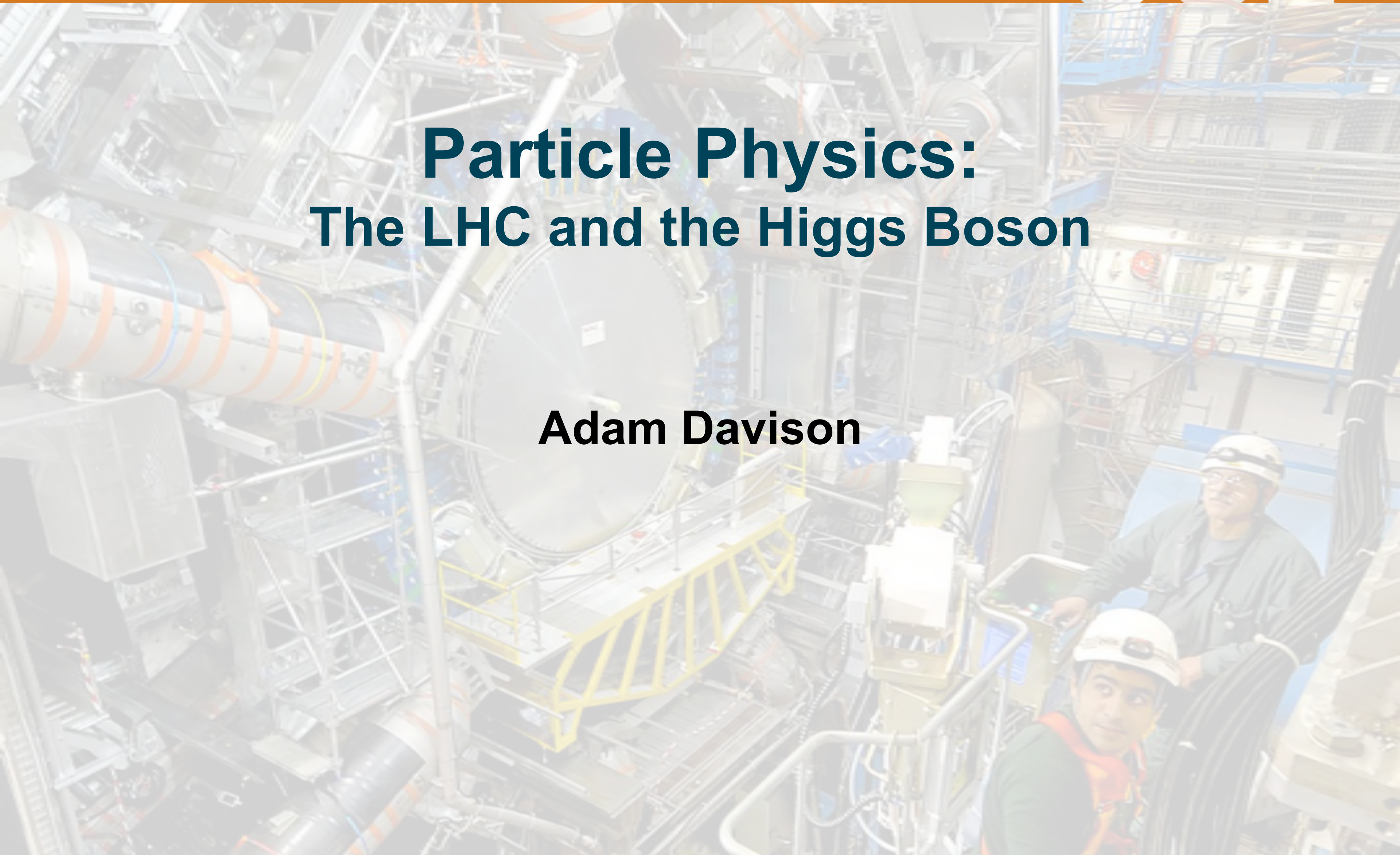
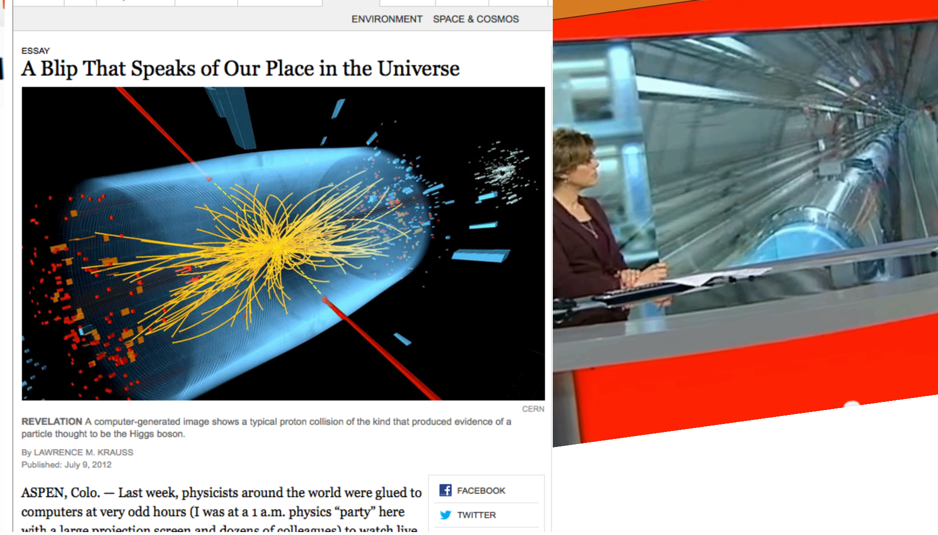
Particle Physics:

The LHC and the Higgs Boson



Adam Davison



Particle Physics

What is it?

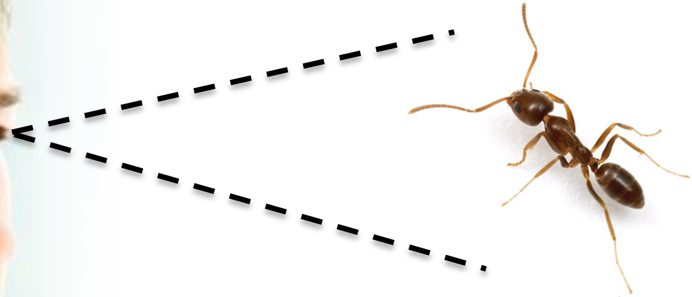
Why do we do it?

What is the LHC?

What is the Higgs boson?

Why?

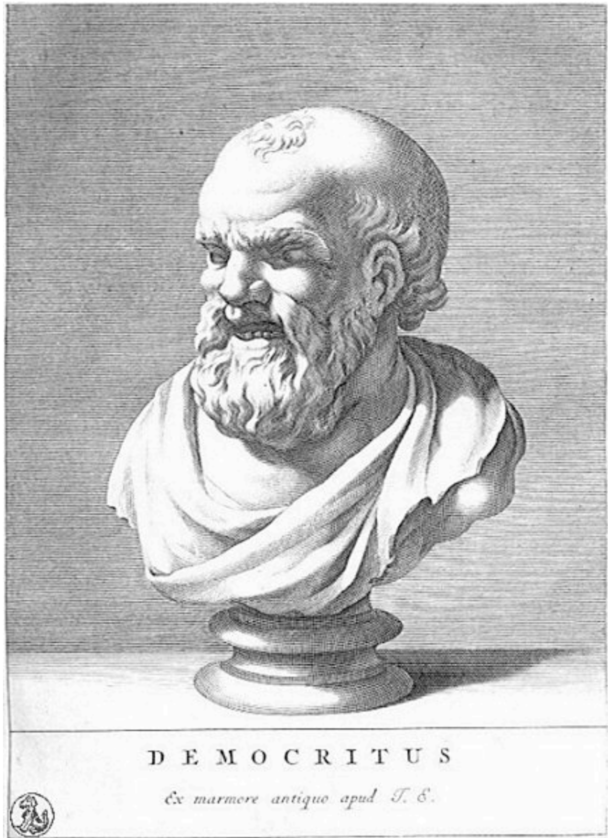
- Humans have always asked hard questions
- How did I get here?
- Where is here?
- What else is there?
- How does all of it work?
- Serious business…



The human eye can see objects as small as about 1 mm or 0.001 m or 10^{-3} m

500 BCE

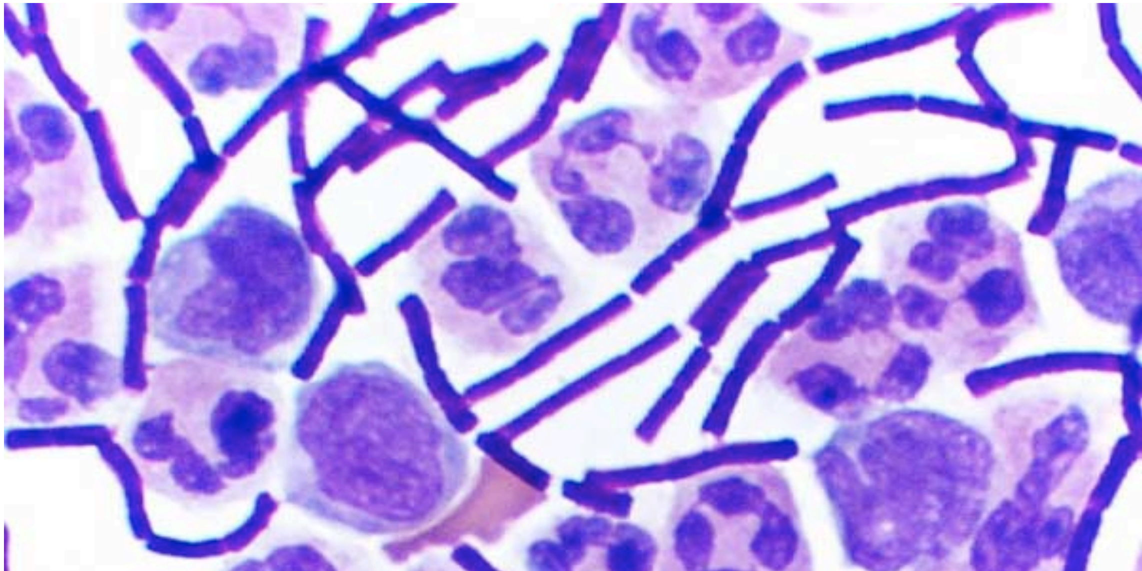
Democritus (right) proposes that everything is made of indivisible "atoms". But there is no concept of size, except that they are too small to see.



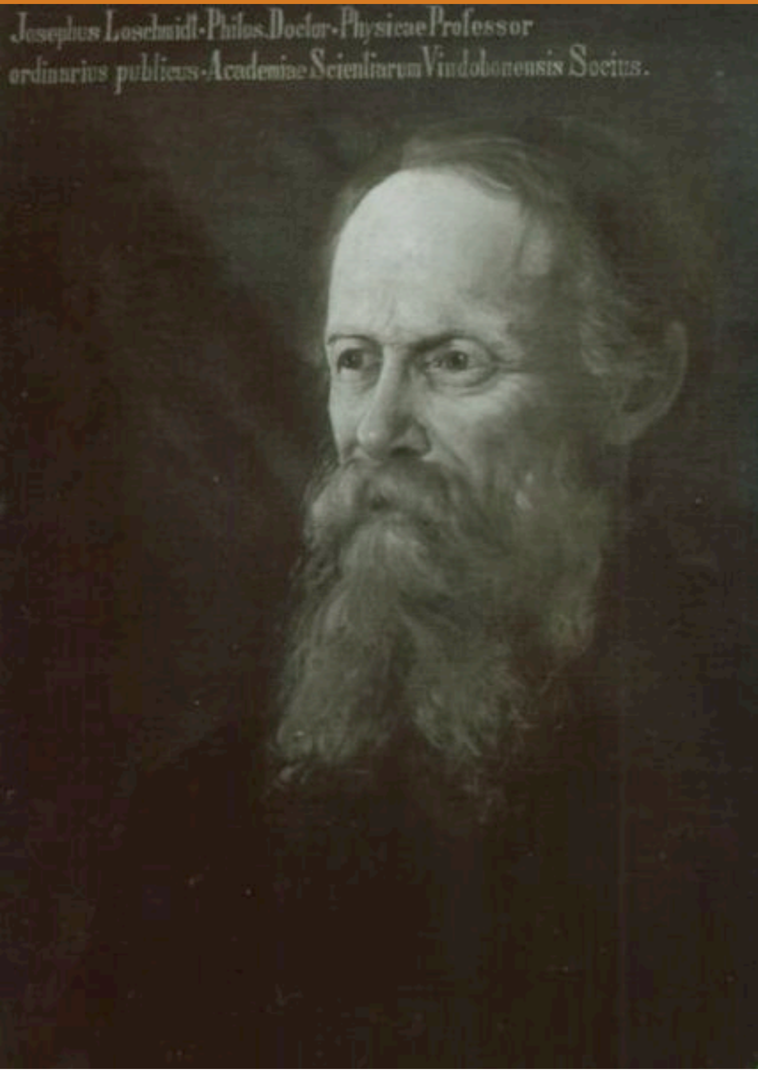
van Leeuwenhoek builds a pretty good microscope.

It allows him to see things around 0.00001 m (10^{-5} m) in size

1674

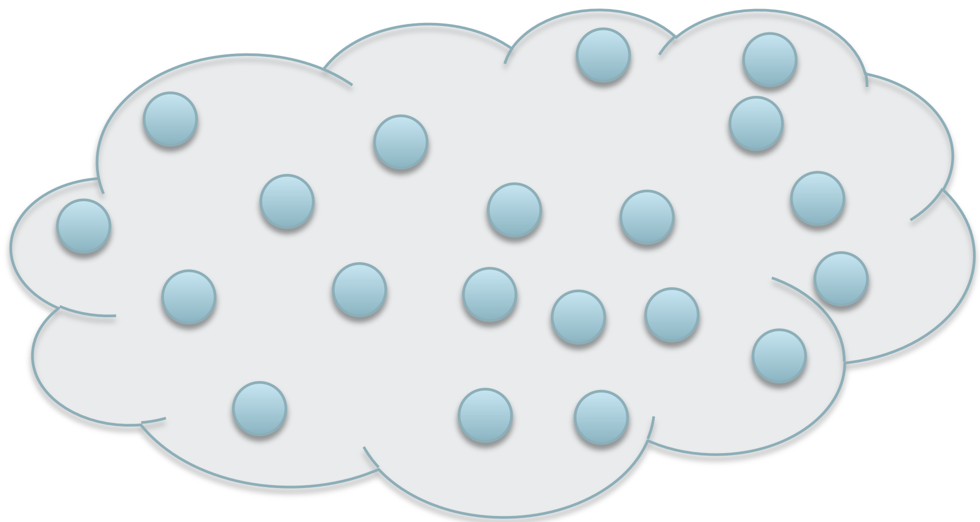


He is one of the first to discover cells and bacteria



Johann Josef Loschmidt uses recent research into the properties of gasses to calculate that air is made of atoms around 10^{-9} m or 0.000000001 m in size

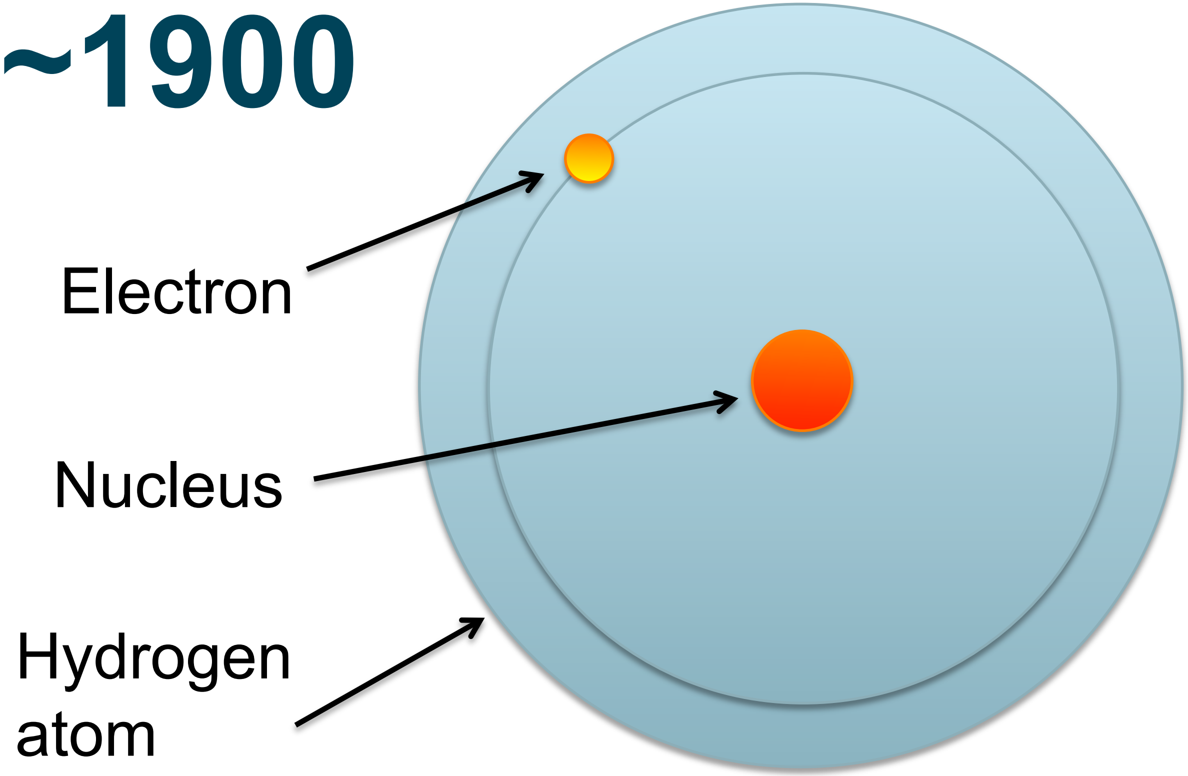
1865



He isn't far off…

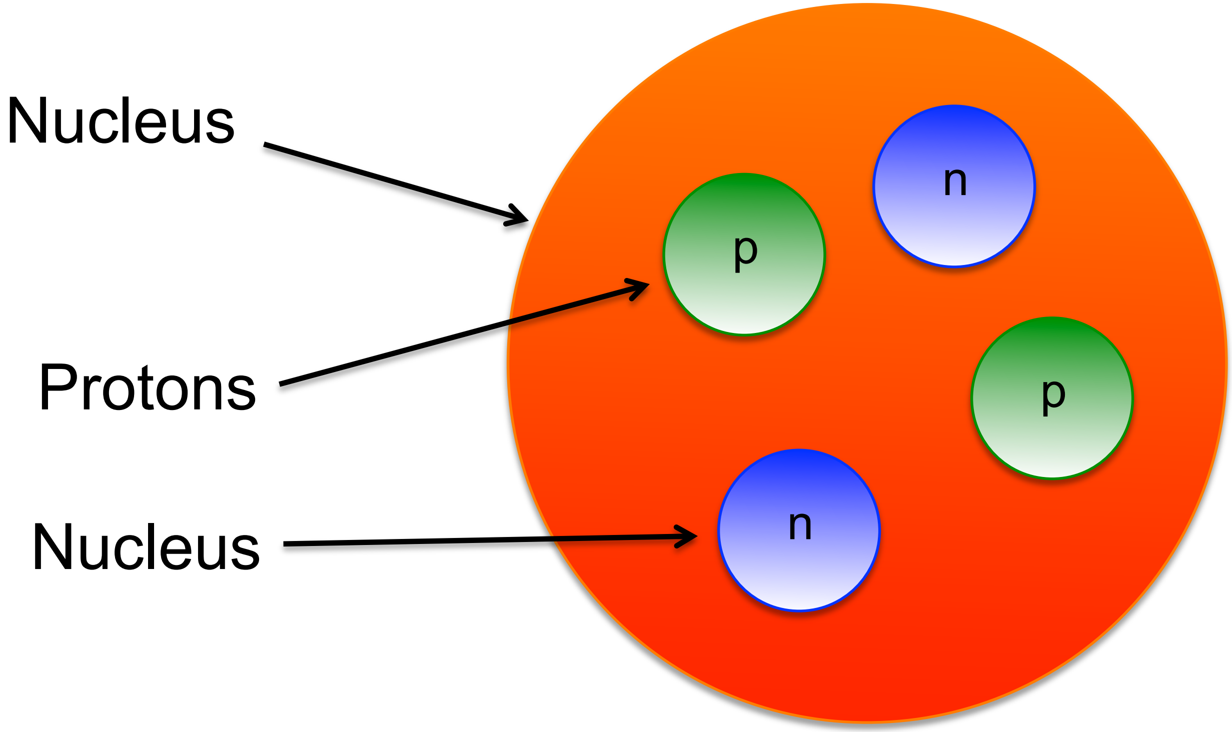
Rutherford and Thompson discover atoms are made up of electrons orbiting a nucleus around 0.00000000000001 m in size (10^{-14} m)

~1900



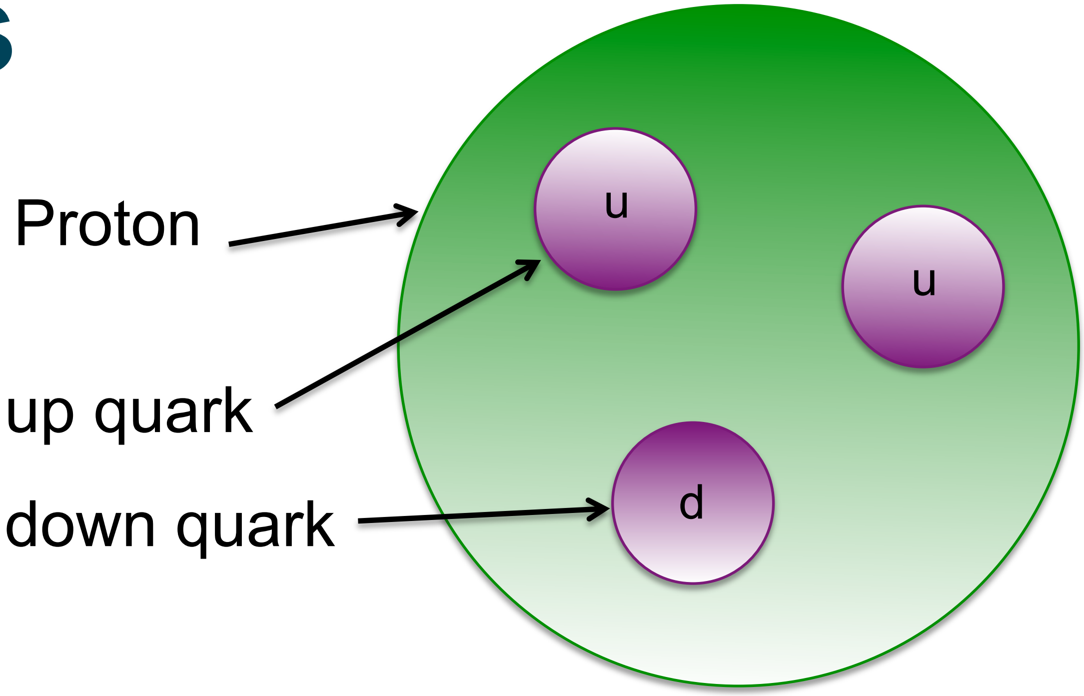
Rutherford and Chadwick discover the nucleus of an atom is made up of protons and neutrons, another 10x smaller (10^{-15} m)

1917-32



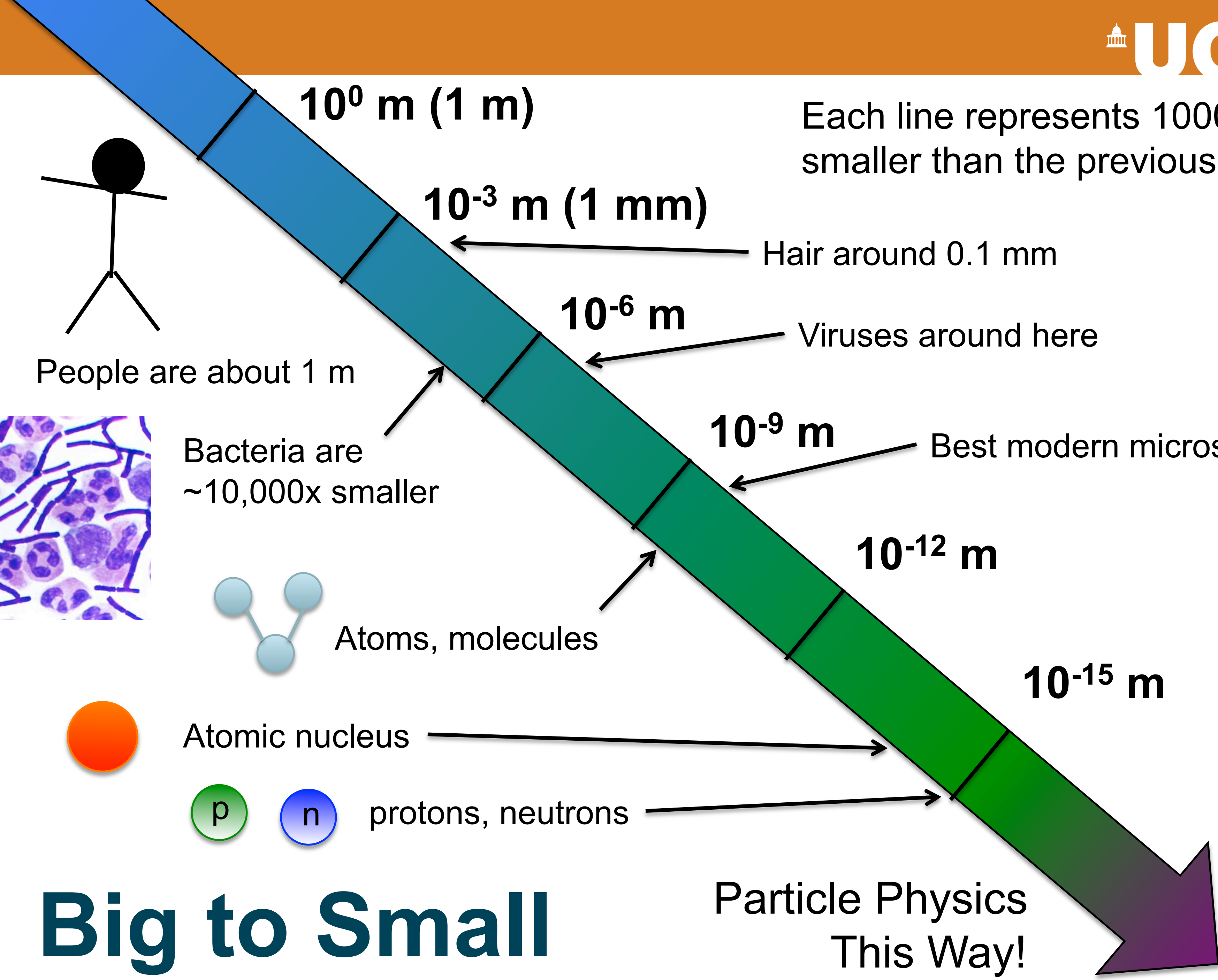
In California, scientists working at SLAC discover quarks in protons. Around this time high-energy particle physics begins. Now studying the universe at scales of less than 10^{-16} m or 0.0000000000000001 m

1960s



SLAC NATIONAL ACCELERATOR LABORATORY

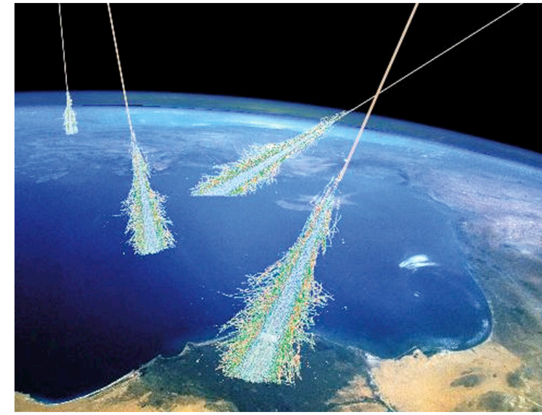
Big to Small



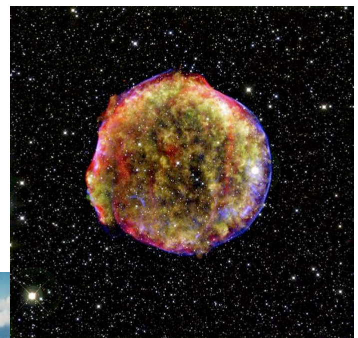
10^0 m (1 m)
Each line represents 1000x smaller than the previous one
10^{-3} m (1 mm)
Hair around 0.1 mm
10^{-6} m
Viruses around here
People are about 1 m
10^{-9} m
Best modern microscopes
Bacteria are ~10,000x smaller
10^{-12} m
Atoms, molecules
10^{-15} m
Atomic nucleus
p
n
protons, neutrons
Particle Physics This Way!

Other Ways…

There are many ways to learn new particle physics



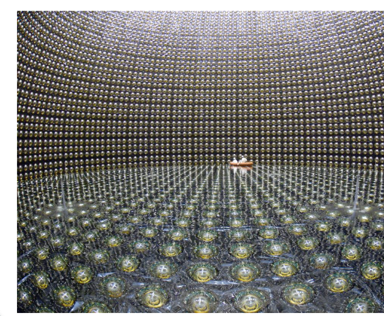
Astro-particle Physics



Cosmic neutrinos

UHE neutrinos

Cosmology
Cosmic rays



LHC

Double-beta decay

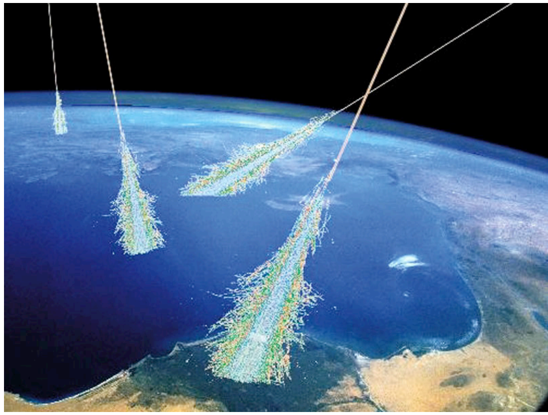
Colliders

Flavour-physics
Neutrino beams

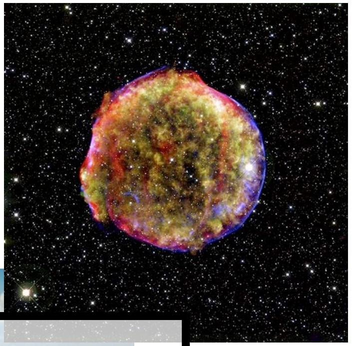
Rare Processes

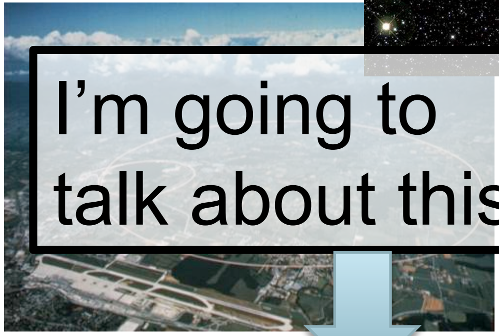
Other Ways…

There are many ways to learn new particle physics



Astro-particle Physics



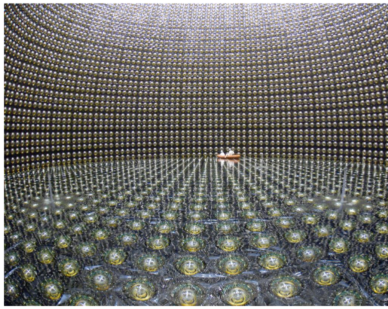


I'm going to talk about this

Cosmology
Cosmic rays

Cosmic neutrinos

UHE neutrinos



LHC

Double-beta decay

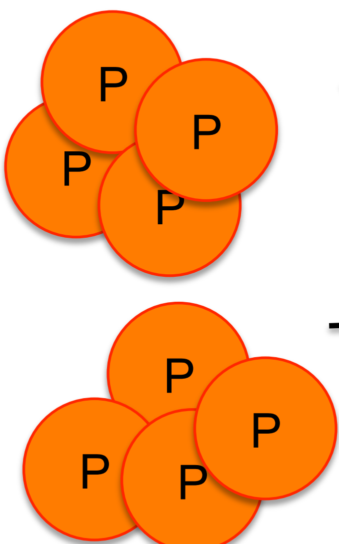
Colliders

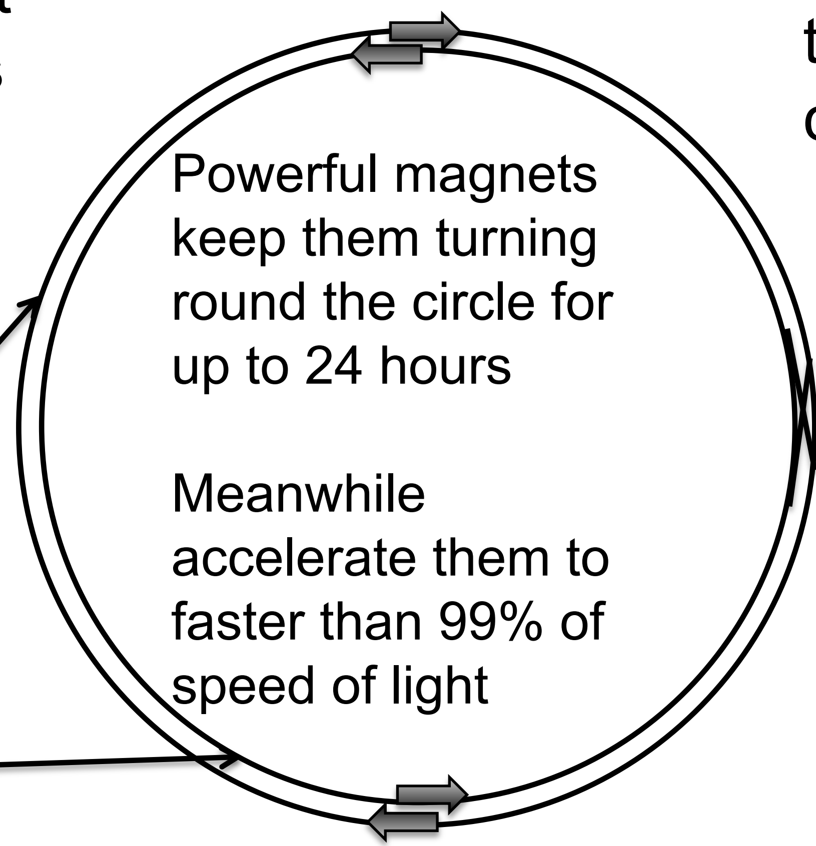
Flavour-physics
Neutrino beams

Rare Processes

How to Build a Particle Accelerator in 60 Seconds

Take protons, put them in two rings going in different directions

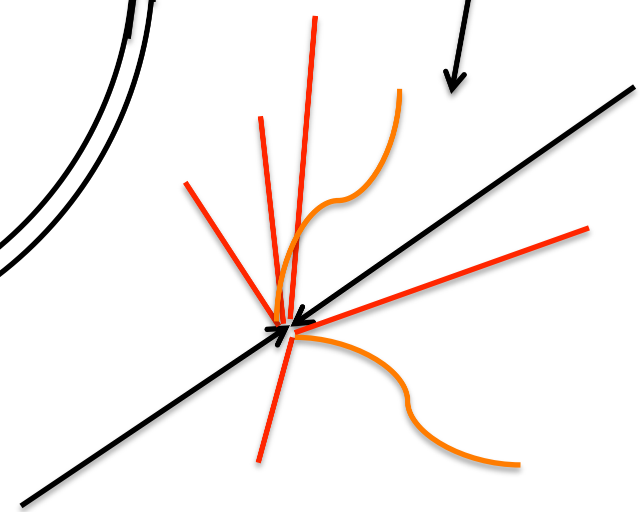




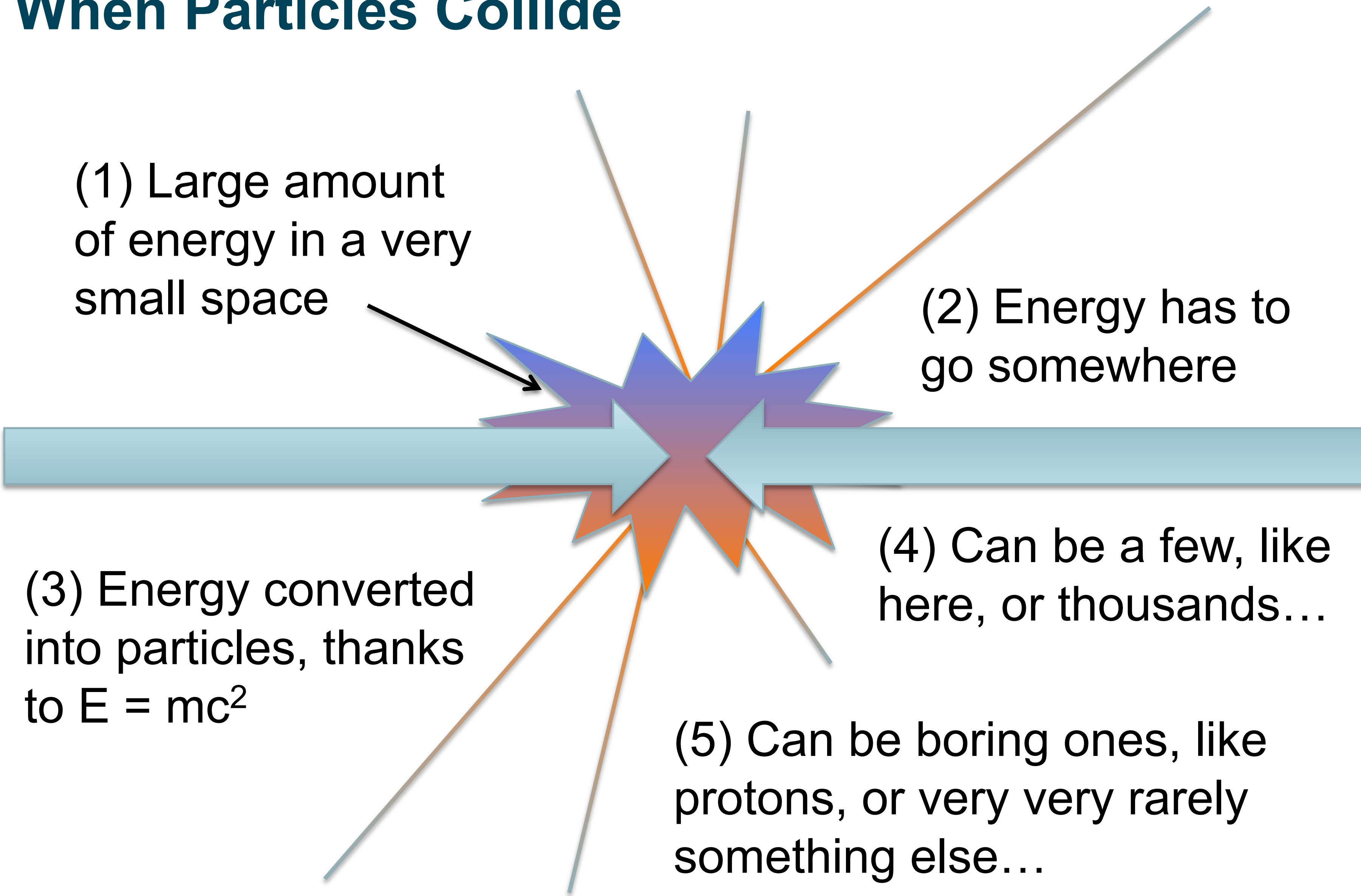
Powerful magnets keep them turning round the circle for up to 24 hours

Meanwhile accelerate them to faster than 99% of speed of light

Cross the beams to make them collide and watch

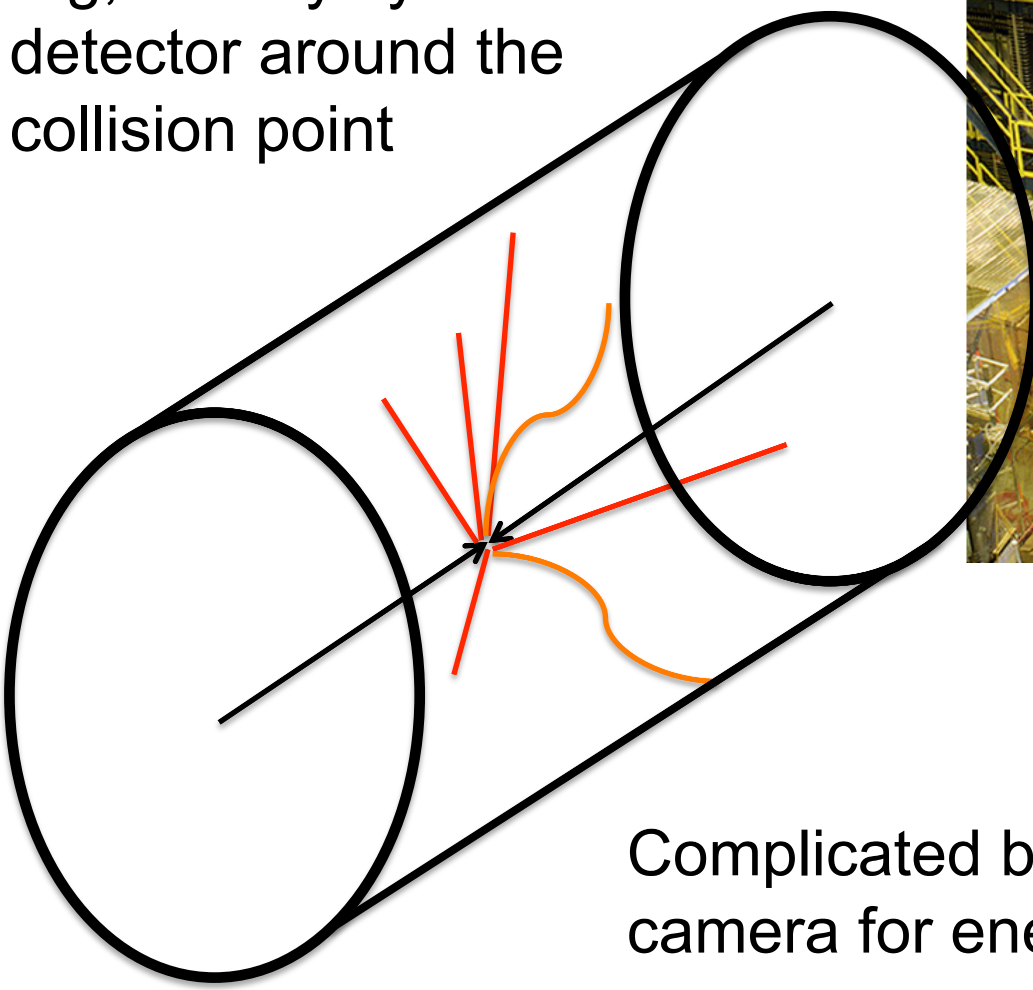


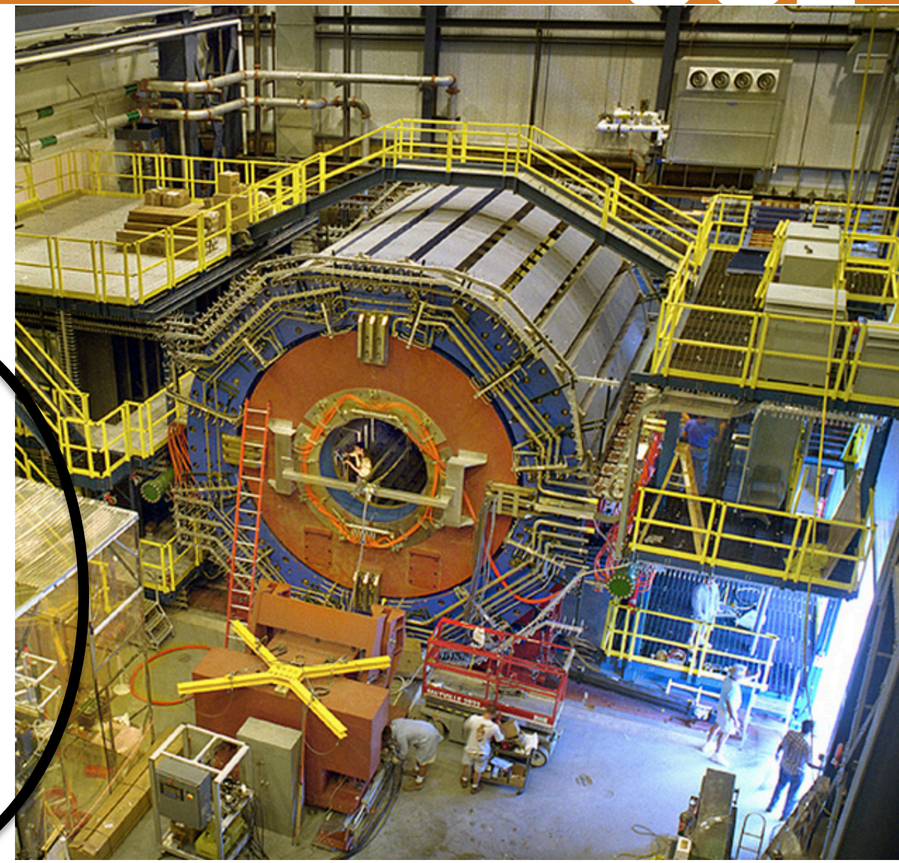
When Particles Collide



How do you Watch?

Big, usually cylindrical detector around the collision point





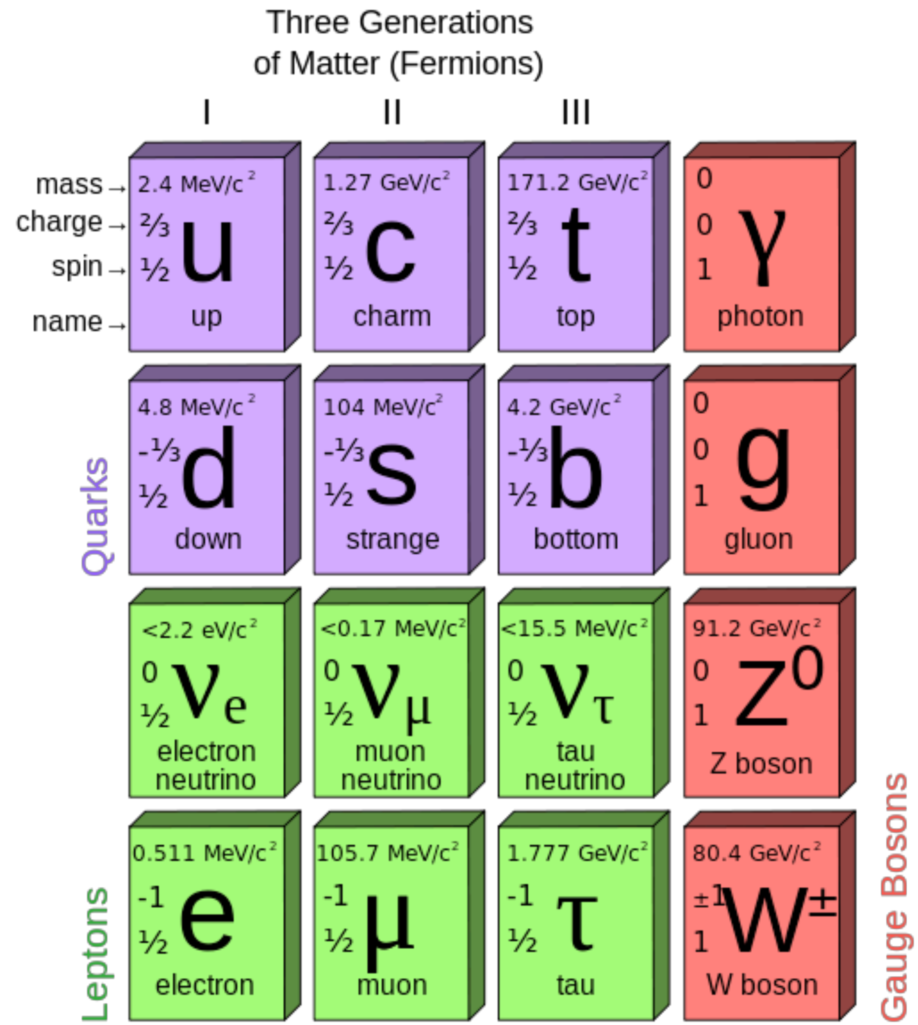
Example: PHENIX at RHIC

Complicated but acts a bit like a camera for energetic particles

The Standard Model

Since the 1960s particle accelerators have taught us that the Universe is described by the Standard Model

Increasing accelerator energies have allowed us to observe heavier and heavier particles ($E = mc^2$ again)



Going Further

- We've learned a lot of great stuff
- Basically how most things work
- To learn more, need **more energy**, make heavier particles
- So, take:
  - 10,000 scientists from more than 100 countries
  - About £6 billion ….
  - … and wait around 20 years
- And you get a **Large Hadron Collider**…

CERN

On the border between France and Switzerland

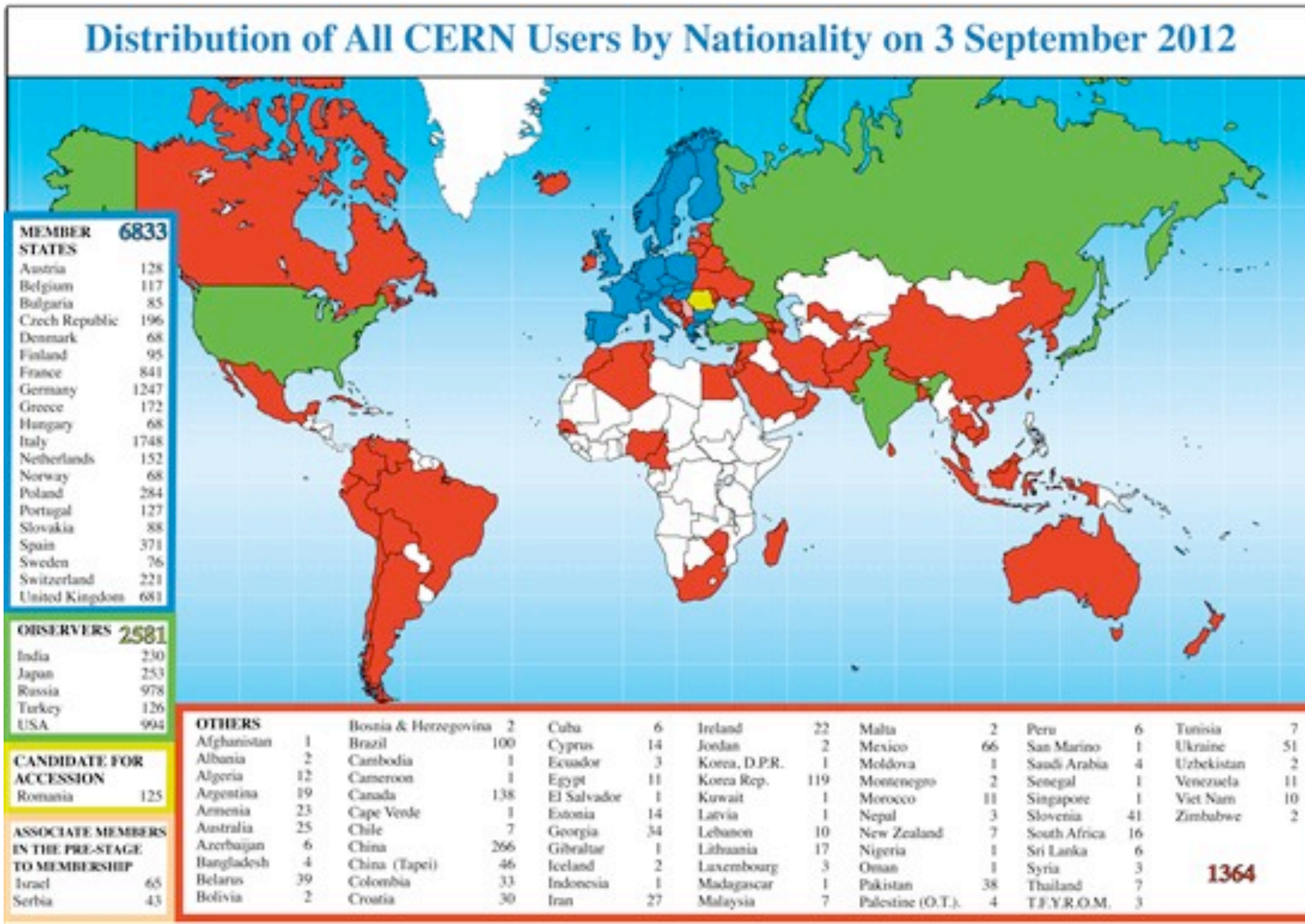
Building particle accelerators since shortly after WWII

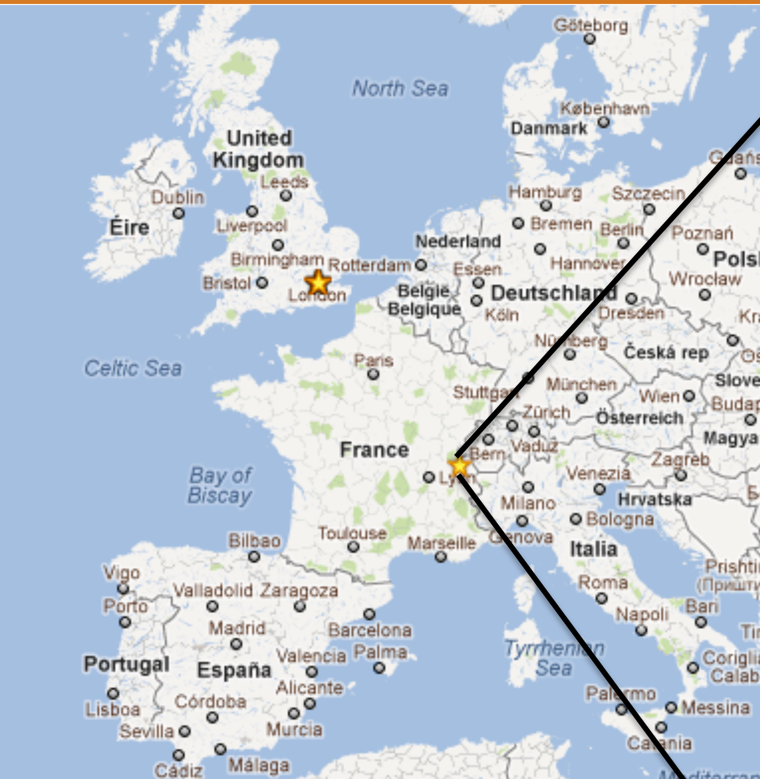
Supported by 25+ countries including the UK

The People

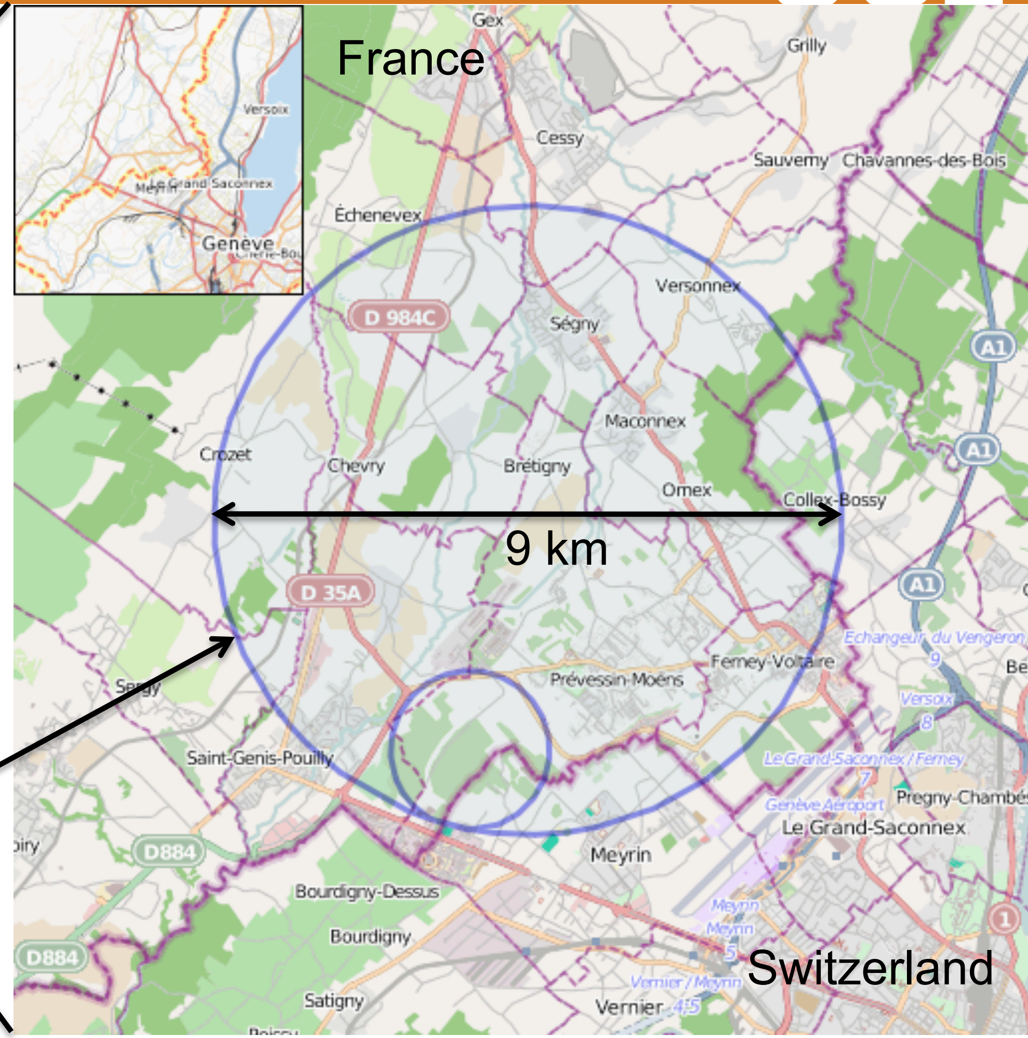
PhD students
Academics
Technicians
etc…

Mostly employed by universities in member states





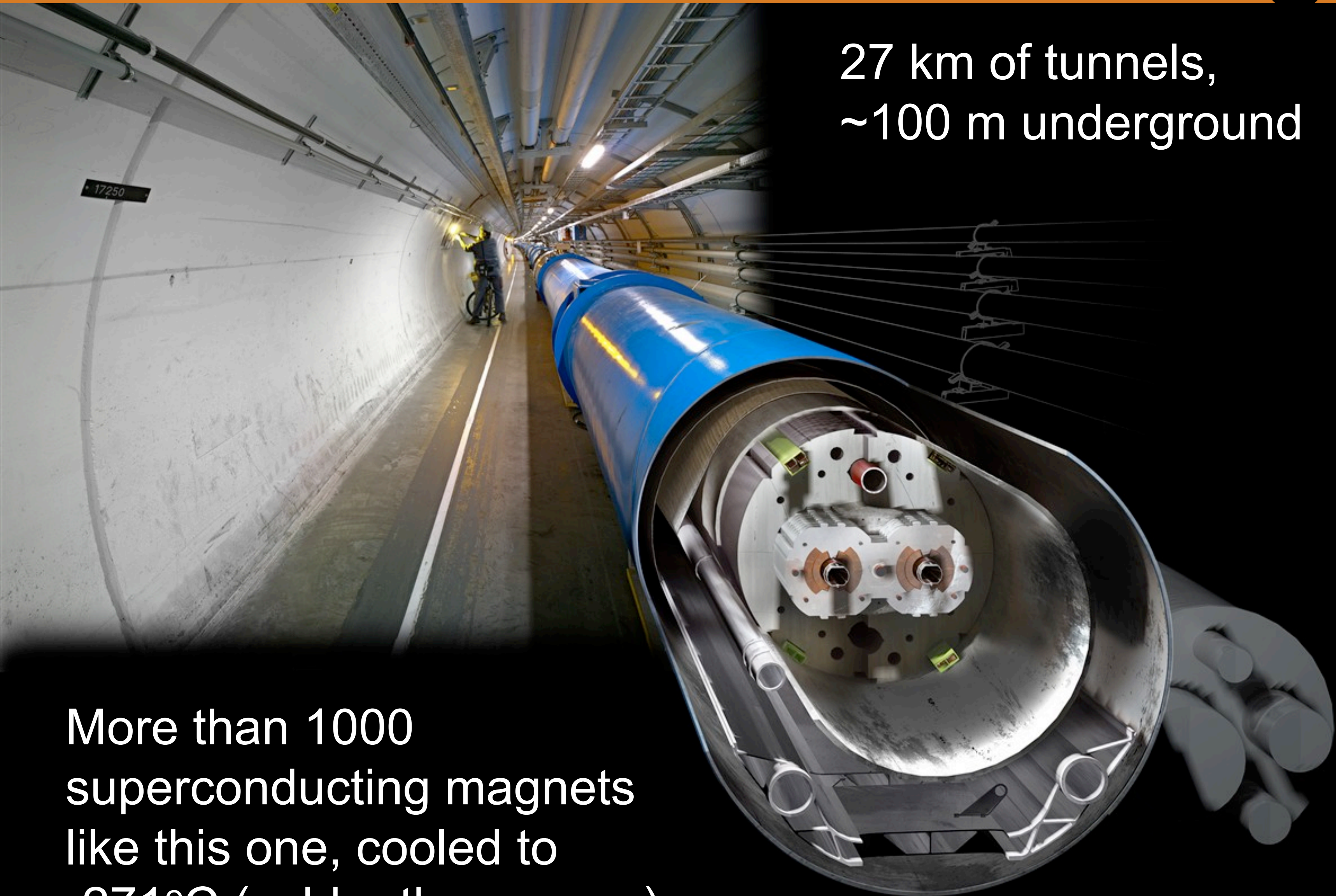
The LHC



The product of 50+ years of worldwide experience

Started running seriously in 2010 at 50% of full power

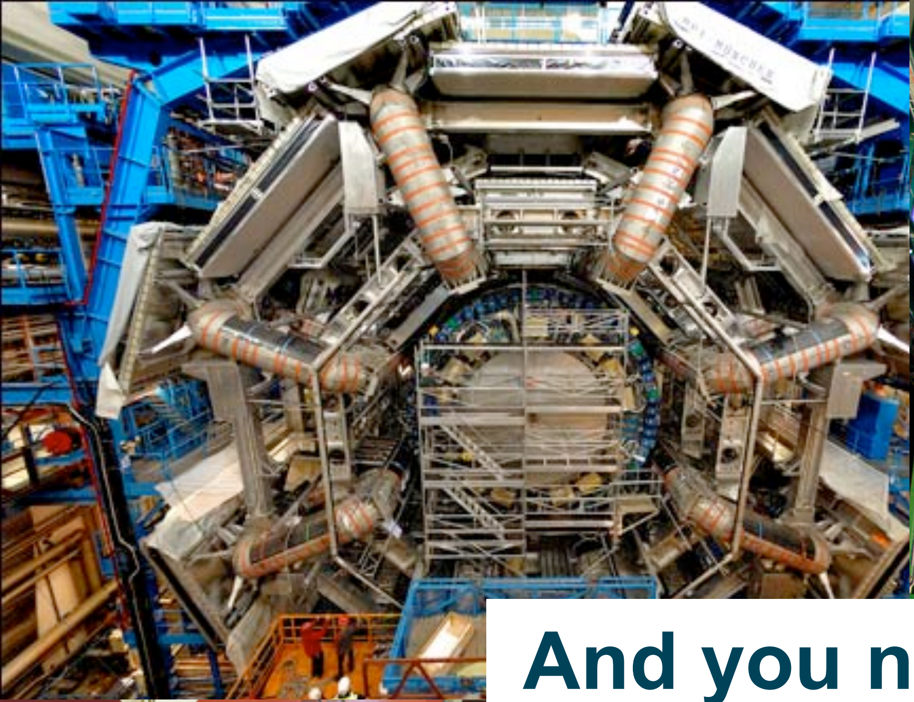
27 km of tunnels,
~100 m underground

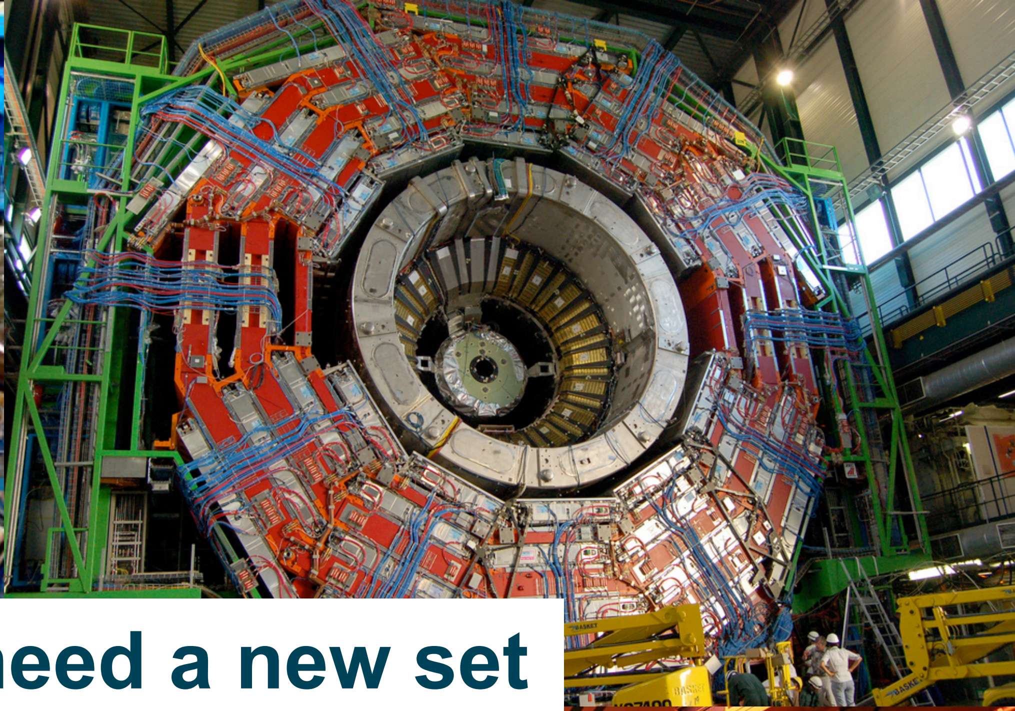


More than 1000 superconducting magnets like this one, cooled to -271°C (colder than space)

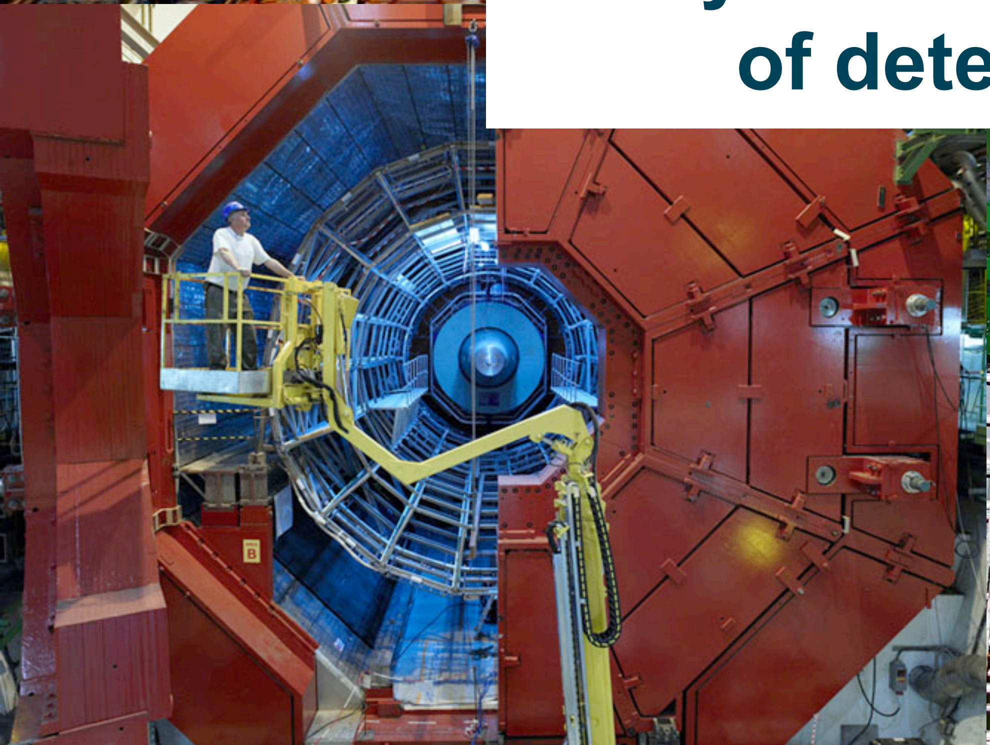
What do you get?

- Two beams, about 300 million million protons each
- Travelling in opposite directions around the ring
  - At 99.9999991% of the speed of light (670 million miles per hour)
- Energy up to 7 TeV (Trillion electron Volts) per proton
- Beam energy is equivalent to a train going 100 mph
- Enough energy in the beams to melt a tonne of copper
- (In fact stopping it when you're done is hard too)

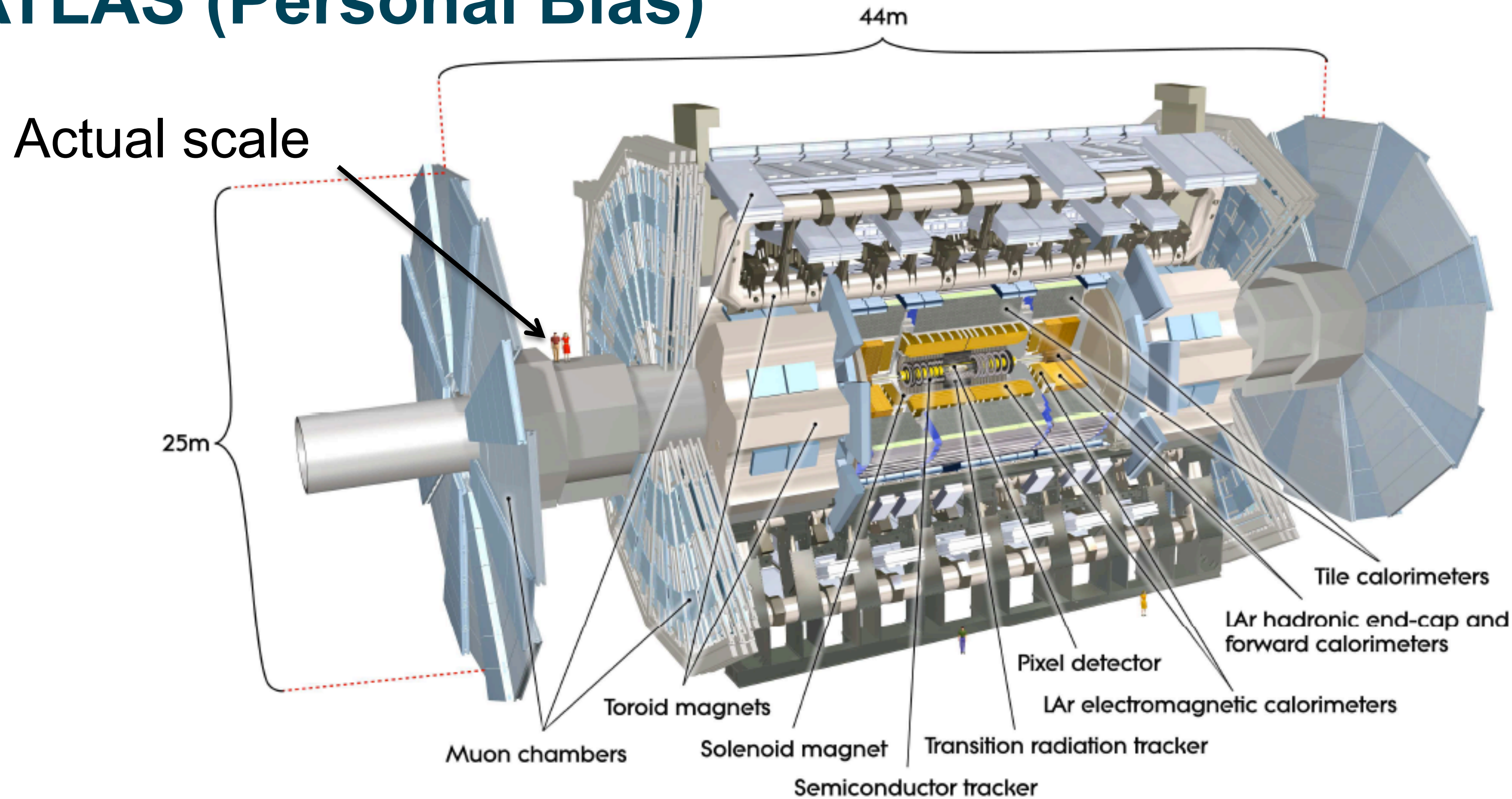




And you need a new set of detectors!



ATLAS (Personal Bias)



Cost ~£1 bn but weighs around 7,000 tonnes (hard to steal)

Different bits help identify and measure different types of particle

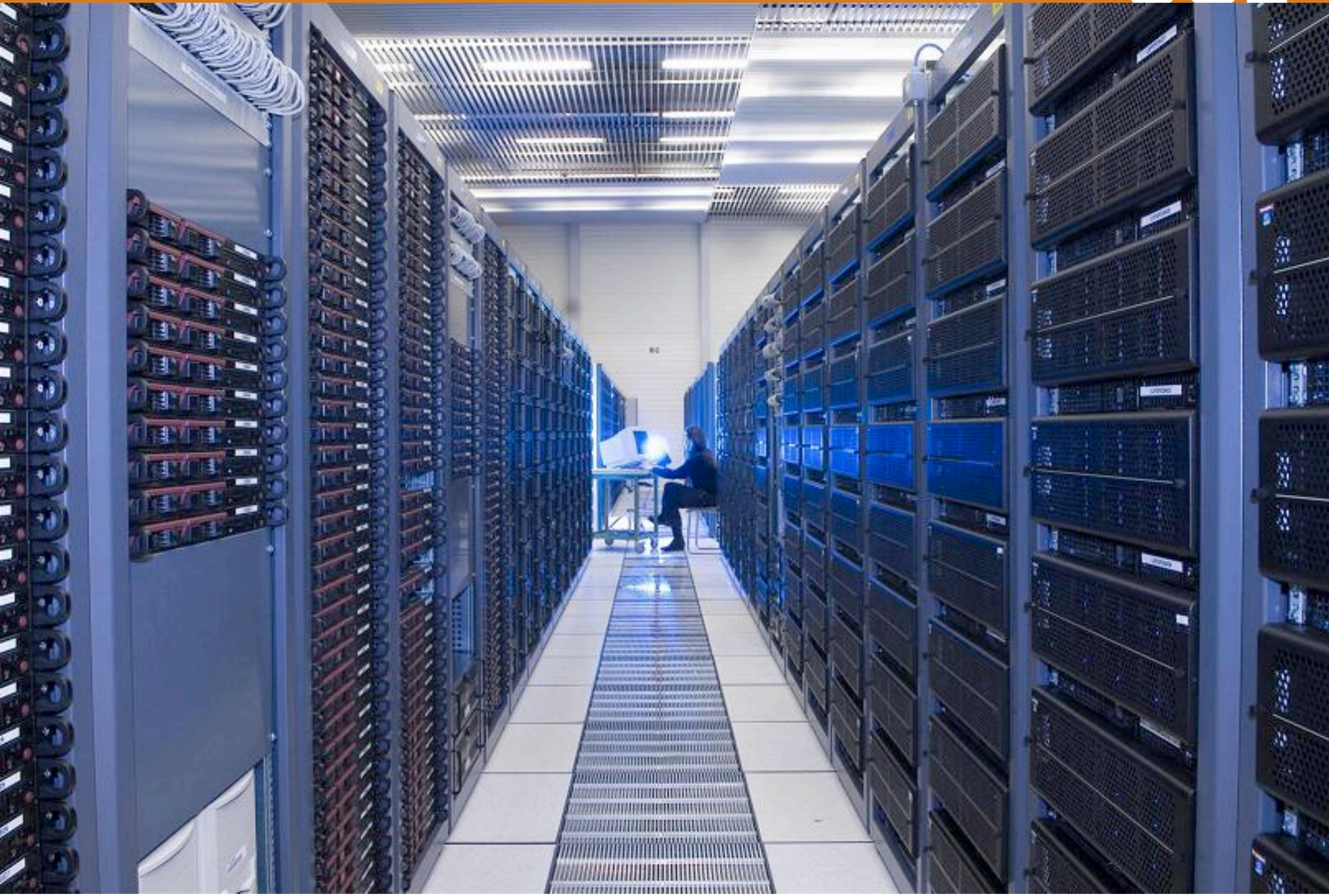
Too Much

- Beams collide 400 million times a second
- ATLAS alone, about 100,000 DVDs worth of data a second
- Can't keep it all
- Store about a CDs worth a second (~500 MB)
  - (Not actually on CDs…)
- Still too much for any single organisation
- Data is sent worldwide to a "grid" of computer centres

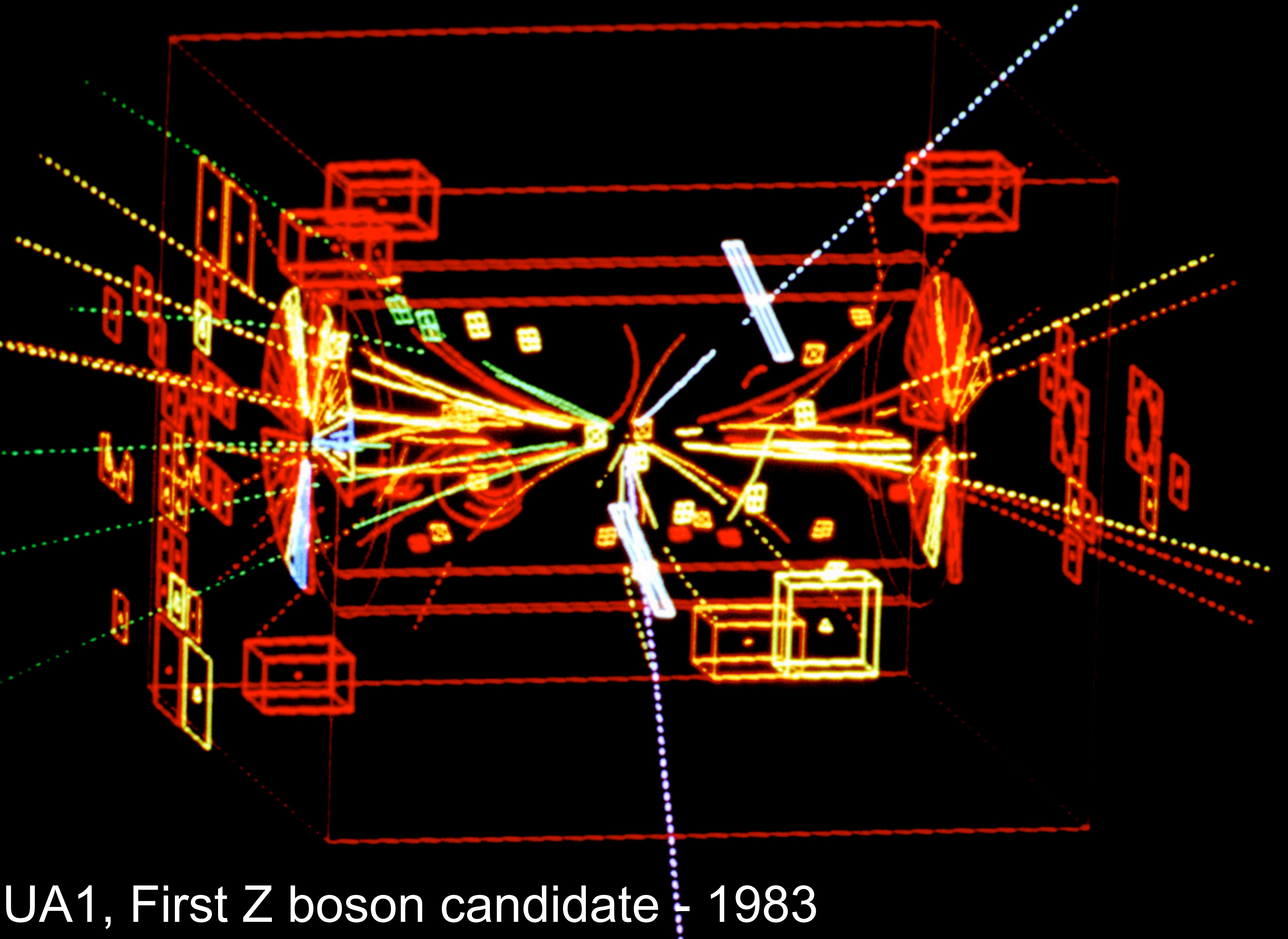
LHC Computing Links (Europe Only)

More than 100 sites store up to 15 PB of data a year…

… enough to fill a regular computer disk ~50,000x over



What do you see?

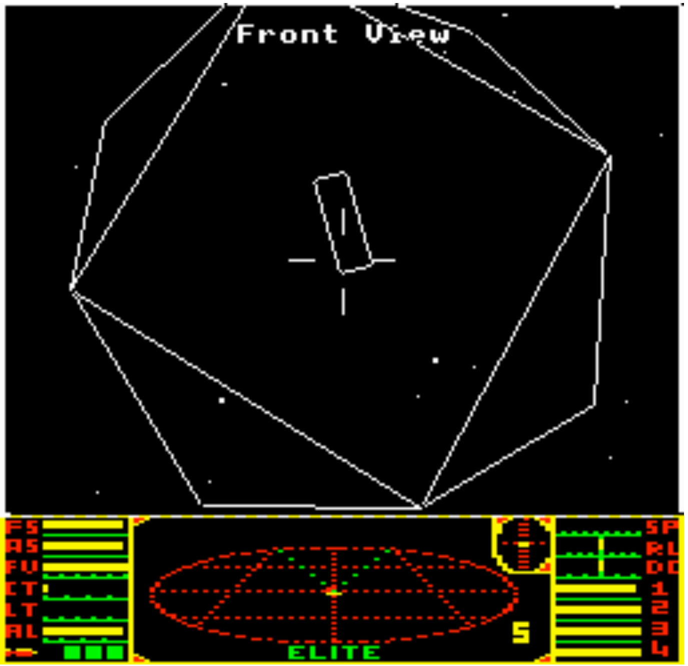


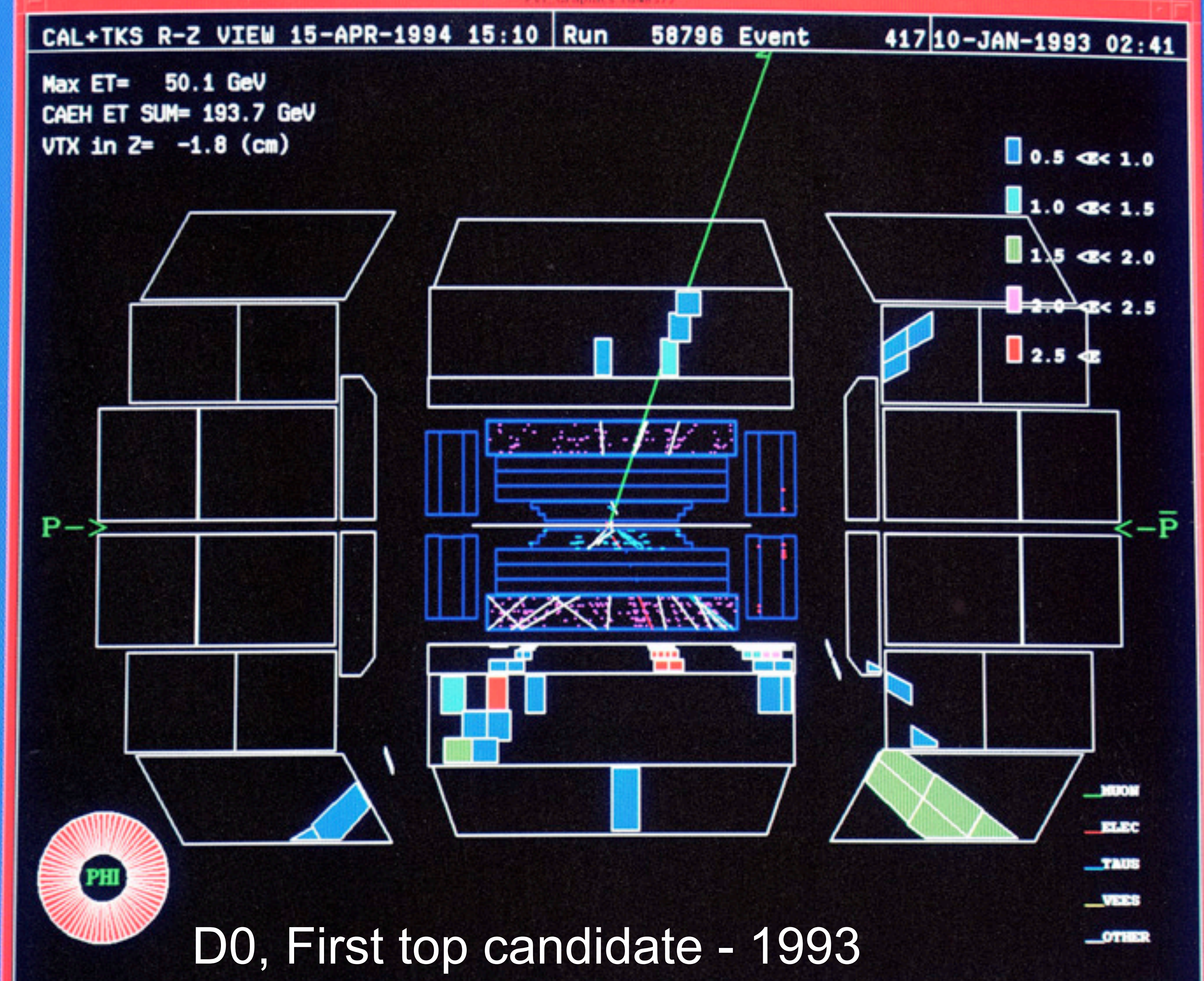
UA1, First Z boson candidate - 1983

Manic Miner, 1983

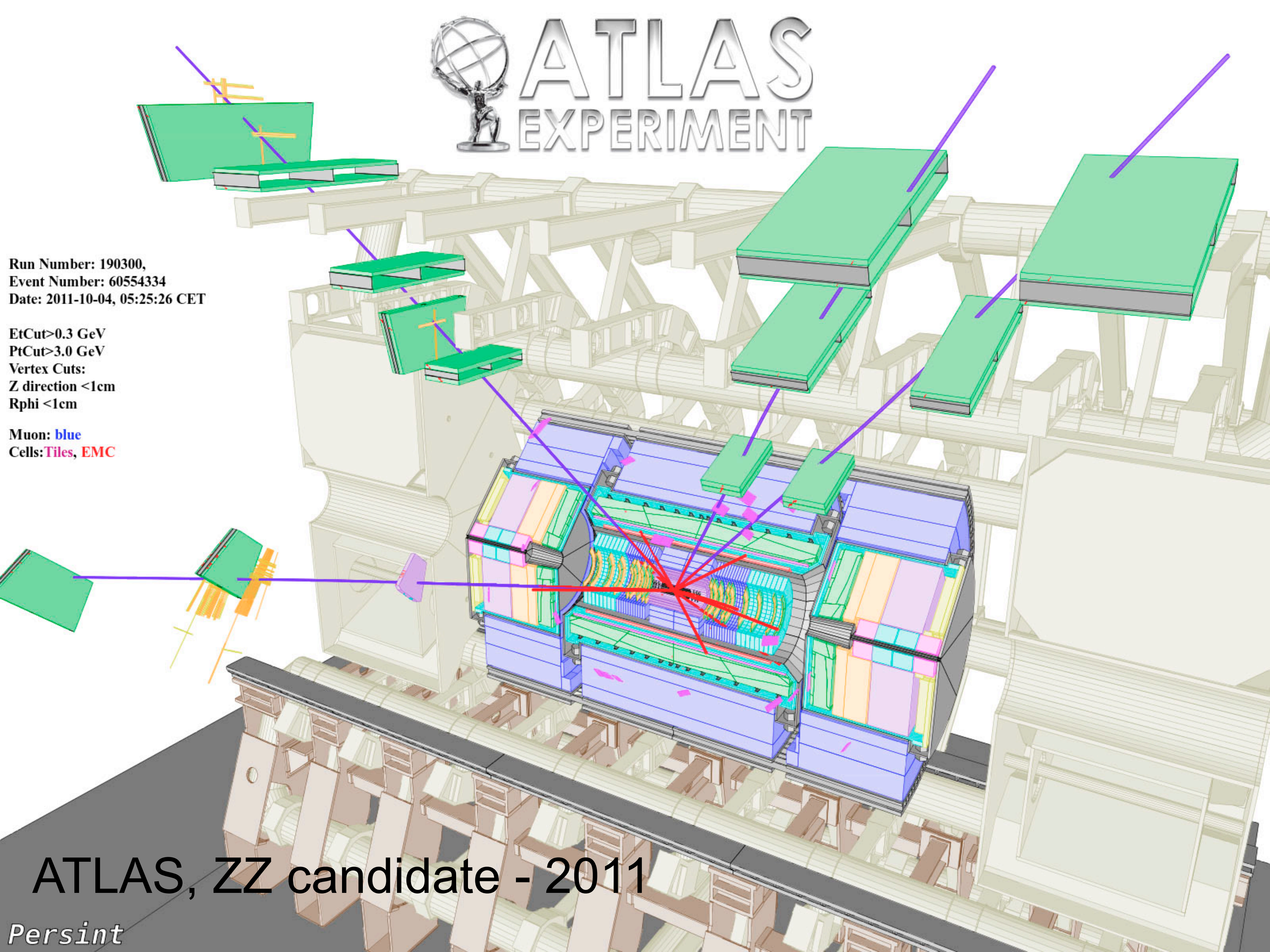
Star Wars, 1983

Elite, 1984

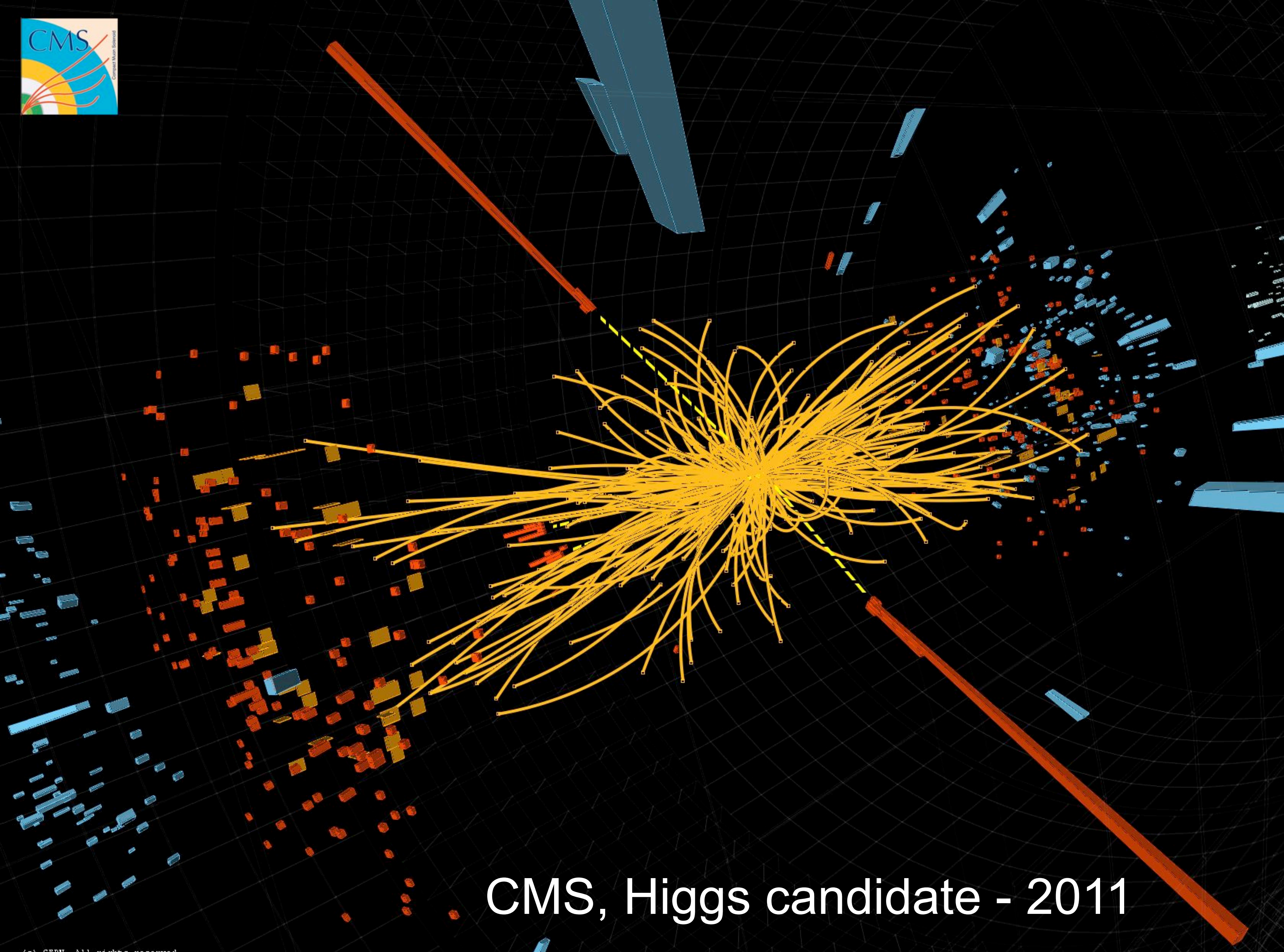




D0, First top candidate - 1993



ATLAS, ZZ candidate - 2011



CMS, Higgs candidate - 2011

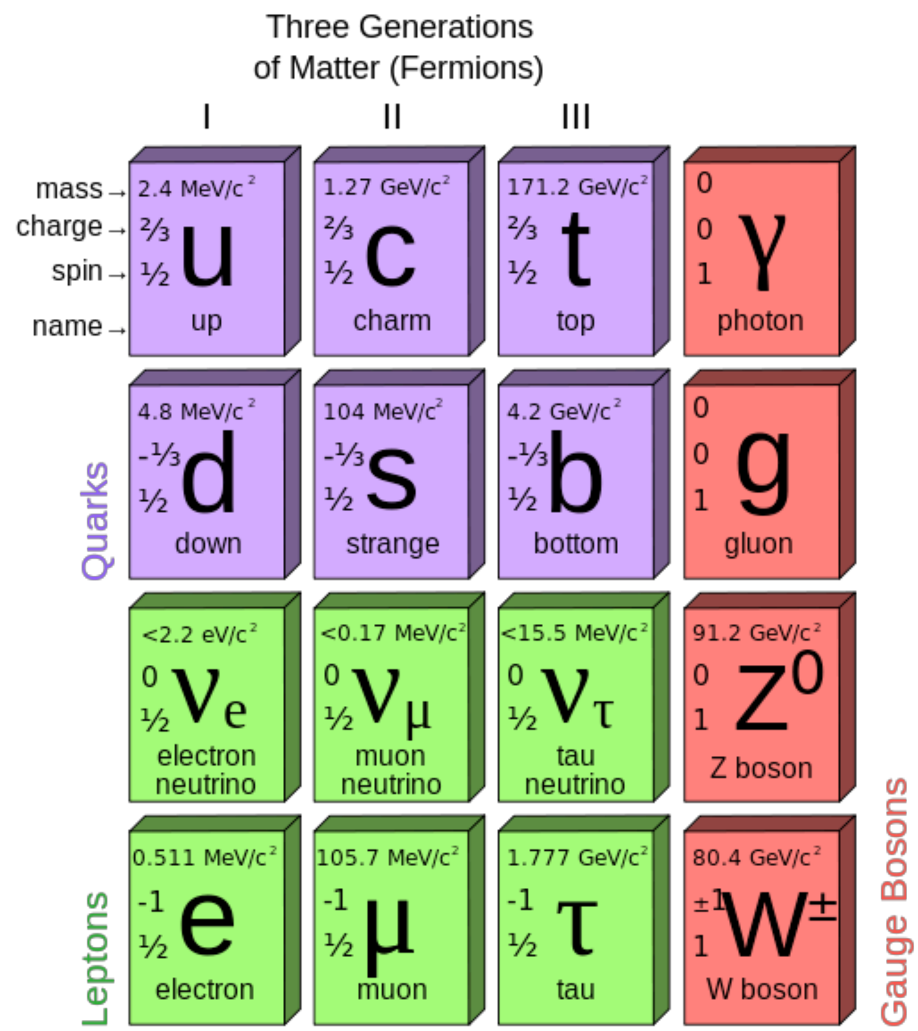
The Higgs

Particles have mass

How do they get mass?

Can’t just write it into the maths, everything breaks!

One idea is that they’re connected to a “Higgs field” which gives them mass

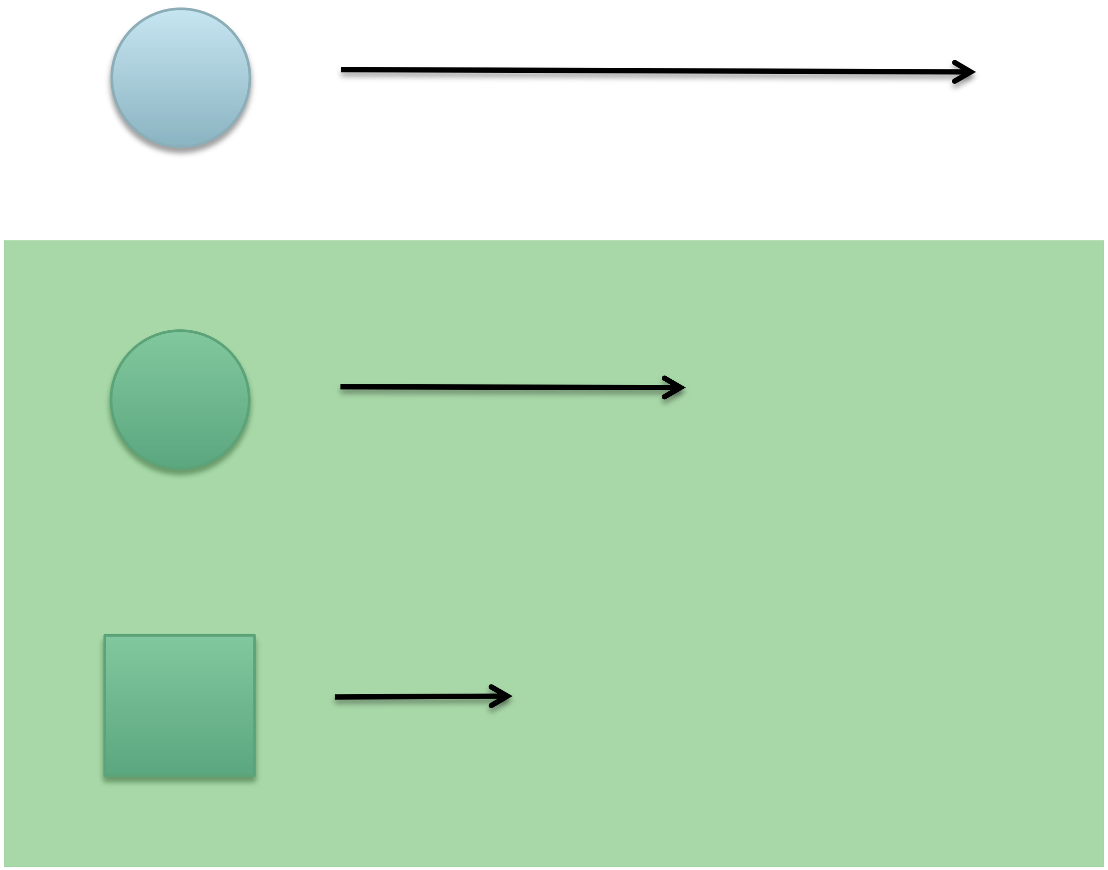


The Higgs – By (Bad) Analogy

Something very light, push it, it goes

Put it in liquid, it goes more slowly…

It's essentially the same but goes slower….

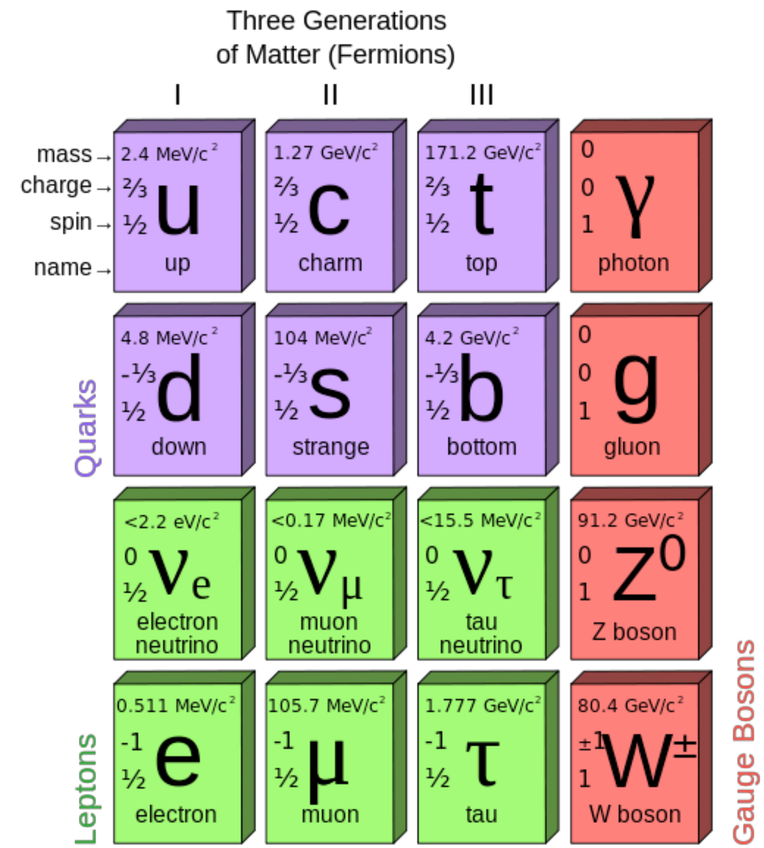


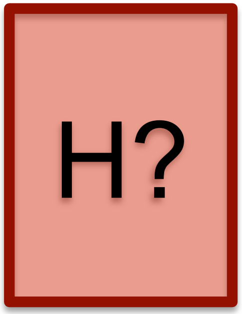
The Higgs

One prediction of this approach is that there's a new particle, the "Higgs boson"

It's fairly distinctive too…

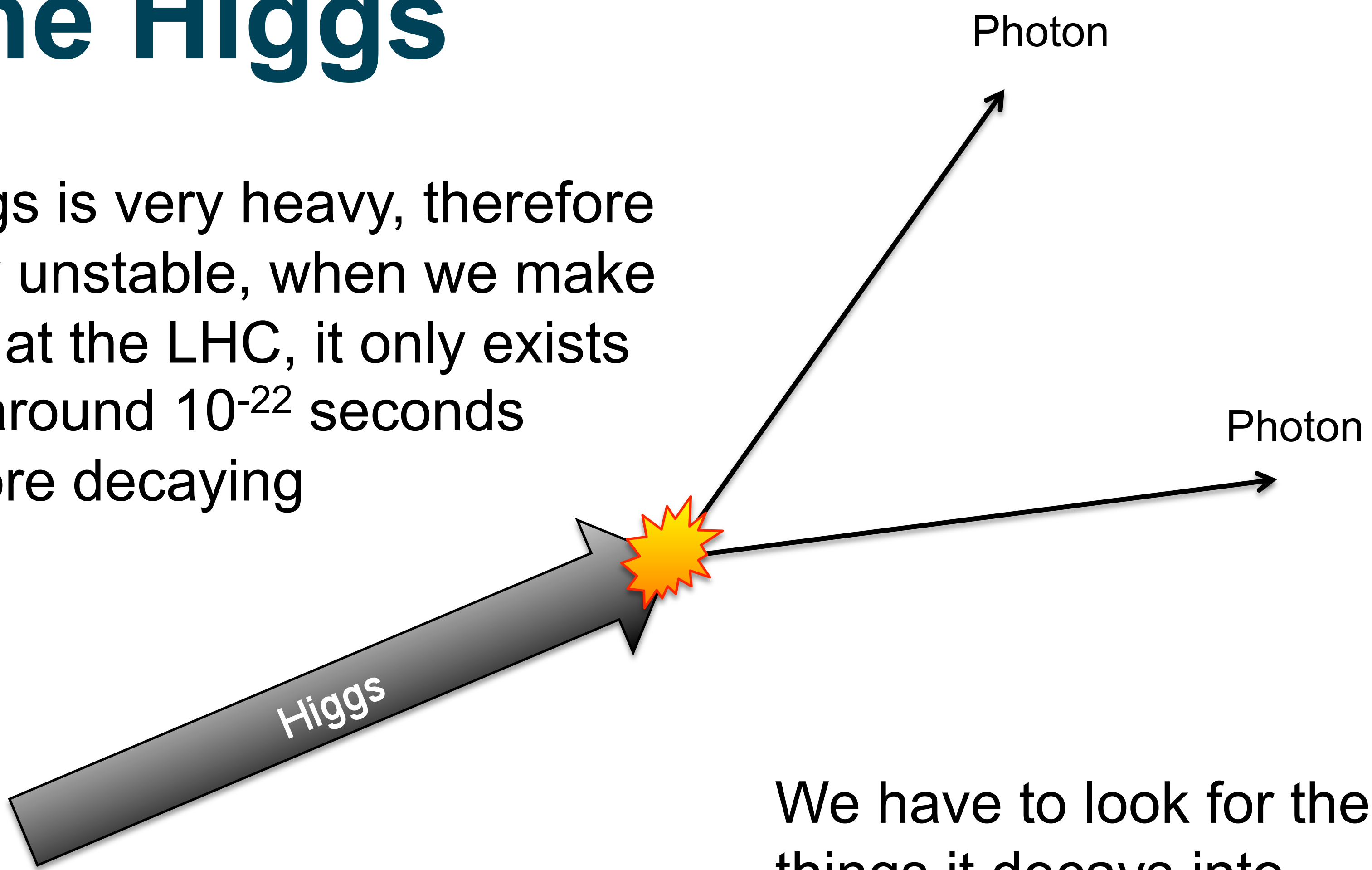
We have enough energy to search for this particle for the first time at the LHC!





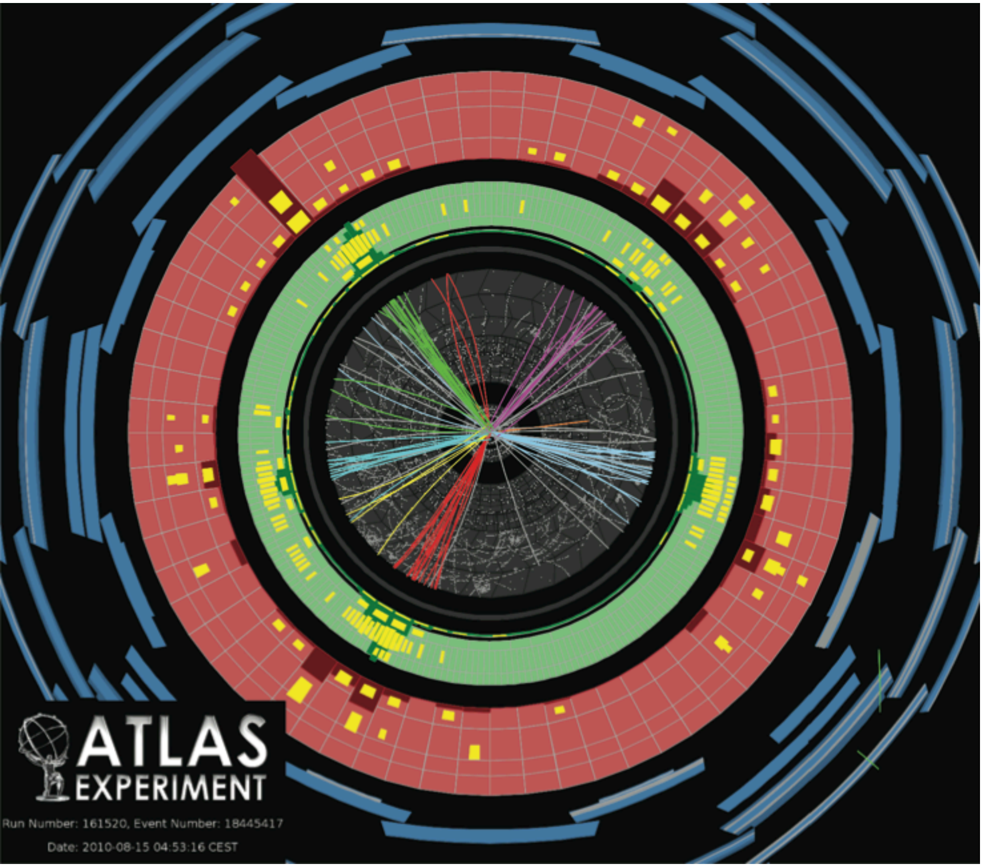
The Higgs

Higgs is very heavy, therefore very unstable, when we make one at the LHC, it only exists for around 10^{-22} seconds before decaying



We have to look for the things it decays into

Higgs Boson Decays

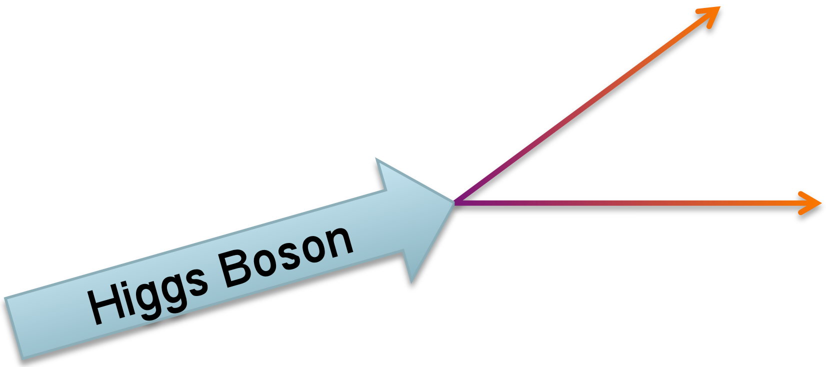


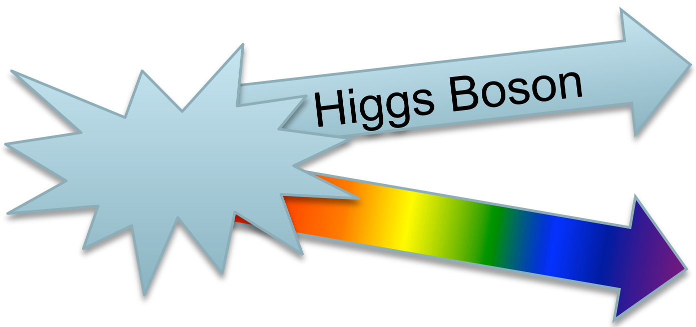
- A 126 GeV Higgs decays mostly to hadrons
- At Large Hadron Colliders there are lots of those though
- Make hundreds of thousands of Higgses

- But can't see most of them…

The Long Way Round

- Higgs bosons can rarely decay to more distinctive particles



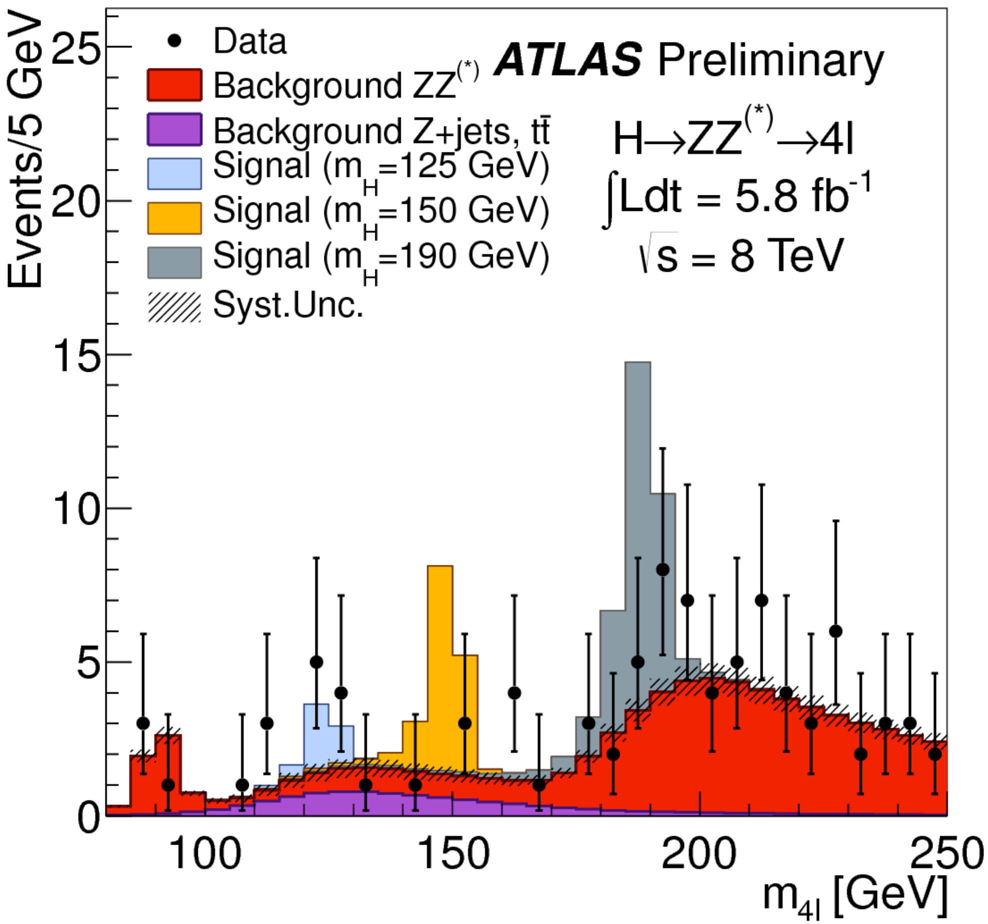


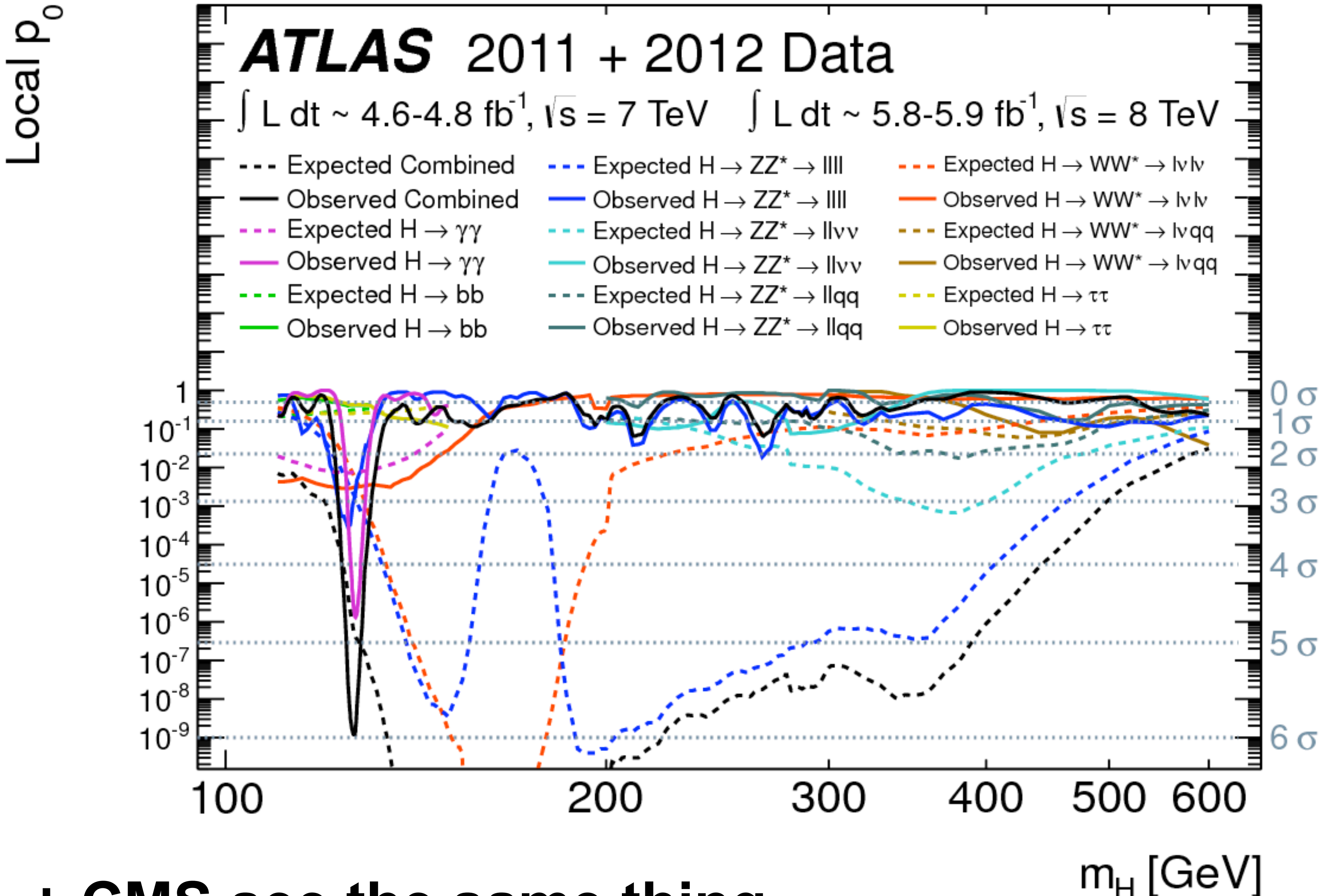
- Also rarely produced along with something more distinctive

- We're forced to search for these rarer process to be able to spot the Higgs, need more data!

Higgs Decays to Two Zs

- A very rare decay, happens only 0.06% of the time
- But 2 Zs are really easy to spot!
- Actually one of the most sensitive places to look





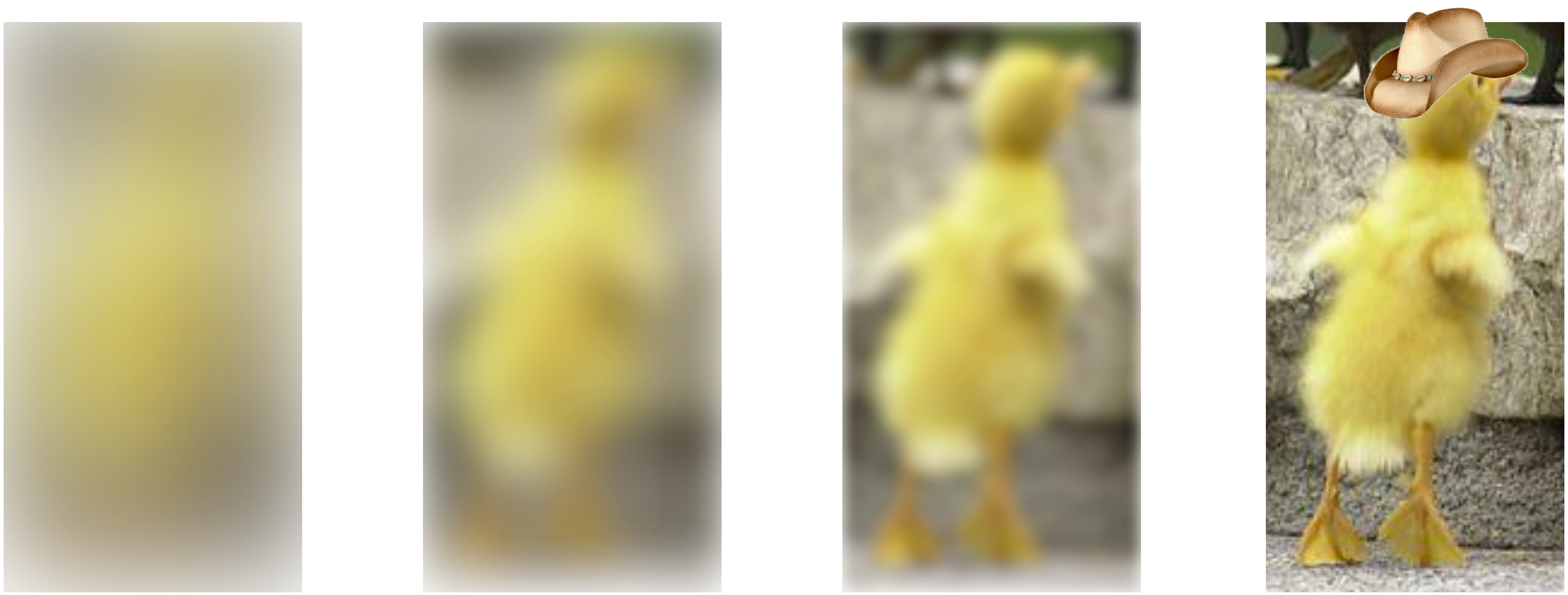
+ CMS see the same thing…

The Higgs

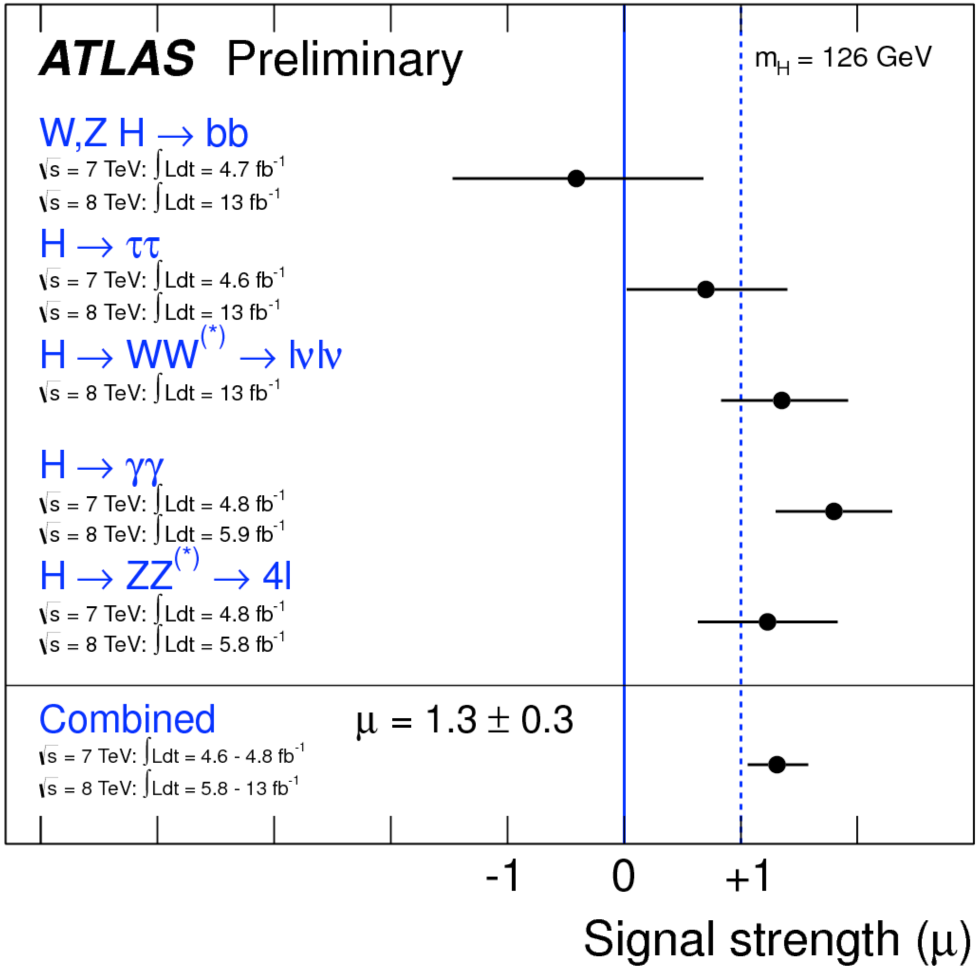
- The LHC has definitively found a new particle
- Most important discovery in fundamental physics for at least a decade, probably longer…
- Consistent so far with the predictions of a Higgs boson

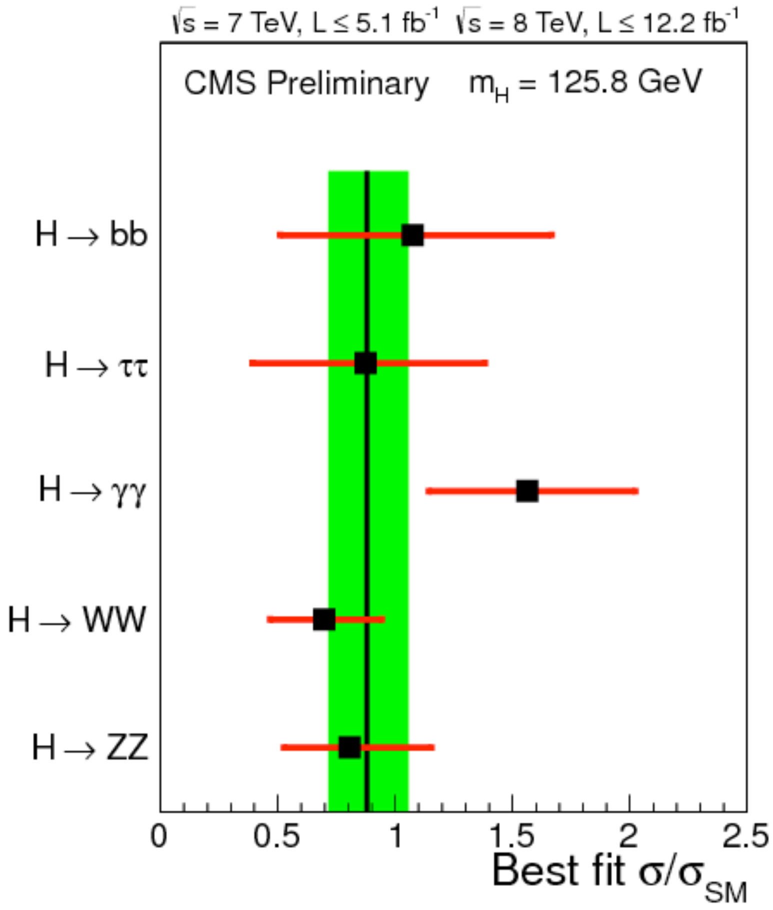
What Now?

- What exactly did we find?
- Need to measure everything!



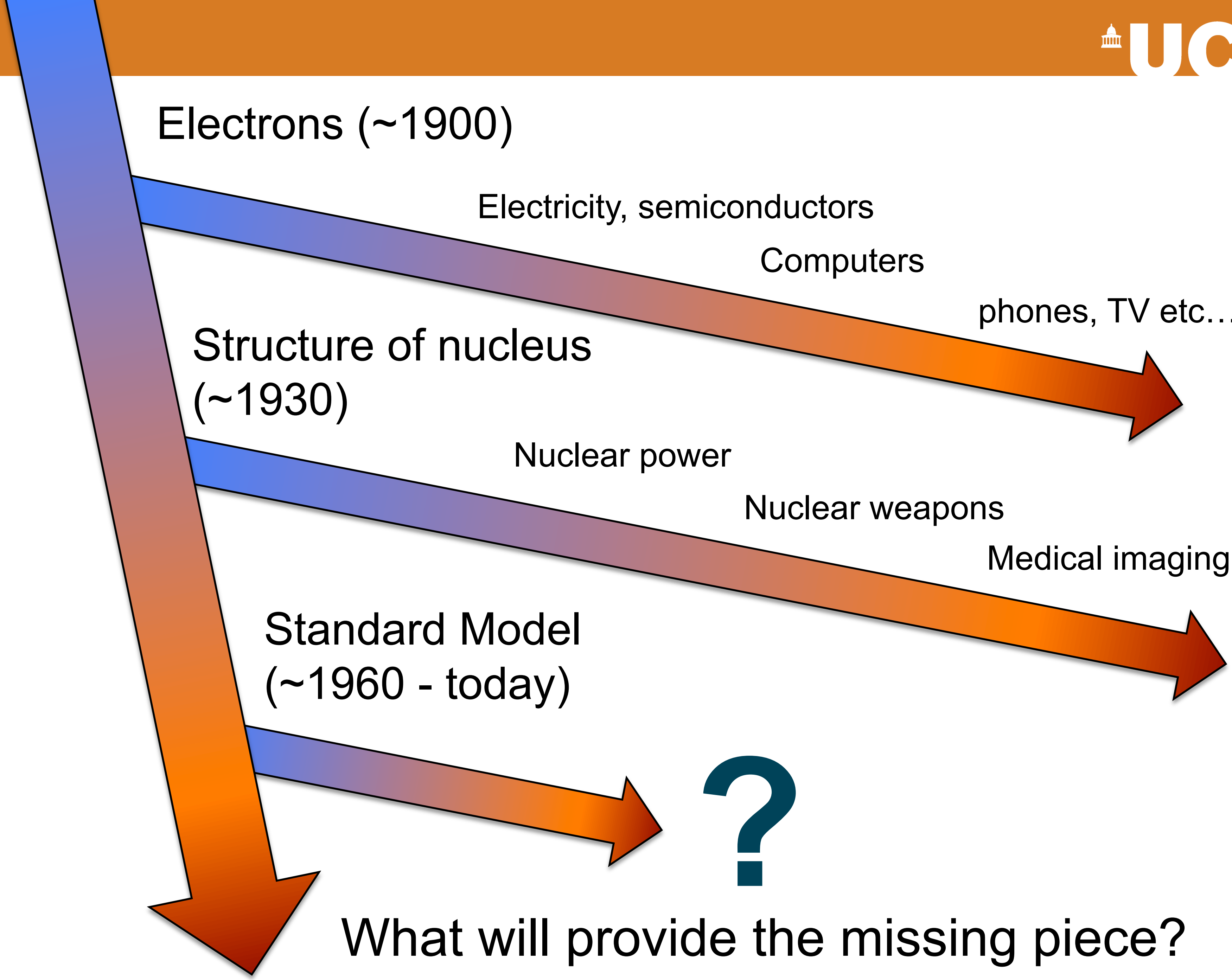
The First Steps…





So…

- Particle physics is helping to answer really hard questions:
  - How did I get here?
  - How does the universe work?
  - What is it made of?
- The Higgs is the next step in a long journey
  - How do things get mass?
- Only leads to more questions though…
  - … why do they have the masses they do???


Electrons (~1900)
Electricity, semiconductors
Computers
phones, TV etc…
Structure of nucleus
(~1930)
Nuclear power
Nuclear weapons
Medical imaging
Standard Model
(~1960 - today)
?
What will provide the missing piece?

The End

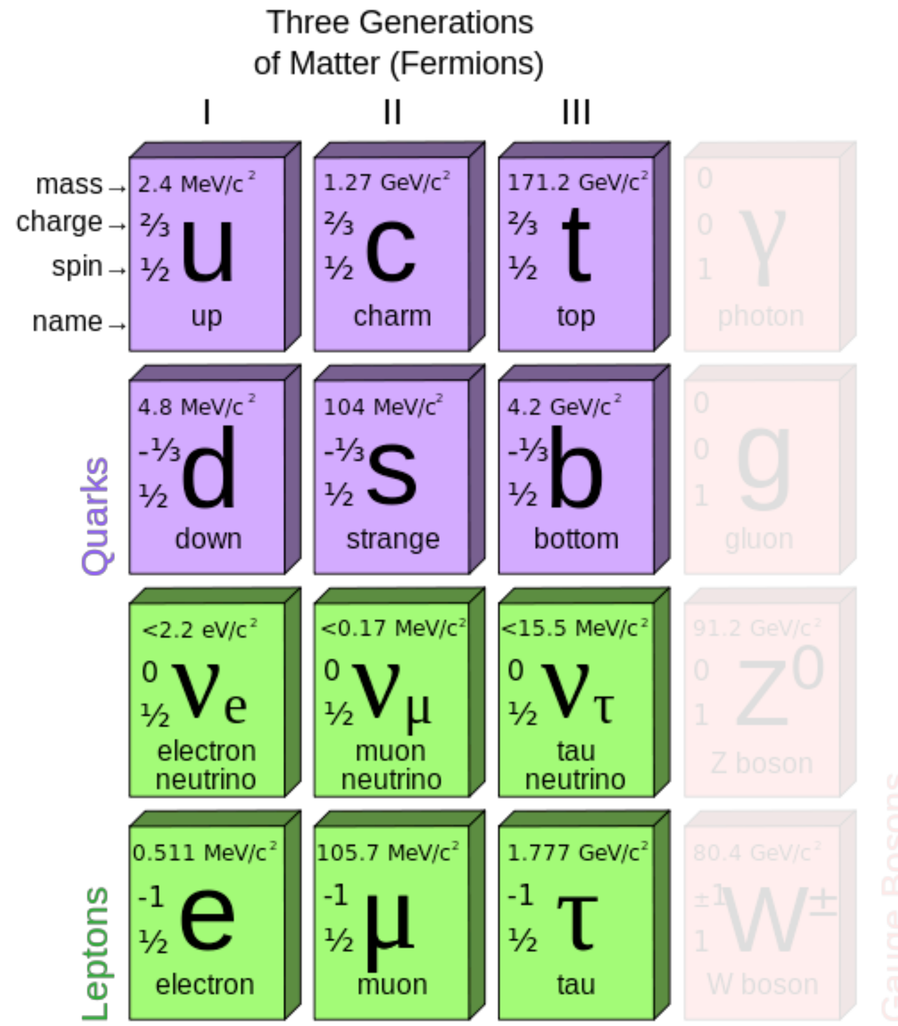
- Particle physics is hard
- By building a giant machine we can probe the very small
- And in the process help answer really basic questions
- The Large Hadron Collider is the next step in a journey
- The discovery of a Higgs(-like) boson is great
- Nobody knows what else we'll find…

The Standard Model

Since the 1960s particle accelerators have taught us that the Universe is described by the Standard Model

The up and down quarks and electron make up most everyday matter

But also 4 more quarks, muons, taus and neutrino

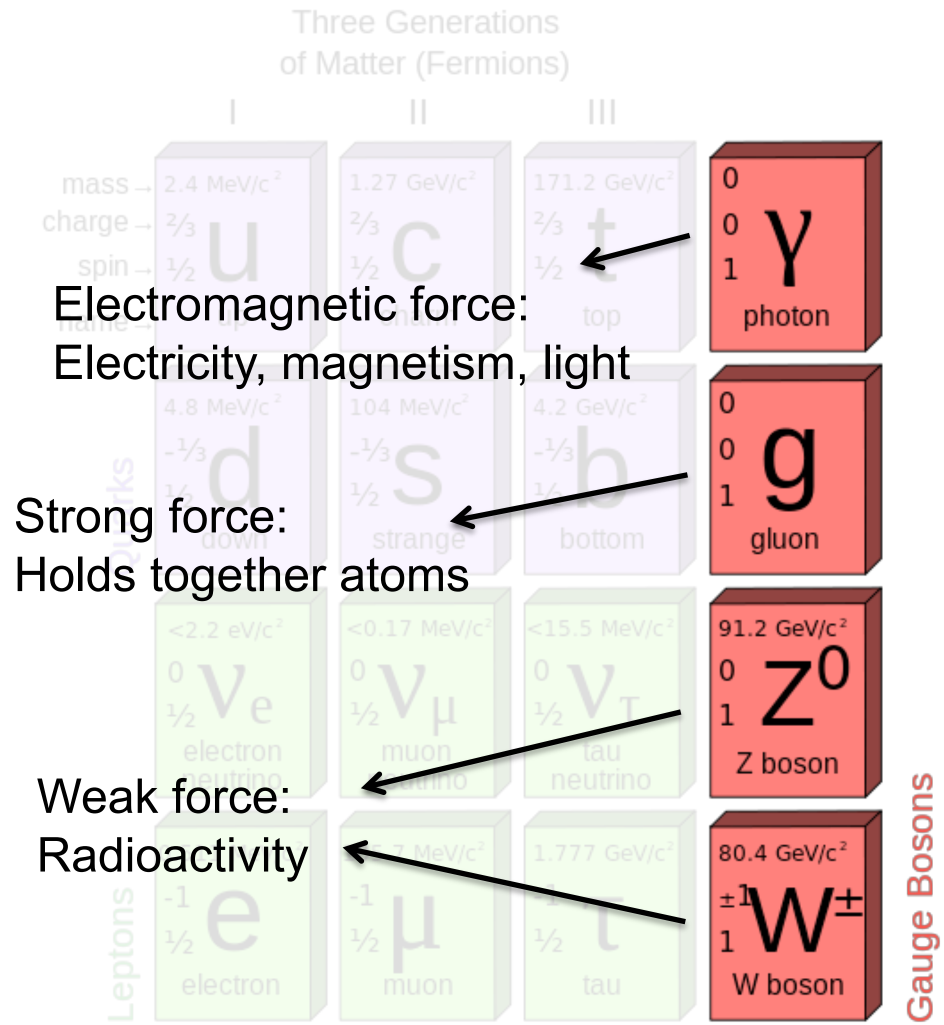


The Standard Model

Since the 1960s particle accelerators have taught us that the Universe is described by the Standard Model

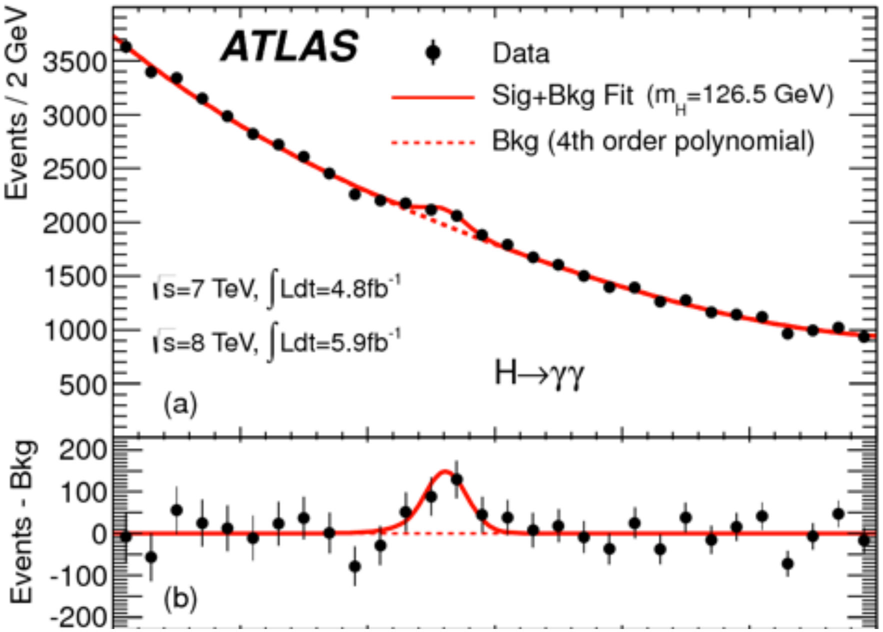
Four particles give us three forces which affect matter

Overall a very complete picture (except gravity)

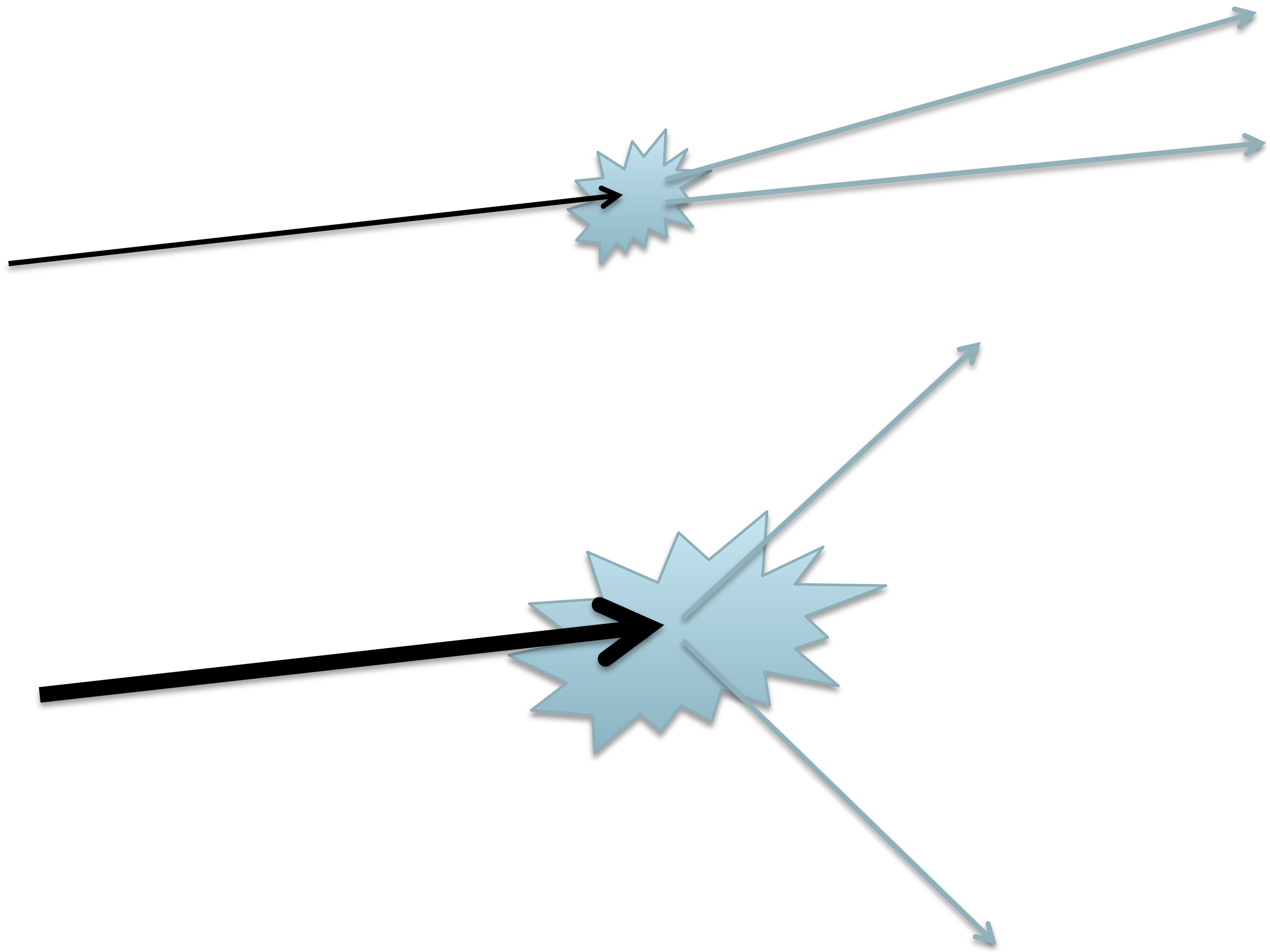


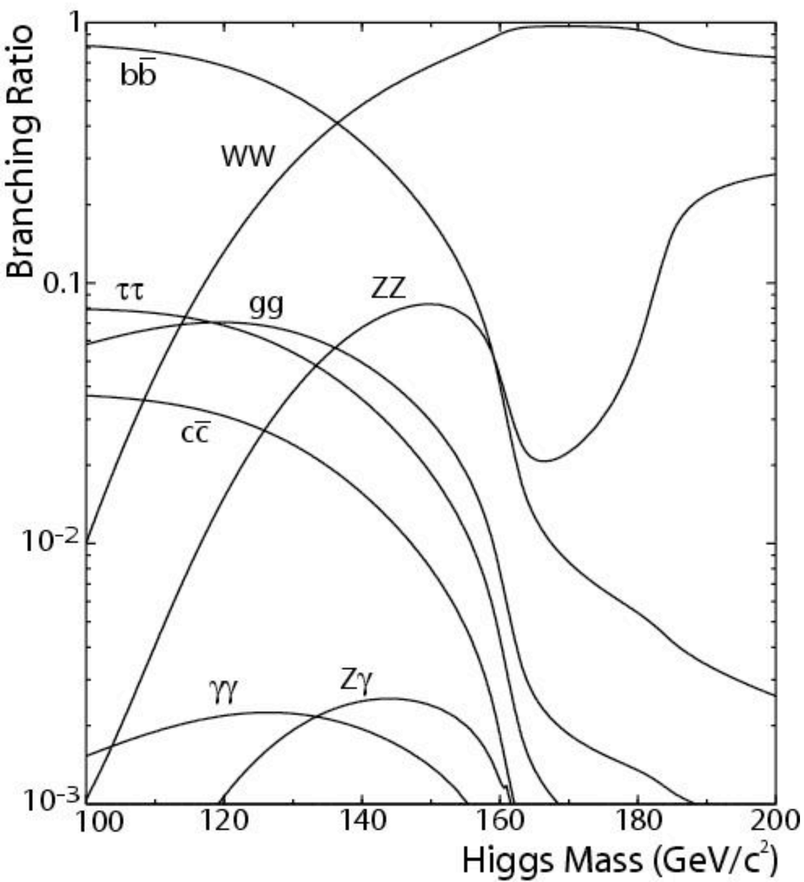
Higgs Decays to Photons

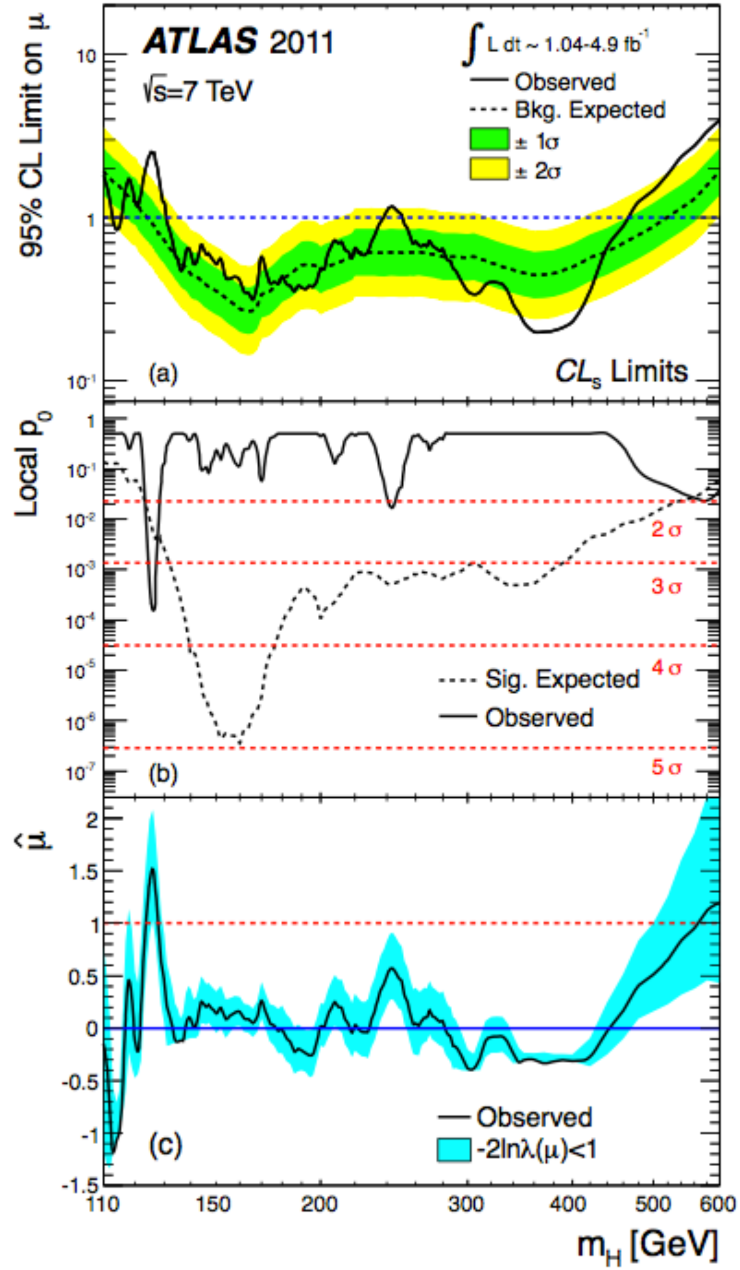
- A bit less rare, happens 0.2% of the time
- But also more background here
- No single channel is perfect…



Invariant Mass




Branching Ratio
1
0.1
10^{-2}
10^{-3}
100
120
140
160
180
200
Higgs Mass (GeV/c^2)
$b\bar{b}$
WW
$\tau\tau$
gg
ZZ
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$


ATLAS 2011
$\sqrt{s}$=7 TeV
$\int L\,dt \sim 1.04\text{-}4.9\ fb^{-1}$
Observed
Bkg. Expected
$\pm 1\sigma$
$\pm 2\sigma$
95% CL Limit on μ
(a)
CL_s Limits
Local p_0
2σ
3σ
4σ
5σ
Sig. Expected
Observed
(b)
$\hat{\mu}$
Observed
$-2\ln\lambda(\mu)<1$
(c)
110
150
200
300
400
500
600
m_H [GeV]