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Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs

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ABSTRACT

Constraints are presented on the total width of the recently discovered Higgs boson, Γ_H, using its relative on-shell and off-shell production and decay rates to a pair of Z bosons, where one Z boson decays to an electron or muon pair, and the other to an electron, muon, or neutrino pair. The analysis is based on the data collected by the CMS experiment at the LHC in 2011 and 2012, corresponding to integrated luminosities of 5.1 fb^{-1} at a center-of-mass energy $\sqrt{s} = 7$ TeV and 19.7 fb^{-1} at $\sqrt{s} = 8$ TeV. A simultaneous maximum likelihood fit to the measured kinematic distributions near the resonance peak and above the Z-boson pair production threshold leads to an upper limit on the Higgs boson width of $\Gamma_H < 22$ MeV at a 95% confidence level, which is 5.4 times the expected value in the standard model at the measured mass of $m_H = 125.6$ GeV.

The discovery of a new boson consistent with the standard model (SM) Higgs boson by the ATLAS and CMS Collaborations was recently reported [1–3]. The mass of the new boson (m_H) was measured to be near 125 GeV, and the spin-parity properties were further studied by both experiments, favoring the scalar, $J^{PC} = 0^{++}$, hypothesis [4–7]. The measurements were found to be consistent with a single narrow resonance, and an upper limit of 3.4 GeV at a 95% confidence level (CL) on its decay width (Γ_H) was reported by the CMS experiment in the four-lepton decay channel [7]. A direct width measurement at the resonance peak is limited by experimental resolution, and is only sensitive to values far larger than the expected width of around 4 MeV for the SM Higgs boson [8,9].

It was recently proposed [10] to constrain the Higgs boson width using its off-shell production and decay to two Z bosons away from the resonance peak [11]. In the dominant gluon fusion production mode the off-shell production cross section is known to be sizable. This arises from an enhancement in the decay amplitude from the vicinity of the Z-boson pair production threshold. A further enhancement comes, in gluon fusion production, from the top-quark pair production threshold. The zero-width approximation is inadequate and the ratio of the off-shell cross section above $2m_Z$ to the on-shell signal is of the order of 8% [11,12]. Further developments to the measurement of the Higgs boson width were proposed in Refs. [13,14].

The gluon fusion production cross section depends on Γ_H through the Higgs boson propagator

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}, \quad (1)$$

where g_{ggH} and g_{HZZ} are the couplings of the Higgs boson to gluons and Z bosons, respectively. Integrating either in a small region around m_H, or above the mass threshold $m_{ZZ} > 2m_Z$, where $(m_{ZZ} - m_H) \gg \Gamma_H$, the cross sections are, respectively,

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \text{ and } \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}. \quad (2)$$

From Eq. (2), it is clear that a measurement of the relative off-shell and on-shell production in the $H \to ZZ$ channel provides direct information on Γ_H, as long as the coupling ratios remain unchanged, i.e. the gluon fusion production is dominated by the top-quark loop and there are no new particles contributing. In particular, the on-shell production cross section is unchanged under a common scaling of the squared product of the couplings and of the total width Γ_H, while the off-shell production cross section increases linearly with this scaling factor.

The dominant contribution for the production of a pair of Z bosons comes from the quark-initiated process, $q\bar{q} \to ZZ$, the diagram for which is displayed in Fig. 1(left). The gluon-induced diboson production involves the $gg \to ZZ$ continuum background production from the box diagrams, as illustrated in Fig. 1(center). An

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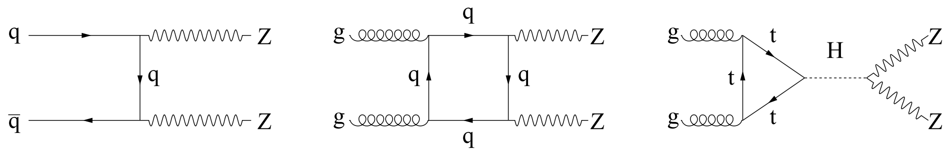

Fig. 1. Lowest order contributions to the main ZZ production processes: (left) quark-initiated production, $q\bar{q} \to ZZ$, (center) gg continuum background production, $gg \to ZZ$, and (right) Higgs-mediated gg production, $gg \to H \to ZZ$, the signal.

example of the signal production diagram is shown in Fig. 1(right). The interference between the two gluon-induced contributions is significant at high m_{ZZ} [15], and is taken into account in the analysis of the off-shell signal.

Vector boson fusion (VBF) production, which contributes at the level of about 7% to the on-shell cross section, is expected to increase above $2m_Z$. The above formalism describing the ratio of off-shell and on-shell cross sections is applicable to the VBF production mode. In this analysis we constrain the fraction of VBF production using the properties of the events in the on-shell region. The other main Higgs boson production mechanisms, $t\bar{t}H$ and VH ($V = Z, W$), which contribute at the level of about 5% to the on-shell signal, are not expected to produce a significant off-shell contribution as they are suppressed at high mass [8,9]. They are therefore neglected in the off-shell analysis.

In this Letter, we present constraints on the Higgs boson width using its off-shell production and decay to Z-boson pairs, in the final states where one Z boson decays to an electron or a muon pair and the other to either an electron or a muon pair, $H \to ZZ \to 4\ell$ (4ℓ channel), or a pair of neutrinos, $H \to ZZ \to 2\ell 2\nu$ ($2\ell 2\nu$ channel). Relying on the observed Higgs boson signal in the resonance peak region [7], the simultaneous measurement of the signal in the high-mass region leads to constraints on the Higgs boson width Γ_H in the 4ℓ decay channel. The $2\ell 2\nu$ decay channel, which benefits from a higher branching fraction [16,17], is used in the high-mass region to further increase the sensitivity to the Higgs boson width. The analysis is performed for the tree-level HVV coupling of a scalar Higgs boson, consistent with our observations [4,7], and implications for the anomalous HVV interactions are discussed. The Higgs boson mass is set to the measured value in the 4ℓ decay channel of $m_H = 125.6$ GeV [7] and the Higgs boson width is set to the corresponding expected value in the SM of $\Gamma_H^{SM} = 4.15$ MeV [8,9].

The measurement is based on pp collision data collected with the CMS detector at the LHC in 2011, corresponding to an integrated luminosity of 5.1 fb^{-1} at the center-of-mass energy of $\sqrt{s} = 7$ TeV (4ℓ channel), and in 2012, corresponding to an integrated luminosity of 19.7 fb^{-1} at $\sqrt{s} = 8$ TeV (4ℓ and $2\ell 2\nu$ channels). The CMS detector, described in detail elsewhere [18], provides excellent resolution for the measurement of electron and muon transverse momenta (p_T) over a wide range. The signal candidates are selected using well-identified and isolated prompt leptons. The online selection and event reconstruction are described elsewhere [2,3,7,16]. The analysis presented here is based on the same event selection as used in Refs. [7,16].

The analysis in the 4ℓ channel uses the four-lepton invariant mass distribution as well as a matrix element likelihood discriminant to separate the ZZ components originating from gluon- and quark-initiated processes. We define the on-shell signal region as $105.6 < m_{4\ell} < 140.6$ GeV and the off-shell signal region as $m_{4\ell} > 220$ GeV. The analysis in the $2\ell 2\nu$ channel relies on the transverse mass distribution m_T,

$$m_T^2 = \left[\sqrt{{p_{T,2\ell}}^2 + {m_{2\ell}}^2} + \sqrt{{E_T^{miss}}^2 + {m_{2\ell}}^2}\right]^2 - \left[\vec{p}_{T,2\ell} + \vec{E}_T^{miss}\right]^2, \qquad (3)$$

where $p_{T,2\ell}$ and $m_{2\ell}$ are the measured transverse momentum and invariant mass of the dilepton system, respectively. The missing transverse energy, E_T^{miss}, is defined as the magnitude of the transverse momentum imbalance evaluated as the negative of the vectorial sum of transverse momenta of all the reconstructed particles in the event. In the $2\ell 2\nu$ channel, the off-shell signal region is defined as $m_T > 180$ GeV. The choice of the off-shell regions in both channels is done prior to looking at the data, based on the expected sensitivity.

Simulated Monte Carlo (MC) samples of $gg \to 4\ell$ and $gg \to 2\ell 2\nu$ events are generated at leading order (LO) in perturbative quantum chromodynamics (QCD), including the Higgs boson signal, the continuum background, and the interference contributions using recent versions of two different MC generators, GG2VV 3.1.5 [11,19] and MCFM 6.7 [20], in order to cross-check theoretical inputs. The QCD renormalization and factorization scales are set to $m_{ZZ}/2$ (dynamic scales) and MSTW2008 LO parton distribution functions (PDFs) [21] are used. Higher-order QCD corrections for the gluon fusion signal process are known to an accuracy of next-to-next-to-leading order (NNLO) and next-to-next-to-leading logarithms for the total cross section [8,9] and to NNLO as a function of m_{ZZ} [14]. These correction factors to the LO cross section (K factors) are typically in the range of 2.0 to 2.5. After the application of the m_{ZZ}-dependent K factors, the event yield is normalized to the cross section from Refs. [8,9]. For the $gg \to ZZ$ continuum background, although no exact calculation exists beyond LO, it has been recently shown [22] that the soft collinear approximation is able to describe the background cross section and therefore the interference term at NNLO. Following this calculation, we assign to the LO background cross section (and, consequently, to the interference contribution) a K factor equal to that used for the signal [14]. The limited theoretical knowledge of the background K factor at NNLO is taken into account by including an additional systematic uncertainty, the impact of which on the measurement is nevertheless small.

Vector boson fusion events are generated with PHANTOM [23]. Off-shell and interference effects with the nonresonant production are included at LO in these simulations. The event yield is normalized to the cross section at NNLO QCD and next-to-leading order (NLO) electroweak (EW) [8,9] accuracy, with a normalization factor shown to be independent of m_{ZZ}.

In order to parameterize and validate the distributions of all the components for both gluon fusion and VBF processes, specific simulated samples are also produced that describe only the signal or the continuum background, as well as several scenarios with scaled couplings and width. For the on-shell analysis, signal events are generated either with POWHEG [24–27] production at NLO in QCD and JHUGEN [28,29] decay (gluon fusion and VBF), or with PYTHIA 6.4 [30] (VH and $t\bar{t}H$ production).

In both the 4ℓ and $2\ell 2\nu$ channels the dominant background is $q\bar{q} \to ZZ$. We assume SM production rates for this background, the contribution of which is evaluated by POWHEG simulation at NLO in QCD [31]. Next-to-leading order EW calculations [32,33], which predict negative and m_{ZZ}-dependent corrections to the $q\bar{q} \to ZZ$ process for on-shell Z-boson pairs, are taken into account.

All simulated events undergo parton showering and hadronization using PYTHIA. As is done in Ref. [7] for LO samples, the parton