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Higgs boson production at the LHC

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After the discovery at the LHC, the main goal of the Higgs boson measurements at ATLAS and CMS is to fully elucidate the nature of this new particle. In this contribution we will discuss the Higgs boson production and decay properties at the LHC and the main analyses which build the foundation for the current Higgs boson property measurements. Inclusive rates as well as differential measurements in the main bosonic and fermionic channels, and searches for rarer decay modes will be presented.

1 Introduction

The Higgs boson discovery [1,2] delivered the most significant result of the LHC in Run-1. Moreover, the breathtaking progress in Higgs physics understanding since the discovery is similarly remarkable. Already within two to three years after the discovery, the Higgs boson production cross section was measured with a 15% accuracy and its mass was known to a 0.2% accuracy. This mass measurement is still limited by the statistical uncertainty. This note will discuss the fundamental measurements which are the basics of this progress and which made such a rich phenomenology possible at the LHC.

The two LHC experiments which delivered these results are ATLAS [3] and CMS [4]. Both are general purpose detectors with a precision tracking, surrounded by a hermetic calorimeter system and outer muon detectors. In the ATLAS design the emphasis was set on excellent jet and missing transverse momentum resolution, particle identification, and standalone muon measurement. In CMS the emphasis was on excellent electron and photon resolution, and on good tracking (hence also muon) resolution. Both detectors are well understood, have a stable operation and data taking efficiencies above 90%.

The LHC collider operated remarkably well in Run-1 and delivered a large dataset of more than 25 fb^{-1} to each experiments. This, however, came with significant challenges because of the high instantaneous luminosity, which resulted in 21 additional proton-proton interaction (pileup) per beam collision on average in 2012. In order to cope with these challenges the experiments had to continuously improve their event triggering, reconstruction and identification algorithms. The main impact was on jets, missing transverse momentum and tau lepton reconstruction, as well as on trigger rates and computing. The most effective way to mitigate effects from pileup interactions is to use information from the tracking detectors, and both experiments developed several algorithms which were used also in Higgs boson measurements. As an example, we mention the track based measurement of low momentum objects in the missing transverse momentum calculation, which resulted in an $O(20\%)$ resolution improvement for $H \to WW$ decays in gluon-fusion production.

2 Higgs boson production and decay at the LHC

The main process to produce Higgs bosons at the LHC with 8 TeV collisions is through the fusion of two gluons (gluon-fusion production). Although this is a loop induced production, it has the largest production cross section with roughly 19 pb. This is followed by vector boson fusion (VBF) production, which has an order of magnitude smaller cross section. In this process the incoming quarks radiate electroweak bosons, which produce the Higgs boson. These quarks fragment to particle jets which can be observed in the forward directions. One expects only the Higgs boson decay products between the two jets, which are strongly separated in rapidity. This distinct signature can be used to strongly suppress many background processes. Other production processes are the associated productions with either a vector boson (VH) or top-quarks (ttH), which have an even smaller cross section at 8 TeV proton-proton collisions. These different production modes give us already the possibility to measure the Higgs boson couplings to vector bosons and top quarks.

In Run-1 500 000 Higgs bosons were produced at both, ATLAS and CMS. Although this is a large number, Higgs bosons are in fact the most rarely produced Standard Model (SM) particles and only one in 10^{10} collisions produce a Higgs boson at the LHC, while all the other processes are backgrounds to the Higgs boson measurements. For this reason it is important to develop an efficient event triggering and analysis selection. In fact, only less then a precent of all the produced Higgs bosons are selected and used in the final measurements.

The Higgs boson branching ratios strongly vary with its mass, and the particular Higgs boson mass which nature realised enables a rich collider phenomenology. At the Higgs mass of 125 GeV, all the decays to bosons and to the heavier fermions provide large enough rates at the LHC. Some of the decays have overwhelming backgrounds or branching ratios which are not large enough to be observed within the Run-1 dataset. For this reason, there are mainly five decay channels which are presently driving the Higgs boson measurements. More than every second Higgs boson decays to a pair of b-quarks. The second largest branching ratio is to a pair of W-bosons. The best mass resolution comes from the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ decay signatures, which played a key role in the Higgs boson discovery. Finally, the decay to tau pairs gives currently the best sensitivity for a leptonic decay mode.

The main experimental signatures and strategies are driven by the decay modes. These decay channels are further divided into sub-channels to separate the different production modes and to increase the overall significance. As such, a large number of final states are investigated at the LHC.

3 High resolution channels

3.1 Signal rate measurements

Due to their simple signatures and excellent mass resolution the $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ final states are unambiguous Higgs boson decay signatures. Interestingly, these two channels with very small branching ratios played a pivotal role in the discovery. These fully reconstructed final states play also a crucial role in current measurements, such as the mass and spin determination.

Although the expected signal yield in the $H \to ZZ \to 4\ell$ channel is very small, $O(20)$ events, it is the only channel which has a signal-over-background ratio above one [5,6]. Hence this channel will be particularly powerful in the future LHC programme with a larger dataset. Given the very low branching ratio of $H \to 4\ell$, it is important to maintain a very high lepton selection efficiency over a broad range of momenta, and also a good 4-lepton mass resolution since we are looking for a cluster of events in the 4ℓ invariant mass distribution, cf. Fig.1a. The main backgrounds to this search are the SM ZZ^* production, which is irreducible and is estimated from Monte Carlo (MC) simulation. Other backgrounds are top-quark production and Z plus jets. These sub-leading backgrounds are minimised with isolation and small impact parameter

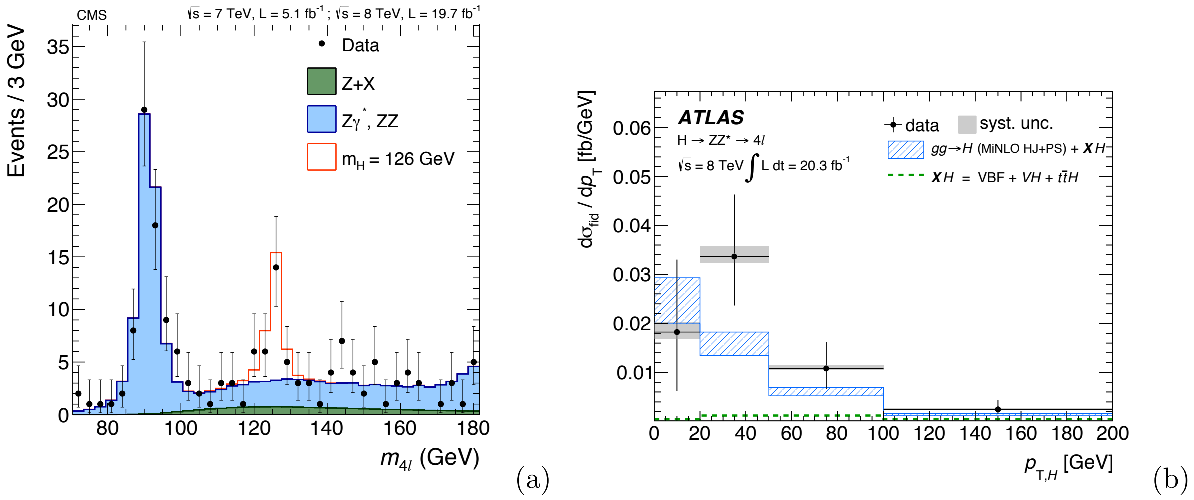


Figure 1 – Invariant mass distribution in the CMS $H \rightarrow 4\ell$ analysis (a), and the Higgs boson transverse momenta measured in the same final state at ATLAS (b).

requirements.

To exploit the simple signature of the diphoton decay mode, two isolated photons with high transverse momenta are selected and the excess of events around 125 GeV is quantified in the steeply falling diphoton mass spectra [7,8]. This channel as well, has reducible and irreducible backgrounds. The reducible background is mainly photon plus jet production where a leading parton fragments into a π^0 which then decays to two photons. Since this background is several orders of magnitude larger compared to the signal, it is critical to reach rejections of $O(10^{-4})$, which is achieved with electromagnetic shower-shapes in the calorimeter. The irreducible background is SM continuum diphoton production.

To obtain the best signal significance and mass measurement in the $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$ final states, the precise knowledge of the lepton and photon energy scale and the achievement of the best possible resolution is a central goal. Electron and muon scale and resolution corrections and uncertainties are determined from a large Z and J/ψ samples. The relative difference in the Z mass scale between data and simulation is less than 0.1% for both experiments. To determine the precise photon energy scale one needs an accurate detector material description for the electron to photon extrapolation. The material distribution of the inner detectors is studied with several in-situ measurements.

Each Higgs boson analysis is further separating the events into categories with different signal over background ratios, resolutions and different relative contributions of signal production modes. As an example, this is illustrated on the ATLAS diphoton analysis, which has 14 analysis categories. Two are targeting the ttH production, four the VH production, three the VBF production and the rest are mainly selecting gluon-fusion production. There is more than one category per production mode, because these are further optimised to improve the sensitivities, for example by targeting different signal over background ratios. Finally, these sub-channels are combined to extract the common signal yield in the invariant mass distribution. The obtained signal strengths will be discussed at the end of this note, in combination with all decay signatures.

3.2 Differential cross sections

For a more general probe of its underlying kinematic properties one can measure differential cross sections of the Higgs boson. The two high resolution channels are best suited for these measurements [9,10]. To extract differential distributions, the analysis strategy is identical to the signal strength measurements. The variables are binned and the signal strengths are extracted in each of these categories. To minimise the dependence on theoretical assumptions, these

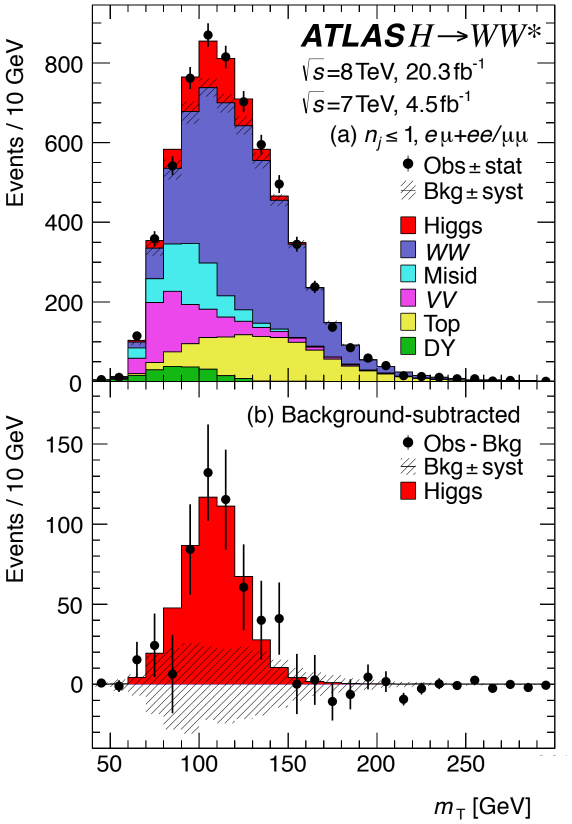


Figure 2 – Transverse mass distribution in the ATLAS $H \to WW$ measurement (a) and the background-subtracted data residual (b).

measurements are not extrapolated to the total production times branching ratio, but rather defined in a fiducial volume which is close to detector level selection. Several variables have been looked at, which are sensitive to spin-parity, to the different production modes or to higher-order corrections. As an example, Fig.1b shows the transverse momenta of the Higgs boson in the 4ℓ final state. The statistical uncertainties are still large, but the measurements are compatible with the SM predictions. These differential cross sections measurements will especially profit from the larger dataset in Run-2 and will be a powerful probe of the electroweak symmetry breaking sector.

4 Decays to a pair of W-bosons

4.1 Signal rate measurement

The $H \to WW^* \to \ell\nu\ell\nu$ decay signature belongs to the three channels which contributed to the Higgs boson discovery. With the leptonic W boson decays most of the backgrounds can be suppressed significantly, while still retaining a large signal yield [11,12]. The main Drell-Yan contribution is minimised with various missing transverse momentum related cuts. The overall analysis strategy is to divide the events in several categories depending on the number of jets which are produced in addition to the Higgs boson decay signature and in categories of different lepton flavours. The most sensitive category is the one with opposite flavour leptons and no accompanying jets in the event. The largest background in this sub-channel is SM WW^* production. Finally, several topological requirements are applied to further reduce the backgrounds and to isolate the VBF production signature. One important aspect that can be exploited with this selection is to make use of the spin correlation properties of the bosons. It is expected that the two leptons from the spin-0 decay have small azimuthal separation, while

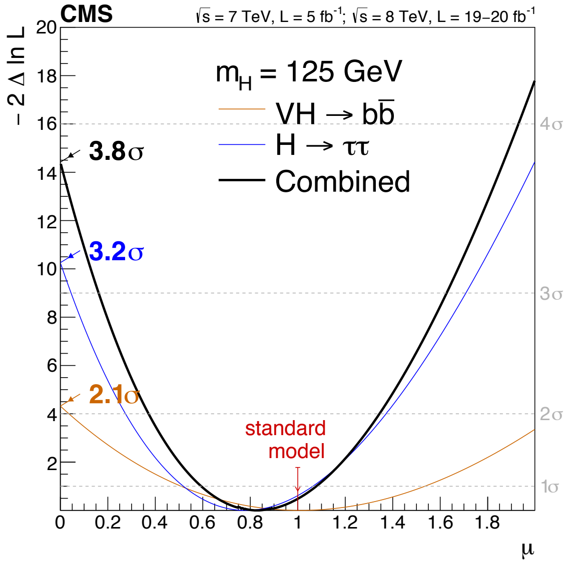


Figure 3 – Scan of the profile likelihood as a function of the signal strength relative to the expectation for the production and decay of a standard model Higgs boson for $m_H = 125$ GeV.

the contrary is true for SM WW^* production.

Due to the large missing transverse momentum in the final state, this analysis cannot rely on the Higgs boson invariant mass distribution. Instead, the transverse mass is the most sensitive variable in the measurement. Figure 2 shows the transverse mass variable from the ATLAS analysis for the events with less then 2 jets. As can be seen from the plot, many high-energy SM backgrounds contribute with a similar magnitude as the signal, hence this analysis requires a good understanding of all these processes. The bottom of the plot shows the background subtracted data residual, which agrees well with a Higgs boson as expected from the SM.

4.2 Evidence for vector boson fusion production

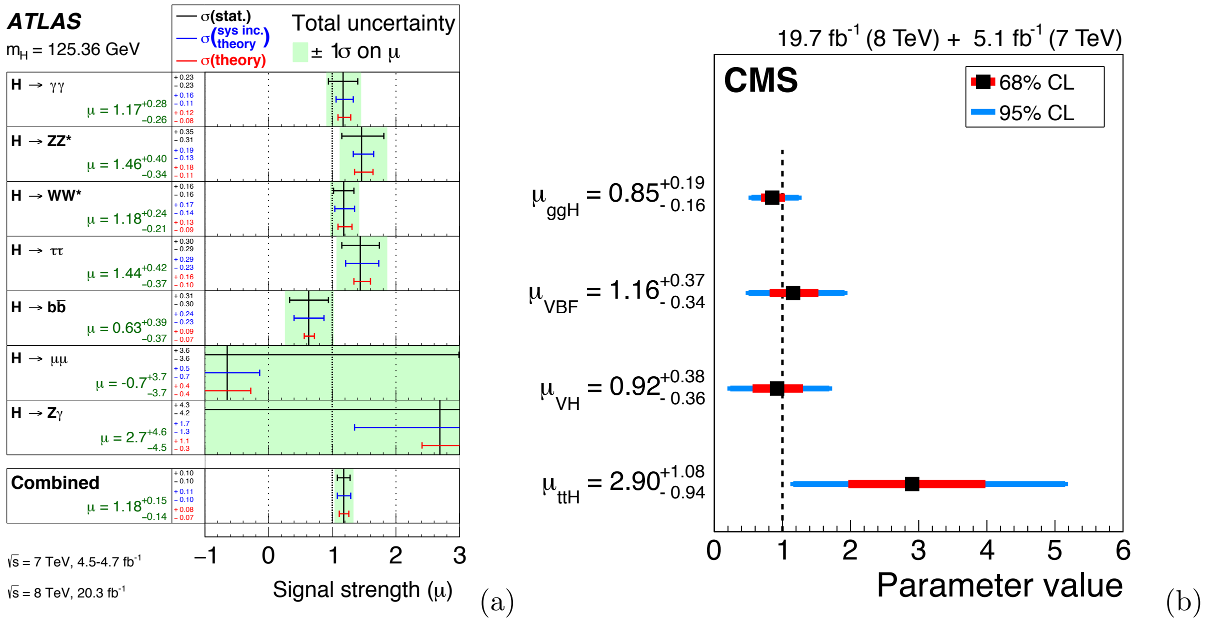
By isolating VBF production events with forward jet tagging, the gluon-fusion and vector boson fusion productions can be disentangled in the measurement. The ratio of the two production modes gives a 3σ evidence for a non-vanishing VBF production at ATLAS. A significant separation of the production modes is not only a crucial test of the SM Higgs sector, but it is also the basis for the coupling measurements to disentangle the information from production and decay.

5 Couplings to fermions

5.1 Evidence for Higgs-Yukawa coupling

The two Higgs decay final states which can probe Higgs-Yukawa couplings are $H \to bb$ [13,14] and $H \to \tau\tau$ [15,16]. Both channels suffer from large multi-jet backgrounds, hence they need the additional signatures of the exclusive production modes (e.g. an isolated lepton from VH production). Due to the large backgrounds and signal resolutions which are significantly worse compared to the high resolution channels, these analyses also rely on multivariate techniques to separate the signal from the backgrounds. These channels require as well an excellent understanding of the various SM backgrounds, which are constrained in signal depleted control regions.

While the $H \to bb$ results are not yet significant enough, both experiments observed the Higgs boson with more than 3σ significance in the di-tau decay signature and in the combination of the two channels. Figure 3 shows the scan of the profile likelihood as a function of the signal



(a) (b)

Figure 4 – Measured Higgs boson signal strengths by the ATLAS experiment in the different decay modes and their combination, normalised to the SM expectation (a). Measured Higgs boson production cross sections by the CMS experiment normalised to the SM expectation (b).

strength relative to the SM expectation for the two individual channels and their combination at CMS. This evidence for Higgs fermion couplings is among the most important results of the Run-1 Higgs searches. Yukawa couplings are not required to break electroweak symmetry, but they are a fundamental part of the SM to obtain fermion masses.

5.2 Coupling limits to second generation fermions

The LHC dataset in Run-1 provided mainly sensitivity for Higgs-Yukawa couplings of third generation fermions. Measuring the couplings to other fermion generations will be an important test of the SM as well, and will be possible for second generation fermions at the LHC. For this the most promising measurement is the coupling to muons, and the analysis already started in Run-1 to exclude models with enhanced production [18,19]. The analysis for $H \to \mu\mu$ decays is very similar to the $H \to \gamma\gamma$ analysis where one can search for an excess of events in the steeply falling mass distribution, exploiting the excellent mass resolution in di-muon decays. As expected simply from the order of magnitude smaller branching ratio compared to $H \to \gamma\gamma$, no significant excess of events is observed yet in this channel. At an invariant mass of 125 GeV, the current limit is roughly a factor 7 away from the SM prediction. However, this analysis will be one of the important measurements of the future HL-LHC upgrade.

6 Combined results on Higgs boson production

Figure 4a summarises the Higgs boson production rates per decay channel from ATLAS. These results are normalised to the SM expectation. Hence, if the measurements agree with the SM, the results from the various channels should align around 1. As one can see from the plot, this is indeed the case within the measurement uncertainties. Also the combination of all these decays is in good agreement with the SM, both experiments measure the total production rate with a 15% uncertainty [20,21]. It is also worth noting, that in most of these measurements the statistical, experimental and theoretical uncertainties are at a similar size. Hence in the future LHC data analyses the systematic uncertainties will often dominate these results.

From the various measurements one can also extract the production rates in the different production processes. This is illustrated in Fig.4b, which are the results from CMS. All productions agree well with the SM expectation. An exception is the ttH production mode, which has still very large uncertainties. This measurement will be much more powerful in Run-2 because of the four times larger signal cross section with 13 TeV collisions. The extraction of the top-Yukawa coupling will be one of the most important measurements of the LHC in Run-2.

7 Conclusions

The most remarkable highlight of the LHC in Run-1 was the Higgs boson discovery. With this discovery an entirely new field emerged, with a large number of interesting analyses to test the electroweak symmetry breaking sector of the SM. In this contribution we summarised the main analyses which form the fundament for most of the Higgs boson property measurements so far. The main drivers are still the three channels which contributed to the discovery, however evidence for Higgs-Yukawa couplings in the di-tau decay mode is also one of the most important result of the LHC in Run-1. The production and decay rates agree within the uncertainties with the SM, and the total cross section is measured with a 15% accuracy. We can look ahead to a further exciting and rich Higgs physics programme during the next LHC run periods.

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