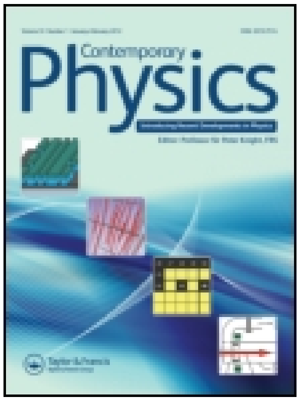
This article was downloaded by: [Rutgers University]
On: 12 December 2013, At: 09:58
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Contemporary Physics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tcph20

Higgs boson: beginning of the end or end of the beginning?

Frank Close [a]
[a] Rudolf Peierls Centre for Theoretical Physics, University of Oxford , Oxford , OX1 3NP , UK

Published online: 20 Jul 2012.

To cite this article: Frank Close (2012) Higgs boson: beginning of the end or end of the beginning?, Contemporary Physics, 53:4, 295-300, DOI: 10.1080/00107514.2012.711578

To link to this article: http://dx.doi.org/10.1080/00107514.2012.711578

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Contemporary Physics
Vol. 53, No. 4, July–August 2012, 295–300

Higgs boson: beginning of the end or end of the beginning?

Frank Close*

Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford OX1 3NP, UK

(*Received 10 July 2012; final version received 10 July 2012*)

The announced discovery of the Higgs boson at CERN's Large Hadron Collider on July 4 is described, put into context, and its implications assessed.

Keywords: Higgs boson; Large Hadron Collider

That CERN would make an announcement on July 4 about results from the Large Hadron Collider (LHC) had been known for weeks. What was not known was whether they would be able to announce a clear discovery of the long sought Higgs boson, or still be left with a tantalising hint, a "maybe, but we need more data to be sure". Reading media reports, and rumours on blogs, there seemed little doubt. A signal at around 4 sigma seemed assured; 5 sigma however is what the physicists seemed to require in order to claim a discovery. As July 4 approached, the rumours became a metaphor for the physics: did hearing the same rumour from different sources imply signal or mere noise? Everyone had known for more than a year that the ATLAS and CMS experiments at the LHC were seeing interesting data, which had the characteristics of decays of the Higgs boson but which could also be due to other mechanisms within the standard model. Separating signal from noise was the challenge, for public and scientists both.

That such stories had credibility was, in my opinion, remarkable for two reasons. First was a scientific one.

In December 2011 the two teams had announced results of searches for decays of the Higgs in various channels that, theoretically, ought to be rather clean. These primarily were its decays to two photons, or to two Z bosons revealed by their subsequent decay to 4 leptons – pairs of electrons and positrons or of muons. The experiments had reported tentative signals with a significance of around 3 sigma, at a mass of about 125 GeV for their parent, the putative Higgs boson. There was, however, a potential problem, which disturbed many: the two experiments did not agree precisely on the actual mass for their signals. This was probably just a quirk in the statistics, but for some it raised questions as to whether two fluctuations in two experiments were being incorrectly fused together in people's perception falsely as evidence for a single genuine effect.

By early June 2012 I was talking with Rolf Heuer, the Director General of CERN. The LHC had taken as much data in the previous six months as it had accumulated previously in total. From this alone, the expected statistical significance of any genuine signal could be expected to increase by the square root of 2. Given increased understanding of the experiment, of potential backgrounds, and other intelligence that always grows during an ongoing experiment, one might hope for somewhat greater than that. So, simple statistics brought one to a sigma around 4 or above. Physicists capable of multiplying by the square root of 2 gained guru status in some media. Such considerations were the source of many rumours. However, among all this noise was there some signal that had leaked?

The second reason for my scepticism was that, during most of the 10 days leading up to July 4, I was privileged to be with Peter Higgs. We were at a summer school on particle physics at Erice, in Sicily (Figures 1 and 2). This was far enough away from the media to provide him some peace, and near enough to central players in the LHC experiments to expect some insight as to what might happen. In summary: until at least June 30, even Peter Higgs would have had to admit, like Manuel in Fawlty Towers: "I know nothing".

But then events conspired to change everything. To understand how, we first should review some of the history of the boson, in order to introduce characters, and assess the significance of what is now unfolding.

I have narrated the history at length in my book *The Infinity Puzzle* [1]. Here in a nutshell is part of it.

---

*Email: f.close@physics.ox.ac.uk

ISSN 0010-7514 print/ISSN 1366-5812 online

http://dx.doi.org/10.1080/00107514.2012.711578
http://www.tandfonline.com

Figure 1. Peter Higgs with A. Zichichi, Director of the school; in rear D. Nanopoulos, who with Ellis and Gaillard first discussed detailed Higgs phenomenology in 1976, G. 't Hooft, Nobel Prize 1999 after using Higgs mechanism to prove renormalisability of Quantum Flavordynamics, and F. Close.

Figure 2. Peter Higgs trapped by a field of young physics students at Erice, gains inertia and re-enacting David Miller's famous explanation of the mass mechanism, as described in *The Infinity Puzzle* [1].

In 1963 Anderson [2], inspired by superconductivity, noted that the finite range of magnetic field penetration into the surface of a superconductor is as if the photon has become effectively massive. The received wisdom was that if a gauge boson (such as the photon, or W and Z) gains mass by a mechanism known as hidden symmetry, or spontaneously broken symmetry, a massless "Goldstone boson" should arise.

Attempts to apply such ideas in particle physics had stalled due to the empirical absence of such Goldstone bosons. Anderson, however, pointed out that in superconductivity, empirically there is no massless Goldstone boson. He conjectured, correctly, that the two massless fields – the photon and the Goldstone – could somehow mutually disappear, leaving a massive photon. However, he did not demonstrate a mechanism for this.

He did, however, provide a pedagogic example, which is the nub of the subsequent developments that have now born fruit.

Anderson considered the propagation of electromagnetic waves through plasma [1 (see Chapter 8),2]. Only waves with frequencies above the plasma frequency can penetrate (you can see starlight through the ionosphere even though radio waves may be reflected). A creature living inside the plasma would perceive electromagnetic waves only above that minimum frequency, which by the relation between frequency and energy, together with $E = mc^2$, makes it appear as if the photon has a mass. Furthermore, whereas in a vacuum a photon only has transverse oscillations, within the plasma it induces a longitudinal plasma wave, which provides the "missing" longitudinal vibration associated with a massive vector boson. Thus in the presence of a suitable additional field, a vector field can gain the attributes of a massive particle, without destroying gauge invariance. Replace Anderson's plasma by an all-pervading scalar field, with certain special properties, and there is the possibility of a vector boson gaining mass.

In 1964, within the space of a few weeks, three independent sets of theorists demonstrated this mechanism in relativistic field theory. This has become known as the Higgs mechanism, which is unfairly named as Higgs was but one of the six, and moreover, Robert Brout and Francois Englert had beaten him into print. Shortly afterwards, Gerry Guralnik, Dick Hagen and Tom Kibble, published their paper on the subject. They too had independently discovered the mass mechanism, and been scooped (see [1], Chapter 10, note 11).

As I discovered when researching *The Infinity Puzzle*, two young Russians, Sacha Migdal and Sacha Polyakov had already discovered this mass mechanism. However, they were discouraged by negative comments from senior scientists. They eventually published, but only after the above sextet had done so [3].

Unique among these, Higgs drew attention to a consequence of the theory, and, importantly, one that is the essence of testing the idea. The theory implies the existence of a massive boson, which has no spin – in the simplest version as discovered by the sextet in 1964. In 1966 he wrote a Lagrangian for the decay of this massive boson into two massive gauge bosons, for the case where the gauge boson masses had been generated by the mass mechanism [4].This amplitude is proportional to that mass, with the result that the pattern of decays of the massive "Higgs boson" into families of such particles favours heavier rather than lighter particles (once phase space effects are taken into account). This is unusual, and a test of the mechanism, which is the root of the searches at the LHC: produce the boson and study the pattern of its decays.

In 1967 Tom Kibble developed the ideas further by incorporating aspects of group theory for situations where several gauge bosons are present [5]. He showed presciently how it is possible for some gauge bosons to gain mass while others remain massless. This we now realise is how the real world operates, with the W and Z bosons, of the weak force, being massive (over 80 GeV) while the photon remains massless.

Kibble's 1967 work had other consequences for the development of physics. It directly inspired Abdus Salam to incorporate such ideas onto the model that he and J.C. Ward had constructed, which marries electromagnetic and weak forces. And it also led Weinberg to his celebrated "model of leptons" that same year [6]. It was for these ideas that Salam and Weinberg subsequently shared the 1979 Nobel prize for physics.

Weinberg's paper made a further step in applying the idea. Up to that point the mass mechanism had been invoked as a means to generate masses for gauge bosons; Weinberg suggested that it also apply to leptons – the fundamental fermions, such as the electron, which do not feel the strong force. He did not apply it to quarks because, as he told me, he did not at that time believe in them.

Thus in principle one ought to keep in mind the possibility that the mass mechanism might be universal or selective. That it applies to gauge bosons is the original motivation, addressed by the sextet in 1964 to resolve fundamental problems in symmetry breaking that had been noticed by Goldstone and others in the early 1960s. That it may also apply to leptons is logically separate. There is no reason why it is required, nor any why it should not be. Thus one of the empirical questions to be resolved at LHC is whether the mechanism applies to leptons, and quarks, as well as to gauge bosons.

Contrary to many media reports, the Higgs field is not the source of all mass, only that of the most basic of particles. It is the atomic nuclei in your body that give about 99.5% of your weight. This has nothing to do with the Higgs field, but is a consequence of quarks being confined within nucleons. What the Higgs field does is potentially give structure by acting on the fundamental particles, such as the electron found in the outer reaches of atoms, and the quarks, which are the ultimate seeds of the atomic nucleus. Your weight has little to do with the "Higgs mechanism", but your size does.

The size of the hydrogen atom is determined by the dimensionless quantity alpha, which is approximately 1/137, and the mass of the electron. Were the electron mass zero, the hydrogen atom would have infinite size – i.e. would not exist.

The mass of the proton is only slightly affected by whether or not quarks have mass. However, according to chiral symmetry, the masses of the up and down quarks (the constituents of nucleons) are proportional to the square of the mass of a pion [7]. As it is the pion that gives the strong force between protons and neutrons, which form atomic nuclei, and the range of this force is inversely proportional to the pion's mass, the compact size of atomic nuclei is directly related to the mass of these quarks. Thus the existence of compact complex nuclei, which seed the chemical elements, is linked to the quarks having mass.

Whereas the photon, the agent of the electromagnetic force, has no mass, its analogue for the weak force as manifested in beta decay – known as the W boson – is massive. This weak force controls the first stage of the solar fusion cycle, where protons transmute through a series of processes to form helium. The weak force is so feeble that, if you were a proton in the sun at its birth, today, 5 billion years later, there would still be only a 50:50 chance that you had undergone fusion. Had the W had no mass at all, like the photon, the sun would have expired very quickly. Thus the fact that intelligent life has managed to evolve is, in part, because the sun has lasted so long. Thus our existence is consequential on the Higgs field.

The actual mass of the Higgs boson is not predicted by the theory, but its production and decay properties are. Theorists used these to calculate the circumstances at the LHC where the boson, assuming that it exists, might show up most cleanly against competing backgrounds. For a boson in the region around 125 GeV, where it was eventually confirmed, these included the decay into two photons, and into four leptons (Figure 3), with the possibility of decays onto pairs of bottom quarks also being a possibility at the lower energy Fermilab Tevatron.

It was news of these channels that was eagerly awaited at the end of June 2012.

Rumours in the media were rife. As I said earlier, even Peter Higgs had no inside information. Although no one leaked details, we received hints that ATLAS would be able to say something "one way or the other", and as one cannot prove a negative, this was thought to be positive. The news finally reached Erice by a bizarre sequence of events.

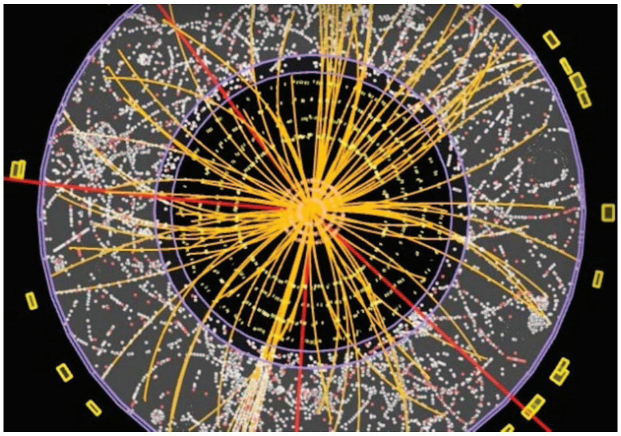


Figure 3. An event that is consistent with the decay of a Higgs boson into four leptons (the red trails). Courtesy CERN.

CERN had not issued any formal invitations to the five surviving theorists, contrary to reports in British newspapers. If they had done, this would have implied that CERN had a definite discovery to announce, and that they were certain that they had found the eponymous boson. Until both experiments had reported, and each collaboration seen the other's data for the first time, this would be premature. What in fact had happened was that, about a week before the conference was due to take place, CERN learned that two of the five, the Americans Gerry Guralnik and Dick Hagen, planned to attend. This led CERN to alert the remaining trio, including Peter Higgs, with the news that they would be welcome and that, although no details could be released of what would be said, CERN suspected that "Peter [Higgs] will regret it if he is not there" [8]. So the presence of four of the theorists (Tom Kibble remained in London) had less significance than the media believed.

Following this news from CERN, we learned at Erice that ATLAS had finalised their presentation and were near to the critical 5 sigma. Peter Higgs' understated response: "That sounds good enough", with the afterthought, "provided that CMS are more or less in agreement" [9]. There was one possible hiccup remaining: did the two experiments agree? If they did not, doubt would remain; if they did … ..

When the CMS leader, who was due to come to Erice the next day, cancelled at the last minute, this was taken to be positive, the alternative possibility that he had discovered a bug in some crucial program after two years being regarded as unlikely. Peter Higgs rebooked his tickets so as to fly from Palermo to Geneva via Rome. I was due to return to the UK via Milan. Aware of the approaching media storm, and in the hope of protecting Higgs for some while further, Alan Walker, his aide from Edinburgh, took a photo of Higgs and me after check-in, and this was tweeted to media, referring to our separate travels but written in such a way that it would be easy to expect that Higgs would be arriving in Geneva from Milan, rather than Rome. This seems to have bought him one more day of privacy. From July 4, everything changed.

ATLAS and CMS agree that they see a boson decaying into two photons, and also into two Z (revealed by the decays into four leptons). Fermilab reported on July 2 that they see hints (at between 2 and 3 sigma) of a signal in decays to bottom quarks. However, there are some differences of detail to be settled, once more data accumulate.

The observation of the boson in two photons almost certainly implies that it has spin 0, in accord with the theory. It is not possible for a boson with spin 1 to decay into two real photons, whereas spin 0 or 2 can do so. Eventually angular distributions of the decay products will show which of these is correct, but as there is no other example in particle physics where a spin 2 arises lighter than a spin 0 sibling (apart perhaps from the graviton), I expect it to be spin 0. Whether it is scalar or pseudoscalar, 0^+ or 0^-, remains open until more data are analysed.

The actual rate of production and decay into pairs of photons seems slightly different to expectations from the standard model, but whether this is mundane – uncertainties in the production mechanism, or exciting – hints of a novel Higgs boson – remain for the future.

In theory, there is no direct decay of Higgs into photons, so observation of it in this channel offers intriguing possibilities. In standard theory, the mechanism for the Higgs to decay into two photons involves the intermediary of a virtual "loop" of particles: either due to the Higgs decaying into a pair of electrically charged W, which radiate the photons, or into a top quark and antiquark which annihilate into two photons. The latter is predicted to dominate [10]. If so, the observation of Higgs in this channel implies that it couples to top quarks. It is possible that the relative role of the W and quark channels are slightly different than thought, and the resulting interference thereby modifies the production rate. More exciting is that there may be a third contribution, due to as yet unknown particles. The Higgs decay to two photons is due to the intermediate role of virtual particles, courtesy of quantum field theory, so any other contributions arise at the same order and need not be mere "perturbative corrections" to what is already included.

There is a hint that the Higgs does not show up in pairs of tau leptons. These are the most massive leptons, and hence should be the most favoured in Higgs decays (assuming that leptons indeed gain their masses through the eponymous mechanism) but are not the easiest to detect. It is likely that this is a result of low statistics and further data will reveal taus as predicted. Nonetheless, there remains a tantalising possibility that all is far from over with the Higgs boson. The accumulation of data over the coming months and years will provide precision measurements of branching ratios, and may reveal the presence of unexpected perturbations caused by novel virtual particles.

Powerful though the LHC is, it takes us less than half way, in energy terms, from the heat of a summer's day to the Planck energy. The Planck scale is so far away that its effects are indiscernible by the most sensitive experiments. So there is no practical implication in our lack of knowing the theory of everything: TOE. That is the irony of research. The realm of quantum gravity is so remote that we can ignore it, but the very lack of any observable effects also leaves us clueless on how to proceed in constructing the necessary theory. The LHC is unlikely to move us perceptibly nearer to realising this goal.

As I said, the LHC is only half way towards the Planck extreme. In the first half we have life, molecules and atoms, the atomic nucleus, quarks and now the Higgs boson. So many riches. Is there nothing but a desert from here to the Planck limit? There are theoretical arguments that favour the existence of a family of supersymmetric particles. As yet none has shown up at the LHC (unless the first hints of them is being revealed in the two photon decays of the Higgs, as mentioned above).

Although the Higgs may indeed be the final piece in the cast of characters needed to describe our world, over 90% of the universe consists of "dark stuff", which does not shine but gives itself away by its gravitational pull on the galaxies of stars. There are no candidate particles known with the required dark properties, but supersymmetry theory contains such possibilities. If the LHC finds supersymmetric particles, there arises the question of how they get their mass. In such a world, it is anticipated that there is a whole family of "higgsons" awaiting discovery.

If, as seems likely, we now know how the fundamental particles gain mass, this leaves open the question of why they have the particular masses that they do. If the electron were slightly heavier, essential examples of beta radioactivity would not occur, elements would not form, and we would not exist. Were it much lighter, these processes would change in other ways, once again unfavourable for life. Exactly what determines the strength of the Higgs' affinity for one particle or another is what experiment might reveal, but to do so will require some quirk in the data, some clue to guide us. At present, the pattern of particle masses, and the disparate forces, is an unknown unknown.

More immediate questions, in my opinion, are these.

Does the Higgs boson give mass to just the carriers of forces – ‘‘gauge bosons’’ – as in the original formulation of the idea, or is it also responsible for the masses of ‘‘fermions’’ – the basic elements of matter, including the electron and quarks?

This we should soon know.

The results announced on July 4 imply that the Higgs gives mass to the carriers of the weak nuclear force – the ‘‘W and Z bosons’’ – and possibly the quarks too, but there is not yet evidence that it gives mass to the electron and its siblings. The Z and W are the carriers of the weak force, which transmutes elements and keeps the sun shining, so we understand why the sun has lasted 5 billion years, long enough for sentient life to evolve. Proving that the Higgs boson is responsible for the mass of the electron, and hence for the origins of chemistry, will be harder to establish, but should be settled one way or the other in a year or two.

Notes on contributor

Frank Close is a professor of Theoretical Physics at Oxford University, Emeritus Fellow of Exeter College Oxford, and author of *The Infinity Puzzle* (Oxford University Press, Oxford, 2011) – a popular history of quantum field theory, and the quest for the Higgs boson.

References

[1] F. Close, *The Infinity Puzzle*, Oxford University Press, Oxford, 2011.

[2] P.W. Anderson, *Plasmons, Gauge Invariance, and Mass*, Phys. Rev. 130 (1963), p. 439.

[3] A.A. Migdal and A.M. Polyakov, *Spontaneous Breakdown of Strong Interaction Symmetry and the Absence of Massless Particles*, Sov. Phys. JETP 24 (1967), pp. 91–98.

[4] P.W. Higgs, *Spontaneous Symmetry Breakdown without Massless Bosons*, Phys. Rev. 145 (1966), p. 1156.

[5] T.W.B. Kibble, *Symmetry Breaking in Non-Abelian Gauge Theories*, Phys. Rev. 155 (1967), pp. 1554–1561.

[6] S. Weinberg, *A Model of Leptons*, Phys.l Rev. Lett. 19 (1967), pp. 1264–1266.

[7] See, for example, J. Gasser and H. Leutwyler, Nucl. Phys. B250 (1985), p. 465.

[8] The source is utterly reliable, but anonymous and was not Peter Higgs.

[9] P. Higgs remark to F. Close at 21:55 CET on 30 June 2012.

[10] F. Wilczek, *Decays of heavy vector mesons into Higgs particles*, Phys. Rev. Lett. 39 (1977), 1304–1306.