October 11, 2012 FERMILAB-Pub-12-557-T
Revised: February 26, 2013

Coupling spans of the Higgs-like boson

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Abstract

Using the LHC and Tevatron data, we set upper and lower limits on the total width of the Higgs-like boson. The upper limit is based on the well-motivated assumption that the Higgs coupling to a W or Z pair is not much larger than in the Standard Model. These width limits allow us to convert the rate measurements into ranges for the Higgs couplings to various particles. A corollary of the upper limit on the total width is an upper limit on the branching fraction of exotic Higgs decays. Currently, this limit is 47% at the 95% CL if the electroweak symmetry is broken only by doublets.

1 Introduction

The discovery of a Higgs-like particle (h^0) in the $\gamma\gamma$ and 4ℓ final states by the ATLAS [1] and CMS [2] Collaborations, of mass M_h roughly in the $125 - 126.5$ GeV range, provides multiple opportunities for probing phenomena beyond the Standard Model (SM). The SM Higgs boson [3] in that mass range has a very small total width, $\Gamma_h^{\rm SM}/M_h \simeq 3.2 \times 10^{-5}$, due to the small Yukawa coupling of the b quark ($y_b \sim 0.02$) and the severe phase-space suppression of the WW^* final state. Therefore, if new particles lighter than about 60 GeV have a coupling to the Higgs doublet larger than 10^{-2}, the Higgs-like boson can have a large branching fraction $\mathcal{B}_X$ into exotic final states, and consequently a larger total width, $\Gamma_h > \Gamma_h^{\rm SM}$. The exotic Higgs decays could escape detection for a long time, for example in the case of the four gluon-jet final state arising from $h \to A^0 A^0 \to 4g$ where A^0 is a gauge-singlet spin-0 particle [4].

Thus, it is important to analyze whether a relatively large Γ_h can be observable. The prospects for measuring the line shape of h^0 are rather dim, barring a high-luminosity muon collider running at $\sqrt{s} = M_h$. Nevertheless, one may hope to determine Γ_h indirectly, given that all the rates for Higgs signals at colliders are inversely proportional to Γ_h. It turns out, however, that the effect on rates of a larger Γ_h can be compensated by

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

an universal increase of the h^0 couplings. In fact, at hadron colliders the only observables based on rates are a product of the squared couplings for producing and decaying h^0 divided by Γ_h, so that the width itself cannot be measured even indirectly at the LHC.[1]

The impossibility of measuring Γ_h at the LHC hampers the extraction of Higgs couplings from the rate measurements. In order to go around this problem, several groups have relied on assumptions about the width. For example, it has been assumed that only SM decays are allowed [5, 6, 7], or that all nonstandard final states include particles escaping the detector [8, 9, 10], or that nonstandard final states are allowed only when certain couplings to SM particles are the same as in the SM [11]. A more general framework is allowed in [12], but the problem of rescaling both the width and the couplings is avoided by imposing an ad-hoc upper limit on some of the couplings.

In this paper we use the ATLAS and CMS rate measurements to derive an upper limit on Γ_h based on the rather robust theoretical assumption that the Higgs coupling to a W pair is not much larger than in the SM.[2] In many models, the h^0WW coupling is substantially smaller than in the SM, and only in the unusual case [14, 15, 16, 17] of large VEVs for higher $SU(2)_W$ representations does the coupling exceed its SM value.[3] We then translate this limit on Γ_h into an upper limit on the exotic branching fraction, $\mathcal{B}_X$. Furthermore, we derive a lower limit on Γ_h from the Tevatron [18] and LHC [1, 2] rate measurements, especially for the $b\bar{b}$ and WW^* decay modes. Having bounded Γ_h from above and below, we can then extract nearly-model independent upper and lower limits on the general couplings of the Higgs-like particle allowed by various rate measurements. Our method of deriving the spans of the couplings could be used by the CMS and ATLAS Collaborations in order to translate their measurements into information about the couplings of the Higgs-like particle in a way that is as model-independent as possible at hadron colliders.

In Section 2 we parametrize the general couplings of the Higgs-like boson to SM particles, and summarize the existing rate measurements. The upper and lower limits on Γ_h are derived in Section 3. In Section 4 we compute the upper limit on the branching fraction of exotic Higgs decays, and then we obtain the coupling spans. Our conclusions

[1] At e^+e^- or $\mu^+\mu^-$ colliders the recoil of the Z produced in association with h^0 would allow a measurement of the h^0ZZ coupling, and consequently Γ_h can be determined from the rates for various processes.

[2] This procedure was mentioned in Refs. [6, 8, 13] but was not explored in detail in the general case where all couplings are free parameters and nonstandard decay modes are allowed.

[3] An h^0WW coupling larger than in the SM also leads to unitarity violation in longitudinal WW scattering unless there are isospin-2 resonances [17].

are included in Section 5.

2 Measurable quantities

A Higgs boson is a scalar particle h^0 that couples to the W and Z bosons according to

$$\frac{g}{M_W}\, h^0 \left(C_W M_W^2 W^+ W^- + C_Z \, \frac{M_Z^2}{2} Z Z \right) \ , \tag{2.1}$$

where g is the $SU(2)_W$ gauge coupling, and C_W and C_Z parametrize the deviation from the SM couplings: $C_W^{\rm SM} = C_Z^{\rm SM} = 1$. If electroweak symmetry breaking is due entirely to VEVs of $SU(2)_W$ doublets, then [19, 6, 8]

$$0 < C_W = C_Z \leq 1 \quad \text{for doublet VEVs} \ . \tag{2.2}$$

In models where triplets or higher $SU(2)_W$ representations acquire VEVs it is possible to have $C_W \neq C_Z$ as well as values for C_W and/or C_Z above 1 or negative [15]. However, such models predict additional scalars, including doubly-charged and singly-charged particles, whose effects are tightly constrained by the electroweak data [20] and by collider searches [21]. As a result, one can still derive some upper bounds on the couplings:

$$|C_W| < C_W^{\rm max} \quad , \quad |C_Z| < C_Z^{\rm max} \ . \tag{2.3}$$

with $C_W^{\rm max}, C_Z^{\rm max} = O(1)$.

For example, the Georgi-Machacek model [14] includes a real triplet and a complex triplet (such that custodial invariance may arise due to a cancellation between the contributions of the two triplets), and also a complex doublet whose VEV is necessary for giving the top mass. Due to the loop contributions of charged scalars to the $Zb\bar{b}$ vertex [20], the deviations from the SM couplings have upper limits $C_W^{\rm max}, C_Z^{\rm max} \approx 1.5$ [15].

The couplings of a Higgs boson to third generation fermions can be written as

$$-C_t \frac{m_t}{v_h}\, h^0\, \bar{t}t - C_b \frac{m_b}{v_h}\, h^0\, \bar{b}b - C_\tau \frac{m_\tau}{v_h}\, h^0\, \bar{\tau}\tau \ , \tag{2.4}$$

where m_t, m_b and m_τ are the t, b and τ masses, $v_h \approx 246$ GeV is the electroweak scale, and C_t, C_b, C_τ are real parameters that are equal to 1 in the SM.

The Higgs boson coupling to the top quark, and possibly to new colored particles, induces a 1-loop coupling of h^0 to a pair of gluons. In the approximation where M_h/m_t effects are negligible (they turn out to be below 7% for $M_h \approx 125$ GeV) and where new

colored particles that couple to h^0 can be integrated out, the Higgs coupling to a pair of gluons is given by a dimension-5 operator:

$$C_g \, \frac{\alpha_s}{12\,\pi v_h} \, h^0 \, G^{\mu\nu} G_{\mu\nu} \quad , \tag{2.5}$$

where $G^{\mu\nu}$ is the gluon field strength, and C_g is a real parameter (equal to 1 in the SM). If there are new colored particles with mass not much larger than M_h that couple to h^0 (such as a color-octet scalar [22]), then C_g should be replaced by a function of M_h.

The only other Higgs couplings relevant here involve photons and arise also at one loop. These lead to the $h^0 \to \gamma\gamma$, $Z\gamma$ decays. Given that the dominant contributions to these decays in the SM arise from W loops [3], it is not accurate to parametrize these couplings by the dimension-5 operators $h^0 \, F^{\mu\nu} F_{\mu\nu}$ and $h^0 \, Z^{\mu\nu} F_{\mu\nu}$. For example, in the SM the full 1-loop $\Gamma^{\rm SM}(h^0 \to \gamma\gamma)$ width is 50% larger than the result based on the dimension-5 operator for $M_H \approx 125$ GeV. We are thus led to define the deviations from the SM effective couplings to photons by

$$C_\gamma \equiv \left(\frac{\Gamma(h^0 \to \gamma\gamma)}{\Gamma^{\rm SM}(h^0 \to \gamma\gamma)} \right)^{1/2} \quad ,$$

$$C_{Z\gamma} \equiv \left(\frac{\Gamma(h^0 \to Z\gamma)}{\Gamma^{\rm SM}(h^0 \to Z\gamma)} \right)^{1/2} \quad . \tag{2.6}$$

There are several processes at hadron colliders that can be studied in order to determine the couplings shown in Eqs. (2.1), (2.4), (2.5) and (2.6). Higgs production proceeds mainly through gluon fusion, vector boson fusion (VBF), Wh^0 or Zh^0 associated production, or radiation off a top quark ($t\bar{t}h^0$). The cross sections for these five processes are proportional to C_g^2, $(C_W^2 + r C_Z^2)$, C_W^2, C_Z^2, and C_t^2, respectively. The parameter r that sets the ratio of rates for ZZ to WW fusion is typically between 0.3 and 0.5 in pp collisions, and depends on the center-of-mass energy [23].

The widths for the Higgs decays to $b\bar{b}$, $\tau^+\tau^-$, WW, ZZ, $\gamma\gamma$, $Z\gamma$, are proportional to $C_{\mathcal{P}}^2$ where $\mathcal{P} = b, \tau, W, Z, \gamma, Z\gamma$, respectively. Additional decay modes, to final states involving SM particles (*e.g.*, $h^0 \to A^0 A^0 \to 4j$ where A^0 is a new spin-0 particle [4]), or new stable particles may have large contributions to Γ_h.

The narrow width approximation is accurate for $M_h \approx 125$ GeV even if new physics contributions to Γ_h were three orders of magnitude larger than $\Gamma_h^{\rm SM}$, the total Higgs width in the SM. Thus, the cross section for a process of Higgs production and decay is

proportional to

$$\frac{C^2_{\rm prod.}\, C^2_{\rm decay}}{\Gamma_h} \quad , \tag{2.7}$$

where $C_{\rm prod.}$ and $C_{\rm decay}$ are the $C_{\mathcal{P}}$ coefficients entering the production and decay, respectively, as discussed above. It is convenient to define the "apparent squared-couplings"

$$a_{\mathcal{P}} \equiv C^2_{\mathcal{P}} \left(\frac{\Gamma_h^{\rm SM}}{\Gamma_h}\right)^{1/2} \quad , \quad \text{for } \mathcal{P} = W, Z, g, \gamma, Z\gamma, t, b, \tau \quad , \tag{2.8}$$

so that the cross section for a Higgs process [proportional to the quantity in Eq. (2.7)] over the SM cross section for the same process is simply a product of two $a_{\mathcal{P}}$ quantities.[4]

The measurements of various Higgs processes allow the determination of the $a_{\mathcal{P}}$ apparent squared-couplings. For example, a_b and a_W may be extracted from the measured total cross sections for $pp \to W^* \to Wh^0$ followed by $h^0 \to b\bar{b}$ or $h^0 \to W^+W^-$, through the relations:

$$\begin{aligned} \left(\frac{\sigma}{\sigma_{\rm SM}}\right)(Wh \to Wb\bar{b}) &= a_W\, a_b \quad , \\ \left(\frac{\sigma}{\sigma_{\rm SM}}\right)(Wh \to WWW) &= a_W^2 \quad , \end{aligned} \tag{2.9}$$

where σ is the measured cross section and $\sigma_{\rm SM}$ is its theoretical value in the SM. Likewise, measurements of the cross sections for various Higgs production mechanisms followed by various Higgs decays determine other products of $a_{\mathcal{P}}$'s, as shown in Table 1.

A fit to the measured cross sections listed in Table 1 can determine $a_{\mathcal{P}}$ for $\mathcal{P} = b, W, Z, g, \tau, \gamma$. Only channels that are already measured or will be probed in the near future are included in Table 1. Many other channels such as $gg \to h^0 \to Z\gamma$ (proportional to $a_g a_{Z\gamma}$), Wh^0 production followed by $h^0 \to ZZ^*$ (proportional to $a_W a_Z$), Zh^0 production followed by $h^0 \to \tau\tau$ (proportional to $a_Z a_\tau$), or $t\bar{t}h$ production followed by $h^0 \to W^+W^-, ZZ, \tau^+\tau^-$, will likely require a sizable integrated luminosity due to their small rates or large backgrounds.

The measurements on the rows labelled by $gg \to h^0$ are dominated by gluon fusion but also contain some contributions of order 10% from VBF and from associated production with a W or Z decaying hadronically. For simplicity we neglect those contributions.

The measurements on the rows labeled by VBF include two forward jets. The selections used make VBF the dominant production mechanism, but do not eliminate completely the gluon fusion mechanism with two additional jets (simulations within the SM

[4]In the notation of [13], our $C_{\mathcal{P}}$ parameters are labelled by $\kappa_{\mathcal{P}}$, and $a_{\mathcal{P}} = \kappa^2_{\mathcal{P}}/\kappa_H$.

h^0 decay	h^0 production	observable	measured $\sigma/\sigma_{\rm SM}$; $M_h = 125$ GeV
WW^*	$gg \to h^0$	$a_g a_W$	1.3 ± 0.5, ATLAS [1] ; 126 GeV $0.6^{+0.5}_{-0.4}$, CMS [2] ; 125.5 GeV $0.3^{+0.8}_{-0.3}$, Tevatron [24] our average: 0.9 ± 0.4
	VBF	$(a_W + r a_Z)/(1+r)\, a_W$	$0.3^{+1.5}_{-1.6}$, CMS [25]
	$W^* \to W h^0$	a_W^2	$-2.9^{+3.2}_{-2.9}$, CMS [25]
	$Z^* \to Z h^0$	$a_Z a_W$	
ZZ^*	$gg \to h^0$	$a_g a_Z$	$1.3^{+0.7}_{-0.5}$, ATLAS [26] $0.7^{+0.5}_{-0.4}$, CMS [2] ; 125.5 GeV our average: $1.0^{+0.4}_{-0.3}$
	VBF	$(a_W + r a_Z)/(1+r)\, a_Z$	
$\gamma\gamma$	$gg \to h^0$	$a_g a_\gamma$	1.7 ± 0.6 , ATLAS [27] ; 126.5 GeV 1.4 ± 0.6 , CMS [25] $3.6^{+3.0}_{-2.5}$, Tevatron [24] our average: 1.6 ± 0.4
	VBF	$(a_W + r a_Z)/(1+r)\, a_\gamma$	2.6 ± 1.3 , ATLAS [27] ; 126.5 GeV $2.1^{+1.4}_{-1.1}$, CMS [25] our average: $2.3^{+1.0}_{-0.9}$
$b\bar{b}$	$W^* \to W h^0$	$a_W a_b$	0.5 ± 2.2 , ATLAS [1] ; 126 GeV $0.5^{+0.9}_{-0.8}$, CMS [25] 2.0 ± 0.7, Tevatron [24] our average: 1.4 ± 0.6
	$Z^* \to Z h^0$	$a_Z a_b$	
	$t\bar{t} h^0$	$a_t a_b$	$-0.8^{+2.1}_{-1.9}$, CMS [25]
$\tau^+\tau^-$	$gg \to h^0$	$a_g a_\tau$	$0.4^{+1.6}_{-2.0}$, ATLAS [1] ; 126 GeV 1.3 ± 1.1 , CMS [25] our average: 1.0 ± 0.9
	VBF	$(a_W + r a_Z)/(1+r)\, a_\tau$	$-1.8^{+1.0}_{-0.9}$, CMS [25]
	$W^* \to W h^0$	$a_W a_\tau$	$0.7^{+4.1}_{-3.2}$, CMS [25]

Table 1: Combinations of parameters (3rd column) that can be extracted from cross section measurements of various processes. Existing measurements for $M_h = 125$ GeV (except where M_h is explicitly specified) are shown in the last column. Our averages do not include any correlations, and are obtained by combining asymmetric errors as in [28].

show that this contamination is about 30% [2]). This effect will convolute the determination of the a_g, a_W, and a_Z parameters, but taking it into account is beyond the scope of this article.

3 Limits on the total Higgs width

In this section we derive the lower and upper limits on the total width Γ_h of h^0.

3.1 Upper limit on Γ_h

The existence of a stringent upper limit $\Gamma_h^{\max}$ (with $\Gamma_h^{\max} \ll M_h$) on the total h^0 width is not obvious. After all, the observable quantities $a_{\mathcal{P}}$ can be kept fixed when Γ_h is increased by increasing all the couplings $C_{\mathcal{P}}$. The reason that there is a useful upper limit stems from the fact that there are upper limits on C_W and C_Z, which are related to the W and Z masses.

Once the a_W and a_Z quantities are extracted from a fit to the data, each of the upper limits on the Higgs couplings to WW and ZZ gives an upper limit on Γ_h. Using the upper limits on C_W and C_Z as parametrized in Eq. (2.3), we find that Eq. (2.8) implies the following upper limit on the total h^0 width:

$$\Gamma_h \leq \Gamma_h^{\max} = \mathrm{Min}\left\{ \frac{(C_W^{\max})^4}{a_W^2}\,,\, \frac{(C_Z^{\max})^4}{a_Z^2} \right\} \Gamma_h^{\mathrm{SM}} \quad . \tag{3.1}$$

Note that this upper limit relies solely on the existence of an upper limit on the Higgs couplings to the W or Z; for example, it allows any contribution to the width from exotic Higgs decays.

In the case where the electroweak symmetry is broken only by the VEVs of $SU(2)_W$ doublets (which covers the majority of theories discussed in the literature), the upper limit takes the form

$$\Gamma_h \leq \Gamma_h^{\max} = \frac{\Gamma_h^{\mathrm{SM}}}{a_V^2} \quad , \tag{3.2}$$

where a_V is now obtained by the fit performed with the $a_W = a_Z \equiv a_V$ constraint. Note that a_V can be measured directly from VBF or associated Vh^0 production followed by $h^0 \to WW$ or ZZ. The experimental uncertainties in these channels are too large for now, so that we use a more indirect method for extracting a_V.

Let us first combine the $gg \to h^0 \to WW^*$ and $gg \to h^0 \to ZZ^*$ rate measurements shown in Table 1, using the prescription of Ref. [28] for asymmetric errors:

$$(\sigma/\sigma_{\rm SM})(gg \to h \to VV^*) = 0.96^{+0.27}_{-0.24} \ , \tag{3.3}$$

where $V = W$ or Z. For $C_W = C_Z$, the observable quantity a_V can be extracted from the current measurements of $\sigma/\sigma_{\rm SM}$ for h^0 production followed by decay into VV^* and $\gamma\gamma$:

$$a_V^2 = (\sigma/\sigma_{\rm SM})(gg \to h \to VV^*) \frac{(\sigma/\sigma_{\rm SM})({\rm VBF} \to hjj \to \gamma\gamma jj)}{(\sigma/\sigma_{\rm SM})(gg \to h \to \gamma\gamma)} \ . \tag{3.4}$$

We assume that the quoted experimental uncertainties correspond to Gaussian distributions, or to bifurcated Gaussian distributions (*i.e.*, two half-Gaussians of same central value glued together) in the case of asymmetric errors. It should be emphasized that this is only a rough approximation, which could be avoided once more information about experimental uncertainties becomes available. With the inputs from Table 1, and manipulating the distributions with Monte-Carlo simulations, we find

$$a_V = 1.15^{+0.39}_{-0.29} \ . \tag{3.5}$$

This implies the following upper limit on the total width:

$$\Gamma_h \leq \Gamma_h^{\rm max} = 0.52^{+0.82}_{-0.10} \ \Gamma_h^{\rm SM} \ . \tag{3.6}$$

Note that, assuming the constraint from $SU(2)_W$ doublets ($C_W = C_Z \equiv C_V \leq 1$), $\Gamma_h^{\rm max}$ is a strict upper limit on Γ_h, but the extracted value of $\Gamma_h^{\rm max}$ from current data has an uncertainty; this is indicated at the 1σ level in Eq. (3.6).

Even though we assumed that the experimental inputs are (bifurcated) Gaussian distributions, the values of $\Gamma_h^{\rm max}$ follow a distribution that is quite different from a bifurcated Gaussian, due to the operations on Gaussians with large variances shown in Eqs. (3.2) and (3.4). The $\Gamma_h^{\rm max}$ distribution obtained from current data is shown in Fig. 1. The 95% CL interval for $\Gamma_h^{\rm max}/\Gamma_h^{\rm SM}$ is $0.26 - 3.56$.

3.2 Lower limit on Γ_h

Unlike the above upper limit which relies on a theoretical assumption (upper limit on the hVV couplings), a lower limit on Γ_h can be derived from the rates required for its observation. The total width of the Higgs boson is given by

$$\Gamma_h = \sum_{\substack{\mathcal{P} = W, Z, \\ b, \tau, g, \gamma}} C_{\mathcal{P}}^2 \ \Gamma^{\rm SM}(h^0 \to \mathcal{P}\mathcal{P}) + \ \Gamma_X \ , \tag{3.7}$$

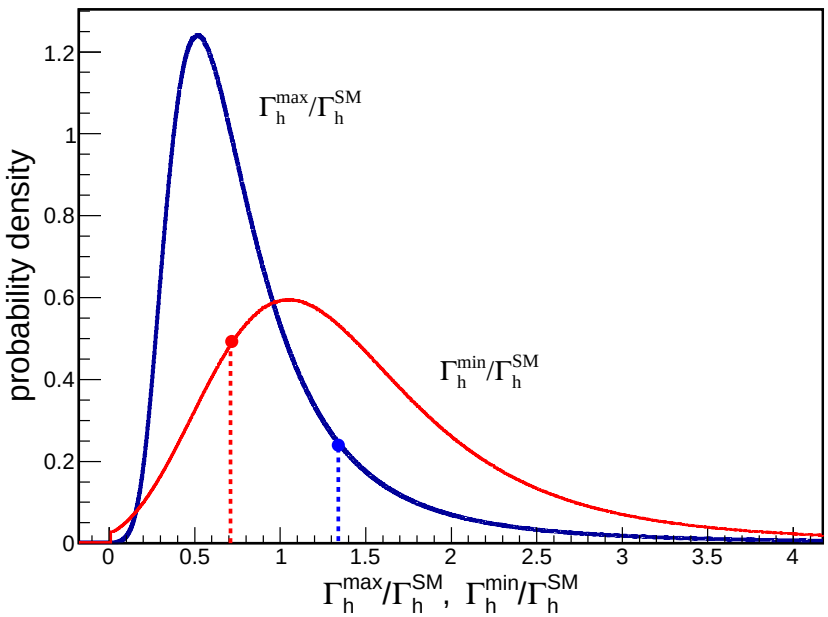

Figure 1: $\Gamma_h^{\rm max}$ distribution obtained from Eq. (3.2), and $\Gamma_h^{\rm min}$ distribution obtained from Eq. (3.8). The span of $\Gamma_h/\Gamma_h^{\rm SM}$ lies between the dashed vertical lines, which mark the lower 1σ limit on $\Gamma_h^{\rm min}$ and the upper 1σ limit on $\Gamma_h^{\rm max}$.

where Γ_X is the h^0 decay width into final states other than the SM ones. For simplicity, we have not included decays into $Z\gamma$, $c\bar{c}$ or light-fermion pairs because their sum is at most 3% of Γ_h in the SM for any $M_h > 120$ GeV. In other words, decays into any of these final states with a width substantially larger than the SM one is included in the exotic width Γ_X.

Given that $\Gamma_X \geq 0$, Eq. (3.7) implies the following lower limit on the total Higgs width:

$$\Gamma_h \geq \Gamma_h^{\rm min} = \left(\sum_{\substack{\mathcal{P} = W, Z, \\ b, \tau, g, \gamma}} a_{\mathcal{P}} \, \mathcal{B}^{\rm SM}(h^0 \to \mathcal{P}\mathcal{P}) \right)^2 \Gamma_h^{\rm SM} \quad , \tag{3.8}$$

where $\mathcal{B}^{\rm SM}(h^0 \to \mathcal{P}\mathcal{P})$ are the theoretically known branching fractions in the SM, and $a_{\mathcal{P}}$ [defined in Eq. (2.8)] can be extracted from a fit to the rate measurements. The fact that there is a lower limit on Γ_h is not surprising given that the observation of a Higgs boson requires a sizable production rate which in turn requires couplings that are not much smaller than the SM ones. However, the exact form of the lower limit was hard to anticipate.

We can extract the distribution for a_b from the measurement of the rate for associated

production followed by $h^0 \to b\bar{b}$:

$$\begin{aligned} a_b &= \frac{1}{a_V}(\sigma/\sigma_{\rm SM})(Vh^0 \to Vb\bar{b}) \\ &= 1.00^{+0.91}_{-0.37} \ . \end{aligned} \tag{3.9}$$

The distribution for a_g can be obtained from the rate for gluon fusion followed by the $h^0 \to WW^*, ZZ^*$ decays:

$$\begin{aligned} a_g &= \frac{1}{a_V}(\sigma/\sigma_{\rm SM})(gg \to h^0 \to VV^*) \\ &= 0.74^{+0.35}_{-0.13} \ . \end{aligned} \tag{3.10}$$

This then allows the determination of the remaining $a_{\mathcal{P}}$ quantities:

$$\begin{aligned} a_\gamma &= \frac{1}{a_g}(\sigma/\sigma_{\rm SM})(gg \to h^0 \to \gamma\gamma) \\ &= 1.88^{+0.65}_{-0.46} \ . \end{aligned} \tag{3.11}$$

$$\begin{aligned} a_\tau &= \frac{1}{a_g}(\sigma/\sigma_{\rm SM})(gg \to h^0 \to \tau^+\tau^-) \\ &= 1.0^{+1.5}_{-0.9} \ . \end{aligned} \tag{3.12}$$

Note that a_τ could also be extracted from the rate for the VBF process followed by $h^0 \to \tau^+\tau^-$. As can be seen from Table 1, the central value for this rate is about 2σ *below* the predicted value for the case of no Higgs boson. This suggests a large negative fluctuation of the background, so we have chosen not to include this VBF process in a fit until more data is analyzed.

The large uncertainty in a_τ shown in Eq. (3.12) raises the issue of what is the meaning of a negative $a_{\mathcal{P}}$. Clearly, negative values for $\sigma/\sigma_{\rm SM}$ represent downward fluctuations of the background. However, $a_{\mathcal{P}}$ are by definition [see Eq.(2.8)] positive quantities, so that it is appropriate to interpret the uncertainties quoted in Eqs. (3.9)-(3.12) as distributions with a boundary at the origin. Following the Feldman-Cousins [29] prescription for that case (and assuming approximate Gaussians with variance given by the negative errors), the 1σ confidence interval for a_τ becomes $0.3 - 2.5$. For the purpose of determining the lower limit on Γ_h, it does not make much difference whether we use this interval or the one indicated by Eq. (3.12), $0.1 - 2.5$, because $\mathcal{B}^{\rm SM}(h^0 \to \tau^+\tau^-)$ is rather small.

For $M_h = 125$ GeV, $\mathcal{B}^{\rm SM}(h^0 \to \mathcal{P}\mathcal{P})$ equals (21.5, 2.64, 57.7, 6.32, 8.57, 0.228)% for $\mathcal{P} = W, Z, b, \tau, g, \gamma$, respectively, and the total SM width is $\Gamma_h^{\rm SM} = 4.07$ MeV. The lower limit on Γ_h can then be computed from Eq. (3.8):

$$\Gamma_h \geq \Gamma_h^{\rm min} = 1.05^{+1.26}_{-0.34}\, \Gamma_h^{\rm SM} \quad . \tag{3.13}$$

We reiterate that $\Gamma_h^{\rm min}$ is a strict lower limit for Γ_h, but that the value of $\Gamma_h^{\rm min}$ extracted from current data has an uncertainty represented here by the 68.3% CL range. The 95% CL interval for $\Gamma_h^{\rm min}/\Gamma_h^{\rm SM}$ is $0.30 - 4.95$.

Using the upper limit at the 68.3% CL for $\Gamma_h^{\rm max}$ given in Eq. (3.6), and the lower limit at the 68.3% CL for $\Gamma_h^{\rm min}$ given in Eq. (3.13), we find that the span of the Higgs width is

$$0.71 \leq \frac{\Gamma_h}{\Gamma_h^{\rm SM}} \leq 1.34 \quad . \tag{3.14}$$

Note that this span is not a standard confidence interval, because the lower and upper limits arise from separate measurements.

The central value of $\Gamma_h^{\rm max}$ is smaller than that of $\Gamma_h^{\rm min}$. This is not a problem given that both $\Gamma_h^{\rm max}$ and $\Gamma_h^{\rm min}$ are currently rather broad distributions (see Fig. 1), so that the 1σ upper limit on $\Gamma_h^{\rm max}$ is larger than the 1σ lower limit on $\Gamma_h^{\rm min}$. It is conceivable, though, that more precise future measurements would yield $\Gamma_h^{\rm max} < \Gamma_h^{\rm min}$ at a confidence level of several standard deviations. The likely interpretation of that situation would be that higher $SU(2)_W$ representations have VEVs, so that $\Gamma_h^{\rm max}$ is rescaled by $(C_V^{\rm max})^4$, with $C_V^{\rm max} > 1$.

4 Limits on Higgs couplings and non-standard decays

In this section we use the constraints on Γ_h obtained in the previous section to set an upper limit on the branching fraction B_X into exotic final states, and to derive nearly model-independent ranges (which we call spans) for the Higgs couplings.

4.1 Upper limit on the exotic branching fraction

An important implication of the upper limit on Γ_h is that it leads to an upper limit on the branching fraction for h^0 decays into non-SM final states, $\mathcal{B}_X$. Dividing Eq. (3.7) by Γ_h gives

$$\mathcal{B}_X = 1 - \frac{1}{\Gamma_h} \sum_{\substack{\mathcal{P} = W, Z, \\ b, \tau, g, \gamma}} C_{\mathcal{P}}^2\, \Gamma^{\rm SM}(h^0 \to \mathcal{P}\mathcal{P}) \quad . \tag{4.1}$$

Using then the upper limit on Γ_h given in Eqs. (3.1) or (3.2), we find the following upper limit on the branching fraction into exotic final states:

$$\mathcal{B}_X \leq \mathcal{B}_X^{\max} = 1 - \left(\frac{\Gamma_h^{\rm SM}}{\Gamma_h^{\max}}\right)^{1/2} \sum_{\substack{\mathcal{P}\,=\,W,\,Z,\\ b,\,\tau,\,g,\,\gamma}} a_{\mathcal{P}}\, \mathcal{B}^{\rm SM}(h^0 \to \mathcal{P}\mathcal{P}) \quad . \tag{4.2}$$

In the case of doublet VEVs ($C_W = C_Z \equiv C_V$), the upper limit takes the simpler form

$$\mathcal{B}_X^{\max} = 1 - a_V \sum_{\substack{\mathcal{P}\,=\,W,\,Z,\\ b,\,\tau,\,g,\,\gamma}} a_{\mathcal{P}}\, \mathcal{B}^{\rm SM}(h^0 \to \mathcal{P}\mathcal{P}) \tag{4.3}$$

The values of $a_{\mathcal{P}}$ given in Eqs. (3.5) and (3.9)-(3.12) lead to the following upper limit:

$$\mathcal{B}_X \leq \mathcal{B}_X^{\max} = -0.33^{+0.39}_{-0.49} \quad . \tag{4.4}$$

Using the Feldman-Cousins prescription for this manifestly positive observable, we find that the extracted theoretical upper limit is $\mathcal{B}_X^{\max} < 14\%$ at the 68.3% CL and $\mathcal{B}_X^{\max} < 47\%$ at the 95% CL. For precise measurements of several cross sections, the uncertainties in $a_{\mathcal{P}}$ may become small enough to turn the upper limit on $\mathcal{B}_X$ into a severe constraint on physics beyond the SM.

The above limits are derived under the assumption $C_V^{\max} = 1$. For larger values of $C_V^{\max}$ the limits are relaxed. For example, using $C_V^{\max} \approx 1.5$ as in the Georgi-Machacek model [14, 15] we find $\mathcal{B}_X^{\max} < 59\%$ at the 68.3% CL and $\mathcal{B}_X^{\max} < 76\%$ at the 95% CL.

4.2 Spans of the Higgs couplings

From Eq. (2.8), we find that the various Higgs couplings discussed in Section 2, $C_{\mathcal{P}}$ for $\mathcal{P} = W, Z, b, \tau, g, \gamma$, can also be bracketed between lower and upper bounds extracted from current data:

$$a_{\mathcal{P}}^{1/2} \left(\frac{\Gamma_h^{\min}}{\Gamma_h^{\rm SM}}\right)^{1/4} < C_{\mathcal{P}} < a_{\mathcal{P}}^{1/2} \left(\frac{\Gamma_h^{\max}}{\Gamma_h^{\rm SM}}\right)^{1/4} \quad . \tag{4.5}$$

Using the distributions for $\Gamma_h^{\max}$ (see Fig. 1), $\Gamma_h^{\min}$ and $a_{\mathcal{P}}$, we find the following 68.3% (95%) spans for the Higgs couplings:

$$\begin{aligned}
&(0.74)\ 0.97 < |C_V| \leq 1 \quad , && (0.32)\ 0.73 < |C_b| < 1.42\ \ (2.34) \quad , \\
&(0.61)\ 0.77 < |C_g| < 1.07\ \ (1.63) \quad , && (0.0)\ 0.3 < |C_\tau| < 1.4\ \ (1.9) \quad , \\
&(0.92)\ 1.19 < |C_\gamma| < 1.54\ \ (1.93) \quad . &&
\end{aligned} \tag{4.6}$$

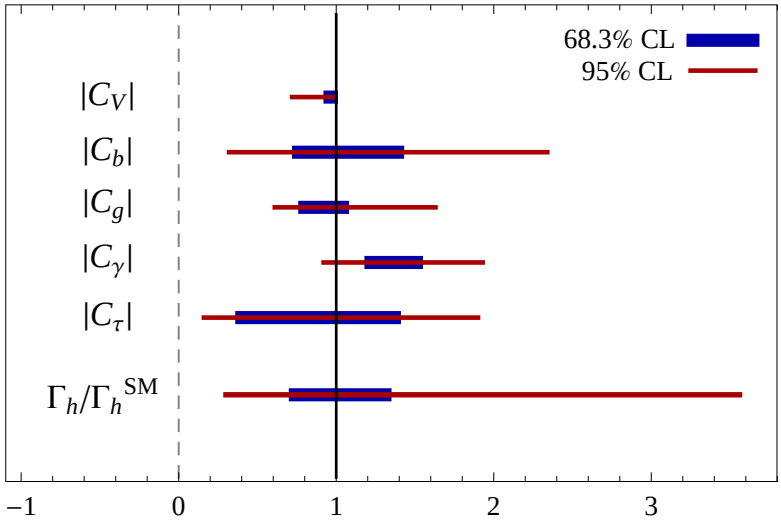

Figure 2: Spans of the Higgs couplings [see Eq. (4.5)] and total width, normalized to the SM values. The vertical lines at 0 and 1 correspond to no Higgs boson, and to the SM, respectively. The left-hand edge of each thick (thin) line represents the lower 1σ (95% CL) point on the distribution for the lower limit, while the right-hand edge represents the upper 1σ (95% CL) point on the distribution for the upper limit (as shown in Fig. 1 for Γ_h). If triplets or higher $SU(2)_W$ representations have VEVs, then the upper limits are pushed to higher values.

These spans arise from the lower limit on $a_{\mathcal{P}}^{1/2}(\Gamma_h^{\rm min})^{1/4}$ and the upper limit on $a_{\mathcal{P}}^{1/2}(\Gamma_h^{\rm max})^{1/4}$, which are obtained from separate experimental inputs, so that they should not be interpreted as standard confidence intervals.

Note that the upper limit on C_V is our input based on the assumption that electroweak symmetry breaking is entirely due to the VEVs of doublets. Using the Feldman-Cousins prescription to take into account this prior, we find that the lower limit on $|C_V|$ is relaxed: $|C_V| > 0.93$ (0.72) at the 68.3 (95)% CL.

The interval for C_τ is the least reliable, given the large uncertainties discussed before Eq. (3.5) and after Eq. (3.12). Using the Feldman-Cousins prescription for the lower limit $|C_\tau| > 0$, this is shifted to 0.16 at the 95% CL. The fact that the SM value of $C_{\mathcal{P}} = 1$ is within the 95% span for each of the above five couplings is remarkable (see Fig. 2). Nevertheless, new physics contributions may still have effects larger than 50% on some of these couplings.

Eq. (3.1) implies that the upper limits on the $C_{\mathcal{P}}$ parameters scale as $C_V^{\rm max}$. The values shown in Eq. (4.6) correspond to $C_V^{\rm max} = 1$, while $C_V^{\rm max} \approx 1.5$ in models with large triplet VEVs [15]. Even larger values of $C_V^{\rm max}$ are allowed if scalars transforming as 4 of $SU(2)_W$

acquire VEVs [16], but models of this type include several charged particles that can be ruled out or discovered at the LHC in the near future.

5 Conclusions

To determine the true nature of the Higgs-like resonance discovered by the ATLAS and CMS experiments, we need precise determinations of its underlying couplings to SM particles, extracted without making unnecessary theoretical assumptions. The impossibility of measuring Γ_h at the LHC therefore poses a significant problem, in addition to masking whether the new resonance has exotic decays that may be difficult to observe experimentally. We have taken a novel approach to this problem, by observing that Γ_h has a model-independent lower bound, and an upper bound that relies only on the weak assumption that the Higgs-like couplings to WW and ZZ is not larger than (or not much larger than) the SM values. We showed that $\Gamma_h^{\rm min}$ and $\Gamma_h^{\rm max}$ can be extracted separately from data for different combinations of Higgs-like signal strengths. This allows to confine Γ_h itself to a certain range between lower and upper limits; this span is not a standard confidence interval, but the limits themselves, being extracted from data, have 68.3% and 95% CL intervals that we have estimated. It is nontrivial that the resulting span for Γ_h is approximately centered on the SM value.

This same information can then be propagated to both an upper limit on the Higgs exotic branching fraction, and pairs of lower and upper limits for various Higgs couplings to SM gauge bosons and fermions. For the exotic branching fraction the extracted value of the upper bound is 14% at 68.3% CL in the underlying data, and 47% at 95% CL. For the Higgs couplings we find the spans displayed in Fig. 2. At 95% CL in the extracted limits all of these spans include the SM value. Notice however that by far the largest uncertainty in the current extraction of limits applies to the determination of $\Gamma_h^{\rm min}$ and $\Gamma_h^{\rm max}$ themselves.

With additional data the methodology described here will give increasingly important constraints on the properties of the newly discovered particle, and is complementary to other approaches currently being pursued. The major shortcoming of our analysis is our ignorance of the details of the experimental uncertainties in the published data; this can be overcome easily if the experimental collaborations themselves perform the analysis that we are advocating.

References

[1] G. Aad *et al.* [ATLAS Collaboration], "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan *et al.* [CMS Collaboration], "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC," Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].

[3] For a review, see A. Djouadi, "Anatomy of electroweak symmetry breaking. I: The Higgs boson in the standard model," Phys. Rept. **457**, 1 (2008) [hep-ph/0503172].

[4] B. A. Dobrescu, G. L. Landsberg and K. T. Matchev, "Higgs boson decays to CP odd scalars at the Tevatron and beyond," Phys. Rev. D **63**, 075003 (2001) [hep-ph/0005308].
C. -R. Chen, M. M. Nojiri and W. Sreethawong, "Search for the Elusive Higgs Boson Using Jet Structure at LHC," JHEP **1011**, 012 (2010) [arXiv:1006.1151 [hep-ph]].
A. Falkowski, D. Krohn, L. -T. Wang, J. Shelton and A. Thalapillil, "Unburied Higgs boson: Jet substructure techniques for searching for Higgs' decay into gluons," Phys. Rev. D **84**, 074022 (2011) [arXiv:1006.1650 [hep-ph]].

[5] D. Zeppenfeld, R. Kinnunen, A. Nikitenko and E. Richter-Was, "Measuring Higgs boson couplings at the LHC," Phys. Rev. D **62**, 013009 (2000) [hep-ph/0002036]; D. Zeppenfeld, "Higgs couplings at the LHC," eConf C **010630**, P123 (2001) [hep-ph/0203123].

[6] M. Duhrssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein and D. Zeppenfeld, "Determination of Higgs-boson couplings at the LHC," hep-ph/0407190.

[7] D. Carmi, A. Falkowski, E. Kuflik and T. Volansky, "Interpreting LHC Higgs Results from Natural New Physics Perspective," JHEP **1207**, 136 (2012) [arXiv:1202.3144]; A. Azatov, R. Contino and J. Galloway, "Model-Independent Bounds on a Light Higgs," JHEP **1204**, 127 (2012) [arXiv:1202.3415 [hep-ph]];
M. Klute, R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, "Measuring Higgs Couplings from LHC Data," Phys. Rev. Lett. **109**, 101801 (2012) [arXiv:1205.2699 [hep-ph]];
F. Bonnet, T. Ota, M. Rauch and W. Winter, "Interpretation of precision tests in the Higgs sector in terms of physics beyond the Standard Model," arXiv:1207.4599.

[8] M. E. Peskin, "Comparison of LHC and ILC Capabilities for Higgs Boson Coupling Measurements," arXiv:1207.2516 [hep-ph].

[9] D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, "Higgs After the Discovery: A Status Report," arXiv:1207.1718 [hep-ph].

[10] C. Englert, M. Spannowsky and C. Wymant, "Partially (in)visible Higgs decays at the LHC," arXiv:1209.0494 [hep-ph].

[11] R. Lafaye, T. Plehn, M. Rauch, D. Zerwas and M. Duhrssen, "Measuring the Higgs Sector," JHEP **0908**, 009 (2009) [arXiv:0904.3866 [hep-ph]];
V. Barger, M. Ishida and W. -Y. Keung, "Total Width of 125 GeV Higgs," arXiv:1203.3456 [hep-ph];
P. P. Giardino, K. Kannike, M. Raidal and A. Strumia, "Is the resonance at 125 GeV the Higgs boson?," arXiv:1207.1347; "Reconstructing Higgs boson properties from the LHC and Tevatron data," JHEP **1206**, 117 (2012) [arXiv:1203.4254 [hep-ph]];
J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, "First Glimpses at Higgs' face," arXiv:1207.1717 [hep-ph]; "Probing for Invisible Higgs Decays with Global Fits," arXiv:1205.6790 [hep-ph].

[12] S. Banerjee, S. Mukhopadhyay and B. Mukhopadhyaya, "New Higgs interactions and recent data from the LHC and the Tevatron," arXiv:1207.3588 [hep-ph].

[13] LHC Higgs Cross Section Working Group, A. David, A. Denner, M. Duehrssen, M. Grazzini, C. Grojean, G. Passarino and M. Schumacher *et al.*, "LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle," arXiv:1209.0040 [hep-ph].

[14] H. Georgi and M. Machacek, "Doubly Charged Higgs Bosons," Nucl. Phys. B **262**, 463 (1985).

[15] H. E. Logan and M. -A. Roy, "Higgs couplings in a model with triplets," Phys. Rev. D **82**, 115011 (2010) [arXiv:1008.4869 [hep-ph]].

[16] I. Low and J. Lykken, "Revealing the electroweak properties of a new scalar resonance," JHEP **1010**, 053 (2010) [arXiv:1005.0872 [hep-ph]];
S. Chang, C. A. Newby, N. Raj and C. Wanotayaroj, "Revisiting Theories with Enhanced Higgs Couplings to Weak Gauge Bosons," arXiv:1207.0493 [hep-ph];

I. Low, J. Lykken and G. Shaughnessy, "Have We Observed the Higgs (Imposter)?," arXiv:1207.1093 [hep-ph].

[17] A. Falkowski, S. Rychkov and A. Urbano, "What if the Higgs couplings to W and Z bosons are larger than in the Standard Model?," arXiv:1202.1532 [hep-ph].

[18] [CDF and D0 Collaborations], "Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson searches at the Tevatron," Phys. Rev. Lett. **109**, 071804 (2012) [arXiv:1207.6436 [hep-ex]].

[19] G. Pocsik and G. Zsigmond, "Decays Of Heavy Higgs Bosons Into Vector Bosons," Phys. Lett. B **112**, 157 (1982).

[20] H. E. Haber and H. E. Logan, "Radiative corrections to the Z b anti-b vertex and constraints on extended Higgs sectors," Phys. Rev. D **62**, 015011 (2000) [hep-ph/9909335].

[21] C. -W. Chiang, T. Nomura and K. Tsumura, "Search for doubly charged Higgs bosons using the same-sign diboson mode at the LHC," arXiv:1202.2014 [hep-ph].

[22] Y. Bai, J. Fan and J. L. Hewett, "Hiding a Heavy Higgs Boson at the 7 TeV LHC," JHEP **1208**, 014 (2012) [arXiv:1112.1964 [hep-ph]];
B. A. Dobrescu, G. D. Kribs and A. Martin, "Higgs Underproduction at the LHC," Phys. Rev. D **85**, 074031 (2012) [arXiv:1112.2208 [hep-ph]];
B. Batell, S. Gori and L. -T. Wang, "Exploring the Higgs Portal with 10/fb at the LHC," JHEP **1206**, 172 (2012) [arXiv:1112.5180 [hep-ph]];
K. Kumar, R. Vega-Morales and F. Yu, "Effects from New Colored States and the Higgs Portal on Gluon Fusion and Higgs Decays," arXiv:1205.4244 [hep-ph].

[23] T. Han, G. Valencia and S. Willenbrock, "Structure function approach to vector boson scattering in p p collisions," Phys. Rev. Lett. **69**, 3274 (1992) [hep-ph/9206246].

[24] Tevatron New Physics Higgs Working Group and CDF and D0 Collaborations, "Updated combination of CDF and D0 searches for Standard Model Higgs boson production with up to 10.0 fb^{-1} of data," arXiv:1207.0449 [hep-ex].

[25] CMS Collaboration, "Observation of a resonance with a mass near 125 GeV in the search for the Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV and 8 TeV", note CMS-HIG-12-020, July 2012; we extract the signal strength for different channels from

Figure 10, right panel. Due to the poor mass resolution of the WW^*, $b\bar{b}$ and $\tau^+\tau^-$ channels, the combination with the ATLAS data for $M_h = 126$ GeV should be rather insensitive to the mass difference.

[26] ATLAS Collaboration, "Observation of an excess of events in the search for the Standard Model Higgs boson in the $H \to ZZ^* \to 4\ell$ channel", note ATLAS-CONF-2012-092, July 2012; we extract the signal strength from Figure 16a for $M_h = 125$ GeV.

[27] ATLAS Collaboration, "Observation of an excess of events in the search for the Standard Model Higgs boson in the $\gamma\gamma$ channel", note ATLAS-CONF-2012-091, July 2012; we extract the signal strength from Figure 14c, which assumes $M_h = 126.5$ GeV. The combination with the CMS data for $M_h = 125$ GeV is warranted under the assumption that the $\gamma\gamma$ mass peaks will migrate toward each other.

[28] R. Barlow, "Asymmetric statistical errors", arXiv:physics/0406120 [physics.data-an]; `http://www.slac.stanford.edu/~barlow/java/statistics5.html`.

[29] G. J. Feldman and R. D. Cousins, "A unified approach to the classical statistical analysis of small signals," Phys. Rev. D **57**, 3873 (1998) [physics/9711021 [physics.data-an]].