Off-shell Higgs boson couplings measurement using $H \rightarrow ZZ \rightarrow 4l$ events at High Luminosity LHC

The ATLAS Collaboration

Abstract

Several studies have shown that the high-mass off-peak regions in the $H \rightarrow ZZ$ and $H \rightarrow WW$ channels above the $2m_V$ threshold ($V = W, Z$) have sensitivity to off-shell Higgs production and interference effects. This feature can be exploited to characterize the Higgs boson off-shell signal strength and its associated couplings. This note reports on prospects on the Higgs boson off-shell couplings in the High-Luminosity LHC (HL-LHC) scenario, assuming 300 fb$^{-1}$ and 3000 fb$^{-1}$ of collision data collected at $\sqrt{s} = 14$ TeV, using a simplified version of the published $H \rightarrow ZZ \rightarrow 4l$ off-shell couplings analysis.

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1 Introduction

This note presents a study on the off-shell Higgs boson signal strength in the $ZZ \rightarrow 4l$ final state at the High Luminosity LHC (HL-LHC). Using the framework for Higgs boson coupling deviations as described in Ref. [1], the off-shell signal strength in the high-mass region selected by the analysis described in this note at an energy scale $\hat{s}$, $\mu_{\text{off-shell}}(\hat{s})$, can be expressed as:

$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{g_{\text{off-shell}}^{gg \rightarrow H^{*} \rightarrow VV}(\hat{s})}{g_{\text{off-shell, SM}}^{gg \rightarrow VV}(\hat{s})} = \kappa_{g, \text{off-shell}}^{2}(\hat{s}) \cdot \kappa_{V, \text{off-shell}}^{2}(\hat{s}),$$

where $\kappa_{g, \text{off-shell}}(\hat{s})$ and $\kappa_{V, \text{off-shell}}(\hat{s})$ are the off-shell coupling scale factors associated with the $gg \rightarrow H^{*}$ production and the $H^{*} \rightarrow VV$ decay. The off-shell signal strength and coupling scale factors are assumed in the following to be independent of $\hat{s}$ in the high-mass region selected by the analysis. The off-shell Higgs boson signal cannot be treated independently from the $gg \rightarrow VV$ background, as sizeable negative interference effects appear (calculated in Ref. [2]). The interference term is proportional to $\sqrt{\mu_{\text{off-shell}}} = \kappa_{g, \text{off-shell}} \cdot \kappa_{V, \text{off-shell}}$.

This study uses the same analysis in the $H \rightarrow ZZ \rightarrow 4l$ final state as those described in Ref. [3]. It is structured as follows: Section 2 will cover the production and validation of MCFM Monte Carlo samples generated at $\sqrt{s}=14$ TeV. Section 3 will describe the method to obtain the extrapolation for the HL-LHC scenario using the generated samples at $\sqrt{s}=14$ TeV while Section 4 will report the results of the off-shell coupling measurement.

2 Monte Carlo event generation at $\sqrt{s}=14$ TeV

Monte Carlo generation at $\sqrt{s}=14$ TeV is performed with MCFM as in Refs. [4][5] for $gg \rightarrow H^{*} \rightarrow ZZ \rightarrow 4l$ signal, $gg \rightarrow ZZ \rightarrow 4l$ continuum background and $gg \rightarrow (H^{*}) \rightarrow ZZ \rightarrow 4l$ (the full process that includes signal, background and interference between signal and background, hereafter referred to as SBI). The Higgs boson mass is set to $m_{H}=125.5$ GeV and the QCD factorisation and renormalisation

\footnote{In this note the symbol $V$ is used to denote a generic SM vector-boson $V = W, Z$.}
Figure 1: (a) Differential cross-sections generated with MCFM at $\sqrt{s}=14$ TeV for the $gg$-initiated processes in the 2e2$\mu$ channel at the matrix element level. (b) Comparison of the Higgs boson signal with the interference contribution.

scales are fixed at $\frac{M_{ZZ}}{2}$. In order to ensure consistency with the baseline sample generated at $\sqrt{s}=8$ TeV in Ref. [3], the same kinematic cuts are applied at generator level. In addition, the $qq \rightarrow ZZ$ sample has been generated with POWHEG-BOX, [6], at $\sqrt{s}=14$ TeV. These samples are used to reweight the baseline 8 TeV samples as detailed in the next Section.

Figure 1 illustrates the $m_{4l}$ distribution generated with MCFM for the various $gg$-initiated processes in the $2e2\mu$ channel at $\sqrt{s}=14$ TeV as well as the contribution of the negative signal-background interference.

3 Outline of the method

In order to extract the upper limit on the off-shell signal strength for the HL-LHC scenario, the matrix element (ME) based kinematic discriminant defined in Refs. [7][8] and already exploited in the previous publication [3] is used.

The workflow of the analysis is described below:

- The distributions of the ME-based kinematic discriminant at $\sqrt{s}=8$ TeV for $gg$-initiated samples, namely signal (S), background (B) and SBI including detector simulation, used in the published analysis in Ref. [8], are scaled to 14 TeV. The scaling is a function of the four-lepton invariant mass computed using the 14 TeV MCFM samples. This is done in order to take into account the increased parton luminosities ratio between 14 TeV and 8 TeV as function of the invariant mass of the ZZ system. The weights are defined as: $w(m_{4l}) = \frac{\sigma_{14\text{TeV}}(m_{4l})}{\sigma_{8\text{TeV}}(m_{4l})}$. Similarly, the ME-based
The kinematic discriminant distribution of the $qq \rightarrow ZZ$ background at $\sqrt{s}=8$ TeV is scaled at 14 TeV using a weight which is a function of the four-lepton invariant mass obtained with the $qq \rightarrow ZZ$ sample generated with POWHEG-BOX at $\sqrt{s}=14$ TeV and $\sqrt{s}=8$ TeV. The distributions of these weights are shown in Figure 2 (a). The same k-factors as those used in Ref. [8], computed for a center-of-mass energy of 8 TeV, are applied since the difference with respect to the k-factors at 14 TeV is of the order of 10% and within the QCD scale uncertainties [9, 10]. The distribution of the ME discriminant for the weighted samples are shown in Figure 2 (b) while the cross section of the processes at 14 TeV in the kinematic range ($220 < m_{4l} < 1000$) GeV are listed in Table 1. The larger yield ratio for the gg-related processes compared to qq is expected and coincides with the ratio of the parton luminosities between $\sqrt{s}=7$ TeV and $\sqrt{s}=14$ TeV.

The $pp \rightarrow VV +2j$ 8 TeV samples have been scaled by the ratio of the cross sections computed at 14 and 8 TeV with POWHEG-BOX. Since this process represent a small correction to the main gg-initiated one, the dependency on the four-lepton invariant mass has been neglected.

Concerning the studies at $\sqrt{s}=14$ TeV, two different integrated luminosities are considered:

1. $L_1 = \int \mathcal{L} dt = 300$ fb$^{-1}$;
2. $L_2 = \int \mathcal{L} dt = 3000$ fb$^{-1}$.

<table>
<thead>
<tr>
<th>$\sqrt{s}$/σ</th>
<th>S (fb)</th>
<th>B (fb)</th>
<th>SBI (fb)</th>
<th>$qq \rightarrow ZZ$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 TeV</td>
<td>0.03</td>
<td>0.67</td>
<td>0.64</td>
<td>16.7</td>
</tr>
<tr>
<td>14 TeV</td>
<td>0.11</td>
<td>1.96</td>
<td>1.86</td>
<td>36.9</td>
</tr>
</tbody>
</table>

Table 1: Cross sections for the various gg-initiated processes and $qq \rightarrow ZZ$ at $\sqrt{s}=8$ TeV and $\sqrt{s}=14$ TeV. The generation cuts are the following: $m_{4l} > 200$ GeV for the gg-initiated processes (MCFM) and $m_{ll} > 40$ GeV for $qq \rightarrow ZZ$ (POWHEG). The $ZZ \rightarrow 2e2\mu$ branching ratio is included.

The main assumption under this extrapolation of the 8 TeV samples at higher center-of-mass energies and luminosities is that the signal and background experimental efficiencies, computed with the 8 TeV fully simulated samples, are preserved in the high-luminosity-high-energy scenario as reported in Refs. [11][12]. Furthermore, the four-lepton invariant mass selection used in this study is identical to that of the published analysis, e.g. ($220 < m_{4l} < 1000$) GeV.

### 3.1 Treatment of the systematic uncertainties

As documented in Ref. [3], the experimental systematic uncertainties have a negligible impact on the upper limit on $\mu_{\text{off-shell}}$, of the order of 0.3%. These uncertainties are therefore not included in this study. In analogy with the published $H \rightarrow ZZ \rightarrow 4l$ analysis [3], the parametrization for the gg-initiated process in the fit is:

$$
\sigma_{gg \rightarrow (H^\ast) \rightarrow ZZ} = \left( K_{H^\ast} (m_{ZZ}) \cdot \mu_{\text{off-shell}} - K_{gg} (m_{ZZ}) \cdot \sqrt{R_{H^\ast} \cdot \mu_{\text{off-shell}}} \right) \cdot \sigma_{SM}^{gg \rightarrow H^\ast \rightarrow ZZ} \cdot \sigma_{cont}^{gg \rightarrow ZZ} 
$$

The treatment of the systematic uncertainties on this model is expressed below:
Figure 2: $m_4l$-dependent reweighting factors from $\sqrt{s}=8$ TeV to $\sqrt{s}=14$ TeV for the $gg \to H^* \to 4l$ signal sample, the background $gg \to ZZ$ contribution, the SBI, comprising signal, background and interference, and the $qq \to ZZ$ term (a). (b) Example of ME discriminant distribution for the various processes of the analysis generated at $\sqrt{s}=14$ TeV for $3000 \text{ fb}^{-1}$.

- $K_H^{H'}(m_{ZZ})$ and $K_{H^*}^{H^*}(m_{ZZ})$ are the signal LO-to-NNLO k-factor for the $pp \to H^* \to ZZ$ and for the k-factor for $gg \to H^* \to ZZ$ processes, respectively. As in the published analysis, a 30% systematic uncertainty, fully correlated among S, SBI and B, is applied.

- $R_{H^*}^{H^*}(m_{ZZ})$ is the background-to-signal k-factor ratio. Two benchmark systematic uncertainties are considered for this ratio: 10% and 30%. This choice is quite arbitrary (this ratio has not been computed yet) but it is based on the assumptions that theory predictions on the $gg$-initiated processes (S, B and SBI) will improve on the timescale of the HL-LHC.

- An additional 10% normalization systematic uncertainty is applied to the $qq \to ZZ$ process, due to QCD and PDF scale uncertainties.

The only missing term with respect to the previous study (Ref. [3]) is the systematic uncertainties on the interference contribution in the formula (2), accounting for a conservative 30% variation on the templates. The explanation of this addition was demonstrated by the definition of $R_{H^*}^{H^*}(m_{ZZ})$ that leads to large cancellations between the interference and the background. This item is now replaced by an ad hoc systematic uncertainty on $R_{H^*}^{H^*}(m_{ZZ})$ for a less conservative approach. This is based on the assumption that in the next years the theorists will improve the computations on this process.

In addition shape systematic uncertainties on the ME distributions have also been implemented in the model. Only the highest shape variations are included, i.e. the QCD scale systematic uncertainties for both $gg$ and $qq$-initiated templates [3]. The effect of these uncertainties on the ME discriminant distributions is shown in Figure 3. The correlation model of the nuisance parameters employed is the following:

- 4 different nuisance parameters:
2 nuisance parameters (different for shape and normalization systematic uncertainties) for \( gg \)-initiated processes. These parameters are treated as fully correlated among S, B and SBI.

2 nuisance parameters for the \( qq \rightarrow ZZ \) template (shape and normalization).

4 Results

As a first step, the results obtained at \( \sqrt{s} = 8 \) TeV with 20.3 fb\(^{-1} \) have been compared to the ones of the published analysis [3]. A maximum likelihood fit is performed using probability density functions generated at 8 TeV for 20.3 fb\(^{-1} \) and the statistics-only as well as statistics+systematic uncertainties upper limits on \( \mu_{\text{off-shell}} \) in the 4 lepton channel are derived and found to be identical to the ones reported in Ref. [3].

The fit is then performed using the samples scaled to the center-of-mass energy of 14 TeV (as explained in previous Sections) for the two integrated luminosity scenarios. Figure 4 and 5 shows the likelihood curves with and without systematic uncertainties (normalisation only and normalisation+shape) in the scenarios \( L_1 \) and \( L_2 \) respectively. The double-minimum structure observed for \( \mu_{\text{off-shell}} < 1 \) is related to the quadratic dependency of the observed yields on the off-shell signal strength and it was already present in the published analysis of Ref. [3]. The SM minimum gets more and more resolved as the statistics grows so that the likelihood function is quite parabolic close to its minimum for 3000 fb\(^{-1} \). It should be noted that the distributions of the ME discriminant are able to constrain the three components S, B and SBI at very high luminosity and the SM minimum is preferred with respect to the second one at a level better than one standard deviation. The systematic uncertainties on the ME shape, in this scenario, play a very important role. It will be therefore very important to obtain improvements on the theory side not only on the values of the k-factors for S, B and SBI but also on the ME distributions.

The fitted values of \( \mu_{\text{off-shell}} \) with the 1\( \sigma \) uncertainties, for the two luminosities labeled with the superscripts (L1) and (L2), assuming a systematic uncertainty on \( R_{H^*}^B \), of 10\% , are:

\[
\mu_{\text{off-shell}}^{(L_1)} = 1.00^{+0.55}_{-0.94} \text{(stat only)}, \quad \mu_{\text{off-shell}}^{(L_1)} = 1.00^{+0.72}_{-0.96} \text{(stat+sys)}.
\]

\[
\mu_{\text{off-shell}}^{(L_2)} = 1.00^{+0.23}_{-0.27} \text{(stat only)}, \quad \mu_{\text{off-shell}}^{(L_2)} = 1.00^{+0.36}_{-0.49} \text{(stat+sys)}.
\]

Figure 6 shows the effect of the various systematic uncertainties on the fitted value of \( \mu_{\text{off-shell}} \) and the constraints provided by the SM pseudo-data at 3000 fb\(^{-1} \) when applying 10\% uncertainty on \( R_{H^*}^B \). The post-fit effect on \( \mu_{\text{off-shell}} \) is calculated by fixing the corresponding nuisance parameter at \( \pm \sigma_\theta \) being \( \sigma_\theta \) the post-fit uncertainty and performing the fit again. All the other nuisance parameters are fixed to the value \( \theta = 0 \), in order to estimate the impact of each single component regardless of the interplay with the other systematic sources. The difference between \( \mu_{\text{off-shell}} = 1 \) and the modified \( \mu_{\text{off-shell}} \), \( \Delta \mu_{\text{off-shell}} \), represents the effect on \( \mu_{\text{off-shell}} \) of each systematic uncertainty. It is worth noting that the uncertainties related to the main systematic sources are reduced from the initial value due to the significant number of SM pseudo-data events available at 3000 fb\(^{-1} \).

The impact of adding an uncorrelated (w.r.t. the signal and background k-factors) normalization systematics on the interference term has been also checked: an additional 10\% (30\%) systematic uncertainty on the interference k-factor will increase the error on the off-shell signal strength by 20\% (40\%).

The obtained values on \( \mu_{\text{off-shell}} \) when the uncertainty on \( R_{H^*}^B \) is assumed to be 30\% are:

\[
\mu_{\text{off-shell}}^{(L_1)} = 1.00^{+0.55}_{-0.94} \text{(stat only)}, \quad \mu_{\text{off-shell}}^{(L_1)} = 1.00^{+0.80}_{-0.97} \text{(stat+sys)}.
\]
Figure 3: Distributions of the nominal samples entering the fit for signal (a), SBI (b), $gg \to ZZ$ (c) and $qq \to ZZ$ (d) backgrounds as well as their up and down shape variations using the highest contributions to the overall systematic uncertainties, i.e. the QCD scale systematic uncertainties for both $gg$ and $qq$-initiated templates as in Ref. [3].
Figure 4: Likelihood scans on $\mu_{\text{off-shell}}$ with and without systematic uncertainties for the configuration $L_1$ and $L_2$. The error on $\mu$ is computed at the 1σ level and the uncertainty on $R^B_{H^*}(m_{ZZ})$ is set to 10%.

Figure 5: Likelihood scans on $\mu_{\text{off-shell}}$ with and without systematic uncertainties for the configuration $L_1$ and $L_2$. The error on $\mu$ is computed at the 1σ level and the uncertainty on $R^B_{H^*}(m_{ZZ})$ is set to 30%.
Figure 6: Fitted values of the nuisance parameters exploiting a fit to SM pseudo-data events generated at 3000 fb$^{-1}$ at $\sqrt{s} = 13$ TeV. A 10% systematic uncertainty on $R_{H^*}^W$ is applied. The points, which are drawn conforming to the scale of the bottom axis, show the deviation of each of the fitted nuisance parameters, $\theta$, from $\theta_0$, which is the nominal value of that nuisance parameter, in units of the pre-fit standard deviation $\Delta \theta$. The red error bars show the post-fit uncertainties, $\sigma_\theta$, that are close to 1 if the pseudo-data do not provide any further constraint on that uncertainty. A value of $\sigma_\theta$ much smaller than 1 indicates a significant reduction with respect to the original uncertainty. Pre-fit and post-fit effect of each nuisance parameter on $\mu_{\text{off-shell}}$, referring to the scale of the top axis, are shown as yellow and hashed blue bars respectively.

$$\mu_{\text{off-shell}}^{(L1)} = 1.00^{+0.24}_{-0.81} \text{(stat only)}, \mu_{\text{off-shell}}^{(L2)} = 1.00^{+0.43}_{-0.56} \text{(stat+sys)}.$$ 

4.1 The $\kappa$ coupling parametrization model

Another way of parametrizing the Higgs boson off-shell couplings is to use the $\kappa$ formalisms defining: $\mu_{\text{off-shell}} = \kappa_{\text{off-shell}}^2$. In this way the measured yields are sensitive to the relative sign of the off-shell couplings with respect to the Standard Model (SM) background process. where $\kappa$ is the product of the couplings of the Higgs boson to the initial and final states. This parametrization is particularly suitable for the description of beyond SM scenarios because it is sensitive to possible non-SM positive interference resulting in negative values of $\kappa$. The likelihood curves for the projections at 300 fb$^{-1}$ and 3000 fb$^{-1}$ are illustrated in Figures 7 and 8. The treatment of the systematic uncertainties on this measurement follows the prescriptions reported in Section 3.1. As for the previous case, the 1$\sigma$ error on the fitted value is reported and the assumed systematic uncertainty on $R_{H^*}^W$ is 10%:

$$\kappa^{(L1)} = 1.00^{+0.24}_{-0.81} \text{(stat only)}, \kappa^{(L1)} = 1.00^{+0.31}_{-0.82} \text{(stat+sys)}.$$ 

$$\kappa^{(L1)} = 1.00^{+0.12}_{-0.14} \text{(stat only)}, \kappa^{(L2)} = 1.00^{+0.15}_{-0.29} \text{(stat+sys)}.$$ 

If the systematic uncertainty on $R_{H^*}^W$ is set to 30%, the following values are extracted:
Figure 7: Likelihood scans on $\kappa$ with (blue) and without (red) systematic uncertainties for the configuration $L_1$ and $L_2$. The error on the limit on $\mu$ is computed at the 1$\sigma$ level and the uncertainty on $R_{Hs}$ is set to 10%.

Figure 8: Likelihood scans on $\kappa$ with (blue) and without (red) systematic uncertainties for the configuration $L_1$ and $L_2$. The error on the limit on $\mu$ is computed at the 1$\sigma$ level and the uncertainty on $R_{Hs}$ is set to 30%.
\[ \kappa^{(L1)} = 1.00^{+0.24}_{-0.81} \text{ (stat only)}, \quad \kappa^{(L1)} = 1.00^{+0.32}_{-0.83} \text{ (stat+sys)}. \]

\[ \kappa^{(L2)} = 1.00^{+0.12}_{-0.14} \text{ (stat only)}, \quad \kappa^{(L2)} = 1.00^{+0.19}_{-0.26} \text{ (stat+sys)}. \]

4.2 Determination of the total width

As explained in Ref [3], the ratio of the off-shell and on-shell Higgs boson couplings can be used to measure the total width under several assumptions briefly summarized in the following. The cross-section for on-shell Higgs production allows a measurement of the signal strength:

\[ \mu_{\text{on-shell}} = \frac{\sigma^{gg \rightarrow H \rightarrow ZZ}_{\text{on-shell}}}{\sigma^{gg \rightarrow H \rightarrow ZZ}_{\text{on-shell, SM}}} = \kappa_{g, \text{on-shell}}^2 \cdot \frac{\kappa_{Z, \text{on-shell}}^2}{\Gamma_H/\Gamma_H^{\text{SM}}}, \tag{3} \]

which depends on the total width \( \Gamma_H \). Assuming identical on-shell and off-shell Higgs couplings, the ratio of \( \mu_{\text{off-shell}} \) to \( \mu_{\text{on-shell}} \) provides a measurement of the total width of the Higgs boson. This assumption is particularly relevant to the running of the effective coupling \( \kappa_g(\hat{s}) \) for the loop-induced \( gg \rightarrow H \) production process, as it is sensitive to new physics that enters at higher mass scales and could be probed in the high-mass \( m_{ZZ} \) signal region of this analysis. More details are given in Refs. [13–17]. It is also assumed that any new physics which modifies the off-shell signal strength \( \mu_{\text{off-shell}} \) and the off-shell couplings \( \kappa_i, \text{off-shell} \) does not modify the predictions for the backgrounds. Further, neither are there sizeable kinematic modifications to the off-shell signal nor new, sizeable signals in the search region of this analysis unrelated to an enhanced off-shell signal strength [18].

Assuming that the on-shell couplings will be measured at high luminosity with much higher precision, the projection on the off-shell Higgs boson coupling can be translated into a projected determination of the Higgs boson total width at 3000 fb\(^{-1}\) (10% systematic uncertainty on \( R_B^H \)):

\[ \Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1} \text{ MeV (stat+sys)}. \]

5 Conclusion

The measurement of the off-shell signal strength of the Higgs boson using ZZ events in the 4l channel has been explored in the HL-LHC scenarios, i.e. \( \sqrt{s}=14 \text{ TeV} \) for integrated luminosities of 300 fb\(^{-1}\) and 3000 fb\(^{-1}\).

The measurement of \( \mu_{\text{off-shell}} \) is carried out in the same way as in the standard analysis, explicitly by employing a likelihood fit using ME-based templates that have been scaled in order to account for different luminosity and energy conditions. A simple treatment of the theoretical uncertainties, considering both normalisation and shape variations, is also introduced in the model. The best fitted value returned by the likelihood fit on \( \mu_{\text{off-shell}} \) at 3000 fb\(^{-1}\) allows to determine the parameter of interest in the fit with an accuracy of approximately 50% at the 1\( \sigma \) level. Assuming that the on-shell couplings will be measured with much higher precision, this projection (under the assumptions mentioned in Ref. [3]) can be translated into a projected determination of the Higgs boson total width of \( \Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1} \text{ MeV} \) when the systematic uncertainty on \( R_B^H \) is set to 10%. 
References


