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Nuclear Physics B 902 (2016) 440–457

NUCLEAR PHYSICS B

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Combining LEP and LHC to bound the Higgs width

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Received 21 September 2015; received in revised form 28 October 2015; accepted 17 November 2015

Available online 27 November 2015

Editor: Hong-Jian He

Abstract

The correlation of on- and off-shell Higgs boson production at the LHC in $gg \to h^* \to ZZ$ has been used to bound the Higgs width. We propose an alternative complementary constraint which is only possible through the combination of LEP and LHC measurements. Precision electroweak measurements at LEP allow for the determination of indirect constraints on Higgs couplings to vector bosons by considering one-loop processes involving virtual Higgs exchange. As the indirect constraint is model dependent we will consider two specific models which modify the Higgs couplings and width, and our results will apply specifically to these models. By combining these LEP constraints with current LHC 8 TeV Higgs measurements a stronger limit on the Higgs width can be achieved than with LHC data alone. Looking to the future, a more robust constraint can be achieved by correlating LEP measurements with WBF Higgs production followed by Higgs decays to WW and ZZ. We will discuss the model dependence of this method in comparison to other proposed methods.

1. Introduction

The discovery of the Higgs boson [1–3] marked a new era of exploration in fundamental physics. Ideally one would like to be able to extract all of the properties of the Higgs, such as the

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http://dx.doi.org/10.1016/j.nuclphysb.2015.11.017
0550-3213/

mass and individual decay widths, as well as detailed information on the coupling magnitudes and Lorentz structures. In practice such an extensive wish list cannot be met with direct measurements alone, and varying degrees of theoretical assumptions must be imposed in order to map from measurement to Lagrangian.

In this work we will consider the total Higgs decay width, which is a crucial parameter for many scenarios beyond the Standard Model (SM). The total Higgs width has received considerable experimental and theoretical attention recently [4–10] after a recent proposal for correlating on- and off-shell Higgs production at the LHC [11–13]. In this paper we consider two specific models which modify the Higgs width and couplings, and pursue a different strategy, which combines the off-shell Higgs information gathered at the Large Electron Positron Collider (LEP) with LHC Higgs measurements. It is important to realise that, although the discovered Higgs falls outside the *kinematic* coverage of LEP, the high precision results of LEP still provide seminal and complementary information to current and future Higgs physics analyses, especially now that it has been established that $m_h \simeq 125$ GeV.

The implications of the Higgs discovery for the combined electroweak parameter fit was analysed in [14]. Our work takes a different approach and uses the indirect Higgs coupling constraints determined from the LEP results in correlation with LHC Higgs measurements to constrain free parameters in specific models. The limits we obtain particularly highlight the power of a concrete LEP + LHC combination.

We organise this work as follows: First we review recent attempts to set limits on the total Higgs width at the LHC in Sec. 2 and argue further in Sec. 3 that for certain specific models LEP can be considered a superior off-shell Higgs constraint. In Sec. 4 we establish this quantitatively by combining LEP and current LHC 8 TeV results to set a constraint on the total Higgs width in the spirit of Refs. [4,5,11]. Keeping in mind potential theoretical shortcomings that such an approach might involve we discuss the potential improvement of the LEP + LHC combination in Sec. 5. We discuss the relationship of this method in comparison to other methods in Sec. 6 and conclude in Sec. 7.

2. Higgs width overview in light of LHC results

Due to its small couplings to light fields, in the SM the Higgs width satisfies $\Gamma_h \ll m_h$ and the narrow width approximation is appropriate for LHC observations of an on-shell Higgs [15]. Specifically, if σ_i is the SM prediction for Higgs production in some channel 'i' at the LHC and BR_j is the SM prediction for the branching ratio into a final state 'j', then a reasonable approximation for the total cross section in these channels at the LHC is

$$\sigma_{ij} = \frac{c_i^2 c_j^2}{R_h} \sigma_i \mathrm{BR}_j \tag{1}$$

$$= \mu_{ij} \sigma_i \mathrm{BR}_j \tag{2}$$

where we have re-scaled the SM Higgs couplings with some factor which takes the value $c \to 1$ in the SM limit, we have similarly rescaled the total decay width by a factor R_h, and shown these two may be absorbed into a single 'signal-strength' variable μ.[1] We have also assumed that the

[1] In reality a simple coupling rescaling is overly simplistic and ideally the effects of new physics above the weak scale should be encoded in higher dimension operators. However, it is worth noting that the existence of complete models which realise free couplings for the Higgs with SM fields have been demonstrated [16], thus the free-coupling interpretation does have consistent UV-completions.

Higgs width is a free parameter ($\Gamma_h = R_h \Gamma_{SM}$) which is not necessarily given by $\Gamma_h \neq \sum_j c_j^2 \Gamma_j$. We are free to make this choice because the Higgs may possess additional decay channels into new invisible states or even into hadronic channels which are difficult to detect at the LHC. This also allows for the fact that couplings to different fields may be altered in uncorrelated ways, for example if the Higgs is coupled to new coloured states, e.g. a sequential chiral generation [17], they may significantly modify the hGG coupling at leading order.

Eq. (2) makes it immediately clear that an unambiguous extraction of the Higgs width is not possible at the LHC from on-shell observations alone as it always appears in combination with Higgs couplings which may also be modified. Essentially there is a flat direction in parameter space along which observed LHC Higgs signal strengths μ_{ij} may take the same set of fixed values for a continuous family of width and coupling variations. For example, taking the form $c_i^2 c_j^2 = R_h$ we have $\mu_{ij} = 1$ and an apparently SM-like Higgs even in the presence of modified couplings. However, this does not imply that no information on the width is obtained. By imposing the assumption of a specific model it is possible to extract constraints. For example, if it is assumed that the Higgs may not decay to additional invisible particles or to visible particles in new exotic channels, then the total width is given by $\Gamma_h = \sum_j c_j^2 \Gamma_j$ and global fits to the LHC data allow for experimental constraints on the Higgs width [16,18,20]. Alternatively, if it is assumed that all couplings are SM-like and the only modification is an increased width due to additional decays then again global fits allow for the extraction of a limit on the Higgs width [21].

A complementary approach which relies on combining additional measurements with the LHC on-shell Higgs observations has also been proposed [11]. This approach exploits processes in which the Higgs is far off-shell but still plays a role. In particular in the many parton-level processes contributing to diboson production $pp \to ZZ$ there is one which involves a virtual Higgs: $gg \to h^* \to ZZ$. This subprocess contributes at a level which is experimentally accessible and hence it is possible to use measurements of ZZ production at high invariant mass to constrain the impact of an off-shell Higgs [12,13] (see [10] for a related study at a future lepton collider). This is very useful in the theoretical interpretation of the Higgs properties for a number of reasons [7,9]. The desired application is that if one considers the usual naïve coupling re-scaling of Eq. (2) then with the Higgs sufficiently off-shell the matrix element does not depend on the Higgs width but simply behaves as $c_{gg} c_{ZZ} \mathcal{M}_{SM}$, where the dependence on the hGG and hZZ couplings is explicit. Thus experimental measurements of high invariant mass ZZ production can be interpreted as constraints on Higgs couplings. These constraints can then be combined with measurements of on-shell observables described by Eq. (2). As the off-shell measurement breaks the degeneracy between coupling and width modifications then, under a specific set of assumptions [7], the combination of on-shell and off-shell measurements allows for an indirect constraint on the total width of the Higgs. Within these limitations both the ATLAS [4] and CMS collaborations [5] have reported limits on the total Higgs width.

There are, however, a number of important caveats and subtleties involved in this mapping from on-shell and off-shell measurements to a width constraint [6,7]. In particular if the Higgs coupling modifications are in any way dependent on the energy at which they are probed the mapping breaks down. For example, if the hGG coupling is modified by loops of new coloured particles with masses of $\mathcal{O}$(100's) GeV [6], if new higher dimensional interactions are present [7], if scalars appear as s-channel resonances, or if electroweak symmetry breaking is not SM-like [7,8], the mapping between the two constraints and thus the interpreted width measurement would be incorrect. While these scenarios can be constrained with other measurements, a generic model-independent interpretation of the width constraint from $gg \to h^* \to ZZ$ is clearly unjustified.

Motivated by these considerations we will now describe a complementary approach which also utilises processes involving an off-shell Higgs.

Prior to the discovery of the Higgs there were already strong constraints on processes involving an off-shell Higgs from the precision electroweak program at LEP. Now that the mass of the Higgs is known these LEP constraints may be interpreted as constraints on Higgs couplings, but only under assumptions on the nature of any additional BSM modifications to the precision electroweak observables. Such LEP Higgs coupling constraints have been considered in a number of works previously [22,23] (see also [24] for a discussion of the role of precision electroweak measurements in understanding the nature of the Higgs boson). The aspect we will focus on is that the LEP Higgs coupling constraints involve an off-shell Higgs and to a good approximation are not dependent on the Higgs decay width, in analogy with the high invariant mass constraints on ZZ production at the LHC. Thus the idea is to perform a similar manipulation to the one described previously: Interpret the LEP constraints as Higgs coupling constraints and then feed these back into observables such as Eq. (2) to extract a bound on the Higgs width.

As an indirect constraint obtained in this way is model dependent, for the sake of demonstrating the use of the LEP + LHC combination we will focus on two specific classes of models which modify the Higgs couplings as examples. The models are:

a) The Higgs mixed with a singlet scalar in a 'Higgs Portal' type of scenario [25]. This model introduces two parameters, the mass of the additional scalar M_S and the mixing angle between the SM Higgs and the singlet scalar θ. This model is manifestly UV complete when the effects of the additional hidden sector Higgs boson are included (which we do throughout our work). In such a scenario the Higgs couplings are rescaled identically in the on- and off-shell regime, allowing for an interpretation of the off-shell measurement as promoted in [11].
b) Rescaled hWW and hZZ couplings by a factor c_V and with a UV cut-off Λ. As in [14] we will also set the cutoff to $\Lambda = \lambda/\sqrt{|1-c_V^2|}$, motivated by effective theory arguments as described in [22].[2] Depending on the constraint considered all other couplings may be assumed to be rescaled in the same way, or in some instances they may be taken as free parameters. We will state which of these two assumptions is taken as and when appropriate. Concrete realisations of such an effective theory-inspired scenario are models with additional vector resonances in the TeV regime, which are expected in composite Higgs scenarios.[3] Due to the intrinsically non-perturbative nature of electroweak symmetry breaking in such scenarios the UV cut-off cannot be removed.

In both of these scenarios the Higgs width may be modified by new physics beyond the simple Higgs coupling modifications in the models described above. In practise the Higgs width may be considered as a free parameter. The essential point (emphasised in e.g. [19]) is that due to a number of factors, including the small bottom quark Yukawa coupling, the Higgs width is already small. Thus if the Higgs is coupled to new light states with even a relatively small coupling the

[2] For comparison with the parameterisation in [22] this parameter is taken to be $\lambda \approx 4\pi v$.

[3] Universal coupling modifications of this kind may also arise due to higher dimension operators such as $(\partial|H|^2)^2/\Lambda^2$. As the analysis here involves low energy observables, as long as $\Lambda \gtrsim m_h$ this analysis will be appropriate, however if Higgs physics is probed at energy scales $E \sim \Lambda$ the model must be UV-completed to include any new states at this energy scale.

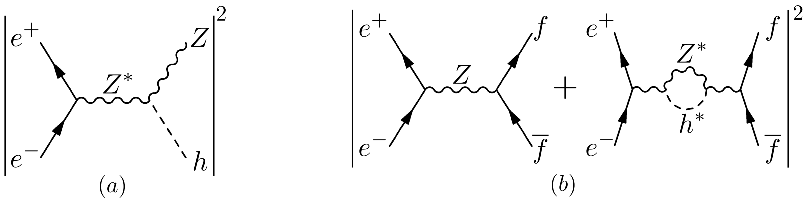

Fig. 1. (a) The dominant Higgs production process at a potential future Higgs factory e^+e^- collider and (b) Z-boson production and decay at an e^+e^- collider including interference of one loop diagrams involving an off-shell Higgs. An analogy between the on-shell and off-shell Higgs factory is drawn because the squared amplitude for the Higgs factory is related to the one-loop amplitude which interferes with tree-level diagrams at an off-shell Higgs factory.

modification to the width may be significant in comparison to the SM value. As the coupling is small, such a width enhancement is possible while maintaining the validity of indirect constraints on Higgs physics from precision electroweak measurements.

Let us take an example and consider the two models above which modify the Higgs couplings and add a small coupling to two light neutral pseudoscalars haa, as in [19]. We will also allow for the pseudoscalar to decay to pairs of jets, following the models described in [19]. Thus the full decay chain is $h \to aa \to jjjj$. As described in [19], currently there are no relevant constraints on this scenario from direct searches, and in such a model $\mathcal{O}(1)$ enhancements of the Higgs width are still possible. Of course, if all the Higgs couplings were SM-like and only this decay channel were introduced there would be strong constraints from overall global signal strength fits, however if the Higgs couplings are also allowed to float as free parameters then this constraint goes away for the reasons discussed above. It is precisely this type of scenario in which the combination of LEP and LHC measurements breaks the degeneracy in coupling and width modifications. Thus although there are other ways in which to modify the Higgs width, this is a simple example demonstrating how the Higgs width may be modified independently of the Higgs couplings. This model should be kept in mind for the remainder of this work.

Constraining the Higgs couplings via electroweak precision observables is not a novel development, but has been a key strategy to constrain BSM physics over decades (see [14,18] for an application to the SM Higgs for instance). As we will demonstrate, the main point of this work is to show that these strategies are, in fact, complementary to off-shell measurements at the LHC.

3. LEP as an off-shell Higgs factory

Currently there is focused discussion on the possibility of a future 'Higgs Factory', an e^+e^- collider that would produce copious numbers of Higgs bosons in a high precision environment. The various possibilities under discussion include the ILC [26], CLIC [27], FCC-ee (TLEP [28]), and CEPC [29]. The common feature among these colliders is that in the initial lower energy stages the dominant production mechanism for the Higgs is associated production $e^+e^- \to hZ$. This is depicted in Fig. 1(a). In terms of diagrams, by squaring Fig. 1(a) we arrive at the interference term of Fig. 1(b). Thus the one-loop corrections to LEP observables are a close cousin to the on-shell production at a Higgs factory. By this connection one could consider LEP as an 'off-shell' Higgs factory and the constraints from the LEP measurements can be interpreted as precision constraints on off-shell Higgs processes.

The Peskin–Takeuchi parameters [30] cleanly frame the LEP constraints on modifications of the SM electroweak sector. Thus the off-shell Higgs constraints are best presented in terms of the S–T–U parameters. The contributions of a Higgs-like scalar of mass m_H, with couplings to vector bosons $g = c_V \times g_{SM}$, to the S–T–U parameters are

$$s_H(m_H, c_V) = \frac{c_V^2}{\pi M_Z^2}\left(B^{OO}_{M_Z^2,Z} - B^{OO}_{0,Z} - M_Z^2\big(B^{O}_{M_Z^2,Z} - B^{O}_{0,Z}\big)\right) \tag{3}$$

$$t_H(m_H, c_V) = \frac{c_V^2}{4\pi M_W^2 S_W^2}\left(B^{OO}_{0,W} - B^{OO}_{0,Z} + M_Z^2 B^{O}_{0,Z} - M_W^2 B^{O}_{0,W}\right) \tag{4}$$

$$\begin{aligned} u_H(m_H, c_V) = \frac{c_V^2}{\pi}\Bigg(&\big(B^{O}_{M_Z^2,Z} - B^{O}_{0,Z}\big) - \big(B^{O}_{M_W^2,W} - B^{O}_{0,W}\big) - \frac{1}{M_Z^2}\big(B^{OO}_{M_Z^2,Z} - B^{OO}_{0,Z}\big) \\ &+ \frac{1}{M_W^2}\big(B^{OO}_{M_W^2,W} - B^{OO}_{0,W}\big)\Bigg) \end{aligned} \tag{5}$$

where the full loop functions are

$$\begin{aligned} B^{O}_{0,V} &= 2\frac{\kappa^2 \log\kappa - (1-\kappa^2)\log\gamma}{1-\kappa^2} \\ B^{OO}_{0,V} &= M_H^2 \frac{\kappa^4 \log\kappa^4 + (1-\kappa^4)(1-4\log\gamma)}{8(1-\kappa^2)} \quad , \end{aligned} \tag{6}$$

and

$$\begin{aligned} B^{O}_{M_V^2,V} = \frac{1}{2\kappa^2}\Bigg(&(1-2\kappa^2)\log\kappa^2 + 2\kappa^2(1-2\log\gamma) + \\ &\sqrt{1-4\kappa^2}\log\left(\frac{1-2\kappa^2+\sqrt{1-4\kappa^2}}{2\kappa^2}\right)\Bigg) \\ B^{OO}_{M_V^2,V} = \frac{M_H^2}{36\kappa^4}\Bigg(&\kappa^2(4\kappa^4+18\kappa^2-3) + \\ &\frac{3}{2}(1-4\kappa^2)^{3/2}\log\left(\frac{1-2\kappa^2-\sqrt{1-4\kappa^2}}{2\kappa^2}\right) \\ &-3(1-6\kappa^2+6\kappa^4+4\kappa^6)\log\kappa - 6\kappa^4(3+2\kappa^2)\log\gamma\Bigg) \quad . \end{aligned} \tag{7}$$

$\kappa = M_V/M_H$ and $\gamma = M_H/\Lambda$, where Λ is the $\overline{\text{MS}}$ UV cutoff.

Thus, for the model with re-scaled Higgs couplings, the deviations of the S, T, and U parameters from the Standard Model prediction are

$$\begin{aligned} S &= s_H(m_h, c_V) - s_H(m_h, 1) \\ T &= t_H(m_h, c_V) - t_H(m_h, 1) \\ U &= u_H(m_h, c_V) - u_H(m_h, 1). \end{aligned} \tag{8}$$

In the limit with modified couplings and a large UV cutoff the leading-log (LL) approximation to the electroweak precision parameters may be found directly from the $\log\gamma^2$ terms of Eq. (7).

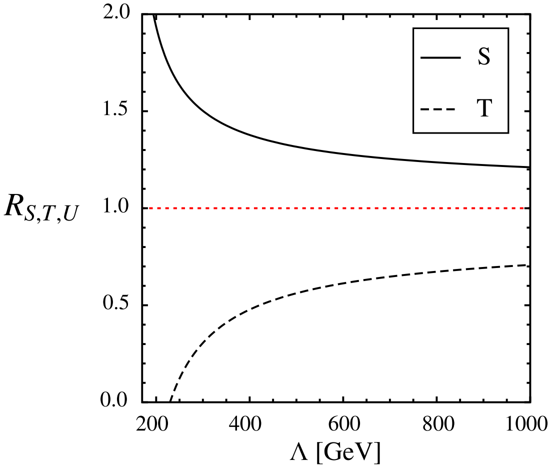

Fig. 2. The ratio of full loop functions in Eq. (8) with the leading-log expressions in Eq. (9) as a function of the UV cutoff Λ. It is clear that the leading-log expressions may underestimate (S) or overestimate (T) the corrections by more than 20%, even with a cutoff extending to 1 TeV where one might expect the leading-log expression to be accurate. However, the leading-log result is often adequate for estimates as it is the dominant contribution for $\Lambda \gtrsim 300$ GeV.

These are

$$\begin{aligned} S_{\rm LL} &= -\frac{1}{6\pi}(1-c_V^2)\log\gamma \\ T_{\rm LL} &= \frac{3M_Z^2}{8\pi M_W^2}(1-c_V^2)\log\gamma \\ U_{\rm LL} &= 0 \end{aligned} \tag{9}$$

in agreement with [14]. It is interesting to consider the full expression versus the leading-log approximation. In Fig. 2 we show the S and T corrections relative to the leading-log approximation as a function of the cutoff Λ. It is clear that for most purposes the leading-log approximation is adequate, however the full loop expressions are desirable for accurate results.

In the Higgs portal model the S–T–U expressions are

$$S = s_H(m_h, \cos\theta) + s_H(M_S, \sin\theta) - s_H(m_h, 1) \tag{10}$$

$$T = t_H(m_h, \cos\theta) + t_H(M_S, \sin\theta) - t_H(m_h, 1) \tag{11}$$

$$U = u_H(m_h, \cos\theta) + u_H(M_S, \sin\theta) - u_H(m_h, 1) \tag{12}$$

In both of the models there is an additional parameter (either Λ, or M_S) in addition to the modified Higgs coupling which must be considered. This is essentially due to the fact that the LEP constraints are logarithmically sensitive to UV physics.

We use the central values, errors, and correlation matrix for the S–T–U parameters from [14]. Using these constraints we find the regions of parameter space allowed by LEP data. In Fig. 3 we show the standard S–T ellipse under the assumption that $U = 0$. This agrees well with similar figures in [14].

In Fig. 4 we plot the constraints on both of the models from LEP measurements. This figure makes it clear that the LEP measurements are effective in constraining modified Higgs couplings. This point has been emphasised previously by many authors [22,23]. The most relevant aspect

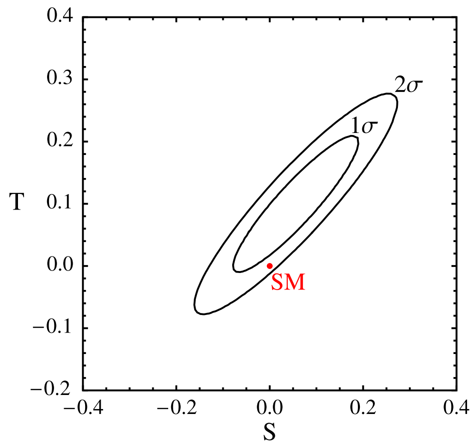

Fig. 3. The standard S–T ellipse for $U = 0$ with the SM point depicted at $S = T = 0$.

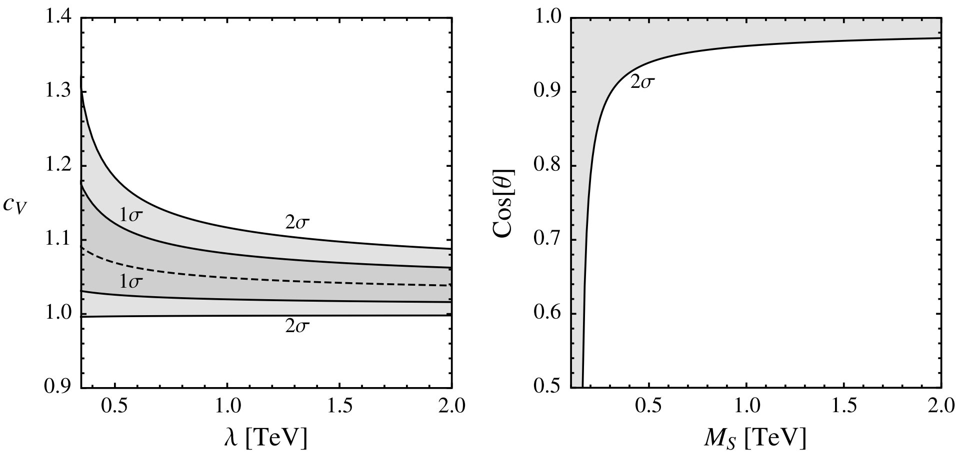

Fig. 4. LEP constraints on modified Higgs couplings in the two models described in Sec. 2. There is already tension at 1σ between precision electroweak fits and the SM, hence in the models model with re-scaled couplings (left panel) the SM limit is only within the 2σ contours. For the Higgs portal model (right panel) we only show the 2σ contour.

for this work, which has not been emphasised previously, is that these coupling constraints are valid irrespective of the Higgs decay width, thus they can later be combined with LHC on-shell Higgs observations in order to determine indirect constraints on the decay width.

4. Combining LEP measurement with LHC8 data

In Sec. 3 it was demonstrated that for specific models constraints on virtual off-shell Higgs corrections at LEP lead to constraints on Higgs couplings which do not depend on the width. On-shell Higgs measurements at the LHC have already placed strong constraints on the overall signal strength μ. In this section we combine the two to determine current constraints on the total Higgs decay width.

The off-shell LEP constraints are of the form

$$c_{min} < c_V < c_{max}, \tag{13}$$

where c_{min} and c_{max} may depend on model parameters. The on-shell LHC constraints are of the form

$$\mu_{min} < \mu \left(= \frac{c_V^4}{R_h} \right) < \mu_{max}. \tag{14}$$

Thus we may rearrange these inequalities to determine indirect constraints on the Higgs width[4]

$$\frac{c_{min}^4}{\mu_{max}} < R_h < \frac{c_{max}^4}{\mu_{min}}, \tag{15}$$

which illustrates how a limit may be derived. In using Eq. (15) if, for example, the 2σ signal strength limit is combined directly with the 2σ LEP constraints then the combined limit on the width from Eq. (15) will in general be weaker than if a combined likelihood function is formed and then the 2σ limit is determined from that function. The reason for this is that a point where c_V saturates the 2σ LEP bounds and μ saturates the 2σ LHC bounds will in general lie outside of the 2σ ellipse from the combined likelihood, unless the ellipse is highly rectangular, however this is not the case here. Thus to obtain the strongest bounds, ideally the LEP and LHC constraints will be merged into a combined likelihood function to allow for a more sophisticated statistical analysis. However, as we will see, a number of the LHC bounds that we will employ are not yet in the Gaussian limit, thus we are unable to estimate the appropriate likelihood function. For this reason we will use the simple combination of Eq. (15) as it serves the purpose of illustrating the use of LEP measurements to determine a constraint on the Higgs width, however it should be kept in mind that this simple combination generally weakens the bounds relative to a full likelihood analysis and thus the plotted constraints err on the conservative side.

4.1. Current limits: universal coupling rescaling

Combining all of the observed channels the current status of the mean and uncertainties in the overall Higgs signal strength are: ATLAS ($\mu = 1.18^{+0.15}_{-0.15}$) and CMS ($\mu = 1.00^{+0.14}_{-0.14}$) (see e.g. [31]). We make an unofficial signal strength combination of $\mu \approx 1.09^{+0.13}_{-0.13}$, where we have combined the statistical errors as standard in quadrature, improving this source of error by a factor $\sim 1/\sqrt{2}$, however the error has not improved significantly as we have assumed systematic and theoretical errors do not improve upon the combination of results from both experiments. Thus from this approximate combination at 2σ confidence level we take $\mu_{min} \approx 0.83$, $\mu_{max} \approx 1.35$. Using Eq. (15) we may combine these limits with the LEP constraints on the Higgs couplings shown in Fig. 4 to find the current constraints on the Higgs width in both models.

In Fig. 5 we show the 2σ confidence contours on the total Higgs width. The constraint from current LHC on-shell signal strength constraints is labelled $\mu_{VV,ff,GG,\gamma\gamma}$. For reference the 2σ limits at new physics scales of 1 TeV for a model with a universal rescaling of couplings are $0.73 \lesssim R_h(\lambda = 1\ \text{TeV}) \lesssim 1.87$, which is already competitive with constraints using other methods [4,5]. For the model of a mixed-in singlet scalar the limits are $0.63 \lesssim R_h(M_S = 1\ \text{TeV}) \lesssim$

4 Similar inequalities have been discussed in [20].

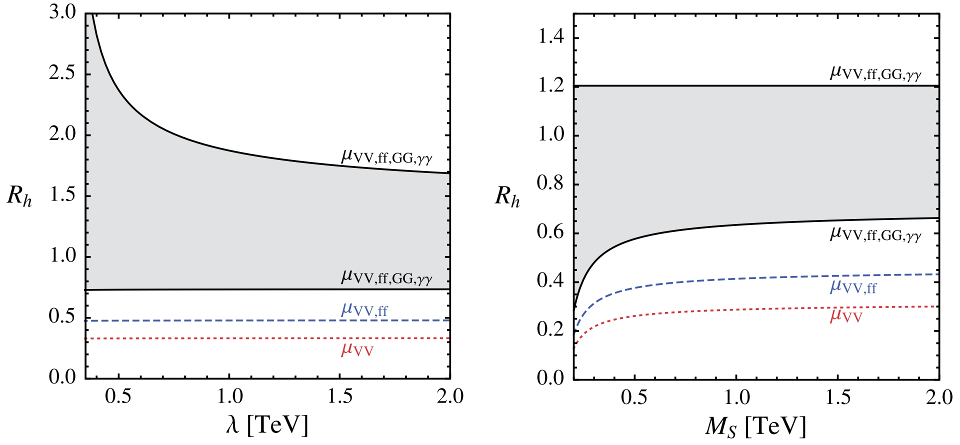

Fig. 5. Combined 2σ LEP and current LHC signal strength constraints on the Higgs width in the model with modified couplings and a UV cutoff (left) and a model with a mixed-in singlet scalar (right). Please see the surrounding text for an explanation of the various contours.

1.20. It is worth noting that in this case the upper limit on the Higgs width is only strong due to the theoretical limitation $\cos(\theta) \leq 1$, thus in Eq. (15) we have $R_h < 1/\mu_{min}$.

4.2. *Current limits: hGG- and $h\gamma\gamma$-independent combination*

In the two models considered thus far it has been assumed that all of the Higgs couplings are rescaled uniformly. However, it is possible that the Higgs is coupled to additional charged or coloured states and this would modify the hGG and $h\gamma\gamma$ couplings in a way which is uncorrelated with the modifications to the hVV couplings. In such a scenario the constraint of Sec. 4.1, which assumed a universal coupling rescaling, becomes invalidated. However, it is still possible to constrain the width by focusing on specific channels. For example, we may constrain the Higgs width in a model in which the hVV and $h\bar{f}f$ couplings have been modified by the same factor and the hGG and $h\gamma\gamma$ couplings are allowed to be rescaled independently as free parameters. This is achieved by choosing LHC production channels and final state decays that are independent of the hGG and $h\gamma\gamma$ couplings. We consider the LHC constraints from Higgs associated production and $\bar{b}b$ decays, $hV, h \to \bar{b}b$. The best fit signal strength in this channel is $\mu = 1.01^{+0.53}_{-0.5}$ [32].[5]

In Fig. 5 the 2σ confidence contour for this constraint is labelled $\mu_{VV,ff}$. An upper bound is not realised as the signal strength in $hV, h \to \bar{b}b$ is consistent with zero at 2σ confidence, thus by Eq. (15) the width is consistent with very large values. For reference the 2σ width lower limit at new physics scales of 1 TeV for a model with any value of hGG and $h\gamma\gamma$ couplings is $0.48 \lesssim R_h(\lambda = 1 \text{ TeV})$. For the model of a mixed-in singlet scalar the lower limit is $0.41 \lesssim R_h(M_S = 1 \text{ TeV})$. These limits are less model-dependent than the limits of Sec. 4.1, however this has come at a price as the more model-independent limits are quantitatively weaker.

[5] It should be kept in mind that the current constraints from WBF production with subsequent Higgs decay to taus are marginally stronger than for associated production. However in this channel for typical cuts there is a significant contribution from gluon fusion. In Sec. 5 we demonstrate that it is possible in future to almost fully remove this gluon fusion contribution, enabling hGG-independent constraints to be set with the production channel also.

4.3. Current limits: hGG-, $h\gamma\gamma$-, and $h\overline{f}f$-independent combination

Building on Sec. 4.2, in addition to new charged or coloured states which could independently modify the hGG and $h\gamma\gamma$ couplings, it is possible that the Higgs couplings to fermions are also modified in a way which is uncorrelated with the modifications to the hVV couplings. This scenario may then be addressed by combining LEP constraints on the hVV couplings with current LHC constraints on production and decay channels which only feature the hVV couplings. This essentially leads to a Higgs width constraint in the 'κ-framework' language which is independent of additional modifications to the hGG-, $h\gamma\gamma$-, and $h\overline{f}f$ couplings. To this end we again choose associated production followed by Higgs decays to W-bosons, $hV, h \to W^+W^-$. The best fit signal strength in this channel is $\mu = 0.80^{+1.09}_{-0.93}$ [32].

In Fig. 5 the 2σ confidence contour for this Higgs width bound is labelled μ_{VV}. Again there is no upper bound. For reference the 2σ width lower limit at new physics scales of 1 TeV for a model with any value for the hGG, $h\gamma\gamma$, and $h\overline{f}f$ couplings is $0.33 \lesssim R_h$ ($\lambda = 1$ TeV). For the model of a mixed-in singlet scalar the lower limit is $0.29 \lesssim R_h$ ($M_S = 1$ TeV). Other than the well-motivated assumption that the hWW and hZZ couplings are scaled in the same way, these limits allow for the hGG-, $h\gamma\gamma$-, and $h\overline{f}f$ Higgs couplings to scale freely and independently. However the theoretical limitations discussed at the end of Sec. 3 still apply.

5. Looking to the future: vector-only LHC Higgs constraints

As discussed in Sec. 4.3 we would ideally like to construct a constraint on the direct production of the Higgs at the LHC which is as independent of the hGG-, $h\gamma\gamma$-, and $h\overline{f}f$ couplings as possible. To this end we use a projection of vector boson-only production and decay mode approaches [6] at the LHC (see also [12,33]). Specifically, we analyse the processes $pp \to (h \to W^+W^- \to l^+l^-\nu\bar{\nu})jj$, $pp \to (h \to ZZ^* \to l^+l^-\nu\bar{\nu})jj$ and $pp \to (h \to ZZ^* \to 4l)jj$. This choice is advantageous as these LHC measurements constrain the same hVV Higgs couplings as the LEP constraint, thus when these observations are combined this will result in a more robust constraint on the Higgs width for the models considered. In particular any dependence on the hGG-, $h\gamma\gamma$-, and $h\overline{f}f$ couplings is essentially removed, implying that the final width constraint will apply to the models considered here, even in the presence of additional charged or coloured states or if the $h\overline{f}f$ couplings have been modified in a way which is independent of the hVV coupling modification. Let us first construct the LHC on-shell observables.

We use VBFNLO v2.7 [34] to simulate the weak boson fusion and gluon fusion events for full leptonic final states at 14 TeV. We use a leading order RGE-improved mode of VBFNLO that uses the t-channel momentum transfer as the relevant scale for parton distributions and strong coupling running [35], and pre-select the Higgs on-shell region.

Subsequently the VBFNLO events are showered and hadronised with HERWIG++ [36]. For the backgrounds we consider continuum ZZ, WW and WZ production including all interference effects, generated with MADGRAPH [37], as well as $t\bar{t}$ production generated using ALPGEN [38]. Detector effects and reconstruction efficiencies are included and based on the ATLAS Krakow parametrisation [39].

Jets are reconstructed with the anti-k_T jet clustering algorithm [40] with $p_T > 35$ GeV, $|y_j| < 5.0$ and resolution parameter $R = 0.4$. We again adopt the ATLAS Krakow parametrisation [39] to include jet resolution effects, b-jet efficiencies and fake rates. We consider light charged leptons (i.e. electrons and muons) to be isolated if $p_{T,l} > 15$ GeV, $|y_l| < 2.5$, and if

Table 1
Results for 2 leptons $+\not{E}_T$ search. The cross sections are given in femtobarns, corresponding to proton–proton collisions at $\sqrt{s}=14$ TeV. Further details on the cuts can be found in the text of Sec. 5.1.

Sample	Lepton cuts	WBF cuts	b-veto	Jet veto	$m_{T,2l}$ cut
$(h\to WW)jj$ WBF	2.803	1.015	0.996	0.958	0.561
$(h\to WW)jj$ GF	0.887	0.105	0.101	0.069	0.039
$t\bar{t}+$jets	18 189.60	24.779	6.496	0.910	0.279
$WW/WZ/ZZ+$jets	556.545	3.019	2.818	1.635	0.344

the hadronic energy deposit within a cone of size $R=0.3$ is smaller than 10% of the lepton transverse momentum.

In the Higgs portal model there may be additional contributions to the Higgs signal region from the heavy scalar. We have thus included the heavy scalar in the simulation and checked that the signal contamination is negligible for the masses and mixing angles that satisfy the LEP constraints, thus it is self-consistent to only consider the 125 GeV Higgs-like scalar contributions in this section.

5.1. $hjj\to WW^*jj\to l^+l^-\nu\bar{\nu}jj$

For the $h\to WW\to 2l+\not{E}_T$ decay mode of WBF production we require exactly two isolated leptons with $\Delta R_{j,l}>0.4$ and reject events with $80<m_{l_1l_2}<100$ GeV to discriminate from $h\to ZZ$. We impose the following WBF cuts on the two hardest jets

$$y_{j_1}\times y_{j_2}<0,\quad |y_{j_1}-y_{j_2}|>4.5,\quad m_{j_1j_2}>800\text{ GeV}. \tag{16}$$

To further suppress the backgrounds we force the Higgs to be central by requesting [41]

$$\min(y_{j_1},y_{j_2})<y_{l_1},y_{l_2}<\max(y_{j_1},y_{j_2}). \tag{17}$$

At this point the dominant background is $t\bar{t}$, see Table 1. To further improve S/B we veto events with a b-tagged jet. To achieve $S/B\sim 1/3$ we require that there be no additional jet between the two tagging jets, i.e. $\min(y_{j_1},y_{j_2})<y_j<\max(y_{j_1},y_{j_2})$ [42]. Finally, we isolate the Higgs peak via the transverse mass

$$m_{T,2l}^2=\left[\sqrt{m_{l_1l_2}^2+p_{T,ll}^2}+|p_{T,\text{miss}}|\right]^2-\left[\mathbf{p}_{T,ll}+\mathbf{p}_{T,\text{miss}}\right]^2, \tag{18}$$

by requiring $80\le m_{T,2l}\le 150$ GeV and obtain $S/B\sim 1$.

5.2. $hjj\to ZZ^*jj\to l^+l^-\nu\bar{\nu}jj$

For the $h\to ZZ\to 2l+\not{E}_T$ final state in WBF, we again require exactly 2 isolated leptons. In this case we impose $85<m_{l_1l_2}<95$ GeV to isolate the $Z\to l^+l^-$ decay. After that we proceed with imposing the WBF cuts of Eqs. (16)–(17).

As in Sec. 5.1 we further improve S/B by imposing a b-jet veto and we reject events if there is an additional jet between the two tagging jets. With $80\le m_{T,2l}\le 150$ GeV, as defined in Eq. (18), we find $S/B\sim 1/3$ for events that pass all cuts, see Table 2.

Table 2
Results for $h \to ZZ^*$ in the 2-lepton + $\not{E}_T$ final state. Further details on the cuts can be found in the text of Sec. 5.2.

Sample	Lepton cuts	WBF cuts	b-veto	Jet veto	$m_{T,2l}$ cut
$(h \to ZZ^* \to l^+l^-\nu\bar{\nu})jj$ WBF	0.151	0.061	0.060	0.057	0.035
$(h \to WW^* \to l^+l^-\nu\bar{\nu})jj$ WBF	0.065	0.029	0.028	0.026	0.016
$(h \to ZZ^* \to l^+l^-\nu\bar{\nu})jj$ GF	0.044	0.005	0.004	0.003	0.002
$t\bar{t}$ + jets	1667.33	2.051	0.539	0.073	0.025
$ZZ/WZ/WW$ + jets	81.822	0.319	0.310	0.168	0.075

Table 3
Results for $h \to ZZ^*$ in the 4-lepton final state. Further details on the cuts can be found in the text of Sec. 5.3.

Sample	Lepton cuts	WBF cuts	b-veto	Jet veto	m_{4l} cut
$(h \to ZZ^* \to 4l)jj$ WBF	0.012	0.006	0.005	0.005	0.005
$ZZ/WZ/WW$ + jets	4.688	0.031	0.030	0.020	<0.001

5.3. $hjj \to ZZ^*jj \to l^+l^-l'^+l'^-jj$

In the $h \to ZZ \to$ charged leptons channel we require exactly 4 isolated leptons with $\Delta R_{j,l} > 0.4$ and impose slightly weaker WBF cuts compared to Secs. 5.1 and 5.2 to retain more signal

$$y_{j_1} \times y_{j_2} < 0, \quad |y_{j_1} - y_{j_2}| > 4.5, \quad m_{j_1 j_2} > 600 \text{ GeV}. \tag{19}$$

After b- and jet vetos, as outlined in Secs. 5.1 and 5.2, the invariant mass of the 4 leptons has to be in a window $115 \le m_{4l} \le 135$ GeV. At the expense of a low signal yield we find $S/B \gg 1$ (Table 3).

5.4. Combining channels

To determine the possible future LHC Higgs signal-strength constraints we use the above signal and background cross sections to determine statistical uncertainties achievable. We treat the small gluon fusion contribution as background. In a particular channel 'i' the total statistical Higgs signal strength uncertainty is taken as

$$\Delta\mu_i = \frac{\sqrt{\mathcal{L}(\sigma_{BG,i} + \sigma_i)}}{\mathcal{L}\sigma_i} \quad , \tag{20}$$

where $\mathcal{L}$ is the integrated luminosity, $\sigma_{BG,i}$ is the background cross section and σ_i is the SM Higgs signal cross section. We estimate the combined statistical uncertainty as

$$\Delta\mu = \frac{1}{\sqrt{\sum_i 1/(\Delta\mu_i)^2}} \quad . \tag{21}$$

Combing all of the channels leads to an expected signal-strength statistical uncertainty of $\Delta\mu = 10\%$ (3%) with an integrated luminosity of $\mathcal{L} = 300$ fb^{-1} (3 ab^{-1}). These numbers are based solely on statistical uncertainties and are thus not conservative. There are many sources of systematic uncertainty and the potential leading source is likely to come from jet vetoes.

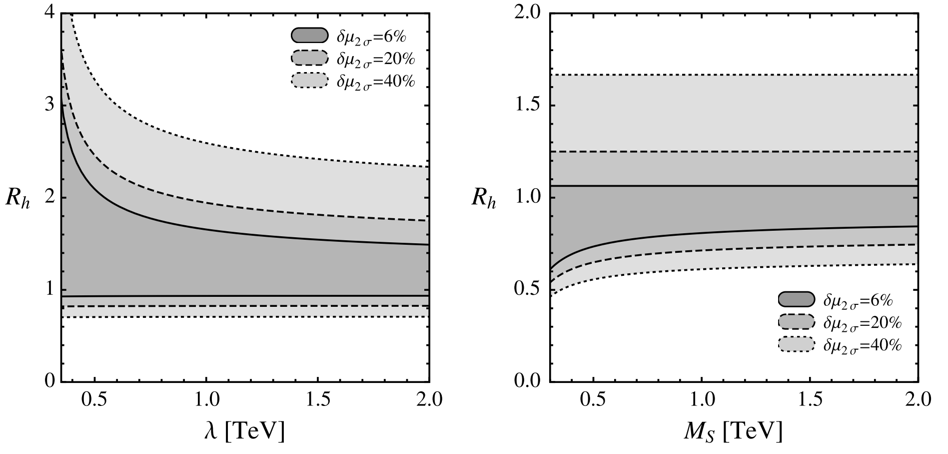

Fig. 6. Combined 2σ LEP and future LHC WBF (or current all-channels) constraints on the Higgs width in the model with modified couplings and a UV cutoff (left) and a model with a mixed-in singlet scalar (right).

We do not have accurate estimates of the systematic uncertainty thus we will take three benchmark scenarios motivated by the statistical uncertainties described above. These benchmarks are $\Delta\mu = 3\%, 10\%, 20\%$. The first estimate is a maximally optimistic estimate which assumes zero systematic error at the 3 ab^{-1} HL-LHC, the second is likely to be more realistic for the 3 ab^{-1} HL-LHC if systematic errors were reduced to the $\sim$10% level, this benchmark is also motivated by the statistics-only scenario for the 300 fb^{-1} LHC, and in the third we have doubled this uncertainty to demonstrate the impact systematic uncertainties may have.

5.5. *Reducing the coupling dependence in future Higgs width constraints*

In Fig. 6 we show the expected 2σ confidence contours on the total Higgs width that could be achieved with a future combination of WBF observations at the LHC with constraints from LEP for both the models of Sec. 2. Although it may be possible to achieve smaller uncertainties on the signal strength we will focus on the constraints determined from the $\delta\mu_{2\sigma} = 40\%$ band as this represents our most conservative estimate for the LHC at 300 fb^{-1} in the WBF channel.

For the model with modified couplings and a cutoff of $\lambda = 1$ TeV the 2σ Higgs width constraints would be $0.71 \lesssim R_h \lesssim 2.59$. The upper limit is much weaker than the lower limit because the precision electroweak constraints prefer increased Higgs couplings (see Fig. 4) and thus the combined constraint of Eq. (15) can tolerate significant increases in the Higgs width. On the other hand, it is interesting that a strong lower limit can be placed on the Higgs total width. For the model of a mixed-in singlet scalar the lower boundary of the constraint is similar to the left panel. At $M_S = 1$ TeV the constraints are $0.61 \lesssim R_h \lesssim 1.67$.

These potential future limits are quantitatively comparable to those obtained in Sec. 4.1 using current LHC data from global signal strength fits, however the purpose of the future constraints considered here is to reduce the coupling dependence of the constraint. From this perspective this combination of past LEP constraints with future LHC Higgs measurements tailored to focus on hVV couplings is very attractive as both constraints depend only on these specific couplings and the final constraint holds even under uncorrelated modifications of the hGG-, $h\gamma\gamma$-, and $h\bar{f}f$ couplings.

6. Complementarity with other methods

As the method considered here and the method based on $gg \to h^* \to ZZ$ constraints [11] may both be used to indirectly constrain the Higgs width it is useful to consider the complementarity between the two proposals.

Let us first consider the two models considered here as they will set the scene for a discussion of more general models. In the Higgs portal model the LEP off-shell constraint explicitly depends on the extra scalar mass M_S, as can be seen in Fig. 4. Based on this one might be tempted to conclude that this constraint is more model-dependent than the LHC off-shell constraint. However in this model for the LHC constraint one must consider not only the $gg \to h^* \to ZZ$ diagrams but also the $gg \to S^* \to ZZ$ diagrams, which will interfere at the same order and, if $M_S \sim M_{ZZ}$, the second diagram may be resonantly enhanced. Thus both constraints explicitly depend on the additional parameter M_S in this model and suffer from model dependence which is qualitatively similar. Ideally in this circumstance all of the available off-shell information, including the LHC and LEP, should be combined to derive the most robust constraint.

We will now consider the model with rescaled couplings and a dimensionful cutoff λ imposed. Once again, the LEP off-shell constraint explicitly depends on this additional parameter. Since no new states have been specified one might be tempted to conclude that the LHC off-shell constraint does not depend on the cutoff, since no specific diagrams which interfere with $gg \to h^* \to ZZ$ may be written down. However, for constraints on width modifications which are large, $\mathcal{O}(\Gamma_{SM} \times$ few), the corresponding coupling deviations are large, and we know that if the Higgs couplings are modified and no new states are introduced unitarity violation would set in for processes involving a Higgs boson far off-shell. Thus although no cutoff dependence has been explicitly included in the LHC off-shell constraint, there must be new physics at some higher energy scale and it is expected that this new physics would also contribute in the $gg \to S^* \to ZZ$ process, and other subprocesses contributing to $pp \to ZZ$. Thus although the required new physics scale may not be explicitly included in the LHC off-shell constraints, it must enter in some way in any scenario in which unitarity is maintained.

Having set the scene with the two specific models considered in this paper, we now turn away and discuss more general scenarios. As the LEP constraint arises at low energies the appropriate language for more general models is that of effective theory, which captures the effects of new physics at high energy scales through higher dimension operators suppressed by the new physics scale. An obvious instance in which the LEP off-shell constraint may be weakened is if the new physics responsible for modifying the Higgs couplings, in this case from an operator such as $(\partial |H|^2)^2$, is accompanied by operators which contribute to the electroweak precision observables but do not modify the Higgs couplings. If one allows for the possibility of cancellations between the effects of the modified Higgs couplings and these additional operators on the relevant observables then the constraints are weakened. Thus again it would seem that in more general scenarios the LEP constraint is more susceptible to interference from additional contributions. However, at the LHC the $gg \to h^* \to ZZ$ process must be extracted alongside Higgs-independent contributing processes such as $\bar{q}q \to ZZ$ and the box diagram in $gg \to ZZ$. Both of these latter processes may be modified by dimension six operators which modify the $Z\bar{q}q$ coupling. Thus the LHC off-shell constraint suffers from qualitatively similar model-dependence to the LEP off-shell constraint when additional higher dimension operators are considered.

To summarise, the most useful consideration is not which of the LHC or LEP off-shell approaches is more or less model-dependent, as they clearly both suffer from similar pitfalls if one tries to construct model independent width constraints. Rather, it is more pertinent to emphasise that in either case it is best to consider any width constraints on a model-by-model basis, with the underlying assumptions for a given model (whether UV-complete or simplified) clearly stated. Then, from the perspective of a specific model, both approaches give complementary handles on off-shell Higgs physics and indirectly on the Higgs width. For the concrete scenarios we discussed in this paper, we find that the LEP constraint is stronger than the constraint from an LHC off-shell measurement.

7. Summary and outlook

In this paper, we have shown that including off-shell Higgs boson coupling constraints from LEP, as performed by e.g. [14], adds important complementary information in the interpretation of LHC Higgs measurements. Accordingly we can break the degeneracy of the signal strength constraints similar to [4,5,11] to formulate a constraint on the total Higgs width under the assumption of a specific model. Bearing in mind certain theoretical issues that can arise if new physics does not follow an SM-pattern [7,8], we have categorised the constraints into groups with varying degree of dependence on additional Higgs couplings. We have also discussed the theoretical limitations of this indirect constraint and complementarity with other methods in Sec. 6.

We find that for the two models we have considered, assuming no new physics contributions to the hGG coupling up to a scale of at least 1 TeV, the Higgs width is constrained to $0.73 \lesssim R_h(\lambda = 1 \text{ TeV}) \lesssim 1.87$, based on the combination of Higgs-coupling measurements from LEP and the Higgs signal strength measurement from LHC8. There is important model-dependence in this particular constraint as it assumes all Higgs couplings, (e.g. hGG, hVV) are rescaled in the same way. This theoretical shortcoming in setting limits on Γ_h can be avoided by considering fully-correlated production and decay modes such as weak boson fusion, which has negligible dependence on the hGG coupling if appropriate cuts are imposed. Following the SM coupling pattern of the two models considered (i.e. we explicitly ignore the possibility of momentum-dependent couplings from higher dimensional operators or the presence of light electroweak degrees of freedom) we can make an estimate for a future limit on the Higgs width using the LEP + LHC combination of $0.71 \lesssim R_h \lesssim 2.59$.

We stress that this result, although competitive with the expectation at a future Lepton Collider, is impacted by the logarithmic sensitivity to UV scales and should not be compared to constraints from a model-independent Lepton Collider measurement of the hZ cross section as a probe of the hZZ coupling. Furthermore, in Sec. 6 we have discussed in some detail the model-dependence of such a constraint and emphasised the necessity of considering specific models when placing this constraint. We have also considered the model dependence of off-shell LHC Higgs measurements when interpreted as a width constraint and argued that the model dependence of the constraint in this case is similar in nature to the model dependence of the LEP constraint. Under the assumptions of the two models considered here we find that the LEP constraint is stronger than the constraint from an LHC off-shell measurement as performed in [4,5].

Both the ATLAS and CMS Collaborations have developed extensive analyses based on individually modified Higgs couplings in a vast number of production and decay mechanisms. We have focused on specific channels in this work, however it is likely that a combined global fit which floats all Higgs couplings and the Higgs width as an independent parameter, and then combines all of the available Higgs data at the LHC in a joint likelihood with the LEP constraints would lead to the strongest constraints on the Higgs width as interpreted within the popular 'κ-framework'. Moving towards the theoretically more robust setting of a Higgs EFT framework, the LEP constraints at tree-level and at one-loop are already well known (see for example the early references in [23]). Thus in this case these constraints could be combined with LHC constraints on the coefficients of higher dimension operators which modify Higgs couplings, and if the Higgs width was included as a free parameter then again a constraint on the Higgs width would result. Such a constraint would fully demonstrate the power in combining the diverse strengths of LEP precision electroweak probes of the Higgs sector with the direct observations of the Higgs at the LHC.

Acknowledgements

MM would like to thank Jure Zupan for insightful comments in the initial stages of this work. CE is supported in part by the IPPP Associateship programme. MM acknowledges support from a CERN COFUND Fellowship. This research was supported in part by the European Commission through the “HiggsTools” Initial Training Network PITN-GA-2012-316704.

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