Higgs discovery: the beginning or the end of natural EWSB?

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ABSTRACT: We use global fits to analyze the most recent Higgs data from ATLAS, CMS and Tevatron and compare the Standard Model (SM) prediction with natural extensions of the SM. In particular we study wide classes of composite Higgs models based on different coset structures (leading at low energy to different Higgs sectors including extra singlets and Higgs doublets) and different coupling structures of the elementary fermions to the strong sector. We point out in what situations the composite models could improve (or worsen) the fit to the data and compare with similar trends in the MSSM.

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A particle consistent with the SM Higgs boson has been discovered: $5\sigma$ deviations have been observed both by CMS [1] and ATLAS [2], in the combination of $\gamma\gamma$ and $ZZ$ channels. Whether this is the beginning or the end of an era of investigation of natural realizations of the electroweak scale, it is not yet clear.

In this note we perform a global analysis of how compatible this excesses are with the SM expectation of a Higgs boson at $m_h \approx 125$ GeV, using the most recent data from ATLAS, CMS and Tevatron. It is then interesting to analyze different natural theories beyond the standard model (SM), to see whether they would be preferred or disfavored by the present trend of data, and to understand towards which direction the parameter space of such theories is more likely to shrink. We first turn our attention to a large variety of composite Higgs models [3], highlighting which features in these models tend to improve/worsen the fit to the data. In section 3, we begin with the minimal composite Higgs models (MCHMs), with coset structure SO(5)/SO(4), but with generic structures of fermion couplings to the strong sector (and hence to the Higgs boson) [3–5].

Larger coset structures can have strikingly different phenomenology. For instance in SO(6)/SO(5), which includes a CP-odd singlet besides the Higgs doublet in its light spectrum [6], the singlet couples to $\gamma\gamma$ through the Wess-Zumino-Witten term; this can enhance $h \to \gamma\gamma$ if the Higgs and the singlet mix with each other. We show this in section 4 and also study the case where, due to extra accidental symmetries, the singlet can manifest itself through invisible Higgs decays. The possibility of mixing raises the question of whether it will be possible at the LHC to understand if the particle we observe is really the one whose VEV gives mass to the gauge bosons; we try to answer this question by
singling out the exclusive channels (the ones with vector boson fusion (VBF) and associated production cuts) that carry mostly this information.

We then turn to the last class of composite models, based on the coset structure $\text{SO}(6)/\text{SO}(4) \times \text{SO}(2)$ which delivers an effective two Higgs doublets model (THDM) at low energy [7]. We compare the predictions of this composite version of the THDM with that of the MSSM in section 5.

Global fits of Higgs data in the context of composite Higgs models, but limited to the MCHM4 [3] and MCHM5 [4] models, have already appeared in refs. [8–12]; see also [13–15].

1 The data

We assume the existence of a unique Higgs-like state with couplings to the SM-gauge bosons and fermions

$$c_t \equiv \frac{y_t}{y_t^{SM}}, \quad c_b \equiv \frac{y_b}{y_b^{SM}}, \quad c_\tau \equiv \frac{y_\tau}{y_\tau^{SM}}, \quad a \equiv \frac{g_{hVV}}{g_{hVV}^{SM}},$$

(1.1)

where we use the SM couplings as reference values and assume $g_{hVV} \equiv g_{hWW} = g_{hZZ}$. We take that the probability density functions (PDFs) of the experiments can be approximated by Gaussian distributions, and we use the theoretical prediction for the ratio [10],

$$\mu^i = \frac{\sum_p \sigma_p(a, c_t, c_b, c_\tau) \xi_p^i \, BR_i(a, c_t, c_b, c_\tau)}{\sum_p \sigma_p^{SM} \xi_p^i \, BR_i^{SM}},$$

(1.2)

for each channel $i$ with production crossections $\sigma_p$ and cut efficiencies $\xi_p^i$ (which we take to be independent from the parameters $a$ and $c_t, c_b, c_\tau$; the values of $\xi_p^i$ are discussed in the appendix). We sum theoretical [16] and experimental errors in quadrature (both errors are first symmetrized by average in quadrature and when negative error bars are not provided by the experimental collaborations, we have assumed symmetric distributions around the mean value). We summarize the data used in table 1.\footnote{When data for the 8 TeV run has been provided only in combination with the 7 TeV run (ATLAS’ ZZ channel), we extract the information about the 8 TeV assuming that the PDFs corresponding to the combined data can be written as the product of uncorrelated PDFs i.e. $\text{PDF}_{7+8} = \text{PDF}_7 \cdot \text{PDF}_8$.}

ATLAS finds that the peak of the combined signal strength’s best fit is at $m_h = 126.5$ GeV, which is within experimental error from $m_h = 125.3$ GeV, where the peak of CMS occurs, so one can assume them to belong to the same resonance. We perform the statistical analysis taking the values at $m_h = 125$ GeV for CMS and Tevatron and $m_h = 126.5$ GeV for ATLAS, where more information is given (56 channels). For comparison we also study the case where $m_h = 125$ GeV is assumed for all experiments (38 channels). Notice that differences with taking $m_h = 125$ GeV for ATLAS will not only come from assuming a different Higgs mass but also because less exclusive subchannels are given.

Taking the ATLAS data at 126.5(125) GeV we obtain for the SM

$$\chi^2_{SM} = 58.7 \ (31.4),$$

(1.3)

which for $N = 56 \ (38)$ independent channels corresponds to $\chi^2/N \approx 1.0 \ (0.8)$. For the parameters mentioned above, in the case with $c \equiv c_t = c_b = c_\tau$, the best fit ($\chi^2 = 55.3 \ (29.5)$)
which, for 56 (38) channels and 2 variables, \( N = 56 - 2 (38 - 2) = 54 (36) \) corresponds to \( \chi^2 / N \approx 1.0 (0.8) \) occurs in

\[
c = -0.7 (-0.6), \quad a = 0.8 (0.8),
\]

while another local probability maximum \( (\chi^2 = 56.3 (29.4), \chi^2 / N \approx 1.0 (0.8)) \) occurs for positive \( c \) at

\[
c = 0.7 (0.7), \quad a = 1.0 (1.0).
\]

In figure 1 we show the 68%,95% and 99% C.L. contours for the parameters \( a \) and \( c \) from a global fit of data from ATLAS and CMS. C.L. regions are found by finding the isocontour of \( P(x, y) = \text{const} \), such that \( \int dx \, dy \, P(x, y) \pi(x, y) = 0.99, 0.95, 0.68 \), where \( x, y \) are any of the parameters (e.g. \( a, c_1, c_5, c_7, BR_{inv} \)) shown in the specific plot, \( \pi(x, y) \) is a flat prior and \( P(x, y) = \prod_i \text{PDF}_i(x, y) \) is the product over all PDFs extracted from the data given for each channel.
Figure 1. In green, yellow and gray, the 68%, 95%, 99% C.L. contours for the parameters $a$ and $c$ with the most recent data (table 1). Left plot: ATLAS with data taken at $m_h = 126.5$ GeV (dashed contours correspond to data taken at $m_h = 125$ GeV). Right plot: CMS with data taken at $m_h = 125$ GeV. A flat prior $a \in [0, 3], c \in [-3, 3]$ is used. Red dot: $a=c=1$.

2 Composite Higgs models

As shown above, the best fits occur for modified couplings of the Higgs boson to the SM fermions and gauge bosons. This is a typical feature of Composite Higgs models [24]: for instance, due to the Pseudo Nambu-Goldstone boson (PNGB) nature of the Higgs, the couplings between $h$ and the $W, Z$ gauge bosons are modified as

$$a = \sqrt{1-\xi},$$

where $\xi = v^2/f^2$, $f$ being the analogue of the pion decay constant and $v = 246$ GeV is the vacuum expectation value (VEV) of the Higgs field. Interestingly, on the one hand $\xi \ll 1$ from constraints coming from electroweak precision data (EWPD); on the other hand $\xi$ is a measure of fine-tuning in these models and is expected to be sizable.

3 SO(5)/SO(4) and different fermion couplings

While the strong sector alone is SO(5) symmetric, the couplings of elementary fermions to the strong sector break this symmetry, since the SM fermions do not fill complete SO(5) multiplets. We can parametrize these couplings as spurions which transform both under the SM-gauge group and under some representation $r$ of SO(5) (the well known minimal models MCHM4 [3] and MCHM5 [4] correspond to $r = 4$ and $r = 5$, respectively). Depending on the size of $r$, the coupling of $h$ to fermions $f$ might deviate from the SM as [5]:

$$c_f = \frac{1 + 2m - (1 + 2m + n)\xi}{\sqrt{1-\xi}},$$

$^2$The loop-induced potential for the PNGBs is a function of $\sin v/f$ and, without any fine-tuned cancellation, would naturally induce $v \approx f$ or $v = 0$.  

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Figure 2. Global fit for the parameters $a$ and $c$, obtained combining CMS and Tevatron for $m_h = 125\text{ GeV}$ and ATLAS for $m_h = 126.5\text{ GeV}$ (black dashed lines use ATLAS data at $m_h = 125\text{ GeV}$); colors and priors as in figure 1. The lines denote predictions of a generic MCHM; the different curves going from highest to lowest correspond to the values of $n = 0, \ldots, 5$ in eq. (3.1) with $m = 0$ ($n = 0, 1$ correspond to the MCHM4 and MCHM5). The red part of the curves is for $0 < \xi < 0.25$ and the blue dashed for $0.25 < \xi < 1$.

where $m, n$ are positive integers which depend on $r$. The specific cases with $m = n = 0$ or $m = 0, n = 1$ correspond to the MCHM4 (with $c = \sqrt{1 - \xi}$) and MCHM5 (with $c = (1 - 2\xi)/\sqrt{1 - \xi}$), where all fermions share the same coupling structure. Models with $m \neq 0$ have deviations w.r.t. the SM of order unity (in the direction $c > 1$), even in the limit $\xi \to 0$ and we shall not consider them any further.

In the specific case with $c \equiv c_t = c_b = c_\tau$, the effects of eq. (2.1) and eq. (3.1) can be well described in the $(a, c)$ plane. We compare this theoretical expectation, for $m = 0$ and $n = 0, \ldots, 5$, with the best fit from the combined results of ATLAS (at $m_h = 126.5\text{ GeV}$) and CMS ($m_h = 125\text{ GeV}$), for the parameters $(a, c)$ in figure 2 (the dashed contours show the same fit taking the ATLAS data at $m_h = 125\text{ GeV}$). We assume that no states, beside the SM ones, contribute via loop-effects to the $hgg$ and $h\gamma\gamma$ vertices.

Interestingly, representations leading to large $n \gtrsim 4$ can fit well the data also in the region with $c < 0$, where the rate $h \to \gamma\gamma$ is enhanced, due to a positive interference between $W$ and $t$ loops in the $h\gamma\gamma$ vertex (the fact that it is possible to have order 1 changes in this coupling, from modification of order $O(v^2/f^2) \ll 1$ is due to the large $n \gtrsim 4$ enhancement). To our knowledge, explicit models of this type do not exist yet in the literature ($n = 4$ would appear in models where the spurions connecting SM fields and the strong sector transform as an irreducible representation $r \in 5 \otimes 5 \otimes 5 \otimes 5$ of SO(5)) and it would be interesting to see if realistic models can be built.

As a final example, we consider the possibility of coupling top and down-type ($b$ and $\tau$) fermions in different ways to the strong sector (models of this type have been proposed, for instance, in refs. [7, 25]). We show examples of this as dots in the $c_t, |c_b|$ plane in figure 6 with $c_t = \sqrt{1 - \xi}$ and $c_b = c_\tau = (1 - 2\xi)/\sqrt{1 - \xi}$ (black dot) and with $c_t = (1 - 2\xi)/\sqrt{1 - \xi}$
and \( c_b = c_t = \sqrt{1 - \xi} \) (gray dot). Figure 6 shows slices of constant \( a \) (\( a = 0.8, \ a = 0.9 \)): for this reason these models, which map into a curve in the 3D \((a, c_b, c_t)\)-space, appear as dots in the figure. The asymmetric couplings do not improve the fit to the data, which shows a preference for the region \( c_b \approx c_t \) for \( c_t > 0 \).

4 SO(6)/SO(5) and the role of the extra singlet

The light spectrum of models based on the SO(6)/SO(5) coset structure contains, beside the Higgs doublet, an extra CP-odd scalar \( \eta \) [6]. In the absence of extra symmetries, the scalar potential is generic and the Higgs scalar mixes with the singlet: this is the most important conceptual difference w.r.t. the SO(5)/SO(4) models as far as \( h \)-phenomenology is concerned. The mass-eigenstate basis reads

\[
\begin{pmatrix} \eta' \\ h' \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \eta \\ h \end{pmatrix},
\]

where we take the mixing angle \( \alpha \) a free parameter. The couplings of \( \eta \) (being a gauge singlet) to the SM fermions and gauge bosons arise only at the non-renormalizable level and are suppressed by powers of \( v/f \). As a consequence, mixing implies that all the couplings of the physical Higgs will be generally suppressed by \( \cos \alpha \).

Now, it is important to notice that in composite Higgs models no enhancement is generally expected for \( h \to \gamma \gamma \) [26, 27] (see however refs. [28, 29] where exceptions are discussed). The reason is that effective operators, mediated by heavy states, of the form

\[
c_B H^\dagger H B_{\mu\nu} B^{\mu\nu}, \quad c_W H^\dagger H W_{\mu\nu} W^{\mu\nu},
\]

are generically supposed to be small by NDA arguments [24]: they break the shift symmetry of the PNGB Higgs and their coefficient should be suppressed by powers of a weak coupling over strong coupling. The coset SO(6)/SO(5), however, admits a Wess-Zumino-Witten (WZW) term in its effective Lagrangian, corresponding to a quantum anomaly of the UV theory. At leading order in \( 1/f \) (and without including the effect of possible couplings of \( \eta \) to the SM fermions) this includes

\[
\mathcal{L} \subset \frac{\eta}{32\pi^2 f} (n_B B_{\mu\nu} \tilde{B}^{\mu\nu} + n_W W_{\alpha}^{\mu\nu} \tilde{W}_{\mu\nu}^{\alpha}).
\]

Therefore, in the SO(6)/SO(5) models, while all cross-section times branching ratios are reduced by \( \cos^2 \alpha \), the WZW term induces a coupling between \( \eta \) and photons and can enhance the BR for photons (only\(^3\)).

\[
\Gamma_{h\gamma\gamma} \to \Gamma_{h\gamma\gamma} \left( \cos^2 \alpha + \sin^2 \alpha \frac{\Gamma_{\eta\gamma\gamma}}{\Gamma_{h\gamma\gamma}} \right),
\]

where \( \Gamma_{\eta\gamma\gamma} \) is the width of \( \eta \to \gamma \gamma \) evaluated at the mass of the mostly-Higgs mass eigenstate (in what follows \( \Gamma_{\eta\gamma\gamma} \) will be taken as a free parameter). Assuming that the SM

\(^3\)We ignore the contribution of eq. (4.3) to the \( hVV \) vertex \( (V = W, Z) \), contribution which will always be smaller then the renormalizable one.
fermions couple universally to the strong sector through spurions in the representation $r = 6$ of SO(6), the actual couplings of $h$ to fermions/vectors become

$$c = \cos \alpha \frac{1 - 2\xi}{\sqrt{1 - \xi}}, \quad a = \cos \alpha \sqrt{1 - \xi}. \quad (4.5)$$

We show this situation in figure 3, where it can be seen that a sizable width of $\eta \rightarrow \gamma \gamma$ and a non-vanishing, but small, mixing angle can improve the fit w.r.t. the SM. Interestingly, as for $\pi_0 \rightarrow \gamma \gamma$, the width of $\eta \rightarrow \gamma \gamma$, being non-renormalized, could carry information about the structure of the UV theory: for instance a large number of colours $N \gg N_c$ in the new strong sector could lead naturally to $\Gamma_{\eta \gamma \gamma} \gg \Gamma_{h \gamma \gamma}$.

The region where $\frac{\Gamma_{\eta \gamma \gamma}}{\Gamma_{h \gamma \gamma}}$ vanishes, corresponds to a situation in which all couplings of the Higgs are reduced w.r.t. their SM values by a factor $\cos \alpha$, on top of the suppression due to compositeness. From the point of view of Higgs searches, this is indistinguishable from the situation in which invisible decays reduce the visible branching fraction, with the identification $\cos^2 \alpha \rightarrow \Gamma_{h}^{\text{vis}}/(\Gamma_{h}^{\text{vis}} + \Gamma_{h}^{\text{inv}})$, where the superscripts differentiate between the total visible and invisible decay width. In the SO(6)/SO(5) models, hidden Higgs decays are possible in the presence of an extra unbroken $Z_2$ symmetry that makes $\eta$ stable, and an approximately unbroken $U(1)_\eta$ symmetry that naturally realizes $m_\eta < m_h/2$ [25]. In figure 4, we analyze this possibility by computing the $\chi^2$ with and without invisible width and for different degrees of compositeness $\xi = 0, 0.1, 0.25, 0.5$ (as described in ref. [25], in order to realize an approximate $U(1)_\eta$, top and bottom quarks must have different coupling structures to the strong sector, corresponding to $r_{tR} \in 15$ and $r_{tL,bL,bR} \in 6$, leading to $c_t = \sqrt{1 - \xi}$ and $c_b = (1 - 2\xi)/\sqrt{1 - \xi}$; such non-universal couplings of the SM fermions

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Figure 3. The best global fit as a function of $\alpha$ (the mixing between $h$ and the singlet $\eta$) and the ratio of the widths $\Gamma_{\eta \gamma \gamma}/\Gamma_{h \gamma \gamma}$; here $\xi = 0.25$ and $m_h = 125$ GeV are fixed and a flat prior in $\alpha \in [-\pi/2, \pi/2]$ and $\Gamma_{\eta \gamma \gamma}/\Gamma_{h \gamma \gamma} \in [0, 10]$ is used. Colors as in figure 1.
with \( h \) lead to a bottom/tau-phobic top-philic \( h \) as \( \xi \rightarrow 1/2 \), a value however disfavored by EWPD). The limit \( \xi \rightarrow 0 \), corresponds to the SM with invisible decays (see also \([30, 31]\)). Although the best fit point corresponds to \( BR_{\text{inv}} \neq 0, BR_{\text{inv}} = 0 \) is inside the 68\% C.L. region. For larger \( \xi \), the preference for \( BR_{\text{inv}} \neq 0 \) is stronger. Furthermore, the situation with a small degree of compositeness \( \xi \) is slightly better than the SM, as shown by the dashed curves in figure 4. This can be readily understood from figure 2: the SM with an increasing invisible decay width corresponds to moving along the line \( n = 0 \) towards the origin, trajectories where \( c \) is suppressed faster than \( a \) are preferred by the data.

4.1 Higgs impostors?

Independently from the composite Higgs realization, the fact that \( h \) can mix with other states that do not necessarily participate in the breaking of the electroweak symmetry (an analog example is the two Higgs doublet model discussed in the next section), raises the question of whether the state observed at the LHC is or is not the one whose VEV generates \( m_W \) and \( m_Z \). This can be done by measuring the parameter \( a \) independently: while the Higgs field can have trilinear renormalizable couplings to \( WW \) and \( a = 1 \), impostors will have to couple to \( WW \) via loops (also the dilaton would couple to matter as \( m/f \) and could reproduce the observed excesses \([12, 32]\); it is however unlikely that, if \( f \approx v \), there would have not been other observable deviations from the SM \([33]\)). Therefore \( a < 1 \) might imply that the state we observe is not \( \text{the} \) Higgs, or that it is a Higgs that mixes with another state.

One possibility to answer this question, is to marginalize over all parameters except \( a \). Since we don’t know whether some of the Higgs couplings have large deviations from the SM values, another possibility is to isolate some channels that are mostly sensitive to
Figure 5. Preferred regions in the plane \((a, c_b)\) using only the \(b\bar{b}\) channels (CMS, ATLAS and Tevatron) and \(WW_2j\) (CMS). Colors as in figure 1. A flat prior is assumed for \(a \in [0, 3]\) and \(c_b \in [0, 3]\) (this choice for the upper limit in \(c_b\) leads to the most conservative conclusions). Red dot: \(c_b = a = 1\).

\(a\) and are sensitive to the least number of other parameters. In particular we choose the exclusive VBF channels \(pp \rightarrow hjj \rightarrow WWjj\) measured by CMS [19], which scale roughly as \(\sim a^4/c_b^2\) and the exclusive associated production \(pp \rightarrow Vh \rightarrow Vb\bar{b}\) measured both at Tevatron [23], CMS and ATLAS, which scale roughly as \(\sim a^2\). These channels are mostly insensitive to \(c_t\) and \(c_\tau\) and allow a study of \(a\) with \(c_b\) as only other parameter. Figure 5 shows that, unless \(c_b \ll 1\), values close to \(a \approx 1\) are preferred by data (we have checked that the effect of varying the other parameters, \(0.5 \leq c_{t,\tau} \leq 1.5\), is negligible).

5 SO(6)/SO(4) \times SO(2) and natural two Higgs doublets models

The SO(6)/SO(4) \times SO(2) coset delivers at low energy 8 PNGBs that can be identified with an effective THDM [7]. Large contributions to the \(\hat{T}\)-parameter can be avoided thanks to the symmetry \(C_2 : (H_1, H_2) \rightarrow (H_1, -H_2)\), which also allows us to differentiate three cases:

\(i)\) If \(C_2\) is exact, the model is a Type I THDM. The second doublet is heavy and inert [35] and there is no mixing between the CP-even states; this model resembles the SO(5)/SO(4) models of section 3.\(^5\)

\(ii)\) If \(C_2\) is spontaneously broken, an effective Type II THDM is realized at low energy, but only at the price of large fine-tuning (both Higgs VEVs have to be tuned much smaller than \(f\)). The couplings of a Type II THDM are [36, 37]

\[
\frac{y_t^{THDM}}{y_t} = \frac{\cos \alpha}{\sin \beta}, \quad \frac{y_b^{THDM}}{y_b} = \frac{-\sin \alpha}{\cos \beta},
\]

where \(\tan \beta = v_1/v_2\) is the ratio between VEVs, and \(\alpha\) is the mixing angle (the analog of eq. (4.1) but for two doublets); the coupling of the lightest Higgs to the vectors is

\(^5\)A similar \(h_0\) phenomenology is realized in the almost inert model of ref. [7], where the \(C_2\) symmetry is unbroken by the top-quark couplings and is broken only by the smaller Yukawas.
reduced, in comparison with the case of only one Higgs doublet, by \( \sin(\beta - \alpha) \). On top of mixing, also higher dimension operators reduce the couplings between \( h \) and the SM vectors and fermions \( f \) (as in all composite Higgs models) and for small \( \xi \) we obtain

\[
\begin{align*}
{a} &= (1 - \xi/2) \sin(\beta - \alpha), \\
{c_t} &= (1 - \xi/2) \frac{\cos \alpha}{\sin \beta}, \\
{c_b,\tau} &= -(1 - \xi/2) \frac{\sin \alpha \cos \beta}{\cos \beta}.
\end{align*}
\]

We compare this model with the tree-level MSSM\(^6\) in figure 6 in the \((c_t, c_b)\)-plane with \( c_b = c_\tau \) and for different slices of \( a = 0.8, 0.9 \) (see ref. [40] for an approach with \( a \) marginalized). The black line shows the prediction for the MSSM varying \( \beta \) (\( \alpha \) is fixed by the slice choice \( a = 0.8, 0.9 \)); the thin part of the line is unaccessible to the tree-level MSSM due to the peculiar relation between the quartic couplings in the potential [36, 37]. The composite THDM is drawn in red.

iii) If \( C_2 \) is explicitly broken, then a small VEV \( \langle H_2 \rangle \neq 0 \), leading to \( \tan \beta \approx \xi^{-1} \), and a small mixing \( \tan \alpha \lesssim \xi \) is generated [7]. In this case a Type III THDM originates, in which both \( H_1 \) and \( H_2 \) couple to each SM fermion \( f \),

\[
\frac{y_f}{\sqrt{2}} f f (H_1 + a_f H_2) = \frac{y_f}{\sqrt{2}} f f (\cos \alpha + a_f \sin \alpha) h_1^0 + \cdots ,
\]

where we have retained only the interactions of the lightest CP-even state \( h_1^0 \), and where \( y_f = (1 - \xi/2) y_f^{SM} \), as discussed above. For FCNC to be suppressed, the Yukawas for \( H_{1,2} \) must be aligned [38]. In figure 6, blue line, we show the situation with \( a_t = a_{b,\tau} \approx 1 \), varying \(-\xi \lesssim \alpha \lesssim \xi \) (lines with \( a_t \neq a_{b,\tau} \) would span a small circle).

As shown in figure 6, the preferred region is along the direction \( c_t \approx -c_b = -c_\tau \) or, with less significance, along \( c_t \approx c_b = c_\tau \). Despite the different possibilities realized in composite THDMs, none touches the first preferred region (in elementary type II THDMs, one finds \( c_t > 1, c_b < 1 \) or \( 0 < c_t < 1, c_b > 1 \), and the models that are preferred by the data are those closer to the line \( c_t \approx c_\tau \approx c_b = c \), which are more similar, in terms of \( h \) phenomenology, to the MCHM with SO(5)/SO(4).

6 Conclusions

Using global fits with the most recent data provided by ATLAS, CMS and Tevatron, we have analyzed the parameter space given by couplings of the Higgs to top and bottom quarks, taus and vector bosons. We have shown that the hypothesis of a SM Higgs with \( m_h \approx 125 \text{ GeV} \) agrees well with the data.

\( ^6\)Notice that if some superpartners (such as staus [41] or other states [42, 43]) are light, the rate \( h \to \gamma \gamma \) can be enhanced and the MSSM fit might change considerably; other loop-effects that contribute to the Higgs quartic, can also change this prediction [40].
Figure 6. C.L. contours (colors as figure 1) in the $(c_t,|c_b|)$-plane for $c_b = c_\tau$ and fixed value of $a=0.8$ (0.9) on the left (right) plot. The black line corresponds to the couplings of the elementary THDM Type II, eq. (5.1), once fixed $a=0.8$ (0.9); the thick part is accessible to the tree-level MSSM. The red line shows the composite THDM Type II (with $\xi = 0.36$ (0.19)), and the blue one the composite Type III (varying $-\xi \lesssim \alpha \lesssim \xi$). Shown are also three points (black, gray and red) corresponding to the SO(5)/SO(4) coset. Black dot: $c_t = \sqrt{1 - \xi}$, $c_b = (1 - 2\xi)/\sqrt{1 - \xi}$. Gray dot: $c_t = (1 - 2\xi)/\sqrt{1 - \xi}$, $c_b = \sqrt{1 - \xi}$. Red dot: $c_t = c_b = (1 - 2\xi)/\sqrt{1 - \xi}$ (MCHM5). A flat prior $c_t \in [-4,4]$ and $c_b \in [0,4]$ is used.

We have then studied different models, in particular in the context of composite Higgs, to see what features could improve/worsen the situation of these scenarios when more data is available. In particular, we have shown that, depending on the coupling structure of elementary fermions to the strong sector, the couplings of $h$ to the SM fields can change considerably w.r.t. the SM case. Some composite models, such as the MCHM4, seem to point towards the disfavored direction. Other models, however, follow better the trend of data: the MCHM5, for instance, reduces the couplings of $h$ to fermions, $c$, more than the one to vectors, $a$, and for small $\xi$ crosses the best fit region with $c > 0$. Models with $n \gtrsim 4$ in eq. (3.1) have an even better trend, as the best fit region with $c_t < 0$ lies within their parameter space even for $f \gtrsim 500$ GeV. Different couplings of top and bottom quarks to the strong sector, on the other hand do not seems to ameliorate much the fit, although more drastic possibilities could be considered, that reproduce the preferred region $c_t = -c_b = -c_\tau$, shown in figure 6.

We have also studied larger coset structures, such as SO(6)/SO(5), which contains an extra singlet in its light spectrum. We have shown that in this case, large invisible decays widths into a stable singlet, start to be in conflict with the data, although a small one cannot be excluded. On the other hand, a situation in which the Higgs mixes with the singlet, which in turn has enhanced anomalous couplings to $\gamma \gamma$, is in good agreement with the data.

Finally we have discussed SO(6)/SO(4)×SO(2) models which, in some cases reduce to a composite model with an inert doublet (Type I THDM) and the light Higgs phenomenology...
is not much affected, thus resembling to the SO(5)/SO(4) coset. If more fine-tuning is allowed, a version of a Type II THDM is possible; compared with the MSSM this has the advantage of having less constrained quartics [39, 40], which allows the model to have both \( c_b > 1 \) and \( c_b < 1 \), thus covering a larger region of parameter space. Despite this, present data show a mild preference for the composite THDM only for sizable deviations from \( a = 1 \) (upper plot of figure 6). Finally, if FCNC can be kept under control, a version of Type III THDM is also possible. In this case the couplings of the second Higgs doublet to fermions enter as new parameters in the theory; despite this freedom, the greatest overlap with the best fit regions occur along \( c_t \approx c_b, \tau \), which is the region also touched by the minimal model. In summary, the composite THDM provides its best fit to the data when the parameter space is such that its phenomenology resembles much that of the minimal composite Higgs model SO(5)/SO(4).

Note added. While this work was in preparation, refs. [34, 44, 45] appeared, also discussing deviations of Higgs couplings from its SM values.

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A Cut efficiencies \( \zeta^i_p \)

The production cross-section for each channel in table 1 receives contributions from gluon gluon fusion (\( \sigma_G \)), vector boson fusion (\( \sigma_{VBF} \)), associated production with a vector boson (\( \sigma_{WH}, \sigma_{ZH} \)) and associated \( t\bar{t} \) production (\( \sigma_{tH} \)), in such a way that the first term of equation [1.2] can be expanded as

\[
\frac{\sum_p \sigma_p \zeta^i_p}{\sum_p \sigma_p^{SM} \zeta^i_p} = \frac{\sum_p \sigma_p \zeta^i_p}{\sum_p \sigma_p^{SM} \zeta^i_p} = \frac{\sum_p \sigma_p \zeta^i_p}{\sum_p \sigma_p^{SM} \zeta^i_p} = \frac{\sum_p \sigma_p \zeta^i_p}{\sum_p \sigma_p^{SM} \zeta^i_p},
\]

where the cut efficiencies \( \zeta^i_p \) for each production mode \( p \) corresponding to each channel \( i \) are reported below in tables 2 and 3.

B Bayesian interval versus \( \chi^2 \) analyses

In figure 7 we compare the effects of using analyses based on \( \chi^2 \) (where the point \( \chi^2_{\text{min}} \) is first found and then the 68%, 95%, 99% C.L. intervals are found as isocountours with, in the case two fitting parameters, \( \chi^2 = \chi^2_{\text{min}} + 2.3, 5.99, 9.21 \)), versus analyses that use Bayesian intervals [46] (as done throughout this work). If \( \mu \) is just a parameter and not a function
Table 2. Cut efficiencies for production modes of the channels of table 1 labeled as $\gamma\gamma X$. Numbers in brackets give the efficiencies at 8 TeV, the others at 7 TeV [17] and the overall normalization in each line factorizes.

| $i$ | $\xi^i_G$ | $\xi^i_{VBF}$ | $\xi^i_{WH}$ | $\xi^i_{ZH}$ | $\xi^i_{ttH}$ |
|-----|------------|--------------|--------------|--------------|--------------|
| $\gamma\gamma_0$ | 0.28(0.45) | 1(1) | 1.52(1.91) | 1.52(1.91) | 2.37(4.00) |
| $\gamma\gamma_1$ | 1.16(1.17) | 1(1) | 1.36(1.43) | 1.36(1.43) | 2.24(2.00) |
| $\gamma\gamma_2$ | 1.80(1.84) | 1(1) | 1.36(1.07) | 1.36(1.07) | 0(0) |
| $\gamma\gamma_3$ | 1.80(1.84) | 1(1) | 1.36(1.43) | 1.36(1.43) | 0(0) |
| $\gamma\gamma_{jj}$ | 0.029 | 1 | 0.019 | 0.019 | 0 |
| $\gamma\gamma_{jj}$ (T) | 0.024 | (1) | (0) | (0) | (0) |
| $\gamma\gamma_{jj}$ (L) | (0.094) | (1) | (0.064) | (0.064) | (0) |
| $\gamma\gamma_{UnCE LPT_t}$ | 1.85 (1.79) | 1 (1) | 0.97 (0.93) | 0.99 (0.97) | 0.74 (0.58) |
| $\gamma\gamma_{UnCE HPT_t}$ | 0.34 (0.41) | 1 (1) | 1.36 (1.13) | 1.44 (1.21) | 2.27 (2.00) |
| $\gamma\gamma_{UnRE LPT_t}$ | 1.90 (1.82) | 1 (1) | 1.11 (1.12) | 1.12 (1.09) | 0.76 (0.60) |
| $\gamma\gamma_{UnRE HPT_t}$ | 0.32 (0.42) | 1 (1) | 1.45 (1.30) | 1.50 (1.35) | 1.66 (1.51) |
| $\gamma\gamma_{CoCE LPT_t}$ | 1.85 (1.74) | 1 (1) | 1.03 (0.91) | 0.99 (0.94) | 0.74 (0.85) |
| $\gamma\gamma_{CoCE HPT_t}$ | 0.35 (0.43) | 1 (1) | 1.41 (1.19) | 1.48 (1.21) | 2.43 (2.06) |
| $\gamma\gamma_{CoRE LPT_t}$ | 1.95 (1.78) | 1 (1) | 1.14 (1.10) | 1.15 (1.06) | 0.78 (0.58) |
| $\gamma\gamma_{CoRE HPT_t}$ | 0.33 (0.40) | 1 (1) | 1.49 (1.33) | 1.46 (1.32) | 1.67 (1.45) |
| $\gamma\gamma_{CoTr}$ | 1.37 (1.19) | 1 (1) | 1.37 (1.19) | 1.30 (1.22) | 0.86 (0.82) |
| $\gamma\gamma_{2j}$ | 0.02 (0.04) | 1 (1) | 0.01 (0.01) | 0.01 (0.01) | 0.02 (0.04) |

Table 3. Assumed cut efficiencies for the channels of table 1 labeled as VBF, A, I and ttH.

| $i$ | $\xi^i_G$ | $\xi^i_{VBF}$ | $\xi^i_{WH}$ | $\xi^i_{ZH}$ | $\xi^i_{ttH}$ |
|-----|------------|--------------|--------------|--------------|--------------|
| I | 1 | 1 | 1 | 1 | 1 |
| A | 0 | 0 | 1 | 1 | 0 |
| VBF | 0.029 | 1 | 0.019 | 0.019 | 0 |
| ttH | 0 | 0 | 0 | 0 | 1 |

depending on $a, c_l, c_b, c_\tau$, the methods do not differ; however, when $\mu = \mu(a, c_l, c_b, c_\tau)$ is a function of the parameters $a, c_l, b, c_\tau$ as in eq. (1.1), then the probability density function is no longer Gaussian in $a, c_l, b, c_\tau$ and the two methods differ. As shown in figure 7, however, the small differences do not alter the qualitative conclusions.
Figure 7. Comparison between data analyses based on Bayesian interval (as used throughout this work) and isocontours of constant $\chi^2 = \chi^2_{\text{min}} + 2.3, 5.99, 9.21$ (dashed lines) for the global fit of figure 2 (with $m_h = 125$ GeV for CMS and Tevatron, and $m_h = 126.5$ for ATLAS). Red dot: $a=c=1$.

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