IL NUOVO CIMENTO Vol. 36 C, N. 1 Gennaio-Febbraio 2013
DOI 10.1393/ncc/i2013-11428-3

Colloquia: IFAE 2012

Searches for the standard model Higgs boson at CMS

E. Di Marco(*) for the CMS Collaboration
California Institute of Technology - Pasadena CA, USA

ricevuto il 31 Agosto 2012

Summary. — We searched for the standard model Higgs boson using approximately $5\,\mathrm{fb}^{-1}$ of 7 TeV pp collisions data collected with the CMS detector at LHC. We exclude at 95% confidence level a standard model 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 most significant excess is observed at 125 GeV with a local significance of 2.8σ. The excess is consistent both with background fluctuation and a standard model Higgs boson with mass of about 125 GeV.

PACS 14.80.Bn – Standard-model Higgs bosons.
PACS 11.15.Ex – Spontaneous breaking of gauge symmetries.
PACS 29.20.db – Storage rings and colliders.

1. – Introduction

The scalar boson of the Brout-Englert-Higgs mechanism is the only block of the standard model (SM) [1-4] whose existence has not been verified experimentally. Therefore its search is one of the most important aspects of the LHC program. The Higgs boson has been ruled out at 95% confidence level (CL) at LEP [5] with mass smaller than 114.4 GeV and at Tevatron [6] with a mass in the vicinity of 160 GeV. Indirect constraints from precision electroweak measurements favour a low mass Higgs boson above the LEP limit and give the upper limit $M_{\mathrm{H}} < 143$ GeV at 95% CL, including direct searches before LHC. The dominant production mode at LHC is the gluon-gluon fusion followed by the vector boson fusion (VBF) and associated production with a vector boson (VH), each of which contributes less than 10% of the total production cross section. The decay branching ratios of the Higgs boson vary with its mass and are dominated by bb and $\tau\tau$ at low mass and by WW and ZZ above 135 GeV. The values of cross section and branching ratios used in the following are taken from the LHC cross section working group [7]. In

(*) E-mail: emanuele.dimarco@cern.ch

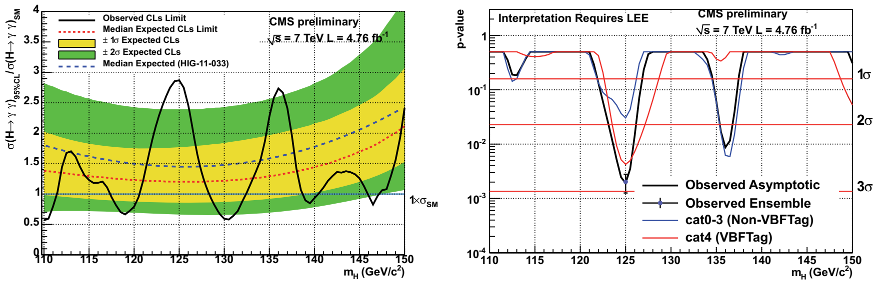

Fig. 1. – Left: 95% exclusion on the relative signal strength to the SM in the $\gamma\gamma$ channel. The dashed line indicates the expected limit for a simplified analysis. The light and dark bands indicate the 1σ and 2σ expectations around the median expected result. Right: local p-value as function of the Higgs mass. The combined p-value is shown and the VBF tag and other inclusive classes individual contributions are also shown.

2011 CMS collected approximately $5\,\text{fb}^{-1}$ of LHC data that are good for all analyses. The CMS detector is a multipurpose detector and is extensively described in [8]. The SM scalar boson search is carried out in the mass range between 110 and 600 GeV. The search channels, as well as their optimization and signal sensitivity, vary as function of the Higgs mass. The most sensitive channel at low mass, below approximately 130 GeV, is the $\gamma\gamma$ channel. Between 130 and 200 GeV the WW channel is most sensitive, and above 200 GeV the various ZZ channels take over.

2. – Low mass channels

2·1. $H \to \gamma\gamma$ *channel*. – The Higgs boson branching ratio for the decay into two photons is approximately 2×10^{-3} between 110 and 150 GeV. The diphoton mass resolution is very good, between 1 and 2% and the signature in this channel is two high E_{T} isolated photons. In case of the VBF there are two additional high p_{T} jets that provide a further handle to discriminate the signal from the background. A signal in this channel would appear like a small, narrow peak above a large and smooth background. After the final selection, the background is dominated by the irreducible two-photon QCD production. However there is also a relevant contribution from events in which at least one of the two identified photons is a jet faking a photon. VBF events are selected by using the same photon identification as for the inclusive analysis described later, slightly increasing the asymmetry on the photon E_{T} cuts and finally applying additional requirements on jet variables. The signal to background ratio in the di-jet tag class is relatively large, and we obtain an improvement on the exclusion sensitivity of approximately 10% in cross section [9, 10]. For the limit and significance calculation, the background is estimated by fitting to a polynomial in the full mass range. We found that the possible bias in the background estimation is always less than 20% of the statistical error. 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, defined as 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 while data exclude at 95% CL the ranges: 110.0–111.0 GeV, 117.5–120.5 GeV, 128.5–132.0 GeV, 139.0–140.0 GeV and 146.0–147.0 GeV. 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.

2·2. *$H \to \tau\tau$ and $H \to bb$ channels.* – These two channels are the only Higgs boson decays into fermions detectable at LHC. They are less sensitive than the $H \to \gamma\gamma$ channel, but they would be important to measure the couplings to leptons and quarks. For the $\tau\tau$ channel we exploit the VBF topology as well as a boosted topology. The mass reconstruction is not very precise due to the presence of neutrinos in the decay and the resolution is approximately 20%. We search in the mass range between 110 and 150 GeV [11]. The expected sensitivity for exclusion is approximately 3 times the SM and we do not observe any significant excess in the data [12, 13]. In case of the Higgs decays to bb, the background from bb, produced via QCD, is much too large, so we need to exploit the VH associated production with W and Z decaying leptonically and we analyze separately all channels: eν, $\mu\nu$, ee, $\mu\mu$ and $\nu\nu$ [14]. We require the bb system to be boosted to improve the background rejection and the mass resolution that becomes about 10%. 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. Also in this channel we see no significant excess in the data.

3. – Channels sensitive in the full mass range

3·1. *$H \to WW \to 2\ell 2\nu$ channel.* – This is the only viable channel for the Higgs boson search around the mass region of $2 \times m_{\mathrm{W}}$ and the most sensitive in the mass range of approximately 125–200 GeV. The Higgs boson mass cannot be precisely measured because of the undetected neutrinos and the resolution is of the order of 20%. The signature is two isolated high p_{T} leptons and the presence of missing transverse energy (MET). The main backgrounds to this channel are due to the WW production, Z plus jets, WZ, ZZ and W plus jets. The main backgrounds are estimated from the data. Due to the fact that the Higgs boson is a scalar and 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 background. The analysis [15] is performed in exclusive jet multiplicities (0, 1 and 2-jet bins) and flavour (ee, $\mu\mu$, eμ) because of the different sensitivities and background contributions. The 2-jet bin corresponds to the VBF analysis and exploits the characteristics of the VBF jets such as large p_{T}, large $\Delta\eta$ and di-jet invariant mass. Different cuts are applied in the different-flavour and same-flavour channels. Cuts are tighter and a Z mass veto is applied in the same-flavour channels because they are more affected by the Drell Yan background. The cut based selection has mass-dependent cuts while the MVA based analysis uses a BDT trained at different masses. The overall uncertainties after the final selection are approximately 20% for the signal efficiency and 15% for the expected background. Figure 2 shows the 95% exclusion confidence level for the cut based and the MVA shape analysis. We observe no significant excess in the full mass range though a small excess is observed at low mass. Therefore the observed limits are similar to the expected ones. For the MVA shape analysis the 95% CL expected exclusion is for M_{H} between 127 and 270 GeV and the range 129–270 GeV is excluded at 95% CL.

3·2. *$H \to ZZ \to 4\ell$ channel.* – The $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ channel is the cleanest channel and it is often referred as the "golden channel". The signal consists of four isolated leptons. For high mass both pairs of opposite charge and same flavour 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 rather small, approximately one per mille at high mass and lower for masses below $2 \times m_{\mathrm{W}}$ but the background is very small, consisting

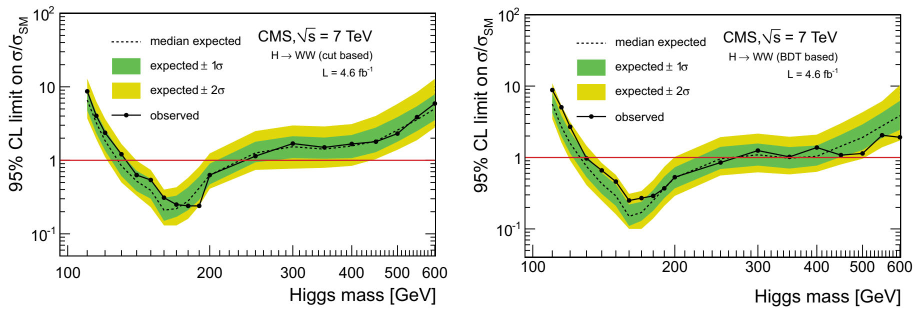

Fig. 2. – 95% exclusion limit on the relative signal strength to the SM for the cut based analysis (left) and for the MVA analysis (right) in the $H \to WW \to 2\ell 2\nu$ channel.

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. The analysis is carried out in the full mass range, from 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 given by an accumulation of 3 events at a mass of approximately 119.5 GeV. It has a local significance of 2.5σ and a global significance of 1.0σ in the full mass range and 1.6σ in the mass range 100–160 GeV (fig. 3).

4. – High-mass channels

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 resolution in ZZ channels. Beyond the previously described channels $H \to WW \to 2\ell 2\nu$ and $H \to ZZ \to 4\ell$ channels, we searched in the channels where one Z decays into ν [17], quark [18] or τ pairs [19]. The first one has high sensitivity in $M_H > 250$ GeV,

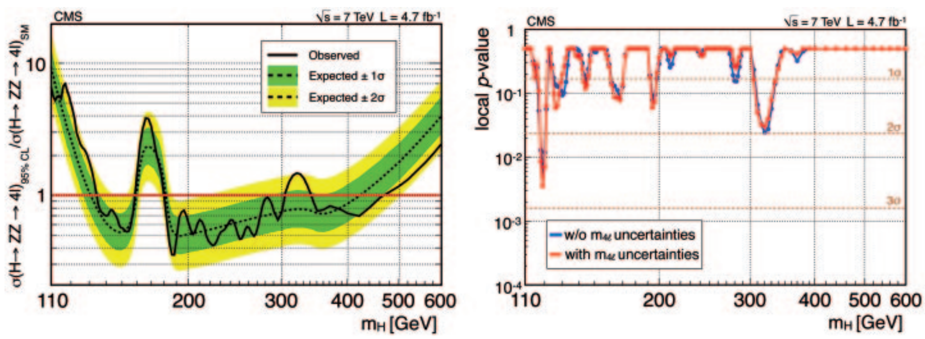

Fig. 3. – 95% exclusion limit on the relative signal strength to the SM (left) and local p-value computed with and without the individual candidate errors on the reconstructed mass in the $H \to ZZ \to 4\ell$ channel.

resulting in a 95% CL exclusion of M_H in 270–440 GeV, the second has a little lower sensitivity, while the last has a sensitivity of about 4 times the SM.

5. – Combination of all channels and summary

All 11 searched channels using approximately $5\,\mathrm{fb}^{-1}$ of 7 TeV pp collision data are combined to obtain the final exclusion and discovery confidence levels. The combination is carried out using the so-called CLs method described in [20]. The present combination that includes preliminary results is described in [21]. SM cross sections and branching ratios are assumed for the combination with their theoretical uncertainties [7]. An overall signal strength multiplier $\mu = \sigma/\sigma_{SM}$ is introduced and limits on its value are derived. 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 in case of no signal because of the excess that is observed in the data in the region between 115 and 128 GeV. The minimum combined p-value is observed at a mass of 125 GeV with a local significance of 2.8σ. A similar significance is expected in presence of a 125 GeV Higgs boson signal. The fitted value of the signal strength multiplier $\mu = \sigma/\sigma_{SM}$ of the excess near 125 GeV is consistent with the SM scalar boson expectation and several channels show some excess, though most of it comes from the $H \to \gamma\gamma$ channel. The data that will be collected in 2012 at 8 TeV CM energy should allow us to discover or exclude the SM scalar boson.

REFERENCES

[1] Weinberg S., *Phys. Rev. Lett.*, **19** (1967) 1264.
[2] Salam A., *Elementary Particle Theory*, (Almquist and Wiksells, Stockholm) 1968, p. 367.
[3] Englert F. and Brout R., *Phys. Rev. Lett.*, **13** (1964) 321.
[4] Higgs P. W., *Phys. Rev. Lett.*, **13** (1964) 508.
[5] Barate R. *et al.*, *Phys. Lett. B*, **565** (2003) 61.
[6] CDF and D0 Collaborations, (July, 2011); CDF Note 10606 and D0 Note 6226.
[7] Dittmaier S. *et al.*, arXiv:1201.3084.
[8] CMS Collaboration, *JINST*, **3** (2008) S08004.
[9] Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Lett. B*, **710** (2012) 403.
[10] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-HIG-12-001 (2012).
[11] Chatrchyan S. *et al.* (CMS Collaboration), arXiv:1202.4083.
[12] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-HIG-12-007 (2012).
[13] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-HIG-12-006 (2012).
[14] Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Lett. B*, **710** (2012) 284.
[15] Chatrchyan S. *et al.* (CMS Collaboration), *Phys. Lett. B*, **710** (2012) 91.
[16] Chatrchyan S. *et al.* (CMS Collaboration), arXiv:1202.1997.
[17] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **03** (2012) 040.
[18] Chatrchyan S. *et al.* (CMS Collaboration), arXiv:1202.1416.
[19] Chatrchyan S. *et al.* (CMS Collaboration), *JHEP*, **03** (2012) 081.
[20] ATLAS and CMS Collaborations, ATLAS-CONF-2011-157, CMS HIG-11-023 (2011).
[21] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-HIG-12-008 (2012).