

# The Composite Higgs Signal at the Next Big Collider\*

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## Abstract

The Gildener-Weinberg (GW) mechanism produces a Higgs boson  $H$  that is a dilaton. That is,  $H$  is both naturally light and naturally aligned. It also predicts additional singly-charged and neutral Higgs bosons all of whose masses are  $\lesssim 500$  GeV and, therefore, within reach of the LHC *now*. I argue that the GW Higgs is composite — a bound state of fermions whose strong interactions are at some high, unknown scale  $\Lambda_H \gtrsim 1$  TeV. The lone harbingers of  $H$  compositeness, ones that may be accessible at the next multi-TeV collider, are isovector vector  $\rho_H$  and axial vector  $a_H$  bound states whose masses are  $\mathcal{O}(\Lambda_H)$ . They decay into the only fermion-antifermion composites lighter than they are, the Higgs boson and longitudinally-polarized weak bosons:  $\rho_H^{\pm,0} \rightarrow W_{\mathcal{L}}^{\pm} Z_{\mathcal{L}}, W_{\mathcal{L}}^+ W_{\mathcal{L}}^-$  and  $a_H^{\pm,0} \rightarrow W_{\mathcal{L}}^{\pm} H, Z_{\mathcal{L}} H$ . Observing these resonant, highly-boosted weak-scale bosons would establish their composite nature.

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\*This paper is dedicated to my friend and collaborator, Eric Pilon.

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# 1. Why I think the Higgs is composite

No one believes that the 125-GeV Higgs boson  $H$  discovered at CERN in 2012 [1, 2] is anywhere near all there is to the Higgs sector. As a theoretical construct,  $H$  has so many shortcomings — which hardly need repeating here<sup>1</sup> — that they overshadow the essential roles it plays in the Standard Model of breaking electroweak symmetry and giving mass to the weak gauge bosons and (most) fermions. Thus, the history of elementary particle physics since 1972 has been dominated by the search for and proposal of solutions to these deficits.

The solutions that have been proposed invariably require additional Higgs bosons. The more popular of these include supersymmetry, little Higgs models, extended weak gauge symmetries, dark sectors and, prosaically, multi-Higgs doublet models which, often, are more or less well-motivated by overarching theoretical constructs such as those just mentioned. After all these years, however, and especially after all the heroic searches for extensions of the Standard Model's  $SU(2) \otimes U(1)$  gauge symmetry [5] and its single complex Higgs doublet, there is *no evidence* that the Higgs boson is anything other than that proposed so long ago [6]. Not only are there no extra Higgs bosons, there are no TeV-scale partners of the top quark and the weak  $W$  and  $Z$  bosons, there are no Higgsinos, squarks, sleptons, gauginos, no experimental support for dark portals such as long-lived particles, no sign of vector-quarks or vector-leptons, nothing new at all since 2012. And, to belabor the point, the Higgs  $H$  appears in every respect to be that expected in the Standard Model: all measurements so far of its interactions with weak bosons and massive fermions are within one standard deviation of the Standard Model's predictions; see Fig. 1.

Yet, we still believe there is more to the Higgs than the Standard Model (SM). A major difficulty of this belief is that, if there are other Higgs bosons, why should exactly one mass eigenstate scalar have SM couplings? The usual answer is “Higgs alignment” [7, 8, 9, 10]. However, alignment often assumes a sizable hierarchy of Higgs masses so that the lightest Higgs decouples and has SM couplings. With a few exceptions that rely on elaborate global sym-

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<sup>1</sup>But to name the most serious, see Refs. [3],[4].

metries or supersymmetry (see, e.g., Refs. [11, 12, 13, 14]), such decoupling suffers from large radiative corrections.

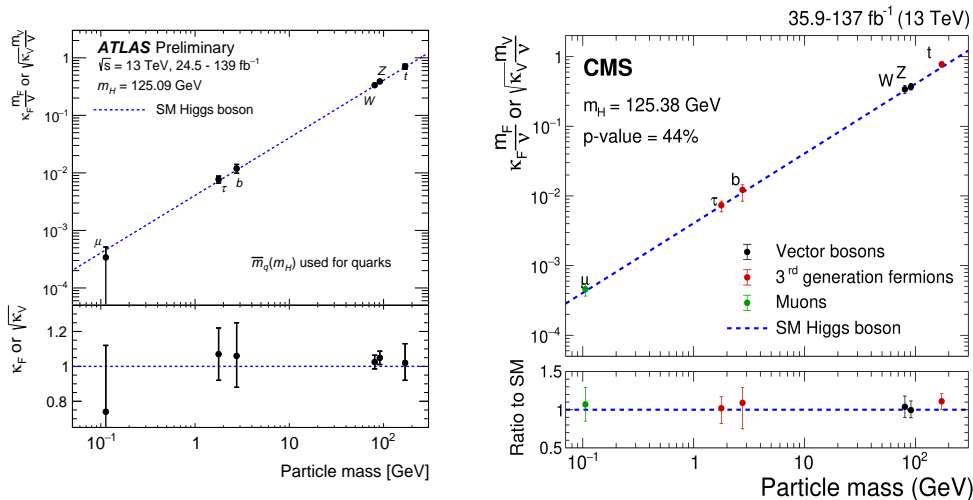


Figure 1: The mass-dependent couplings of quarks, leptons and the  $W$  and  $Z$  as measured by ATLAS (<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/>) and CMS (<https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html>).

Another possibility is that the Higgs boson is composite. This was always the case in technicolor, but there was no obvious reason why the Higgs would be much lighter than the technicolor scale of  $\mathcal{O}(1 \text{ TeV})$ .

The way out of this is that  $H$  is a dilaton, a pseudo-Goldstone boson of spontaneously broken scale invariance that is also explicitly broken at some scale  $f$ . See Ref. [15] for some earlier references on this subject. A major advantage of the dilaton scheme is that its couplings to weak bosons and fermions have the same form as the SM Higgs'. However, those couplings are proportional to  $f$ , and  $f \neq v = 246 \text{ GeV}$  in general. There is one exception to this:  $f = v$  if *only* operators that are charged under the electroweak gauge group have conformal-symmetry-breaking vacuum expectation values, i.e., if the agent responsible for electroweak symmetry breaking, the Higgs boson,

is also the one responsible for explicit scale symmetry breaking [16].

Now, this is an intriguing possibility and one that was realized long ago [17] yet not generally recognized as such. As I'll argue next, I believe this possibility makes sense only if  $H$  is composite.

## 2. Why I think $H$ is the Gildener-Weinberg dilaton

If  $H$  is the massless dilaton of spontaneously-broken scale symmetry, its low-energy Lagrangian must be classically (i.e., at tree level) scale-invariant. How this happens is a mystery. As far as we understand, the responsibility lies with scale-invariant interactions of massless fermions at some higher energy scale  $\Lambda_H$ . Presumably, these are strong gauge interactions (S.I.) that generate  $H$  as a bound state of the fermions [4]. One thing we know about these interactions is that

$$\Lambda_H \gtrsim 1 \text{ TeV}. \tag{1}$$

The S.I. fermions must transform under electroweak  $SU(2) \otimes U(1)$  so that  $H$  does and, therefore, have weak isospin  $\frac{1}{2}$  and 0. Assuming that their chiral symmetry contains the electroweak symmetry, these fermions must also produce the three Goldstone bosons,  $W_{\mathcal{L}}^{\pm}$  and  $Z_{\mathcal{L}}$ , that become the longitudinal ( $\mathcal{L}$ ) components of the electroweak gauge bosons. The four massless bound states ( $H, W_{\mathcal{L}}^{\pm}, Z_{\mathcal{L}}$ ) then form a complex  $(2_L, 2_R)$  doublet  $\Sigma$  under  $SU(2)_L \otimes SU(2)_R$  which is contained in the S.I. fermions' chiral symmetry. The low-energy theory also contains quarks and leptons and, possibly, other scalars. They too must be massless at tree-level to maintain the scale-invariance. This is natural for the known fermions  $\psi$  since they transform as left-handed electroweak doublets and right-handed singlets. Then,  $\Sigma$  couples  $\psi_L$  to  $\psi_R$  to break their chiral symmetry. If there are additional scalars, their self-interactions must be purely quartic, as are their Yukawa and gauge interactions. This must be enforced by the scale-invariant S.I. at  $\Lambda_H$ .

Finally, the scale invariance must be explicitly broken so that all these massless particles including  $H$  (but not the photon) acquire mass. This can happen as a consequence of the renormalization of the low-energy theory with

the appearance of a massive renormalization scale. This is the mechanism of S. Coleman and E. Weinberg for generating masses in a (classically) scale-invariant theory [18].

## 2.a The Gildener-Weinberg 2HDM

The low-energy effective Lagrangian for this picture was written down 46 years ago by E. Gildener and S. Weinberg (GW) [17]. Their aim was to use it to produce a very light Higgs boson. In doing this, GW assumed that all quarks and leptons are light compared to the weak scale (which, of course, they were then) and that all the quartic scalar self-interactions were of order  $e^2$ . (They couldn't be smaller than that because of electroweak radiative corrections.) We now know that the top quark is very heavy and, so, it turns out there is no need for the second assumption on the scalar self-couplings. See Eq. (2) for the need for heavier scalars in the presence of the top quark.

GW did not adopt a specific model of their scheme. However, using the Coleman-Weinberg expansion for the low-energy effective potential, they derived a very important formula for the Higgs mass:

$$M_H^2 = \frac{1}{8\pi^2 v^2} \left( 3 \sum_V M_V^4 + \sum_S M_S^4 - 4 \sum_F M_F^4 \right), \quad (2)$$

where the sums are over the degrees of freedom (polarizations, colors, etc.) of massive gauge bosons  $V$ , scalars  $S$  and fermions  $F$ .

As already alluded to above, another very important consequence of Ref. [17] is that the  $H$  couplings to fermions and weak gauge bosons have the same form as in the SM. When the conformal symmetry is explicitly broken in the one-loop potential, all those couplings are proportional to the Higgs vacuum expectation value,  $v = 246$  GeV. That is, this Higgs is *aligned!* The one-loop corrections to perfect alignment are very small and would be absent altogether were it not for the top quark [19]. Thus, the alignment is natural and the departures from perfect alignment naturally small.

The simplest model employing the GW scheme was proposed by Lee and Pilaftsis in 2012 [20]. The model assumes the standard electroweak gauge symmetry with the known quarks and leptons. It also has two Higgs

doublets so that, in addition to  $\Sigma = (H, W_{\mathcal{L}}^{\pm}, Z_{\mathcal{L}})$ , the second doublet is  $\Sigma' = (H', H^{\pm}, A)$  where  $H'$  is  $CP$ -even and  $A$  is  $CP$ -odd.<sup>2</sup> Because of the dominant role the Gildener-Weinberg mechanism plays in this model, I refer to it as the GW-2HDM.

## 2.b What are the signals of the GW-2HDM?

With  $M_H = 125$  GeV, Eq. (2) implies a sum rule for the masses of the new Higgs bosons:

$$(M_{H'}^4 + M_A^4 + 2M_{H^{\pm}}^4)^{1/4} = 540 \text{ GeV}. \quad (3)$$

This sum rule holds in the one-loop approximation of *any* GW model of electroweak symmetry breaking in which the only weak bosons are  $W$  and  $Z$  and the only heavy fermion is the top quark. Thus, the larger the Higgs sector, the lighter will be the masses of at least some of the BSM Higgs bosons expected in a GW model. In short, these models predict the new Higgs bosons at surprisingly low masses.

These light BSM Higgs bosons are by far the surest way to test the GW-2HDM at the LHC in this decade and, perhaps, for longer than that. The current experimental situation is summarized in Refs. [21, 19]. To avoid conflict with precision measurements of the  $T$ -parameter,  $M_{H^{\pm}} = M_A$  is assumed (see Ref. [20] and references therein). Then,  $M_{H'}$  can be taken from the sum rule (3). The 2HDM parameter  $\tan \beta \lesssim 0.50$  for  $180 \text{ GeV} < M_{H^{\pm}} < 550 \text{ GeV}$ .<sup>3</sup> This limit comes from a CMS search with 8 TeV data for  $H^+ \rightarrow t\bar{b}$  [23]. Subsequent searches by ATLAS [24] and CMS [25] at 13 TeV have not improved on this limit because the  $t\bar{t}$  background is large and grows faster with energy than the signal.<sup>4</sup>

Similar low-energy difficulties afflict other searches. The decay  $A$  or  $H' \rightarrow \bar{t}t$  at and not far above the  $\bar{t}t$  threshold at 350 GeV are subject to theoretical

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<sup>2</sup>The quartic scalar potential is automatically  $CP$ -conserving [20, 15].

<sup>3</sup>The version of the GW-2HDM discussed in Refs. [15, 21, 19] has the structure of the usual type-I 2HDM [22], but with the Higgs doublets  $\Phi_1$  and  $\Phi_2$  interchanged. The effect of this is that experimental lower limits on  $\tan \beta = v_2/v_1$  in other type-I models are lower limits on  $\cot \beta$  in this model.

<sup>4</sup>Above  $M_{H^{\pm}} = M_A \simeq 400 \text{ GeV}$ , the sum rule implies such a light  $M_{H'}$  that it decays to  $b\bar{b}$  or two gluons, a signal that is overwhelmed by the QCD background.

uncertainties in the QCD production rate there [Sirunyan:2019wph]. For lower mass  $A$  or  $H'$ , their decays to  $\bar{b}b$  are swamped by the QCD backgrounds.

There have been many other LHC searches for BSM Higgs bosons, almost exclusively at higher masses. Two examples are  $gg$  or weak-boson fusion of  $H'$  and  $A$  followed by their decay to  $ZH$  or to  $WW$  and  $ZZ$ . These and many other searches have been fruitless. That is expected for the GW-2HDM (and similar models). Many if not most of these searches have been based on processes that are forbidden for an aligned Higgs  $H$ .<sup>5, 6</sup>

### 3. What role can the next big collider play?

Although the low-mass signals of the GW-2HDM are well within reach of the LHC with its 13-14 TeV collision energies and high luminosities, they are not accessible to the ATLAS and CMS detectors because of their difficulty overcoming the QCD backgrounds at such masses. It is to be hoped that the detector and analysis improvements being made for Run 3 will remedy this.

However, there is one signal of these models that must exist somewhere above 1 TeV and which is probably GW-model independent. That is the existence of heavy spin-one bound states of the S.I. fermions. They have an isospin  $I = 1$  (and 0) inherited from the weak isospin of the fermions. Their masses are  $\mathcal{O}(\Lambda_H)$  and, so, unknown. But we look where we can, and the planners for the next big collider being discussed in Europe, the US and China would do well to make searching for these resonances a priority. They and the way they decay will be direct evidence that  $H$  and  $W_{\mathcal{L}}^{\pm}$ ,  $Z_{\mathcal{L}}$  are composites of the S.I. fermions.

The S.I. have a parity-invariance, much like the parity of QCD. Because of the parity inherent in the  $(2_L, 2_R)$  symmetry of  $\Sigma$ , the isovector bosons will be (ordinary) vectors and axial vectors analogous to the  $\rho$  and  $a_1$  of hadron physics. Unlike QCD, they are expected to be nearly degenerate. I will call them  $\rho_H$  and  $a_H$  to emphasize their connection to the Higgs  $H$ . For more theoretical background and details of the S.I. and their symmetry structure,

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<sup>5</sup><https://twiki.cern.ch/twiki/bin/view/AtlasPublic>

<sup>6</sup><https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/SUS.html>

see Refs. [26, 27, 28].

The  $\rho_H$  and  $a_H$  are produced mainly by the Drell-Yan process:

$$\bar{q}'q \rightarrow W^\pm, Z, \gamma \rightarrow \rho_H^{\pm,0}, a_H^{\pm,0} \quad \text{in a hadron collider;} \quad (4)$$

$$\ell^+\ell^- \rightarrow Z, \gamma \rightarrow \rho_H^0, a_H^0 \quad \text{in a lepton collider.} \quad (5)$$

In a  $pp$  collider, there is also weak-boson fusion (VBF) of  $\rho_H$  and  $a_H$ . At the LHC, VBF accounts for only 20% of  $\rho_H$  production and very little for  $a_H$  [27]. This fraction needs to be determined at much higher energies. For an  $\ell^+\ell^-$  collider, the greatest reach, perhaps competitive with a 100 TeV  $pp$  collider, might be achieved by a muon collider.<sup>7</sup> This would be an interesting study for the Snowmass Muon Collider Forum.

The principal decays of  $\rho_H$  and  $a_H$  are to the only S.I. fermion bound states lighter than themselves, namely, the dilaton  $H$  and the longitudinal weak bosons  $W_{\mathcal{L}}^\pm, Z_{\mathcal{L}}$  — the “pions” of S.I. physics. These decays obey the parity of the S.I. interactions.<sup>8</sup>

$$\rho_H^\pm \rightarrow W_{\mathcal{L}}^\pm Z_{\mathcal{L}}, \quad \rho_H^0 \rightarrow W_{\mathcal{L}}^+ W_{\mathcal{L}}^- \quad (\text{but not to } Z_{\mathcal{L}} Z_{\mathcal{L}}); \quad (6)$$

$$a_H^\pm \rightarrow W_{\mathcal{L}}^\pm H, \quad a_H^0 \rightarrow Z_{\mathcal{L}} H. \quad (7)$$

For  $M_{\rho_H}^2 \cong M_{a_H}^2 \gg M_{W,Z,H}^2$  the final-state bosons are highly-boosted and the longitudinal polarization vectors  $\epsilon_{\mathcal{L}} \cong M_{\rho_H}/2M_{W,Z}$ . This makes the otherwise weak-decay rates of Eqs. (6,7) strong. They are [27]

$$\Gamma(\rho_H^0 \rightarrow W^+W^-) \cong \Gamma(\rho_H^\pm \rightarrow W^\pm Z) \cong \frac{g_{\rho_H}^2 M_{\rho_H}}{48\pi}, \quad (8)$$

$$\Gamma(a_H^0 \rightarrow ZH) \cong \Gamma(a_H^\pm \rightarrow W^\pm H) \cong \frac{g_{a_H}^2 M_{a_H}}{48\pi}, \quad (9)$$

where the S.I. couplings  $g_{\rho_H} \cong g_{a_H} = \mathcal{O}(1)$  (presumably). Then,  $\Gamma(\rho_H, a_H) = \mathcal{O}(M_{\rho_H}/100)$ . Finally, since the  $\bar{q}q'$  or  $\ell^+\ell^-$  annihilation to  $\rho_H$  and  $a_H$  occurs with one unit of angular momentum along the beam axis, the decay bosons will be emitted with a  $\sin^2 \theta$  angular distribution in the  $\rho_H/a_H$  rest frame.

<sup>7</sup>I thank Tulika Bose for making this point.

<sup>8</sup>This is *not* the often benchmarked HVT model!



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