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IN MEMORIAM: PETER HIGGS (1929 – 2024)

EN MEMORIA DE PETER HIGGS (1929 - 2024)

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Peter Higgs was a British theoretical physicist, renowned for his 1964 work in which he proposed a mechanism capable of generating masses for elementary particles while conforming to gauge symmetry. Half a century later, two experiments at CERN confirmed that this mechanism is realized in nature. On April 8th, we received the sad news of the passing of this great pioneer in elementary particle physics. This article is dedicated to his memory, and to the mechanism and particle that bear his name.

Peter Higgs fue un físico teórico británico, famoso por su trabajo de 1964 donde propuso un mecanismo que puede generar masas para partículas elementales, conforme a la simetría de norma. Medio siglo después, dos experimentos del CERN confirmaron que este mecanismo está realizado en la naturaleza. El 8 de abril nos llegó la triste noticia del fallecimiento del gran pionero de la física de partículas elementales. Este artículo es dedicado a su memoria, al mecanismo y a la partícula que llevan su nombre.

PACS: 01.60.+q Biographies, tributes, personal notes, and obituaries 01.65.+g History of science 11.15.Ex Spontaneous breaking of gauge symmetries 14.80.Bn Standard-model Higgs bosons

I. BIOGRAPHY AND HISTORICAL CONTEXT

Peter Higgs was born in 1929 in Newcastle, England, spending his youth partially during World War II, circumstances that somewhat complicated his schooling. After the war, he studied in London, first mathematics, then physics. In 1954, only 25 years old, he completed his Ph.D. at King's College.

He then worked temporarily at the University of Edinburgh, University College, and Imperial College, both in London. In 1960, he returned to Edinburgh – a city he loved and where he had first arrived in 1949, as a hitchhiking student – to take up a professorship and stay there for the rest of his life.

In 1964, at the age of 35, he wrote his two famous papers (and another on the same subject in 1966) [1] that attracted attention and led to invitations to present seminars at Princeton and Harvard in 1966. He had to deal with critical audiences; Sidney Coleman later commented that at Harvard, "they had been looking forward to tearing apart this idiot who thought that he could get around the Goldstone Theorem" [2]. It turned out that his concept stood, but still without phenomenological application (his papers dealt with a toy model). Additionally, he learned from Yoichiro Nambu (the referee of one of his papers) about a similar work [3], published 15 days before Higgs' first paper on the subject. The authors were François Englert and Robert Brout, who worked in Brussels, Belgium. Two months later, yet another related paper appeared, written in London by Gerald Guralnik, Carl Hagen, and Tom Kibble [4], but they knew and cited the earlier works of Englert, Brout, and Higgs.

The mechanism proposed in these three articles was not entirely new: it had been established in 1962/3 in the context of condensed matter physics by Philip Anderson [5]. He applied concepts of Julian Schwinger [6] for the theoretical explanation of the mass of a gauge particle to the theory of superconductors. Englert, Brout, and Higgs presented an extension to relativistic models.

Figure 1. Above: Peter Higgs, who published two brief papers on what is now called the Higgs mechanism in 1964, and another more extensive one in 1966. Below: Robert Brout (left) and François Englert (right). In 1959, Brout invited Englert to work at Cornell University for two years as a research associate. Afterwards, Brout and Englert moved to the University of Brussels, Belgium.

Independently, in Moscow in 1964, two 19-year-old boys, both named Alexander (or Sasha), with surnames Migdal and Polyakov, discussed in great detail what the breaking of a symmetry means [7]. They wrote another article, very different but with equivalent conclusions, which was published in 1966 [8]. In 2010, Migdal visited Mexico and narrated about the difficulties they had in publishing this article, as the established physics community in the Soviet Union – under the leadership of Lev Landau – rejected the Quantum Field Theory, which was still very controversial also in the Western world.[1] Finally, this article got published somewhat late, but even later both Sashas became famous for other works — in particular, Polyakov is known for discovering topological excitations that we now call *instantons.*

Figure 2. Further pioneers of the Higgs mechanism: from top to bottom, Carl Hagen, Gerald Guralnik, and Tom Kibble.

Figure 3. When they were still teenagers, Alexander Migdal (left) and Alexander Polyakov (right) discovered the Higgs mechanism independently from the West.

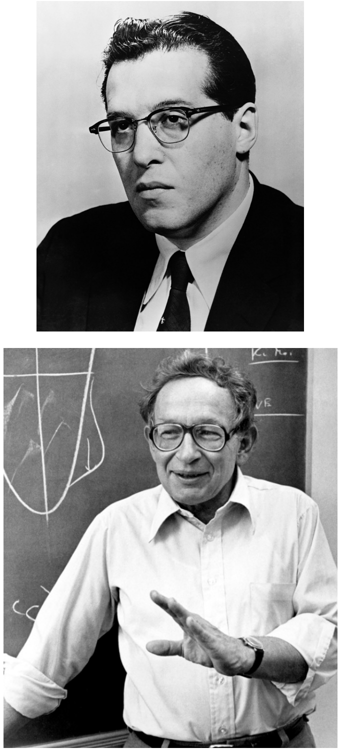

Figure 4. Above: Julian Schwinger: we can trace back the origin of the discovery of the Higgs mechanism to his pioneering work on how gauge symmetry does not always imply a massless gauge boson. Below: Philip Anderson who introduced the mechanism that gives mass to gauge bosons in the context of superconductivity.

The explanation of how gauge particles – and certain particles coupled to them – can have mass soon became known as the *Higgs mechanism*,[2] the subject of Section 2 of this article. Its application to the phenomenology of elementary particles emerged in 1967/8 by Steven Weinberg [9] and Abdus Salam [10]. They incorporated this mechanism into the model of electroweak interaction that Sheldon Glashow had proposed in 1961 [11] during his stay in Copenhagen. In fact, Glashow was present at Higgs' seminar at Harvard, and he appreciated his "nice model" [2], but it did not come to his mind that this mechanism could be the remedy to save his model, which he had already abandoned.

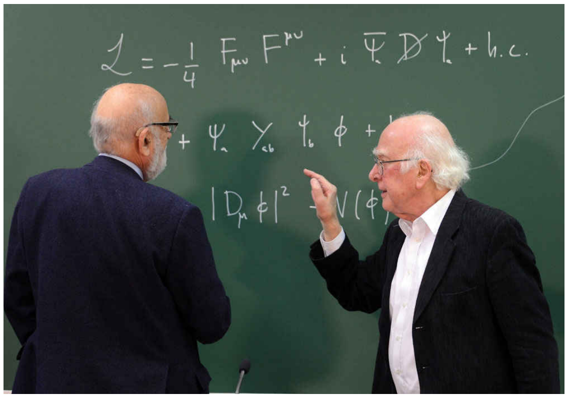

Figure 5. Peter Higgs and François Englert discussing the Lagrangian involving the Higgs field, ϕ. What do you think Higgs is telling Englert? Perhaps he is indicating that the fermionic field $\bar{\psi}_a$ is missing a bar in the second line.

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[1] In Germany, Werner Heisenberg was an influential opponent against Quantum Field Theory; his preference was the S-matrix formalism.

[2] Consulting the original literature does not lead to a clear explanation of why the terminology excludes Brout and Englert.

However, this theory – now known as the *electroweak sector of the Standard Model* – was still not generally accepted as it was considered "non-renormalizable". In Quantum Field Theories, divergences almost always appear at high energies, so they require a "regularization", a mathematical manipulation that turns divergences into finite values. A theory is called *renormalizable* if, at the end of the calculation, the regularization can be completely removed and finite predictions for observables can be obtained (this definition is slightly simplistic).

The physics community changed its view in 1971/2, thanks to the work of Gerard 't Hooft, a brilliant PhD student in Utrecht, Netherlands, who presented evidence in favor of the renormalizability of this model (partially alongside his advisor, Martin Veltman). These works [12] were a sensation at that time that caused a paradigm shift.

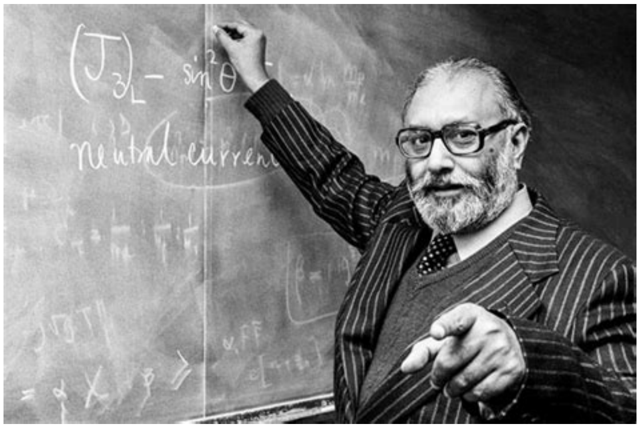

Figure 6. Steven Weinberg (above) and Abdus Salam (below) independently included the Higgs mechanism into the electroweak sector of the Standard Model.

The key to this milestone was a new method, the *dimensional regularization*, which is among the main achievements of physics in Latin America: it was first proposed by two Argentinians, Carlos Bollini and Juan José Giambiagi in 1971, although the publication [13] was delayed until 1972. They worked in La Plata, under difficult circumstances during the military dictatorship [14].

We add that nowadays less importance is given to the question of whether or not the Standard Model is renormalizable: the trend is that it is considered as an effective theory, and its validity in over a large energy range – which does not need to extend to infinity – is sufficient.

Shortly thereafter, in 1973, the Standard Model of elementary particles was completely established, with the electroweak sector [9,10] and another sector of the strong interaction [15]. The Higgs mechanism is essential to provide masses to a large part of the elementary particles. This was a revolution in high-energy physics as we have not seen it anymore in the following half-century; ever since, progress was relatively slow.

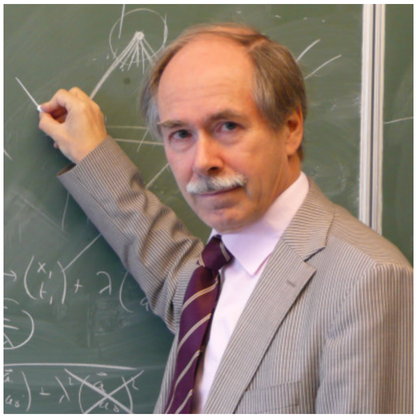

Figure 7. Above: Sheldon Glashow, who invented the original version of the electroweak theory. Below: Gerard 't Hooft, famous for his work on the renormalization of the Standard Model, among other achievements.

In the 21st century, it is popular to speculate about physics beyond the Standard Model. However, for now, none of these proposals have solid support from experimental data. On the other hand, experiments have confirmed the predictions of the Standard Model again and again: often it comes out in the news that the Standard Model has been "refuted" by new results, but at the end of the analysis, and the repetition of the experiments, its predictions have always triumphed.[3]

The Standard Model is somewhat incomplete to describe the

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[3] As a recent example, in the latter part of the last decade, there were news of a tension between the Standard Model and experiments with the decay of heavy mesons known as "B mesons". In the end, this discrepancy was not substantiated. The latest hype is the magnetic moment of the muon, where the experimental value seems slightly different from the calculation based on the Standard Model. If this is true – which is far from certain – the prediction is wrong at the relative level of 10^{-10}: if we compare it, for instance, with the distance between Mexico and Switzerland, about 10,000 km, this corresponds to a possible error of magnitude of millimeters. But calculations with numerical simulations on the lattice lead to results closer to the experimental value [16], a trend that indicates that even this minimal discrepancy could disappear with a more precise analysis, just like all previously supposed discrepancies.

universe (in particular gravity, dark matter, and dark energy are missing), but even so: it is nothing less than the most precise and – in this sense – the most successful theory in the history of science.

Higgs no longer participated in this rapid development. He was already so famous that he could afford to hardly publish research results anymore from the age of 40.

He was known as a quiet and modest person, almost shy, who did not seek media attention or to be in the spotlight at events. With his mindset of abstaining from the show, he can be characterized as the opposite of Feynman. This characterization corresponds to the impression of one of the authors (WB) who participated in a conference in Edinburgh in 1997. Higgs – who had been emeritus since 1996 – appeared at the banquet, but very discreetly, simply to sit at a table without any spectacle.

This does not mean that Higgs did not have convictions: he was temporarily an activist for nuclear disarmament and for the environmental movement as a member of *Greenpeace.*

Once the Standard Model had been established, its exploration progressed with intense work in multiple countries. In the year 2000, all of its particles had already been experimentally found, except for one: the famous "Higgs particle", involved in the corresponding mechanism, as we will describe in Section 2.

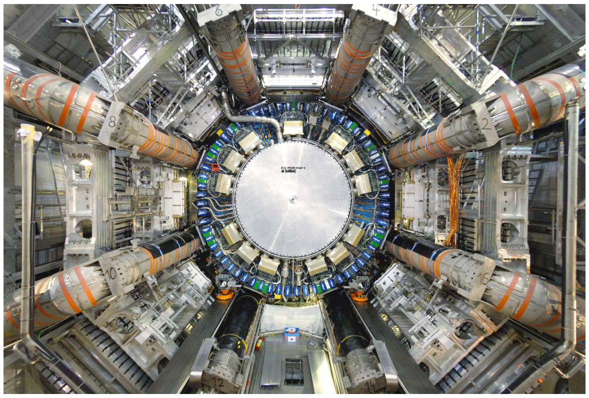

Figure 8. Detectors of the Collaborations ATLAS (above) and CMS (below) at CERN that confirmed the existence of the Higgs boson of the Standard Model. Both are multipurpose detectors, used to analyze collisions between particles of very high energy.

Again, the nomenclature is perhaps a bit unfair to Englert and Brout, but this is the convention of the community. Higgs did not invent this term (this was first done by Ben Lee [2]), but he was also uncomfortable with the absurd nickname "god particle" that does not make the slightest sense. This term was proposed by the editor of a popular science book [17], obviously with a commercial objective, but fully irresponsible. This term became popular and led to endless confusion, for example, the Catholic Church of Spain believed that the work at CERN had something to do with theology [18]. We have to be careful with the terms we use!

In the 21st century, we witnessed an exciting race in the search for the Higgs particle. In its final phase, it was a competition between Fermilab (near Chicago) and CERN (near Geneva, in a bordering region between Switzerland and France). After initial indications in 2011, in 2012 the Collaborations ATLAS and CMS, both working independently at the Large Hadron Collider (LHC) at CERN, presented indirect but compelling evidence for the observation of the so wanted Higgs particle [19].

With this, the entire set of particles of the Standard Model was observed. Thus it was confirmed that the Higgs mechanism is realized in nature, 48 years after its theoretical proposal. This took almost twice as long as the observation of the neutrino (predicted by Wolfgang Pauli in 1930, and detected by Clyde Cowan, Frederick Reines and collaborators in 1956),[4] we see that sometimes it is worth being patient.

In particular, it was worth it for Englert and Higgs, who received the Nobel Prize in 2013 for their correct prediction [7]; sadly, Brout had died shortly before, in 2011. In April 2024, we received news of Higgs' passing away, at the age of 94, after a brief illness.

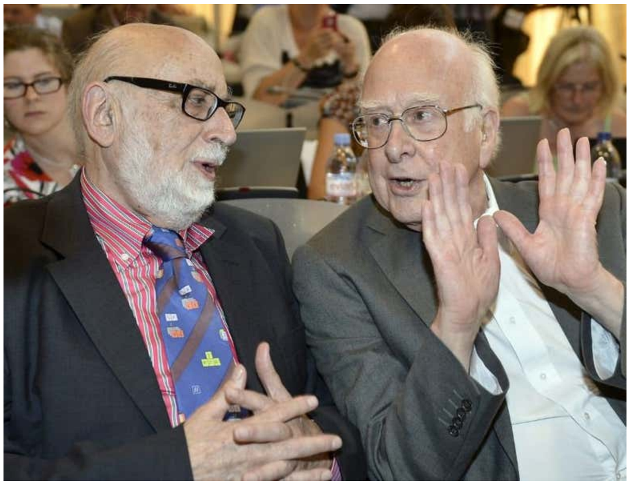

Figure 9. On July 4, 2012, CERN publicly announced the discovery of the Higgs boson. Peter Higgs, moved to tears at the ceremony, said [21]: "... congratulations to everybody involved in this tremendous achievement. For me it is really an incredible thing that this happened in my lifetime". The Royal Swedish Academy of Sciences awarded the Nobel Prize in Physics in 2013 to François Englert (left) and Peter Higgs (right) for "the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles . . . ".

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[4] Ref. [20] reviews the history and properties of neutrinos, from a semi-popular perspective.

II. THE HIGGS MECHANISM

To the best of our knowledge, the world consists of *elementary particles*, which are indivisible, and occur in a few types (say 25, but it depends a bit on how one counts). Famous examples are the electron and the photon (the particle of light).

Their relativistic description is based on "fields", abstract quantities, present throughout the universe, at any time. At some space-point, a field can take different states, depending on time. If the fields in a region are in their ground states, we perceive the vacuum. Excitations are quantized and manifest as elementary particles; this is the idea of *Quantum Field Theory*.

There is a field for each type of elementary particle, and their excitations can move (like waves), interact, generate, and destroy particles (this is a requirement for compatibility with Special Relativity, which is lacking in Quantum Mechanics).[5]

A central concept is *symmetry:* symmetry means the invariance of physical properties under a group of transformations of one or more fields. We distinguish between *global* and *local* symmetries:

- If a symmetry is *global*, a field transforms in the same way everywhere. One can imagine a group of people doing collective gymnastics, all making the same movement, which could be synchronized with music. (The image is a bit simplistic because the fields transform in the same way even throughout space-time.)

- The case of a *local* symmetry can be imagined as chaotic gymnastics: each person moves as he/she wishes, independently. This means that the fields can be transformed independently at each point in space-time.

  It is clear that this type of symmetry allows many more transformations. Achieving local symmetry is far more difficult but leads to stronger restrictions, and therefore to a powerful ability to make predictions.

  Technically, an additional field is introduced, known as the *gauge field*, which transforms in such a way as to compensate for the relative change between nearby points in a simultaneous transformation. This successful concept describes the transmission of interactions, but it only works if local symmetry is exact.

An important category of particles is known as "fermions": the (known) elementary fermions have spin 1/2 in natural units.[6] Spin is an internal degree of freedom that manifests like an angular momentum. The fermions of the Standard Model are the electron, its two heavier "cousins" (the muon and the tauon), neutrinos (much lighter and electrically neutral)[7] and quarks (constituents of composite particles, such as the proton and the neutron).

A fermion can exist in two variants, with "chirality" left or right; it can be imagined as hands,[8] or gloves, which are left or right, but for fermions in an abstract sense.

Suppose *e.g.* an electron without mass: in this case, the left (e_L) and right (e_R) electron are independent, and their spin points against (for e_L) or in (for e_R) their direction of motion (a particle without mass cannot be at rest). This is symbolically illustrated in Figure 10.

Figure 10. Symbolic illustration of a massless electron with left-handed chirality, e_L, and right-handed chirality, e_R. The direction of motion is indicated by the thin arrow, and the direction of spin by the bold arrow. For left-handed chirality, the velocity and spin point in opposite directions, whereas for right-handed chirality, they point in the same direction.

Including a mass term requires a product of the fields of the left and right electrons (one can imagine the two hands holding onto each other). Then they are no longer independent, and under symmetry they have to transform in the same way.

This is, however, not the case in Glashow's electroweak theory [11]: this theory allows, for example, local ("gauge") transformations that only affect e_L, but not e_R. Here was the problem: this theory seemed to be incompatible with the mass term of the electron (and other fermions), but we know that the electron does have a mass of $M_e \simeq 0.511$ MeV (still in natural units).

In fact, the situation was even worse. The gauge particles that transmit weak force are called $W^{\pm}$, Z^0 (with electric charge ±1, 0), for example, the W are responsible for radioactive decay. This force has a very short range (about 10^{-17} m) that can only be explained if $W^{\pm}$, Z^0 have large masses (they are among the heaviest elementary particles we know, with masses of $M_W = 80.4\,\mathrm{GeV}$ and $M_Z = 91.2\,\mathrm{GeV}$). But just like the mass of the electron, it seems that gauge symmetry, which has to be exact, requires $m_W = m_Z = 0$.

The puzzle of where the masses of gauge particles could possibly come from was a "killing question" with which Wolfgang Pauli ruined a seminar by Chen-Ning Yang in Princeton in 1953 on gauge theories with a non-Abelian symmetry group (now known as Yang-Mills theories). Without knowing the Higgs mechanism, Yang could not answer, but Pauli insisted so much that Yang sat down, frustrated. Finally, Robert Oppenheimer had to encourage him to continue his talk [24].

So, how does the salvation of this theory, the Higgs mechanism, work? First, another field is added, the *Higgs field*, we use the notation $\phi(x)$. The variable x is a point in space-time, and ϕ is a scalar field, its fluctuations represent

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[5] Ref. [23] presents a more extensive popular science description of elementary particles.

[6] To use natural units, one sets Planck's constant and the speed of light in vacuum to 1, $\hbar = c = 1$.

[7] The set of the electron, muon, tauon, and the three neutrinos is known as the *leptons*.

[8] Indeed, the term comes from "kheir", which means "hand" in Greek.

[9] We actually need partially anti-fields, which represent anti-particles, but we ignore this aspect in the context of this popular science article.

particles with spin 0. To establish an electron mass term, now a product of *three* fields is formed, e_L, ϕ, and e_R.[9] The Higgs field also transforms under local symmetry, in such a manner that the term as a whole is gauge invariant.

So in this way, a prmissible (gauge invariant) terme can be added, but does this provide mass to the electron? Possibly yes, it can work with the following scenario.

At low energies, the Higgs field "freezes" to its ground state, manifesting almost as a constant. This constant does not have to be zero: indeed, ϕ has 4 real components, but we can imagine there to be only 2, $\phi_1, \phi_2 \in \mathbb{R}$, parameterizing a plane. This field comes with a potential $V(\phi_1, \phi_2)$ shaped like a Mexican hat, with zero value at the center, but there is a ring of minima corresponding to a value $|\phi|^2 = \phi_1^2 + \phi_2^2 > 0$, as illustrated in Figure 11. This "vacuum expectation value" takes on the role of the electron's mass that the model needs (up to a coefficient), $M_e \propto |\phi|$, and similarly, the masses M_W and M_Z are obtained, all in agreement with gauge symmetry (we will return to this point).

It seems all fine, but there is still another problem, and this is the point that Coleman referred to in his comment on Higgs' seminar at Harvard, which we quoted in Section 1. The Mexican hat potential has a symmetry under rotations about the central axis. We assume the field ϕ to choose one of the minima: the process of this choice is denoted as "spontaneous symmetry breaking": from the perspective of a specific minimum, the rotation symmetry is no longer apparent. In Ref. [22], we described this process with the analogy of the *Buridan's Donkey*, which is thirsty and surrounded by a water trough but has to decide which direction to walk in order to drink water.

Small fluctuations of the field beyond its minimum state correspond to particles. If a fluctuation is *radial*, it costs energy because the potential rises – this is a massive particle (the curvature of the potential in the radial direction corresponds to its mass squared). On the other hand, a *tangential* fluctuation does not require any energy, as the field stays at its energy minimum. This is an example of a massless particle, known as a *Nambu-Goldstone boson* [25, 26]. According to the Goldstone Theorem [27], these bosons appear when a continuous symmetry (such as rotation in this example) is spontaneously broken.

If the mechanism works as described above, the question remains: where is this Nambu-Goldstone boson? Being massless, it should play a relevant role and dominate physics at low energies (where very heavy particles are not visible). But no particle of this kind has been observed. So, to justify the mechanism, one has to "get around the Goldstone Theorem", as Coleman put it, but the physicists at Harvard doubted whether this was possible. They were not alone; for example, Klaus Hepp, a prominent mathematical physicist, warned Higgs that this might not work because the Theorem was proven using C* algebra, a formalism that Higgs was not familiar with, but he expressed doubts about the assumptions in this proof [2].

We now know that the Theorem is indeed correct, but it only refers to the breaking of a *global* continuous symmetry – this assumption was hidden. The crucial observation was that the situation is different in the case of a *local* symmetry: in this case, the minima are connected by local transformations, or gauge transformations, thus they are physically identical. So there are no physical fluctuations between the minima, and there are no Nambu-Goldstone bosons. What happens – and this completes the Higgs mechanism – is that the gauge boson acquires mass, meaning that the degree of freedom of the Nambu-Goldstone boson turns into the longitudinal degree of freedom of the gauge boson (without mass, it only has transverse degrees of freedom). In popular language, it is said that the gauge boson *"eats up"* the Nambu-Goldstone boson: the latter is no longer there, but the former becomes "fat".

This had been observed by Anderson before in a typical superconductor: inside it, at very low temperature, the photon acquires mass, hence it can hardly penetrate the superconductor – a phenomenon known as the *Meissner-Ochsenfeld effect*. Brout, Englert, and Higgs extended this effect to relativistic models [1, 3], and Weinberg and Salam to the phenomenology of electroweak interaction [9, 10]. We mentioned that the Higgs field has 4 real components: there is always one massive radial fluctuation, and thus 3 Nambu-Goldstone bosons if we are dealing with a global symmetry. When it is promoted to a local symmetry, the bosons W^+, W^-, and Z^0 "eat up" these Nambu-Goldstone bosons and acquire masses, while the photon remains massless (under normal circumstances) and describes long-range electromagnetism.

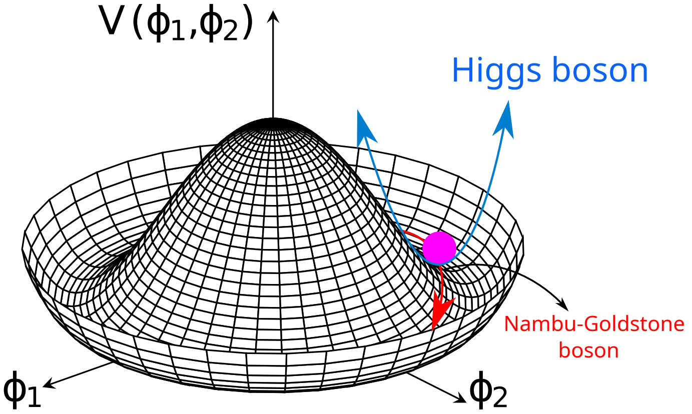

Figure 11. The Higgs potential: from the top perspective, the potential is rotationally symmetric. However, from the perspective of the ball, the potential seems not to exhibit this symmetry, which is "spontaneous broken". Tangential fluctuations of the field along the circle of minima manifest as a Nambu-Goldstone boson if the symmetry is global. If the symmetry is local, this Nambu-Goldstone boson is "eaten up" by a gauge field that acquires mass. Radial fluctuations, perpendicular to the circle of minima, manifest as a massive particle. If dealing with the Higgs potential as in the Standard Model, this massive particle is the famous Higgs boson.

We have seen that the mechanism also provides a mass to the electron, and it similarly applies to the muon, tauon, and all the quarks. And what about the Higgs field? We know that 3 of its 4 components would be Nambu-Goldstone bosons that disappear, but the fourth component remains, corresponding to the radial fluctuation, *i.e.*, to a massive particle. Its existence is a prediction of the Higgs mechanism, and in this respect, the second article by Higgs from 1964 was somewhat more explicit than the other original works. This was still in the context of toy models, but once applied to a phenomenological model, one concluded that such a *Higgs particle* has to be *observable*.

The theory does not predict the mass of the Higgs particle, $M_{\rm H}$ (only bounds could be derived, which were a topic of discussion over many years), so its experimental search was challenging. At the beginning of the 21st century, the experiments of the Large Electron-Positron Collider (LEP) at CERN showed that it must have a mass $M_{\rm H} > 114\,{\rm GeV}$. So it was known to be very heavy (if it exists), requiring high-energy collisions for its creation. This also implies that its lifetime is very short, decaying on average in 10^{-22} seconds, so it cannot leave traces in any detector.

An experiment has to capture the products of its decay that allow the reconstruction of the Higgs particle as an intermediate state, or "resonance" – for a very short time – in a high-energy collision. The analysis of the particles resulting at the end of the process enables the reconstruction of the Higgs particle properties, in particular its mass of $M_{\rm H} \simeq 125\,{\rm GeV}$ and its spin 0, confirming it to be a scalar particle.

In the cleanest channel observed, the decay of the Higgs particle ends with two photons, a final state that would not be possible if, for example, the original particle had spin 1, as Landau had proved [28]. But the ATLAS and CMS experiments studied (independently) many more decays in great detail – such as, for instance, with a final state of four leptons – leaving no doubt about the existence of the Higgs particle, and the corresponding mechanism.

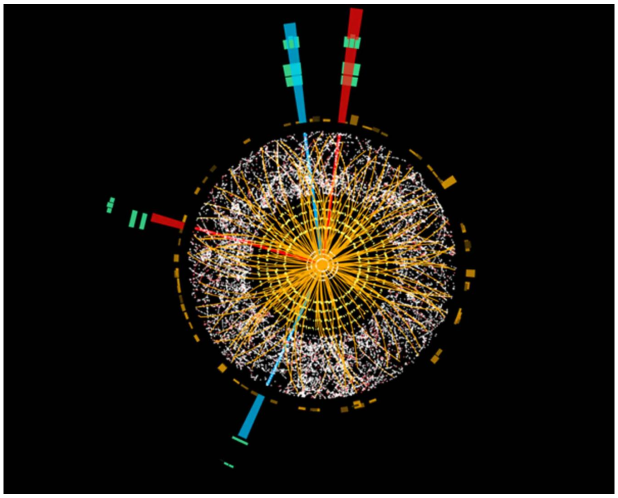

Figure 12. Possible decay channels of the Higgs boson when decaying into two Z bosons, each of which decays into a lepton-antilepton pair. In this picture, we observe two such pairs (red and blue lines) that might have been produced by the decay of a Higgs boson.

This represents a spectacular success of elementary particle physics. Nevertheless, not everything is resolved yet. From a conceptual perspective, the *hierarchy problem* remains, and regarding phenomenology, the Higgs mechanism does not explain the origin of all masses we observe. We end with brief comments on these issues:

- *Hierarchy problem:* If we start with a classical system (without quantum effects) and assume a mass $m_{\rm H}^{(0)}$ on the order of masses of other particles, it is natural that quantum corrections drastically increase this mass to a value $m_{\rm H}$ on the order of the "Planck scale" (determined by the gravitational constant). But this leads to a huge mass $m_{\rm H}$, typically about 10^{17} times its observed value.

  One could assume an extremely negative value of $m_{\rm H}^{(0)}$, so that the quantum effect is almost entirely canceled out, leaving a tiny remainder of 125 GeV. But this approach – with a cancellation between two tremendous contributions leaving a tiny remainder – does not seem natural. This is known as the "hierarchy problem". However, it is not a paradox, one can consistently arrive at 125 GeV, and the question of how severe this problem is, is somewhat philosophical. The extent of the hierarchy gap also depends on the regularization that one applies.

- *Neutrinos* (denoted by ν) play a special role: the traditional form of the Standard Model assumed them to have mass zero, $M_\nu = 0$, and only the left-handed neutrino, ν_L, to exist.

  This is consistent in theory, but at the end of the 20th century, it was observed that neutrinos do have a small mass, $M_\nu > 0$ – we reiterate that Ref. [20] provides a semi-popular review of the topic.

  At first sight, according to our previous description, it seems inevitable that the right-handed neutrino, ν_R, exists. This allows the application of the Higgs mechanism to neutrinos, and also another type of mass, only for the ν_R, known as "Majorana mass".

  However, the ν_R is not observed, and its existence is not truly inevitable: we can construct a mass term involving only the ν_L field [30]. This term is non-renormalizable, but we mentioned in Section 1 that the importance given to of this property is diminished. So this scenario would be the alternative, within the framework of the Standard Model interpreted as an effective theory that works in a certain energy range.

Figure 13. The Large Hadron Collider (LHC) is located on the border region between France and Switzerland. Its four main experiments are called ATLAS and CMS (which independently found evidence of the existence of the Higgs boson), ALICE, and LHCb. The following Latin American countries are involved in these collaborations [29]: Argentina, Brazil, Chile, Colombia, Costa Rica, Cuba, Ecuador, Mexico, Peru.

- Up to this point, the Higgs mechanism explains the masses of elementary particles (with the possible exception of neutrinos), and there are other particles like the photon that remain massless. It seems like a complete picture of the origin of mass.

However, the real world is different: in reality, the mass of a macroscopic object in our everyday life originates only to $1 \ldots 2\,\%$ from the Higgs mechanism, which leads to the masses of quarks.

These everyday masses consist mainly of nucleon masses (protons and neutrons), which essentially consist of energy from *gluons* (other gauge particles, which transmit the strong interaction): they have zero mass, but are confined inside a nucleon (or another particle composed by the strong interaction). Their energy manifests as almost the entire mass of the nucleon, while the masses of quarks only provide the aforementioned contribution of $\sim 1 \ldots 2\,\%$.

The interior of a nucleon is a very, very complex system, for a long time it seemed impossible to calculate anything conclusive about it. However, a little over a decade ago, it became possible to compute, for example, the mass of the nucleon, $M_N \simeq 939\,\mathrm{MeV}$, from first principles, up to an uncertainty of the order of 1 %. This calculation captures the hyper-complicated mess of gluons (and "sea quarks", unstable pairs of a quark and its anti-quark), and the result is compatible with experiments. The question of how these calculations are possible would be a topic for another article ...

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REFERENCES

[1] P.W. Higgs, *Phys. Lett.* **12** (1964) 132-133; *Phys. Rev. Lett.* **13** (1964) 508-509. *Phys. Rev.* **145** (1966) 1156-1163.

[2] P. Higgs, *Int. J. Phys.* **A17** (2002) 86-88.

[3] F. Englert and R. Brout, *Phys. Rev. Lett.* **13** (1964) 321-323.

[4] G.S. Guralnik, C.R. Hagen and T.W.B. Kibble, *Phys. Rev. Lett.* **13** (1964) 585-587.

[5] P.W. Anderson, *Phys. Rev.* **130** (1963) 439-442.

[6] J.S. Schwinger, *Phys. Rev.* **125** (1962) 397-398; *Phys. Rev.* **128** (1962) 2425-2429.

[7] Royal Swedish Academy of Sciences, "Scientific Background: The BEH-Mechanism, Interactions with Short Range Forces and Scalar Particles", www.nobelprize.org/prizes/physics/2013/advanced-information/

[8] A.A. Migdal and A.M. Polyakov, *Zh. Eksp. Teor. Fiz.* **51** (1966) 135-146 [*Sov. Phys. JETP* **24** (1967) 91-98].

[9] S. Weinberg, *Phys. Rev. Lett.* **19** (1967) 1264-1266.

[10] A. Salam, in *Proc. of the 8th Nobel Symposium on "Elementary particle theory, relativistic groups and analyticity"*, editor N. Svartholm (1968) p. 367-377.

[11] S.L. Glashow, *Nucl. Phys.* **22** (1961) 579-588.

[12] G. 't Hooft, *Nucl. Phys.* **B33** (1971) 173-199; *Nucl. Phys.* **B35** (1971) 167-188. G. 't Hooft and M.J.G. Veltman, *Nucl. Phys.* **B44** (1972) 189-213.

[13] C.G. Bollini and J.J. Giambiagi, *Nuovo Cim.* **B12** (1972) 20-26; *Phys. Lett.* **B40** (1972) 566-568.

[14] W. Bietenholz and L. Prado, *Bol. Soc. Mex. Fís.* **26-4** (2012) 227-230; *Physics Today* **67** (2014) 38-43.

[15] H. Fritzsch, M. Gell-Mann and H. Leutwyler, *Phys. Lett.* **B47** (1973) 365-368.

[16] H. Wittig, arXiv:2306.04165 [hep-ph].

[17] L.M. Lederman and D. Teresi, "The God Particle", Dell Publishing, 1993.

[18] Interview with Peter Higgs, published in *The Guardian*, Dec. 6, 2013.

[19] ATLAS Collaboration, *Phys. Lett.* **B716** (2012) 1-29. CMS Collaboration, *Phys. Lett.* **B716** (2012) 30-61.

[20] A. Aguilar-Arévalo and W. Bietenholz, *Rev. Cub. Fís.* **32** (2015) 127-136 [more extensive version: arXiv:1601.04747 [physics.pop-ph]].

[21] https://www.youtube.com/watch?v=m-dNqCbRc_Y

[22] D. Ayala García and W. Bietenholz, *Bol. Soc. Mex. Fís.* **26-3** (2012) 161-166. W. Bietenholz, *Rev. Cub. Fís.* **30** (2013) 109-112.

[23] W. Bietenholz, *Rev. Cub. Fís.* **37** (2020) 146-151.

[24] M. Shifman (editor), "Standing Together in Troubled Times: Unpublished Letters by Pauli, Einstein, Franck and Others", World Scientific, 2017.

[25] Y. Nambu, *Phys. Rev. Lett.* **4** (1960) 380-382. Y. Nambu and G. Jona-Lasinio, *Phys. Rev.* **122** (1961) 345-358; *Phys. Rev.* **124** (1961) 246-254. V.G. Vaks and A.I. Larkin, *ZhETF* **40** (1961) 282-283 [*JETP* **13** (1961) 192-193].

[26] J. Goldstone, *Nuovo Cim.* **19** (1961) 154-164.

[27] J. Goldstone, A. Salam and S. Weinberg, *Phys. Rev.* **127** (1962) 965-970.

[28] L.D. Landau, *Dokl. Akad. Nauk. SSSR* **60** (1948) 207-209.

[29] https://greybook.cern.ch/country/list

[30] S. Weinberg, *Phys. Rev. Lett.* **43** (1979) 1566-1570.