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Scientific Background on the Nobel Prize in Physics 2013

THE BEH-MECHANISM, INTERACTIONS WITH SHORT RANGE FORCES AND SCALAR PARTICLES

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Introduction

On July 4, 2012, CERN announced the long awaited discovery of a new fundamental particle with properties similar to those expected for the missing link of the Standard Model (SM) of particle physics, the Higgs boson. The discovery was made independently by two experimental collaborations – ATLAS and CMS at the Large Hadron Collider – both working with huge all-purpose multichannel detectors. With significance at the level of five standard deviations, the new particle was mainly observed decaying into two channels: two photons and four leptons. This high significance implies that the probability of background fluctuations conspiring to produce the observed signal is less than 3×10^{-7}. It took another nine months, however, and dedicated efforts from hundreds of scientists working hard to study additional decay channels and extract pertinent characteristics, before CERN boldly announced that the new particle was indeed the long-sought Higgs particle. Today we believe that "Beyond any reasonable doubt, it is a Higgs boson." [1]. An extensive review of Higgs searches prior to the July 2012 discovery may be found in [2].

Unification of Interactions

Mankind has probably always strived to find common reasons behind different phenomena. We want to rationalize. The physical world around us with its multitude of physical manifestations would be impossible to understand, had it not been possible to find common frameworks for many different phenomena in Nature. The physical development to be discussed here has its origin in 1865 when James Clark Maxwell described unification of electricity and magnetism in his book *A Dynamical Theory of the Electromagnetic Field*. From then on we talk about electromagnetism. Before they were thought of as two different phenomena in Nature.

A similar simplification occurs when we try to understand Nature at smaller and smaller scales. At the beginning of the last century it was realised that the Newtonian mechanics that works so well in everyday-life is but an approximation of the more fundamental quantum mechanics. It was also realized that matter is quantised (hence the name quantum mechanics) and that there are basic elementary constituents that build up even the most complex form of matter. From then on the fundamental question was: What are the fundamental particles and what are the fundamental interactions that act between them? In a paper from 1931 [3] Paul Dirac (Nobel Prize, 1933) speculated that the final goal of physics to find the underlying laws of Nature could have been reached. Using the *Dirac equation* [4], he could describe the interaction between the electron and the proton in hydrogen, in a seemingly perfect way. We knew the building blocks, the electron and the proton as well as the mediator of the electromagnetic force binding them, the photon, and so it was believed that all matter could be built up.

Quantum Electrodynamics

However, it was soon realized that in a relativistically invariant theory particles could be created and annihilated since mass and energy are connected through Einstein's famous formula $E = mc^2$. One needed a many-particle theory and for that purpose Quantum Electrodynamics

(QED) was developed in the late 1940's. The key physicists here were Richard Feynman [5], Julian Schwinger [6], Sin-Itiro Tomonaga [7] (Nobel Prize to the three, 1965) and Freeman Dyson [8]. They showed that a (seemingly) consistent quantum theory could be formulated for the electromagnetic interaction. In particular they showed that a systematic perturbation expansion could be defined. This means that the amplitude for scattering between electrically charged particles can be written as an expansion in powers of the fine structure constant, α, which is a measure of the strength of the electric force. When computing these terms, most of them are found to be infinite. There is, however, a unique way to absorb all the infinities. This is done by interpreting them as contributions to the electron mass, its charge and to the norm of its wave function. By letting these parameters be free, it is possible to assign finite values to each order in the expansion that can be compared successfully with experiments. The parameters are said to be *renormalised*. A quantum field theory in which only a finite number of parameters need be renormalised to define a finite perturbation expansion is called a *renormalisable theory*. Feynman introduced a very powerful diagrammatical formulation that was to be used routinely in all perturbative calculations, the Feynman diagrams. To each particle he associated an external line describing the free propagation of the particle. The specific quantum field theory then defines the interaction vertices, which are combined with propagators to build diagrams.

Relativistic QED is described by a four-vector potential, the A_μ field, in which the time component has a negative norm relative to the space components. In 1929 Hermann Weyl [9] constructed a *gauge invariant* formulation of QED by introducing a local symmetry into the theory. This symmetry is the local change of the phase of the electron wave function, which cannot be gauged (measured), together with a transformation of the vector field. He introduced the *field strength* $F_{\mu\nu} = \frac{\partial}{\partial x^\mu} A_\nu - \frac{\partial}{\partial x^\nu} A_\mu$, which is explicitly gauge invariant and its six non-zero components are the electric and the magnetic field components. The symmetry is called abelian since two independent phase rotations give the same result regardless of in which order they are performed. The symmetry leads to redundancy of the time and the longitudinal components of the electromagnetic field, and the physical degrees of freedom are carried only by the transverse components. The key to prove the renormalisability of QED was then to prove that the gauge invariance is still preserved by all the renormalised quantum corrections.

The Strong Interaction

Only a year after Dirac's paper was published [3], James Chadwick (Nobel Prize, 1935) [10] discovered electrically neutral radiation from the nucleus and could establish that it consisted of a new type of elementary particle that came to be called the neutron. It was soon realized that there are two distinct nuclear forces at play within the nucleus, a weak force that is responsible for the radioactivity and a strong one that binds the protons and the neutrons together. Both of them act only over a very short range, of the size of the nucleus, hence they have no macroscopic analogue.

In 1935 Hideki Yukawa (Nobel Prize, 1949) [11] proposed that the strong nuclear force is mediated by a new particle in analogy with the electromagnetic force. However, the

electromagnetic force has a long range while the strong force has a short range. Yukawa realized that, while the electromagnetic force is mediated by massless particles, the strong interactions must be mediated by massive particles. The mass then gives a natural scale for the range of the force. The pion as the particle came to be called was not discovered until after the Second World War, in 1947, by Cecil Powell (Nobel Prize, 1950) [12].

Non-Abelian Gauge Theory

Yukawa's theory had been successful to predict a new particle but the attempts to make it into a quantum field theory failed. A new and rather different attempt to achieve this was made in 1954 by Chen-Ning Yang (Nobel Prize, 1957) and Robert Mills [13] who constructed a non-abelian gauge field theory based on the isospin group *SU(2)* (the symmetry between the proton and the neutron). The Swedish physicist Oskar Klein [14] had discussed a similar idea in 1938, but the outbreak of the war and the emphasis on other problems made this idea fade away. In the Yang-Mills theory there are three gauge fields (vector fields) $A^a{}_\mu$, where $a = 1,2,3$, and a spinor field ψ^i with two components describing the proton and the neutron. The gauge transformation is now a local transformation between the two components. The transformation of the vector field has one part which behaves like in QED under a local transformation but also a gauge covariant part transforming as the adjoint representation of *SU(2)*. This time the corresponding *field strength* $F^a{}_{\mu\nu} = \frac{\partial}{\partial x^\mu} A^a{}_\nu - \frac{\partial}{\partial x^\nu} A^a{}_\mu + g f^{abc} A^b{}_\mu A^c{}_\nu$ is gauge covariant. The Lagrangian is constructed as

$$L = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{\psi}^i \left(i \gamma^\mu D^{ij}{}_\mu - m \right) \psi^j,$$

where D is the covariant derivative $D^{ij}{}_\mu = \partial_\mu \delta^{ij} + ig C^{ij}_a A^a_\mu$, and $\partial_\mu \equiv \frac{\partial}{\partial x^\mu}$, and C^{ij}_a is the Clebsch-Gordan coefficient connecting the adjoint representation *(a)* with the doublet representation *(i)*. Apart from the introduction of this derivative instead of the ordinary derivative, the Lagrangian simply consists of the free parts for the vector fields and the spinors. This construction is unique. The freedom is which symmetry (gauge) group to use and which representations of the matter fields to choose.

This was a very attractive new approach but it was soon criticized, especially by Wolfgang Pauli (Nobel Prize, 1945), since the theory contains a massless vector particle mediating the force. No such particle was known and, as noted above, such a particle would mediate a long range force instead of the short-range force of the strong interactions believed to be the fundamental force.

The Proliferation of Elementary Particles

The failure of the Yukawa field theory and the Yang-Mills theory to describe the strong nuclear force satisfactorily led the physics community to doubt the relevance of relativistic quantum field theories. Perhaps the success of QED was an accident; in order to describe the other forces some alternative formalism would perhaps be needed. Many attempts to find such an alternative were made in the following years.

However, the great experimental developments of the 1950's showed that a theory involving only nucleons and pions must be incomplete. When the new particle accelerators at CERN in Geneva and Brookhaven in the USA were brought into operation in 1959–60, many new particles were discovered. Most of them decaying by the strong interaction were extremely short-lived with a lifetime of the order of 10^{-23} s. Others, like the charged pions, have a lifetime of typically 10^{-6} to 10^{-10} s. They decay by the weak nuclear force. The proliferation of new elementary particles showed that, in order to understand the basic laws of Nature, the basic building blocks of Nature must also be known. The physicist to bring order to this plethora of particles was Murray Gell-Mann (Nobel Prize, 1969). He realized that in order to find a systematic description of all these particles, new quantum numbers are needed. In 1961 he introduced the symmetry group *SU(3)* to classify the particles stable under the influence of the strong force [15]. (The new quantum number came to be called flavour.) Yuval Ne'eman also put forward the same idea [16]. The short-lived particles were also found to follow this symmetry pattern. In 1964 Gell-Mann and George Zweig [17, 18] introduced the quark concept. With the help of three quarks and their antiparticles it was possible to build up all the particles known at that time. There was, however, still no dynamical theory for the quarks.

The Weak Interaction

The great theoretical development in the late 1950's was the discovery by Yang and Tsung Dao Lee (Nobel Prize, 1957) [19] that parity is broken in the weak interactions. Shortly thereafter, an effective quantum field theory (the *V-A* theory) was formulated for the weak interactions by Robert Marshak and George Sudarshan [20], and by Feynman and Gell-Mann [21], extending earlier ideas of Enrico Fermi (Nobel Prize, 1938) [22]. This theory was non-renormalisable so the quantum corrections could not be trusted, but since the coupling strength of the weak force is very small the first term is often good enough. This theory described with great precision a multitude of experiments and was clearly an embryo of a correct theory. In fact, already before the *V-A* papers were published, Schwinger proposed a non-abelian gauge theory with gauge group *SU(2)* and the *V-A* structure [23]. Also Feynman and Gell-Mann proposed that the underlying theory could be a non-abelian gauge field theory, but it was commonly believed that such theories were not renormalisable. Furthermore the weak interaction was also known to have a short range, while non-abelian theories lead to long-range forces. The idea was tempting, however, and it survived, but it was pursued only by a small number of physicists. In 1961 Sheldon Glashow (Nobel Prize, 1979) [24] extended Schwinger's idea and constructed a gauge theory based on the group *SU(2) x U(1)* to describe a unified theory of weak interactions and electromagnetism. The short-range forces of the weak interactions were obtained by introducing explicit masses for three of the four vector particles. The theory was not renormalisable but as we shall see later it was the first step towards a unified model for all the interactions. Similar results were obtained by Abdus Salam and J.C. Ward three years later [25].

Spontaneous Symmetry Breaking and the Goldstone Theorem

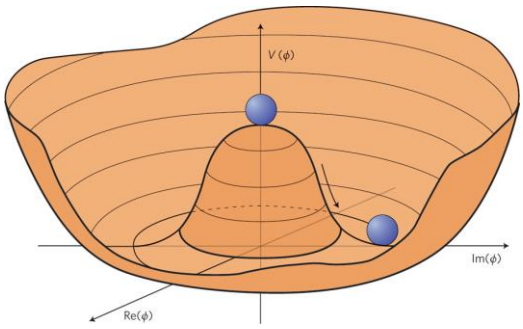
Another remarkable development came around 1960 when Yôichirô Nambu (Nobel Prize 2008) extended ideas from superconductivity [26] to particle physics [27]. He had previously shown

that the BCS ground state (named after John Bardeen, Leon Cooper and Robert Schrieffer, Nobel Prize, 1972) has spontaneously broken gauge symmetry. This means that, while the underlying Hamiltonian is invariant with respect to the choice of the electromagnetic gauge, the BCS ground state is not. This fact cast some doubts on the validity of the original explanation of the Meissner effect within the BCS theory, which, though well motivated on physical grounds, was not explicitly gauge invariant. Nambu finally put these doubts to rest, after earlier important contributions by Philip Anderson (Nobel Prize, 1977) [28] and others had fallen short of providing a fully rigorous theory. In the language of particle physics the breaking of a local gauge symmetry, when a normal metal becomes superconducting, gives rise to a finite mass for the photon field inside the superconductor. The conjugate length scale is nothing but the London penetration depth. This example from superconductivity showed that a gauge theory could give rise to small length scales if the local symmetry is spontaneously broken and hence to short range forces. Note though, that the theory in this case is non-relativistic since it has a Fermi surface. In his paper of 1960 Nambu [27] studied a quantum field theory for hypothetical fermions with chiral symmetry. This symmetry is global and not of the gauge type. He assumed that by giving a vacuum expectation value to a condensate of fields it is spontaneously broken, and he could then show that there is a bound state of the fermions, which he interpreted as the pion. This result follows from general principles without detailing the interactions. If the symmetry is exact, the pion must be massless. By giving the fermions a small mass the symmetry is slightly violated and the pion is given a small mass. Note that this development came four years before the quark hypothesis.

Soon after Nambu's work, Jeffrey Goldstone [29] pointed out that an alternative way to break the symmetry spontaneously is to introduce a scalar field with the quantum numbers of the vacuum and to give it a vacuum expectation value. He studied some different cases but the most important one was that of a complex massive scalar field $\varphi = \frac{1}{\sqrt{2}}\,(\varphi_1 + i\varphi_2)$ with a Lagrangian density of the form

$$L = \partial^\mu\,\bar{\varphi}\,\partial_\mu\,\varphi - \mu_0^2\,\bar{\varphi}\,\varphi - \frac{\lambda_0}{6}\,(\bar{\varphi}\,\varphi)^2,$$

where $\bar{\varphi}$ is the complex conjugate of φ, and the coupling constant λ_0 is positive. This Lagrangian is invariant under a global rotation of the phase of the field φ, $\varphi \longrightarrow e^{i\alpha}\,\varphi$, ie. a *U(1)* symmetry as in QED, although not a local one. Suppose now that one chooses the square of the mass, μ_0^2, *to be a negative number*. Then the potential looks like a "Mexican hat":



It is clear that the lowest value of the Hamiltonian, which is

$$H = \partial^i \bar{\varphi}\ \partial_i \varphi + \mu_0^2 \bar{\varphi}\, \varphi + \frac{\lambda_0}{6} (\bar{\varphi}\, \varphi)^2,$$

where the sum over i runs over the three space directions, does not occur for $\varphi = 0$ but for $|\varphi|^2 = v^2 = -\frac{3\mu_0^2}{\lambda_0}$. There are an infinite number of degenerate minima all lying on a circle of radius v. He then introduced a new complex field φ' as $\varphi = \varphi' + v$, ie. he gave the field φ a vacuum expectation value. The explicit symmetry between the two field components is now broken and this way of breaking was later to be called spontaneous (as we have alluded to above). The Lagrangian is now

$$L = \frac{1}{2}(\partial^\mu \varphi'_1 \partial_\mu \varphi'_1 + 2\,\mu_0^2\, {\varphi'_1}^2) + \frac{1}{2}\partial^\mu \varphi'_2 \partial_\mu \varphi'_2 - \frac{\lambda_0\, v}{6} \varphi'_1 ({\varphi'_1}^2 + {\varphi'_2}^2) - \frac{\lambda_0}{24} ({\varphi'_1}^2 + {\varphi'_2}^2)^2.$$

We see that the field φ'_1 describes a massive field, while φ'_2 is a massless one. It is rather obvious from the potential that this should happen. We now expand around the minimum (one point in the valley of the Mexican hat), where in the direction 1 the potential is like a harmonic potential while in the direction 2 it is flat. The massless particle came to be called the Nambu-Goldstone boson, while the massive one was not given a name yet. We will see that it will get one in the sequel. It should be pointed out that the symmetry is still present in the theory although it is not linearly realized any longer. Only the vacuum state breaks the symmetry.

Like Nambu, Goldstone hence found the necessity of a massless particle when the symmetry was broken spontaneously. From the arguments above it is seen that it looks quite hard to avoid the massless particle. Although the phenomenon of spontaneous breaking of a symmetry was known before, for example from Heisenberg's theory of magnetism from 1928 [30], it was not until now that the full consequences of spontaneous symmetry breaking were understood. In condensed matter, in cases of spontaneous symmetry breaking, the Nambu-Goldstone mode is manifested as a linear dispersion between energy and momentum at low momenta.

The question of how general the conclusion above is, was taken up in a subsequent paper by Abdus Salam and Steven Weinberg (Nobel Prize to the two together with Glashow, 1979), together with Goldstone [31]. They showed under very general assumptions that in a Lorentz invariant theory a spontaneous breaking of a symmetry necessitates a massless particle in the spectrum. This came to be called *Goldstone's theorem*.

Precursors

In an effort parallel to Goldstone's, Schwinger [32] asked the question if a massive vector field always comes together with a massless scalar. His idea was that a massless gauge boson at weak coupling can get a mass at strong coupling without breaking the gauge invariance. He was thinking about a gauge theory for the strong interactions and hence it was natural to think about a theory at strong coupling. Such a scenario could possibly occur due to quantum corrections. He discussed the question in a general framework and investigated a two-point function and wrote it in terms of an unknown function of m^2, where m is the mass of the propagating modes.

He checked the commutation relations for the currents and found situations where the massless case would disappear and one would have a massive case. This was not a proof but a general framework in which to discuss the problem. A definite model was missing.

In 1962 P.W. Anderson [33] in another important development took up Schwinger's problem and discussed it in a specific model, namely that of a charged plasma. Anderson followed Schwinger's analysis by on the one hand considering the current-potential relation from the equations of motion and on the other hand considering the dielectric response of the media to an external field. By introducing a test particle in the plasma with its own potential he could describe the current in two ways and compute the total field. He found that it propagates as a field for a particle with a mass related to the plasma frequency. This was indeed an example of a theory with a spontaneously broken symmetry and with no massless scalar particle or mode, although in a non-relativistic setting.

Anderson pointed out that the longitudinal plasmon is usually interpreted as an attribute of the plasma while the transverse modes are interpreted as modifications of the real photons propagating in the plasma. He further stressed that in a relativistically invariant theory the longitudinal mode would not be possible to separate from the third component of a massive vector boson. He finally discussed Nambu's treatment of superconductivity and showed that also there one could interpret the result as a massive vector field.

This was a very important step forward showing that one could indeed have massive vector particles without having a massless mode, but it did now show how the same phenomenon would work in a relativistically invariant theory. Anderson concluded by saying "*We conclude, then, that the Goldstone zero-mass difficulty is not a serious one, because we can probably cancel it off against an equal Yang-Mills zero-mass problem*."

Anderson's ideas were not pursued much by particle physicists, who instead tried to even further strengthen Goldstone's theorem. However in a paper [34] from March 1964, Abraham Klein and Benjamin W. Lee, inspired by the comment of Anderson took up the question if one would be able to sidestep Goldstone's theorem in a relativistically invariant theory. They set up a non-relativistic version of the arguments by Goldstone, Abdus Salam and Weinberg. They then followed it through and argued that also in this case there should be a massless scalar mode. Finally they showed the flaw in the argument and stated that the same would be valid in a relativistic theory.

Their arguments were immediately criticised by Walter Gilbert (Nobel Prize in chemistry, 1980) [35]. He showed that the arguments of Klein and Lee could be given a seemingly relativistic form by introducing a constant vector $n^\mu = (1, 0,0,0)$. He could then show how terms can cancel each other leading to the absence of a massless pole. In the relativistic case there is only one vector at hand, the momentum, k^μ, and the cancellation cannot occur. This was the situation up to the summer of 1964 when the breakthrough finally came.

The BEH-Effect and the Scalar Particle

The solution to the problem of having a relativistic gauge invariant theory with a massive vector particle and hence a force with short range came in the summer of 1964, first in a paper by François Englert and Robert Brout and a month later in two papers by Peter Higgs.

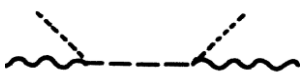
In a paper submitted on June 26, Englert and Brout [36] motivated by the work of Schwinger studied the problem in specific models. They started with an Abelian gauge theory coupled to a complex scalar field, i.e. scalar electrodynamics. They did not specify the complete Hamiltonian but concentrated on the terms involving both the scalar and the vector field which they wrote in the form

$$H_{int} = ie\, A_\mu\, \varphi^* \overleftrightarrow{\partial^\mu}\, \varphi - \, e^2\, \varphi^* \varphi\, A_\mu\, A^\mu,$$

where $\varphi = \frac{1}{\sqrt{2}}(\,\varphi_1 + i\,\varphi_2)$. They then broke the symmetry by giving a vacuum expectation value to the field as $<\varphi> = <\varphi^*> = \, <\varphi_1>/\sqrt{2}$. Hence they gave φ_1 the expectation value, just like Goldstone had done and used the results from Goldstone, Abdus Salam and Weinberg that the other field component φ_2 becomes the Nambu-Goldstone massless particle. They say that φ_1 is orthogonal to φ_2, and one can see that it is not affected by the couplings to the vector field. They did not further comment on this particle but concentrated on the two-point function for the vector field. It is clear from the Hamiltonian that there are now two new contributions to it to lowest order namely the terms

$$H_{int}{}' = -e\, \frac{<\varphi_1>}{\sqrt{2}}\, A_\mu\, \partial^\mu\, \varphi_2 - \frac{e^2}{2}\, <\varphi_1>^2\, A_\mu\, A^\mu.$$

The first term is a coupling where a vector field goes over to the Nambu-Goldstone field and vice versa, while the second term is a pure mass term for the vector field. This is the key observation. In order to keep gauge invariance both terms are necessary. Previous attempts had had only the second term. In a Feynman diagram language the relevant terms to the photon propagator are



The first term comes from the first one in the expression above, where the long-dashed line is the propagator of the Nambu-Goldstone particle φ_2, and the short-dashed line is the insertion of the vacuum expectation value of the remaining field φ_1. This is a completely new type of diagram, while the second diagram comes from the second term, ie. from a new mass term that is treated like an interaction.

Englert and Brout could now compute the two-point function to lowest order to find

$$\Pi_{\mu\nu}(q) = \, (2\pi)^4\, ie^2 <\varphi_1>^2 \left[g_{\mu\nu} - \frac{q_\mu\, q_\nu}{q^2}\right].$$

This expression is gauge invariant and shows that the vector field has acquired a mass of the

form above. The Goldstone theorem holds in the sense that that Nambu-Goldstone mode is there but it gets absorbed into the third component of a massive vector field. A key was to use Feynman diagram techniques. The result was given to first order but they argued that it would go through to all orders, which is straightforward to see using Feynman diagrams.

After this analysis Englert and Brout studied the same problem for a non-Abelian gauge theory and could conclude that also in this case the mechanism works, ie. via spontaneous breaking of the gauge symmetry one gets massive vector particles and no physical massless scalars.

They concluded by showing that the mechanism also works when a condensate is used to break the symmetry as in Nambu's non-relativistic treatment of superconductivity.

In a paper submitted on July 27, Peter Higgs [37] pointed out that there is a case where Gilbert's criticism does not apply, namely in a gauge theory. For such a theory one must choose a gauge and a typical one is the Coulomb gauge which can be written as $\partial_\mu A^\mu - n^\mu \partial_\mu n^\nu A_\nu = 0$, where precisely the constant vector n^μ appears. He then showed how one gets in this case the expressions of Klein and Lee, and how Goldstone's theorem can be violated.

In a second paper submitted on August 31 Higgs [38] studied the same model as Englert and Brout. (He switched indices on the scalar field in comparison with Goldstone and Englert and Brout.) Like Englert and Brout he did not specify the scalar potential completely and called it V, but assumed that it was such that the symmetry is spontaneously broken by a vacuum expectation value $< \varphi_2 > = \varphi_0$. He then studied the equations of motion for small oscillations around this vacuum and introduced a new variable

$$B_\mu = A_\mu - (e\varphi_0)^{-1}\partial_\mu \Delta\varphi_1, \qquad G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu,$$

where he used a gauge transformation to absorb the Nambu-Goldstone mode $\Delta\varphi_1$. He could then read off the equations of motion as

$$\partial_\nu G^{\mu\nu} + (e\varphi_0)^2 B^\mu = 0, \qquad \partial_\mu B^\mu = 0,$$

which he correctly interpreted as the gauge invariant equations of motion for a massive scalar particle. The analysis was performed at the linear level but it was clear that it could be augmented with non-linear terms. He then pointed out that the remaining scalar field φ_2 satisfies the equation of motion

$$[\partial_\mu \partial^\mu - 4{\varphi_0}^2 V''({\varphi_0}^2)]\, \Delta\varphi_2 = 0,$$

which shows the bare mass of the remaining scalar particle. Introducing the specific potential used by Goldstone one gets the mass he got for the field. The fact that Higgs derived an explicit expression for the bare mass of the scalar particle has led to the name "Higgs particle", but as we have seen the particle is also a consequence of the mechanism of Englert and Brout.

Higgs also sketched the generalization to the non-abelian case, namely *SU(3)*, with the scalars forming an octet. He pointed out the possibility of having two non-vanishing vacuum

expectation values which may be chosen to be the two hypercharge $Y = 0$ and isospin $I_3 = 0$ members of the octet. He concluded with a far-sighted sentence, where he pointed out that if there is a mechanism for the weak interactions of this kind it could lead to massive vector particles while the photon can remain massless.

It is clear in retrospect that now all was there to construct a viable unified model for the electroweak theory but it should take some further time.

Further contributions

Goldstone's theorem was also discussed in the Soviet Union. The physicists there at the time were quite isolated but Nambu's, Goldstone's and Schwinger's work was known. It came to be two 19-year old undergraduates, Alexander Migdal and Alexander Polyakov, who found a solution [39]. They had to struggle for about a year to get permission to submit their paper to a journal, since the leading scientists of the time in the Soviet Union did not support their work. The paper could finally be submitted in November of 1965. It is clear though that this paper was completely independent of the development in the West. They set up a field-theoretic framework for a non-abelian gauge theory with a scalar bound state and computed in a spontaneously broken version of the model to all orders in perturbation theory using a Bethe-Salpeter equation to find that the Nambu-Goldstone mode only interacts with virtual particles and is therefore unobservable. Their paper was hence an independent confirmation of the second of Englert's and Brout's mechanisms.

In a paper submitted on October 12, 1964, G.S. Guralnik, C.R. Hagen and T.W.B. Kibble [40] discussed what was essentially the same model as the one by Englert and Brout and by Higgs. They also cited these papers. They showed carefully and in detail how Goldstone's theorem is violated and reached the same conclusions as the previous authors.

Even though there was little excitement about the papers at the time, the authors behind the mechanism did continue to work on it. In a paper from 1966 Brout and Englert together with M.F. Thiry [41] pointed out that the propagator for the massive vector particle has the form

$$\Delta_{\mu\nu}(q) = \frac{g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}}{q^2 - m^2}.$$

In the ultraviolet limit when $q^\mu \to \infty$, the propagator goes like $1/q^2$ just like the propagator for a massless vector particle. For a massive vector particle with an explicit breaking of the gauge symmetry the propagator looks like

$$\Delta_{\mu\nu}(q) = \frac{g_{\mu\nu} - \frac{q_\mu q_\nu}{m^2}}{q^2 - m^2}$$

with much worse divergence properties in the UV limit. This result would be very important for the proof of the renormalisability that was to come.

Higgs also published a longer version of his results in 1966 [42], where he studied scattering processes. He pointed out the important result that the three-point couplings to produce the scalar particle from the vector particle are proportional to the m^2 of the vector particle. This is in fact easy to see. Consider the original coupling

$$A^\mu A_\mu \varphi^2 .$$

Introduce the shifted field φ' as in the work of Goldstone. Then the coupling looks like

$$A^\mu A_\mu (\varphi' + \varphi_0)^2 .$$

Remember that φ_0 is a constant number. By expanding the square and normalizing correctly the expression will look like

$$m^2 A^\mu A_\mu (1 + 2\frac{\varphi'}{\varphi_0} + \cdots),$$

which shows the mass dependence of the three-point coupling.

Also Kibble came back to the problem in a paper in 1967 [43] where he showed carefully how the results are indeed gauge invariant and he also discussed the non-abelian case in more detail than in the work of Englert and Brout. He finally stressed that it would be possible to break only a subgroup of the gauge group and have theories with both massive and massless vector particles. Also Higgs had discussed that in his second paper.

The Weinberg-Salam Model, Renormalisability and the Standard Model

In 1967 Steven Weinberg [44] finally tied the pieces together. He set up a non-abelian gauge theory based on the group *SU(2) x U(1)* like Glashow and Salam and Ward had done much earlier and used the BEH-mechanism to provide masses for the W^+,W^- and the Z^o particles. He introduced masses to leptons by coupling them to the scalar field. This was done by dividing the lepton fields into their chiral parts and having the two parts transform differently. In this way the neutrinos could stay massless. By introducing masses this way Weinberg could show that the three-point coupling where a fermion emits a scalar particle is proportional to the fermion mass, a fact which was to become important later on. Abdus Salam [45] presented essentially the same model in a Nobel Symposium about half a year later. The model was a remarkably attractive proposal but came also a bit early for the physics community. There was a general mistrust in quantum field theory and in the possibility to have a renormalisable such theory with massive vector particles.

The breakthrough came in 1971 when Gerhard 't Hooft [46] presented his first proof that a spontaneously broken non-abelian gauge theory is in fact renormalisable. In the next few years he completed the full proof with Martinus Veltman [47] (Nobel Prize to both, 1999). The result came as a bomb. Finally one had a theory that could give precise numerical predictions for various scattering processes and most of the attention of the particle physics community now focused on the electroweak theory. The proof of 't Hooft and Veltman works for all gauge

theories and many gauge groups would give the same results to leading order in the perturbation expansions. Since the effective weak coupling is very small it took some years of dedicated experiments to settle that indeed the originally suggested gauge group *SU(2) x U(1)* is the correct one. The Nobel Prize to Glashow, Abdus Salam and Weinberg was given in 1979. The experimental discovery of the W^+, W^- and the Z^0 particles [48] with the masses predicted from the model came in 1983 further strengthening the belief in the Weinberg-Salam model. (Nobel Prize to Carlo Rubbia and Simon van der Meer, 1984)

The idea of having a gauge theory also for the strong interactions was a very attractive one. We have seen how Yang and Mills and Schwinger but also Englert, Brout, Higgs, Migdal and Polyakov had had such ideas. In the second half of the 1960's it became clear that such a theory should involve the quarks. In 1965 Han and Nambu [49] suggested a non-abelian gauge theory based on the gauge group *SU(3)* but with quarks with integer charges. Before that O.W. Greenberg [50] had suggested that quarks should satisfy parastatistics which can be interpreted as if they have an *SU(3)* quantum number. In 1967 new experiments were started at SLAC, where electrons were scattered off protons in deeply inelastic scattering processes. The results could be interpreted as if the photons scattered from point-like constituents with the quantum numbers of quarks [51] (Nobel Prize to Jerome Friedman, Henry Kendall and Richard Taylor, 1990). The experimental results also showed remarkable scaling properties in the asymptotic limit proving earlier theoretical results of James Bjorken [52]. The idea now was to understand how a physical theory could include scaling, and in 1970 Kurt Symanzik [53] argued that only theories where the effective coupling constant goes to zero when the energy goes to infinity could have this property. The theory should be "asymptotically free". Few believed that an ordinary quantum field theory could have this property. It was known that in QED the opposite is true. However in 1973 David Gross and Frank Wilczek [54] and David Politzer [55] reported that indeed non-abelian gauge theories could have this property. (Nobel Prize to the three, 2004). Now the road for a theory for the strong interactions was opened and Gross and Wilczek [56] suggested that the correct theory was a theory with an *SU(3) colour gauge group* with quarks in the triplet representation ("three colours"). This came to be called *Quantum ChromoDynamics (QCD)*. The possibility of having quarks in a triplet representation interacting with a vector particle had been discussed the year before by Harald Fritzsch and Gell-Mann [57] in an attempt to catalogue all possible models.

The Standard Model for Particle Physics (SM) had now been born, based on the gauge symmetry *SU(3) x SU(2) x U(1)*, with the symmetry spontaneously broken to *SU(3) x U(1)*. This model has in the last thirty years been verified with exquisite precision. The last remaining piece has been to show how the symmetry was spontaneously broken, which of the two mechanisms that Englert and Brout had suggested - the one with a fundamental particle or the one with composite, is chosen by Nature. The favourite choice has been to look for a new scalar particle, but not until one was found could this question be settled. We now know the answer thanks to an unprecedented effort by thousands of experimental particle physicists.

The Experimental Hunt for the Higgs Boson

The Large Hadron Collider (LHC) at CERN is at present the world's most powerful particle accelerator. It has been built in the 27 km long tunnel that previously housed LEP (the Large Electron Positron Collider) and incorporates – in addition to hundreds of beam focusing magnets – 1232 superconducting 8.3T dipole magnets, bending the beams around the circumference of the LHC. The LHC is capable of accelerating protons to energies of 7 TeV. The LHC design allows circulating beams of protons and heavy ions such as lead to collide at four interaction points where the collision outcome is studied by (at the moment) seven experiments: the general-purpose complexes ATLAS [58], CMS [59] and ALICE [60], and the specialised LHCb, TOTEM, LHCf and MoEDAL [61].

The start of the LHC-era dates back to two workshops, which took place in Switzerland in 1984, the year following the discovery of the weak force carriers W and Z. The discovery had established the SM as the correct theory with $SU(2)\times U(1)$ as the correct gauge symmetry describing its electro-weak segment, excluding other speculations. A puzzle remained, however: The SM uses the BEH-effect in order to spontaneously break the gauge symmetry to U(1). As we have seen before there are two different ways to implement this. Which of these two had Nature chosen?

The physical manifestation of a new field would be a new fundamental particle, now commonly called the Higgs boson (or Higgs for short), and the ultimate confirmation of the validity of this mass-generating mechanism – the experimental discovery of this new particle. Unfortunately, the Brout-Englert-Higgs (BEH) theory does not predict the mass of the particle. It is given by [62]

$$m_H = \sqrt{\frac{\lambda}{2}}\, v,$$

where λ, the self-coupling parameter, is not predicted by the theory but must be determined experimentally by a precise measurement of m_H. (Note that a slightly different normalisation is used than in the original paper by Goldstone [29].) The vacuum expectation value v for the gauge field of the Higgs particle is, on the other hand, fixed within the Standard Model by the experimentally determined Fermi constant G_F:

$$v = (\sqrt{2}\, G_F)^{-1/2} \approx 246 \text{ GeV/c}^2.$$

Since λ is unknown, the mass of the Higgs boson cannot be predicted but a lower and an upper bound can be determined indirectly from theoretical arguments. If m_H is too small the electro-weak vacuum is meta-stable and the Higgs potential has a second (global) minimum to which the Universe will eventually repair. If, on the other hand, m_H is too large the Higgs self-coupling diverges at some energy scale Λ below the Planck scale. This is the scale where the SM breaks down and new physics must enter. Furthermore, if m_H would be much larger than 1 TeV

"unitarity" would be threatened with, for instance, the (perturbatively determined) probability for the process $W + W \rightarrow W + W$ exceeding unity.

In 1984, the only realistic alternative for an accelerator to achieve beam energies in the TeV range was a hadron collider, relying on well-known technology used most recently then at the CERN $Sp\bar{p}S$ and at the Tevatron in the USA. No high-energy electron-positron collider had yet been built and those in the planning stage aimed at energies on the order 0.1 TeV. So, while Europe decided to go for the LHC, the U.S. – in competition – elected to aim for a machine with an energy reach at least twice that achievable in the planned LHC/LEP tunnel (i.e. 40 TeV). This so-called Superconducting Super Collider (SSC) project was eventually discontinued in 1993 due to escalating costs. Since then USA has turned its attention to the LHC project and to the two collaborations ATLAS and CMS and contributed massively to them.

The LHC project was enthusiastically supported by Rubbia, Director General of CERN during the critical period 1989 – 1993, and by his successor C. Llewellyn Smith, and was finally approved by CERN Council in 1994. The accelerator design based on superconducting magnet technology was worked out under the leadership of G. Brianti, Technical Director for CERN during 1981 – 1989 and hence Associate Director for Future Accelerators (1990 – 1993). His successor, L. Evans, was responsible for the LHC project during the critical construction and commissioning phase. S. Meyers followed him in 2009; a year before LHC started physics runs.

The LHC project was supported not only by CERN member states. In 1997, USA agreed to participate, contributing $ 531 M to the machine and the experiments. Today, more than 1700 researchers engage in ATLAS and CMS. In the addition to the U.S., Japan, Canada, India and Russia also made significant contributions, making the LHC a world project.

Higgs particle searches at LEP and the Tevatron

Higgs searches prior to the commissioning of SLC, LEP and the Tevatron were only sensitive to Higgs masses below a few GeV and will not be mentioned further [63].

Experimental Higgs searches are challenging for at least two reasons: the theoretically allowed mass range is large and the predicted Yukawa couplings to the fundamental fermions (quarks and leptons i.e. the essential components of colliding beams) are proportional to the fermion mass and hence small (except perhaps for the top quark). For this reason, the probability for direct Higgs detection at an electron-positron collider like LEP, i.e. the reaction $e^+ + e^- \rightarrow H^0$, is tiny. The most important process at LEP1, which operated at a centre-of-mass energy close to the Z^0 mass, was instead the so-called *Higgs-strahlung*

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

with the virtual Z-boson (Z^*) decaying into a lepton-anti-lepton pair (like $\mu^+ \mu^-$ or $e^+ e^-$) or a quark-anti-quark pair, $q\bar{q}$. The reaction cross section for this process involves the triple boson

coupling ZHH which is relatively large, proportional to the square of the Z-boson mass. The LEP experiments achieved maximum sensitivity for the channel

$$e^+ + e^- \rightarrow Z^0 \rightarrow Z^* + H^0 \rightarrow \nu + \bar{\nu} + b + \bar{b}$$

with the virtual Z branching into neutrinos and the Higgs decaying to b-quarks. During phase 1 of LEP, which lasted 6 years, the four LEP experiments recorded and analysed in total over 17 million Z decays. In the absence of an observation, the mass region below 63.9 GeV/c^2 could be excluded at 95% confidence level (C.L.) by the ALEPH experiment [64].

LEP2 started operation in the summer of 1995 at a centre-of-mass energy (E_{CM}) of 130 GeV. The energy was then increased in steps up to 209 GeV until the year 2000 when LEP running was discontinued. During that time, the four experiments collected approximately 2.5 fb^{-1} at E_{CM} above 189 GeV. The dominant reaction at LEP2 was again *Higgs-strahlung* but with the final state Z-boson on the mass shell, which improved the sensitivity. Maximum experimental sensitivity was attained for the process

$$e^+ + e^- \rightarrow Z^0 + H^0 \rightarrow q + \bar{q} + b + \bar{b}\,,$$

where q stands for any quark (lighter than top) and b again for the b-quark. The well-known mass of the Z^0 could now be used to suppress background reactions of no interest. No Higgs particle was found and a final combined lower mass limit from all four LEP experiments was published in 2003: 114.4 GeV/c^2 (at 95% C.L.) [65].

Using the LEP data together with more than half-a-million analysed Z^0's from the SLAC Linear Collider (SLC) at Stanford, and later also measurements from the Tevatron at Fermilab, the allowed mass range for the presumptive Higgs boson could be constrained considerably within the framework of the SM. Including the latest precisely determined values for the mass of the top-quark [66] and the W-boson [67] in a global fit of all available precision electroweak data (like the Z^0 line shape and asymmetries in fermion production at the resonance) results in a predicted Higgs mass of 94^{+29}_{-24} GeV/c^2 (68% C.L.) and an upper mass limit of 152 GeV/c^2 [68].

Since the direct searches at LEP2 exclude Higgs masses below 114.4 GeV/c^2, the allowed mass range for a SM Higgs boson becomes: 115 – 152 GeV/c^2. This is illustrated in the so-called *blue band* plot, which shows the result of the global χ^2 fit of the SM to the precision electro-weak measurements – in terms of the Higgs boson mass. The blue band represents the theoretical (SM) uncertainty. The mass region excluded by the LHC experiments is also shown.

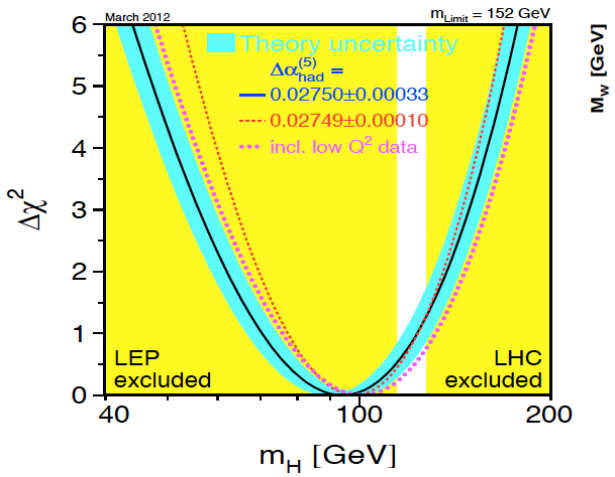


Figure 1: "The blue-band plot" [68] shows the global fit of the Higgs mass based on precision electro-weak measurements at LEP, SLC and the Tevatron. Measurements at low energies have been included but play only a minor role. The blue band shows the theoretical uncertainty within the SM. The mass region excluded by the LHC (as of December 2011) is also shown.

The primary production processes for Higgs at a $p\bar{p}$ collider like the Tevatron are the so-called gluon fusion $g + g \rightarrow H^0$ and again *Higgs-strahlung* $q + q\,(\bar{q}) \rightarrow W(Z) + H^0$. The Higgs production cross-section is much higher than at LEP but at a hadron collider it is much harder to disentangle signal from background. The most recent results combine data from the two experiments CDF and D0 using the full Tevatron Run II integrated luminosity of up to 10 fb^{-1} per experiment. The mass range 90 – 200 GeV/c^2 was investigated and two mass regions were excluded: 90 – 120 GeV/c^2 and 140 – 184 GeV/c^2. Fig. 2 shows the ratio of the experimentally determined upper limit on the SM Higgs boson production rate and the predicted SM rate. An excess of events with respect to the background-only hypothesis (the dashed line in the middle of the green band) is seen in the mass interval 115 – 140 GeV/c^2. When correcting for the possibility of picking a random background fluctuation (*the look-elsewhere effect*), the significance at 125 GeV/c^2 (the Higgs-boson mass estimate from LHC) is somewhat above 2 standard deviations [69].

Higgs searches at the LHC

The first physics run of the LHC started on March 30, 2010, at a centre-of-mass energy of 7 TeV, i.e. proton energy of 3.5 GeV per beam. This was sufficient to search for new particles with mass below 1 TeV.

By that time, the original proto-collaborations founded in 1989 – 1992 had coalesced into several large international projects: ATLAS and CMS running huge multi-purpose particle detectors with the aim of exploring *pp* collisions, ALICE aiming to study heavy ion events – and a smaller project LHC*b* with interest in *b*-quark production at high energies. ATLAS and CMS presently count about 3000 researchers, each.

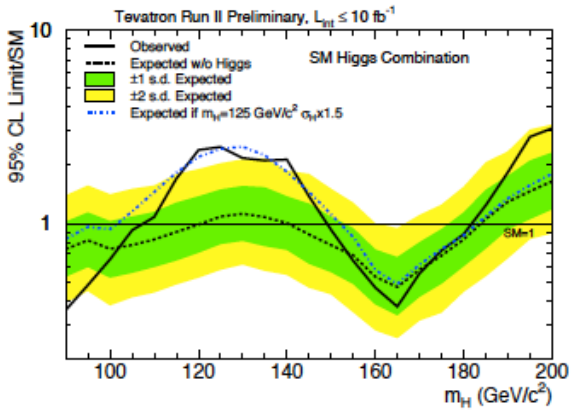


Figure 2: Preliminary result from the Tevatron. A small excess of events (significance 2.2 standard deviations) is observed in the mass 115 – 140 GeV/c² [69].

To convey some idea of the complexity and size of the LHC detectors, fig.3 shows as an example the ATLAS detector with its cylindrical geometry and axial symmetry with respect to the direction of the colliding beams. ATLAS (like CMS) consists of several sub-detectors, which can identify the particle species created in *pp* collisions, reconstruct their trajectories with 10 μm precision and measure the momenta and energies. The huge amount of recorded information allows the LHC experiments to pick out single *pp* collisions among the score or so occurring when two accelerated proton bunches with 10^{14} protons each collide at the centre of the detector every *50* ns. The final state of the individual *pp* collisions can be reconstructed over more than 98% of the total solid angle.

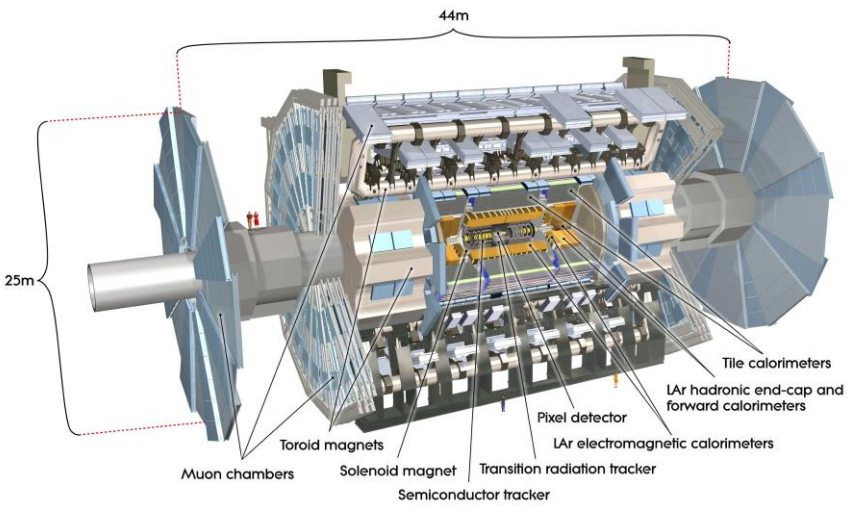


Figure 3: The ATLAS detector with its most important components. ATLAS has a length of 44 m, a diameter of 25 m and registers information from about 90 million individual sensors.

To have a reasonable chance of recognising the interesting Higgs events against a billion times larger background of "ordinary" inelastic collisions, the experiments need to focus on Higgs decays with an easily recognisable signature. It turns out that the decays

$$H^0 \rightarrow \gamma + \gamma \text{ (called } \gamma\gamma \text{ decay) and } H^0 \rightarrow Z + Z^* \rightarrow l^+ + l^- + l'^+ + l'^- \text{ (called } 4l \text{ decay)}$$

although rare – give a high sensitivity over a wide mass range. The l (l') above stands for electron or muon.

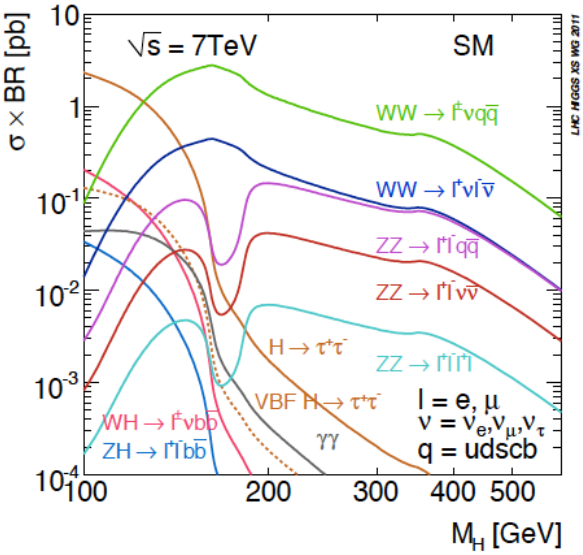


Figure 4: Production cross-section × branching fraction for various Higgs boson decay channels, as a function of the Higgs boson mass – at E_{CM} = 7 TeV ($s=E_{CM}^2$).

Fig. 4 shows the – within the SM – predicted Higgs production cross section (in pico-barn) times the branching fraction for various possible decay modes of the Higgs, at a centre-of-mass energy E_{CM} = 7 TeV and as a function of the Higgs mass. Although the reconstruction of the decay channels "$\gamma\gamma$" and "$4l$" may be relatively "easy", fig. 4 shows clearly that the probability for the Higgs boson to decay that way is tiny – only 0.2% (0.013 %) of all Higgs bosons with mass around 125 GeV/c^2 decay to $\gamma\gamma$ ($4l$). It is also apparent from fig. 4, that the decay

$$H^0 \rightarrow W^+ + W^- \rightarrow l^+ + \nu_l + l'^- + \bar{\nu}_{l'}$$

(again with l (l') indicating electron or muon) is more likely than either $\gamma\gamma$ or $4l$ over a large fraction of the investigated mass range 100 – 600 GeV/c^2. However, due to the escaping neutrinos this channel cannot be used for a precise mass determination.

Both ATLAS and CMS took data from the very beginning, when the first physics runs at the LHC started in March 2010. Each experiment recorded about 35 pb^{-1} that year at E_{CM} = 7 TeV. No significant deviation from background was observed in any of the Higgs searches [70, 71].

During 2011, the experiments registered another 4700 pb^{-1} (4.7 fb^{-1}) each at 7 TeV and with this increased statistics searches started to show small deviations from background at a Higgs mass close to *125* GeV/c^2. According to expectation (fig. 4) for this integrated luminosity, each experiment should at that time have "caught" about 200 $\gamma\gamma$ decays and a few $4l$ decays.

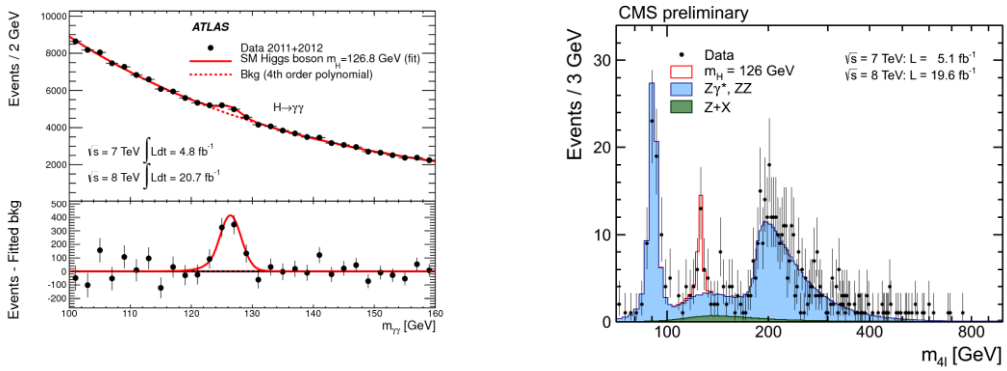


Figure 5: The reconstructed mass of the Higgs-particle in the $\gamma\gamma$ channel (ATLAS [75]) and in the $4l$ channel (CMS [76]).

In 2012, the LHC successfully increased the beam energy to 4 TeV and the instantaneous luminosity by a factor 1.8 to 6.8 $\times 10^{33}$ cm^{-2}s^{-1}. Until the end of June that year, each experiment registered ~ 5.6 fb^{-1} at the centre-of-mass energy 8 TeV and could study the combination of data from 2011 and 2012. In July that year, both ATLAS and CMS could finally claim discovery (at a significance of more than 5 standard deviations which is the norm in particle physics) of a new particle with properties consistent with those expected for a SM Higgs boson [72,73]. This "Higgs-like" particle has a mass of 125 – 126 GeV/c^2. The fact that both experiments independently made the observation strengthened the claim – which was further consolidated by the updated Higgs results from the Tevatron, which appeared on July 2 [74].

The LHC experiments continued to increase their data sets until the end of the year 2012 when LHC was closed for technical upgrades with the aim to achieve the design beam energy of 7 TeV and the design luminosity of 10^{34} cm^{-2}s^{-1} in 2015. Fig. 5 includes the full two-year data set (2011 + 2012) and shows the mass of the new particle reconstructed from the photon energies and directions in the $\gamma\gamma$ channel (ATLAS) and from the lepton energies and directions in the $4l$ channel (CMS). Averaging over all decay channels, CMS [77] finds the mass value

$$m_H = 125.3 \pm 0.4\,(stat) \pm 0.5(syst)\ \mathrm{GeV/c^2}\,.$$

ATLAS finds somewhat different mass in the $\gamma\gamma$ and the $4l$ channels (although the mass difference is consistent with zero within 2.4 standard deviations). The channel averaged mass value from ATLAS [75] is consistent with that found by CMS, and given by

$$m_H = 125.5 \pm 0.2(stat) \pm^{+0.5}_{-0.6}(syst)\ \mathrm{GeV/c^2}$$

The available LHC data has been scrutinized in every which way to establish if the characteristics of the new particle indeed are those expected for the Higgs boson within the framework of the SM. Besides mass and electric charge, this implies careful measurement of the branching fractions for decays into various final states (fig. 6) and – importantly – determination of the spin and parity quantum numbers. The Higgs particle is unique among the fundamental particles by carrying the quantum numbers of the vacuum $J^P = 0^+$.

The results from all these measurements confirm the consistency with the expectations for the SM Higgs. ATLAS measurements of the branching fractions show minor discrepancies mainly in the $\gamma\gamma$ channel at less than 2 standard deviations. The CMS measurements agree well with expectations.

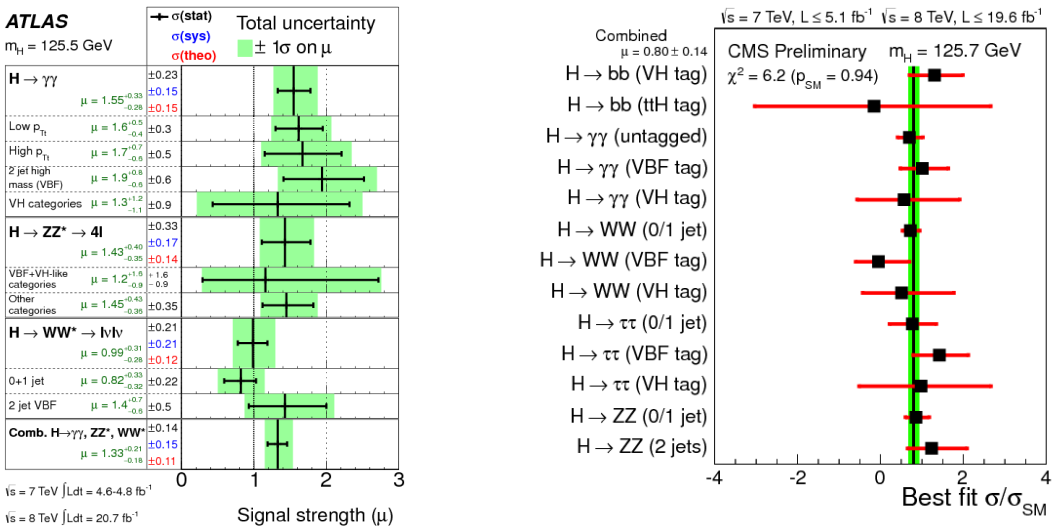


Figure 6: The measured signal strengths for Higgs boson decays normalised to the SM prediction ($\mu=\sigma/\sigma_{SM}$); Left panel: ATLAS [75] and right panel: CMS [78].

The measured branching fractions allow determination of couplings of the Higgs boson to the fundamental fermions (quarks and leptons)

$$g_{Hff} = \frac{m_f}{v}$$

and to the weak force mediators, the vector (V) bosons W and Z

$$g_{HVV} = 2\frac{{m_V}^2}{v}.$$

The definitions follow from ref. [62]. The Higgs self-couplings g_{HHH} and g_{HHHH} – although important – can most probably not be measured at the LHC unless the luminosity can be increased far above the design value. The analysis is complicated and what is shown in fig. 7 are

the ratios of the measured couplings to SM predictions expected to reflect such deviations as may exist.

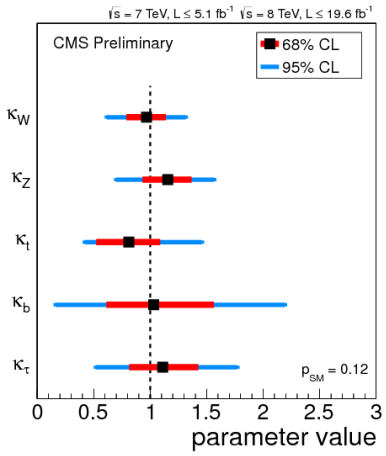


Figure 7: Summary of fits for deviations of the Higgs couplings to the τ lepton, the b and t quarks, and the W and Z. The scaling factors κ are defined in such a way that cross-sections and decay widths scale as κ^2 compared to the SM prediction. The best-fit value of κ should be 1 if there is no deviation from SM. (twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13005Twiki#Test_of_Fermion_and_Vector_Boson)

Updated results from analyses aiming to determine more precisely the Higgs boson spin, its production properties and its couplings are reported continuously, at conferences and in journal publications. In July this year, the ATLAS collaboration submitted two manuscripts to Physics Letters B [75, 79] based on analysis of all data from 2011 – 2012 corresponding to an integrated luminosity of about 25 fb^{-1}. In [79], data is studied to compare the SM hypothesis for spin-parity $J^P = 0^+$ for the Higgs with the alternative hypotheses: $J^P = 0^-, 1^+, 1^-$ and 2^+. The decay channels $\gamma\gamma$, $4l$ and $H^0 \rightarrow W + W \rightarrow l^+ + \nu_l + l'^- + \bar{\nu}_{l'}$ (with l = e or μ) are investigated since they all provide variables which depend on the spin and parity of the decaying particle (ex. the angular distributions of the photons or leptons). According to the Landau-Yang theorem [80, 81], a spin-1 particle cannot directly decay into a pair of photons. Therefore, the spin-1 hypothesis is strongly disfavoured by the observation of the $\gamma\gamma$ decay. The ATLAS analysis shows that data is consistent with the SM expectation 0^+ whereas the alternatives are excluded with high confidence. Fig. 8 from [79] shows as an example the distribution of the test statistic q (logarithm of the ratio of likelihoods) used to distinguish between the two hypotheses 0^+ and 0^- in the $4l$ decay channel. The solid blue line corresponds to 0^+ and the dashed red to 0^-. The solid vertical line indicates the observed value of q. The data is in agreement with the 0^+ hypothesis whereas 0^- is excluded at C.L. 97.8 %. The CMS collaboration has published a similar study [76] also finding that the 0^+ hypothesis is favoured over $J^P = 0^-, 1^+, 1^-$ and 2^+.

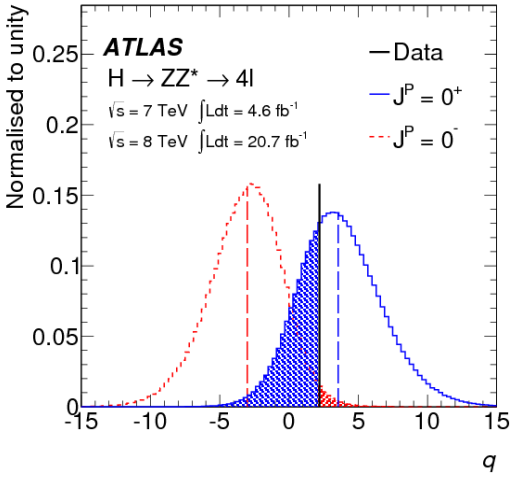


Figure 8: Comparison of the hypotheses 0^+ and 0^- in the 4l decay channel, ATLAS collaboration [79].

Outlook

All measurements to date confirm that the properties of the newly discovered particle are consistent with those expected for the fundamental scalar boson predicted by the BEH-mechanism. The discovery is a milestone for particle physics and a tremendous success for the Standard Model. However, far from closing the book it opens a number of new exciting possibilities: Theorists believe that the SM most probably is but a low-energy approximation of a more complete theory. If this were not so, quantum mechanical corrections to the Higgs mass would drive m_H towards the Planck scale – unless "unnatural" cancellations occur. Therefore, extensions of the SM are proposed, keeping the successful features of the SM but at the same time introducing "new physics" in a way, which stabilises m_H at its low value, which is in accordance with SM expectations (fig. 1). Supersymmetric extensions of the SM predict in their minimal form the existence of five Higgs bosons, three neutral and two charged. The lightest of the neutrals should have couplings similar to the SM Higgs and a mass below 130 GeV/c^2. An alternative is "Little Higgs" models where new strong interactions are introduced at the scale (of tens) of TeV. The lightest scalar in these models also resembles the SM Higgs. In yet other models, electro-weak symmetry breaking can be achieved without introducing fundamental scalar fields but with composite scalar or pseudo-scalar new particles. In some of these theories, a composite light scalar could mimic the Higgs. In addition certain models, which explore addition of extra space dimensions beyond the standard 3+1 spacetime, may also feature a Higgs-like particle. For a discussion of all these models see [62].

To discriminate between these theories one would – apart from searching for additional new particles – need to precisely measure the Higgs boson self-coupling. Unfortunately, such a measurement has to wait for the presently discussed High Luminosity LHC (HL-LHC) and will be challenging even then since the Higgs pair production cross section is small. What can be done on a much shorter time scale is to precisely measure the mass and the branching fractions

of the Higgs and search for its rare decays. Persistent deviations from SM expectations will help distinguish between the different theoretical possibilities.

The year 2015, when the LHC in 2015 finally reaches its design parameters, will in this sense mark the start of a new era, that of precision Higgs measurements.

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