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# Constraining anomalous Higgs interactions

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The recently announced Higgs discovery marks the dawn of the direct probing of the electroweak symmetry breaking sector. Sorting out the dynamics responsible for electroweak symmetry breaking now requires probing the Higgs interactions and searching for additional states connected to this sector. In this work we analyze the constraints on Higgs couplings to the standard model gauge bosons using the available data from Tevatron and LHC. We work in a model-independent framework expressing the departure of the Higgs couplings to gauge bosons by dimension-six operators. This allows for independent modifications of its couplings to gluons, photons and weak gauge bosons while still preserving the Standard Model (SM) gauge invariance. Our results indicate that best overall agreement with data is obtained if the cross section of Higgs production via gluon fusion is suppressed with respect to its SM value and the Higgs branching ratio into two photons is enhanced, while keeping the production and decays associated to couplings to weak gauge bosons close to their SM prediction.

## I. INTRODUCTION

The electroweak symmetry breaking (EWSB) mechanism has been elusive for many decades. However the recently announced discovery of a 125 GeV Higgs boson [1–6] at the CERN Large Hadron Collider (LHC) [7, 8] opens a new era in particle physics. The pressing questions now are related to the properties of this new observed state, like its spin and couplings, in order to extend our knowledge of the EWSB sector. In this work we employ the data used for the Higgs discovery to constrain its couplings to gauge bosons.

Presently there are many possible EWSB scenarios ranging from the Higgs being elementary and weakly interacting [9], as in the Standard Model, to it being composite and related to a new strongly interacting sector [10, 11]. In this last case the precision electroweak measurements and flavor changing neutral currents lead to strong constraints. However, recent theoretical advances have made possible the construction of models in agreement with the experimental bounds [12]. The distinction between the different scenarios can be carried out by looking for further new states associated with the EWSB mechanism and/or by careful studies of the Higgs boson couplings.

In this work we assume that the observed Higgs boson is part of a  $SU(2)_L$  doublet and that possible additional states are heavy enough not to play a direct role in the low energy phenomenology. This assumption is realized in models where the Higgs boson is a pseudo-Goldstone boson of a larger broken global symmetry [13–19]. Under this assumption we consider the most general dimension-six effective Lagrangian invariant under linear  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  transformations to describe the interactions of the Higgs boson with the electroweak gauge bosons, as well as with

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the gluons [20, 21]. For the sake of simplicity we assume that the Higgs has the same interaction with fermions as in the SM, nevertheless this hypothesis still has to be tested further<sup>1</sup>. This scenario can be falsified by the discovery of new states or by the non-observation of its predictions to the triple electroweak-gauge-boson vertices.

The effective operators describing the Higgs anomalous interactions modify both the Higgs production mechanisms and its decay patterns, therefore we combine several channels to unravel the contribution of the different operators. In our analyses we use the most recent data from the Tevatron [22] and LHC at 7 TeV [23, 24] and at 8 TeV [7, 8, 25–27]. Anomalous interactions also enhance the Higgs decay into  $Z\gamma$  as well as its production in association with a photon. Nevertheless, the available statistics is not enough to make these channels visible.

This article is organized as follows. In Section II we introduce the dimension-six effective operators and the different scenarios studied in this work. Details of our analyses are presented in Section III and Section IV contains their results. Finally we discuss the main conclusions in Section V.

## II. HIGGS ANOMALOUS INTERACTIONS

In this work we assume that even if there is new physics associated with the electroweak symmetry breaking sector, the Higgs boson observed at LHC is still part of a  $SU(2)_L$  doublet, the SM gauge invariance holds and no additional light states, relevant to the Higgs observables, are present in the spectrum. Under these assumptions the new effects can be parametrized in a model independent way by extending the SM with the addition of higher dimension operators that are invariant under linear  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  transformations.

In this framework the first corrections to the Higgs couplings to gauge bosons are expressed as dimension-six operators that can be written as

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n \quad , \quad (1)$$

where the operators  $\mathcal{O}_n$  involve vector-boson and/or Higgs-boson fields with couplings  $f_n$  and where  $\Lambda$  is a characteristic scale. Requiring the operators  $\mathcal{O}_n$  to be  $P$  and  $C$  even, there are only seven dimension-six operators that modify the Higgs-boson couplings to electroweak vector bosons and one to gluons [20, 21]:

$$\begin{aligned} \mathcal{O}_{GG} &= \Phi^\dagger \Phi G_{\mu\nu}^a G^{a\mu\nu} \quad , & \mathcal{O}_{WW} &= \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad , & \mathcal{O}_{BB} &= \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \quad , \\ \mathcal{O}_{BW} &= \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad , & \mathcal{O}_W &= (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \quad , & \mathcal{O}_B &= (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi) \quad , \\ \mathcal{O}_{\Phi,1} &= (D_\mu \Phi)^\dagger \Phi^\dagger \Phi (D^\mu \Phi) \quad , & \mathcal{O}_{\Phi,2} &= \frac{1}{2} \partial^\mu (\Phi^\dagger \Phi) \partial_\mu (\Phi^\dagger \Phi) \quad , \end{aligned} \quad (2)$$

where  $\Phi$  stands for the Higgs doublet,  $D_\mu$  is the covariant derivative,  $\hat{B}_{\mu\nu} = i(g'/2)B_{\mu\nu}$  and  $\hat{W}_{\mu\nu} = i(g/2)\sigma^a W_{\mu\nu}^a$ , with  $B_{\mu\nu}$ ,  $W_{\mu\nu}^a$ , and  $G_{\mu\nu}^a$  being respectively the  $U(1)_Y$ ,  $SU(2)_L$  and  $SU(3)_c$  field strength tensors. We denote the  $SU(2)_L$  ( $U(1)_Y$ ) gauge coupling as  $g$  ( $g'$ ) and the Pauli matrices as  $\sigma^a$ .

The effective operators in Eq. (2) give rise to anomalous  $Hgg$ ,  $H\gamma\gamma$ ,  $HZ\gamma$ ,  $HZZ$ , and  $HW^+W^-$  couplings, which in the unitary gauge are given by

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{\text{HVV}} &= g_{Hgg} H G_{\mu\nu}^a G^{a\mu\nu} + g_{H\gamma\gamma} H A_{\mu\nu} A^{\mu\nu} + g_{HZ\gamma}^{(1)} A_{\mu\nu} Z^\mu \partial^\nu H + g_{HZ\gamma}^{(2)} H A_{\mu\nu} Z^{\mu\nu} \\ &+ g_{HZZ}^{(1)} Z_{\mu\nu} Z^\mu \partial^\nu H + g_{HZZ}^{(2)} H Z_{\mu\nu} Z^{\mu\nu} + g_{HZZ}^{(3)} H Z_\mu Z^\mu \\ &+ g_{HWW}^{(1)} (W_{\mu\nu}^+ W^{-\mu} \partial^\nu H + \text{h.c.}) + g_{HWW}^{(2)} H W_{\mu\nu}^+ W^{-\mu\nu} + g_{HWW}^{(3)} H W_\mu^+ W^{-\mu} \quad , \end{aligned} \quad (3)$$

where  $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$  with  $V = A, Z$  and  $W$ . The effective couplings  $g_{Hgg}$ ,  $g_{H\gamma\gamma}$ ,  $g_{HZ\gamma}^{(1,2)}$ ,  $g_{HWW}^{(1,2,3)}$  and  $g_{HZZ}^{(1,2,3)}$  are

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<sup>1</sup> The preliminary CMS [8] results indicate that the SM values for the Higgs couplings to fermions are within the 90–95% CL allowed region.

related to the coefficients of the operators appearing in (1) through,

$$\begin{aligned}
g_{Hgg} &= \frac{f_{GG}v}{\Lambda^2} \equiv -\frac{\alpha_s}{8\pi} \frac{f_g v}{\Lambda^2} , \\
g_{H\gamma\gamma} &= -\left(\frac{gM_W}{\Lambda^2}\right) \frac{s^2(f_{BB} + f_{WW} - f_{BW})}{2} , \\
g_{HZ\gamma}^{(1)} &= \left(\frac{gM_W}{\Lambda^2}\right) \frac{s(f_W - f_B)}{2c} , \\
g_{HZ\gamma}^{(2)} &= \left(\frac{gM_W}{\Lambda^2}\right) \frac{s[2s^2 f_{BB} - 2c^2 f_{WW} + (c^2 - s^2)f_{BW}]}{2c} , \\
g_{HZZ}^{(1)} &= \left(\frac{gM_W}{\Lambda^2}\right) \frac{c^2 f_W + s^2 f_B}{2c^2} , \\
g_{HZZ}^{(2)} &= -\left(\frac{gM_W}{\Lambda^2}\right) \frac{s^4 f_{BB} + c^4 f_{WW} + c^2 s^2 f_{BW}}{2c^2} , \\
g_{HZZ}^{(3)} &= \left(\frac{gM_W v^2}{\Lambda^2}\right) \frac{f_{\Phi,1} - f_{\Phi,2}}{4c^2} , \\
g_{HWW}^{(1)} &= \left(\frac{gM_W}{\Lambda^2}\right) \frac{f_W}{2} , \\
g_{HWW}^{(2)} &= -\left(\frac{gM_W}{\Lambda^2}\right) f_{WW} , \\
g_{HWW}^{(3)} &= -\left(\frac{gM_W v^2}{\Lambda^2}\right) \frac{f_{\Phi,1} + 2f_{\Phi,2}}{4} ,
\end{aligned} \tag{4}$$

where  $s$  and  $c$  stand for the sine and cosine of the weak mixing angle respectively. We notice that we have rescaled the coefficient  $f_{GG}$  of the gluon-gluon operator in terms of a coupling  $f_g$  also including a loop suppression factor. In this way an anomalous gluon-gluon coupling  $f_g \sim \mathcal{O}(1-10)$  gives a contribution comparable to the SM top loop. For the operators involving electroweak gauge bosons we have kept the normalization commonly used in the pre-LHC studies, for example, in Refs. [28–32]. The couplings  $g_{HZZ}^{(3)}$  and  $g_{HWW}^{(3)}$  include the effects arising from the contribution of the operators  $\mathcal{O}_{\Phi,1}$  and  $\mathcal{O}_{\Phi,2}$  to the renormalization of the weak boson masses and the Higgs field wave function.

For the sake of concreteness in this work we focus our attention on modifications of the Higgs couplings to gauge bosons associated with the five operators  $\mathcal{O}_{GG}$ ,  $\mathcal{O}_{BB}$ ,  $\mathcal{O}_{WW}$ ,  $\mathcal{O}_B$ , and  $\mathcal{O}_W$ . The operator  $\mathcal{O}_{BW}$  contributes at tree level to the  $W^3$ – $B$  mixing and is therefore very strongly constrained by the electroweak precision data [28, 29, 33, 34]. Similarly  $\mathcal{O}_{\Phi,1}$  contributes to the  $Z$  mass but not to the  $W$  mass and it is severely constrained by the  $\rho$  parameter. Moreover the operators  $\mathcal{O}_{\Phi,1}$  and  $\mathcal{O}_{\Phi,2}$  lead to a multiplicative contribution to the SM Higgs couplings to  $ZZ$  and  $WW$ . Thus in the present analysis we do not consider effects associated with  $\mathcal{O}_{BW}$ ,  $\mathcal{O}_{\Phi,1}$  and  $\mathcal{O}_{\Phi,2}$  as their coefficients are already very constrained or their possible effect on the measured Higgs observables is degenerated with that of the five operators considered. Their impact on the Higgs phenomenology can be seen in Refs. [8, 35–41].

Notice also that one expects the contribution of new physics to the five operators considered to take place at loop level [42]. Therefore, we expect that the largest effect of these effective interactions should appear in the couplings of the Higgs to photon–photon and gluon–gluon since these couplings take place through loop effects in the SM.

One important property of the operators  $\mathcal{O}_B$  and  $\mathcal{O}_W$  is that they also modify the triple gauge–boson couplings  $\gamma W^+ W^-$  and  $Z W^+ W^-$ . Consequently they can be directly probed in additional channels not directly involving the Higgs boson [31, 43, 44]. The triple gauge–boson effective interaction can be rewritten in the standard parametrization of the  $C$  and  $P$  even interactions [45]:

$$\mathcal{L}_{WWV} = -ig_{WWV} \left\{ g_1^V \left( W_{\mu\nu}^+ W^{-\mu} V^\nu - W_\mu^+ V_\nu W^{-\mu\nu} \right) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} W_{\mu\nu}^+ W^{-\nu\rho} V_\rho^\mu \right\} , \tag{5}$$

where  $g_{WW\gamma} = e$  and  $g_{WWZ} = e/(sc)$ . In general these vertices involve six dimensionless couplings  $g_1^V$ ,  $\kappa_V$ , and  $\lambda_V$  ( $V = \gamma$  or  $Z$ ). Notwithstanding the electromagnetic gauge invariance requires that  $g_1^\gamma = 1$ , while the remaining five

free couplings are related to the dimension–six operators that we are considering:

$$\begin{aligned}
\Delta g_1^Z &= g_1^Z - 1 = \frac{1}{2} \frac{m_Z^2}{\Lambda^2} f_W \ , \\
\Delta \kappa_\gamma &= \kappa_\gamma - 1 = \frac{1}{2} \frac{m_W^2}{\Lambda^2} (f_W + f_B) \ , \\
\Delta \kappa_Z &= \kappa_Z - 1 = \frac{1}{2} \frac{m_Z^2}{\Lambda^2} (c^2 f_W - s^2 f_B) \ , \\
\lambda_\gamma &= \lambda_Z = 0 \ .
\end{aligned} \tag{6}$$

In summary, in the theoretical framework that we are using the observables depend upon 5 parameters,  $f_g$ ,  $f_B$ ,  $f_W$ ,  $f_{BB}$  and  $f_{WW}$ . In what follows for the sake of simplicity we focus on two different scenarios:

- **Scenario I:** we impose that  $f_W = f_B$  and  $f_{BB} = f_{WW}$ . This scenario has three free parameters ( $f_W$ ,  $f_{WW}$  and  $f_g$ ) and it exhibits a constraint between the three couplings of the Higgs to electroweak vector bosons. This scenario predicts the existence of anomalous triple electroweak gauge–boson interactions.
- **Scenario II:** we set  $f_W = f_B = 0$  and  $f_{WW} = f_{BB}$ . This scenario has two free parameters ( $f_g$  and  $f_{BB} = f_{WW}$ ) and it can be considered the low–energy limit of an extension of the SM that contains an extra heavy scalar multiplet; for details see Ref. [34]. Moreover, this scenario cannot be constrained by data on triple gauge–boson couplings.

The above relations (6) allow us to constrain the couplings  $f_B$  and  $f_W$  using the available experimental bounds on the effective couplings  $\Delta g_1^Z$ ,  $\Delta \kappa_\gamma$  and  $\Delta \kappa_Z$  [46]. Nevertheless these experimental bounds are usually obtained assuming only one anomalous operator different from the SM value at a time, an assumption which is not consistent with our scenario I. For this reason strictly speaking one cannot apply the exclusion limits in Ref. [46] to this scenario. Nevertheless if we assume no strong cancellations between the contributions of the different triple gauge–effective operators we can estimate the size of the exclusion limits on  $f_W$  and  $f_B$ . Using the 95% CL regions from Ref. [46] on  $\Delta g_1^Z$ ,  $\Delta \kappa_\gamma$  or  $\Delta \kappa_Z$  we obtain that in scenario I the 95% CL regions on  $f_W = f_B$  are  $[-13, 7]$  TeV<sup>−2</sup>,  $[-18, 9]$  TeV<sup>−2</sup>, and  $[-85, 20]$  TeV<sup>−2</sup> respectively. Notice also that, LHC already with present runs has potential to constraint the triple-gauge boson vertices [47] and the collaborations are starting to look for deviations [43, 44]. However, at present, their individual limits have not reached the level of the LEP bounds yet.

### III. ANALYSES FRAMEWORK

In order to obtain the present constraints on the Higgs anomalous interactions we perform a chi–square test using the available data on the signal strength ( $\mu$ ) from Tevatron, LHC at 7 TeV and LHC at 8 TeV. We assume that the correlations between the different channels are negligible except for the theoretical uncertainties which are treated with the pull method [48, 49] in order to account for their correlations.

Schematically we can write

$$\chi^2 = \min_{\xi_{pull}} \sum_j \frac{(\mu_j - \mu_j^{\text{exp}})^2}{\sigma_j^2} + \sum_{pull} \left( \frac{\xi_{pull}}{\sigma_{pull}} \right)^2 \tag{7}$$

where  $j$  stands for channels presented in Tables I and II. We denote the theoretically expected signal as  $\mu_j$ , the observed best fit values as  $\mu_j^{\text{exp}}$  and errors as  $\sigma_j^{+,-}$ . As we can see from these tables the errors are not symmetric, showing a deviation from a Gaussian behavior as expected from the still low statistics. In our calculations we make the errors in each channel symmetric by taking

$$\sigma_j = \sqrt{\frac{(\sigma_j^+)^2 + (\sigma_j^-)^2}{2}} \ . \tag{8}$$

Concerning the theoretical uncertainties, the largest are associated with the gluon fusion subprocess and to account for these errors we introduce two pull factors, one for the Tevatron ( $\xi_T$ ) and one for the LHC at 7 TeV and LHC at 8 TeV ( $\xi_L$ ). They modify the corresponding predictions as shown in Eqs. (12) and (13). We consider that the errors associated with the pulls are  $\sigma_T = 0.4$  and  $\sigma_L = 0.15$ . As statistics build up it will be necessary to introduce pulls associated with the theoretical uncertainties for the other production mechanisms as well as possible systematic correlated errors, however at this moment these are sub–leading effects.

Channel	$\mu^{exp}$	Comment
$p\bar{p} \rightarrow W^+W^-$	$0.3^{+1.1}_{-0.3}$	CDF & DØ [22]
$p\bar{p} \rightarrow b\bar{b}$	$2.0^{+0.7}_{-0.7}$	CDF & DØ [22]
$p\bar{p} \rightarrow \gamma\gamma$	$3.6^{+3.0}_{-2.5}$	CDF & DØ [22]
$pp \rightarrow \tau\bar{\tau}$	$0.2^{+1.7}_{-1.9}$	ATLAS [23]
$pp \rightarrow b\bar{b}$	$0.5^{+2.1}_{-2.0}$	ATLAS [23]
$pp \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$	$1.4^{+1.3}_{-0.8}$	ATLAS [23]
$pp \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu}$	$0.5^{+0.6}_{-0.6}$	ATLAS [23]
$pp \rightarrow \gamma\gamma$	$2.2^{+0.8}_{-0.8}$	ATLAS [27]
$pp \rightarrow \tau\bar{\tau}$	$0.6^{+1.1}_{-1.2}$	CMS [24]
$pp \rightarrow b\bar{b}$	$0.5^{+1.1}_{-1.0}$	CMS [26]
$pp \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$	$0.6^{+0.9}_{-0.6}$	CMS [24]
$pp \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu}$	$0.4^{+0.6}_{-0.6}$	CMS [24]
$pp \rightarrow \gamma\gamma$ Untagged 0	$3.2^{+1.9}_{-1.8}$	CMS [25]
$pp \rightarrow \gamma\gamma$ Untagged 1	$0.7^{+0.9}_{-1.0}$	CMS [25]
$pp \rightarrow \gamma\gamma$ Untagged 2	$0.7^{+1.2}_{-1.1}$	CMS [25]
$pp \rightarrow \gamma\gamma$ Untagged 3	$1.5^{+1.6}_{-1.6}$	CMS [25]
$pp \rightarrow \gamma\gamma jj$	$4.2^{+2.0}_{-2.0}$	CMS [25]

Table I: Processes considered in our analyses for the LHC 7 TeV run and for the Tevatron. We present the errors and best fit point for the signal strength for each topology.

Channel	$\mu^{exp}$	Comment
$pp \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$	$1.3^{+0.6}_{-0.6}$	ATLAS @ 7 and 8 TeV [7]
$pp \rightarrow \gamma\gamma$	$1.8^{+0.6}_{-0.7}$	ATLAS [27]
$pp \rightarrow \tau\bar{\tau}$	$-0.2^{+0.8}_{-0.7}$	CMS @ 7 and 8 TeV [8]
$pp \rightarrow b\bar{b}$	$0.4^{+0.9}_{-0.8}$	CMS [26]
$pp \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$	$0.7^{+0.6}_{-0.4}$	CMS [26]
$pp \rightarrow WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu}$	$0.6^{+0.4}_{-0.4}$	CMS @ 7 and 8 TeV [8]
$pp \rightarrow \gamma\gamma$ Untagged 0	$1.5^{+1.2}_{-1.2}$	CMS [25]
$pp \rightarrow \gamma\gamma$ Untagged 1	$1.5^{+1.0}_{-1.0}$	CMS [25]
$pp \rightarrow \gamma\gamma$ Untagged 2	$1.0^{+1.1}_{-1.2}$	CMS [25]
$pp \rightarrow \gamma\gamma$ Untagged 3	$3.8^{+1.7}_{-1.8}$	CMS [25]
$pp \rightarrow \gamma\gamma jj$ loose	$-0.6^{+2.1}_{-2.0}$	CMS [25]
$pp \rightarrow \gamma\gamma jj$ tight	$1.3^{+1.5}_{-1.6}$	CMS [25]

Table II: Available data including the 8 TeV run. We present the errors and best fit point for the signal strength for each channel. The data that have been combined is indicated as “@ 7 and 8 TeV”.

One important approximation in our analyses is that we neglect the effects associated with the distortions of the kinematical distributions of the final states due to the Higgs anomalous couplings arising from their non SM-like Lorentz structure. Thus we implicitly assume that the anomalous contributions have the same detection efficiencies as the SM Higgs. A full simulation of the Higgs anomalous operators taking advantage of their special kinematical features would increase the current sensitivity on the anomalous couplings. It would also allow for breaking degeneracies with those operators which only lead to an overall modification of strength of the SM vertices. But at present there is not enough public information to perform such analysis outside of the experimental collaborations.

In order to predict the modification of the observables we need to include the effect of the anomalous operators in the production channels as well as in the decay branching ratios. At this time, the evaluation of all cross sections containing anomalous Higgs couplings is not available in the literature, therefore we assumed, as a first approximation,

Channel	$\epsilon_{gg}$	$\epsilon_{VBF}$	$\epsilon_{VH}$	$\epsilon_{t\bar{t}H}$
$pp \rightarrow \gamma\gamma$ Untagged 0	0.13	0.46	0.70	1
$pp \rightarrow \gamma\gamma$ Untagged 1	0.57	0.49	0.67	1
$pp \rightarrow \gamma\gamma$ Untagged 2	1	0.56	0.76	0
$pp \rightarrow \gamma\gamma$ Untagged 3	1	0.56	0.76	0
$pp \rightarrow \gamma\gamma jj$	0.029	1	0.019	0

Table III: Weight of each production mechanism for the different  $\gamma\gamma$  categories in the CMS analyses of the 7 TeV data.

that the  $K$  factor associated with higher order corrections is the same for the SM and anomalous contributions<sup>2</sup>. We write

$$\sigma_Y^{ano} = \frac{\sigma_Y^{ano}}{\sigma_Y^{SM}} \Big|_{tree} \sigma_Y^{SM} \Big|_{soa} \quad (9)$$

where the ratio of the anomalous and SM cross sections of the subprocess  $Y$  ( $= gg, VBF, VH$  or  $t\bar{t}H$ ) is evaluated at tree level and it is multiplied by the value for the state-of-the-art SM cross section calculations ( $\sigma_Y^{SM}|_{soa}$ ) presented in Ref. [50]. Analogously we write the decay width into the final state  $X$  as

$$\Gamma^{ano}(h \rightarrow X) = \frac{\Gamma^{ano}(h \rightarrow X)}{\Gamma^{SM}(h \rightarrow X)} \Big|_{tree} \Gamma^{SM}(h \rightarrow X) \Big|_{soa} \quad (10)$$

where the SM result  $\Gamma^{SM}(h \rightarrow X)|_{soa}$  is also obtained from Ref. [50]. The total width and branching ratios are evaluated following this recipe. We use the SM cross sections and decay widths and compute our predictions for  $m_H = 125$  GeV. The observed Higgs mass by ATLAS (126.5 GeV) [7] and CMS (125.3 GeV) [8] are compatible within the experimental errors. We verified that the impact of changing the Higgs mass to 126.5 GeV is a sub-leading effect and does not alter our results. We did not include in our analyses an eventual invisible decay of the Higgs [51, 52], therefore the total width is obtained by summing over the decays into the SM particles.

The search for Higgs decaying into  $b\bar{b}$  pairs takes place through Higgs production in association with a  $W$  or a  $Z$  so we can write

$$\mu_{b\bar{b}} = \frac{\sigma_{WH}^{ano} + \sigma_{ZH}^{ano}}{\sigma_{WH}^{SM} + \sigma_{ZH}^{SM}} \otimes \frac{\text{Br}^{ano}[h \rightarrow b\bar{b}]}{\text{Br}^{SM}[h \rightarrow b\bar{b}]} \quad (11)$$

with the superscripts  $ano$  ( $SM$ ) standing for the value of the observable considering the anomalous and SM interactions (pure SM contributions).

The CMS analyses of the 7 (8) TeV data separate the  $\gamma\gamma$  final into 5 (6) categories and the contribution of each production mechanism to a given category is presented in Table 2 of Ref. [25]. Therefore, we write the theoretical signal strength in these cases as

$$\mu_{\gamma\gamma}^{CMS} = \frac{\epsilon_{gg}\sigma_{gg}^{ano}(1 + \xi_g) + \epsilon_{VBF}\sigma_{VBF}^{ano} + \epsilon_{VH}(\sigma_{WH}^{ano} + \sigma_{ZH}^{ano}) + \epsilon_{t\bar{t}H}\sigma_{t\bar{t}H}^{ano}}{\epsilon_{gg}\sigma_{gg}^{SM} + \epsilon_{VBF}\sigma_{VBF}^{SM} + \epsilon_{VH}(\sigma_{WH}^{SM} + \sigma_{ZH}^{SM}) + \epsilon_{t\bar{t}H}\sigma_{t\bar{t}H}^{SM}} \otimes \frac{\text{Br}^{ano}[h \rightarrow \gamma\gamma]}{\text{Br}^{SM}[h \rightarrow \gamma\gamma]}, \quad (12)$$

where  $\xi_g$  is the pull associated with the gluon fusion cross section uncertainties, and the branching ratio and the anomalous cross sections are evaluated using the prescriptions (9) and (10). The weight of the different channels to each category is encoded in the parameters  $\epsilon_X$  with  $X = VBF, gg, VH$ , and  $t\bar{t}H$  and they are presented in Tables III and IV.

With the exception of the above processes, all other channels are treated as inclusive, so we write the expected signal strength of the final state  $F$  as

$$\mu_F = \frac{\sigma_{gg}^{ano}(1 + \xi_g) + \sigma_{VBF}^{ano} + \sigma_{WH}^{ano} + \sigma_{ZH}^{ano} + \sigma_{t\bar{t}H}^{ano}}{\sigma_{gg}^{SM} + \sigma_{VBF}^{SM} + \sigma_{WH}^{SM} + \sigma_{ZH}^{SM} + \sigma_{t\bar{t}H}^{SM}} \otimes \frac{\text{Br}^{ano}[h \rightarrow F]}{\text{Br}^{SM}[h \rightarrow F]}. \quad (13)$$

<sup>2</sup> With the present statistics, our results are not sensitive to the theory pulls (see below) indicating that this approximation is reasonable for the time being.

Channel	$\epsilon_{gg}$	$\epsilon_{VBF}$	$\epsilon_{VH}$	$\epsilon_{t\bar{t}H}$
$pp \rightarrow \gamma\gamma$ Untagged 0	0.11	0.25	0.48	1
$pp \rightarrow \gamma\gamma$ Untagged 1	0.59	0.50	0.72	1
$pp \rightarrow \gamma\gamma$ Untagged 2	1	0.54	0.58	0
$pp \rightarrow \gamma\gamma$ Untagged 3	1	0.54	0.78	0
$pp \rightarrow \gamma\gamma jj$ loose	0.094	1	0.064	0
$pp \rightarrow \gamma\gamma jj$ tight	0.024	1	0	0

Table IV: Same as Table III but for the 8 TeV CMS data.

Here we also use Eqs. (9) and (10) to obtain the anomalous cross sections and branching ratios.

For some final states the available LHC 8 TeV data has been presented combined with the 7 TeV results. Given the limited available information on errors and correlations, we construct the expected theoretical signal strength as an average of the expected signal strengths for the center-of-mass energies of 7 and 8 TeV. We weight the contributions by the total number of events expected at each energy in the framework of the SM, *i.e.* given a final state  $X$  we evaluate

$$\mu_X^{comb} = \frac{\mu_X^{7\text{TeV}} \sigma_X^{SM,7\text{TeV}} \mathcal{L}_{7\text{TeV}} + \mu_X^{8\text{TeV}} \sigma_X^{SM,8\text{TeV}} \mathcal{L}_{8\text{TeV}}}{\sigma_X^{SM,7\text{TeV}} \mathcal{L}_{7\text{TeV}} + \sigma_X^{SM,8\text{TeV}} \mathcal{L}_{8\text{TeV}}}, \quad (14)$$

where  $\mathcal{L}_{7(8)\text{TeV}}$  stands for the integrated luminosity at 7 (8) TeV accumulated in the channel being analyzed. When considering the full available data set we consider all the processes in Table I and II, neglecting the LHC 7 TeV processes whose data has been combined with the 8 TeV run; we indicate in Table II that the data has been combined by “@ 7 and 8 TeV”.

The evaluation of the relevant tree level cross sections was done using the package MadGraph5 [53] with the anomalous Higgs interactions introduced using FeynRules [54]. We also cross checked our results using COMPHEP [55, 56] and VBFNLO [57]. The evaluation of the partial width was done using the expressions presented in Ref. [32].

#### IV. CONSTRAINTS ON THE HIGGS ANOMALOUS INTERACTIONS

We next derive the allowed values of the Higgs interactions to vector bosons using the available Tevatron data [22], ATLAS 7 TeV [23, 27] and 8 TeV [7, 27] results, and CMS 7 TeV [24–26] and 8 TeV [8, 25, 26] data. The results are presented in Fig. 1–Fig. 5 where several one-dimensional and two-dimensional projections of the  $\Delta\chi^2 = \chi^2 - \chi_{min}^2$  function(s) are shown. We find  $\chi_{min}^2 = 12.12$  (12.13) in scenario I (II) for the global analysis (*i.e.* for a total number of 26 data points). The SM lays at  $\chi_{SM}^2 = 20.87$  *i.e.* within the 96.7% (98.7%) CL region in the three- (two-)dimensional parameter space. The corresponding best fit values and 95% allowed ranges are summarized in Table V.

Figure 1 shows  $\Delta\chi^2$  as a function of each of the operator coefficients in scenario I after marginalizing with respect to the two undisplayed ones. To illustrate the effect of the different data sets, the results are shown for three combinations of the available data: the dotted (dashed) line stands for the results obtained using only the LHC 7 TeV (LHC 7 TeV and Tevatron) data while the solid line is derived using the full available data set. The central panel of this figure displays the  $\Delta\chi^2$  dependence on  $f_W$ . As we can see the analysis of the LHC 7 TeV data only leads to a large flat region around the minimum indicating that this data set has a small sensitivity to  $f_W$ , *i.e.* the Higgs couplings to  $W$  and  $Z$  pairs. This is expected since the  $\gamma\gamma$  channel is the dominant observable in this sample. The addition of the Tevatron data, dominated by the Higgs associated production, enhances the sensitivity to deviations in  $HZZ$  and  $HW^+W^-$ , that is, to smaller values of  $f_W$ . The addition of the LHC 8 TeV results further tightens the allowed values giving, for the global analysis, the constraint  $-13 \leq f_W \leq 20$  at 95% CL.

$\Delta\chi^2$  as a function of  $f_g$  is shown in the left panel of Figure 1 where we see that the analysis present two totally degenerate minima leading to two distinct allowed ranges. This degeneracy – as others that we encounter in this work – is due to the interference between the SM and anomalous contributions. We see that before the inclusion of LHC 8 TeV data, the two allowed ranges overlapped at CL higher than 90 %, while in the global analysis they are separated at more than  $3\sigma$ . The value of the gluon fusion cross section at the minima is around 43% of its SM value (see left panel of Fig. 4) and this cross section is highly suppressed in the region between the minima. This highly suppressed gluon fusion cross section was not completely disfavored before the 8 TeV data because the CDF & DØ and CMS @ 7 TeV  $b\bar{b}$  channels still allowed for a larger  $f_W$  coupling to enhance associated production, compensating the large reduction of the gluon fusion cross section (see also discussion of Fig. 3). After the inclusion of the LHC 8 TeV data



this is no longer possible. So altogether the global analysis constrains  $f_g$  to lie in one of the two intervals  $[-0.3, 7.3]$  or  $[15, 23]$  at 95% CL.

The  $\Delta\chi^2$  dependence on  $f_{WW}$  in the scenario I is presented in the right panel of Fig. 1. A salient feature of this plot is that  $\Delta\chi^2$  is concentrated around two narrow non-overlapping regions centered around almost (but not totally) degenerate minima. Unlike for  $f_g$ , the two minima in  $f_{WW} = f_{BB}$  are not fully degenerated because these operators modify not only the Higgs coupling to photons but also to  $WW$  and  $ZZ$  and the contributions to these last two vertices are slightly different at the two minima. Moreover, we also see that Tevatron data has a limited impact on this parameter while the inclusion of the LHC 8 TeV results tighten the bounds on  $f_{WW}$  which at 95% CL is bounded to lie in one of the two intervals  $[-0.8, -0.1]$  or  $[1.5, 2.2]$ .

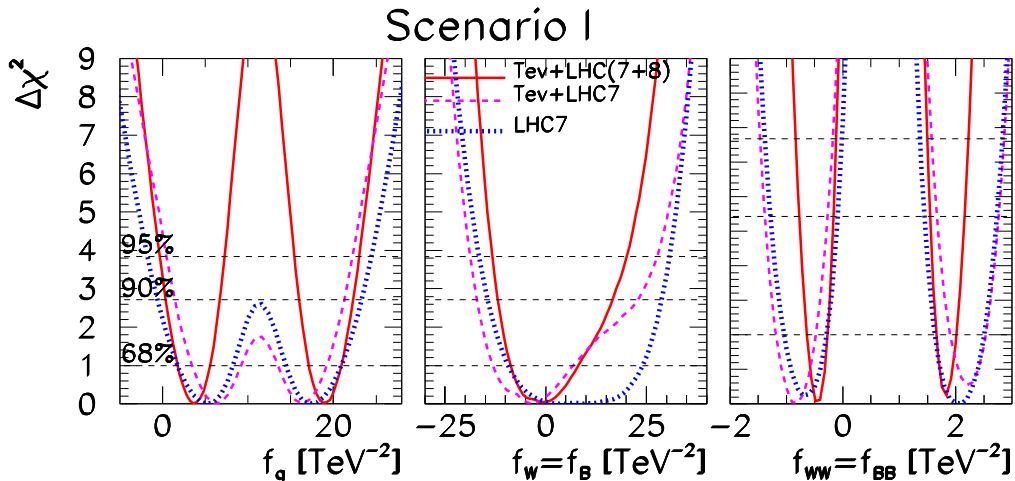


Figure 1: The left (central, right) panel exhibits  $\Delta\chi^2$  as a function of  $f_g$  ( $f_W$ ,  $f_{WW}$ ) in the framework of scenario I. Each panel contains three lines: the dotted (dashed) line was obtained using only the LHC 7 TeV (LHC 7 TeV and Tevatron) data while the solid line stands for the result using all the available data. In each panel  $\Delta\chi^2$  is marginalized over the two undisplayed parameters.

The dependence on the scenario considered is illustrated in Figure 2 where we plot the  $\Delta\chi^2$  dependence on  $f_g$  and  $f_{WW}$  of the global analysis in scenarios I and II. As we can see the results for both scenarios are almost coincident in both panels. This is due to the fact that in scenario I the full available data set is well described by  $f_W = f_B \simeq 0$  for all allowed values of  $f_{WW}$  and  $f_g$ , consequently the two scenarios give very similar results.

Let us turn our attention towards the correlations between the three free parameters of scenario I. Figure 3 depicts 68%, 90%, 95%, and 99% CL (2dof) allowed regions of the  $f_{WW} \otimes f_g$  (upper right panel),  $f_W \otimes f_g$  (upper left panel) and  $f_W \otimes f_{WW}$  (lower panel) planes using all attainable data. We obtained these plots marginalizing over the free parameter not appearing in each of the panels.

We can see from the upper right panel of Fig. 3 that there are four well isolated allowed “islands” in the  $f_{WW} \otimes f_g$  plane. Moreover, within each of these islands  $f_{WW}$  and  $f_g$  are strongly correlated or anti-correlated. As mentioned before, the existence of degenerate islands is due to the interference between the SM and anomalous contributions which allow two different values of the anomalous couplings to lead to the same cross section or branching ratio. In the case at hand, the gluon fusion cross section preferred by the fit is around 43% of its SM value. It is interesting to notice that if the results from the  $b\bar{b}$  channel are removed from the fit the vertical gap between the two islands on the left (or on the right) disappears – that is, intermediate values of  $f_g$  (which correspond to further suppressed gluon fusion production) become allowed. This happens because the  $b\bar{b}$  data, which is dominated by associated production, constrains the coupling of the Higgs to  $W$  and  $Z$  pairs. In our framework, this leads to (a) an associated upper bound on the  $H\gamma\gamma$  branching ratio, and (b) an upper bound on VBF and associated production.  $\gamma\gamma$  data mainly restricts the product of the gluon fusion cross section and the Higgs branching ratio into photons, thus weakening the upper bound on the latter allows the former to have smaller values. Furthermore even smaller gluon fusion cross sections are permitted because of the possible increase in the VBF and associated production processes.

The upper left panel of Figure 3 shows the presence of two isolated regions in the  $f_W \otimes f_g$  plane and that there is a very weak correlation between the parameters within each region. Here again, the removal of the  $b\bar{b}$  data leads

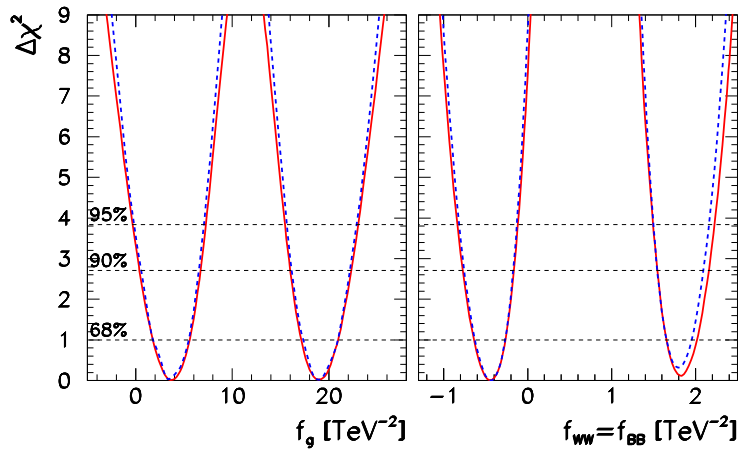


Figure 2:  $\Delta\chi^2$  as a function of  $f_g$  (left panel) and  $f_{WW} = f_{BB}$  (right panel) for the full combined analysis. The solid lines correspond to scenario I in which  $\Delta\chi^2$  is marginalized over the two undisplayed parameters in each panel:  $f_{WW} = f_{BB}$  and  $f_W = f_B$  in the left panel, and  $f_g$  and  $f_W = f_B$  in the right panel. The dashed lines correspond to scenario II, *i.e.* imposing first the prior  $f_W = f_B = 0$  and then marginalizing over  $f_{WW} = f_{BB}$  (left) and  $f_g$  (right).

to the disappearance of the gap between the allowed regions. The lower panel displays a behavior similar to the one observed in the upper left, but in the  $f_W \otimes f_{WW}$  plane.

For the sake of completeness we also show the results of the global analysis in scenario I in terms of the allowed ranges of Higgs production cross sections and decay branching ratios in Fig. 4 and Fig. 5. The results shown in these figures are obtained by projecting the three-dimensional  $\Delta\chi^2$  function on the displayed observables and marginalizing on the independent undisplayed combination(s).

Finally we also verified that the results do not change significantly when we do not employ the pulls to perform the fit. This behavior could be anticipated since the experimental errors are still much larger than the errors described by the pulls; a situation that will change as more statistics accumulate.

## V. DISCUSSION

Once a Higgs boson like state has been discovered we must study its properties to establish if it is indeed the state predicted by the SM. In addition to that, it is also important to look for additional states that might play a role in the electroweak symmetry breaking. In this article we have studied the Higgs couplings to gauge bosons using a model-independent characterization of the deviations with respect to the SM values in terms of dimension-six operators and the available data from Tevatron and LHC at 7 TeV and 8 TeV. This approach still assumes that the Higgs field is a doublet of the  $SU(2)_L$  symmetry and that the deviations of its couplings from the SM values are due to additional heavy states. Notwithstanding, our framework allows for independent modifications of the couplings to gluons, photons and weak gauge bosons.

In this study we have demonstrated that the present available data is enough to start gaining some information on the different Higgs couplings to gauge bosons. For instance, our analyses indicate that a reduced gluon fusion cross section is preferred when we use the full available data set, with the most favored value being 43% of the SM value. We can see this preference for a reduced gluon fusion cross section in the right panel of Figure 4 while the VBF and associated production cross sections are in agreement with the SM prediction. From this panel we can extract that the 95% CL allowed region of the gluon fusion cross section is  $[0.1, 1.1]$  times the corresponding SM value. This is consistent with the CMS analyses [8] which, using a different framework, also points in this direction as a reduced coupling of the Higgs to top quarks is preferred by their results.

Taking into account that the presently measured  $\gamma\gamma$  yield is above the SM prediction, the diminished gluon fusion cross section points to an enhanced Higgs branching ratio in  $\gamma\gamma$ ; a fact that can be observed in our analyses. The left panel of Figure 4 shows that the  $\gamma\gamma$  branching ratio is indeed augmented, with a best fit value of 2.9 times the SM value and the 95% CL allowed region being  $[1.4, 5.4]$  times the SM branching ratio. Furthermore, we can see from this panel that the Higgs branching ratio into  $W^+W^-$  and  $ZZ$  is in agreement with the SM expectations.

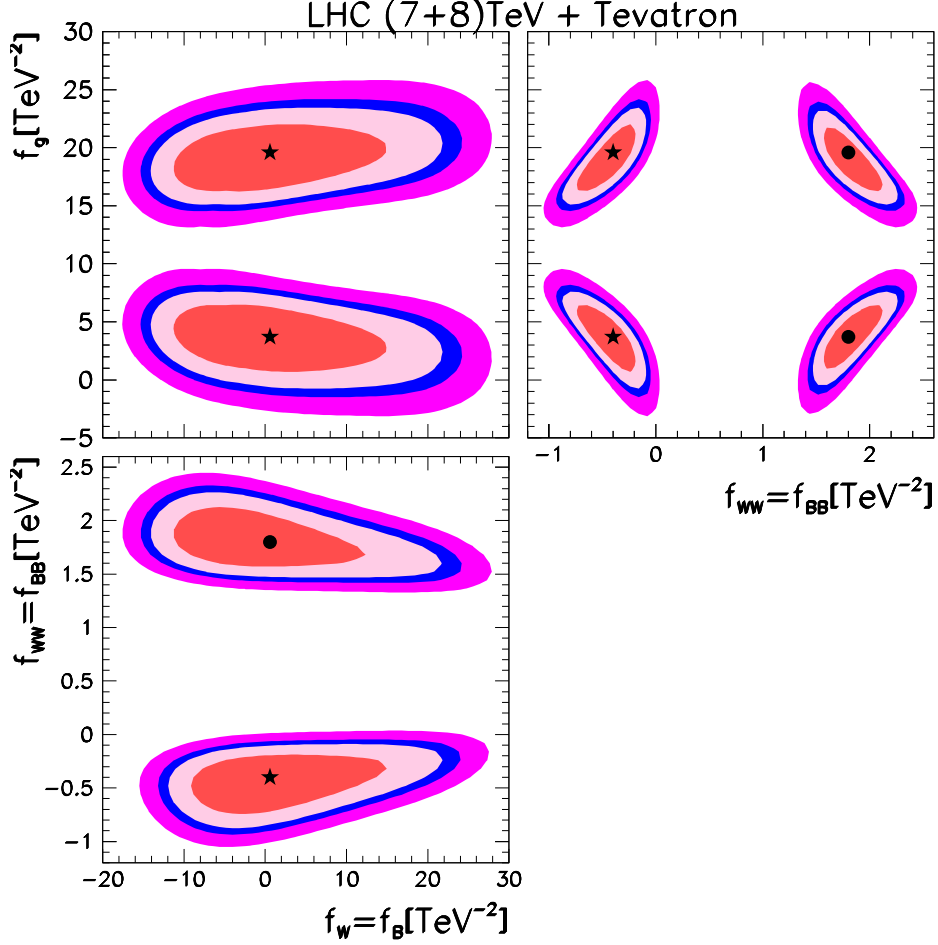


Figure 3: 68%, 90%, 95%, and 99% CL (2dof) allowed regions of the plane  $f_{WW} \otimes f_g$  (upper right panel),  $f_W \otimes f_g$  (upper left panel) and  $f_W \otimes f_{WW}$  (lower panel) using all available data. These results are obtained for scenario I and after marginalization over the undisplayed parameter in each panel. The best fit points are indicated by a star while the second local minima are indicated with a dot.

Presently the  $\gamma\gamma$  channel is the best measured channel and its rate is above the SM prediction. The operators  $\mathcal{O}_{WW}$ ,  $\mathcal{O}_{BB}$  and  $\mathcal{O}_{GG}$  are the ones affecting this channel, therefore they are the ones showing the largest impact of the full data set. This can be seen from the strong correlations and the well isolated islands present in the upper right panel of Figure 3 as well as by the correlations between the gluon fusion cross section and the Higgs branching ratios into electroweak gauge bosons in Figure 5. From the upper left panel of this figure we can see an anti-correlation between the gluon fusion cross section and the Higgs branching ratio into two photons; once again it is clear that there is a preference for reduced gluon fusion cross sections and enhanced decay into photon pairs. The other two panels of Figure 5 show the mild dependence of the Higgs branching ratio into  $W^+W^-$  with the gluon fusion cross section or the two photon branching ratio.

Our analyses of scenario I also shows that the presently available data prefers small values of  $f_W = f_B$ ; see the central panel of Figure 1. This indicates that large deviations in  $HZZ$  and  $HW^+W^-$  interactions, as well as to triple gauge-boson couplings, are not favoured. This behavior was expected because the data points for Higgs couplings to  $W$ 's and  $Z$ 's are in agreement with the SM within  $1\sigma$ ; see Figure 4 left panel. Furthermore, the present direct constraints on triple gauge-boson vertices lead to bounds on  $f_W$  that are of the same order as the ones derived here from Higgs phenomenology. So in the future the combined analysis of Higgs data and measurements of the anomalous triple gauge-boson couplings can be used to reduce the degeneracies observed in our results since they present a different dependence on the anomalous couplings  $f_W$  and  $f_B$ ; see Eqs. (4) and (6). In this respect, it is interesting to notice that electroweak precision measurements still give rise to the tightest limits on the Higgs

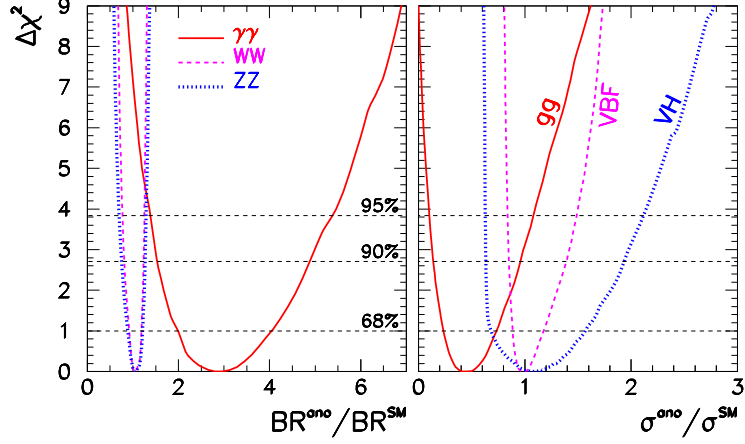


Figure 4:  $\Delta\chi^2$  as a function of Higgs branching ratios into electroweak gauge bosons (left panel) and the cross section for different production processes (right panel) normalized to the SM values. In the left panel the solid (dashed, dotted) line stands for the branching ratio into  $\gamma\gamma$  ( $W^+W^-$ ,  $ZZ$ ), while, in the right panel, the solid (dashed, dotted) line represents the gluon fusion (VBF, VH) production cross section.

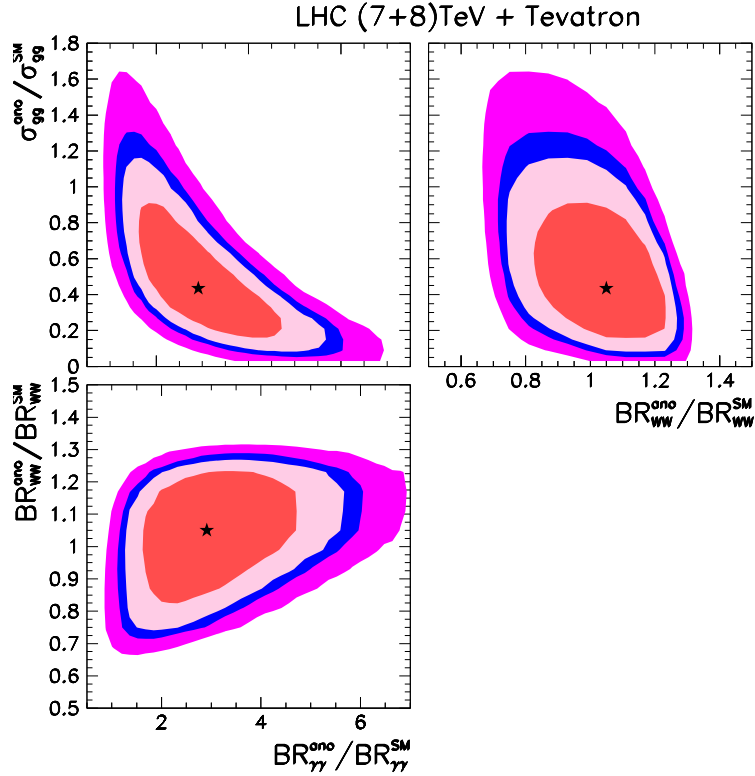


Figure 5: Allowed regions for several combinations of Higgs branching ratios and production cross section. In each panel  $\Delta\chi^2$  is marginalized with respect to the combination of couplings independent of the two displayed observables. As in Figure 3 the regions are shown at 68%, 90%, 95%, and 99% CL (2dof).

anomalous interactions [30, 34].

We finish with a word of warning. The precise numerical results presented here, that are summarized in Table V,

	Best fit	95% CL allowed range
$f_W = f_B$ ( $\text{TeV}^{-2}$ )	-0.8	$[-13, 20]$
$f_{WW} = f_{BB}$ ( $\text{TeV}^{-2}$ )	-0.4, (1.8)	$[-0.8, -0.1]$ and $[1.5, 2.2]$
$f_g$ ( $\text{TeV}^{-2}$ )	3.7, 19	$[-0.3, 7.3]$ and $[15, 23]$
$BR_{\gamma\gamma}^{ano}/BR_{\gamma\gamma}^{SM}$	2.9	$[1.4, 5.4]$
$BR_{WW}^{ano}/BR_{WW}^{SM}$	1.1	$[0.8, 1.3]$
$BR_{ZZ}^{ano}/BR_{ZZ}^{SM}$	1.1	$[0.7, 1.3]$
$\sigma_{gg}^{ano}/\sigma_{gg}^{SM}$	0.4	$[0.1, 1.1]$
$\sigma_{VBF}^{ano}/\sigma_{VBF}^{SM}$	1.0	$[0.8, 1.5]$
$\sigma_{VH}^{ano}/\sigma_{VH}^{SM}$	1.1	$[0.6, 2.1]$

Table V: Best fit values and 95% CL allowed ranges for the combination of all available data. For  $f_g$  we show the two degenerate best fit values. For  $f_{WW} = f_{BB}$  together with the best fit we show in parenthesis the value at the second minimum.

should be taken with a grain of salt; due to the simplifying hypothesis used in our analyses we should be aware that details can change if a more complete approach is used. Nevertheless we verified that our results are rather robust when we use only parts of the available data.

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