Abstract

The ATLAS and CMS collaborations of the LHC have observed that the Higgs boson decays into the bottom quark-antiquark pair, and have also established that the Higgs coupling with the top quark-antiquark pair is instrumental in one of the modes for Higgs production. This underlines the discovery of the Yukawa force at the LHC. We demonstrate the impact of this discovery on the Higgs properties that are related to the dynamics of electroweak symmetry breaking. We show that these measurements have considerably squeezed the allowed window for new physics contributing to the Higgs couplings with the weak gauge bosons and the third generation quarks. The expected constraints at the HL-LHC are also shown. We project these constraints on the parameter space of a few motivated scenarios beyond the Standard Model. We picked them under two broad categories, namely, the composite Higgs and its RS dual, as well as various types of multi-Higgs models. The latter category includes models with singlet scalars, Type I, II and BGL-type two-Higgs doublet models, and models with scalar triplets à la Georgi and Machacek.

1 Introduction

Since the discovery of the Higgs boson in 2012 at the CERN Large Hadron Collider (LHC) [1, 2], one of the most notable achievements by the ATLAS and CMS Collaborations has been the measurements of the Yukawa force between the Higgs boson ($h$) and the third generation quarks ($t$ and $b$). Although Yukawa interaction was postulated long back in the context of the pion-nucleon scattering, advent of Quantum Chromodynamics showed that it is but an artefact of the strong gauge force. Do the present measurements of $hb\bar{b}$ [3, 4] and $ht\bar{t}$ [5, 6] couplings constitute a discovery of a fundamental Yukawa force, or, is it again a low energy manifestation of some unknown UV dynamics? Even if the Higgs boson is an elementary object, is it the only neutral scalar that Nature offered us? Precision measurements of these Yukawa couplings can shed important light on both these questions. In the Standard Model (SM), the Yukawa couplings are precisely known in terms of the fermion masses. Any departure would indicate physics beyond the SM (BSM) triggering electroweak symmetry breaking [7, 8]. In this paper, we review the status of some BSM physics in the light of the LHC data armed with the new measurements of the Yukawa forces. Since the flavor changing couplings of the 125 GeV Higgs boson are already too constrained, increasingly precise measurements of the flavor diagonal couplings at the LHC are essential to probe the Yukawa structure. In order to quantify the BSM window we employ a $\chi^2$-analysis using the Higgs signal strength data from the ATLAS and CMS Collaborations. The Run 2 data [9, 10] with improved measurements of the $hb\bar{b}$ and $ht\bar{t}$ couplings, compared to what Run 1 could achieve [11–17], penetrate rather deep into the BSM parameter space, leading to new constraints. To show the future prospects, we also give projections for these measurements at the high luminosity runs of the LHC (HL-LHC) [18]. For our purpose, we employ a simple model independent phenomenological Lagrangian upto two-derivative order, which essentially captures modification of the Higgs couplings [18–20]. We also translate the limits of our model independent parameter space to

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the space of two broad BSM categories, namely, the composite Higgs and multi-Higgs models, under
the guise of their different *avatars*, which can address the questions raised above.

2 Theoretical framework

Broadly speaking, two types of BSM physics can modify the Higgs boson couplings:

- Mixing with other spin-0 bosons can alter the Higgs couplings. Examples of this type are found
  in models with additional SU(2)_L multiplets.

- Higher dimensional operators, obtained by integrating out heavy degrees of freedom, can modify
  the Higgs couplings. Composite Higgs scenario is a typical example of this type. We note that
  the absence of any signature of new physics at the LHC, till date, strongly motivates the use
  of model independent effective field theoretic frameworks, involving only the SM particles as
  the low energy degrees of freedom. Among the various effective theory frameworks, Standard
  Model effective field theory [21–27] and strongly interacting light Higgs scenario [28–31] are
  worth mentioning.

In the present analysis, we use a simple model independent phenomenological Lagrangian, in the
broken phase of electroweak symmetry, which captures the modifications of the Higgs couplings arising
from both the above sources [18–20]. We expand the terms in the Lagrangian in powers of h as well
as in the number of derivatives. Since our primary interest lies in the production and decay of a single
Higgs boson, we will only keep terms up to a single insertion of h. The Lagrangian involving the SM
fields after the electroweak symmetry breaking, up to two-derivative terms is given below:

\[ \mathcal{L} = \mathcal{L}_{(0)} + \mathcal{L}_{(2)}, \]  

(2.1)

where the lowest order in derivative \( \mathcal{L}_{(0)} \) is given as

\[ \mathcal{L}_{(0)} = \frac{h}{v} \left[ c_V \left( 2 M_W^2 W^{\mu} W^{\mu} + M_Z^2 Z^{\mu} Z^{\mu} \right) - \sum_f c_f m_f \bar{f} f \right]. \]  

(2.2)

The two-derivative terms, which may arise by integrating out the BSM states, are given by

\[ \mathcal{L}_{(2)} = -\frac{h}{4\pi v} \left[ \alpha_c c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} + \alpha_c c_{Z\gamma} Z_{\mu\nu} Z^{\mu\nu} - 2 \alpha_s c_{gg} G^{a}_{\mu\nu} G^{a}_{\mu\nu} \right]. \]  

(2.3)

The coefficients \( c_i \) are free parameters capturing the impact of BSM physics, and to be constrained
by the experimental data. In the SM, \( c_V = c_f = 1 \) and \( c_{\gamma\gamma} = c_{Z\gamma} = c_{gg} = 0 \). We also assume those
coefficients to be real, i.e. we assume the 125 GeV Higgs boson to be CP even. Implications of CP odd
Higgs couplings have been discussed in [32,33]. The Higgs production cross sections and decay widths,
normalized to their SM values, can be expressed solely in terms of these coefficients. Throughout this
paper, we fix \( c_{Z\gamma} = 0 \), since the \( h \to Z\gamma \) data is too constrained from the electroweak precision
observables and, not unexpectedly, is still unobserved at the LHC [34,35]. We will also assume that
\( c_{\tau} = c_b \) and \( c_c = c_s = c_t \), to simplify the analysis.
3 Analyzing the LHC data

The Higgs signal strength ($\mu$) of a specific process $i \rightarrow h \rightarrow f$ is conventionally defined as

$$\mu_i^f = \frac{\sigma_i^{SM}}{\Gamma_i^{SM}} \frac{B_f}{\Gamma_f^{SM}} = \frac{\sigma_i}{\sigma_i^{SM}} \frac{\Gamma_f}{\Gamma_f^{SM}}$$ \quad (3.1)

where $\sigma_i$, $\Gamma_f$ and $B_f$ denote the cross section of the $i$th production mode of the Higgs boson, the partial decay width of the Higgs into a final state $f$, and the corresponding branching ratio, respectively. In the total decay width of the Higgs, $\Gamma_h$, we shall generally assume that the Higgs can decay only to the SM particles. Towards the end, however, we shall comment on the possibility of the Higgs boson having a non-vanishing branching fraction to invisible decay modes. In terms of the ‘$\kappa$-framework’ [36, 37], we can express the cross-sections and decay widths normalized to their SM values as

$$\frac{\sigma_i}{\sigma_i^{SM}} = \kappa_i^2, \quad \frac{\Gamma_f}{\Gamma_f^{SM}} = \kappa_f^2.$$ \quad (3.2)

The mapping between the $\kappa$-framework and the coefficients $c_i$ can be found in [38]. To put limits on $c_i$’s, we define a $\chi^2$-function using the individual signal strengths. We use ATLAS Run 2 data with 80 $fb^{-1}$ luminosity [9] and CMS Run 2 data with 137 $fb^{-1}$ luminosity [10]. For the purpose of comparison, we also show the results obtained from the combined ATLAS and CMS Run 1 data [11]. Note that, in case of the CMS Run 2 data, due to the unavailability of the full correlation matrix, we have assumed that the Higgs signal strength measurements are all independent. As for the HL-LHC projections, with luminosity 3000 $fb^{-1}$, we use the SM predictions as central values, and the uncertainties are obtained from [18]. Some crucial observations regarding the present data are the following. First, the processes involving $t\bar{t}h$ production mode have been measured with unprecedented precision at Run 2. Similarly, the errors for the $hbb$ decay channels have got significantly reduced, in particular in the associated Higgs production channel. Besides, $gg \rightarrow h \rightarrow \gamma\gamma$ and $gg \rightarrow h \rightarrow ZZ^*$ processes, which were already measured with less than 30% errors in the Run 1 phase, now stand better with around 15% errors after the Run 2 data were analyzed.

We also define new variables by normalizing all the signal strengths by that of the gold-plated $gg \rightarrow h \rightarrow ZZ^*$ process, measured with maximum precision. This way the inherent uncertainties in the total decay width of the Higgs coming from possible invisible modes get eliminated. The other advantage is that, if we assume only the SM particles are running inside the loops for processes like $gg \rightarrow h$ and $h \rightarrow \gamma\gamma$, all the ratios can be expressed in terms of only two variables, viz. $c_t/c_V$ and $c_b/c_V$. Then the constraints from the Higgs signal strength measurements can be represented in a two-dimensional $c_b/c_V - c_t/c_V$ plane. Admittedly, even if the $\Gamma_h$ dependence is eliminated in this approach, the errors and correlations among the ratios of signal strengths get slightly jacked up compared to the approach where we have analyzed individual signal strengths.

4 Results

It has been shown in [19,39,40] that the LEP data admit around 10% – 20% deviation in $c_V$ from its SM value at 95% CL. In the present analysis we have observed that the present Higgs signal strength data provide competitive, if not better, limits on $c_V$.

The parameter $c_t$ receives major constraints from the gluon fusion and $t\bar{t}h$ production modes of the Higgs boson as well as from its diphoton decay channel. On the other hand, constraints on $c_b$ primarily
Figure 1: In the left panel, the allowed regions in the plane of $c_b/c_V$ and $c_t/c_V$ are shown at 68% CL (area inside the solid lines) and 95% CL (area inside the dashed lines). We use the ratios of signal strengths from the Run 1 (grey) and Run 2 (red) LHC data, as well as the HL-LHC projections (blue), to extract the limits. The HL-LHC projection is magnified and shown in the inset. In the right panel, we use the individual signal strengths and put limits on $c_t = c_b = c_\tau = c_f$ and $c_V$. While plotting, $c_{gg} = c_{\gamma\gamma} = 0$ is assumed.

| Figure          | Quantity     | Run 1          | Run 2          | HL-LHC         |
|-----------------|--------------|----------------|----------------|----------------|
| Fig. 1 left panel | $c_b/c_V$    | [0.55 – 1.24]  | [0.81 – 1.16]  | [0.95 – 1.05]  |
|                 | $c_t/c_V$    | [0.86 – 1.96]  | [0.90 – 1.30]  | [0.96 – 1.05]  |
| Fig. 1 right panel | $c_f$        | [0.70 – 1.21]  | [0.90 – 1.16]  | [0.96 – 1.04]  |
|                 | $c_V$        | [0.88 – 1.11]  | [0.96 – 1.08]  | [0.98 – 1.02]  |
| Fig. 2          |              |                |                |                |
|                 | $c_{gg}$     | [-0.17 – 0.10] | [-0.06 – 0.08] | [-0.02 – 0.02] |
|                 | $c_{\gamma\gamma}$ | [-0.57 – 1.02] | [-0.36 – 0.44] | [-0.11 – 0.11] |

Table 1: The range of allowed values for different coupling modification parameters at 95% CL, extracted from the Figs. 1 and 2, are tabulated. Though there are two disjoint sets of limits on $c_b$, one on positive and the other on negative side, as evident from the left panel of Fig. 1, for brevity we display in this Table the positive side range only. Assuming $c_b = c_t = c_f$, the allowed 95% CL ranges of $c_f/c_V$ is obtained using the ratios of signal strengths as: Run 1: [0.86 – 1.22], Run 2: [0.92 – 1.14], HL-LHC: [0.97 – 1.03].

The limits on $c_V$ from the Run 2 data are already competitive to those obtained from the electroweak precision tests. This happened primarily due to the increasingly precise measurements of $h t\bar{t}$ and $h b\bar{b}$ couplings.

In the right panel of Fig. 1, we use the conventional approach of using the individual signal strengths to extract the limits. Here we assume $c_t = c_b = c_\tau = c_f$ to show the allowed region in the $c_f/c_V$ plane. In Table 1 we display the allowed ranges of parameters at 95% CL. Two major points are worth noting here. First, the limits on $c_V$ from the Run 2 data are already competitive to those obtained from the electroweak precision tests. Second, the window for new physics through $c_f$
Figure 2: Constraints on $c_{gg} - c_{\gamma\gamma}$ plane at 95% CL are displayed. The solid cyan, purple and brown lines denote the contributions to $ggh$ and $h\gamma\gamma$ triangle loops by color triplet BSM particles with electric charges $Q = 1/3$, $Q = 2/3$ and $Q = 5/3$, respectively. We have fixed $c_f = c_V = 1$. The color codes are: Run 1 (grey), Run 2 (red), HL-LHC (blue).

has significantly narrowed down, only 10% – 15% deviation is allowed from the SM reference point. This improvement in Yukawa force measurement helps discriminate various BSM scenarios. We note that the combined Run 1 + Run 2 data improve the limits obtained from Run 2 data alone by at most 2% – 3%. In obtaining the above constraints we have assumed $c_{gg} = c_{\gamma\gamma} = 0$. The inherent assumption is that any new BSM particle(s) which might have contributed to the triangle loops creating the effective $ggh$ and $h\gamma\gamma$ vertices are sufficiently heavy and decoupled.

Then we go to the other extreme. Keeping $c_b = c_t = c_\tau = c_V = 1$, we display the limits in $c_{gg} - c_{\gamma\gamma}$ plane in Fig. 2. Here we capture the effects of the new BSM particles floating in the triangle loops, e.g. if the SM is extended with additional colored and electrically charged particles. The solid lines represent the contributions from colored particles, transforming as triplets of SU(3)$_c$ and having electric charges $Q = 1/3$ (cyan), $Q = 2/3$ (purple) and $Q = 5/3$ (brown), respectively. The exact location of a model-point on each straight line, however, depends on the mass and model-dependent couplings of the new particles with the Higgs boson [19].

If a non-vanishing branching fraction for the invisible decay mode ($Br_{inv}$) of the Higgs boson is admitted, all the individual signal strengths of the Higgs boson receive a scaling by an overall factor of $(1 - Br_{inv})$. Assuming $c_f = c_V = 1$ and $c_{gg} = c_{\gamma\gamma} = 0$, we observe that the Run 1 (Run 2) data exclude $Br_{inv} \gtrsim 18\%$ (7%), while the HL-LHC would exclude $Br_{inv} \gtrsim 3\%$. Admittedly, these limits will relax considerably, if deviations in $c_i$ parameters are allowed (e.g. the Particle Data Group excludes a rather conservative $Br_{inv} \gtrsim 24\%$ [41]).
4.1 Composite Higgs models

In generic composite Higgs scenario, the modification in the $hVV$ coupling is universal [42,43]

$$c_V = \sqrt{1 - \xi},$$  \hspace{1cm} (4.1)

where $\xi = v^2/f^2$ parametrizes the hierarchy between the electroweak scale and the composite scale $f$. The Yukawa couplings, however, depend on the details of the particular model. In the minimal composite Higgs model, with coset $SO(5)/SO(4)$ [44–46], the Yukawa coupling modifiers are controlled by the specific representations of $SO(5)$ in which the SM quarks and leptons are embedded. A generic parametrization for $c_f$ in such cases can be given as

$$c_f = 1 + \Delta_f \xi,$$  \hspace{1cm} (4.2)

where $\Delta_f$ is a free parameter which depends on the number of Yukawa operators. If only one Yukawa operator exists, as in cases where the SM fermions are embedded in $\mathbf{4}$, $\mathbf{5}$ or $\mathbf{10}$ of SO(5), $c_f$ is determined only by $\xi$ [47–52]. For example, if the top quark is embedded in the fundamental $\mathbf{5}$ of SO(5) (MCHM$_5$), we find $\Delta_t = -3/2$, while putting the top in spinorial $\mathbf{4}$ (MCHM$_4$), we obtain $\Delta_t = -1/2$. When more than one operator can be constructed, $\Delta_f$ depends on the microscopic parameters of the composite dynamics. Such possibilities may occur when either of the left- or right-handed fermions are embedded in the symmetric $\mathbf{14}$ dimensional representations of SO(5) [51,53–58].

Here we discuss three specific cases for which we have obtained new limits:

- $\Delta_t = \Delta_b = \Delta_\tau = -3/2$ (MCHM$_5$): This is an oft-quoted example when both the left- and right-chiral top quark are kept in $\mathbf{5}$ of SO(5). In this case, the $\chi^2$-function depends on a single parameter $\xi$. We obtain $f \gtrsim 1.2$ TeV at 95% CL using the Run 2 data, while in HL-LHC we expect $f \gtrsim 1.8$ TeV.

- $\Delta_b = \Delta_\tau = -3/2$: Here, we keep $\Delta_t$ as a free parameter, which implies either the left- or the right-handed top quark is embedded in $\mathbf{14}$ of SO(5). The allowed region at 95% CL in the $\Delta_t - \xi$ plane is shown in the left panel of Fig. 3. Clearly, the constraint on $f$ gets relaxed, as alluded in [58]. For a generic value of $\Delta_t$, we obtain the most conservative limit $f \gtrsim 660$ GeV after inclusion of the Run 2 data.

- $\xi$ = constant: We fix two representative values of $\xi = 0.1$ and 0.06, to put simultaneous limits in $\Delta_t - \Delta_b$ plane as shown in the right panel of Fig. 3. We observe that while the present data have not yet gathered enough strength to discriminate between the choices of representations in which the top and bottom quarks are embedded, future measurements with better statistical significance can do the job.

We have kept $c_{gg} = c_{\gamma\gamma} = 0$. This is motivated by the observation that in the composite pseudo-Goldstone Higgs scenario the top partner loop contribution cancels against the contribution of the anomalous dimension of the top quark [53,59].

Composite Higgs models are often seen as dual to some variants of the weakly coupled warped extra dimensional models using the AdS / CFT correspondence [60]. We take a custodial Randall-Sundrum (RS) setup with the Higgs boson localized near the IR brane to study the constraints on the scale of the Kaluza-Klein states ($M_{KK}$) [61–65]. Adapting the expressions for the Higgs coupling modifiers from [65], including the Run 2 data, we obtain a conservative lower limit on the mass of the first excited KK-gluon, $M_g \gtrsim 9$ TeV (which translates into $M_{KK} \gtrsim 3.7$ TeV). The projected limit from HL-LHC is $M_g \gtrsim 12$ TeV.
4.2 Multi-Higgs models

Here we deal with theories involving multiple Higgs bosons with non-trivial SU(2)$_L \times$ U(1)$_Y$ charges. The question is whether the 125 GeV Higgs boson discovered at the LHC is the only one of its genre. Since a long time, searches for additional Higgs multiplets are going on in colliders including the LHC. The most trivial extension of the SM is the addition of a gauge singlet CP-even scalar boson [67, 68]. Due to the ensuing doublet-singlet scalar mixing, parametrized by an angle $\alpha$, the 125 GeV Higgs couplings pick up a factor of $\cos \alpha$. At 95% CL, from Run 1 (Run 2) data we obtain $\sin \alpha \lesssim 0.31$ ($0.18$), while the HL-LHC expectation is $\sin \alpha \lesssim 0.12$.

Now we focus on two-Higgs doublet models (2HDM) [69–75]. The $hVV$ coupling modifications in 2HDM depends on two mixing angles as

$$c_V = \sin(\beta - \alpha). \quad (4.3)$$

Above, the angle $\beta$ parametrizes the mixing between the two doublets, while $\alpha$ is a measure of mass-mixing between the two CP even neutral scalars. In Type-II 2HDM, which also forms the basis of constructing the minimal supersymmetric standard model, the Yukawa coupling modifiers are given by

$$c_t = \frac{\cos \alpha}{\sin \beta}, \quad c_b = -\frac{\sin \alpha}{\cos \beta}. \quad (4.4)$$

Note that, $c_t \neq c_b$ in this case. We have shown the limits on $\tan \beta$ and $\cos(\beta - \alpha)$ in the top-left panel of Fig. 4. The narrow window of allowed region around the alignment limit $\beta - \alpha = \pi/2$ have shrunk considerably with respect to earlier data. In Type-I 2HDM, however, the top and bottom Yukawa couplings are modified by the same factor as

$$c_t = c_b = \frac{\cos \alpha}{\sin \beta}. \quad (4.5)$$
Figure 4: The top-left (top-right) panels show the constraints on parameter space of Type-II (Type-I) 2HDM respectively, while the bottom-left panel corresponds to the BGL (t-type) model. For 2HDM, the solid (dashed) black lines denote the contours of constant $c_t/c_V$ ($c_b/c_V$). The results for Type-I and Type-II 2HDM conform to those obtained in [9, 66]. The bottom-right panel displays the limits on the GM model, for which the solid lines denote the contours for $c_t = c_b$ and the dashed lines denote the same for $c_V$. The color codes are: Run 1 (grey), Run 2 (red), HL-LHC (blue).

In this case, constraints are displayed in the top-right panel of Fig. 4. The results we found for both Type-I and Type-II 2HDM are compatible with those reported in [9, 66]. A special category of 2HDM postulated by Branco, Grimus and Lavoura (the BGL scenario) admits flavor changing neutral current interactions at the tree level, suppressed by the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [76–78]. In some variants of the BGL model (t-type), the expression for $c_t$ resembles that of Type-I 2HDM, while $c_b$ receives an additional contribution proportional to $(\tan \beta + \cot \beta)$ as follows [77]:

\[
c_t = \frac{\cos \alpha}{\sin \beta}, \quad c_b = \frac{\cos \alpha}{\sin \beta} - \cos (\beta - \alpha) (\tan \beta + \cot \beta) (1 - |V_{tb}|^2).
\]

In the low $\tan \beta \lesssim 1$ regime, the constraints on the BGL (t-type) model follow that of the Type-I scenario (see the bottom-left panel of Fig. 4). But with the increasing $\tan \beta \gg 10$, owing to the second
term in $c_b$ in Eq. (4.6), tighter limits are obtained compared to the Type-I model. Notably, the LHC data provide complementary constraints in the low $\tan \beta$ region, which is otherwise less sensitive to the flavor observables [77].

Next, we discuss the triplet-extended scenarios, in particular Georgi-Machacek (GM) model [79–86]. In this model the custodial symmetry is protected by the tree level scalar potential, even if the triplets receive a vev ($v_t$). Without going into the details of the model, we give the expressions for $c_V$, $c_t$ and $c_b$ for this case as

$$c_V = \cos \alpha \cos \beta + 2 \sqrt{\frac{2}{3}} \sin \alpha \sin \beta, \quad c_t = c_b = \frac{\cos \alpha}{\cos \beta}. \quad (4.7)$$

The limits obtained using the Run 1 and Run 2 data from the LHC and the HL-LHC projections are shown in the $v_t - \sin \alpha$ plane in the bottom-right panel of Fig. 4.

A few comments on our analysis are in order. First, in deriving these constraints for 2HDM and the GM model, we assumed that the contribution of the charged Higgs bosons decouple in the $h\gamma\gamma$ decay width and thus can be neglected. However, as shown in [87, 88] the decoupling of the charged Higgs contribution to diphoton decay channel depends on the details of the particular model in question. Indeed, our limits would change accordingly. Second, the limits are obtained assuming only renormalizable interactions. The presence of higher dimensional operators [31, 58, 89–94] would lead to further modifications of all the couplings in addition to what comes out of the mixing in the renormalizable setup. As shown in [95] in the context of 2HDM and in [94] for the GM model, these additional modifications would leave indelible imprint on the ranges of the model parameters.

5 Conclusions and outlook

We summarize below the important points raised in this paper. The LHC Run 2 data contain a significantly improved information on the Yukawa couplings. Their inclusion has allowed us to extract important limits.

- The ATLAS and CMS Collaborations have made an important breakthrough in getting a grip on the Yukawa force for the first time. If the Higgs boson turns out to be elementary, then it signifies the observation of a new fundamental force. The experimental measurements have made a huge impact in constraining the allowed region of BSM physics manifesting through modified Yukawa couplings. The Run 2 data are particularly instrumental in squeezing the $2\sigma$ BSM window in the Yukawa couplings from 25% to 15% around their SM values when compared to the performance of the Run 1 data. HL-LHC would bring it down to within 5%. The limits on $hVV$ ($V = W, Z$) couplings from the LHC are now competitive with those obtained from electroweak precision tests. The Run 1 (Run 2) data allow not more than 18% (7%) of the total branching fraction of the Higgs boson in the invisible channel. However, larger leak into invisible mode can be accommodated if the $hVV$ and $hf\bar{f}$ couplings substantially deviate from their SM reference points.

- We consider a few motivated BSM scenarios and recast the constraints from our model independent analysis on the parameter space of those specific models using the latest Higgs data. We have observed that, in the context of the SO(5)/SO(4) minimal composite Higgs model, more precise measurements of Yukawa forces have improved the limits on the compositeness scale. The limits depend on the representations of SO(5) in which we embed the left- and right-chiral
top quark. At 95% CL, our new limits are

\[ f \gtrsim 660 \text{ GeV} \text{ (most conservative)}, \quad f \gtrsim 1.2 \text{ TeV} \text{ (MCHM}). \]

We have shown how the future HL-LHC data would further sharpen the limits. In the RS scenarios with the Higgs boson localized near the IR brane, the first excited KK-gluon weighs more than \( \mathcal{O}(10) \) TeV. The exact limit depends on the details of the model parameters.

- The amount of mixing between the SM Higgs with any additional scalar singlet is observed to be rather constrained by the present data, given by \( \sin \alpha \lesssim 0.18 \). For Type-II 2HDM, only a narrow region around the alignment limit is acceptable, while for the Type-I case a considerable area in the large \( \tan \beta \) region is still allowed. In the BGL (t-type) model the constraints in the low \( \tan \beta \lesssim 1 \) region is in the same ballpark as in the Type-I scenario, while for \( \tan \beta \gg 10 \) the BGL (t-type) receives stronger constraints than Type-I. We have also shown that for the Georgi-Machacek model \( v_t \lesssim 48 \text{ GeV} \) and \(-0.3 \lesssim \sin \alpha \lesssim 0.5\) are allowed by the present data. If data continue to push the Higgs couplings towards the SM-like limits, certain scenarios might still accommodate additional light scalars; however, their hunt at the LHC would require special strategies.

- Once the HL-LHC data become available, a better handle on the Yukawa couplings, including those involving other fermions (e.g. \( \tau \) lepton), would unravel even inner layers of underlying dynamics.

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