Constraints on the Higgs boson width from off-shell production and decay to $ZZ \rightarrow \ell\ell'\ell'\ell$ and $\ell\ell\nu\nu$

The CMS Collaboration

Abstract

We constrain the total Higgs boson width, $\Gamma_H$, using off-shell production and decay to four leptons, $4\ell$, or two leptons plus two neutrinos, $2\ell2\nu$, with $\ell = e, \mu$. The analysis is based on the data collected in 2012 by the CMS experiment at the LHC, corresponding to an integrated luminosity $\mathcal{L} = 19.7\text{fb}^{-1}$ at a center-of-mass energy $\sqrt{s} = 8\text{TeV}$. The $4\ell$ analysis uses the $ZZ$ invariant mass distribution as well as a matrix element likelihood discriminant to separate the $ZZ$ components originating from gluon- and quark-initiated processes. The $2\ell2\nu$ analysis relies on the transverse mass or missing transverse energy distributions in jet categories. An unbinned maximum-likelihood fit of the above distributions, combined with the $4\ell$ measurement near the resonance peak, leads to an upper limit on the Higgs boson width of $\Gamma_H < 4.2 \times \Gamma_H^{SM}$ at the 95% confidence level, assuming $\Gamma_H^{SM} = 4.15\text{MeV}$. This result considerably improves over previous experimental constraints from the measurement near the resonance peak.
1 Introduction

The discovery of a new boson consistent with the standard model (SM) Higgs boson by the ATLAS and CMS collaborations has been recently reported \[1–3\]. The mass of the new boson \(m_H\) has been measured to be around 125 GeV, and the spin-parity properties have been further studied by both experiments, favouring the scalar hypothesis \[4–7\]. The measurement was found consistent with a single narrow resonance and direct constraints of 3.4 GeV at the 95\% confidence level (CL) in the 4\(\ell\) decay channel \[7\] and of 6.9 GeV at the 95\% CL in the \(\gamma\gamma\) decay channel \[8\] on the new boson width \(\Gamma_H\) have been reported by the CMS experiment. With the currently available data, the sensitivity for a direct width measurement at the resonance peak is therefore far beyond the expected width of around 4 MeV for the SM Higgs boson.

In a recent paper \[9\], it has been proposed to constrain the Higgs boson width using the off-shell Higgs boson production and decay in ZZ away from the resonance. In the gluon fusion production mode, the off-shell production cross section has been shown to be sizeable at high ZZ invariant mass \(m_{ZZ}\) \[10, 11\], with a ratio relative to the on-peak cross section of the order of 8\% at a center-of-mass energy \(\sqrt{s} = 8\) TeV. This ratio can be enhanced up to about 20\% when a kinematical selection used to extract the signal in the resonant region is taken into account. This arises from the vicinity of the on-shell Z pair production threshold, and is further enhanced at the on-shell top pair production threshold.

The production cross section as a function of \(m_{ZZ}\) can be written as:

\[
\frac{d\sigma_{gg\to H\to ZZ}}{dm_{ZZ}^2} \propto g_{ggH}^2 g_{HZZ}^2 \frac{F(m_{ZZ})}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2},
\]

where \(g_{ggH}\) (\(g_{HZZ}\)) is the coupling constant of the Higgs boson to gluons (to Z bosons), and \(F(m_{ZZ})\) is a function which depends on the (virtual) Higgs and Z boson production and decay dynamics. In the resonant and off-shell regions, the integrated cross sections are

\[
\sigma_{on-peak}^{gg\to H\to ZZ} \propto \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}, \quad \sigma_{off-peak}^{gg\to H\to ZZ} \propto g_{ggH}^2 g_{HZZ}^2.
\]

The on-peak cross section is therefore unchanged if the squared product of the coupling constants \(g_{ggH}^2 g_{HZZ}^2\) and the total width are scaled by a common factor. On the contrary, away from the resonance the cross section is independent of the total width and therefore increases linearly with the above factor. From Eqs. (1, 2) it is evident that the ratio of off-shell and on-shell production and decay rates in the \(H \to ZZ\) channel leads to a direct measurement of \(\Gamma_H\) as long as the ratio of coupling constants remains invariant, e.g. if there are no new light particles in the gluons fusion loop which would affect the coupling constants differently at the low and high \(m_{ZZ}\) values. The above formalism is presented for the gluon fusion process, but it equally applies to the vector boson fusion (VBF) production.

In this document, a method for the measurement of the Higgs boson width is presented. From the significant \(H \to ZZ \to 4\ell\) on-shell signal we infer the lower bound \(\Gamma_H > 0\) and the upper bound is obtained from the ratio of off-shell production and decay rates in the \(H \to ZZ \to 4\ell\) and \(H \to ZZ \to 2\ell2\nu\) channels to the above on-shell rate, where \(\ell = e, \mu\). The analysis is based on the dataset collected by the CMS experiment during the 2012 LHC running period. The data correspond to an integrated luminosity of 19.7 fb\(^{-1}\) of pp collisions at a center-of-mass energy of \(\sqrt{s} = 8\) TeV. The analysis uses the same algorithms for lepton, jet, and missing transverse energy reconstruction and event selection as presented and used in Refs. \[7, 12\].
2 CMS detector and object reconstruction

A detailed description of the CMS detector can be found in Ref. [13]. The key components of the detector include a silicon pixel and strip tracker, covering the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$, and $\theta$ is the polar angle of the trajectory of the particle with respect to the beam direction. The tracker is surrounded by a crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadron calorimeter (HCAL), which cover $|\eta| < 3.0$. A steel/quartz-fiber Cherenkov forward detector (HF) extends the calorimetric coverage to $|\eta| < 5.0$. The tracking and calorimeter systems are housed in a 3.8 T solenoidal magnet. Muon chambers are embedded in the steel return yoke of the magnet up to $|\eta| < 2.4$.

Electrons are reconstructed in the pseudorapidity range $|\eta| < 2.5$ by requiring the matching of an energy cluster in the ECAL with a track in the silicon tracker [14–17]. Electron identification relies on a multivariate technique that combines observables sensitive to the amount of bremsstrahlung along the electron trajectory, the geometrical and momentum matching between the electron trajectory and associated clusters, as well as shower-shape observables. Additional requirements are imposed to reject electrons produced by photon conversions.

Muons are reconstructed within $|\eta| < 2.4$ using two algorithms [18]: one in which tracks in the silicon tracker are matched to signals in the muon detectors, and the other in which a global track fit is performed, combining the silicon tracker and the muon system information in the fit. The muon candidates used in the analysis are required to be successfully reconstructed by both algorithms. Further identification criteria are imposed on the muon candidates to reduce the misidentification rate. These include the number of measurements in the tracker and in the muon systems, the fit quality of the global muon track and its compatibility with the primary vertex.

Electrons and muon energy corrections and calibration as described in Ref. [7] are applied. The leptons from a Z boson decay are expected to be isolated from hadronic activity in the event. This is achieved by imposing a maximum value (typically about 10%) on the ratio of the scalar sum of particle-flow objects [19, 20] momentum within a cone of $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ (where $\phi$ is the azimuthal angle) around the lepton candidate direction, to the transverse momentum ($p_T$) of the candidate.

Jets are reconstructed from particle-flow objects using the anti-$k_T$ clustering algorithm [21] with a distance parameter of 0.5, as implemented in the FASTJET package [22, 23]. Jet energy corrections are applied as a function of $\eta$ and $p_T$ of the jet [24]. Jets that originate from the hadronization of b quarks are referred to as “b jets”. The CSV b-tagging algorithm [25] is used to identify such jets.

The missing transverse energy, $E_T^{\text{miss}}$, is defined as the magnitude of the momentum imbalance, which is the negative of the vectorial sum of transverse momenta of all particle-flow objects identified in the event.

3 Analysis strategy

We employ the method discussed in Eqs. (1, 2) for a direct measurement of $\Gamma_H$. It is convenient to express the width through a dimensionless parameter $r = \Gamma_H/\Gamma_H^{SM}$ using the fixed value of SM expectation $\Gamma_H^{SM} = 4.15$ MeV calculated at $m_H = 125.6$ GeV [26]. This $\Gamma_H^{SM}$ value is treated as a reference without associated uncertainties. It is also convenient to express Eqs. (1, 2) in terms of the $\kappa$ scaling factors for SM couplings introduced in Ref. [27], $\kappa_8 = g_{ggH}^S/g_{ggH}^{SM}$ and
\[ \kappa_Z = \frac{g_{hZZ}}{g_{hZZ}^{SM}}, \]

\[ \sigma_{on-peak}^{gg \rightarrow H \rightarrow ZZ} = \frac{\kappa_Z^2}{\kappa_\gamma^2} (\sigma \cdot B)_{SM} \equiv \mu (\sigma \cdot B)_{SM}, \quad (3) \]

where \((\sigma \cdot B)\) is the cross section times branching fraction to ZZ at the measured mass of \(m_H = 125.6\) GeV, and the quantity \(\mu\) defined by this relationship is referred to as the “signal strength”.

In the off-peak region:

\[ \frac{d\sigma_{off-peak}^{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}} = \kappa_Z^2 \frac{d\sigma_{on-peak}^{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}} = \mu r \frac{d\sigma_{off-peak,SM}^{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}}, \quad (4) \]

The above relations of Eqs. (3) and (4) can be used as a direct and model-independent constraint on the total Higgs boson width \(\Gamma_H\). As a matter of fact, once a value of \(\mu\) is constrained from an independent measurement or calculation, using for example \(\mu = 1\) assuming the SM expectations in the peak, or using the measured value from the the 4\(\ell\) on-peak analysis [7], one obtains the result that the off-peak cross section as a function of \(m_{ZZ}\) is proportional to \(\Gamma_H\).

The VBF production mechanism is expected to also produce an off-shell tail and interference with VBF background processes. Since simulation studies show that this effect may be as large as 10% in the invariant mass regions considered, this component is taken into account in this analysis. Equation similar to Eqs. (3) and (4) can be written for the VBF production, but the coupling scalings to be considered are different \((\kappa_V^2)\) since in the VBF case both production and decay involve interactions with vector bosons. The partial signal strengths for the gluon fusion \((\mu_F)\) and VBF \((\mu_V)\) production can be constrained from independent measurements with the on-peak Higgs boson production. However, in this analysis we assume that \(\mu_V = \mu_F = \mu\), which is a mild assumption in this analysis given that the gluon fusion production is known to dominate.

The above formalism considers pure signal production, while analysis of the data requires treatment of background and its interference with signal for the processes with the same initial and final states (gluon fusion and VBF). For example, the non-resonant \(gg \rightarrow ZZ\) contribution through a fermion box diagram leads to a destructive interference with the signal process and a decrease of the signal yield in the off-peak region. This effect is negligible in the on-peak region due to the narrow signal peak.

Probability distribution functions are constructed for each event to be either signal or background. The parameterization of the \(gg \rightarrow ZZ\) and VBF processes includes three correlated distributions for signal, background, and their interference. Each process is characterized by the expected number of events \(N_{\text{process}}\) and the likelihood for each event \(i\) can be written following Refs. [9, 28]

\[ L_i = N_{gg \rightarrow ZZ} \left[ \mu r \times P_{\text{sig}}^{gg} + \sqrt{\mu r} \times P_{\text{int}}^{gg} + P_{\text{bkg}}^{gg} \right] \\
+ N_{VBF} \left[ \mu r \times P_{\text{VBF}}^{VBF} + \sqrt{\mu r} \times P_{\text{int}}^{VBF} + P_{\text{bkg}}^{VBF} \right] \\
+ N_{q\bar{q} \rightarrow ZZ} P_{\text{bkg}}^{q\bar{q}} + ..., \quad (5) \]

where \(P_{\text{sig}}, P_{\text{int}}\) and \(P_{\text{bkg}}\) are the signal, interference, and background probability distribution functions, respectively, in a given production mode and defined as functions of observables discussed below. The list of background processes is extended beyond those included above depending on the final state. The analysis of the on-shell production of \(H \rightarrow ZZ \rightarrow 4\ell\) [7] has a similar parameterization, with the exception that interference contribution is negligible and \(\mu\) stands on place of \(\mu r\), see Eqs. (3) and (4).
The measurement of the off-shell production leads to the measurement of the product $\mu r$, while the measurement of the on-shell production of $H \rightarrow ZZ \rightarrow 4\ell$ provides $\mu$ [7]. The combined analysis leads to a self-contained measurement of $r$, that is $\Gamma_H$, within the $H \rightarrow ZZ$ channel. It allows to implement all correlations and also allows for the cancellation of systematic uncertainties that are common to the on-peak and off-peak analyses, such as mass-independent terms of the cross-section calculation or the LHC luminosity. The other approach is to constrain $\mu = 1$ with associated systematic uncertainties from theoretical calculations. Finally, this analysis can be used to constrain $\kappa_g$, $\kappa_Z$, and $\kappa_W$ directly in a joint fit of LHC data. We do not pursue the last two approaches in this analysis, but provide the options to do so as an extension of analysis presented here.

4 Event samples and Monte Carlo simulation

The data and background process Monte Carlo (MC) samples used in this analysis are the same as those described in Refs. [7] and [12]. Data were recorded by the CMS experiment during 2012 and correspond to an integrated luminosity of $L = 19.7 \pm 0.5$ fb$^{-1}$ at a center-of-mass energy of 8 TeV [29].

In addition, $gg \rightarrow 4\ell$ and 2$\ell$2$\nu$ events have been generated at the leading order (LO) including the Higgs boson signal as well as the background and their interference using recent versions of two different MC generators: GG2VV 3.1.5 [11, 30, 31] and MCFM 6.7 [32, 33], in order to cross-check theoretical inputs. The Higgs boson mass is set to the measured value obtained in Ref. [7] ($m_H = 125.6$ GeV) and the Higgs boson width is set to the corresponding expected SM width ($\Gamma_H = 4.15$ MeV). The use of LO is necessary because the two component processes are generated at the same time, and no calculation is available for the fermion box $gg \rightarrow ZZ$ continuum process beyond LO. Unphysical samples containing signal only and background only components have also been generated to model the corresponding probability density functions. Samples with scaled couplings and widths corresponding to $r = 25$ have also been generated to check the normalization of the components.

The $gg \rightarrow 4\ell$ samples have been generated with CTEQ6L LO parton density functions (PDFs) [34]. The renormalization and factorization scales are set to $m_{ZZ}/2$ (running scales) for MCFM samples. Fixed scales equal to $m_H/2$ have been used for the generation of the GG2VV samples, and they are therefore reweighted using an $m_{ZZ}$-dependent factor corresponding to the ratio of the running scale over the fixed scale cross sections. The $gg \rightarrow 2\ell 2\nu$ samples have been generated with MSTW2008 LO PDFs [35]. The renormalization and factorization scales are set to $m_{ZZ}/2$ (running scales). To avoid limitations in the theoretical computation a few very loose requirements at generator level are applied in GG2VV. It has been checked that their effect is negligible ($\ll 1\%$) using the MCFM samples, which do not have these limitations.

Higher-order corrections for the gluon fusion signal process are known to next-to-next-to-leading order (NNLO) and next-to-next-to-leading logarithm (NNLL) for the inclusive cross section [26] and to NNLO as a function of $m_{ZZ}$ [36]. Even if, for the continuum background, no exact calculation exists for any higher order than LO, it has been recently shown in Ref. [37] that the soft collinear approximation can describe the background cross section and therefore the interference at NNLO with good precision. Following Ref. [37], we assign to the LO background cross section a K-factor equal to the one used for the signal, and consequently also the same K-factor to the interference contribution. For all samples, a MC reweighting based on the generated value of $m_{ZZ}$ is used for this purpose. The limited theoretical knowledge of the background K-factor at NNLO (and therefore of the interference) is accounted for by
including a systematic uncertainty. It has to be noticed that the impact of the choice of this uncertainty on the measurement is small, since in both analyses the dominant source of background is $q \bar{q} \rightarrow ZZ$. In this measurement we assume SM production rates for this background component.

After the application of the K-factors, an agreement better than 3% is found for the on-peak cross-section with the value given in Ref. [26] at the measured mass of 125.6 GeV. The difference is accounted for by applying a flat correction factor over $m_{ZZ}$.

All MC events undergo parton showering and hadronization using PYTHIA 6.4 [38]. In the same way as performed in [7] for LO samples, the parton showering settings have been tuned in order to reproduce approximately the four-lepton transverse momentum $p_T$ spectra predicted in NNLO predictions for Higgs boson production [39]. A GEANT4-based [40] simulation is subsequently run on MC events.

Vector-boson fusion (VBF) $qq' \rightarrow 4\ell qq'$ and $qq' \rightarrow 2\ell 2vqq'$ events have been generated with PHANTOM [41] in order to take into account the VBF contribution, in addition to the dominant $gg$ production process. Off-shell and interference effects are included at LO in these samples. Samples of events with scaled width and couplings are also used to model the different components as a function of the Higgs boson width. The event yield is normalized to the cross section at NNLO QCD and NLO EWK [26, 42], with a normalization factor independent of $m_{4\ell}$ [43]. Acceptance and efficiency effects are determined from detector simulation by applying an $m_{ZZ}$-dependent reweighting of the generated events.

For what concerns Higgs boson production mechanisms other than gluon fusion and VBF, we notice that both $t\bar{t}H$ and $VH$ productions are not expected to produce a significant off-shell tail, as these mechanisms are suppressed at high mass.

The dominant $q\bar{q} \rightarrow ZZ$ background is evaluated from POWHEG [44] and MADGRAPH [45] MC simulation, while its cross section is obtained from MCFM.

5 \textbf{Analysis of } H \rightarrow ZZ \rightarrow 4\ell

The $4\ell$ analysis uses the same event reconstruction and selection as those used in the previous measurement of Higgs boson properties in this final state [7].

Events are selected online requiring the presence of a pair of electrons or muons, or a triplet of electrons. Triggers requiring an electron and a muon are also used. The minimal $p_T$ of the first and second lepton are 17 and 8 GeV, respectively, for the double lepton triggers, while they are 15, 8 and 5 GeV for the triple electron trigger. Events with at least four identified and isolated electrons or muons, compatible with being produced at the primary vertex, are then selected offline. We require a Z candidate originating from a pair of leptons of the same flavour and opposite charge. The pair with an invariant mass closest to the nominal Z mass is retained and is denoted $Z_1$ if it satisfies $40 \leq m_{Z_1} \leq 120$ GeV. A second $\ell^+\ell^-$ pair, denoted $Z_2$, is required to satisfy $12 \leq m_{Z_2} \leq 120$ GeV. If more than one $Z_2$ candidate satisfies all criteria, the pair of leptons with the highest scalar $p_T$ sum is chosen. At least one lepton should have $p_T \geq 20$ GeV, another one $p_T \geq 10$ GeV and any opposite-charge pair of leptons among the four selected must satisfy $m_{4\ell} \geq 4$ GeV. Finally the phase space is reduced to $220$ GeV $< m_{4\ell} < 1600$ GeV to isolate the off-shell region and avoid the rapid background rise at $m_{4\ell} \sim 2m_Z$.

After the selection, the main background originates from the $q\bar{q} \rightarrow ZZ$ process, while a much smaller contribution, the reducible background, comes from the production of $Z$ and WZ in
association with jets, as well as t\bar{t}, with one or two jets misidentified as an electron or a muon. The dominant q\bar{q} \rightarrow ZZ background is evaluated from simulation, following Ref. [7]. The reducible background is evaluated using a tight-to-loose “fake rate” method. Two independent implementations are combined, which differ by the definition of the control regions in the data and by the difference in the composition of the samples where the fake rates are measured. The shape of the \( m_{4\ell} \) distribution for the reducible background is obtained by fitting the \( m_{4\ell} \) distributions in two different control regions with empirical functional forms. More details on the background evaluation can be found in Ref. [7].

Figure 1(a) shows the \( 4\ell \) invariant mass distribution in the region \( m_{4\ell} > 220 \text{ GeV} \) for the data, as well as for all the expected contributions. A good agreement is observed between the data and the SM expectations.

The analysis uses a dedicated kinematic discriminant \( D_{gg} \) which characterizes the event topology in the ZZ center-of-mass frame using the observables \( (m_{Z_1}, m_{Z_2}, \tilde{\Omega}) \) for a given value of \( m_{4\ell} \), where \( \tilde{\Omega} \) are five angles defined in Ref. [46]. The discriminant is built from probabilities \( P_i \) for an event to come either from gg \( \rightarrow ZZ \) or q\bar{q} \( \rightarrow ZZ \) processes. We adopt the matrix element likelihood approach (MELA) [2, 28, 47] for probability computation using the MCFM matrix elements for both gg \( \rightarrow ZZ \) and q\bar{q} \( \rightarrow ZZ \) processes. The probability \( P_{gg} \) for the gg \( \rightarrow ZZ \) process includes signal, background, and their interference, as introduced in Ref. [28].

The discriminant is defined as:

\[
D_{gg} = \frac{P_{gg}}{P_{gg} + P_{q\bar{q}}^{-1}} = \left[ 1 + \frac{P_{q\bar{q}}}{a \times P_{gg}^\text{sig} + \sqrt{a} \times P_{gg}^\text{int} + P_{gg}^\text{bkg}} \right]^{-1},
\]

where the \( P_{q\bar{q}}^\text{bkg} \) includes a correction factor \( c(m_{4\ell}) \) tuned to adjust the relative normalization of probabilities at a given value of \( m_{4\ell} \) taking into account detector acceptance effects. This correction factor does not affect the separation power. The discriminant is defined for a relative signal-weight parameter \( a \), where \( a = 1 \) corresponds to the SM. Preliminary studies indicated that a target exclusion of the order of \( r = 10 \) could be achieved in the analysis, and \( a \) is therefore set to \( a = 10 \) in constructing the discriminant. We have indeed observed that such a value of \( a \) is optimal and that the expected results do not vary strongly when we change \( a \) by a factor of 2 either up or down. Figure 1(b) shows the distribution of the \( D_{gg} \) variable for all expected contributions, as well as for the data.

The expected and observed yields in the off-shell analysis region, as well as in a signal-enriched region defined by \( m_{4\ell} \geq 330 \text{ GeV} \) and \( D_{gg} > 0.65 \) are reported in Table 1. The total expected yield for the gg plus VBF contribution is smaller than the one expected for the background only contribution due to the negative interference, which is larger than the pure signal contribution in the SM. The expected yields for an hypothesis corresponding to \( r = 15 \) are also presented in Table 1. The distribution of \( m_{4\ell} \) and of \( D_{gg} \) with these selections applied are shown in Figure 1(c,d), together with the SM expectations as well as for an hypothesis corresponding to \( r = 25 \).

6 Analysis of \( H \rightarrow ZZ \rightarrow 2\ell2\nu \)

The 2\( \ell2\nu \) analysis uses the same event reconstruction and selection as those used in the previous searches for high-mass Higgs bosons in the same channel [12].

The final state in this channel is characterized by two oppositely charged leptons of the same
A very large potential background arises from $Z + \text{jets}$ events with large mis-measured $E_T^{\text{miss}}$ from hadronic recoil, which is hard to model. Other relevant backgrounds are top-quark production ($t\bar{t} \to 2\ell 2\nu 2b$ and $tW \to 2\ell 2\nu b$), and diboson production ($WZ \to 3\ell \nu$, $ZZ \to 2\ell 2\nu$, and $WW \to 2\ell 2\nu$). The top-quark background is suppressed by rejecting events containing a bottom-quark decay identified by either the presence of a tagged b-jet or a soft muon. The tagged b-jet is required to have $p_T > 30 \text{ GeV}$ and to be reconstructed within the tracker acceptance volume. The soft muon is required to have $p_T > 3 \text{ GeV}$, which is typically produced in the leptonic decay of a bottom quark. To reduce the $WZ$ background in which both bosons decay leptonically, events containing additional electrons or muons with $p_T > 10 \text{ GeV}$ are rejected. The presence of large $E_T^{\text{miss}}$ is a fundamental feature of the signal signature. To reject the bulk of the $Z + \text{jets}$ background, $E_T^{\text{miss}} > 80 \text{ GeV}$ is required. In addition, events are removed if the angle in the azimuthal plane between the $E_T^{\text{miss}}$ vector and the closest jet with $p_T > 30 \text{ GeV}$ is smaller than 0.5 radians.

Selected events are categorised according to the number and topology of reconstructed jets with $p_T > 30 \text{ GeV}$. An event is assigned to the VBF category if the following requirements satisfied: the two highest-$p_T$ jets in the event have a minimal pseudo-rapidity separation of $|\Delta \eta| > 4$ and invariant mass $> 500 \text{ GeV}$; their pseudo-rapidities are used to define the bounds of the so-called central region of the event; the pseudo-rapidity of both lepton candidates lies in the central region and no other selected jet with $p_T > 30 \text{ GeV}$ is found in this central region. The other events are assigned to the "0-jet" and "$\geq1$-jet" categories according to number of jets.

The $WZ$ and $ZZ$ backgrounds are modelled using MC simulation, and are normalized to their respective NLO cross sections computed with MCFM. The $Z + \text{jets}$ background is modelled from an orthogonal control sample of events with a single isolated photon produced in association with jets ($\gamma + \text{jets}$). The contribution of $t\bar{t}$, $tW$ and $WW$ backgrounds is estimated by
using a control sample of events with dileptons of different flavors ($e^\pm\mu^\mp$) that pass all other analysis selections. A more detailed description of the background evaluations can be found in Ref. [12].

Following this selection, the analysis uses the reconstructed transverse mass ($m_T$) and $E_T^{\text{miss}}$ distributions as final discriminant variables. The $m_T$ variable is defined as follows:

$$m_T^2 = \left[ \sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \sqrt{E_{T}^{\text{miss}}^2 + m_{\ell\ell}^2} \right]^2 - \left[ \vec{p}_{T,\ell\ell} + E_T^{\text{miss}} \right]^2$$

where $p_{T,\ell\ell}$ and $m_{\ell\ell}$ are the measured transverse momentum and invariant mass of the dilepton system, respectively.
The two lepton flavors (\(e\) and \(\mu\)) and three jet categories (0, \(\geq 1\) and VBF) define six statistically independent samples used in the analysis. The \(m_T\) distributions for the 0 and \(\geq 1\) jets categories and the \(E_{\text{miss}}\) distribution for the VBF category are used as final discriminant variables. The distributions corresponding to the baseline selection are shown in Fig. 2. As can be seen, the observed data are consistent with the SM predictions.

Figure 2: Comparison between the expected and observed \(m_T\) and \(E_{\text{miss}}\) distributions in the different event categories. The expected distributions from the different background processes are stacked on top of each other. The shapes of inclusive process (SBI) of \(gg \rightarrow ZZ \rightarrow 2\ell 2\nu\) and \(qq' \rightarrow ZZqq' \rightarrow 2\ell 2\nu qq'\) processes for a \(r = 10\) scenario are superimposed. Dielectron (dimuon) events are shown on the top (bottom). 0-jet, \(\geq 1\)-jet and VBF events are shown on the left, middle and right.

Table 2 shows the event yields in a further signal-enriched region, defined by \(E_{\text{miss}} > 100\) GeV and \(m_T > 350\) GeV.

7 Systematic uncertainties

Systematic uncertainties comprise experimental uncertainty on efficiency and background estimation and uncertainties on the signal and background yields as well as on shapes from theory. Since the measurement is performed in wide \(m_{ZZ}\) regions there are sources of systematic uncertainty which affect the total normalization only and others which affect both normalization and shape of the distributions used in the analysis. The shapes and normalizations on the signal and on each background component are allowed to vary within their uncertainties, and the correlations in the sources of systematic uncertainty are taken into account.

Among the normalization uncertainties, experimental systematic uncertainties are evaluated
Table 2: Event yields in a signal-enriched region expected for the signal and background processes and observed in the data for the ee and $\mu\mu$ channels. The abbreviation gg is used to denote the process $gg \rightarrow ZZ \rightarrow 2\ell 2\nu$. The abbreviation VBF is used to denote the process $q\bar{q}' \rightarrow ZZqq' \rightarrow 2\ell 2\nu q\bar{q}'$. The signal-enriched region is defined by $E_{\text{miss}}^{T} > 100$ GeV and $m_T > 350$ GeV.

<table>
<thead>
<tr>
<th>Process</th>
<th>ee</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(a)$ gg + VBF (signal, $\Gamma_H/\Gamma_{SM}^H = 1$)</td>
<td>$2.30^{+0.03}_{-0.03}$</td>
<td>$2.72^{+0.03}_{-0.03}$</td>
</tr>
<tr>
<td>gg + VBF (background)</td>
<td>$5.4^{+0.2}_{-0.2}$</td>
<td>$6.5^{+0.2}_{-0.2}$</td>
</tr>
<tr>
<td>gg + VBF (total, $\Gamma_H/\Gamma_{SM}^H = 1$)</td>
<td>$4.8^{+0.1}_{-0.1}$</td>
<td>$5.7^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>$(a+b)$ Total expected ($\Gamma_H/\Gamma_{SM}^H = 1$)</td>
<td>$19.2^{+0.6}_{-0.6}$</td>
<td>$22.6^{+1.2}_{-1.2}$</td>
</tr>
<tr>
<td>$qq' \rightarrow ZZ$</td>
<td>$25.0^{+0.5}_{-0.5}$</td>
<td>$29.4^{+0.5}_{-0.5}$</td>
</tr>
<tr>
<td>WZ</td>
<td>$11.6^{+0.4}_{-0.4}$</td>
<td>$13.5^{+0.4}_{-0.4}$</td>
</tr>
<tr>
<td>$t\bar{t}/tW/WW$</td>
<td>$3.3^{+1.1}_{-1.1}$</td>
<td>$4.2^{+1.4}_{-1.4}$</td>
</tr>
<tr>
<td>$Z + $ jets</td>
<td>$1.5^{+0.9}_{-0.9}$</td>
<td>$2.4^{+1.4}_{-1.4}$</td>
</tr>
<tr>
<td>Observed</td>
<td>$46.2^{+1.6}_{-1.6}$</td>
<td>$55.3^{+2.1}_{-2.1}$</td>
</tr>
<tr>
<td>Expected</td>
<td>$39$</td>
<td>$52$</td>
</tr>
</tbody>
</table>

from data for lepton trigger efficiency and combined object reconstruction, identification and isolation efficiencies [7]. In the $2\ell 2\nu$ final-state analysis, the effect of lepton momentum scale and jet energy scale is also taken into account and is propagated to the evaluation of $E_{T}^{\text{miss}}$. The uncertainty on the b-jet veto is estimated by measuring the b-tagging efficiency in data from dijet and $t\bar{t}$ decays [12].

Theoretical uncertainties on the normalization of the $q\bar{q}$ background contribution are between 4% and 10% [7, 12]. The systematic uncertainty on the amount of reducible background is evaluated following the methods developed in Refs. [7, 12].

Theoretical uncertainties on the gg-induced processes, which affect both normalization and shape are especially important in this analysis, in particular for the signal and interference contributions that can be scaled by large factors ($r$ and $\sqrt{r}$ respectively). The following are included:

- In the main approach used in this analysis, all signal systematics for the $4\ell$ final state depending only on its total normalization cancel when using the measured on-peak signal strength as a reference. The $\mu$ variable with its statistical uncertainty, in the approach using its expected (observed) value, is taken from Ref. [7] to be $1.00^{+0.27}_{-0.24} (0.93^{+0.26}_{-0.24})$. This contribution affects the total $gg \rightarrow ZZ$ shapes as well, since it leaves the background contribution unvaried, but changes the signal and correspondingly the interference;

- QCD renormalization and factorization scales are varied by a factor two both up and down, producing new LO MC samples and using scale variations from Ref. [36] in a correlated way;

- In the $4\ell$ analysis, shape uncertainties from PDF variations are extracted by changing NLO PDF sets from CT10 [48] to MSTW2008 and NNPDF2.1 [35, 49]. In the $2\ell 2\nu$ analysis, this is treated as a normalization uncertainty;

- In the $4\ell$ analysis, a further systematic uncertainty is applied to VBF shapes to account for the approximate simulation: the difference between the reweighting method and an alternative technique, based on lepton-momentum smearing, is used;
• For the continuum $gg \rightarrow ZZ$, following Ref. [37], we assign to the LO background cross section a K-factor equal to the one used for the signal. To further account for the limited knowledge on the background cross section at NNLO (and therefore on the interference), we assign an additional systematic uncertainty of 10% following Ref. [37] and taking a conservative coverage which takes into account the different mass range and selections on the specific final state [50]. This contribution affects the total $gg \rightarrow ZZ$ shapes as well, since it leaves the signal contribution unvaried, but changes the background and correspondingly the interference.

8 Results

Using the normalization and shape of the signal and background processes, we perform a statistical analysis of the results using the formalism described in Ref. [51]. Shapes are derived from either analytical descriptions, or template distributions from MC or data control region, as in Refs. [7, 12]. The two decay channels are combined in an unbinned maximum-likelihood fit of the data to a signal-plus-background model, the final likelihood of the fit serving as test statistic. Systematic uncertainties are included as nuisance parameters and are treated according to the frequentist paradigm.

In the $4\ell$ analysis, we first perform a one-dimensional fit, using the $m_{4\ell}$ or $D_{gg}$ variable only. The observed exclusion limits at the 95% CL for the two fits are found to be $\Gamma_H \leq 26.3 \times \Gamma_H^{SM}$ and $\Gamma_H \leq 7.1 \times \Gamma_H^{SM}$, respectively, in the approach where the observed value of $\mu$ is used. The corresponding expected exclusion limits at the 95% CL for the two fits are found to be $\Gamma_H \leq 17.0 \times \Gamma_H^{SM}$ and $\Gamma_H \leq 12.7 \times \Gamma_H^{SM}$, respectively. The $2\ell2\nu$ analysis is first performed using a counting approach. With the event yields reported in Table 2, the observed (expected) exclusion limit at the 95% CL from the counting experiment is $\Gamma_H \leq 12.4(16.4) \times \Gamma_H^{SM}$, in the approach where the observed value of $\mu$ is used.

In the final analysis, the $4\ell$ kinematic discriminant is combined with $m_{4\ell}$ in a two-dimensional fit. The expected improvement in sensitivity with respect to the use of $m_{4\ell}$ only is about 30%. The fit is performed using MC templates for the three $gg \rightarrow ZZ$ components (signal, background and interference) and similarly for the VBF components. The shapes of the $m_{T}$ and $E_{T}^{miss}$ distributions for the baseline selection are used for the $2\ell2\nu$ channel. The fit results for $r$ are shown in Fig. 3, where the scans of the negative log-likelihood are shown as a function of $r$. The red lines correspond to the 68% and 95% CL exclusion values. The relevant numerical results as obtained using the observed value of $\mu$ are reported in Table 3. The combination of the two channels leads to an observed (expected) exclusion of $\Gamma_H \leq 4.2(8.5) \times \Gamma_H^{SM}$ at the 95% confidence level, that is $\Gamma_H \leq 17.4(35.3)$ MeV.

<table>
<thead>
<tr>
<th></th>
<th>4$\ell$</th>
<th>2$\ell2\nu$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected 95% CL limit, (r)</td>
<td>11.5</td>
<td>10.7</td>
<td>8.5</td>
</tr>
<tr>
<td>Observed 95% CL limit, (r)</td>
<td>6.6</td>
<td>6.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Observed 95% CL limit, (\Gamma_H) (MeV)</td>
<td>27.4</td>
<td>26.6</td>
<td>17.4</td>
</tr>
<tr>
<td>Observed best fit, (r)</td>
<td>$0.5^{+2.3}_{-0.5}$</td>
<td>$0.2^{+2.2}_{-0.2}$</td>
<td>$0.3^{+1.9}_{-0.3}$</td>
</tr>
<tr>
<td>Observed best fit, (\Gamma_H) (MeV)</td>
<td>$2.0^{+9.6}_{-2.0}$</td>
<td>$0.8^{+9.1}_{-0.8}$</td>
<td>$1.4^{+6.1}_{-1.4}$</td>
</tr>
</tbody>
</table>

Table 3: Expected and observed 95% CL limits for the 4$\ell$ and 2$\ell2\nu$ analyses and for the combination. For the observed results, the central fitted values and the 68% CL total uncertainties are also quoted. All quoted values are obtained using the observed value of $\mu$.

The observed limit is tighter than the expected limit due to a deficit of four-lepton events in
the high $m_{4\ell}$ and high $D_{gg}$ region (see Figs. 1(c) and 1(d)) and a deficit in the $2e2\nu$ channel (see upper part of Fig. 2). The compatibility of the observed results with expectation under the SM hypothesis is statistically consistent with a p-value of 0.02. The statistical coverage of the results obtained in the likelihood scan has also been tested with the Feldman-Cousins approach [52] for the combined analysis leading to consistent, though slightly tighter constraints.

9 Conclusions

We have presented an analysis of the Higgs boson width using its off-shell production and decay to four leptons or two leptons plus two neutrinos. The analysis is based on the 2012 dataset, corresponding to an integrated luminosity of $L = 19.7\, \text{fb}^{-1}$ at a center-of-mass energy $\sqrt{s} = 8\, \text{TeV}$. The four-lepton analysis uses the invariant mass distribution near the peak and above the $Z$ pair production threshold as well as a kinematic discriminant to separate the Higgs boson production from the ZZ continuum background. The two leptons plus two neutrinos analysis relies on the transverse mass or missing transverse energy distributions, depending on the jet categories. Using the Higgs boson event yield measurement at the peak in the four-leptons final state, the combination of the two channels leads to an observed (expected) constraint of $\Gamma_H < 4.2(8.5) \times \Gamma_{H}^{\text{SM}}$, that is $\Gamma_H \leq 17.4(35.3)\, \text{MeV}$, at the 95% confidence level. This result improves by more than two orders of magnitude over previously published experimental constraints on the new boson width from the measurement near the resonance mass.

10 Acknowledgments

We wish to thank theory experts, and in particular Alessandro Ballestrero, John Campbell, Fabrizio Caola, Keith Ellis, Stefano Forte, Nikolas Kauer, Kirill Melnikov, Giampiero Passarino, Ciaran Williams, and Marco Zaro for the very useful discussions, for providing numbers related to their calculations, and helping with the use of MC programs.
Figure 3: Scans of the negative log-likelihood, as a function of $r = \Gamma_H / \Gamma_{H}^{SM}$ for the $4\ell$ (a) and $2\ell 2\nu$ (b) analyses separately and for the combined result (c). The green and yellow bands correspond respectively to 68% and 95% quantiles of the distribution of the negative log-likelihood at the corresponding value on the dashed red line in MC pseudo-experiments.
References


[39] D. De Florian, G. Ferrera, M. Grazzini, and D. Tommasini, “Higgs boson production at the LHC: transverse momentum resummation effects in the \( H \to \gamma\gamma, H \to WW \to \ell\nu\ell\nu \) and \( H \to ZZ \to 4\ell \) decay modes”, arXiv:1203.6321v1.


[50] F. Caola. private communication.
