

Higgs Boson Physics: The View Ahead

Howard E. Haber

Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA

Abstract

Eleven years ago, the Higgs boson was discovered at the LHC. I briefly survey the status of Higgs boson physics today and explore some of the implications for future Higgs studies. Although current experimental measurements are consistent with interpreting the observed Higgs boson as being consistent with the predictions of the Standard Model of particle physics, it is still possible that the Higgs boson is a member of an extended scalar sector that lies beyond the Standard Model. Nevertheless, an extended Higgs sector is already highly constrained. The Higgs sector can also serve as a portal to new physics beyond the Standard Model. Finally, two Higgs wishlists are assembled that merit future study and clarification at the LHC and future collider facilities now under development.

Keywords: Higgs boson, Standard Model, electroweak symmetry breaking, extended Higgs sectors, 2HDM
DOI: 10.31526/LHEP.2023.451

1. INTRODUCTION

The W^\pm and Z gauge bosons, which mediate the weak nuclear force, were discovered in 1983 (see, e.g., L. Di Lella and C. Rubbia in [1]). Due to electroweak symmetry breaking, nonzero masses for the W^\pm and Z are generated, whereas the photon (which mediates the electromagnetic force) remains massless. A priori, one could have imagined a plethora of possible dynamical models responsible for electroweak symmetry breaking. Remarkably, the simplest possible model, a self-interacting complex doublet of elementary scalar fields that yields a physical scalar particle—the Higgs boson, is consistent with all current experimental data. Nevertheless, there are a number of profound theoretical questions which suggest that the complete story of electroweak symmetry breaking has not yet been written. In this short review, I will briefly discuss the current status of Higgs boson physics and explore some of the implications for future Higgs studies.

2. THE CURRENT STATUS OF THE HIGGS BOSON

On July 4, 2012, the discovery of an electrically neutral scalar particle with a mass of about 125 GeV at the Large Hadron Collider (LHC) was announced (see, e.g., P. Jenni and T. S. Virdee in [1]). After ten years of data collection and analysis, it has been determined that the properties of this scalar particle closely resemble those of the Higgs boson that was predicted by the Standard Model (SM) of particle physics [2]. At the LHC, Higgs bosons are produced by a variety of mechanisms, the most important of which is gluon-gluon fusion (ggF). Once produced, the Higgs boson (denoted by H) can decay into a variety of final states. The relevant experimental observable is the product of the cross section (σ) of a given production mechanism multiplied by the branching ratio (B) for Higgs boson decay into the observed final state. In Figure 1, the product σB for the various Higgs production mechanisms and final state decay products, observed by the ATLAS Collaboration [3], is compared with the corresponding SM predictions. A similar plot obtained by the CMS Collaboration can be found in [4].

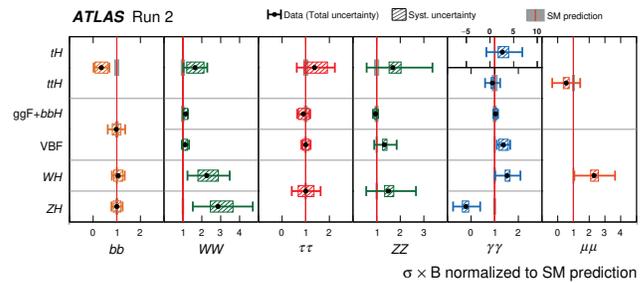


FIGURE 1: Ratio of observed rate to predicted SM event rate for different combinations of Higgs boson production and decay processes, as observed by the ATLAS Collaboration (based on 139 fb^{-1} of data). The horizontal bar on each point denotes the 68% confidence interval. The narrow grey bands indicate the theory uncertainties in the SM cross section times the branching fraction predictions. The p -value for compatibility of the measurement and the SM prediction is 72%. Taken from [3].

The Higgs boson is intimately connected with the mechanism of mass generation for the fundamental particles of the SM (quarks, charged leptons, and gauge bosons). As a result, the SM Higgs boson couples to fermions [gauge bosons] with a strength that is proportional to the corresponding fermion mass [gauge boson squared mass]. This expected behavior is experimentally reproduced in Figure 2 based on results obtained by the CMS Collaboration [4]. A similar plot obtained by the ATLAS Collaboration can be found in [3]. The results shown in Figures 1 and 2 provide a quantitative measure of the consistency of the Higgs boson properties with those predicted by the SM.

Although the SM has been remarkably successful in describing the behavior of the fundamental particles and their interactions, the SM cannot be the ultimate theory of particle physics. Putting aside a few experimental anomalies that could be statistical flukes or could be evidence of cracks in the SM, there exist a number of important clues that strongly suggest the need for new physical laws beyond the Standard Model (BSM). For example, the astrophysical evidence for dark matter cannot be explained in the context of the SM, and may be a consequence of a new particle associated with BSM physics [5]. Another hint for BSM physics arises when attempting to devise a theory of baryogenesis in the early universe to explain the

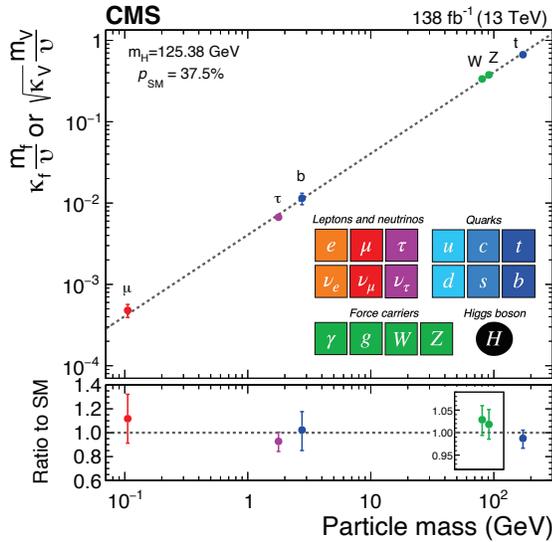


FIGURE 2: The measured coupling modifiers of the Higgs boson to fermions and heavy gauge bosons, observed by the CMS Collaboration, as functions of fermion or gauge boson mass, where v is the vacuum expectation value of the Higgs field. For gauge bosons, the square root of the coupling modifier is plotted, to keep a linear proportionality to the mass, as predicted in the SM. The p -value with respect to the SM prediction is 37.5%. Taken from [4].

observed asymmetry between baryons and their antiparticles, which cannot be explained by SM physics alone [6]. Finally, the origin of the energy scale of electroweak symmetry breaking remains a mystery. Employing an old argument first advanced by Weisskopf in 1939 [7], the quadratic divergence of the self-energy of an elementary scalar H is interpreted as implying the existence of a new energy scale of order $\Lambda \sim m_H/g \sim 1$ TeV (where g is a weak coupling constant). The scale Λ characterizes the BSM physics that governs the fundamental dynamics of electroweak symmetry breaking. The TeV energy scale is now being probed at the LHC, although so far no evidence for BSM physics has been detected. In the absence of new physics near the TeV scale, the Higgs sector of the SM is *unnatural*; see [8] for further details.

In many approaches, hints for the existence of BSM physics will emerge from theoretical and experimental studies of the Higgs sector. Here is one interesting example. The Higgs field of the SM has a local minimum at a field value of $v = 246$ GeV. However, it is possible that a second minimum develops at very large scalar field values as shown in Figure 3. For field values larger than the Planck energy scale, $M_P = 10^{19}$ GeV, calculations within the SM are not reliable, as gravitational effects can no longer be neglected. However, at field values below M_P , one can reliably compute the shape of the SM scalar potential to determine whether our vacuum is stable.

As shown in Figure 4, a theoretical computation most recently carried out in [9] indicates that in the SM, the electroweak vacuum is in fact metastable (after using the observed values of the top quark and Higgs mass along with the measured value of the strong coupling constant α_s evaluated at the Z boson mass). The same authors estimate that the lifetime of this metastable vacuum is 10^p years, where $p = 139_{-51}^{+102}$. That

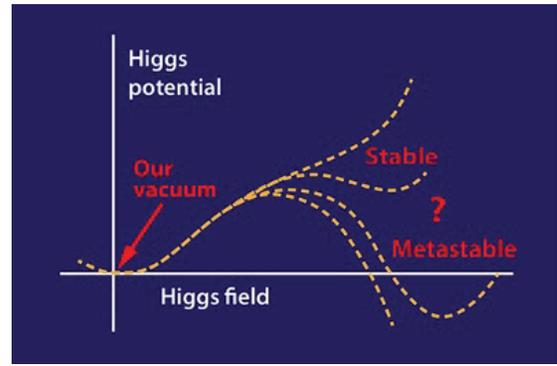


FIGURE 3: The electroweak vacuum may not be stable depending on the behavior of the scalar potential at large Higgs field values (figure courtesy of A. Kusenko).

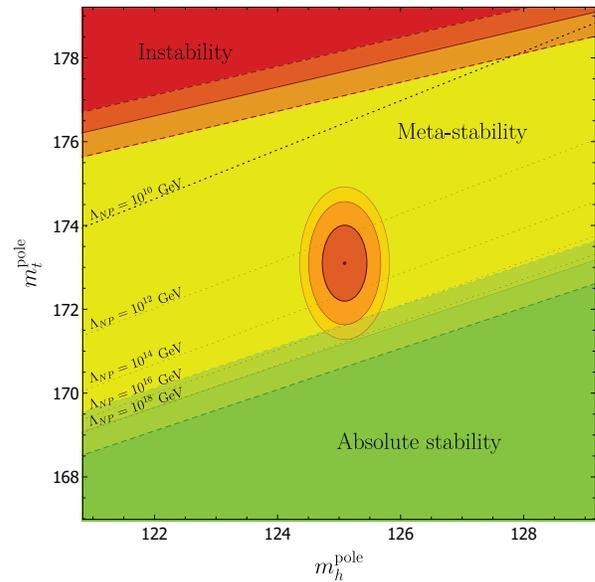


FIGURE 4: The results of a computation presented in [9] indicate that the electroweak vacuum of the SM is metastable. The ellipses show the 68%, 95%, and 99% contours based on the experimental uncertainties in the top quark and Higgs boson pole masses. The dotted lines indicate the energy scale at which the addition of higher-dimensional operators could stabilize the SM.

is, the lifetime of the electroweak vacuum is enormous as compared with the age of the universe (which is roughly 14 billion years). Although this result alleviates any concern about the future demise of our universe, it is nevertheless unsettling that our present vacuum may not be absolutely stable. Moreover, as indicated in Figure 4, if new BSM physics enters at an energy scale between LHC energies and the Planck scale, then the metastability properties of the electroweak vacuum could be significantly altered (and perhaps rendered absolutely stable).

In July, 2022, Run 3 of the LHC commenced, with an expectation of collecting 250 fb^{-1} of data over the next four years. After completion of Run 3, preparations will begin for the

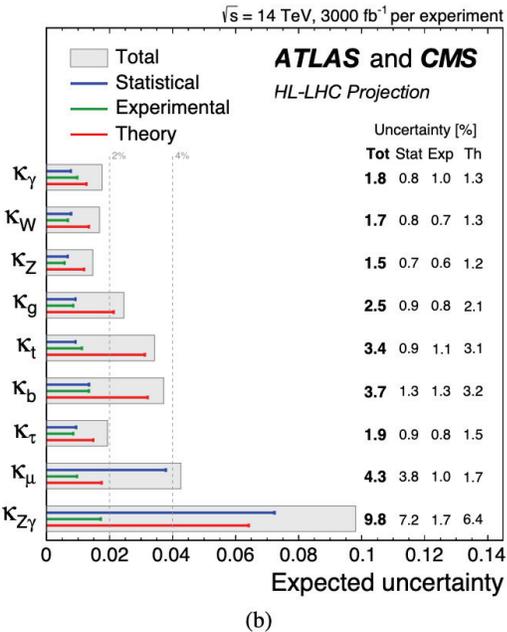
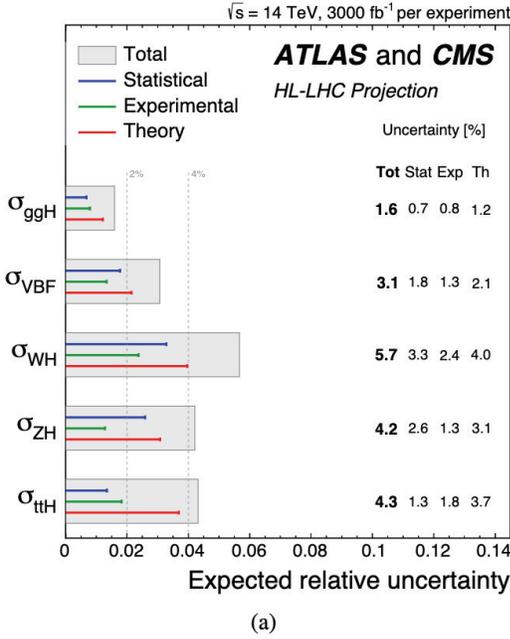


FIGURE 5: Summary plots showing the total expected uncertainties on (a) the per-production-mode cross sections normalized to the SM predictions and (b) the coupling modifier parameters (κ), for the combination of ATLAS and CMS extrapolations. For each measurement, the total uncertainty is indicated by a grey box while the statistical, experimental, and theory uncertainties are indicated by a blue, green, and red line, respectively. Taken from [10].

High Luminosity phase of LHC (HL-LHC). It is expected that the HL-LHC will begin its run at the end of this decade, and will deliver 3 ab^{-1} of data during its lifetime (after roughly ten years of operation). The expected improvement of the experimentally measured Higgs boson properties is exhibited in Figure 5.

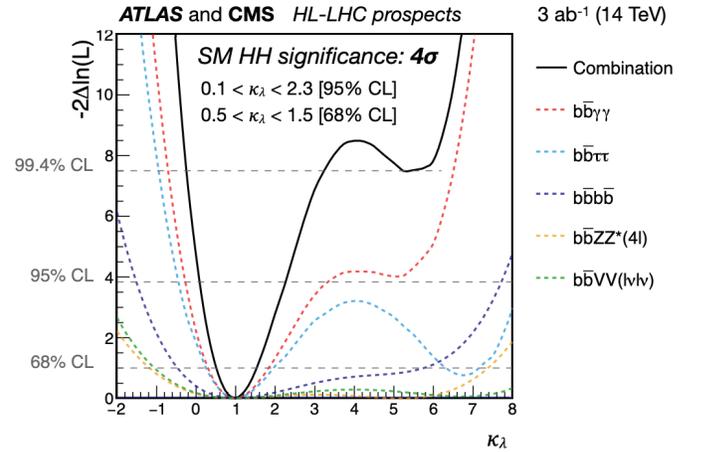


FIGURE 6: Negative-log-likelihood scan as a function of κ_λ , calculated by performing a conditional signal+background fit to the background and SM signal. The colored dashed lines correspond to the combined ATLAS and CMS results by channel, and the black line is their combination. Taken from [10].

One of the most critical measurements not shown in Figure 5 is the triple Higgs coupling, which would provide the first evidence for the shape of the scalar Higgs potential away from its minimum. The triple Higgs coupling λ can be deduced from the observation of HH production. In particular, the HH production amplitude consists of two contributions: one term that is proportional to λ and a second term that is independent of λ . If the triple Higgs coupling is given by its SM value, then a combined analysis by the ATLAS and CMS Collaborations with the full HL-LHC dataset of 3 ab^{-1} anticipates an observation of HH production with a significance of 4σ , as shown in Figure 6. Due to the destructive interference of the two contributions to the HH production amplitude noted above, the triple Higgs coupling modifier κ_λ (where $\kappa_\lambda = 1$ corresponds to the SM expectation) is projected to be measured with an accuracy of 50% at the HL-LHC, as indicated in Figure 6.

Although the Higgs boson H appears to be SM-like, there are numerous questions that must be addressed by future experiments. Some of these questions can be addressed by the HL-LHC, whereas others will require a new generation of colliders.¹ The following Higgs wishlist consists of some key questions to be answered in future Higgs studies.

- (1) What are the coupling strengths of H to second-generation quarks (c, s)?
- (2) Can the coupling strengths of H to first-generation quarks (u, d) and/or gluons be determined?
- (3) Is it possible to measure the coupling strength of H to electrons?
- (4) Will sufficient precision ever exist to measure the invisible decay partial width expected in the SM ($H \rightarrow ZZ^* \rightarrow \nu\bar{\nu}\nu\bar{\nu}$)? How well can one constrain the branching ratio of H into invisible final states (that might be present in certain BSM scenarios)?

¹The next generation of colliders under consideration includes e^+e^- colliders with a center of mass energy starting at 250 GeV and eventually reaching 1 TeV and beyond, a $\mu^+\mu^-$ collider with a center of mass energies between 3 and 10 TeV, and a pp collider with a center of mass energy of 100 TeV [11].

- (5) With what ultimate accuracy can one predict the properties (cross sections, partial widths, etc.) of the SM Higgs boson? What are the important missing theoretical computations that need to be done?
- (6) How well can one determine the Higgs self-coupling? To what extent (and with what accuracy) can one experimentally reconstruct the Higgs scalar potential?
- (7) With what accuracy and reliability can one experimentally determine the total decay width of H ?
- (8) Will experimental deviations from SM Higgs boson properties, if observed, be convincing? Will they reveal a new energy threshold for BSM physics?
- (9) Do Higgs bosons couple to a dark sector made up of new particles that are completely neutral with respect to the SM (the so-called ‘‘Higgs portal’’ [12])?
- (10) Will convincing data emerge that implies that H is not an elementary scalar but is in fact a composite state of more fundamental entities?

3. BEYOND THE SM HIGGS BOSON

One notable feature of the SM is the minimal structure of the scalar sector of the theory. In light of the nonminimality of the fermion and gauge sectors, it is tempting to suggest that the scalar sector of the theory should be nonminimal as well. Indeed, there are numerous motivations for considering an extended Higgs sector. For example, extended Higgs sectors can provide a dark matter candidate and can modify the electroweak phase transition in a way that facilitates baryogenesis in the early universe. In addition, many models of BSM physics (often introduced to address the naturalness problem of the Higgs sector) require the introduction of additional scalar states beyond the SM Higgs boson.

One cannot arbitrarily extend the Higgs sector of the SM due to a number of important constraints arising from observed experimental data. For example, the electroweak ρ parameter, which is measured to be very close to 1 [13], significantly restricts the possible scalar multiplets. Given a scalar multiplet of weak isospin T and hypercharge² Y ,

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = 1 \quad \Leftrightarrow \quad (2T+1)^2 - 3Y^2 = 1, \quad (1)$$

independently of the scalar field vacuum expectation values. The simplest solutions to the Diophantine equation given in equation (1) correspond to singlet scalars $(T, Y) = (0, 0)$ and hypercharge-one complex scalar doublets $(T, Y) = (\frac{1}{2}, 1)$.

More generally, one can achieve a tree-level value of $\rho = 1$ by fine-tuning the parameters of the scalar potential if the following condition is satisfied [14]:

$$\sum_{T,Y} \left[4T(T+1) - 3Y^2 \right] |V_{T,Y}|^2 c_{T,Y} = 0, \quad (2)$$

where $V_{T,Y} \equiv \langle \Phi(T, Y) \rangle$ is the vacuum expectation value of the scalar field Φ , and $c_{T,Y} \equiv 1$ [$c_{T,Y} = \frac{1}{2}$] for a complex [real] representation of scalar fields. For example, the Georgi-Machacek model [15], which extends the SM Higgs sector by adding a

hypercharge-two complex scalar triplet $(T, Y) = (1, 2)$ and a hypercharge-zero real scalar triplet $(T, Y) = (1, 0)$, satisfies the condition specified in equation (2) by choosing a scalar potential in which $V_{1,2} = V_{1,0}$. However, this scalar potential is not stable with respect to radiative corrections, and thus requires a fine-tuning of scalar potential parameters to impose the required condition on the triplet scalar field vacuum expectation values.

The experimental rarity of flavor-changing neutral currents imposes significant restrictions on the structure of the Higgs couplings to fermion pairs. This implies that Higgs-mediated flavor-changing neutral currents (FCNCs) must be significantly suppressed. In addition, charged Higgs exchange at tree level (which can mediate $\bar{B}_d \rightarrow D^{(*)} \tau^- \nu_\tau$) and at one loop (which can contribute to $b \rightarrow s\gamma$) yields significant constraints on the charged Higgs mass and the corresponding Yukawa couplings [16]. Extended Higgs sectors also provide new sources for CP violation, which are constrained by the nonobservation of electric dipole moments for the neutron and electron [17]. Finally, given that the Higgs boson appears to be SM-like, any model that extends the Higgs sector beyond the SM must contain one scalar state that can be identified with the SM-like Higgs boson observed at the LHC.

The absence of tree-level scalar-mediated FCNCs and the presence of a SM-like Higgs boson in the scalar spectrum are features of certain limiting cases of extended Higgs models, called the flavor alignment limit and the Higgs alignment limit, respectively. Flavor alignment [18] posits that all Higgs-fermion Yukawa matrices are aligned with the corresponding fermion mass matrices (which eliminates flavor-changing neutral currents mediated by a neutral scalar exchange in the Higgs Lagrangian). Higgs alignment [19, 20, 21, 22, 23] posits that in a scalar field basis where only one of the Higgs doublet fields possesses a nonzero vacuum expectation value, the associated neutral scalar field that resides in the same doublet is an approximate mass eigenstate field (to be identified with the SM-like Higgs boson observed at the LHC).

To illustrate the constraints arising from imposing these two alignment conditions, consider the two Higgs doublet model (2HDM), in which a second Higgs doublet is added to the SM [24]. The two Higgs doublet fields are denoted by Φ_1 and Φ_2 . After minimizing the scalar potential, the neutral components of the two doublet fields acquire vacuum expectation values $\langle \Phi_i^0 \rangle = v_i / \sqrt{2}$, where $v^2 \equiv |v_1|^2 + |v_2|^2 \simeq (246 \text{ GeV})^2$. It is convenient to introduce the Higgs basis fields [25, 26, 27, 28, 29, 30]:

$$H_1 = v_1^* \Phi_1 + v_2^* \Phi_2, \quad H_2 = -v_2 \Phi_1 + v_1 \Phi_2, \quad (3)$$

which satisfy $\langle H_1^0 \rangle = v / \sqrt{2}$ and $\langle H_2^0 \rangle = 0$. The most general renormalizable gauge-invariant scalar potential, in terms of the Higgs basis fields, is given by [30]

$$\begin{aligned} \mathcal{V} = & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + \left[Y_3 H_1^\dagger H_2 + \text{h.c.} \right] \\ & + \frac{1}{2} Z_1 \left(H_1^\dagger H_1 \right)^2 + \frac{1}{2} Z_2 \left(H_2^\dagger H_2 \right)^2 \\ & + Z_3 \left(H_1^\dagger H_1 \right) \left(H_2^\dagger H_2 \right) + Z_4 \left(H_1^\dagger H_2 \right) \left(H_2^\dagger H_1 \right) \\ & + \left\{ \frac{1}{2} Z_5 \left(H_1^\dagger H_2 \right)^2 + \left[Z_6 H_1^\dagger H_1 + Z_7 H_2^\dagger H_2 \right] H_1^\dagger H_2 + \text{h.c.} \right\}. \end{aligned} \quad (4)$$

²The hypercharge Y is normalized such that the electric charge of the scalar field is $Q = T_3 + Y/2$.

Minimization of the scalar potential fixes $Y_1 = -\frac{1}{2}Z_1v^2$ and $Y_3 = -\frac{1}{2}Z_6v^2$. The charged Higgs squared mass is given by

$$m_{H^\pm}^2 = Y_2 + \frac{1}{2}Z_3v^2. \quad (5)$$

The neutral Higgs squared masses are given by the eigenvalues of a 3×3 neutral Higgs squared mass matrix (see [31] for further details).

One can introduce a \mathbb{Z}_2 symmetry that enforces flavor alignment, which leads to the so-called Type I, II, X, and Y Higgs-fermion Yukawa interactions of the 2HDM [32, 33]. If CP conservation is imposed on the scalar potential, then the Higgs basis field H_2 can be rephased such that all scalar potential parameters (and the vacuum expectation values v_1 and v_2) are real. In this case, the neutral scalar spectrum consists of two CP-even scalars h and H (with $m_h \leq m_H$) and a CP-odd scalar A with mass:

$$m_A^2 = m_{H^\pm}^2 + \frac{1}{2}(Z_4 - Z_5)v^2. \quad (6)$$

The masses of h and H are obtained by diagonalizing the 2×2 squared mass matrix:

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1v^2 & Z_6v^2 \\ Z_6v^2 & m_A^2 + Z_5v^2 \end{pmatrix}, \quad (7)$$

with respect to the Higgs basis states, $\{\sqrt{2}\text{Re } H_1^0 - v, \sqrt{2}\text{Re } H_2^0\}$. In particular,

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos(\beta - \alpha) & -\sin(\beta - \alpha) \\ \sin(\beta - \alpha) & \cos(\beta - \alpha) \end{pmatrix} \begin{pmatrix} \sqrt{2}\text{Re } H_1^0 - v \\ \sqrt{2}\text{Re } H_2^0 \end{pmatrix}, \quad (8)$$

where α is the mixing angle of the matrix that diagonalizes the CP-even Higgs squared-mass matrix when written with respect to the basis of scalar fields, $\{\sqrt{2}\text{Re } \Phi_1^0 - v_1, \sqrt{2}\text{Re } \Phi_2^0 - v_2\}$, and $\tan \beta \equiv v_2/v_1$.

The departure from the Higgs alignment limit is characterized by the parameter $\cos(\beta - \alpha)$, which is zero in the limit of exact Higgs alignment. In the CP-conserving 2HDM in the approximate Higgs alignment limit,

$$\cos(\beta - \alpha) \simeq \frac{Z_6v^2}{m_h^2 - m_H^2}, \quad (9)$$

where h is the SM-like Higgs boson. Thus, the Higgs alignment limit is approximately realized if either $m_H \gg m_h$ (called the decoupling limit [34, 35]) and/or if $|Z_6| \ll 1$. In Figure 7, regions of the 2HDM parameter space highlighted in yellow are excluded by the current precision of the LHC Higgs data by the ATLAS Collaboration [36], which implies that the parameters of the 2HDM must respect an approximate Higgs alignment limit in order to be consistent with current LHC observations.

One specialized version of the 2HDM of some interest is the inert doublet model (IDM) [37, 38], where $Y_3 = Z_6 = Z_7 = 0$. This model possesses an exact \mathbb{Z}_2 symmetry, which remains unbroken after imposing the scalar potential minimum conditions. This implies that the gauge fields and the Higgs basis field H_1 are even under the \mathbb{Z}_2 symmetry, whereas the Higgs basis field H_2 is odd under the \mathbb{Z}_2 symmetry. In particular, the IDM possesses an exact Higgs alignment in light of equation (9). The observed Higgs boson along with the neutral and charged Goldstone bosons reside completely inside the Higgs

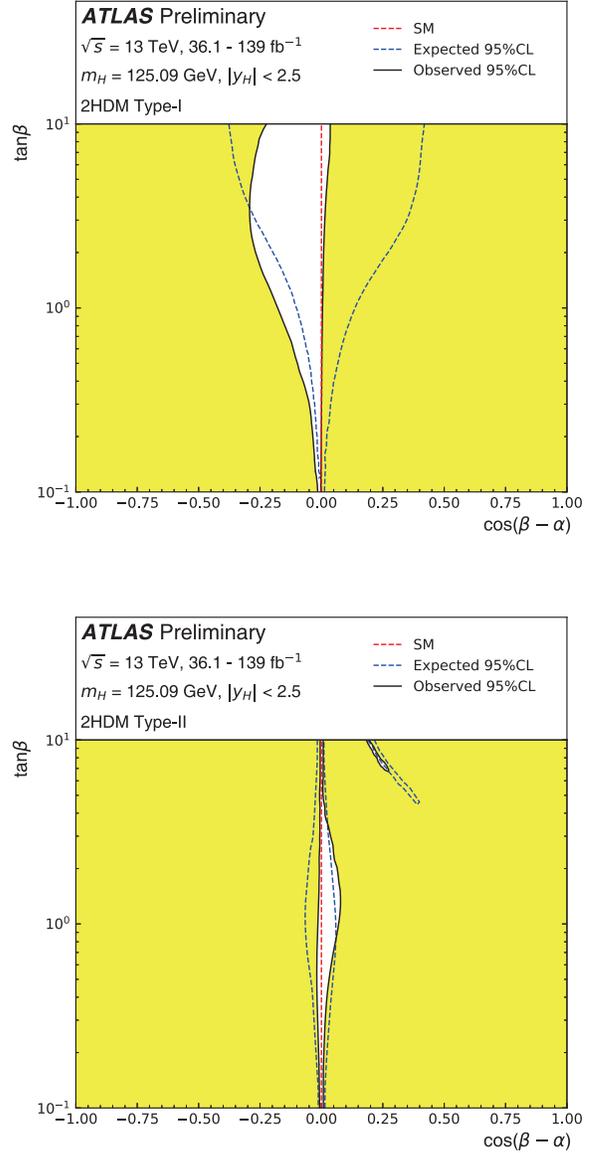


FIGURE 7: Regions excluded (at 95% CL) by fits to the measured rates of the productions and decay of the Higgs boson (assumed to be h of the 2HDM), highlighted in yellow. The observed best-fit values for $\cos(\beta - \alpha)$ are -0.006 for the Type-I 2HDM and 0.002 for the Type-II 2HDM. Taken from [36].

basis field H_1 with tree-level Higgs couplings that coincide with those of the SM Higgs boson.

Moreover, by insisting that all fermions are even under the \mathbb{Z}_2 symmetry, the resulting Yukawa interactions are of Type I, thereby satisfying the requirement of flavor alignment. The only fields of the model that are odd under \mathbb{Z}_2 are the charged Higgs boson pair H^\pm and two new neutral Higgs bosons, which reside in the Higgs basis field H_2 . Assuming that the lightest \mathbb{Z}_2 -odd particle (LOP) is neutral, then the LOP is stable and is a candidate for dark matter. A parameter regime of the IDM exists in which the LOP accounts for the observed dark matter relic density, as shown in [39].

More generically, if we allow for CP-violating scalar potential, then the physical scalars of the 2HDM consist of three neutral scalars h_1 , h_2 , and h_3 (with indefinite CP quantum numbers) and a charged scalar pair H^\pm . The neutral scalars can be expressed in terms of the scalar doublet fields Φ_1 and Φ_2 and their vacuum expectation values, $\langle \Phi_i^0 \rangle = v\hat{v}_i/\sqrt{2}$, as follows:

$$h_k = \frac{1}{\sqrt{2}} \sum_{i=1}^2 \left[(\bar{\Phi}_i^0)^\dagger (q_{k1}\hat{v}_i + q_{k2}\hat{w}_i) + \text{h.c.} \right], \quad (10)$$

where $\hat{v} = (\cos\beta, e^{i\xi}\sin\beta)$, the (complex) unit vector \hat{w} is orthogonal to \hat{v} , and the shifted neutral fields are defined by $\bar{\Phi}_i^0 \equiv \Phi_i^0 - \langle \Phi_i^0 \rangle$. The quantities q_{k1} and q_{k2} (where $k \in \{1, 2, 3\}$) can be expressed in terms of mixing angles that arise in the diagonalization of the 3×3 neutral scalar squared mass matrix (detailed expressions can be found in [31]).

In the general 2HDM, the scalar couplings to two vector bosons are given by

$$\mathcal{L}_{V VH} = \left(g m_W W_\mu^+ W^{\mu-} + \frac{2}{2 \cos\theta_W} m_Z Z_\mu Z^\mu \right) \sum_k q_{k1} h_k. \quad (11)$$

It is also instructive to exhibit the Higgs-quark Yukawa couplings³:

$$\begin{aligned} \mathcal{L}_Y = & -\frac{1}{v} \sum_k \bar{U} \left\{ q_{k1} M_U + \frac{v}{\sqrt{2}} \left[q_{k2}^* \rho^U P_R + q_{k2} \rho^{U\dagger} P_L \right] \right\} U h_k \\ & -\frac{1}{v} \sum_k \bar{D} \left\{ q_{k1} M_D + \frac{v}{\sqrt{2}} \left[q_{k2} \rho^{D\dagger} P_R + q_{k2}^* \rho^D P_L \right] \right\} D h_k \\ & - \left\{ \bar{U} \left[K \rho^{D\dagger} P_R - \rho^{U\dagger} K P_L \right] D H^+ + \text{h.c.} \right\}, \end{aligned} \quad (12)$$

where $P_{R,L} \equiv \frac{1}{2}(1 \pm \gamma_5)$, $U = (u, c, t)$ and $D = (d, s, b)$ are three families of quark fields, with corresponding *diagonal* up-type and down-type quark mass matrices M_U and M_D , respectively, K is the CKM mixing matrix and ρ^U , ρ^D are complex 3×3 matrices.

In the exact Higgs alignment limit,

$$q_{11} = q_{22} = -iq_{32} = 1, \quad q_{21} = q_{31} = q_{12} = 0. \quad (13)$$

Inserting these values into equations (11) and (12), it follows that in the exact Higgs alignment limit, the properties of h_1 coincide with those of the SM Higgs boson. However, since the matrices ρ^U , ρ^D , and ρ^E are in general nondiagonal (complex) matrices, it follows that tree-level FCNCs mediated by h_2 and h_3 are present, along with new CP-violating phases in the h_2 , h_3 , and H^\pm couplings to fermions.

To eliminate flavor-nondiagonal and CP-violating Yukawa couplings of h_2 and h_3 to quarks and leptons, one can impose flavor alignment by assuming that

$$\rho^F = a^F M_F, \quad \text{for } F = U, D, E, \quad (14)$$

³Equation (12) is easily extended to include the Higgs boson couplings to leptons. Since neutrinos are massless in the two-Higgs doublet extension of the Standard Model, one obtains the Higgs boson couplings to charged leptons and neutrinos by making the following replacements: $D \rightarrow E = (e, \mu, \tau)$, $U \rightarrow N = (\nu_e, \nu_\mu, \nu_\tau)$, $\rho^D \rightarrow \rho^E$, $M_D \rightarrow M_E$, and $M_U \rightarrow M_N$, where M_E is the diagonal charged lepton mass matrix and $M_N = 0$.

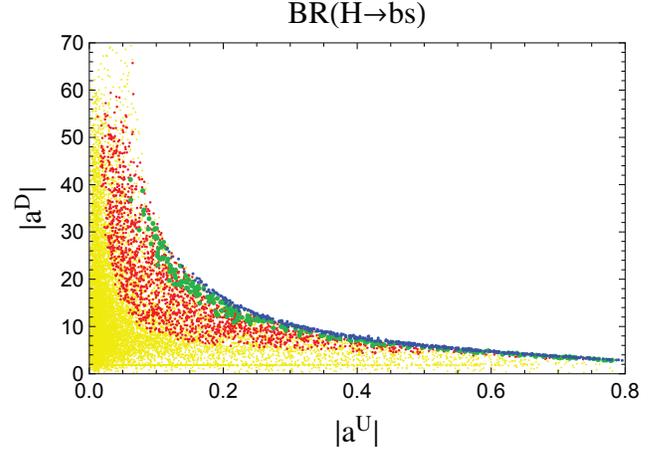


FIGURE 8: Branching ratio (BR) of the CP-even Higgs boson $H \rightarrow \bar{b}s + b\bar{s}$ for $m_H = 400$ GeV obtained by scanning the parameter space, with $\cos(\beta - \alpha) = 0$ and $|a^E| = 10$ fixed, as a function of the flavor alignment parameters a^U and a^D . The yellow, red, green, and blue points correspond to $\text{BR}(H \rightarrow \bar{b}s + b\bar{s}) < 0.0005$, $[0.0005, 0.01]$, $[0.01, 0.1]$, and > 0.1 , respectively. Taken from [43].

where the quantities a^F are real flavor alignment parameters. Equation (14), if implemented generically, is not stable under renormalization group evolution [40]. The diagonality condition can be imposed either at the electroweak scale by fine-tuning [18] or at an energy scale $\Lambda \gg v$ where equation (14) is satisfied as a consequence of some new ultraviolet physics (e.g., see [41, 42]), in which case tree-level scalar-mediated FCNCs are generated at the electroweak scale and provide potential signals for discovery [43]. For example, a nonzero branching ratio for $H \rightarrow \bar{b}s + b\bar{s}$ can be generated, whose value depends on the values of a^U and a^D , as shown in Figure 8.

Alternatively, as previously noted, one can impose a \mathbb{Z}_2 discrete symmetry on the Higgs Lagrangian to eliminate tree-level scalar-mediated FCNCs without the fine-tuning of parameters. Different choices of the discrete symmetries yield the Types I, II, X, and Y Yukawa couplings previously mentioned. Such models are special cases of equation (14). For example, Type I corresponds to $a^D = a^E = a^U$ and Type II corresponds to $a^D = a^E = -1/a^U$.

As noted in Section 2, the properties of the Higgs boson discovered at the LHC approximate those of the SM Higgs boson. Consequently, if additional Higgs bosons exist, then the Higgs alignment limit of the extended Higgs sector must be approximately realized. Although no additional scalar states beyond the Higgs boson with a mass of 125 GeV have been found so far at the LHC, evidence for additional scalar states (which would arise in models of extended Higgs sectors) and/or other BSM phenomena could emerge in future runs at the LHC or at new collider facilities that might be constructed in the future. The discovery of any additional scalar states would yield important clues to the underlying structure of the nonminimal Higgs sector. As an example, the authors of [44] provided some techniques for discriminating among different choices for the Yukawa interactions of the 2HDM, as illustrated in Figure 9.

However, a more flexible framework for analyzing the properties of the new scalars should avoid imposing model assumptions that are stronger than those required for the consis-

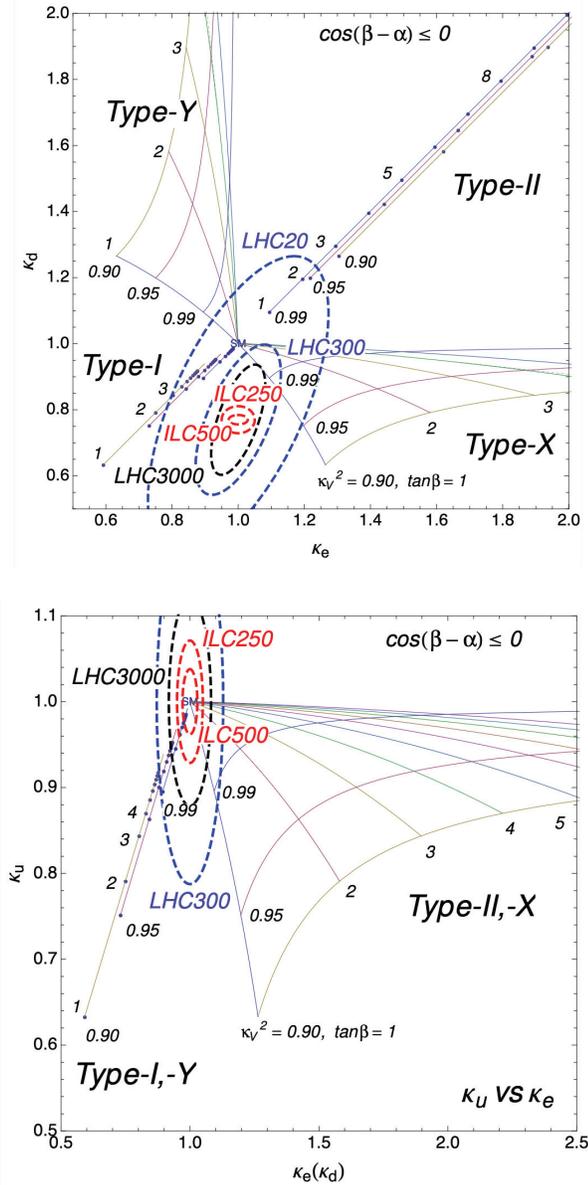


FIGURE 9: The scaling factors for the Yukawa interaction of the SM-like Higgs boson in 2HDMs in the case of $\cos(\beta - \alpha) < 0$. Taken from [44].

tency with experimental constraints. Instead of imposing the Type I, II, X, and Y frameworks on the 2HDM Yukawa couplings, one could instead impose a weaker flavor alignment constraint that is determined phenomenologically [18] (instead of being a consequence of a symmetry). For example, the work in [45] provides an example of a scenario where new scalars of a flavor-aligned 2HDM are discovered that cannot be described by Yukawa couplings of Types I, II, X, and Y. If evidence for an extended Higgs sector is revealed, then one should rely on the experimental observations (with minimal theoretical prejudice) to determine the structure of the corresponding Yukawa couplings.

The Higgs sector can serve as a portal to BSM physics. Indeed, many models of BSM physics require an extension of the SM Higgs sector. For example, the Higgs sector of the minimal

supersymmetric extension of the SM (MSSM) is a 2HDM with Type II Yukawa couplings and a CP-conserving scalar potential whose dimensionless couplings are constrained by supersymmetry. The supersymmetry-breaking squared mass terms of the scalar potential are responsible for electroweak symmetry breaking. The MSSM possesses a SM-like Higgs boson h in the decoupling limit (where $m_A \gg m_h$).

At the tree level, the MSSM yields $m_h \leq m_Z$ in conflict with observation. However, radiative corrections raise the upper limit; an approximate one-loop computation produces the following result:

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \left[\ln \left(\frac{M_S^2}{m_t^2} \right) + \frac{|X_t|^2}{M_S^2} \left(1 - \frac{|X_t|^2}{12M_S^2} \right) \right], \quad (15)$$

where X_t is the top squark (stop) mixing parameter and M_S is the geometric mean of the two top squark masses (further details can be found in [47]). The results of a more complete computation (which includes higher-order loop calculations and renormalization group improvements) are shown in Figure 10. These results suggest that supersymmetric particle masses (characterized by M_S) are likely to be closer to 10 TeV (rather than 1 TeV as initially anticipated), thereby explaining why no supersymmetric particles have yet been observed at the LHC.

Concerning Higgs physics beyond the SM, a second Higgs wishlist can be constructed that poses additional questions that one hopes can be answered in future Higgs studies.

- (1) How many generations of Higgs scalars exist at or below the TeV scale and what are their electroweak quantum numbers?
- (2) Are there any new elementary scalars not yet discovered with masses below the mass of the SM-like Higgs boson? For example, do axion-like particles exist?
- (3) How small is the departure from the Higgs alignment limit, and what is the underlying mechanism that yields an approximate Higgs alignment?
- (4) Does the unitarization of the scattering of longitudinal gauge bosons require additional scalars from an extended scalar sector?
- (5) How small is the departure from the flavor alignment limit of the neutral Higgs-fermion Yukawa couplings? Will quark/lepton flavor off-diagonal couplings of neutral scalars be observed?
- (6) Are there new sources of CP violation associated with the extended scalar sector? Can these be experimentally observed (and can the corresponding sources be identified)?
- (7) How does the extended scalar sector affect the electroweak phase transition? Does it permit electroweak baryogenesis? Does it play other significant roles in early universe cosmology (e.g., inflation)? Will future gravitational wave experiments shed any light on these matters?
- (8) If additional scalars are discovered, how will these discoveries impact the question of the stability of the electroweak vacuum?
- (9) Do neutral (inert) scalars comprise a significant fraction of the dark matter?
- (10) How does the scalar sector inform the identification of the BSM physics? Will this shine any light on the apparent unnatural nature of the SM Higgs sector?

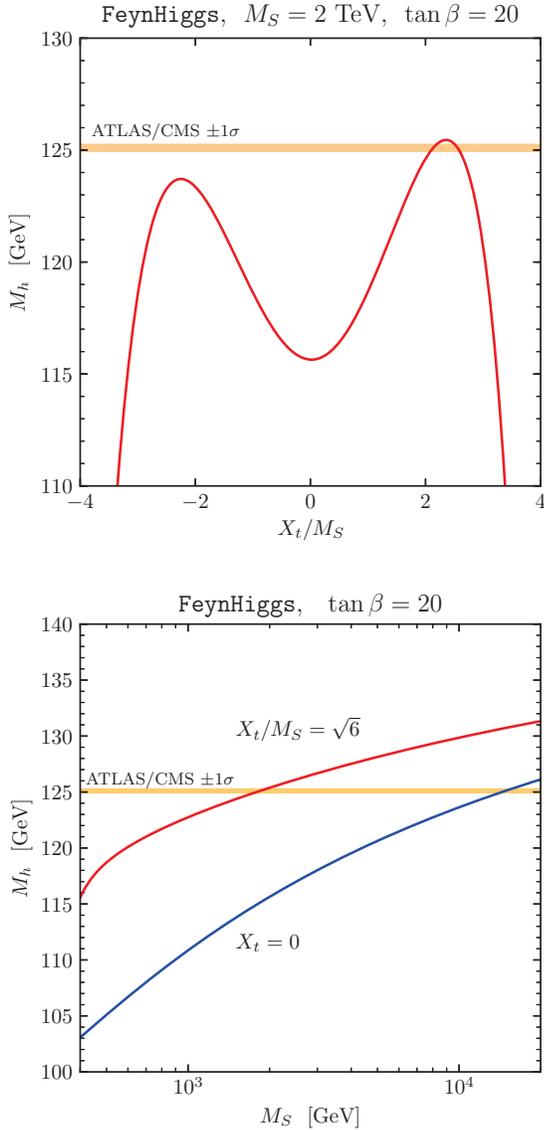


FIGURE 10: The lighter CP-even Higgs mass in the MSSM as a function of a common supersymmetric mass parameter M_S and of the stop mixing parameter X_t (normalized to M_S). Taken from [46].

4. CONCLUSIONS

Future Higgs studies have the potential to address many profound questions concerning the theory of fundamental particles and their interactions. With expectations of data samples that are 20 times larger than the Higgs data collected in Runs 1 and 2 of the LHC, there are considerable opportunities for discoveries at the LHC during the next 10 to 15 years.

Nevertheless, Nature may demand more precision than the LHC can ultimately provide. As the particle physics community ponders the roadmap of future collider facilities, one should consider which paths provide the best opportunities for addressing the questions posed by the two Higgs wishlists presented in Sections 2 and 3.

CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

ACKNOWLEDGMENTS

An earlier version of this review, which was originally based on the summary talk given at the 2021 SLAC Summer Institute, was contributed to the CERN celebration of the 10th anniversary of the discovery of the Higgs boson. I am grateful to Tom Rizzo for the original SLAC invitation and to Panagiotis Charitos for the opportunity to participate in the CERN celebration. I would also like to thank Stefan Pokorski for inviting me to present this review at the PLANCK 2023 meeting in Warsaw, Poland. In addition, I am pleased to acknowledge the inspiring working atmosphere of the Aspen Center for Physics, supported by the National Science Foundation Grant No. PHY-1066293, where this write-up was prepared. The author is supported in part by the U.S. Department of Energy Grant No. DE-SC0010107.

References

- [1] H. Schopper and L. Di Lella, editors, *60 Years of CERN Experiments and Discoveries*, Adv. Ser. Direct High Energy Phys. **23** (2015) pp. 1–436 (World Scientific, Singapore, 2015).
- [2] P. Langacker, *The Standard Model and Beyond* (CRC Press, Boca Raton, FL, 2017).
- [3] The ATLAS Collaboration, “A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery,” *Nature* **607**, no. 7917, 52–59 (2022) [arXiv:2207.00092 [hep-ex]].
- [4] The CMS Collaboration, “A portrait of the Higgs boson by the CMS experiment ten years after the discovery,” *Nature* **607**, no. 7917, 60–68 (2022) [arXiv:2207.00043 [hep-ex]].
- [5] S. Profumo, *An Introduction to Particle Dark Matter* (World Scientific, Singapore, 2017).
- [6] G. A. White, *Electroweak Baryogenesis—An Introduction*, 2nd Edition (IOP Publishing Ltd, Bristol, UK, 2022).
- [7] V. F. Weisskopf, “On the self-energy and the electromagnetic field of the electron,” *Phys. Rev.* **56**, 72 (1939).
- [8] N. Craig, “Naturalness: A Snowmass White Paper,” [arXiv:2205.05708 [hep-ph]].
- [9] A. Andreassen, W. Frost, and M. D. Schwartz, “Scale invariant instantons and the complete lifetime of the Standard Model,” *Phys. Rev. D* **97**, 056006 (2018) [arXiv:1707.08124 [hep-ph]].
- [10] The ATLAS and CMS Collaborations, “Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors,” ATL-PHYS-PUB-2022-018 and CMS PAS FTR-22-001.
- [11] M. Narain, L. Reina, A. Tricoli, M. Begel, A. Belloni, T. Bose, A. Boveia, S. Dawson, C. Doglioni, and A. Freitas et al. “The Future of US Particle Physics—The Snowmass 2021 Energy Frontier Report,” arXiv:2211.11084 [hep-ex].
- [12] B. Patt and F. Wilczek, “Higgs-field portal into hidden sectors,” [arXiv:hep-ph/0605188 [hep-ph]].
- [13] J. Erler and A. Freitas, “Electroweak Model and Constraints on New Physics,” in R. L. Workman et al. [Particle

- Data Group], *Review of Particle Physics*, PTEP **2022**, 083C01 (2022).
- [14] J. F. Gunion, H. E. Haber, G. L. Kane, and S. Dawson, *The Higgs Hunter's Guide* (Westview Press, Boulder, CO, 2000).
- [15] H. Georgi and M. Machacek, "Doubly charged Higgs bosons," Nucl. Phys. B **262**, 463 (1985).
- [16] A. Arbey, F. Mahmoudi, O. Stal, and T. Stefaniak, "Status of the Charged Higgs Boson in Two Higgs Doublet Models," Eur. Phys. J. C **78**, 182 (2018) [arXiv:1706.07414 [hep-ph]].
- [17] W. Altmannshofer, S. Gori, N. Hamer, and H. H. Patel, "Electron EDM in the complex two-Higgs doublet model," Phys. Rev. D **102**, 115042 (2020) arXiv:2009.01258 [hep-ph]].
- [18] A. Pich and P. Tuzon, "Yukawa Alignment in the Two-Higgs-Doublet Model," Phys. Rev. D **80**, 091702 (2009) [arXiv:0908.1554 [hep-ph]].
- [19] N. Craig, J. Galloway, and S. Thomas, "Searching for Signs of the Second Higgs Doublet," [arXiv:1305.2424 [hep-ph]].
- [20] H. E. Haber, "The Higgs data and the Decoupling Limit," in the Proceedings of the 1st Toyama International Workshop on Higgs as a Probe of New Physics 2013, 13–16, February, 2013 [arXiv:1401.0152 [hep-ph]].
- [21] D. M. Asner, T. Barklow, C. Calancha, K. Fujii, N. Graf, H. E. Haber, A. Ishikawa, S. Kanemura et al. "ILC Higgs White Paper," [arXiv:1310.0763 [hep-ph]].
- [22] M. Carena, I. Low, N. R. Shah, and C. E. M. Wagner, "Impersonating the Standard Model Higgs Boson: Alignment without Decoupling," JHEP **04**, 015 (2014) [arXiv:1310.2248 [hep-ph]].
- [23] P. S. Bhupal Dev and A. Pilaftsis, "Maximally Symmetric Two Higgs Doublet Model with Natural Standard Model Alignment," JHEP **12**, 024 (2014) [erratum: **11**, 147 (2015)] [arXiv:1408.3405 [hep-ph]].
- [24] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, "Theory and phenomenology of two-Higgs-doublet models," Phys. Rept. **516**, 1–102 (2012) [arXiv:1106.0034 [hep-ph]].
- [25] H. Georgi and D. V. Nanopoulos, "Suppression of Flavor Changing Effects From Neutral Spinless Meson Exchange in Gauge Theories," Phys. Lett. B **82**, 95 (1979).
- [26] L. Lavoura, "Signatures of discrete symmetries in the scalar sector," Phys. Rev. D **50**, 7089 (1994) [arXiv:hep-ph/9405307].
- [27] L. Lavoura and J. P. Silva, "Fundamental CP violating quantities in a $SU(2) \times U(1)$ model with many Higgs doublets," Phys. Rev. D **50**, 4619 (1994) [arXiv:hep-ph/9404276].
- [28] F. J. Botella and J. P. Silva, "Jarlskog-like invariants for theories with scalars and fermions," Phys. Rev. D **51**, 3870 (1995) [arXiv:hep-ph/9411288].
- [29] G. C. Branco, L. Lavoura, and J. P. Silva, *CP Violation* (Oxford University Press, Oxford, UK, 1999).
- [30] S. Davidson and H. E. Haber, "Basis-independent methods for the two-Higgs-doublet model," Phys. Rev. D **72**, 035004 (2005) [erratum: **72**, 099902 (2005)] [arXiv:hep-ph/0504050 [hep-ph]].
- [31] H. E. Haber and D. O'Neil, "Basis-independent methods for the two-Higgs-doublet model. II. The Significance of $\tan\beta$," Phys. Rev. D **74**, 015018 (2006) [erratum: **74**, 059905 (2006)] [arXiv:hep-ph/0602242 [hep-ph]].
- [32] L. J. Hall and M. B. Wise, "Flavor-changing Higgs boson couplings," Nucl. Phys. B **187**, 397 (1981).
- [33] M. Aoki, S. Kanemura, K. Tsumura, and K. Yagyu, "Models of Yukawa interaction in the two Higgs doublet model, and their collider phenomenology," Phys. Rev. D **80**, 015017 (2009) [arXiv:0902.4665 [hep-ph]].
- [34] H. E. Haber and Y. Nir, "Multiscalar Models With a High-energy Scale," Nucl. Phys. B **335**, 363–394 (1990).
- [35] J. F. Gunion and H. E. Haber, "The CP conserving two Higgs doublet model: The Approach to the decoupling limit," Phys. Rev. D **67**, 075019 (2003) [arXiv:hep-ph/0207010 [hep-ph]].
- [36] The ATLAS Collaboration, "Combined measurements of Higgs boson production and decay using up to 139 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$ collected with the ATLAS experiment," ATLAS-CONF-2021-053 (December 15, 2021).
- [37] R. Barbieri, L. J. Hall, and V. S. Rychkov, "Improved naturalness with a heavy Higgs: An Alternative road to LHC physics," Phys. Rev. D **74**, 015007 (2006) [arXiv:hep-ph/0603188 [hep-ph]].
- [38] L. Lopez Honorez, E. Nezri, J. F. Oliver, and M. H. G. Tytgat, "The Inert Doublet Model: An Archetype for Dark Matter," JCAP **02**, 028 (2007) [arXiv:hep-ph/0612275].
- [39] A. Goudelis, B. Herrmann, and O. Stål, "Dark matter in the Inert Doublet Model after the discovery of a Higgs-like boson at the LHC," JHEP **09**, 106 (2013) [arXiv:1303.3010 [hep-ph]].
- [40] P. M. Ferreira, L. Lavoura, and J. P. Silva, "Renormalization-group constraints on Yukawa alignment in multi-Higgs-doublet models," Phys. Lett. B **688**, 341 (2010) [arXiv:1001.2561 [hep-ph]].
- [41] H. Serodio, "Yukawa Alignment in a Multi Higgs Doublet Model: An effective approach," Phys. Lett. B **700**, 133 (2011) [arXiv:1104.2545 [hep-ph]].
- [42] D. Egana-Ugrinovic, S. Homiller, and P. R. Meade, "Higgs bosons with large couplings to light quarks," Phys. Rev. D **100**, 115041 (2019) [arXiv:1908.11376 [hep-ph]].
- [43] S. Gori, H. E. Haber, and E. Santos, "High scale flavor alignment in two-Higgs doublet models and its phenomenology," JHEP **06**, 110 (2017) [arXiv:1703.05873 [hep-ph]].
- [44] S. Kanemura, K. Tsumura, K. Yagyu, and H. Yokoya, "Fingerprinting nonminimal Higgs sectors," Phys. Rev. D **90**, 075001 (2014) [arXiv:1406.3294 [hep-ph]].
- [45] J. M. Connell, P. Ferreira, and H. E. Haber, "Accommodating Hints of New Heavy Scalars in the Framework of the Flavor-Aligned Two-Higgs-Doublet Model," Phys. Rev. D **108**, 055031 (2023) [arXiv:2302.13697 [hep-ph]].
- [46] P. Slavich, S. Heinemeyer et al., "Higgs-mass predictions in the MSSM and beyond," Eur. Phys. J. C **81**, 450 (2021) [arXiv:2012.15629 [hep-ph]].
- [47] H. K. Dreiner, H. E. Haber, and S. P. Martin, *From Spinors to Supersymmetry* (Cambridge University Press, Cambridge, UK, 2023).