Special Report

Higgs Boson Live Blog: Analysis of the CERN Announcement

Philip E. Gibbs*

Abstract

We report here live on LHC Higgs results announcement by CERN on December 13, 2011. The result is very convincing if one starts from the assumption that there should be a Higgs Boson somewhere in the range. Everywhere is ruled out except 115 GeV to 130 GeV and within that window there is a signal with the right strength at around 125 GeV with 3 sigma significance. CERN will have to wait for that to reach 5 sigma to claim discovery and next year's data should be enough to get there or almost. I calculate that they will need 25/fb per experiment at 7 TeV to make the discovery. A big congratulation goes to everyone from the LHC, ATLAS and CMS who found the clear hints of Higgs when it hid in the hardest place.

Key Words: Higgs Boson, announcement, CERN, LHC, ATLAS, CMS.

December 13, 2011: Higgs Boson Live Blog: Analysis of the CERN Announcement

Good morning and welcome to what is expected to be an exceptional day for physics as CERN announces important new results in their hunt for the elusive Higgs Boson. Here in one mammoth expanding post I will be reporting on the search for the Higgs Boson in straight forward terms free form silly analogies and patronizing phrases such as "for the layman". I hope that many interested people with varying degrees of foreknowledge will find the level helpful. I will explain the basic preliminaries first but if there is anything you don't understand just Google it or wing it.

The present excitement started to build during the summer when it became clear that the Large Hadron Collider experiment was gathering data at a much higher rate than anticipated, meaning that they would soon be able to tell whether the Higgs boson exists or not and most importantly, what mass it has.

I am a theoretical particle physicist based near London independent of the teams working at CERN, and I have been following events at the Large Hadron Collider and blogging about them since it started colliding protons in 2009. In a minute I will answer a few basic questions about the Higgs for the uninitiated, including the Paxman question "What does the Higgs boson look like?" Then I will be live-blogging the events from CERN as they happen, so first let's look at the schedule of today's events.

- **14:00** – Fabiola Gianotti, spokesperson for the ATLAS collaboration delivers a 30 minute summary of their latest developments. ATLAS is the largest particle detector

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ever built and it sits on an intersection point of the Large Hadron Collider rings to observe the trillions of particle collision events taking place.
- **14:30** – Guido Tonelli will talk about similar observations at the CMS experiment. CMS is another equally sophisticated but different and complementary detector placed diametrically opposite ATLAS on the LHC ring gathering another independent set of collision data.
- **15:00** – When the talks end, which may not be on time, there will be an hour long technical discussion between the scientists about each others results. Until these talks the two 3000 strong teams of physicists had not officially compared their data so there will be much to talk about.
- **15:20** – At this time we expect a release of information and pictures to the press as the scientific discussion continues.
- **16:30** – Press conference. Questions and Answers from the experts

During these events I will be posting news and exclusive analysis right here as it happens. You can refresh this page for updates and post your own views and observations in the comments section. However, please accept that I may delete comments that I consider unhelpful to a general audience. You can continue to post broader material on the previous post about the rumours

Amongst other things I will be attempting to combine the results in real time as soon as the necessary plots become available. The CERN director General has forewarned us that the announcement today will not provide conclusive evidence for the existence, or non-existence of the Higgs boson, but that could be because the two experiments have not had time to combine their results. The official combination will not be ready until next year because the full computational process is long and difficult. However, it is possible to do a quick approximate "bloggers" combination that will allow us to anticipate what the eventual result will look like. In fact the method has been shown to be reasonably accurate in the past. I will be doing more combinations right here today.

Let me just reiterate that again. ***My combinations are approximate***. They assume a flat normal probability distribution. That is a good approximation that improves as more data is added. They also assume that there are no correlations between uncertainties among the different parts of the experiments. This is not the case. Such correlations have a small effect that does not diminish with more data. In order to claim a discovery using a combination the collaborations will have to get together and do an official version the hard way and that will take time. However, my quick combination method is good enough to give a very good idea of what the final result will look like and it is certainly not “Nonsense” as some of the experimenters have tried to claim.

Why is the Higgs Boson so special?

During the 1960s and 1970s theoretical physicists using data from the first generation of particle accelerators assembled a theory of elementary particles known as the Standard Model. It included familiar particles such as the electron, photon and neutrinos as well as unseen quarks that bind to form protons and neutrons inside the atom. All the particles in the standard model are of two types with one exception.

The particles which build up matter are all *spin-half fermions* which obey an equation formulated by Dirac in 1928. This includes the three generation of quark pairs and the three corresponding pairs of leptons, the electron, muon and tauon with their neutrino partners. Each of these has an antimatter partner so there are 24 distinct fermions in the Standard Model. The second set of particles are the *spin-one bosons*. These play the role of binding together the fermions with the electromagnetic force (the photon) the strong nuclear force (the gluons) and the weak nuclear force (the W and Z bosons) Of these only the W is charged and so has a distinct anti-particle, meaning that there are 5 different bosons.

Aside from these it was found that the standard model required one further particle. It was known that a consistent model of spin-half fermions and spin-one bosons free from infinities required gauge symmetry, that is a mechanism that would in theory make the bosons massless. On the other hand, nature had shown that the bosons that mediate the weak nuclear force must have mass. The solution was a mechanism worked out around 1960 by a number of physicists that introduces an unusual field into the theory. The field has an unorthodox energy potential that is minimised away from the central point of symmetry so that the value of the field in the vacuum state of space-time must be shifted away from the central point, thus breaking the underlying symmetry and giving mass to some of the particles.

Peter Higgs, one of the pioneers of this mechanism, pointed out that the remnant of this field in its broken form would have excitations corresponding to a unique elementary particle that might be observed as final confirmation of the theory. Unlike the other particles in the Standard Model, this one would be a *spin-zero boson.* Observation of this hypothetical particle named the Higgs Boson in his honour is what the Large Hadron Collider has been looking for 50 years later.

What does the Higgs Boson look like?

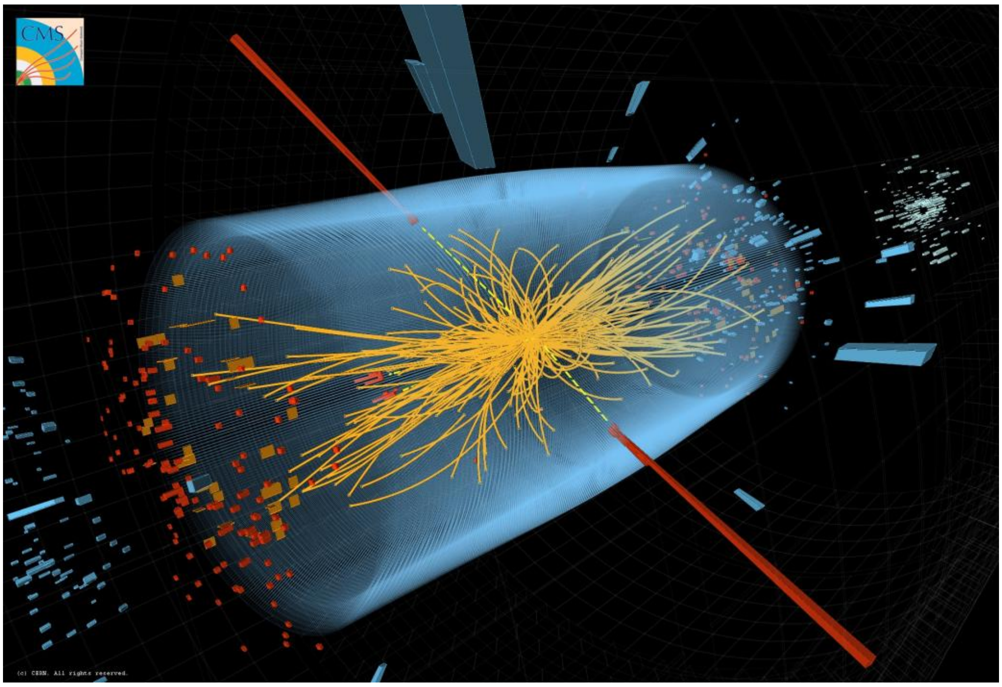
The Higgs Boson exists only for fleeting moments as a fuzzy quantum wave on scales smaller than the inner workings on the proton. It is therefore impossible both theoretically and practically to “see” it in the normal sense of the word. What we can see are traces of its existence in data gathered from countless collisions between high energy protons in the Large Hadron Collider.

In the LHC at CERN on the Swiss-Franco border near Geneva, physicists have been accelerating protons to unprecedented high energies in a circular underground ring 27 km in circumference. When the protons are brought together in a head-on collision the energy can form new particles, perhaps including some never observed before such as the Higgs boson. Many trillions of collisions have been observed but the processes that form a Higgs boson are so rare that only a few thousand are likely to have been created in the experiment so far.

Once created a Higgs boson should live for a fleeting 10^{-22} seconds, enough time for it to travel between 10 and a hundred times the width of the protons from which it emerged. Then it decays, usually into other particles, most often a matched pair of bottom/anti-bottom quarks which have a much longer lifetime of 10^{-12} seconds. As the bottom quarks fly apart a string of gluon flux stretches between them before breaking to form new quarks. These emerge along with the decay products of the bottom quarks as jets of hadrons that reach the detectors. Sometimes the bottom quarks will each decay into another quark plus a lepton (electron or muon) with an accompanying neutrino. The lepton makes tale-tale tracks in the detector while the neutrino flies off without a trail only to be guessed at when they add up the energy of all the other particles and notice that some is missing. Unfortunately there are many other less remarkable processes that produce similar jets and leptons at the LHC making it very difficult to observe the Higgs Boson when it decays in this way.

If the latest rumours about the measurements at CERN are correct the Higgs Boson could have a mass approximately equal to that of a Caesium atom. If this is correct about one in 500 of the Higgs bosons produced will decay into two high energy photons that fly away in opposite directions. Unlike the bottom quarks these fly away cleanly carrying all their energy and momentum to the inner layers of the detectors where a surrounding vessel of liquid argon has been placed to capture them. There they produce a shower of lower energy particles that are carefully tracked so that their energy and trajectory can be measured to reveal the parameters of the original photon. During all of this years run at the LHC this may have happened only a dozen times in each detector, but it could be enough to reveal the Higgs Boson.

Such photons will be thousands of times more energetic than the harmful gamma rays that emanate from nuclear reactions, but they are still photons identical to those of light which differ only by having less energy. If you want to know what the Higgs boson looks like it is the faint glow of these rare photons that answers the question most directly. In the LHC they shine faintly among the brighter radiation of other processes that produce equally energetic gamma rays. The ones coming from the Higgs Boson can only be noticed when enough have been detected to show up as a slightly brighter peak in the energy spectrum of thousands of observations. It is this that we are hoping to hear news of today.



A typical event with two high energy photons as recorded in CMS

Will the LHC find the Higgs Boson?

The theory of the Higgs Boson has been around a long time and all the other particles of the standard model have been found. Several of them were found after they were predicted by the model, especially the gluons, W and Z bosons and top quark. This means that the theory of the Standard Model is in very good stead experimentally. Indeed, physicists have been hoping for some experimental deviation from its predictions for decades and have come away disappointed. Every experiment just seems to confirm its correctness with ever more accuracy. (There are some exceptions such as measurement of the muon magnetic anomaly and the cosmological observation of dark matter that seem to point to something beyond the standard model at higher energy)

With such success it is no wonder that the theorists are quite confident that the Higgs Boson will be found as the last missing piece of the Standard Model. However, experiment is the ultimate judge of nature and theorists are not always right. A minority of physicists notably including Stephen Hawking and Nobel laureate Martinus Veltman have said that they do not believe the Higgs Boson will be found because according to their theories it cannot exist. They are considered contrarians by other physicists but until the “Goddamned” particle has been found nobody can be certain.

One thing that is sure is that the Large Hadron Collider will either discover the Higgs Boson or rule it out as predicted by the Standard Model. If all goes well this will be achieved before the end of 2012, perhaps much sooner. It has been said that if the Standard Model Higgs Boson is ruled out it will be an even greater discovery than its mere existence. This is not just excuses for what some people may portray as a failure. Such a result would indeed by a breakthrough inevitably leading to a new and better understanding of physics.

It is also possible that the Higgs Boson exists but that its characteristics are different from those of the Standard Model. In particluar, it may decay into other lighter unknown particles making it hard to detect. In that case it might appear not to be there even though it is. That will still count as ruling out the Standard Model Higgs but until further experiments are done it will not be known whether it does not exist at all, or is merely hidden from view by non-standard processes. Another even more exciting possibility is that there is more than one Higgs Boson possibly including some heavier versions that are charged. This is predicted by some grander theories such as supersymmetry

However, results from the LHC so far suggest that whatever happens there will be something positive to report today. It will not be quite a full discovery but it will be a strong signal that something like a Higgs Boson exists. Although we have heard some quite detailed rumours already, it is only by seeing the actual graphs that we can get a good idea of what the possibilities are. All physicists are now eagerly waiting to see them.

What will we learn?

You might think that since the Higgs Boson was predicted 50 years ago its discovery today will not be very exciting news. Indeed, before the LHC started collecting data, many physicists saw its discovery as inevitable and uninteresting. This view has changed, partly because nothing else has been quick to manifest itself at the LHC as hoped. This means that the Higgs Boson is likely to be the leading discovery of any new physics.

The mass of the Higgs Boson is a free parameter in the Standard Model. Once it is known, all other features such as its lifetime and interaction rates can be calculated. However, analysis of the physics of the Standard Model shows that if the mass is not within strict limits the theory will break down at higher energies. In particular, if it is too light the vacuum will not be sufficiently stable, but we know that this cannot be happening in the real world. The mass range left where the Higgs Boson can still be found includes a range where this would be a problem for the theory.

If it is lighter than 126 GeV then that may be an indication of new physics that could be found with more data. The theory of supersymmetry which is very popular with theorists actually favours the lighter Higgs and corrects problems with the stability of the vacuum, but it does not support well a heavier mass. For these reasons today’s announcement could signal the directions of research for future physics depending on what mass is indicated by the experiments.

What will we be looking out for today?

Despite the rumours, it is not certain exactly what will be shown today, but we are hoping for full reporting of all the results in the Higgs search from the two individual experiments. This would include the analysis of each possible decay mode that the experiments can currently observe plus two combination of results from all channels, one for ATLAS and one for CMS. The amount of data collected this year corresponds to an integrated luminosity of 5 inverse femtobarns (5/fb) in each experiment so anything less than this is not complete.

There are three sets of decay channels that are currently of special relevance to the search,

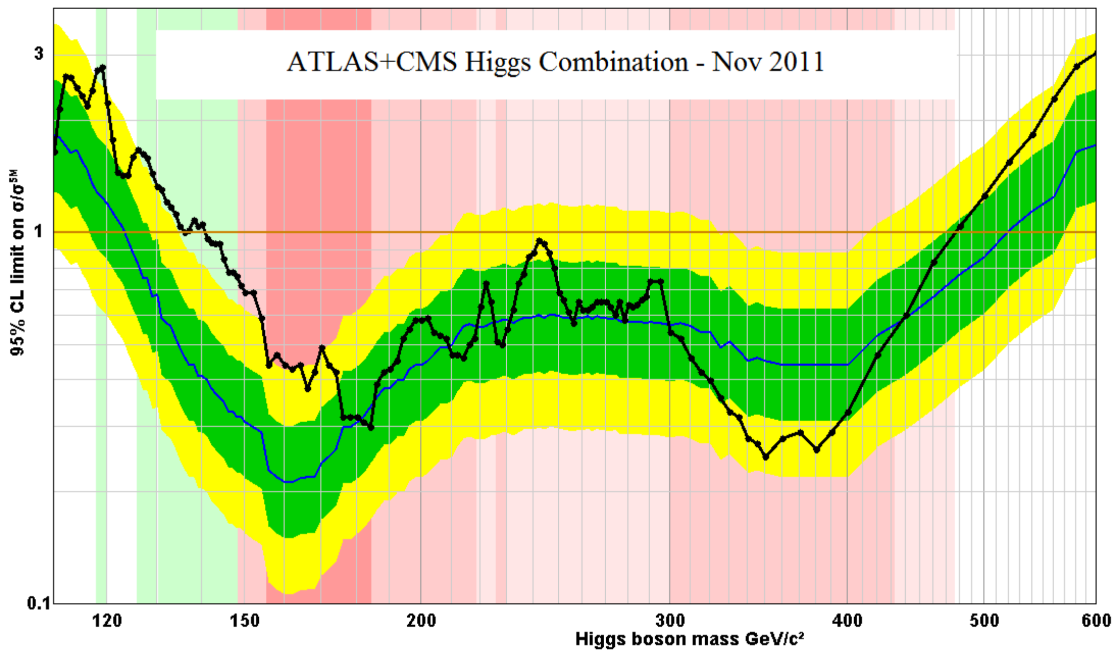
- **diphoton** (a.k.a. digamma) where the Higgs Boson decays directly to two photons
- **WW -> lvlv** where the Higgs Boson decays to two oppositely charged W bosons which then decay to electrons or muons and associated neutrinos
- **ZZ -> 4l** where it decays to two neutral Z bosons that then each decay to two oppositely charged electons or muons making four leptons in total.

If recent rumours are correct it is the diphoton channel that holds the most interest with a signal of a possible Higgs Boson at a mass of 125 GeV, but we will be very interested in the other channels to see if there is any supporting evidence or signs of anything at other masses. It will be especially interesting to see of the earlier weak signal at 140 GeV has gone away entirely. These and other channels may provide signs of something interesting at higher masses but most likely there will just be a strengthening of the evidence for exclusion above 140 GeV.

What do the plots mean?

During the presentations delivered by the collaborations today we will see a lot of new graphs. If you are not familiar with these they will require some explanation. The ones that everyone will be looking out for are the “Brazil band” plots, named for their distinctive green and yellow bands. These plots are the main way of showing the results from each Higgs Boson decay mode as well as the all important combinations.

Here is the best LHC combination plot for Higgs boson searches made public prior to today. It incorporates about a third as much data as gathered during the whole year and was shown in November at the Hadron Collider Physics conference, but I have redrawn it to add some extra features. (With any plot on this blog you can click on the image to enlarge for a clearer picture)



The horizontal axis is marked with the range of possible masses for the Higgs Boson. The units are Giga electron-Volts as an energy equivalent of mass. This is the standard way to measure mass in an accelerator experiment. If the Higgs Boson has a mass of 125 GeV as rumoured you should be able to see where it would appear on this plot.

The black line is usually called "Observed CL_s" and represents the calculated result from all the experiments. Its value for any given mass gives a quantity labelled "95% Confidence Level limit for σ/σ^{SM}" on the vertical axis. What does this mean exactly? Take an example; At 200 GeV the observed CL_s has a value of about 0.6. What this says is that if the signal cross-section over all the decay modes were just 0.6 times the amount expected if the Standard Model is correct and the Higgs Boson has a mass of 200 GeV, then there would be a 95% probability of seeing more events than they did. This is a roundabout way of saying that we have seen far too few events, so we can rule out the Higgs Boson at this mass with some confidence.

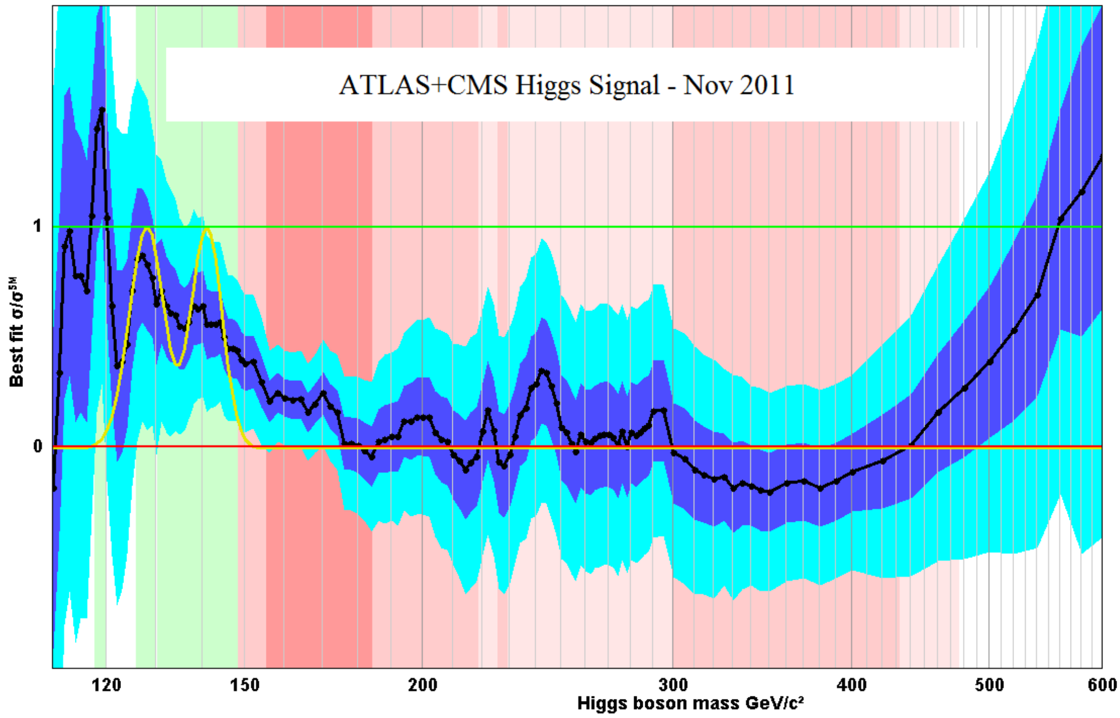
When the black line descends below the red horizontal line at 1.0 on the vertical axis, people sometimes say that the Higgs Boson has been ruled out at 95% confidence level at this mass. This is not strictly correct because such confidence would depend on our prior assessment of the probability for the existence of the Higgs Boson in this mass range in the first place, and also the "Look Elsewhere Effect" would have to be considered. Such knowledge is subjective and dependent on outside influences, but loosely thinking you can interpret it that way.

In the background of the plot I have shaded areas in various grades of pink. The lightest pink indicates an exclusions at 95% confidence. This is often stated as 2-sigma significance because statistically it corresponds to 2 standard deviations away from the normal expectation. Darker shades of pink indicate 3-sigma and 4-sigma confidence. Until recently it was generally accepted that 2-sigmas was enough to rule out the presence of the Higgs Boson at a given mass, but recently people have said they want 5-sigma significance, the same as for the discovery of a new particle. I think in reality most people will accept 3-sigma for exclusions.

But we are no longer just interested in exclusions. How do we know from this plot if the Higgs Boson has been seen? This is where the yellow and green bands come in. The central blue line indicates the expected value under the condition that no Higgs Boson exists at a given mass. The green and yellow bands are the 1-sigma and 2-sigma deviations from that expectation. This means that if there is no Higgs Boson the observed CLs line should wander within these two bands. Statistically it is likely to go outside the yellow bands for about 5% of its range. When we look at the plot we see that this is indeed the case. Despite the excess exceeding 2-sigmas around the 140 GeV region we can only say that the result is consistent with the lack of a Higgs Boson over the whole range. That is not a very encouraging way to put it. Notice that mass ranges where there are excesses will be background shaded in grades of green.

Can we at least say that the plot is also consistent with the hypothesis that there is a Higgs Boson somewhere in the mass range? We can see that it is excluded over the range from 140 GeV to 480 GeV at 2-sigma significance but we can still accept the possibility that it is in the low or high mass region. there are theoretical reasons to strongly doubt that it is at the high mass end so the range 115 GeV to 140 GeV is the best bet.

It is possible to display the same results in a different way that handles the existence and exclusion of the Higgs Boson in a more symmetrical way. This is sometimes called the "best fit" plot or "signal" plot and for the combination above it would look like this.



The experimenters don't often display their results this way, but as theorist I find it the best plot to give a feel for where we stand. If I can get the data from the talks today I may show some of these plots.

The black line varies around a range of signal values where a signal of zero would indicate just the Standard Model background with no Higgs Boson and a signal of one is just the right strength for its existence. The blue and cyan bands are error bands (mostly statistical) around the observed data. When the blue and cyan error bands extend over the whole range between the red line at zero and the green line at one we really have no indication either way for a Higgs Boson or its exclusion in the mass range. However, when it starts to settle on one of either the red or green line and moves clear of the other, then we know that we have the right signal strength for the presence or absence of the Higgs Boson.

What will happen after today?

Whatever comes out today there will still be a lot more work to be done. At the moment the LHC is shutdown for the Winter to allow for maintenance and to save electricity at a time when domestic demand is highest. It will startup again in February next year. Meanwhile the physicists will be using the time to continue the analysis of the data already collected during 2011 and that will include preparing the official combination of today's results from ATLAS and CMS.

Next year the LHC will run again, probably at a slightly higher energy of 8 TeV rather than the 7 TeV used this year. It is expected to collect three times as much data in 2012 as it did in 2011 so by the end of the year they will have a total of at least 20/fb on tape for each of ATLAS and CMS. If they don't already have enough data to know whether the Higgs Boson exists they almost certainly will by then.

More importantly, they will start to study the properties of the Higgs Boson to check that it matches the standard model by decaying into all types of lighter particle at the predicted rates. If it doesn't then they will know that there is new physics outside the Standard Model to be understood.

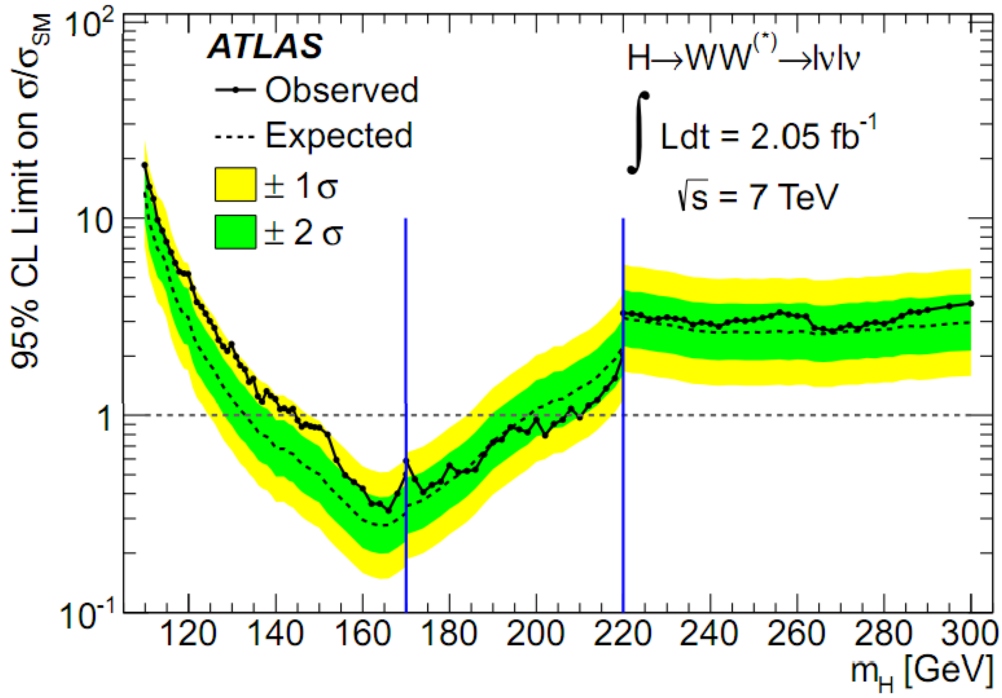
That assumes that the standard Higgs Boson will show up. If it doesn't they will have the job of looking for what replaces it . That can be done by looking at interactions between W bosons which should get stronger with increasing energy if there is no Higgs Boson until something gives. Present rumours suggest that the Higgs does exist but these WW scattering experiments will still be interesting.

After 2012 the LHC will shutdown for about 18 months to prepare it for running at higher energies, probably 13 TeV during 2015 and 14 TeV later. They will be searching for more new particles but they will also checking the parameters of the Standard Model including the Higgs Boson in more detail to eek out any signs of dark matter or anything else not seen before. The LHC will continue to run at higher luminosity and possibly even higher energy for perhaps another 30 years. This is just the beginning of what it has to do.

Live Blog Starts Here

09:00 (times are Central European)

This morning ATLAS have released an update to the Higgs search in the WW -> lvlv channel. They are using 2.05/fb in place of the previous 1.66/fb so it is only a small advance. This had been around for some time unofficially but was not shown at the HCP2011 conference, Hopefully it will be obsolete in a matter of hours but here is the plot anyway. It provides 95% exclusion from 145 GeV to 200 GeV.



11:45

Just to remind everyone, the official build-up for this event is as follows: "These results will be based on the analysis of considerably more data than those presented at the summer conferences, sufficient to make significant progress in the search for the Higgs boson, but not enough to make any conclusive statement on the existence or non-existence of the Higgs."

If you come here expecting a life-changing discovery to be announced you will be disappointed, but if you want to see some science in action taking a small step forwards you may enjoy.

12:00

With two hours to go the auditaurium was already full.

13:47

Here in the UK the BBC are already running reports on the network news. They are saying that each experiment is finding a blip in the same place giving a strong hint of the Higgs.

14:00

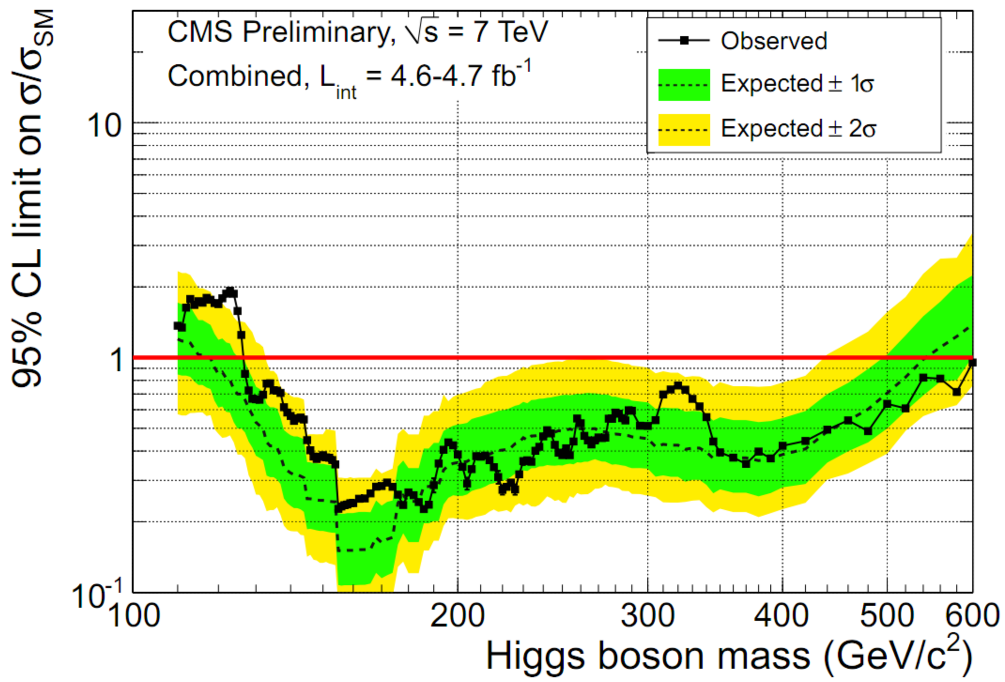
Speakers introduced, talks getting underway

14:15

ATLAS have updated the three most sensitive channels diphoton to 4.9/fb ZZ->4l to 4.8/fb and WW->lvlv to 2.1 (as above)

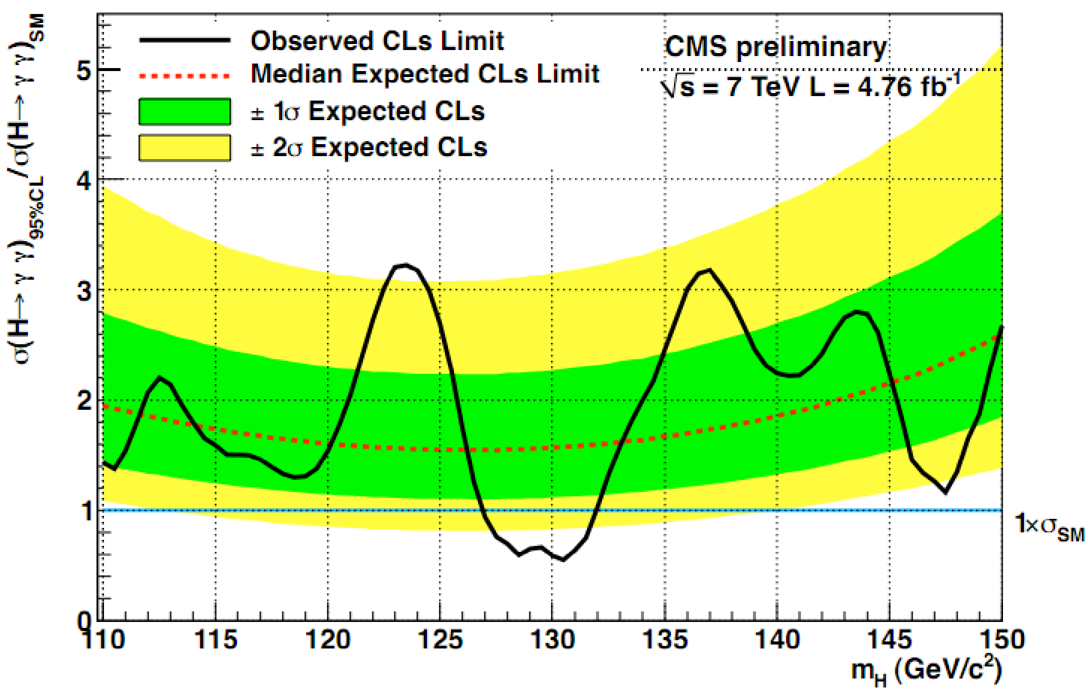
14:25

I have the CMS Combo, here it is with exclusion from 130 GeV up. Excess seen at about 123 GeV of 2.5 Sigma



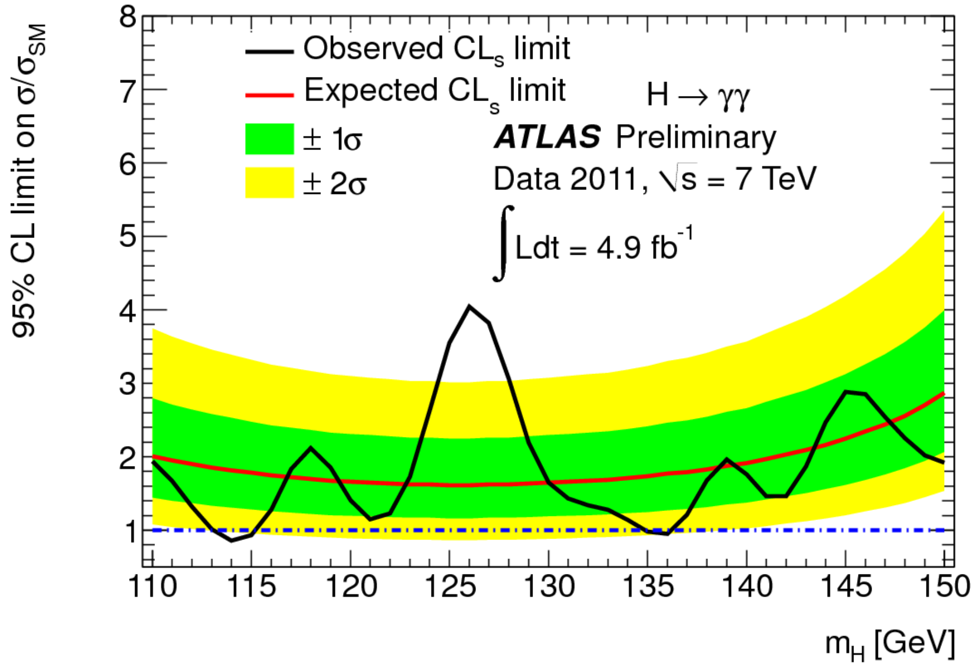
14:30

Here is the CMS diphoton plot shwoing where the excess comes from, but there are other excesses nearly as big



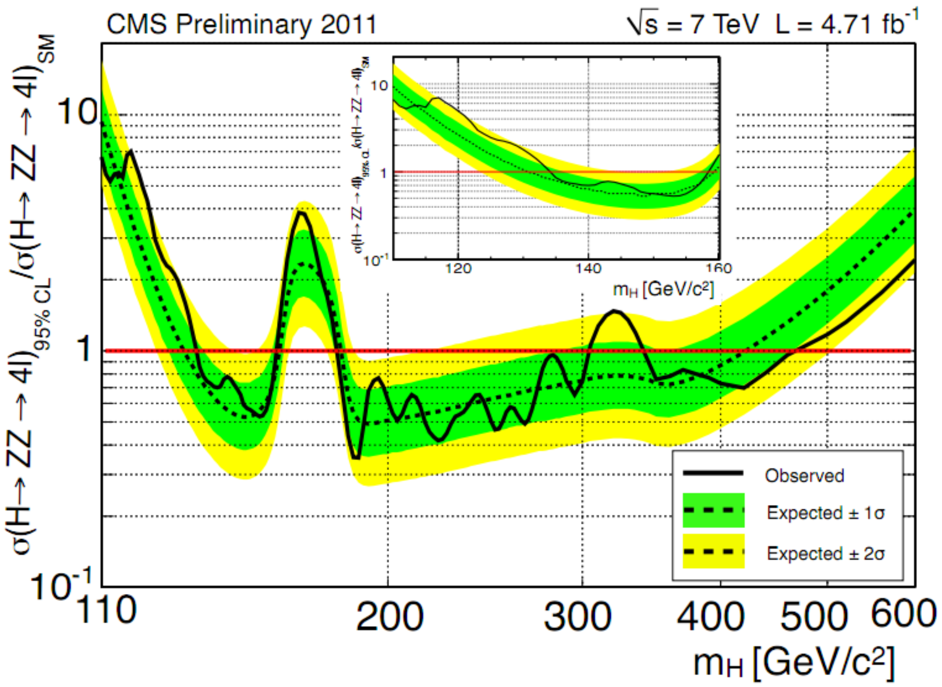
14:32

Here is the ATLAS version from the talk. Updated from conference notes.



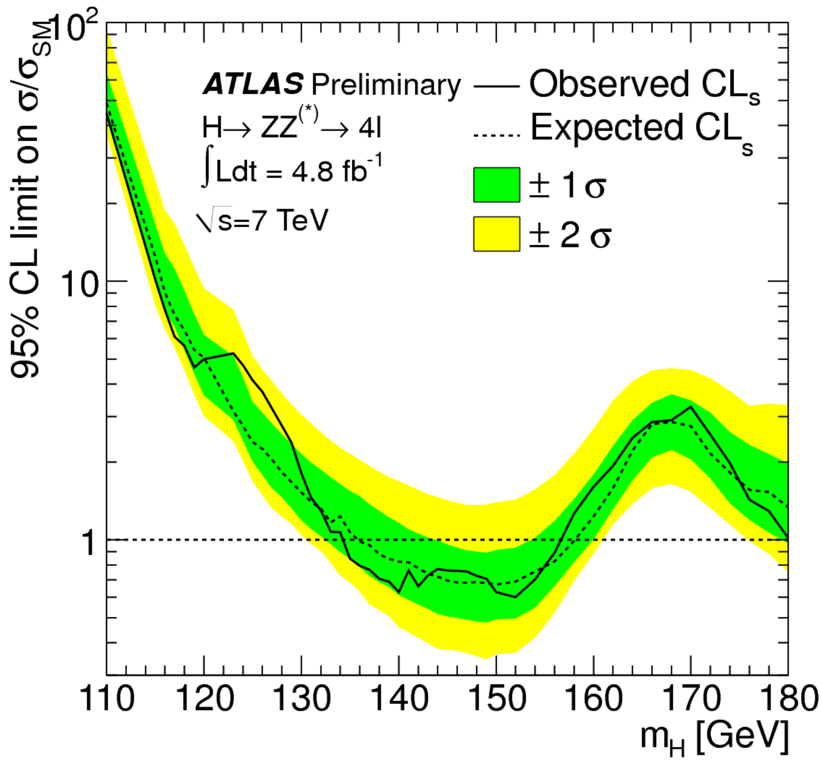
14:36

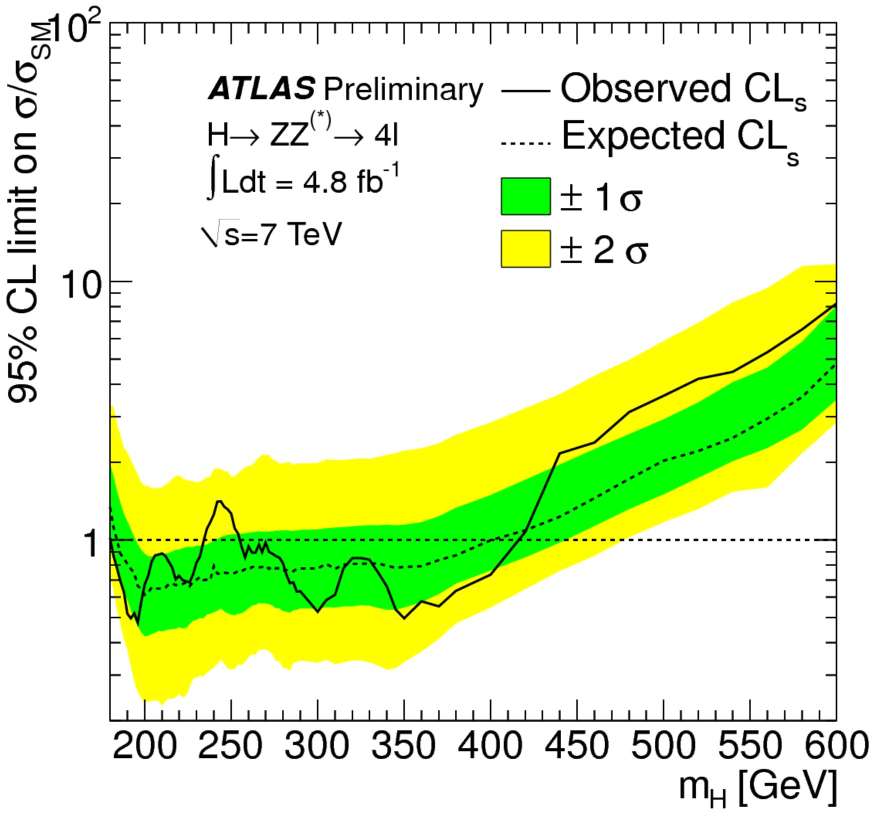
The CMS ZZ->4l clearly rules out the 140 GeV possibility, but has an excess at lower mass.



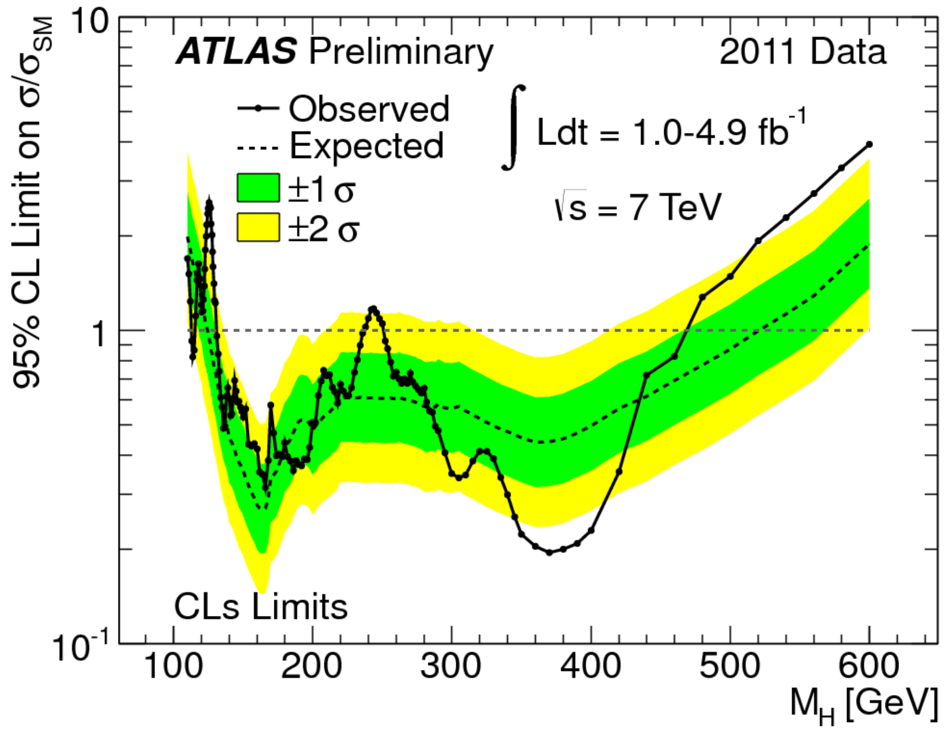
14:43

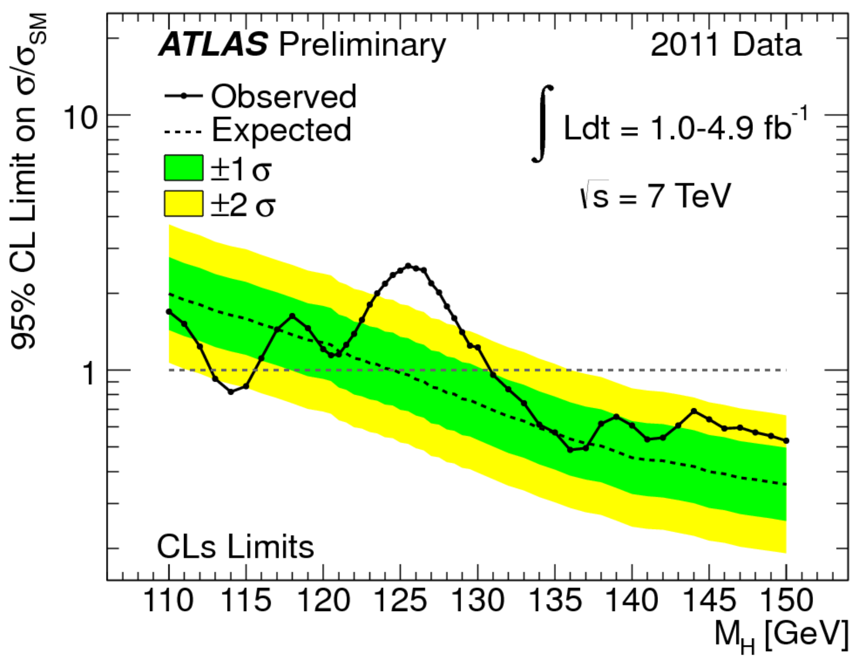
ATLAS ZZ->4l and full combo from the talk. Updated from conference notes.



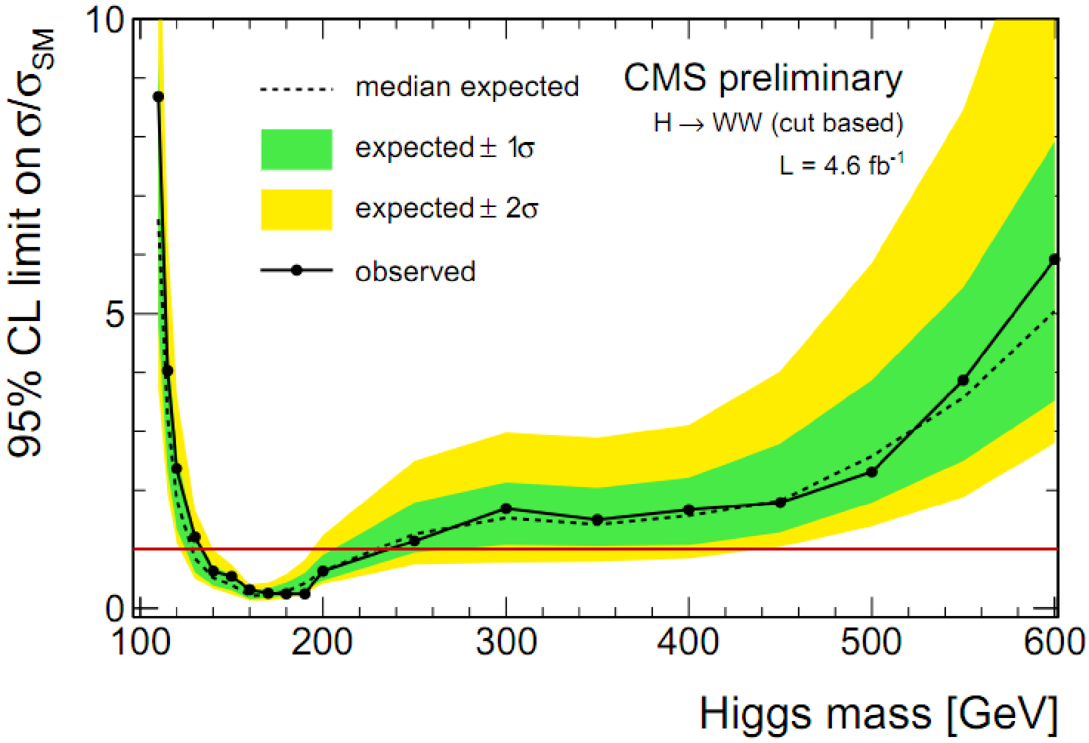


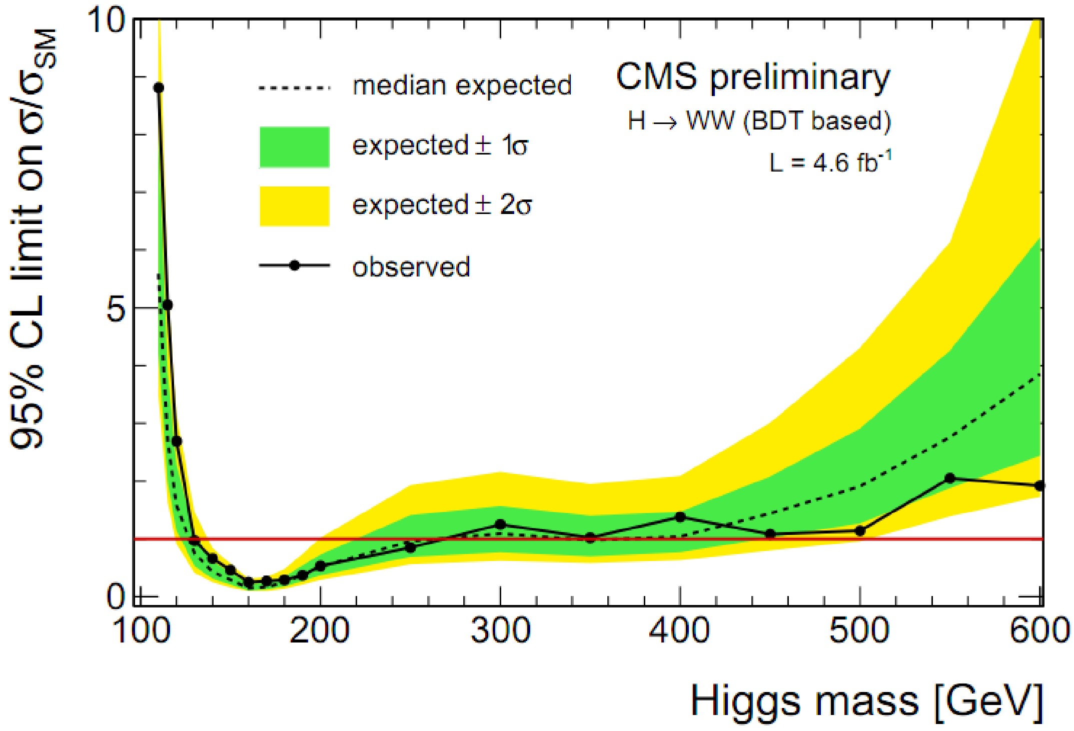
ATLAS full combo from the talk. Updated from conference notes.





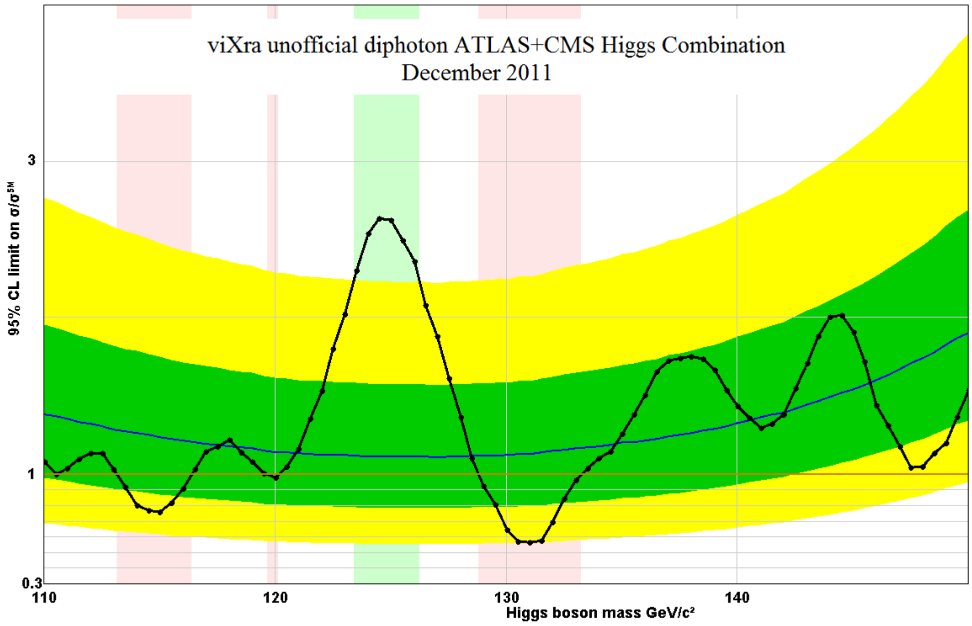
14:49
First talk is over, now over to CMS
CMS have two versions of the WW channel, cutbased and BDT





14:49

Here is the first of my unofficial combinations as the discussion time ends. This is the diphoton channels combined for ATLAS+CMS. Remember that this is approximate and you should not try to read the number of sigmas from this. I may revise it later when better version of the plots become available.

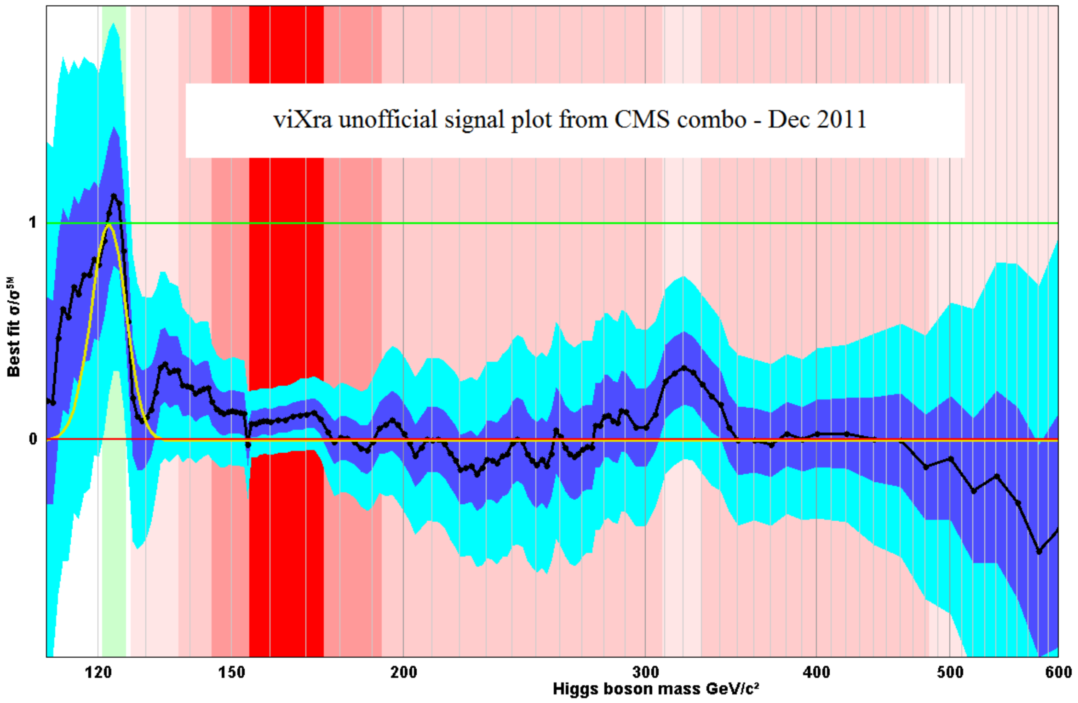


14:56

ATLAS have now released 3 new conference notes so I will update the pixtures

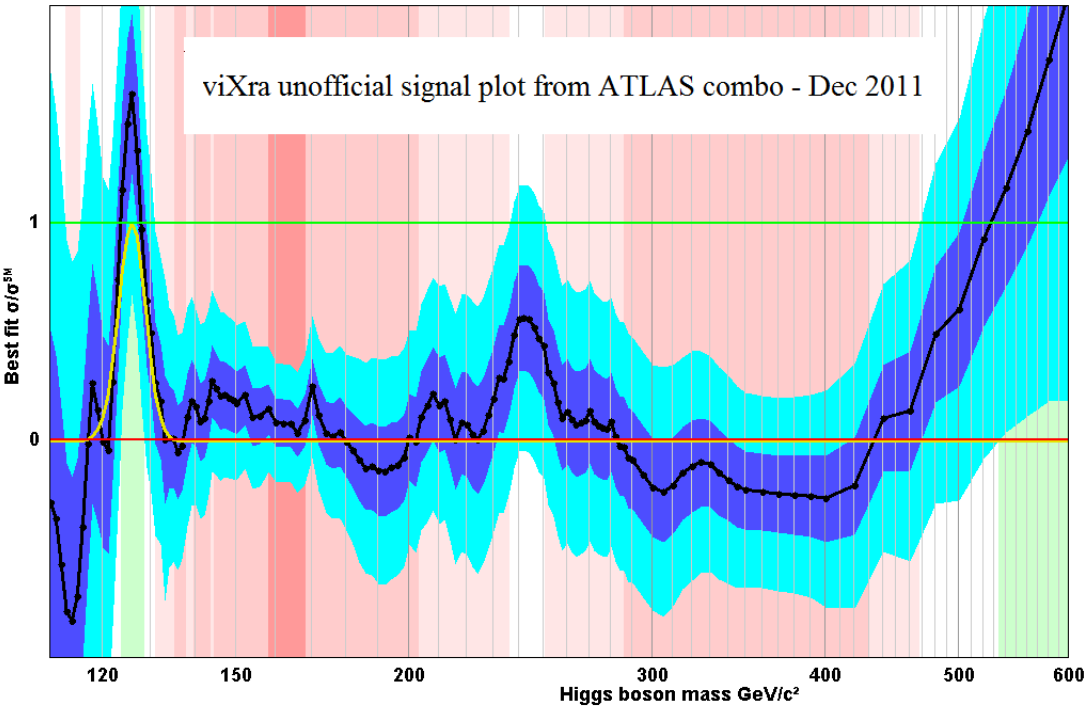
17:00

I have now digitised the CMS combined plot and produced this signal plot. It gives a clean indication for no Higgs about 130 GeV and the right size signal for a Higgs at about 125 GeV, but there is still noise at lower mass so chance that it could be moved.



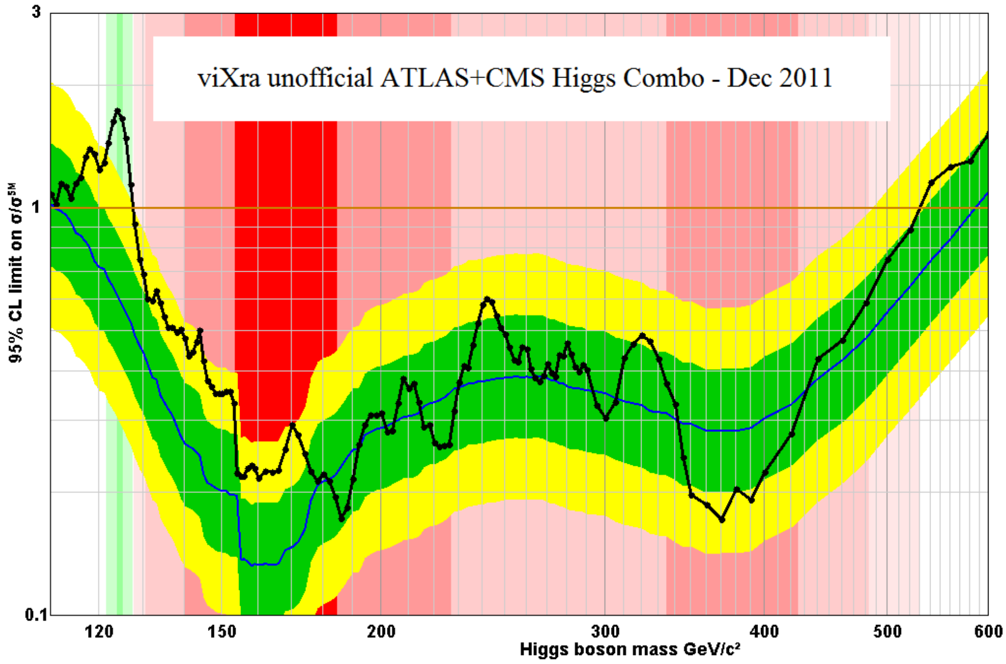
17:42

Here is the same thing for the ATLAS data



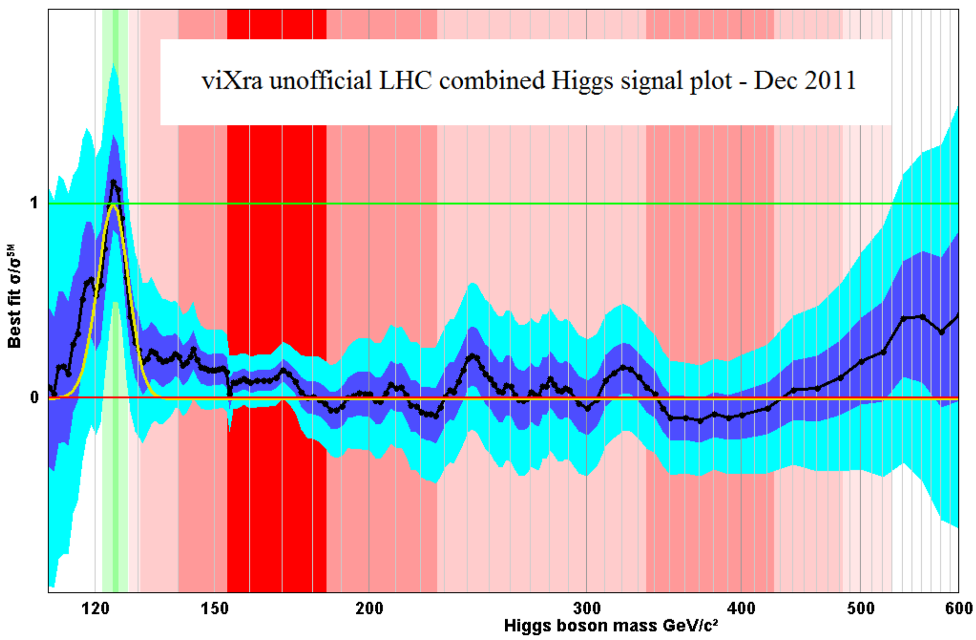
17:49

Here is the fully combined exclusion plot. The signal fits best at 124 GeV and just makes 3-sigma. Remember the official version is likely to be a little different. This is just a quick approximation.



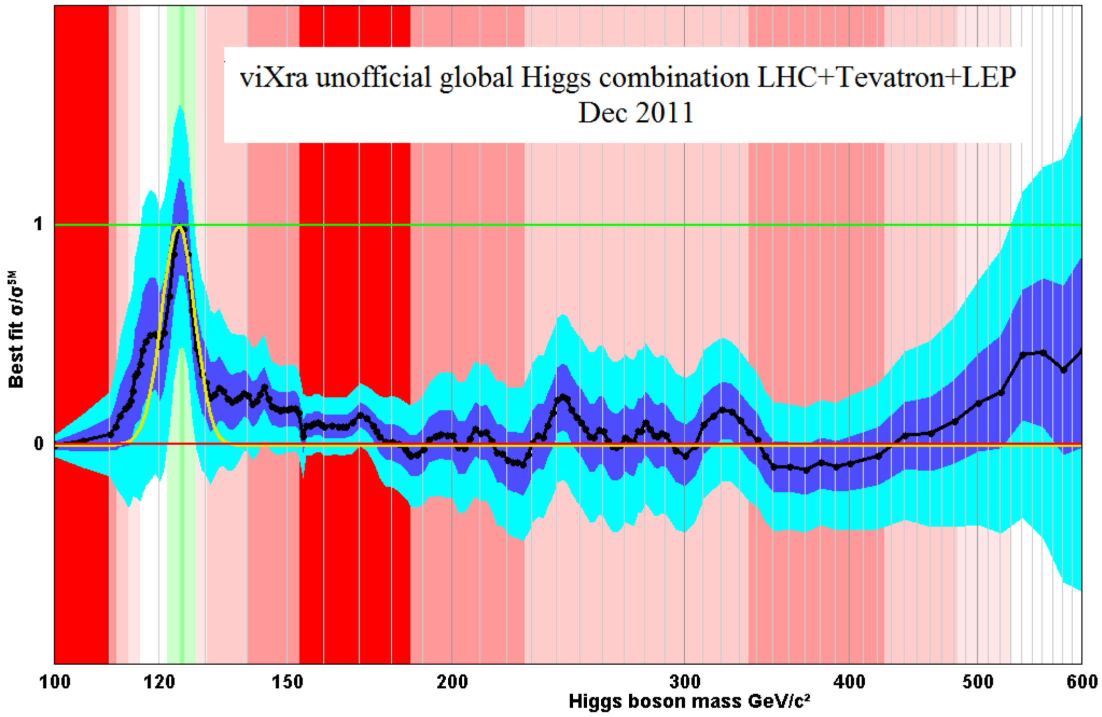
17:57

Here is the fully combined signal plot. It looks very convincing but the region below 120 GeV is not resolved yet. Until it is there will be a little room for doubt.

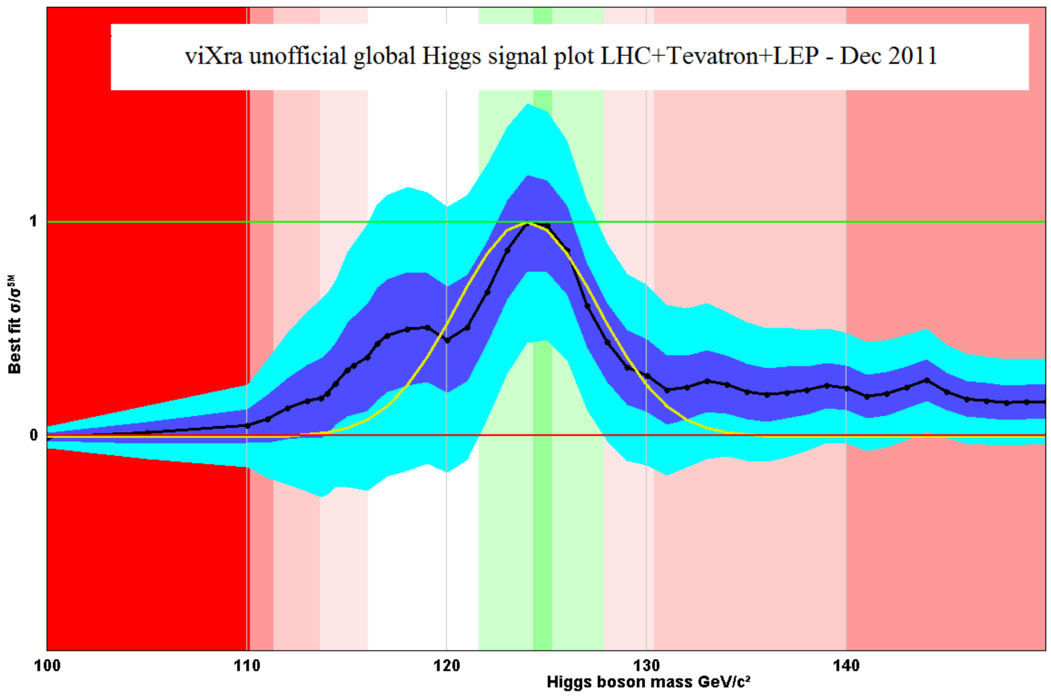


18:11

But of course we can clean up the lower region by including LEP and Tevatron too. An official combination with Tevatron data included is also planned

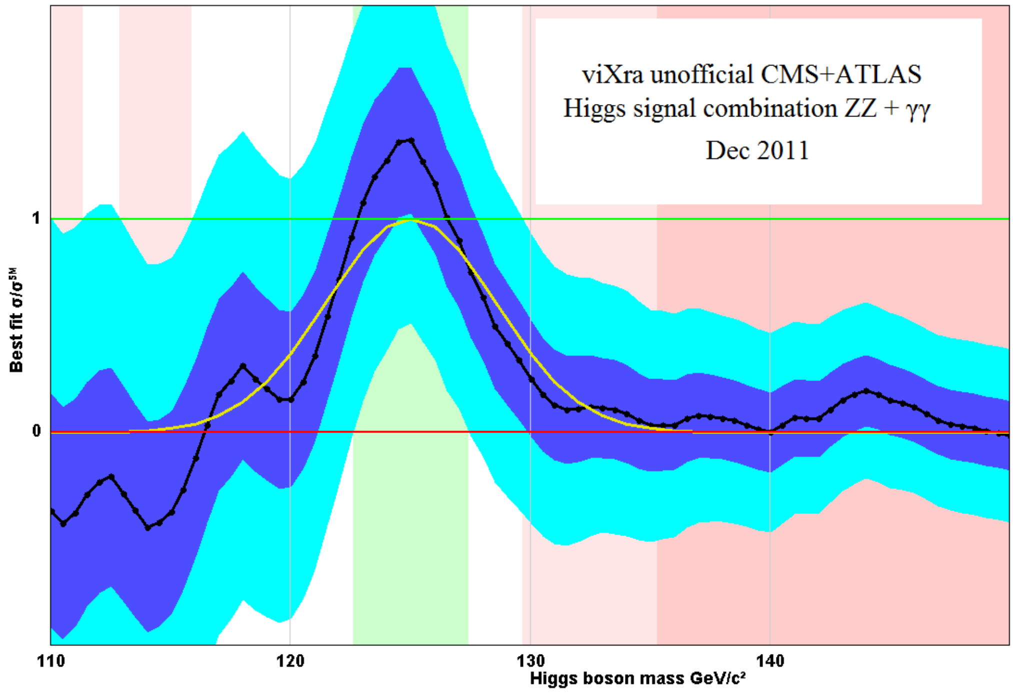


A zoomed version



20:57

Finally here is one last combination for diphoton + ZZ in CMS and ATLAS. These are the high-resolution channels so they give a cleaner signal, but without WW the significance is less.



Conclusions

The result is very convincing if you start from the assumption that there should be a Higgs Boson somewhere in the range. Everywhere is ruled out except 115 GeV to 130 GeV and within that window there is a signal with the right strength at around 125 GeV with 3 sigma significance. They will have to wait for that to reach 5 sigma to claim discovery and next years data should be enough to get there or almost. I calculate that they will need 25/fb per experiment at 7 TeV to make the discovery. A big congratulations to everyone from the LHC, ATLAS and CMS who found the clear hints of Higgs when it hid in the hardest place.

I was lucky enough to meet Peter Higgs many years ago when I was a postdoc at Edinburgh and I have a big smile knowing that this has been achieved in his lifetime. Congratulations to him and the other physicists involved in discovering the mechanism of symmetry breaking. Finally, in case they are forgotten, well done also to all the phenomenologists who did the calculations to work out how the Higgs Boson could be found, not least John Ellis.

From here there is much more work to do in order to check that this particle seen today has exactly the characteristics of the Higgs, if indeed it is confirmed with more data. That will take many more years of runs at the LHC. It will also be exciting to see how this mass affects our understanding of what other physics could be in reach. I hope there are some Campaign corks popping at CERN this evening. They have had a remarkable year.

References

1. http://blog.vixra.org/2011/12/13/the-higgs-boson-live-from-cern/