Search for the Standard Model Higgs Boson at CMS

Adolf Bornheim for the CMS Collaboration
Charles C. Lauritsen Laboratory, 1200 E. California Blvd., Pasadena CA, 91125, USA

We searched for the standard model Higgs boson in 11 different decay channels using approximately 5 fb^{-1} of 7 TeV pp collisions data collected with the CMS detector at LHC. Combining the results we exclude at 95% confidence level the standard model Higgs boson with a mass between 127.5 and 600 GeV. The expected 95% confidence level exclusion if the Higgs boson is not present is from 114.5 and 543 GeV. The observed exclusion is weaker than expected at low mass because of some excess of events observed in the data. The most significant excess is found at 125 GeV with a local significance of 2.8σ, a global significance of 0.8σ in the full search range and of 2.1σ in the range 110–145 GeV. The excess is consistent both with background fluctuation and a standard model Higgs boson with mass of about 125 GeV. More data are needed to investigate its origin.

1 Analysis strategy

A search for the Standard Model (SM) Higgs Boson [1,2] is carried out in the mass range from 110 and 600 GeV in the decay modes summarized in Table 1, along with the corresponding integrated luminosity, the number of subchannels, the investigated mass range and the approximate Higgs boson mass resolution. At mass below approximately 130 GeV the sensitivity is dominated by $\gamma\gamma$ and $\mathrm{ZZ}^{(*)} \rightarrow 4\ell$ decay channels, between 130 and 200 GeV by the WW channel and above 200 GeV various ZZ channels.

Table 1: The 11 Higgs boson search channels. The most relevant information is indicated for each of the analyses.

Channel	m_H range (GeV)	Luminosity (fb^{-1})	Sub-channels	m_H resolution	Comment
$\mathrm{H} \rightarrow \gamma\gamma$	110–150	4.8	2	1–2%	updated
$\mathrm{H} \rightarrow \tau\tau \rightarrow e\tau_\mathrm{h}/\mu\tau_\mathrm{h}/e\mu + X$	110–145	4.6	9	20%	
$\mathrm{H} \rightarrow \tau\tau \rightarrow \mu\mu + X$	110–140	4.5	3	20%	new
$W\mathrm{H} \rightarrow e\mu\tau_h/\mu\mu\tau_h + \nu$'s	100–140	4.7	2	20%	new
$(\mathrm{W/Z})\mathrm{H} \rightarrow (\ell\nu/\ell\ell/\nu\nu)(\mathrm{bb})$	110–135	4.7	5	10%	
$\mathrm{H} \rightarrow \mathrm{WW}^* \rightarrow 2\ell 2\nu$	110–600	4.6	5	20%	
$W\mathrm{H} \rightarrow \mathrm{W}(\mathrm{WW}^*) \rightarrow 3\ell 3\nu$	110–200	4.6	1	20%	new
$\mathrm{H} \rightarrow \mathrm{ZZ}^{(*)} \rightarrow 4\ell$	110–600	4.7	3	1–2%	
$\mathrm{H} \rightarrow \mathrm{ZZ}^{(*)} \rightarrow 2\ell 2q$	130–164 200–600	4.6	6	3% 3%	
$\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow 2\ell 2\tau$	190–600	4.7	8	10–15%	
$\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow 2\ell 2\nu$	250–600	4.6	2	7%	

2 Low mass channels

2.1 $H \rightarrow \gamma\gamma$ channel

The Higgs boson branching ratio for the decay into two photons is approximately 2×10^{-3} between 110 and 150 GeV. A signal in this channel would appear as a small, narrow peak on a large background. The background is dominated by the irreducible two photon QCD production, from events in which jets are misidentified as a photon. The sensitivity of this analysis depends crucially on a very good mass resolution of the detector which ranges between approximately 1 the pseudorapidity of the photons and the extend to which they interact with the material in front of the electromagnetic calorimeter. As reported in [8,9], the sensitivity of the analysis is increased by splitting the data set into four non overlapping event classes based on the photon pseudorapidity and shape of the shower in the electromagnetic calorimeter. In the new analysis that we present here, categories are defined in a more optimal way using a multi variant analysis technique (MVA) based approach that results in a higher sensitivity. Specifically the event by event mass resolution, photon identification discriminant, di-photon kinematic variables and vertex probability are combined using a boosted decision tree (BDT). This exploits the detector performance and the differences in the kinematics of the di-photon system between signal and background. The event by event mass resolution as well as the actual energy reconstruction of the photons are also based on a BDT to optimally utilize the information of the electromagnetic calorimeter. To enhance the sensitivity of the analysis further, events which are produced via Vector Boson Fusion (VBF) are treated in one separate event class which features an enhanced signal to background ratio, resulting in an improvement on the combined exclusion sensitivity of approximately 10% in cross section. Table 2 shows the number of expected signal events, the number of data events per GeV and the estimate of the mass resolution in all classes for the MVA analysis.

Table 2: Number of selected events in different event classes, for a SM Higgs boson signal (m_{H}=120 GeV), for data in a one GeV window around 120 GeV as well as the mass resolution in each event class.

m_{H}=120 GeV	Class 0	Class 1	Class 2	Class 3	Dijet class
Total signal expected events	3.4	19.3	18.7	33.0	2.8
Data (events/GeV)	4.5	55.1	81.3	229.1	2.1
Resolution FWHM/2.35 (%)	0.9	0.9	1.2	1.7	1.1

The background shape is estimated by fitting the di-photon mass spectrum to a polynomial in of (3^{rd} to 5^{th} order, depending on the event class) over the mass range 100 to 180 GeV. We found that the possible bias in the background estimation is always less than about 20% of the statistical error. As a cross check a background model based on side bands around the signal hypothesis is used, yielding consistent results. The signal line shape is dominated by the detector resolution. The line shape from MC used in the extraction of the result is adjusted to match the detector resolution measured in data on $Z \rightarrow ee$ events. Figure 1 shows the results in terms of 95% CL exclusion on the cross section normalized to the SM cross section and the local p-value where the p-value is the probability that a background only fluctuation is more signal-like than the observation. The expected 95% CL exclusion varies between 1.2 and 2 times the SM. We observe the largest excess around 125 GeV with a local significance of 2.9σ. Its global significance is 1.6σ when taking into account the look elsewhere effect (LEE) estimated in the full mass range 110–150 GeV. The p-values are also shown for the inclusive and the VBF categories separately. The minima of the p-value at 125 GeV has a strong contribution from the VBF category.

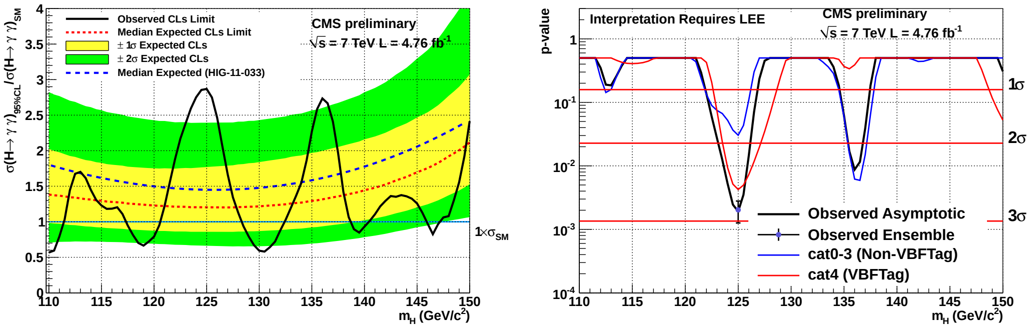

Figure 1: Left: 95% exclusion on the relative signal strength to the SM in the $\gamma\gamma$ channel for the MVA based analysis (red dotted line) and the cut based analysis (blue dashed line). as well as the 1 and 2σ (yellow and green band) expectations around the median expected result for the MVA analysis. Right: Local, combined p-value as function of the Higgs mass as well as the contribution from the individual classes.

2.2 $H \to ZZ \to 4\ell$ channel

In this channel, the cleanest and often referred to as the "golden channel", the signal consists of four isolated leptons. For high mass both pairs of opposite charge and same flavor leptons are consistent with Z decays while for lower masses at least one of the pairs has lower mass. The Higgs branching ratio for this channel is small, approximately one per mille at high mass and lower for masses below $2 \times m_{\mathrm{W}}$. The background however is very small, consisting mainly of irreducible continuum ZZ production and, to a lesser extent, Z plus jets and especially Zbb. The mass resolution is very good and ranges between 1 and 2%. The p_{T} of the lower p_{T} leptons is rather small and one of the most important features of the analysis is the achievement of a very high lepton efficiency down to very low p_{T}. Figure 2 shows the invariant mass spectrum of the selected data compared to the background expectations in the mass range 110 to 600 GeV ^{16} . We do not observe any significant excess of the data and we exclude at 95% CL the SM Higgs boson with M_{H} in 134–158, 180–305 and 340–465 GeV. The most significant excess is at a mass of approximately 119.5 GeV with a local significance of 2.5σ and a global significance of 1.0σ in the full mass range and 1.6σ in the range 100–160 GeV. In this mass range we observe 13 event with an expected background of 9.7 ± 1.3 events while in the full mass range up to 600 GeV we observe 72 events with 67 ± 6 events expected.

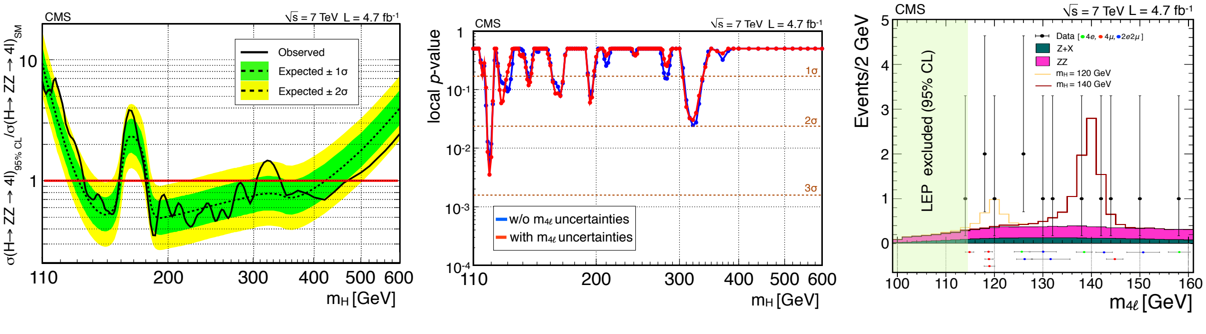

Figure 2: 95% exclusion limit on the relative signal strength to the SM (left) and local p-value computed with and without the individual candidate errors on the reconstructed mass in the $H \to ZZ \to 4\ell$ channel.

2.3 $H \to \tau\tau$ and $H \to bb$ channels

In both channels the background for the inclusive searches is huge and sensitivity is improved by requiring additional final state tags such as jets or charged leptons from VBF or VH production. The mass resolution is approximately 20% due to the presence of neutrinos in the final state for the $\tau\tau$ final state. For the bb final state the mass resolution becomes about 10% by requiering the final state to be boosted which also improves the background rejection.

In the $\tau\tau$ final state we search in the mass range between 110 and 150 GeV [10]. The expected sensitivity for exclusion is approximately 3 times the SM and we do not observe any significant excess in the data. We have recently extended the search to cases where the both τ leptons decay into muons [11] and to the channel WH→ $e\mu\tau_h, \mu\mu\tau_h$ [12] for which we use same sign eμ and $\mu\mu$ to reduce the background from Z plus jets. In the $H \to bb$ final state we exploit the VH associated production with W and Z decaying leptonically and we analyze separately all channels: $e\nu$, $\mu\nu$, ee, $\mu\mu$ and $\nu\nu$ [13]. We search in the mass range between 110 and 135 GeV and the expected sensitivity for exclusion ranges from 3 to 6 times the SM. We do not find a significant excess in data in this channel.

3 Channels sensitive at intermediate and high masses

The $H \to WW \to 2\ell 2\nu$ channel is very sensitive from around 120 GeV up to 600 GeV. The signature is two isolated high p_{T} leptons and the presence of missing transverse energy (MET). The Higgs mass resolution is of the order of 20%. The main backgrounds in this channel are irreducible WW production, Z plus jets, WZ, ZZ and W plus jets. Since the Higgs boson is a scalar and due to the V-A structure of the W decay, the two charged leptons tend to be aligned. This favours a small difference in azimuthal angle $\Delta\phi$ and provides some handle to discriminate the signal from the irreducible background. The analysis [14] is performed in exclusive jet multiplicities (0, 1 and 2-jet bins) and flavour (ee, $\mu\mu$, eμ) to profit from the different sensitivities and background contributions. The 2-jet bin corresponds to the VBF analysis and again exploits the characteristics of the VBF jets such as large p_{T}, large $\Delta\eta$ and di-jet invariant mass. Two variants of analyses are carried out: the first is a cut-and-count for all sub channels and the second is a multivariate analysis that is applied to the 0 and 1-jet bins that are the most sensitive ones. Figure 3 shows the the final distribution of the BDT discriminant for the opposite flavor 0 (left) and 1-jet bin (center) that is used to derive the final confidence level and the 95% exclusion confidence level (right) for the the MVA shape analysis. The opposite flavour signature yields sensitive since the signal is larger, the signal/background is favorable and the background is dominated by the irreducible WW that has less uncertainties than the Z plus jets or tt contributions. We observe no significant excess in the full mass range. At low masses there is only a small upward trend of the observed limit with respect to the expected ones. For the MVA shape analysis the 95% C.L. expected exclusion is for a Higgs boson mass between 127 and 270 GeV while the observed exclusion range is 129–270 GeV at 95% CL. The results of the cut-and-count analysis are very similar.

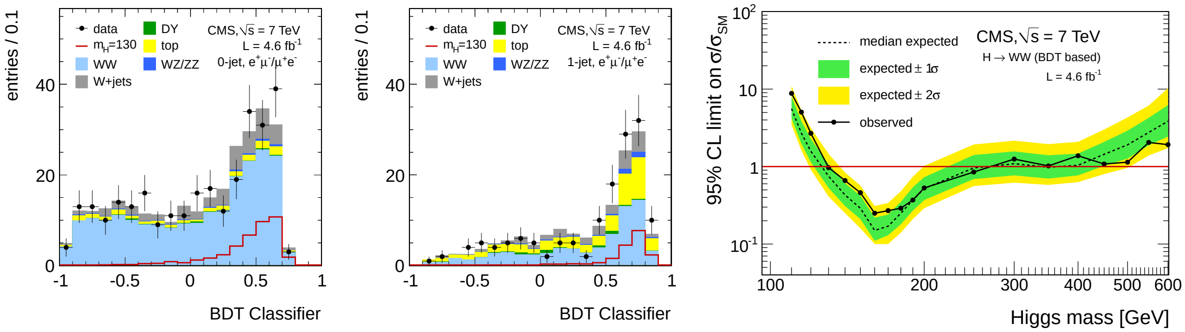

Figure 3: 95% exclusion limit on the relative signal strength to the SM for the cut based analysis(left) and for the MVA analysis (right) in the $H \to WW \to 2\ell 2\nu$ channel.

We recently added the WH→WWW→ $3\ell 3\nu$ channel [15]. This analysis is very similar to the WW channel with the main backgrounds estimated from data. It is a mass independent cut-and-count analysis and it is sensitive to about 4 times the SM in the most sensitive region around $2 \times m_{\mathrm{W}}$.

A SM Higgs boson above a mass of approximately 200 GeV almost exclusively decays into WW and ZZ and above about 300 GeV the Higgs boson width starts to be larger than the detector resolution in the ZZ channels. Beyond the previously described channels $H \to WW \to 2\ell 2\nu$ and $H \to ZZ \to 4\ell$, we searched in the channels where one Z decays into ν, quark and τ pairs. In the $H \to ZZ \to \ell\ell\nu\nu$ channel we did not observe any excess in the data and the observed exclusion from this channel alone is similar to the one expected in presence of background only. The expected 95% CL exclusion using this channel alone is M_{H} in 290–480 GeV and the observed is M_{H} in 270–440 GeV. The $H \to ZZ \to \ell\ell$qq channel [18] is used both for the high mass, where its sensitivity is similar but a little lower than the other ZZ channels, and for lower masses where it only gives a small contribution to the sensitivity.

4 Combination of all channels

All channels are combined to obtain the final exclusion and discovery confidence levels using the so-called CLs method described in [20]. The combination of the previously published results is reported in [21]. Here we present the combination that includes the new preliminary results presented at this conference [22]. SM cross sections and branching ratios are assumed for the combination with their theoretical uncertainties [5,6]. An overall signal strength multiplier $\mu = \sigma/\sigma_{\mathrm{SM}}$ is introduced and limits on its value are derived. Figure 4 shows the SM exclusion confidence level as function of the Higgs boson mass. The SM Higgs boson is excluded by our search at 95% confidence level in the range 127.5–600 GeV and at 99% confidence level in the range 129–525 GeV. The expected 95% exclusion is 114.5–543 GeV. The observed CMS upper limit on the Higgs boson mass is higher than expected because of an excess of event observed in the data in the region between 115 and 128 GeV. Figure **??** shows the 95% exclusion limit on the signal strength multiplier μ in the different Higgs decay channels.

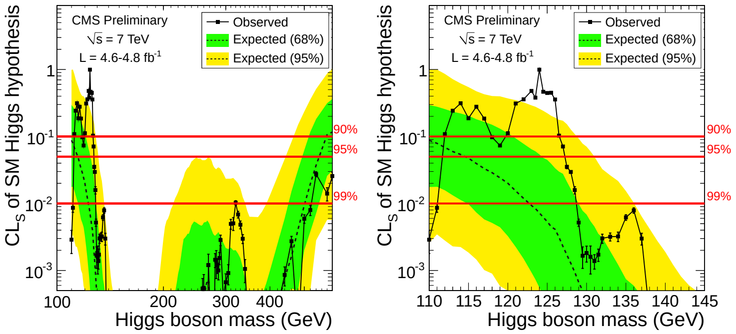

Figure 4: Exclusion confidence level for the combined SM Higgs search in the full mass range 110–600 GeV (left) and low mass zoom (center). The solid line indicates the observed confidence level and the dashed line the expected one. 95% exclusion confidence level on the signal strength multiplier for the SM Higgs search in the 5 Higgs decay channels (right). The solid lines indicate the observed exclusion and the dashed lines the expected.

Figure 5 shows the local p-value as function of the Higgs boson mass in the low mass region. The minimum combined p-value is observed at a mass of 125 GeV with a local significance of 2.8σ. If we consider the probability of observing a local significance larger than 2.8σ anywhere in the search range, we obtain a global significance of 0.8σ relative to the full mass range 110–600 GeV and of 2.1σ for the mass range 110–145 GeV. The observed significance fitted μ of the excess near 125 GeV is consistent with the SM scalar boson expectation.

5 Summary

We searched for the SM Higgs boson in 11 independent channels using approximately 5 fb^{-1} of 7 TeV pp collision data collected with the CMS detector at LHC. Combining the results of the different searches we exclude at 95% confidence level a SM Higgs boson with mass between 127.5 and 600 GeV. The expected 95% confidence level exclusion if the Higgs boson is not present is from 114.5 and 543 GeV. The observed exclusion is weaker than expected at low mass because

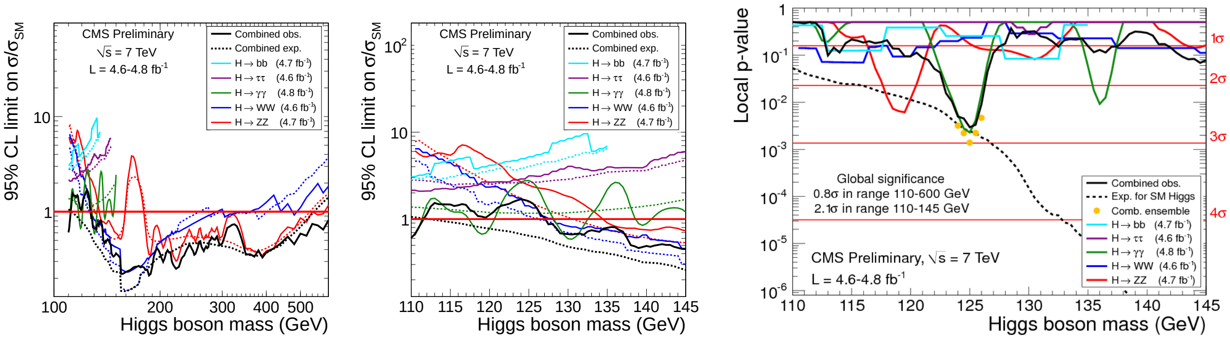

Figure 5: 95% exclusion confidence level on the signal strength multiplier for the SM Higgs search in the 5 Higgs decay channels. The solid lines indicate the observed exclusion and the dashed lines the expected.

of some excess that is observed below about 128 GeV. The most significant excess is found at 125 GeV with a local significance of 2.8σ, a global significance of 0.8σ when evaluated in the full search range and of 2.1σ in the range 110–145 GeV. The excess is consistent both with background fluctuation and a SM Higgs boson with mass of about 125 GeV and more data are needed to investigate its origin. As of the writing of these proceedings the first 5 fb^{-1} of 2012 data are being analysed.

References

1. S. Weinberg, "A Model of Leptons", *Phys. Rev. Lett.* **19** (1967) 1264. ; A. Salam, "Elementary Particle Theory", p. 367. Almquist and Wiksells, Stockholm, 1968.
2. P. W. Higgs, "Broken symmetry and the mass of gauge vector mesons", *Phys. Rev. Lett.* **13** (1964) 508. ; F. Englert and R. Brout, "Broken symmetries and the masses of gauge bosons", *Phys. Rev. Lett.* **13** (1964) 321.
3. R. Barate and others (LEP Higgs Working Group [ALEPH, DELPHI, L3, and OPAL Coll.]), "Search for the SM Higgs boson at LEP", *Phys. Lett.* **B565** (2003) 61–75.
4. M. Baak *et al.*, arXiv:1107.0975 [hep-ph].
5. S. Dittmaier *et al.*, arXiv:1201.3084 [hep-ph].
6. S. Dittmaier *et al.* [LHC Higgs Cross Section Working Group], arXiv:1101.0593 [hep-ph].
7. CMS Collaboration,"The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004.
8. S. Chatrchyan *et al.* [CMS Coll.], Phys. Lett. B **710**, 403 (2012) [arXiv:1202.1487 [hep-ex]].
9. CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-HIG-12-001 (2012).
10. S. Chatrchyan *et al.* [CMS Coll.], arXiv:1202.4083 [hep-ex].
11. CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-HIG-12-007 (2012).
12. CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-HIG-12-006 (2012).
13. S. Chatrchyan *et al.* [CMS Coll.], Phys. Lett. B **710**, 284 (2012) [arXiv:1202.4195 [hep-ex]].
14. S. Chatrchyan *et al.* [CMS Coll.], Phys. Lett. B **710**, 91 (2012) [arXiv:1202.1489 [hep-ex]].
15. CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-HIG-11-034 (2011).
16. S. Chatrchyan *et al.* [CMS Coll.], arXiv:1202.1997 [hep-ex].
17. S. Chatrchyan *et al.* [CMS Coll.], JHEP **1203**, 040 (2012) [arXiv:1202.3478 [hep-ex]].
18. S. Chatrchyan *et al.* [CMS Coll.], arXiv:1202.1416 [hep-ex].
19. S. Chatrchyan *et al.* [CMS Coll.], JHEP **1203**, 081 (2012) [arXiv:1202.3617 [hep-ex]].
20. ATLAS and CMS Collaborations, ATLAS-CONF-2011-157, CMS HIG-11-023 (2011).
21. S. Chatrchyan *et al.* [CMS Coll.], Phys. Lett. B **710**, 26 (2012) [arXiv:1202.1488 [hep-ex]].
22. CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-HIG-12-008 (2012).