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Review of Higgs results at LHC (ATLAS and CMS results)

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The status of Higgs sector studies at the Large Hadron Collider from the ATLAS and CMS experiments is reviewed. The Run 1 legacy on Higgs-boson discovery is presented: the combined data samples of the two experiments were used for the measurements of the Higgs-boson mass and couplings; the CP and spin analysis done separately by the CMS and ATLAS experiments are also described and the searches for $H \to b\bar{b}$ decay channel are illustrated.
Finally, a first look to Run 2 data with few searches for additional Higgs-boson states beyond that of the Standard Model are presented. Emphasis is given to searches that include b-quarks in the final state, and profit from their presence.
Presently no statistically significant deviations from the Standard Model predictions are observed.

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1. Introduction

The study of the mechanism of the electroweak symmetry breaking is one of the main goals of the ATLAS [1] and CMS [2] detectors at the CERN Large Hadron Collider (LHC). The Brout-Englert-Higgs electroweak symmetry breaking mechanism [3, 4] is, within the Standard Model (SM), a model described by only two parameters defining the shape of the scalar field potential. The vacuum expectation value of the Higgs field is fixed by the measured masses of the electroweak gauge bosons, leaving the model with only one free parameter, which determines the mass of the predicted unique physical state, the neutral Higgs-boson scalar. After the discovery of a 125 GeV Higgs-boson by the ATLAS [5] and CMS [6] Collaborations, a big effort has focused on studying its properties and searching for potential additional particles in the electroweak symmetry breaking sector. Couplings to all Standard Model particles, proportional to their mass for fermions and to their mass squared for bosons, are exhaustively determined by the model. So far all measured properties of the discovered scalar state are consistent with the Higgs-boson particle predicted by the Standard Model. However, these results alone do not rule out a variety of Beyond Standard Model (BSM) scenarios. The current quest includes questions whether the observed Higgs-boson state is the only one or maybe there exists an extended scalar sector, whether the Higgs-boson is responsible for the entire mass of the Standard Model particles and, finally, whether it is a fundamental particle.

These proceedings describe the results, based on Run 1[1] data, of the combined measurement of the Higgs-boson mass, as well as the measurements of the Higgs-boson production and decay rates and the constraints on its couplings from combined ATLAS and CMS analyses. The results of the Higgs-boson spin and CP measurements separately published by the two experiments are reported. Moreover the Run 1 searches for $H \to b\bar{b}$ decay channel are illustrated. Finally a first look to Run 2[2] data with few searches for additional Higgs-boson states beyond that of the Standard Model are presented. Emphasis is given to searches that include b-quarks in the final state, and profit from their presence.

2. Run 1 legacy on Higgs discovery

2.1 ATLAS and CMS combination

The Higgs-boson mass measurements from the ATLAS and CMS experiments, in fully reconstructed $H \to ZZ \to 4l$ and $H \to \gamma\gamma$ channels, are combined leading to the LHC average value $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{scale}) \pm 0.02(\text{other}) \pm 0.01(\text{theory})$ GeV [7]. The combined measurement of the Higgs-boson mass improves the results of the individual experiments and gives the highest measurement precision. The total error is dominated by the statistical uncertainty. The systematic uncertainty is divided into different terms where the dominant one is related to the leptonic energy/momentum scales and resolutions. Other systematic sources have only a very minor effect

[1] Run 1 corresponds to LHC proton-proton data from years 2011 and 2012 at the centre of mass energies of 7 TeV and 8 TeV. The collision data sets correspond to approximately 5 fb^{-1} at centre of mass energy of $\sqrt{s} = 7$ TeV and 20 fb^{-1} at $\sqrt{s} = 8$ TeV.

[2] Run 2 corresponds to LHC proton-proton data from 2015, hence after the machine technical stop of 2013-2014, at the centre of mass energy of 13 TeV. The collision data sets correspond to approximately 3 fb^{-1} so far.

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on the mass measurement. Compatibility tests are performed to check the consistency between measurements in different decay channels and between the two experiments. The four measurements (two different decay channels in two experiments) show an agreement within 2σ.

The combined results of the ATLAS and CMS determination of the Higgs boson couplings to Standard Model particles [8] include Higgs couplings to W and Z bosons, t, b and τ fermions, as well as an upper limit for the muon coupling. The latter allows to establish that lepton couplings to the Higgs-boson are not universal, but rather consistent with being proportional to the mass. The combination is based on the measured $\sigma \times BR(H \to XX)$ for all investigated Higgs boson decay modes, i.e. $H \to ZZ$, $H \to \gamma\gamma$, $H \to WW$, $H \to b\bar{b}$, $H \to \tau\tau$ and $H \to \mu\mu$. Additional event categorisation (number of jets, b-tagged jets, leptons, etc.) allows to distinguish between different Higgs-boson production modes, i.e. gluon-gluon fusion (ggF), vector boson fusion (VBF), production associated with electroweak vector bosons (VH), and production in association with a top-quark pair ($t\bar{t}H$). Measurements of the couplings constitute a stringent probe of various BSM Higgs scenarios. So far, all measured values remain consistent with their Standard Model predictions and follow the expected mass scaling.

The same decay channels were used to determine the overall strength of the Higgs-boson signal, μ, defined as the ratio of the actually observed signal event rate to the one predicted by the Standard Model. The combined result yields $\mu = 1.09 \pm 0.11$ where the uncertainty includes statistical and systematic experimental uncertainties, as well as systematic uncertainties on theoretical predictions for both the signal and the underlying background. The observed signal strength remains compatible with Standard Model expectation within its uncertainty. Moreover the combination of the two experiments leads to observed significances of the VBF production process and of the $H \to \tau\tau$ decay at the level of 5.4σ and 5.5σ, respectively, as well as to the combined significance for the VH production process above 3σ. The combined significance for the $t\bar{t}H$ process is 4.4σ, whereas only 2.0σ is expected, owing to the measured excess of 2.3σ with respect to the Standard Model prediction.

Both experiments also performed analyses probing multiple J^{CP} scenarios of the observed Higgs-boson using the kinematic distributions of the decay products [9, 10]. The $ZZ \to 4l$ decay channel gives access to the full kinematics of the final state providing the most stringent constraints. The $WW \to l\nu l\nu$ decays retain partial sensitivity via variables such as the invariant mass, transverse momentum or the transverse plane opening angle of the lepton pair and the transverse mass of the leptons plus the missing momentum. The $\gamma\gamma$ decays allow to analyse the di-photon angular distribution. The results exclude all considered non-SM spin hypotheses at more than 99% confidence level (CL).

2.2 $\mathbf{H \to b\bar{b}}$

The Higgs-boson coupling is predicted to be proportional to the mass of the quarks, hence the $H \to b\bar{b}$ decay has the highest BR ($\sim 58\%$) as the $H \to t\bar{t}$ decay is not kinematically allowed for $m_H = 125$ GeV. This means that the only way to probe the Higgs-boson top-quark Yukawa coupling is through its associated production $t\bar{t}H$, which produces very complex final states with a lot of jets and some of them being b-jets. On the other hand, an inclusive search for $H \to b\bar{b}$ is not feasible at hadron colliders because of the overwhelming background from QCD multi-jet production. So the only feasible way for this measurement is through production modes that have lower cross-section with respect to *ggF* but containing other particles in the final state that are more easily identifiable:

- *VBF*: two forward/backward jets with large $|\Delta\eta|$ between them and large invariant mass;
- *VH*: leptonic decay of the vector boson;
- $t\bar{t}H$: leptonic or hadronic decay of the top-quarks.

2.2.1 VBF

At the LHC the vector boson fusion (*VBF*) process $pp \to qqH$ has the second largest production cross section of a 125 GeV Standard Model Higgs-boson following gluon-gluon fusion (*ggF*). The prominent feature of the *VBF* process $qqH \to qqb\bar{b}$ is the presence of four energetic jets in the final state. Two jets are expected to originate from a light-quark pair (u or d), which are typically two valence quarks from each of the colliding protons scattered away from the beam line in the *VBF* process. These "*VBF*-tagging" jets are expected to be roughly in the forward and backward directions relative to the beam direction. Two additional jets are expected from the Higgs-boson decay to a $b\bar{b}$ pair in more central regions of the detector. The CMS Collaboration published [13] a search performed with Run 1 data on selected four-jet events that are characterised by the response of a multivariate discriminant trained to separate signal events from background without making use of kinematic information on the two b-jet candidates. Subsequently, the invariant mass distribution of two b-jets is analysed in each category in the search for an excess above the smooth contribution from the Standard Model background. The data used for this analysis were collected using two different trigger strategies that result in two different data samples for analysis. First, a set of dedicated trigger event selections was specifically designed and deployed for the *VBF* specific signal search. Then, a more general trigger was employed that targeted *VBF* signatures in general. The first (nominal) set of triggers collected the larger fraction of the signal events, while the second trigger supplemented the search with events that failed the stringent nominal trigger requirements. The dominant background to this search is from QCD production of multi-jet events. Other backgrounds arise from hadronic decays of Z or W bosons produced in association with additional jets, hadronic decays of top-quark pairs, and hadronic decays of singly produced top-quarks. The observed (expected) significance for a $H \to b\bar{b}$ signal at a mass of 125 GeV is $2.2(0.8)\sigma$, corresponding to a fitted signal strength of $\mu = \sigma/\sigma_{SM} = 2.8^{+1.6}_{-1.4}$.

2.2.2 VH

As mentioned before, despite a cross section more than an order of magnitude lower than the dominant *ggF* process, associated production of a Higgs-boson with a vector boson, W or Z, offers a viable alternative thanks to leptonic decays of the vector boson. Both experiments [11, 12] efficiently used $W \to l\nu$, $Z \to ll (l = e, \mu)$ and $Z \to \nu\nu$ for triggering and background reduction purposes. In addition, CMS included the $W \to \tau\nu$ decay mode, with the hadronic decay of the τ. Both experiments developed two approaches:

- Categorisation: events are categorised on lepton multiplicity and on the transverse momentum of the vector boson $p_T(V)$ in order to increase the sensitivity. ATLAS has a further categorisation according to jets and b-tagged jets multiplicity;

- Multivariate analysis (MVA): various kinematic variables are incorporated in addition to the di-jet mass, as well as b-tagging information, in order to provide the final discriminating variable. Looser selection criteria are applied to maximise the information available to the final discriminant.

The main backgrounds to the VH production comes from V+jets, $t\bar{t}$, single top, di-boson production and QCD multi-jets. The ATLAS result shows an observed (expected) deviation from the background-only hypothesis corresponding to a significance of $1.4(2.6)\sigma$ and the ratio of the measured signal yield to the Standard Model expectation for a Higgs-boson mass of 125.36 GeV is found to be $\mu = 0.52 \pm 0.32$ (stat.) ± 0.24 (syst.). On the other hand, CMS measured a signal strength relative to that of the Standard Model Higgs-boson of $\mu = 1.0 \pm 0.5$. This corresponds to an observed excess of events above the expected background with a local significance of 2.1σ for a Higgs-boson mass of 125 GeV, consistent with the expectation from the production of the Standard Model Higgs-boson.

2.2.3 $\mathbf{t\bar{t}H}$

The Standard Model Higgs-boson production in association with a top-quark pair ($t\bar{t}H$) with subsequent Higgs decay into b-quarks addresses heavy-quark couplings in both production and decay. Due to the large measured mass of the top-quark, the Yukawa coupling of the top-quark (y_t) is much larger than that of other quarks. The observation of the $t\bar{t}H$ production mode would allow for a direct measurement of this coupling, to which other Higgs boson production modes are only sensitive through loop effects. Since y_t is expected to be close to unity, it is also argued to be the quantity that might give insight into the scale of new physics. ATLAS and CMS analyses [14, 15] focused on final states containing one or two electrons or muons from the decay of the $t\bar{t}$ system, referred to as the single-lepton and di-lepton channels, respectively. Selected events are further classified into exclusive categories (regions), according to the jets and b-jets multiplicities. ATLAS employed a neural network (NN) in the regions with a significant expected contribution from the $t\bar{t}H$ signal to separate it from the background. Simpler kinematic variables are used in regions that are depleted of the $t\bar{t}H$ signal, and primarily serve to constrain uncertainties on the background prediction. A combined fit to signal-rich and signal-depleted regions is performed to search for the signal while simultaneously obtaining a background prediction. On the other hand CMS used an analytical matrix element method (MEM) for improving the separation of signal from background. Within the MEM technique, to each reconstructed event is assigned a probability density value based on the theoretical differential cross section. The ratio between the probability density values for signal and background provides a discriminating variable. The main source of background comes from top-quark pairs produced in association with additional jets. The dominant source is $t\bar{t}+b\bar{b}$ production, resulting in the same final-state signature as the signal. A second contribution arises from $t\bar{t}$ production in association with light-quark (u, d, s) or gluon jets, and from $t\bar{t}$ production in association with c-quarks. No significant excess of events above the background expectation is found. ATLAS measures a signal strength of $\mu = 1.5 \pm 1.1$, and CMS a value of $1.2^{+1.6}_{-1.5}$, assuming a Higgs-boson mass of 125 GeV. The CMS collaboration recently updated this result [16], adding 2015 $\sqrt{s} = 13$ TeV Run 2 data, using almost the same analysis strategy: the MEM analysis has been combined with a boosted decision tree (BDT) approach. The idea is to use the MEM when it's more powerful, and a BDT otherwise. The increased center of mass energy of $\sqrt{s} = 13$ TeV results in a $t\bar{t}H$ production cross section 3.9 times larger than at $\sqrt{s} = 8$ TeV, while the cross-section of the dominant background ($t\bar{t}$+jets) is only increased by a factor of 3.3, resulting in a more favourable signal-to-background ratio. The best-fit value of the signal strength is $\mu = -2.0 \pm 1.8$, which is 1.7 standard deviations from the Standard Model expectation of $\mu = 1$.

The ATLAS Collaboration recently published [17] a search for the all-hadronic $t\bar{t}H(H \to b\bar{b})$ decay mode using Run 1 data. Among all $t\bar{t}H$ final states, the one where both W bosons from $t \to Wb$ decay hadronically and the Higgs-boson decays into a $b\bar{b}$ pair has the largest branching ratio, but also the least signal purity. The signal signature is eight jets, four of which are b-quark jets. The dominant background is the non-resonant production of multi-jet events. To maximise the signal sensitivity, the events are categorised according to their number of jets and b-jets. A BDT algorithm, based on event shape and kinematic variables, is used to discriminate the signal from the background. The best-fit value for the signal strength is $\mu = 1.6 \pm 2.6$ times the Standard Model expectation for $m_H = 125$ GeV.

3. First look at 13 TeV data - BSM Higgs boson

The start of the LHC Run 2 in 2015, at an increased center-of-mass energy of $\sqrt{s} = 13$ TeV, opens the way for an era of new precision measurements of the Higgs-boson, which will involve the observation and study of its rare production modes such as vector boson fusion (*VBF*), associated production with a vector boson (*VH*) and with a top-quark pair ($t\bar{t}H$). However, the statistics of Run 2 data is limited compared with Run 1 so far, so the experiments are not fully sensitive yet to the re-discovery of the 125 GeV Higgs-boson ($\sim 3\sigma$ reached so far).

As already mentioned in the introduction the 125 GeV Higgs-boson looks very much like the Standard Model Higgs-boson. However there is no theoretical reason to have only one Higgs-boson. There are many theoretical models that predict additional, usually heavier, states in the scalar sector, allowing SM-like light Higgs boson phenomenology with smaller or larger modifications to the couplings. The current experimental road-map naturally splits in two complementary approaches.

- Precision measurements of the properties of the discovered Higgs-boson state: production rates in different channels such as ggF, *VBF*, *VH*, $t\bar{t}H$ associated production and searches for yet unobserved Higgs-boson pair production (HH) or associated production (tH, $b\bar{b}H$); widths of the observed decay modes ($\gamma\gamma$, ZZ^*, WW^*, $b\bar{b}$, $\tau\tau$) and searches for rare ones ($\mu\mu$, $Z\gamma$, etc.); combination of these measurements to infer couplings of the Higgs to Standard Model particles; spin and parity quantum numbers of the Higgs boson; searches for rare Higgs decays, such as lepton-flavour-violating (LFV) decays, invisible decays or decays to light still unobserved particles.

- Direct searches for new states expected within the extended Higgs sector: heavy neutral CP-even and CP-odd states in their decays to $\gamma\gamma$, ZZ^*, WW^*, $b\bar{b}$, $\tau\tau$, HH, HZ and $t\bar{t}$; heavy charged Higgs decaying to $\tau\nu$, tb, WZ, cs, etc.

Both approaches try to answer common questions: are all observations consistent with the Standard Model predictions? How much of the BSM scenario phases-space can current data exclude? Clearly, the answer is highly model dependent.

3.0.1 H $\rightarrow$ hh

In this section two examples of searches for heavy neutral Higgs-bosons decaying to di-Higgs bosons using proton-proton collisions at $\sqrt{s} = 13$ TeV are given. While the production cross section for Higgs-boson pairs is extremely small in the Standard Model, it is enhanced in many BSM models. Searches for a heavy neutral scalar Higgs (H) decaying into a pair of Standard Model Higgs (h) thus offer great potential in the search for new phenomena. The first example is the ATLAS search that exploit the dominant $h \rightarrow b\bar{b}$ decay mode, with the four b-jets either reconstructed as distinct jets, or as a pair of large-radius jets [18]. The resolved analysis is used up to resonance masses of 1.1 TeV (where its expected sensitivity is higher), while the boosted analysis is used above 1.1 TeV. The analysis sensitivity is increased by including in the boosted analysis a channel with only three b-tagged jets, in addition to the channel with four b-tagged jets. The dominant multi-jet background source, as well as the contribution from $t\bar{t}$ events, are modelled using data. No significant excess of events is observed above the estimated background, and limits are set on the cross section times branching ratio to the $b\bar{b}b\bar{b}$ final state.

The second example is the CMS search for a heavy resonance decaying to two Higgs-bosons in the $H \rightarrow hh \rightarrow b\bar{b}\tau\tau$ decay channel [19]. In this search, three $\tau\tau$ final states have been considered: $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$, where τ_h corresponds to the hadronic decay of the τ lepton. A kinematic fit is used to reconstruct the resonance mass. The main backgrounds are $t\bar{t}$, multi-jet and Z+jets, which are estimated using simulation with corrections derived from data. Good agreement between data and the background only prediction is observed in these searches.

3.1 Conclusions

Extensive studies of the Higgs-boson properties have been performed using Run 1 proton-proton data. The combined measurement of the Higgs-boson mass using the ATLAS and CMS detectors leads to the most precise value $m_H = 125.09 \pm 0.24$ GeV. The combination of the ATLAS and CMS results is available also for the Higgs-boson couplings and signal strength measurements. The global signal strength is found to be $\mu = 1.09 \pm 0.11$ which is in a good agreement with the Standard Model expectations. The measurements of the spin and parity of the Higgs-boson performed by the ATLAS and CMS experiments show a good agreement with a SM-like Higgs-boson with $J^{CP} = 0^{++}$. So, within the current experimental uncertainties, the 125 GeV Higgs looks very SM-like. Moreover no evidence for BSM phenomena in the scalar sector is visible.

In the next years, the larger σ_H at LHC proton-proton energy of 13 TeV together with the larger integrated luminosity will make possible to fully explore the *VBF* and the W or Z associated production. Moreover the $t\bar{t}H$ associated production and the production of Higgs-boson pairs will be further enhanced. These will allow for direct measurement of the tH coupling as well as probing the di-Higgs cross-section, which are highly sensitive to extended Higgs scenarios. The cross-section for production of heavier states is naturally increased at 13 TeV extending the discovery potential.

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