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ATLAS and CMS review of SM Higgs boson searches: bosonic and fermionic decays

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The most recent results from the ATLAS and the CMS experiments at CERN on the Standard Model Higgs boson, are reviewed. Emphasis is given to its production and decay through bosonic as well as fermionic modes. Presently no statistically significant deviations from the Standard Model predictions are observed.

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1. Introduction

On 4th July 2012 both the ATLAS and CMS experiments in a common seminar announced indications for the existence of a Higgs-like particle with a mass of 125.5 GeV/c^2. The resulting papers which were published back-to-back in September 2012 [1], [2], reported the detection of the discovered particle through its "clean" bosonic decay modes (H→γγ, H→ZZ* and H→WW*) with a combined significance with respect to the Standard Model (SM) background-only prediction of 5.9σ for ATLAS and 5.0σ for CMS. The word "clean" means that the decay modes could have low branching ratios, but clean signatures which were combined with the excellent detector capabilities of both experiments.

Later, the properties of the discovered particle were measured (spin, CP, rates) and in March 2013 CERN dropped the word "like" from the boson's name. Before Christmas 2013, both experiments reported for the first time direct evidence for the fermionic decays of the Higgs boson. A lot of new results on the Higgs boson were presented during the winter and summer conferences of 2014. Now both experiments are finalizing their Run I results and preparing for Run II which will provide both higher $\sqrt{s}$ energy and luminosity.

Run I finished at the end of 2012, providing the experiments with integrated luminosity of around 26 fb^{-1} (~ 5 fb^{-1} at $\sqrt{s}$ =7 TeV and ~21 fb^{-1} at $\sqrt{s}$ =8 TeV). Both experiments run extremely well and in a very efficient way, maintaining excellent detector understanding; as a consequence they were able to use around 95% (90%) of recorded (delivered) luminosity for the physics analysis studies. In addition, the experiments had to cope with high pile-up conditions, since the average number of interactions per beam crossing was around twenty one.

This report focuses on the observation, production and decay modes of the SM Higgs boson and therefore does not cover its mass measurements (including the combinations from different decay channels), its properties (spin and CP) and its couplings; moreover, it does not cover searches for Beyond the SM (BSM) Higgs bosons.

The SM Higgs boson production cross sections at different $\sqrt{s}$ energies has been calculated by theory including the most recent higher order corrections and are tabulated in [3]. At the LHC, the dominant production mode is through the gluon-gluon fusion (ggF) mechanism which accounts for the 87% of the total production, at the Higgs boson mass of 125 GeV. The other mechanisms, the vector-boson fusion (VBF), the associated vector production with a W or Z boson (VH) and the associated production with a pair of top quarks ($t\bar{t}H$) are at the few % level, while the extra particles produced with the Higgs boson are extremely useful in tagging the events, measuring its fermionic couplings and studying the production modes. Concerning the decays modes, the bosonic decays provide "cleaner" detection signals and are proportional to the mass squared of the bosons involved. On the other hand, the fermionic modes are predicted to be proportional to the mass of the fermions; prediction which should be experimentally established. Up to now, more than two years after the discovery, there is only strong indirect evidence for the Higgs boson coupling to up-type quarks (and top) from the photon loop of the H→γγ decay and from the ggF overall cross section, which are in agreement with the SM prediction. Nevertheless, it is important to measure the Higgs boson couplings to up-type and down-type fermions and thus to probe directly the Yukawa couplings Y_t, Y_b, Y_μ, Y_τ.

The ATLAS and CMS experiments have presented a large number of recent results which cover a wide range of the SM Higgs boson decays as well as searches for different BSM ones. In these proceedings only a few relevant results will be presented, concerning mainly the H→4l (where l=μ or e) and H→γγ decays, as well as H→ττ, VH→$b\bar{b}$ and the associated $t\bar{t}H$→various final states. Moreover, only a few key highlights of the analysis of each channel will be presented, focusing on recent improvements. A recent major achievement has been the fact that both experiments have recalibrated their electromagnetic and muon energy scales with J/ψ, Y and Z (plus Z→llγ) reaching a per mil accuracy and as a consequence greatly reducing their systematic uncertainties and improving the resolutions.

2. Bosonic decay modes

The bosonic decays were used as a tool for the discovery at the initial stage and subsequently as a tool for the measurement of the properties and the confirmation of the discovery.

2.1 Higgs to four lepton decay

This is the so-called "golden" decay channel, where H→ZZ* and each Z boson decays to a pair of electrons or muons, thus, four isolated leptons from the primary vertex are produced in the final state.

The cross section times the branching ratios (BR) of H→ZZ* followed by Z →2l is small (~2.5fb) but the mass of the Higgs boson is fully reconstructed as a peak sitting on a small background of about ~1-1.9 times the signal. This channel is ideal to study the mass, spin, CP, couplings and width. The ZZ* irreducible continuum background is estimated using Monte Carlo data, whereas the reducible one consisting of Z plus jets, $Zb\bar{b}$ and $t\bar{t}$ is calculated in both experiments using data driven techniques with control regions (CMS uses two different methods with same-sign and opposite-sign leptons, which give consistent results).

Recent ATLAS results [4] which greatly improved the systematics (by a factor of 2-10), use the new calibration of the electromagnetic calorimeters based on MultiVariate Analysis [5] (MVA) for optimization of the energy scales and in addition a new muon momentum scale determination. Also the electron identification is based on a likelihood method instead of a cut-based analysis and Boosted Decision Trees (BDT's) variables are used to separate the ZZ* background from the signal as well as, the different production mechanisms.

CMS on the other hand, in their final Run I results [6], profit from new alignments, calibrations and a new kinematic discriminant variable which uses the mass of the lepton pair closest to the Z boson (m_{Z1}), the mass of the second pair (m_{Z2}) and the five decay angles to separate signal from backgrounds. The events are divided in different categories (according to $\sqrt{s}$, the different final states and the number of jets in order to disentangle the different production mechanisms) and a 3D likelihood is used. Figure 1 shows the invariant mass distributions of all four lepton (4l) combinations for ATLAS and CMS.

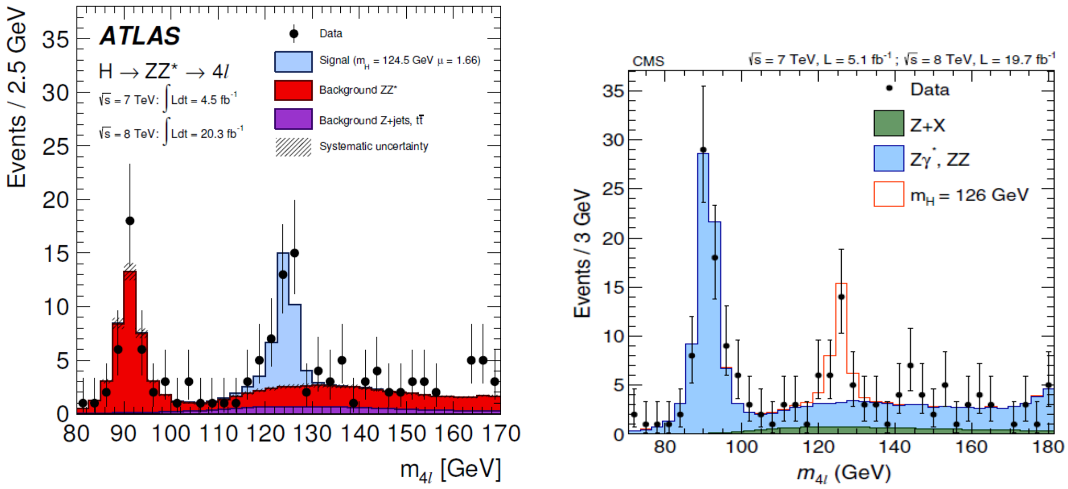

Figure 1: Distribution of the 4l reconstructed mass for the sum of the 4e, 4μ, and 2e2μ channels, for the low-mass region and for the combined 7 TeV and 8 TeV data samples. On the left are ATLAS and on the right CMS results [4], [6].

For the mass determination, ATLAS uses a 2D fit based on m_{4l} and BDT. The data are fitted in four categories according to leptons' final state. The Higgs boson mass value for the 4l decay mode is given as m_H=124.51±0.52(stat)±0.06(sys). The latest observed signal significance is 8.1σ (6.2 σ expected[2]) at the mass of 125.36 GeV, which is the mass determined from the combination of the 4l and two photon decay [7].

CMS using a per-event uncertainty based on the single lepton resolutions and 3D likelihood functions in order to determine the mass as m_H=125.6±0.4(stat)±0.2(syst) with statistical significance of 6.8σ (6.7) at 125.7 GeV (which is the value at minimum local probability p_0).

In addition, ATLAS has measured the cross section for the Higgs to 4l's using standard analysis methods in signal bins [8] (only for the $\sqrt{s}$ =8 TeV data). ATLAS uses fiducial regions in order to minimize the model dependences and acceptance corrections and then the cut-and-count method is used to measure the differential cross section as a function of different variables of the Higgs boson production and decay, for instance p_T^H, y^H, number of jets etc. Furthermore, ATLAS uses bin-by-bin unfolding and compares the unfolded distributions to several different generators. The resulting total fiducial cross section of $\sigma_{\rm tot}^{\rm fid} = 2.11^{+0.53}_{-0.47}({\rm stat})^{+0.08}_{-0.08}({\rm syst})$ fb shows no significant deviation with respect to the SM prediction (1.30±0.13 fb).

[2] Everywhere in the text the number of σ's without parenthesis is the observed one, whereas in parenthesis is given the expected one.

2.2 Higgs to two photon decay

The decay $H \rightarrow \gamma\gamma$ has a small BR ~0.2% at the discovered mass, since it goes through loops, but provides a clean $m_{\gamma\gamma}$ peak which sits on top of the diphoton continuum background. Since the signal to background is only ~3%, an excellent detector performance is necessary. The signal consists of two high p_T isolated photons; the irreducible background is the diphoton continuum and the reducible one is the γ-jet and jet-jet (20%). Both experiments have recently improved their analysis methods, their calorimeter calibration and cluster definition. This reduces the uncertainties on the resolutions; in ATLAS the uncertainty in energy resolution is reduced by a factor of two.

ATLAS [9] uses a cut-based method and separates all production mechanisms (ggF, VBF, VH, $t\bar{t}H$). The signal and background are modeled with analytical functions. Both experiments divide the samples in categories according to the characteristics of the final states of the different production modes.

CMS [10] extracts the signal by simultaneous fit to all categories; the background is determined from a fit to data. A BDT analysis uses the shower shapes, isolation information and energy density per unit area, in order to separate prompt photons from misidentified ones. Kinematic discriminating variables are used to reconstruct the diphoton vertex. A new background modeling, as well as a new event selection is employed. Figure 2 shows the weighted invariant mass diphoton mass distributions for all the categories for ATLAS and CMS.

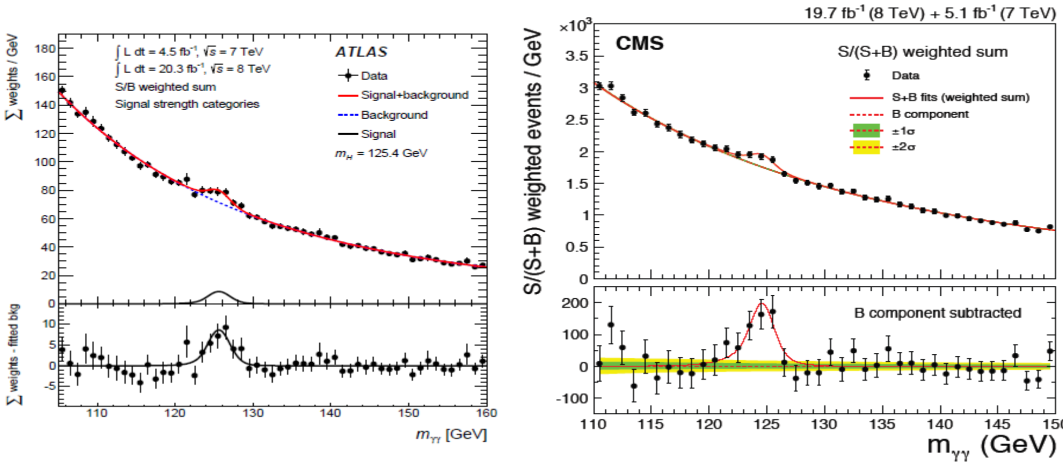

Figure 2: The diphoton invariant mass $m_{\gamma\gamma}$ spectra observed in the sum of the 7 TeV and 8 TeV data. Each event is weighted by the signal-to-background ratio [9], [10].

After the new energy calibrations, the ATLAS diphoton mass resolution is improved by 10% and the value of mass is m_H=125.98±0.42(stat)±0.28(sys) GeV. The main systematic uncertainty of ±0.22% is mainly due to the photon energy scale. The latest signal significance is 5.2σ (4.3) at 126.5 GeV.

CMS uses a per-event estimate of the resolution and kinematical variables to measure a mass value of m_H=124.70±0.31(stat)±0.15(sys) GeV. The main uncertainty is the electron-photon differences and the linearity of the energy scale. The observed significance of the signal is 5.7σ (5.2) at a mass value of 124.7 GeV.

ATLAS has also measured the cross section for the Higgs boson to two photon decay [11] using the method explained in section 2.1. The resulting total fiducial cross section of $\sigma_{\rm tot}^{\rm fid} = 43.2 \pm 9.4({\rm stat})^{+3.2}_{-2.9}({\rm syst}) \pm 1.2({\rm lumi}){\rm fb}$ is in agreement at the 1σ level with the SM predictions (30.5±3.3 fb).

2.3 Higgs to WW decay, where both W bosons decay leptonically

This decay mode has a large BR (second largest after the $H \rightarrow b\bar{b}$), but since both experiments detect the W bosons through their e/μ decays, the effective BR is ~2%. The signal to background ratio, depending on the production mechanism, ranges from 0.1 to 1.0 but the Higgs boson mass is not fully reconstructed. There are two missing neutrinos in the final state and the signal appears as a broad peak in the transverse mass m_T distribution. The signal consists of two isolated high p_T opposite sign leptons plus missing energy. The main irreducible background is the WW(*) and the reducible one comes from single top, $t\bar{t}$, W/Z plus jets, Drell-Yan, dibosons, W plus photon. The data driven background is estimated from control regions formed by the two opposite sign dileptons having invariant mass not close to the Z boson and extrapolating to the signal regions. In both experiments the dominant uncertainty comes from theory (QCD scale).

ATLAS [12] uses a cut-based analysis method, 1D fit on the discriminant variable m_T, categories based on number of jets (0 jet, 1 jet which is defined as ggF, 2 jets which is defined as VBF), the flavor of leptons and the mass of the two leptons m_{ll}. The result (which will be updated soon) is a significance of 4.0σ (3.8) at a mass of 125 GeV if the VH channel -which is included in the CMS standard analysis- is added.

CMS [13] divides the signal to categories according to the flavor, number of jets. The final states investigated are: 2l2ν plus 0/1 jet which is defined as ggF, 2l2ν plus 2 jets which is defined as VBF/VH, WH→3l3ν plus 2jets and ZH→3lν plus 2jets. For the 0/1 jet category a 2D analysis based on m_{ll} and m_T is performed. The observed signal is 4.3σ (5.8) at a mass of 125.6 GeV

2.4 Higgs to Z plus photon decay

This is a rare decay but since it goes through loop diagrams it is sensitive to new physics. The signal times the BR is similar to the H→γγ one, but the signal to background ratio is even smaller (at the level of 1%). The irreducible background consists of the Z plus photon continuum (82%), Z plus photon radiation and Z plus jets (17%). The H→Zγ→llγ cross section is even smaller (about 5% of H→γγ). The signal is two opposite sign same flavor isolated leptons close to the Z mass plus one isolated high p_T photon.

The measurement is statistically limited and both experiments do not see any excess of events over the SM prediction and thus set limits. ATLAS sees no excess of events in the 120-150 GeV mass range with M_{ll}>80 GeV [14] and sets a limit for the ratio to the SM at 95% CL and mass of 125.5 GeV of 11 times the SM expectation (9 expected). CMS does not see any excess of events either in 120-160 GeV mass range with M_{ll}>50 GeV [15] and sets the corresponding limit at 125 GeV to 9.5 (10) times with respect to SM.

3. Fermionic decays

Up to now there has been no evidence for the discovery (~5σ) of the Higgs boson decay to fermions but only evidence for their existence at ~3.5σ level, so for these studies it is important to combine as many decay channels as possible. Since the Higgs boson coupling is predicted to be proportional to mass of the quarks, the decay $H\rightarrow t\bar{t}$ should have been the one with the highest BR. However, this decay is not kinematically allowed for m_H=125 GeV. This means that the $H\rightarrow b\bar{b}$ decay has the highest BR (~58%) and 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, the $H\rightarrow b\bar{b}$ decay is swamped by a huge QCD background, being about 10^7 times more than the signal. So the only feasible way for this measurement, is through the use of the associated production of VH or $t\bar{t}H$, where one can use the extra handle of triggering on a lepton from the V decay or the t→bW→blν decay, for tagging and background rejection. Moreover, the $VH\rightarrow b\bar{b}$ decay is important for the down-type fermion coupling measurement being complimentary to the H→ττ measurement.

Finally, concerning the Higgs boson decay to leptons and assuming that the couplings are proportional to the mass of the leptons, it is obvious that H→μμ and H→ee decays are highly suppressed and very difficult to be detected

3.1 Higgs decay to a pair of tau leptons

This decay was the first Higgs boson fermionic decay, for which evidence was announced around the end of 2013. This channel is the decay of the Higgs boson to leptons with the highest BR~6.2%, resulting to the product of cross section times the BR being about~1.3 pb, which is almost an order of magnitude higher than the "golden" decay channel. However, since the final states are harder to identify and in order to get enough statistics, all possible decay modes of the ττ pair have to be exploited (their relative rate is given in parenthesis):

- $H\rightarrow\tau_{lep}\tau_{lep}$ (12%) small BR but very clean signature consisting of two opposite sign leptons: μμ, ee and eμ

- $H \rightarrow \tau_{lep}\tau_{had}$ (46%) clean signature consisting of one lepton (e or μ) plus a τ decaying hadronically
- $H \rightarrow \tau_{had}\tau_{had,}$ (42%) the final state consists of high multiplicity jets and no lepton (e or μ) and thus provides a challenge in reconstructing it.

The other big challenge is to separate the H→ττ decay from the much more copious Z →ττ decay, having the mass values of the H and the Z close together. Nevertheless, the Z →ττ provides a tool in calculating the main background from Z→ll by data driven methods, modeling it in "embedded" samples from Z→μμ where the μ's are replaced by τ's. There are also reducible backgrounds-depending on the decay states- from QCD multijets, W plus jets, dibosons, $t\bar{t}$ and single t, which are calculated by data driven methods.

The following production modes of the H→ττ are investigated: ggF, VBF (which provides the characteristic signature of two forward jets) and VH. Both experiments categorize the events by the production channels and kinematics and the $m_{\tau\tau}$ is calculated using missing mass calculation methods since the events contain one or more missing neutrinos.

ATLAS [16] uses a BDT MVA with several trained discriminating kinematic variables to separate the signal from the background. The "boosted" Higgs boson category - requiring p_T^H>100 GeV- is used to exploit the ggF and VH topologies. The invariant ττ mass, $m_{\tau\tau}^{MMC}$, is reconstructed using the missing mass calculator [17]. ATLAS has performed so far only the analysis of the $\sqrt{s}$ =8 TeV sample and finds excess in all three decay channels, determining a significance of 4.1σ (3.2) at 125 GeV.

CMS [18] has investigated both $\sqrt{s}$ energies, using the one jet samples for the ggF, two jets for the VBF and two jets plus leptons for the VH production respectively. CMS categorizes events according to the number of jets, the final states, the p_T of the leptons and the $p_T^{\tau\tau}$. In this search, the decay VH(→WW), which produces similar signatures to the H→ττ, namely having extra one or two leptons from the W decays or two jets from the hadronic decay of both W bosons, is treated as background. CMS finds an excess of 3.2σ (3.7) over the SM.

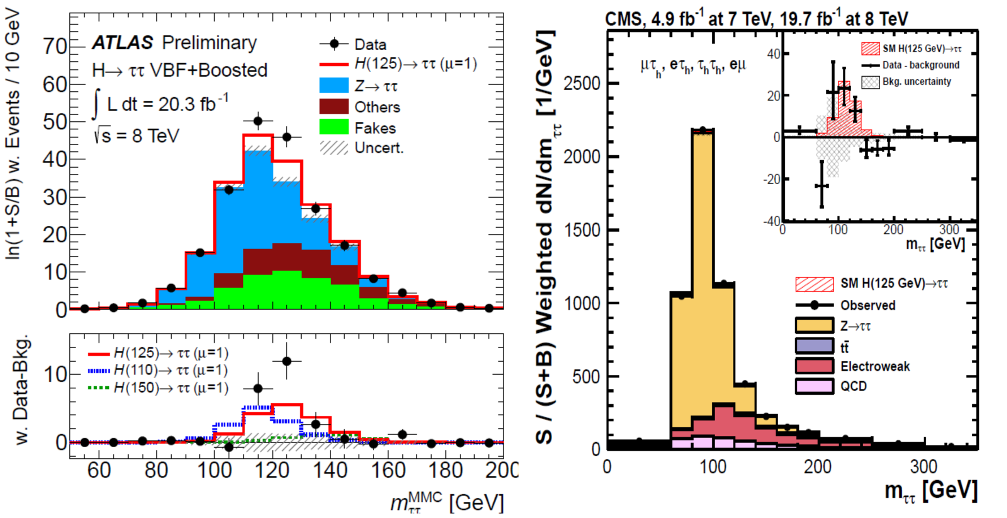

Figure 3: Left, ATLAS, distributions for $m_{\tau\tau}^{MMC}$ where the events are weighted by ln(1+S/B) for all channels for the $\sqrt{s}$ =8 TeV sample [16]. Right, CMS, observed and predicted $m_{\tau\tau}$ distributions for the $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, and eμ channels [18].

Figure 3 shows the weighted events missing mass distributions of the candidate ττ events for ATLAS [16], [17] and CMS [18] for indicative categories. The events in each category are weighted by signal over the sum of signal plus background.

3.2 VH production with Higgs decaying to a pair of b-quarks

The $H \rightarrow b\bar{b}$ decay as mentioned in section 3 has the largest BR of all Higgs boson decays and in addition provides a direct probe of down-type quark couplings. Unfortunately, as already mentioned in the same section, the inclusive measurement is not possible since the decay is hidden by the QCD $b\bar{b}$ production which is many orders of magnitude larger. The only way to observe this decay is through the Higgs boson associated production: the VH one is summarized here and the $t\bar{t}H$ one, in subsection 3.6. The background to the VH production comes from V plus jets, $t\bar{t}$, top, dibosons and multijets.

Since the final states are complex consisting of several jets out of which at least two are b-jets, both experiments use similar techniques to validate their analysis. Both measure the associated production of the Z decaying in the same final states as the Higgs boson, namely VZ with Z→b$\bar{b}$, as benchmark in order to validate their analysis. Simpler analysis methods, are also used by both experiments, based on a fit of the invariant mass of the candidate events, in order to check their MVA's (which use several variables). The resulting reconstructed b$\bar{b}$ invariant mass distribution has a broad peak (σ~10%).

ATLAS [19] has very recent results (just released for this conference) where a MVA is performed (for the 8 TeV data set) which includes the various kinematic variables, the dijet mass as well as the b-tagging information. ATLAS asks for two b-tagged jets and looks at the following associated vector boson decays: Z→νν, W→lν and Z→ll (l=e, μ). The data are divided in bins of p_T^V, number of leptons, number of jets and number of b-jets. Control regions for the background and data driven methods for the QCD background are used as well. ATLAS new result shows for first time a significance of 1.4σ (2.6) above background.

CMS [20] includes the W→τν decay in the analysis of the 8 TeV data set. Several kinematic variables are used in BDT's for signal to background separation. A fit is performed at the shape of the output of the event BDT discriminant in order to calculate the limits. CMS observes an excess above the SM background of 2.1σ (2.1). Figure 4 shows the dijet mass distributions for both ATLAS and CMS.

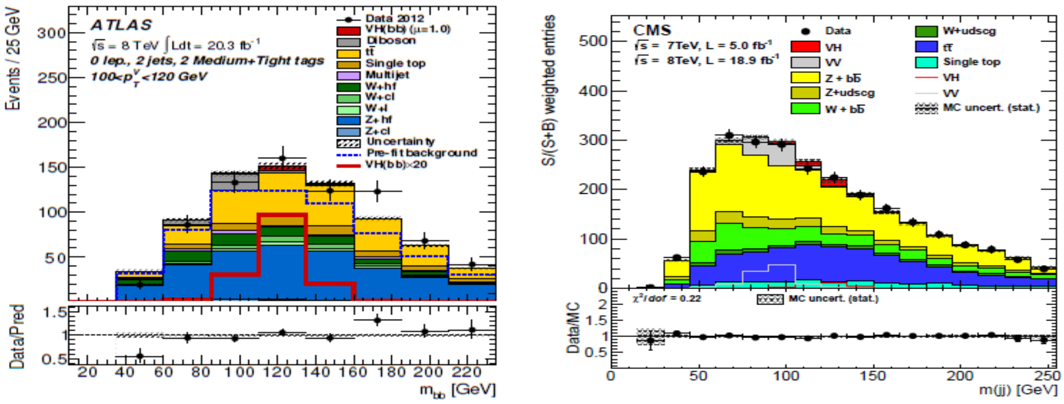

Figure 4: Left, ATLAS, the dijet mass distribution observed in data, in the 0-lepton channel with the medium and tight b-tagging categories combined, for the 2 jet signal region in the 100<p_T^V<120 GeV interval [19]. Right, CMS, the dijet mass weighted invariant mass distribution, combined for all channels [20].

3.4 Combination of Higgs decay to a pair of tau leptons and VH production with decay to a pair of b-quarks

The combination is used to enhance the evidence for the Higgs boson fermionic decay since none of the individual channels gives enough significance for claiming a discovery. Both experiments combine their results from the above two channels. ATLAS [21] found evidence –before the updating of the VH→b$\bar{b}$ channel– for direct decay into fermions at the 3.7σ level with a signal strength μ (defined as the measured cross section times BR relative to the expected one for the SM Higgs boson production) $\mu = 1.09 \pm 0.24(\text{stat})^{+0.27}_{-0.21}(\text{sys})$. CMS [22] finds evidence for Higgs boson coupling to down-type fermions quarks with significance of ~3.8 σ (4.4) and $\mu = 0.83 \pm 0.24$.

3.5 Higgs decay to a pair of muons

Since the Higgs boson coupling to fermions is predicted to be proportional to the mass of the corresponding fermions, the BR for this decay is very small ~2* 10^{-4}. The signal to background ratio is small as well ~ 0.2%, but the dimuon spectrum provides a very clean signature with a very good mass resolution and at the same time is the only means of measuring the second generation fermionic couplings. The signal is exactly two isolated opposite sign muons, while the huge background consists of Z/γ*→ μμ (96%) and t$\bar{t}$ (3%). Both experiments see no signal and set limits.

ATLAS [23] uses a cut-based method and the analysis of the signal and background are done using analytical modeling. The data are separated into the ggF and VBF categories using central μ's and non-central μ's. The main source of systematics comes from theory. No excess of events is observed, leading to limit with respect to the SM at 95% CL and mass 125.5 GeV of ~7.0 (7.2). This corresponds to a BR<1.5* 10^{-3} which proves that there is no universal coupling to the different leptons.

CMS [24] employs two independent analysis with similar results, divides to event categories according to the number of jets and sets a limit with respect to the SM of ~7.4(5.1) at a mass of 125 GeV.

3.6 $t\bar{t}H$ production with Higgs decaying to various final states

This is the only channel that can contribute to the evaluation of the top Yukawa coupling which is predicted by theory to be Y_t~1. Both experiments have previously given limits for the following individual decay channels: $t\bar{t}H\to\gamma\gamma$ and $t\bar{t}H\to b\bar{b}$. Recently both experiments combined the above two channels and CMS gives limits for the $t\bar{t}H$ decay to a combination of diphoton, multileptons and hadronic final states.

The ATLAS limit with respect to SM [25] from the $t\bar{t}H\to\gamma\gamma$ and $t\bar{t}H\to b\bar{b}$ combination at 95% CL and 125.4 GeV is 3.9 (2.3).

The recent CMS results [26] use an MVA lepton analysis based on BDT for signal to background separation. The result for the combination of $t\bar{t}H\to\gamma\gamma$, $t\bar{t}H\to b\bar{b}$, $t\bar{t}H\to WW$, $t\bar{t}H\to ZZ$ and $t\bar{t}H\to\tau_h\tau_h$ at 95% CL upper limit is 4.5σ (2.7) at 125.6 GeV. The best fit for the signal strength is μ=2.8±1.0 at 68% CL which represents an excess of events of 2σ over SM.

4. Summary of all channels and their combination

A summary of all the decay modes described in the text and the corresponding results for the significance and the signal strengths with respect to the SM for both experiments is given in Table I.

Higgs boson decay mode	ATLAS σ/σ_{SM} observed	ATLAS σ/σ_{SM} expected	ATLAS μ signal strength	CMS σ/σ_{SM} observed	CMS σ/σ_{SM} expected	CMS μ signal strength
$H\to ZZ$	8.1	5.8	$1.44^{+0.40}_{-0.33}$	6.8	6.7	$0.93^{+0.29}_{-0.24}$
$H\to\gamma\gamma$	5.2	4.3	1.17±0.27	5.7	5.2	$1.14^{+0.26}_{-0.23}$
$H\to WW$	3.8	3.8	$1.00^{+0.32}_{-0.29}$	4.3	5.8	$0.72^{+0.20}_{-0.13}$
H-ττ	4.1	3.2	$1.4^{+0.5}_{-0.4}$	3.2	3.7	0.78±0.27
$VH(H\to b\bar{b})$	1.4	2.6	0.52±0.40	2.1	2.1	1.0±0.5
$H\to\tau\tau+b\bar{b}$	3.7	3.4	$1.09^{+0.36}_{-0.32}$	3.8	4.4	0.83±0.24
Limits at 95% Confidence Level						
$H\to\mu\mu$	<7.0	<7.2		<7.4	<5.1	
$H\to Z\gamma$	<11	<9		<9.5	<10	
$t\bar{t}H$ $(H\to b\bar{b})$	<4.4	<2.7		<4.1	<5.0	
$t\bar{t}H$ $(H\to\gamma\gamma)$	<6.5	<4.9		<7.4	<5.7	
$t\bar{t}H$ $(H\to b\bar{b}$ and $H\to\gamma\gamma)$	<3.9	<2.3				
$t\bar{t}H$ $(H\to\gamma\gamma$, $H\to b\bar{b}$, $H\to WW$, $H\to ZZ$ and $H\to\tau_h\tau_h)$				<4.5	<2.7	

Table I: Summary of the significance (or limits) σ/σ_{SM} and the ratio μ of the signal strength over the SM prediction for the various Higgs boson decay modes reviewed in the text.

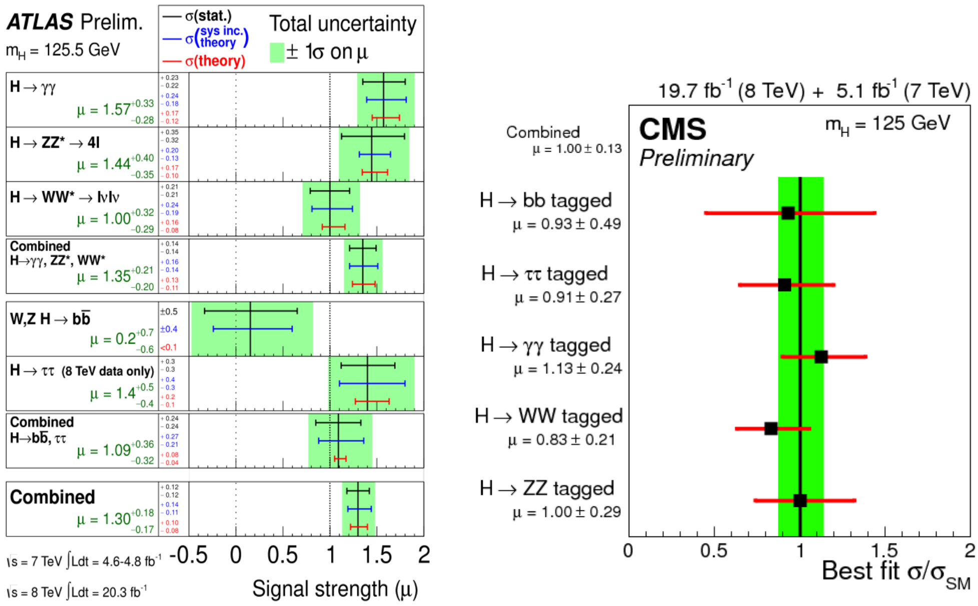

Figure 5: Left, ATLAS results on the measured production strengths for a Higgs boson of mass m_H=125.5GeV, normalized to the SM expectations, for the individual diboson final states and their combination [21]. Right, CMS results on the best-fit for μ for m_H=125.0GeV by predominant decay modes [27].

Both experiments have produced overall coupling strength results by combining the fermionic and bosonic channel decays and in particular the five main channels (H→ZZ, H→γγ, H→WW, H→ττ and VH→$b\bar{b}$). Both experiments measure signal strengths consistent with the SM prediction of μ=1 as shown in Figure 5. The combined number for ATLAS [21] is $\mu = 1.30 \pm 0.12(\text{stat})^{+0.14}_{-0.11}(\text{sys})$ (not using the most recent VH→$b\bar{b}$ results). A 4.1σ evidence for the VBF Higgs boson production is claimed.

CMS [27] has produced new results tagged by production and decay channel. The overall signal strength is μ=1.00 $\pm$ $0.13[\pm 0.09(\text{stat})^{+0.08}_{-0.07}(\text{theo}) \pm 0.07(\text{syst})]$. A 3.6σ evidence for the VBF boson production and -for first time- an excess of 2.0σ above SM for the $t\bar{t}$H production are reported.

5. Conclusions/Future

Both experiments have discovered the Higgs boson through its bosonic decays (ZZ*, γγ, WW*) and also found evidence (>3.6σ) for its decay to fermions (combing the ττ and $b\bar{b}$ decay channels).

There is a plethora of new precision results, for example, the Higgs boson mass is measured with per mil accuracy. Despite many efforts to discover additional Higgs bosons or coupling/properties which deviate significantly from the SM predictions, the newly discovered boson looks "very" SM-like. The final analysis of all data of Run I will be finished by the end of 2014. Some results are approaching the theory precision or are limited by systematic uncertainties, whereas some other decay modes (i.e Zγ, μμ) need more statistics which will come from Run II.

Run II will permit for the experiments to collect integrated luminosities of the order to 75 to100 fb^{-1}; in addition almost all Higgs boson production cross sections will be increased by a factor of 2 to 5 (5 is the increase for the $t\bar{t}$H production). On the other hand, there will be harsher data taking conditions due to the higher pile-up. Nevertheless, Run II will permit for precision measurements (namely improve the accuracy in the couplings' determination; see for example the ATLAS projection [28]), the measurement of the VH mode with higher statistics in order to reach the discovery significance in the fermionic modes. Moreover, the searches for additional Higgs bosons BSM, or charged ones (which is the subject of the present workshop) will continue in Run II, making profit of the additional data. The main uncertainty in the future will be on the parton distribution functions for the ggF process.

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