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Study of Higgs boson production and decay in the ZZ and WW channels

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The CMS Higgs boson studies with the $H \rightarrow ZZ^{*} \rightarrow 4l$ and $H \rightarrow WW^{*} \rightarrow 2l2\nu$ decay channels are presented. In particular the results of all the analyses exploring these final states with enough sensitivity to contribute to the measurement of the properties of the new boson are discussed. The full CMS dataset collected so far has been analysed and it corresponds to $5.0\,\mathrm{fb}^{-1}$ of 7 TeV and $19.5\ \mathrm{fb}^{-1}$ of 8 TeV pp collisions.

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†The spin-parity separation studies are not discussed in this document; a dedicated presentation on this topic was made during the conference.

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PoS(EPS-HEP 2013)263

1. Introduction

The standard model (SM) of electroweak interactions relies on the existence of the Higgs boson (H, with mass m_H), a scalar particle associated with the field responsible for the spontaneous electroweak symmetry breaking. In July 2012, the CMS and ATLAS experiments announced [1, 2] the discovery of a new boson at a mass around 125 GeV. As the properties of the Higgs boson are uniquely predicted by the SM for a given mass value, from that moment the study of the new boson properties, with the full dataset collected during the 2011 and 2012 LHC runs, has been the highest priority of the CMS collaboration. In particular the two high-sensitivity channels, $H \to ZZ^* \to 4l$ and $H \to WW^* \to 2l2\nu$, have been used to measure with the highest possible accuracy the mass of the new state, its couplings to vector bosons, and extract information on the production mechanisms. A detail description of the CMS detector is given in [3].

2. $H \to ZZ^* \to 4l$

2.1 Analysis description

The four lepton channel provides the cleanest possible experimental signature, a peak in the four lepton mass spectrum on top of a flat and small background. The main drawback is the low branching ratio, therefore this analysis relies critically on the reconstruction and identification efficiency of prompt and isolated leptons. The background sources include an irreducible four-lepton contribution from direct ZZ (or $Z\gamma^*$) production via $q\bar{q}$ annihilation and gg fusion. Reducible contributions arise from the $Zb\bar{b}$ and $t\bar{t}$ processes where the final states contain two prompt leptons and two b jets producing secondary leptons. Additional background of instrumental nature arises from Z+jets, $Z+\gamma$+jets and WZ+jets where jets are misidentified as leptons. The analysis relies on simulation to evaluate the irreducible ZZ background contribution and on a data-driven method, based on the probability for a reconstructed secondary lepton to pass the isolation and identification requirements, to evaluate the reducible and instrumental background contributions. The analysis makes use of the measured four-lepton mass, kinematic discriminants, and event categories based on jet multiplicity.

First of all the $4l$ signal candidates are selected; the details of the event selection can be found in [4]. The m_{4l} distribution, combining the $4e$, 4μ, and $2e2\mu$ channels is shown in Fig. 1 and compared with the expectation from SM background processes. The observed distribution is in good agreement with the expectation. The $Z \to 4l$ resonance peak at $m_{4l} = m_Z$ is observed with the expected normalisation and shape. The event distribution at higher mass is dominated by the irreducible ZZ background. A clear peak around $m_{4l} = 126$ GeV is seen, confirming the results reported in [1].

A multi-dimensional analysis is performed in order to exploit the kinematic differences of the $4l$ decay in a Higgs-boson event with respect to a ZZ-background event. A matrix element likelihood approach is used to construct a kinematic discriminant (K_D) based on the probability ratio of the signal and background hypotheses. The leading-order matrix elements define the probabilities for each value of m_{4l} as a function of five angles and the masses of the two reconstructed Z bosons, which fully define the kinematic of the event.

Then, to improve the sensitivity to the production mechanisms the event sample is split into two

PoS(EPS-HEP 2013)263

categories based on the jet multiplicity. The two categories are defined in the following way: category I contains the events with fewer than two jets, category II contains the events with at least two jets. The jets must have p_T greater than 30 GeV and the details of their selection are described elsewhere [4]. In each of the categories an extra discriminating variable is used as an additional dimension in the fit together with m_{4l} and K_D: in category I the transverse momentum divided by the mass of the four lepton system (p_T/m_{4l}) is used to discriminate the vector-boson-fusion (VBF) and the vector-boson-associated (VH) production mechanisms from gluon fusion. In category II a linear discriminant (V_D) is formed combining two VBF sensitive variables, the difference in pseudorapidity and the invariant mass of the two leading jets. The discriminant is tuned to separate VBF from gluon fusion processes. In category I (II), about 5% (20%) of the signal events are expected to come from the VBF production mechanism.

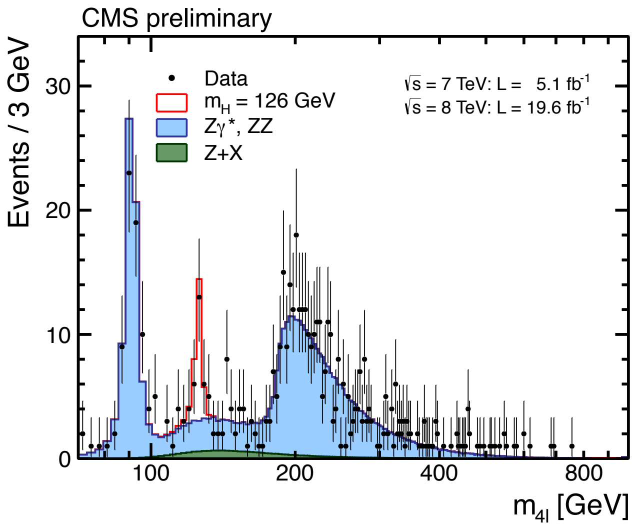

Figure 1: Distribution of the four-lepton reconstructed mass in for the sum of the $4e$, 4μ, and $2e2\mu$ channels. Points represent the data, shaded histograms represent the background and the unshaded histogram the signal expectation. The expected distributions are presented as stacked histograms. The measurements are presented for the sum of the data collected at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. No event is observed for m_{4l} >800 GeV.

2.2 Statistical Interpretation of the results

The selected events are split into twelve sub-categories based on three final states, two running periods (7 and 8 TeV) and two jet categories. These events are examined for 187 hypothetical SM-like Higgs boson masses in a range between 110 GeV and 1000 GeV. For events in category I, a three dimensional model of (m_{4l}, K_D, p_T/m_{4l}) is used for masses below 180 GeV while for higher masses a two dimension one of (m_{4l}, K_D) is used. In category II a three dimensional model of (m_{4l}, K_D, V_D) is used for the full mass range. The modified frequentist construction CL_s is adopted for reporting exclusion limits. A SM-like Higgs boson is excluded by the four-lepton channels at 95% confidence level (CL) in the mass range 130-827 GeV (for an expectation of 113.5-778 GeV). The minimum of the local p-value, representing the significance of local excesses relative to the

PoS(EPS-HEP 2013)263

background expectation, is reached around $m_H = 125.8$ GeV and corresponds to a local significance of 6.7σ (for an expectation of 7.2σ). This constitutes an observation of the new boson in the four-lepton channel alone. As a cross-check, the 1D (m_{4l}) and 2D (m_{4l}, K_D) models have also been used and significances of 4.7 and 6.6 standard deviations are observed (5.6 and 6.9 expected). All this is shown in Fig. 2 (left).
The signal strength relative to the expectation of the SM Higgs boson, $\mu = \sigma/\sigma_{SM}$, is measured to be $\mu = 0.91^{+0.30}_{-0.24}$ at 125.8 GeV. When considering the two categories separately, μ is $0.85^{+0.32}_{-0.26}$ in category I and $1.22^{+0.84}_{-0.57}$ in category II. The jet categorisation, the transverse momentum spectrum and the VBF-sensitive variables are used to disentangle the production mechanisms of the observed state. The production mechanisms are split into two categories depending on whether the production is induced by vector bosons (VBF, ZH, WH) or fermions (gluon fusion loop with quarks, or the associated production with a top pair). Two respective signal strength modifiers (μ_F, μ_V) are introduced as scale factors to the SM expected cross sections. A two dimensional fit is performed for the two signal strength modifiers assuming a mass hypothesis of $m_H = 125.8$ GeV. The likelihood contours for the signal strength modifiers associated with fermions and vector bosons are shown for 68% and 95% CL in Fig. 2 (right). The best fit values are $\mu_V = 1.0^{+2.4}_{-2.3}$ and $\mu_F = 0.9^{+0.5}_{-0.4}$. The measured values are consistent with the expectations from the production of a SM Higgs boson.

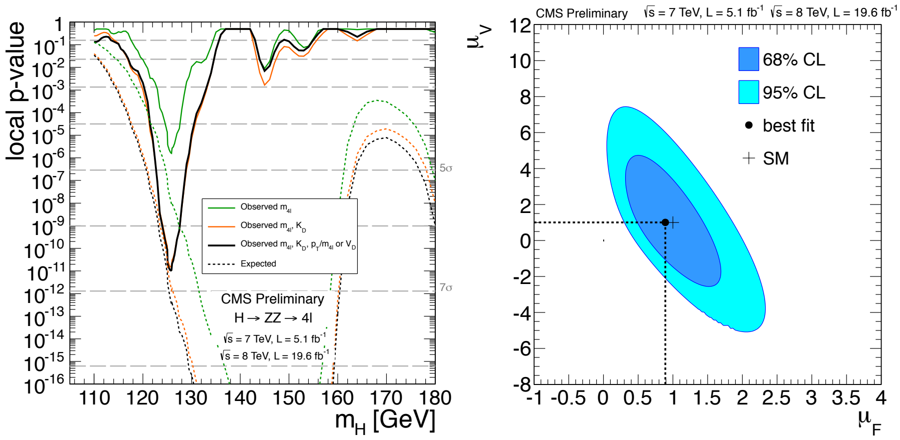

Figure 2: Significance of the local excess with respect to the SM background expectation as a function of the Higgs boson mass for the 1D(m_{4l}), 2D(m_{4l}, K_D), 3D(m_{4l}, K_D, p_T/m_{4l} or V_D) models (left). Likelihood contours on the signal strength modifiers associated with fermions (μ_F) and vector bosons (μ_V) shown at 68% and 95% CL (right).

3. $H \to WW^* \to 2l2\nu$

3.1 The inclusive search

The search strategy for $H \to WW^* \to 2l2\nu$ is based on a signature with two isolated, oppositely charged, high p_T leptons (electrons or muons) and large missing transverse energy due to the undetected neutrinos. The experimental signature is very clean and compared to the $H \to ZZ^* \to 4l$ case the search is favoured by the larger $H \to WW$ branching ratio. The main drawback is the poor mass resolution, and for this reason the main analysis challenge is the control of the background

PoS(EPS-HEP 2013)263

processes. Data-driven techniques are used to predict the contributions for the top, W+jets and DY backgrounds. The di-boson WZ and ZZ contributions are taken from simulation and the WW irreducible background is determined from data fitting the sidebands of the event distributions. All the details about the background estimation can be found in [5].

To improve the signal sensitivity, the events are separated according to lepton flavour into same-flavour (e^+e^- and $\mu^+\mu^-$) and opposite-flavour ($e^\pm\mu^\mp$) samples and according to jet multiplicity into 0-jet and 1-jet samples. Events with more than 1 jet are considered in the dedicated search for VBF events that will be discussed in the next paragraph. The details of the event selection can be found elsewhere [5]. In general a cut-based approach is chosen for the final selection in all categories. Because the kinematics of signal events change as a function of the Higgs mass, separate optimisations are performed for different m_H hypotheses in a cut-based analysis. In addition, a two-dimensional shape analysis technique is also pursued for the different-flavor final state in the 0-jet and 1-jet categories. This second analysis is more sensitive to the presence of the signal and it is used as baseline for the final results. The two-dimensional shape analysis exploits the correlation of two kinematic variables: the invariant mass of the dilepton system and the Higgs boson transverse mass.

The combination of the searches using the 7 TeV and 8 TeV data excludes a SM-like Higgs boson with a mass in the range 128-600 GeV at 95% CL. The expected exclusion range under the background only hypothesis is 115-575 GeV. An excess of events is observed for hypothetical low Higgs boson masses, which makes the observed limits weaker than the expected ones. Due to the poor mass resolution of this channel the excess extends over a large mass range. The significance of the excess with respect to the background only hypothesis at $m_H = 125$ GeV is 4.0 standard deviations. The best fit value of σ/σ_{SM} in the low mass range is shown in Fig. 3, as well as the observed significance together with the expected one for the $m_H = 125$ GeV Higgs signal hypothesis.

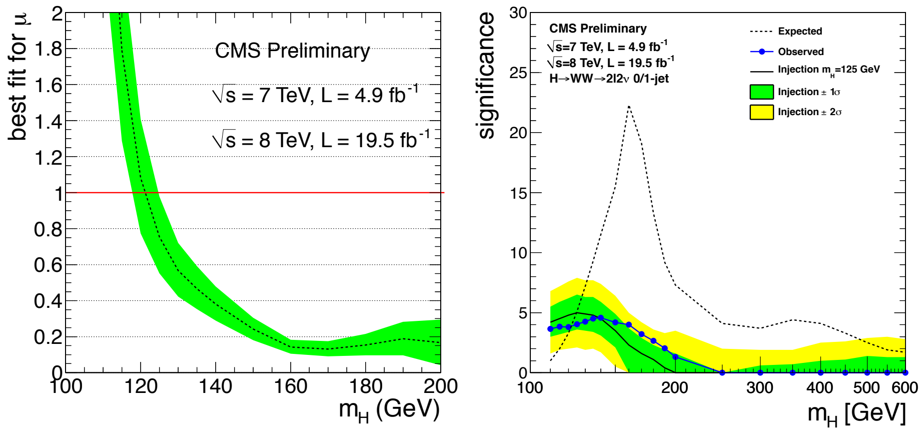

Figure 3: The best fit value of σ/σ_{SM} (left) and the observed and expected significances (right) as function of m_H for the combined 7+8 TeV analysis. The dashed line shows the significance expected for the search for a Higgs boson with mass m_H if a Higgs boson of this mass exists. The solid line and coloured bands show the expected significance at a mass m_H if the true Higgs boson mass is 125 GeV. The dots show the observed significance of the excess.

PoS(EPS-HEP 2013)263

3.2 Measurement of production mechanisms

Additional analyses of the $H \to WW^* \to 2l2\nu$ final state have been performed targeting specific production mechanisms for the Higgs boson. In particular the CMS collaboration have published so far a search for the associated WH production in the three lepton final state, and a search for VBF production not yet updated to the full dataset (it makes use of all the 7 TeV data and of the first 12.1 fb^{-1} of the 8 TeV data). The WH analysis [6] selects events with three isolated leptons (electrons or muons) and large missing transverse energy, targeting events where the associated W boson decays leptonically. To improve the sensitivity to the signal the events are split into two categories: events that have at least an opposite-sign same-flavour lepton pair and events that don't have any. While only $1/4$ of the signal events are selected in the second category, the expected background is also smaller since SM processes leading to this final state have small cross section. For the signal extraction a shape-based analysis is carried out, based on the distribution of the smallest distance between opposite-charge leptons. The VBF analysis [7] uses the same event selection of the inclusive search, but it requests the presence of at least 2 jets with $p_T > 30$ GeV satisfying the typical VBF event topology: the two jets must be well separated in pseudorapidity and with large di-jet invariant mass. With this selection about 80% of the signal events are expected to be produced via VBF. The cut-based approach of the inclusive search is used for the signal extraction. The VH and VBF tags provided by these two analyses are used together with the inclusive search to disentangle the production mechanisms of the observed state. As for the $4l$ analysis, the production mechanisms are split into two categories depending on whether the production is induced by vector bosons (VBF, ZH, WH) or fermions (gluon fusion loop with quarks, or the associated production with a top pair). The two signal strength modifiers μ_F, μ_V are introduced and the two dimensional fit is performed assuming a mass hypothesis of $m_H = 125.8$ GeV. The best fit values are $\mu_V = 0.2^{+0.7}_{-0.6}$ and $\mu_F = 0.7^{+0.2}_{-0.2}$, consistent with the expectations from the production of a SM Higgs boson.

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PoS(EPS-HEP 2013)263