PROCEEDINGS OF SCIENCE

Higgs Search Status

Bill Murray[*†]
RAL
E-mail: bill.murray@stfc.ac.uk

An overview of this subject is presented in some 10 pages. It covers the areas of electroweak fits, LEP and TeVatron Higgs results and the expectations from the LHC. There is of course a hugely larger literature available on this subject; I particularly recommend the following resources:

LEP Electroweak Working Group, http://lepewwg.web.cern.ch/LEPEWWG/

LEP Higgs working group pages, http://lephiggs.web.cern.ch/LEPHIGGS/www/Welcome.html

TeVatron Higgs working group pages, http://tevnphwg.fnal.gov/

ATLAS Performance book, http://cdsweb.cern.ch/record/1125884?ln=en

CMS TDR, http://cmsdoc.cern.ch/cms/cpt/tdr/index.html

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*Speaker.
†To the organisers for inviting me

1. Introduction

The search for the Higgs boson[1] is one of the major goals for LHC, and has been an important driver in the designs of the experiments there. The global status is reviewed here, at the brink of LHC start-up. Within a few years we should have major new developments in our knowledge of the the Higgs model, but will the searches return sufficient detail to know whether the Higgs boson has indeed been found?

The current knowledge from data at LEP and the TeVatron are summarised in section 2, the ongoing TeVatron searches are in 3 and the LHC is discussed in section 4. The LHC discussion uses the ATLAS experiment to illustrate the discussion; similar expectations hold for CMS.

2. Current knowledge

The current data relevant to the Higgs boson search comes both from indirect and direct studies. These are discussed in the following sub-sections.

2.1 Indirect evidence

The Higgs boson in the Standard Model is the missing piece in two overlapping jigsaws: The first are massless electroweak vector bosons A, B and W^+ W^-, where the neutral A and B mix to produce the γ and Z. The second is the scalar components of the family of W^+ W^- Z and H bosons. As is well known the W^+ W^- and Z become massive vector bosons while the photon remains a massless vector and the Higgs a massive scalar.

It is therefore not surprising that detailed studies of those bosons allow some constraints upon the properties of the Higgs. Indeed these studies are always referred to as electroweak fits. These fits use a large amount of data from ALEPH, CDF, D0, DELPHI, OPAL, L3 and SLD[2]. They produce firstly the highly non-trivial result that the W boson mass can be predicted to within one per mille through consistency of the Z properties, especially the asymmetries which are directly linked to it. This result has tightly constrained alternative theories of mass generation such as technicolour which need special treatment to produce this result.

The current status of the electroweak fits, see Fig. 1, is a reasonable χ^2 for the Standard Model with $m_H = 87^{+35}_{-26}$ GeV. This can also be described as an upper limit on the Higgs mass of 157 GeV. It is important to keep in mind that this fit assumes there is nothing beyond the Standard Model (which is manifestly untrue in the presence of dark matter and even gravity) and that the bound moves rapidly depending upon how the fit is done. For example, imposing a lower limit of 114.4 GeV, as comes from the LEP searches described next, moves the upper limit upwards by 29 GeV.

2.2 LEP Searches

Prior to the 21st Century, by far the most useful Higgs limits came from the LEP e^+e^- collider. These stemmed largely from associated Higgs production, in the process $e^+e^- \rightarrow Z^{(*)}H$. A second process, vector boson fusion, was included in the production expectations, but tended to have a rather minor role in the overall results.

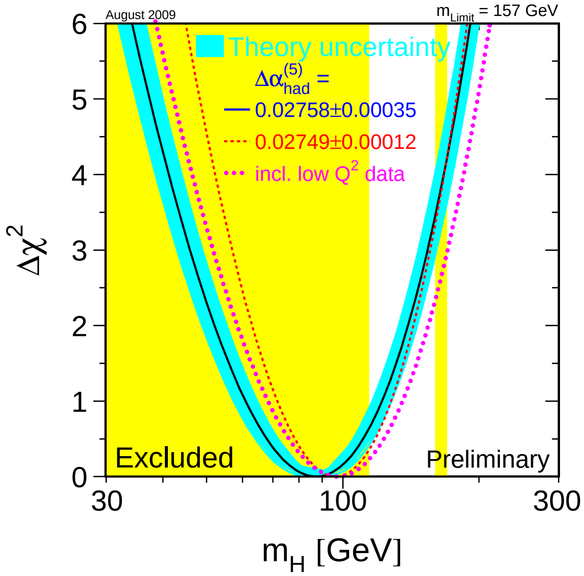

Figure 1: The χ^2 from the combined electroweak fits.

The decay of the Higgs boson depends upon its mass and in the LEP searches have covered stable through $\gamma\gamma$, ee, $\mu^+\mu^-$, $\pi\pi$, $\tau^+\tau^-$ and $b\bar{b}$ for the Standard Model Higgs, with searches also in W^+W^-, generic quarks and invisible channels. These have been taken with the Z boson decays to ee, $\mu^+\mu^-$, $\tau^+\tau^-$ $\nu\bar{\nu}$, and $q\bar{q}$. Some combinations were too rare or had too much background to be considered. The clean predictable environment of the e^+e^- collision allowed for low and calculable backgrounds, and the search was mostly conducted by directly comparing observations with predictions from simulation. The

The first phase of operation of LEP was at the mass of the Z, and the large resonant production would have allowed subsequent decay to an on-shell Higgs boson and off-shell Z with a rate decreasing as the Higgs boson mass rises. The searches were restricted to leptonic (including neutrino) decays of the Z* which had a cleaner signature as there is of course no mass constraint which can be applied to reject background and improve mass resolution. No surprising numbers of Higgs candidates were observed, and an exclusion was set which covers the standard model Higgs boson from 65GeV for all lower masses, right the way to zero.

In the second phase, LEP II, the centre of mass energy was raised in stages to 208 GeV, and the most important possibility was production of both Z and Higgs on mass-shell. Now all the Z decay modes listed above were employed. The standard model search produced a small excess, consistent with a Higgs boson of around 115GeV but not inconsistent with background expectations. The lower limit on the Higgs mass was then set at 114.4GeV.

3. TeVatron

The TeVatron has been running since 1987 at around 1 TeV per beam and has produced an integrated luminosity which has passed 7 fb^{-1}. The D0 and CDF experiments have broadly comparable sensitivity to a Standard Model Higgs coming from that data. This sensitivity is low - no single channel in one experiment has any hope of making a convincing discovery, but the combination of many channels and both experiments is beginning to have an impact[3].

The TeVatron searches can be divided into low mass channels, where the decay to $b\bar{b}$ is the most sensitive, and high mass ones where the WW decay dominates the search potential. This is illustrated by Fig. 5, which shows the Higgs branching ratios as a function of its mass. There is already sensitivity to a Higgs in the mass range around 165 GeV coming from the large branching ratio to W boson pairs.

The productions mechanisms relevant for the LHC and TeVatron are shown in Fig 5.

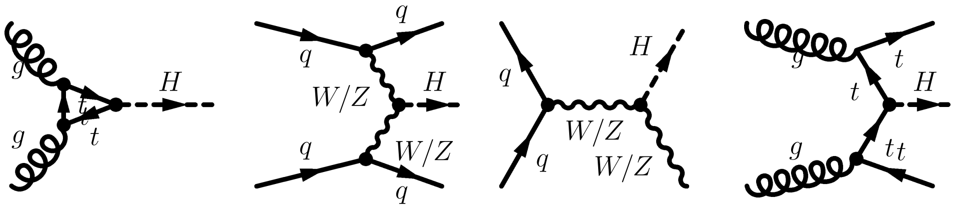

Figure 2: The main Higgs production process at a proton collider. From left to right: gluon fusion, vector boson fusion, vector boson associated and top associated

The backgrounds at a proton collider are complex - essentially anything kinematically possible must be considered. There will be production of systems which are 'irreducible background'; they produce an identical set of particles to the signal being considered. These backgrounds may still in fact be controlled by kinematic selections.

There is also a much larger rate of 'QCD events'; interactions mediated by gluons which produce quark or gluon jets in the detector. These fake the signature of interest, which will normally contain leptons, rather rarely - but there is an enormous production rate. There are therefore two challenges: to reduce the jet misidentification rate, and to know precisely what level of background it creates.

3.1 Low mass Higgs

The low mass search relies mainly only the $H \to b\bar{b}$ mode, augmented by rarer channels. The QCD production of $b\bar{b}$ pairs is so large that it is not effective to use this channel in an inclusive manner, but an associated production mechanism must be required. Association with a leptonically-decaying W or Z boson gives an acceptable signal rate with much improved signal to background and a clean lepton trigger except for $Z \to \nu\bar{\nu}$.

The signal to background is about 1:20; this difficult situation is made worse by the accuracy of the prediction for vector boson plus b quarks which is around 30%. The extraction of the background rates from control samples is essential in this channel, as in all these searches. Typically the shapes of the distributions are taken from simulation and the rates from data.

The status at time of writing is that from about 5 fb^{-1} of data analysed the *sensitivity* for a 95% upper limit on the signal rate is at 1.8 times the rate expected from the standard Model, while the limit actually set is at 2.7 times the rate expected, owing to a small excess in data. The expected factor of two in data will need to be accompanied by a similar factor from analysis improvements and additional channels in order to have a reasonable chance of three sigma evidence if there is a Standard Model Higgs at this mass.

3.2 High mass Higgs

At the TeVatron, a high-mass Higgs means around 160 GeV in mass. From this mass upwards the decay to W bosons gives two on-shell products, giving the explosion in decay rate seen in Fig 5. The ZZ decay does not have a similar increase until just over 180 GeV and so the WW branching ratio dominates between these masses.

The search channel which is most useful at these masses is the Higgs to WW followed by electron or muon decays of both W bosons. The is has a branching ratio of 22%, and so the product rate is around 5%. In contrast only 6% of Z bosons decay to electron or muon, and so the 'Golden' mode of H to ZZ to $l^+l^-l^+l^-$ is suppressed by a product branching ratio of 4 per mille, as well as being less common to start with, and is thus simply too rare to be important at the TeVatron.

Because it is doubly leptonic, this WW decay mode has no need of further enhancement to suppress the QCD background, and the gluon fusion process, the most frequent production one, can be used. The largest background is real WW production, and this is suppressed by using the spin of the Higgs boson. As this particle is spinless the spins of the W's must be opposite, but so too are their particle/antiparticle natures. Thus when they decay the charged leptons produced tend to head in roughly the same direction, and this is used to suppress and measure the WW rate.

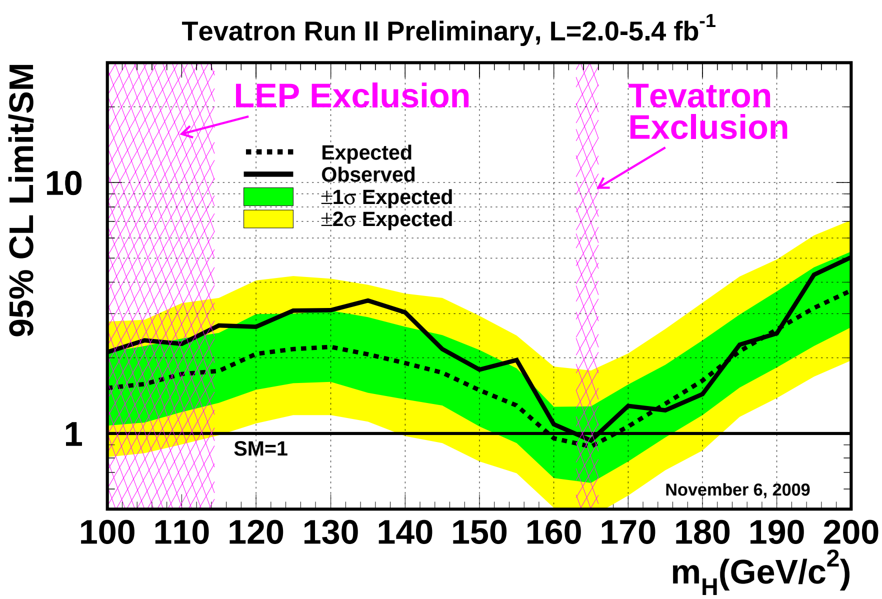

Figure 3: The Higgs combination produced by the TeVatron, as of November 2009.

The individual experiments are now very close to sensitivity at 165 GeV, and the combination has excluded a small mass region of Higgs boson masses since 2008, see Fig 3. This is currently 163 to 166 GeV, but we should expect significant increases fairly soon.

Finally, all three analyses (electroweak fit, LEP and TeVatron searches) provide likelihood-ratio outputs. We can sum these and invert to find the probability density. This implicitly assumes making a Bayesian flat prior in mass. This is done here and the result is shown in Fig. 4.

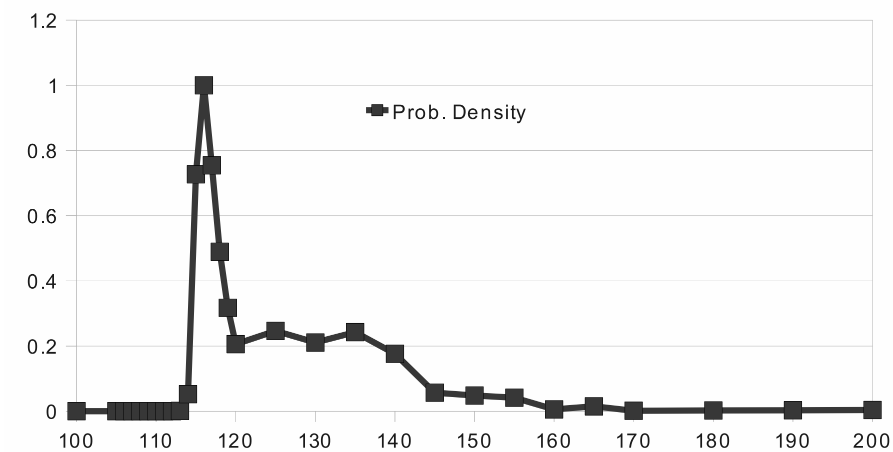

Figure 4: The combination of all data on Higgs mass. This assumes that the Standard Model is correct and merely asks what mass the Higgs boson has.

4. The LHC

The LHC collider at CERN has started taking data at the end of 2009, with a short commissioning run largely at injection energy. In 2010 is is expected to produce of order 0.2 to 0.5 fb^{-1} at beam energies of 3.5 to 5 TeV. This will probably be followed by a significant shutdown before data measured in fb^{-1} is recorded at 7 TeV per beam. The 2010 LHC experimental expectations are in gross terms similar to the TeVatron, with a greater sensitivity to a Higgs mass of around 160 GeV and a lesser one to a Higgs boson close to the lower mass limit. Note that, as can be seen in figure 4, this means that a Standard Model Higgs is unlikely to be discovered for some time.

It must be emphasised that the detectors will need to do detailed studies of many known processes in order to understand the events they are recording, and it will be some time before confident statements about the presence or absence of new physics should be believed.

4.1 Production

The production process are as shown in Fig. 2, with rates as shown in Fig. 5. For example, the 40 pb cross-section of a Higgs of 115 GeV means that at design luminosity of $10^{34}cm^{-2}s^{-1}$ some 3 million would be produced per year. The problems come from the enormous background cross-sections. The minimum bias rate is some 10^{10} larger than the Higgs signatures of interest, and even top production is one or two orders of magnitude more common. Thus the theme of the search is finding ways of distinguishing the signal from the backgrounds.

The discussion here uses examples from ATLAS[4].

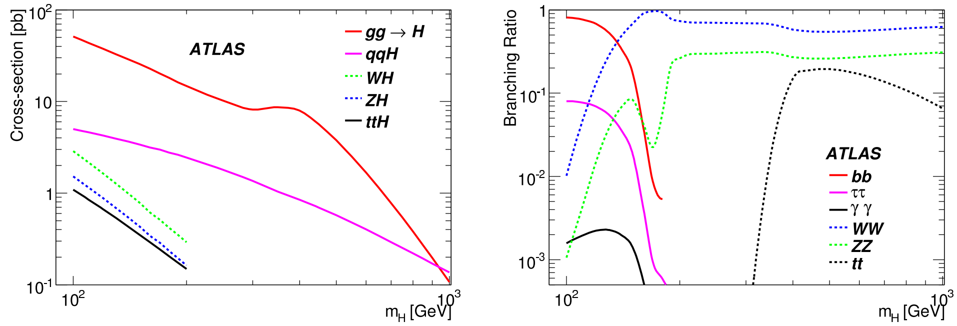

Figure 5: The Higgs production cross-sections at 14TeV (left) and its branching ratios into final states important for hadron collider searches (right).

4.2 Low Mass

The low mass Higgs should be very copiously produced at LHC. So frequently in fact that the rare decay mode, $H \to \gamma\gamma$ becomes accessible. This mode can be accessed experimentally through the very good momentum resolution available in photon calorimetry. This, combined with a natural width measured in MeV, gives rise to a very narrow experimental peak, and the ability to find a small signal in a large background, see Fig‘6 (left). This mass distribution is augmented by fits using the numbers of jets, photon quality, and candidate p_T, which significantly enhance the sensitivity.

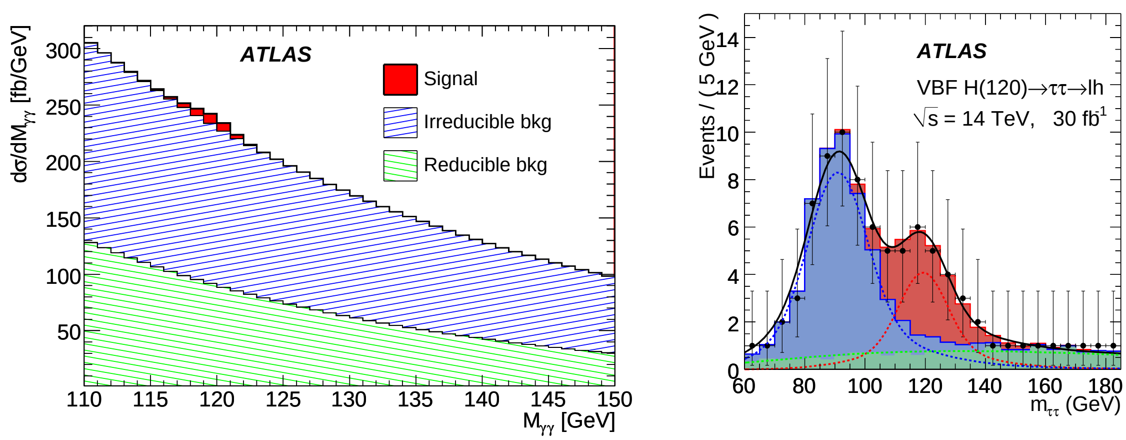

Figure 6: Mass plots illustrating the low mass Higgs searches in ATLAS. Left is the Higgs to $\gamma\gamma$ and right the Higgs to $\tau\tau$.

The Higgs to $\tau^+\tau^-$ decay mode is the second largest branching ratio at the lowest masses and when at least on of the τs decays leptonically it provides a strong QCD suppression and clear trigger object. However, the presence of neutrinos complicates the mass measurement, and an additional background suppression is required to make this a discovery channel. This is provided by the use of the VBF production mode. The tag jets coming from the quarks which emitted the vector bosons give a large component of this background suppression, and when this is complemented by requiring an absence of hadronic activity between the two tag jets, reflecting the fact that the vector bosons are colour neutral, a very good signal to background appears to be achievable.

There are residual uncertainties about the efficiency with which a jet veto can be applied, especially in the presence of background, and suitable control samples will need to be found to measure this.

The ttH channels was once thought to be a leading candidate for a low mass Higgs discovery. However, increasing accuracy in the calculation and modelling has stressed the difficulties associated with large numbers of jets from gluon radiation and precise jet measurement, and it currently seems challenging.

Conversely, the WH and ZH channels, where the Higgs boson decays to b quark pairs, which were at one time believed to be swamped in background at LHC now seem to be measurable[5], and should contribute comparably to the first two channels mentioned here. This is excellent news, as it means the the Higgs to $b\bar{b}$ coupling, which gives the leading decay mode, should be measurable.

4.3 Intermediate Mass

This mass region, as at the TeVatron, is the region where the Higgs to WW decay dominates the search results. ATLAS characterises this search by the number of jets seen with the WW pair. The gluon fusion process produces few jets, while vector boson fusion has two ‘tag’ jets associated with the recoiling quarks. The expected distributions can be seen in figure 7.

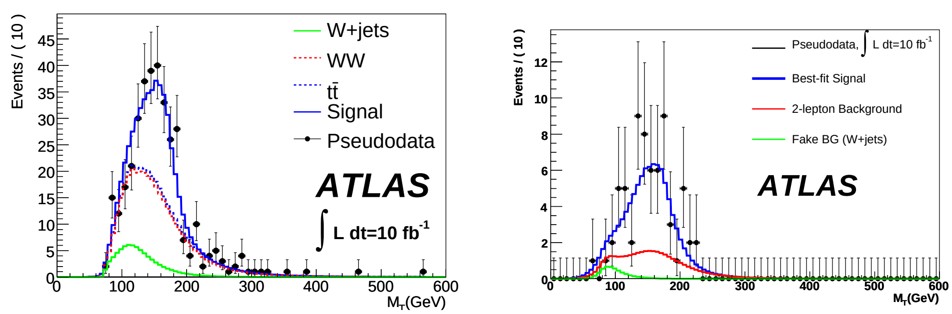

Figure 7: The Higgs transverse mass distributions expected in the Higgs to WW channel. On the left is the search requiring 0 jets, while on the right two jets are required, selecting the vector boson fusion process.

The region of Higgs mass around 165GeV is the easiest to access at LHC. Here the expected data sets for 2010 should produce sensitivity to the Standard Model Higgs boson. Note that the kinematics of Higgs to WW decay does not lend itself to a precise mass measurement; this will probably come largely from the ZZ channel, which is also measurable in the same area.

4.4 High Mass

This refers to a Higgs boson above around 200GeV. From this point the decay to two on-shell Z bosons offers such a good suppression of the background, even ZZ background through the good mass resolution producing a narrow signal peak, that this channel dominates the analyses.

However, as the mass rises to several hundred GeV then the natural width increases; see figure 8. Eventually this removes the advantage of making a precise mass measurement, and the WW channel becomes useful again. In this case the vector-boson fusion cross-section is approaching the gluon-fusion one, and it again makes sense to tag the forward jets produced in this mechanism to enhance the signal to background.

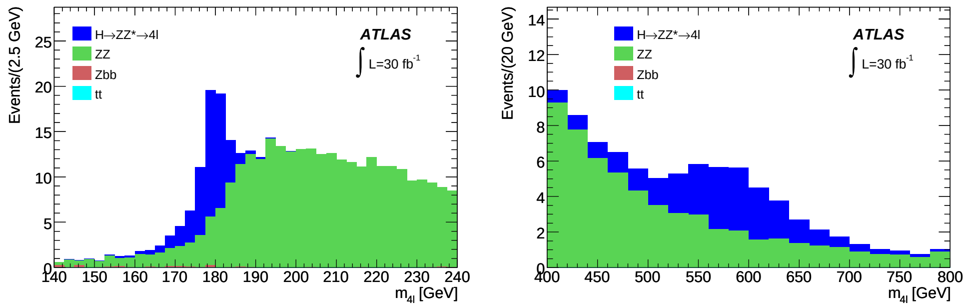

Figure 8: The mass distributions expected in the ZZ channel for a Higgs boson mass of 180GeV (left) and 600GeV (right).

4.5 Combined search sensitivity expectations

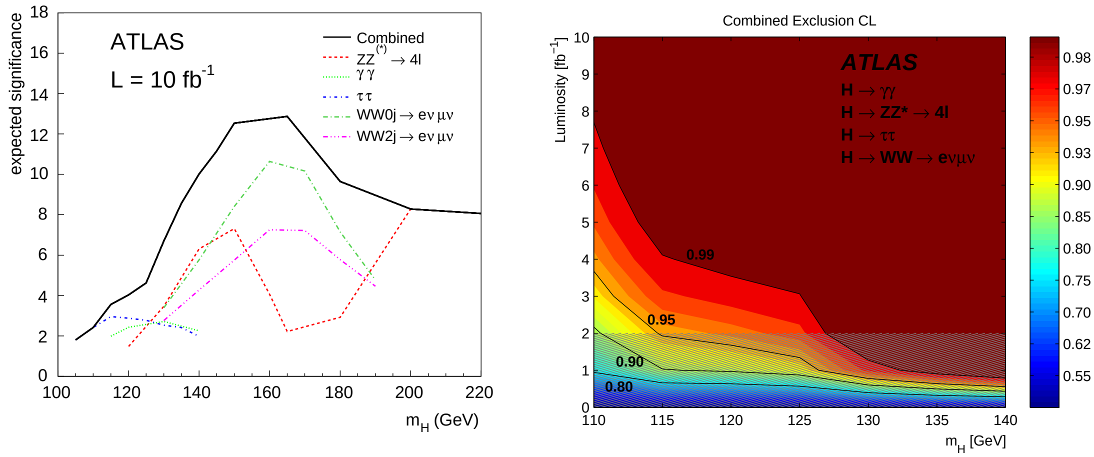

Figure 9: The combined sensitivity of the ATLAS experiment. Left shows the expected significance as a function of mass from 10 fb^{-1} while right is the confidence level to which a Higgs can be excluded as a function of the luminosity recorded. Note that these results do not include the W/Z+H channel, an important addition at low mass.

The Fig 9 shows the ATLAS sensitivity to a Higgs boson as a function of its mass. It appears that 2 fb^{-1} of data at design energy should be sufficient to excluded the standard model Higgs. However, rather more is required for a convincing discovery at the lowest masses.

4.6 Higgs properties

While it would appear that the searches designed to find a Standard Model Higgs are able to determine whether something falling into their selections exists, that is quite different from actually establishing its properties. We would like to establish the mass, spin and parity of the particles, and its couplings to as many different other particles as possible. Finally, the self-coupling is what drives the Higgs potential negative and gives spontaneous symmetry breaking, so a measurement of that would be highly desirable.

The mass should be well measured at LHC. The low mass Higgs has the $\gamma\gamma$ decay mode to a narrow resonance, see fig. 6 (left) and the high mass Higgs can be measured in ZZ decay, see Fig 8. In each case the precision should be at least 0.5%, depending upon the establishment of the energy scales. This is somewhat easier for the ZZ decay, which can be calibrated on the known Z mass.

The width is not likely to be directly measurable at LHC. For masses below 140GeV the width is below 10MeV, which is far less than the experimental resolution of 1GeV or more. However, once the Higgs mass is greater than the WW and ZZ thresholds it broadens to about a GeV, and the measurement may become possible.

Much more promising is the extraction of the couplings. As has been seen there is a range of possible Higgs boson production mechanism and decay modes, and each gives another piece of information. The couplings cannot be extracted without making some sort of assumption, as the total width is not available, but within certain assumptions measurements of the coupling to W, Z τ and top should all be extractable with errors of order 40% by two experiments with 30 fb^{-1} if the b coupling can be measured somehow[6].

The spin is known not to be one if the $\gamma\gamma$ decay is observed, and the use of the Z mass or WW di-lepton mass, can also provide information. The tag jets from the VBF process can be used to check the parity, and so there should both be determinable with enough data.

The self-coupling does appear to be very difficult. One study[7] showed some sensitivity with SLHC luminosities if the mass was around 165GeV, but that region is now excluded. This is still being investigated.

5. Summary and conclusion

The Standard Model Higgs will be discovered at LHC if it exists. Some of its properties will be determined, such as the couplings with errors in the tens of percent range, and the mass to much better than a percent. The subject is a very large one intensively studies over the last few decades. It will be a great relief to settle the discussion, one way or the other.

It is of course impossible to prove a theory true, it can only be demonstrated that it has not been found to be false. If a particle passing these tests is discovered then that will persuade the current author that it is a Higgs boson.

However, both the accelerator and the experiments are new and a phenomenal amount of painstaking work is still required in order to make this happen.

6. Acknowledgements

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References

[1] P Higgs, *Broken Symmetries and the Masses of Gauge Bosons, P*hy. Rev. Lett. **13:** 508-509 (1964).

[2] The ALEPH, CDF, D0, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, the Tevatron Electroweak Working Group, and the SLD electroweak and heavy flavour

groups, *Precision Electroweak Measurements and Constraints on the Standard Model*, CERN-PH-EP/2009-023

[3] The CDF Collaboration, the D0 Collaboration, the Tevatron New Physics, Higgs Working Group, *Combined CDF and D0 Upper Limits on Standard Model Higgs-Boson Production with 2.1 - 5.4 fb*$^{-1}$ *of Data*, arXiv:0911.3930

[4] ATLAS Collaboration, *Expected Performance of the ATLAS Experiment Detector, Trigger and Physics*, CERN-OPEN-20080020, Geneva 2008.

[5] ATLAS Collaboration, *ATLAS Sensitivity to the Standard Model Higgs in the HW and HZ Channels at High Transverse Momenta*, ATL-PHYS-PUB-2009-088.

[6] M. Duhrssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld, *Title: Extracting Higgs boson couplings from LHC data Phys. Rev.* **D70:** 113009, 2004. (hep-ph/0406323).

[7] U. Baur, T. Plehn, D. Rainwater, *Examining the Higgs boson potential at lepton and hadron colliders: a comparative analysis Phys. Rev.* **D68:** 033001, 2003. (hep-ph/0304015).