Editorial

The Higgs Boson and the Power of Consistency

Philip E. Gibbs[*]

Abstract

The momentous discovery of the Higgs boson announced on July 4, 2012 by CERN brought tremendous excitements both in the physics communities and general public. As the dust settles, we can start to ask some questions. In this editorial, we discuss the central element of the story which is often forgotten in the noise of celebration and the outlook of research in particle physics.

Key Words: Higgs Boson, discovery, CERN, July 4th, 2012, LHC, ATLAS, CMS, power of consistency.

As the dust settles following the momentous discovery of the Higgs boson (or Higgs-like boson if you are naturally skeptic) we can start to ask some questions. Reports in the mass media have tried to explain what the Higgs boson is. The answer most often given is that the Higgs is a particle of special importance because it gives mass to the elementary particles of the standard model through spontaneous symmetry breaking. This is a beautifully poetic answer giving the Higgs boson almost god-like status in its power and uniqueness, but is it really the central element of the story?

In particle theory the physics of any system is derived from a function of the field variables known as the Lagrangian. Normally mass can be introduced just by including mass terms in the Lagrangian that take a quadratic form.

$$L_m = m \psi \psi^*$$

This works perfectly well in gauge theories such as Quantum Electro Dynamics (QED) and Quantum Chromo Dynamics (QCD). The quarks and leptons are given mass terms which are gauge invariant. Mass terms for the gauge bosons would not be gauge invariant but luckily these particles (photons and gluons) are observed to be massless. Other mass is added to composite particles such as protons and neutrons from their internal energy content. If electrodynamics and the strong nuclear force were all that mattered in particle physics then no Higgs boson would be needed, but there is also the weak nuclear force which presents problems for mass.

Firstly the weak nuclear force is short range. By 1960 it was well-known the carrier for the weak force must be a charged spin one boson, but because the force is short range the boson needs to be massive. Glashow proposed an elegant partial theory in which the weak interaction was also a

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gauge theory similar to QED and QCD. This would work fine provided you ignored the fact that any gauge boson had to be massless. Apart from a different gauge group the main other difference from the other forces was that the weak force theory was chiral. The weak force couples to all the leptons and quarks, but only to one chirality half of the spin states. This explains parity violation observed in the weak interactions. An unavoidable consequence of this is that the simple mass term is not invariant under chiral gauge invariance for fermions as well as the bosons. So Glashow's theory was just right except that it predicted all known fundamental particles to be massless by gauge invariance.

The solution to the problem was to be spontaneous symmetry breaking. Around 1964 as many as four independent groups found the same mechanism for breaking gauge invariance in a way that gave mass to the vector bosons. One of the discoverers was Peter Higgs who was the only one to stress the importance of a scalar boson in the theory as a characteristic experimental signature. Initially the theory was considered as a possible solution for the strong nuclear force because at that time QCD was not understood. In 1967 Weinberg and Salam realised that it worked perfectly when applied to Glashow's weak force gauge theory, giving mass to the gauge bosons and the quarks and leptons in a gauge invariant way through the symmetry breaking.

In the Higgs theory the mass terms in the Lagrangian of the standard model have merely been replaced with interaction terms linking the Higgs scalar boson to other particles. When the particle is a fermion such as an electron or quark these terms take the form of a Yukawa coupling

$$L_Y = c\ \varphi\ \psi\ \psi^*$$

The constant c is a coupling constant indicating how strongly the Higgs field φ interacts with the fermionic field ψ. In the unbroken form the Higgs field is a doublet state over the weak force gauge group with a "Mexican hat" shaped potential in the Lagrangian of the form

$$L_H = \lambda(|\varphi|^4 - 2|\varphi|^2)$$

At low energies the scalar field moves around a point at the minimum of this potential at $|\varphi| = 1$. The Higgs field can be rewritten by a substitution $\varphi = \varphi' + 1$ so that the Yukawa term becomes

$$L_Y = c\ \varphi'\ \psi\ \psi^* + c\ \psi\ \psi^*$$

Now it looks like a new Yukawa term plus a mass term demonstrating the characteristic feature of the Higgs boson that its coupling to each particle is proportional to its mass.

Swapping one term for another in the Lagrangian is not a simplifying or unifying step. The standard model remains complex with about 20 free parameters that must be determined by experiment. The three forces remain separated with distinct gauge groups and coupling constants. The Higgs mechanism has added a scalar boson, a new type of particle that looks nothing like the spin half fermions and spin one gauge bosons previously seen, and it has its own interaction terms that are not explained except through the necessity to break the symmetry. This is certainly not a unifying step, so what has really been achieved? What really gives the theory its convincing power? What makes it such a unique solution that so many different theorists all came up with it independently almost 50 years before technology had advanced sufficiently to test it? The answer in a word is *consistency*.

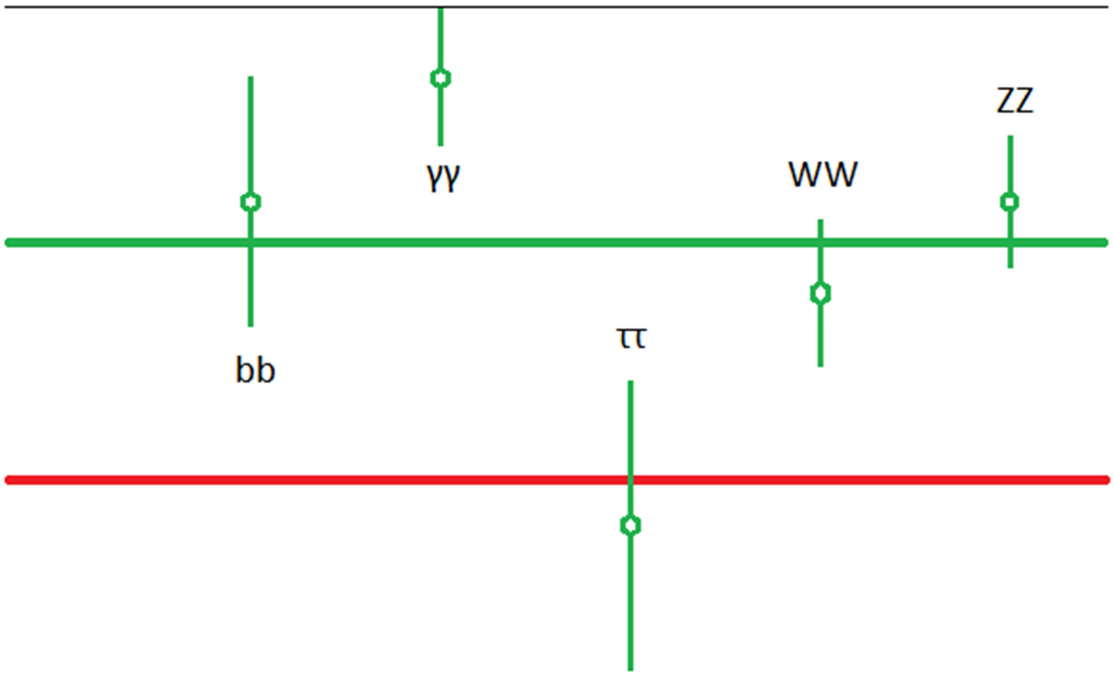
The theory of QED has the important feature of being renormalisable. Its infinites are not exactly a beautiful feature of nature but they can be dealt with in a consistent way that permits calculations to be done. When physicists saw how important this was they looked for ways to generalise the solution in the hope that other forces could also be explained in a similarly consistent way. What they found was that the gauge symmetry principles that underlie quantum electrodynamics can be generalised to other non-abelian gauge theories and that these theories would also be renormalisable provided the interactions between particles were limited to a few specific types of interaction term.

For example the fermion fields could interact through gauge invariant couplings with the gauge field, but self-interaction of the spin half fermion fields would be non-renormalisable, even if they were gauge invariant. Scalar fields can also couple to the gauge fields but crucially they *can* also have self-interactions but only using interaction terms in the Lagrangian up to the 4th power. Anything involving higher powers would be non-remormalisable. Finally gauge invariant Yukawa terms can be included but any other type of interaction between the fermions and scalars will not work. So now you can see how so many physicists came up with the same solutions. They had a very limited set of tools to play with and every one of those tools was required to build the theory. The fourth powers allowed for the scalar field was just what was required for a potential that would break the symmetry. The need for self-consistency combined with the need to fit with the limited experimental observations of the time was enough to pin down the standard model with just a few unknown parameters left for experimenters to measure over the next 50 years.

The importance of this consistency requirement is underlined by the fact that the electroweak theory was overlooked for several years after its construction in 1967. Although all the elements in the theory were known to be remormalisable, this was only valid in the context of perturbation theory about the unbroken symmetric point of the theory. The spontaneous symmetry breaking was a non-perturbative feature of the theory and it was not at all obvious that it would remain renormalisable in the perturbation theory of the broken phase. In 1974 two things came to fruition that gave power to the standard model. Firstly it was realised through the work of Gross and Wilczek that QCD was an asymptotically free theory meaning that it had the potential to explain the full spectrum of hadronic physics. Secondly, ‘t Hooft and Veltman showed through an exhaustive effort that the electroweak theory was indeed renormalisable in the broken phase. It is because of these theoretical consistency checks followed by a series of experimental checks that we now find the standard model so convincing *despite* its lack of unity and elegance. Any alternative theory or anything that goes beyond the standard model must meet the same standards, both in terms of self-consistency and consistency with experiment. It is not an easy requirement.

How well then does the current set of observations comply with predictions? No measurement is exact so we can never prove that any theory is exactly the right one. However, the Higgs mechanism predicts a boson with couplings to other particles that is proportional to their mass and just such a boson has been found in the right place at the LHC. We must agree that it is at least Higgs-like and is most probably responsible for electro-weak symmetry breaking, but its couplings may not exactly match predictions. This could happen because there is more than one Higgs boson or because there are other particles that affect the decay rates. If this is the case it must happen in a way that is consistent with all experimental results and also in a way that leads to a self-consistent renormalisable theory. These are tough constraints.

Here is the latest unofficial combined versions of the measured decay rates in the channels to which the LHC and Tevatron are sensitive. They are plotted on a scale where the red line would be agreement with a Higgsless model while the green indicates the standard model prediction.



Higgs signal at 125 GeV using global combination

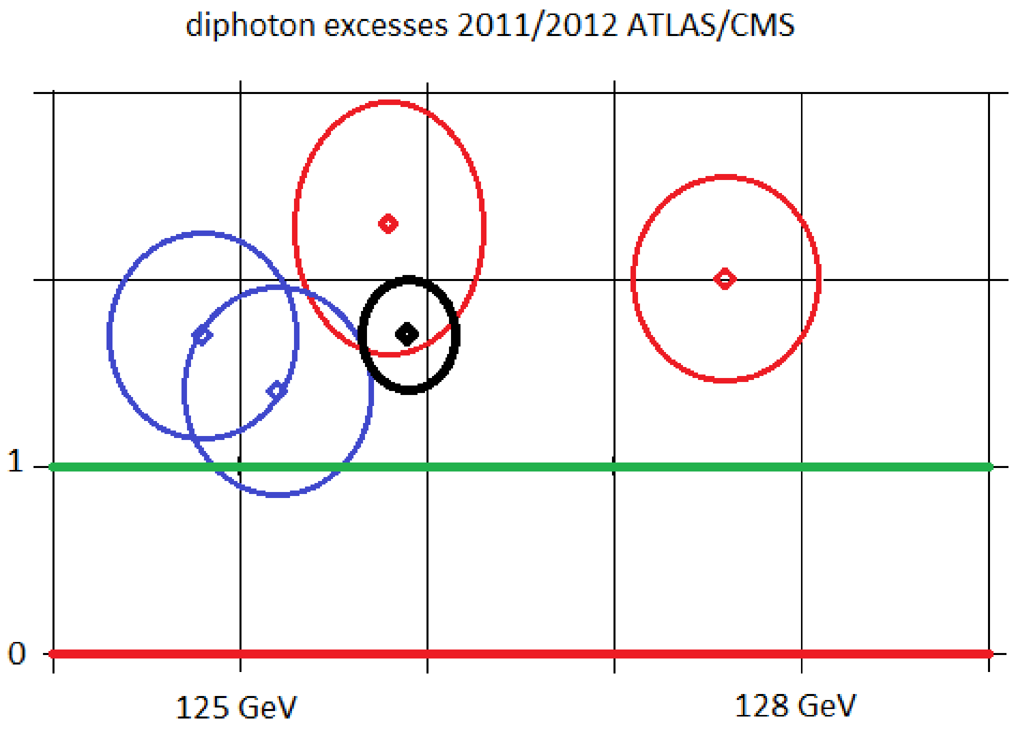
The first thing to notice is that the agreement with the standard model Higgs at 125 GeV is mostly very good. If we were looking at a different type of boson such decay rates could easily be different by large factors. In all cases except the ϒϒ diphoton decay mode these rates measure directly the coupling of the Higgs to each particle. Of these, only the tau lepton is far off the mark but sensitivity to this channel remains low and ATLAS have not yet released their full results. We should reserve judgement until more data is available. The bb, WW and ZZ decays each come out close to predictions indicating that the coupling to both fermions and bosons is right for these cases.

In saying that, we must remember that these data points also measure the production rate of the Higgs boson. This depends on a top quark loop that mediates gluon fusion to produce the Higgs. The safest bet here is that the production rate and branching ratios are both right, but we must not forget that the results are also consistent with a production rate that is wrong by a certain factor with the observed decay rates reduced or increased by the inverse factor. There are limits to how big or small this factor could be before it would affect the other rates. For now I will just assume that the production rate is correct.

That leaves just one channel of real interest at this stage. The diphoton channel is different from the others in that there is no direct coupling between the photon and the Higgs because the photon is massless. The decay is mediated by a loop whose main contribution comes from the W boson, but it is also sensitive to loops involving other charged particles. Here is a plot showing approximate error ellipses for the four results using 7 TeV and 8 TeV for CMS (in blue) and ATLAS (in red). The black ellipse shows the unofficial combination. Again the green line shows the standard model.

What you should take from this plot is that the results are persistently above the green line. It is as if they had thrown four dice and scored four sixes. The significance is not yet sufficiently high and results that purport to show effects beyond the standard model require high significance, but it is enough to justify some speculation about what could cause it.

Although there are many ways to explain modifications to Higgs decay rates, by far the simplest way to explain an enhancement of the diphoton channel without a big change to any other channel is to add a new particle that contributes to the diphoton loop. Let’s call it mystery particle X. X would have to be charged to interact with the photons and massive to interact with the Higgs. It would most likely be a boson because fermions in loops take a negative sign that would depress the channel instead of enhancing it, but it could be spin zero or spin one. We also know that it must not affect the production rate of the Higgs which is mostly due to gluon fusion, so a particle with colour charge is ruled out. Finally we need to explain how it avoided detection so far. If it had a mass less than 105 GeV it would have been produced and detected at LEP.



There are many other considerations. Many types of particle that would fit the bill such as W' particles have already been ruled out to quite high masses. A complete analysis would be quite involved, but it is likely that if such a particle exists it would already be possible to eliminate many possibilities and identify what it is like by a process of elimination. Then a need to find a new consistent theory that included particle X would lead to a whole new range of possibilities. It may be that X has the characteristics of one of the particles predicted by SUSY models e.g. a scalar lepton or a charged Higgs.

As I write, the LHC is once again collecting luminosity at a fast rate. By the time of the mid-September technical stop it will have once again doubled the amount of data available for analysis. That will be enough to settle whether the diphoton excess is just a lucky fluctuation or not and it is most likely that it will not go away so easily. If the excess remains as big as it is now systematic faults and theory errors will also not be enough to explain it. Physicists will start to believe that it is real physics. Other channels may also start to provide further clues, narrowing down further the range of possibilities.

Does X exist or not? By the end of the year we should know. The future of experimental particle physics will depend on the answer. If one new particle exists then others will be predicted to preserve consistency. We will need an accelerator powerful enough (such as CLIC) to find them and measure their properties. If there is nothing new beyond the standard model by the end of the year a lower energy linear collider such as the ILC will be needed as a Higgs factory to make precision measurements of the Higgs properties, while the LHC progresses to higher energies and luminosities in search of something else. The ILC is currently the favoured option with Japan the most likely location. All that could change depending on the next set of results.