LHC Higgs Boson searches

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A summary of the Higgs boson searches by the ATLAS and CMS collabrations using $1\,fb^{-1}$ of LHC data is presented, concentrating on the Standard Model Higgs boson. Both experiments have the sensitivity to exclude at 95% CL a Standard Model Higgs boson in most of the Higgs boson mass region between about 130 GeV and 400 GeV. The observed data allow the exclusion of a Higgs Boson of mass 155 GeV to 190 GeV and 295 GeV to 450 GeV (ATLAS) and 149 GeV to 206 GeV and 300 GeV to 440 GeV (CMS). The lower limits are not as constraining as might be expected due to an excess in both experiments of order 2-3σ which could be related to a low mass Higgs boson or to a statistical fluctuation.

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1. Introduction

The Higgs boson[3, 4, 5] search at the LHC has entered its prime. Results in 2010 were groundbreaking in many areas, especially in the MSSM searches for neutral Higgs bosons[1, 2], but it is only with the advent of datasets of the scale of an inverse femtobarn that the possible existence of the Standard Model (SM) Higgs boson can start to be tested. This the experiments have done with great enthusiasm.

However, the fast moving nature of the search and the rapidly improving LHC performance and hence integrated luminosity mean that this report on these searches is already most interesting as a historical snapshot of the knowledge at the time of the conference and the methodologies used by the experiments; the actual results having been in most cases superseded. This review attempts to present that snapshot, without updating with later results. The Standard Model Higgs boson was the star of the conference, and other results are either very briefly summarised or skipped entirely.

In this document, the word lepton, ℓ, should normally be interpreted as referring to electrons or muons and their antiparticles. Limits are all quoted at 95% CL.

2. MSSM Higgs Bosons

The Higgs mechanism, the introduction of a complex doublet field with a quartic self-coupling and negative quadratic term, is rather general and while the simplest version is employed in the SM, it can be extended in many ways. One of the interesting extensions is the addition of a second Higgs doublet, and in particular the so-called 'type II' doublet[6] required by supersymmetry. Within this framework there are 5 physical Higgs scalars, two charged and three neutral, whose properties are completely defined at tree level by two parameters, often taken to be m_A and $\tan\beta$(the ratio of the vacuum expectation values of the two doublets). The three neutral bosons are the lighter and heavier scalars, respectively h and H, and the pseudo-scalar A.

The search for the lightest scalar, h, is in most scenarios closely related to the SM Higgs Boson search described later, but this section sketches the results of the search for neutral or charged MSSM Higgs bosons.

2.1 Neutral MSSM Higgs Boson searches

The heavy MSSM Higgs bosons, A and H, do not couple to the W and Z bosons, but have a coupling to the down-type fermions proportional to $\tan\beta$. Searches at the LHC[7] have so far focused on the decay mode H/A to $\tau\tau$, which has a sensitivity roughly proportional to $\tan\beta^2$. The production comes either through gluon fusion, dominant for low $\tan\beta$, or from associated production with one or more b quarks, which grows proportional to $\tan\beta^2$. The CMS collaboration presented results[8, 9] (given in Fig. 1), on this search using 1.1 fb^{-1} of data and a detailed analysis of the production mode. That is to say, three production modes were considered, gluon fusion, b-quark associated and vector boson fusion or VBF. The second is especially appropriate for high $\tan\beta$ MSSM Higgs bosons.

The τ pairs were studied in $e\mu$, $\mu\mu$, $e\tau_{had}$ and $\mu\tau_{had}$ decay modes, with no evidence seen for Hihhs boson production.
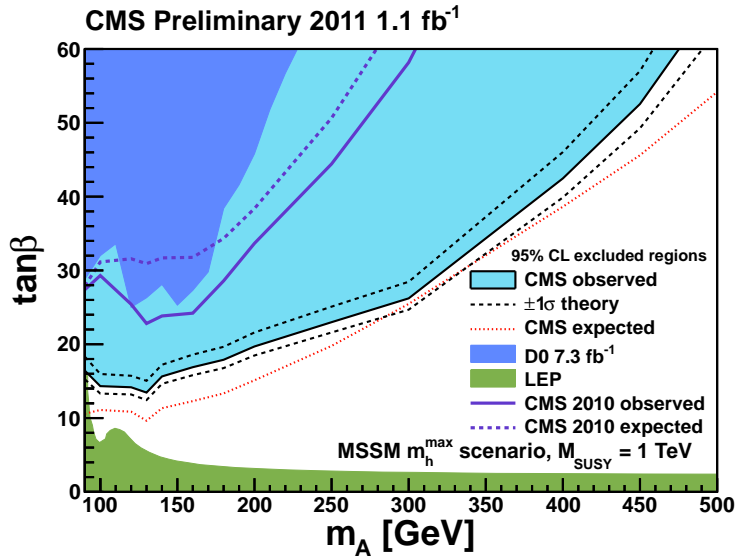
Figure 1: Limits on the m_A-$\tan\beta$ plane coming from the H/A to $\tau\tau$ search in CMS.

## 2.2 Charged MSSM Higgs boson search

The charged Higgs boson presents a tempting search target as it is an unambiguous indicator of physics beyond the Standard Model. The coupling between the charged Higgs and the top quark is strong, but the phenomenology depends crucially upon the relative masses and hence which decays into which. If the charged Higgs weighs less than the top quark it can be produced with a large rate in top decay. If not the production cross-sections are not yet accessible at the LHC. The mass in the MSSM is similar to the heavy neutral Higgs bosons, and for many parameters there is greater sensitivity to those.

The production via top decay to H^+b has been searched for, and limits have bee derived on the hadronic decay $c\bar{s}$[10] by ATLAS and more stringently on the decay $H^+ \rightarrow \tau\nu$[11, 12] by CMS. The latter analysis considers three final states: electron plus muon, muon plus a hadronic tau, and no leptons plus a hadronic tau. The combined limits extracted from the three channels are shown in Fig. 2 in terms of the top decay fraction, which is limited to below about 4% for the masses tested and in the m_A-$\tan\beta$ plane.

3. SM Higgs Boson

The most promising aspect of the LHC Higgs boson analyses is the search for the SM Higgs boson. Radically new sensitivity is available for this decades-old search, combining information from multiple decay modes to enhance the overall sensitivity. To roughly summarize, the individual experiments, with $1 fb^{-1}$ each, each have at least one-sigma sensitivity to Higgs bosons with masses between about 120 GeV and 560 GeV, and considerably more for most masses. This allows the most sensitive test of the Higgs mechanism ever.

Within the Standard Model, the only unknown aspect of the Higgs boson is its mass; after that everything is predicted. For Higgs boson masses above about 125 GeV the search is dominated
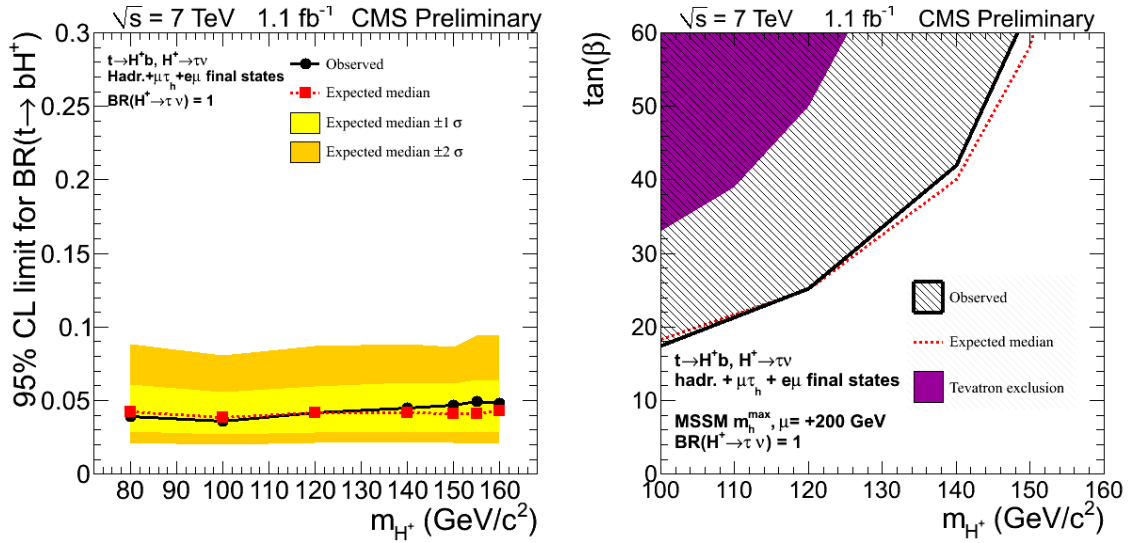
Figure 2: Limits on charged Higgs boson production from CMS, expressed in terms of (left) the top branching ratio to charged Higgs boson and (right) the m_A-$\tan\beta$ plane.

by the bosonic decay modes, WW and ZZ. These have so far been searched for in channels where at least one vector boson decays to leptons: $WW \to \ell\nu\ell\nu$, $WW \to \ell\nu qq$, $ZZ \to \ell\ell\ell\ell$, $ZZ \to \ell\ell\nu\nu$ and $ZZ \to \ell\ell qq$. For lower masses, down to 110 GeV, the decays to $b\bar{b}$, $\tau\tau$ and especially $\gamma\gamma$ play a gradually increasing role but are not sensitive to the Higgs boson at its expected Standard Model rate with the data available at this meeting.

The main production modes are, in order of importance to the searches reported here, gluon fusion, vector boson fusion (VBF) and associated production with a W or Z boson or a pair of top quarks. The cross-section calculations have been made by many groups over many years, but all the numbers used here are collated in the LHC Higgs cross-section working group report[13].

3.1 Higgs boson decay to $b\bar{b}$

The dominant decay mode by rate for Higgs bosons masses below 135 GeV is to a pair of bottom quarks, but searches are complicated by the enormous LHC b-quark production rates in other processes. The situation is somewhat improved in the associated production modes, which can also be used to provide a trigger. ATLAS presented searches in $WH \to l\nu bb$ and $ZH \to llbb$ modes[14, 15]. The resulting mass spectra can be seen in Fig 3.

These searches would be sensitive to a signal with around fifteen times the SM rate. Significant improvements will be needed, and the use of the those events with high p_T where the signal to background ratio improves, is one route[16].

3.2 Higgs boson decay to $\tau\tau$

The MSSM tau pair searches mentioned in section 2.1 can also be used to look for a SM Higgs boson. In this case the VBF production mode is an important mechanism giving adequate production rate with sufficient rejection of backgrounds. ATLAS re-interpreted their MSSM search[7] in a SM context. The CMS collaboration presented results from $e\mu$, $\mu\mu$, $\mu\tau$ and $e\tau$ searches[8]; the example of the $e\mu$ channel in the VBF production mode is shown in Figure 4. The analysis
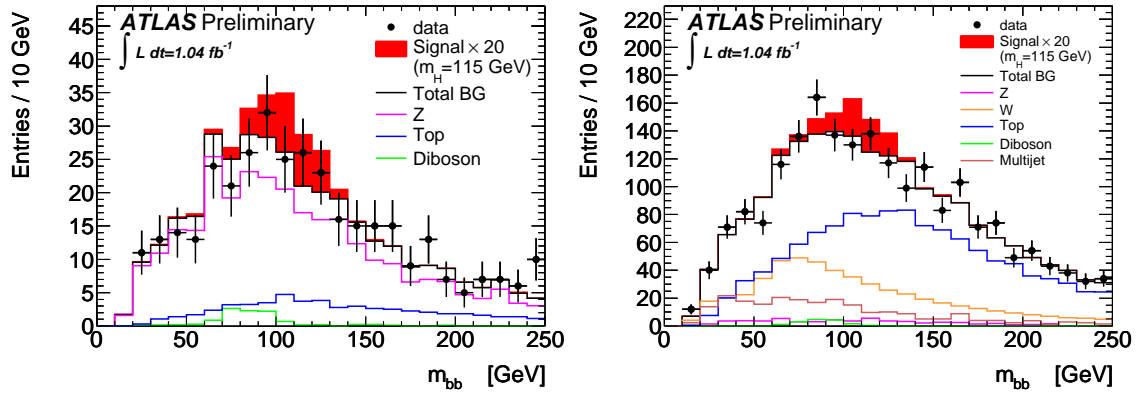
Figure 3: Mass spectra found by ATLAS in the ZH (left) and WH (right) searches.

focussing on vector boson fusion production is, as expected, significantly more powerful than the inclusive gluon fusion search, but the use of a central jet veto adds systematic errors to the signal acceptance.
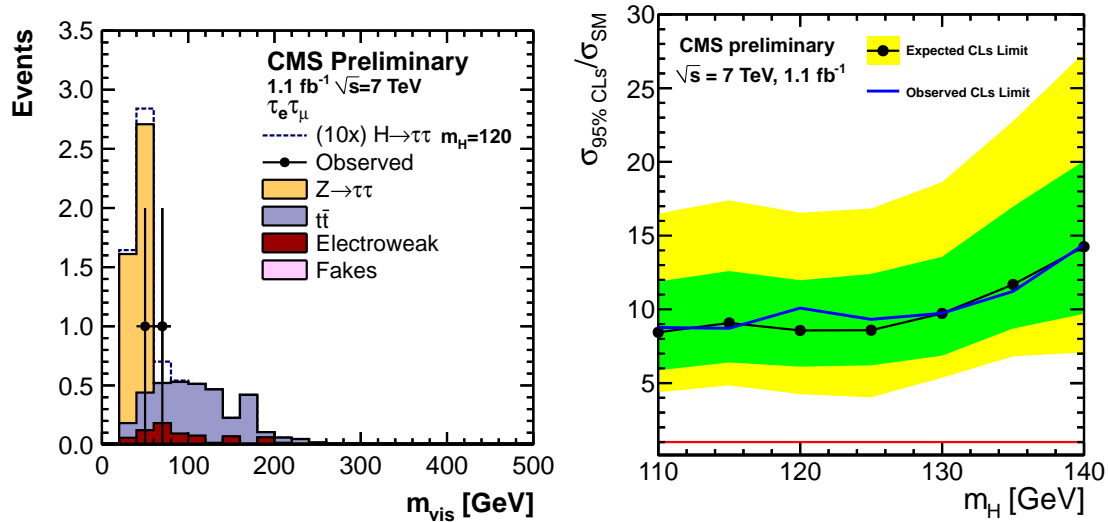

Figure 4: Left: The mass spectrum from CMS VBF $H \to \tau\tau \to e\mu$ search. Right: The limits expected and observed in the $H \to \tau\tau$ search as a function of m_H in units of the Standard Model cross-section.

The CMS search is sensitive to eight or more times the SM Higgs bosons cross-section, and the observed data match the expectations from background.

3.3 Higgs boson decay to $\gamma\gamma$

The requirements of measuring the $\gamma\gamma$ decay process[17, 18, 19, 20] have driven the performance of the electromagnetic calorimeters of ATLAS and CMS. The CMS crystal calorimetry offers superior energy resolution (though complete calibration is still ongoing) while the ATLAS segmented calorimetry allows a simultaneous measurement of the photon angle. This means that the Higgs candidate decay vertex location in CMS is identified using tracking system, while AT-LAS relies on the calorimetry. The complete mass spectra of both experiments are shown in Fig 5,

but the analysis is done in six or eight sub-samples of different signal to background depending upon the kinematics or quality of the photon candidates.
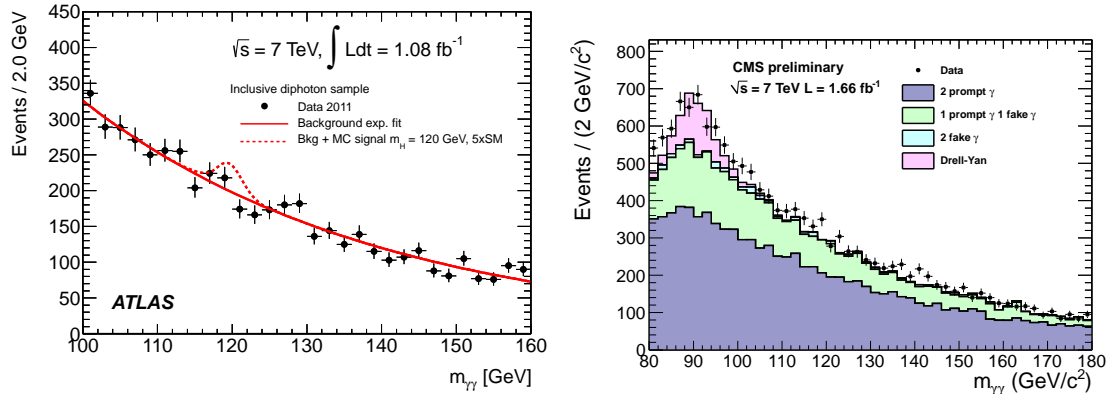
Figure 5: The two-photon mass spectrum as measured by ATLAS (left) and CMS (right).

The background modelling is done using exponential functions (ATLAS) or Bernstein polynomials (CMS). Each experiment has sensitivity to three to four times the SM signal rate, remarkably consistent given the different design choices. There are no deviations of more than two sigma from the background expectations at present.

3.4 Higgs boson decay to WW

The largest decay mode of the SM Higgs boson is to W boson pairs, which approaches 100% for masses around 165 GeV. The purely- and semi-leptonic decay modes have both been searched for using the leptons as triggers.

#### 3.4.1 $H \rightarrow WW \rightarrow \ell\nu qq$

The largest branching ratio is in $WW \rightarrow \ell\nu qq$, which ATLAS has reported on in Ref. [21]. The properties of the single missing neutrino are estimated using missing energy constraints and requiring the reconstructed W to be on mass shell, which results in a quadratic equation for p_z. This allows the mass to be calculated and the search becomes a counting experiment like $H \rightarrow \gamma\gamma$, looking for a peak on a smooth background.

The results, shown in Fig. 6 show sensitivity to a cross-section about 2.7 times that of the SM. The problem for this search is the very large W plus jets background which masks any potential signal

#### 3.4.2 $H \rightarrow WW \rightarrow \ell\nu\ell\nu$

The most powerful search at present is the doubly leptonic WW decay. The presence of two leptons and substantial missing energy allows for excellent QCD suppression, and the spin-zero nature of the Higgs boson aligns the spin of the Ws and hence the decay leptons tend to be emitted in similar directions, while the dominant WW background does not have this feature[22].

The search is done by first removing, so far as possible, backgrounds other than *WW* production via tight identification of two isolated leptons and missing energy. Lepton pairs compatible with the *Z* mass are excluded and the events are divided into subcategories dependent upon the
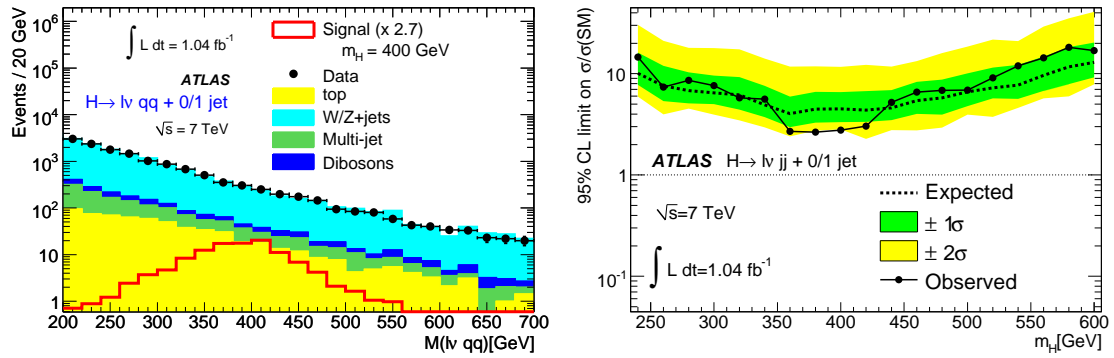
Figure 6: Left: The observed mass spectrum in the ATLAS $H \to WW \to \ell\nu qq$ search. Right limits on the Higgs boson productions rate, in units of the SM Higgs boson rate, coming from this search.

number of associated jets. In the 0 jets category the background is dominantly non-resonant WW, while the 1 jet events have a sizeable top contribution and in the exclusive two jet case, used only by CMS, additional cuts on the rapidities of the jets are applied to enhance sensitivity to the vector boson fusion production process. As a final step the ATLAS analysis[23] selects a region in the transverse mass[24], while the CMS collaboration, in addition, uses a boosted decision tree to select candidates[25].
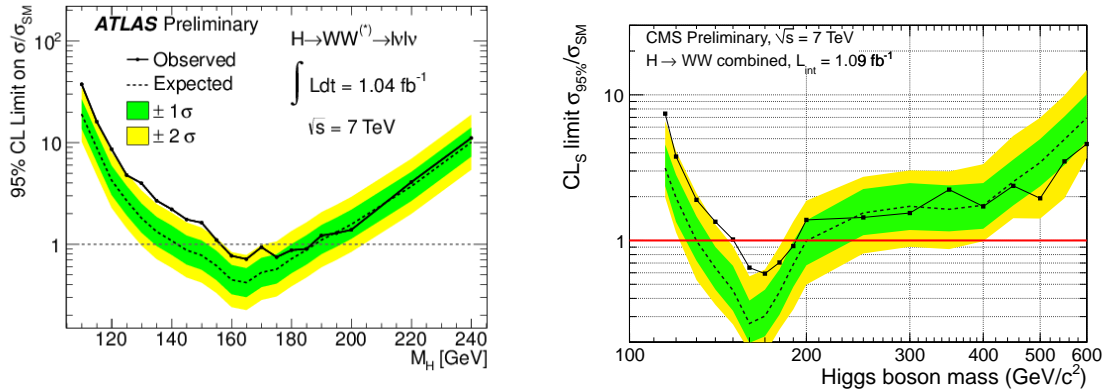
Figure 7: The multiple of the SM rate which can be excluded by ATLAS (left) and CMS(right) in the $h \to WW \to l\nu l\nu$ search as a function of m_H.

This channel has important sensitivity, with expected exclusions of 142 GeV to 186 GeV in ATLAS and 130 GeV to 200 GeV in CMS. The observed exclusions are rather less, being 158-186 GeV in ATLAS and 150-193 GeV in CMS. The reason for the discrepancy between expected and observed is a noticeable excess of candidates, in both experiments. The mass resolution is very poor, owing to the two missing neutrinos, and this excess manifests itself over a wide mass region.

3.5 Higgs boson decay to ZZ

The decay to pairs of Z bosons has the potential for very clean searches due to the attractive features of the subsequent Z boson decays: particle-antiparticle pairs allow cross-checks and it is

often possible to use the well-known Z mass as a powerful constraint. ATLAS and CMS have both studied events where one Z decays to leptons and the other to leptons, neutrinos or quarks[26, 27].

3.5.1 $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$

The cleanest channel for the Higgs boson search at the LHC is the decay to pairs of Z bosons with their subsequent decay to electron or muon pairs[26, 27, 28, 29]. The multiple constraints of four clean leptons and one or two resonant Z bosons means that the selected sample is dominated by real diboson production, with potentially a narrow Higgs boson signal in addition. When looking for Higgs bosons weighing less than twice the Z mass then one of the Z bosons must be off mass shell, and the kinematic selection is looser; this can be partially compensated by tightening the lepton identification criteria, but in general the emphasis is on maximising the signal efficiency while preserving the low background.

The background is dominated by the irreducible non-resonant ZZ production, for which the shape is predicted by MCFM[30]. There are complications when one boson is significantly off mass shell and for production from gluon induced processes; both of these affect the low mass region especially. This region also has significant backgrounds from Z plus jets and $t\bar{t}$. These are constrained from the data. The observed mass spectra, and predicted backgrounds, can be seen in Fig 8.
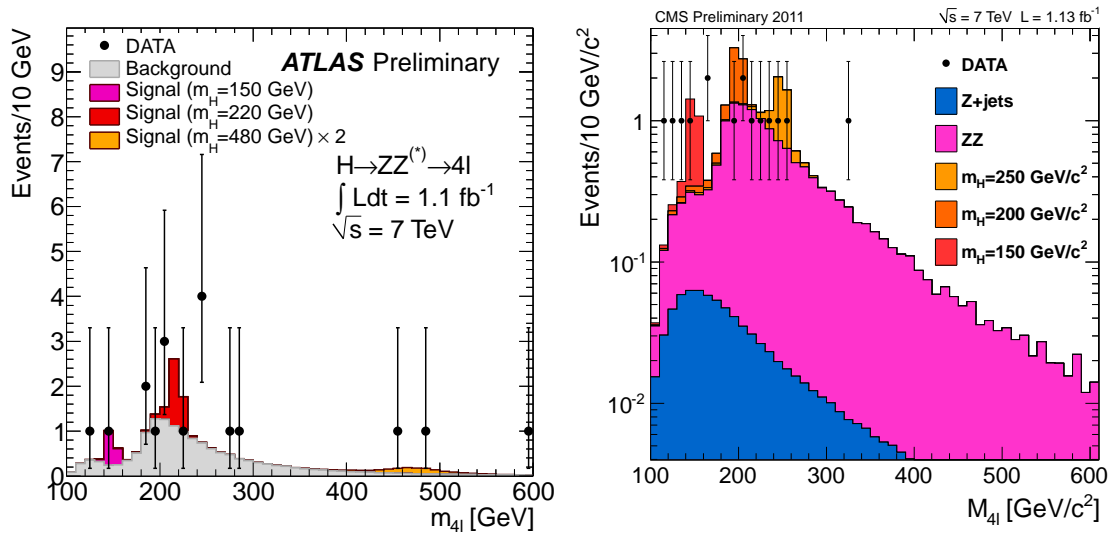
Figure 8: The selected event candidates in the $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ search of ATLAS (left) and CMS (right). The CMS curve breaks the background into ZZ and Z plus jets; similar fractions are seen in ATLAS.

The sensitivity of these searches is close to being able to exclude the SM Higgs boson at 200 GeV, but with the current luminosity a very small mass region is excluded by this result alone. Attention is drawn by the low mass events; ATLAS and CMS taken together have three candidates near 143 GeVwhich is consistent with the expectation for a signal there.

3.5.2 $H \rightarrow ZZ \rightarrow \ell\ell qq$

The *llqq* decay mode has a higher rate than a purely leptonic decay, but also allows complete reconstruction of the Higgs boson candidates. Indeed it has much in common with the decay

$WW \to \ell\nu qq$. One Z boson is reconstructed through its decay to electrons or muons and the other is looked for as a pair of jets. The ZZ rate (from a Higgs boson or non-resonant) is so much smaller than the Z plus jets background that it is not possible to observe the peak of the Z in the jet jet continuum. Thus a window is selected which should, in simulation, contain most of the second Z events. One effect of this is that if the jet energy scale is incorrectly measured in either direction the efficiency for selecting signal candidates reduces.

Having obtained two candidate Z bosons, the putative Higgs boson mass is easily reconstructed, and the distribution of these masses is tested for a signal. The sensitivity is improved by tagging b-quarks as they are produced in a much larger fraction of ZZ decays than in the Z plus jets background. The experiments use b-tagged and untagged candidates separately. CMS further subdivides to have a category of events with one clear b-tag and also rejects events from the untagged sample where the jets are identified by a gluon jet tagger. They also employ a likelihood discriminant based upon the angles of the decay to reject backgrounds[31]. ATLAS uses different kinematic selections depending upon whether the Higgs boson mass hypothesis tested is above or below 300 GeV[32]. The mass distributions in the (high-mass) b-tagged channel can be seen in Fig 9, which provides approximately half of the total sensitivity.
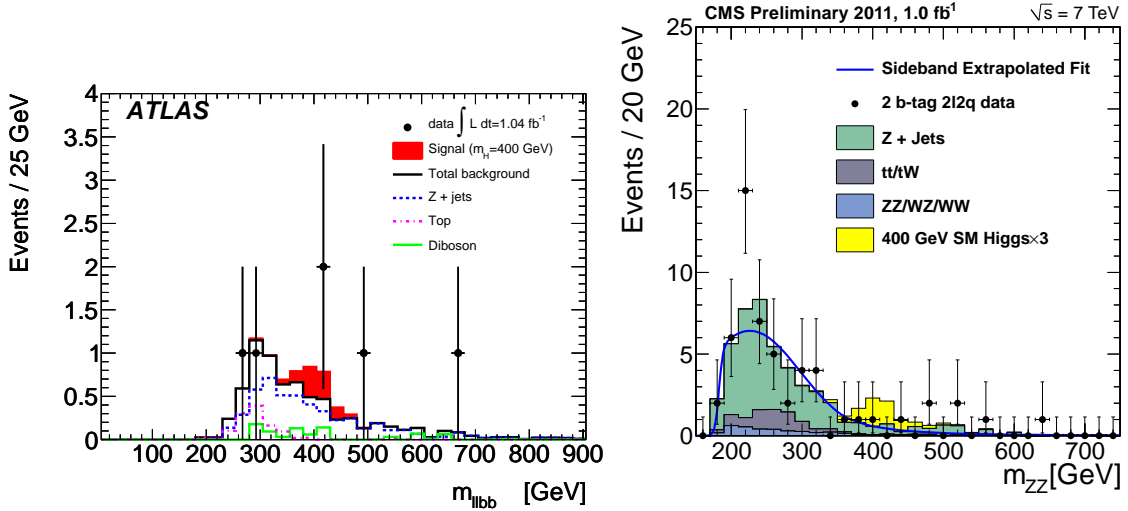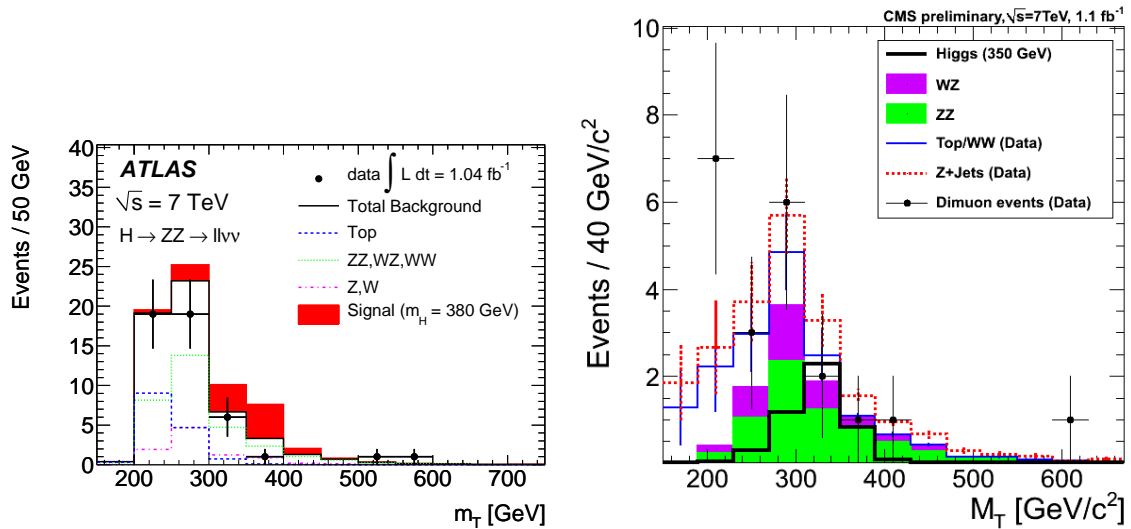

Figure 9: The mass distributions measured by ATLAS (left) and CMS (right) in the search for $ZZ \to \ell\ell qq$. In each case only the $\ell\ell bb$ distribution is shown here.

The $ZZ \to \ell\ell qq$ searches do not reveal any striking excess, never departing from the two-sigma expected region. Limits are set which are at best about 1.7 times the Standard Model cross-section.

3.5.3 $H \to ZZ \to \ell\ell\nu\nu$

The ZZ Higgs boson decay mode, with subsequent decay of one Z to charged leptons and the other to neutrinos has many attractive features for an LHC search. The two hard leptons give a good trigger signature, and the purely leptonic signature allows excellent background rejection. however, unless the p_T of the Z which decays to neutrinos is large it is hard to detect, and the background from inclusive Z production is overwhelming. For large Higgs boson masses this is easily satisfied and this becomes the most sensitive analysis for Higgs boson masses over about 300 GeV.

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The reconstruction of the Higgs boson mass is not possible in the presence of two neutrinos, but by assuming they arise from the decay of an on-shell Z boson the transverse mass can be reconstructed. An important item then is the modelling of backgrounds from single Z boson production, where ATLAS and CMS have taken different strategies. ATLAS models this in their simulation, and makes some verification's on the data that the performance is as expected[33], while CMS uses γ events to measure the missing E_T distribution and correct for the difference in mass to obtain the expected missing E_T distribution in Z events[34]. The transverse mass distributions measured by the two experiments can be seen in Fig. 10.

Figure 10: The mass distributions observed by ATLAS (left) and CMS (right) in the $h \to ZZ \to \ell\ell\nu\nu$ search. The ATLAS distribution includes both lepton flavours, in the case of CMS, only the muon channel is shown.

3.6 Combined search results

The only unknown parameter in the SM Higgs boson search is its mass; this makes it ideally suited to a combination approach where all the disparate channels are considered together. Each channel has its own region of applicability, as shown in Table 1. The results of the individual channels in the two experiments are displayed in Fig 11. The most powerful channels are common to the two experiments, but at low mass ATLAS has analysed the $b\bar{b}$ decay mode while CMS searches for the $\tau\tau$ decay. At high masses CMS has used the $WW \to \ell\nu\ell\nu$ decay mode while ATLAS looks at $WW \to \ell\nu$qq.

In many respects the two experiments are very similar. The sensitivity is largely from the $\gamma\gamma$ search for Higgs boson masses below about 120 GeV, but then the $WW \to \ell\nu\ell\nu$ search dominates to 200 GeV with $ZZ \to \ell\ell\ell\ell$ then taking a major role. For Higgs boson masses above about 300 GeV the $ZZ \to \ell\ell\nu\nu$ search has the greatest power. One striking fact is that the $WW \to \ell\nu\ell\nu$ search by CMS at high mass is important to very high masses and is not even considered by ATLAS.

Both collaborations have produced combinations of their own results, and the limits extracted from these searches can be seen in Fig. 12.

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	ATLAS		CMS	
	Luminosity fb^{-1}	Mass range GeV	Luminosity fb^{-1}	Mass range GeV
$\gamma\gamma$	1.08	110-150	1.1	110-140
$\tau\tau$	-	-	1.1	110-140
$b\bar{b}$	1.04	110-130	-	-
WW $\rightarrow \ell\nu\ell\nu$	1.04	110-240	1.1	110-600
WW $\rightarrow \ell\nu$qq	1.04	240-600	-	-
ZZ $\rightarrow \ell\ell\ell\ell$	1.1	110-600	1.1	110-600
ZZ $\rightarrow \ell\ell\nu\nu$	1.04	200-600	1.1	250-600
ZZ $\rightarrow \ell\ell$qq	1.04	200-600	1.0	226-600

Table 1: The channels used by each of the experiments, along with the amount of data contributing to them and the mass range for which they produce results.
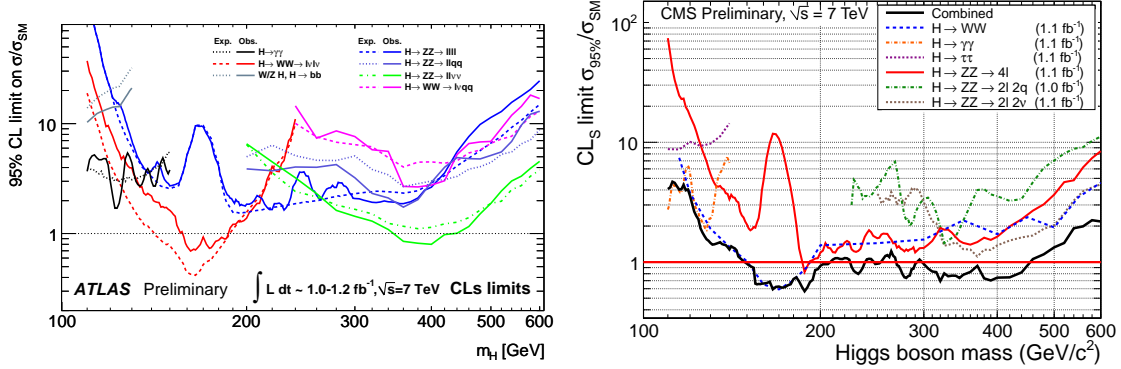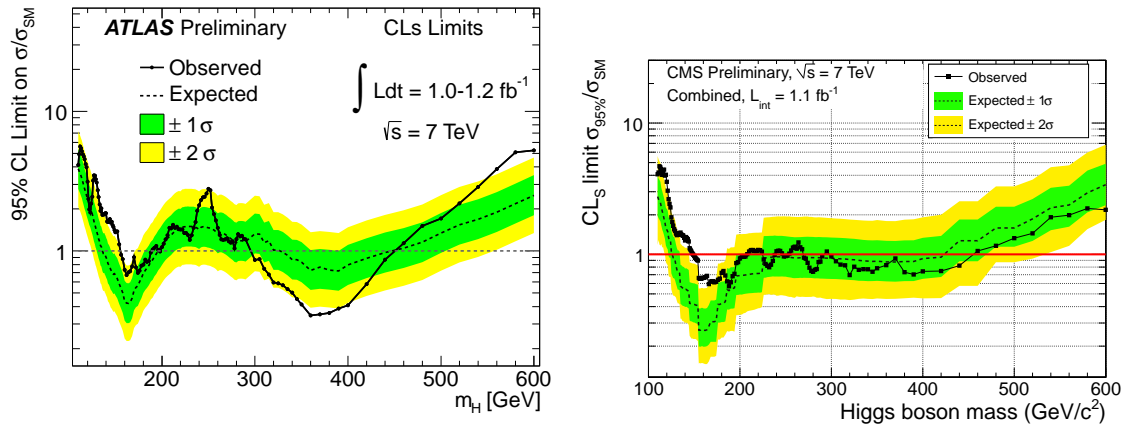

Figure 11: The multiple of the SM rate which is excluded by ATLAS (left) and CMS(right) by the individual Standard Model search channels. ATLAS show the expected as well as the observed limits, while CMS display the combined result, which excludes a large region at high mass where no single channel does.

The sensitivity is high across a wide range of Higgs boson masses, and ATLAS excludes the mass regions 155 to 190 GeV and 295 to 450 GeV, while CMS rules out 149 to 206 GeV, 270 to 290 GeV and 300 to 400 GeV, all at 95% CL.

The expected sensitivity of the two experiments can be compared. The low mass region, dominated by $\gamma\gamma$, both are very similar, while the CMS sensitivity around 160 GeV is noticeably better. This comes at least in part from the use of a multivariate analysis by CMS in the WW $\rightarrow \ell\nu\ell\nu$ search while ATLAS use a cut-based approach. Around 250 GeV the CMS search is again more powerful largely due to the same WW search which was optimised also for this region, but also from a more sensitive ZZ $\rightarrow \ell\ell\ell\ell$ search. Above 340 GeV ATLAS has greater sensitivity, largely coming from the ZZ $\rightarrow \ell\ell\nu\nu$ channel.

The other striking feature of the data is the difference between the observed and expected limits at low mass. This is occasioned by an excess of candidates compared with expectations, and is a feature of the data of both ATLAS and CMS, and can be seen in Fig 13. At high masses ATLAS has excesses at 246 GeV and 580 GeV; neither of these are strongly seen in the CMS data.

Figure 12: The multiple of the SM rate which can be excluded by ATLAS (left) and CMS(right) by the combination of Standard Model search channels used.
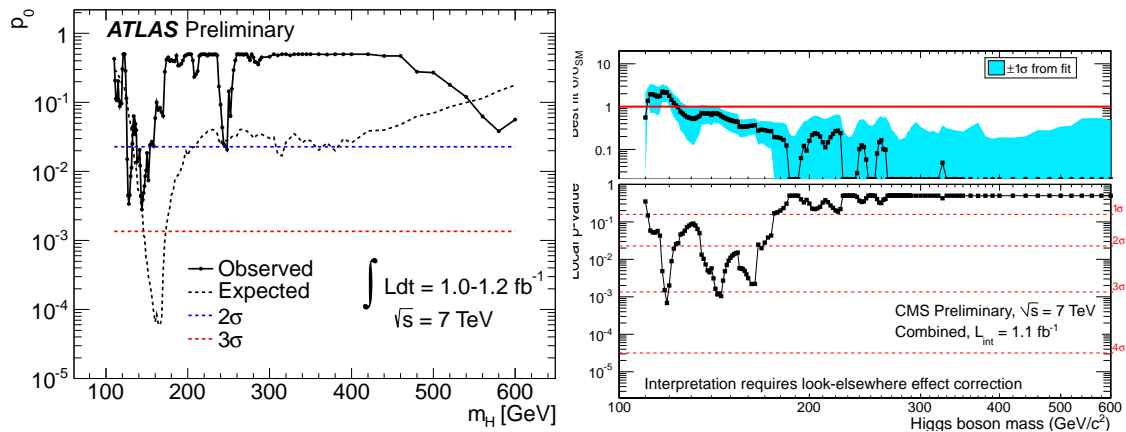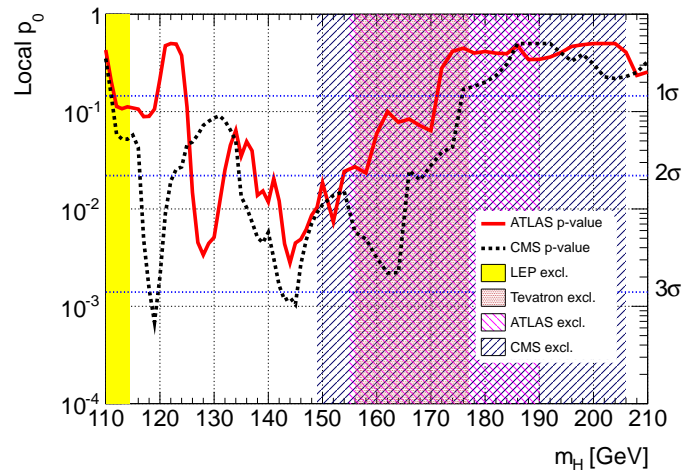

Figure 13: The probability of getting as signal-like an excess in the presence of only backgrounds, as a function of the Higgs boson mass, for ATLAS (left) and CMS (right). Deficits appear at 0.5 by construction. ATLAS also show the expected evidence if there were a signal, while CMS show the strength of the observed excess in units of the Standard Model Higgs boson cross-section. No look-elsewhere effect is considered in these plots.

The low mass situation, see in Fig 14, reflects a broad excess in both channels. This is mostly driven by the WW searches, but is given definition by peaks in the $\gamma\gamma$ mass spectrum and individual candidates in the $ZZ \to \ell\ell\ell\ell$ search. ATLAS has local minima at 128 and 145 GeV while CMS has similar at 119, 146 and 164 GeV. The match between the peaks near 145 GeV is interesting, but more data will be required to disentangle the situation.

4. Outlook

The first inverse femtobarn of integrated luminosity from the LHC have produced a huge sensitivity to the SM Higgs boson, with median exclusion sensitivities of both experiments at, or close to, 95% CL for all masses between 135 GeV and 450 GeV. Most of this region is in fact excluded, but the upper limits on a low mass Higgs boson set by ATLAS and CMS, 155 GeV

Figure 14: The probability of getting as signal-like an excess in the presence of only backgrounds, as a function of the Higgs boson mass, for the two experiments. Deficits appear at 0.5 by construction. No look-elsewhere effect is considered in this plot.

and 149 GeV are noticeable higher than might be expected, reflecting mostly the excess of events observed in the $H \rightarrow WW$ searches. These are of course the most sensitive search channel for much of this range, but whether this is the start of an observation, systematic bias, or merely random fluctuation will best be resolved by more data.

The LHC performance continues to be excellent and it is clear that substantially more data will be collected in 2011 and beyond which will answer the question of the existence or otherwise of the SM Higgs boson.

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