Higgs results from ATLAS and CMS

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Abstract

Measurements of production, couplings and spin properties of the recently discovered Higgs boson using the most sensitive channels, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow WW \rightarrow l\nu l\nu$, are presented. The results are based on the first LHC run of pp collision data recorded by the ATLAS and CMS experiments at the CERN Large Hadron Collider at centre-of-mass energies of 7 and 8 TeV, corresponding to an integrated luminosity of about 25 fb^{-1} . Other important final states are also briefly described, such as $H \rightarrow \tau\tau$, $H \rightarrow bb$, $H \rightarrow Z\gamma$ and $H \rightarrow \mu\mu$. All studies are consistent with the expectation for the Standard Model Higgs boson. Finally, two searches for resonances up to 1 TeV are summarised, namely $H \rightarrow ZZ \rightarrow 2l2\nu$ and $H \rightarrow WW \rightarrow l\nu J$. No evidence for an additional signal is found in the region 248–930 GeV.

Keywords: Higgs, ATLAS, CMS, LHC

1. Introduction

The discovery of a new particle [1, 2] in the search for the Standard Model (SM) Higgs boson at the Large Hadron Collider (LHC) [3], performed with the ATLAS [4] and CMS [5] detectors in July 2012, is an important achievement in the understanding of the electroweak symmetry breaking mechanism [6].

	ATLAS	CMS
$H \rightarrow \gamma\gamma$	7.4 (4.2)	3.2 (3.9)
$H \rightarrow ZZ$	6.6 (4.4)	6.7 (7.1)
$H \rightarrow WW$	3.8 (3.0)	3.9 (5.3)
$H \rightarrow \tau\tau$	1.1 (1.7)	2.8 (2.6)
$H \rightarrow bb$	-	2.0 (2.2)

Table 1: Observed (expected) significance for different Higgs boson decay channels by the ATLAS [9] and CMS [8] collaborations. The ATLAS $H \rightarrow \tau\tau$ results are taken from reference [7].

In March 2013 both the ATLAS [7] and CMS [8] collaborations reported results with the full 7 and 8 TeV datasets corresponding to an integrated luminosity of about 25 fb^{-1} , using the high sensitivity channels

$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow WW \rightarrow l\nu l\nu$ (di-boson channels). The ATLAS Collaboration has recently presented final updated results on the di-boson channels [9, 10] which supersede the winter analyses and will be used throughout this paper unless stated otherwise.

The invariant mass of the two-photon final state by the ATLAS collaboration from the $H \rightarrow \gamma\gamma$ analysis can be seen in Fig. 1, and the four leptons invariant mass by the CMS collaboration from the $H \rightarrow ZZ \rightarrow 4l$ analysis in Fig. 2. The observed and expected significance for different final states is presented in Table 1, using a luminosity of about 5 fb^{-1} for 7 TeV and $13\text{--}21 \text{ fb}^{-1}$ for 8 TeV. For ATLAS the $H \rightarrow \tau\tau$ numbers are taken from reference [7]. The combined significance from reference [7] using the di-bosons channels together with $H \rightarrow \tau\tau$ and $H \rightarrow bb$ is presented in Fig. 3, showing an observed combined significance of almost 10σ . This observed significance together with Figs. 1 and 2 makes evident the discovery of a new particle. The next step is to measure production, couplings and spin properties and study as many final states as possible.

Figure 1: Invariant mass distribution of diphoton candidates for the combined $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV ATLAS data samples. The result of a fit to the data described by the sum of a signal component fixed to $m_H = 126.8$ GeV and a background component fitted by a fourth-order Bernstein polynomial is superimposed. The bottom inset displays the residuals of the data with respect to the fitted background component. Figure taken from reference [9].

Figure 2: Distribution of the four-lepton reconstructed mass in the full mass range for the sum of the $4e$, 4μ and $2e2\mu$ channels. Points represent the data, shaded histograms represent the background and the unshaded histogram the signal expectation. The expected distributions are presented as stacked histograms. The measurements are presented for the sum of the data collected at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. No event is observed for $m_{4l} > 800$ GeV. Figure taken from reference [8].

Figure 3: The local probability p_0 for a background-only experiment to be more signal-like than the observation as a function of m_H for the combination of all channels. The dashed curve shows the median expected p_0 under the hypothesis of a Standard Model Higgs boson production at that mass. The horizontal dashed lines indicate the p-values corresponding to significances of 0σ to 10σ . Taken from reference [7].

2. Higgs properties

In this section the studies of mass, strength parameter, couplings to fermion and bosons, and spin of the new particle are presented.

2.1. Measurement of mass

The measurement of the mass of the new particle is done with the more accurate channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$.

In ATLAS the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ mass determinations are only compatible within 2.4σ , the present explanation being a statistical fluctuation. This should be revisited with 2015 data. The combined value is $m_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(sys)$.

The measurement of the CMS experiment is presented in Fig. 4 and the combination is $m_H = 125.7 \pm 0.3(stat) \pm 0.3(sys)$.

2.2. Measurement of signal strength

The signal strength μ is defined as the measured cross-section over the expected SM cross-section and it is calculated assuming a fix value of m_H .

The recent ATLAS final result on di-boson channels is shown in Fig. 5.

The CMS collaboration uses di-boson channels, $H \rightarrow \tau\tau$ and $H \rightarrow bb$ and measures $\mu = 0.80 \pm 0.14$.

Good compatibility with the expected SM value $\mu = 1$ is observed.

The strength of the different Higgs production mechanisms can be studied within different analysis categories, defined, e.g., by the kinematics of additional jets.

Figure 4: One-dimensional scan of the test statistics estimate versus the Higgs boson candidate mass m_X for the $\gamma\gamma$ and $4l$ final states separately and for their combination. In this combination three independent signal strengths, $gg \rightarrow H \rightarrow \gamma\gamma$, $VBF + VH \rightarrow \gamma\gamma$, and $H \rightarrow ZZ \rightarrow 4l$, are profiled together with all other nuisance parameters. Figure taken from reference [8].

The most important production mechanism is gluon-gluon Fusion (ggF), which has a cross-section ten times bigger than the next most frequent one, Vector Boson Fusion (VBF). The other two production mechanisms are associated production with a vector boson (VH) and associated production with $t\bar{t}$ (ttH).

The production modes VBF and VH (ggF and ttH) are combined together into μ_{VBF+VH} ($\mu_{ggF+ttH}$) because the data is not very sensitive to VH (ttH) and because both VBF and VH (ggF and ttH) scale with the V-H (t-H) coupling.

The CMS plot of μ_{VBF+VH} versus $\mu_{ggF+ttH}$ using di-boson channels, $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$, is shown in Fig. 6. The individual channels are consistent with the SM prediction ($\mu_{VBF+VH} = 1$ and $\mu_{ggF+ttH} = 1$).

2.3. Measurement of couplings

Coupling scale factors to vector and fermions (κ_V and κ_F , respectively) are the ratio between the measured and the SM expected value.

The coupling scale factor κ_V is measured directly and indirectly in many channels. The coupling scale factor κ_F is measured in two ways: (1) directly in $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$, but data is not very sensitive to these channels yet; (2) indirectly via loops in $gg \rightarrow H$.

The final determinations of κ_V versus κ_F by the ATLAS collaboration using di-boson channels are presented in Fig. 7.

Figure 5: The measured production strengths for a Higgs boson of mass $m_H = 125.5$ GeV, normalised to the SM expectations, for di-boson final states and their combination. The best-fit values are shown by the solid vertical lines, with the total $\pm 1\sigma$ uncertainty indicated by the shaded band, and the statistical uncertainty by the superimposed horizontal error bars. The numbers in the second column specify the contributions of the (symmetrised) statistical uncertainty (top), the total (experimental and theoretical) systematic uncertainty (middle), and the theory uncertainty (bottom) on the signal cross section (from QCD scale, PDF, and branching ratios) alone; for the individual categories only the statistical uncertainty is given. Figure taken from reference [9].

Figure 6: The 68% (solid lines) CL region for the signal strength in the $ggF+ttH$ and in the $VBF+VH$ production mechanisms, $\mu_{ggF+ttH}$ and μ_{VBF+VH} , respectively. The different colours show the results obtained by combining data from each of the five analysed decay modes: $\gamma\gamma$ (green), WW (blue), ZZ (red), $\tau\tau$ (violet), bb (cyan). The crosses indicate the best-fit values. The diamond at (1,1) indicates the expected values for the SM Higgs boson. A combination of the different decay modes is not possible without making assumptions on the relative branching fractions. Figure taken from reference [8].

Figure 7: Likelihood contours (68% CL) of the coupling scale factors κ_F and κ_V for fermions and bosons as obtained from fits to the three di-boson channels and their combination (for the later, the 95% CL contour is also shown). The best-fit result (x) and the SM expectation (+) are also indicated. Figure taken from reference [9].

Fermion and vector couplings are non-zero and consistent with the SM.

2.4. Measurement of spin

The SM prediction of J^P for a Higgs boson is 0^+ . The value $J = 1$ is strongly disfavoured after the $H \rightarrow \gamma\gamma$ observation due to the Landau-Yang theorem [11].

The channels $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow l\nu l\nu$ are used to study the spin hypotheses 0^- , 1^{+-} , and 2_m^+ (a simplified graviton inspired model for the 2^+ hypothesis in which the fraction of qq and gg production modes is not fixed).

A relevant variable in these studies is the angle θ^* which is the polar angle of the decay products in the Higgs rest frame and can be built in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ analyses. In addition to this, in the $H \rightarrow WW \rightarrow l\nu l\nu$ analysis, the presence of neutrinos avoids the reconstruction of the angle θ^* or other Higgs rest frame angular variables. However, other final state variables with spin information are accessible, as the transverse mass of the system, the invariant mass of the two leptons, together with their total transverse momentum and their azimuthal separation.

The combination of the $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow l\nu l\nu$ analysis is performed in Fig. 8 by the CMS collaboration [8]. The hypothesis 2_m^+ is excluded with 99.4 % C.L.

The summary plot for ATLAS spin measurements [10] is presented in Fig. 9, where the CL_s values for the different spin-parity hypothesis are shown. Table 2 compiles the CL exclusion limits for the spin-parity hypotheses. The conclusion for these studies is that the SM spin-parity value 0^+ is strongly favoured.

	0^-	1^+	1^-	2_m^+
CL limit	97.8	99.9	99.6	99.9

Table 2: Combined exclusion CL limits for the different spin-parity hypotheses studied by the ATLAS collaboration. Figure taken from reference [10].

3. Fermionic final states

3.1. $H \rightarrow \tau\tau$

This channel is relevant as the Higgs boson coupling to fermions of third generation is tested and the branching fraction of $H \rightarrow \tau\tau$ is non-zero in the SM.

Figure 8: Post-fit model distributions of the test statistic comparing the signal J^P hypotheses 0^+ and $2_m^+(gg)$ in the best fit to the data. The observed value is indicated by the arrow and disfavours the $2_m^+(gg)$ signal hypothesis with a CL_s value of 0.60%. Figure taken from reference [8].

Figure 9: Expected (blue triangles/dashed lines) and observed (black circles/solid lines) confidence level CL_s for alternative spin-parity hypotheses assuming a $J^P = 0^+$ signal. The green band represents the 68% $CL_s (J^P_{alt})$ expected exclusion range for a signal with assumed $J^P = 0^+$. For the spin-2 hypothesis, the results for the specific 2_m^+ model are shown. On the right y-axis, the corresponding numbers of Gaussian standard deviations are given, using the one-sided convention. Figure taken from reference [10].

In the ATLAS and CMS analyses [12] all decays of the $\tau\tau$ pair are considered: leptonic-leptonic (12.4%), leptonic-hadronic (45.6%), and hadronic-hadronic (42%). The events are classified according to the final state topologies: in the VBF class, two jets with high rapidity separation are present together with the $\tau\tau$ system; in the VH class there are two jets with different characteristics from the vector boson accompanying the $\tau\tau$ pair; in other categories also the ggF mechanism is studied.

The CMS collaboration has analysed the full 7 and 8 TeV datasets and the observed and expected significance can be seen in Fig. 10. The ATLAS analysis is preliminary and done on a smaller data set. Both the ATLAS and CMS results are consistent with the presence of a SM Higgs signal at 125 GeV.

Figure 10: Observed and expected p-value and the corresponding significance in number of standard deviations. These results include the search for a SM Higgs boson decaying into a τ pair and produced in association with a W or Z boson decaying leptonically. Figure taken from reference [12], CMS.

3.2. $VH, H \rightarrow b\bar{b}$

It is important to study this mode because the coupling to fermions is tested and also because this decay channel has the highest branching ratio for a SM Higgs of 125 GeV.

In the ATLAS and CMS analyses [13] events are divided in categories according to the decay products of the associated vector boson: two leptons, one lepton and zero leptons. The main background is V + heavy flavour jets, and top processes. The ATLAS collaboration performs the analysis with a cut-based approach, whilst the CMS collaboration applies a multivariate technique.

Figure 11 depicts the expected and observed 95% CL upper limits on the product of the VH production cross section times $H \rightarrow b\bar{b}$ branching ratio by the CMS collaboration. A local significance of 2.1σ at 125 GeV is observed.

Figure 11: Expected and observed 95% CL upper limits on the product of the VH production cross section times $H \rightarrow b\bar{b}$ branching ratio, with respect to the expectations for a standard model Higgs boson. The limits are combined for the 2011 7 TeV and 2012 8 TeV data. The red dashed represents the expected observed limits obtained from replacing the data with the sum of expected background and signal for a Higgs boson at a mass of 125 GeV. Figure taken from reference [13], CMS.

4. Rare decays

4.1. $H \rightarrow Z\gamma$

The branching ratio of the SM Higgs decay to $Z\gamma$ is of the order of 2×10^{-3} . Therefore it is not accessible experimentally but its value is interesting to corroborate the nature of the new boson. Measurement of (or limits on) the $H \rightarrow Z\gamma$ decay rate can provide insight into models beyond the SM. The decay rate can help determine whether the new boson is the Higgs boson or a member of other electroweak singlets or triplets. Moreover, because the $H \rightarrow Z\gamma$ decay proceeds via electroweak loop couplings to the Higgs boson, it can provide direct evidence of new heavy particles appearing there.

ATLAS and CMS descriptions of this analysis can be found in [14]. The invariant mass of the two leptons from the Z is reconstructed and ATLAS takes as discriminating variable the difference (Δm) between the invariant mass of the two leptons plus the photon ($m_{ll\gamma}$) and the invariant mass of the two leptons (m_{ll}). This

variable is depicted in Fig. 12 for data and for a third order polynomial fit.

The observed and expected limits are still far from the SM sensitivity.

Figure 12: Background-only fits to the distribution of the mass difference Δm of selected events in data, for $Z \rightarrow \mu\mu$ at $\sqrt{s} = 8$ TeV. A third order polynomial is used for the fit. Dots correspond to data, the blue line is the fit result and the gray and light red bands are the 1σ and 2σ uncertainty bands from the statistical uncertainties on the fitted background model parameters. The dashed histograms correspond to the SM signal expectation, for a Higgs boson mass of 125 GeV, scaled by a factor 20 for clarity. Figure taken from reference [14], ATLAS.

4.2. $H \rightarrow \mu\mu$

The $H \rightarrow \mu\mu$ channel is another fermionic final state studied by the ATLAS collaboration [15]. This time the coupling to a second generation particle is tested. It has a clean final state signature but a small branching ratio in the SM (between 28×10^{-5} to 6×10^{-5} in the Higgs boson mass range 100-150 GeV). However, possible extensions of the SM, such as the Minimal Supersymmetric extension (MSSM), postulate the existence of additional Higgs boson-like particles with enhanced branching ratios to muons.

In this channel the dominant irreducible SM background is $Z/\gamma \rightarrow \mu\mu$ process with a very high production rate compared to an expected Higgs signal. The discriminating variable is the invariant mass of the dimuon system, which is shown in Fig 13, where also the different background contributions are presented.

No signal is found with this analysis at the moment.

5. High mass resonances

After the discovery publications [1, 2] the region above 559 GeV is still unexplored. Therefore, this study should extend up to 1 TeV.

Figure 13: The distribution of the di-muon invariant mass $m_{\mu\mu}$ with the requirements on the muon track quality, muon isolation and minimum momentum for both muons applied. The signal is shown for $m_H=125$ GeV. The yellow band in the ratio plots shows statistical uncertainty of the MC samples. Figure taken from reference [15].

5.1. $H \rightarrow ZZ \rightarrow 2l2\nu$

This decay mode is especially sensitive in the region between 200 GeV and 1 TeV owing to its distinct signature and to a competitive branching fraction which is six times higher with respect to the $ZZ \rightarrow 2l2l$ channel.

In reference [16] the CMS collaboration reports results on this channel using the full 7 and 8 TeV datasets. With respect to the previous publication, besides expanding the search to the full recorded dataset, they improved the data-driven estimates of the reducible backgrounds, included corrections to the simulated Higgs-boson mass line-shape as well as interference effects with the background based on recent calculations. Also, the event selection and the analysis strategy are improved.

The analysis distinguishes between two categories: VBF in which two high-energy forward jets are produced in addition to the leptons, and ggF in which the VBF selection is not fulfilled and there is zero or one jet in the event. The upper limits at 95% using the ggF category can be seen in Fig. 14. From this analysis, the observed exclusion region is between 248-930 GeV.

5.2. $H \rightarrow WW \rightarrow l\nu J$

This analysis is performed by the CMS collaboration [17] using the full 8 TeV dataset. The obtained results are interpreted as a search for a SM Higgs boson, as well as in the context of a BSM scenario, based

Figure 14: Upper limits at 95% CL set on the gluon-gluon production cross section of a SM-like Higgs boson in the $H \rightarrow ZZ \rightarrow l\nu l\nu$ analysis as function of its mass. Figure taken from reference [16].

on an effective theory where a second scalar particle besides the resonance at 125 GeV completes the unitarisation of the WW scattering.

In this analysis both W's are very boosted. One decays into $l\nu$ and the other W into jj . Due to the boost, both jets from the hadronically decaying W are merged together into a “fat” jet (“J”). A special technique is used to recover the mass of the fat jet, and to disentangle it from the invariant mass of the WW system.

As can be seen in Fig 15, the observed limits are approaching the theory line especially at low mass.

Figure 15: The 95% CL limit on σ/σ_{SM} for a Higgs boson decaying to $WW \rightarrow l\nu q\bar{q}'$. Figure taken from reference [17].

6. Conclusions

In this article the properties of the new discovered boson have been reviewed using data accumulated by the LHC at 7 and 8 TeV. There is good agreement with the expectation for a SM Higgs boson.

The mass has been measured using the most sensitive decay channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$, and the values are $m_H = 125.5 \pm 0.2$ (stat) $^{+0.5}_{-0.6}$ (sys) GeV (ATLAS), $m_H = 125.7 \pm 0.3$ (stat) ± 0.3 (sys) GeV (CMS).

The signal strength and the couplings to fermions and bosons have been measured and the result is compatible with the SM.

The spin-parity is analysed and non-SM spin-parity is disfavoured.

These results together with fermionic final state studies and rare decay analyses strongly favour that the recent discovered Higgs boson is very much like the SM Higgs boson.

References

- [1] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. **B 716** (2012) 1, arXiv:1207.7214 [hep-ex].
- [2] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. **B 716** (2012) 30, arXiv:1207.7235 [hep-ex].
- [3] L. Evans and P. Bryant, *LHC Machine*, JINST **3** (2008) S08001.
- [4] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** S08003 (2008).
- [5] CMS Collaboration, *The CMS Experiment at the CERN LHC*, JINST **0803 3** (2008).
- [6] F. Englert and R. Brout, *Broken symmetry and the mass of gauge vector mesons*, Phys. Rev. Lett. **13** (1964) 321.
P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, Phys. Lett. **12** (1964) 132.
P. W. Higgs, *Broken symmetries and the masses of gauge bosons*, Phys. Rev. Lett. **13** (1964) 508.
G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, *Global conservation laws and massless particles*, Phys. Rev. Lett. **13** (1964) 585.
P. W. Higgs, *Spontaneous symmetry breakdown without massless bosons*, Phys. Rev. **145** (1966) 1156.
T. W. B. Kibble, *Symmetry breaking in non-Abelian gauge theories*, Phys. Rev. **155** (1967) 155.
- [7] ATLAS Collaboration, *Combined measurements of the mass and signal strength of the Higgs-like boson with the ATLAS detector using up to 25 fb⁻¹ of proton-proton collision data*, ATLAS-CONF-2013-014, <http://cds.cern.ch/record/1523727>.
ATLAS Collaboration, *Combined coupling measurements of the Higgs-like boson with the ATLAS detector using up to 25 fb⁻¹ of proton-proton collision data*, ATLAS-CONF-2013-034, <http://cds.cern.ch/record/1528170>.
- [8] CMS Collaboration, *Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV*, CMS-PAS-HIG-13-005, <http://cds.cern.ch/record/1542387>.
- [9] ATLAS Collaboration, *Measurements of Higgs boson production and couplings in di-boson final states with the ATLAS detector at the LHC*, arXiv:1307.1427v1 [hep-ex], submitted to Phys. Lett. **B**.
- [10] ATLAS Collaboration, *Evidence for the spin-0 nature of the Higgs boson using ATLAS data*, arXiv:1307.1432 [hep-ex], submitted to Phys. Lett. **B**.
- [11] L. D. Landau, *On the angular momentum of a two-photon system*, Dokl. Akad. Nauk Ser. Fiz. **60** (1948) 207.
C.-N. Yang, *Selection Rules for the Dematerialization of a Particle Into Two Photons*, Phys. Rev. **77** (1950) 242.
- [12] ATLAS Collaboration, *Search for the Standard Model Higgs boson in $H \rightarrow \tau\tau$ decays in proton-proton collisions with the ATLAS detector*, ATLAS-CONF-2012-160, <http://cds.cern.ch/record/1493624>.
CMS Collaboration, *Search for the Standard-Model Higgs boson decaying to tau pairs in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV*, CMS-PAS-HIGG-13-004, <http://cds.cern.ch/record/1528271>.
- [13] ATLAS Collaboration, *Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to bottom quarks with the ATLAS detector*, ATLAS-CONF-2012-161, <http://cds.cern.ch/record/1493625>.
CMS Collaboration, *Search for the standard model Higgs boson produced in association with W or Z bosons, and decaying to bottom quarks for LHCp 2013*, CMS-PAS-HIGG-13-012, <http://cds.cern.ch/record/1546801>.
- [14] ATLAS Collaboration, *Search for the Standard Model Higgs boson in the $H \rightarrow Z\gamma$ decay mode with pp collisions at $\sqrt{s} = 7$ and 8 TeV*, ATLAS-CONF-2013-009, <http://cds.cern.ch/record/1523683>.
CMS Collaboration, *Search for the standard model Higgs boson in the Z boson plus a photon channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV*, CMS-PAS-HIGG-13-006, <http://cds.cern.ch/record/1523674>.
- [15] ATLAS Collaboration, *Search for the Standard Model Higgs boson in $H \rightarrow \mu\mu$ decays with the ATLAS detector*, ATLAS-CONF-2013-010, <http://cds.cern.ch/record/1523695>.
- [16] CMS Collaboration, *Search for a heavy Higgs boson in the H to ZZ to $2l2\nu$ channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV*, CMS-PAS-HIGG-13-014, <http://cds.cern.ch/record/1546776>.
- [17] CMS Collaboration, *Search for a Standard Model-like Higgs boson decaying into WW to $l\nu q\bar{q}$ in pp collisions at $\sqrt{s} = 8$ TeV*, CMS-PAS-HIGG-13-008, <http://cds.cern.ch/record/1546778>.