THE HIGGS PARTICLE: WHAT IS IT, AND WHY DID IT LEAD TO A NOBEL PRIZE IN PHYSICS?

LA PARTÍCULA DE HIGGS: ¿QUÉ ES, Y POR QUÉ CONDUJO A UN PREMIO NOBEL EN FÍSICA?

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Back in 1964, the theoretical physicists François Englert and Robert Brout, as well as Peter Higgs, suggested an explanation for the fact that most elementary particles —such as the electron— have a mass. This scenario predicted a new particle, which has been observed experimentally only just now at CERN (the European Organization for Nuclear Research). This discovery led to the Physics Nobel Prize 2013. Here we sketch in simple terms the concept of the Higgs mechanism, and its importance in particle physics.

En 1964, los físicos teóricos François Englert y Robert Brout, así como Peter Higgs, sugirieron una explicación para el hecho de que las partículas más elementales —como el electrón— tienen masa. Este modelo predijo la existencia de una nueva partícula, que ha sido observada recientemente en el CERN (la Organización Europea para las Investigaciones Nucleares). Este descubrimiento condujo al Premio Nobel en Física 2013. En esta contribución, ilustramos en términos simples el concepto del mecanismo de Higgs, y su importancia en la física de partículas.

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To the best of our knowledge, the world consists of only very few types of elementary particles, the smallest entities of matter, which are indivisible. They are described successfully by the Standard Model (SM) of particle physics, a great scientific achievement of the 20th century. All phenomena observed so far with elementary particles are compatible with the SM, which made a large number of correct predictions.

There is *one* particle that the SM needs in order to work, which has been observed only very recently: the famous *Higgs particle*. After intensive and careful work, the collaborations ATLAS and CMS, working at the Large Hadron Collider at CERN near Geneva (Switzerland), reported in December 2011 first hints of its observation. These hints were further substantiated in 2012, and the discovery of the Higgs particle is now generally accepted. Therefore Englert and Higgs have been awarded the 2013 Nobel Prize in Physics for their correct prediction (Brout passed away in 2011).

Hence the Higgs particle is now in the focus of interest in physics, and also in popular science. Unfortunately, the latter often denotes it as the "particle of god", which sounds spectacular, but which does not make any sense whatsoever. If one assumes the creation of the Universe by some kind of god, then *all* particles are "particles of god", and otherwise none is linked to theology, but there is no way to assign this rôle specifically to the Higgs particle. Here we hope to disseminate a better view what this myth-enshrouded particle is about.

Figure 1: François Englert (on the left), Peter Higgs (center-left) and CERN director Rolf-Dieter Heuer (on the right) celebrating the discovery of the Higgs boson, and the consequential Nobel Prize. The existence of this particle had been predicted in 1964. It was finally confirmed in 2011/2 at CERN.

The SM is formulated as a *Quantum Field Theory*. In physics, *fields* are abstract functions of space and time, *i.e.* on each point and at any time some field value is introduced.[1] This could be the temperature or the pressure in each point of a hall during one hour, or in an ocean during one year. A field may also have several components, which can be of a more abstract kind than

1 Here we refer to the "functional integral formulation" of Quantum Field Theory. Alternatively, the "canonical formulation" deals with operator valued fields, but the resulting physics is the same.

real numbers.[2] If we assign a specific field value to each space-time point under consideration, we obtain one *configuration*.

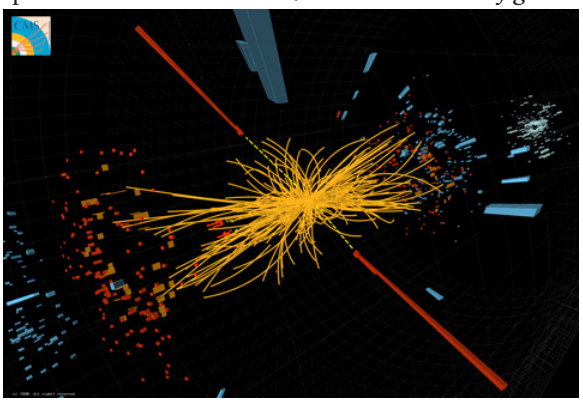

Figure 2: Tracks of elementary particles detected by the CMS Experiment at CERN in Geneva. The picture shows an event, which could give a hint about the Higgs particle, with two high energy photons (red bars that look long and straight in the picture) and other particles (yellow lines that look "curvy" in the picture), generated in a powerful proton–proton collision.

The occurrence of elementary particles is described by various types of fields. Their properties and dynamics are characterized by a function of the field configurations involved, known as the *action*. Classical field theory only considers one specific configuration of each field, the one that minimizes the action. For instance, if one performs this minimization for the electromagnetic fields, one obtains the Maxwell equations.

Quantum Field Theory, however, keeps track of the sum over all possible configurations. The one with minimal action or energy[3] —it could be the zero fields— corresponds to the absence of particles, the *vacuum*. The additional energy that it takes for a fluctuation around this vacuum to generate just one particle is the *mass* of this particle.

Various fields —and the associated particles— may feel each other, *i.e.* they can interact, if the action contains a product of distinct fields that occur at the same point. In our understanding of the emergent complicated systems, *symmetries* play a key rôle. A symmetry is a group of transformations of the fields, which do not alter the action, so they are in general not observable. We distinguish *global* and *local* symmetries. A *global* symmetry allows us to change a field in the same way all over space and time —like an Aerobic session where many people move simultaneously in the same manner. *Local* symmetries are even more stringent: here the field can be changed in each space-time point in a different way, and still the action remains invariant. That appears like a chaotic Aerobic session, where everyone moves as he or she likes.

If one requires such a local symmetry to hold, a huge a number of field transformations are allowed, and it is a delicate challenge to maintain invariance under all of them. For the actions that one usually starts with, this is not the case —they do change under most local field transformations. However, one can repair the invariance by introducing additional fields, which transform exactly such that these changes are compensated. These are the *gauge fields*, which transmit an interaction between the "matter fields" that we had before. Moreover they represent own kinds of particles, such as the *photon* (the particle of light). In fact, the dominant interactions among the SM particles are transmitted by a set of gauge fields. This only works if the local symmetry is preserved exactly.

When this concept was developed, people noticed its virtues, but also a severe problem: the requirement of a local symmetry does not allow us to include any term in the action, which would simply specify some energy that it costs to "switch on the field", *i.e.* to deviate from a zero configuration, and therefore to represent a *particle mass* in its simplest form. Still we know that particles like the electron do have a mass. This was the puzzle that physics was confronted with in the 1950s, and which was later overcome by the famous Higgs mechanics.

The idea of this mechanism is that one does not necessarily need to refer to the zero field configuration. Instead one couples for instance the electron field to a new *Higgs field*, which is endowed with a self-interaction such that it takes its energy minimum for non-zero configurations. Then fluctuations away from this minimum require some energy, specifying a particle mass, while fully preserving the local symmetry. Now there is a whole set of non-zero field configurations corresponding to the minimal energy. The configurations in this set are related by local symmetry transformations, so physics is indeed invariant, and they all correspond to the same vacuum.

To provide an intuitive picture, we refer to a historic *Gedankenexperiment* (a "thought experiment"), known as "Buridan's donkey". *Jean Buridan* was a French scholastic

Figure 3: Jean Buridan, French philosopher and scientist of the 14th century, best known for the *Gedankenexperiment* with a hungry donkey.

Regarding Buridan's biography, we know that he was born in France around 1295, he studied philosophy at the University of Paris, where he was subsequently appointed professor in the Faculty of Arts, and also rector for two years. Around 1340 he condemned the views of his teacher and mentor William of Ockham, which has been interpreted as the dawn of religious skepticism and the scientific revolution. In the 15th century, Ockham's partisans placed Buridan's works on the Index of Forbidden Books.

Beyond that, Buridan's life is even more myth-enshrouded than the Higgs particle: according to some sources, he was forced to flee from France, spent time in Germany and also founded the University of Vienna in 1356 (or at least attended its foundation). Other records describe him as a charismatic and glamorous figure with numerous amorous affairs, which even involved the French Queen Jeanne de Navarre. Therefore King Philippe V (supposedly) sentenced him to be thrown in a sack into the Seine River, but he was saved by one of his students. Still another legend claims that he violently hit Pope Clement VI over the head with a shoe, trying to gain the affection of a German shoemaker's wife. Buridan died around 1358, possibly as a victim to the Black Plague.

2Field values can also be given by vectors, tensors or matrices (representing group elements), and their components could be complex numbers, or anti-commuting "Grassmann numbers".

3For simplicity, our discussion treats the *action* and *energy* as equivalent properties of a given field configuration. A transition to "imaginary time" is —for equilibrium states— a mathematically allowed transformation, which justifies this identification.

philosopher of the 14th century, who was interested in logic, mechanics, optics, and in the existence and meaning of a "free will".

As a general background, even before classical mechanics was worked out mathematically,[4] scholars often had an entirely deterministic view of the world. In fact, mechanics seems to suggest that the course of any future evolution is strictly determined by the present state of the Universe, given by the current positions and velocities of all objects. Then the future should follow an inevitable pattern, like a huge machine proceeding step by step in a fully predictable way. Without knowledge about quantum physics (and discarding sudden jumps against the Laws of Nature), it is not obvious to find an objection against this picture.

However, its strict application would even capture mental processes in the brains of animals and human beings. This conclusion appeared confusing, since it implies that our "free will" is a plain illusion. In the context of this discussion, *Buridan's donkey* was invented as a fictitious, extreme example.[5] One imagines a hungry donkey, to whom one offers two piles of hay. However, they are fully identical and placed at exactly the same distance to its left and to its right. Hence the donkey has to make a decision for one direction in order to be able to eat. If nothing favors one of the piles, and its mind is fully deterministic, the poor donkey will stay in the middle and finally starve to death, although its salvation is so close. Taking a sudden decision corresponds to a process, which is denoted as "Spontaneous Symmetry Breaking" in Quantum Field Theory. Upon arrival at one of the piles, the donkey does not perceive the left/right symmetry (or "parity") anymore.

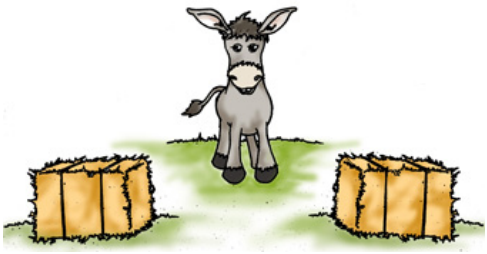

Figure 4: Buridan's donkey between two piles of hay, faced with the dilemma if it should walk to the left or to the right in order to eat. Taking a decision corresponds to the process of Spontaneous Symmetry Breaking.

To translate this setting into the Higgs mechanism, we should better talk about a thirsty donkey in the center of a circular water ditch. Now there is a continuous set of favored positions —corresponding to the energy minimum— anywhere next to the ditch. If we sum over all possible positions (all possible "donkey field configurations"), these favored positions provide the statistically dominant contributions. So if we evaluate the expectation value of its water supply, we conclude that the quantum donkey is better off than its classical cousin: it is able to drink. This reveals the importance of Quantum Field Theory[6]: in fact, it can be *live saving!*

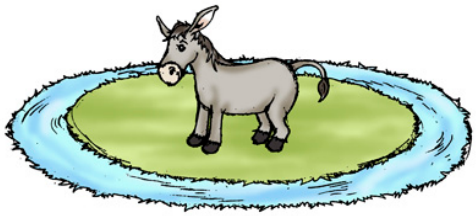

Figure 5: A modified donkey, now thirsty and surrounded by a water ditch. There is an infinite number of directions where it could go in order to drink. Its preferred positions are displaced from the starting point (at zero), next to the water. If it arrives there somehow, a motion along the ditch corresponds to a massless particle, known as a Nambu-Goldstone boson.

Once the donkey has attained the water, it can freely move along the ditch and keep on drinking. This kind of motion keeps the energy at its minimum. The corresponding fluctuation of the donkey field configuration does not cost any energy, hence it corresponds a massless particle, known as a *Nambu-Goldstone boson*.

If we now couple the donkey field —which takes the rôle of the Higgs field— to other fields, such as the one of the electron, the shift of the favored position away from the center (*i.e.* away from the zero configuration) yields the electron mass.

With gauge fields included, all positions at the ditch (with the energy minimum) are physically identical, since they are now related by local symmetry transformations. Thus a walk along the ditch is not a real motion anymore, and the Nambu-Goldstone bosons disappear again. Instead some of the gauge particles pick up a mass, in a subtle indirect way, which fully preserves the local symmetry.[7]

This happens for a suitable system a low temperature (in an infinite volume). The situation at high temperature could be sketched as pouring a lot of water into the area, hence the donkey does not need to move in order to drink. Then the procedure works with respect to its zero position, and no symmetry breaking occurs.

Let us repeat that any deviation away from the vacuum state costs energy, and here we capture the masses, for the electron and for other particles, without breaking the sacred principle of local symmetry. Several physicist noticed this property in the early 1960s. A corresponding mechanism was known in solid state physics, and applied also to particle physics by

4 Buridan himself worked on a theory of "impetus", which is similar to our modern term "momentum".

5 According to some sources, it was actually invented by Buridan's opponents to ridicule the deterministic point of view, by *reductio ad absurdum*.

6 Even in Quantum Mechanics —the theory that preceded Quantum Field Theory in the first half of the 20th century— the phenomenon of Spontaneous Symmetry Breaking does not occur.

7 The literature often calls this process a "spontaneous gauge symmetry breaking", although any local symmetry (or gauge symmetry) transformation preserves the physical state, which solely describes the donkey's proximity to the water. Therefore, strictly speaking the gauge symmetry does *not* break. In the SM this process provides masses for the three gauge bosons of the weak interactions ($W^{\pm}$, Z^0), and for all the fermions (quarks and leptons), but not for the photon and the gluons, which transmit the electromagnetic and the strong interaction, respectively.

François Englert and Robert Brout (in Bruxelles, Belgium), and independently by Peter Higgs. In particular, it was Peter Higgs —at that time a young lecturer at the University of Edinburgh (Scotland)— who (encouraged by Yoichiro Nambu) pointed out that this mechanism, when applied to particle physics, brings about a new particle, which should be observable. Its mass, however, could not be predicted,[8] and the emerging mass of the other SM particles neither. This may be considered as a short-coming of the SM: it contains a number of free parameters (about 26, neutrino masses included), which one would like to reduce. On the other hand, for describing practically the whole Universe, this number is *not* alarming. For comparison, many fashionable theories beyond the SM (like "supersymmetry") do not only lack any observational support, but they introduce in addition an avalanche of further free parameters.

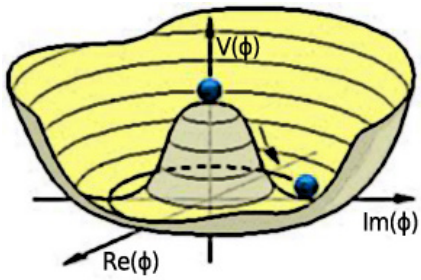

Figure 6: A potential $V(\phi)$ for a complex scalar field ϕ, which takes its minimal energy for non-zero field configurations $|\phi| > 0$. There is a continuous set of minima. Fluctuations within this set correspond to a Nambu-Goldstone boson. Once the field is gauged, all minima are physically identical, the Nambu-Goldstone boson disappears, but the gauge field picks up a mass.

Now the observation of the Higgs particle has been confirmed, so we can feel proud of a very well-established and elegant theory that describes all the elementary particles that we know of. So are we then done, and physicist will end up unemployed? Not really, even the great SM has its short-comings, that we still have to work on:

- It does not capture all interactions: the most obvious one in contemporary life, *gravity,* is not included. Intensive attempts (over several decades) to incorporate it have failed. Gravity is described successfully by a different theoretical framework, Einstein's Theory of General Relativity, which seems simply incompatible with Quantum Field Theory. While this is an outstanding challenge, for practically all issues in particle physics it can be ignored, since gravitational effects are usually negligible in the microscopic context (an exception was the very early Universe).
- We have nowadays indirect but clear evidence of further ingredients to the Universe, denoted as *Dark Matter* and *Dark Energy.* Their nature is mysterious, and the SM cannot capture them —another tremendous challenge to work on.
- Even with known matter —consisting of the SM particles— *complex structures,* as they occur for instance in biology, are not simply understood based on the SM as the fundamental theory. Here a deep understanding of the collective behavior of many particles has to be supplemented, which has been accomplished only in part.
- Finally the SM has an intrinsic reason for being incomplete. A naïve treatment of Quantum Field Theories yields infinities in quantities that we want to compute. They diverge when we take field fluctuations at all energy scales into account. We can render them finite by introducing an energy cutoff, which should be done in a subtle way, preserving again the local symmetries. In some cases we can later —in the final result for physical observables— remove this cutoff by sending it to infinity. However, in case of the Higgs sector of the SM this does not work: it would lead to a decoupling of the Higgs field from all other fields, and therefore again to vanishing particle masses; that property is known as *triviality.*

So we have to live with such an energy cutoff, which is acceptable as long as it is far above the Higgs particle mass, but not high enough to render the Higgs field "trivial", *i.e.* free of interactions. This implies that the validity of the SM is limited to a certain energy range —at even higher energies it requires the extension to a superior theory, that we do not know yet. The specialized literature suggests candidate theories in abundance, but so far none has been substantiated.

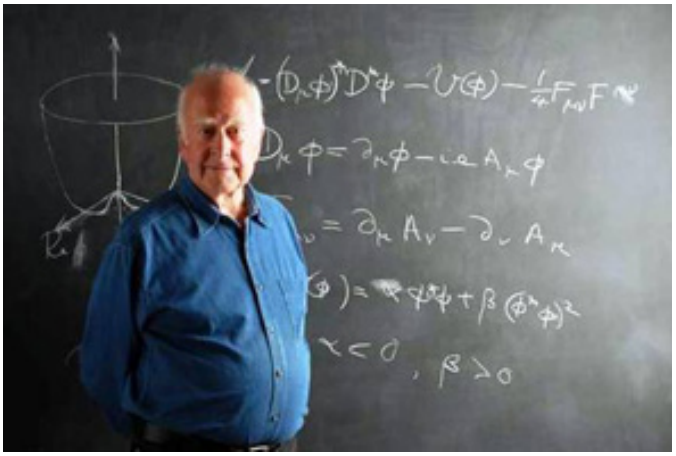

Figure 7: Peter Higgs, explaining the theory that predicts the famous particle named after him.

Nevertheless, even if we find one day corrections to the SM (under extreme conditions), it will always remain the appropriate description of particle physics in the energy range, which is most relevant to us —just like Newton's theory of gravity, or the continuous description of thermodynamic systems, remain highly useful, although they are not exact.

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8 The "triviality" of the Higgs model (see below) implies at least an upper limit for the theoretically possible mass of the Higgs particle.