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Measurements of the Higgs properties with Run 2 data in the bosonic channels at CMS

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Recent results on the Higgs boson decays into WW^*, ZZ^* and $\gamma\gamma$, obtained with the 2016 data collected by the CMS experiment, are presented. The decays into a pair of W bosons was observed with a significance of 9.1 σ and has achieved a comparable precision in signal strength compared to the other two channels. The Higgs boson mass has been measured in the channel with a pair of Z bosons decaying into four leptons as $m_{\mathrm{H}} = 125.26 \pm 0.20$ (stat) ± 0.08 (syst) $= 125.26 \pm 0.21$ GeV, achieving the highest precision to-date.

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1. Introduction

The discovery at the LHC [1, 2] of a scalar boson at a mass around 125 GeV and with properties compatible with the standard model (SM) Higgs boson has been a milestone in particle physics. The SM Higgs boson decays at that mass value into WW* (hereafter simply referred to as WW), in ZZ* (hereafter referred to as ZZ) and in $\gamma\gamma$, with branching fractions of 22%, 2.7% and 0.23%, respectively. The diphoton and ZZ$\rightarrow 4\ell$ ($\ell = e,\mu$) decays have been the golden channels for the discovery and for measuring its properties, thanks to the excellent resolution in mass.

This report presents results based on proton-proton collision data collected at $\sqrt{s}$=13 TeV in 2016 by the CMS detector [3] and corresponding to 35.9 fb^{-1} of integrated luminosity. The recent new result in the WW channel, with first observation in the CMS data alone, will be reported, together with measurements in the two photons and 4 leptons channels. Further related measurements are described in different contributions to these proceedings for the rare decay in Zγ and $\gamma^*\gamma$ [4] and for the Higgs cross sections [5].

In all the decay channels, categories with additional objects target the different production modes: additional jets for vector boson fusion (VBF), additional leptons for associated vector boson (WH or ZH) or top quarks candidates for top associated production (t$\bar{\rm t}$H). The remaining untagged categories select events mainly originating from the dominant gluon gluon fusion (ggH) process. The results are quoted in terms of the signal strength modifier μ, defined as the ratio of the measured cross section times the branching fraction to the SM expectation.

2. Higgs into WW

The Higgs boson decay into a W pair was first studied in Run 1 at center-of-mass energies of 7 and 8 TeV in the leptonic channel. CMS obtained a significance of 4.3 standard deviations for a Higgs boson mass of 125.6 GeV [6] or 4.7 when combining with the associated top production channel [7]. Here the analysis on the 2016 Run 2 data [8] is presented. The branching ratio in the WW channel is relatively high, however the cleanest signature is in the leptonic channel, which implies that the Higgs mass can be poorly reconstructed due to the missing neutrinos. The signature is two opposite-sign leptons (either electrons or muons), missing transverse energy p_T, and additional jets or leptons when targetting different production modes. Both the different flavour (DF), $e\mu$, and same flavour (SF) e^+e^- and $\mu^+\mu^-$ channels are considered. The DF channel is affected by top background, but gives the highest sensitivity, especially in the 0-jet category. The SF channel is dominated by the Drell Yan (DY) background. The double-W boson production (WW) represents an irreducible source of background, which can however be reduced exploiting the spin zero nature of the Higgs boson, resulting in final state leptons closer in space in the signal compared to the WW background process.

Figure 1 shows in a schematic way the various categories for the selection and the fraction of production modes which are included in each of them. The signal strength modifiers are extracted from a binned maximum-likelihood fit of the signal and backgrounds processes to the data. The non-prompt lepton, top and DY backgrounds are estimated in a data-driven way, while the nonresonant WW background is estimated from the simulation with normalization taken from the fit procedure. In the DF ggH category, the signal is extracted from a 2-dimensional fit to the invariant mass $m_{\ell\ell}$ of the two leptons and to the transverse mass m_T, while the other categories use 1-dimensional fits.

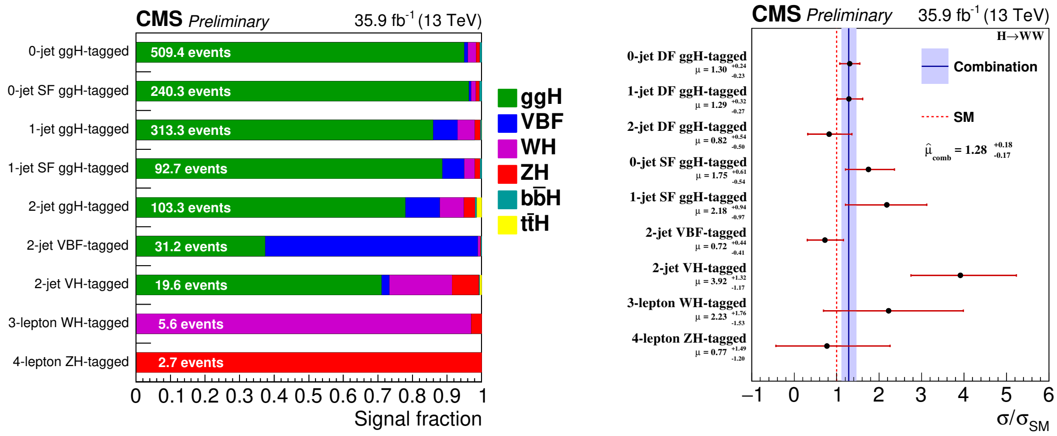

Figure 1: Left: Expected number of events in each category in the WW channel and composition of the production mode. Right: Observed signal strength modifiers for each category. The vertical continous line represents the combined value, together with its uncertainty at 68% confidence level shown as the shaded band. From [8].

The resulting signal strength modifiers, which are measured assuming $m_{\mathrm{H}} = 125.09$ GeV, are shown in Figure 1. A combined fit to all categories assuming the SM proportions yields

$$\mu = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10(\mathrm{stat}) \pm 0.11(\mathrm{syst})^{+0.10}_{-0.07}(\mathrm{theo}), \tag{2.1}$$

where the uncertainties are reported separately for statistical, experimental systematics and theoretical. The dominant ones are due to the estimation of the backgrounds and the lepton efficiencies. By combining all categories the observed (expected) significance correponds to 9.1 (7.1) standard deviations, giving the first observation of $\mathrm{H} \to \mathrm{WW}$ in the CMS experiment alone.

In the so-called k-framework, the two coupling modifiers for the vector and fermion couplings can be used to scale the expected production cross section and expected branching fractions to match the observation:

$$\sigma \times B(X \to \mathrm{H} \to \mathrm{WW}) = k_i^2 \frac{k_V^2}{k_{\mathrm{H}}^2} \sigma_{\mathrm{SM}} \times B_{\mathrm{SM}}(X \to \mathrm{H} \to \mathrm{WW}), \tag{2.2}$$

where k_{H} is the Higgs total width modifier, and $k_i = k_{\mathrm{F}}$ for ggH and $\mathrm{t\bar{t}H}$, $k_i = k_{\mathrm{V}}$ for VBF and VH. The two-dimensional likelihood profile from the fit to the data is shown in Fig. 2, demonstrating the strong constraint to the k_{V} coupling, $k_{\mathrm{V}} = 1.10 \pm 0.08$, in this decay channel.

3. Higgs into ZZ

The $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$, where $\ell = e, \mu$, suffers from low statistics, but it has the highest signal-to-background ratio. The final state leptons allow a full reconstruction of the kinematics of the Higgs boson, and therefore also to constrain properties like its spin-parity and a mass measurement. Figure 3 shows the invariant mass of the 4 leptons after all selection cuts in the 2016 data [9]. A

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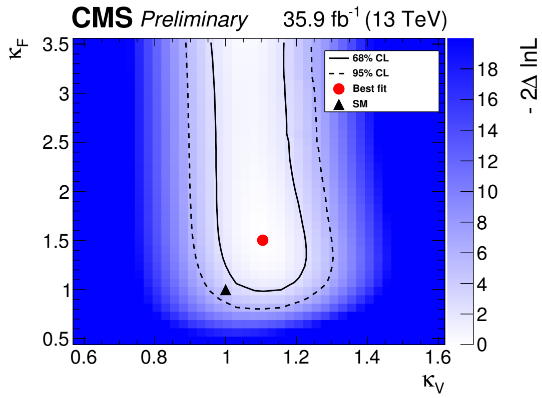

Figure 2: Likelihood profile as a function of the coupling modifiers associated to the fermion (k_{F}) and vector boson (k_{V}) couplings. From [8].

clear peak around 125 GeV is seen, in very good agreement with the expectation for a SM Higgs boson. The irreducible background due to ZZ is evaluated from the simulation, with k-factors to correct the normalization to NNLO, while the Z+X background is estimated with a data-driven technique. In order to improve the sensitivity, the events are classified according to seven exclusive categories, targeting the different production modes, as shown by the labels on the vertical axis in Fig. 3-left. The signal strength modifiers μ are extracted from a two-dimensional fit to the reconstructed four-lepton mass $m_{4\ell}$ and a discriminant that takes into account the kinematics of the decay products, which differs between the signal and the dominant ZZ background.

The observed μ values are shown for the seven categories in Fig. 3. A simultaneous fit to all categories yields $\mu = 1.05^{+0.15}_{-0.14}(\mathrm{stat})^{+0.11}_{-0.09}(\mathrm{syst})$. The dominant systematic uncertainty is due to the determination of the lepton efficiency (ranging from 2.5 to 9% according to the final state) and to the luminosity measurement (2.5%). The main theoretical sources of systematics are due to the ggH prediction and the migrations across categories.

For the determination of the mass a three-dimensional fit is performed, which also takes into account the per-lepton p_T resolution. In addition the mass of the on-shell Z in the Higgs decay is constrained to be equal to the Z nominal mass. Using these constrains, m_{H} is measured to be $m_{\mathrm{H}} = 125.26 \pm 0.20(\mathrm{stat}) \pm 0.08(\mathrm{syst}) = 125.26 \pm 0.21$ GeV, which is more precise than the Run 1 ATLAS+CMS combination of $m_{\mathrm{H}} = 125.09 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})$ [10]. The uncertainty is still dominated by the statistical one, while the systematic uncertainty is mainly due to the lepton energy scale.

4. Higgs into $\gamma\gamma$

The final results on Higgs properties in the diphoton channel with the 2016 data have been recently published by CMS [11]. Despite the small branching ratio this channel provides precise measurements of the Higgs boson properties, thanks to the excellent mass resolution. Boosted decision trees (BDTs) are used for the identification of the prompt photons, for the vertex assignment and for the diphoton selection. The energy of the photons is reconstructed with a multivariate re-

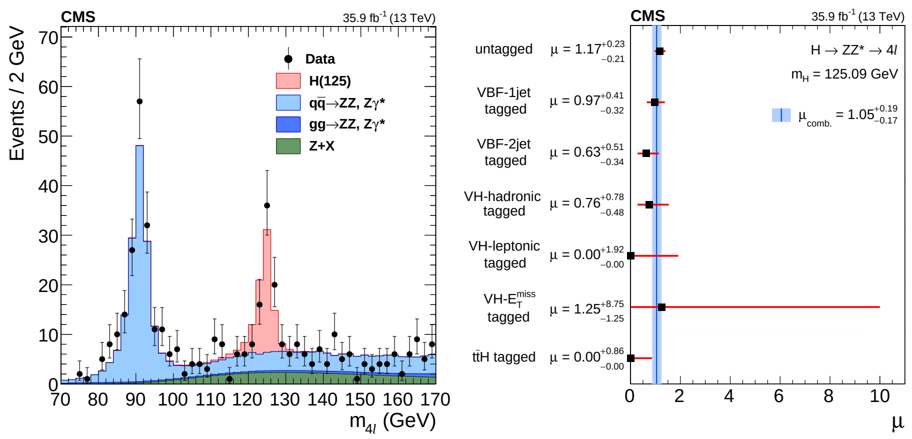

Figure 3: Left: Distribution of the reconstructed invariant mass of the four leptons, in the region around the Higgs boson mass. Right: Observed signal strength modifiers for the seven categories in the H$\to$ ZZ $\to \ell\ell$ decay channel. The combined value is shown by the continous vertical line, and its uncertainty as the shaded region. From [9].

gression technique and calibrated in data on Z$\to$ *ee* events. Thirteen categories are optimized to enhance the different production processes. The mass resolution, computed as the width at half maximum of the distribution, varies from 1.3% to 2.3% according to the category.

Figure 4-left displays the invariant mass of the two photons after all selections for the categories combined, showing the high statistics of the signal in this decay channel. The dashed line shows the fit to the background which is extracted from the data themselves. Figure 4-right shows the extracted μ values grouped per production mode. The combined signal strength yields a value $\mu = 1.18^{+0.12}_{-0.11}(\mathrm{stat})^{+0.09}_{-0.07}(\mathrm{syst})^{+0.07}_{-0.06}(\mathrm{theo})$, obtained profiling m_{H}. The main experimental systematic uncertanties are due to the modelling of the photon shower shape and energy scale and to the luminosity. For the VBF categories the jet energy scale is dominant. The main theory uncertainties, besides those on the signal production cross sections, are on the QCD effects on the signal acceptance, estimated by varying the renomalization and factorization scales, and on the diphoton branching ratio.

5. Summary

The three decay bosonic channels have been measured with more and more precision by the CMS Collaboration with the 2016 data. The events have been splitted in categories targeting the different production modes and enhancing the sensitivity. The WW channel has by now a μ value with similar precision to the $\gamma\gamma$ and ZZ channels. All three are included in the overall preliminary combination [12] of $\mu = 1.17 \pm 0.10$. Up to now all the extracted couplings confirm the expectations inside uncertainties for a standard model Higgs boson. The ZZ decay channel provides the most precise mass measurement to-date, $m_{\mathrm{H}} = 125.26 \pm 0.21$ GeV.

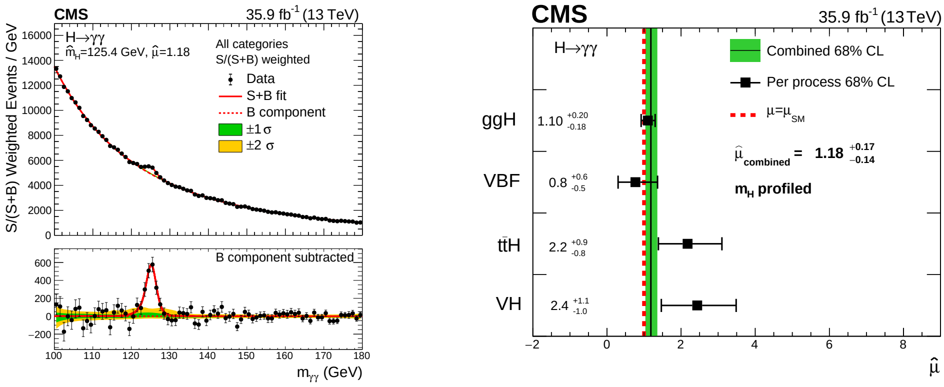

Figure 4: Left: Distribution of the reconstructed invariant mass of the two photons. The 13 categories are here all summed together, weighted by their sensitivity. The lower panel shows the data after the subtraction of the background, with the green and yellow bands showing the uncertainties on the background, which is derived from a fit to the data. Right: Signal strength modifiers observed in the data for each production mode (dots) and for the combination (vertical green line with its uncertainty band). From [11].

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