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Higgs Boson at the CMS experiment

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The results of the Standard Model Higgs Boson search with the CMS detector at the Large Hadron Collider at CERN with proton-proton collision data corresponding to integrated luminosities of around 5 fb^{-1} at 7 TeV and 20 fb^{-1} at 8 TeV center-of-mass energies are presented. The analysis in the most sensitive decay modes in 2 photons, $ZZ^* \rightarrow 4\ell$, $WW \rightarrow 2\ell 2\nu$, tau lepton pair and bottom quark pair final states followed by the discovery of the Higgs Boson around a mass of 125 GeV is reported. In addition, a measurement of the properties of the Higgs boson is presented showing its consistency with Standard Model expectations.

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HIGGS BOSON AT THE CMS EXPERIMENT

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Abstract. The results of the Standard Model Higgs Boson search with the CMS detector at the Large Hadron Collider at CERN with proton-proton collision data corresponding to integrated luminosities of around 5 fb^{-1} at 7 TeV and 20 fb^{-1} at 8 TeV center-of-mass energies are presented. The analysis in the most sensitive decay modes in 2 photons, $ZZ^* \rightarrow 4\ell$, $WW \rightarrow 2\ell 2\nu$, tau lepton pair and bottom quark pair final states followed by the discovery of the Higgs Boson around a mass of 125 GeV is reported. In addition, a measurement of the properties of the Higgs boson is presented showing its consistency with Standard Model expectations.

1 Introduction

The ATLAS and CMS collaborations in July 2012 came out with the observation of the Higgs Boson [1, 2] using proton-proton collision data from the Large Hadron Collider (LHC) at CERN corresponding to integrated luminosities of around 5 fb^{-1} at 7 TeV and 5 fb^{-1} at 8 TeV center-of-mass energies. The LHC has completed its first run with the detectors having recorded about 95% of delivered collision data, among which about 90% were certified and used to obtain the results reported here. The final analysis presented here is based on integrated luminosity of 20 fb^{-1} at 8 TeV in addition to the 5 fb^{-1} at 7 TeV collected by the CMS detector [3]. The observation of the Higgs boson around a mass of 125 GeV in the high resolution bosonic decay channels motivates the search for the major fermionic decay modes as both the decays of the Higgs boson to tau pairs and bottom quark pairs have significantly large branching fraction in this mass regime.

For the physics object reconstruction in a collision event, CMS uniquely employs particle flow technique which provides event description in the form of mutually exclusive particles identifying all stable particles produced in the event by combining the capabilities of each sub-detector with the most precise measurement of the energy and direction for each particle and then individual measurements from each sub-detector are combined by a geometrical linking algorithm. The experiment had to establish methods to cope with a high number of multiple collisions per beam crossing (pileup), which occurs at high luminosity. The average number of pileup events is about 9 and 21 interactions in the years 2011 and 2012 respectively. The successful mitigation of pileup was demonstrated and an almost flat response of the missing transverse energy resolution as a function of the number of primary vertices in the event is achieved. The analysis utilises all the Higgs boson production mechanisms in pp collisions in order of decreasing cross-sections namely gluon fusion, vector boson fusion (VBF), associated production with vector bosons (VH) and in association with top quarks. The major decay modes relevant to the Standard Model (SM) Higgs boson analysis are the decays to 2 photons [4], ZZ^* to 4 leptons [5], WW to $2\ell 2\nu$ [6], tau pair [7] and

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bottom quark pair [8,9]. A measurement of the properties of the new boson is crucial to understand its consistency with the Standard Model expectations [10].

2 Decay Modes

2.1 $H \rightarrow \gamma\gamma$

The Higgs boson branching ratio for the decay into two photons is approximately 2×10^{-3} for Higgs boson mass between 110 and 145 GeV. The diphoton mass resolution is excellent, between 1 and 2% and the signature in this channel is two isolated photons with high transverse energy (E_T). A signal in this channel would appear as a small and narrow peak above a large and smoothly falling background coming from prompt diphoton production and photon + jet production with the jet misidentified as a photon. The search results are presented for an analysis that uses Multi-Variate-Analysis (MVA) techniques both for photon identification and event classification, and extracts the signal from the background using a fit to the diphoton mass spectrum (referred to as mass-fit-MVA). To achieve the best sensitivity to a Standard Model Higgs boson decaying to two photons, the events are separated into classes based on a Boosted Decision Tree (BDT) output and on production mechanisms of the Higgs boson. The multivariate classifier incorporates the kinematic properties of the diphoton system (excluding diphoton mass), a per-event estimate of the diphoton mass resolution and the photon identification BDT output value for the two photons. This choice of inputs is justified by the fact that the signal-to-background ratio varies as a function of the diphoton kinematics. In addition, the diphoton mass resolution depends on several factors: the location of the associated energy deposits in the calorimeter; whether or not one or both photons converted in the detector volume in front of the calorimeter; and the probability that the true diphoton vertex has been identified. In addition to the event classes for the MVA in the untagged category, the analysis uses a di-jet tag for the vector boson fusion category, and lepton / missing transverse energy tag for the production in association with vector bosons. The analysis observes an excess of events at a mass around 125 GeV, with a local significance of 3.2 standard deviations (σ), where a local significance of 4.2σ is expected from a Standard Model Higgs boson. The best-fit signal strength, σ/σ_{SM} , is 0.78 ± 0.27 at $m_H = 125$ GeV, with the best fit to the mass of the new boson at $125.4 \pm 0.5(\text{stat.}) \pm 0.6(\text{syst.})$ GeV.

2.2 $H \rightarrow ZZ^* \rightarrow 4\ell$

The Higgs boson decay in four lepton final state provides a very clean experimental signature with 4 isolated leptons (4 electrons, 4 muons or 2 electrons + 2 muons) originating from a common primary vertex with a low flat background from ZZ production in the low Higgs boson mass range of interest. The analysis relies strongly on the understanding of leptons and on this perspective, the uncertainty on the muon momentum scale is 0.1% and for the electron momentum scale is 0.2% for transverse

momentum (p_T) over 35 GeV and up to 1.5% for $p_T < 35$ GeV. The di-lepton invariant mass is well understood in a wide range of lepton transverse momenta from J/ψ and Υ decays up to Z boson decay. The analysis uses the measured 4 lepton invariant mass, the mass uncertainty, kinematic discriminants and information sensitive to the production mechanism. The search strategy requires at least one of the reconstructed di-lepton invariant mass to be around the nominal Z boson mass. The Z boson decay to 4 leptons resulting from internal photon conversion serves as a standard candle to the analysis. A clean Higgs boson mass peak from 4ℓ decay is observed around 126 GeV with an excellent resolution and a very good control over the dominant ZZ background. The boson is observed with 6.7σ significance above the expected background, for measured mass of $125.8 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.})$ GeV. The signal strength μ is measured to be $\mu = 0.91^{+0.30}_{-0.24}$. The signal strength modifiers associated with vector bosons and fermions in production are measured to be $\mu_V = 1.0^{+2.4}_{-2.3}$ and $\mu_F = 0.9^{+0.5}_{-0.4}$, thus consistent with SM expectations. No other significant SM Higgs-like excess is found and the mass range 130-827 GeV is excluded at 95% confidence level.

Figure 1: The diphoton invariant mass distribution with each event weighted by the Signal / (Signal + Background) value of its category, for the mass-fit-MVA analysis (on the left). Distribution of the four-lepton reconstructed mass in the full mass search range for the combination of the $4e$, 4μ , and $2e2\mu$ channels (on the right).

2.3 $H \rightarrow WW \rightarrow 2\ell 2\nu$

The W^+W^- candidates are selected in events with two oppositely charged leptons and large missing transverse momentum. Events are classified according to exclusive jet multiplicities: 0, 1 and 2. The events are further separated in same-flavour (ee and $\mu\mu$) and different-flavour ($e\mu$) final states in each jet multiplicity bin. The main backgrounds (WW , top, Drell Yan, W +jets) are estimated with data-driven techniques. The

uncertainty on the background normalization represents the largest source of systematics, together with theoretical uncertainties on the Higgs cross section. A cut and count analysis is performed, optimized for each mass point in all jet multiplicity categories. The same-flavour final states have limited sensitivity to the signal and suffer from larger systematic uncertainty due to the large fake missing E_T background in events with high pileup. A 2D shape analysis of the di-lepton invariant and transverse masses for the different-flavour 0 and 1 jet final state which increases the sensitivity to the SM Higgs boson is combined with the cut and count analysis in the same-flavour final state. An excess of events above background is observed which is consistent with the expectations from the SM Higgs boson of mass around 125 GeV and has a statistical significance of 4.0σ for this mass. The best fit value of the signal strength for $m_H=125$ GeV is 0.76 ± 0.21 . Additional SM Higgs-like bosons are excluded in the mass range 128-600 GeV at 95% confidence level.

2.4 $H \rightarrow \tau\tau$

The $H \rightarrow \tau\tau$ search is performed using the final state signatures $e\mu$, $\mu\mu$, $e\tau_{had}$, $\mu\tau_{had}$, $\tau_{had}\tau_{had}$, where electrons and muons arise from leptonic τ decays and τ_{had} denotes a τ lepton decaying hadronically. Each of these categories is further divided into exclusive sub-categories based on the number and the type of jets in the event: (i) 2-jet category: events with one forward and one backward jet, consistent with the VBF topology, (ii) 1-jet category: events with at least one high p_T hadronic jet but not selected in the previous category. The second category is further split in two bins of reconstructed τ lepton p_T . In each of these categories, we search for a broad excess in the reconstructed $\tau\tau$ mass distribution. No signal is fitted to the zero-jet category which is used to constrain background normalisations, identification efficiencies and energy scales. The main irreducible background, $Z \rightarrow \tau\tau$ production, is evaluated from $Z \rightarrow \mu\mu$ events in data with muons replaced by simulated taus. The largest reducible backgrounds (W +jets, multijet production, Z +jets) are evaluated from various control samples in data. A broad excess of events is observed over a range of the Higgs boson mass consistent with the 125 GeV scalar boson. The observed (expected) significance for Higgs boson mass of 125 GeV is 2.85σ (2.62σ). The best-fit value of the signal strength is $\mu=1.1 \pm 0.4$, obtained in the global fit combining all channels included in this analysis. This result provides the first direct indication of the Higgs boson coupling to leptons.

2.5 $H \rightarrow b\bar{b}$

The Higgs boson search in bottom quark pair decay mode uses the most sensitive Higgs boson production mechanism in this channel, which is in association with a W or Z boson with the following decay modes: $W \rightarrow e\nu/\mu\nu$ and $Z \rightarrow ee/\mu\mu/\nu\nu$. The search is also performed for vector boson fusion process with 2 forward light quark jets in the event. The Higgs boson candidate is reconstructed by requiring two b-tagged jets in the event. The search is divided into events where the vector bosons have medium

Figure 2: The best-fit values of the signal strength μ for different di-tau final states and for the global fit combining all sub-channels (on the left). Expected and observed p-value plots for the combination of VHbb and VBFbb production (on the right).

or large transverse momentum and recoil away from the candidate Higgs boson. An MVA regression to better estimate the b-jet p_T is optimized for jets in simulated signal events and achieves a final di-jet mass resolution of 8-9% for $m_H = 125$ GeV. The performance of the regression algorithm is checked in data using W/Z+jets and top pair events. Events with higher transverse momentum bosons have smaller backgrounds and a better di-jet mass resolution. An MVA classifier, optimized for several different values of the Higgs boson mass, is used to separate signal and background events. The rates of the main backgrounds, consisting of W/Z+jets and top-quark events, are derived from signal-depleted control samples in data. The WZ and ZZ backgrounds with a Z boson decaying to a pair of b-quarks, as well as the single-top background, are estimated from simulation. The MVA classifier output distribution is used as the final discriminant in the limit setting. A mild broad excess is observed with a significance of 2.1σ at $m_H = 125$ GeV and signal strength $\mu = 0.97 \pm 0.48$ combining both the vector boson associated and vector boson fusion production processes.

3 Combination and Properties

The mass of the new boson is measured to be 125.7 ± 0.3 (stat.) ± 0.3 (syst.) GeV in the high resolution 2 photons and 4 leptons channels. The event yields obtained by the different analyses targeting specific decay modes and production mechanisms are consistent with those expected for the SM Higgs boson. The best-fit signal strength for all channels combined is 0.80 ± 0.14 at the measured mass. The consistency of the couplings of the observed boson with those predicted for the SM Higgs boson is tested in various ways, and no significant deviations are found. The spin-parity of the new boson is studied in the $ZZ^* \rightarrow 4\ell$ channel and the pure scalar hypothesis is found to be consistent with the observation when compared to six other spin-parity hypotheses. The data disfavors pure pseudoscalar hypothesis 0^- with a CLs value of 0.16%,

and disfavours the pure spin-2 hypothesis of a narrow resonance with the minimal couplings to vector bosons with a CLs value of 1.5%. The spin-1 hypotheses are disfavoured with an even higher confidence. The 2D shape analysis in the $WW \rightarrow 2\ell 2\nu$ channel of the di-lepton invariant and transverse masses for the different-flavour final state allows to perform the hypothesis separation test between the SM Higgs boson for quantum numbers and couplings against spin-2 hypothesis of a narrow resonance produced through the gluon fusion mechanism and with minimal couplings to the W^+W^- pair. Assuming the best fit value of the signal strength obtained for the individual hypotheses, the spin-2 hypothesis is disfavoured with respect to the SM with a CLs value of 16.3%.

4 Conclusion

The Higgs boson has been discovered in the high mass resolution bosonic decay modes $\gamma\gamma$ and $ZZ^* \rightarrow 4\ell$ at around 125 GeV. The $WW \rightarrow 2\ell 2\nu$ decay mode shows an excess compatible with the observed new boson. A broad excess of events is observed in the tau pair decay mode consistent with the 125 GeV Higgs boson signal providing the first direct indication of the Higgs boson coupling to leptons. The bottom quark pair decay in vector boson associated and vector boson fusion process shows a mild excess also consistent with the SM Higgs boson. Combining tau pair and b-quark pair decay modes, the significance for Higgs boson decay to fermions is more than 3σ showing the first direct evidence of Higgs-fermion coupling at the LHC. The spin / parity of the new boson is compatible with 0^+ , disavouring pure pseudoscalar and graviton-like states. The value of the mass measured for the Higgs boson is 125.7 ± 0.3 (stat) ± 0.3 (syst) GeV. The couplings of the new boson to fermions and vector bosons are found to be consistent with the Standard Model.

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