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Higgs boson properties and decays, searches for high mass Higgs bosons, and Higgs boson pair production

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Summary. — The study of the scalar sector of the standard model of particle physics is one of the main goals of the LHC physics programme. A precise characterisation of the Higgs boson, searches for extensions of the scalar sector, and the study of Higgs boson pair production are complementary in this exploration. This paper describes the status of Higgs boson physics analyses performed by the ATLAS and CMS Collaborations, focusing on the latest results from pp collisions at $\sqrt{s} = 13$ TeV recorded in 2016, for an integrated luminosity of about $36\,\text{fb}^{-1}$.

1. – Introduction

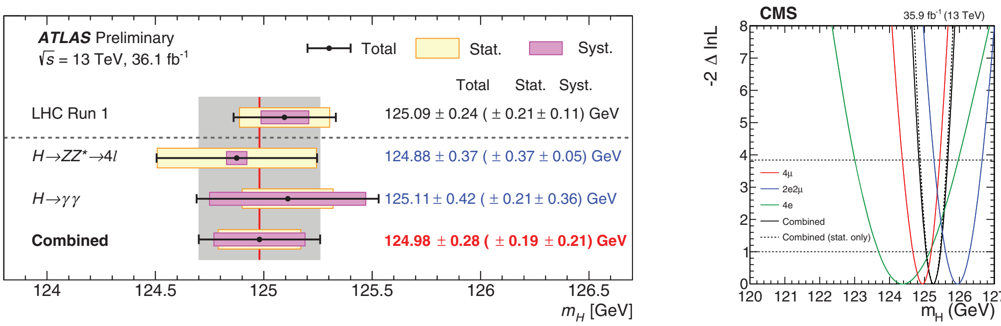
The ATLAS [1] and CMS [2] Collaborations at the CERN LHC are pursuing a broad experimental study of the scalar sector of the standard model of particle physics (SM).

The characterisation of the Higgs boson (H) properties allows to determine fundamental parameters of the SM and test the validity of its predictions. Here the measurement of the H mass, m_{H}, and of its width, Γ_{H}, are discussed, while the study of its couplings is discussed separately in ref. [3].

Extensions of the scalar sector, as predicted in many models of physics beyond the SM (BSM), can be probed in searches for new resonances or Higgs boson decays. For example, extensions of the scalar sector with a doublet field as in two Higgs doublet models (2HDM) and their realisation as the minimal supersymmetric SM (MSSM) predict the existence of four new particles: an heavy scalar, a pseudoscalar, and two charged Higgs bosons. Next-to-minimal extensions of the SM (NMSSM) predict, in addition, a light scalar and a pseudoscalar, with a rich phenomenology of new states and Higgs boson decays.

Finally, the study of Higgs boson pair (HH) production allows the determination of the Higgs boson self coupling λ_{HHH}, and consequently the study of the shape of the scalar potential, thus probing the very fundamental nature of the electroweak symmetry breaking mechanism and the possible existence of BSM physics behind it.

This document presents an overview of the experimental searches in these three complementary research topics. The discussion focuses on the latest results obtained with



(a) ATLAS (b) CMS

Fig. 1. – Higgs boson mass measurement performed by the ATLAS [4] and CMS [5] Collaborations. The $\gamma\gamma$ and $\ell^+\ell^-\ell'^+\ell'^-$ decays channels, and the Run I and Run II combined results, are shown in (a). The three final states of the ZZ* decay channel are compared in (b).

the full dataset collected by the experiments in 2016 at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of approximately 36 fb^{-1}.

2. – Higgs boson mass and width measurement

The mass and width of the Higgs boson are studied at the LHC using the high resolution decay modes $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mathrm{ZZ}^* \to \ell^+\ell^-\ell'^+\ell'^-$ $(\ell, \ell' = \mathrm{e}, \mu)$.

The ATLAS Collaboration has performed a combination of the measurements in the two channels [4], obtaining a measurement of $m_{\mathrm{H}} = 124.98 \pm 0.19\,(\mathrm{stat.}) \pm 0.21\,(\mathrm{syst.})$ GeV. The relative contribution of the $\gamma\gamma$ and $\ell^+\ell^-\ell'^+\ell'^-$ decay channels can be observed in fig. 1(a). The CMS Collaboration measured a value of $m_{\mathrm{H}} = 125.25 \pm 0.20\,(\mathrm{stat.}) \pm 0.08\,(\mathrm{syst.})$ GeV using solely the four lepton decay mode [5]. The relative contribution of the three ZZ* decay channels (eeee, ee$\mu\mu$, $\mu\mu\mu\mu$) can be observed in fig. 1(b). The remarkable precision of approximately 0.18% achieved by the two experiments results from the excellent performance of the detectors with an accurate determination of the lepton and photon energy scale. The precision in the four lepton channel is limited by the statistical error and thus expected to improve with larger datasets that will be collected at the LHC in the Run II and beyond.

The CMS Collaboration studied the width Γ_{H} of the Higgs boson in the four lepton channel [5], setting an upper limit of 1.1 GeV at the 95% confidence level (CL). This direct and model-independent limit on Γ_{H} should be compared to the CMS Run I result [6] of $\Gamma_{\mathrm{H}} < 13$ MeV (3.2 times the SM prediction), which however depends on assumptions on the correlations between the on and off-shell H production.

3. – Searches for BSM scalars and Higgs boson decays

BSM models with extended scalar sectors result in a rich phenomenology that includes heavy and light scalars and charged Higgs bosons. Given their coupling structure that is similar to the one of the SM Higgs boson, experimental searches can exploit a variety of final states with decays to heavy fermions, vector bosons, and photon pairs. Decay chains involving lighter scalars and decays to undetectable particles are also considered.

3˙1. *Heavy neutral scalars decaying to fermions.* – Searches for heavy scalars decaying to $\tau\tau$ have been performed by the ATLAS [7] and the CMS [8] Collaborations. The ATLAS search considered the three $\mathrm{e}\tau_\mathrm{h}$, $\mu\tau_\mathrm{h}$, and $\tau_\mathrm{h}\tau_\mathrm{h}$ decay modes, where τ_h indicates the decay of a τ lepton to hadrons and a neutrino, while the CMS search also analysed the $\mathrm{e}\mu$ decay mode.

Both collaborations explored the production modes via gluon fusion and in association with a pair of b quarks. The event selection uses the number of b tagged jets in the final state to categorise the events in regions where the contributions from the two production modes are enhanced.

The main backgrounds are the Drell-Yan production of a τ lepton pair, that is modelled from a simulation, and the misidentification of quark and gluon jets as τ_h. An accurate modelling of the latter is crucial for the sensitivity of the searches and sophisticated data driven methods have been developed as detailed in refs. [7, 8].

The total transverse mass of the $\tau\tau$ system, $m_\mathrm{T}^\mathrm{tot}$, is used to search for the presence of a signal, and is defined as

$$(1) \qquad \left(m_\mathrm{T}^\mathrm{tot}\right)^2 = \left(p_\mathrm{T}^{\tau_1} + p_\mathrm{T}^{\tau_2} + p_\mathrm{T}^\mathrm{miss}\right)^2 - \left(\vec{p_\mathrm{T}}^{\tau_1} + \vec{p_\mathrm{T}}^{\tau_2} + \vec{p_\mathrm{T}}^\mathrm{miss}\right)^2,$$

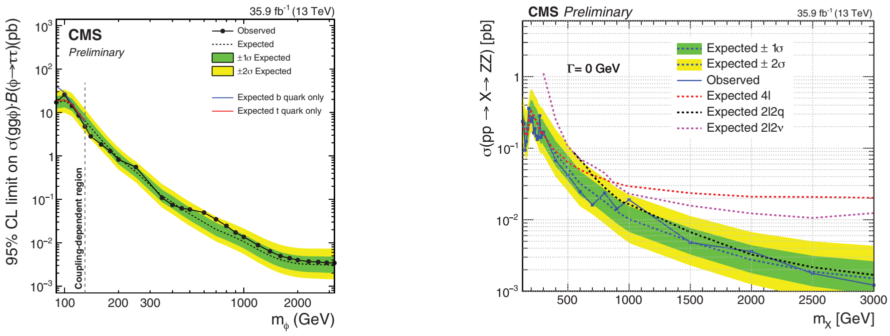
where $p_\mathrm{T}^\mathrm{miss}$ is the "missing tranverse momentum", *i.e.* the negative vector sum of the transverse momenta of the particles reconstructed in the final state.

As no evidence for a signal is observed, 95% CL upper limits on the production cross section of an heavy scalar are derived as illustrated in fig. 2(a) for the gluon fusion production mode. The sensitivity is dominated by the $\ell\tau_\mathrm{h}$ decay channels for $m_\mathrm{H} \lesssim$ 600 GeV (because of the lower trigger thresholds) and by the $\tau_\mathrm{h}\tau_\mathrm{h}$ decay channel at higher m_H values (because of the higher branching fractions). These results constrain the parameter space of MSSM scenarios.

The CMS Collaboration also searched for heavy scalars decaying to bb [9], investigating only the b associated production mode to suppress the large QCD multijet background. The four b quark final state calls for an efficient b jet identification (b tagging), both at trigger and in the offline reconstruction. The search uses events collected with b tagging triggers, requiring three b-tagged jets offline using an operating point with 65% efficiency and 1% misidentification rate of light flavour and gluon jets. The invariant mass of the leading jet pair is used to search for the presence of a peak over a smooth background, that is fit in three separate regions. The results constrain the parameter space of MSSM models.

3˙2. *Heavy neutral scalars decaying to bosons.* – Searches for heavy scalars have performed in the WW decay channel by the ATLAS Collaboration [10] and in the ZZ decay channel by both the ATLAS [11] and the CMS [12] Collaborations. In both cases, different hypotheses for the production mechanism (gluon and vector boson fusion), width and mass of the scalar (between 100 GeV and 4 TeV) are investigated. More details on searches for high mass resonances decaying to bosons can be found in ref. [13].

In general, with leptons in the final state are explored because of their clean signature. The WW search uses $\mathrm{e}\nu_\mathrm{e}\,\mu\nu_\mu$ decays, and is mostly affected by top quark backgrounds that are constrained from control regions in the data. The ZZ search uses the $\ell\ell\ell'\ell'$ and $\ell\ell\nu\nu$ decay channels (ATLAS), where diboson production is the main background, as well as the $\ell\ell qq$ channel (CMS), where the Z production in association with jets is the dominant background. The invariant mass of the final state objects is used to search for



(a) Heavy scalar decays to $\tau\tau$ (b) Heavy scalar decays to ZZ

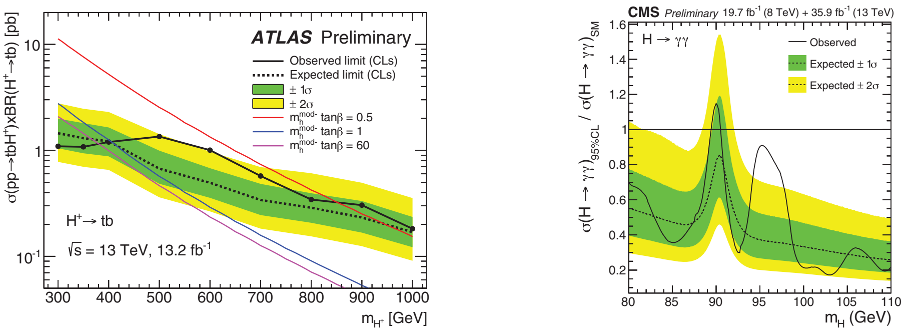
Fig. 2. – 95% CL upper limits on the production cross section of a heavy scalar decaying to (a) $\tau\tau$ [8] and (b) ZZ [12].

the presence of a signal when the final state can be entirely reconstructed, while in final states that include neutrinos the transverse mass is used. It is interesting to compare the sensitivity achieved by the different final states, as shown in fig. 2(b) for the ZZ CMS search. The four lepton final state dominates at low mass values, because of the small background contribution, while the $\ell\ell qq$ and, to a lesser extent, $\ell\ell\nu\nu$, achieve better sensitivities at higher mass values because of the higher branching fractions.

3·3. *Heavy charged scalars.* – Charged heavy scalars $H^{\pm}$ predominantly couple to heavy fermions, with the largest coupling being associated to a $tbH^{\pm}$ vertex. Consequently, they can be produced from the decay of a top quark ($t \rightarrow bH^{+}$) if $m_{H^{\pm}} < m_t$, or in association with a t quark if kinematically allowed.

The ATLAS Collaboration focused on the latter production mode performing a search for $H^{\pm}$ production in association with a top and a bottom quark, using the decay channel $H^{\pm} \rightarrow tb$ [14]. The final state where one top quark decays to hadrons and the other decays to leptons is explored, resulting in a complex event topology with four b jets, two light flavour jets, one electron or muon and missing transverse momentum. A multivariate approach consisting of a boosted decision tree (BDT) is adopted to fully exploit the kinematic properties of the final state and discriminate a signal contribution from the dominant top quark induced backgrounds. Signal enriched regions are defined depending on the number of additional jets and b-tagged jets and are fitted simultaneously to orthogonal background enriched regions, defined by modifying the selection criteria, to constrain the systematic uncertainties on the background contributions. Results are derived as 95% CL upper limits on the production cross section times branching fraction for $m_{H^{\pm}}$ ranging between 300 and 1000 GeV, as illustrated in fig. 3(a), and constrain the parameter space of MSSM models in the low $m_{H^{\pm}}$, low $\tan\beta$ regions.

3·4. *Light neutral scalars.* – Non-minimal extensions of the SM predict the existence of scalars with a mass smaller than the one of the Higgs boson. The CMS Collaboration has performed a search for such scalars in their decay mode to photon pairs [15]. The data analysis strategy includes a multivariate method for the identification of the $\gamma\gamma$ candidate and its classification in four categories to maximise the sensitivity. As the scalar mass values investigated range between 70 and 110 GeV, dedicated triggers for low p_T photons have been developed to record such events. The photon pair invariant



(a) Charged Higgs boson (b) Light scalars decays to $\gamma\gamma$

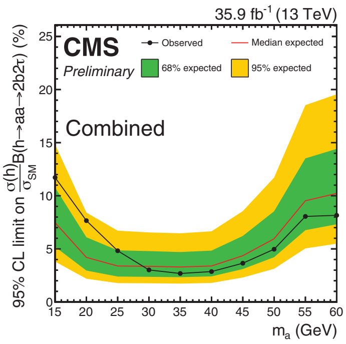
Fig. 3. – 95% CL upper limits on the production cross section of (a) a charged Higgs boson decaying to tb [14] and (b) of a light scalar decaying to $\gamma\gamma$ [15].

mass $m_{\gamma\gamma}$ is used to search for the contribution of the signal as a localised excess over the smooth background distribution. A modest excess of events over the background prediction is observed at a mass of about 95 GeV. Once combined with the results from the same search performed with the Run I dataset, this translates in a local and global significance of 2.8σ and 1.3σ, respectively. The 95% CL upper limits from the Run I and Run II combinations are reported in fig. 3(b).

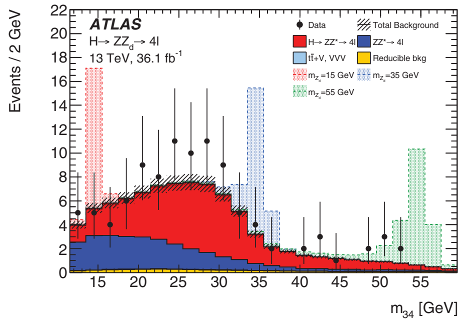
3˙5. *Higgs boson decays to light BSM resonances.* – Resonances predicted in extensions of the SM can also be produced in the decays of the Higgs boson if kinematically allowed. The CMS Collaboration performed a search for the decay of the Higgs boson to pairs of light pseudoscalars a in the mass range $15 < m_{\rm a} < 60\,$GeV using the $\rm bb\tau\tau$ decay channel [16], that has been investigated for the first time at the LHC. The $\rm e\tau_h$, $\mu\tau_{\rm h}$, and $\rm e\mu$ final states of the $\tau\tau$ system are considered because of the leptonic signatures used to trigger such events. The two b jets are typically soft and only one is required for the event selection since the other is usually outside the reconstruction acceptance. Events are categorised depending on the mass of the $\rm b\tau\tau$ system and the distribution of the $\tau\tau$ invariant mass is used to search for the presence of a signal. The main backgrounds are $\rm t\bar{t}$ and $\rm Z \to \tau\tau$ production, that are estimated from a simulation, and the misidentification of hadron jets as $\tau_{\rm h}$, that is estimated from the data. Upper limits on the decay branching fraction $\mathcal{B}(\rm H \to aa \to bb\tau\tau)$ are derived as a function of $m_{\rm a}$ and range between 3 and 12%, as shown in fig. 4(a).

The ATLAS Collaboration investigated the decays of the Higgs boson to a pair or vector or pseudoscalar bosons x, or to a single x in association to a Z boson, using the four lepton final state ($\rm H \to Zx/xx \to \ell^+\ell^-\ell'^+\ell'^-$) [17]. The clean leptonic signature results in a small background contamination and allows for probing low $m_{\rm x}$ values. Remarkably, the dominant background for the Zx search is the production a H boson in its four lepton decay channel, with smaller contributions from triboson events, as illustrated in fig. 4(b). Limits on the Zx production cross section are set for $m_{\rm x}$ between 15 and 55 GeV, while limits on the xx production are set in the range $1 < m_{\rm x} < 60$ GeV, where the region between 1 and 15 GeV is probed in the four muon final state only.

3˙6. *Decays to invisible particles.* – Decays of the Higgs boson to undetectable particles can be experimentally observed as an enhancement in the missing transverse momentum



(a) H$\to$ aa $\to$bb$\tau\tau$



(b) H $\to$ Zx $\to$ $\ell\ell'\ell'$

Fig. 4. – (a) 95% CL upper limits on the decay branching fraction of a Higgs boson to light pseudoscalars a in the bb$\tau\tau$ decay channel [16]. (b) Distribution of the dilepton invariant mass for events selected in the H $\to$ Zx $\to$ $\ell\ell'\ell'$ search [17].

distribution of events. They are searched for at the LHC in the production modes via gluon fusion, vector boson fusion, and in association to a vector boson. The combination of these searches performed in Run I and with the 2015 datasets by the CMS Collaboration [18] gives the current best upper limit at the 95% CL on $\mathcal{B}$(H $\to$ invisible) of 24%.

A recent search for invisible Higgs boson decays performed by the ATLAS Collaboration on the 2016 dataset focuses on the ZH associated production, with Z $\to$ $\ell\ell$ decays [19], where the main background are diboson and Z production in association with jets. The search observed a 95% CL upper limit on $\mathcal{B}$(H $\to$ invisible) of 67%, with an expected limit of 39%, corresponding to an improvement of about 40% on the expected sensitivity compared to the results in the same channel obtained in Run I.

4. – Higgs boson pair production

Higgs boson pair production at the LHC mainly proceeds through gluon fusion, with a cross section $\sigma_{\mathrm{HH}}^{\mathrm{SM}} = 33.49^{+7.3\%}_{-8.4\%}$ fb, that is computed at the next-to-next-to-leading order (NNLO) of the perturbative QCD expansion with next-to-next-to-leading logarithm corrections and finite top quark mass effects [20]. Because of such tiny cross section, arising from the interference of the two loop induced processes involved at the tree level, LHC experiments are not yet sensitive to SM HH production with the current data.

However, BSM effects can strongly modify the HH production cross section and kinematics and be observed at the LHC, making it one ideal place to look for the presence of BSM physics. The direct production of new states X decaying to HH, or resonant production, is predicted in many models such as scalars sectors extended with a doublet or a singlet, or extra dimension theories. Although different in motivation, they result in a similar experimental signature, but require experimentally the study of a broad m_{X} range to be sensitive to a large variety of models. The HH production can also be modified by BSM physics that has a scale beyond the direct reach of the LHC. This results effectively in anomalous Higgs boson couplings that affect the nonresonant production, and may manifest with large modifications of both the cross section and the HH kinematic properties.

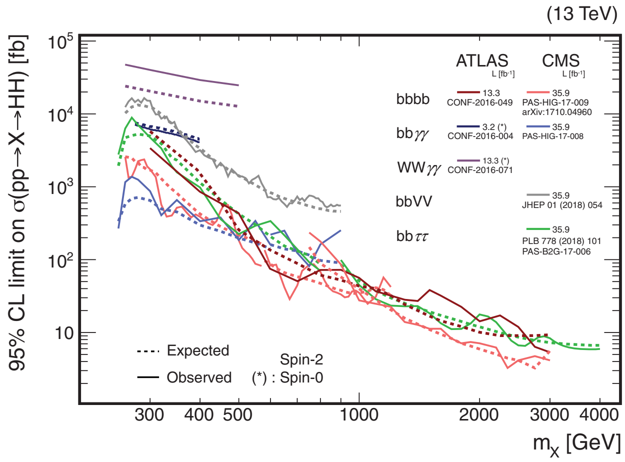


Fig. 5. – Comparison of the 95% CL upper limits on HH production in the decay channels explored at $\sqrt{s} = 13$ TeV.

The exploration of many HH decay channels is crucial in this context to ensure a broad coverage of the possible BSM effects thanks to the complementarity of the different final states. Using the full 2016 dataset, the CMS Collaborations has explored the bb$\gamma\gamma$ [21], bbVV [22], bb$\tau\tau$ [23], and bbbb [24, 25] decay channels. Using a smaller fraction of the Run II dataset, the ATLAS Collaboration has investigated the bb$\gamma\gamma$ [26], WW$\gamma\gamma$ [27], and bbbb [28] channels. At the time of writing this documents, updated results in the bbbb channels have also been released [29].

The sensitivities of HH searches are compared in table I for the SM nonresonant production and in fig. 5 for the resonant production. In the latter, the bb$\gamma\gamma$ final state dominates the sensitivity at low m_{X} because of the small background contamination, while the bbbb channel is the most sensitive at high m_{X} values thanks to the large branching fraction. In the intermediate mass region, the bb$\gamma\gamma$, bb$\tau\tau$, and bbbb decay channels have similar sensitivities, which is also the m_{HH} region where most of the

Table I. – *Sensitivities to nonresonant SM HH production in the searches performed by the ATLAS and CMS Collaborations using the data collected at* $\sqrt{s} = 13$ *TeV.*

		bbbb	bbVV	bb$\tau\tau$	bb$\gamma\gamma$	WW$^*\gamma\gamma$
ATLAS	Int. luminosity [fb^{-1}]	13.3	–	–	3.2	13.3
	Obs. (exp.) lim. on $\sigma_{\mathrm{HH}}^{\mathrm{SM}}$	29 (38)	–	–	117 (161)	747 (386)
	Anomalous couplings	–	–	–	–	–
	Reference	[28]	–	–	[26]	[27]
CMS	Int. luminosity [fb^{-1}]	2.3	35.9	35.9	35.9	–
	Obs. (exp.) lim. on $\sigma_{\mathrm{HH}}^{\mathrm{SM}}$	342 (308)	79 (89)	31 (25)	18 (17)	–
	Anomalous couplings	–	✓	✓	✓	–
	Reference	[30]	[22]	[23]	[21]	–

nonresonant SM events are distributed. This illustrates the complementarity of the decay channels to explore HH production, and highlights the importance of their combined analysis.

5. – Conclusions

A precise study of the Higgs boson properties, the search for manifestations of BSM physics as additional scalars or new decays of the Higgs boson, and the investigation of HH production represent complementary aspects of the extensive programme of the exploration of the scalar sector at the LHC. These challenging experimental measurements cover a broad range of experimental signatures. Thanks to the excellent performance of the ATLAS and CMS detectors in collecting an integrated luminosity of about $36\,\text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV in 2016, the two experimental collaborations have obtained many interesting results that have been briefly discussed in this document. The exciting exploration of the scalar sector of the standard model of particle physics is continuing as more data will be collected and analysed by the two collaborations in the Run II and beyond.

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