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Off-shell Higgs signal and total width determination at the LHC

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A substantial off-shell Higgs boson signal in the gluon fusion and vector boson fusion $H \to ZZ$ and $H \to WW$ channels at the Large Hadron Collider (LHC) facilitates a novel, complementary approach to constraining the total Higgs width Γ_H. With LHC Run 1 data, experimental analyses by CMS and ATLAS find $\Gamma_H < 5.4\,\Gamma_H^{\mathrm{SM}}$ and $\Gamma_H < [4.5, 7.5]\,\Gamma_H^{\mathrm{SM}}$ at 95% confidence level, respectively, where Γ_H^{SM} is the expected value in the Standard Model at the measured Higgs boson mass. I review the theoretical basis of the new approach and discuss its significance in comparison to other methods to bound and measure the Higgs width at the LHC and future colliders.

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1. Introduction

The fundamental particle predicted by the Standard Model (SM) Higgs mechanism [1], i.e. the Higgs boson, was discovered at the LHC in 2012 [2]. A thorough examination has since taken place and its properties have been found to be in agreement with theoretical expectations. No compelling deviations from the SM have been discovered so far. An important property of the Higgs boson is its total decay width, with a predicted SM value of $\Gamma_H^{\rm SM} \approx 4$ MeV, which is more than two orders of magnitude smaller than the experimental Higgs mass resolution at the LHC, which is of order 1 GeV. At the LHC, any direct Higgs width measurement via the resonance shape is thus limited to an uncertainty of $\Delta\Gamma_H \sim 1$ GeV.[1] Since the resonant ("on-peak") Higgs cross section depends on Γ_H, the Higgs couplings and width cannot be determined independently at the LHC without relying on theoretical assumptions [4,5]. For instance, in models without triplett or higher $SU(2)$ representations an upper limit for the HWW or HZZ coupling exists and an upper bound for the Higgs width can be obtained that is of the order of the SM Higgs width [6,7]. Assuming no beyond-SM (BSM) Higgs decays, and suggestive Higgs coupling parameterisations, one can fit the Higgs width to data and finds similar agreement with $\Gamma_H^{\rm SM}$ [8–12]. At a future e^+e^- collider, a largely model-independent indirect determination of the Higgs width will be possible, with a predicted accuracy of 5–10% at the International Linear Collider [12–14]. A future muon collider could permit a direct Higgs width measurement via threshold scan with an estimated accuracy of 4–9% [15]. Two novel, complementary methods to constrain the Higgs width at the LHC are reviewed in Section 2.

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2. Off-shell Higgs signal enabled total width determination at the LHC

The existence of a substantial off-shell Higgs boson signal in the gluon fusion $H \to ZZ$ and $H \to WW$ channels at the LHC was first pointed out in Ref. [16].[2] In Fig. 1, representative graphs for the Higgs signal and continuum background processes are shown as well as M_{VV} distributions that show the enhanced off-shell Higgs signal, which constitutes an $\mathcal{O}(5\text{–}10\%)$ correction to inclusive $gg \to H \to VV$ production in narrow-width approximation (NWA). With typical experimental LHC selection cuts this correction increases to $\mathcal{O}(10\text{–}20\%)$. Also shown in Fig. 1 is the sizeable signal-background interference in the off-shell region, which facilitates unitarity at high energies and has been calculated in Refs. [16,18–25]. Note that the interfering $gg \to VV$ continuum background at LO is formally part of the NNLO corrections to $pp \to VV$ [26,27].

A proposal to exploit the Higgs width independence of the off-shell Higgs signal in order to break the NWA scaling degeneracy

$$\sigma_{i\to H\to f} \overset{\rm NWA}{\propto} \frac{g_i^2 g_f^2}{\Gamma_H}\,, \quad \sigma \text{ invariant if } \; g_i \to \xi\, g_i,\;\; g_f \to \xi\, g_f,\;\; \Gamma_H \to \xi^4 \Gamma_H$$

of the on-peak Higgs signal in $gg \to H \to ZZ \to 4\ell$ was first made in Ref. [28], which also provided a proof-of-concept phenomenological analysis which suggested that Higgs width constraints of $\Gamma_H < [20,38]\,\Gamma_H^{\rm SM}$ are feasible. A more detailed phenomenological analysis was subsequently

[1] For instance, Ref. [3] finds $\Gamma_H < 3.4$ GeV at 95% confidence level (CL).

[2] The significance of the off-shell $H \to VV$ signal at a linear collider is discussed in Ref. [17].

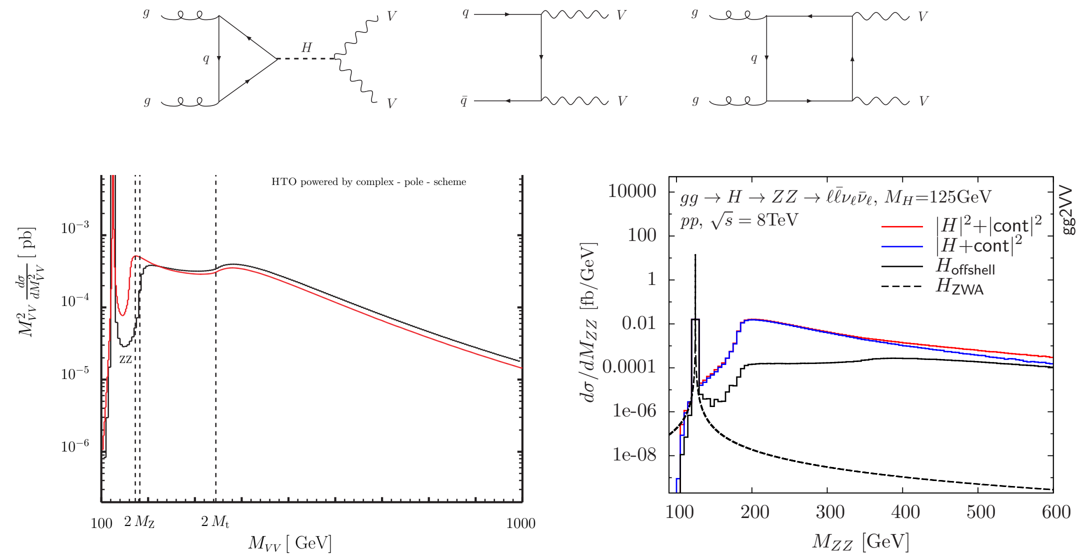

Figure 1: Representative Feynman graphs for the $gg \to H \to VV$ signal process (left) and the $q\bar{q}$- (centre) and gg-initiated (right) continuum background processes at LO as well as M_{VV} distributions that show the enhanced off-shell Higgs signal and sizeable Higgs-continuum interference (from [16]).

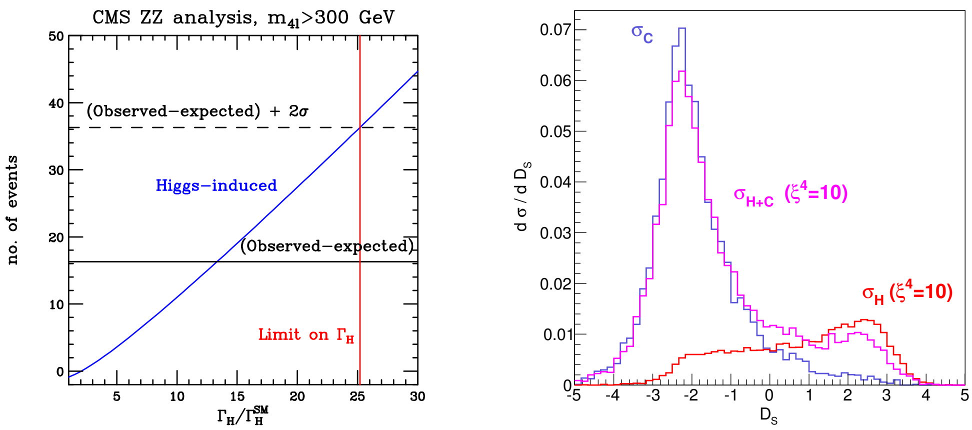

Figure 2: Results of a detailed phenomenological study of the off-shell Higgs width constraint approach (from [29]).

carried out in Refs. [29, 30], which optimized the sensitivity of the method by exploiting the full differential cross section information using the Matrix Element Method [31] (see Fig. 2). After these phenomenological studies, CMS [32] (see Fig. 3) and ATLAS [33] (see Fig. 4) carried out full experimental simulations which also took into account the $2\ell 2\nu$ final state, vector boson fusion contributions and higher-order corrections. CMS and ATLAS thus found $\Gamma_H < 5.4\,\Gamma_H^{\text{SM}}$ and $\Gamma_H < [4.5, 7.5]\,\Gamma_H^{\text{SM}}$ at 95% CL, respectively. More recently, theorists have demonstrated that the ZZ+jet channel can be used to improve the obtained constraints [34]. That the off-shell Higgs width constraint approach is *a priori* model dependent was first pointed out in Ref. [35] and has been further studied in Refs. [36, 37].

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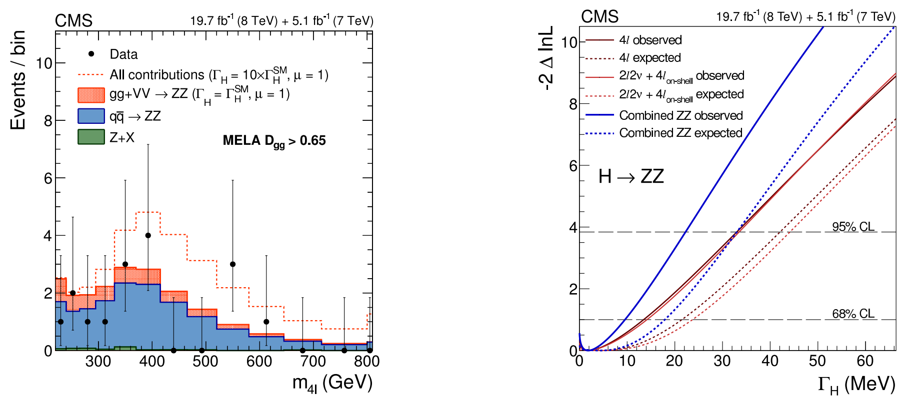

Figure 3: CMS study of off-shell Higgs width constraint approach (from [32]).

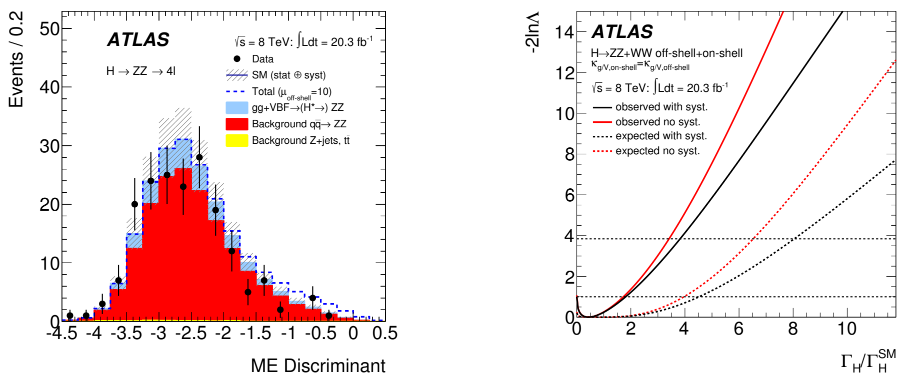

Figure 4: ATLAS study of off-shell Higgs width constraint approach (from [33]).

More generally, the off-shell $H \to VV$ signal can be used to disentangle degeneracies in parametric BSM studies or constrain higher dimensional operators in effective field theory (EFT) studies [36, 38–43]. For instance, Refs. [40, 41, 43] analyse SM deviations of the effective ggH and $Ht\bar{t}$ coupling strengths in an EFT approach:

$$\mathscr{L} = -c_t \frac{m_t}{v} \bar{t}th + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

$$\mathscr{M}_{gg\to ZZ} = \mathscr{M}_h + \mathscr{M}_{bkg} = c_t \mathscr{M}_{c_t} + c_g \mathscr{M}_{c_g} + \mathscr{M}_{bkg}$$

One has: $\sigma \sim |c_t + c_g|^2$. The on-peak degeneracy $c_t + c_g = \text{const}$ is broken by off-shell data. Results of Ref. [41] are shown in Fig. 5.

An alternative method to constrain the total Higgs width was proposed in Ref. [44]. It exploits a sizeable asymmetric signal-background interference in the $gg \to H \to \gamma\gamma$ channel at the LHC, which was first pointed out and calculated at LO in Ref. [45].[3] A NLO calculation and analysis was carried out in Ref. [44] (see Fig. 6). This method is expected to yield competitive Higgs width constraints with 3 ab^{-1} of LHC14 data.

[3] Signal-background interference and mass peak shift effects in the qg and $q\bar{q}$ channels have been analysed at LO in Refs. [46, 47].

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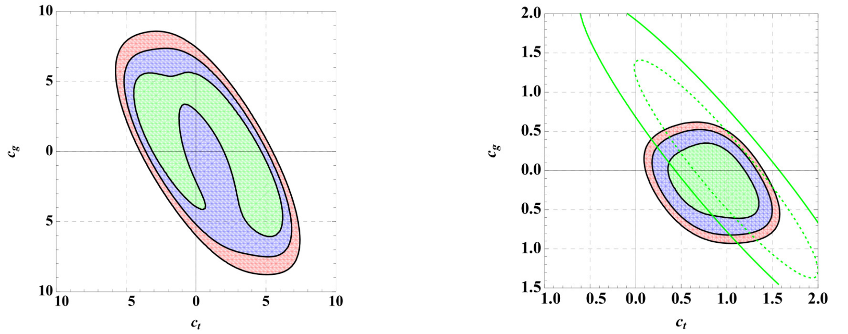

LHC 8 TeV CMS data LHC 14 TeV 3 ab^{-1} data

Figure 5: Constraints in (c_t, c_g) plane: 68%, 95% and 99% probability contours are shown (from [41]).

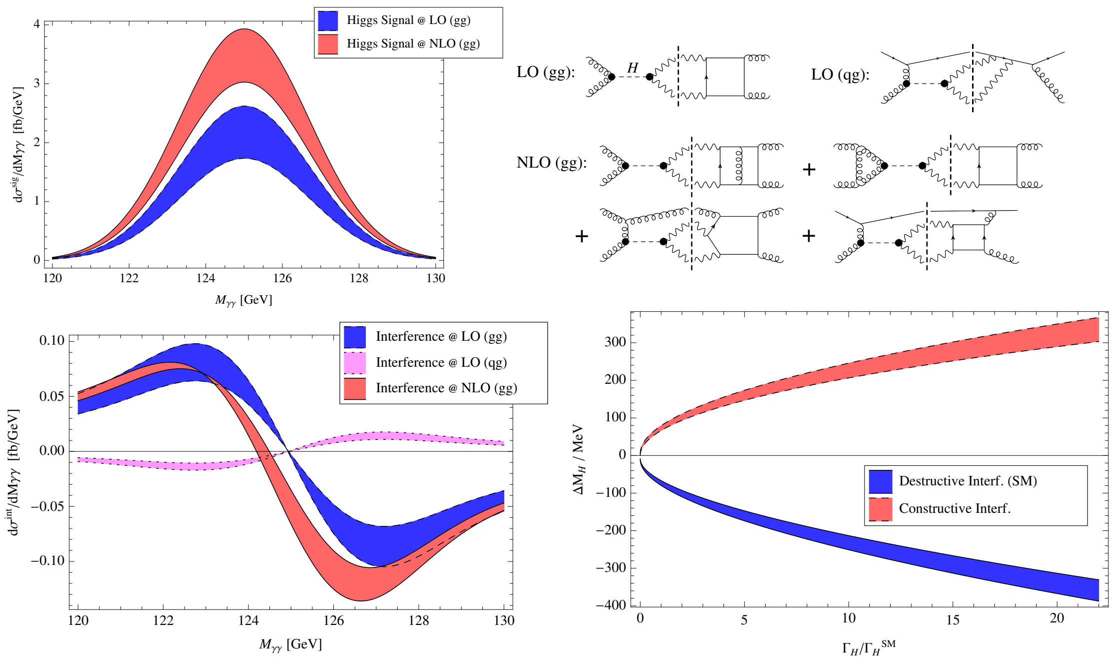

Figure 6: Signal-background interference enabled Higgs width constraints in $gg \to H \to \gamma\gamma$ (from [44])

3. Conclusions

Two novel, complementary methods to constrain the total Higgs width at the LHC have been reviewed. The first method relies on the experimental sensitivity to the Higgs-width-independent off-shell signal cross section in the $gg \to H \to VV$ channels, and with LHC Run 1 data yields a Higgs width constraint of $\Gamma_H \lesssim 5\Gamma_H^{\rm SM}$. The second method relies on a sizeable asymmetric signal-background interference in the $gg \to H \to \gamma\gamma$ channel that results in a Higgs mass peak shift which is expected to yield competitive Higgs width constraints with 3 ab^{-1} of LHC14 data.

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