# Constraining the Higgs boson width with $ZZ$ production at the LHC

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We point out that existing measurements of $pp \to ZZ$ cross-section at the LHC in a broad range of $ZZ$ invariant masses allow one to derive a model-independent upper bound on the Higgs boson width, thanks to strongly enhanced off-shell Higgs contribution. Using CMS data and considering events in the interval of $ZZ$ invariant masses from 100 to 800 GeV, we find $\Gamma_H \le 38.8\ \Gamma_H^{\rm SM} \approx 163$ MeV, at the 95% confidence level. Restricting $ZZ$ invariant masses to $M_{ZZ} \ge 300$ GeV range, we estimate that this bound can be improved to $\Gamma_H \le 21\ \Gamma_H^{\rm SM} \approx 88$ MeV. Under the assumption that all couplings of the Higgs boson to Standard Model particles scale in a universal way, our result can be translated into an upper limit on the branching fraction of the Higgs boson decay to invisible final states. We obtain ${\rm Br}(H \to {\rm inv}) < 0.84$ (0.78), depending on the range of $ZZ$ invariant masses that are used to constrain the width. We believe that an analysis along these lines should be performed by experimental collaborations in the near future and also in run II of the LHC. We estimate that such analyses can, eventually, be sensitive to a Higgs boson width as small as $\Gamma_H \sim 10\ \Gamma_H^{\rm SM}$.

Since the discovery of the Higgs-like particle by ATLAS and CMS collaborations about a year ago [1, 2], much has been learned about its properties. We know that the mass of the new particle is around 126 GeV [3, 4], that its spin-parity is most likely $0^+$ [5–7] and that its production cross-sections as observed in particular production and decay channels are consistent with Standard Model expectations [4, 8]. It is customary to translate the latter result into a statement about Higgs boson couplings to Standard Model particles but, as it is well-known, such a translation is only possible under the assumption that the Higgs boson width is the same as in the Standard Model (SM). Indeed, since after imposing selection cuts the Higgs boson production at the LHC can be described in a narrow width approximation [9–13], we can write a production cross-section for the process $i \to H \to f$ as

$$\sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}, \tag{1}$$

where $g_{i,f}$ are the Higgs boson couplings to initial and final states and $\Gamma_H$ is the Higgs boson width. Therefore, all measured cross-sections can be kept fixed if one simultaneously rescales couplings of the Higgs boson to Standard Model particles and the Higgs boson width by appropriate factors. Indeed, if $g = \xi g_{\rm SM}$ and $\Gamma_H = \xi^4 \Gamma_{\rm H,SM}$, the measured Higgs production cross-sections in all channels will coincide with expected Standard Model values, $\sigma_{i\to H\to f} = \sigma^{\rm SM}_{i\to H\to f}$. We conclude that current LHC data allow for infinitely many solutions for the Higgs couplings to SM particles, the Higgs width and the branching fraction of the Higgs boson to invisible (or so far unobserved) states. To break this degeneracy, independent measurements of the Higgs boson width or the Higgs couplings are required.

Direct measurement of the Higgs boson width is not possible at a hadron collider unless $\Gamma_H \gtrsim \mathcal{O}(1)$ GeV, or more than 250 times larger than its Standard Model value. The only facility where a direct measurement of the width can be performed is a future muon collider where by scanning the production cross-section for $\mu^+\mu^- \to H \to X$ around $m_H$, the Higgs width can be directly measured to high precision [14, 15]. At any other facility, the Higgs boson width should be obtained indirectly, using information on the Higgs couplings to Standard Model particles or information about the Higgs boson branching ratio to invisible final states, provided that such information is available from independent sources.

A number of ways were suggested to constrain the Higgs couplings and the Higgs branching fraction into invisible final states. For example, under certain theoretical assumptions about electroweak symmetry breaking, one can argue [16] that the SM value of the Higgs boson coupling to $W$-bosons provides an *upper* bound for all possible $HWW$ couplings. From this, the upper limit on the Higgs width $\Gamma_H < 1.43\ \Gamma_H^{\rm SM}$ is obtained [17]. Imposing even stronger constraints on the Higgs couplings to Standard Model particles, one can obtain tighter bounds on the Higgs boson width [18, 19]. Under the assumption of the Standard Model production rate for $pp \to ZH$, the ATLAS collaboration derives an upper bound on the Higgs branching ratio to invisible final state ${\rm Br}(H \to {\rm inv}) < 0.65$ at the 95% confidence level [20]. A related CMS study with a similar conclusion has also appeared recently [21].

On the other hand, it is more difficult to obtain model-independent constraints on the Higgs boson couplings. It was suggested in Ref. [22] to use differences in the measured values of the Higgs boson masses in $\gamma\gamma$ and $ZZ$ channels, caused by the interference of $gg \to H \to \gamma\gamma$ and $gg \to \gamma\gamma$ amplitudes, as a tool to constrain the product of $Hgg$ and $H\gamma\gamma$ couplings, independent of the Higgs boson width. Once the couplings are measured, one can derive the value of the Higgs boson width from the narrow width cross-section, see Eq.(1).

The purpose of this paper is to point out that a constraint on the product of $Hgg$ and $HZZ$ couplings and the resulting model-independent constraint on the Higgs

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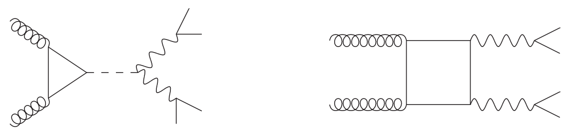

FIG. 1: Sample signal (left) and background $gg \to ZZ$ (right) diagrams for the process $pp \to ZZ \to 4l$. The two amplitudes can interfere.

boson width can be obtained from the observed number of $ZZ$ events at the LHC *above* the Higgs boson mass peak in the $pp \to ZZ$ process. Interestingly, this can already be done with the current data. The main reason for that is an enhanced contribution to the Higgs signal from invariant masses above the $ZZ$ threshold, as was first pointed out in Ref. [12]. Interestingly, useful limits on the Higgs width can already be derived with the current data. To show how this works, we recall how Eq.(1) is obtained. We focus on the $H \to ZZ \to ee\mu\mu$ final state and write the production cross-section as a function of the invariant mass of four leptons $M_{4l}$

$$\frac{\mathrm{d}\sigma_{pp\to H\to ZZ}}{\mathrm{d}M_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}. \tag{2}$$

The total cross-section receives the dominant contribution from the resonant region $M_{4l}^2 - m_H^2 \sim m_H\Gamma_H$, where integral of Eq.(2) gives Eq.(1). However, the total cross-section also receives off-peak contributions from larger or smaller invariant masses, where Eq.(2) is still proportional to squares of $Hgg$ and $HZZ$ couplings *but it is independent of* $\Gamma_H$.

Suppose now that in Eq.(2), the product of coupling constants $c_{gZ} = g_{Hgg}^2 g_{HZZ}^2$ and the width $\Gamma_H$ are scaled by a common factor $\xi$ and that this factor is still sufficiently small to make the narrow width approximation applicable. Under this circumstance, the resonance contribution remains unchanged and is given by Eq.(1), while the off-shell contribution from the region $M_{4l}^2 \gg m_H^2$ increases *linearly* with $\xi$ and can, therefore, be bounded from above by the total number of events observed in $pp \to ZZ$ process above the Higgs boson peak in the $ZZ$ invariant mass spectrum. This is the main idea behind this paper.

There are two sources of Higgs-related $ZZ$ events off the peak. One is the off-shell production of the Higgs boson followed by its decay to $ZZ$ final states. The second source of events is the interference between $gg \to H \to ZZ$ and $gg \to ZZ$ amplitudes, see Fig. 1. The interference exists, but is numerically irrelevant *in the peak* [12, 13] while, as we show below, it significantly changes the number of expected Higgs-related events off the peak. We account for both of these effects in the following discussion. To estimate the number of Higgs events in $gg \to H \to ZZ$, including the interference, we use the program gg2VV described in Refs. [12, 23].

To calculate the number of Higgs-related events that are expected off peak, we compute 7 and 8 TeV production cross-sections for $pp \to H \to ZZ \to e^+e^-\mu^+\mu^-$ at *leading order* in perturbative QCD requiring that the invariant mass of four leptons is either smaller or larger than 130 GeV. We refer to the former case as the "on peak" cross-section and to the latter case as the "off peak" one .

| Energy | $\sigma_{\rm peak}^{\rm H}$ | $\sigma_{\rm off}^{H}$ | $\sigma_{\rm off}^{\rm int}$ |
|---|---|---|---|
| 7 TeV | 0.203 | 0.044 | -0.108 |
| 8 TeV | 0.255 | 0.061 | -0.166 |
| $N_{2e2\mu}^{\rm SM}$ | 9.8 | 1.73 | -4.6 |
| $N_{\rm tot}^{\rm SM}$ | 21.1 | 3.72 | -9.91 |

TABLE I: Fiducial cross-sections for $pp \to H \to ZZ \to 2e2\mu$ in fb, and the corresponding number of events expected for integrated luminosities $L_7 = 5.1$ fb$^{-1}$ at 7 TeV and $L_8 = 19.6$ fb$^{-1}$ at 8 TeV. All cross-sections are computed with leading order MSTW 2008 parton distribution functions [24]. The renormalization and factorization scales are set to $\mu = m_H/2$. The peak cross-section is defined with the cut $M_{4l} < 130$ GeV, while off-peak and interference cross-sections are defined with the cut $M_{4l} > 130$ GeV. The total number of events in the last row includes contributions from $4e$ and $4\mu$ channels. The number of events is obtained using procedures outlined in the text.

We employ the CMS selection cuts [6] requiring $p_{\perp,\mu} > 5$ GeV, $p_{\perp,e} > 7$ GeV, $|\eta_\mu| < 2.4$, $|\eta_e| < 2.5$, $M_{l_-l_+} > 4$ GeV, $M_{4l} > 100$ GeV. In addition, the transverse momentum of the hardest (next-to-hardest) lepton should be larger than 20 (10) GeV, the invariant mass of a pair of same-flavor leptons closest to the $Z$-mass should be in the interval $40 < m_{ll} < 120$ GeV and the invariant mass of the other pair should be in the interval $12 - 120$ GeV. We also take the Higgs boson mass to be 126 GeV, and set renormalization and factorization scales to $m_H/2$.

The corresponding cross-sections for the Higgs signal on and off the peak as well as the interference contributions to cross-sections are shown in Table I. The number of $2e2\mu$ events in that Table is computed starting from the number of on-peak events reported in Table I of Ref. [6]. According to Table I in [6], the CMS collaboration expects 9.8 Higgs-related events in the $ee\mu\mu$ channel *on the peak*.[1] We estimate the number of Higgs-related events for $M_{4l} > 130$ GeV by taking ratios of cross-sections weighted with luminosity factors. We also include additional suppression factor due to the fact

[1] This number of events is a combination of $gg \to H$ (88%), weak boson fusion (7%) and $VH$ production (5%). Although a detailed study of the channels besides $gg \to H$ is beyond the scope of this paper, we believe that they will contribute to the number of high-mass $ZZ$ events in a way that is similar to $gg \to H \to ZZ$; for this reason we decided to keep the number of events in the peak unchanged when performing numerical estimates.

that the appropriate scale choice for the strong coupling constant in $gg \to H^* \to ZZ$ is the invariant mass of the $Z$ boson pair divided by two, rather than $m_H/2$, as appropriate for the on-shell cross-section [25]. We take 300 GeV as a typical value of the invariant mass for Higgs-related events produced off the peak. The corresponding suppression factor is then given by $\eta = (\alpha_s(150\text{ GeV})/\alpha_s(m_H/2))^2 \approx 0.75$. We find

$$N_{2e2\mu}^{H,\text{off}} = 9.8 \times \eta \frac{L_7 \sigma_{\text{off}}^H(7) + L_8 \sigma_{\text{off}}^H(8)}{L_7 \sigma_{\text{peak}}^H(7) + L_8 \sigma_{\text{peak}}^H(8)} \approx 1.73, \quad (3)$$

where we use the integrated luminosities $L_7 = 5.1\text{ fb}^{-1}$ at 7 TeV and $L_8 = 19.6\text{ fb}^{-1}$ at 8 TeV.

We combine this estimate with results for other lepton channels by similarly rescaling CMS data on $4e$ and $4\mu$, and conclude that 3.72 four-lepton events produced by decays of an off-shell Higgs boson can be expected in the current data. Repeating this calculation with the interference contribution, we find that $-9.91$ events are expected. Since cross-sections that we use are computed in the leading order QCD approximation and do not include any detector effects, one may wonder if the number of events estimated using them is reliable. While a detailed answer to this question requires careful studies, we believe that, by taking ratios of cross-sections, accounting for the dominant effects of the running of the strong coupling constant when relating on- and off-peak events and by normalizing our computation to the CMS number of the expected Higgs events in the peak, we obtain estimates for the off-peak number of events that are sufficiently reliable for the purposes of this paper.[2]

We note that the estimated number of events in Table I looks quite striking for two reasons. The first one is that the off-shell contributions related to $gg \to H \to ZZ$ are *large*; the off-peak cross-section is close to twenty percent of the peak cross-section. This large off-peak contribution in $ZZ$ final state was first emphasized in Ref. [12]. It was explained as the consequence of a relatively large probability to produce the Higgs boson with the off-shellness larger than $2m_Z$ where decays to longitudinally-polarized $Z$-bosons rapidly become important and compensate for the decrease in the cross-section caused by the off-shell Higgs propagator. This leads to a contribution to the invariant mass distribution Eq.(2) which, although small, extends over a large invariant mass range $2m_Z \lesssim M_{4l} \lesssim 800$ GeV and gives rise to a sizable contribution to the total cross-section. The second reason is due to a large destructive interference. Note, however, that the interference is an *off-peak* phenomenon; it does not contribute to the peak cross-section to a very good approximation [12, 13].

The expected number of Higgs-related events shown in Table I refers to the Standard Model. Relaxing this assumption by allowing for correlated changes in the Higgs couplings and the Higgs boson width, so that the number of events in the peak remains intact, we write the number of off-peak events as

$$N_{4l}^{\text{off}} = 3.72 \times \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} - 9.91 \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}}. \quad (4)$$

For $\Gamma_H \gg \Gamma_H^{\text{SM}}$, we can interpret Eq.(4) as an additional source of $ZZ$ events in the current data; these $ZZ$ events are broadly distributed over a large invariant mass range, roughly from the $ZZ$ threshold up to the highest $ZZ$ invariant masses of order 800 GeV. Therefore, as the first step, we can look at the total number of $ZZ$-events in the current data and ask how many additional events can be tolerated given the number of observed events and the current uncertainty on the number of expected events. CMS currently observes 451 events in the $pp \to ZZ \to 4l$ channel, while $432 \pm 31$ events are expected [6]. The expected number of events does not include the off-shell Higgs production and the off-shell interference. Therefore, we estimate the total number of events that are expected if the Higgs couplings and width differ from the Standard Model using the following equation

$$N_{\text{exp}} = 432 + 3.72 \times \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} - 9.91 \times \sqrt{\frac{\Gamma_H}{\Gamma_H^{\text{SM}}}} \pm 31, \quad (5)$$

where we assume that the sign of the interference is the same as in the Standard Model. Note that we obtain the above error estimate by adding errors for the $4e$, $4\mu$ and $2e2\mu$ channels reported in Ref. [6] in quadratures, assuming that they are uncorrelated. While not exact, this is also not an unreasonable assumption,[3] but a detailed analysis of error correlations is beyond the scope of this paper.

Requiring that the expected and observed numbers of events are within two standard deviations from each other, we derive an upper limit on $\Gamma_H$ at the 95% confidence level. We find

$$\Gamma_H \leq 38.8\, \Gamma_H^{\text{SM}} \approx 163\text{ MeV}, \quad (6)$$

where we used $\Gamma_H^{\text{SM}} \approx 4.2$ MeV [27].[4]

The upper limit on the Higgs boson width can be turned into an upper limit on the branching fraction for

[2] We note that by rescaling both off-peak and interference contributions in the same way, we implicitly assume that QCD corrections to the signal and the interference are comparable. This is supported by the analysis of higher-order corrections to the interference in $pp \to H \to W^+W^-$ process reported in [26].

[3] Note that errors for the expected number of background events for all channels in Table I of Ref. [6] are of the same order as the square root of the expected number of events reported there.

[4] We note that, if we add the errors for the number of expected events in the $4e$, $4\mu$ and $2e2\mu$ channels *linearly*, the 95% confidence level limit for the width will degrade to $\Gamma_H \leq 52\, \Gamma_H^{\text{SM}}$.

| Energy | $\sigma^{\rm H}_{\rm peak}$ | $\sigma^{H}_{\rm off}$ | $\sigma^{\rm int}_{\rm off}$ |
|---|---|---|---|
| 7 TeV | 0.203 | 0.036 | -0.046 |
| 8 TeV | 0.255 | 0.049 | -0.10 |
| $N^{\rm SM}_{2e2\mu}$ | 9.8 | 1.39 | -2.71 |
| $N^{\rm SM}_{\rm tot}$ | 21.1 | 2.99 | -5.84 |

TABLE II: Same of Table I, but with the cut $M_{4l} > 300$ GeV applied to the off-peak cross-section and interference. See text for details.

the Higgs boson decay into invisible final states. To this end, we write

$$\Gamma_H = \Gamma_{\rm inv} + \sum_{i \in {\rm vis}} \Gamma_i, \tag{7}$$

where the sum extends over all visible channels. We note that $\Gamma_{i\in{\rm vis}} \sim g_i^2$, and that ratios $g_i^2 g_f^2/\Gamma_H$ should be equal to their Standard Model values, to keep all narrow-width Higgs boson production cross-sections to be the same as in the Standard Model. Assuming that all Higgs couplings to SM particles differ by identical factors relative to their Standard Model values, we find that the Higgs boson width and the branching fraction to invisible final states satisfy the following constraint

$$\Gamma_H \left(1 - {\rm Br}_{\rm inv}\right)^2 = \Gamma_H^{\rm SM}. \tag{8}$$

This constraint translates into an upper limit on ${\rm Br}_{\rm inv}$

$${\rm Br}_{\rm inv} = 1 - \sqrt{\Gamma_H/\Gamma_H^{\rm SM}} < 0.84. \tag{9}$$

Can the above analysis be improved? We believe that there is, most likely, an affirmative answer to this question. To show this, we note that an upper bound on the Higgs width was derived by using the total number of $pp \to ZZ$ events observed in a broad range of four-lepton invariant masses. However, this may not be an optimal mass range since the invariant mass distribution of the four-lepton events produced in the "decays" of the off-shell Higgs boson is almost flat. To illustrate this point, we repeat the above analysis but now select events where the invariant mass of four leptons is larger than 300 GeV. The corresponding leading order cross-sections are shown in Table II. By comparing Tables I and II, it is clear that the off-shell production decreases by a smaller amount than the interference. The observed number of events for $M_{4l} > 300$ GeV is $N_{\rm obs} = 87$ and the expected number of events is estimated to be $N_{\rm exp} = 70.7$ without off-shell Higgs production and the interference [6]. It is not possible for us to obtain the error estimate for expected number of events from the CMS paper [6]; we therefore take $\delta N_{\rm exp} = 10$ which is about 15 percent of $N_{\rm exp}$. Repeating the same analysis as in the case of the full mass range, we find an improved 95% confidence level limit on the Higgs boson width

$$\Gamma_H \leq 21\ \Gamma_H^{\rm SM} \approx 88\ {\rm MeV}. \tag{10}$$

Further refinements should, therefore, include a careful selection of the invariant mass window and, perhaps, the use of angular correlations of four lepton momenta to disentangle $gg \to H \to ZZ$ off-peak events from $q\bar{q} \to ZZ$ background. Such angular correlations are already used by the CMS collaboration [6] to improve their measurement in the Higgs peak region; it is probably straightforward to apply these techniques off the peak as well. We note that polarization effects may play a more substantial role at high-invariant masses since $Z$ bosons that are produced in decays of the off-shell Higgs boson are, most likely, longitudinally polarized.

With increased luminosity, one can expect the error on the number of $ZZ$ events to be dominated by systematic uncertainties; we will optimistically assume that this uncertainty will, eventually, become as small as 3%. This may require extending existing theoretical computations for $pp \to ZZ$ to NNLO QCD but this appears to be a realistic target on a few years time-scale; see e.g. Ref. [28] as an example of recent progress. If such an error is reached and about half of the background events are rejected, the 95% confidence level upper limit on the Higgs boson width $\Gamma_H \lesssim 5-10\ \Gamma_H^{\rm SM} = 20-40$ MeV may, eventually, be obtained. This appears to be the ultimate limit of what can be reached with the methods that are advocated in this paper.

In conclusion, we suggested that the total Higgs boson width can be constrained in a model-independent way by studying the $ZZ$ events off the Higgs boson invariant-mass peak. We pointed out that already with the current data one can put a 95% confidence limit $\Gamma_H \leq 20-38\ \Gamma_H^{\rm SM}$ depending on the four-lepton invariant mass range chosen for the analysis. We also note that if the interference contribution in Eq.(4) changes sign and becomes constructive, bounds on the Higgs width become much stronger, $\Gamma_H \leq 7-13\ \Gamma_H^{\rm SM}$. While we believe that our estimates are sufficiently accurate, the present study is crude and ignores the many details of experimental event selection. We tried to mitigate that by normalizing our calculations to the number of Higgs boson events that CMS collaboration expects to observe in the peak. However, it will be best if experimental collaborations perform a detailed analysis of $ZZ$ events at high invariant masses and, as suggested in this paper, derive model-independent constraints on the Higgs boson width.

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