The Higgs boson – its discovery and what we have learnt since

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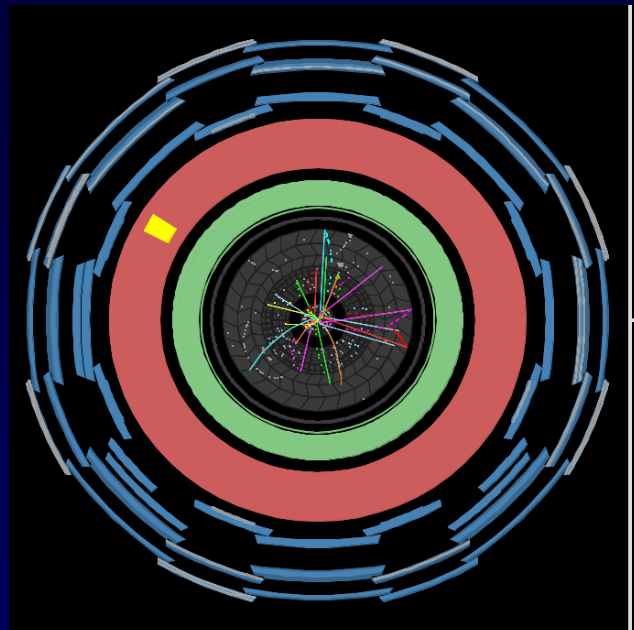


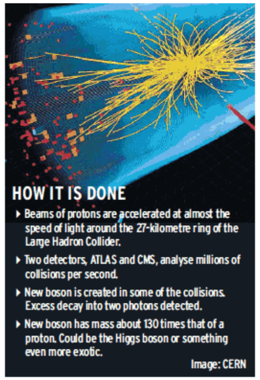
CCE Lecture

Quarks to the Cosmos

14th November, 2019

THE UNIVERSITY OF SYDNEY

Back in July 2012 there was lot's of media interest



In that other big hit-up, science finds Higgs boson

Deborah Smith
SCIENCE EDITOR

IT EXISTS.

In a discovery that throws light on the very fabric of space and time, a new subatomic particle has been found that is very likely the long-sought Higgs boson.

Making one of the most anticipated and exciting announcements in modern science last night, two teams of researchers using the world's biggest atom smasher, the Large Hadron Collider near Geneva, Switzerland, announced they had observed the new particle in collisions in the giant instrument.

"We have reached a milestone in our understanding of nature," the director-general of CERN, Rolf Heuer, said.

"This is the physics version of the discovery of DNA," Sir Peter Knight, president of the Institute of Physics said.

More studies, however, will be needed to pin down the exact nature of the boson, which is the most massive ever seen, scientists said.

"This is indeed a new particle," Joe Incandela, spokesman for one of the discovery teams, said. "The implications are very significant and it is precisely for this reason that we must be extremely diligent in all our studies and cross-checks."

The Higgs boson is the last undiscovered particle predicted to exist by the Standard Model of matter, and scientists have been hunting it for almost 50 years.

It is thought to give all other particles their mass, and some have dubbed it the God particle because of its importance, to the annoyance of scientists.

Researchers will now look to see if the new particle has the same properties as the Higgs boson predicted by the standard model, or whether it is an even more exotic particle.

If this is the case, it would be a revolutionary find, possibly leading to the discovery of more new particles and new dimensions in space, Professor Incandela said.

"It could be a gateway to the next phase of exploring the deepest parts of the fabric of the universe, which is pretty profound."

Researchers using the CMS and ATLAS detectors announced the results of their searches at a joint scientific seminar in Geneva and Melbourne, where the International Conference on High Energy Physics is being held.

The two teams had been blinded to each other's data, to avoid influencing their independent analyses. They each found a particle consistent with a Higgs boson with a mass of 125-126 gigaelectronvolts – about 130 times the mass of a proton.

"This is a milestone for human understanding of the fundamental laws that govern the universe," Geoff Taylor, of the University of Melbourne, said.

Peter Higgs, of the University of Edinburgh, who predicted the existence of the Higgs boson in 1964, congratulated the scientists on their achievement.

"I am astounded at the amazing speed with which these results have emerged. I never expected this to happen in my lifetime," Professor Higgs said.

Anthony Thomas, of the University of Adelaide, said it was a very exciting discovery.

"There's more work yet to be done to prove that this is the Higgs boson, but it certainly looks like it," Professor Thomas said.

Australians helped design and build parts of the ATLAS detector and analyse the results.

HOW IT IS DONE

- Beams of protons are accelerated at almost the speed of light around the 27-kilometre ring of the Large Hadron Collider.
- Two detectors, ATLAS and CMS, analyse millions of collisions per second.
- New boson is created in some of the collisions. Excess decay into two photons detected.
- New boson has mass about 130 times that of a proton. Could be the Higgs boson or something even more exotic.

Image: CERN

SMH 5th July 2012

ATLAS and CMS experiments

Seems such a long time ago ...

ICHEP Conference Melbourne July 4, 2012

Live webcast from CERN

CERN press conference

CERN Auditorium

Image: Associated Press

ICHEP conference Melbourne

Image: Laura Vanags

What is the Universe made of?

Image:http://particleadventure.org

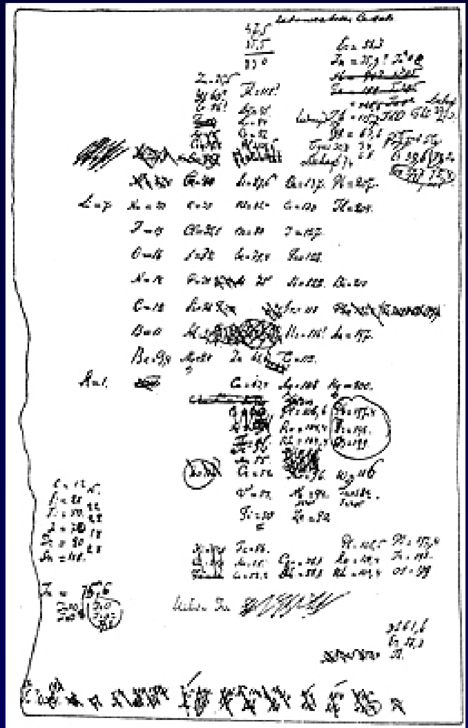
Empedocles C 450 BC

Image:Science Photo Libray

What is the Universe made of?

Democritus c. 400 BC

What is the Universe made of?



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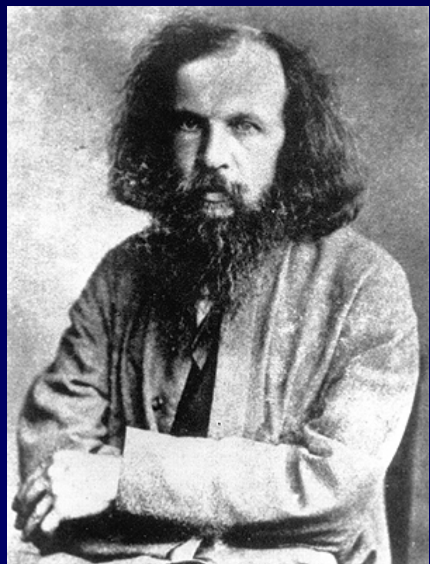
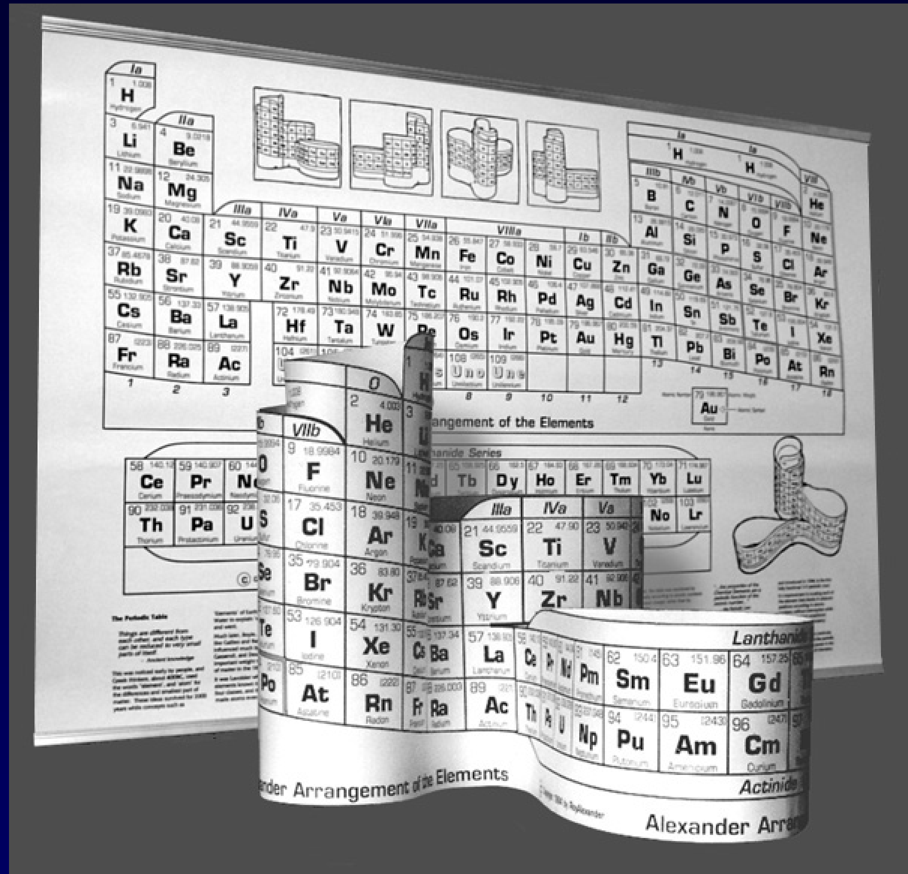
Mendeleev
1834-1907

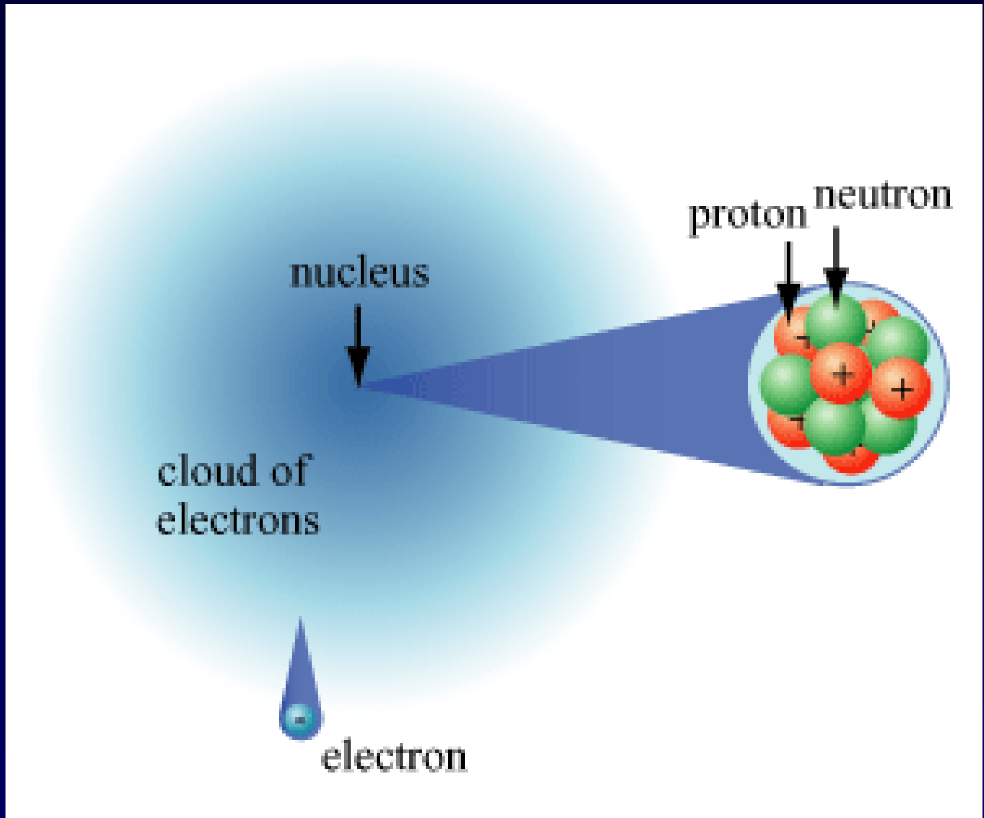


http://www.nndb.com/

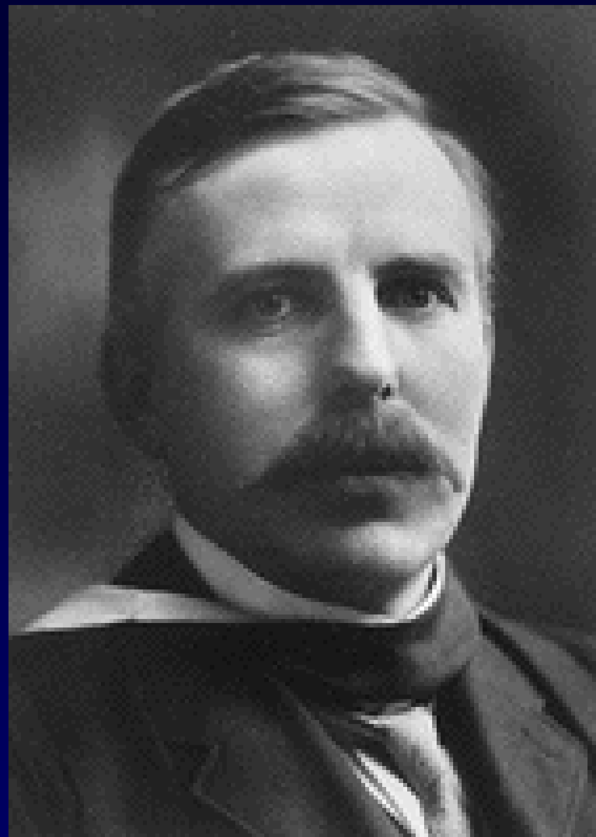


http://www.super-science-fair-projects.com/

What is the Universe made of?



http://www.hk-phy.org/



http://www.nobelprize.org/

Rutherford 1871-1937

The very large to the very small

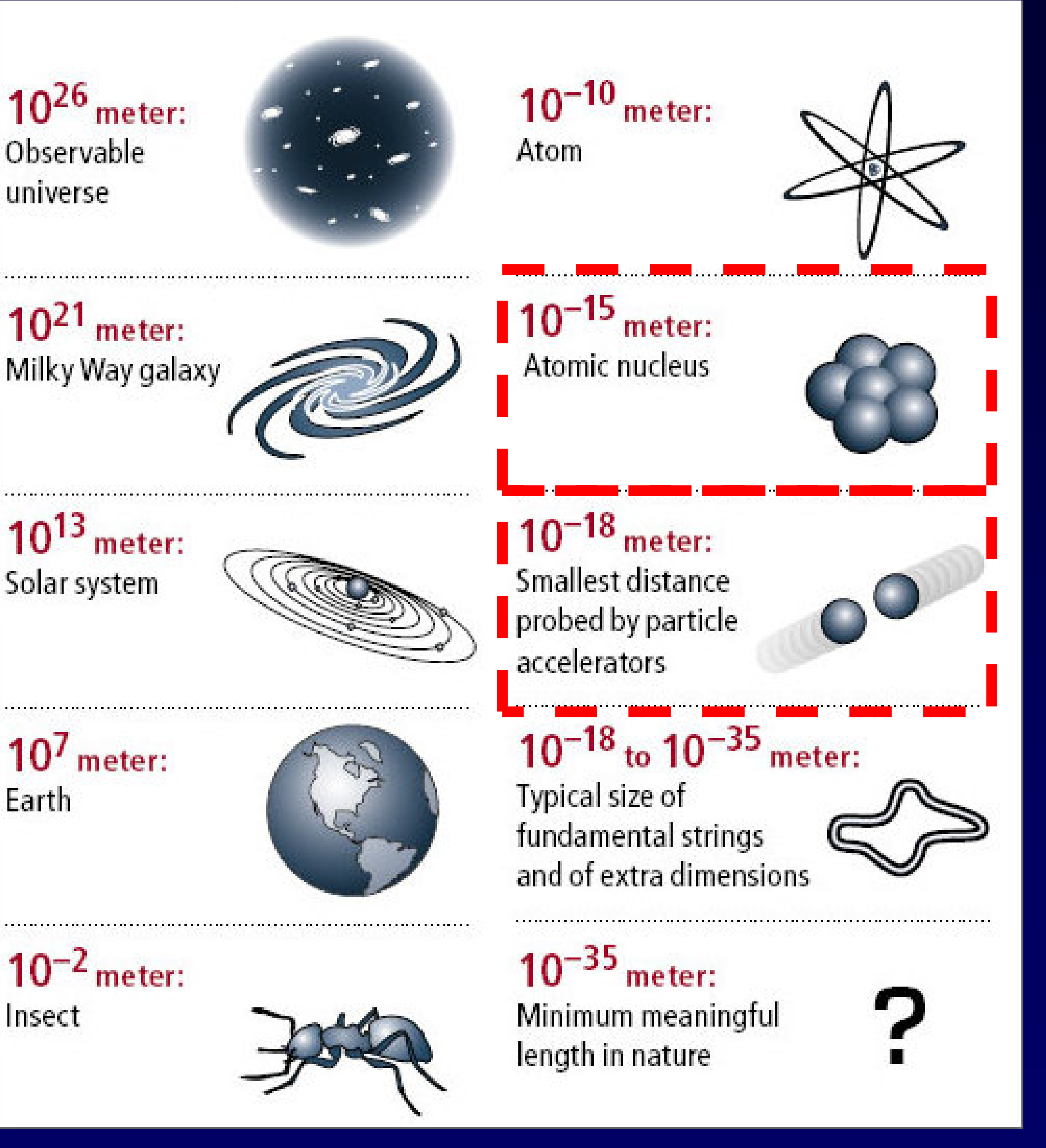


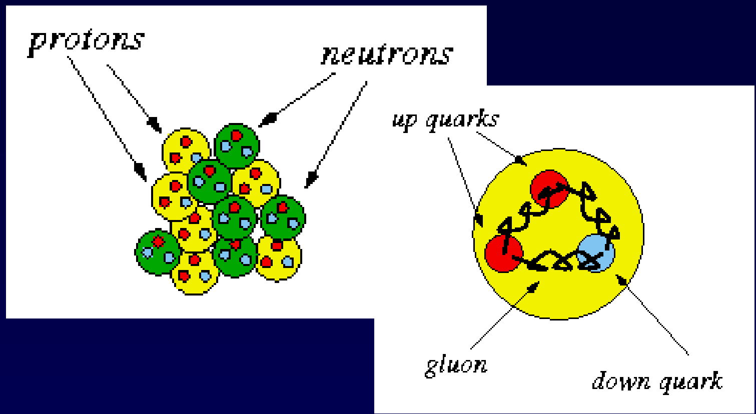
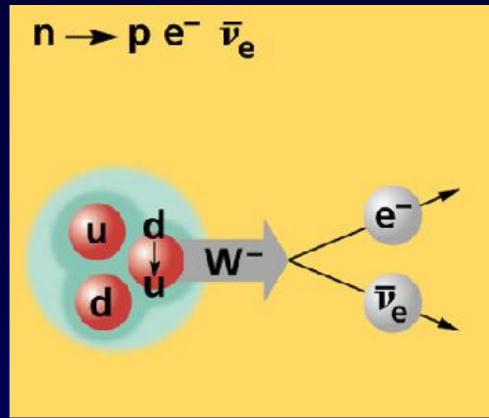
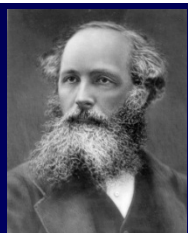
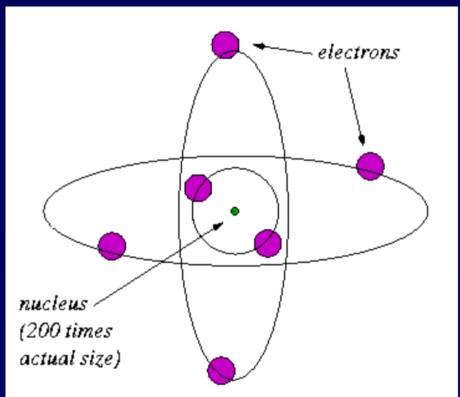
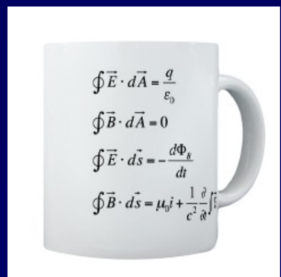
Image:http//thelongzoom.com

One definition of Particle (High Energy) Physics …

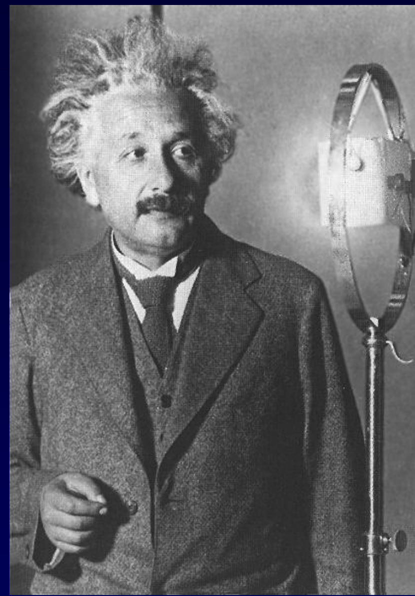
Particle physics studies the fundamental constituents of matter and their interactions

… down to very very small dimensions
(of order 0.000000000000000001 metres or less)

Maxwell took a step along the path of unifying the forces of nature

Strong	Weak
	e.g. Nuclear beta decay 
Electromagnetic  Photo: Cavendish Laboratory   Photo: cafepress.com	**Gravity** 

We can probe matter with high energies



Because of this equivalence of mass and energy, ($E=mc^2$) we can use high energies to create new, massive particles

High energy or momentum corresponds to high resolution allowing us to probe short distances

Wavelength → $$\lambda = \frac{h}{p}$$ ← Planck's constant ← Momentum

How to make new particles .... fruit analogy

This is a better analogy than colliding e.g. clocks and studying the clock bits that fly out

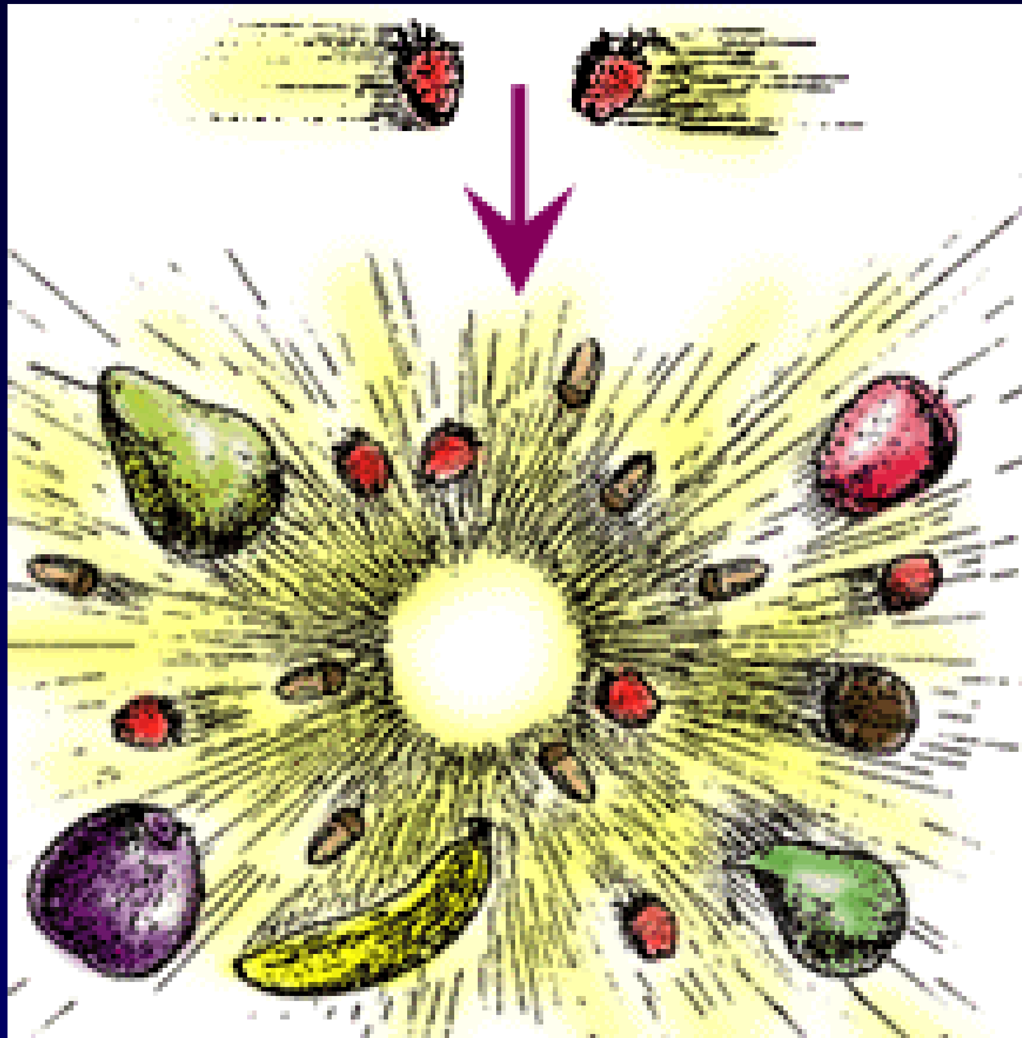


Image: http://particleadventure.org

A century of research since Rutherford arrived at a set of basic building blocks for matter, the particles of the Standard Model

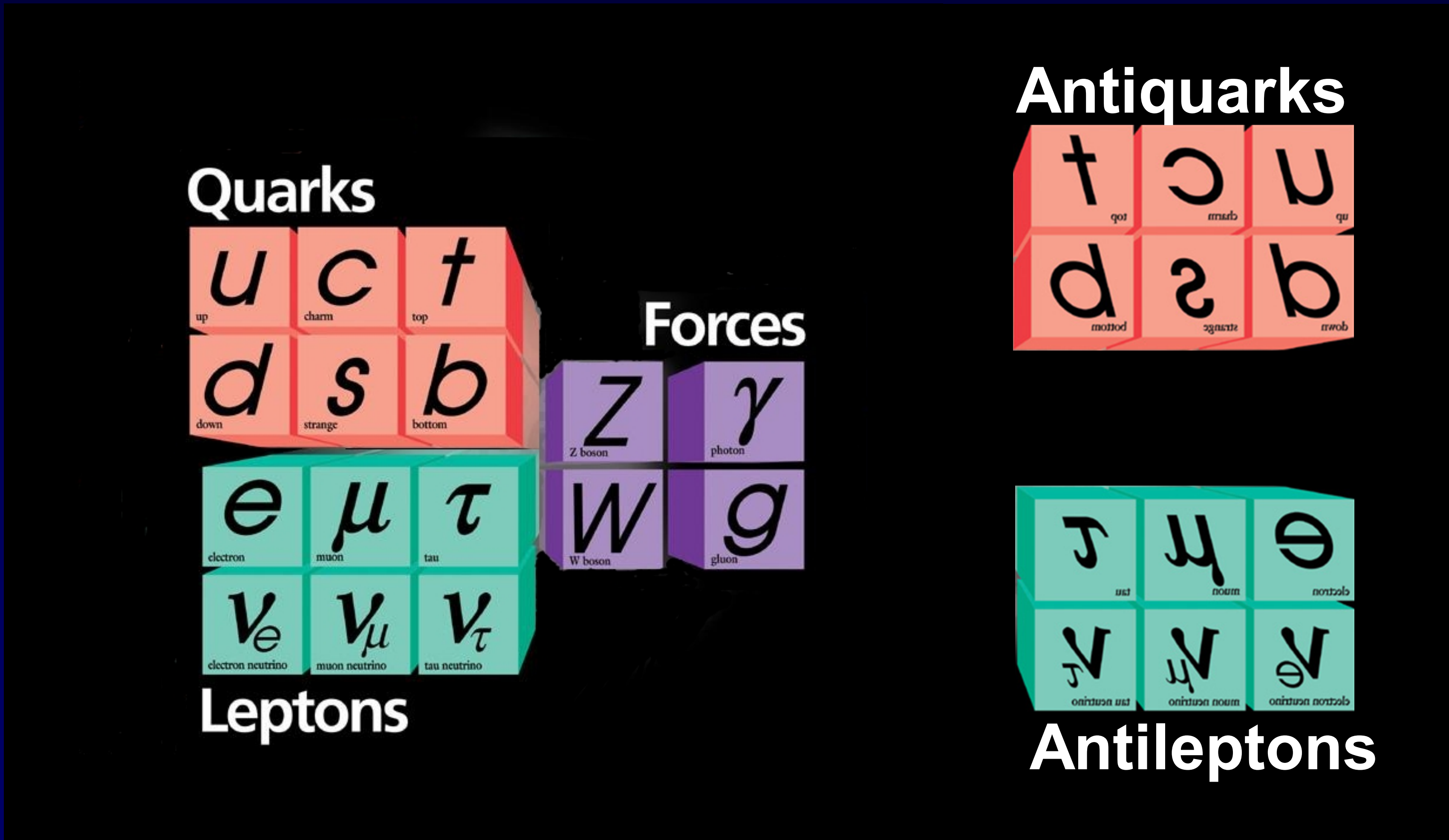
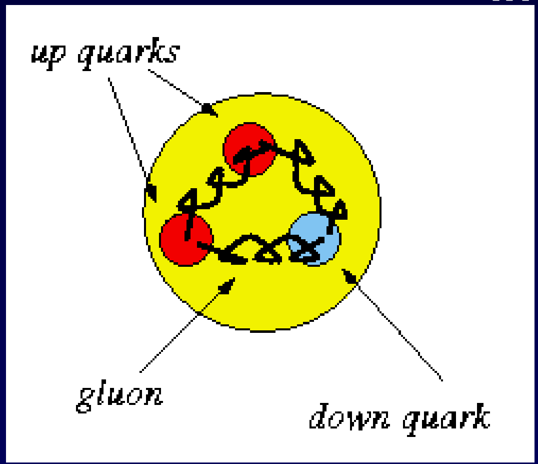


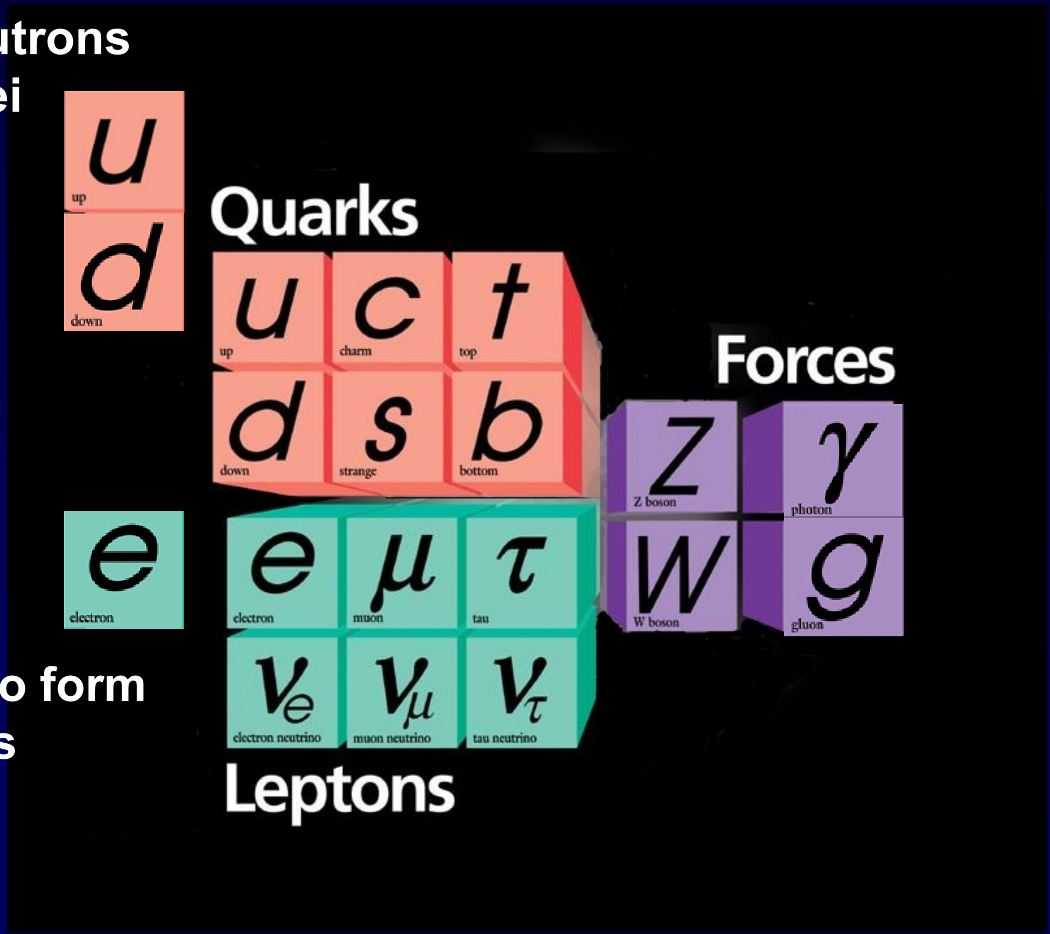
Image: Adapted from Fermilab Visual Media Services

We only need three of these fundamental particles (plus forces) to build everything we see around us

Make protons and neutrons in nuclei



Proton



Add to form atoms

Image: Adapted from Fermilab Visual Media Services

There are a number of unanswered questions about the Standard Model

Why are there at least three “families” of quarks and leptons?

Why do the particles have the masses they do?
(or mass at all?)

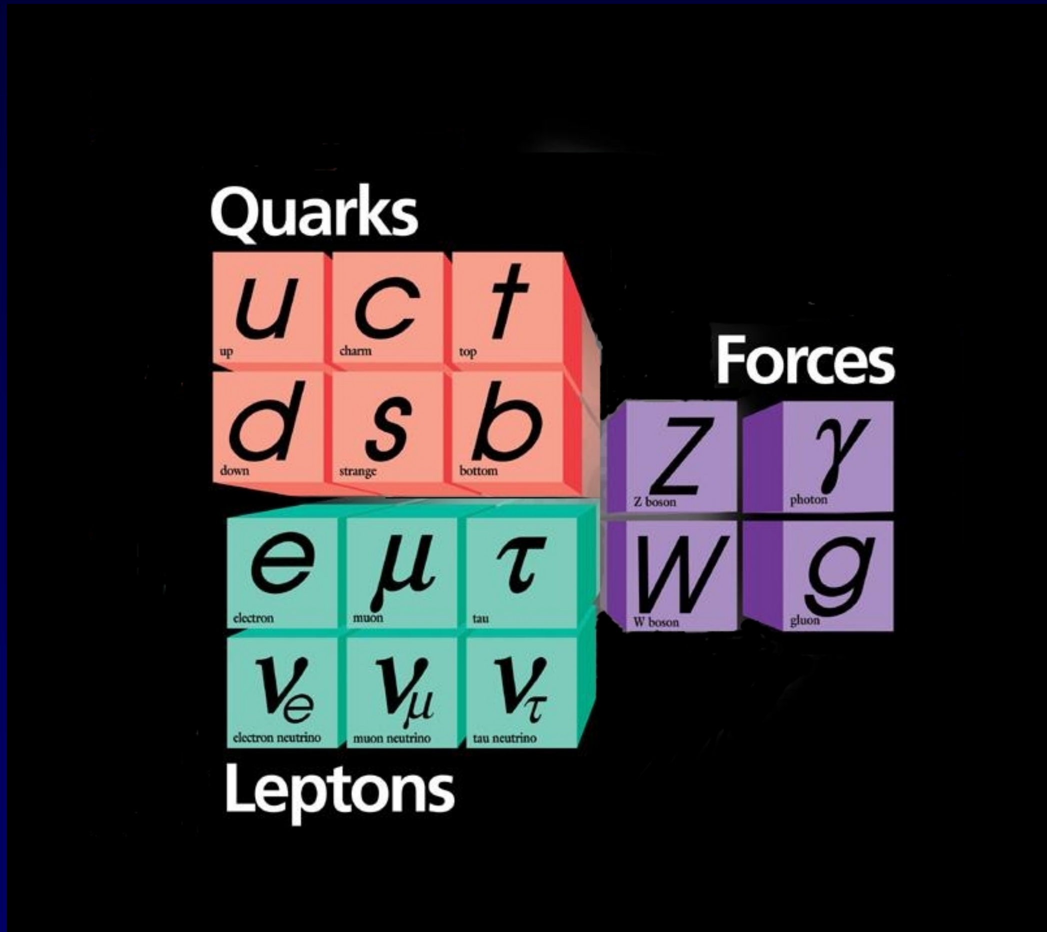


Image: Fermilab Visual Media Services

What is the origin of mass? Why do the particles have the masses that they do?

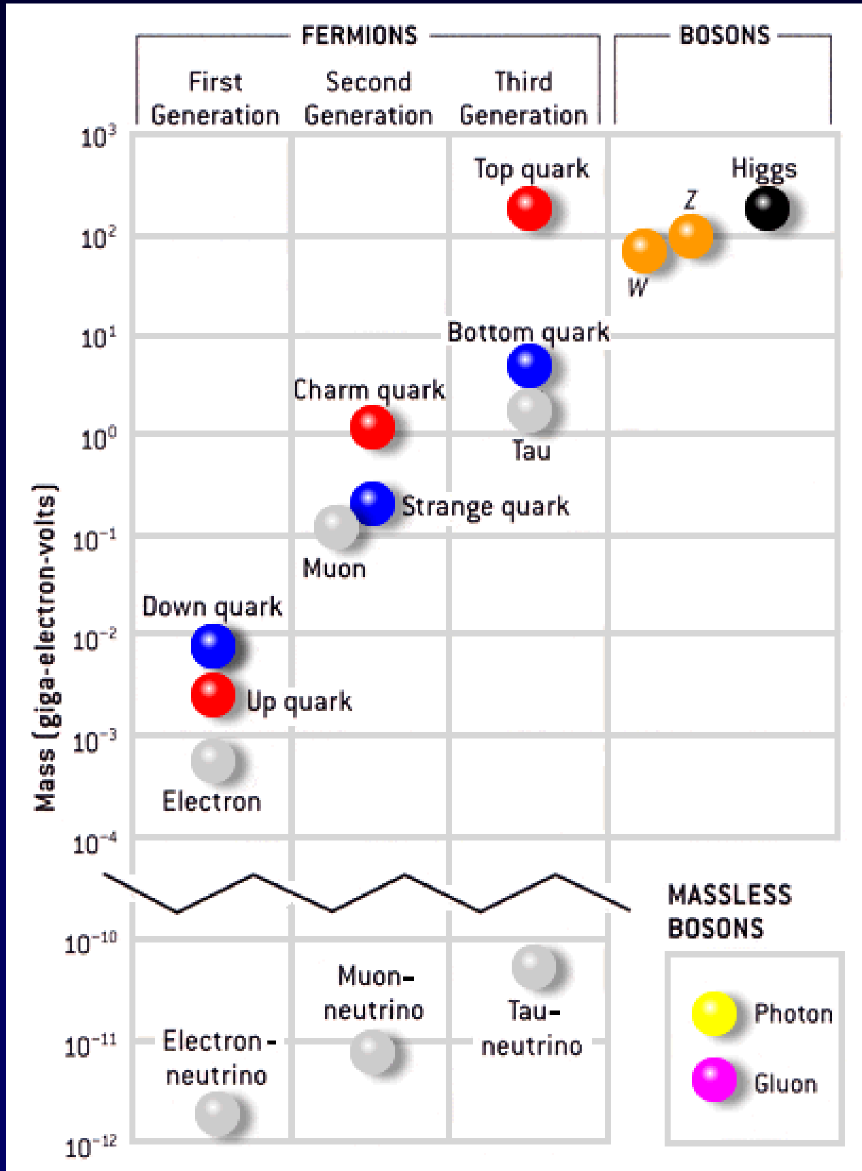
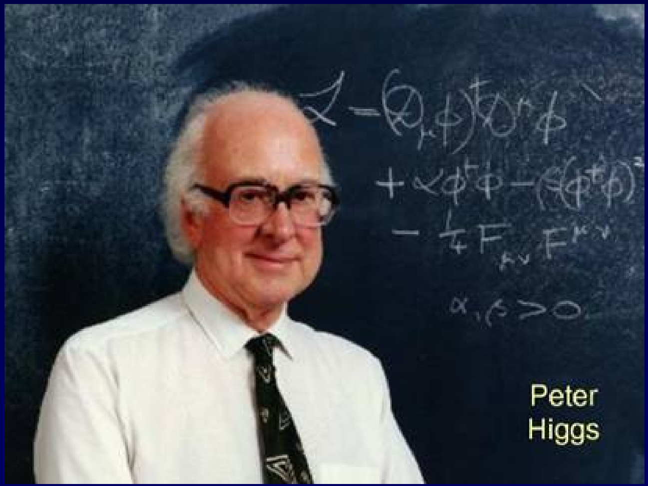


Image: https://scienceblogs.com/

What is the origin of mass? Why do particles have mass at all?

Unification of the electromagnetic and weak forces (late 1960s)

- needed the Higgs field (1964)

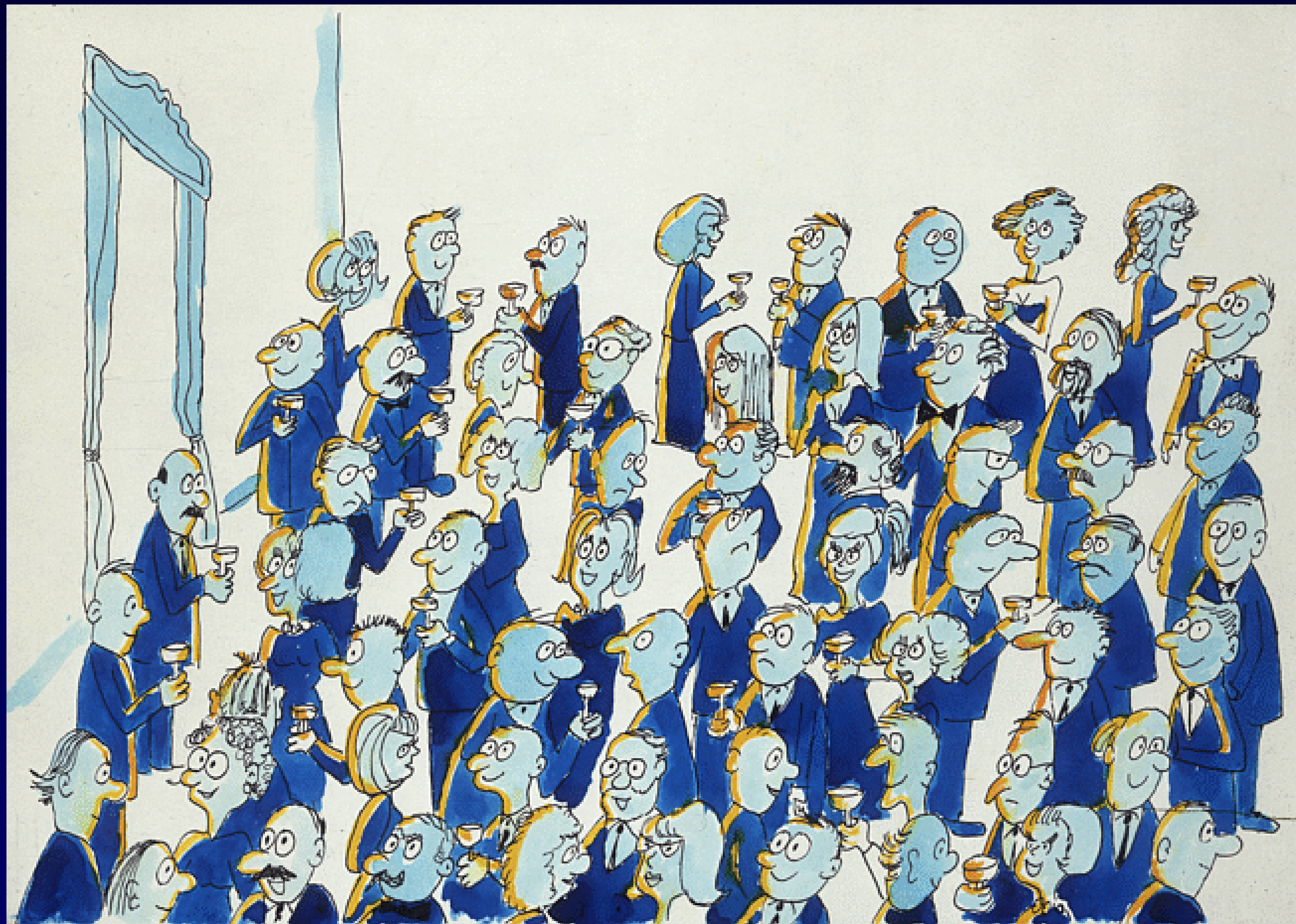


Particles which would otherwise be mass-less, interacting with the Higgs field, get a mass

There is a particle associated with the Higgs field, called the

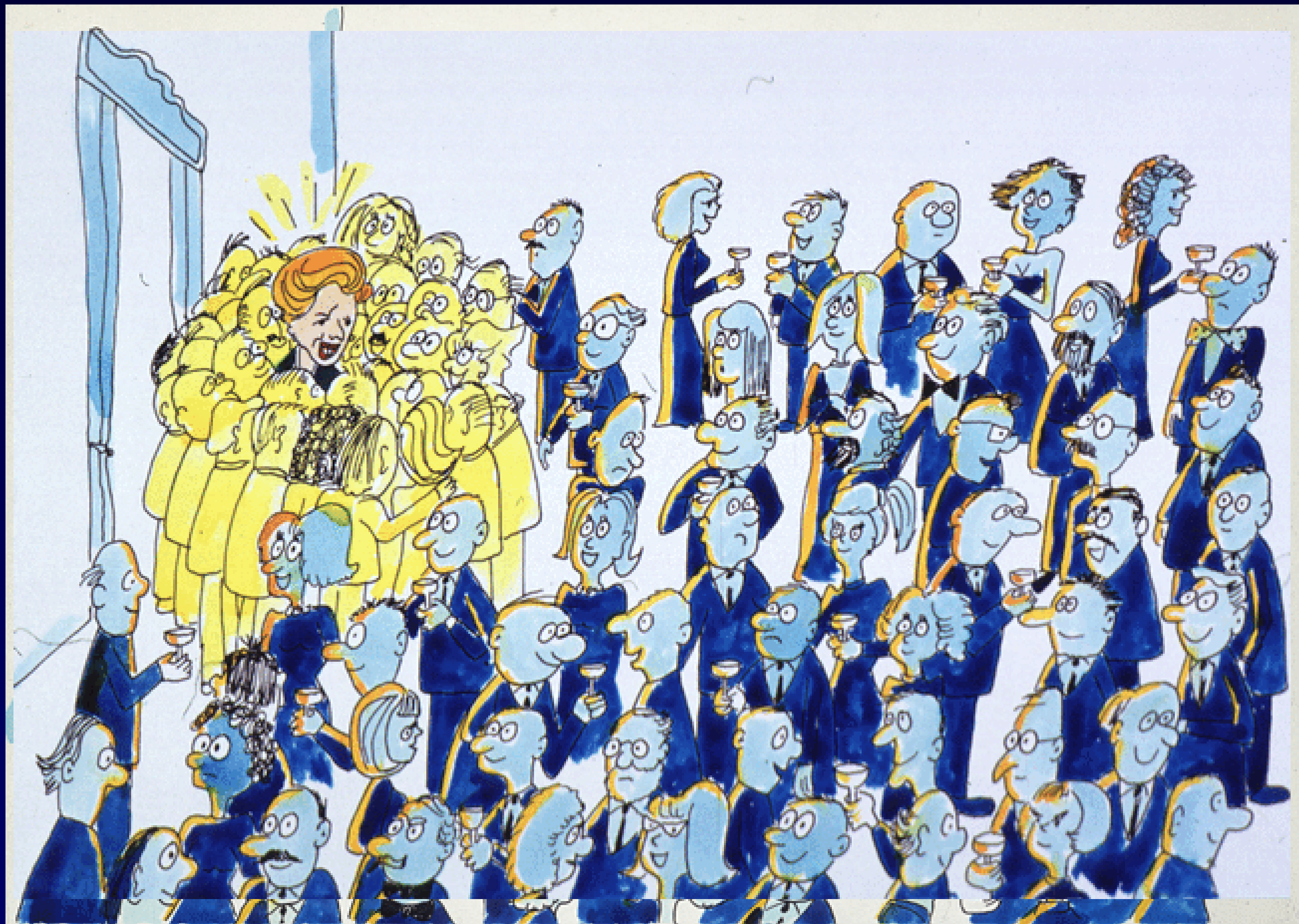
Higgs boson

The Cocktail Party Higgs Analogy



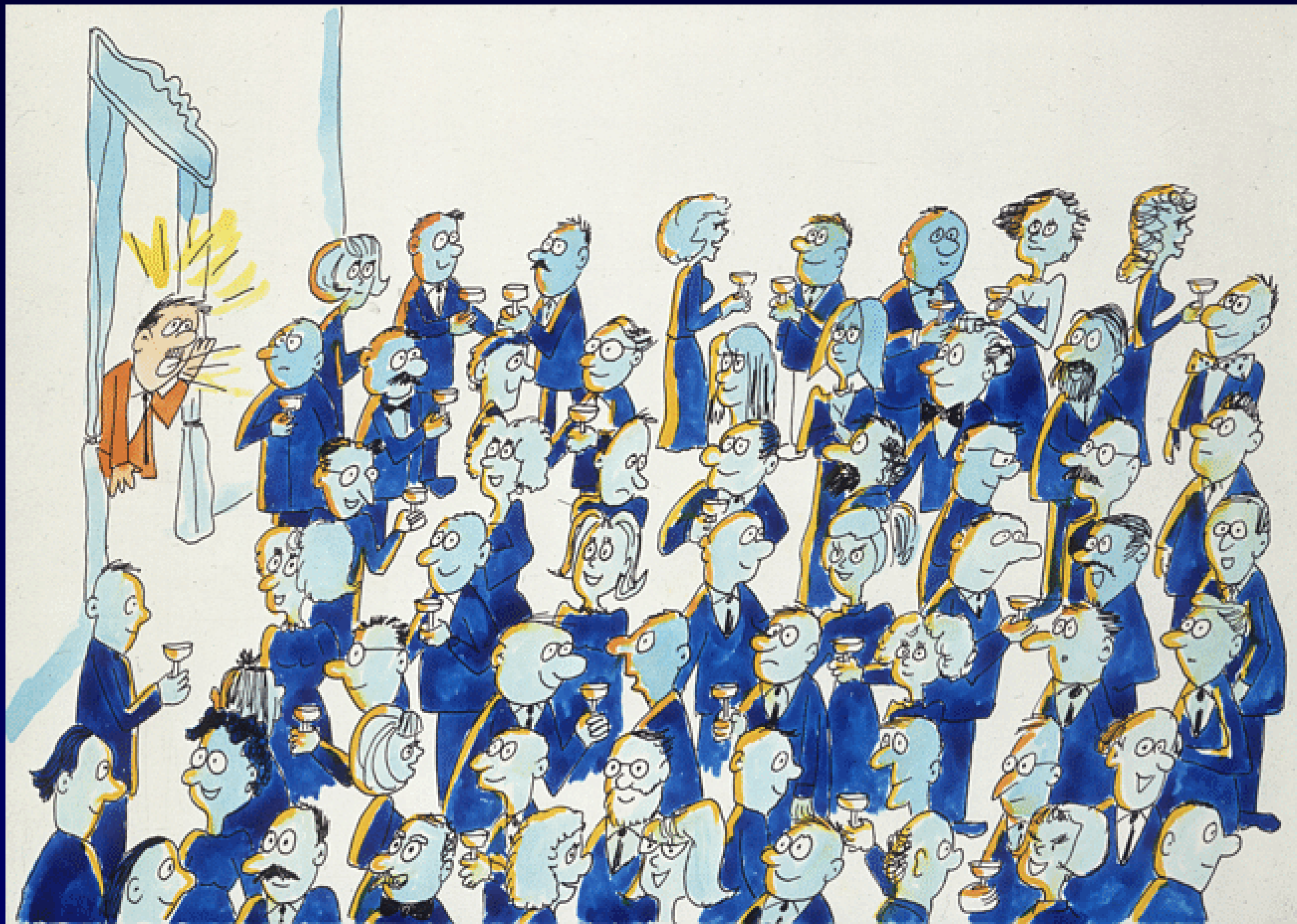
The Higgs Field

The Cocktail Party Higgs Analogy



A particle in the Higgs Field

The Cocktail Party Higgs Analogy



A disturbance

The Cocktail Party Higgs Analogy

A Higgs Boson

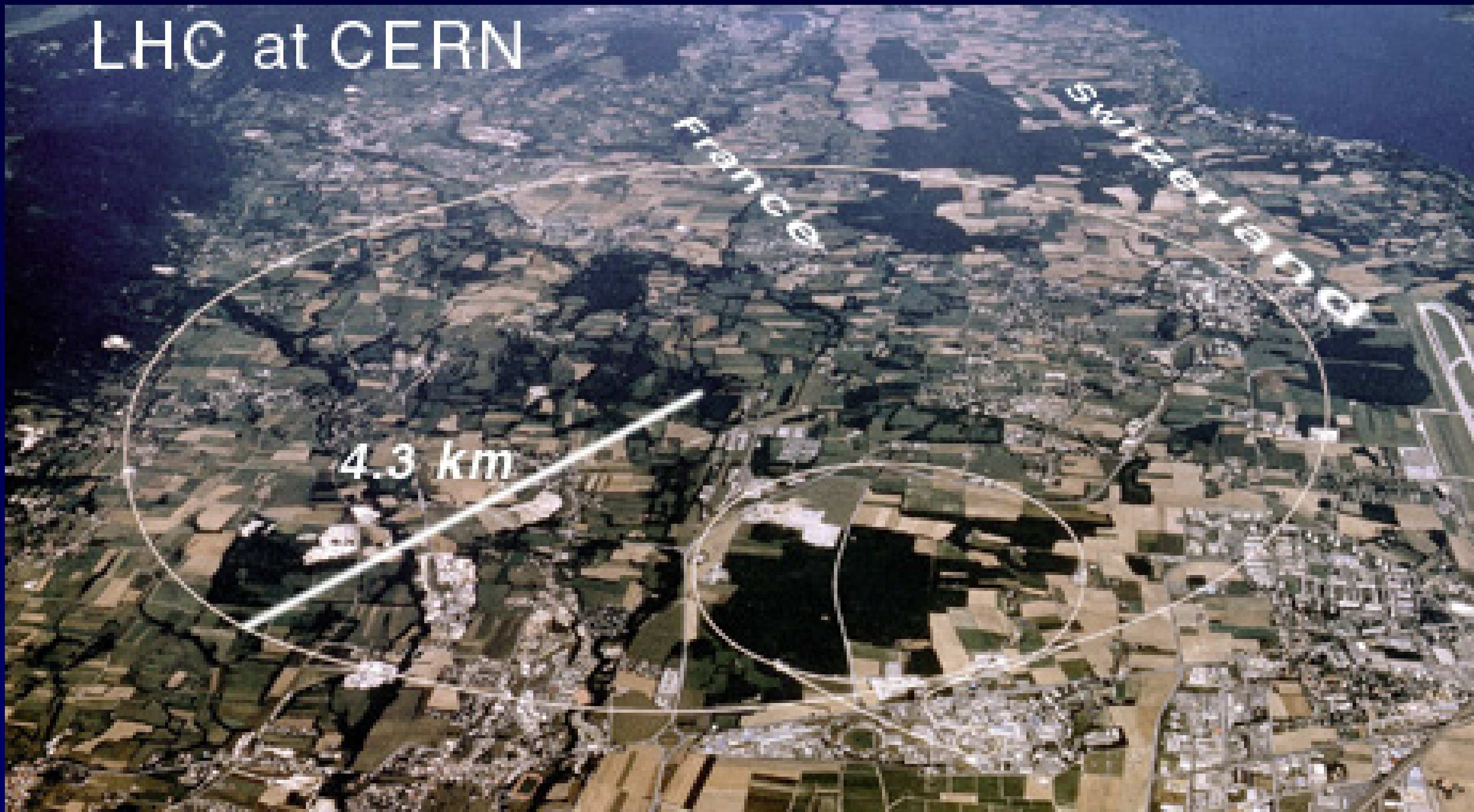
One thing that we didn’t know was the Higgs mass

It was expected to be in the range of approximately 100 -1000 times the proton mass

(based on things we did know and had measured already)

Image:http://particlezoo.net/individual_pages/shop_higgsboson.html

A very sophisticated machine was needed to search for the Higgs



Some machine!

Image: CERN

LHC Machine Parameters		
Beam energy	E	7.0 TeV
Dipole magnetic field	B	8.4 T
Luminosity	L	10^{34} cm^{-2} s^{-1}
Injection energy	E_i	450 GeV
Circulating current/beam	I_{beam}	0.53 A
Number of bunches	k_b	2835
Time between bunches	τ_b	24.95 ns
Protons per bunch	n_b	1.05×10^{11}
Stored beam energy	E_s	334 MJ
r.m.s. beam radius at intersection point	σ^*	16 μm
Crossing angle	ϕ	200 μrad
Number of events per crossing	n_c	19
Beam lifetime	τ_{beam}	22 h
Luminosity lifetime	τ_L	10 h

Each proton crosses the French-Swiss border 11,200 times per second

The 27km tunnel contains some 1200 superconducting bending magnets

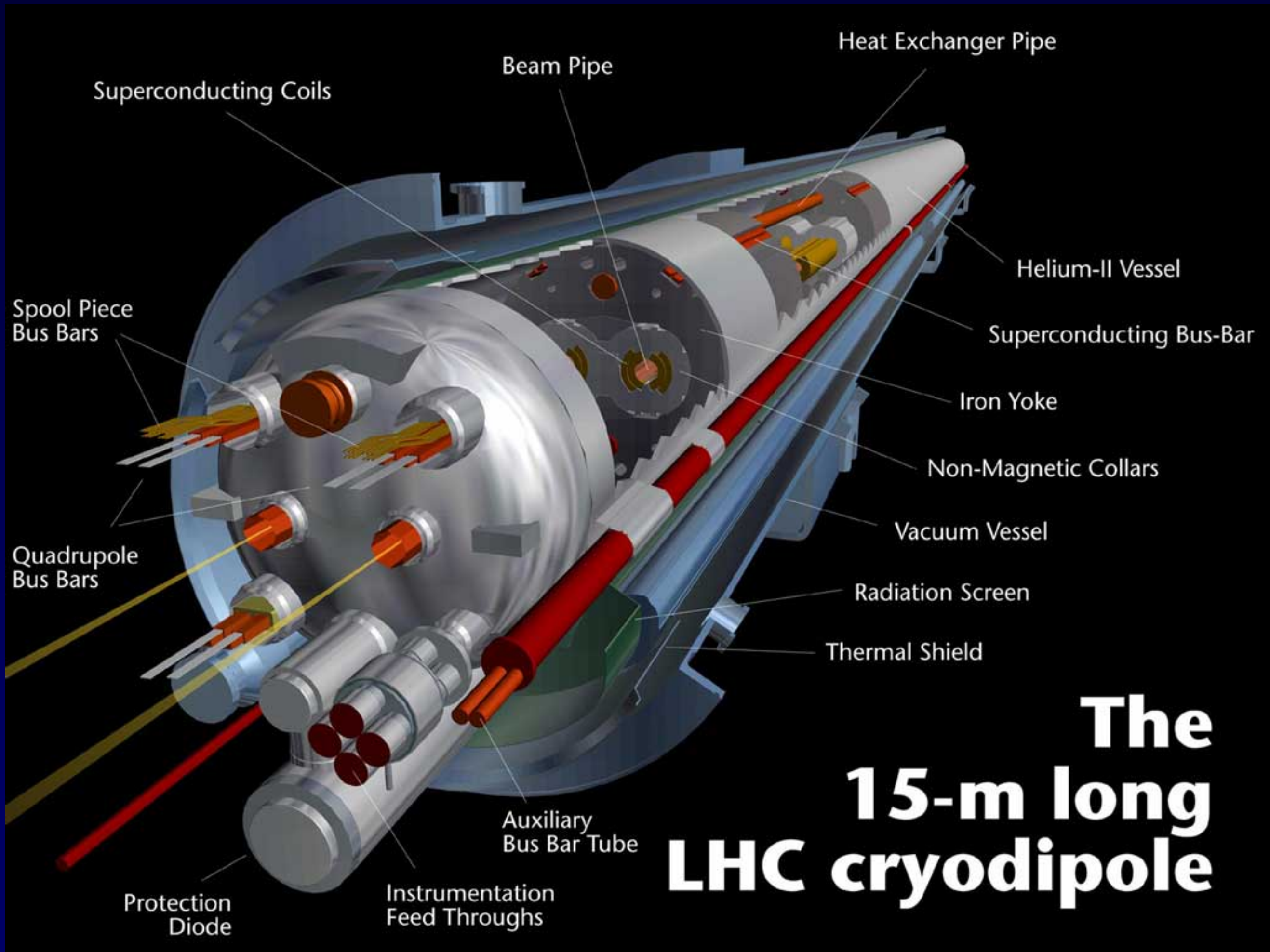


Image: CERN

Operates at 1.9K

Experimental collaborations are truly global

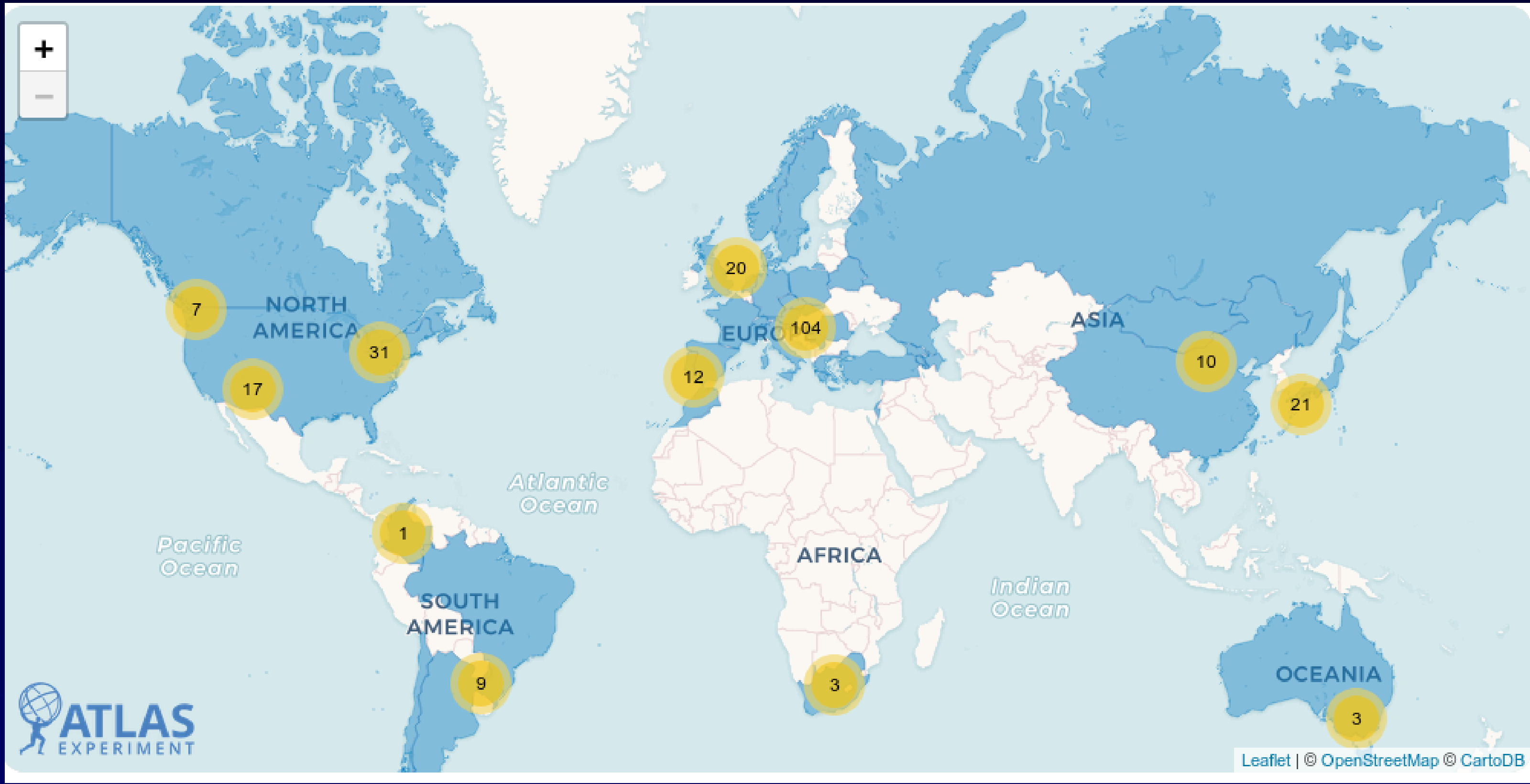


Image: https://atlas.cern/discover/collaboration

38 countries
183 institutions
> 3000 scientific authors

We need a method of observing the products of the collisions

CMS is similar

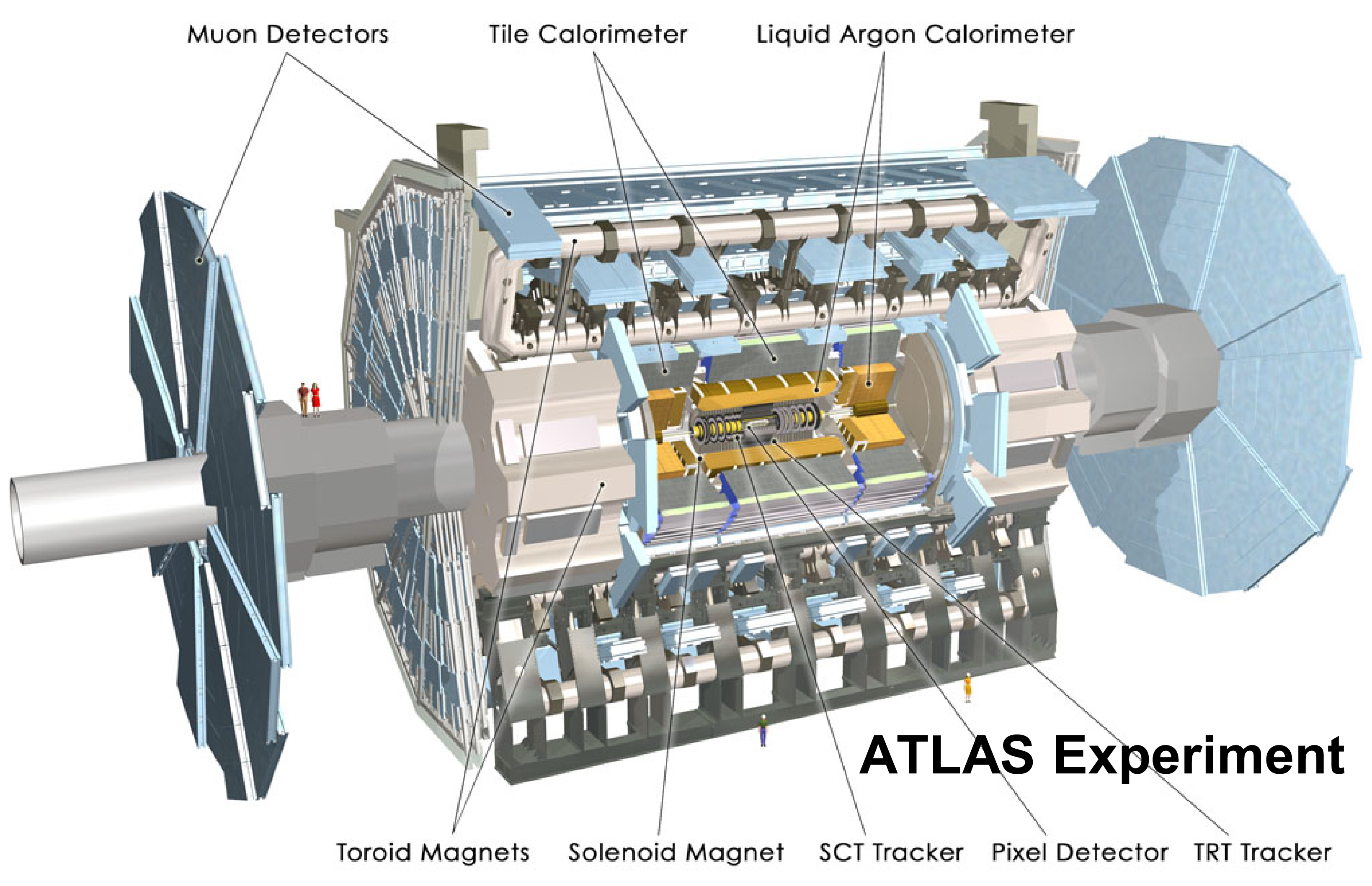
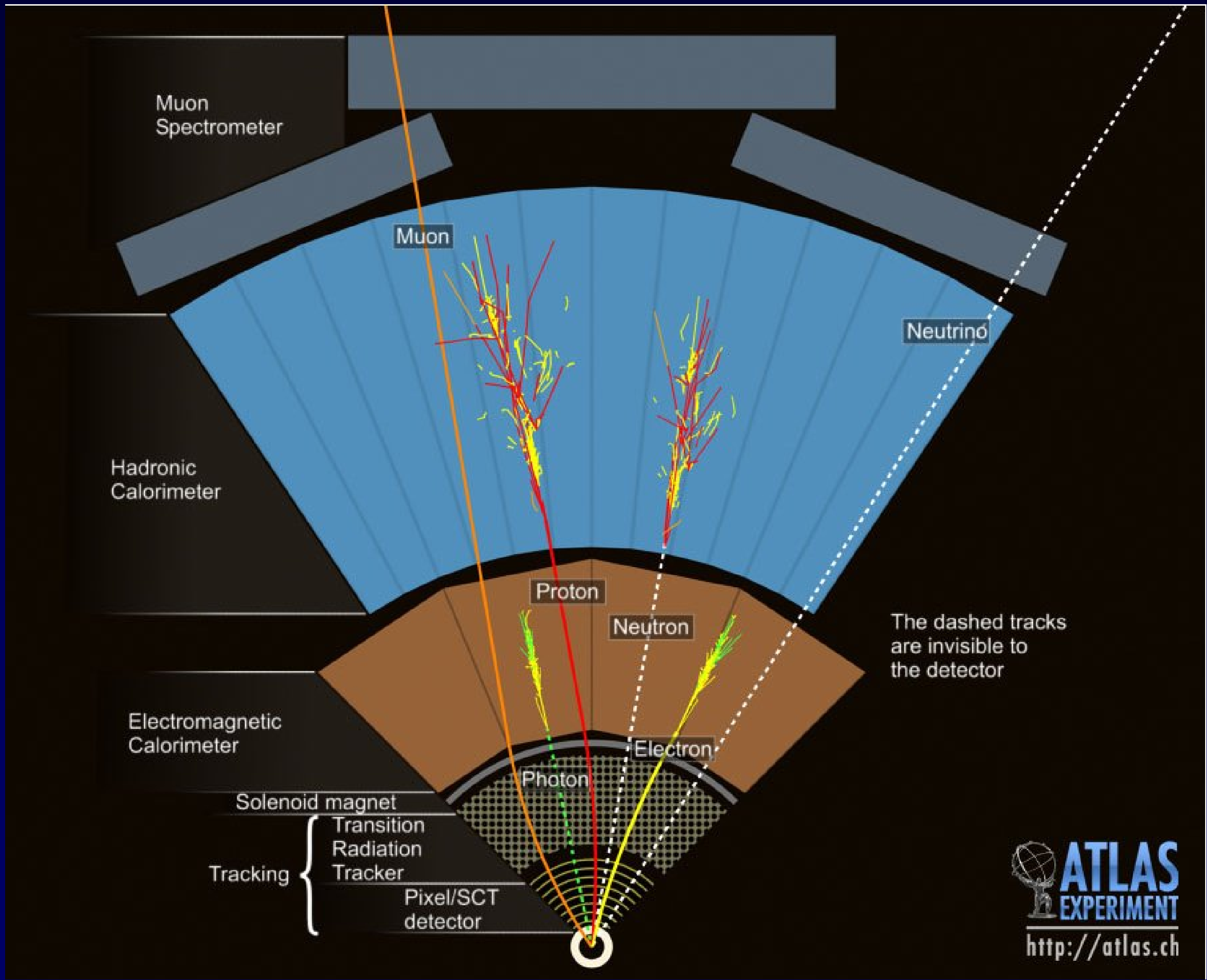


Image: ATLAS@CERN 2012

Mass 7000 tonnes

Different types of particle require different detection techniques



The LHC started up on 10th September 2008

Image:CERN

The LHC on 19th September 2008

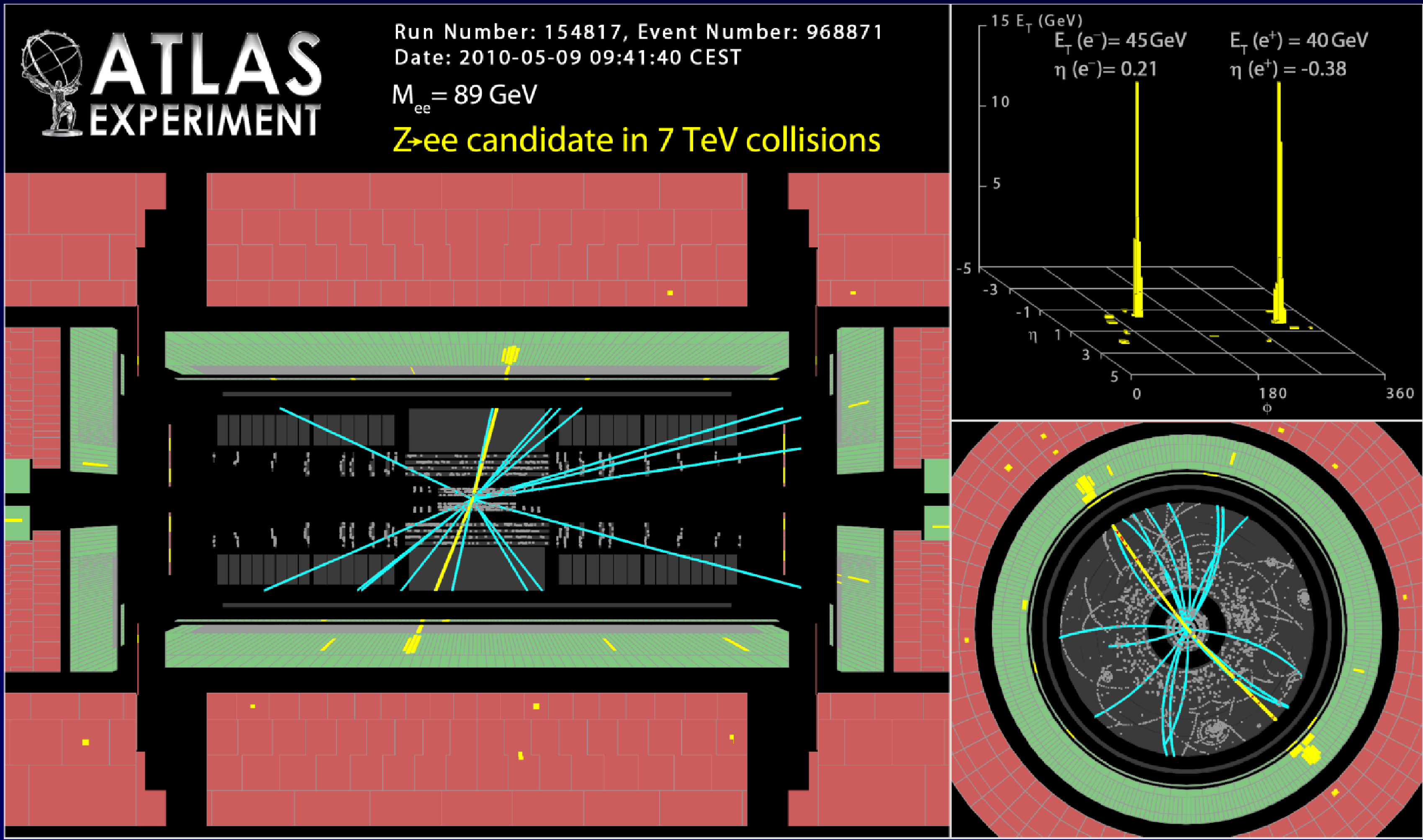
Image:CERN

The LHC recommenced after a year of repairs

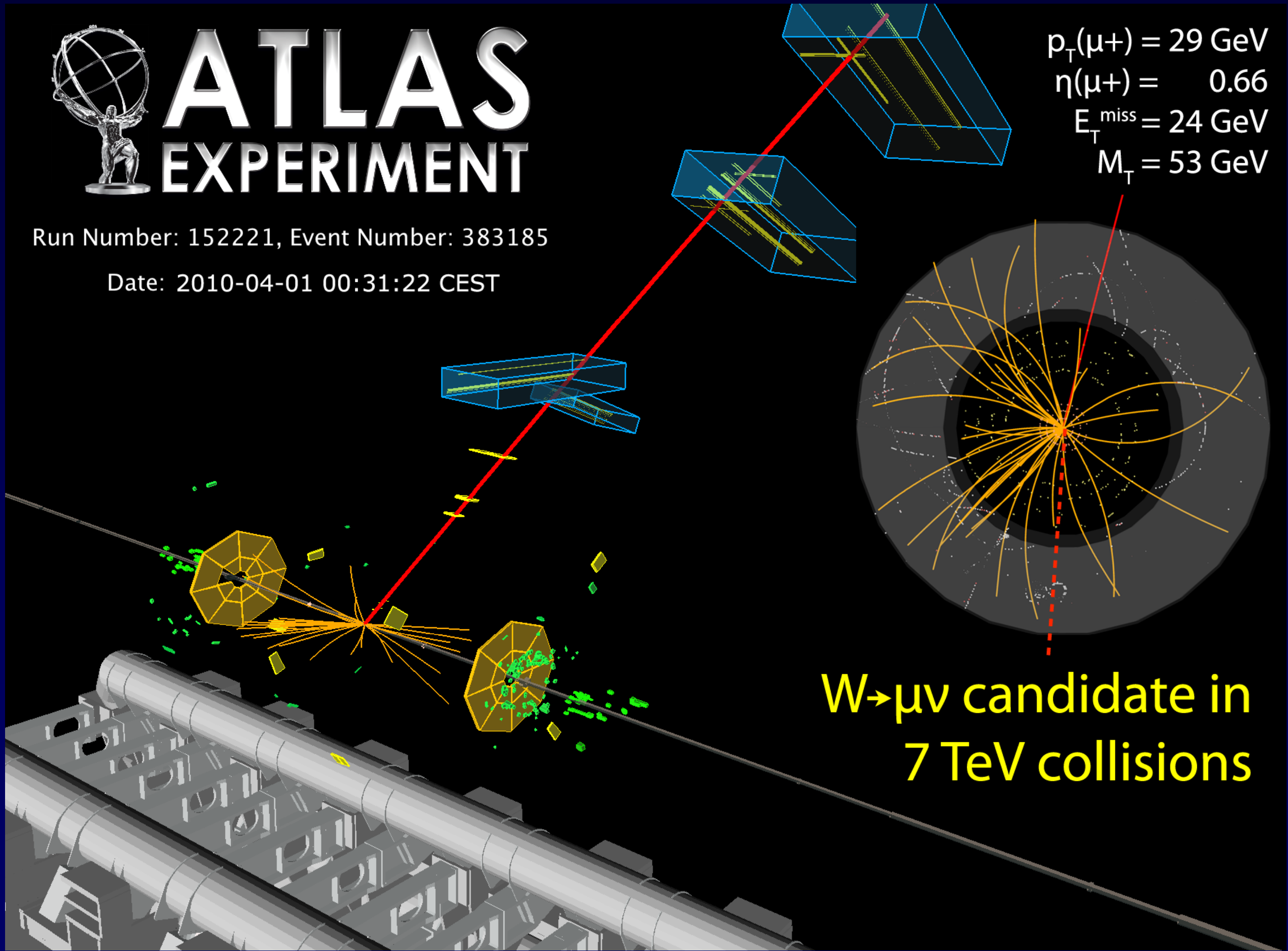
Albeit at 50% design energy

The first task was to rediscover the Standard Model that we know

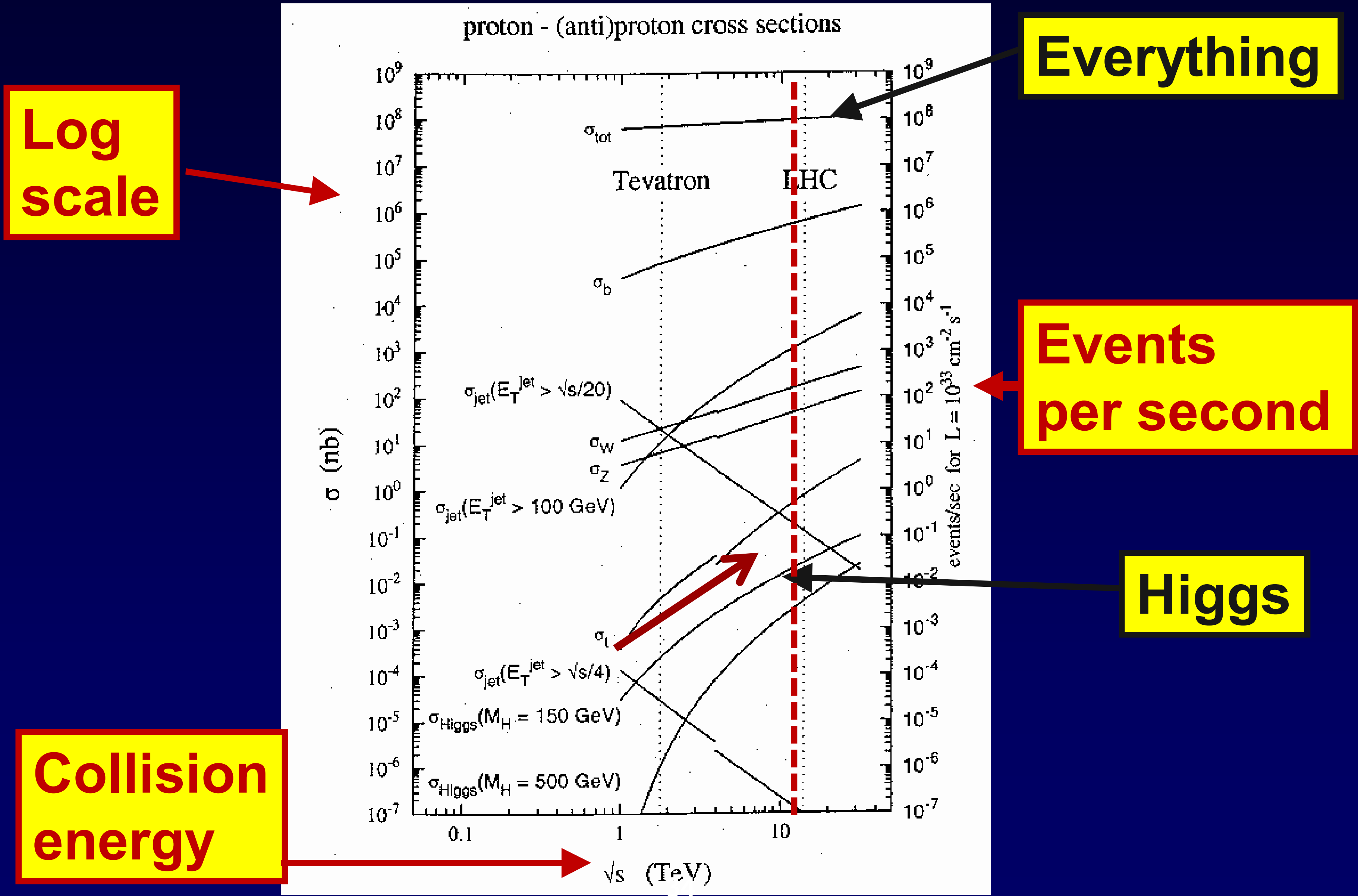
$Z^0 \rightarrow e^+e^-$



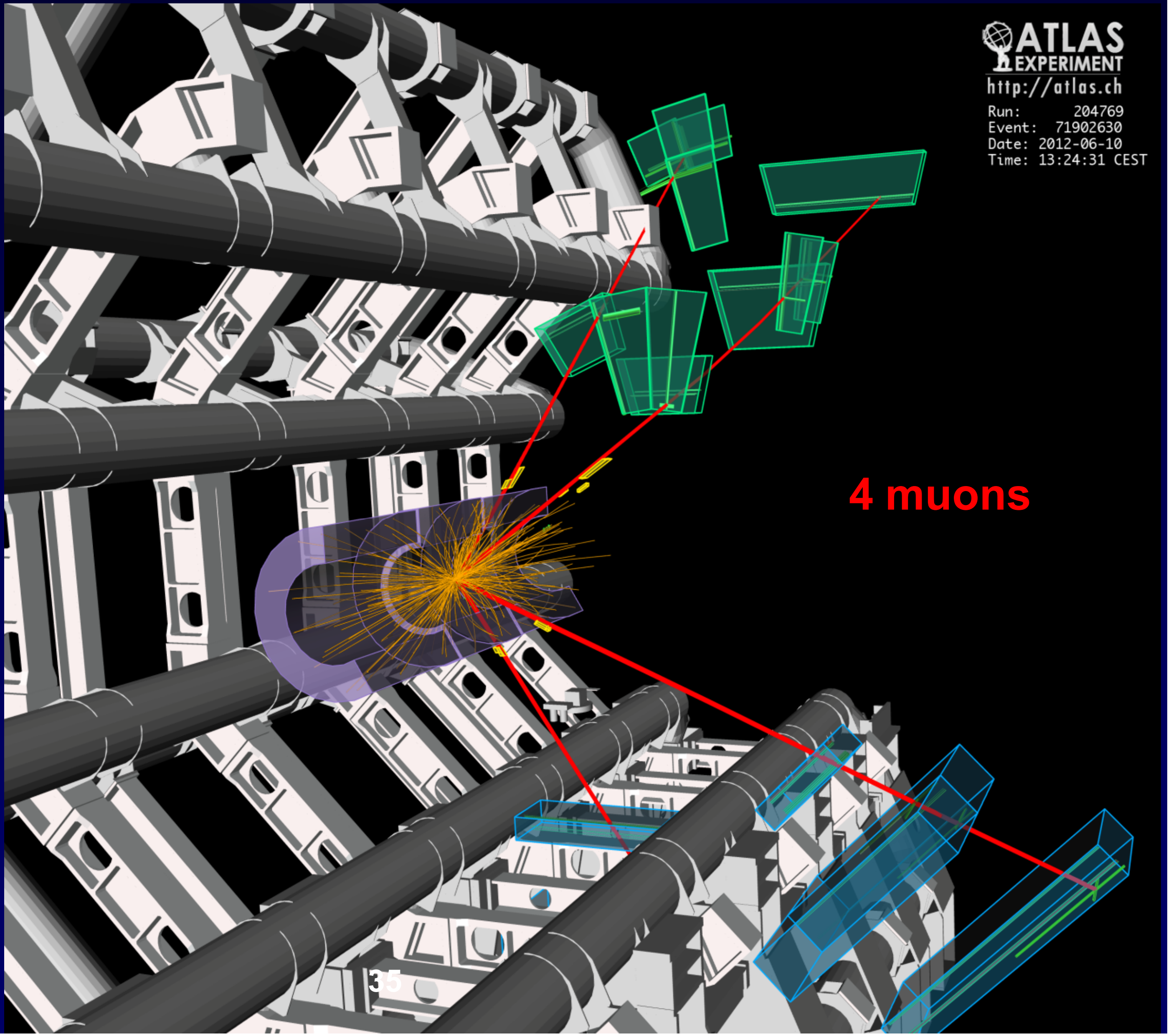
The first task was to rediscover the Standard Model that we know



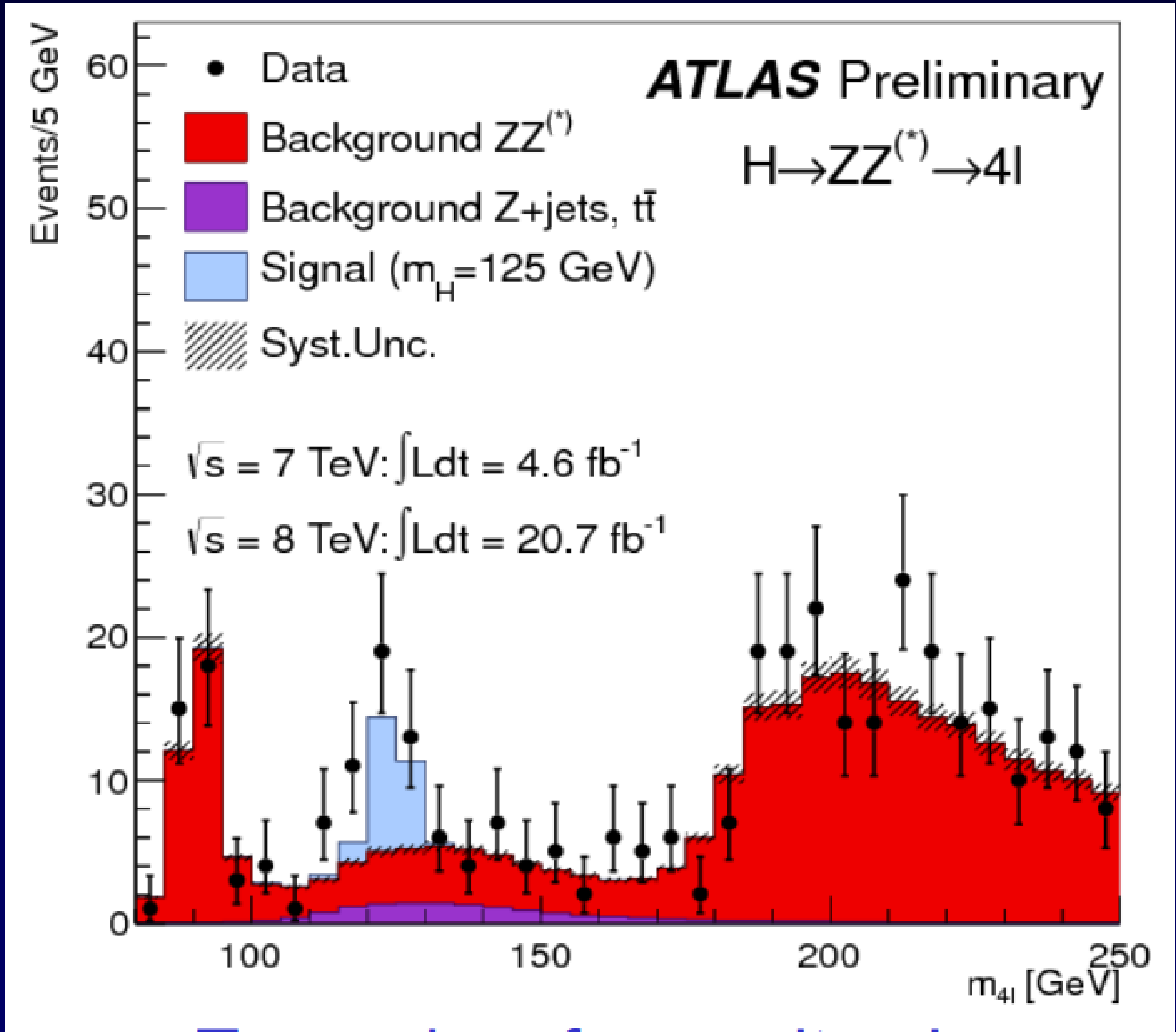
It's not easy to sort the Higgs out from the rest



Here is an example of what a Higgs boson candidate looks like in ATLAS



The evidence that there really are Higgs bosons



Higgs candidate decaying to a pair of photons

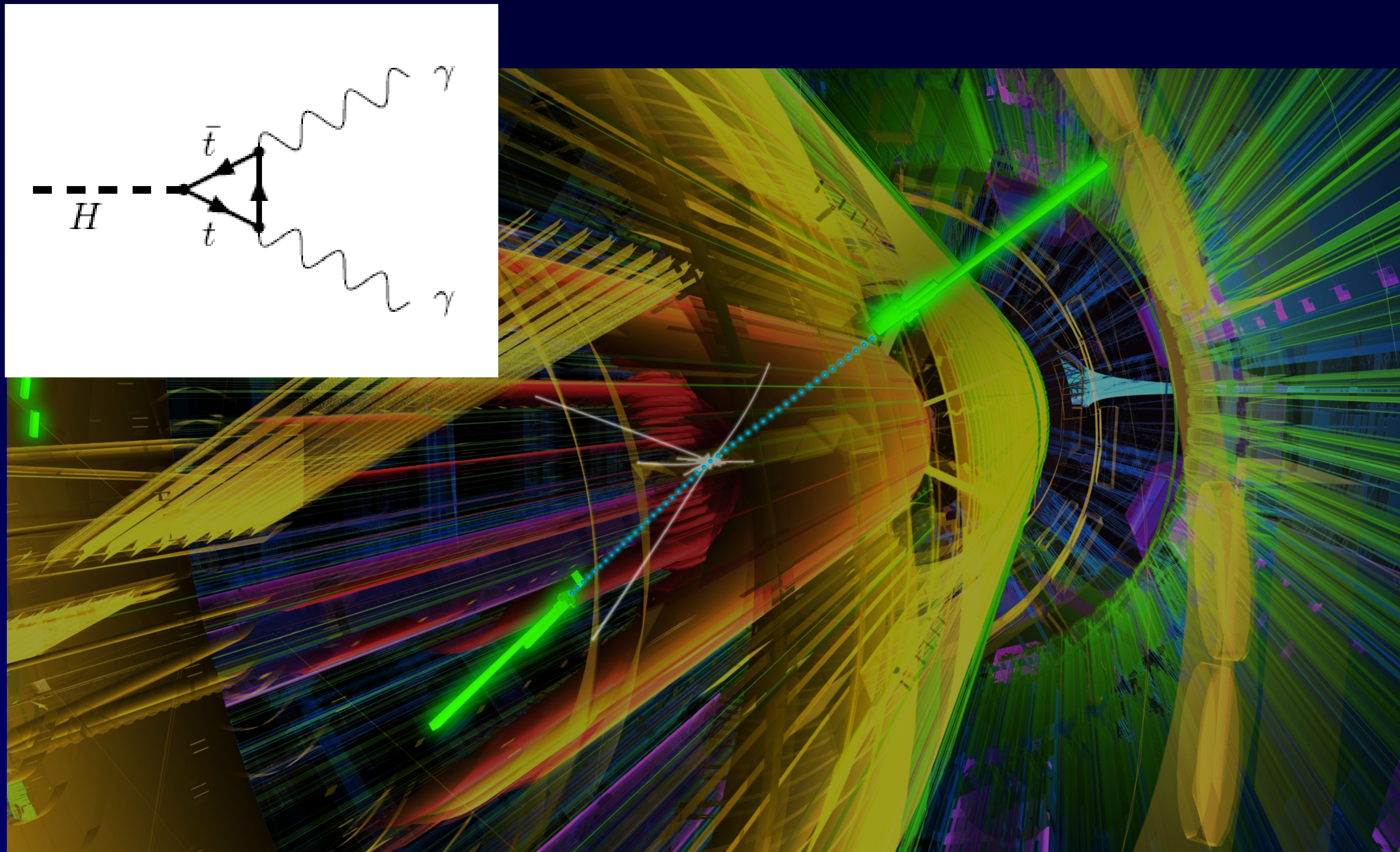
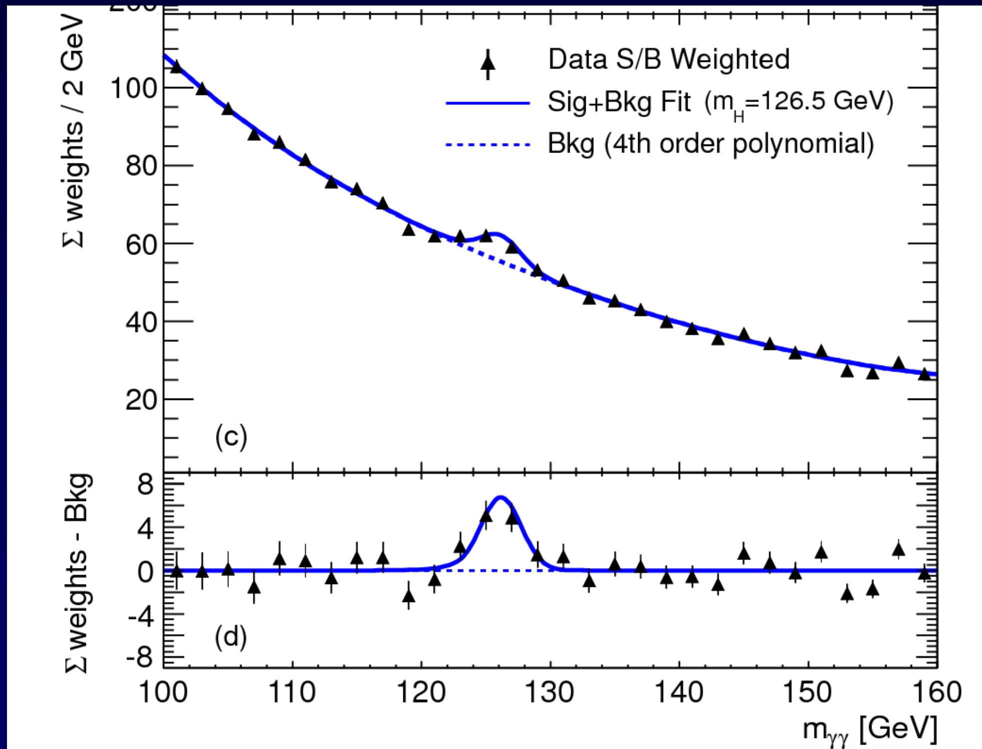


Image: ATLAS@CERN 2012

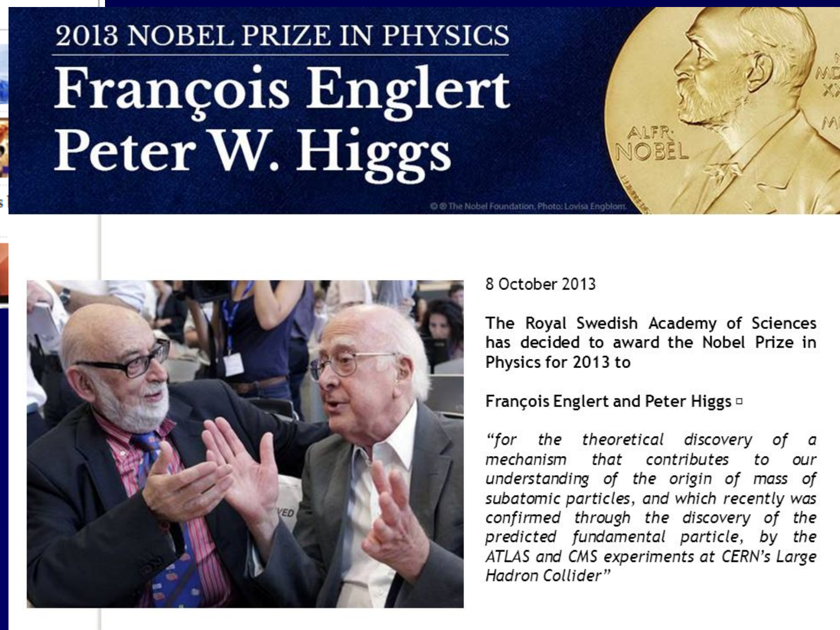
ATLAS result of search for Higgs decaying to 2 photons, July 2012



CMS had a similar result

Let's jump ahead to 2013 ...

SMH 9th October 2013



With the Higgs discovery, the set of fundamental building blocks is expanded by one

The particles of the Standard Model

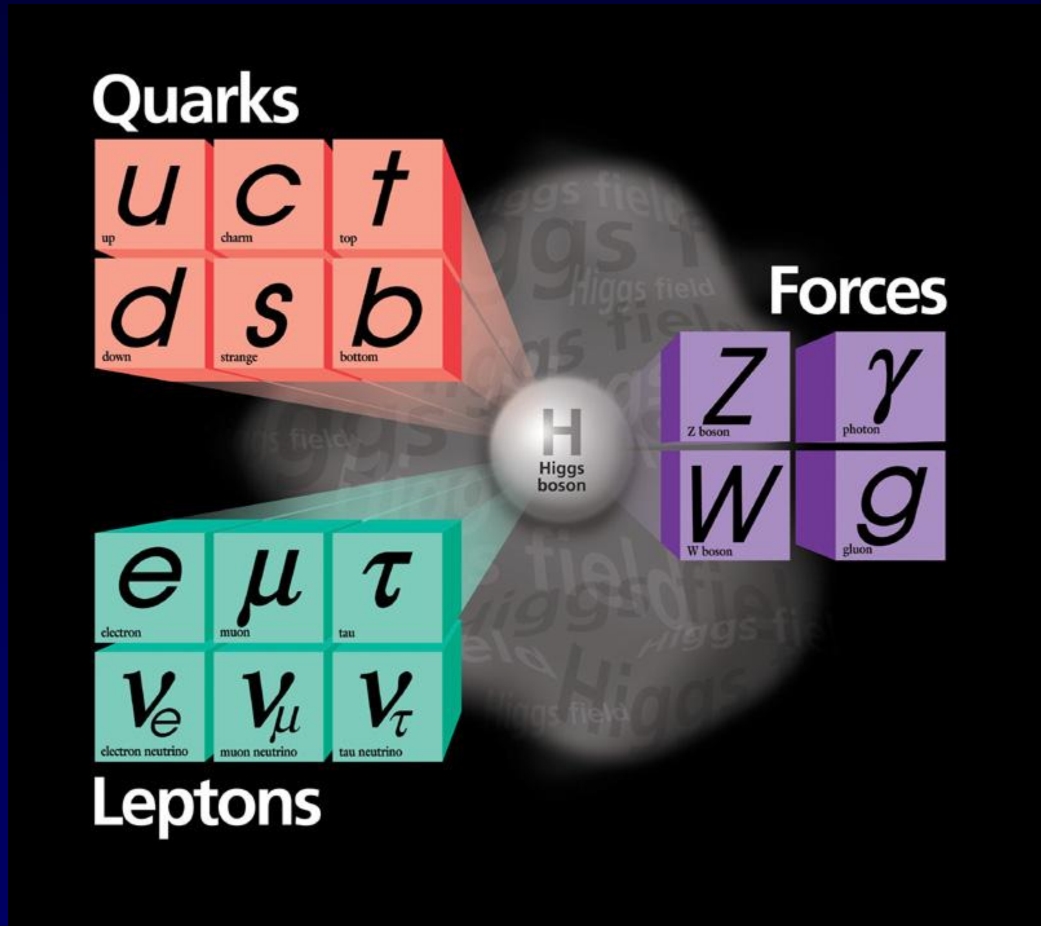


Image: Fermilab Visual Media Services

In 2019 we know much more about the Higgs

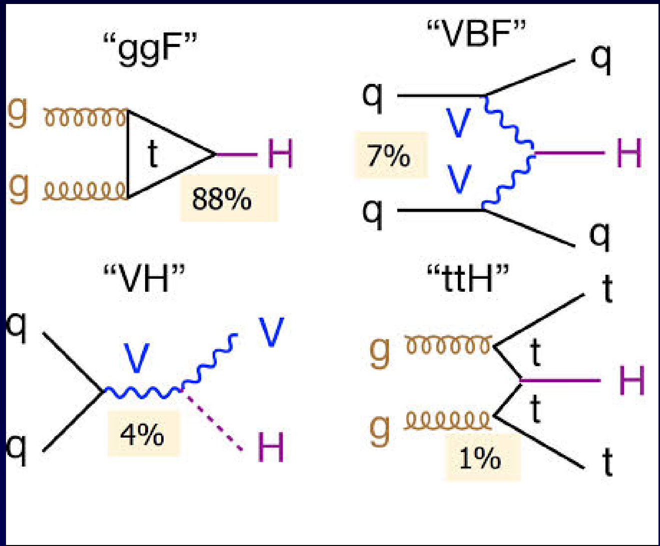
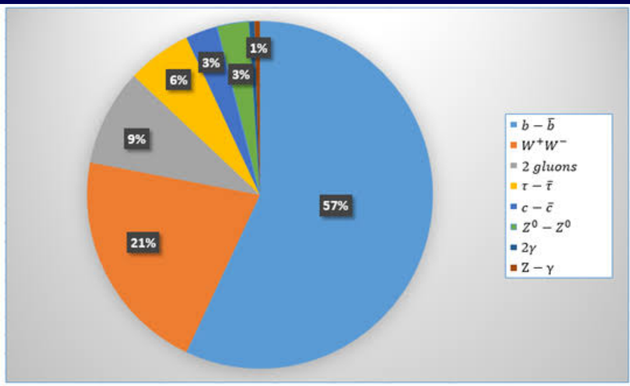
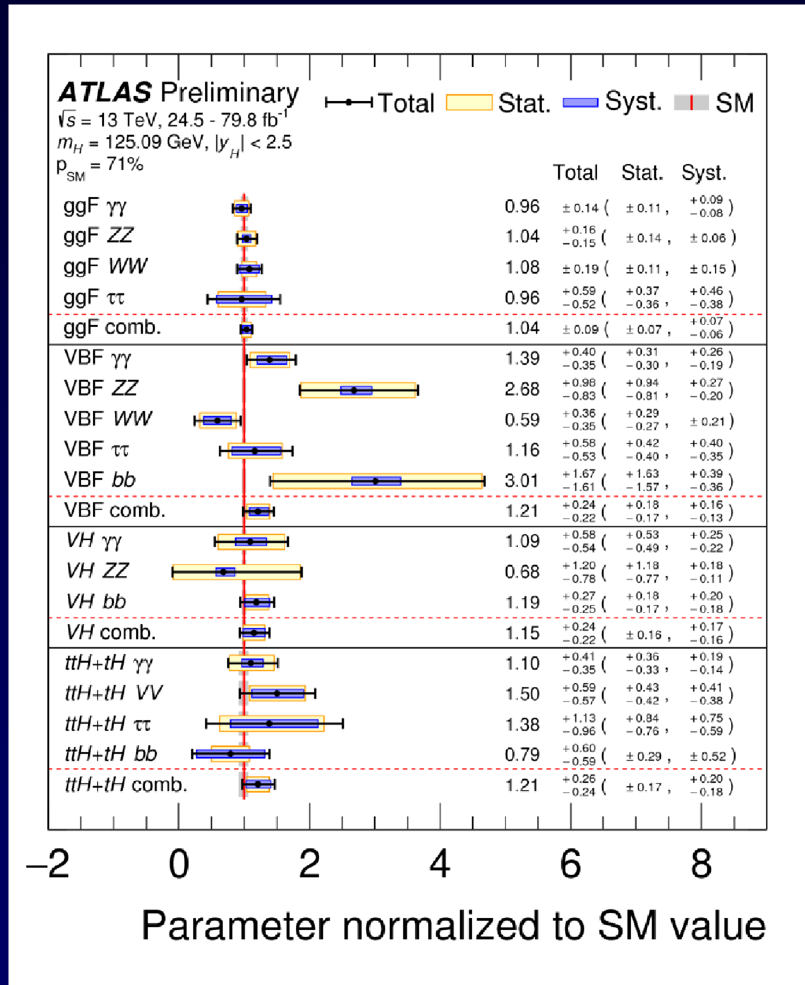


Image: https://msneubauer.github.io/projects/4_project/



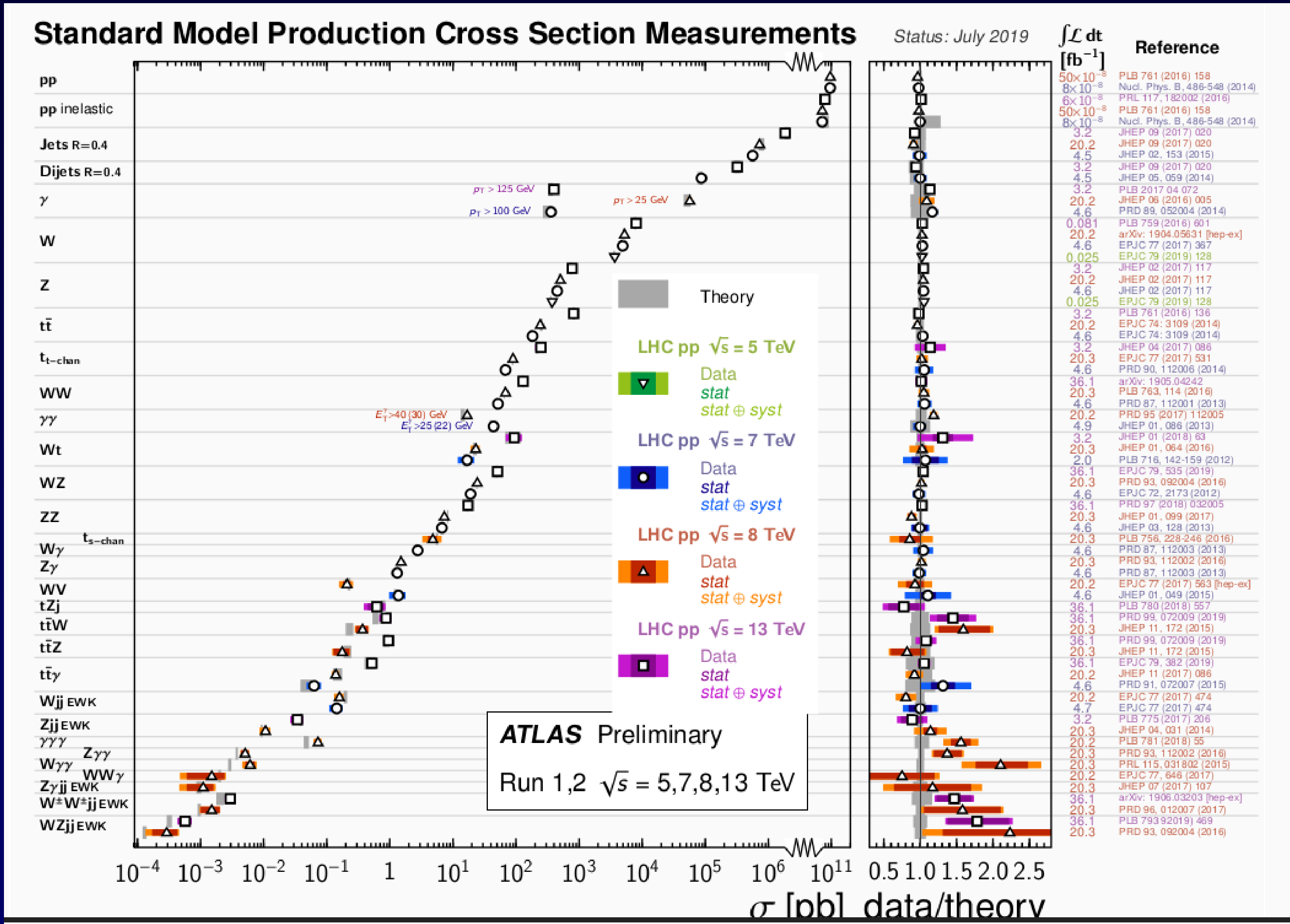
Higgs $\rightarrow b+\bar{b}$	b quark and its antiquark
Higgs $\rightarrow \tau^+ + \tau^-$	τ lepton and its antiparticle
Higgs $\rightarrow \gamma + \gamma$	Two photons
Higgs $\rightarrow W^+ + W^-$	W boson and its antiparticle
Higgs $\rightarrow Z^0 + Z^0$	Two Z bosons

Image: https://cosmicglimpses.blog/



It also has the expected spin

The Standard Model works – too, too well



But the Standard Model can't be the whole story

All known Standard Model particles

We still don't understand the pattern of masses

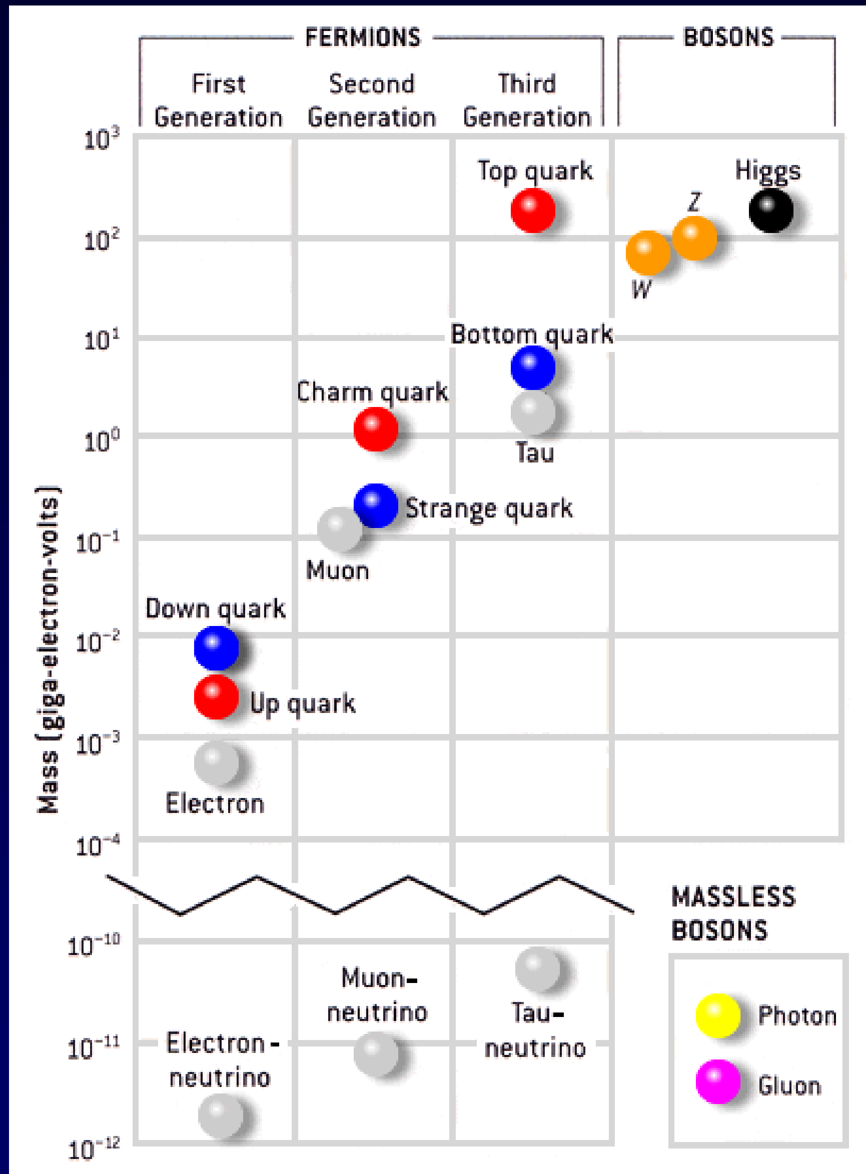


Image: https://scienceblogs.com/

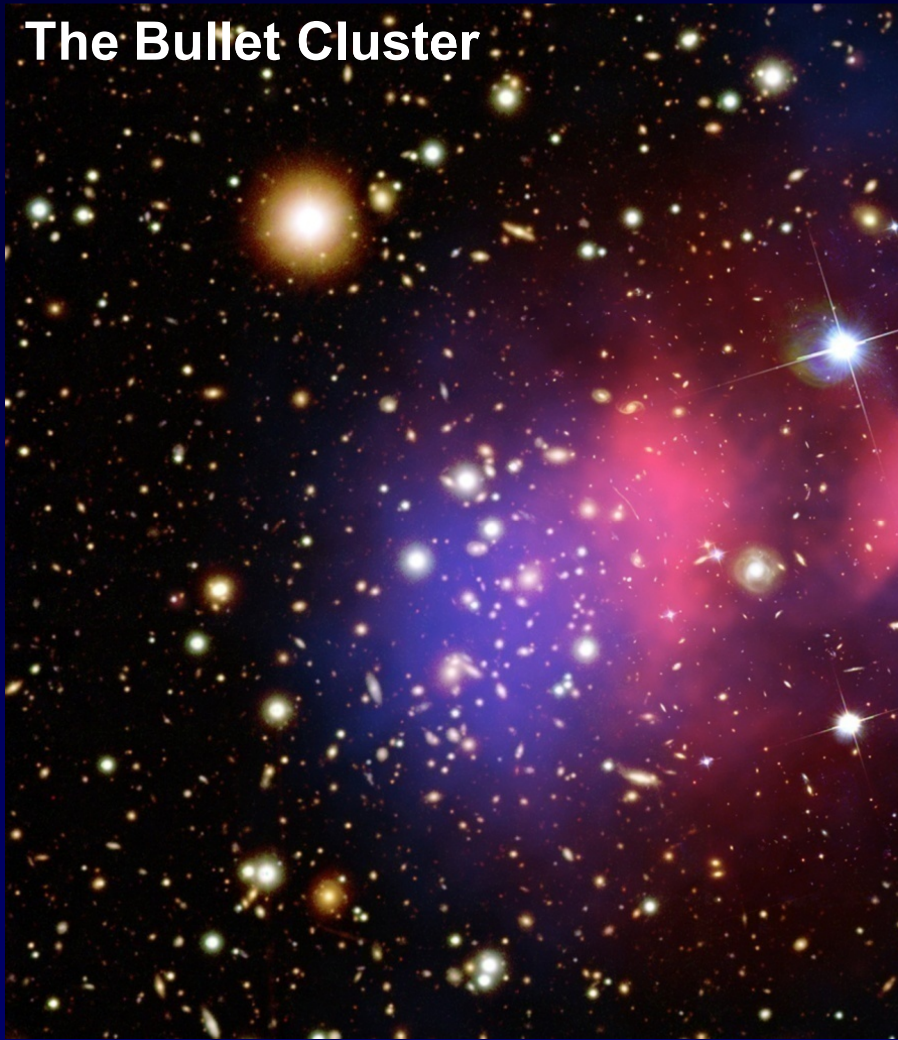
Indeed, if the Standard Model is all that there is, then we actually have a very big mystery

The Higgs mass would be expected to be more like 10,000,000,000,000,000 times the mass of a proton, or even greater ...

... rather than about 135 times larger

Also, what is dark matter?

Pink – Hot gas
Blue – Dark Matter



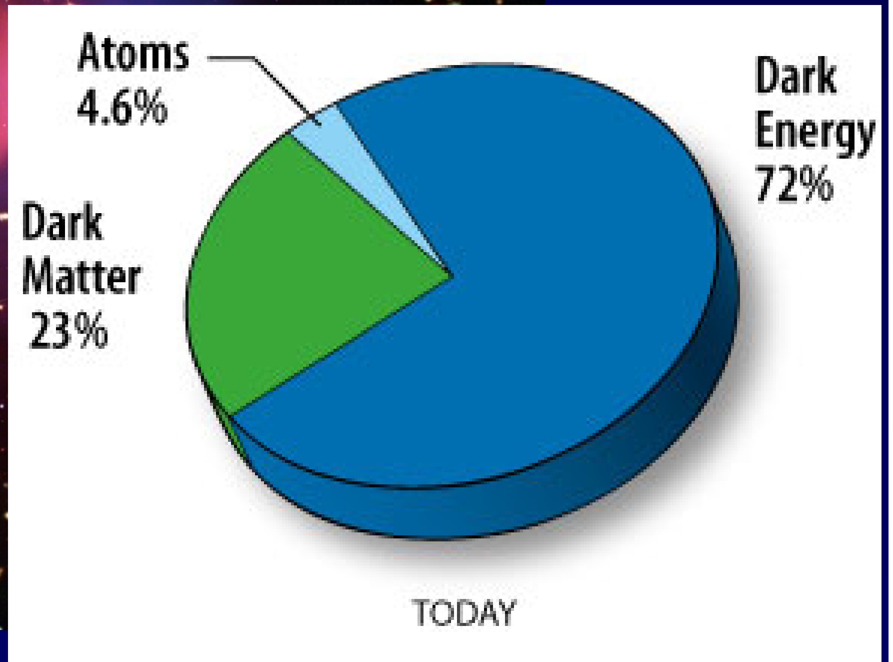


Image: http://apod.nasa.gov/apod/ap060824.html

Could Supersymmetry (SUSY) be the answer?

A symmetry between fermions and bosons

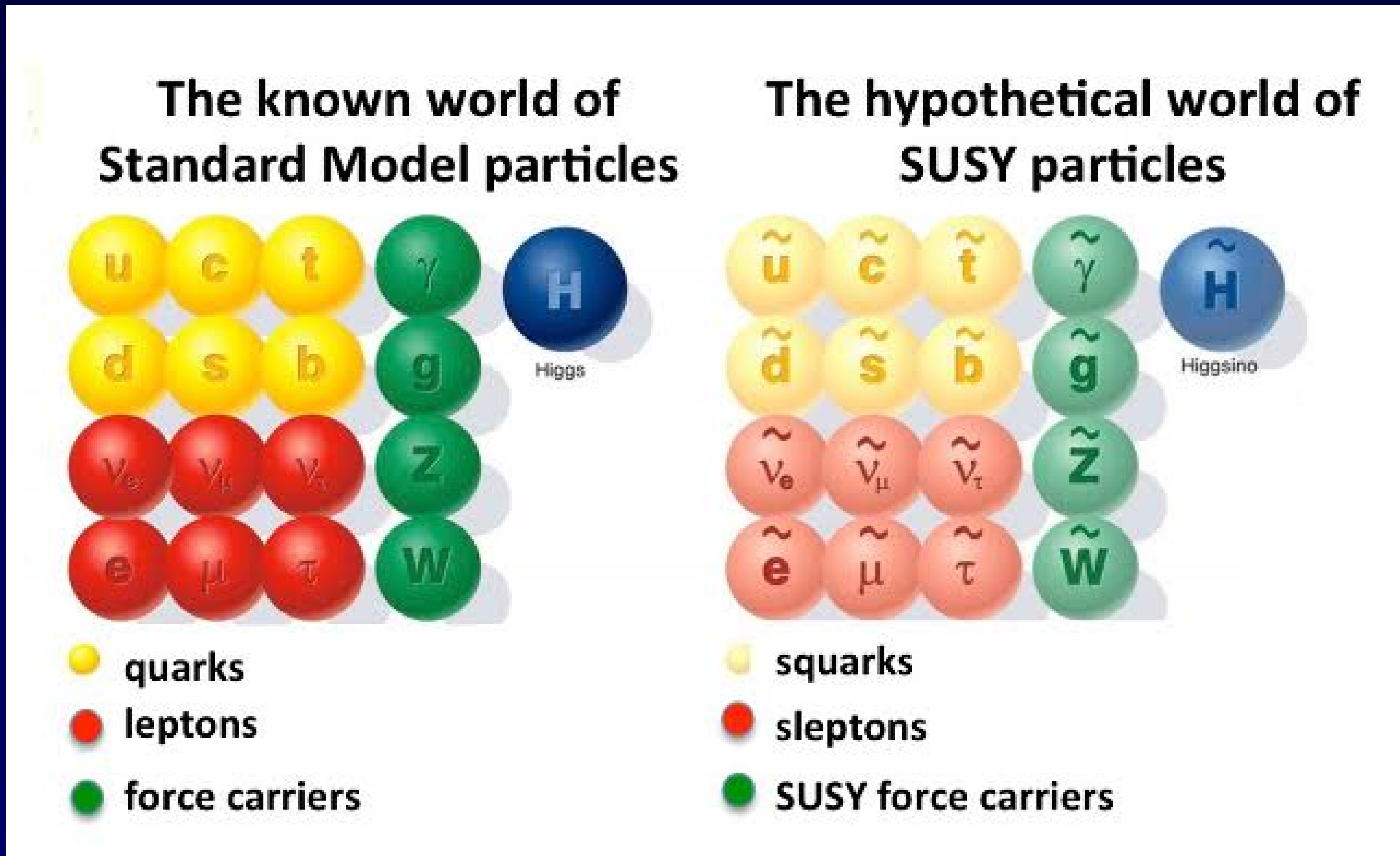


Image: https://arstechnica.com/

SUSY could potentially unify the forces of nature

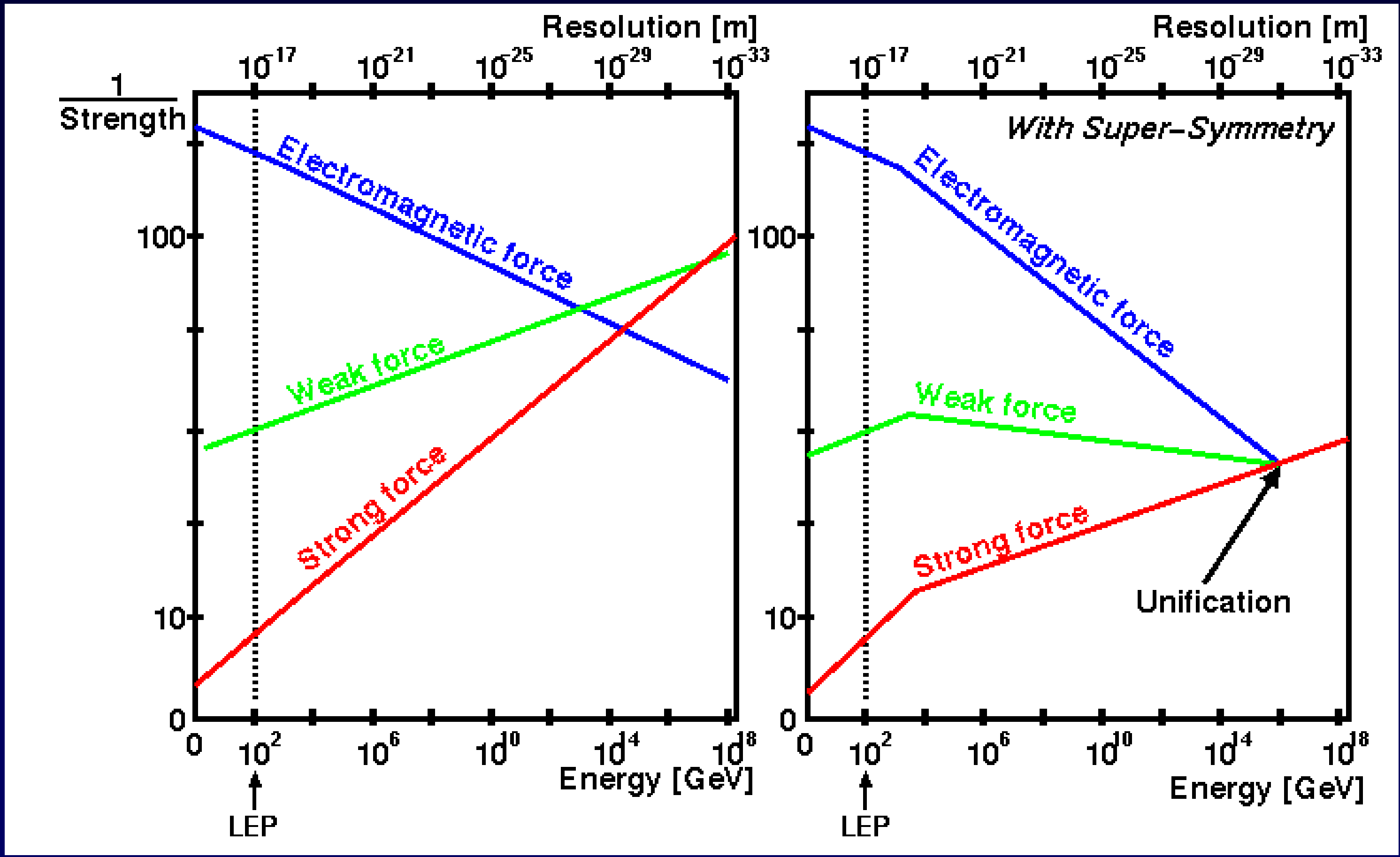
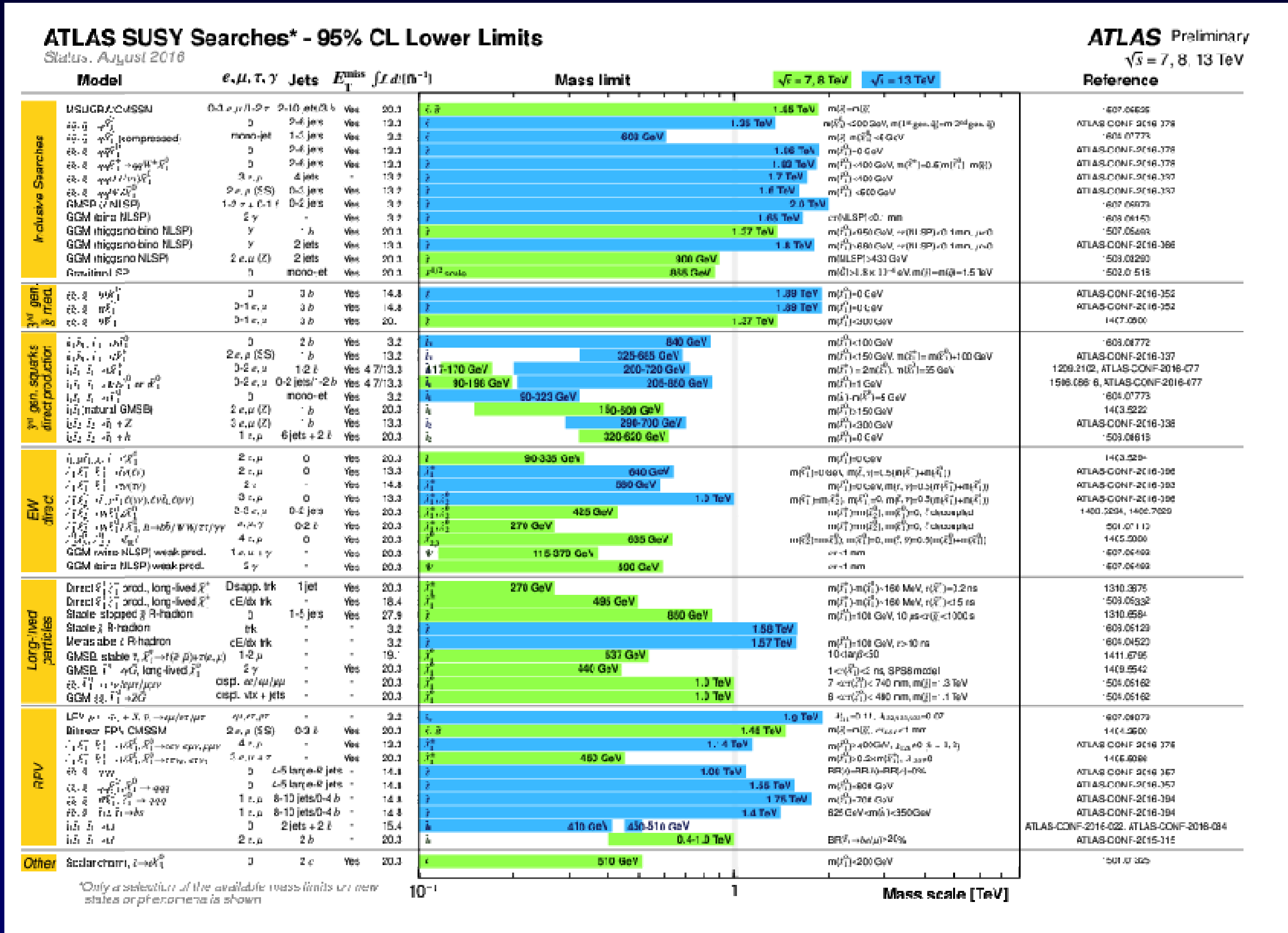


Image: CERN

SUSY has not appeared – not for lack of searching



So there is a long way to go towards our ultimate aim, to understand all of this ...

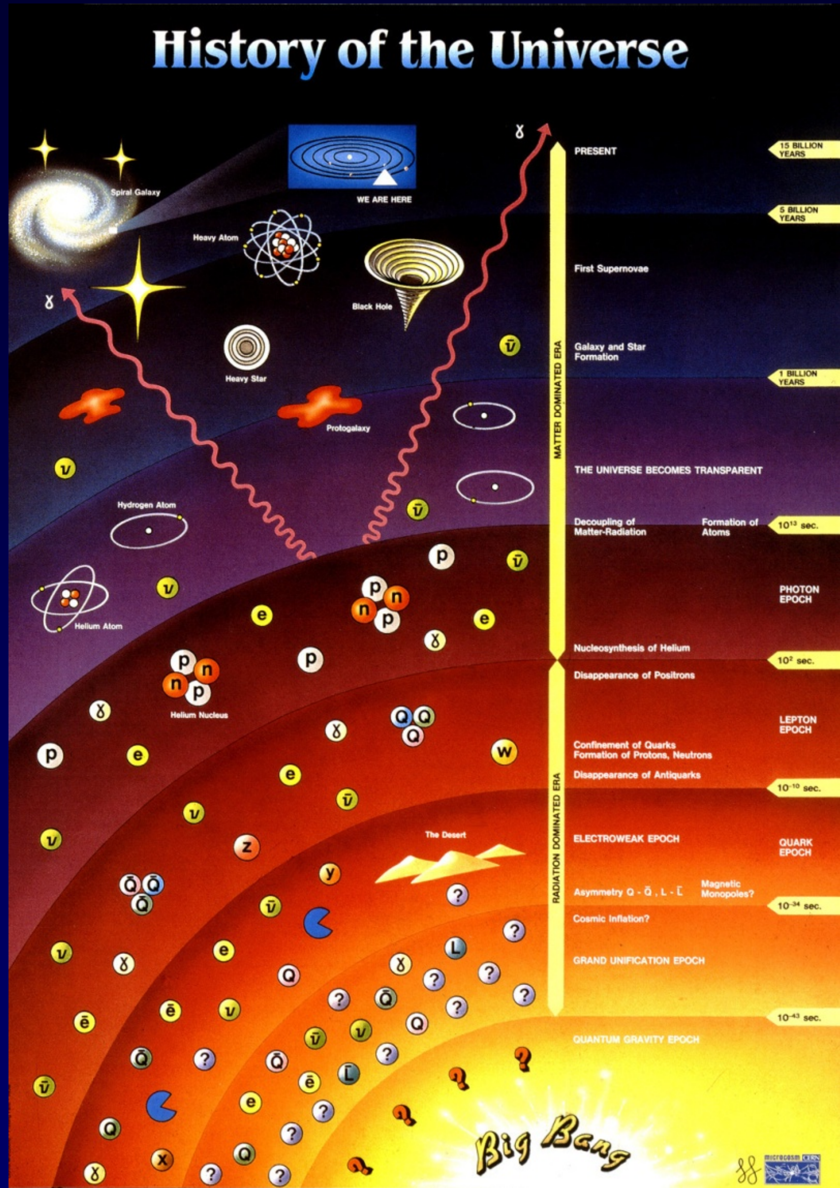


Image: CERN

And of course things might be quite different to what we currently think ...