BSM Higgs Physics at the ILC

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SNOWMASS ENERGY FRONTIER WORKSHOP

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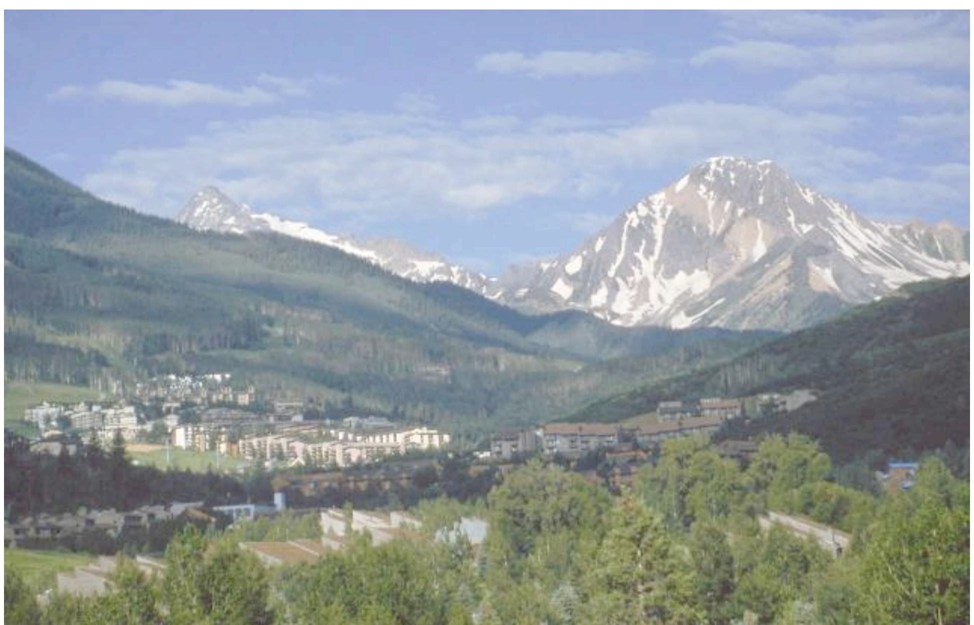

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2. Higgs Bosons beyond the Standard Model
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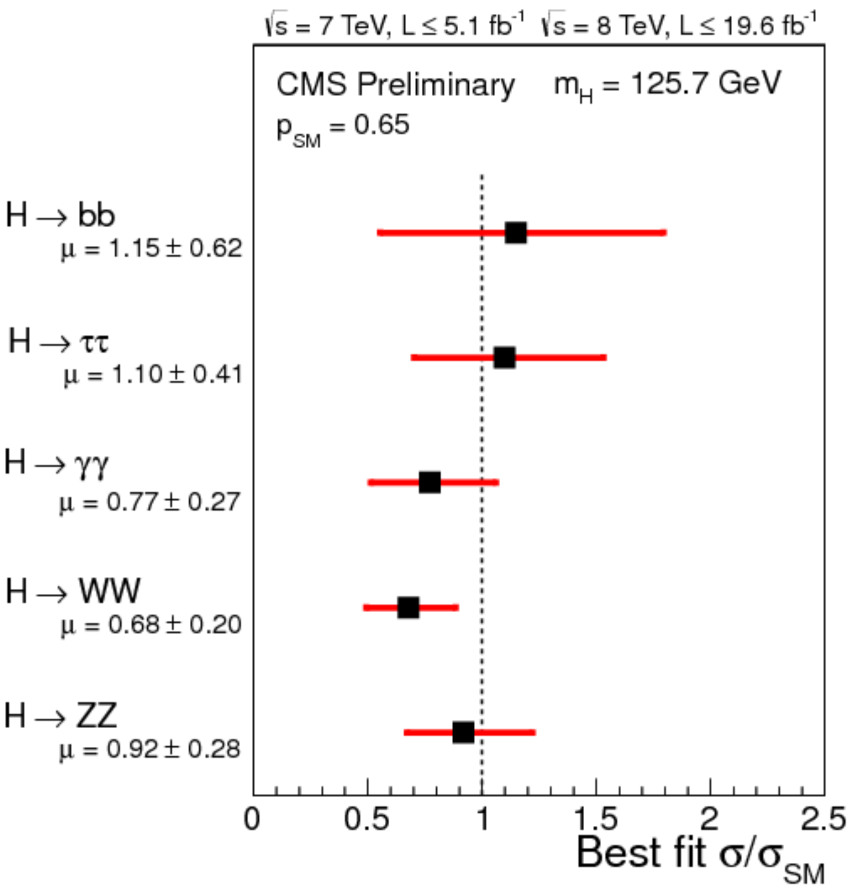
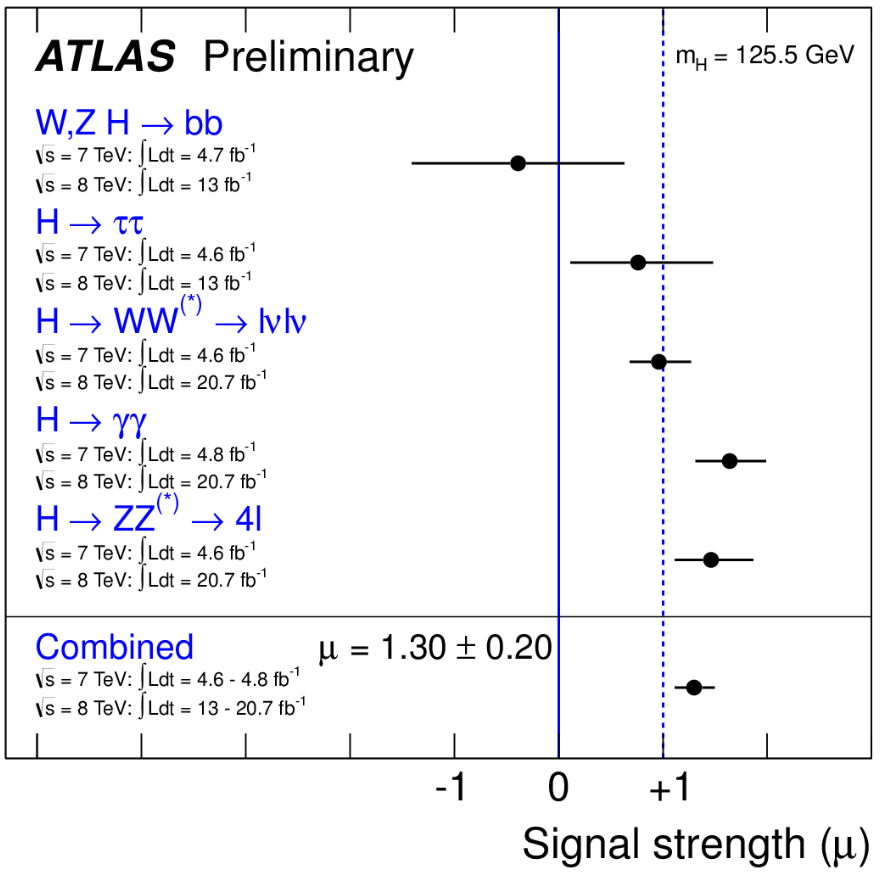
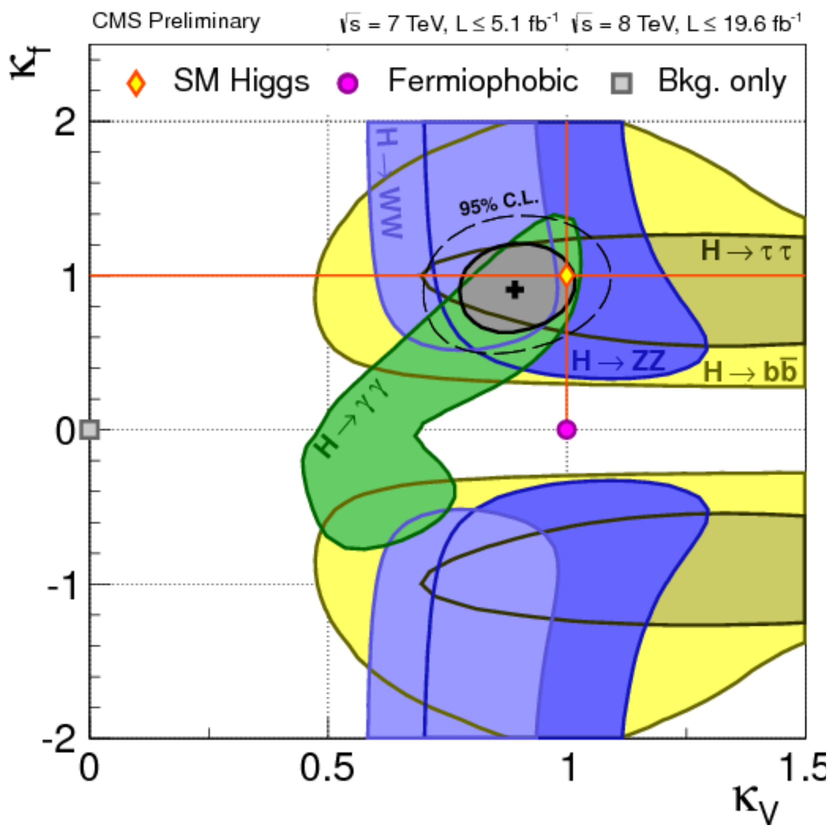
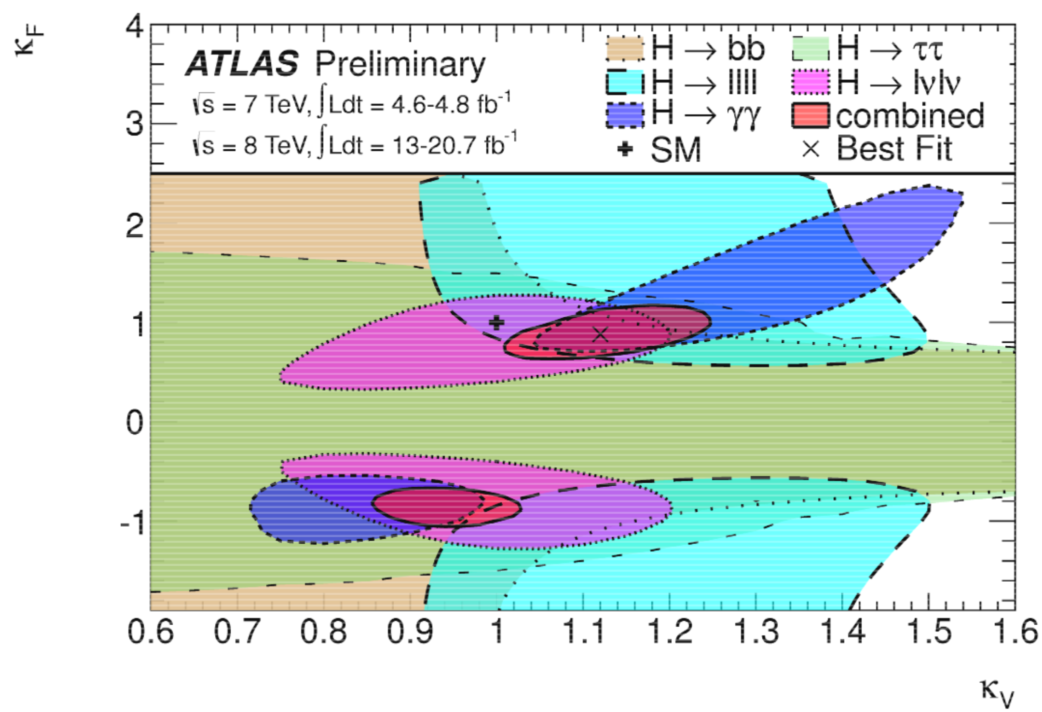
A Standard Model (SM) Higgs--like boson?






CMS Preliminary
√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
SM Higgs
Fermiophobic
Bkg. only
95% C.L.
H → WW
H → ττ
H → ZZ
H → bb̄
H → γγ
κ_f
κ_V


ATLAS Preliminary
√s = 7 TeV, ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV, ∫Ldt = 13-20.7 fb⁻¹
H → bb
H → ττ
H → llll
H → lνlν
H → γγ
combined
SM
Best Fit
κ_F
κ_V

Beyond the Standard Model (SM) Higgs boson

Three generations of fermions appear in nature, with each generation possessing the same quantum numbers under the SU(3)×SU(2)×U(1)$_{\rm Y}$ gauge group. So, why should the scalar sector be of minimal form?

For an arbitrary Higgs sector, the tree-level ρ-parameter is given by

$$\rho_0 \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_{T,Y}[4T(T+1)-Y^2]|V_{T,Y}|^2 c_{T,Y}}{\sum_{T,Y} 2Y^2|V_{T,Y}|^2}\,,$$

where $V_{T,Y} \equiv \langle\phi(T,Y)\rangle$ defines the vacuum expectation values (vevs) of each neutral Higgs field, and T and Y specify the total SU(2) isospin and the hypercharge of the Higgs representation to which it belongs. Y is normalized such that the electric charge of the scalar field is $Q = T_3 + Y/2$, and

$$c_{T,Y} = \begin{cases} 1, & (T,Y) \in \text{complex representation}, \\ \frac{1}{2}, & (T,Y=0) \in \text{real representation}. \end{cases}$$

For the SM Higgs sector with a single multiplet $(T, Y, c) = (\frac{1}{2}, 1, 1)$, it follows that $\rho_0 = 1$, independently of the value of the scalar vev, as strongly suggested by the electroweak data. The same result follows from a Higgs sector consisting of multiple complex Higgs doublets (independent of the neutral Higgs vevs). One can also add Higgs singlets $(T = Y = 0)$ without changing the value of ρ_0.

But, one cannot add arbitrary Higgs multiplets in general* unless their corresponding vevs are very small (typically $|V_{T,Y}| \lesssim 0.05v \sim 10 \text{ GeV}$).

A clever workaround (Georgi and Machacek) considered the case of two Higgs triplet multiplets: $(T, Y, c) = (1, 2, 1) \oplus (1, 0, \frac{1}{2})$ with equal vevs.

In this talk, I will focus on the simplest extension of the SM Higgs sector: the two-Higgs doublet model (2HDM).

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*To automatically have $\rho_0 = 1$ independently of the Higgs vevs, one must satisfy $(2T + 1)^2 - 3Y^2 = 1$ for integer values of $(2T, Y)$. The smallest nontrivial solution beyond the complex $Y = 1$ Higgs doublet is a Higgs multiplet with $T = 3$ and $Y = 4$.

The 2HDM Framework

The scalar fields of the 2HDM are complex SU(2) doublet, hypercharge-one fields, Φ_1 and Φ_2, where the corresponding vevs are $\langle\Phi_i\rangle = v_i$, and $v^2 \equiv |v_1|^2 + |v_2|^2 = (246\ \mathrm{GeV})^2$. The most general renormalizable SU(2)×U(1) scalar potential is given by

$$\begin{aligned}
\mathcal{V} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + [m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.}] + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 \\
& + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
& + \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \big[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\big] \Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right\} ,
\end{aligned}$$

In the most general 2HDM, the fields Φ_1 and Φ_2 are indistinguishable. Thus, it is always possible to define two orthonormal linear combinations of the two doublet fields without modifying any prediction of the model. Performing such a redefinition of fields leads to a new scalar potential with the same form as above but with modified coefficients.

The Higgs basis

It is convenient to define new Higgs doublet fields:

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1^*\Phi_1 + v_2^*\Phi_2}{v}\,, \qquad\qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{-v_2\Phi_1 + v_1\Phi_2}{v}\,.$$

It follows that $\langle H_1^0\rangle = v/\sqrt{2}$ and $\langle H_2^0\rangle = 0$. This is the *Higgs basis*, which is uniquely defined up to $H_2 \to e^{i\chi}H_2$. The scalar potential is:

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

where Y_1, Y_2 and $Z_1, \ldots, Z_4$ are real and uniquely defined, whereas Y_3, Z_5, Z_6 and Z_7 are complex and transform under the rephasing of H_2,

$$[Y_3, Z_6, Z_7] \to e^{-i\chi}[Y_3, Z_6, Z_7] \quad \text{and} \quad Z_5 \to e^{-2i\chi} Z_5\,.$$

After minimizing the scalar potential, $Y_1 = -\frac{1}{2}Z_1 v^2$ and $Y_3 = -\frac{1}{2}Z_6 v^2$. This leaves 11 free parameters: 1 vev, 8 real parameters and two relative phases.

The Higgs mass eigenstates

The charged Higgs boson is the charged component of the Higgs-basis doublet H_2, and its mass is given by $m^2_{H^\pm} = Y_2 + \frac{1}{2}Z_3 v^2$. The three physical neutral Higgs boson mass-eigenstates are determined by diagonalizing a 3×3 real symmetric squared-mass matrix that is defined in the Higgs basis

$$\mathcal{M}^2 = v^2 \begin{pmatrix} Z_1 & \mathrm{Re}(Z_6) & -\mathrm{Im}(Z_6) \\ \mathrm{Re}(Z_6) & \frac{1}{2}Z_{345} + Y_2/v^2 & -\frac{1}{2}\mathrm{Im}(Z_5) \\ -\mathrm{Im}(Z_6) & -\frac{1}{2}\mathrm{Im}(Z_5) & \frac{1}{2}Z_{345} - \mathrm{Re}(Z_5) + Y_2/v^2 \end{pmatrix},$$

where $Z_{345} \equiv Z_3 + Z_4 + \mathrm{Re}(Z_5)$.The diagonalizing matrix is a 3×3 real orthogonal matrix that depends on three angles: θ_{12}, θ_{13} and θ_{23}. The corresponding neutral Higgs masses will be denoted: m_1, m_2 and m_3. Under the rephasing $H_2 \to e^{i\chi} H_2$,

$$\theta_{12}\,,\ \theta_{13} \text{ are invariant, and } \quad \theta_{23} \to \theta_{23} - \chi\,.$$

The Higgs–fermion Yukawa couplings

Consider first the most general Higgs–quark couplings in the Higgs basis. After identifying the quark mass eigenstates,

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{Y}} = {} & \overline{U}_L(\kappa^U H_1^{0\,\dagger} + \rho^U H_2^{0\,\dagger})U_R - \overline{D}_L K^\dagger(\kappa^U H_1^- + \rho^U H_2^-)U_R \\
& + \overline{U}_L K(\kappa^{D\,\dagger} H_1^+ + \rho^{D\,\dagger} H_2^+)D_R + \overline{D}_L(\kappa^{D\,\dagger} H_1^0 + \rho^{D\,\dagger} H_2^0)D_R + \mathrm{h.c.},
\end{aligned}
$$

where $U = (u, c, t)$ and $D = (d, s, b)$ are the mass-eigenstate quark fields, K is the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix and κ and ρ are 3×3 Yukawa coupling matrices.

By setting $H_1^0 = v/\sqrt{2}$ and $H_2^0 = 0$, one can relate κ^U and κ^D to the diagonal quark mass matrices M_U and M_D, respectively,

$$
M_U = \frac{v}{\sqrt{2}}\kappa^U = \mathrm{diag}(m_u\,,\, m_c\,,\, m_t)\,, \qquad M_D = \frac{v}{\sqrt{2}}\kappa^{D\,\dagger} = \mathrm{diag}(m_d\,,\, m_s\,,\, m_b)\,.
$$

The complex matrices ρ^Q $(Q = U, D)$ are unconstrained up to an overall phase. That is, $\rho^Q \to e^{-i\chi}\rho^Q$, under the rephasing $H_2 \to e^{i\chi}H_2$.

Since physical couplings cannot depend on χ, it is convenient to define the following two 3×3 hermitian matrices,

$$\rho_R^Q \equiv \frac{v}{2\sqrt{2}} M_Q^{-1} \left\{ e^{i\theta_{23}}\rho^Q + [e^{i\theta_{23}}\rho^Q]^\dagger \right\}, \qquad \text{for } Q = U, D\,,$$

$$\rho_I^Q \equiv \frac{v}{2i\sqrt{2}} M_Q^{-1} \left\{ e^{i\theta_{23}}\rho^Q - [e^{i\theta_{23}}\rho^Q]^\dagger \right\}, \qquad \text{for } Q = U, D\,.$$

<u>Remarks</u>

If $\rho_{R,I}^Q$ are non-diagonal matrices, then there exist flavor-changing neutral currents (FCNCs) mediated at tree-level by neutral Higgs exchange.

If $\rho_I^Q \neq 0$, then there is a new source of CP-violation in the interactions of the neutral Higgs bosons with the fermions.

The decoupling limit

In the limit of $Y_2 \gg v$ [assuming that $|Z_i| \lesssim \mathcal{O}(1)$], the second doublet of the Higgs basis becomes very massive. Integrating out this field, the effective Higgs theory at an energy scale below Y_2 is that of the SM Higgs boson!

It is convenient to order the neutral scalar masses such that $m_1 \leq m_{2,3}$ and define the invariant Higgs mixing angles accordingly. Thus, we expect one light CP-even Higgs boson, h_1, with couplings nearly identical to those of the Standard Model (SM) Higgs boson. Since m_1^2, $|Z_i|v^2 \ll m_2^2$, m_3^2, $m_{H^\pm}^2$ in the decoupling limit,

$$s_{12} \equiv \sin\theta_{12} \simeq \frac{\mathrm{Re}(Z_6 e^{-i\theta_{23}})v^2}{m_2^2} + \mathcal{O}\left(\frac{v^4}{m_2^4}\right) \ll 1\,,$$

$$s_{13} \equiv \sin\theta_{13} \simeq -\frac{\mathrm{Im}(Z_6 e^{-i\theta_{23}})v^2}{m_3^2} + \mathcal{O}\left(\frac{v^4}{m_3^4}\right) \ll 1\,,$$

$$\mathrm{Im}(Z_5 e^{-2i\theta_{23}}) \simeq \frac{2m_2^2 s_{12}s_{13}}{v^2} \simeq -\frac{\mathrm{Im}(Z_6^2 e^{-2i\theta_{23}})v^2}{m_3^2} \ll 1\,.$$

Table 1: 2HDM couplings of the SM-like Higgs boson normalized to those of the SM Higgs boson, in the decoupling limit. The normalization of the pseudoscalar coupling of the Higgs boson h to fermions is relative to the corresponding scalar coupling to fermions. In the Higgs self-couplings, $Z_{6R} \equiv \mathrm{Re}(Z_6 e^{-i\theta_{23}})$ and $Z_{6I} \equiv \mathrm{Im}(Z_6 e^{-i\theta_{23}})$.

Higgs interaction	2HDM coupling	decoupling limit
hW^+W^-	$c_{12}c_{13}$	$1 - \frac{1}{2}s_{12}^2 - \frac{1}{2}s_{13}^2$
hZZ	$c_{12}c_{13}$	$1 - \frac{1}{2}s_{12}^2 - \frac{1}{2}s_{13}^2$
hhW^+W^-	1	1
$hhZZ$	1	1
hhh		$1 - 3(s_{12}Z_{6R} - s_{13}Z_{6I})/Z_1$
$hhhh$		$1 - 4(s_{12}Z_{6R} - s_{13}Z_{6I})/Z_1$
$h\overline{D}D$	$c_{12}c_{13}\mathbb{1} - s_{12}\rho_R^D - c_{12}s_{13}\rho_I^D$	$\mathbb{1} - s_{12}\rho_R^D - s_{13}\rho_I^D$
$ih\overline{D}\gamma_5 D$	$s_{12}\rho_I^D - c_{12}s_{13}\rho_R^D$	$s_{12}\rho_I^D - s_{13}\rho_R^D$
$h\overline{U}U$	$c_{12}c_{13}\mathbb{1} - s_{12}\rho_R^U - c_{12}s_{13}\rho_I^U$	$\mathbb{1} - s_{12}\rho_R^U - s_{13}\rho_I^U$
$ih\overline{U}\gamma_5 U$	$-s_{12}\rho_I^U + c_{12}s_{13}\rho_R^U$	$-s_{12}\rho_I^U + s_{13}\rho_R^U$

Unsuppressed CP-violating interactions for the heavy h_2 and h_3 scalars

Although $\mathrm{Im}(Z_5 e^{-2i\theta_{23}}) \ll 1$ in the decoupling limit, there is no requirement that $\mathrm{Im}(Z_6 e^{-i\theta_{23}})$ and $\mathrm{Im}(Z_7 e^{-i\theta_{23}})$ should be small. Additional CP-violation can enter via the ρ_I^Q.

A SM-like Higgs boson without heavy Higgs masses

1. In the case of $m^2_{1,2,3} \sim |Z_i| v^2$ and in the limit of $Z_6 \to 0$, we again have s_{12}, $s_{13} \ll 1$ (for some mass ordering of the neutral Higgs states), which yields one state with approximately SM Higgs couplings. Thus, the observation of a SM-like Higgs boson at LHC does not necessarily imply (yet) that the other Higgs bosons of the 2HDM are heavy!

2. If in the generic basis, $m^2_{12} = 0$, then there are only two independent squared-mass parameters in the scalar potential, which are related to the scalar vevs via the minimum conditions. In this case, no decoupling limit exists in which $m^2_{2,3} \gg m^2_1$. Nevertheless, there can still be a SM-like Higgs boson as indicated in point 1 above.

The CP-conserving 2HDM

Here, we will focus on the case of a CP-conserving scalar potential and vacuum. In this case, one can choose χ such that Y_3, Z_5, Z_6 and Z_7 are all real. If $Z_6 \neq 0$, then the so-called *real Higgs basis* is not unique since we can still redefine $H_2 \to -H_2$. We shall use this freedom to fix $Z_6 > 0$, after which the real Higgs basis is unique Then, we can identify

$$c_{12} = \sin(\beta - \alpha)\,,$$

$$s_{12} = -\cos(\beta - \alpha)\,,$$

$$\theta_{13} = \theta_{23} = 0\,,$$

where β and α refers to some generic basis which a priori has no special meaning, but $\beta - \alpha$ is an observable. If $Z_6 = 0$, then the couplings of one of the Higgs bosons (which we shall designate by h_1) are precisely those of the SM, in which case $\cos(\beta - \alpha) = 0$.

Notation: $c_{\beta-\alpha} \equiv \cos(\beta - \alpha)$ and $s_{\beta-\alpha} \equiv \sin(\beta - \alpha)$.

Table 2: 2HDM couplings of the SM-like Higgs boson normalized to those of the SM Higgs boson, in the decoupling limit. The scalar Higgs potential is taken to be CP-conserving. Then, $c_{\beta-\alpha} \simeq -Z_6 v^2/m_A^2$.

Higgs interaction	2HDM coupling	decoupling limit
hW^+W^-	$s_{\beta-\alpha}$	$1 - \frac{1}{2}c^2_{\beta-\alpha}$
hZZ	$s_{\beta-\alpha}$	$1 - \frac{1}{2}c^2_{\beta-\alpha}$
hhW^+W^-	1	1
$hhZZ$	1	1
hhh		$1 + 3(Z_6/Z_1)c_{\beta-\alpha}$
$hhhh$		$1 + 4(Z_6/Z_1)c_{\beta-\alpha}$
$h\overline{D}D$	$s_{\beta-\alpha}\mathbb{1} + c_{\beta-\alpha}\rho^D_R$	$\mathbb{1} + c_{\beta-\alpha}\rho^D_R$
$ih\overline{D}\gamma_5 D$	$-c_{\beta-\alpha}\rho^D_I$	$-c_{\beta-\alpha}\rho^D_I$
$h\overline{U}U$	$s_{\beta-\alpha}\mathbb{1} + c_{\beta-\alpha}\rho^U_R$	$\mathbb{1} + c_{\beta-\alpha}\rho^U_R$
$ih\overline{U}\gamma_5 U$	$c_{\beta-\alpha}\rho^U_I$	$c_{\beta-\alpha}\rho^U_I$

Constraining the Higgs-fermion Yukawa couplings

To avoid Higgs-mediated tree-level FCNCs, the ρ^Q must be diagonal. This can be achieved by imposing Type-I or Type-II discrete symmetries on the dimension-four terms of the Higgs Lagrangian.

The discrete symmetries are manifest in a basis in which $\langle\Phi_1^0\rangle = v\cos\beta$ and $\langle\Phi_2^0\rangle = v\sin\beta$. The parameter $\tan\beta$ in this case is promoted to a physical parameter of the theory.

Type-I: $\rho_R^D = \rho_R^U = \mathbb{1}\cot\beta\,, \qquad \rho_I^D = \rho_I^U = 0.$

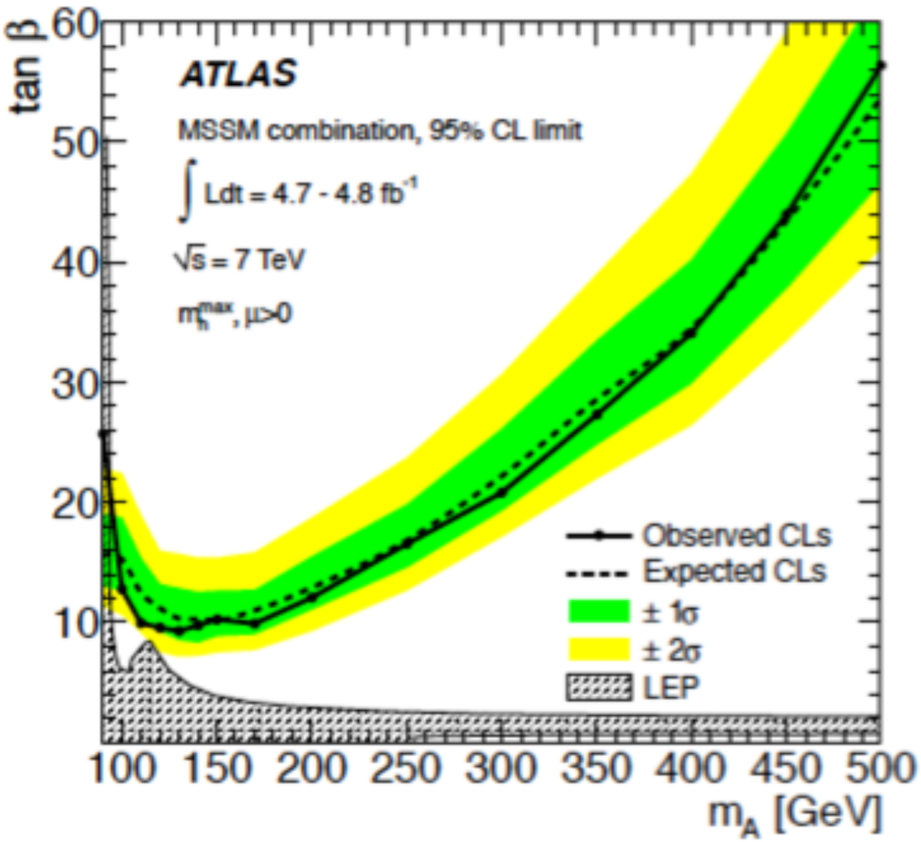
$$h\overline{D}D\,,\; h\overline{U}U : \frac{\cos\alpha}{\sin\beta} = s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta\,.$$

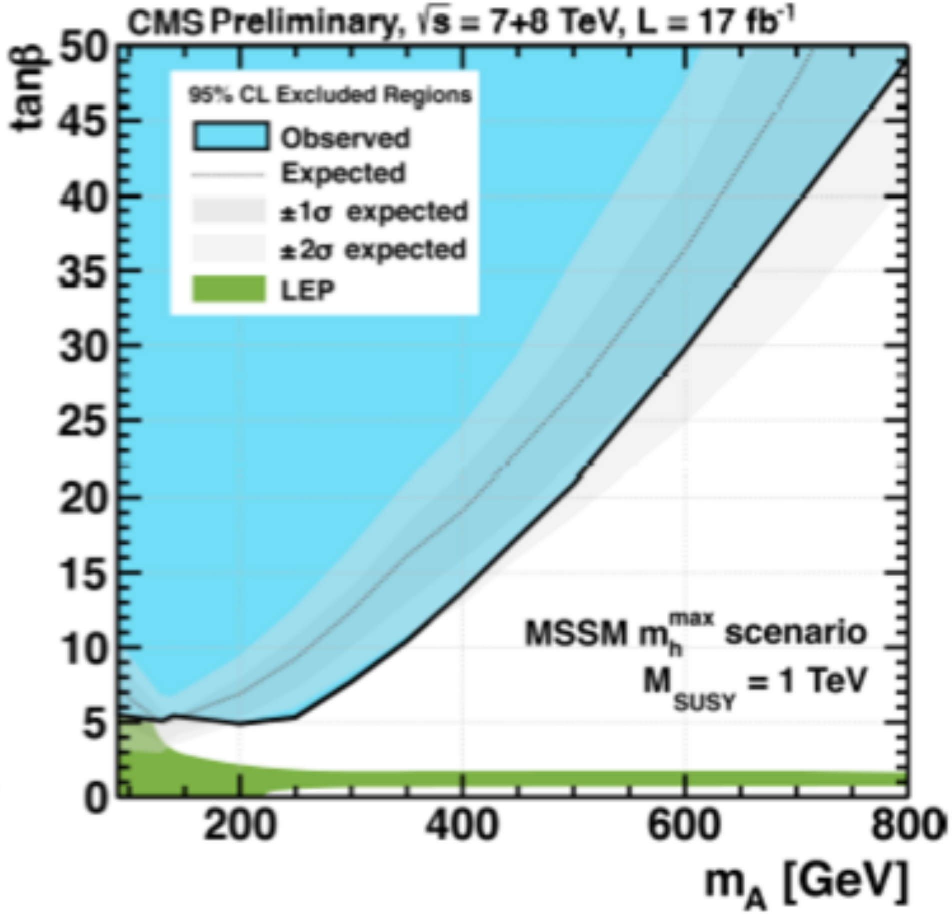
Type-II: $\rho_R^D = -\mathbb{1}\tan\beta\,, \qquad \rho_R^U = \mathbb{1}\cot\beta\,, \qquad \rho_I^D = \rho_I^U = 0.$

$$h\overline{D}D : \; -\frac{\sin\alpha}{\cos\beta} = s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta\,,$$

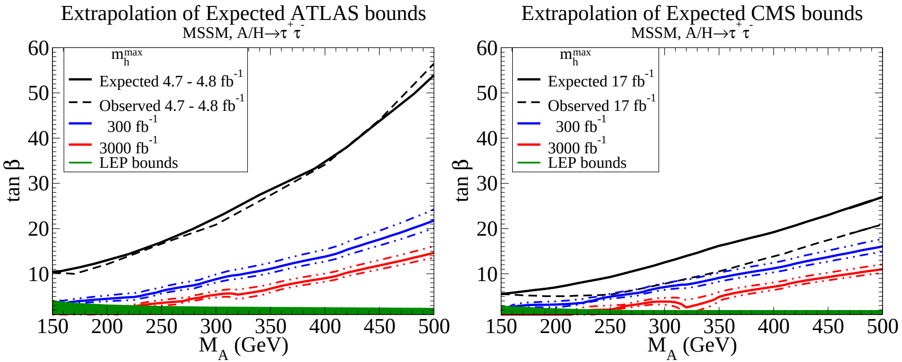
$$h\overline{U}U : \quad \frac{\cos\alpha}{\sin\beta} = s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta\,.$$

Approaching the decoupling limit





Projection of bounds to 300 and 3000 fb^{-1}



- Included conservative error bands of $\Delta\sigma(\Phi)\times \mathrm{BR}(\Phi\to\tau^+\tau^-) = \pm 25\%$

Baglio, Djouadi, 1012.0530; Djouadi, Quevillon, 1304.1787

ILC Higgs phenomenology in the decoupling limit

Assumptions:

1. The couplings of $h(126)$ measured at the LHC are consistent with those of the SM Higgs boson within the experimental uncertainties.

2. Additional Higgs states have not been found at the LHC.

   - LHC Higgs challenge: discover or rule out H, A and $H^\pm$ with masses $\gtrsim 300$ GeV and $1 \lesssim \tan\beta \lesssim 5$ (the infamous "wedge region").

ILC Opportunities

1. Small deviations of $h(126)$ couplings from SM expectations.

   - Look for systematics in deviations from SM coupling predictions.
   - Expect largest deviation in hbb and $h\tau^+\tau^-$ couplings if $\tan\beta \gtrsim 1$. Expect no significant deviations in hVV couplings ($V = W$ or Z).

2. $e^+e^- \to HA$, H^+H^- unsuppressed in the decoupling limit ($c_{\beta-\alpha} \to 0$). However p-wave production near threshold means that discovery reach in mass is somewhat below $\frac{1}{2}\sqrt{s}$.

The properties of the three-point and four-point Higgs boson-vector boson couplings are conveniently summarized by listing the couplings that are proportional to either $s_{\beta-\alpha}$ or $c_{\beta-\alpha}$ or are angle-independent.

$c_{\beta-\alpha}$	$s_{\beta-\alpha}$	angle-independent
HW^+W^-	hW^+W^-	—
HZZ	hZZ	—
ZAh	ZAH	ZH^+H^-, γH^+H^-
$W^\pm H^\mp h$	$W^\pm H^\mp H$	$W^\pm H^\mp A$
$ZW^\pm H^\mp h$	$ZW^\pm H^\mp H$	$ZW^\pm H^\mp A$
$\gamma W^\pm H^\mp h$	$\gamma W^\pm H^\mp H$	$\gamma W^\pm H^\mp A$
—	—	$VV\phi\phi$, $VVAA$, VVH^+H^-

where $\phi = h$ or H and $VV = W^+W^-$, ZZ, $Z\gamma$ or $\gamma\gamma$.

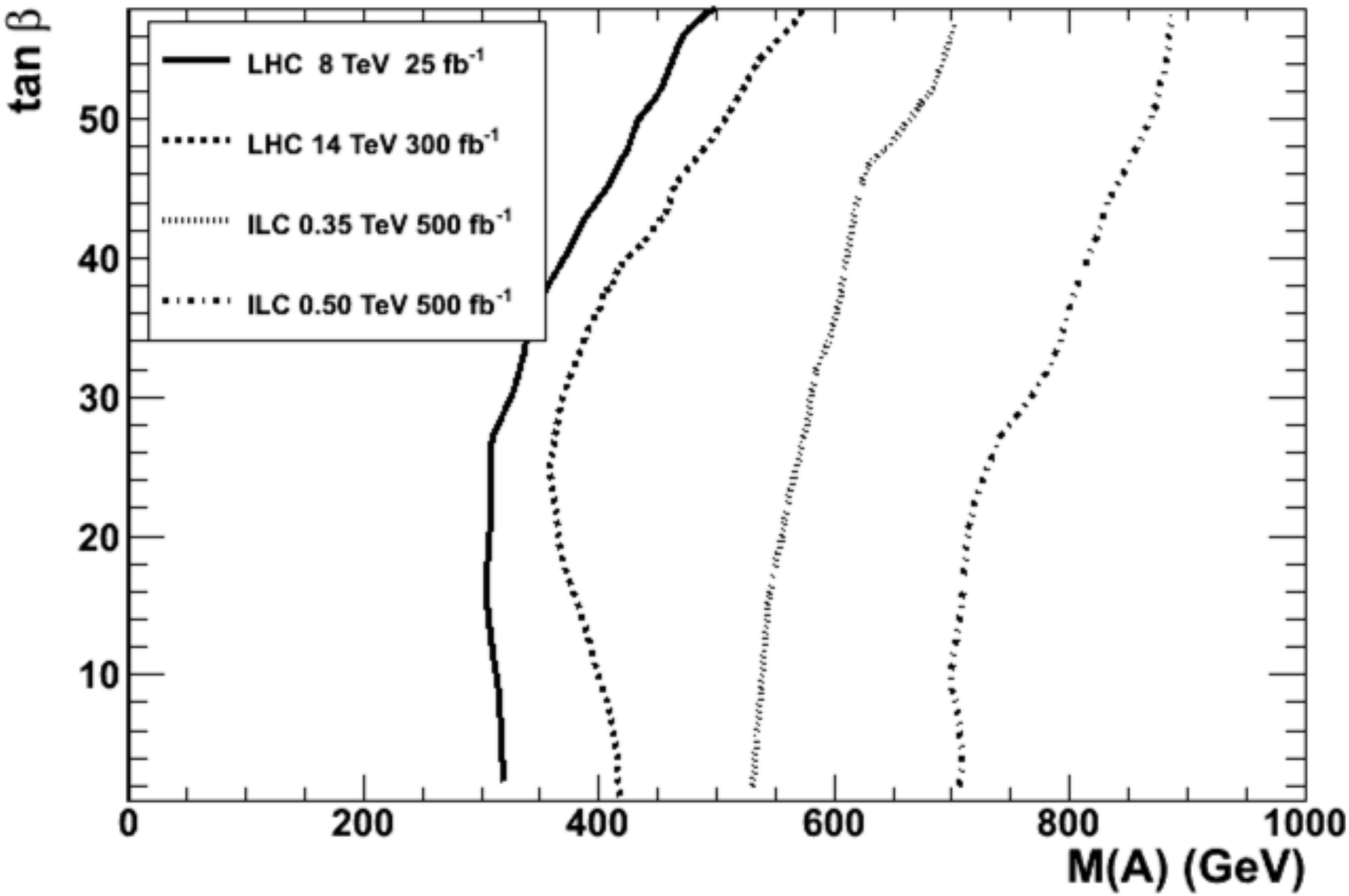
3. In Type-II models, heavy Higgs boson couplings to down-type fermions are $\tan\beta$-enhanced in the decoupling limit. The couplings of the neutral Higgs bosons to $f\bar{f}$ relative to the Standard Model value, $gm_f/2m_W$, are given by

$$\begin{aligned}
Hb\bar{b} \quad (\text{or } H\tau^+\tau^-): &\qquad \frac{\cos\alpha}{\cos\beta} = c_{\beta-\alpha} + s_{\beta-\alpha}\tan\beta\,, \\
Ht\bar{t}: &\qquad \frac{\sin\alpha}{\sin\beta} = c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta\,, \\
Ab\bar{b} \quad (\text{or } A\tau^+\tau^-): &\qquad \gamma_5\tan\beta\,, \\
At\bar{t}: &\qquad \gamma_5\cot\beta\,,
\end{aligned}$$

Similarly, the charged Higgs boson couplings to fermion pairs, with all particles pointing into the vertex, are given by

$$\begin{aligned}
g_{H^-t\bar{b}} = &\quad \frac{g}{\sqrt{2}m_W}\left[m_t\cot\beta\, P_R + m_b\tan\beta\, P_L\right], \\
g_{H^-\tau^+\nu} = &\quad \frac{g}{\sqrt{2}m_W}\left[m_\tau\tan\beta\, P_L\right].
\end{aligned}$$

In contrast, the heavy Higgs boson couplings to both up-type and down-type fermions in Type-I models are $\tan\beta$ suppressed.



From Marco Battaglia, presented at this workshop

Beyond the 2HDM

2HDM and additional BSM physics

The MSSM is perhaps the best motivated 2HDM. Supersymmetry imposes strong constraints on the 2HDM interaction terms. For example, the scalar potential parameters in the Higgs basis are given by:

$$Z_1 = Z_2 = \tfrac{1}{4}(g^2 + g'^2)\cos^2 2\beta\,, \qquad Z_3 = Z_5 + \tfrac{1}{4}(g^2 - g'^2)\,, \qquad Z_4 = Z_5 - \tfrac{1}{2}g^2\,,$$
$$Z_5 = \tfrac{1}{4}(g^2 + g'^2)\sin^2 2\beta\,, \qquad Z_7 = -Z_6 = \tfrac{1}{4}(g^2 + g'^2)\sin 2\beta\cos 2\beta\,.$$

The MSSM employs Type-II Higgs-fermion Yukawa couplings.

- One-loop radiative corrections to Higgs couplings to SM particles can sometimes compete with tree-level effects due to Higgs mixing (the latter are small in the decoupling limit), due to $\tan\beta$ enhancements. This can complicate the interpretation of deviations from SM Higgs coupling behavior.
- If the full 2HDM structure survives below the scale of SUSY-breaking, then the effect of SUSY loops induces so-called "wrong-Higgs" couplings. This yields a completely general effective 2HDM at low-energies (including possible CP-violating Higgs couplings).

Unexpected behavior in Higgs couplings to vector bosons

Consider a CP-conserving extended Higgs sector that has the property that $\rho_0 = 1$ and no tree-level $ZW^\pm\phi^\mp$ couplings (where $\phi^\pm$ are physical charged scalars that might appear in the scalar spectrum). Then it follows that

$$\sum_i g^2_{h_iVV} = g^2 m_W^2\,, \qquad\qquad m_W^2 g_{h_iZZ} = m_Z^2 g_{h_iWW}\,,$$

where the sum is taken over all neutral CP-even scalars h_i. In this case, it follows that $g_{h_iVV} \leq g_{hVV}$ for all i (where h is the SM Higgs boson). Models that contain only scalar singlets and doublets satisfy the requirements stated above and hence respect the sum rule and the coupling relation given above. However, it is possible to violate $g_{h_iVV} \leq g_{hVV}$ and $m_W^2 g_{h_iZZ} = m_Z^2 g_{h_iWW}$ if tree-level $ZW^\pm\phi^\mp$ and/or $\phi^{++}W^-W^-$ couplings are present. A more general sum rule is:

$$\sum_i g^2_{h_iVV} = g^2 m_W^2 + \sum_k |g_{\phi_k^{++}W^-W^-}|^2\,.$$

The Georgi-Machacek model provides an instructive example. This model consists of a complex Higgs doublet with $Y = 1$, a complex Higgs triplet with $Y = 2$ and a real Higgs triplet with $Y = 0$, with doublet vev $a/\sqrt{2}$ and triplet vevs b, such that $v^2 = a^2 + 8b^2$.

It is convenient to write

$$c_H \equiv \cos\theta_H = \frac{a}{\sqrt{a^2 + 8b^2}}\,,$$

and $s_H \equiv \sin\theta_H = (1 - c_H^2)^{1/2}$. Then, the following couplings are noteworthy:

$$H_1^0 W^+ W^- : \quad g c_H m_W\,, \qquad H_1^{\prime\,0} W^+ W^- : \quad \sqrt{8/3}\, g m_W s_H\,,$$

$$H_5^0 W^+ W^- : \quad \sqrt{1/3}\, g m_W s_H\,, \qquad H_5^{++} W^- W^- : \quad \sqrt{2}\, g m_W s_H\,.$$

$H_1^{\prime\,0}$ and H_5^0, H_5^{++} have no coupling to fermions, whereas

$$H_1^0 f \bar{f} : \quad \frac{g m_q}{2 m_W c_H}\,.$$

In general H_1^0 and $H_1^{\prime\,0}$ can mix.

In the absence of H_1^0–$H_1^{\prime\,0}$ mixing and $c_H = 1$, we see that the couplings of H_1^0 match those of the SM. But consider the strange case of $s_H = \sqrt{3/8}$. In this case, the $H_1^{\prime\,0}$ coupling to W^+W^- matches that of the SM. Nevertheless, this does not saturate the HWW sum rule! Moreover, it is possible that the $H_1^{\prime\,0} W^+ W^-$ coupling is *larger* than $g m_W$, without violating the HWW sum rule. Including H_1^0–$H_1^{\prime\,0}$ mixing allows for even more baroque possibilities not possible in a multi-doublet extension of the SM.

Conclusions

1. The discovery of a SM-like Higgs boson at LHC does not foreclose the possibility of an extended Higgs sector beyond the Standard Model.
2. Typical extended Higgs sectors possess a robust parameter regime in which the lightest scalar is SM-like and the additional Higgs scalars are somewhat heavier. This is the decoupling limit.
3. To explore the decoupling limit of the general 2HDM, the framework of the Higgs basis is particularly useful as it isolates the physical couplings of the model in an elegant way.
4. As the non-decoupling scenario becomes less likely, one can begin to exploit the decoupling limit in more detail in phenomenological Higgs studies.
5. The precision Higgs program at the ILC can reveal patterns of deviations from SM Higgs couplings, which would provide critical clues to the structure of the extended Higgs sector.
6. Certain regimes of the Higgs parameter space present challenges for LHC searches and windows of opportunity for ILC studies.
7. There is still room for surprises in the exploration of Higgs physics.