Abstract

After the discovery of a scalar resonance, resembling the Higgs boson, its couplings have been extensively studied via the measurement of various production and decay channels on the invariant mass peak. Recently, it has been suggested the possibility to use off-shell measurements: in particular, CMS has published results based on the high-invariant mass cross section of the process $gg \rightarrow ZZ$, which contains the contribution of the Higgs. While this measurement has been interpreted as a constraint on the Higgs width after very specific assumptions are taken on the Higgs couplings, in this letter we show that a much more model-independent interpretation is possible.

Since the discovery of a scalar boson at the LHC by the ATLAS and CMS collaborations, much effort has been devoted to the study of its properties. So far, most of the information has been obtained by extracting its couplings from the cross-section measurements in various production/decay modes on the resonance peak [1,2]. Interpreting those results in a Beyond the Standard Model (BSM) context can be easily done in terms of a handful of parameters encoding the modification of the couplings to standard particles and, among the many proposals, one has been chosen as an official recommendation by experimentalists and theorists together [3]. Recently, a novel kind of measurement has been put forward, where Higgs couplings are extracted from the cross-section integrated away from the resonance peak [4,5], and the first results from CMS on the $H \rightarrow ZZ \rightarrow 4$ leptons have been published [6]. This new class of measurements is most welcome, since it carries information on the Higgs couplings at a different mass scale than its mass shell, and such a dependence on the partonic centre of mass energy $\sqrt{s}$ is paramount to distinguishing BSM effects. Although

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the measurement \cite{7} was initially proposed as a mean of determining the Higgs width, it was quickly recognised in \cite{8} that such an extraction was too model-dependent to be meaningful. In this short letter, we want to point out that the measurement can be primarily interpreted as a bound on the coupling of the Higgs to tops and on the loop contribution of new heavy states to the coupling to gluons, in the limit of heavy new physics coloured states. The direct sensitivity to the new loop is novel, as it is not possible to disentangle it from on-peak measurements.

In the experimental analysis \cite{7} the signal region is defined in order to enhance the rate of events coming from the $gg \to ZZ$ process, which consists of a box diagram plus the $s$-channel Higgs, over the $q\bar{q} \to ZZ$ background. The Higgs contribution consists mainly of a gluon fusion production followed by the decay to two $Z$ bosons, which interferes with the box diagram. Off-shell, the cross section does not depend explicitly on the Higgs width: however, one can always compensate for a different value of the width in the peak region by rescaling appropriately the couplings of the Higgs to tops and $ZZ$, thus it is the rescaling of the couplings that affects the off-shell cross section. The interpretation in terms of width, therefore, only works under very specific assumptions: a large contribution to the total width coming from new decay channels, and the absence of new particles running in the Higgs to gluons loop. The latter point, already properly stressed in \cite{8}, arises from the fact that at a partonic centre of mass energy away from the Higgs mass peak, the loops participating in the production (and decay) of the Higgs may be resolved if the mass of the exchanged particle is light. This is the case for Standard Model (SM) loops. To be specific, the measurement in \cite{7} is dominated by the gluon fusion production, which is mainly mediated by a top loop in the SM. This loop form factor does depend on the scale and is significantly different at the Higgs mass shell $\sqrt{s} = 125.5$ GeV and in an off-peak region $\sqrt{s} > 350$ GeV above the top pair threshold. If the particle running in the loop were much heavier, say around 1 TeV, the scale dependence would be quite different. In BSM scenarios, one can typically expect both modifications of the tree level couplings to the top and new heavy coloured states running in the loop. Due to direct searches at the LHC, the mass of the new states is bound to be quite heavy, thus the approximation of heavy new states is justified. For an on-shell Higgs, a cancellation between the two effects may and often does occur \cite{7} so that the presence of New Physics may not appear in on-peak measurement. Then it is clear that only measurements at different $\sqrt{s}$ can distinguish the two effects since the top and the New Physics contribution have a different scale dependence. In this perspective, the parametrisation of the Higgs couplings we proposed in \cite{9,10} is very handy, as it suggests to separate into two independent parameters the tree level modification of the top coupling and the effect of any loop of New Physics states.

\footnote{A famous example is the case of a heavy vector-like quark mixing to the top via Yukawa-like interactions, as in models of Composite Higgs with top partners.}
The two parameters, relevant for our discussion, are defined as

\[ \kappa_t = \frac{g_{h\ell\ell}}{g_{t\ell\ell}^{SM}} \quad \text{and} \quad \kappa_{gg} = \frac{A_{h\rightarrow gg}^{NP}}{A_{h\rightarrow gg}^{t,SM}}, \]

(1)

where \( A_{h\rightarrow gg} \) stands for the on-shell amplitude of the process, \( ^{NP} \) stands for the contribution from new particles while \( t,SM \) is the contribution from the top loop with SM coupling to the Higgs. The contribution of new physics in the loop is normalised to the top loop following the expectation that the main contribution comes from new particles associated with the top mass generation. The two parameters enter in the calculation of the cross section in two different combinations on-peak and off-shell, so that the two effects can be clearly separated by using this parametrisation.

Figure 1: Left: Dependence on the new-physics mass of the cross section of the \( gg \rightarrow VV \) process in the off-shell region, normalized to the SM cross section for the same process. Right: Regions allowed at 1 and 2 \( \sigma \) by the on-peak coupling constraints (diagonal bands), compared to the off-shell iso-cross section lines for the \( gg \rightarrow VV \) process at 1.2, 1.50 and 2 times the SM cross section. The dot and black line correspond to the \( \kappa_{gg} = 0 \) case where the CMS bound can be recast to the constraint \( \kappa_t < 2.3 \).

The form factor associated with \( \kappa_{gg} \) depends on the mass of the particle(s) running in the loop, however this dependence is suppressed for large values of the mass, as the loop can be replaced by a higher order operator. To quantify this statement, we considered the process \( 3 \)

In the usually recommended parametrisation \( 3 \), \( \kappa_t \) is defined in the same way, while the coupling to the gluons is defined as

\[ \kappa_g = \sqrt{\frac{\Gamma_{h\rightarrow gg}}{\Gamma_{h\rightarrow gg}^{SM}}} \]

On-shell, the parameters in the two sets are simply related: \( \kappa_g = \kappa_t + \kappa_{gg} \), while this degeneracy is removed off-shell. The difference between the two choices for the coupling to the gluons is crucial for the study of BSM effects from off-shell measurements.
\( gg \to ZZ \to l^+l^-l'^+l'^- \) and study the dependence of the off-shell cross section. Following the experimental study \[7\], by off-shell cross section we define the cross section integrated over a range \( \sqrt{s} > 330 \) GeV after the basic experimental cuts. Note however that this is an intermediate definition between the off-shell region defined in \[7\] \((m_{4\ell} > 220 \text{GeV})\) and the signal-enriched region \((m_{4\ell} > 330 \text{ GeV} \text{ plus a cut on a matrix element MELA discriminant}), since our cross sections is estimated before the MELA discriminant cut. Our calculation has been performed by using the code \textit{gg2VV} \[11\], modified by us in order to include the effect of a heavy particle loop. To be specific, all the results in this paper are based on a top-like fermion running in the loop. In the left panel of Figure 1 we show the dependence of the off-shell cross section as a function of the new fermion mass, fixing \( \kappa_t = 1 \) (so that the top loop is standard) and \( \kappa_{gg} = 1 \). From the plot we can see that the value starts becoming fairly independent on the mass between 500 GeV and 1 TeV: considering the typical direct bounds from LHC on coloured new particles, the approximation of infinite mass is very effective.

In the right panel of Figure 1 we also show iso-cross section contours as a function of \( \kappa_t \) and \( \kappa_{gg} \) together with the region of parameters preferred by on-peak measurements and for large new physics mass. The degenerate direction \( \kappa_t + \kappa_{gg} \sim \pm 1 \) is now resolved, thus an interpretation of the experimental bound in terms of these two parameters can be useful to resolve this degeneracy and directly probe new physics loops in the Higgs to gluon coupling.

In Table 1 of \[7\], the off-shell signal-enriched region after MELA discrimination is shown to contain 11 events against the expected 11.4 \( \pm 0.8 \): these numbers, when compared to the 1.8 expected \( gg \to VV \to 4\ell \) events, show that at 95% C.L. the study is sensitive to an approximate doubling of the \( gg \to VV \) cross section. The actual bound is extracted from a signal enhanced region, thanks to a matrix element discriminant. However, the experimental analysis is performed in absence of the new physics loop, therefore a direct reinterpretation of the bound cannot be done because the energy dependence and kinematics of the top and new physics loops can differ substantially. We leave a full analysis for a future publication, and for the experimental collaborations.

The main advantage of our proposal is that the analysis results will contain much more information that the interpretation in terms of the Higgs width. The Higgs width bound can be recovered in the limit \( \kappa_{gg} = 0 \): in this case, a rescaling of the width by a factor \( \Gamma_H = \xi \Gamma_{H}^{\text{SM}} \) can be compensated on-peak by \( \kappa_t = \sqrt{\xi} \). Therefore, the published bound \( \Gamma_H < 5.4 \Gamma_{H}^{\text{SM}} \) at 95% C.L can be re-expressed as an upper bound on \( \kappa_t < \sqrt{5.4} = 2.3 \) (dot in Figure 1 with the excluded line on the right side). We can see that this dot is close to the iso-contour giving a doubled cross section, consistently with the previous remark about numbers of events. This bound, however, only applies to positive values of \( \kappa_t \) and it does not cover the possibility of negative couplings, for which the interference term has different sign.

To compare this bound with the constraints from the on-peak measurements, in Figure 1 we show the result of the fit \[10\] where we leave the two parameters \( \kappa_t \) and \( k_{gg} \) free, profile over the new physics loop in the di-photon coupling in order to fit the di-photon signal, and set all the other couplings to the standard model value. The plot clearly show that the on-peak measurements have a degeneracy for \( \kappa_t + \kappa_{gg} \sim \pm 1 \), which is removed by the off-shell measurement. An analysis of the off-shell measurement in terms of the two parameters would clearly add important information on the Higgs couplings, independently on its width. It
is finally interesting to quote the direct bound on $\kappa_t$ coming from the measurement of the $t\bar{t}h$ associated production. Assuming that the decay rate in $b\bar{b}$ is standard model like, the cross section is simply proportional to $\kappa_t^2$: from the CMS published bound [12] based on an integrated luminosity of 5 fb$^{-1}$ at 8 TeV, we can extract $|\kappa_t| < \sqrt{5.8} = 2.4$, while the ATLAS measurement with full 8 TeV dataset leads to $|\kappa_t| < \sqrt{4.1} = 2.02$ at 95%CL [13].

The simple analysis in this letter shows that the off-shell measurement of $gg \to ZZ$, performed by CMS [7], can be recast to a model-independent bound on the couplings of the Higgs to the top and on the contribution of new states in the Higgs to gluon coupling. In this perspective, the parametrisation of the Higgs couplings that we proposed in previous publications [9][10], where two independent parameters are used for the tree level top coupling and new physics loops, are very useful for a model-independent interpretation of off-shell measurements.

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