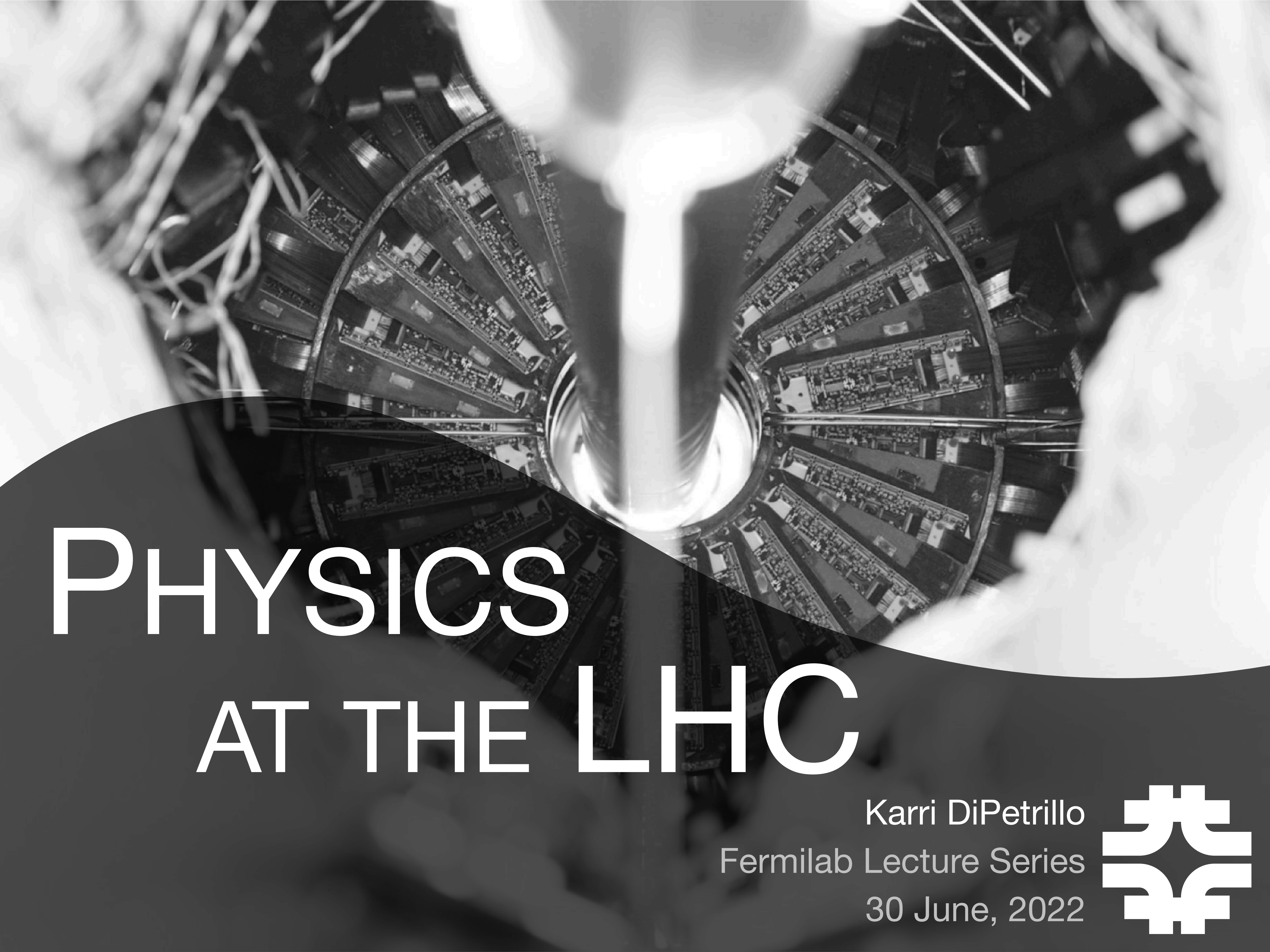


Physics at the LHC

Karri DiPetrillo
Fermilab Lecture Series
30 June, 2022

About Me

- High school in Providence, RI
- ScB from Brown in 2013
  - Research & concentration in biological physics
- PhD from Harvard in 2019
  - Searches for long-lived particles
  - ATLAS Muon Spectrometer
- Now: Lederman Fellow at Fermilab
  - CMS searches for new physics with unconventional signatures
  - Precision timing with silicon detectors

About Me

I enjoy…

trashy tv

bike riding

my dog, Peanut!

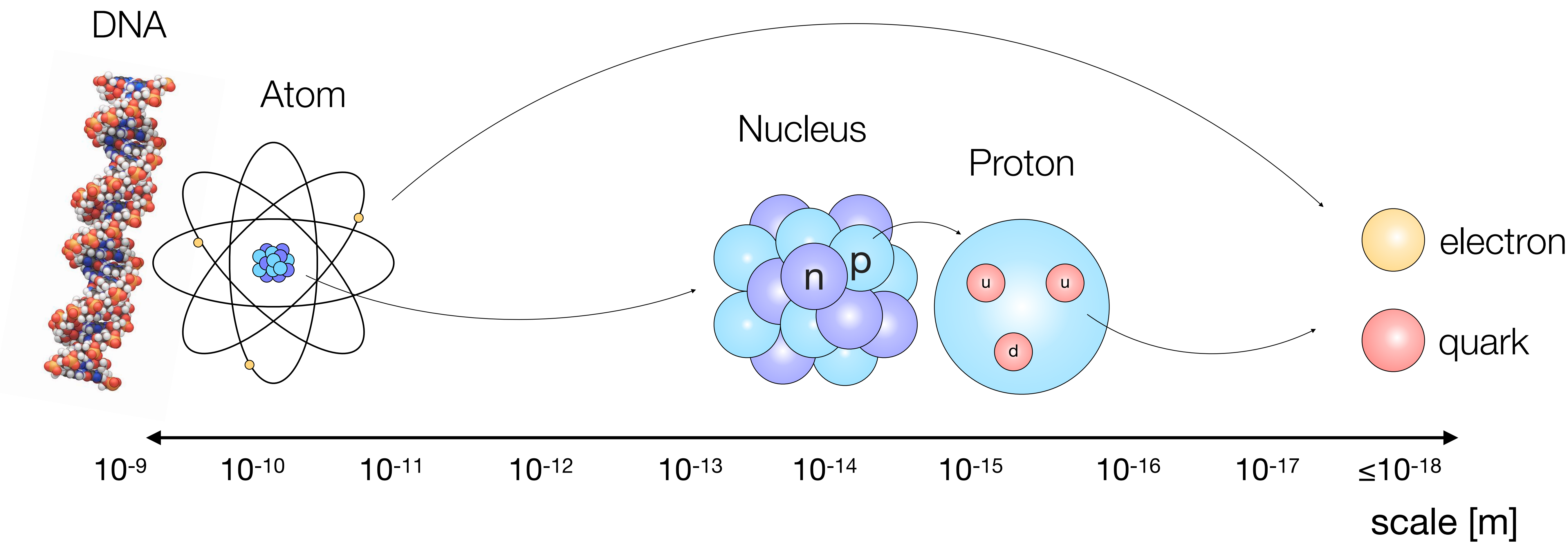
email: kdipetri@fnal.gov

About this lecture

- Adapted from a Saturday Morning Physics lecture for high school students
    - joint with Christian Herwig and Alexx Perloff
- We'll talk about
    - Why particle physicists use colliders
    - What kinds of questions we want to answer at the LHC
    - How the CMS and ATLAS experiments works
    - How to do an example analysis
- Other great resources
    - CERN Summer Student Lecture Series [2019]
    - Proceedings of other intros to LHC physics
        - https://arxiv.org/abs/1004.5564
        - https://arxiv.org/abs/1611.07864
    - Physics motivation for ATLAS/CMS detector design
        - At the Leading Edge: Chapter 1

Particle physics

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



And the forces that govern these particles

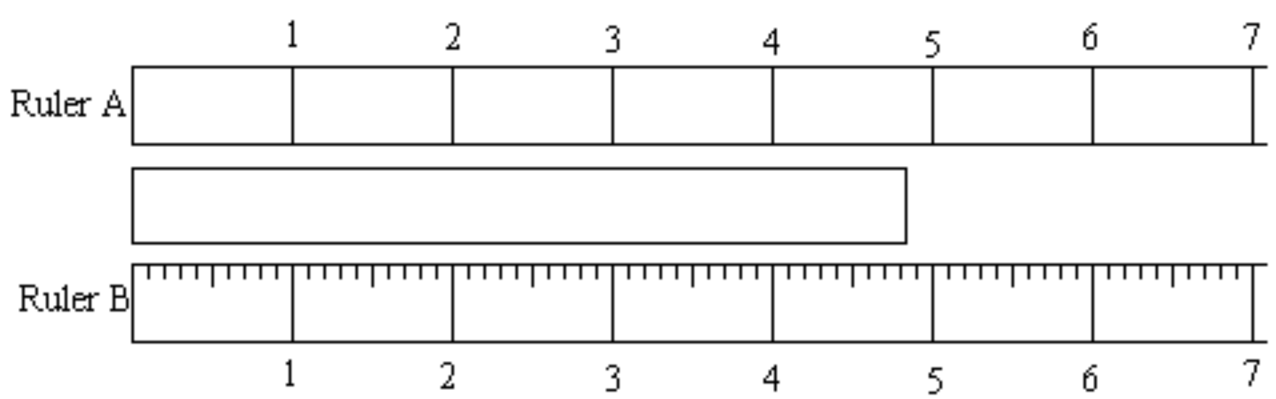
How do we access small scales?

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)

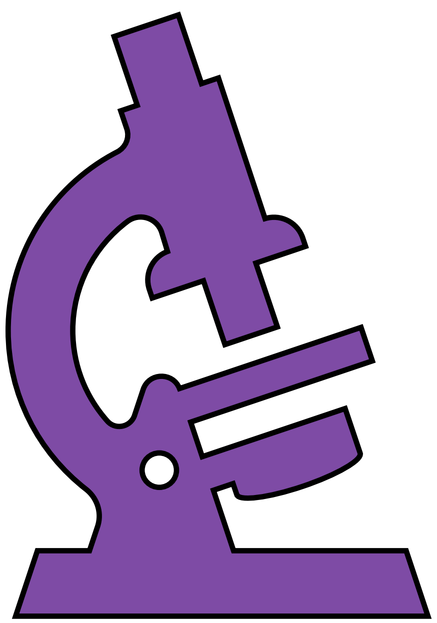


Small wavelengths probe small scales

Colliders as a Microscope

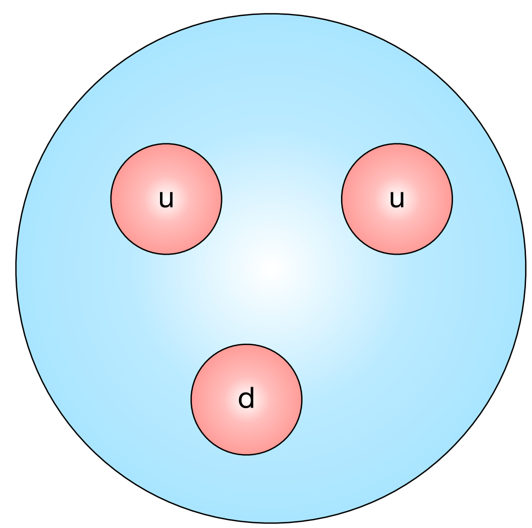
→High-energy collisions access small scales

Visible light



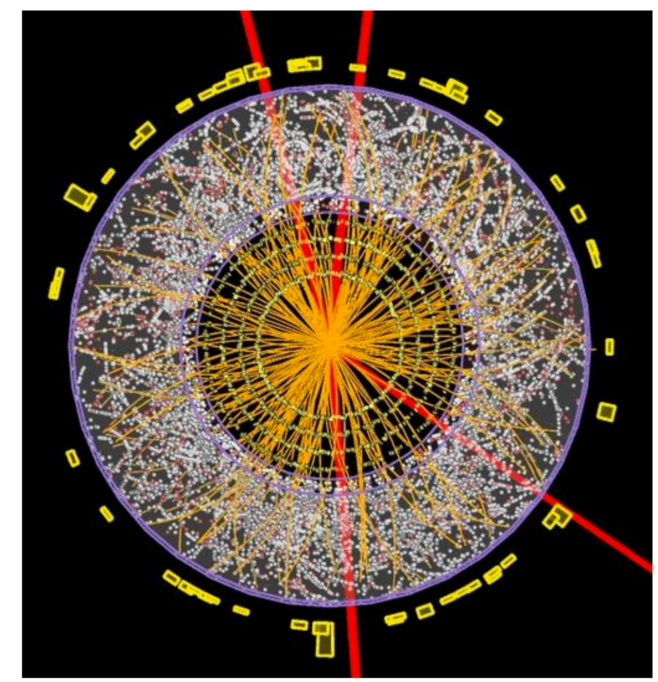
~ 2 eV
~ 5x10^{-7} m

Proton



~ 1 GeV
~ 10^{-15} m

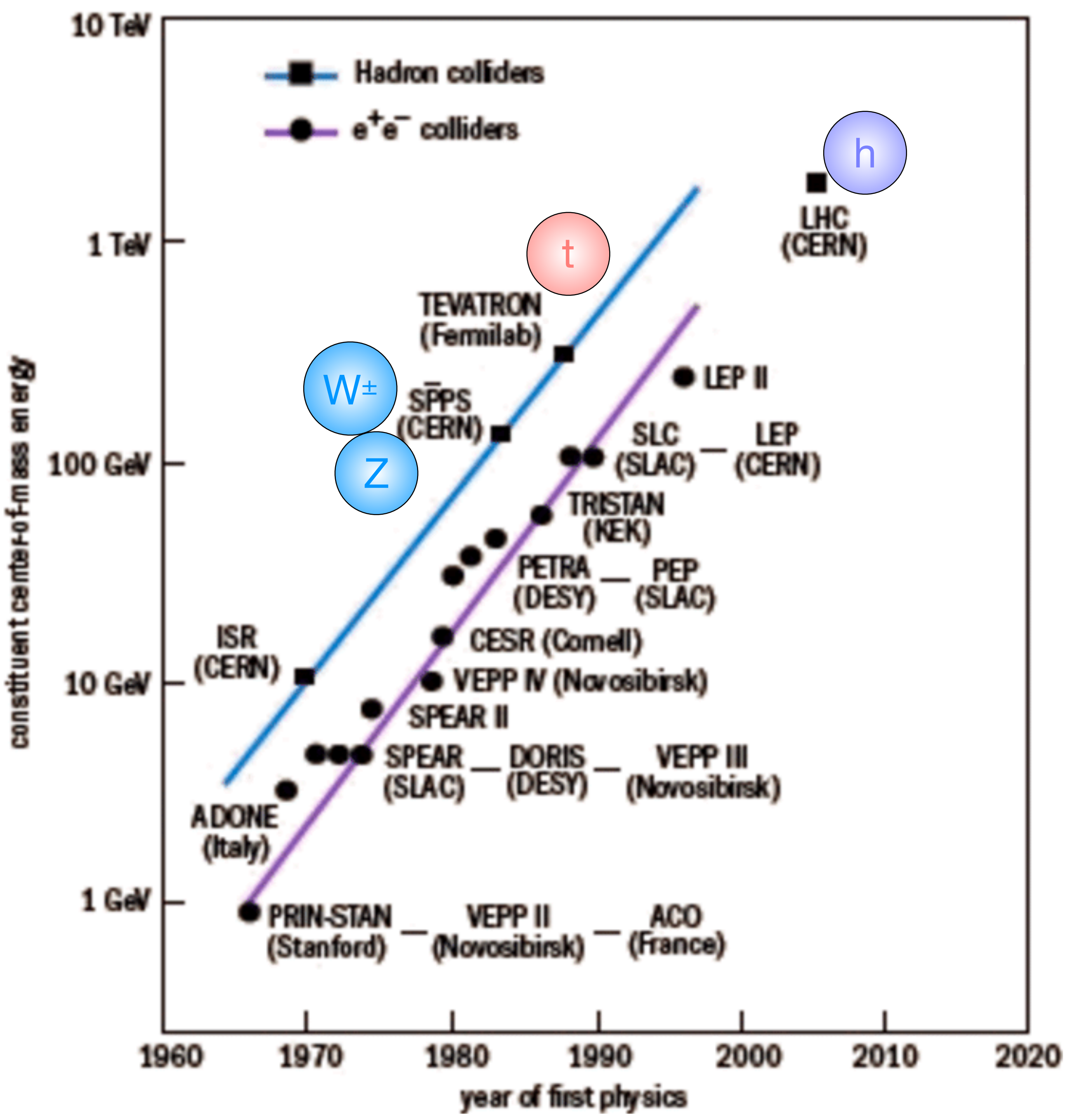
LHC Collision



13.6 TeV
~ 10^{-19} m

*eV = energy an electron gains over 1 volt
Giga ↔ billion, Tera ↔ trillion

Long history of success!



Exciting & effective way to discover new fundamental particles

1985: W and Z @SppS

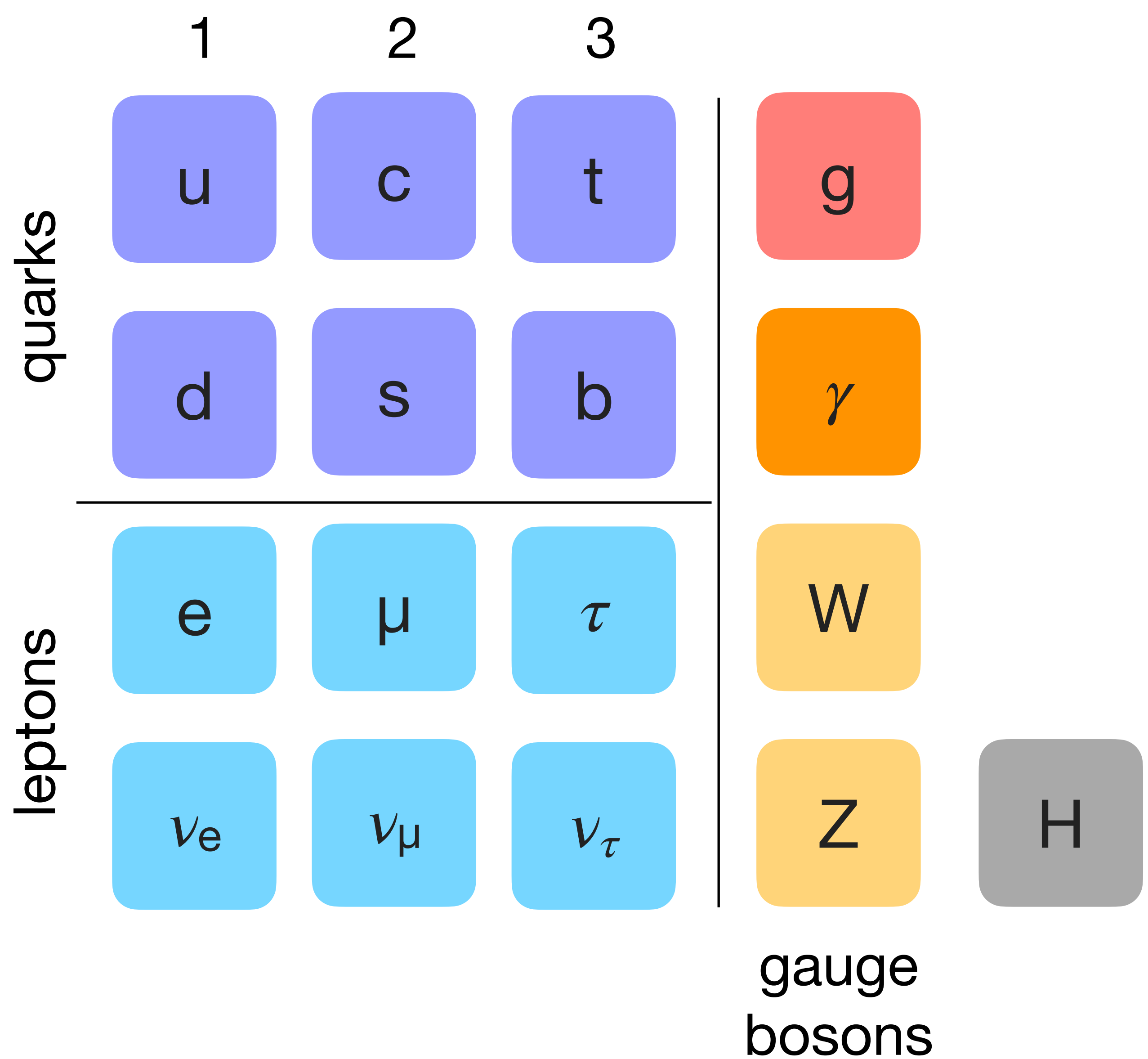
1995: Top Quark @Tevatron

2012: Higgs Boson @LHC

Long tradition of looking to smaller scales to achieve a simpler description of nature

Best known description

The Standard Model



17 fundamental particles

12 matter particles

4 force carriers

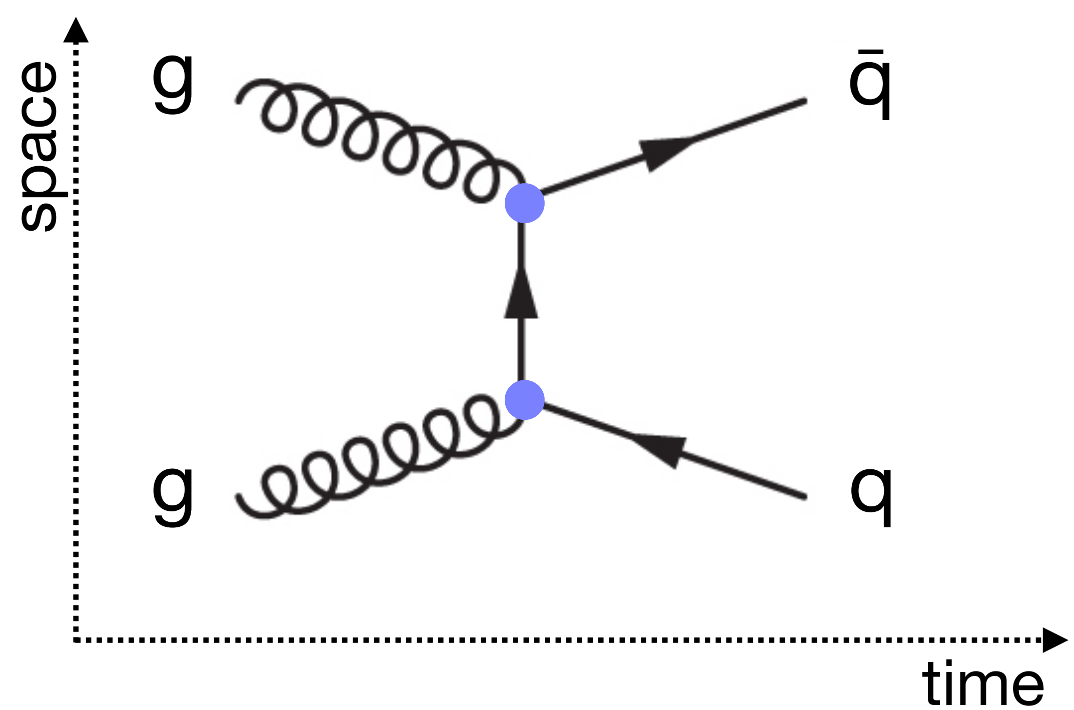
1 scalar boson

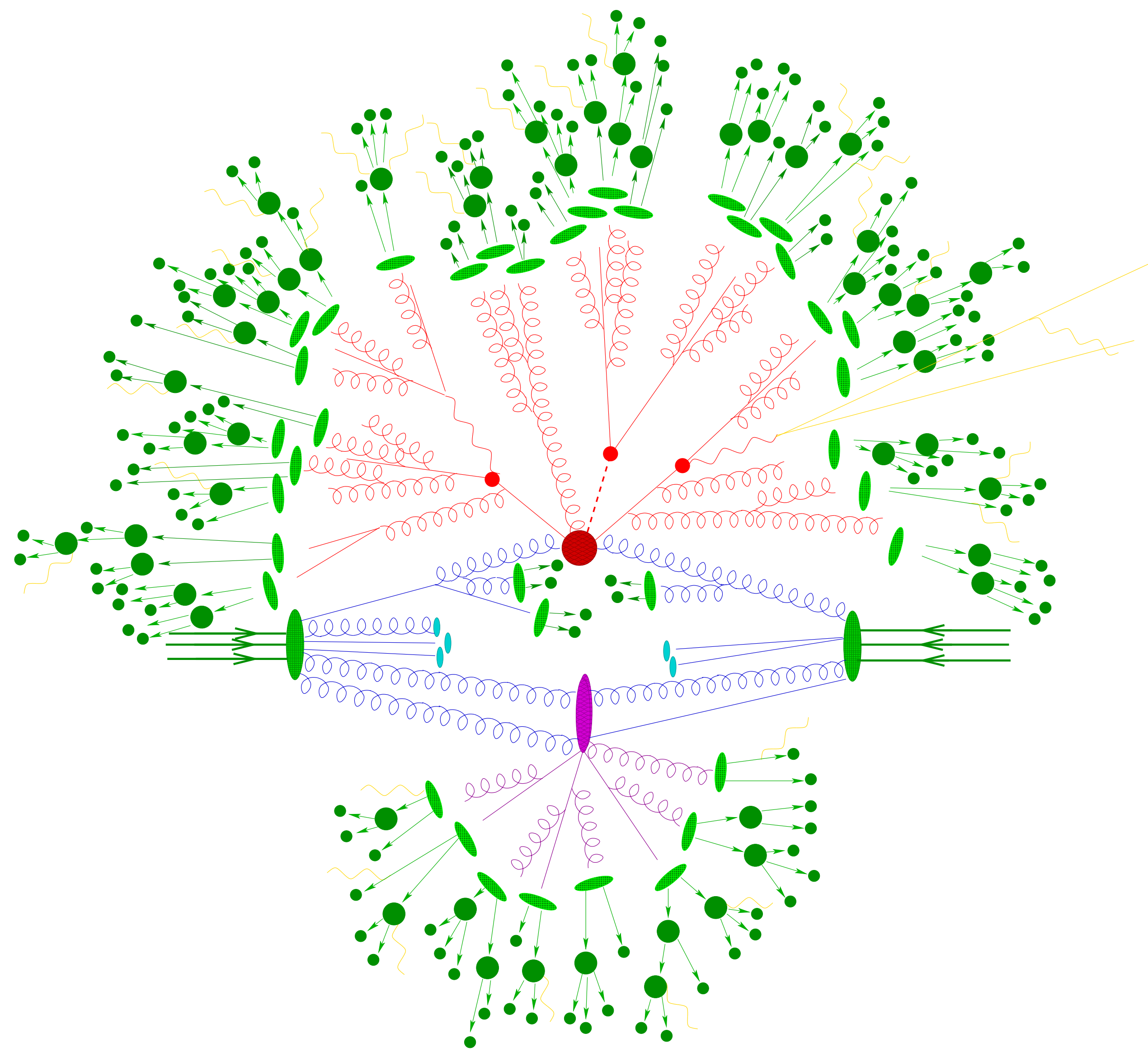
Simplicity = predictive power

Strong force: interaction structure + a single coupling

Predicts VAST range of phenomena:

proton, neutron masses
'excited' states
gluon force carrier



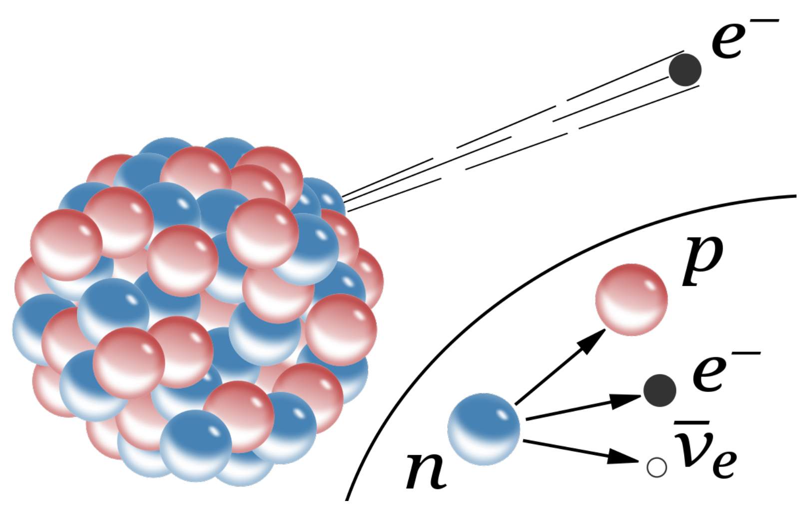


LHC collision

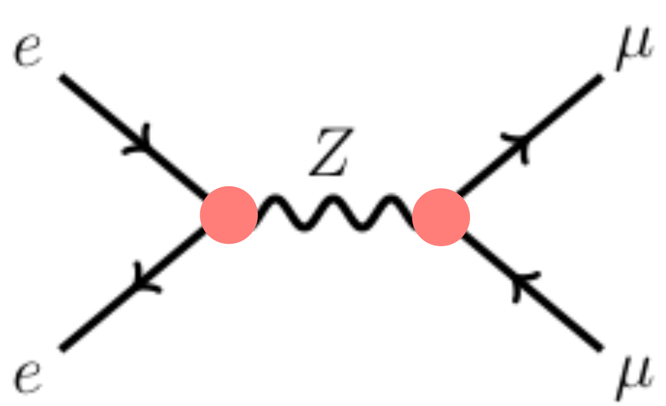
Simplicity = predictive power

Similarly, weak interactions explained by a single coupling!

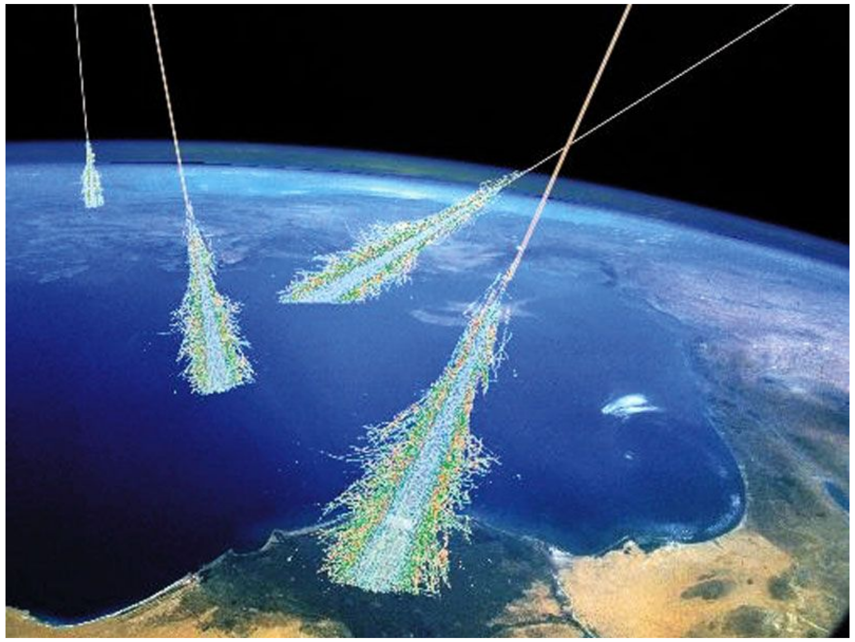
Radioactive decay

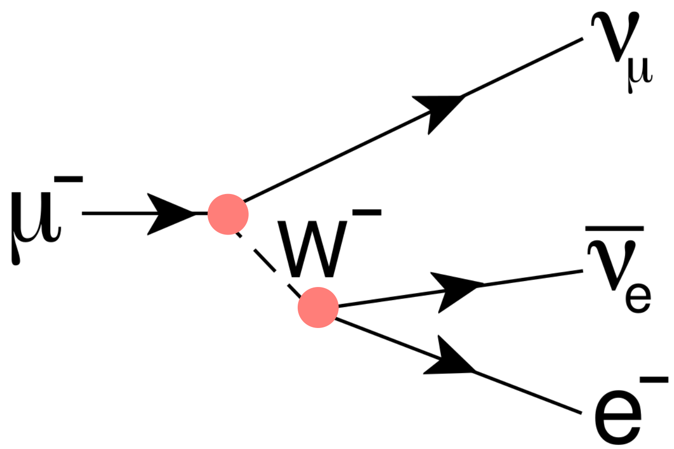


Z boson production at particle colliders



Muon decay in cosmic rays

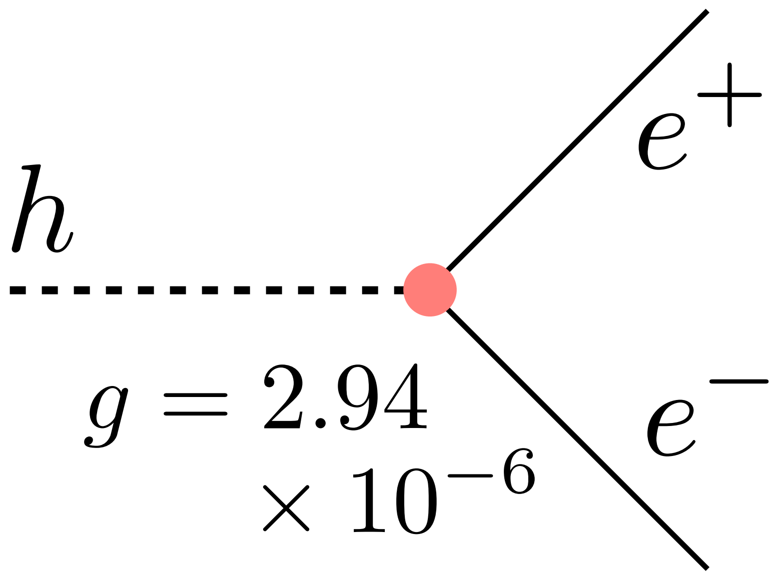




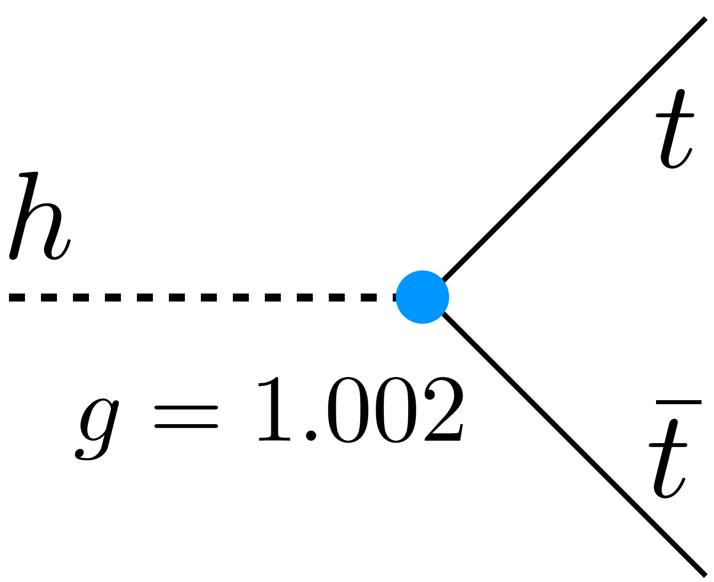
But the Higgs is different

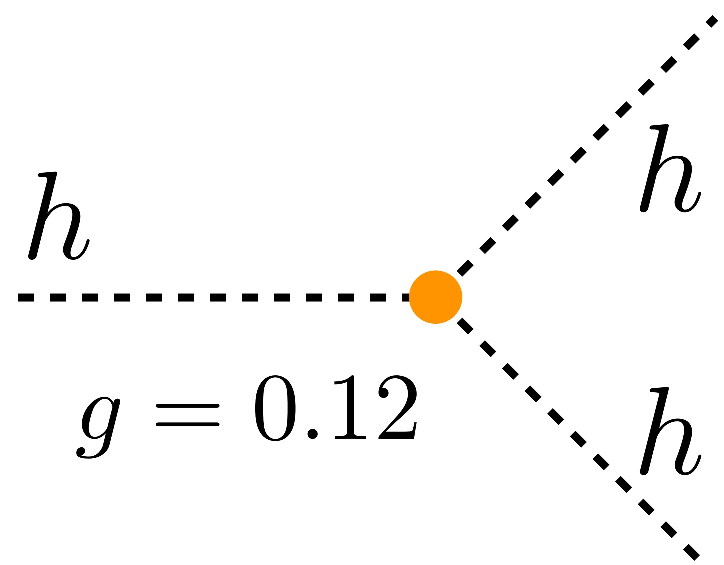
The Higgs field: couples to ALL massive particles.

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!

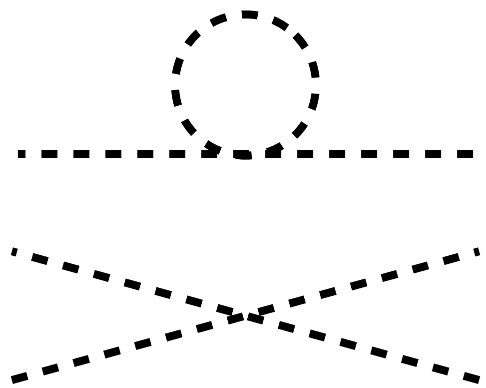
Beyond the Higgs?

- Many questions revolve around the Higgs — the newest and least-understood component of the Standard Model
  - Why are there so many different masses/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?

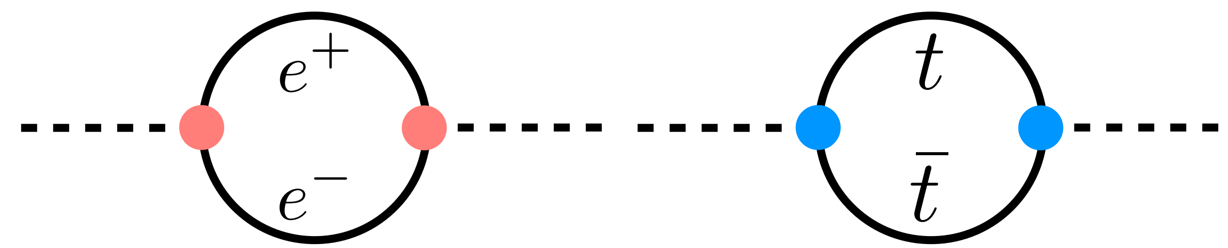
The hierarchy puzzle

Try to calculate Higgs mass. Find two contributions:

Higgs mass =



+

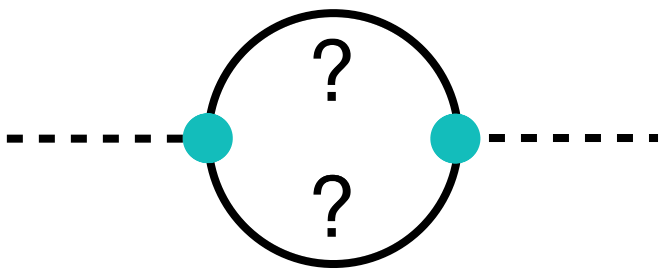


measured! 125 GeV

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

Experimental question: where are the super-partners?

Expect their masses to be near the Higgs.

We can look for these new particles at the LHC!

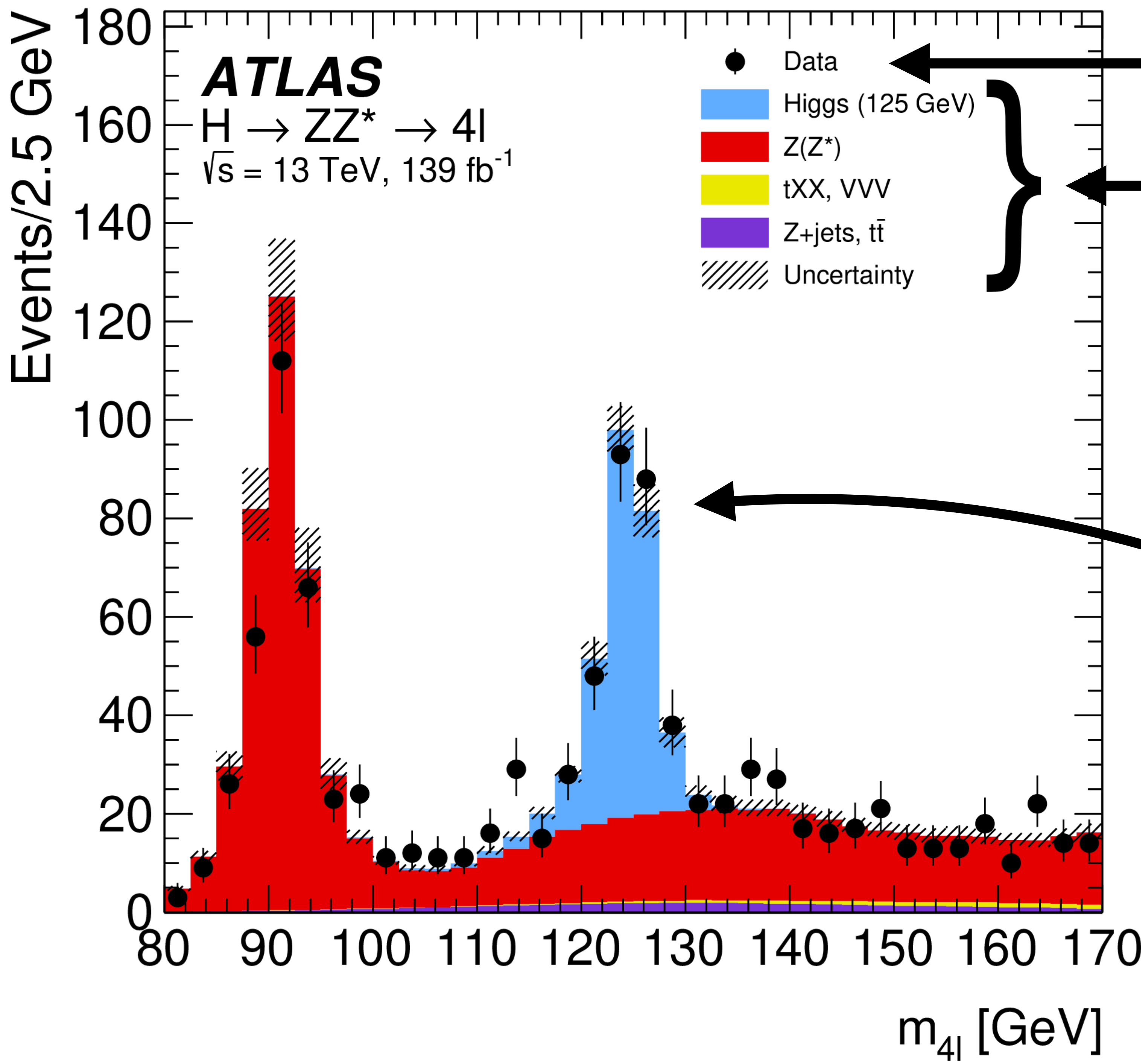
And there are even more questions

- Unexplained by the Standard Model
    - Why are there three generations of quarks and leptons?
    - Are all leptons the same?
    - Why is there more matter than anti-matter in the universe?
    - What is dark matter? Can we make dark matter particles at high energy colliders?
    - What about gravity?
    - ….
- A high energy collider is a generic way to probe all of these questions!

How to do physics at the LHC

Example: How to find a Higgs

arXiv:2004.03969

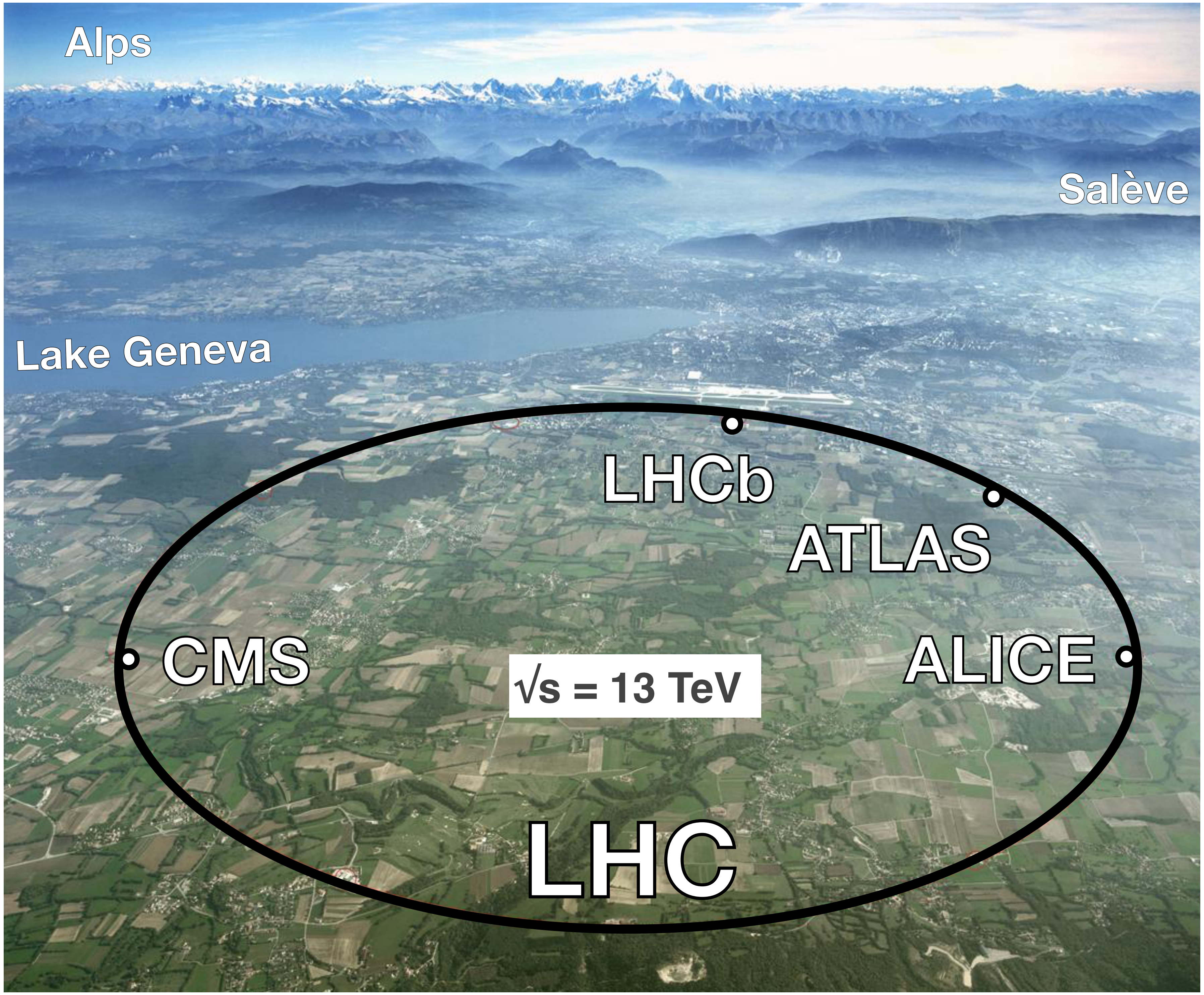


Real LHC data

Standard Model Prediction

The Higgs!

The Large Hadron Collider



The LHC =
source of particles

27 km circumference

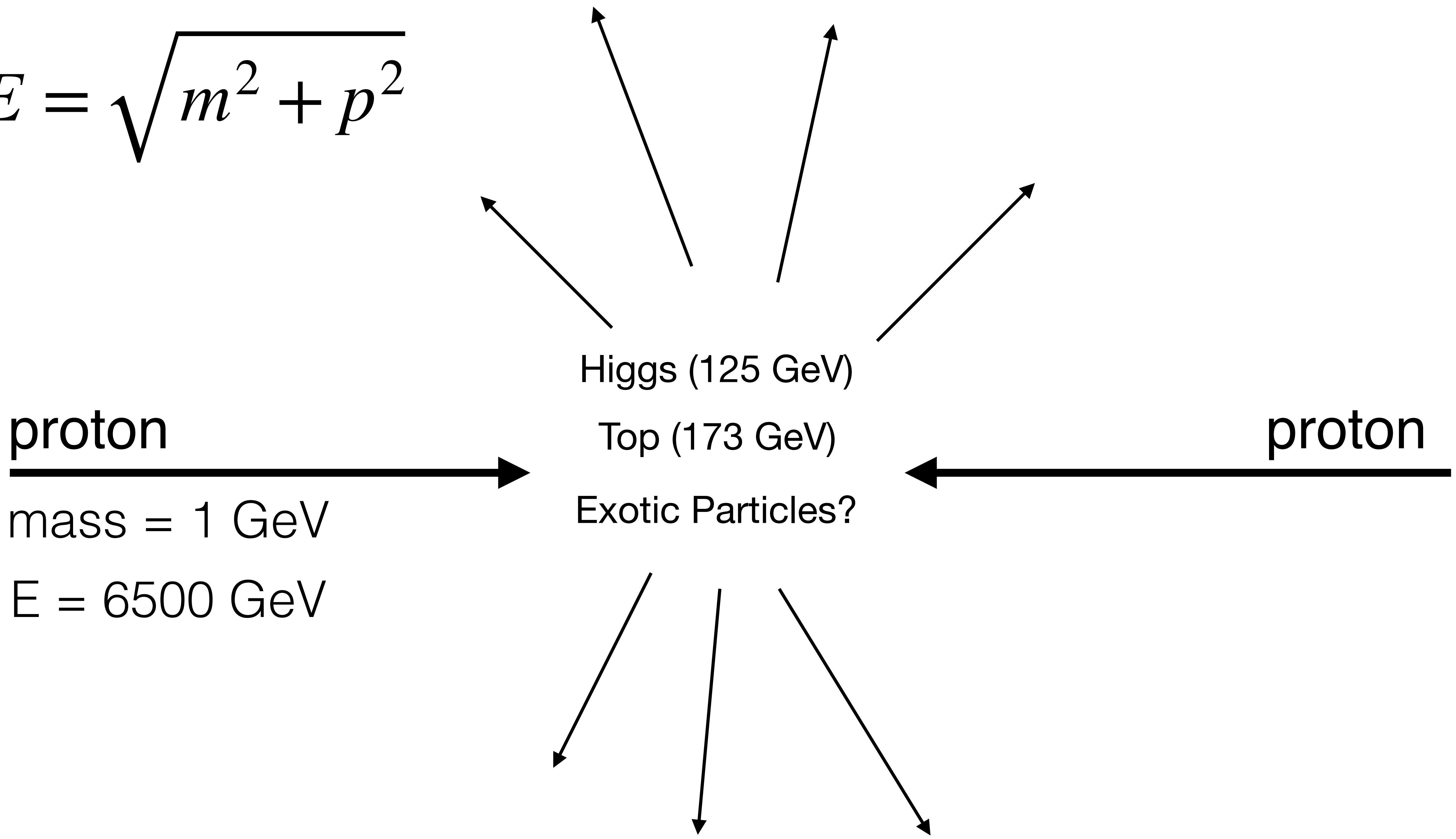
protons travel at
99.999 999 99%
the speed of light

Lives on the border of Geneva, Switzerland & France

Making heavier particles

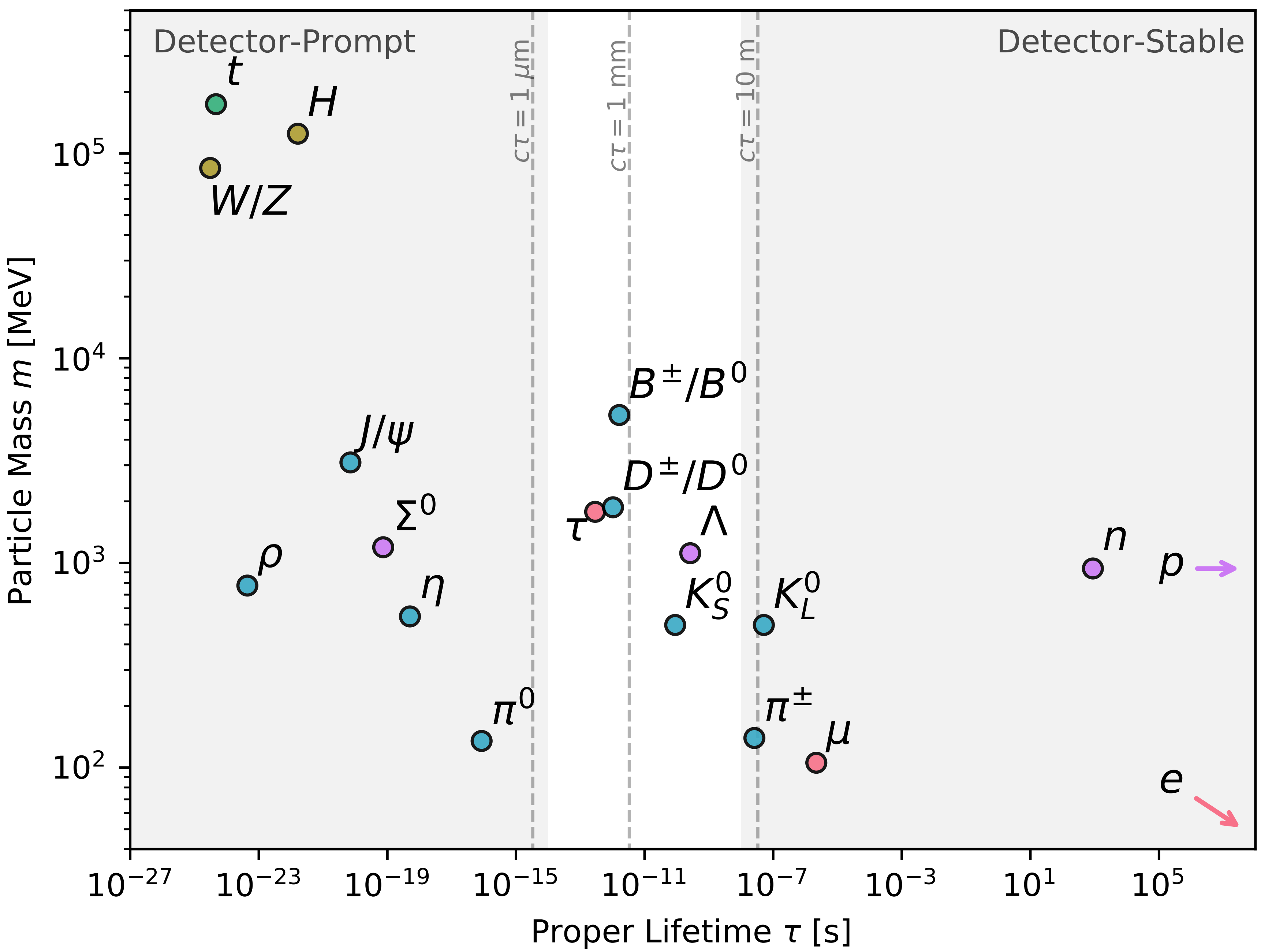
LHC = Highest energy collider in the world

$$E = \sqrt{m^2 + p^2}$$



We don’t see the Higgs, it decays…

Three categories of particles, based on lifetime

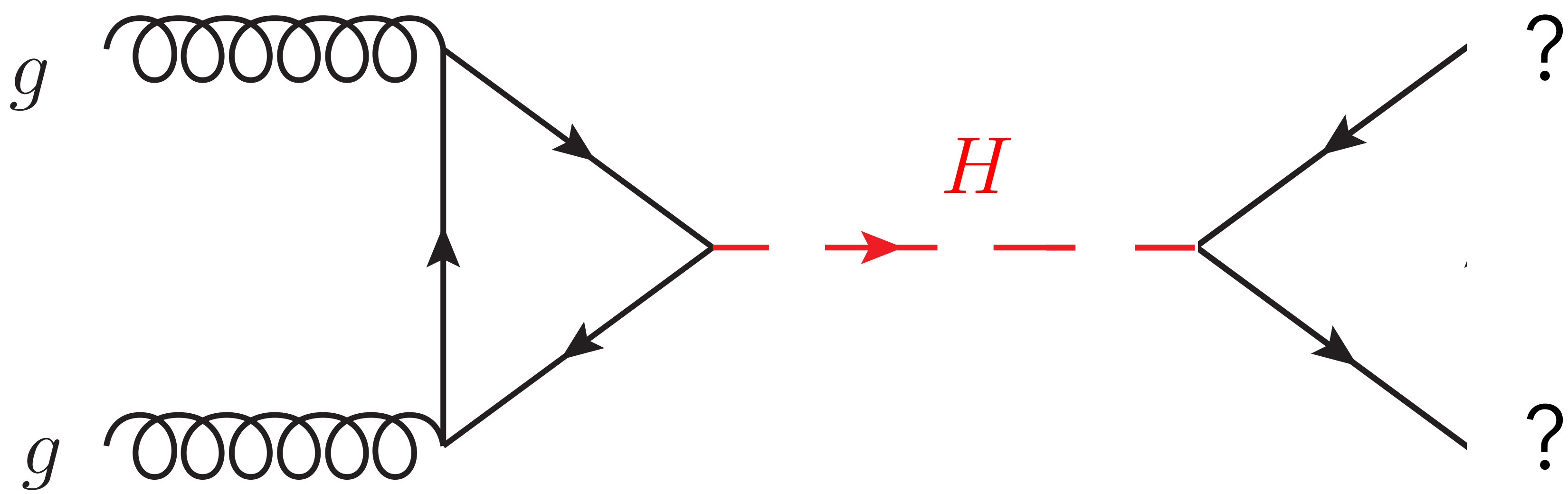


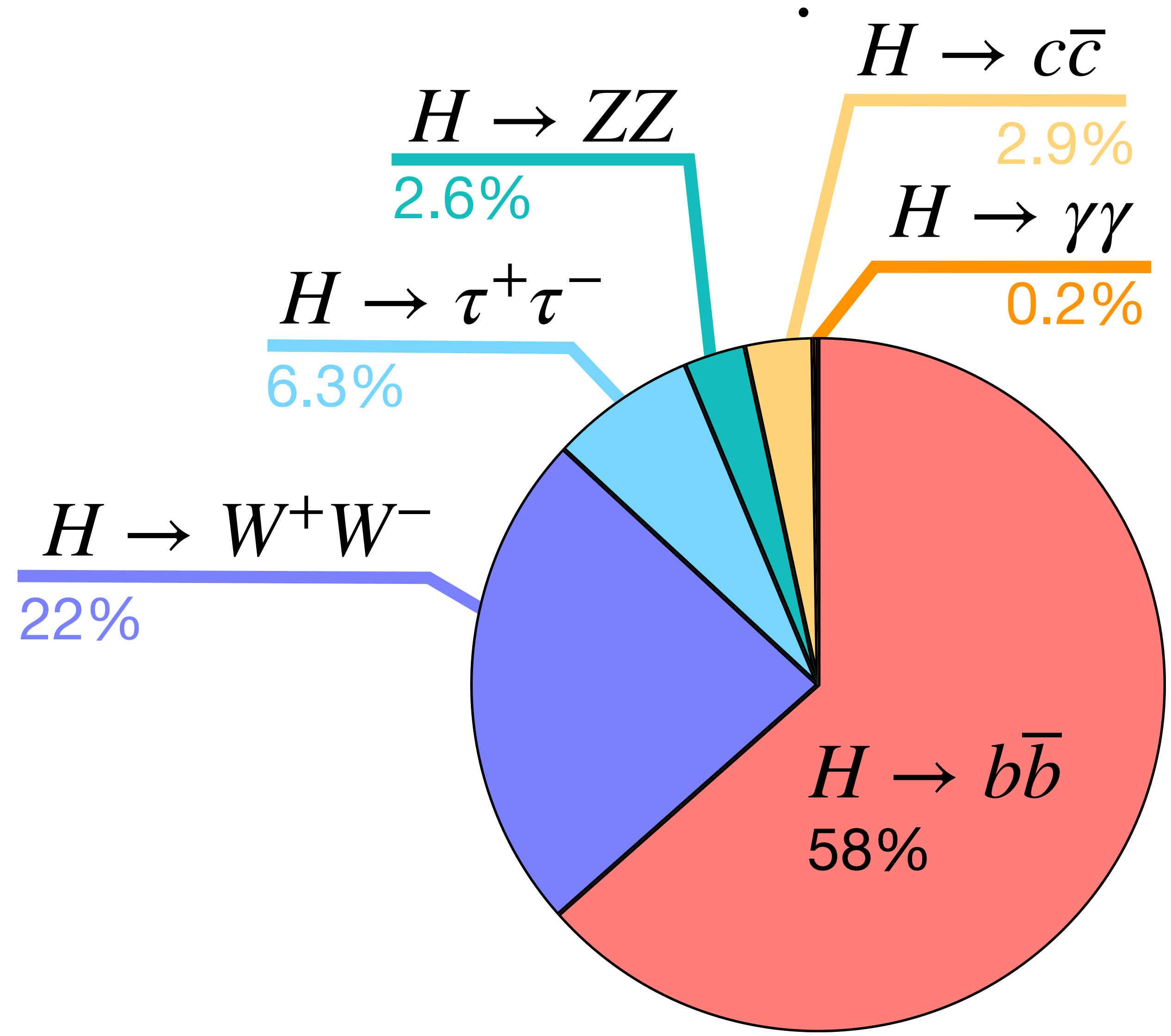
How does the Higgs decay?

produce

detect

(87%)



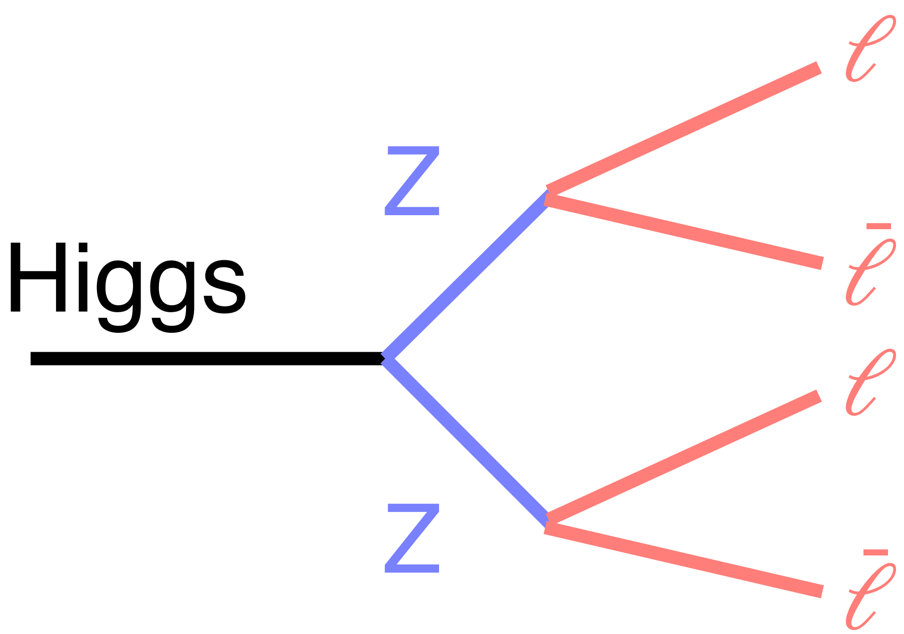


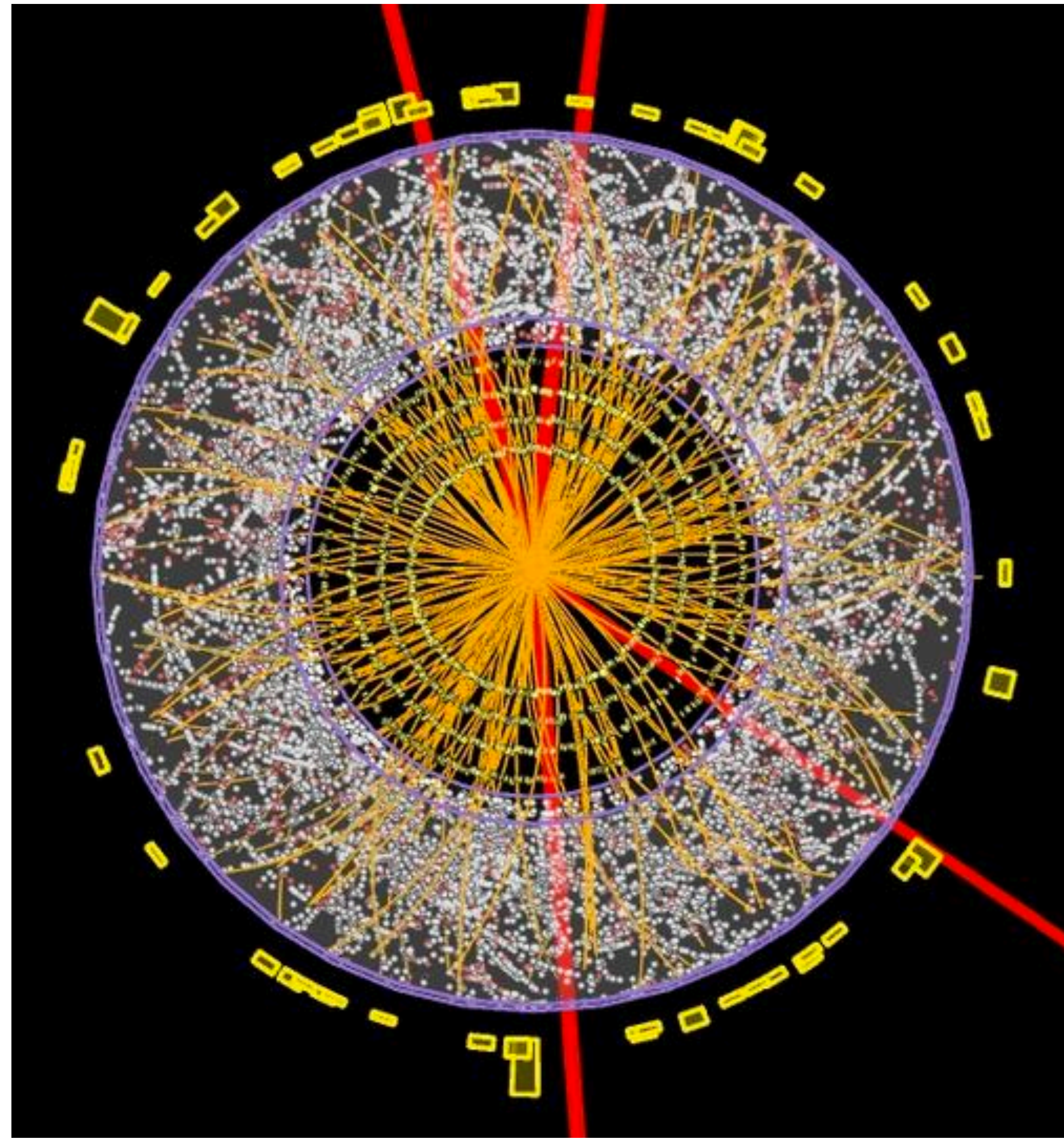
H→γγ and *H→ZZ* have small rate but are very "clean"

H→bb is large, but more difficult due to large backgrounds

What we see in the detector

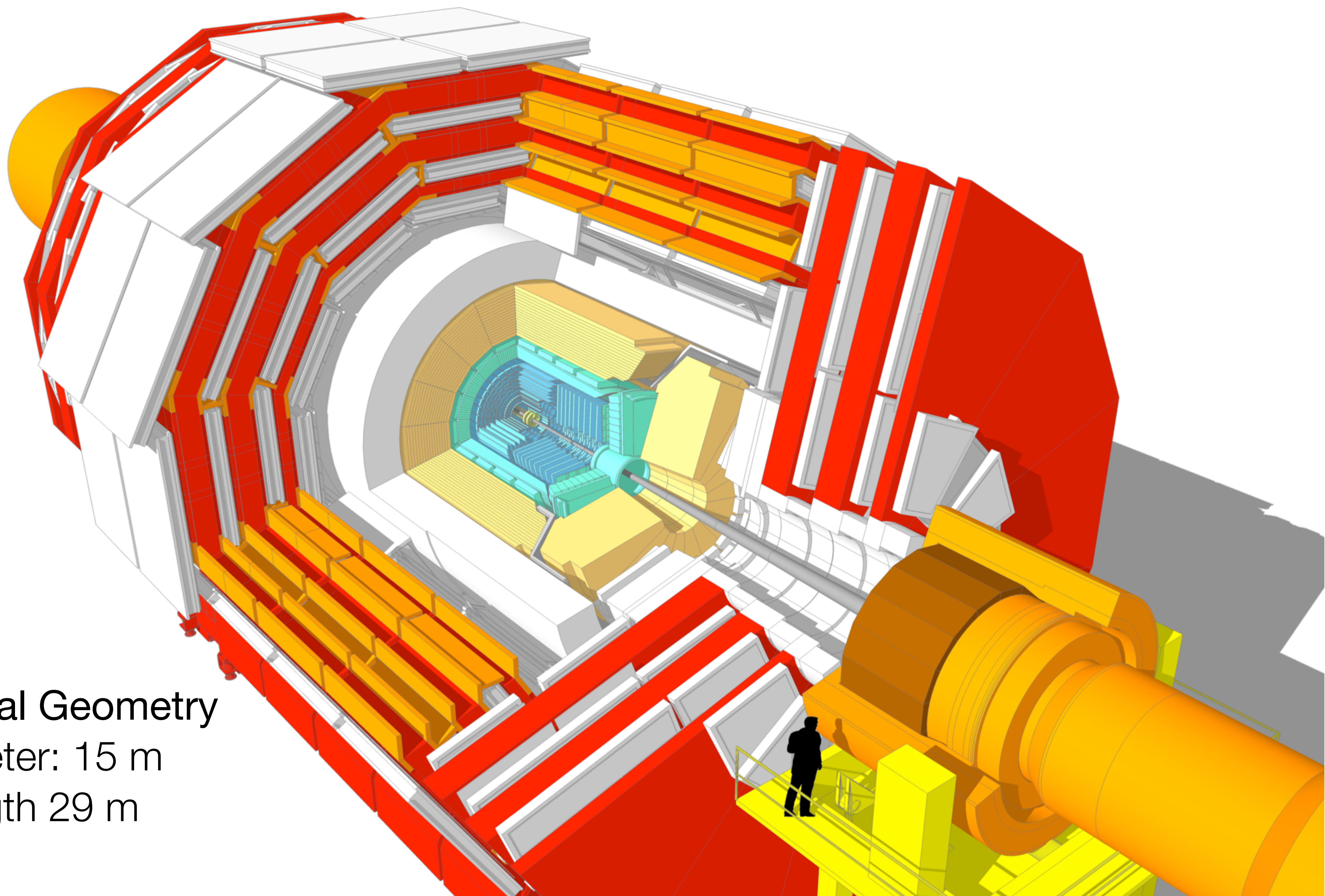
Means we never see the Higgs
Just it’s decay products





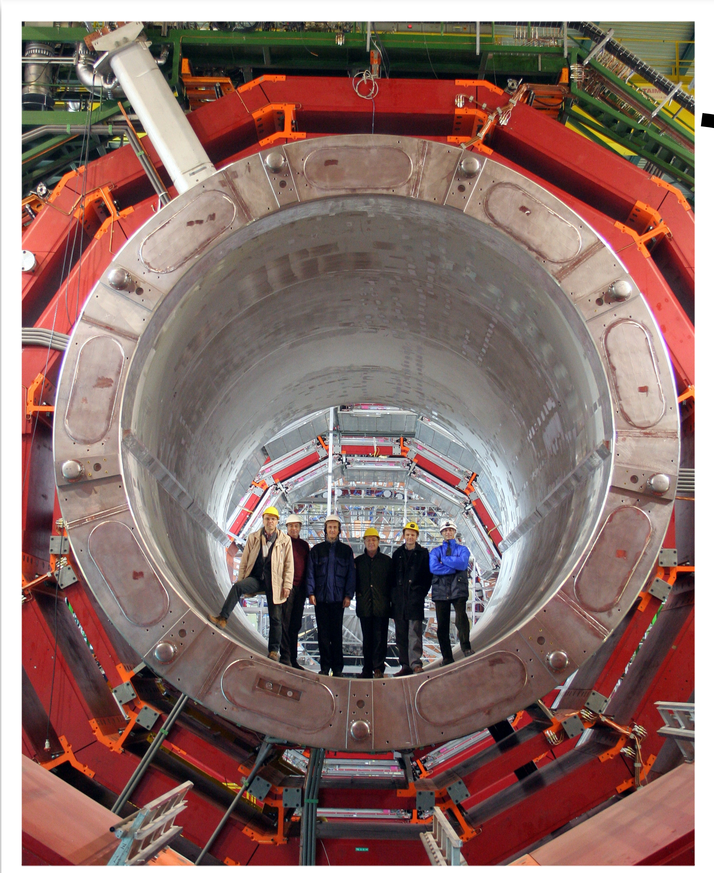
CMS detector design

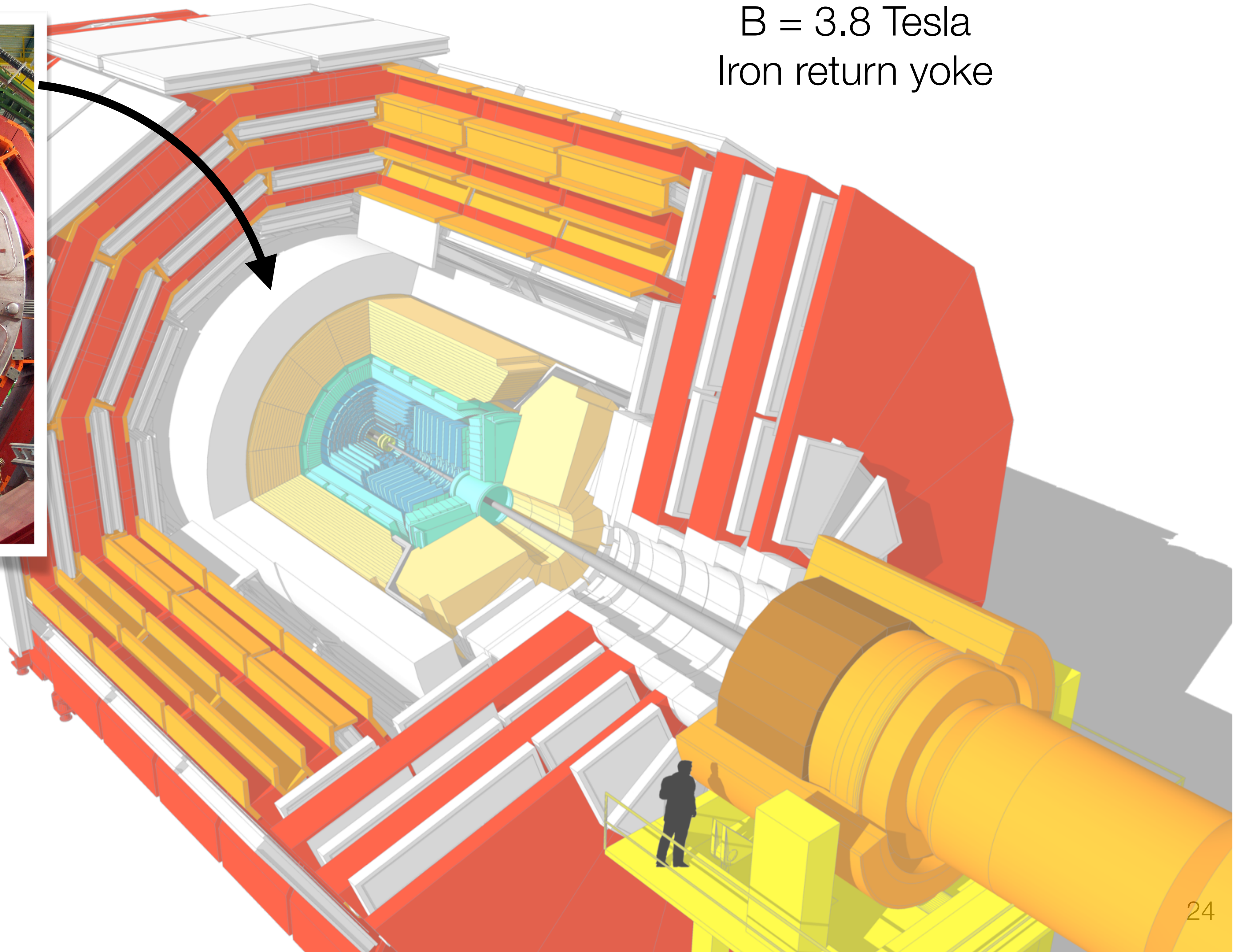
Detector goal: detect all stable Standard Model Particles



Cylindrical Geometry
Diameter: 15 m
Length 29 m

CMS detector design





Superconducting Solenoid

Largest in the world

B = 3.8 Tesla

Iron return yoke

Bends charged particles

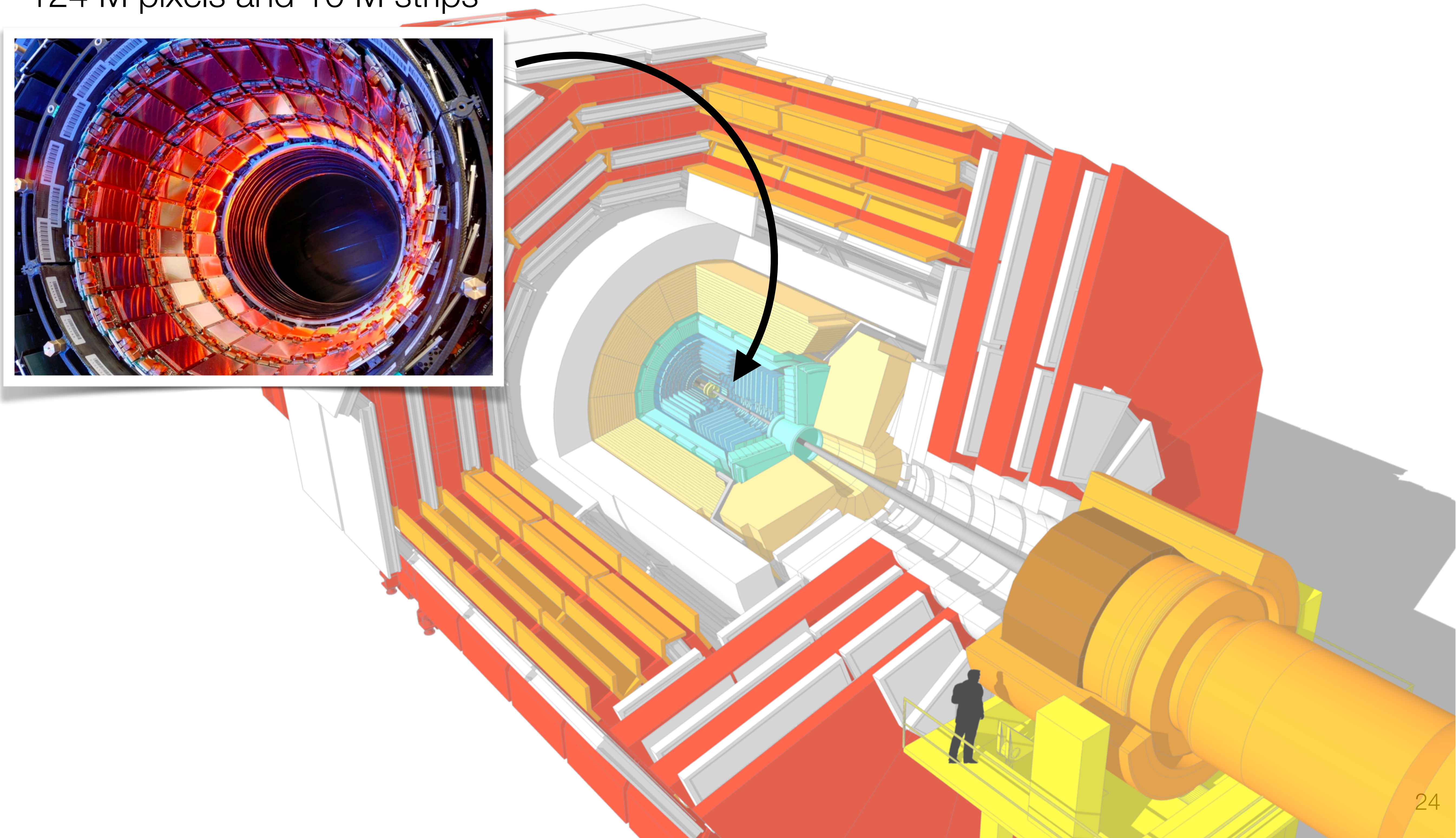
$$R = \frac{p}{q \cdot B}$$

CMS detector design

Silicon Tracker

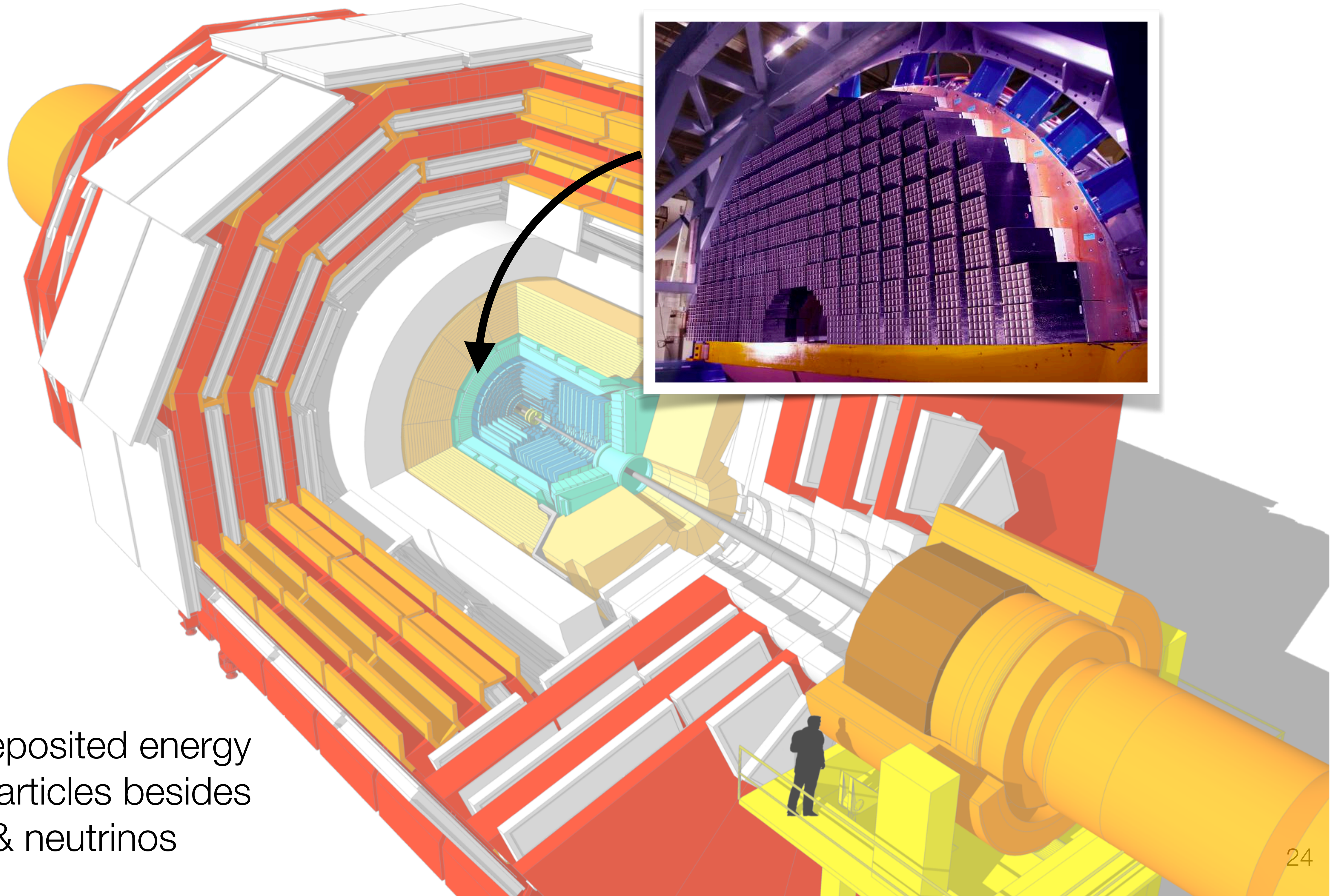
Trajectories of charged particles

124 M pixels and 10 M strips



CMS detector design

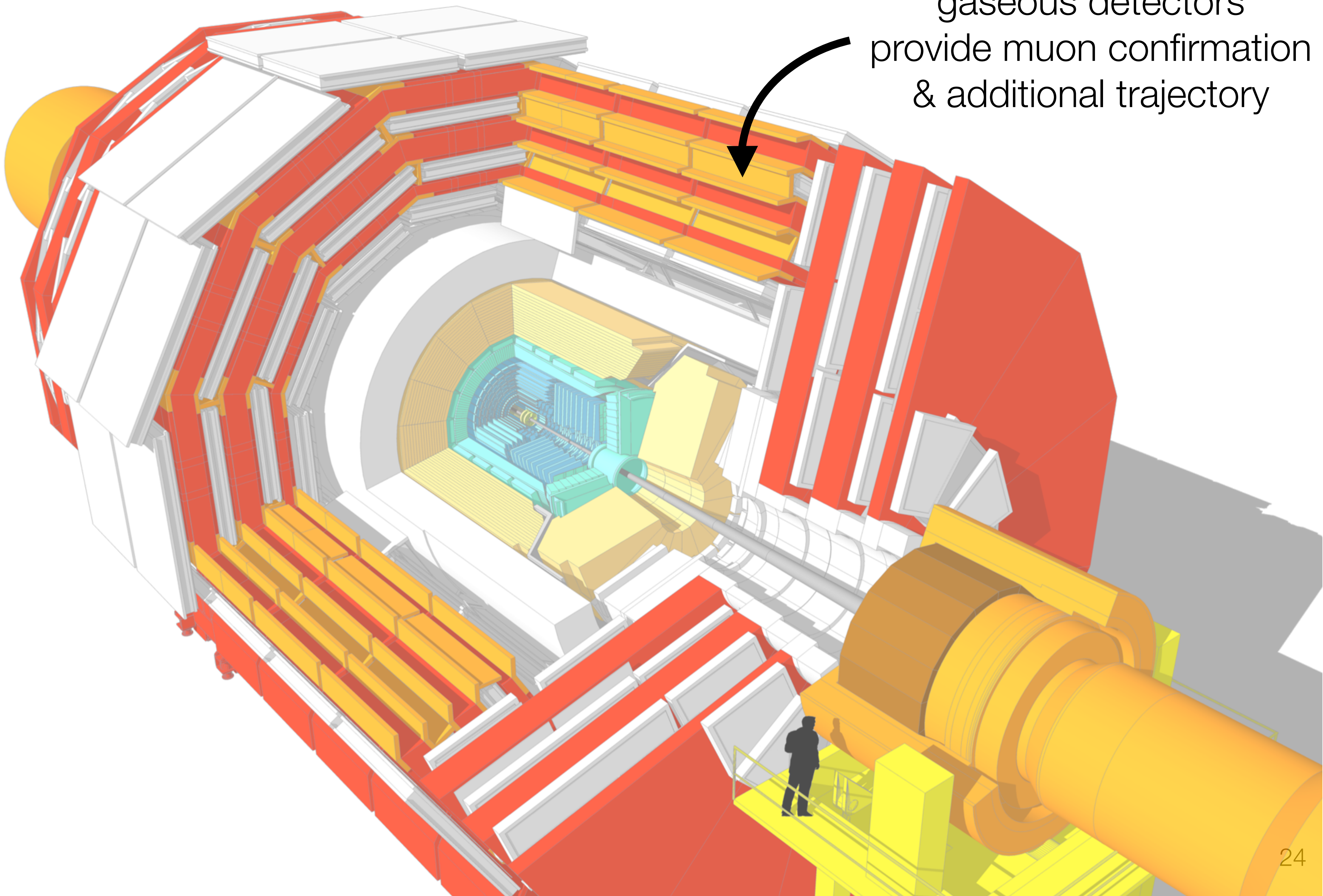
Electromagnetic and
Hadronic Calorimeters



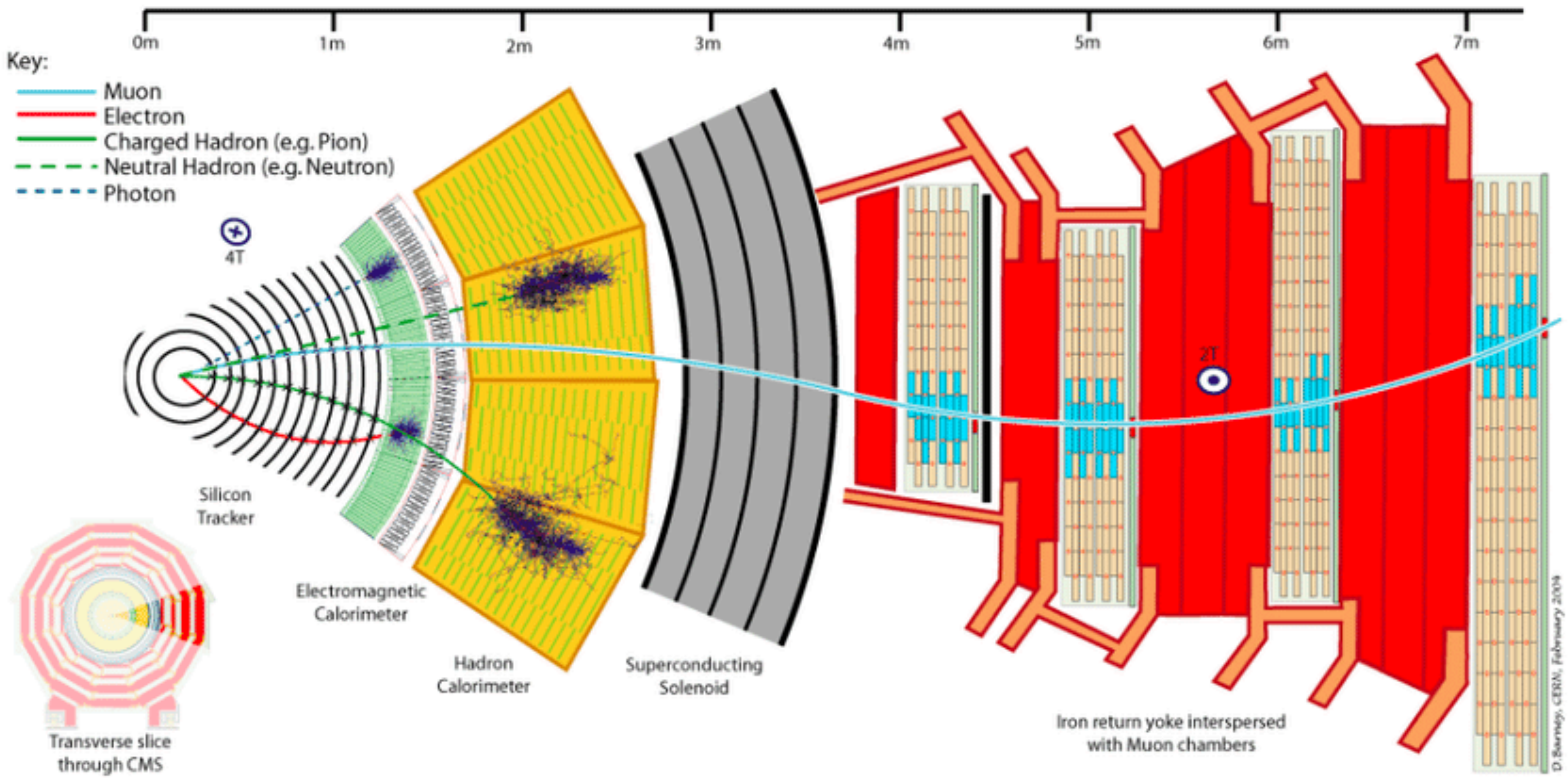
Measures deposited energy
& stops all particles besides
muons & neutrinos

CMS detector design

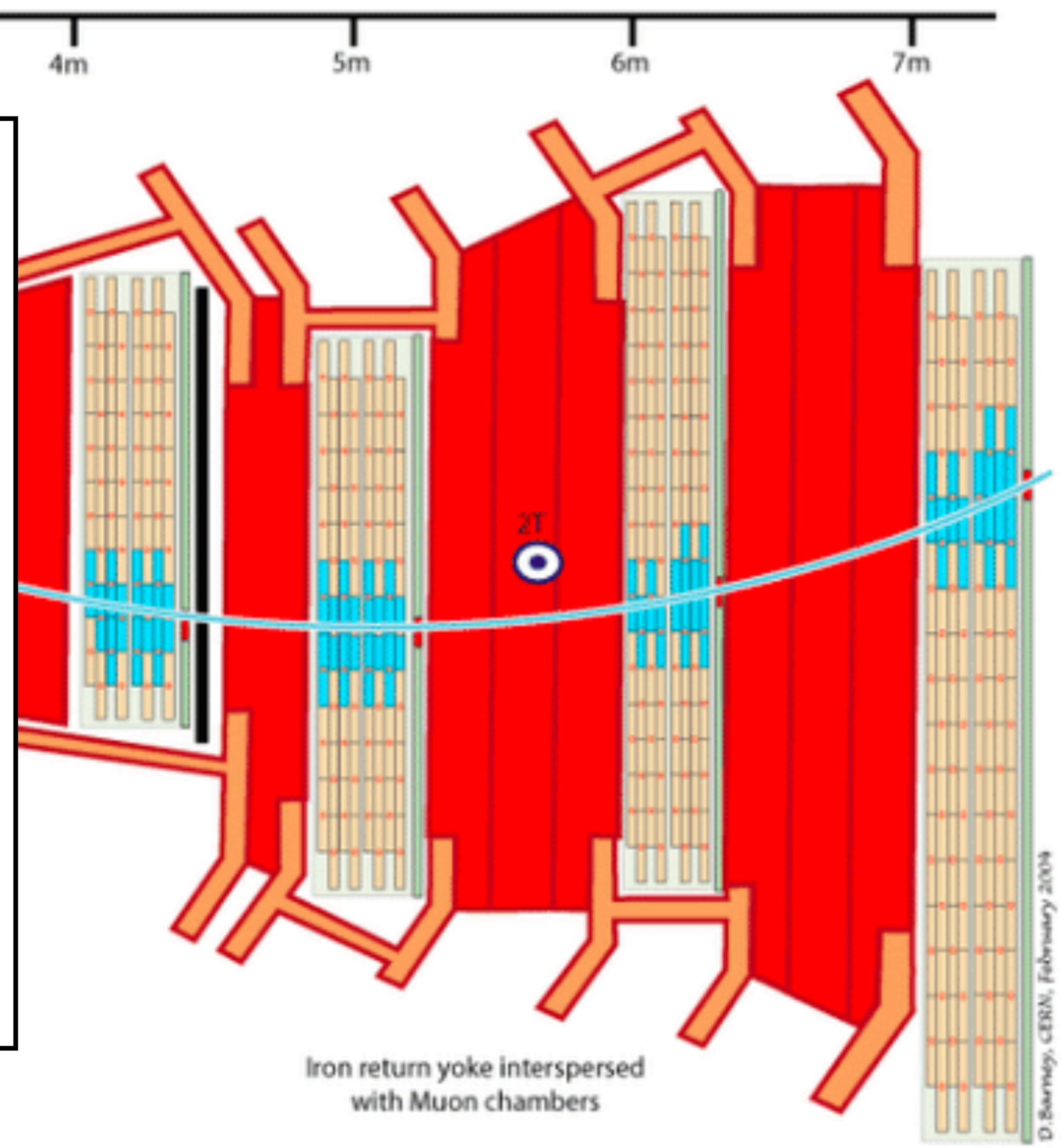
Muon Spectrometer
gaseous detectors
provide muon confirmation
& additional trajectory



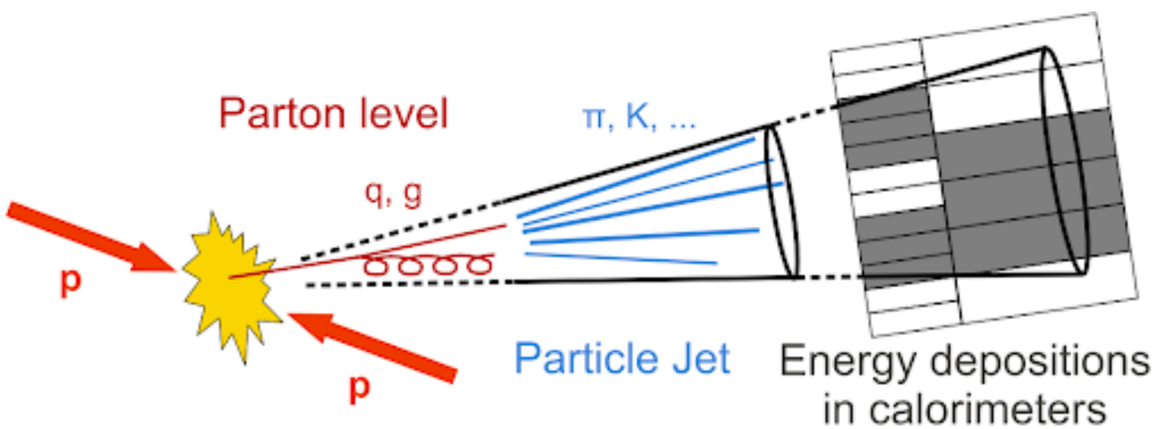
How we identify particles



How we identify particles

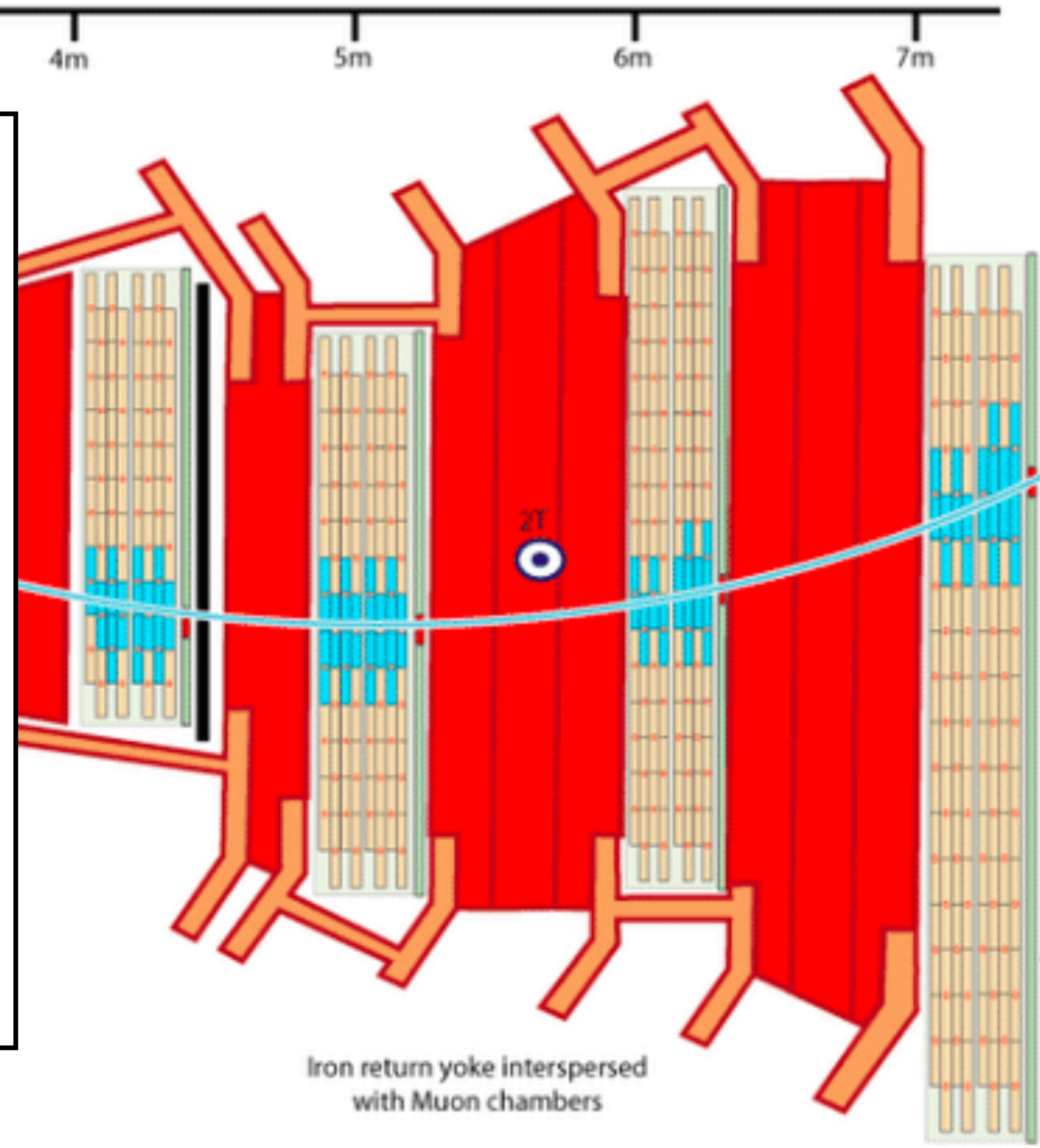


Build up more complicated objects

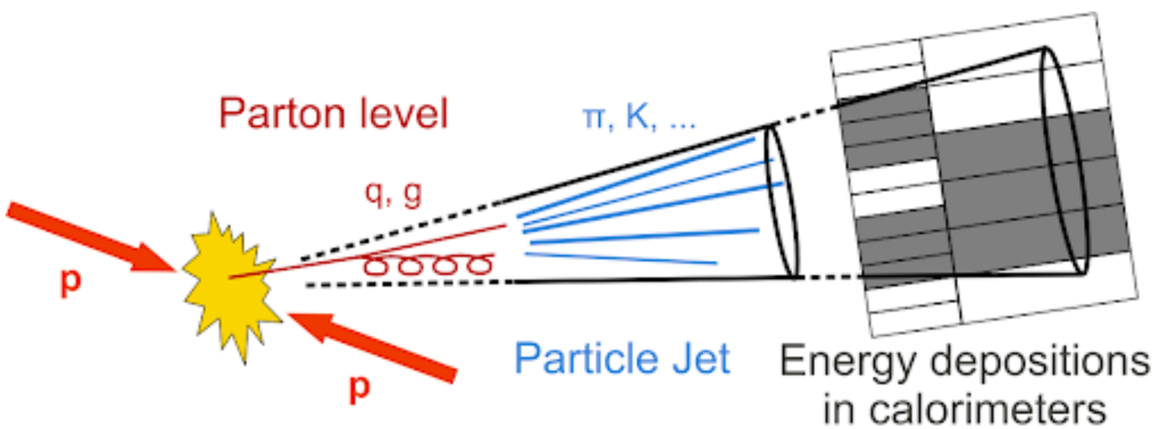


eg. quarks & gluons produce collimated sprays of particles called *jets*

How we identify particles



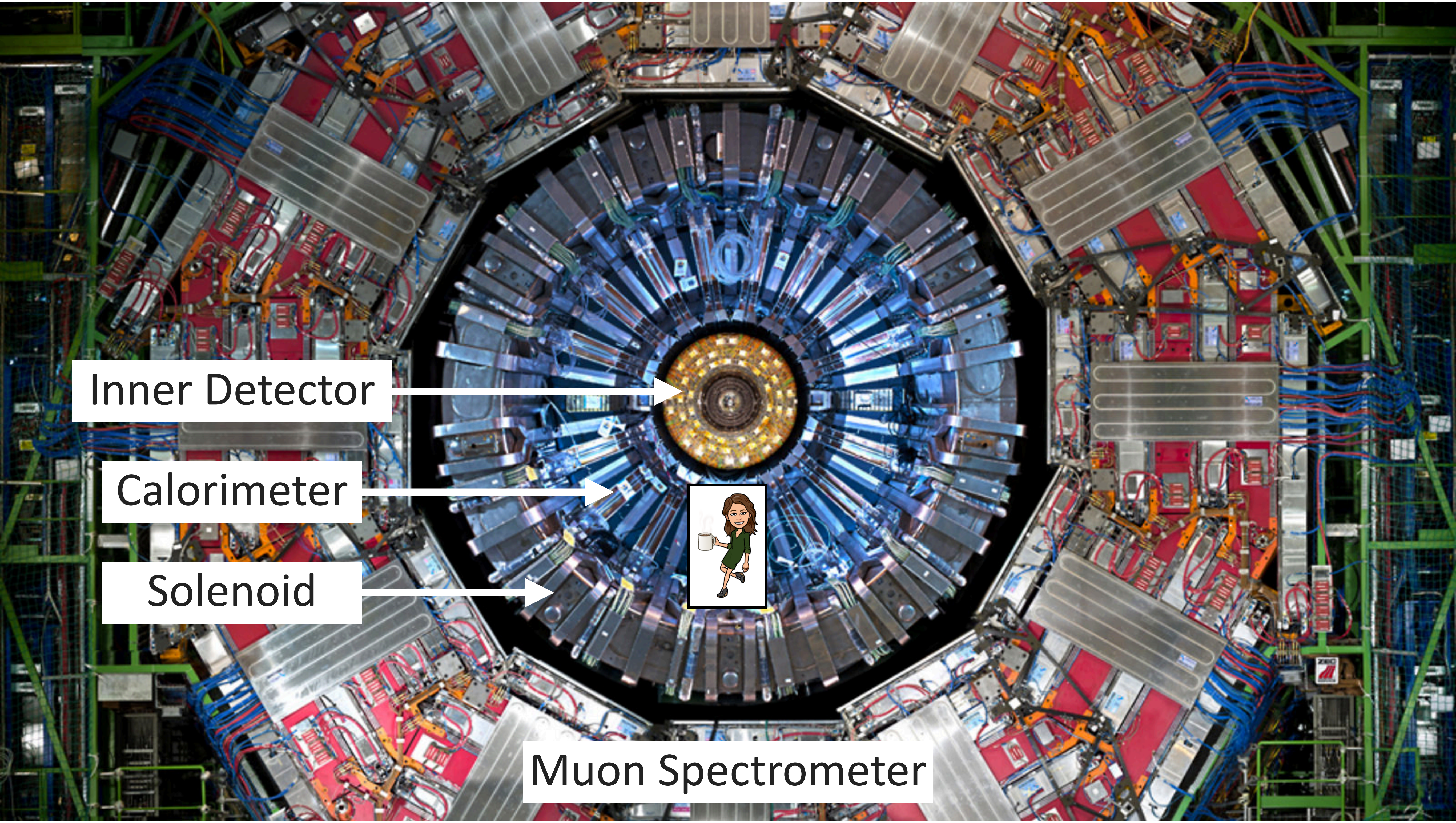
Build up more complicated objects



eg. quarks & gluons produce collimated sprays of particles called *jets*

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

The real detector!



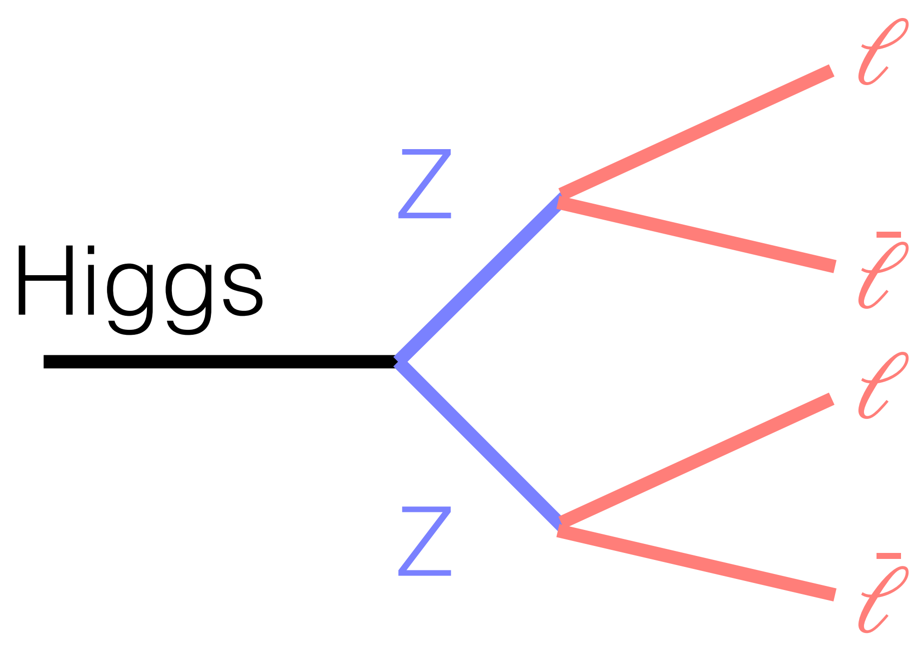
How we find a Higgs

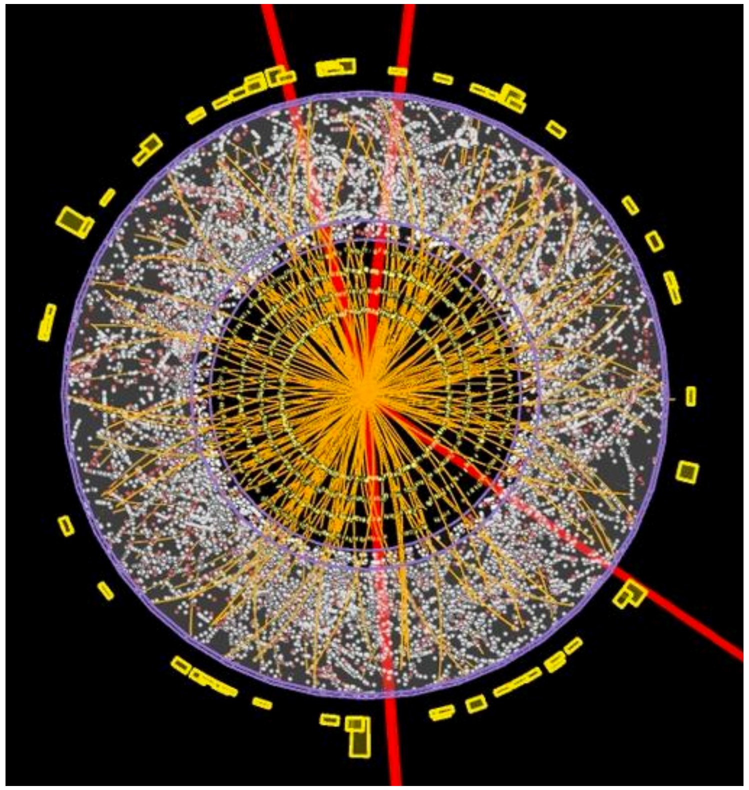
Select events with 4 leptons (e or μ)

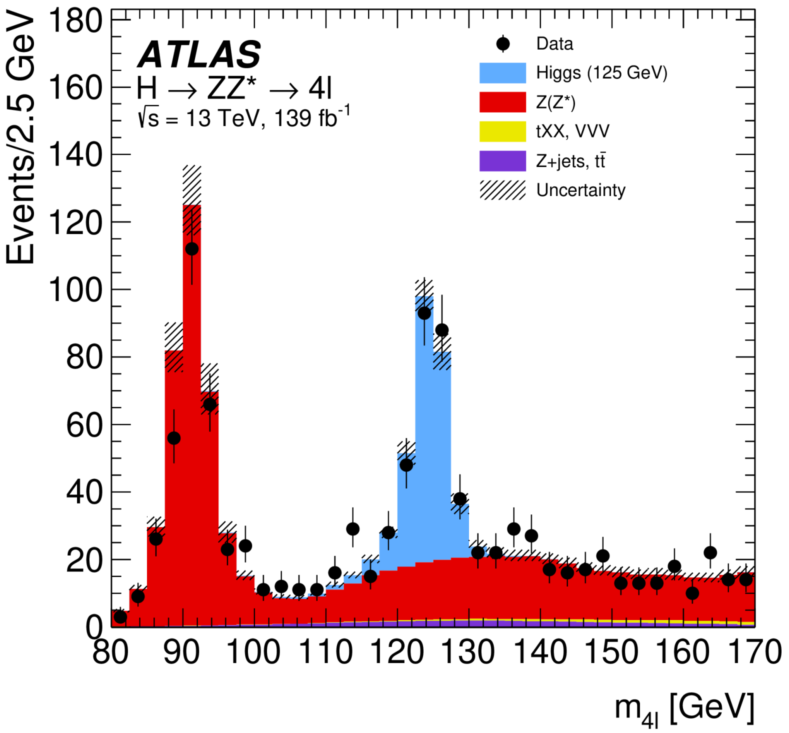
Identify pairs of leptons from Z bosons

Compute the Higgs mass

Fill histogram → see a bump!





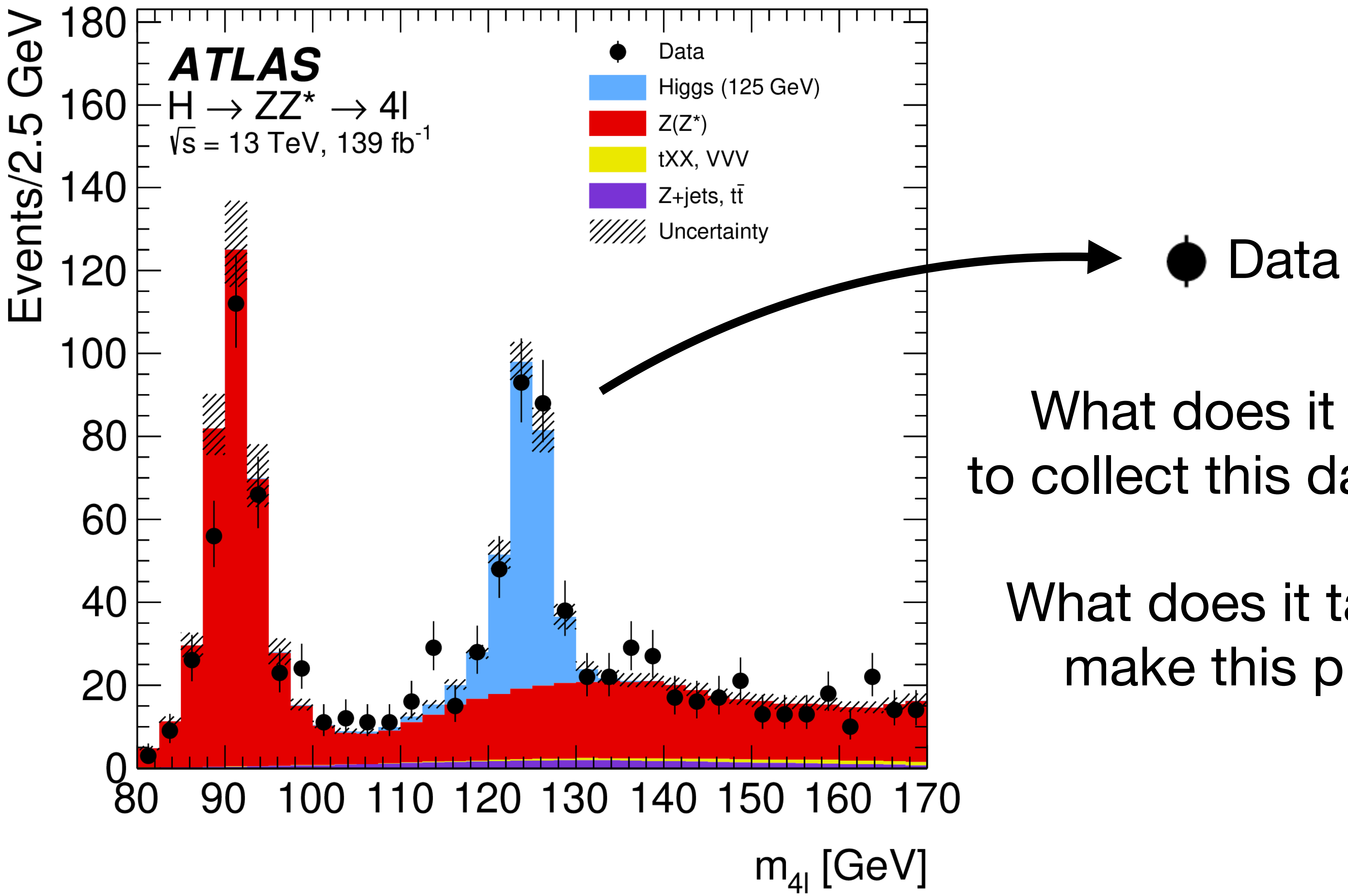


Challenge #1

The Detector

Example: How to find a Higgs

arXiv:2004.03969



What does it take to collect this dataset?

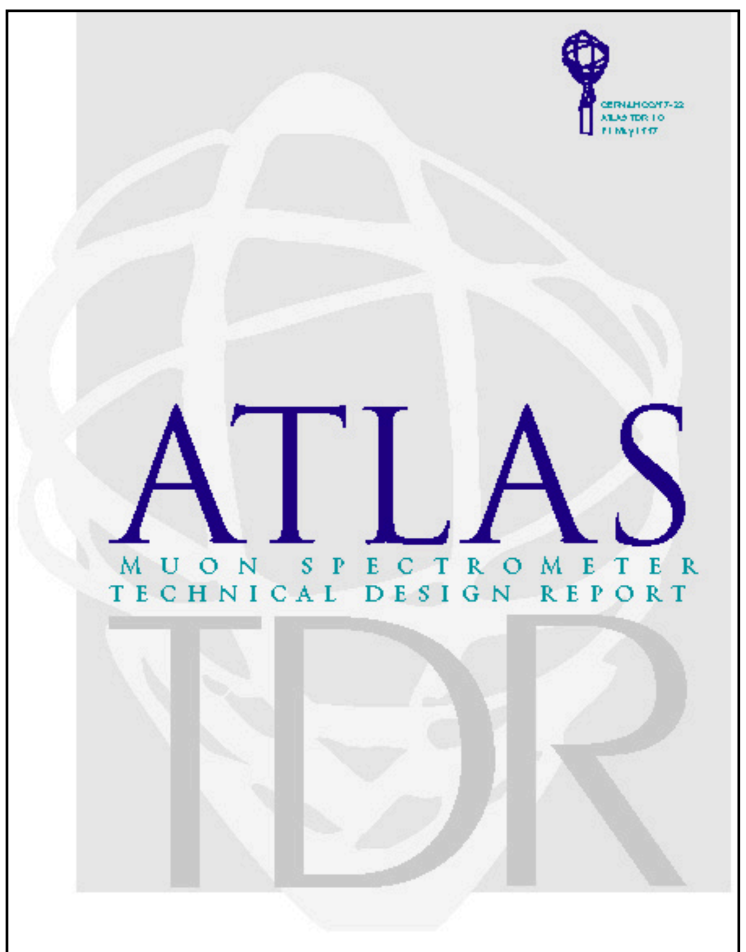
What does it take to make this plot?

It’s hard work to make a detector

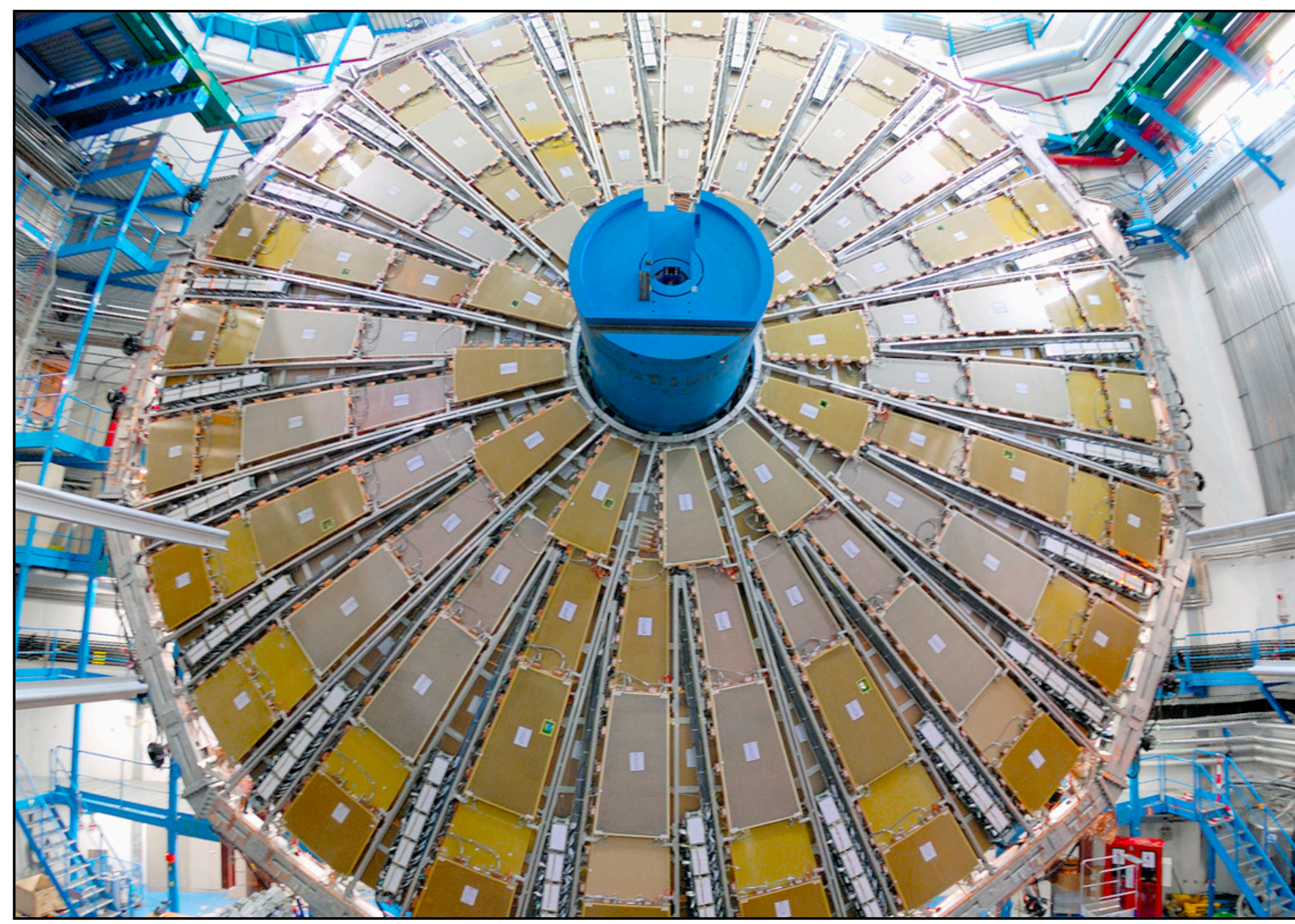
~complete design | installation

1997 → 2008

hundreds? of people to build ATLAS Muon Spectrometer



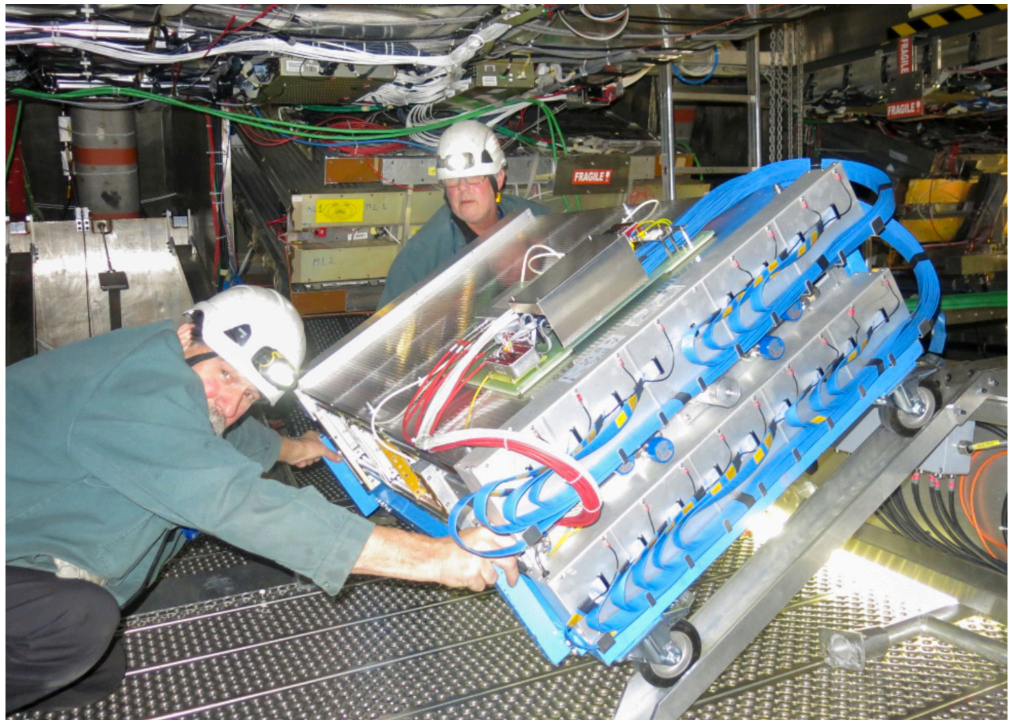
20 m

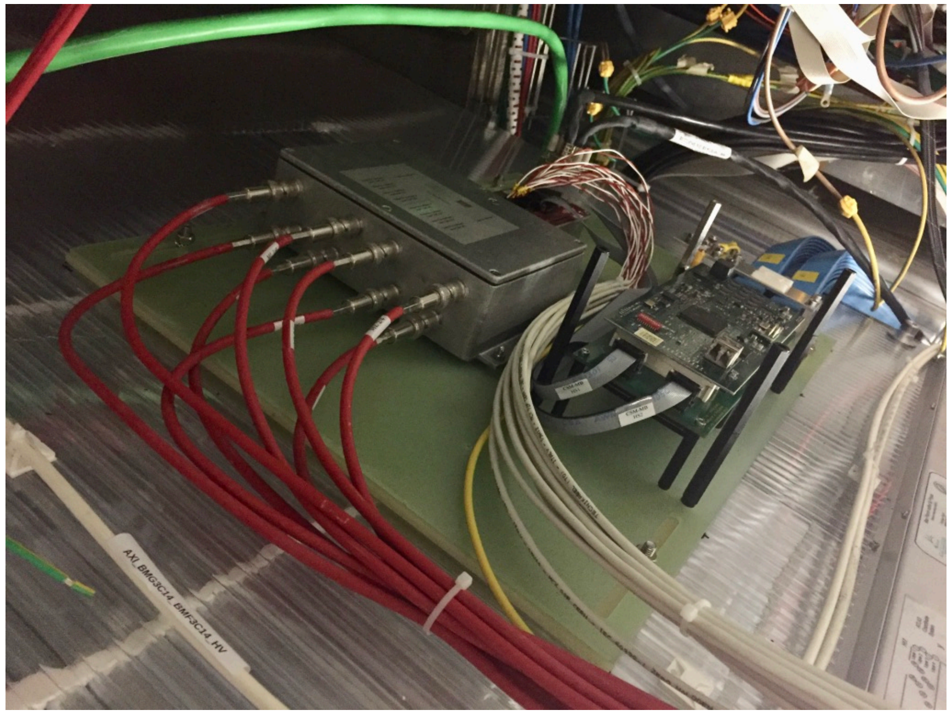


Even installing one chamber is hard

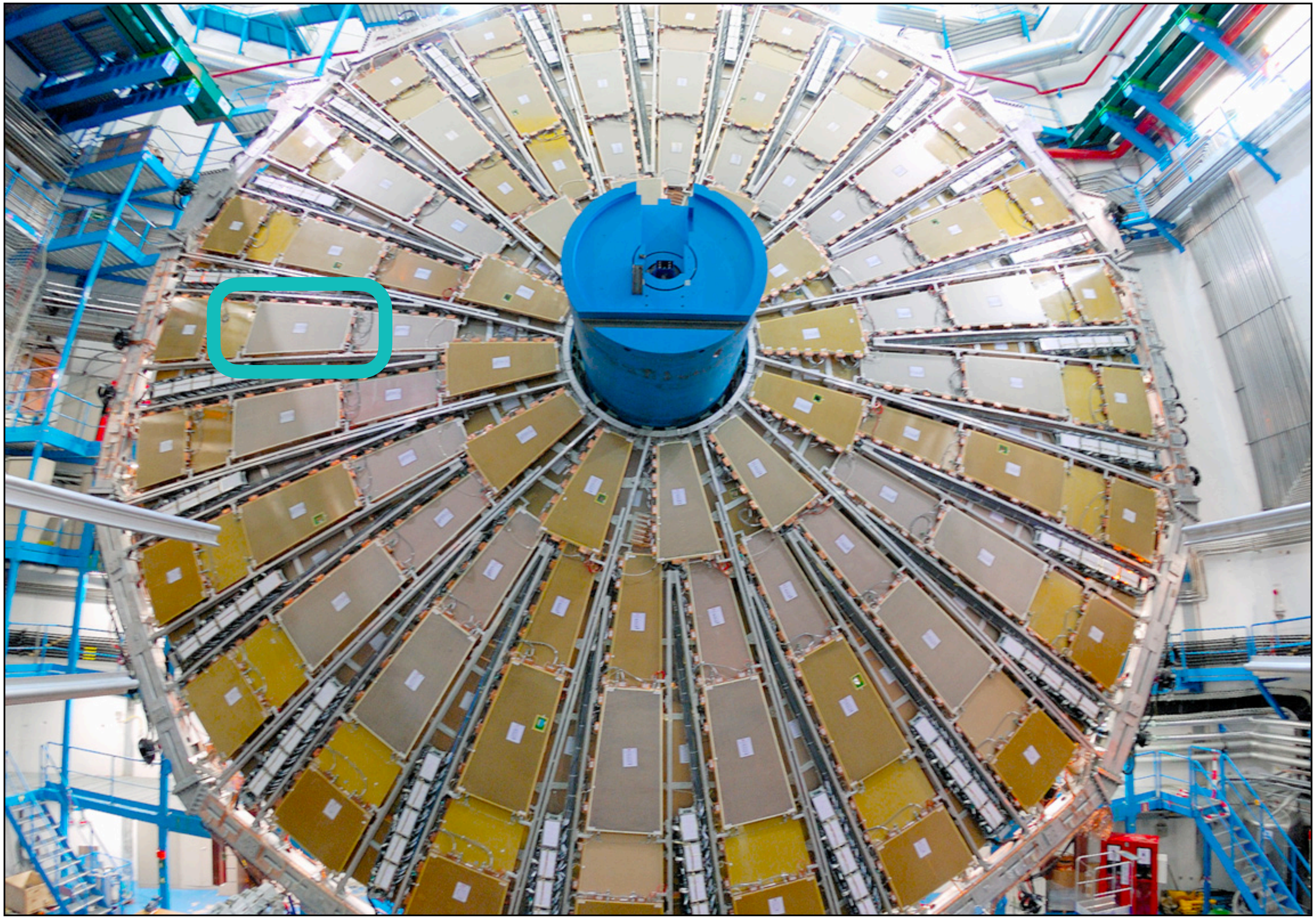
It probably takes 2 weeks per chamber
to go from the surface inside ATLAS/CMS
to be fully connected and turned ON

if nothing breaks…



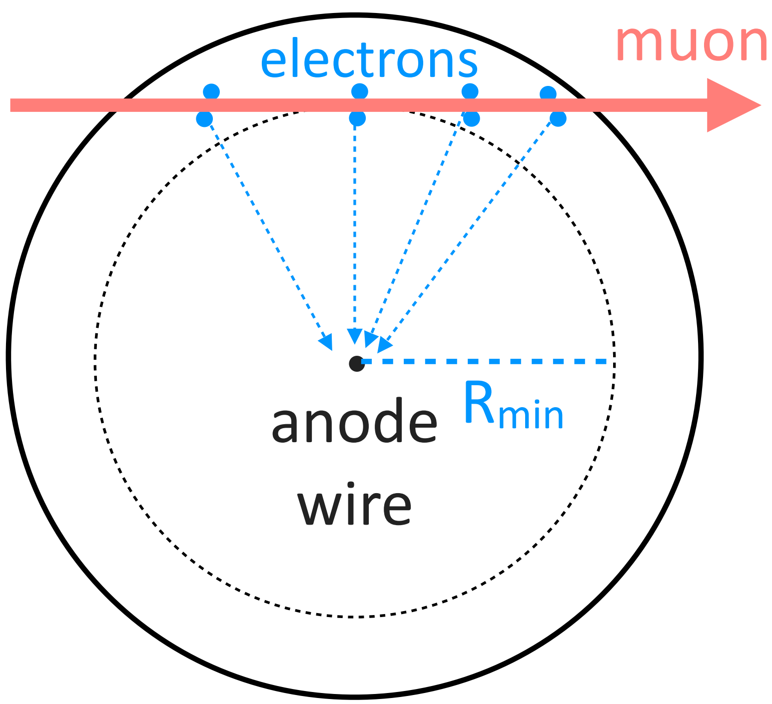


There are thousands of chambers

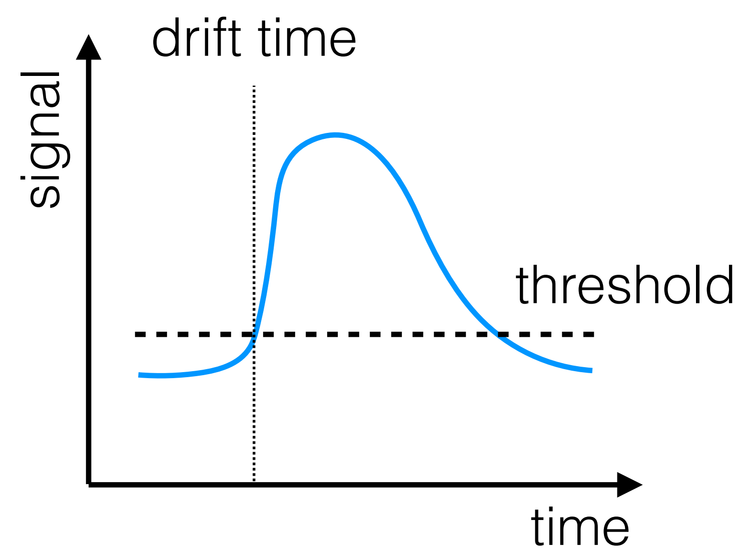


How a detector works

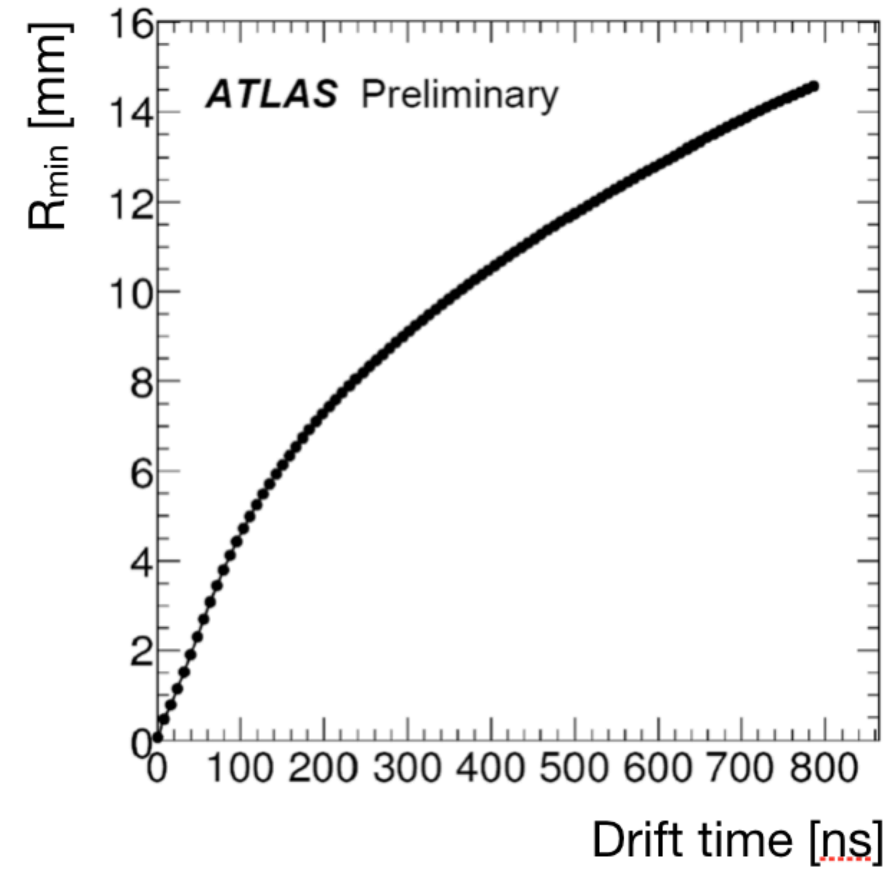
Muon chambers are made up of drift tubes
a single drift tube → position measurement



cathode tube
3 cm diameter



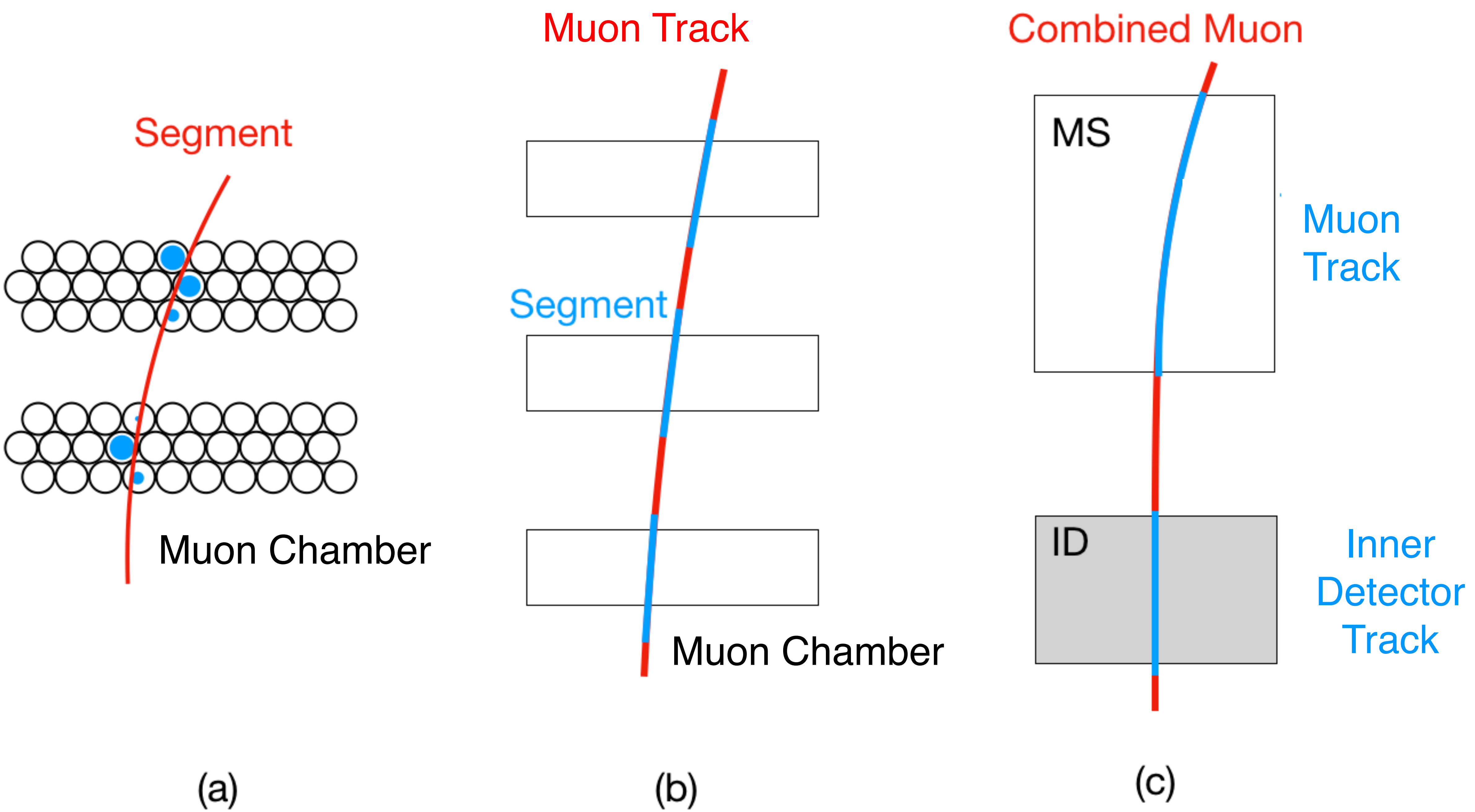
after some electronics
signal shaping



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

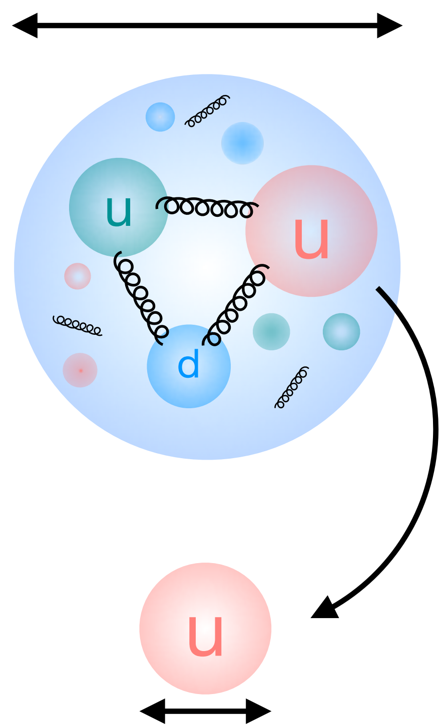


Challenge #2

The Event Rate

Protons = composite particles

Protons
10^{-15} m



Partons
quarks, gluons
$\leq 10^{-18}$ m

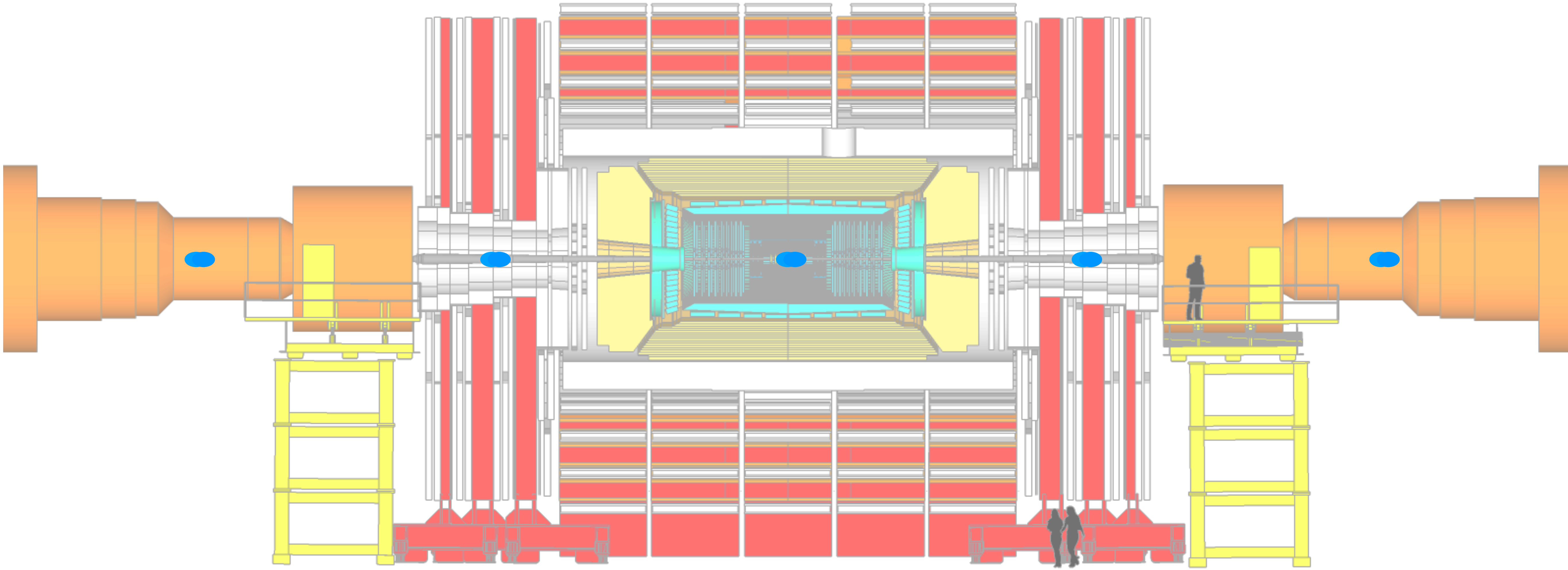
LHC actually collides quarks/gluons
carry a fraction of proton's momentum

Most collisions are low momentum
not so interesting

Every so often we have a "hard" collision

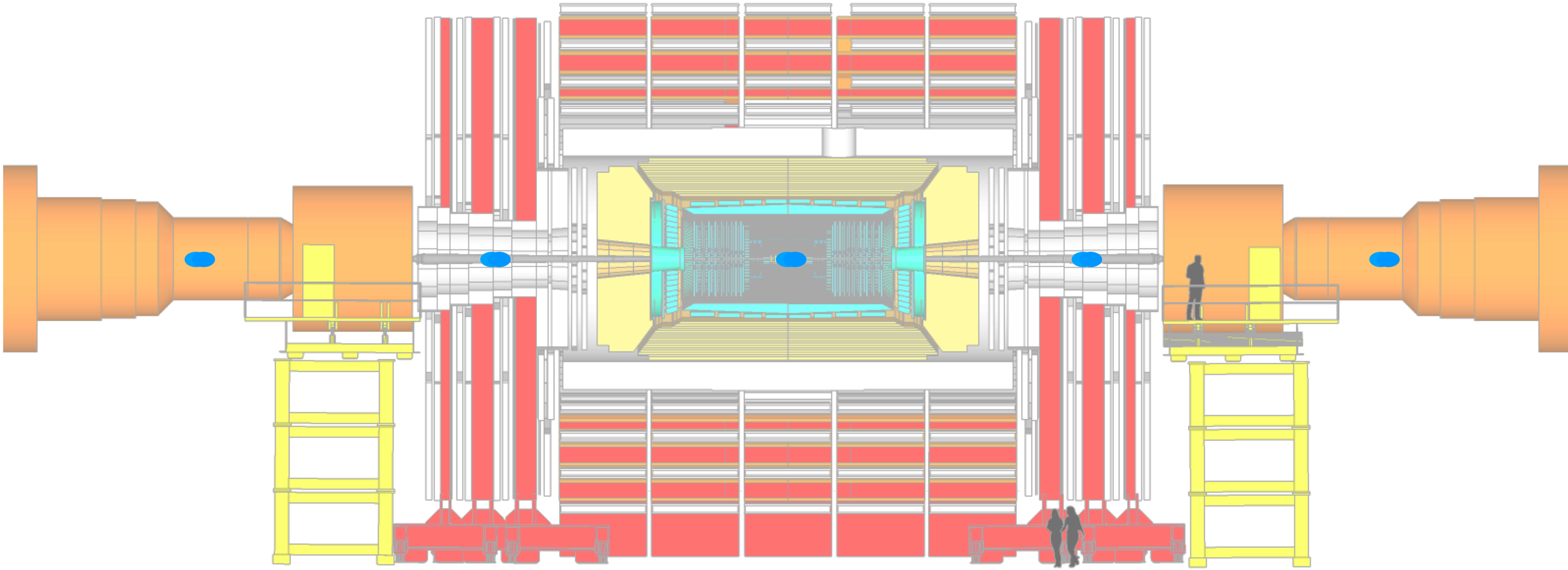
Top pair: ~1 out of 75,000,000
Higgs boson: ~1 out of 1,200,000,000
3.5 TeV Z prime: ~1 out of 120,000,000,000,000

Collision rates



Collision rates

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



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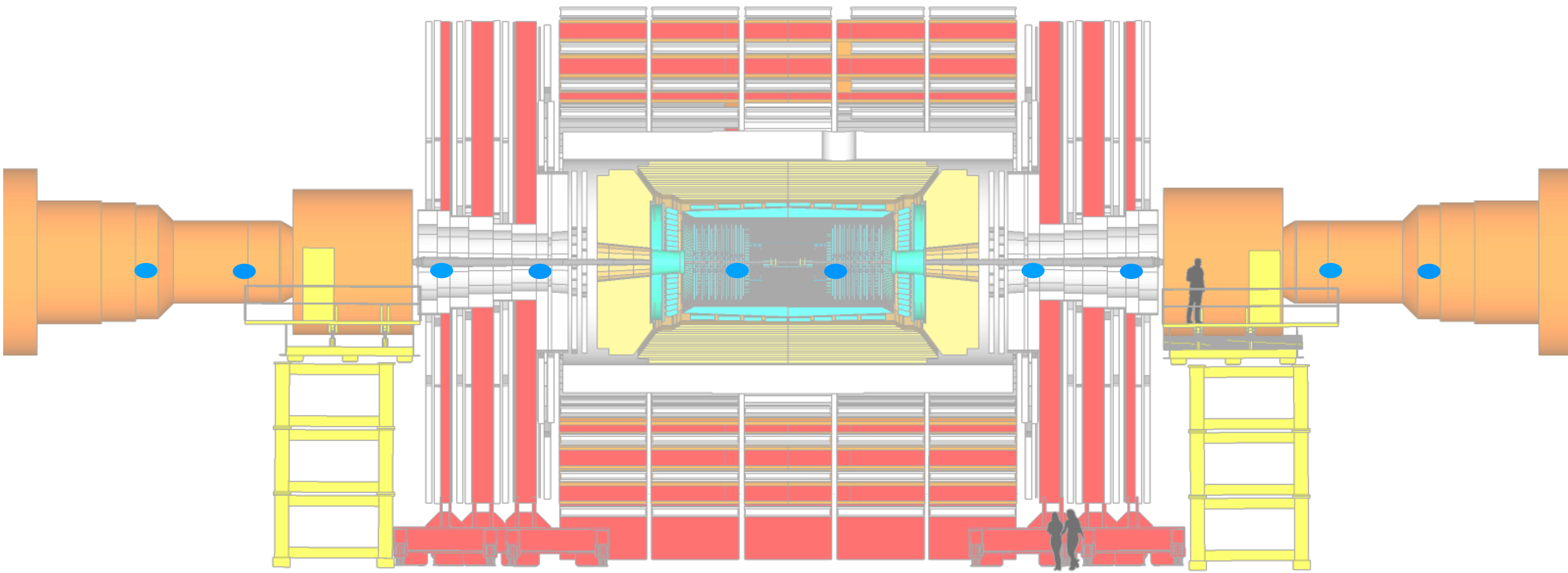

Collision rates

LHC circulates "bunches" of protons, which collide every 25 ns
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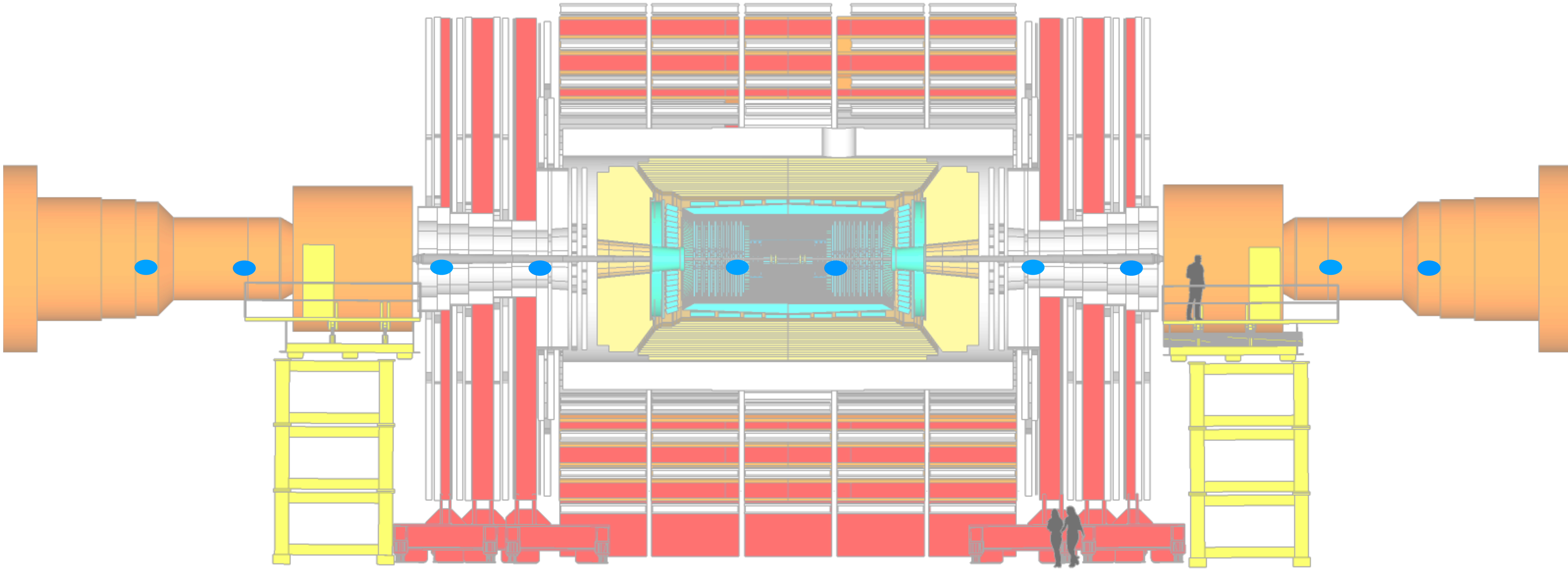


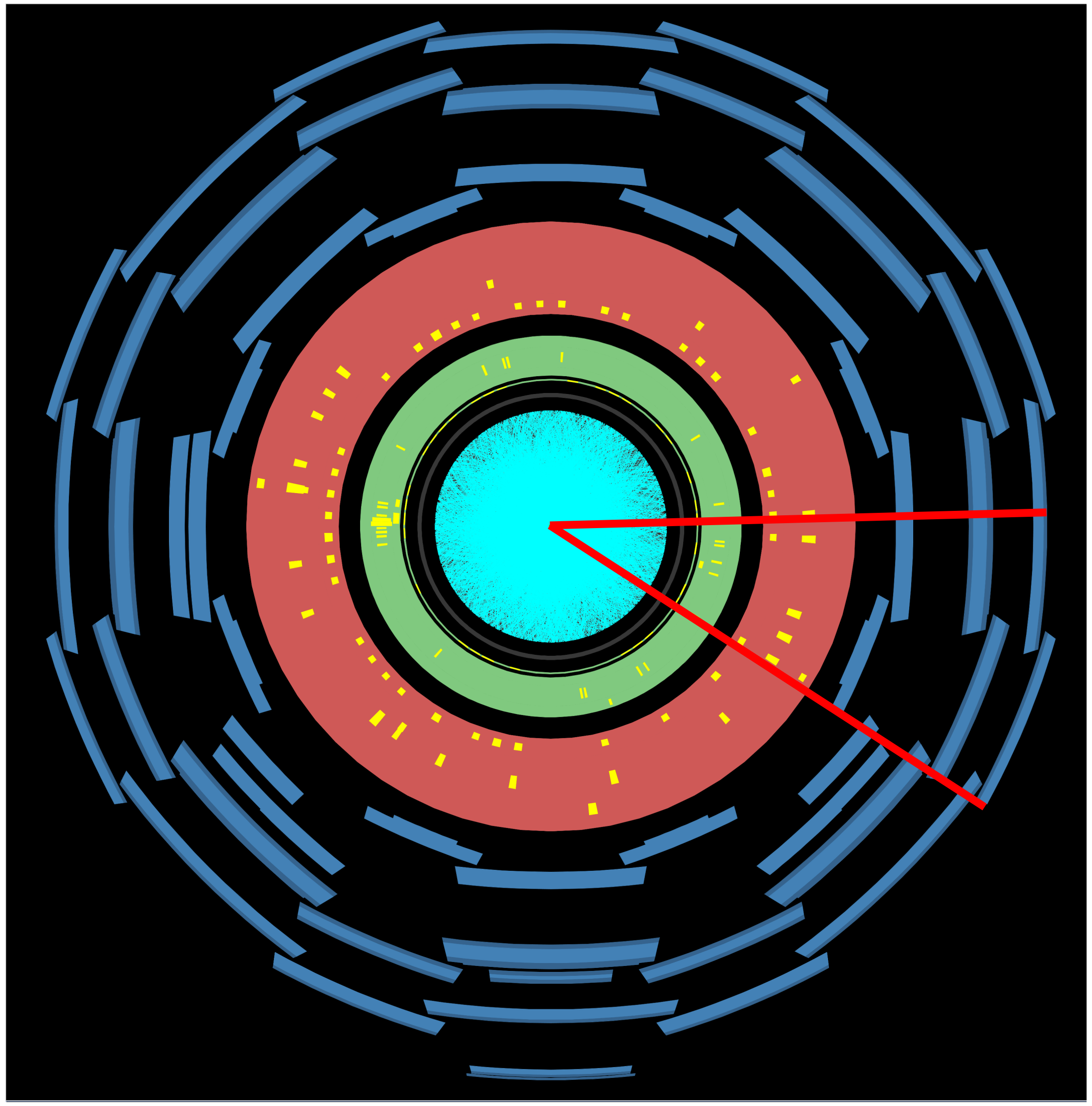
Imagine speeding that up (2 billion collisions/s)
and trying to pick out the ~one higgs event!

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

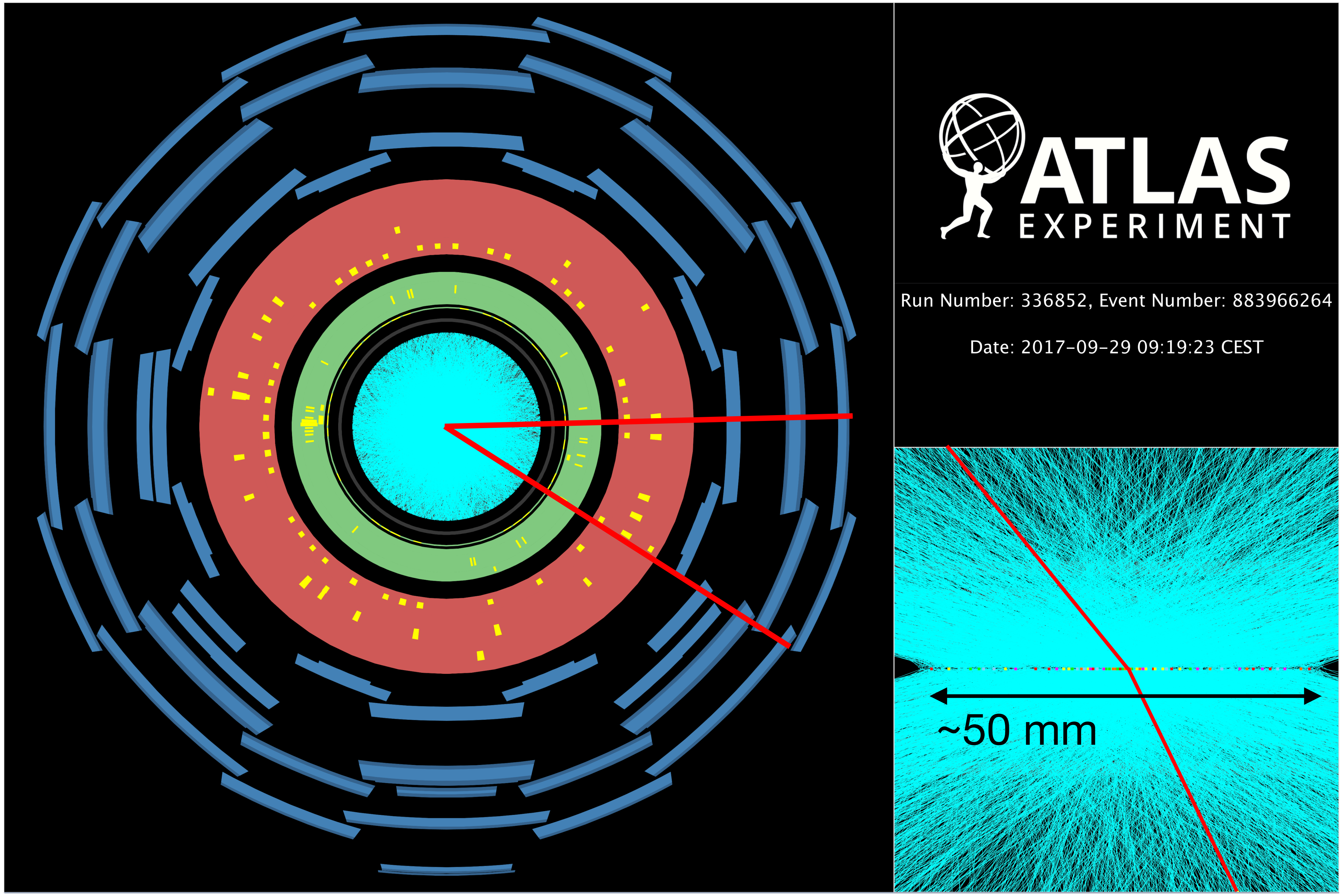
Can only select ~1 in a million collisions
And we need to do it quickly!



How can we pick out the interesting events?

The pile-up challenge

LHC events are busy!

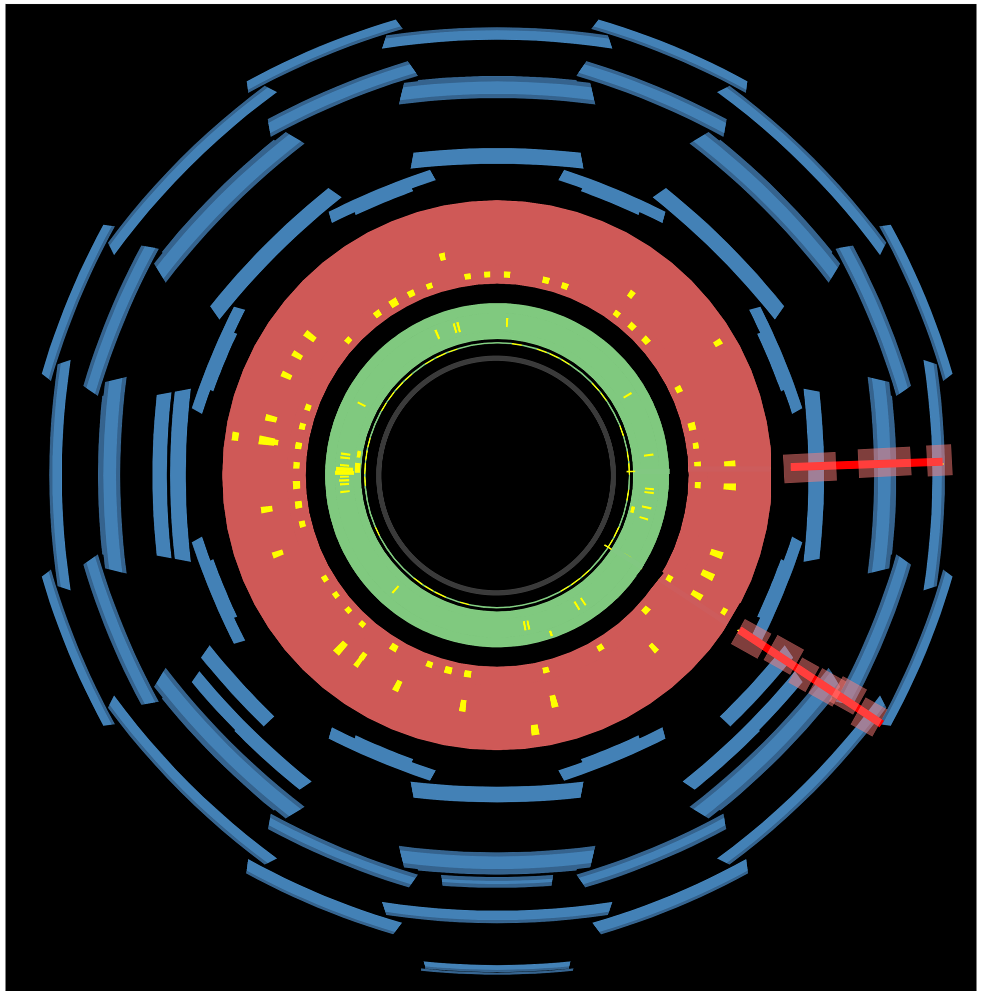


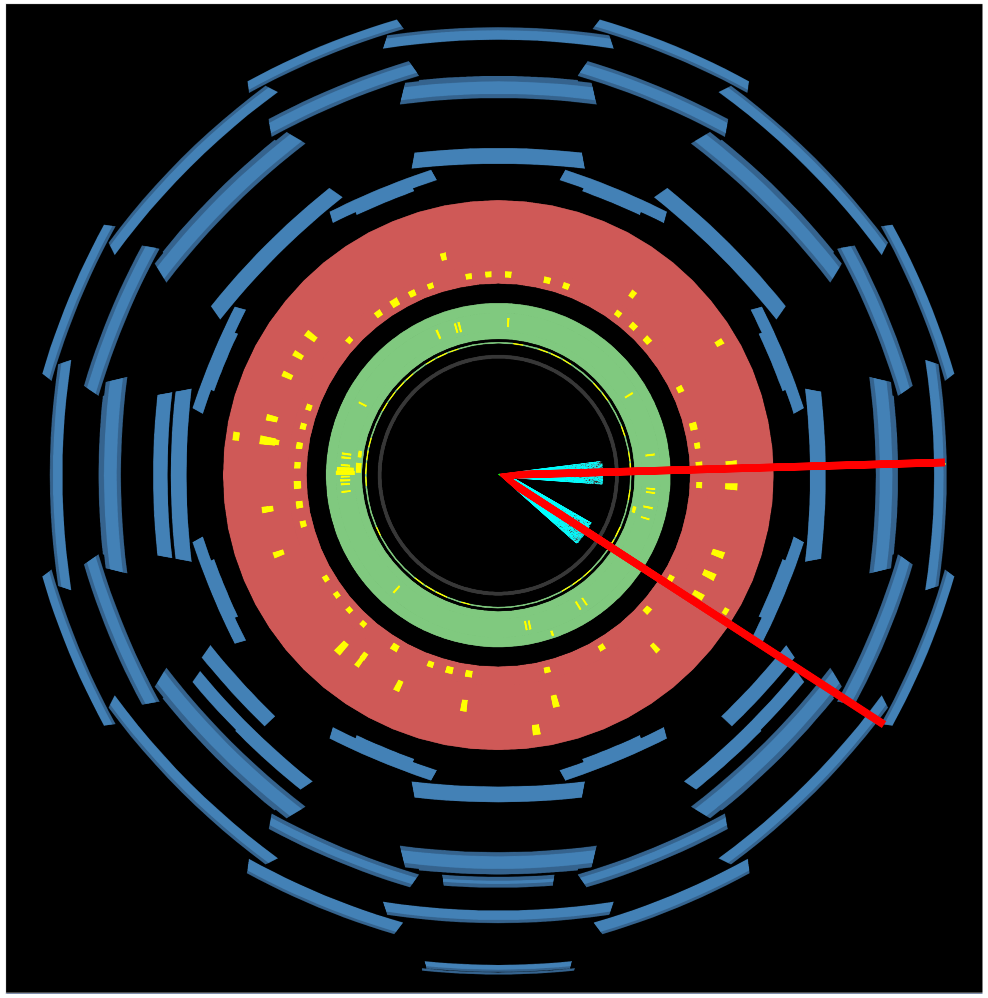
A 2017 Z→μμ candidate,
with 65 additional "pile-up" vertices

Trigger = two step process

Step 1.
coarse muon and calorimeter information
decision time: 3.2 μs
keeps 1/400 crossings

Step 2.
nearly full detector in region of interest
decision time: 200 ms
keeps 1/100 crossings





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

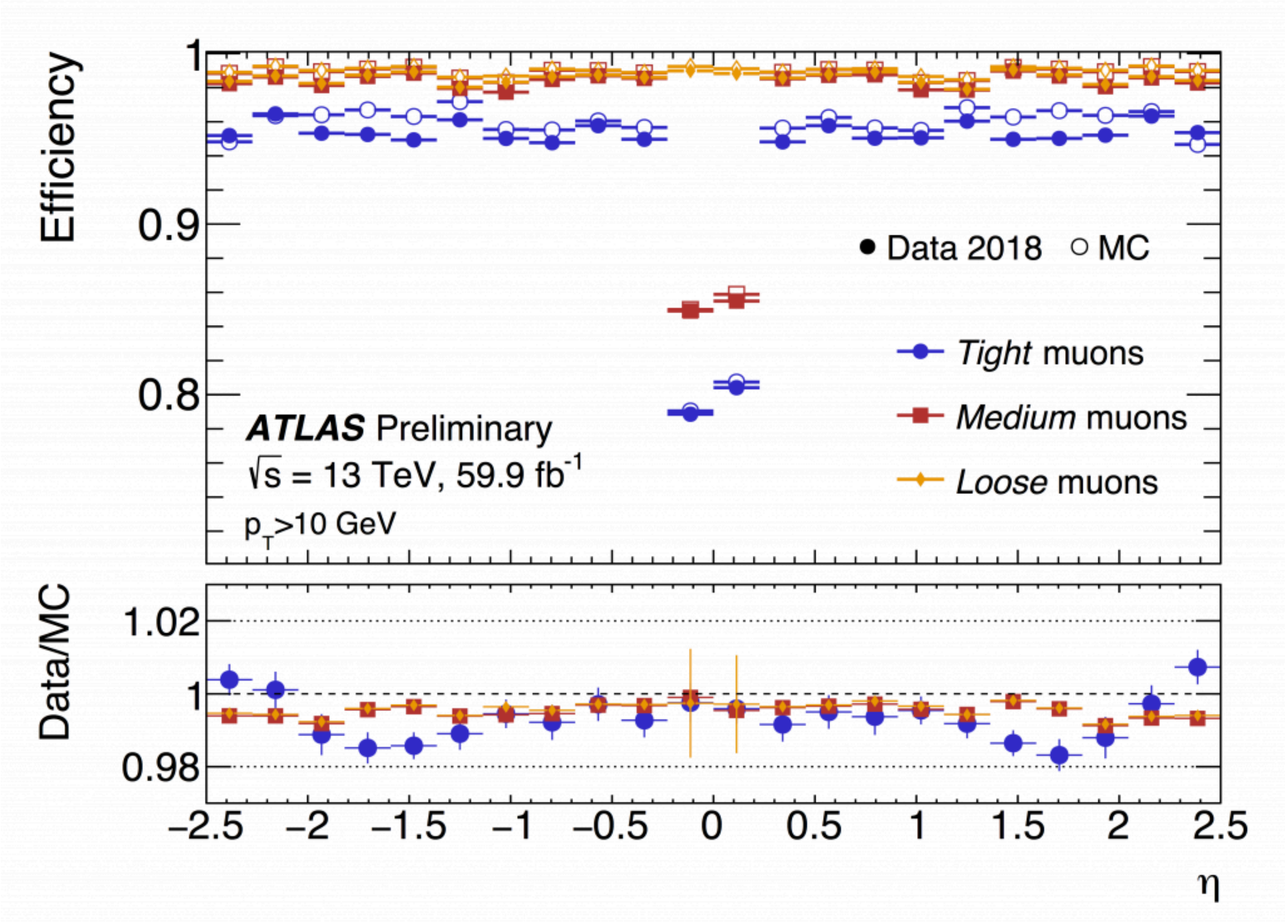
The work doesn't stop there

After data taking

Quantify detector performance

Make projections to ensure detectors will keep working

Ensure good agreement between predictions & data



Requires many people!

The CMS collaboration

2700 physicists
900 are students!

Fermilab’s LHC Physics Center

350 users & 100 residents
from 50 universities

Finally our data is ready for physics

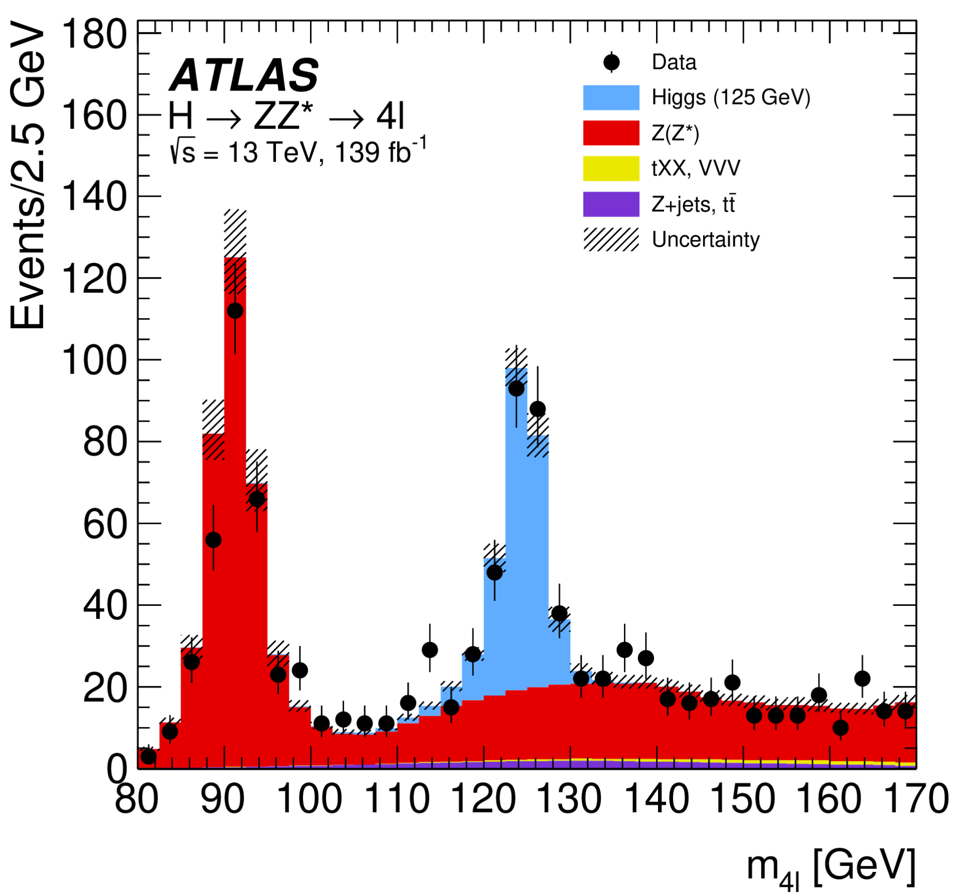
And it's not just used for one Higgs measurement

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



=

!

What's next?

- Run 3 + High Luminosity LHC
  - we've only collected 5% of the LHC's data so far
  - improvements to the ATLAS and CMS detectors
  - could we discover a new rare process or a particles with challenging signatures?
- Next machine is likely to be a lepton collider
  - Future Circular Collider
  - Compact Linear Collider
  - International Linear collider
  - Muon Collider???
- We should know more soon!
  - European Strategy Report in favor of future lepton collider
  - US Snowmass process is ongoing

Conclusions

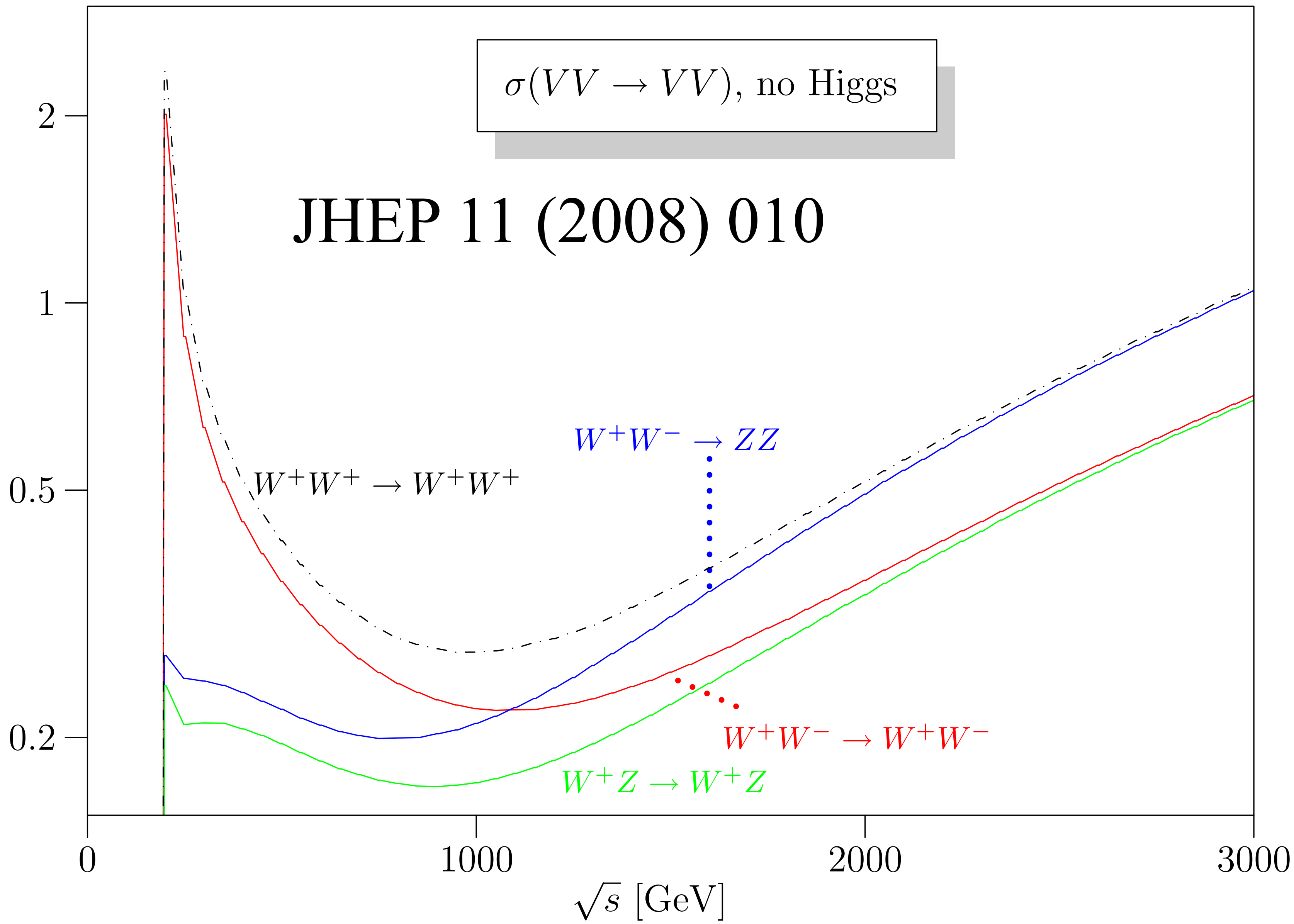
- Standard Model isn't complete picture of the universe
- High energy particle colliders are
  - one of the most effective ways to look for new particles
  - and to do measurements which try to "break" the Standard Model
- Being a scientist at the Large Hadron Collider means
  - you have MANY wonderful collaborators
  - working together on fun detector, trigger, and analysis challenges
- The future is bright: new physics could be lurking just around the corner!

BACKUP

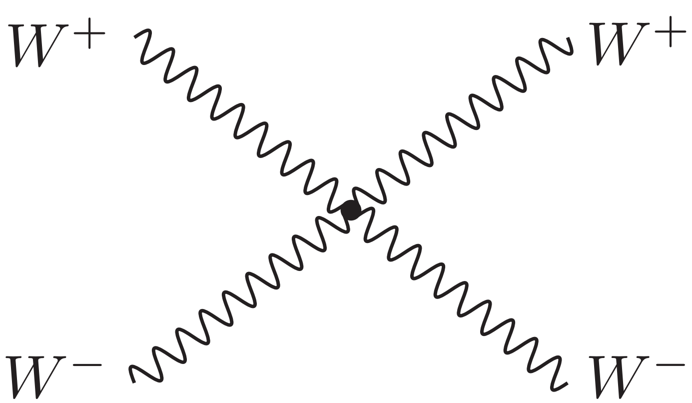
Karri DiPetrillo
Fermilab Lecture Series
30 June, 2022

But something is missing

Big hole: particle masses not included in theory so far
AND if we go to even smaller distances the theory breaks



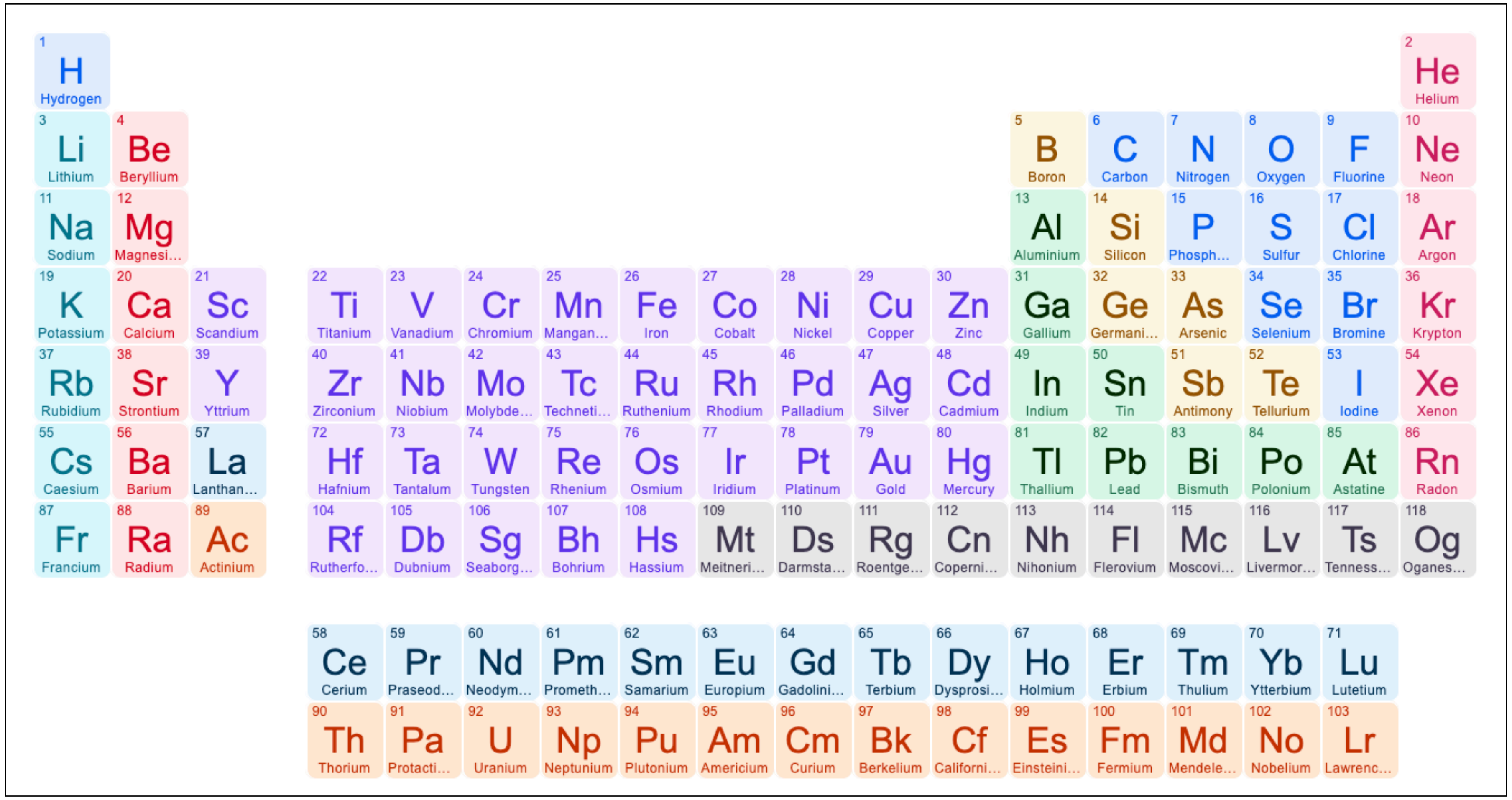
At high energies
Predict probabilities
> 1 !!!



An example

Start with the periodic table

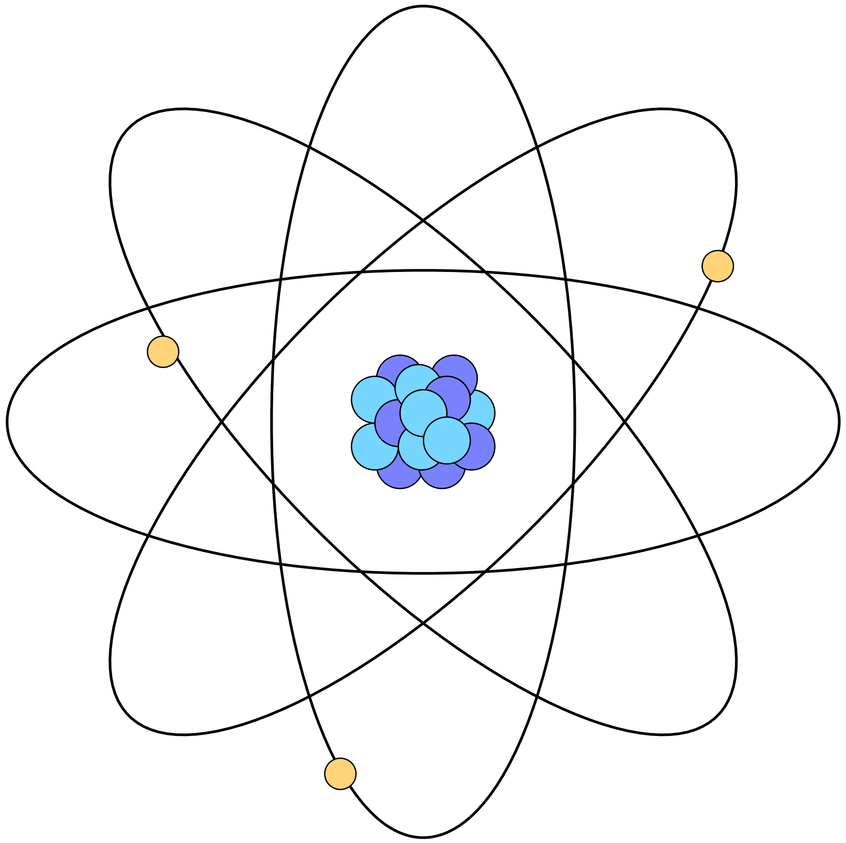
A set of fundamental (chemical) elements and prescriptions for how they may combine with each other.



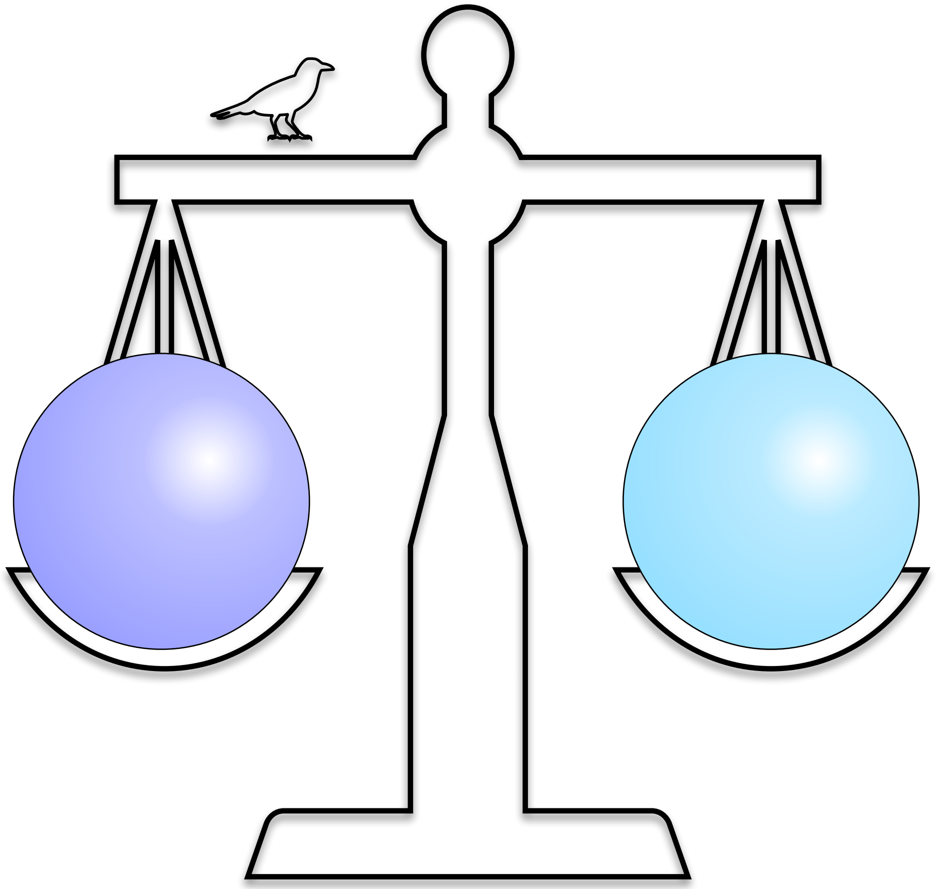
Why so many columns and rows? Does it go on forever?

Hints at a deeper structure

Atomic Nuclei



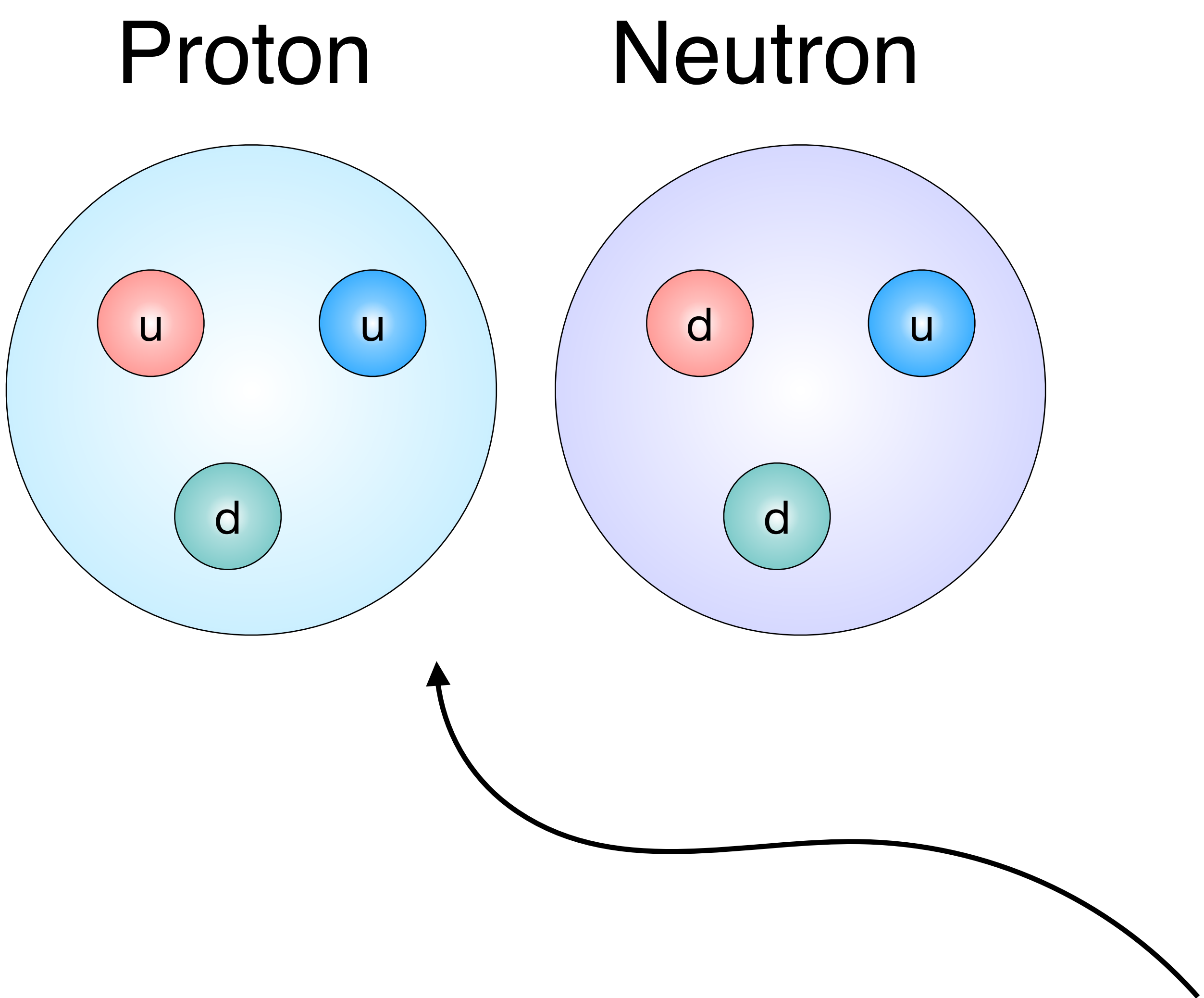
Nuclei are just collections of
protons and neutrons
With electrons, only need 3 ingredients
for ordinary matter!



Interesting coincidence?
m_{proton} = 0.9383 GeV
$m_{neutron}$ = 0.9396 GeV

Hint of even deeper structure!

Not a coincidence!



First level of understanding

Protons and Neutrons consist of quarks

up quarks = +2/3 e

down quarks = -1/3 e

gluons hold everything together

If we look deeper

in addition to the three “valence” quarks
there’s a “sea” of quarks and gluons

q and q pairs popping in and out of existence