Article

Higgs Discovery on the Brink, but Is It the Higgs? & What Is the Deal with H → WW?

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Abstract

Once we have the data from the first 2012 run in our hands, we will already have enough data to say that the new particle looks like a Higgs boson. We may even be able to make some preliminary statements about any deviations from the standard model. These will improve in time. There will always be those who say that we don't really know for sure that this is the Higgs boson rather than some other scalar neutral particle that happened to be around, but the fact is that this particle turned up just about where the Higgs boson was most expected and with the right properties. With respect the WW channel, it is now several standard deviations below the standard model and is more consistent with no branching to WW. Even taking into account that these combinations are unofficial and approximate there is clearly something odd here. From a theoretical point of view this is very perplexing because the digamma decay is in theory dominated by loops involving the W boson. If the direct decay to WW is lower than predicted then the diphoton decay should be too. This really cannot be made sense of and if it is correct then the Higgs nature of the observed resonance would have to be questioned, but let's not be too hasty.

Key Words: Higgs Boson, discovery, brink, 4 sigma, ATLAS, CMS, CERN.

I. Higgs Discovery on the Brink, but Is It the Higgs?

By now you should know that physicists working on the CMS and ATLAS experiments at the Large Hadron Collider are about to announce important new results in the search for the Higgs boson. The announcement will be made on the morning of the 4th July at CERN in advance of the ICHEP conference in Melbourne where more details may emerge. The expectation is that this update will actually be a discovery announcement for the Higgs Boson. This is based on vague rumours, plus the fact that CERN PR are not saying that it is not a discovery, plus the fact that it would make no sense to have such an update at CERN before a big conference unless it were a discovery, plus the fact that they would not have been so sure so soon that there was something big to say unless the signal had come through very clear and strong.

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The details will have to wait for the day and of course I will be here to add my independent analysis and unofficial Higgs combinations as the story unfolds. Others will be live blogging including Tommaso Dorigo of CMS who says he will be in the auditorium. I hope he has a seat reserved for him so that he does not have to camp outside the door overnight to get in. I will be watching the live webcast from home instead.

How do they know it is the Higgs Boson?

This is now the most frequently asked question, how do they know it is the Higgs boson and not some other particle they are seeing? In the scientific papers we can expect that the physicists of the collaborations will be careful about how they word the discovery. They will say something like: "We have found a new resonance (i.e. particle) in the search for the Higgs boson which is consistent (or maybe not) with the standard model Higgs Boson. Further measurements will be needed to confirm that its properties are as predicted." And of course they will quantify what they mean by this with a slew of numbers and plots. In the press you will simply hear that they have discovered the Higgs boson. Dont by upset by this, you can't expect a report in the New York times to read like a paper in Physical Review D, but it is fair to ask to what extent its known properties so far indicate that it really is the Higgs boson.

What is the Spin?

The most distinctive characteristic of the Higgs Boson is that it is a scalar, i.e. it has no spin. Other elementary particles in the standard model are either fermions with spin one-half or gauge bosons with spin one. Particles with spin that is any multiple of one half are possible and it is a quantity that needs to be checked experimentally. The channel where they are seeing the signal for the Higgs boson most strongly is through its decay into two high energy photons. The photons have spin one but spin is conserved because the two photons take away spin in opposite directions that cancel. It is not possible for fermions that have a odd-integer spin to decay without producing at least one new fermion so we know already that the particle observed is a boson. By a theoretical result known as the Landau-Yang theorem it is not possible for a spin-one particle to decay into two photons either, but it is possible for a spin-two particle to decay into two photons with spins in the same direction.

So we know already that the new particle has spin zero or spin two and we could tell which one if we could detect the polarisations of the photons produced. Unfortunately this is difficult and neither ATLAS nor CMS are able to measure polarisations. The only direct and sure way to confirm that the particle is indeed a scalar is to plot the angular distribution of the photons in the rest frame of the centre of mass. A spin zero particle like the Higgs carries no directional information away from the original collision so the distribution will be even in all directions. This test will be possible when a much larger number of events have been observed. In the mean time we can settle for less certain indirect indicators.

In March the Tevatron presented their final observations in their search for the Higgs boson. Their detectors are more sensitive to the decay of the Higgs to two bottom quarks. A weakly significant signal was seen at the same mass of 125 GeV where the LHC is seeing its resonance. This too will be confirmed with more certainty by the LHC later. This shows (or will show) that the particle can decay into two spin half fermions. This is certainly possible for a spin zero particle and also for a spin one particle but is it possible for a spin two particle? If not we would know that the spin must be zero by a simple process of elimination. In fact it is possible for a spin-two particle to decay into two spin halfs provided the extra spin one is carried away either as orbital angular momentum (p-wave) or as a soft photon that is not seen, but neither of these possibilities is very likely. We can therefore be reasonably sure already that the observed particle is indeed spin zero, but for absolute certainty we will have to wait for more detailed studies.

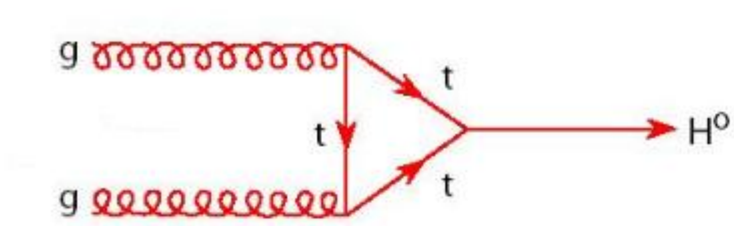
What about other quantum numbers?

As well as spin, any elementary particle is partially classified by other quantum numbers including electric charge, colour charge, baryon number, CP, etc. The charges are strictly conserved due to gauge invariance and are zero in the decay products so we know for sure that the particle is neutral. We also know that the baryon number is zero otherwise the particle would provide a mechanism for baryon number violation that would probably destabilise the proton. The quantity CP can be either even or odd but it is hard to know for sure which it is because CP is known to be unconserved at an observable level. Given that the decay modes are predominantly into a particle and its anti-particle or into two particles that are the same, it is unlikely that the CP is odd, but we will have to wait for more carefull tests to be reasonably sure. In any case there are versions of the Higgs boson in theories outside the standard model that have odd CP so this question does not really affect whether or not they are seeing the Higgs.

What about other Higgs properties?

The mass of the Higgs boson is the last parameter of the standard model to be determined. With the imminent discovery we now believe it to be about 125 GeV. With this quantity known every other property of the standard model can in principle be calculated, but it is not always easy due to non-perturbative effects that are difficult to model. Uncertainty in other measurements also adds more uncertainty to any calculation. The decay time (or width) of the Higgs boson can be calculated but because 125 GeV is less than twice the W or Z masses, the boson is relatively stable and the width is a few MeV. This is far too narrow to be measured at the LHC where the mass resolution is in the order of a GeV.

However, the most distinctive characteristic of the Higgs boson is its coupling to massive particles. By the nature of the Higgs mechanism that gives mass to the fundamental particles in the standard model, the coupling is always proportional to the mass. according to the theory the fermions and gauge bosons do not have any mass in the unbroken electroweak phase due to gauge symmetry and chiral symmetry (however the fact that neutrinos have a small mass already takes us beyond the standard model) This affects all the production rates and branching ratios for the decays so if these are measured and found to be in agreement with the standard model we will have a useful test that what we have found really is the Higgs boson. Only by producing the unbroken state can we get a clearer sign that it is the real Higgs mechanism that breaks electro-weak symmetry but that is not accessible to present day technology.

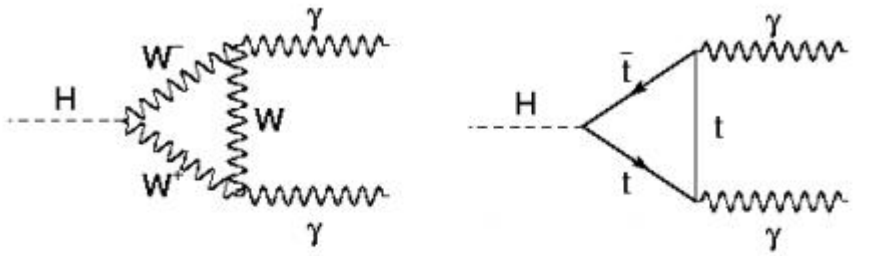


The decay rates for the Higgs to ZZ, WW and bb all go by direct couplings to the Higgs boson so these provide particularly good tests. We can’t measure them directly because the rates at which we see these processes also depend on the production rate for the Higgs boson. The predominant mechanism for Higgs boson production is gluon fusion. This can be calculated in the standard model to an accuracy of about 15%, but it can be suppressed or enhanced by physics beyond the standard model. This is because the process involves a quark loop that is dominated by the top quark in the standard model. In some SUSY theories it is enhanced due to the bottom quark getting a stronger role, or it can be suppressed if there is a stop quark with a mass near that of the top quark. Even if the production rate is unreliable the ratios of the decay rates to ZZ, WW and bb should be fairly robust and will make a good test of the Higgs mechanism.

What would enhance the diphoton channel?

In the 2011 data we saw an enhancement of the diphoton channel amounting to 80% above the standard model in the unofficial ATLAS + CMS combination. The local significance is about 1.6

sigma, so nothing special, but the fact that they have opted for a special update so soon after looking at the new 2012 data with perhaps only 3/fb revealed suggests that this enhancement could have persisted. Even the collaborations wont know for sure until the final results which will probably not be ready yet. However it is certainly something worthwhile for a blogger to speculate about. So what could cause such an enhancement and does it mean this particle may not be the Higgs boson?



The decay mode to photons is more interesting because it also involves a loop that is dominated by the W boson but which also has (negative) contributions from the top quark. This can also easily be suppressed or enhanced by new physics such as any new massive charged particle with mass near the electro-weak scale. A boson will tend to enhance it while a fermion has a negative sign in any loop so will tend to suppress it. Prime candidates for enhancement would be a scalar top (stop) or a scalar tau (stau) The stop also suppresses the Higgs production rate because it has colour so it works both ways, but the stau is pure enhancement.

The diphoton channel can also be enhanced indirectly along with the ZZ and WW if the dominant bb channel is suppressed, e.g. if the Higgs is partially fermiophobic. We can distinguish this from the direct enhancements by observing the ZZ and WW channels, especially through the ZZ to 4 leptons decays which is a very clean and predictable measurement.
Together, observations of these channels should add up to an excellent test for the presence of beyond standard model physics and will provide narrow clues as to what type of physics it is. However the Higgs boson will still be a Higgs boson even if it is not quite the standard model Higgs boson.

Can they say they discovered the Higgs boson then?

Once we have the data from the first 2012 run in our hands in ten days time we will already have enough data to say that the new particle looks like a Higgs boson. We may even be able to make some preliminary statements about any deviations from the standard model. These will improve in time.

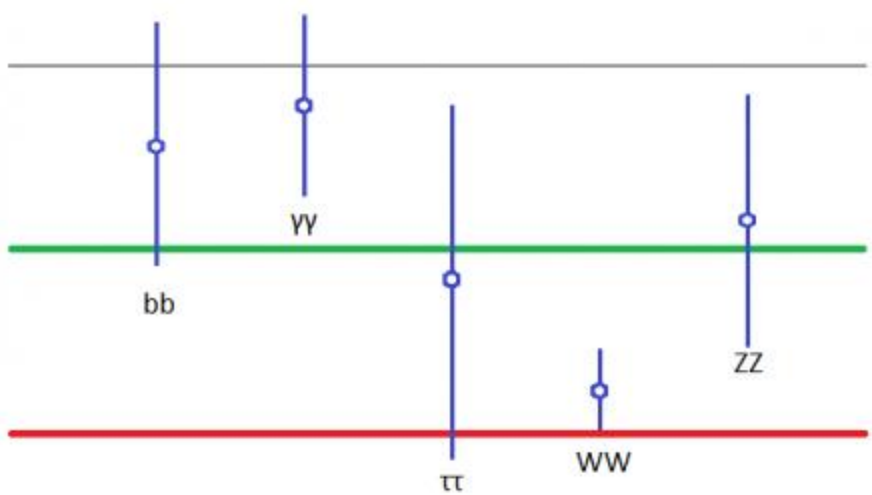
There will always be those who say that we dont really know for sure that this is the Higgs boson rather than some other scalar neutral particle that happened to be around, but the fact is that this particle turned up just about where the Higgs boson was most expected and with the right properties. We already know from the discovery of the W and Z bosons and many other tests that the standard model is a good one and it is a model based on electroweak symmetry breaking.

Something is required to break that symmetry and now we have found a particle that fits nicely the characteristics of such a particle. Only the most obstinate skeptic would complain if CERN claim to have discovered the Higgs boson given the evidence we expect to see very soon.
If it swims on a pond and quacks like a duck it is not unreasonable to say it is a duck, especially when you were expecting to find a duck. Further observations will just tell us more about what kind of duck it is.

II. What Is the Deal with H → WW?

In a few days we will get the next big update from CERN on the Higgs boson and it is likely that the main question they are investigating will switch from "*Is there a Higgs Boson*?" to "*Is it the standard model Higgs Boson*?" Already the 2011 data shown during the winter carried signs that the cross-sections for some decay signatures are quite different from the standard model predictions. In particular the digamma rate is high and the WW is very low. Significance levels were not strong but if this is reinforced by the 2012 data people are going to suspect that new beyond-standard-model physics is at play. Many theory papers will be written as I predicted a year ago, but how well can the numbers be relied on? The ATLAS and CMS discuss many of the details behind closed doors and do not publish every detail. If theorists want to be sure that the results are good they will have to ask some probing questions at the talks. They need to go along to the conference prepared.

So let's look at the data so far. Using the unofficial combinations for CDF, D0, CMS and ATLAS the μ signal at 126 GeV for the accessible decay channels looks like this



Higgs global combination up to 2011

In this diagram the green line represents the prediction for a standard model Higgs while the red line is the background level with no Higgs. The first observation is that the Higgs is clearly favoured across the channels. After that, much has been said about the digamma excess because it is a high-resolution channel and an enhancement of this branching ratio could indicate new physics such as a new heavy charged boson. But what about the WW channel? It is now several standard deviations below the standard model and is more consistent with no branching to WW. Even taking into account that these combinations are unofficial and approximate there is clearly something odd here.

From a theoretical point of view this is very perplexing because the digamma decay is (in theory) dominated by loops involving the W boson. If the direct decay to WW is lower than predicted then the diphoton decay should be too. This really cannot be made sense of and if it is correct then the Higgs nature of the observed resonance would have to be questioned, but let's not be too hasty.

There are several sources of error that can affect these results so let's take a step back and think about those first. They can be broken down along these lines:

1. Statistical errors from the limited amount of experimental data
2. Theoretical errors in the approximate calculations of the standard model production rates and branching ratios
3. Errors from the measured standard model parameters such as the masses of the W,Z, top etc.
4. Statistical and other errors from the monte carlo simulations used to predict the background and signal
5. Measurement errors from the detectors

All these things should have been taken into account and included in the error bars but before we draw too many conclusions and new theories we should ask questions, especially since the results do not make good theoretical sense. I think it is instructive to look at how the WW channel plot has evolved in ATLAS and CMS from the early days when they had 1/fb to the full 5/fb from last year. I'm not going to copy all the plots here but you can look at them on the Higgs combination plot. When there was only 1/fb of data we got excited because of an excess in the WW channel. It was most significant at about 144 GeV with over 3-sigmas but it was a broad excess which at the time suggested a Higgs in the range 135 ± 10 GeV, so with hindsight it was consistent with the present signal at 125 GeV. Sadly this signal faded as more data came in even though it was present in both CMS and ATLAS and is now nearly completely gone. What happened? Let's walk through some of te possibilities.

1. Statistical fluctuations – On the face of it this seems like the most likely explanation. The original excess after just 1/fb faded slowly in both CMS and ATLAS. This then was a remarkable fluke but given enoigh things to look at we will always find remarkable flukes somewhere, so perhaps this is it. The present low signal for the Higgs in WW at 125 GeV where digamma is strong could equally well be part of that fluke. The 2012 data will tell us whether it is or not but the WW analysis is harder and we may not get full results until after ICHEP

2. and 3. Theoretical errors – The calculation of production rates is thought to be good to about 15%, but some theorists sat less and some more. The branching ratios are known to about 5%. Background estimates are another source of theoretical errors. Putting it altogether we may expect errors as high as 25% and it is not clear that this much error has been included in the analysis. This could eat into some of the significance of the observed deviations from the standard model.

4. Errors from the monte carlo - We have to assume that the monte carlo simulations have been run long enough so that statistical errors are sufficiently small to be negligible, but what about other errors. As far as I understand it, ATLAS and CMS have detailed simulators of their detectors that include everything from pile-up to the efficiency of the parts in the detector. One thing that could be very relevant is the effect of the pile-up. WW at low Higgs masses decays to leptons and neutrinos so there is missing energy to be accounted for. Pile-up has been said to make this difficult because particles from one event contaminate another. The simulations must include not just the pile-up but also the triggers and the algorithms used to reconstruct the individual events. How well has this been done? The first inverse femtobarn of data had low pile-up numbers so if they have not understood the effects of pile-up correctly it could account for the fact that the signal faded as high pile-up data was added. I dont know if this is a plausible explanation but it is something the collaborations should be talking about and if they don't say anything about it theorists should be asking them questions.

5. measurement errors – From the 2011 data it was noticed that the CMS signal peak was at a lower mass than the ATLAS peak in the digamma channel. The difference was only about 1 or 2 GeV, well within the expected errors from the detectors, but this can still be significant. The WW channel has much lower mass resolution so how good is the estimate for the reconstructed Higgs mass? The reason that this is so important id that the WW branching ratio increases rapidly at around 125 GeV. If there are systematic errors that result in a mass offset they could be comparing experimental measurements with theoretical branching ratios and backgrounds at a slightly offset mass and this could result in big errors. For the digamma channel the problem is less acute because the branching ratio is a maximum at 125 GeV so it varies slowly in this region. the background also varies quite slowly.

Another part of the measurement process that could affect the result is the resolution of the detectors. How well is this resolution understood for different parts of the detector? This effects how much the signal is spread out over different energy bins. If the resolution is better than expected there would be more events in the central bin than expected and the signal would be bigger than expected. The opposite happens if the resolution is worse than expected. How well have they taken this into account?

The moral of this story is that if CMS and ATLAS do report significant deviations from the standard model next week, we as theorists should keep an element of skepticism in our interpretations. It ios easy to get excited by results that appear to agree with what we want to see, i.e. new physics rather than plain old standard model Higgs Boson. It will be impossible to resist speculating about what new physics can explain it and it will be a healthy excercise to do so, but don't be surprised if more careful analysis sees some of the results fade away.

We have become addicted to the beguiling green and yellow brazil-band plots that have been produced in hundreds to show where the Higgs does and does not show up, but as we move into the next stage of exploration at the electro-weak scale these need to be put to one side. What will count next is estimates for the mass of the Higgs and the actual cross sections for the different decay channels with error bars. The cross-sections need to be independent of the mass estimate so that we don't get messed around by the ways these errors combine when branching ratios are varying rapidly, It may take a little longer before we can really be sure whether or not we are seeing the SM Higgs or a BSM Higgs. Reults from the LHC may improve as we head into the long-shutdown next year and we may need a linear collider to get really good measurements of the Higgs Boson properties. But meanwhile theorists imaginations may run wild.

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