The Higgs boson

The origin of mass

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UAM CSIC Consejo Superior de Investigaciones Científicas

The Standard Model of Elementary Particles

What are we made of?

Everything around us is made up of elementary particles, for instance the quarks within protons and neutrons in atomic nuclei, and the leptons, like the electrons which orbit around nuclei. Together they form the atoms which are constituents of matter.
Quarks and leptons are elementary particles: they are not composed of smaller constituents (as far as we have been able to probe experimentally).

What holds particles together?

Elementary particles are subject to forces associated to four fundamental interactions: electromagnetism, the weak interaction, the strong force, and gravity. Each one of these interactions is associated with one or several force particles, the gauge bosons: the photon, the Z y W bosons, the gluons, and the (still hypothetical) graviton.

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

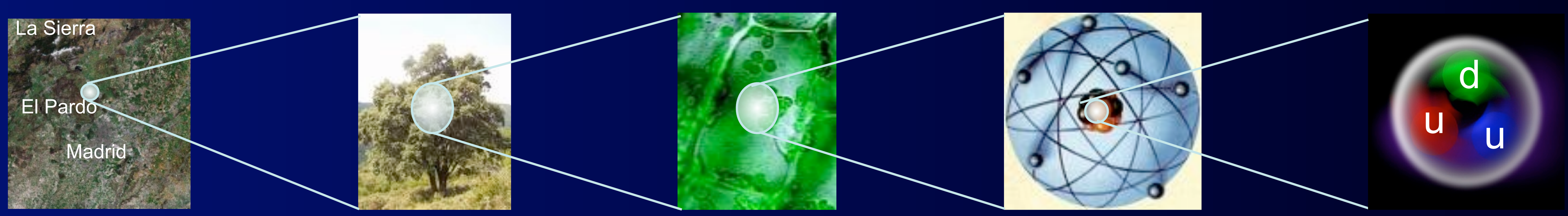
Leptons	spin =1/2	
Name	Approx. Mass (Gev/c²)	Electric charge
ν_L lightest neutrino*	$<10^{-9}$	0
e electron	0.0005	–1
ν_M middle neutrino*	$<10^{-9}$	0
μ muon	0.1	–1
ν_H heaviest neutrino*	$<10^{-9}$	0
τ tau	1.8	–1

Quarks	spin =1/2	
Name	Approx. Mass (Gev/c²)	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Bosons: The glue of the Universe

Unified Electroweak spin = 1		
Name	Approx. Mass (Gev/c²)	Electric charge
γ photon	0	0
W^- W bosons	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1		
Name	Mass (Gev/c²)	Electric charge
g gluon	0	0



10^5 m = 100 Km — Satellite image of the Madrid area, centered on the El Pardo forest

1m — A holm oak tree in the El Pardo forest

10^{-5} m = 10 μm — Plant cell

10^{-10} m = 0.1nm — Carbon atom

10^{-15} m — Internal structure of the proton

The mystery of mass

In our daily life we define mass as the quantity of matter in a body. Essentially all the mass of atoms making up matter is due to the mass of their nuclei. And the mass of atomic nuclei is essentially due to that of the protons and neutrons it is made of.

However, the mass of a proton or a neutron is much larger than the sum of the masses inside it (their mass is so small that it only explains 1% of the total mass). 99% of the mass of protons and neutrons is due to the kinetic energy and color field energy of quarks inside them. The mass thus corresponds to an internal energy of constituents inside protons or neutrons.

On the other hand, this kind of internal energy cannot explain the mass of elementary particles (like quarks themselves, or leptons or the Z and W bosons), since they are not made out of smaller particles.

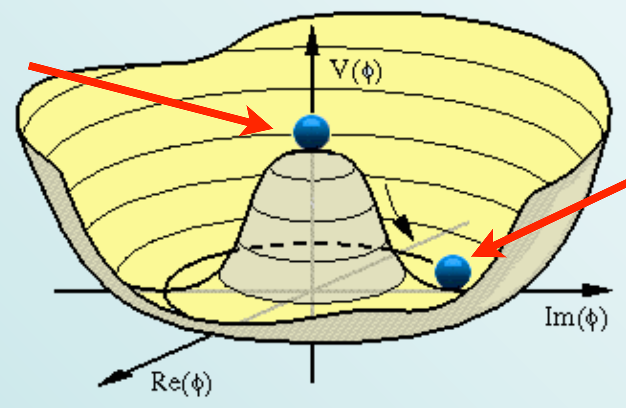
What is the origin of the mass of elementary particles?

Spontaneous symmetry breaking

The mediators of weak interactions, the Z and W bosons, are the only interaction particles with non-zero mass, in contrast with photons and gluons.

The existence of mass for the Z and W bosons is intimately related to the breaking of a symmetry, the electroweak symmetry, which relates electromagnetic and weak interactions.

The Brout-Englert-Higgs mechanism is the description of spontaneous breaking of electroweak symmetry, which as a consequence makes the Z and W bosons acquire mass, while the photon remains massless.



The vacuum and the Higgs field

The existence of mass for elementary particles is explained by the Higgs field. A field is a magnitude defined at any point in space and any instant in time, for instance the electric field or the gravitational field. The Higgs field is similar, with the difference that **it has a non-zero value in the vacuum, which is constant throughout space and time**, but does not introduce a preferred direction (it is a scalar field). The Higgs field is part of the vacuum of the universe.

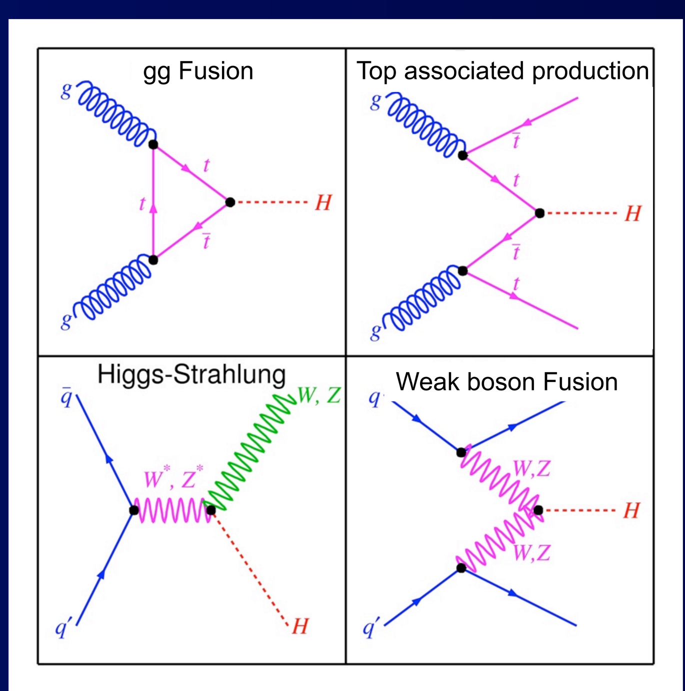
The different particles have different interaction strength with the Higgs field. When a particles sits or moves in the vacuum, it is actually interacting with the Higgs field, and this interaction contributes to its energy, even when it is at rest. According to Einstein's equation $E=mc^2$, this energy corresponds to a rest mass for the particle.

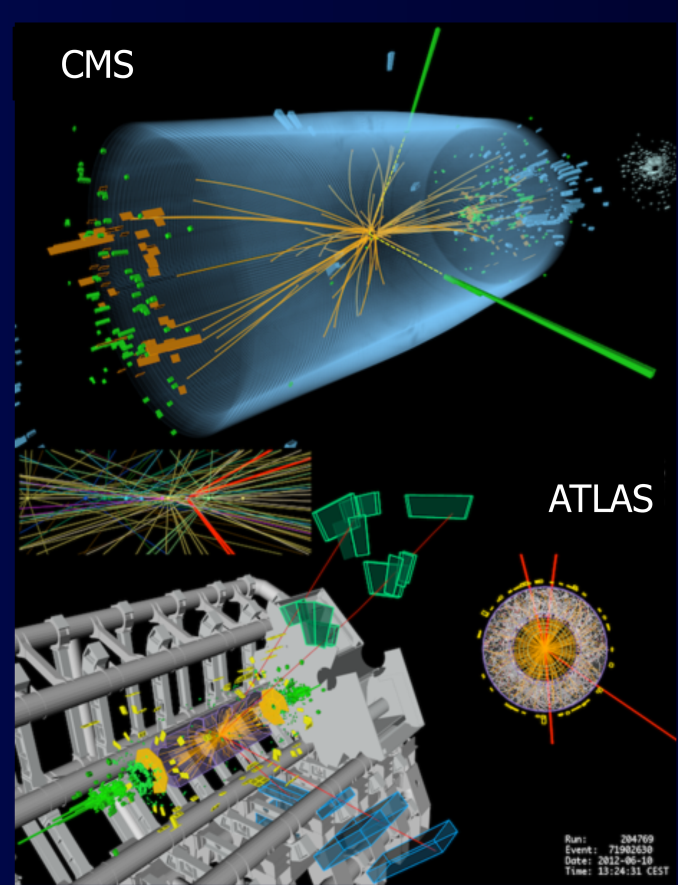
A possible analogy is to imagine the Higgs field as a fluid, and the mass for a particle as its resistance or inertia to move due its interaction with the fluid. The analogy is a useful picture for certain properties, but it is not accurate since the Higgs field is relativistically invariant, and in contrast with the fluids in our daily life, it does not decelerate or change the state of motion of particles, nor it defines a preferred absolute rest frame.

The Higgs boson

The existence of the Higgs field implies a prediction. If we concentrate enough energy in a small enough region, it should be possible to create excitations of the Higgs field. The quantum of the Higgs field is a very special particle, known as the Higgs boson. Its properties are determined very precisely in the model. It is a spin 0 particle, and its interaction with any other particle is proportional to the other particle's mass. The Higgs boson interacts with the Higgs field itself, and thus acquires its own mass.

The Higgs particle was discovered in 2012, 48 years after its theoretical prediction in 1964. Experiments at the **Large Hadron Collider LHC,** in the accelerator complex at CERN in Geneva, confirmed the existence of the Higgs boson in July 4th 2012. This discovery allowed François Englert and Peter Higgs to receive the Nobel Prized in Physics 2013 for the discovery of the theoretical mechanism responsible for the origin of masses of elementary particles.



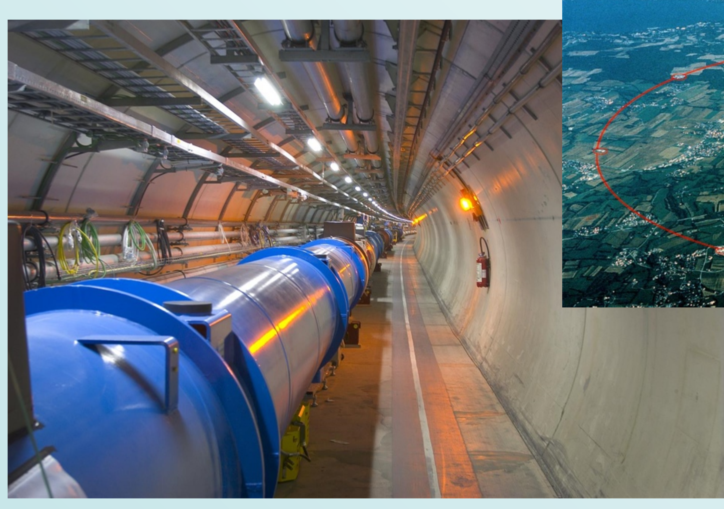


LHC: the Large Hadron Collider

The LHC is an particle collider at CERN, in the French-Swiss border near Geneva. It accelerates protons along a 27 km long circle shaped tunnel, taking them to speeds very close to that of light and collides them at the center of its detectors.

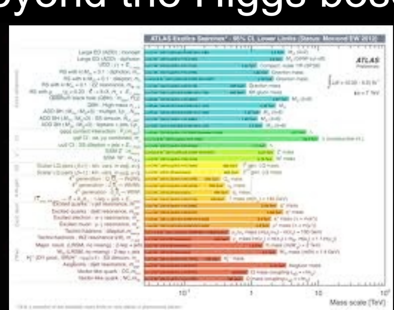
The ATLAS and CMS detectors are enormous machines the size of whole buildings but built with exquisite precision, which detect the collision products. The millions of Gigabytes of data from outgoing particles are distributed for analysis in a network of computing resources in research centers worldwide, called the GRID.

The results conclusively confirm the existence of the Higgs particle from its decay products. Presently, LHC continues to explore the properties of the Higgs boson and to search for other new particles at even higher energies.



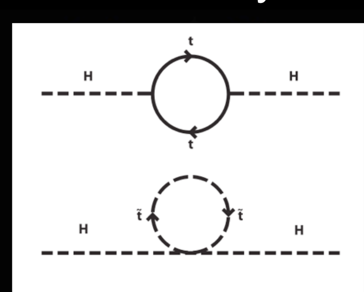
Open puzzles

Beyond the Higgs boson



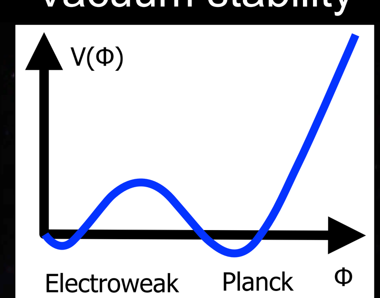
The properties of the Higgs boson measured at the LHC agree with the simplest version of the Brout-Englert-Higgs mechanism. There are active searches for hints or direct detection of possible new particles at the accessible energy scale.

Hierarchy



The Higgs boson mass is many orders of magnitude smaller than other scales in Nature, like the Planck scale (which controls gravitational interactions). What is the mechanism underlying this enormous difference?

Vacuum stability



The Higgs boson mass measured at the LHC is such that quantum corrections could de-stabilize the vacuum. Just like in an overheated liquid, there could exist nucleation of bubbles of a new vacuum with Higgs field values close to the Planck scale.

Masses

The Brout-Englert-Higgs mechanism explains the existence of masses for elementary particles, but it does not explain the specific values of these masses. The origin of these numerical values remains a mystery...

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