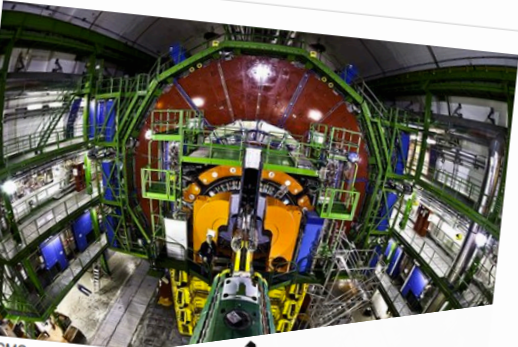


A large, complex industrial facility, likely a particle accelerator, with various pipes, scaffolding, and machinery. Two workers in hard hats and safety gear are visible in the lower right corner, one operating a control panel.

Particle Physics: The LHC and the Higgs Boson

Adam Davison

28 June 2010 Last updated at 01:49
LHC smashes beam collision record
 By Katia Moskvitch
 Science reporter, BBC News, Cern in Geneva

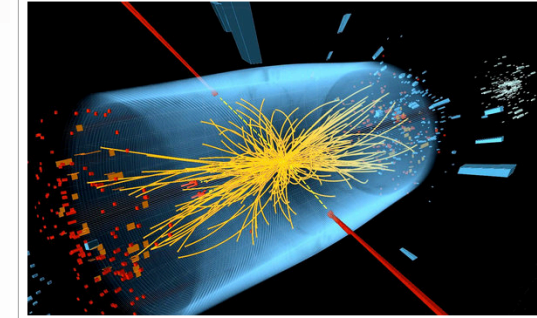


Experiments set to begin
at the Big Bang

For the first time in 20 years, the world's largest particle accelerator, the Large Hadron Collider (LHC), is set to begin its first two days, the biggest experiment of all time will begin.

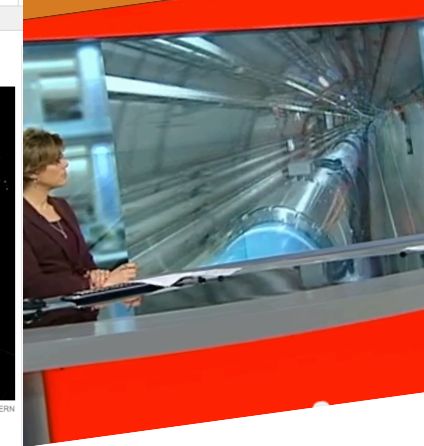
Physicists are attempting to re-create conditions that existed just a billionths of a second after the Big Bang, the beginning of the universe.

ESSAY
A Blip That Speaks of Our Place in the Universe



REVELATION A computer-generated image shows a typical proton collision of the kind that produced evidence of a particle thought to be the Higgs boson.
 By LAWRENCE M. KRAUSS
 Published: July 9, 2012

ASPEN, Colo. — Last week, physicists around the world were glued to computers at very odd hours (I was at a 1 a.m. physics "party" here with a large projection screen and dozens of colleagues) to watch live



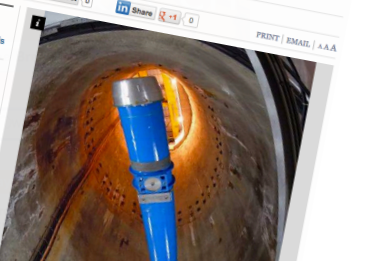
HOME » SCIENCE » SCIENCE NEWS
New result from LHC reinforces belief that the Higgs Boson has been found
 They were 99.999 per cent sure they had found the "the God particle" last month. Now they are even more certain.



Wednesday 21 November 2012
 THE INDEPENDENT
 NEWS VOICES SPORT FOOTBALL LIFE PROPERTY ARTS & ENTS TRAVEL MONEY
 UK World Business People Science Environment Media Technology Education Culture Diary
LHC 'atom smasher' restart delayed yet again

Are we all going to die next Wednesday?

Two nightmare scenarios, two ends of the world. In the first, there is little warning. For maybe a month there will be no sign that life was about to come to an abrupt and nasty end for all living things on Earth.
 Then, earthquakes would start unexpectedly, alerting geologists that something terrible, unimaginable, was afoot.
 After a few days, these seismic disturbances would reach catastrophic proportions.
 Cities would be levelled, the oceans would rise and wash in a series of mega-tsunamis that would attack the world's coastlines, killing millions.



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...

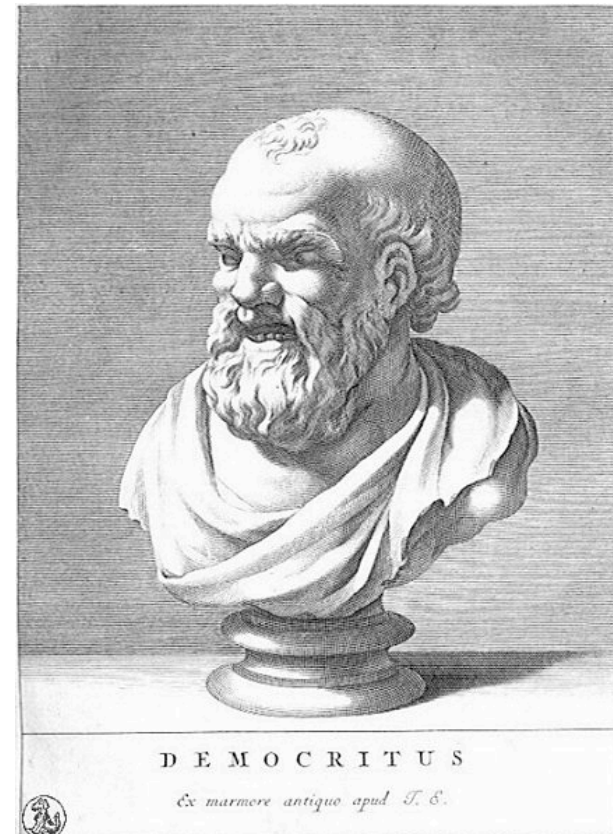




The human eye can see objects as small as about 1 mm or 0.001 m or 10^{-3} m

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.



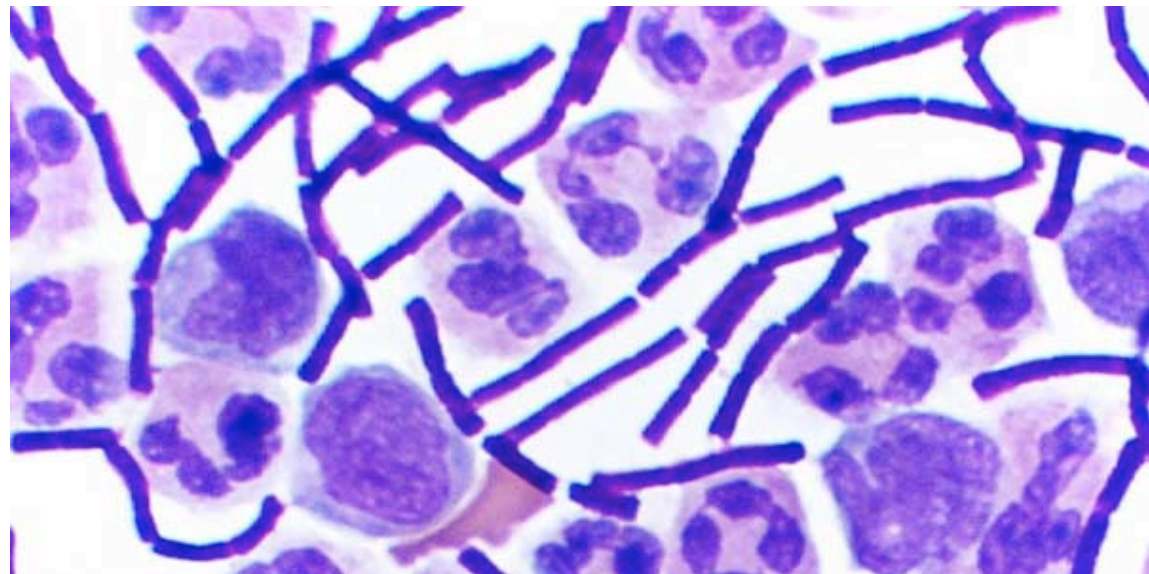


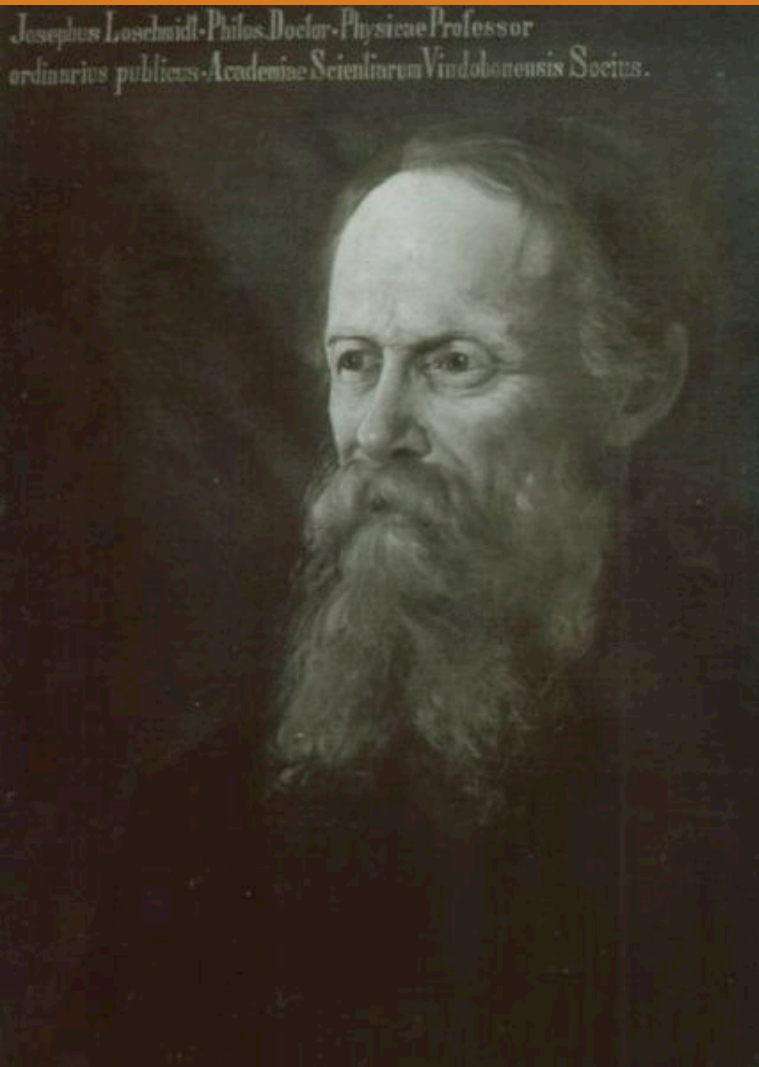
van Leeuwenhoek builds a pretty good microscope.

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

1674

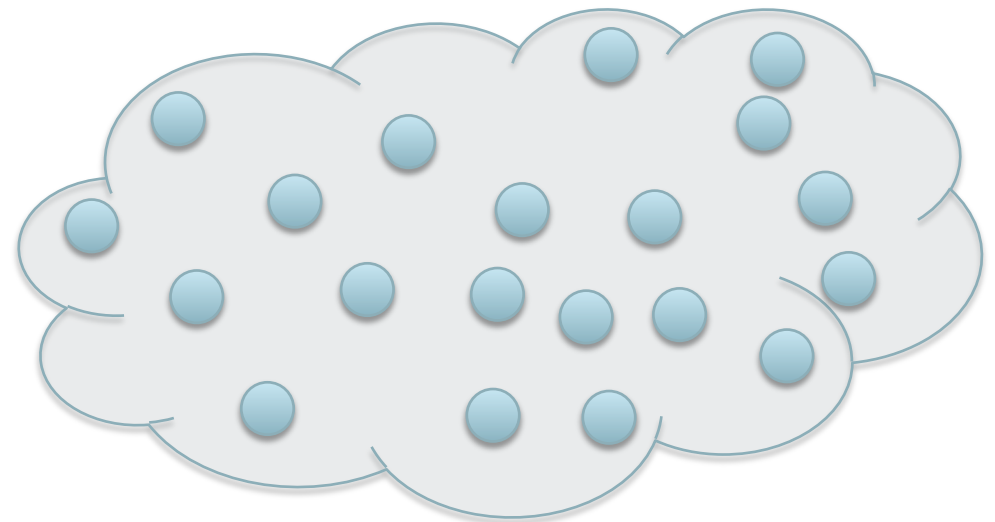
He is one of the first to discover cells and bacteria





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

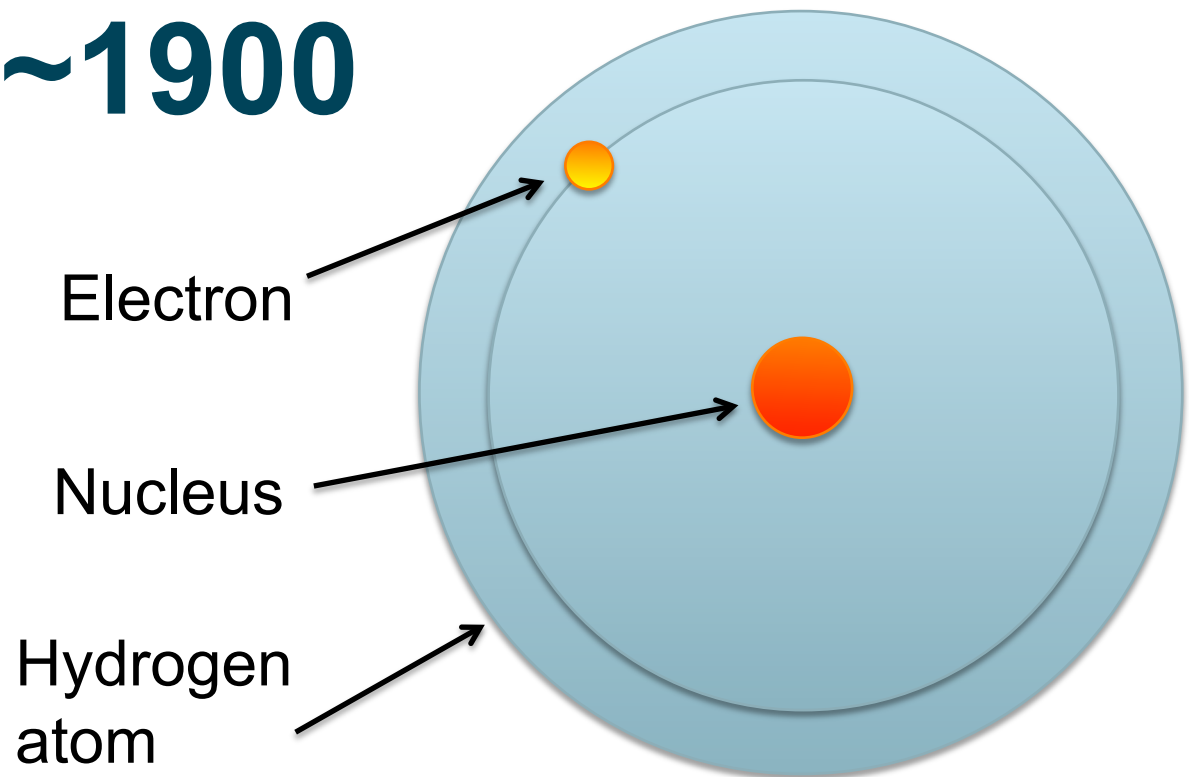


He isn't far off...



Rutherford and Thompson discover atoms are made up of electrons orbiting a nucleus around 0.000000000000001 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)

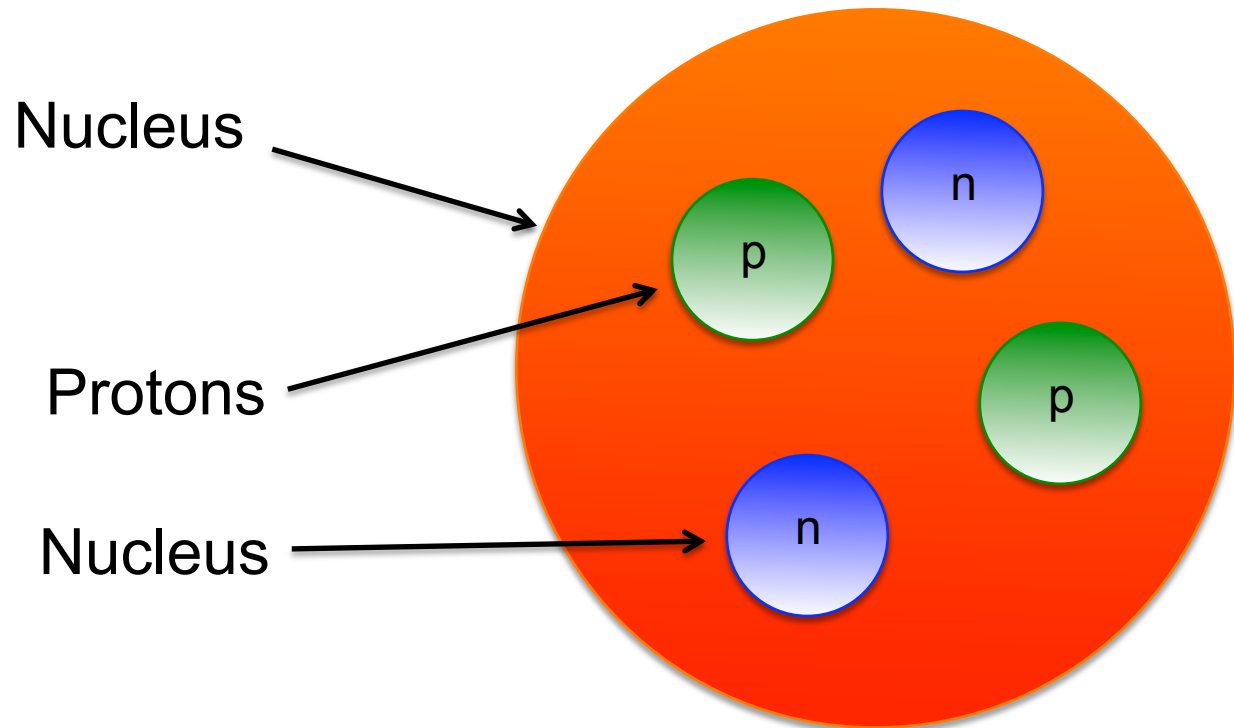
1917-32



Nucleus

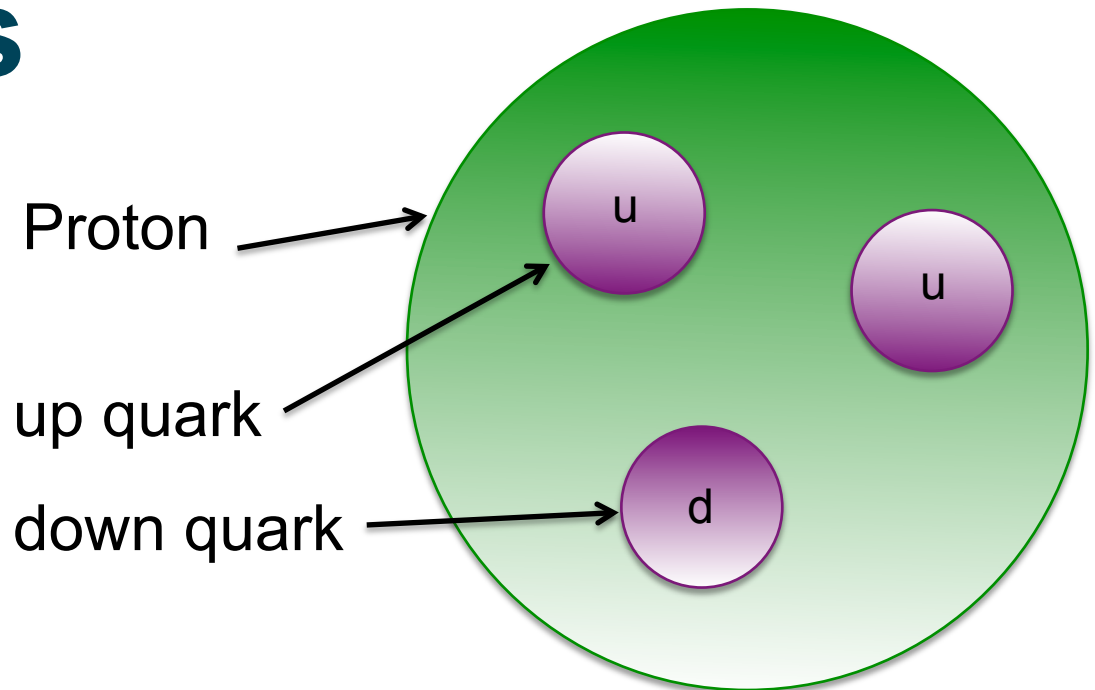
Protons

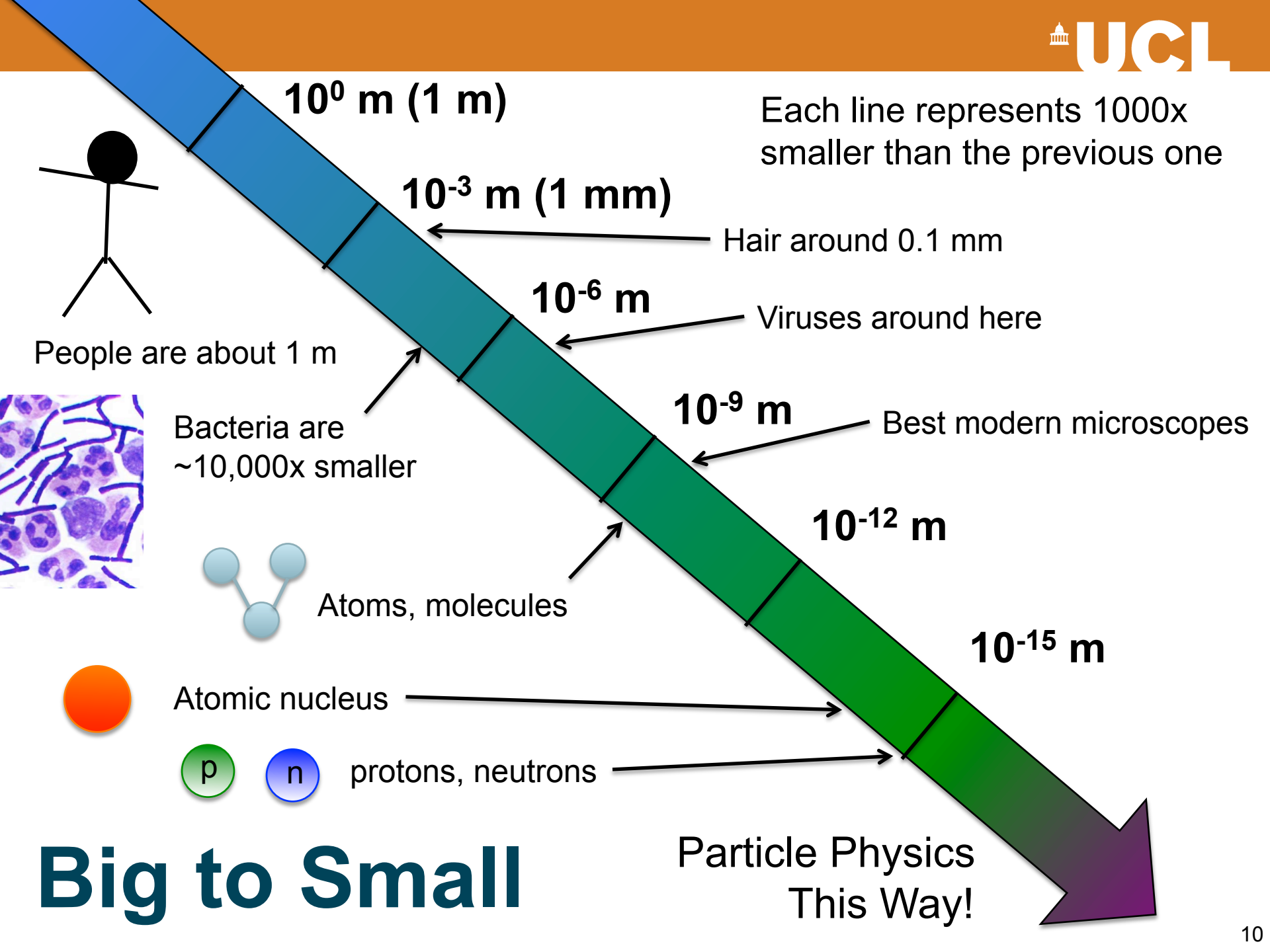
Nucleus



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 0.000000000000000001 m

1960s

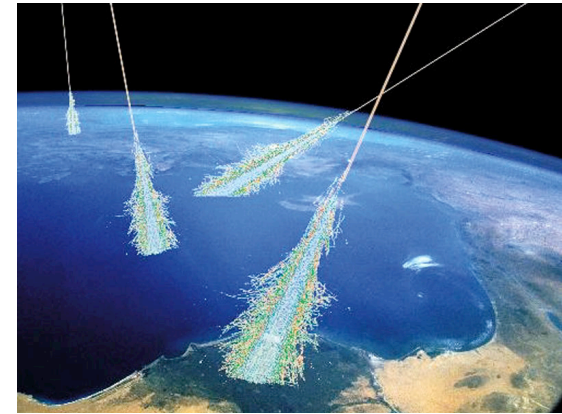




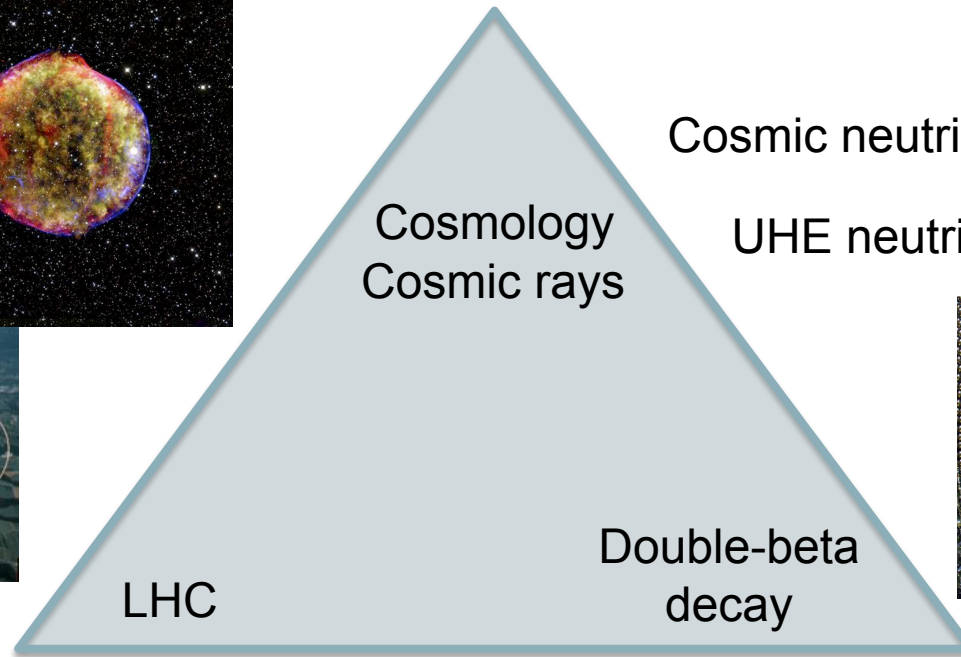
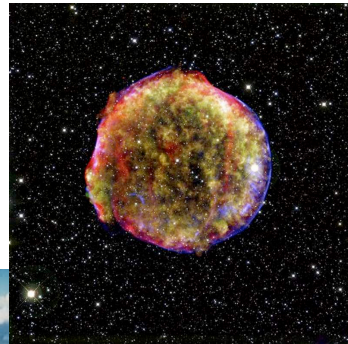
Big to Small

Other Ways...

There are many ways to learn new particle physics



Astro-particle Physics



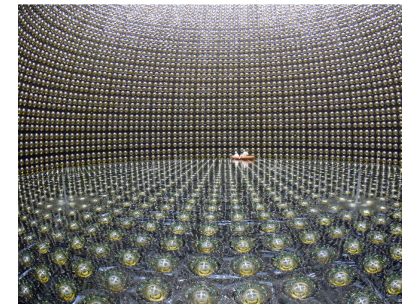
Cosmic neutrinos

UHE neutrinos

Cosmology
Cosmic rays

Double-beta
decay

LHC



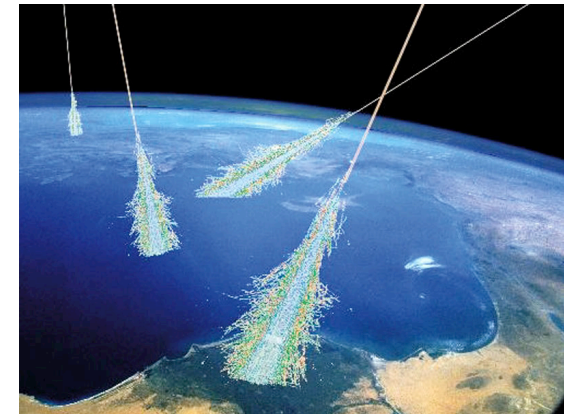
Colliders

Flavour-physics
Neutrino beams

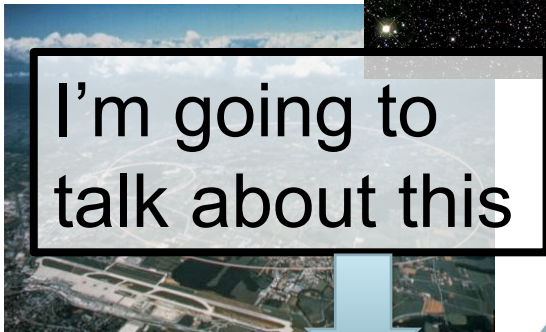
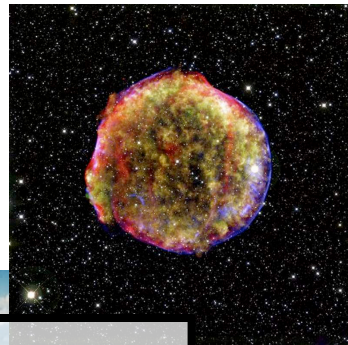
Rare Processes

Other Ways...

There are many ways to learn new particle physics



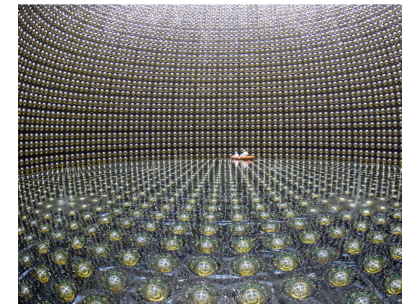
Astro-particle Physics



Cosmic neutrinos

Cosmology
Cosmic rays

UHE neutrinos



Double-beta decay

LHC

Rare

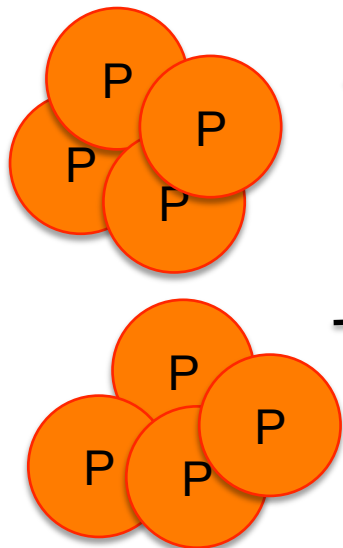
Processes

Colliders

Flavour-physics
Neutrino beams

How to Build a Particle Accelerator in 60 Seconds

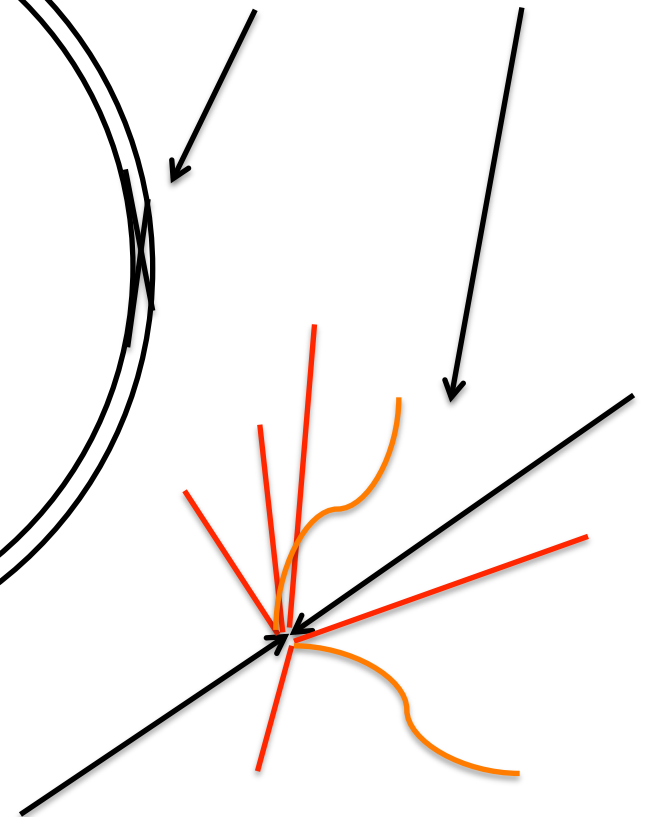
Take protons, put them in two rings going in different directions



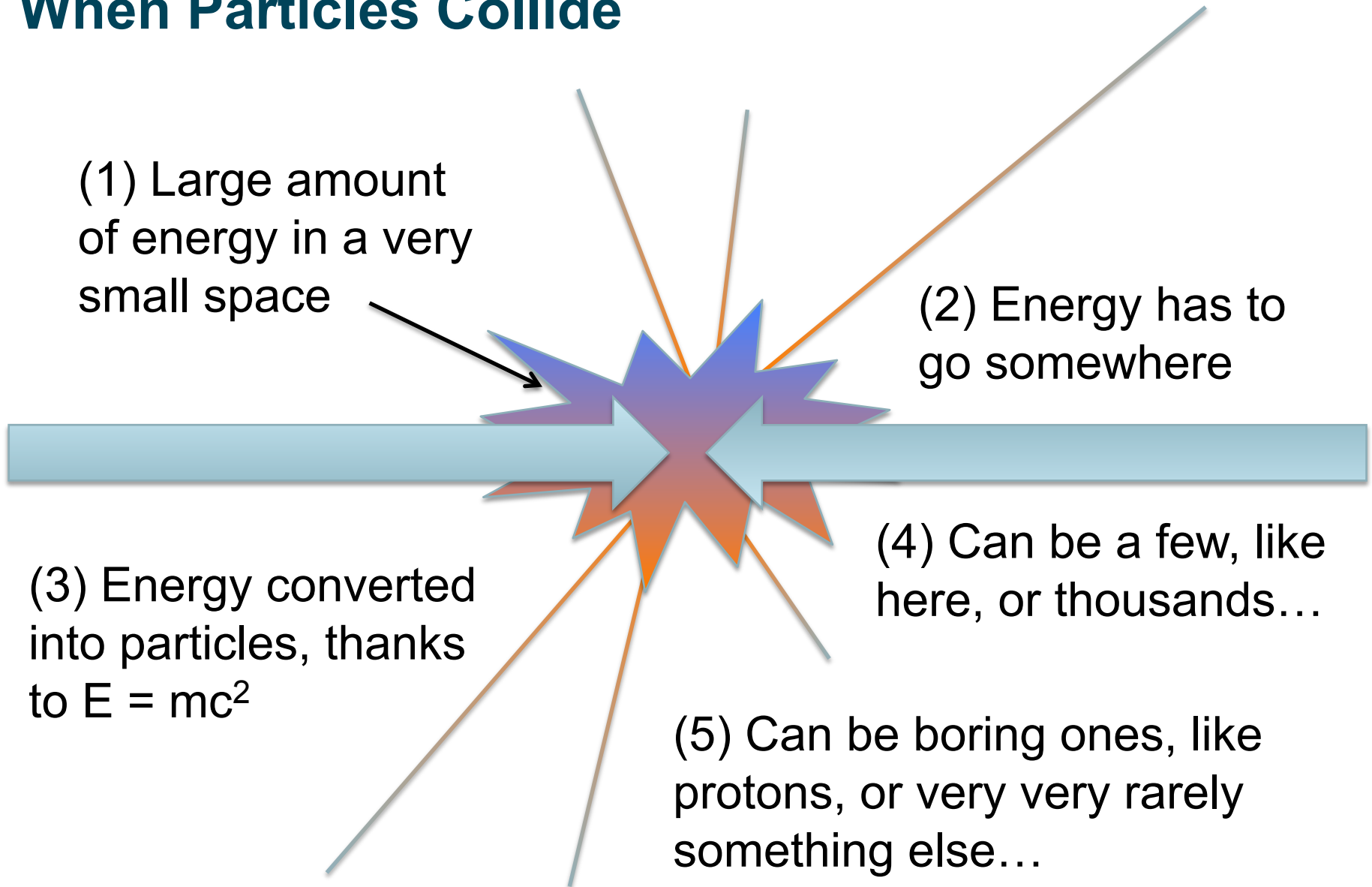
Powerful magnets keep them turning round the circle for up to 24 hours

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

Cross the beams to make them collide and watch

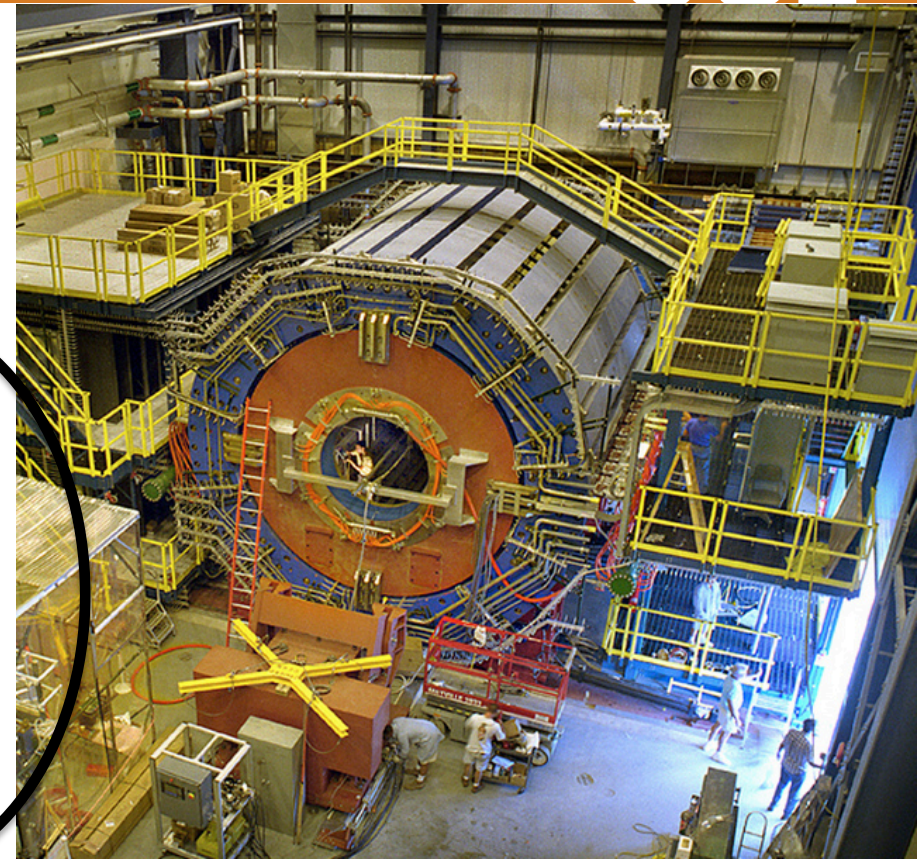
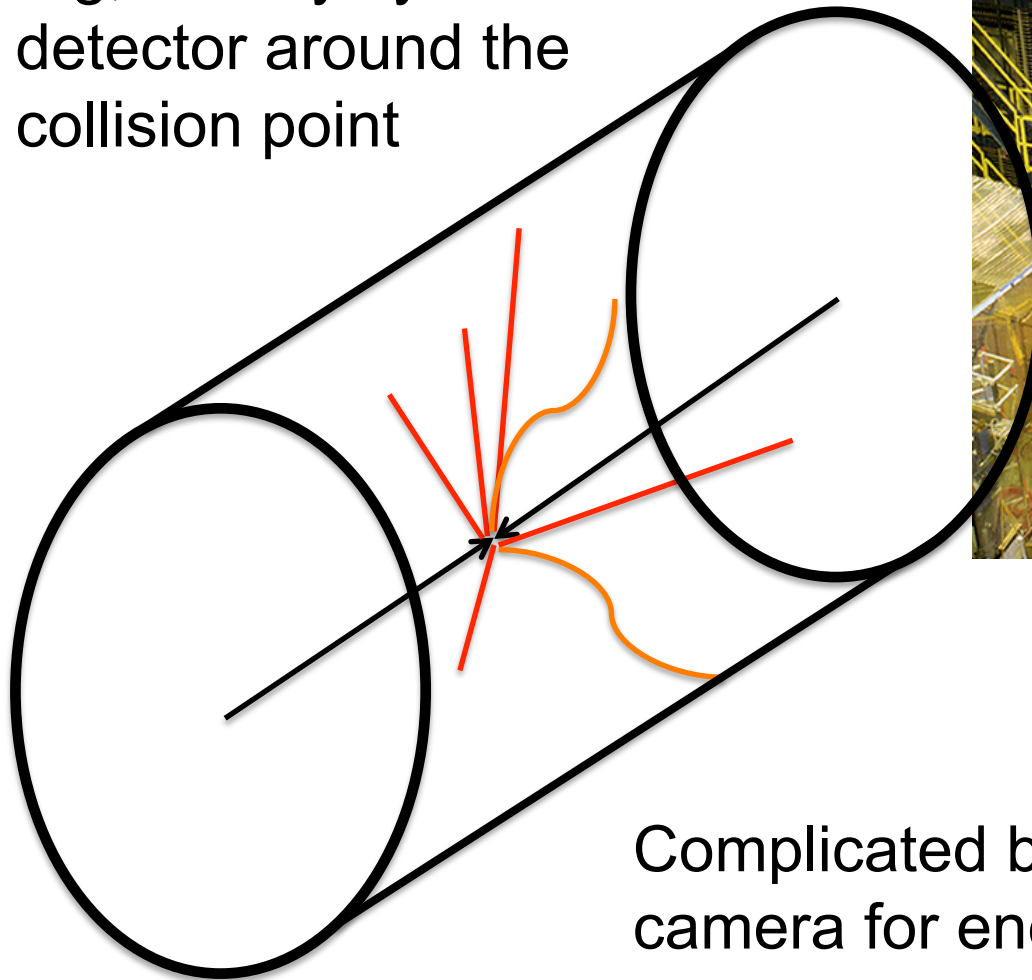


When Particles Collide



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)

Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	d down	s strange	b bottom	g gluon
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ Z boson
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptons	e electron	μ muon	τ tau	W[±] W boson

Gauge Bosons

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

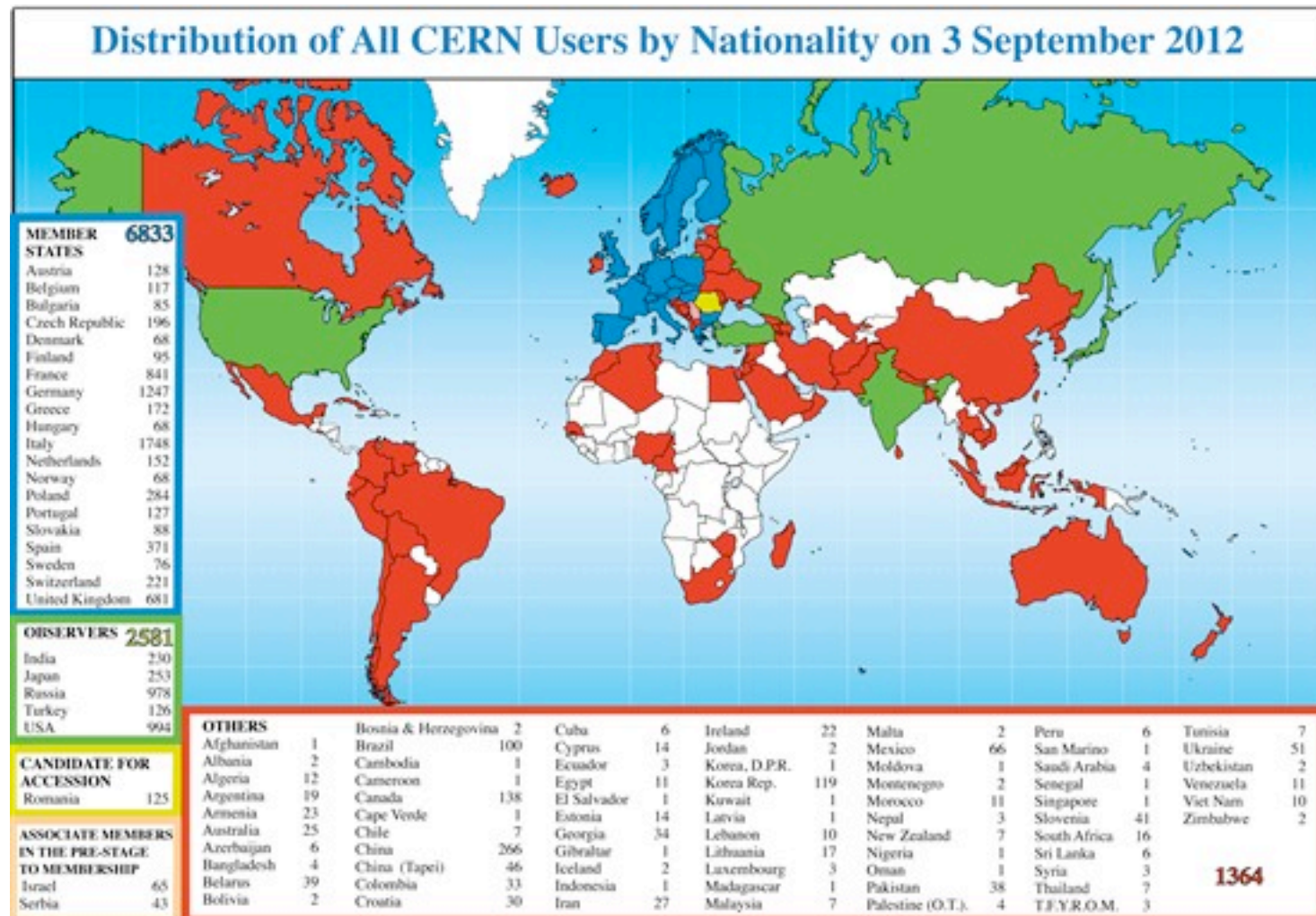


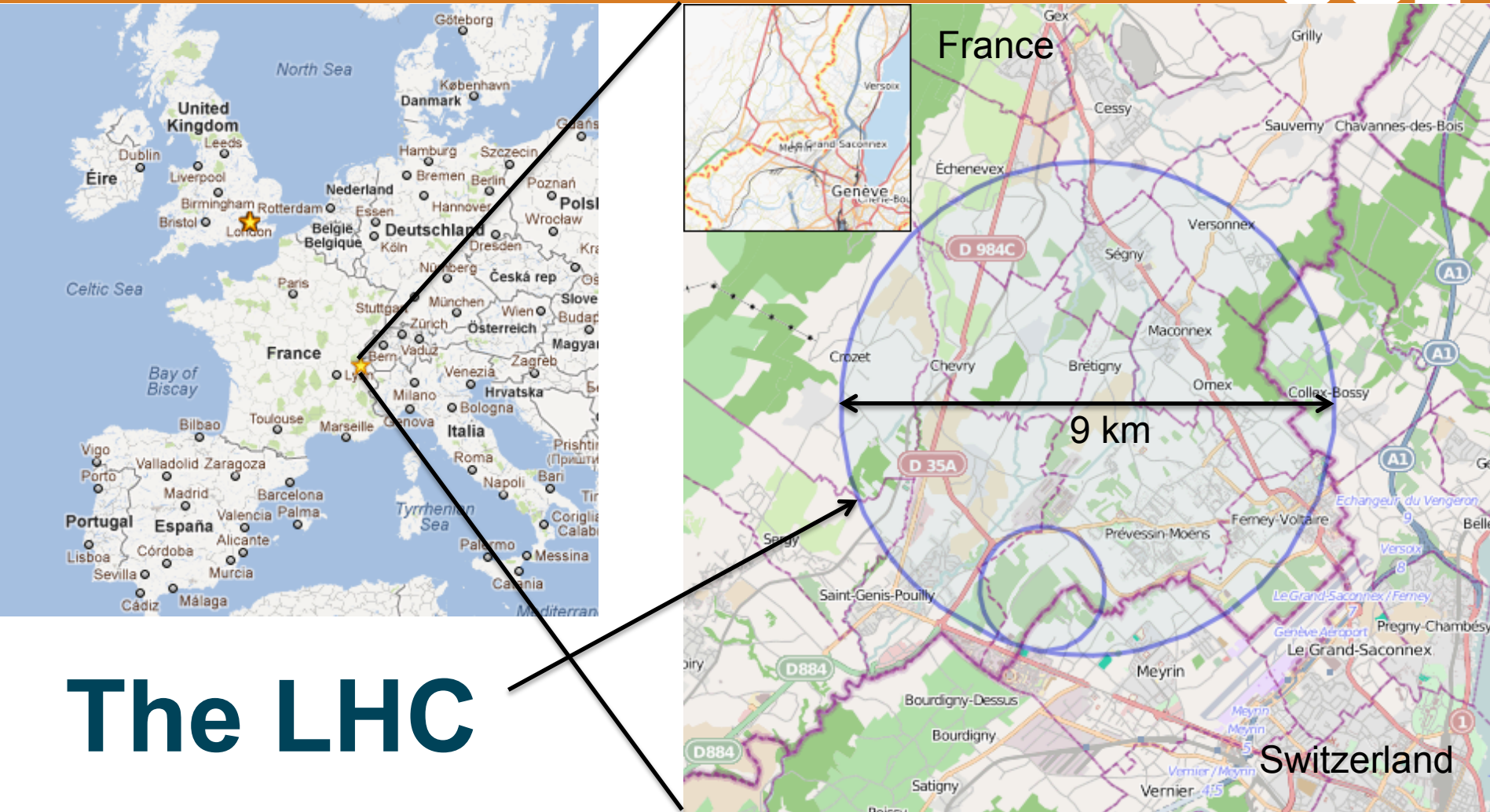
On the border between France and Switzerland
Building particle accelerators since shortly after WWII
Supported by 25+ countries including the UK

The People

PhD students
Academics
Technicians
etc...

Mostly
employed by
universities in
member
states





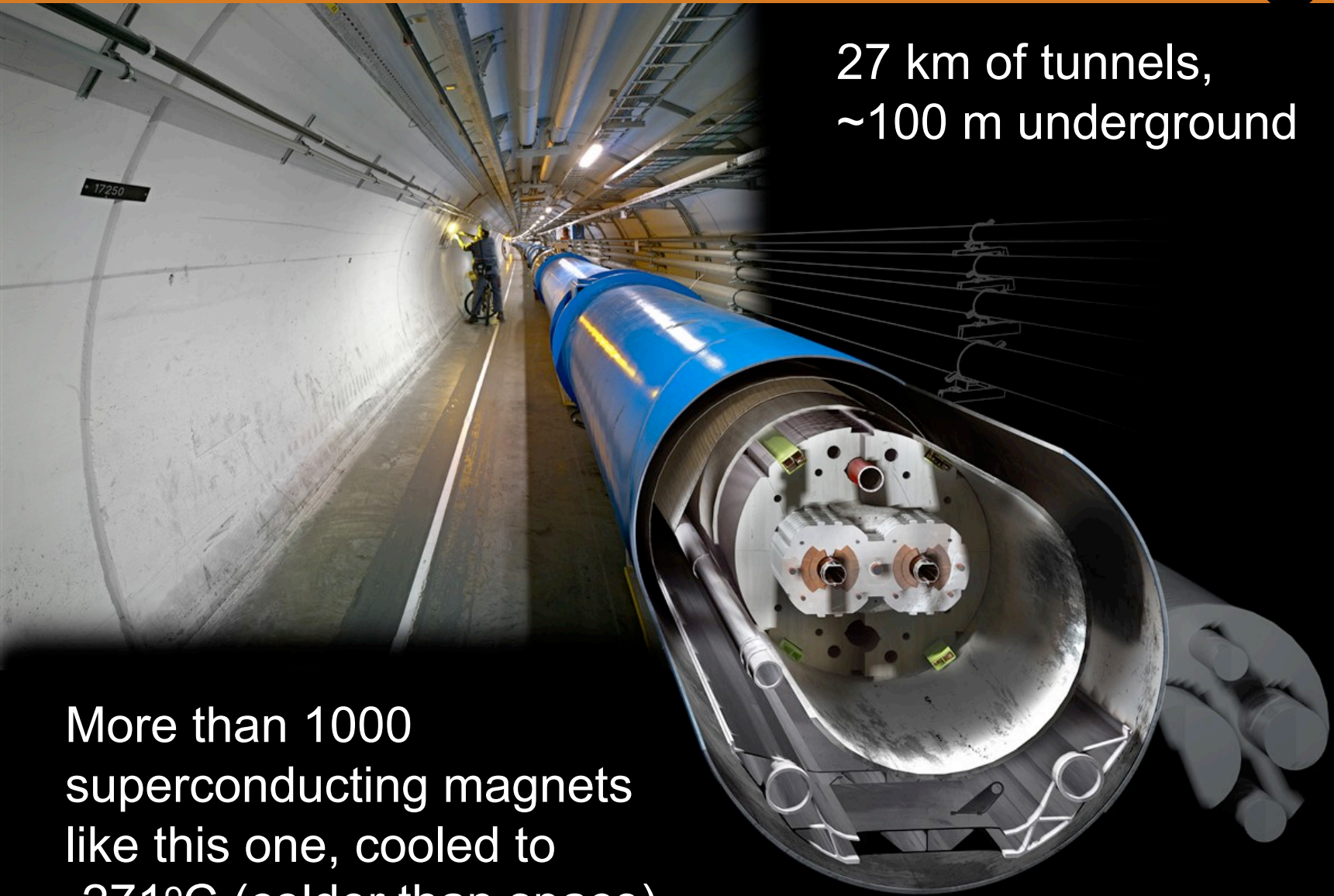
The LHC

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

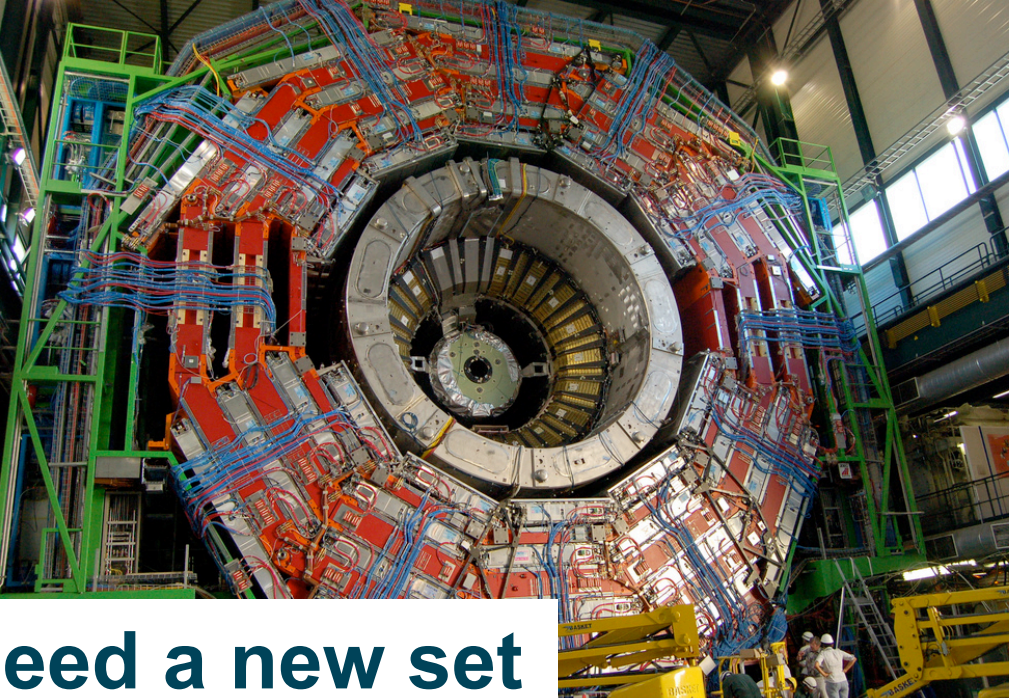
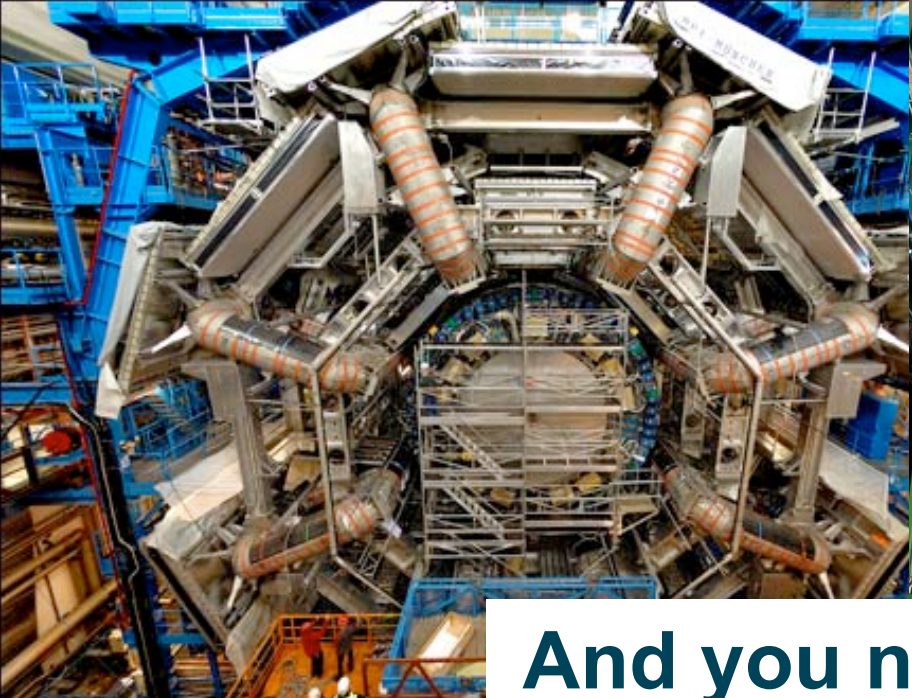
More than 1000
superconducting magnets
like this one, cooled to
 -271°C (colder than space)



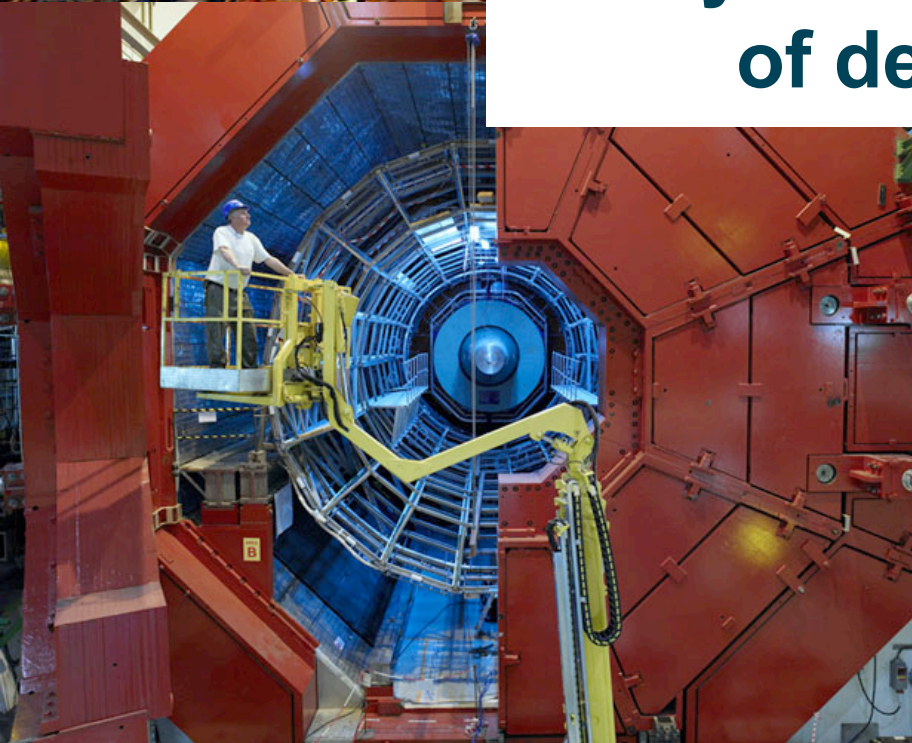
What do you get?



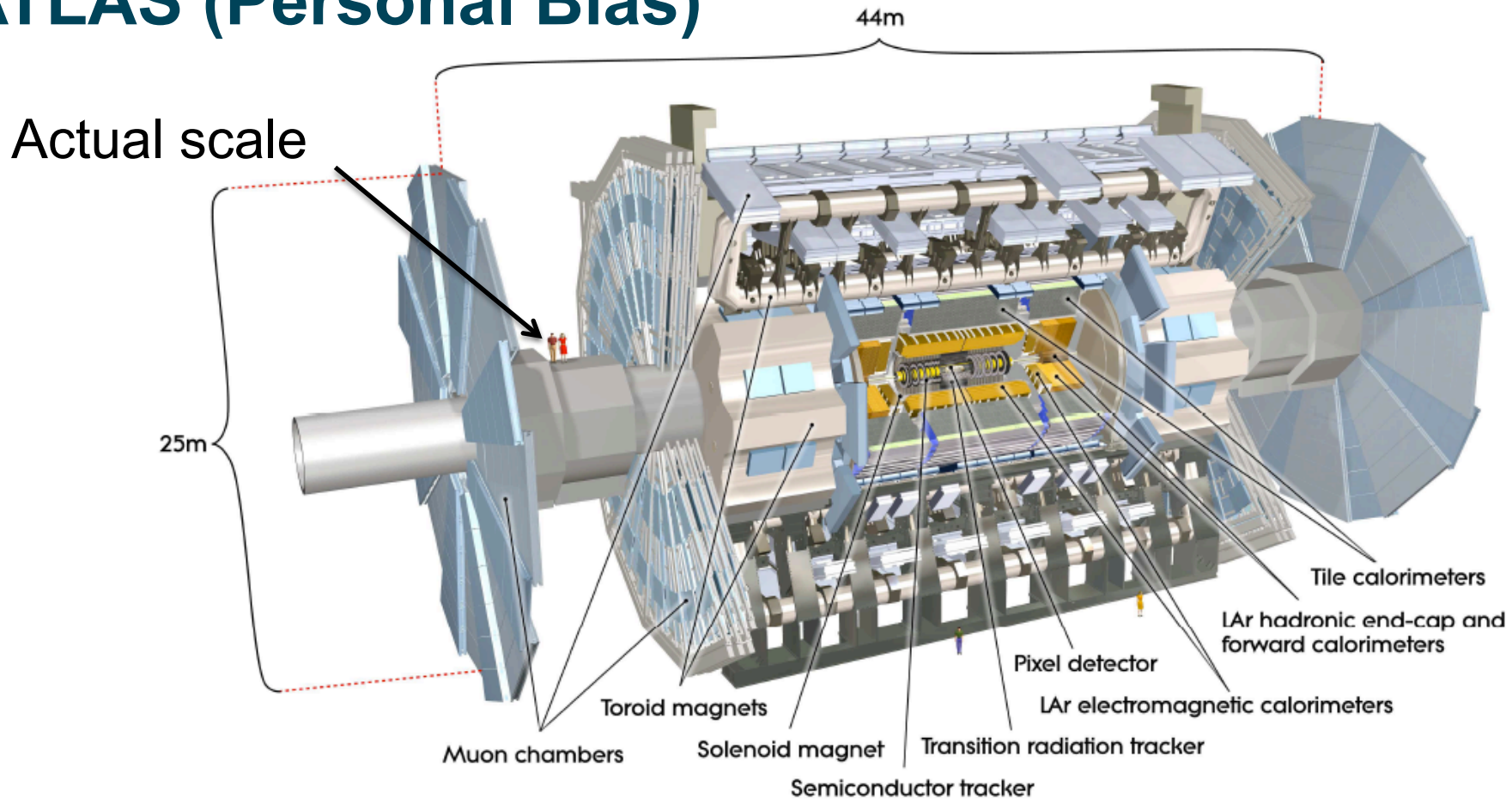
- Two beams, about 300 million million protons each
- Travelling in opposite directions around the ring
 - At 99.9999991% of the speed of light (670 million miles per hour)
- Energy up to 7 TeV (Trillion electron Volts) per proton
- Beam energy is equivalent to a train going 100 mph
- Enough energy in 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

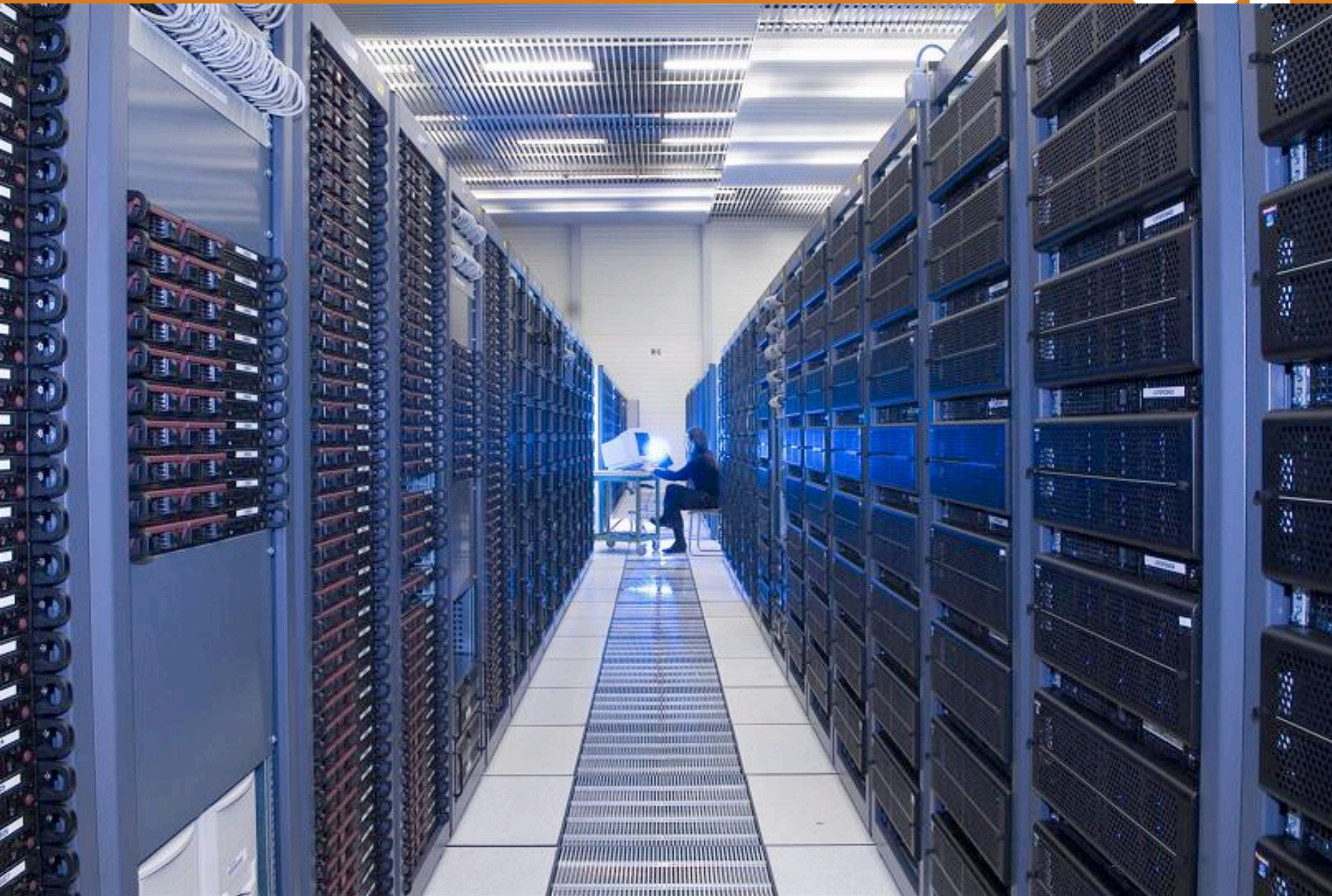


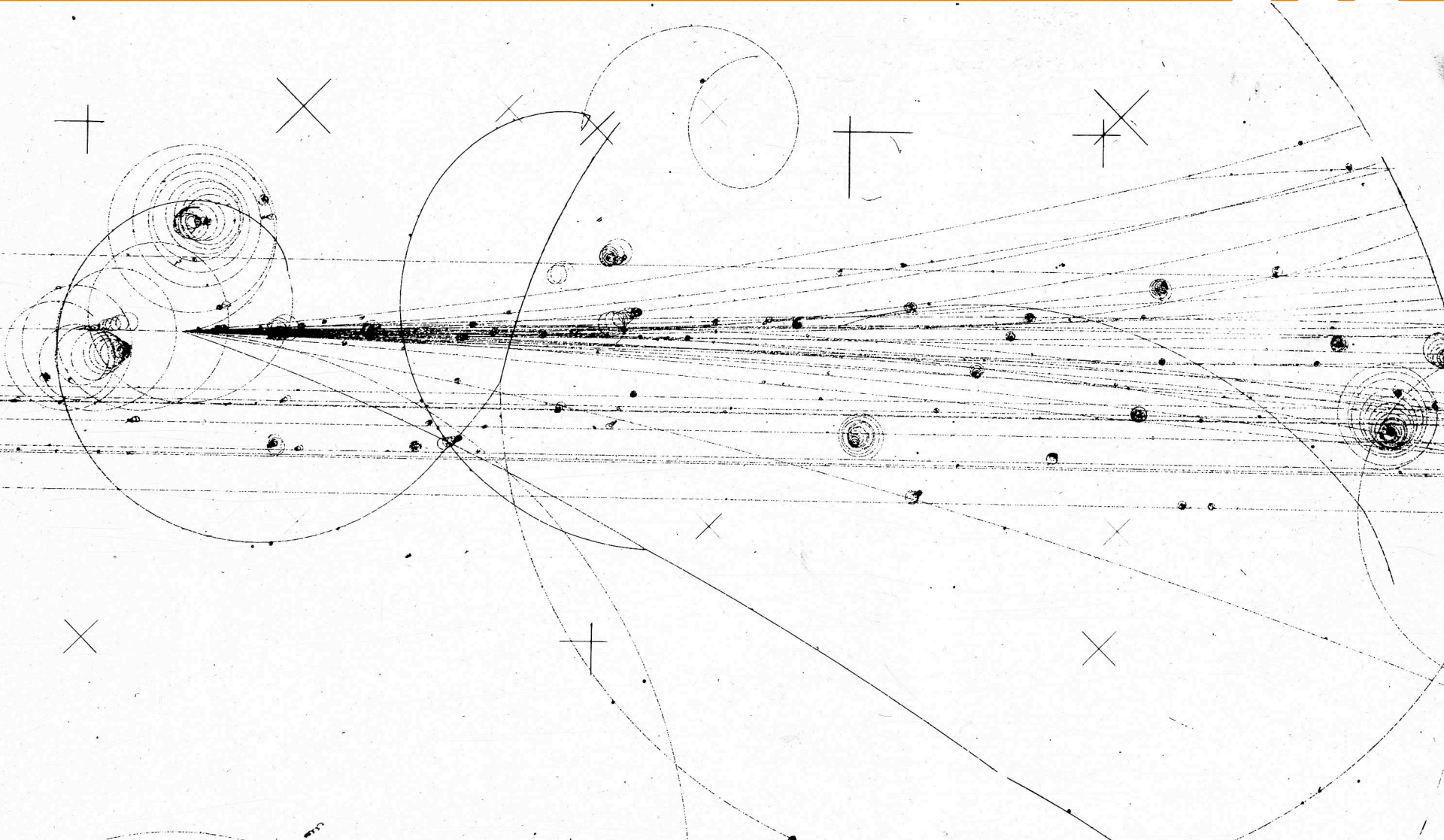
LHC Computing Links (Europe Only)

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

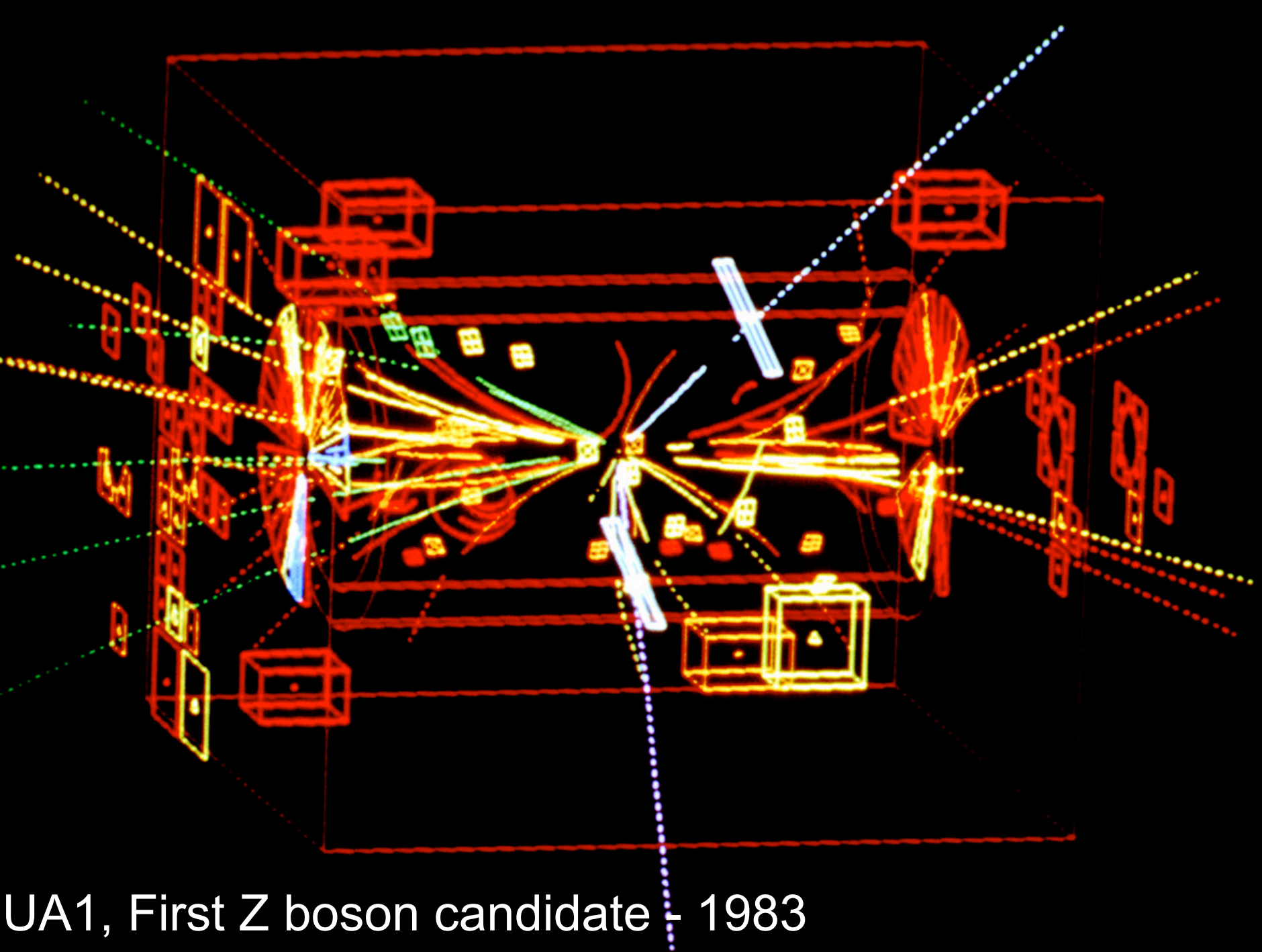


... enough to fill a regular computer disk $\sim 50,000x$ over





What do you see?



UA1, First Z boson candidate - 1983

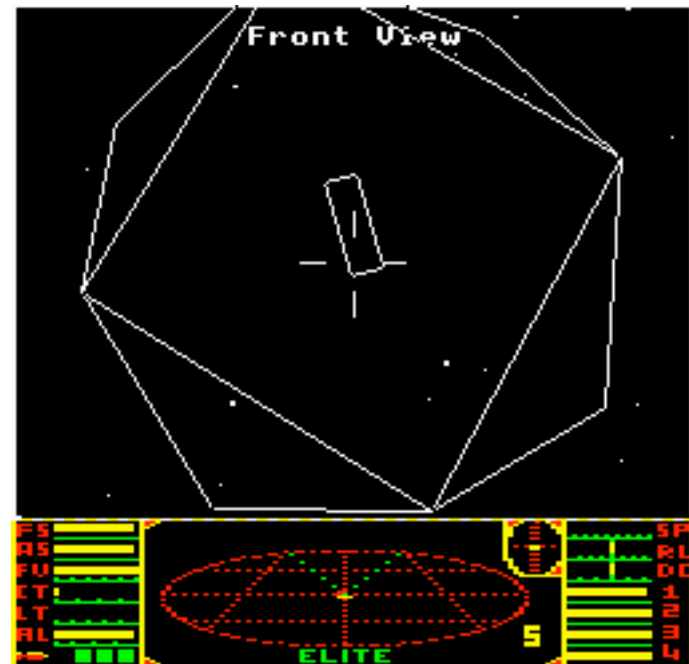


Manic Miner, 1983

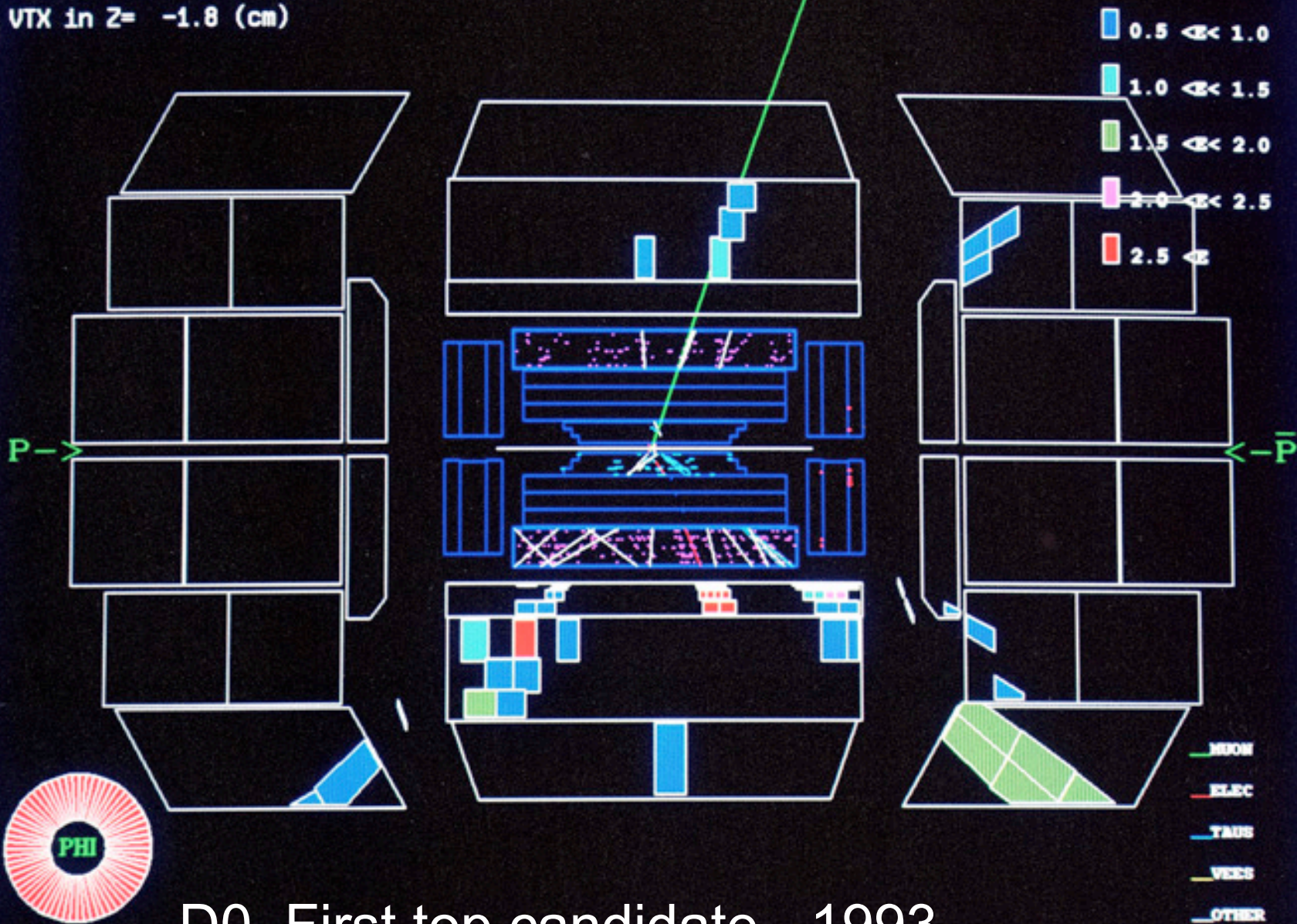
Star Wars, 1983



Elite, 1984



Max ET= 50.1 GeV
CAEH ET SUM= 193.7 GeV
VTX in Z= -1.8 (cm)



D0, First top candidate - 1993

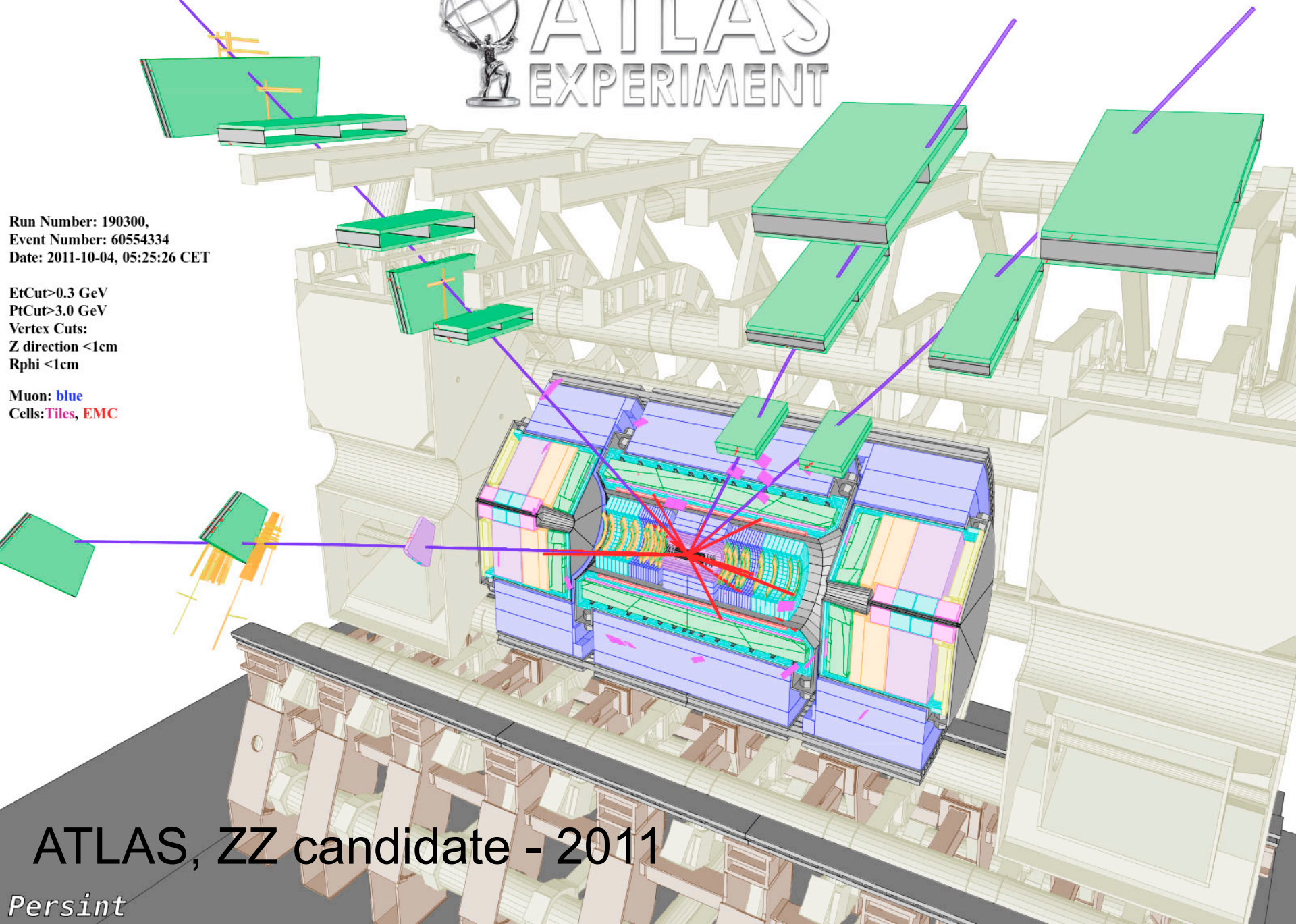


ATLAS EXPERIMENT

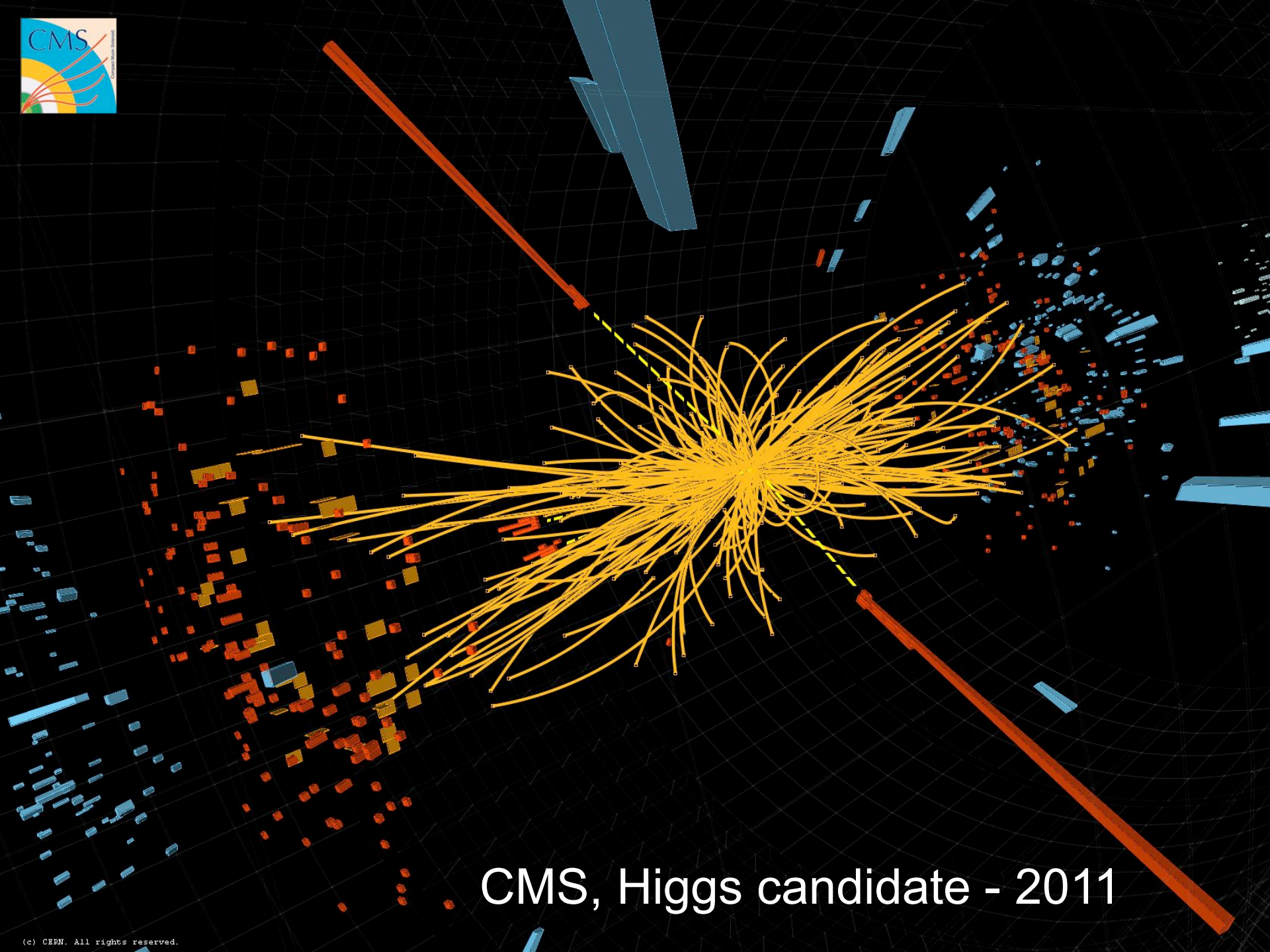
Run Number: 190300,
Event Number: 60554334
Date: 2011-10-04, 05:25:26 CET

E_t Cut > 0.3 GeV
 P_t Cut > 3.0 GeV
Vertex Cuts:
Z direction < 1cm
 R_{ϕ} < 1cm

Muon: blue
Cells: Tiles, EMC



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

Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	d down	s strange	b bottom	g gluon
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ Z boson
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptons	e electron	μ muon	τ tau	W[±] W boson

Gauge Bosons

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....

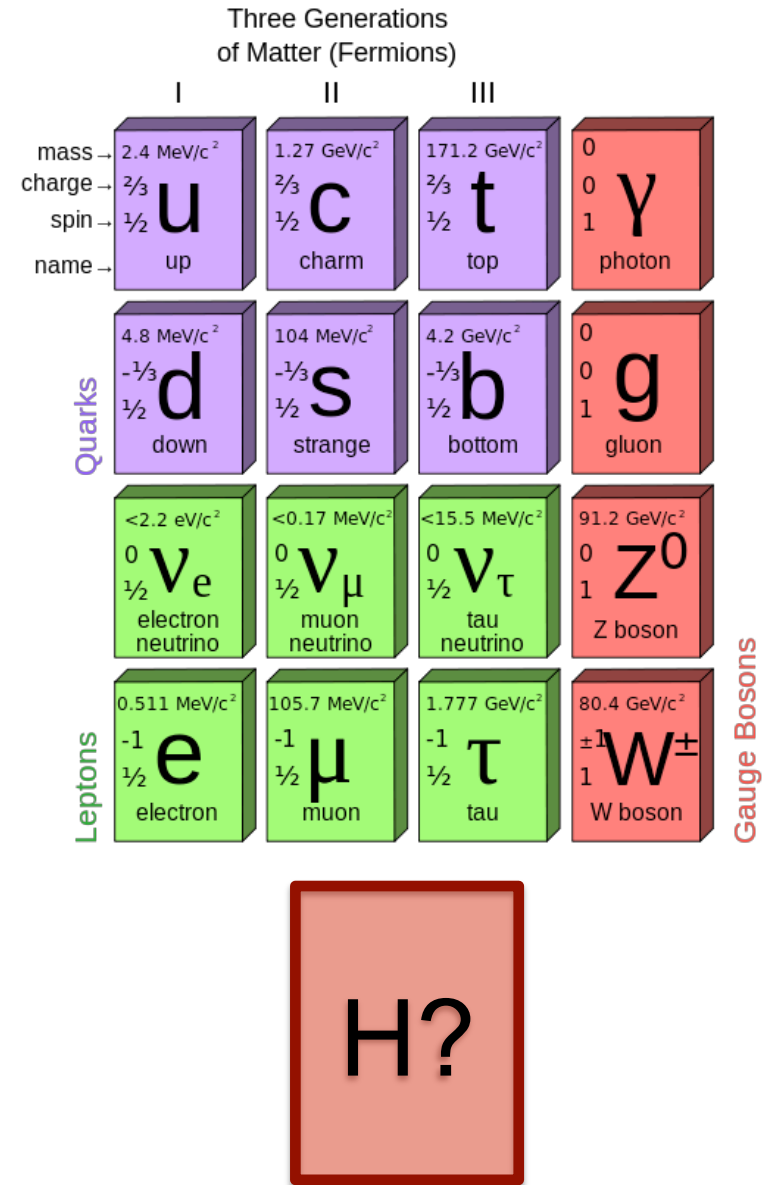


The Higgs

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

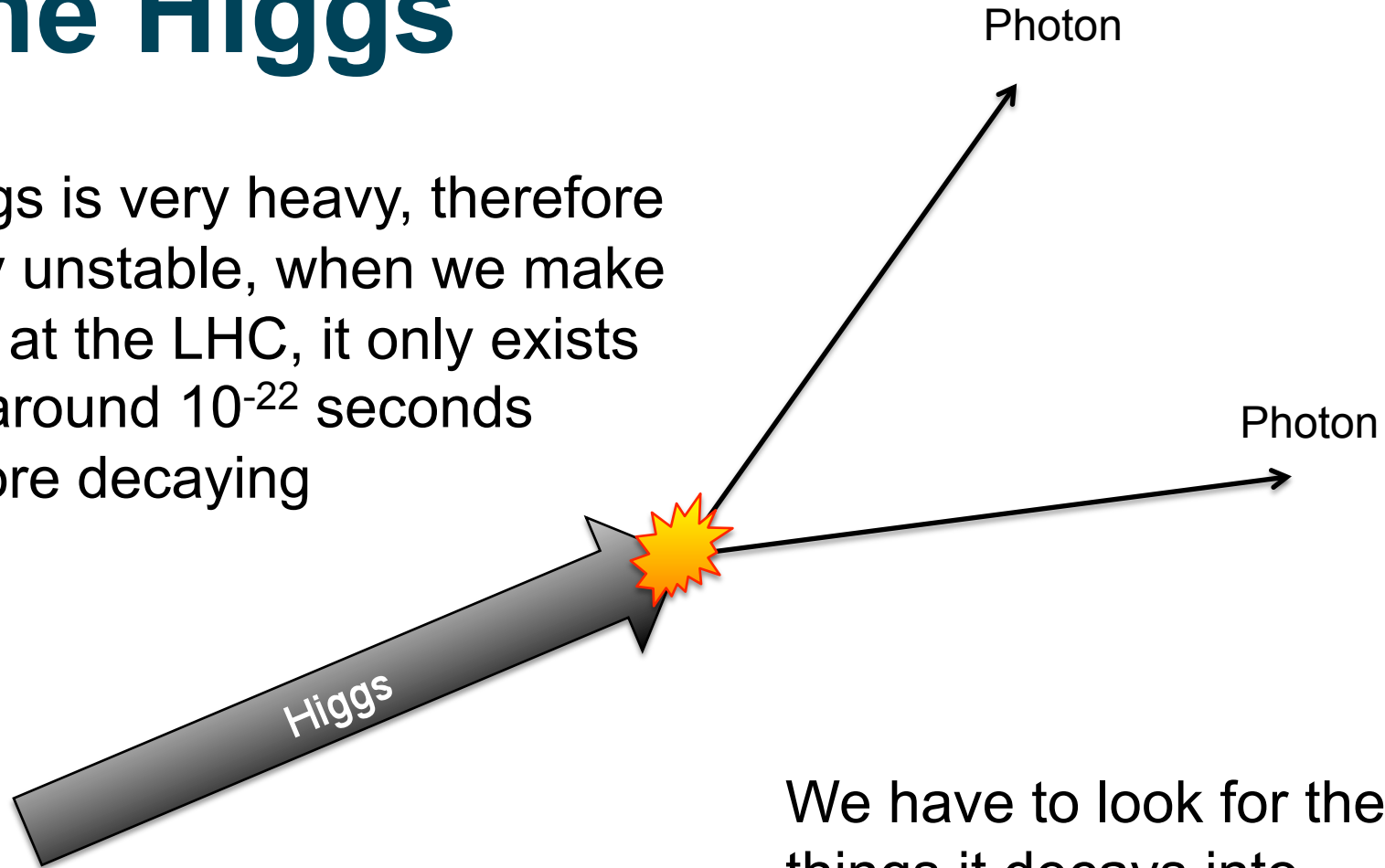
It's fairly distinctive too...

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



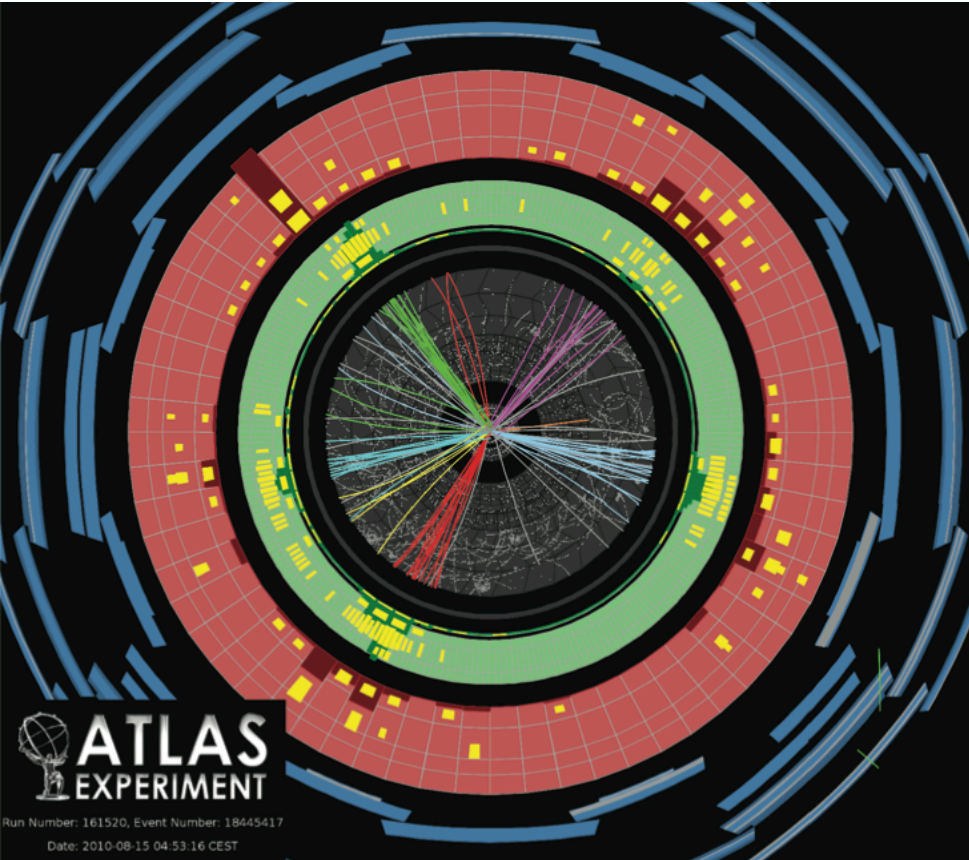
The Higgs

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

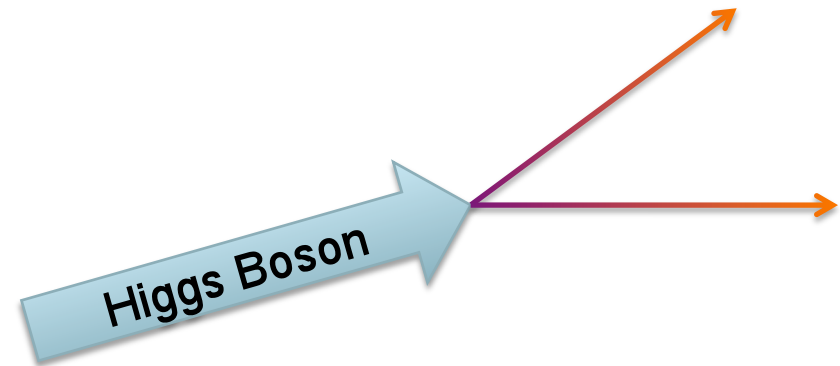
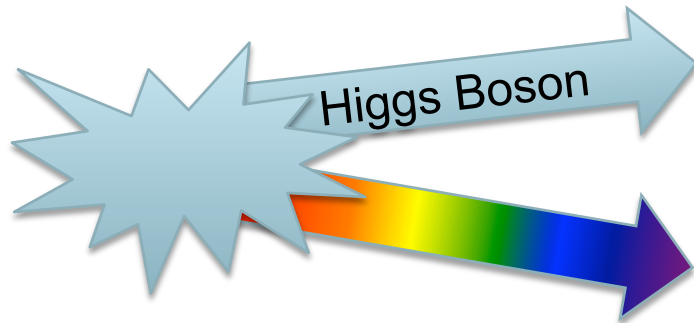


- A 126 GeV Higgs decays mostly to hadrons
- At Large Hadron Colliders there are lots of those though
- Make hundreds of thousands of Higgses

- But can't see most of them...

The Long Way Round

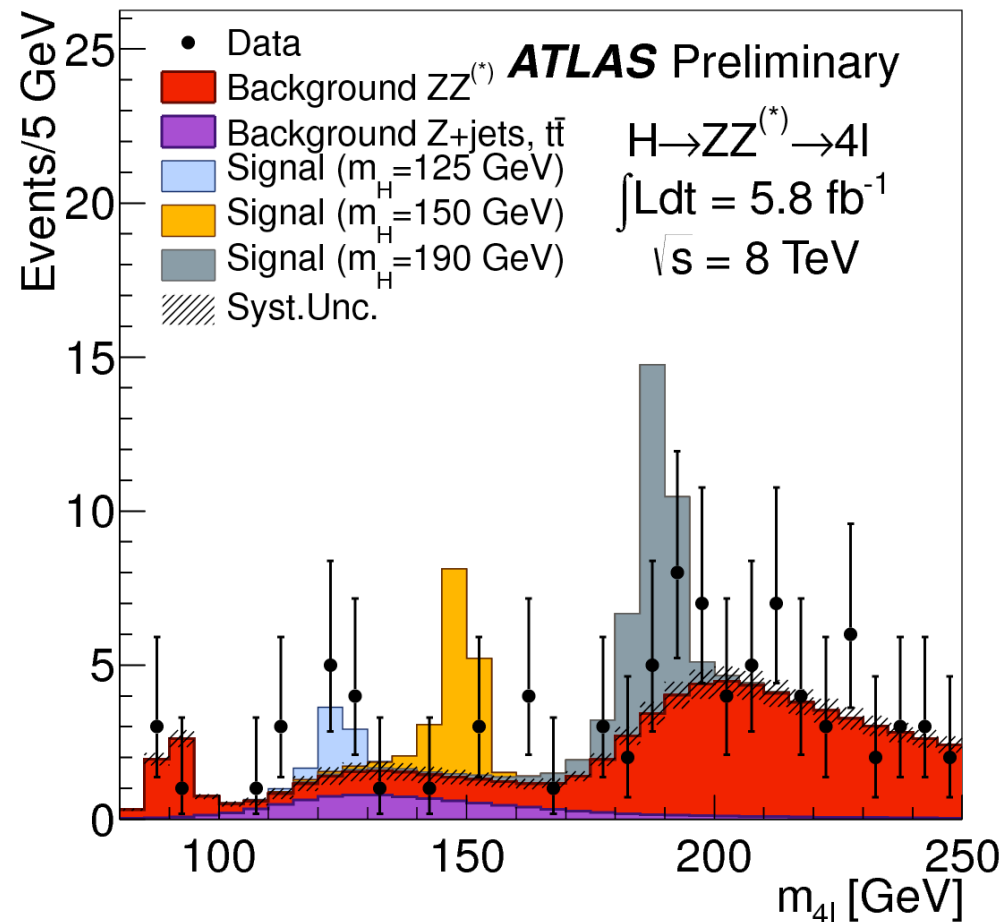
- Higgs bosons can rarely decay to more distinctive particles



- Also rarely produced along with something more distinctive
- We're forced to search for these rarer processes 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

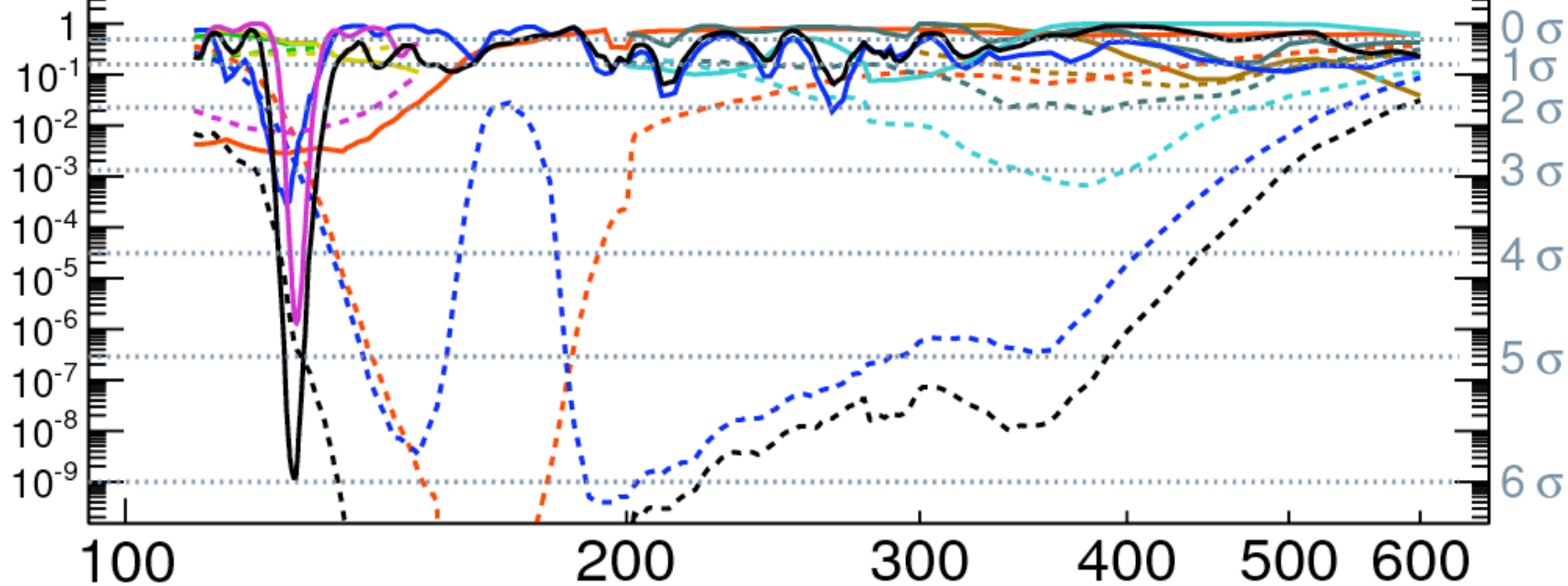


Local p_0

ATLAS 2011 + 2012 Data

$\int L dt \sim 4.6-4.8 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV}$ $\int L dt \sim 5.8-5.9 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV}$

- | | | |
|---|---|---|
| --- Expected Combined | --- Expected $H \rightarrow ZZ^* \rightarrow \text{llll}$ | --- Expected $H \rightarrow WW^* \rightarrow \text{lvlv}$ |
| — Observed Combined | — Observed $H \rightarrow ZZ^* \rightarrow \text{llll}$ | — Observed $H \rightarrow WW^* \rightarrow \text{lvlv}$ |
| --- Expected $H \rightarrow \gamma\gamma$ | --- Expected $H \rightarrow ZZ^* \rightarrow \text{ll}\nu\nu$ | --- Expected $H \rightarrow WW^* \rightarrow \text{lvqq}$ |
| — Observed $H \rightarrow \gamma\gamma$ | — Observed $H \rightarrow ZZ^* \rightarrow \text{ll}\nu\nu$ | — Observed $H \rightarrow WW^* \rightarrow \text{lvqq}$ |
| --- Expected $H \rightarrow b\bar{b}$ | --- Expected $H \rightarrow ZZ^* \rightarrow \text{llqq}$ | --- Expected $H \rightarrow \tau\tau$ |
| — Observed $H \rightarrow b\bar{b}$ | — Observed $H \rightarrow ZZ^* \rightarrow \text{llqq}$ | — Observed $H \rightarrow \tau\tau$ |



+ CMS see the same thing...

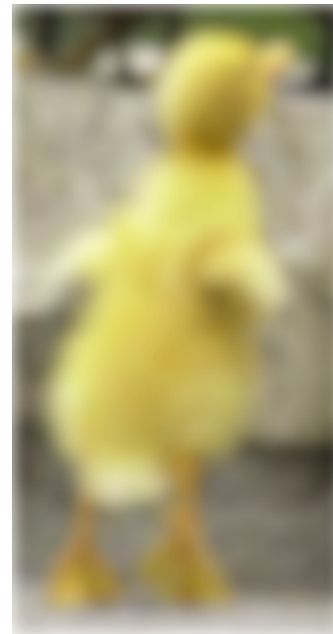
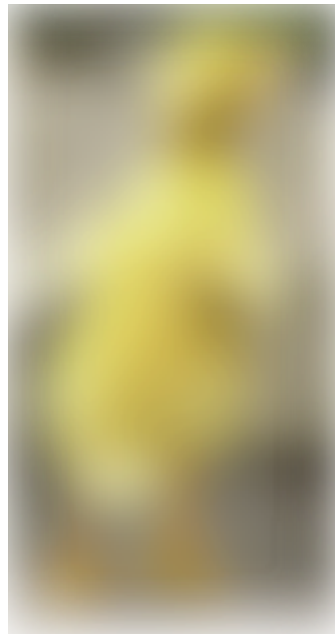
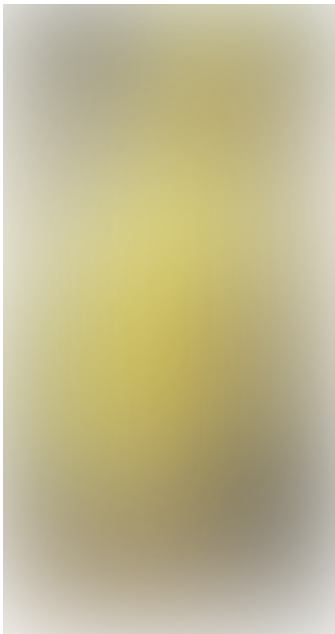
m_H [GeV]

The Higgs

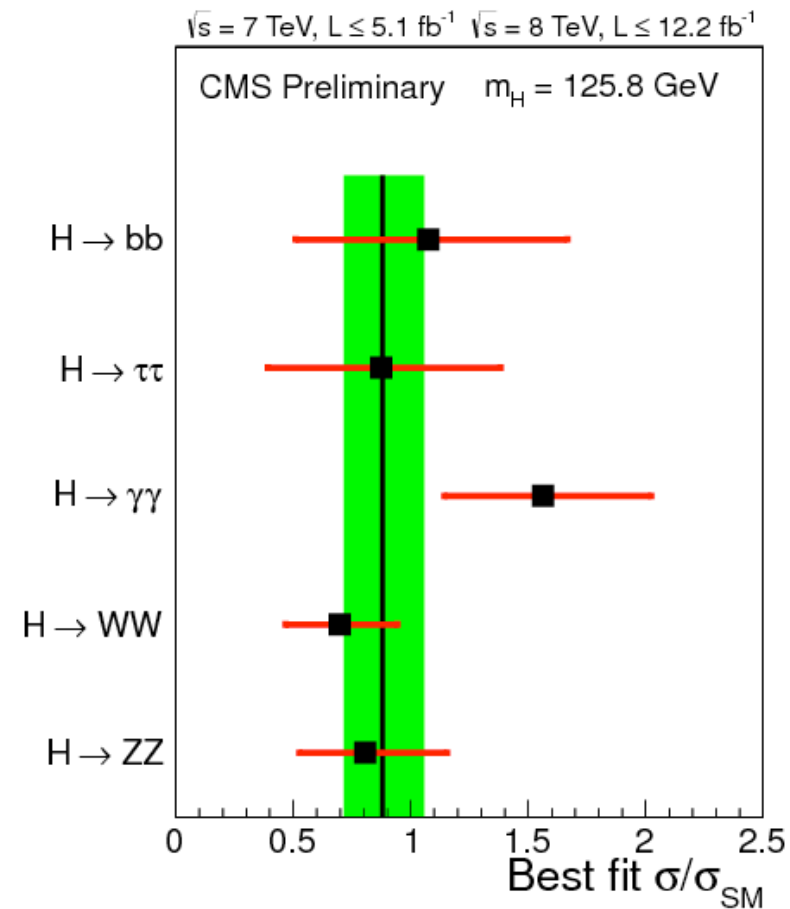
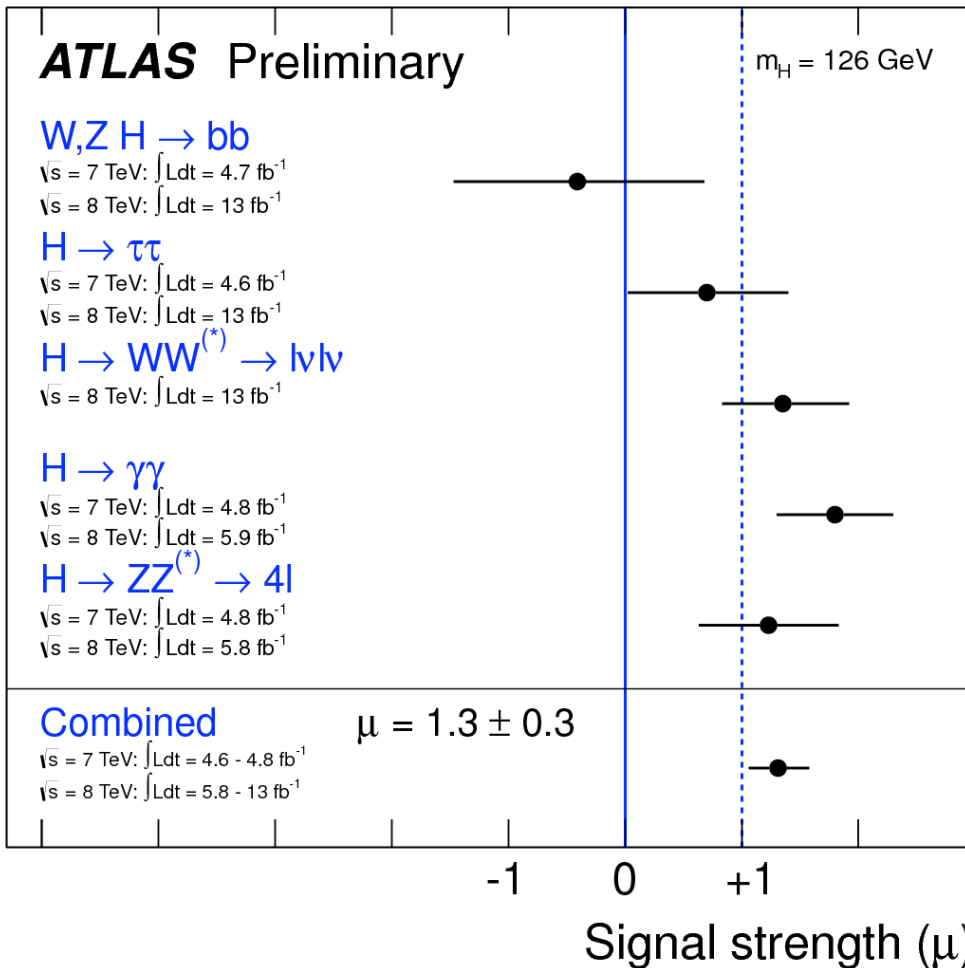
- The LHC has definitively found a new particle
- Most important discovery in fundamental physics for at least a decade, probably longer...
- Consistent so far with the predictions of a Higgs boson

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

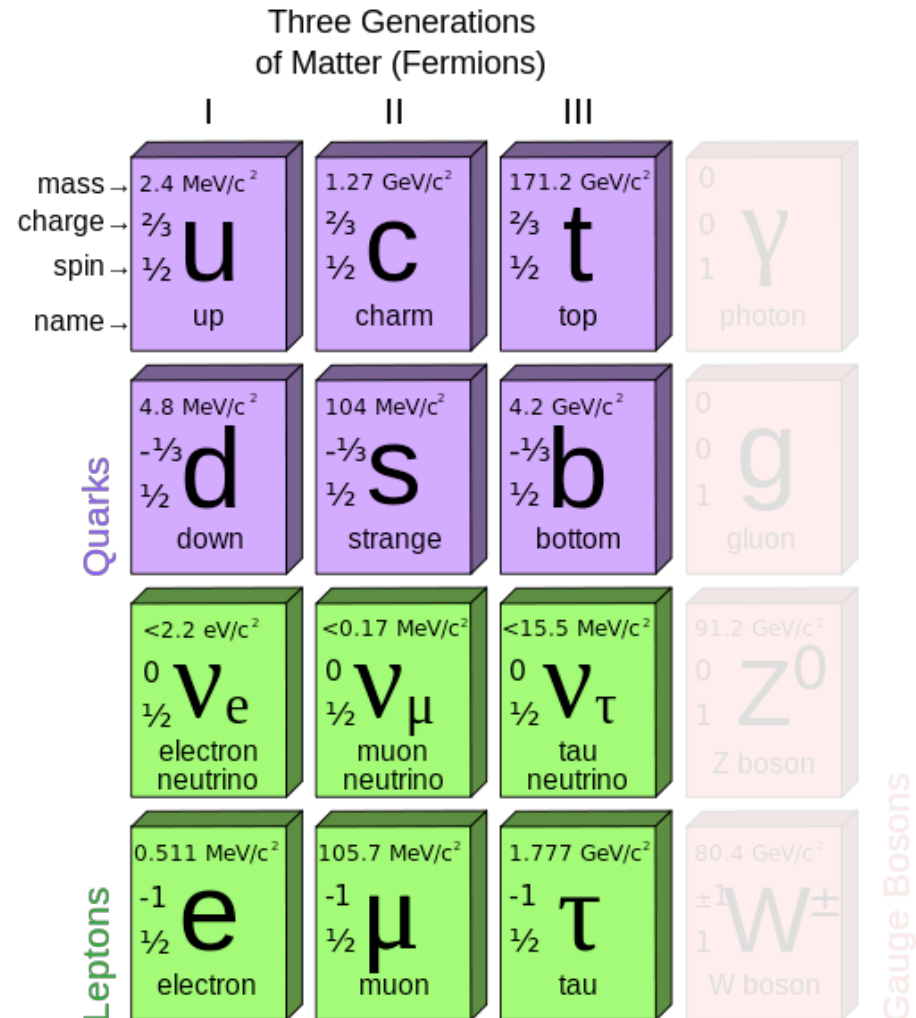
- Particle physics is hard
- By building a giant machine we can probe the very small
- And in the process help answer really basic questions
- The Large Hadron Collider is the next step in a journey
- The discovery of a Higgs(-like) boson is great
- Nobody knows what else we'll find...

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

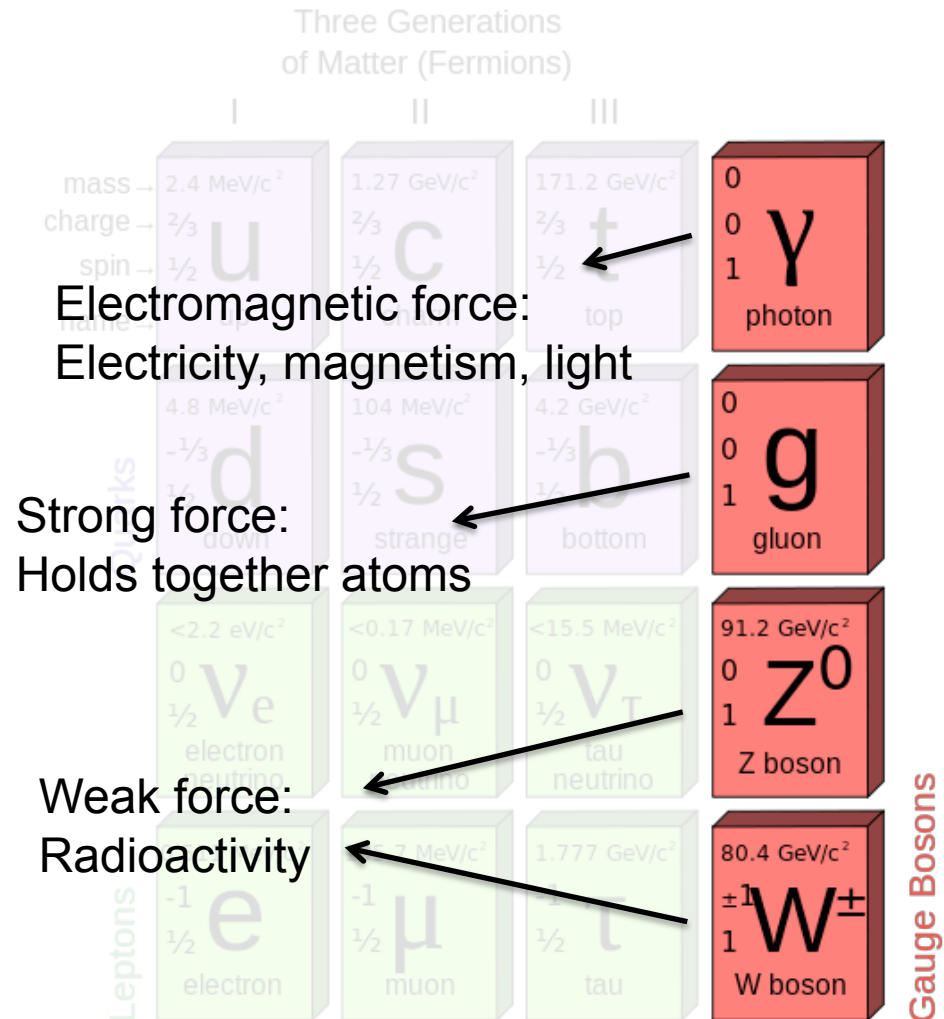


The Standard Model

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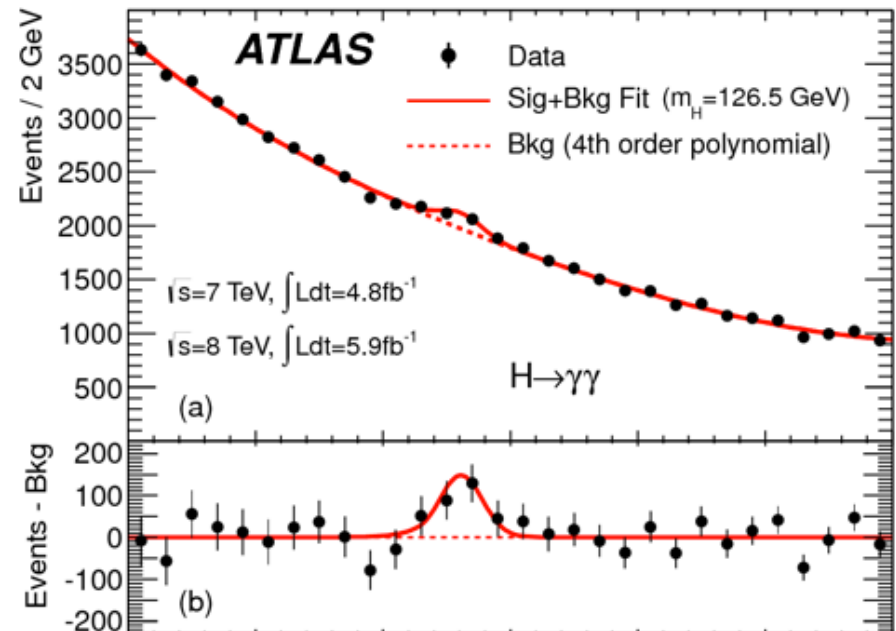
Four particles give us three forces which affect matter

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

