Plenary talk on CMS/ATLAS Higgs results

Juan Carlos Sanabria Arenas for the ATLAS, CMS and Higgs collaborations.

Abstract

The latest results from the ATLAS and CMS experiments on the Higgs boson properties, using 25 fb-1 of data from pp collisions at 7 and 8 TeV are presented. Both experiments perform studies in various channels with different final states. Each experiment; combine all the results to extract the best overall sensitivity. We report the results from the different final states, and the combined sensitivity, from each experiment.

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Higgs Results from ATLAS and CMS.

J. C. Sanabria,
on behalf of the ATLAS and CMS Collaborations.

Department of Physics, Universidad de Los Andes,
Bogota, Colombia

Abstract

The properties of the Higgs boson, measured by the ATLAS and CMS experiments during the first run of the LHC, are presented. These results were obtained from pp collisions at a center-of-mass-energy of $\sqrt{s} = 7$ TeV in 2011, and at $\sqrt{s} = 8$ TeV in 2012. The measurements of the Higgs boson mass, width, spin-parity, as well as several cross sections and couplings are reported. Results from searches of physics beyond the standard model in the Higgs sector are reported also.

Keywords:
Higgs, ATLAS, CMS, LHC, SM, BSM

1. Introduction

In July of 2012 the ATLAS and CMS collaborations announced the discovery of a neutral boson with a mass of about 125 GeV, whose properties were consistent with those of the standard model (SM) Higgs boson [1, 2]. Since then both experiments have performed a series of measurements of the properties of the new particle using the data collected during the first run of the LHC, with an integrated luminosity of about 5 fb$^{-1}$ at a collision energy of 7 TeV, and of about 20 fb$^{-1}$ at 8 TeV. The precision on the measurements of the mass and of several cross sections, the measurement of the spin-parity and of several couplings to other particles, have confirmed, to a high confidence level, the Higgs nature of the boson.

The experimental program to study the Higgs boson properties, developed by ATLAS and CMS, has been guided by the different combinations of the production and decay channels. The main production mechanisms at the LHC-Run-1 energies for pp collisions are: gluon fusion (ggH), vector boson fusion (VBF), higgsstrahlung off a vector boson (VH), and production in association with a t$\bar{t}$ pair (t$\bar{t}$H). Of these, the dominant channel is gluon fusion. However, since the other channels can be identified experimentally with some efficiency (tagged) by looking for a Higgs boson in combination with the decay products of the associated particles, they can provide improved kinematical information, as well as information about the coupling of the Higgs boson to top quarks and vector bosons.

For the decay mechanisms not only the branching ratio, but also the signal-to-background ratio are important to determine the main channels to explore. Since the Higgs boson coupling to other states is proportional to the mass of those states, the main decay channels, for a Higgs boson of 125 GeV mass, would be: $H \rightarrow ZZ'$, $H \rightarrow WW'$, $H \rightarrow bb$ and $H \rightarrow \tau\tau$, in addition to the channel $H \rightarrow \gamma\gamma$, that proceeds via loops of massive states (top quarks and vector bosons mainly). Other channels, like for instance $H \rightarrow Z\gamma$, $H \rightarrow \mu\mu$, and $H \rightarrow c\bar{c}$ have small branching ratios at the energies and luminosities of the first run of the LHC and produce smaller signals.

Of all the channels, the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ' \rightarrow 4f$ are the ones that provide full reconstruction of the boson mass with good resolution; they also provide very detailed final-state kinematical information, that is crucial...
for the measurement of properties like spin, parity and width. From the $H \rightarrow \tau \tau, H \rightarrow b \bar{b}$, and even $H \rightarrow W W^*$ channels the mass of the bosons can be reconstructed also, but with poor resolution.

By the time of the X SILAFAE conference, ATLAS and CMS had published results for most of the combinations of the main production mechanisms and the main decay channels of the discovered Higgs boson. Measurements of the mass, spin, parity, various couplings, and upper limits for the width have been reported, as well as the first results for differential cross sections.

In the search for physics beyond the SM (BSM) in the Higgs sector, results have been published for neutral and charged Higgs bosons, invisible decays, flavor changing neutral currents (FCNC), lepton flavor violations (LFV), etc.

2. Higgs main decay channels

As mentioned in the previous section, the main Higgs decay channels, at the energies and luminosities of the first run of the LHC, at the discovery stage, and later for the study of the properties of the boson, were:

- $H \rightarrow \gamma \gamma$
- $H \rightarrow ZZ^* \rightarrow 4 \ell$
- $H \rightarrow WW^* \rightarrow \ell \nu \ell \nu$
- $H \rightarrow \tau \tau$
- $H \rightarrow b \bar{b}$

The $H \rightarrow \gamma \gamma$ channel: The diphoton channel provides a clean final-state topology, allowing the reconstruction of the mass of the decaying state with high precision, in spite of its small branching ratio. The search for a narrow resonance in the $\gamma \gamma$ invariant-mass plot ($m_{\gamma \gamma}$) provided the main evidence of the existence of the boson. The most recent results published by ATLAS [3] and CMS [4] for this channel include values for the individual signal strengths $\mu$, relative to the SM prediction ($\mu = \sigma/\sigma_{SM}$) for the different production mechanisms.

Figures 1 and 2 show the signal strengths and the combined result.

In the case of ATLAS, a clear signal was observed at a mass of [5]:

\[ m_H = 125.98 \pm 0.42 \text{ (stat.)} \pm 0.28 \text{ (syst.) GeV}, \]

with an observed local significance of $5.2\sigma$ (4.6$\sigma$ expected); the combined signal strength for this channel, reported by this experiment is [3]:

\[ \mu = 1.17 \pm 0.23 \text{ (stat.)} ^{+0.16}_{-0.11} \text{ (syst.)}. \]

In the case of CMS, a clear signal is observed at a mass of [4]:

\[ m_H = 124.70 \pm 0.31 \text{ (stat.)} \pm 0.15 \text{ (syst.) GeV}, \]

with an observed local significance of $5.7\sigma$ (5.2$\sigma$ expected); the combined signal strength for this channel, reported by this experiment is [4]:

\[ \mu = 1.14 \pm 0.21 \text{ (stat.)} ^{+0.09}_{-0.05} \text{ (syst.)} ^{+0.13}_{-0.09} \text{ (theo.)}. \]
The $\mathcal{H} \to ZZ' \to 4\ell$ channel: In this channel events are selected by looking for two pairs of same-flavor, opposite-charge, well identified and isolated leptons, $e^+e^-,\mu^+\mu^-$, compatible with a ZZ state, where one or both of the Z bosons can be off-shell, and reconstruct a narrow resonance in the $m_{4\ell}$ invariant mass plot. Due to the demand of the four leptons in the final state, this channel has a small rate, but excellent signal-to-background ratio. The detailed kinematical information of the final state provides several independent observables that can be used to measure properties like cross section, mass, width, spin and parity of the state.

In the case of ATLAS, a clear signal is observed at a mass of [5]:

$v_0 = 7$ TeV, $20.3$ fb$^{-1}$

$\mathcal{H}$ boson mass of $125.36$ GeV

In the case of CMS, the combined signal strength for this channel, reported by this experiment is [6]:

$\mu = 1.44^{+0.34}_{-0.31} \text{ (stat.)}^{+0.21}_{-0.11} \text{ (syst.)}$

In the case of CMS, a clear signal is observed, at a mass of [7]:

$\mathcal{H}$ boson mass of $125.6 \pm 0.4$ GeV,

with an observed local significance of $6.8\sigma$ ($6.7\sigma$ expected); the combined signal strength for this channel, reported by this experiment is [7]:

$\mu = 0.93^{+0.26}_{-0.23} \text{ (stat.)}^{+0.13}_{-0.09} \text{ (syst.)}$

The $\mathcal{H} \to WW^* \to l\nu l\nu$ channel: This channel has the second largest branching fraction (22%), but since only leptonic decays involving electrons and muons are considered, this quantity reduces to about 1%; however, it still provides an experimental signature. The two experiments report results for the production mechanisms: $\mathcal{g}\mathcal{H}$, $\mathcal{V}$BF and $\mathcal{V}$H ($\mathcal{V} = \mathcal{Z},\mathcal{W}$); the contribution of the $t\bar{t}$ channel is negligible for this channel.

In the case of ATLAS, the signal strength reported is [8]:

$\mu = 1.09^{+0.16}_{-0.15} \text{ (stat.)}^{+0.17}_{-0.14} \text{ (syst.)}$

with a significance of $6.1\sigma$ ($5.8\sigma$ expected), for a Higgs boson mass of $m_{\mathcal{H}} = 125.36$ GeV.

In the case of CMS, the signal strength reported for this channel is [9]:

$\mu = 0.72^{+0.12}_{-0.12} \text{ (stat.)}^{+0.12}_{-0.10} \text{ (th. syst.)}^{+0.10}_{-0.10} \text{ (exp. syst.)}$

with a significance of $4.3\sigma$ ($5.8\sigma$ expected), for a Higgs boson mass of $m_{\mathcal{H}} = 125.6$ GeV.

The $\mathcal{H} \to \tau\tau$ channel: This channel is the result of the combination of the different production mechanisms of the Higgs boson and the different $\tau$ reconstruction techniques:

- Lepton-lepton: $\tau_{\text{lep}}\tau_{\text{lep}}$ (lep = $e, \mu$; Branching Ratio = 12.4%); reconstructed from two opposite-charge leptons.
- Lepton-hadronic: $\tau_{\text{lep}}\tau_{\text{had}}$. (Branching Ratio = 45.6%); reconstructed from one charged lepton and one hadronic tau.
- Hadronic-hadronic: $\tau_{\text{had}}\tau_{\text{had}}$. (Branching Ratio = 42%); reconstructed from two hadronic taus.

In Figures 3 and 4 partial signal strengths, reported by ATLAS and CMS, for the $\tau\tau$ channel are presented.

In the case of ATLAS, the combined signal strength for this channel is [10]:

$\mu = 1.43^{+0.27}_{-0.26} \text{ (stat.)}^{+0.32}_{-0.25} \text{ (syst.)} \pm 0.09 \text{ (theory syst.)}$

with a significance of $4.5\sigma$ ($3.4\sigma$ expected), for a Higgs boson mass of $m_{\mathcal{H}} = 125.36$ GeV.
In the case of CMS, the combined signal strength for this channel is [11]:

\[ \mu = 0.78 \pm 0.27, \]

with a significance of 3.2\( \sigma \) (3.7\( \sigma \) expected), for a Higgs boson mass of \( m_H = 125 \text{ GeV} \).

The \( H \rightarrow b\bar{b} \) channel: In this case an inclusive search is not possible at hadron colliders due to the overwhelming background from multijet production. Since the decay branching fraction of the \( H \rightarrow b\bar{b} \) is of 58%, the production of the Higgs boson in association with a vector boson, \( W \) or \( Z \), offers a possibility in spite of being one order of magnitude lower than the main production mechanism: gluon fusion. The identification of the associated \( W \) or \( Z \) can be used efficiently for triggering and background reduction purposes. For the analysis ATLAS and CMS considered the vector boson decay channels: \( W \rightarrow \ell\nu \), \( Z \rightarrow \ell\ell \), \( Z \rightarrow \nu\nu \), where \( \ell = e, \mu \). CMS also included the channel \( W \rightarrow \tau\nu \), but only with the 8 TeV data.

In the case of ATLAS, the combined signal strength for this channel is [12]:

\[ \mu = 0.51^{+0.40}_{-0.37}, \]

with a significance of 1.4\( \sigma \) (2.6\( \sigma \) expected), for a Higgs boson mass of \( m_H = 125 \text{ GeV} \).

In the case of CMS, the combined signal strength for this channel is [13]:

\[ \mu = 1.0 \pm 0.5, \]

with a significance of 2.1\( \sigma \) (2.1\( \sigma \) expected), for a Higgs boson mass of \( m_H = 125 \text{ GeV} \).

### 3. Higgs properties

The main properties of the Higgs boson, like its mass, signal strength, spin, parity, etc. are extracted from combinations of the data for the different channels. In this section the results of these studies are presented.

Higgs signal strength: The ATLAS experiment has combined the signal strengths of the channels: \( H \rightarrow \gamma\gamma \), \( H \rightarrow ZZ^* \rightarrow 4\ell \), \( H \rightarrow WW^* \rightarrow \ell\nu\ell\nu \), \( H \rightarrow \tau\tau \) and \( H \rightarrow b\bar{b} \), with the result [14]:

\[ \mu = 1.30 \pm 0.12 \text{ (stat.)}^{+0.14}_{-0.11} \text{ (sys.),} \]

for a Higgs boson mass of \( m_H = 125.5 \text{ GeV} \). In Figure 5 an updated version of the individual strengths, published by ATLAS, is presented.

In the case of CMS, the signal strengths of the channels \( H \rightarrow \gamma\gamma \), \( H \rightarrow ZZ^* \rightarrow 4\ell \), \( H \rightarrow WW^* \rightarrow \ell\nu\ell\nu \), \( H \rightarrow \tau\tau \) and \( H \rightarrow b\bar{b} \), have been combined, with the result [16]:

\[ \mu = 1.00 \pm 0.09 \text{ (stat.)}^{+0.08}_{-0.07} \text{ (theo.)} \pm 0.07 \text{ (syst.),} \]

for a Higgs boson mass of \( m_H = 125 \text{ GeV} \). In Figure 6 the results of the signal strength studies of CMS are presented.

Higgs mass: The mass of the Higgs boson is extracted from a combined fit to the invariant mass spectra of the decay channels \( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ^* \rightarrow 4\ell \). The results of this analysis for ATLAS and CMS are shown in the Figures 7 and 8. In the case of ATLAS the best value for the mass of the state is [5]:

\[ m_H = 125.36 \pm 0.37 \text{ (stat.)} \pm 0.18 \text{ (syst.) GeV.} \]

In the case of CMS the best value of the mass of the state is [16]:

\[ m_H = 125.02^{+0.26}_{-0.27} \text{ (stat.)}^{+0.14}_{-0.15} \text{ (syst.) GeV.} \]

Higgs width: The SM expectation for the Higgs boson width is \( \Gamma_H^{\text{SM}} \sim 4 \text{ MeV} \). The LHC operates in the region of the TeV, and the detectors are designed to have energy resolutions in the region of the GeV. It is therefore challenging to measure a width in the region of the few MeV. However, it is possible to constrain the Higgs boson width using its off-shell produc-
tion and decay into ZZ, away from the resonance peak [17]. In the dominant gluon fusion production mode the off-shell cross section is sizable; this cross section depends on \( \Gamma_H \) through the Higgs boson propagator in the form [17, 18, 19]

\[
\frac{d\sigma_{gg\rightarrow H\rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^4 \Gamma_H^2},
\]

where \( g_{ggH} \) and \( g_{HZZ} \) are the couplings of the Higgs boson to gluons and Z bosons. Integrating in a small region around \( m_H \) for the on-shell case, and above the mass threshold \( 2m_Z \) for the off-shell case, the cross sections behave like [17, 19]

\[
\sigma_{\text{on-shell}}^{gg\rightarrow H\rightarrow ZZ} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H^4 \Gamma_H^2},
\]

\[
\sigma_{\text{off-shell}}^{gg\rightarrow H\rightarrow ZZ} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}.
\]

From these expressions it is clear that a measurement of the relative off-shell to on-shell production in the \( H \rightarrow ZZ \) channel provides direct information on \( \Gamma_H \). The dominant contribution to the ZZ final state comes from \( gg \rightarrow ZZ \), while the gluon-induced production has contributions from \( gg \rightarrow ZZ \) and \( gg \rightarrow H^* \rightarrow ZZ \); the interference between these two terms, in the off-shell region, is large and has to be taken into account. In the analysis performed by ATLAS and CMS the ZZ \( \rightarrow 4\ell \) and ZZ \( \rightarrow 2\ell 2\nu \) channels were included (\( \ell = e, \mu \)). Due to the lack of calculations beyond leading order (LO) for the \( gg \rightarrow ZZ \) continuum background, a K-factor is included for the LO background cross section.

In the case of ATLAS, the results take into account the unknown background K-factor by defining the quantity

\[
P_H^B = \frac{K(gg \rightarrow ZZ)}{K(gg \rightarrow H^* \rightarrow ZZ)}.
\]

and letting it vary in the range \( 0.5 < R_H^B < 2.0 \). The analysis yields an observed (expected) 95% confidence
Higgs spin and parity: In order to determine the spin and parity of the discovered boson, the $J^P = 0^+$ hypothesis of the SM is compared to several alternative hypotheses with $J^P = 0^+, 1^+, 1^-, 2^+$, by studying the kinematic properties of the final states of the channels: $H \rightarrow \gamma\gamma, \ H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, where $\ell = e, \mu$.

In the case of ATLAS, in a combined study using data from the channels: $H \rightarrow \gamma\gamma, \ H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, the $J^P = 0^+$ hypothesis is strongly favored and the other hypotheses are rejected [20]:

- $J^P = 0^-$ rejected at 97.8% confidence level.
- $J^P = 1^+$ rejected at 99.7% confidence level.
- $J^P = 1^-$ rejected at 99.7% confidence level.
- $J^P = 2^+$ rejected at 99.9% confidence level.

In the case of CMS, the data from the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel provide the results [7]:

- $J^P = 0^-, 1^+, 1^-$ rejected at 99% confidence level.
- $J^P = 2^+, 2^-$ rejected at 95% confidence level.

and the data from the channel $H \rightarrow \gamma\gamma$ provides the result [4]:

- $J^P = 2^+$ rejected at 94% confidence level.

The $J^P = 0^+$ is consistent with the data, in agreement with the SM expectation.

Higgs couplings: One of the distinguishing features of the SM Higgs boson is the dependence of its couplings to the mass of the states to which it couples. The couplings to vector bosons and fermions are:

$$g_v = \frac{2m_t^2}{v}, \quad \lambda_1 = \sqrt{2}m_t \frac{v}{v}, \quad (5)$$

where $v = 246.22$ GeV is the vacuum expectation value of the Higgs field. In order to compare the best SM predictions with the ATLAS and CMS data, and at the same time take into account possible deviations from the SM

In the case of CMS, a soft collinear approximation to describe the background cross section is assumed, which allows to take the unknown K-factor equal to the one of the signal; the uncertainty associated with the K-factor is taken into account as a systematic. The resulting upper limit on the Higgs boson width is $\Gamma_H < 22$ MeV at a 95% confidence level, which is 5.4 times the expected value from the SM [19].
values for the different couplings, the LHC Higgs Cross Section Working Group defined scale factors $\kappa_i$, where $i$ refers to a SM particle. For example, in the case of the channel $gg \to H \to \gamma\gamma$ one would have [21]:

$$\left(\sigma \cdot \text{BR}(gg \to H \to \gamma\gamma) = \sigma_{\text{SM}}(gg \to H) \cdot \text{BR}_{\text{SM}}(H \to \gamma\gamma) \right) \frac{\kappa_H^2 \cdot \kappa_\gamma^2}{\kappa^2}.$$  \quad (6)

The SM predictions are recovered when $\kappa_i = 1$.

Since some of the couplings depend on other couplings, the functions $\kappa_{VBF}^2(k_W, k_Z, m_H)$, $\kappa_{g}^2(k_b, k_t, m_H)$, $\kappa_{ff}^2(k_f, m_H)$ are defined.

Due to the large number of couplings, different benchmark parametrizations are defined in order to explore diverse aspects of the coupling space [21]:

- **Common scale factor:**
  
  the same $\kappa$ for all production and decay channels.

- **Scaling of vector boson and fermion couplings:**
  
  $\kappa_V = k_W = k_Z$
  
  $\kappa_f = k_t = k_b = k_\gamma$

- **Probing custodial symmetry:**
  
  $k_{WZ} = k_W/k_Z$

- **Probing the fermion sector:**
  
  $\lambda_{db} = k_d/k_u$
  
  $\lambda_{uu} = k_4 = k_e$
  
  $k_4 = k_b = k_t = k_\tau = k_\mu$

- **Probing the loop structure and invisible decays:**
  
  $\kappa_g, \kappa_\gamma$ are left as free parameters.

- **Minimal parametrization:**
  
  free parameters: $k_g, \kappa_\gamma, k_V, \kappa_f$.

ATLAS and CMS have used these benchmarks in order to perform several fits to their data. The results of these studies can be found in references [14, 16]. As an example, in Figures 9 and 10 68% C.L. regions for several channels, using the scaling of vector boson and fermion couplings benchmark, are presented. The main general conclusion of the probing of the Higgs boson coupling structure by ATLAS and CMS is a statistical agreement with the SM expectation. In Figure 11 the results of the fits of the couplings to fermions and vector bosons, as a function of the mass of the particle, performed by CMS, are presented. As can be seen from the figure, the couplings behave in a way consistent with that of the SM Higgs boson.

4. **Other studies**

Due to smaller branching ratios or high backgrounds, other channels played a less important role during the

![Figure 9: Results of fits for the 2-parameter benchmark model that probe different coupling strength scale factors for fermions and vector bosons, assuming only SM contributions to the total width: Correlation of the coupling scale factors $\kappa_\gamma$ and $\kappa_f$ overlaying the 68% CL contours derived from the individual channels and their combination [14].](image)

![Figure 10: The 68% CL confidence regions for individual channels (coloured swaths) and for the overall combination (thick curve) for the $\kappa_V$ and $\kappa_f$ parameters. The cross indicates the global best-fit values. The dashed contour bounds the 95% CL confidence region for the combination. The diamond represents the SM expectation, $(\kappa_f, \kappa_V) = (1, 1)$. The plot shows the likelihood scan in the positive quadrant [16].](image)
first run of the LHC, in spite of being potentially important, specially when looking at possible signals of physics BSM in the Higgs sector. ATLAS and CMS performed searches for rare decays like: H → μμ, H → γZ → γνν, H → γγ → γνν; studies of the Yukawa coupling of the top quark to the Higgs boson in channels like t(Hγγ, bb) and t(t(Hγγ); measurements of differential cross sections for the H → γγ and H → ZZ → 4ℓ channels; etc. In this section the results of some of these studies are presented.

The H → μμ channel: The ATLAS experiment has obtained a dimuon invariant mass distribution consistent with the SM background-only hypothesis in the 120 - 150 GeV search range. For a Higgs boson with a mass of 125.5 GeV, the observed (expected) upper limit at the 95% confidence level is 7.0 (7.2) times the SM expectation. This corresponds to an upper limit, at the 95% confidence level, on the branching fraction of 0.0016. Similarly, for e+e−, an upper limit, at the 95% confidence level, of 0.0019 is placed on the branching fraction, which is ≈ 3.7 × 10^5 times the SM value [23].

The H → γZ → γνν channel: The ATLAS experiment has obtained a distribution of the invariant mass of the three final-state particles, m_{γνν}, consistent with the SM hypothesis in the investigated mass range of 120 - 150 GeV. For a Higgs boson with a mass of 125.5 GeV, the observed upper limit, at the 95% confidence level, is 11 times the SM expectation. Upper limits were set on the cross section times branching ratio of a neutral Higgs boson with mass in the range 120 - 150 GeV between 0.13 and 0.5 pb for √s = 8 TeV at 95% confidence level [24].

In the case of CMS no excess above SM predictions has been found in the 120 - 160 GeV mass range and limits on the Higgs boson production cross section times the H → γγ branching fraction at the LHC have been derived. The observed limits, at the 95% confidence level, are between about 4 and 25 times the SM cross section times the branching fraction. The observed and expected limits for m_{γγ} at 125 GeV are within one order of magnitude of the SM prediction [25].

Higgs production in association with top quarks: For the tH channel, ATLAS has not observed a significant excess of events over the background prediction, and upper limits were set on the production cross section. The observed exclusion upper limit at 95% confidence level is 6.7 times the predicted SM cross section value. In addition, limits were set on the strength of the Yukawa coupling between the top quark and the Higgs boson, taking into account the dependence of the tH and tH cross sections as well as the H → γγ branching fraction on the Yukawa coupling. Lower and upper limits at 95% confidence level were set at −1.3 and +8.0 times the Yukawa coupling strength in the SM [26].

CMS performed a search in the tH channel based on the following signatures of the Higgs boson decay: H → hadrons, H → photons, and H → leptons. The results are characterized by an observed tH signal strength relative to the SM cross section, μ = σ_tH/σ_SM, under the assumption that the Higgs boson decays as expected in the SM. The best fit value is μ = 2.8 ± 1.0 for a Higgs boson mass of 125.6 GeV [27].

Fiducial and differential cross sections: The ATLAS experiment has reported the results of measurements of fiducial and differential cross sections for the H → ZZ* → 4ℓ and H → γγ channels in references [28, 29]. In Figure 12 the differential cross section in p_T for the H → γγ channels is presented as an example.
5. Higgs and BSM

The new Higgs sector of the SM offers several possibilities in the search for physics BSM; for instance: new charged and neutral Higgs bosons, evidences of flavor-changing neutral currents, evidences of lepton flavor violations, invisible decays beyond SM expectations, etc. ATLAS and CMS have performed these searches with the LHC-Run 1 data. In this section the result of some of these studies are presented.

Searches for MSSM neutral Higgs: Two Higgs doublet models (2HDM) predict the existence of scalar, pseudoscalar and charged scalar Higgs bosons. The Higgs sector of the Minimal Standard Supersymmetric Model (MSSM) has two Higgs doublets. The expected observables are: two neutral scalars, \( h^0 \) and \( H^0 \); one neutral pseudoscalar \( A^0 \); and two charged scalars, \( H^+ \). Therefore, higher-mass neutral bosons might exist: \( H^+ \), \( A^0 \). It may be also, that the discovered boson corresponds to \( H^0 \), and therefore a lighter Higgs boson should be searched for. Here we will refer to any neutral Higgs boson as \( \Phi \), meaning \( \Phi = h^0, H^0, A^0 \).

ATLAS and CMS have searched for \( \Phi \) in the channel \( \Phi \rightarrow \tau \tau \) in the energy range between 100 - 1000 GeV [30, 31].

Searches for \( \gamma \gamma \) resonances in a wide range of invariant mass have been performed. In the case of ATLAS in the range: 65 - 600 GeV [32]. In the case of CMS in the range: 150 - 850 GeV [33].

Searches for high-mass Higgs boson decaying to WW and ZZ have been performed. In the case of ATLAS excluding a SM-like Higgs boson in the range 260 - 642 GeV (at 95% CL) [34]. In the case of CMS excluding a SM-like Higgs boson in the range 145 - 710 GeV (at 95% CL) [35]. No significant deviations from SM expectations have been observed in any of these channels.

Searches for MSSM Charged Higgs: The ATLAS experiment has performed searches in the channels: \( H^+ \rightarrow \tau \nu \) [36], \( H^+ \rightarrow c\bar{s} \) [37]. In the case of CMS, searches have been performed in the channels: \( H^+ \rightarrow t\bar{b} \) [38], \( H^+ \rightarrow \tau \nu \) [39], \( H^+ \rightarrow c\bar{s} \) [40]. No significant deviations from SM expectations have been observed in these channels.

Higgs invisible decays: The ATLAS experiment has not observed deviations from the SM expectation in this channel. An upper limit of 75% at 95% CL was set on the Branching Ratio to invisible particles, for \( m_H = 125.5 \text{ GeV} \) [41].

In the case of CMS no deviations from the SM expectation have been observed. An upper limit of 58% at 95% CL was set on the Branching Ratio to invisible particles, for \( m_H = 125 \text{ GeV} \) [42].

Searches for FCNC in the Higgs sector: Flavor changing neutral currents are forbidden at tree level in the SM; they are present at higher order, but suppressed by the GIM mechanism [43]. Due to the large coupling of the top quark to the Higgs sector there is a motivation to search for FCNC in top quark decays into Higgs. ATLAS has set an upper limit to the Branching Ratio of the decay \( t \rightarrow qH \) of 0.79% at a 95% CL [44]. CMS has set an upper limit to the Branching Ratio of the decay \( t \rightarrow cH \) of 0.56% at 95% CL [45].

Search for LFV in the Higgs sector: Lepton flavor violations can occur as a result of the presence of LFV Higgs couplings, predicted by several theoretical models BSM. CMS has performed a search for LFV decays in the channels: \( H \rightarrow \mu \tau \) and \( H \rightarrow \tau \nu \). A slight excess of signal events, with a significance of 2.5\sigma was observed. Interpreted as a statistical fluctuation it constrains the Branching Ratio to \( \text{BR}(H \rightarrow \mu \tau) \leq 1.57\% \) at 95% CL (0.75% CL expected). Interpreted as a signal it would give \( \text{BR}(H \rightarrow \mu \tau) = (0.89^{+0.40}_{-0.37}) \% \) [46].
6. Conclusions

As a result of the first run of the LHC the SM has been consolidated experimentally at an impressive level. A Higgs boson has been discovered. The H → γγ, H → ZZ* → 4ℓ and H → ℓνℓν, channels have been measured with a precision at the level of ∼ 5σ. The H → ττ channel has been measured with a precision at the level of ∼ 4σ. The VH → Vb¯b has been measured with a precision at the level of ∼ 2σ. The combinations of spin and parity for the state JP = 0+, 1+, 1−, 2+, 2− have been rejected at the level of ∼ 3σ to 4σ; the JP = 0+ combination is strongly favored by the data. Several Higgs couplings have been measured, and their dependence on the mass of the states to which it couples have allowed to established the nature of the discovered state as a Higgs boson. All other results are in agreement with the SM expectation. No solid evidence of new physics in the Higgs sector has been observed. For the second run of the LHC, one order of magnitude more Higgs events will be recorded, allowing precision measurements, observation of rare decays and improved searches for new physics.

References