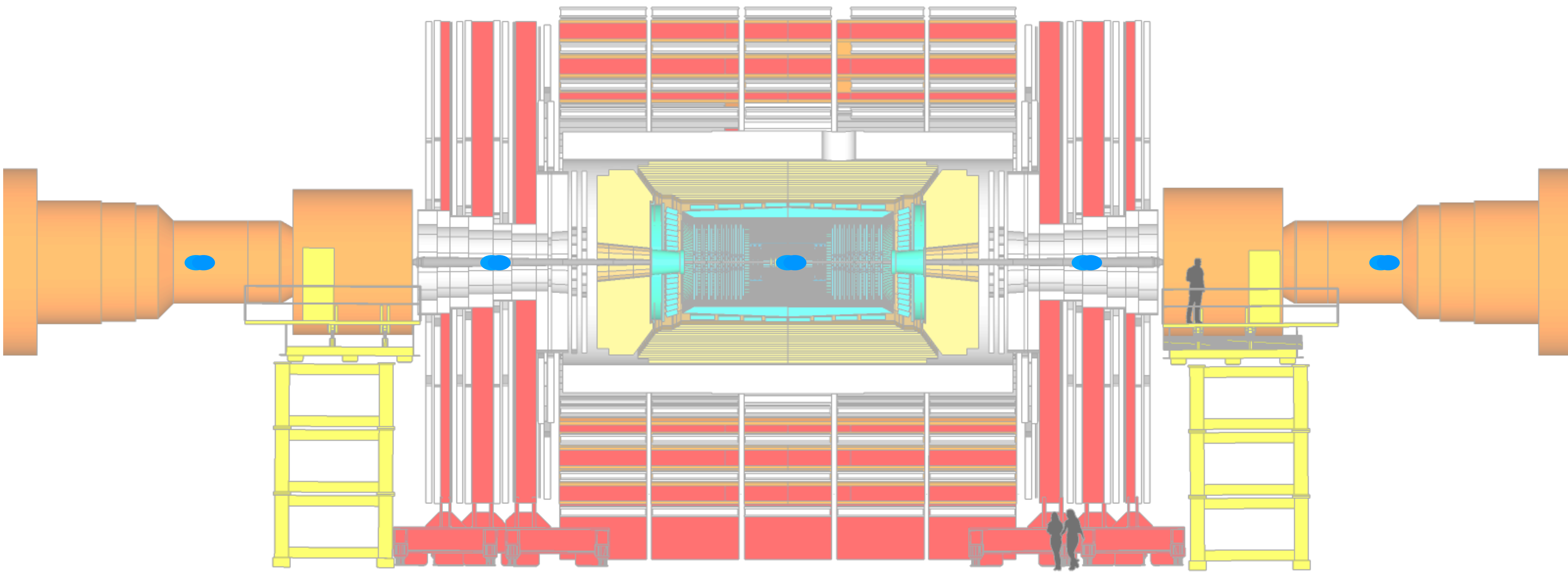
Every so often we get a "hard" collision and produce heavy particles ($E=mc^2$)

Top pair: ~1 out of 75,000,000

Higgs boson: ~1 out of 1,200,000,000

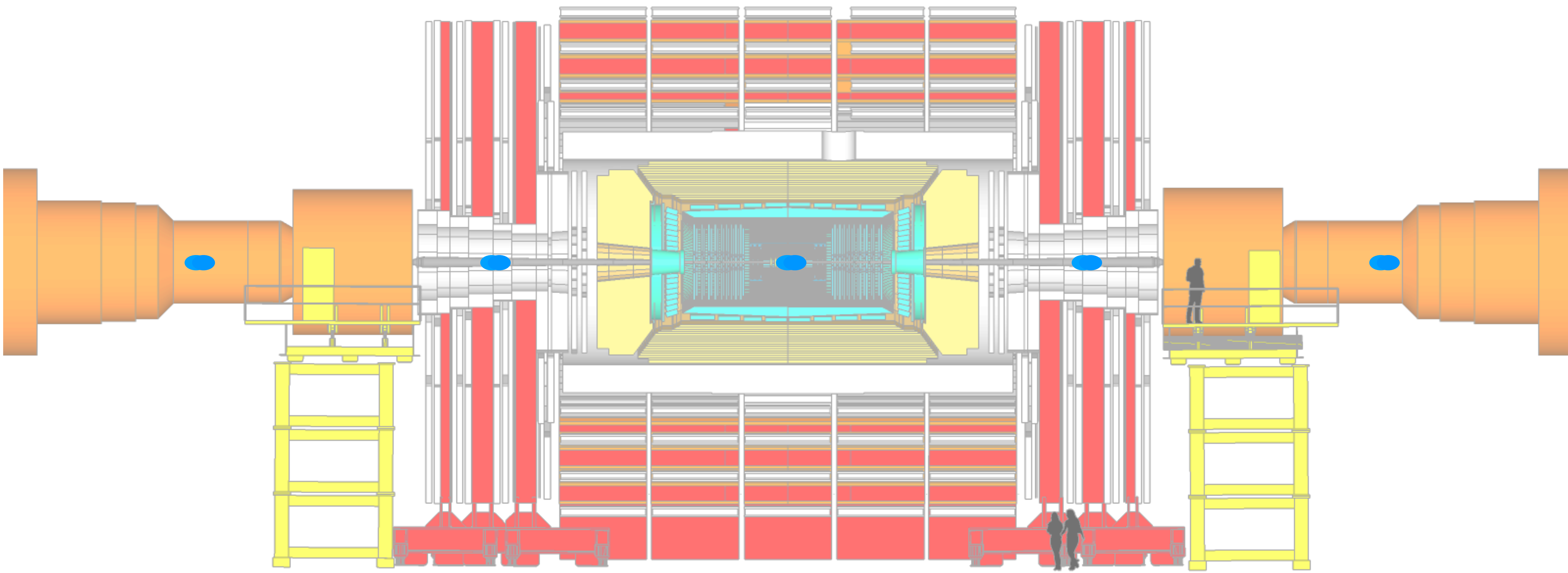
3.5 TeV Z prime: ~1 out of 120,000,000,000,000

Collision rates



Collision rates

LHC circulates “bunches” of protons, which collide every 25 ns
~50 overlapping collisions per event



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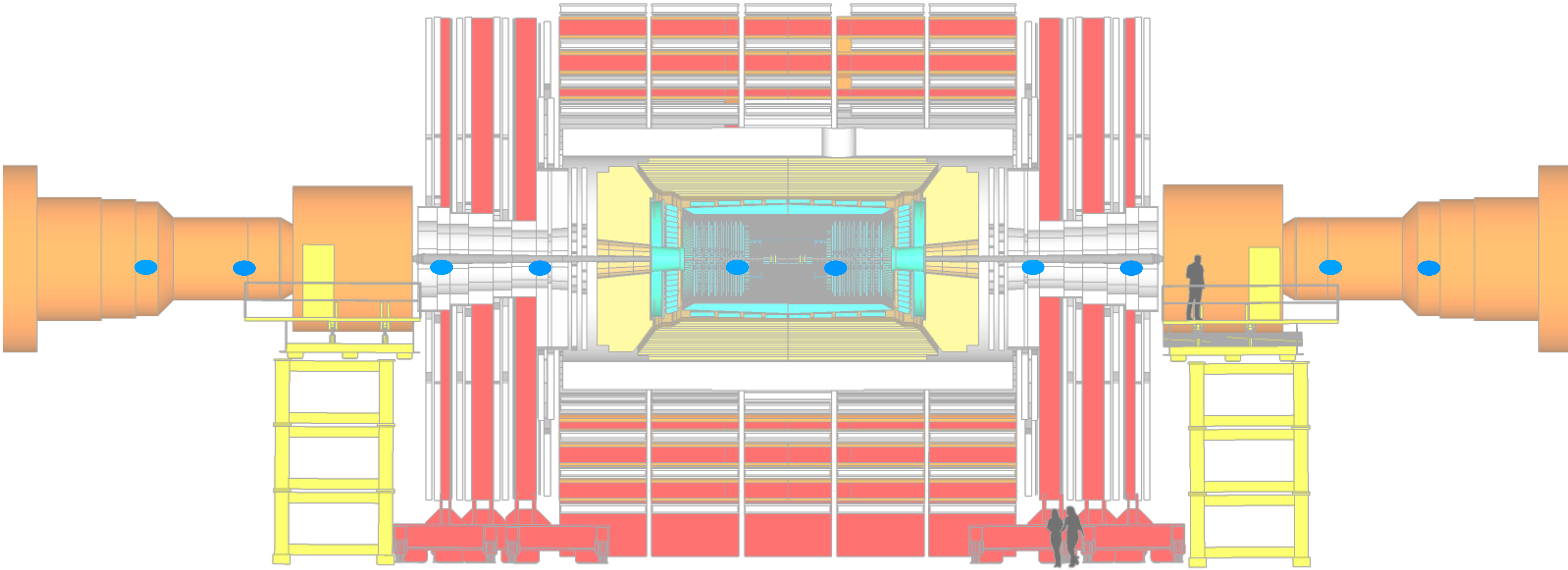

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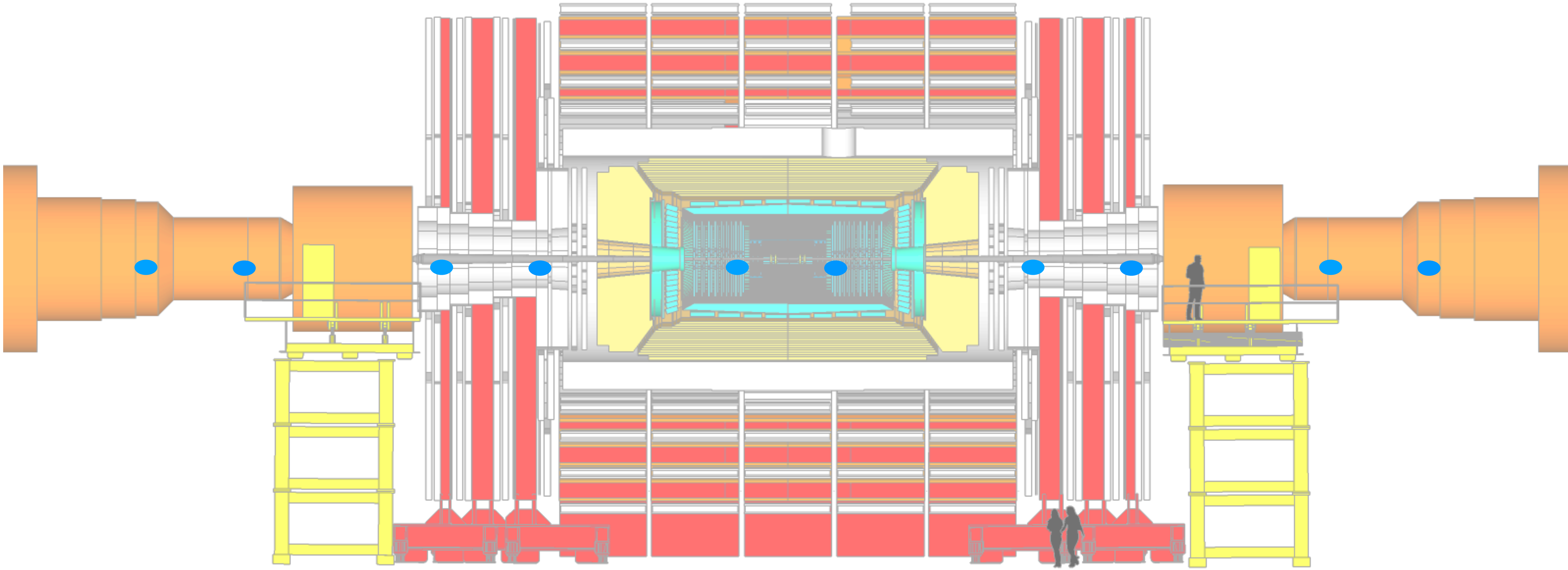


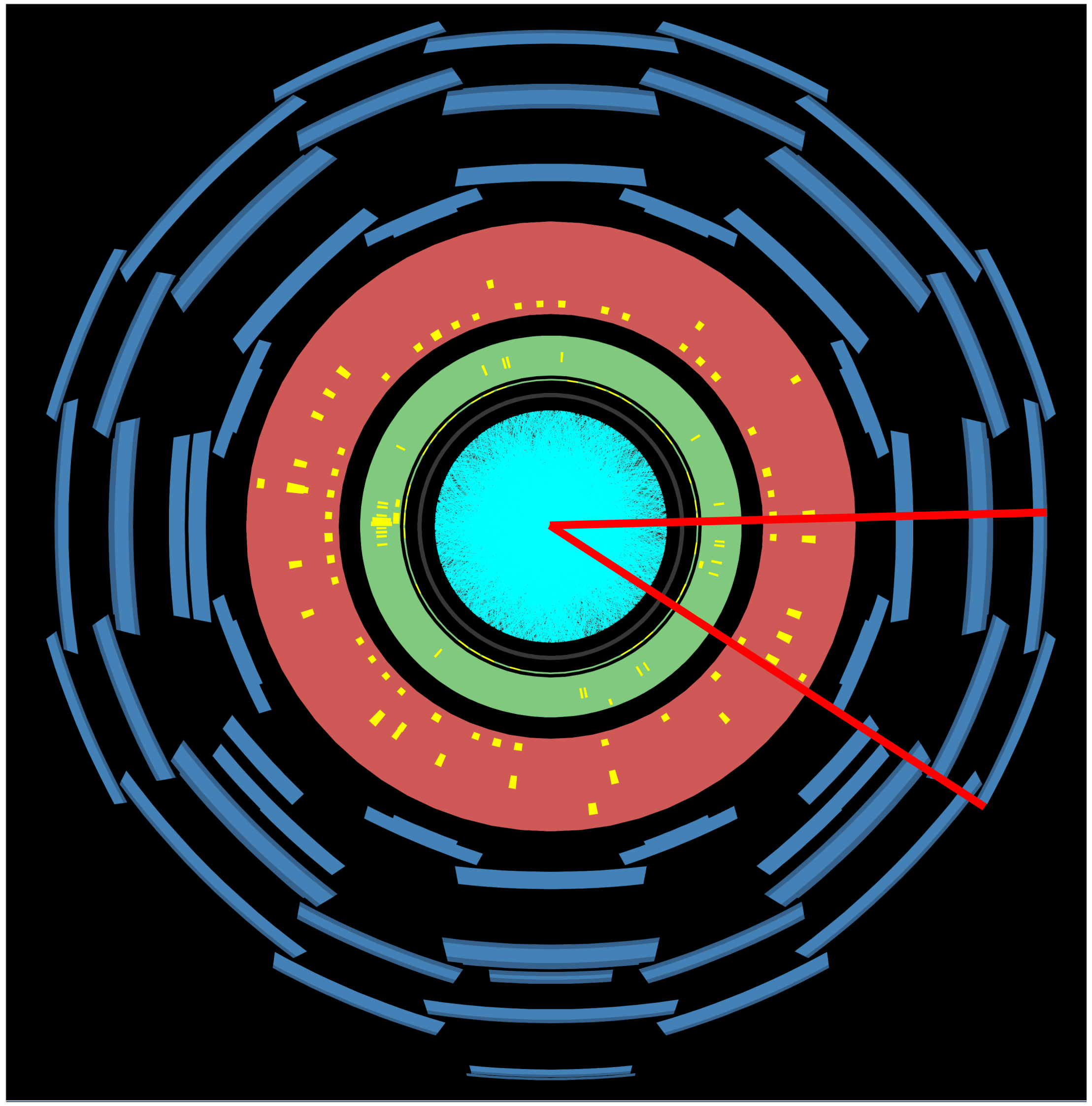
Imagine speeding that up and trying to pick out the higgs!

The trigger challenge

If we saved every LHC event
in an hour we'd accumulate
as much data as as one year of
Facebook uploads

We can only save one thousand
events (or crossings) per second

Can only select ~1 in a million collisions
And we need to do it quickly!



how can we pick out the interesting events?

The Trigger

We can only store ~1 in 10^5 events for analysis

The trigger makes this high stakes decision in real time

The Trigger

We can only store ~1 in 10^5 events for analysis

The trigger makes this high stakes decision in real time

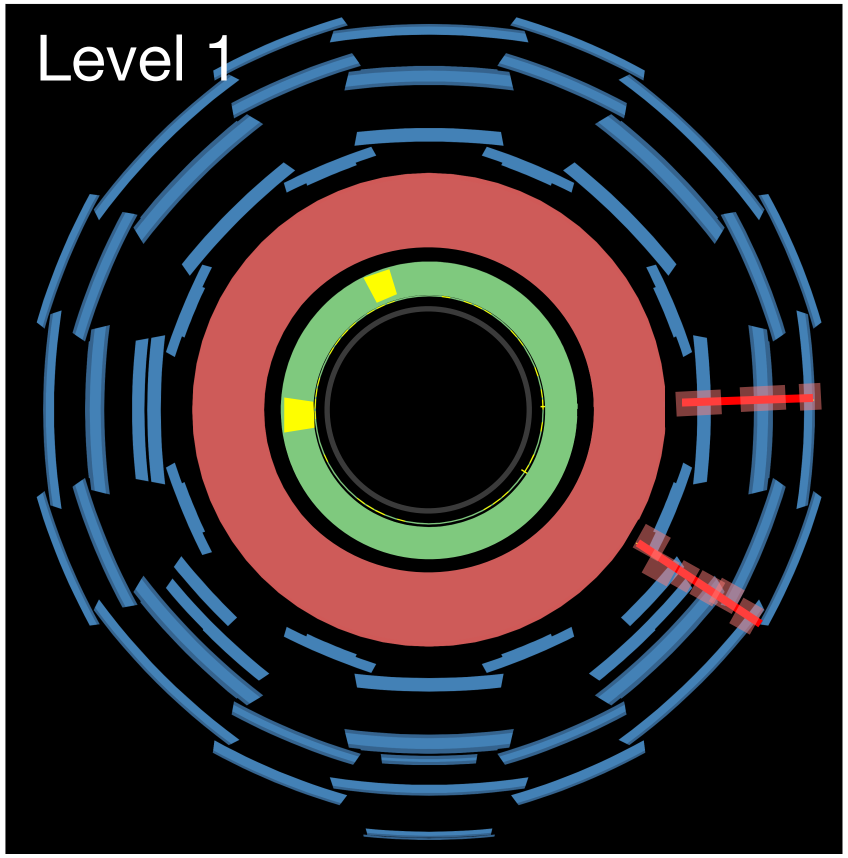
First step:

6 μs to make a decision

hardware based

coarse muon and calorimeter information

Keep ~1/400 events



The Trigger

We can only store ~1 in 10^5 events for analysis
The trigger makes this high stakes decision in real time

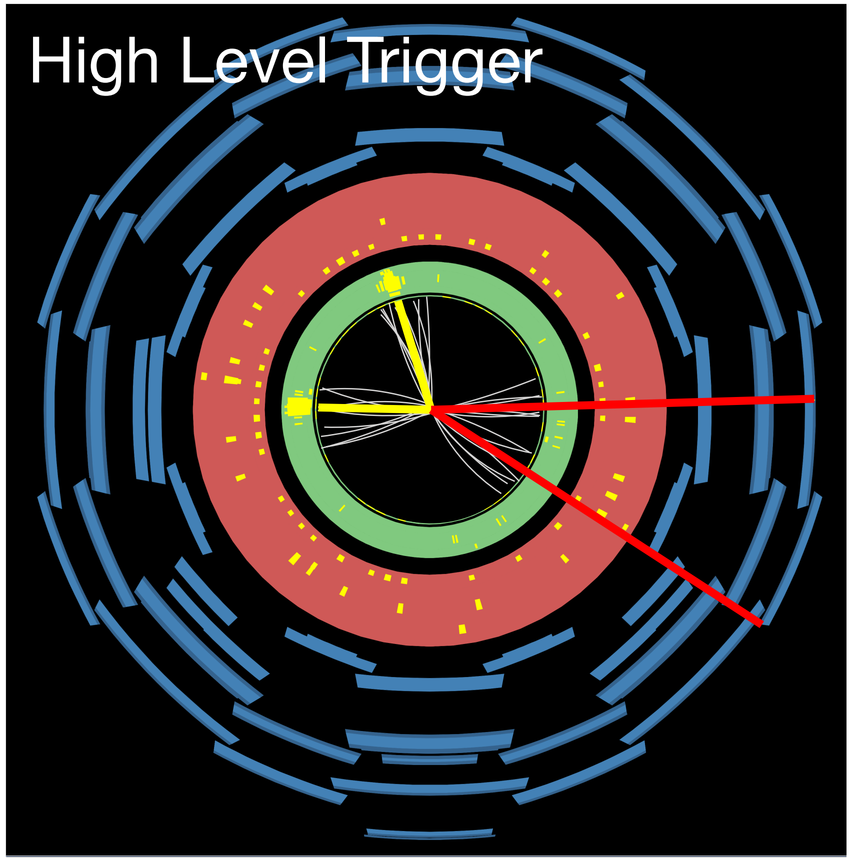
Second step:

300 ms to decide

software based

Refine information &
add limited tracking

Keep ~ 1/100 events



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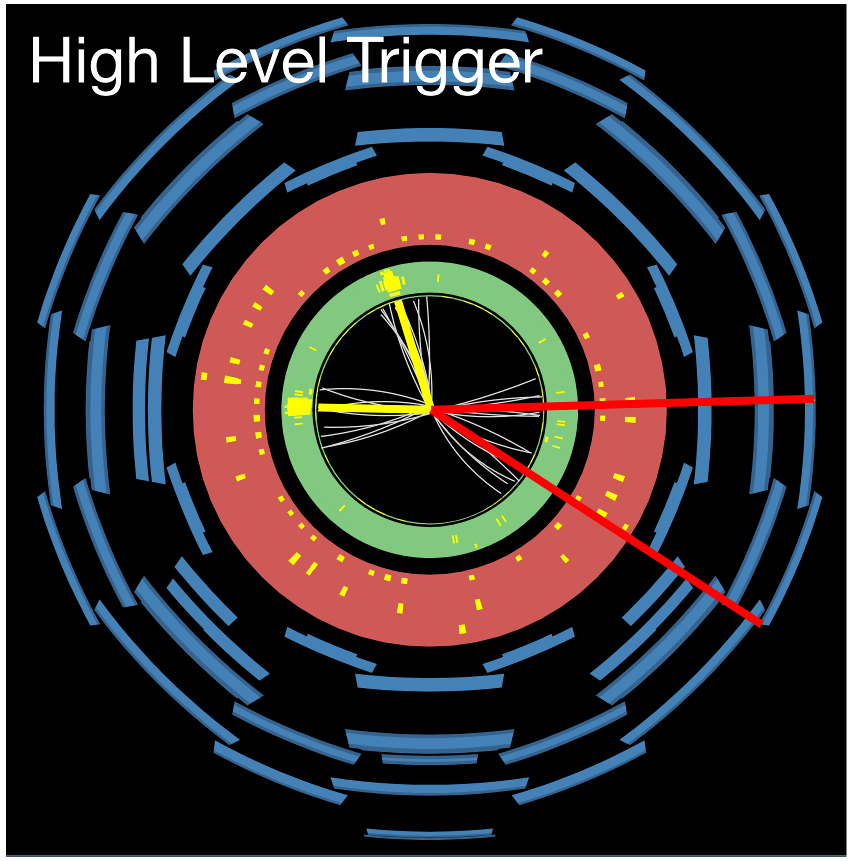


Designed for prompt, high momentum objects, and works very well!

No room for error!

Data taking is a high stakes environment

If the trigger throws your event away, it's lost forever

If something goes wrong with your detector
can't use that data for physics

ATLAS and CMS take data 24/7

8 shifters in the Control Room

~30 people reachable by phone

Teams of experts who
work to maintain detectors

Teams of experts who
work to maintain computers

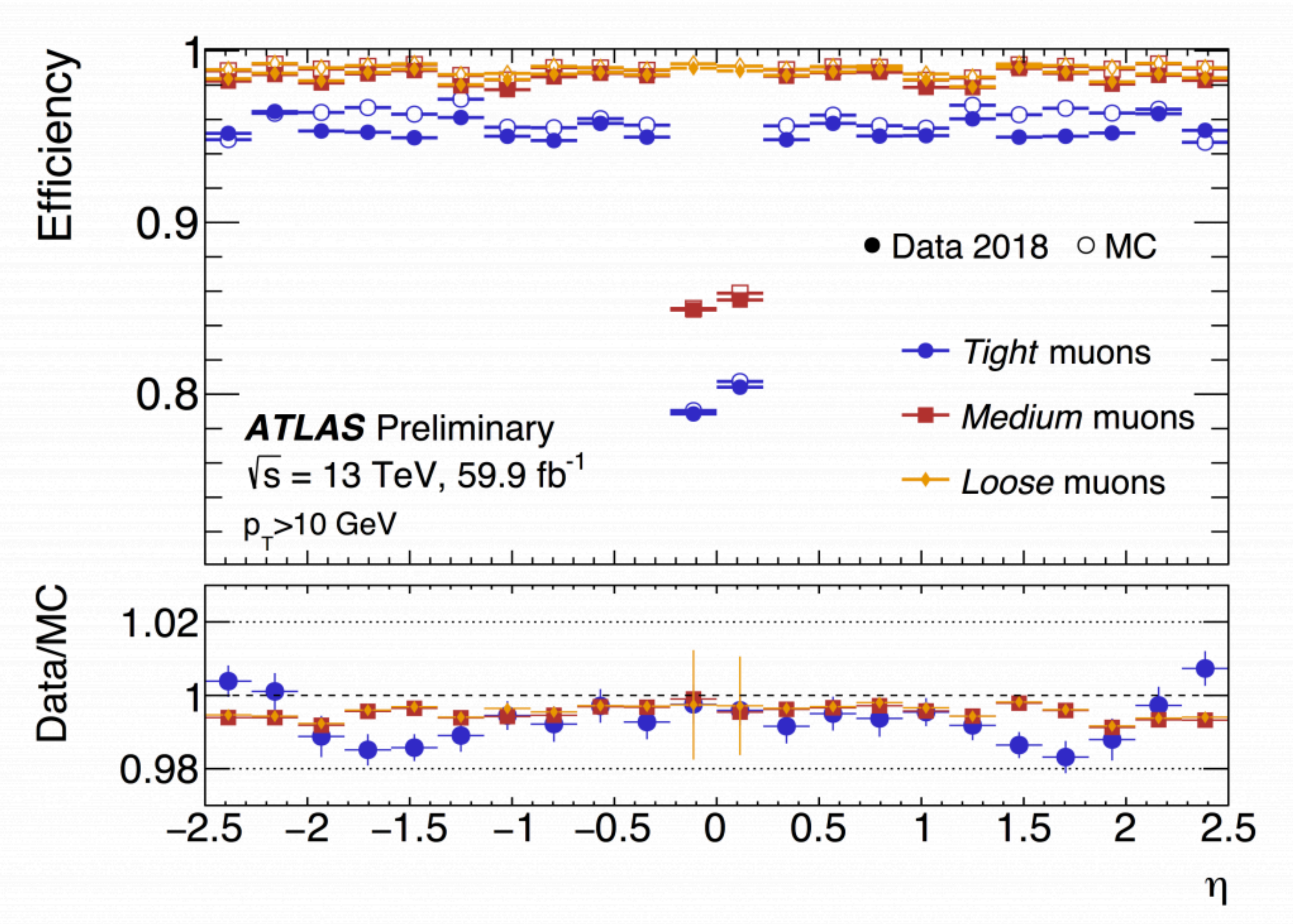
The work doesn't stop there

After data taking

Quantify detector performance

Make projections to ensure detectors will keep working

Ensure good agreement between predictions & data



Finally our data is ready for physics

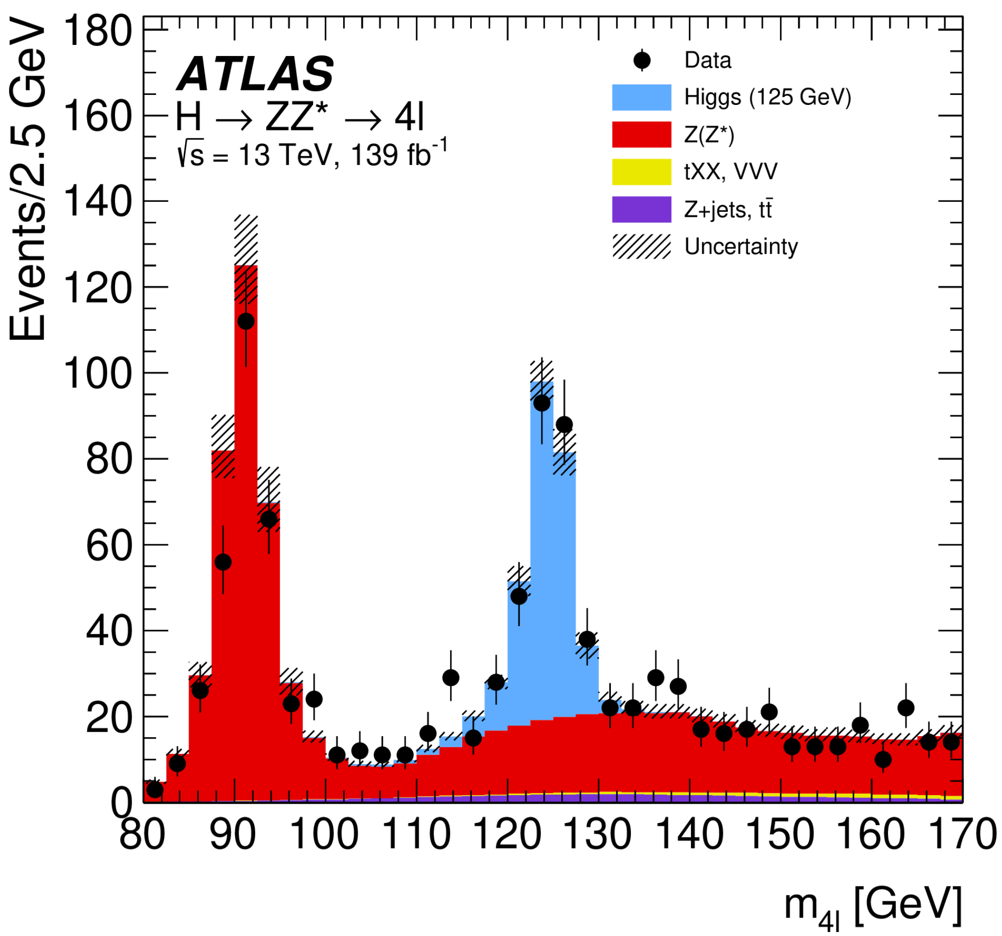
And it's not just used for one Higgs measurement

measure top quark mass

study properties of W/Z bosons

look for new exotic particles!

Every analysis we do is incredibly rewarding
and tells us something new about particle physics



=

!

A communal effort

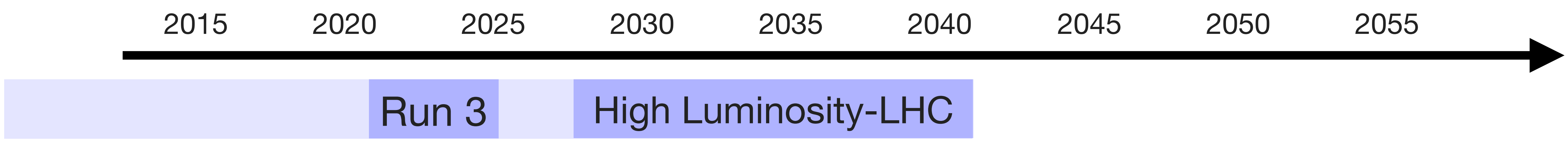
CMS isn't possible without all these wonderful colleagues!

The CMS collaboration
2700 physicists
900 are students!

Fermilab's LHC Physics Center
350 users & 100 residents
from 50 universities

What’s next?

What’s next?



Today

Major detector upgrades

Higgs Factory

Higher Energies

we’ve only collected 5% of the LHC’s data so far!

Next machine is likely to be an e+e- collider designed to study the Higgs boson in a clean environment

Followed by an even higher energy collider (proton or munons)

We should know more soon!

US planning process is ongoing

Conclusions

Standard Model is not the complete picture of the universe

High energy particle colliders are
one of the most effective ways to look for new particles
and to do measurements which try to “break” the Standard Model

Being a scientist at the Large Hadron Collider means
you have MANY wonderful collaborators
working together on fun detector, trigger, and analysis challenges

The future is bright: new physics could be lurking just around the corner!