Finding the Secret Code of Nature

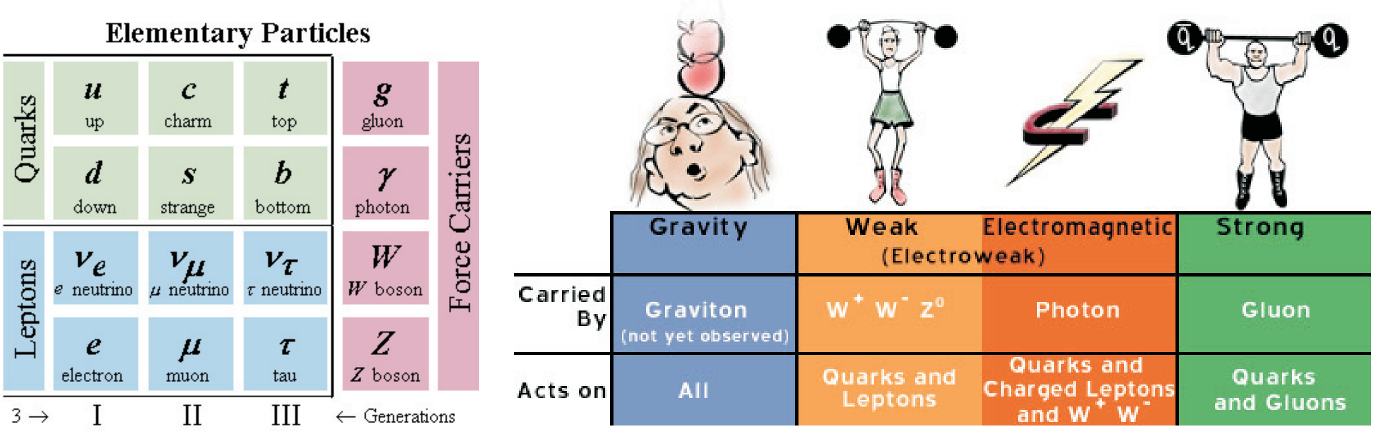
At the Large Hadron Collider (LHC) in the high energy particle physics facility CERN near Geneva, in Switzerland, thousands of physicists from all over the world have built the next instrument that is going to help them decode the secrets of Nature: the ATLAS detector. Located one hundred meters under ground, in one of the four points where protons moving at the speed of light collide, ATLAS will provide us new keys to the understanding of our Universe.

A painter looks at Nature and is inspired to write down with colors the essence of what he observes. In the same manner, a particle physicist looks at Nature and sees at its deepest level particles and forces. He sees patterns, symmetries, in the forces acting between particles, and writes all this down with the language of mathematics.

The symmetry in Maxwell equations connecting electric and magnetic forces and their sources tells us that the two forces are in reality only one: the electromagnetic force. After a century of theoretical ideas and observations, always being guided by the idea that symmetries are the key to crack Nature's secret code, we now know that also the weak and electromagnetic forces were in reality only one force at some point: the electroweak force. This knowledge is summarized in our Model for particles and forces called the Standard Model, and shown in Fig 1.

Although it seems like we have gone far, we still have a lot to lern about Nature. We don't know yet how (if) the electroweak and strong and gravitational force can also be seen as only one force. Furthermore, the symmetries are not exact in the Univercse today. We believe this was not the case in the early Universe or at high energy. We do not know for sure how these symmetries were broken. Finally, the particles we have observed so far have very different masses, and we have no idea why. So we have not yet really cracked Nature's code.

The Nobel prize for physics in 2008 was assigned to people who provided a theoretical explanation for how some symmetries are broken in Nature. In particular, Nambu's work on spontaneous symmetry breaking is at the basis of the Standard Model formulation late in the 1970s. In the Standard Model the symmetry between electromagnetic and weak forces (which allows them to be described by one force only) is broken by the generation in the early Universe of a field, called the Higgs field, see also Fig. 2. Such field, permeating all Universe, would act figuratively speaking as a "mud" in which particles move. Some particles



	I	II	III	
Quarks	u up	c charm	t top	g gluon
	d down	s strange	b bottom	γ photon
Leptons	ν_e e neutrino	ν_μ μ neutrino	ν_τ τ neutrino	W W boson
	e electron	μ muon	τ tau	Z Z boson

	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Fig 1. The particles and forces in the Standard Model of particle physics

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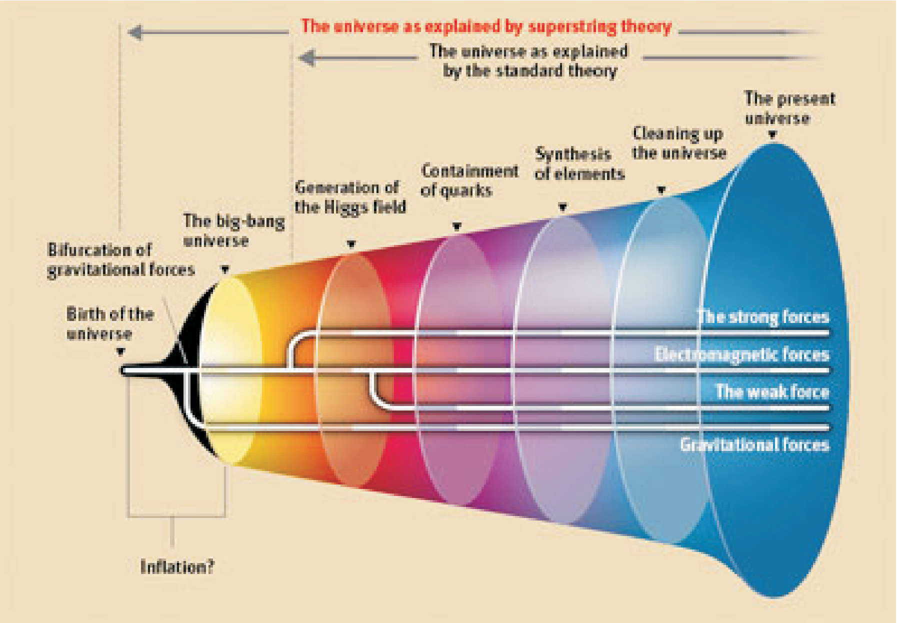

Fig. 2 Current understanding of the evolution of the Universe

wear boots and more easily gather mud and are slowed down, some others wear tiny shoes and gather little mud and move fast through. This should, in simple words, explain the difference between the photon and the Z, W bosons masses and the broken symmetry between the two types of forces. This field could also explain why matter particles like the electron, or the b quark, have such different masses.

How can we prove that this idea is correct? We should be able to observe a Higgs field. How can we do that? Together with the Higgs field, a new particle is expected to appear, the Higgs boson (a particle of spin zero). Such particle is a fluctuation, an excitation of the Higgs field, and therefore if we observe a Higgs boson we can state that our description of Nature and the Universe evolution is correct. It would basically bring us one giant step forward in cracking Nature's code.

How Can we Find the Higgs Boson at the LHC ?

We have not observed yet the Higgs boson, mainly because the particle accelerators we have built in the past century could not provide collisions with enough energy to create such particle. This is why such a big effort (men and money wise) has been invested in the last 20 years to build the LHC at CERN.

In the LHC bunches of protons of extremely high density are brought to collide with very high energies in a infinitesimally small space among the proton ring, where the ATLAS detector is located. These collisions recreate the conditions of energy density characteristics of the Universe in its early stages, just around the times when the Higgs field was generated, and there was enough energy available to create a Higgs boson during particle collisions.

The lifetime of the Higgs boson is extremely short, a fraction of a fraction of a fraction of a nanosecond. Therefore this particle will decay into other particles even before entering the ATLAS detector. What ATLAS can detect are its decay products among the output debris of the collisions. Some "debris" particles and the traces they leave in the ATLAS detector are shown in Fig. 3.

Despite the fact that protons collide inside the LHC at the rate of ten million times per second, finding the Higgs is like finding a needle in a haystack. There are several reasons: it is harder to produce a Higgs than to produce a bunch of quarks and gluons, every time the protons collide (partly due to the different strength of

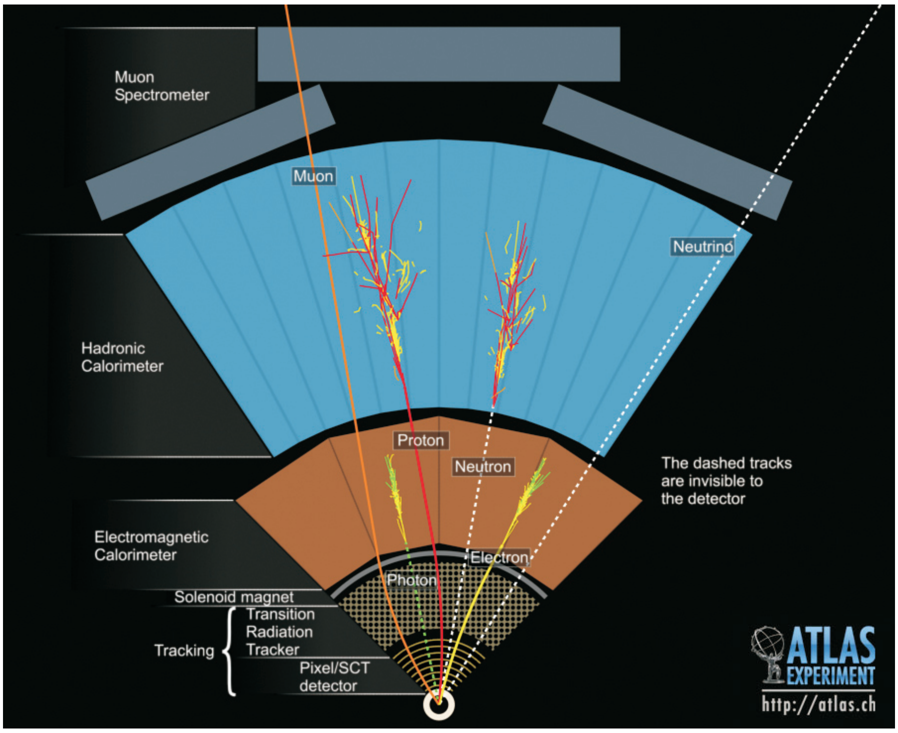

Fig. 3 Traces of various types of "debris" particles in the ATLAS detector.

the strong vs electroweak interaction). It is also harder to see it once produced, because its decay products are not always easily distinguishable from the jets of particles coming from ordinary quark and gluons produced at LHC. So we need to look for a long time, roughly two to three years, before we can see it clearly in the data.

From previous high energy particle physics experiments, we know more or less where to look, we have an indirect hint of what the mass of the Higgs boson should be. It should be roughly one to two hundred times heavier than the proton. If it turns out to be heavier than that, then we know that there is something wrong, inconsistent, in the Standard Model.

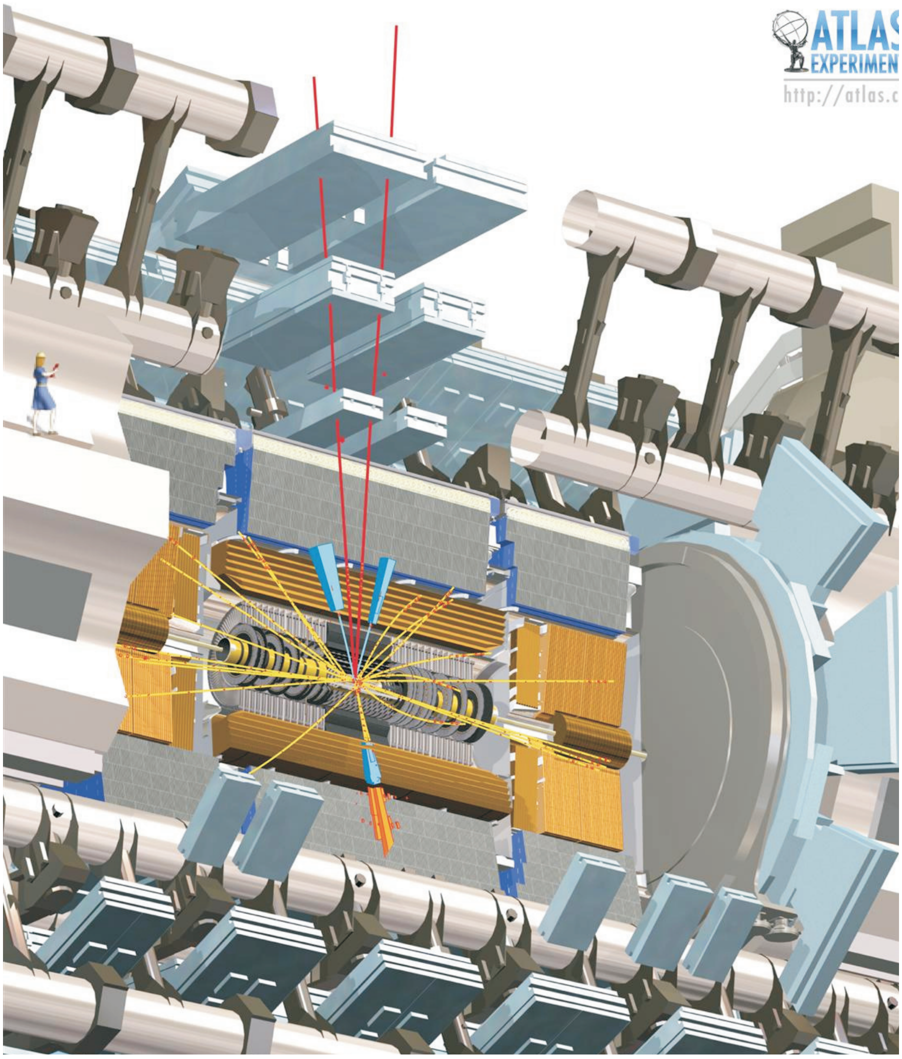

Fig. 4 Higgs boson decay into two Z bosons, with subsequent decay into two electrons (blue cones, at the center of the figure) and two muons (red lines crossing the whole detector). Debris particles, originating from the center of the ATLAS detector where the collisions among protons occur, are visible.

What are the signs we are looking for in the data? The strategy is already very well tested and optimized on simulated data.

If the Higgs particle is around one hundred times heavier than the proton, then we look for two clear energetic energy deposits in the calorimeter part of ATLAS (Higgs decay into two photons) or four energetic jets of particles and large missing energy in the detector (Higgs decay into tau leptons). If the Higgs particle is heavier than that, then we look for two electrons or muons and large missing energy (Higgs decay into two W bosons), or four electrons or muons (Higgs decay into two Z bosons). Fig. 4 shows a Higgs particle decay into two Z bosons, and how it will be seen in the ATLAS detector.

LHC operation has started in 2008, and first proton collisions are expected in the early summer of 2009. The ATLAS detector has been taking data successfully during LHC running in 2008, and is continuously taking data when LHC is not operating, observing muons from cosmic rays. All is ready for the discovery of the Higgs, and honestly... we cannot wait!

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