Higgs Physics---Approaching the Decoupling Limit

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July 25, 2013

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References

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2. H.E. Haber and D. O'Neil, *Basis-independent methods for the two Higgs doublet model II: the significance of tan* ß, Phys. Rev. D 74, 015018 (2006).

3. H.E. Haber, *2HDM Benchmarks for LHC Higgs Studies,* presentations to the BSM Heavy Higgs Meeting at CERN.

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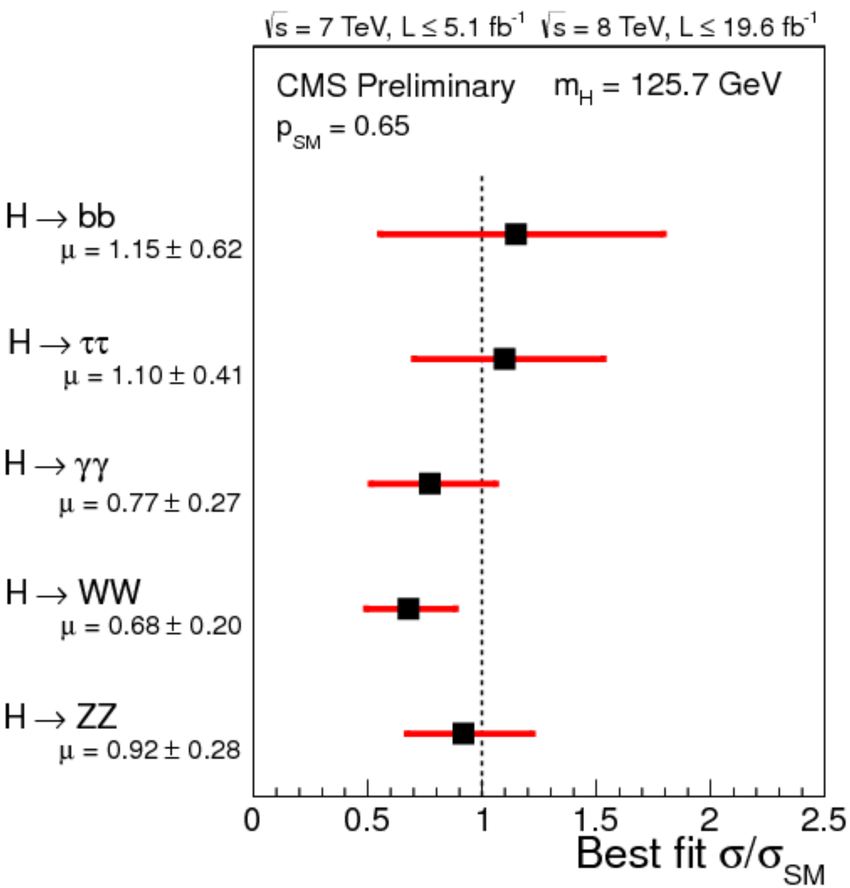
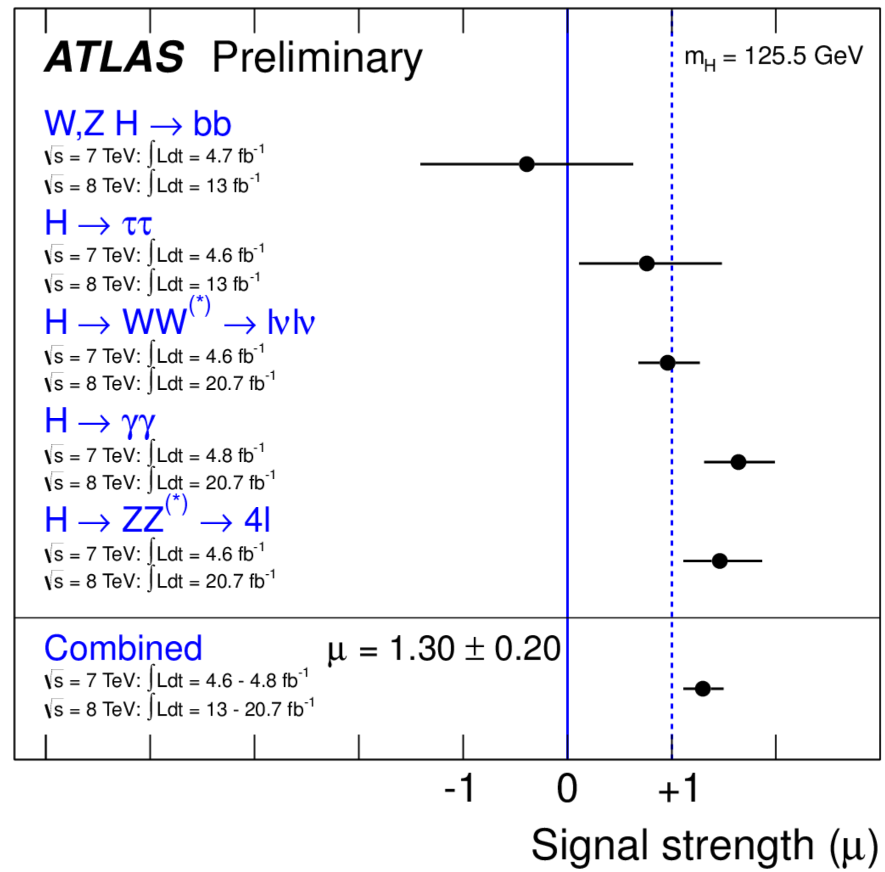
Has ATLAS and CMS discovered *the* Higgs boson?

A Standard Model (SM) Higgs--like boson?

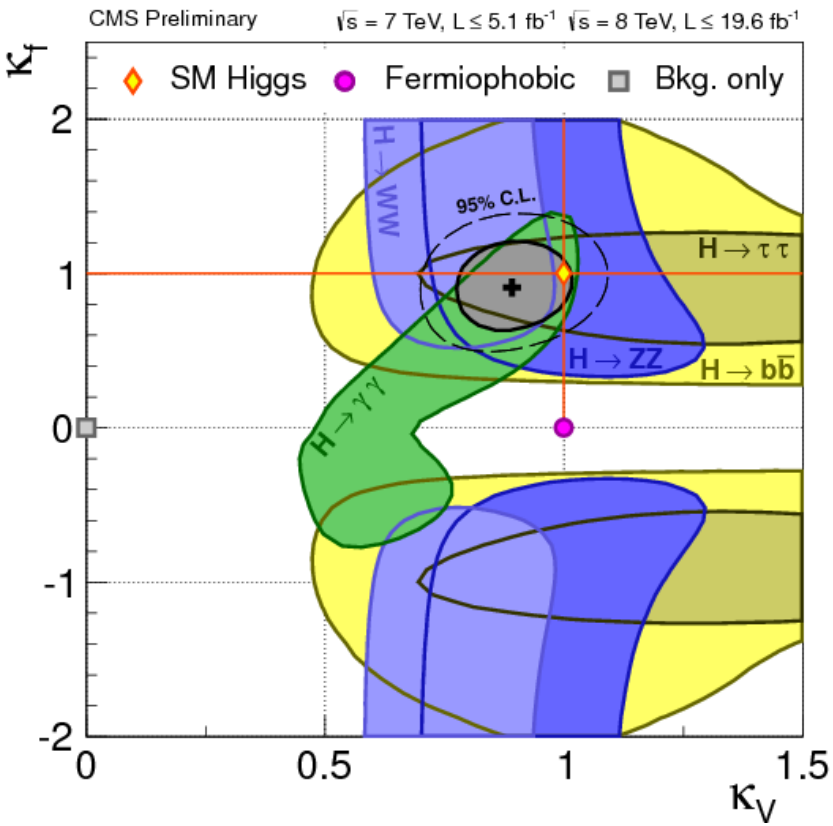




Taken from CMS-PAS-HIG-130-005 (March, 2013)

Taken from ATLAS-CONF-2013-034 (March, 2013)

Search for deviations from SM-Higgs couplings to fermions and WW/ZZ



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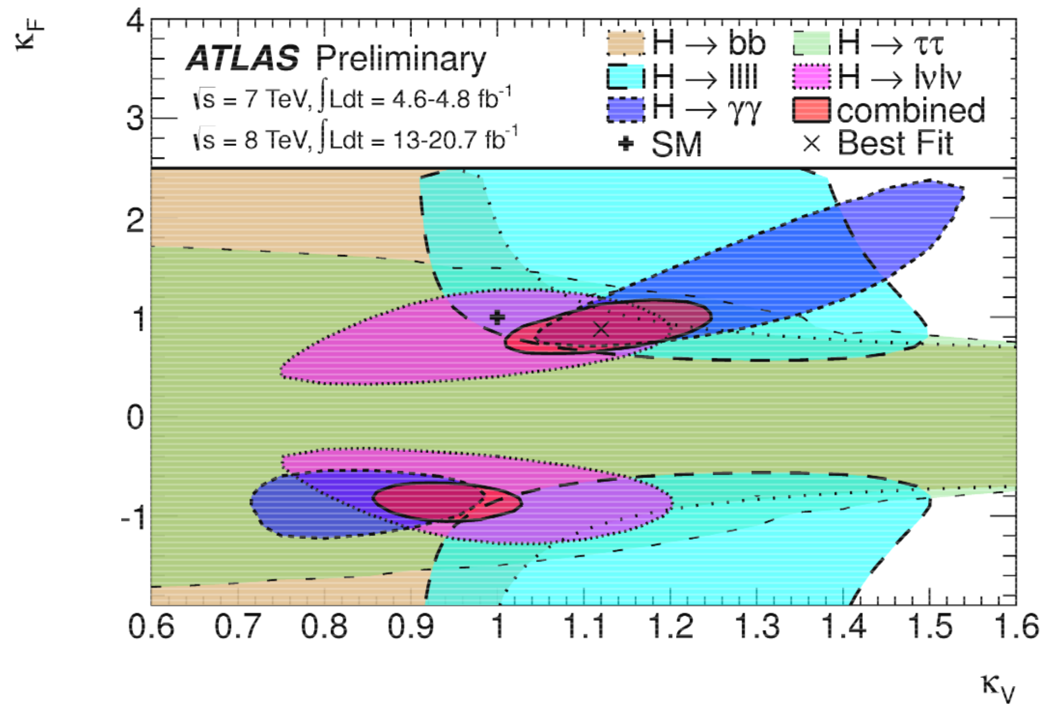


Fits for 2-parameter benchmark models probing different coupling strength scale factors for fermions and vector bosons, assuming only SM contributions to the total width: (a) Correlation of the coupling scale factors κ_F and κ_V; (b) the same correlation, overlaying the 68% CL contours derived from the individual channels and their combination; (c) coupling scale factor κ_V (κ_F is profiled); (d) coupling scale factor κ_F (κ_V is profiled). The dashed curves in (c) and (d) show the SM expectation. The thin dotted lines in (c) indicate the continuation of the likelihood curve when restricting the parameters to either the positive or negative sector of κ_F.

Taken from ATLAS-CONF-2013-034 (March, 2013)

2HDM—Framework for extended Higgs sectors

The scalar fields of the 2HDM are complex SU(2) doublet, hypercharge-one fields, Φ_1 and Φ_2, where the corresponding vevs are $\langle\Phi_i\rangle = v_i/\sqrt{2}$, 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

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

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:

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

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,

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

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,

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

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 3×3 hermitian matrices,

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

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

Remarks

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/alignment limit

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. We examine the conditions in which h_1 is the SM-like Higgs boson. Noting that

$$\frac{g_{h_1VV}}{g_{h_{\rm SM}VV}} = c_{12}c_{13}\,, \qquad \text{where } V = W \text{ or } Z\,,$$

and $h_{\rm SM}$ is the SM Higgs boson, we demand that

$$s_{12}\,,\, s_{13} \ll 1\,.$$

The following (exact) relations are noteworthy:

$$\begin{aligned}
{\rm Re}(Z_6\, e^{-i\theta_{23}})\, v^2 &= c_{13}s_{12}c_{12}(m_2^2 - m_1^2)\,,\\
{\rm Im}(Z_6\, e^{-i\theta_{23}})\, v^2 &= s_{13}c_{13}(c_{12}^2 m_1^2 + s_{12}^2 m_2^2 - m_3^2)\,,\\
{\rm Im}(Z_5\, e^{-2i\theta_{23}})\, v^2 &= 2s_{12}c_{12}s_{13}(m_2^2 - m_1^2)\,.
\end{aligned}$$

We assume no mass degeneracies in the neutral scalar sector.

In the decoupling/alignment limit,

$$s_{12} \equiv \sin\theta_{12} \simeq \frac{\mathrm{Re}(Z_6 e^{-i\theta_{23}})v^2}{m_2^2 - m_1^2} \ll 1\,,$$

$$s_{13} \equiv \sin\theta_{13} \simeq -\frac{\mathrm{Im}(Z_6 e^{-i\theta_{23}})v^2}{m_3^2 - m_1^2} \ll 1\,,$$

$$\mathrm{Im}(Z_5 e^{-2i\theta_{23}}) \simeq \frac{2(m_2^2 - m_1^2)s_{12}s_{13}}{v^2} \simeq -\frac{\mathrm{Im}(Z_6^2 e^{-2i\theta_{23}})v^2}{m_3^2 - m_1^2} \ll 1\,.$$

The decoupling limit (heavy mass decoupling) [Haber and Nir]

In the limit of $Y_2 \gg v$ [with $|Z_i| \lesssim \mathcal{O}(1)$], H_2 becomes very massive. Integrating out these fields, the effective Higgs theory at an energy scale below Y_2 is that of the SM Higgs boson! In this limit m_1^2, $|Z_i|v^2 \ll m_2^2$, m_3^2, $m_{H^\pm}^2$, and h_1, with $m_1^2 \simeq Z_1 v^2$, has couplings nearly identical to those of $h_{\rm SM}$.

The alignment limit (weak coupling decoupling) [Craig, Galloway and Thomas]

In the limit of $Y_3 \to 0$ (no H_1–H_2 mixing), the scalar potential minimum condition, $Y_3 = -\frac{1}{2}Z_6 v^2$ implies that $Z_6 \to 0$. In this case, the mass eigenstate h_1 aligns with the Higgs-basis state $\mathrm{Re}(H_1^0 - v/\sqrt{2})$. Again we find that h_1, with $m_1^2 \simeq Z_1 v^2$, has couplings nearly identical to those of $h_{\rm SM}$.

2HDM couplings of the SM-like Higgs boson $h \simeq h_1$ normalized to those of the SM Higgs boson, in the decoupling/alignment 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/alignment limit
hW^+W^-, hZZ	$c_{12}c_{13}$	$1 - \frac{1}{2}s_{12}^2 - \frac{1}{2}s_{13}^2$
hhh		$1 - 3(s_{12}Z_{6R} - s_{13}Z_{6I})/Z_1$
$hhhh$		$1 - 4(s_{12}Z_{6R} - s_{13}Z_{6I})/Z_1$
$h\overline{D}D$	$c_{12}c_{13}\mathbb{1} - s_{12}\rho_R^D - c_{12}s_{13}\rho_I^D$	$\mathbb{1} - s_{12}\rho_R^D - s_{13}\rho_I^D$
$ih\overline{D}\gamma_5 D$	$s_{12}\rho_I^D - c_{12}s_{13}\rho_R^D$	$s_{12}\rho_I^D - s_{13}\rho_R^D$
$h\overline{U}U$	$c_{12}c_{13}\mathbb{1} - s_{12}\rho_R^U - c_{12}s_{13}\rho_I^U$	$\mathbb{1} - s_{12}\rho_R^U - s_{13}\rho_I^U$
$ih\overline{U}\gamma_5 U$	$-s_{12}\rho_I^U + c_{12}s_{13}\rho_R^U$	$-s_{12}\rho_I^U + s_{13}\rho_R^U$

The approach to decoupling/alignment is fastest in the Higgs coupling to gauge bosons and slowest in the coupling to fermions. For the Higgs self-couplings, the approach to alignment is faster than the approach to decoupling.

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

In the decoupling/alignment limit, the CP-violating couplings of h_1 are suppressed. But, some CP-violating couplings of h_2, h_3 may be unsuppressed.

Higgs interaction	2HDM coupling	decoupling/alignment limit
$h_2W^+W^-, h_2ZZ$	$s_{12}c_{13}$	s_{12}
$h_2\overline{D}D$	$s_{12}c_{13}\mathbb{1} + c_{12}\rho_R^D - s_{12}s_{13}\rho_I^D$	$s_{12}\mathbb{1} + \rho_R^D$
$ih_2\overline{D}\gamma_5 D$	$-c_{12}\rho_I^D - s_{12}s_{13}\rho_R^D$	$-\rho_I^D$
$h_2\overline{U}U$	$s_{12}c_{13}\mathbb{1} + c_{12}\rho_R^U - s_{12}s_{13}\rho_I^U$	$s_{12}\mathbb{1} + \rho_R^U$
$ih_2\overline{U}\gamma_5 U$	$c_{12}\rho_I^U + s_{12}s_{13}\rho_R^U$	ρ_I^U
$h_3W^+W^-, h_3ZZ$	s_{13}	s_{13}
$h_3\overline{D}D$	$s_{13}\mathbb{1} + c_{13}\rho_I^D$	$s_{13}\mathbb{1} + \rho_I^D$
$ih_3\overline{D}\gamma_5 D$	$c_{13}\rho_R^D$	ρ_R^D
$h_3\overline{U}U$	$s_{13}\mathbb{1} + c_{13}\rho_I^U$	$s_{13}\mathbb{1} + \rho_I^U$
$ih_3\overline{U}\gamma_5 U$	$-c_{13}\rho_R^U$	$-\rho_R^U$

The parameter $\tan\beta$ is not physically meaningful!

With respect to an arbitrary basis, $\tan\beta \equiv \langle\Phi_2^0\rangle/\langle\Phi_1^0\rangle$. But in the general 2HDM, there is no physical significance to this basis. Hence, $\tan\beta$ is unphysical. Indeed, $\tan\beta$ does not appear in the 2HDM couplings. In contrast, the 3×3 matrix parameters $\rho^Q_{R,I}$ (for $Q = U$ or D) are physically meaningful.

Does the decoupling/alignment limit exist?

In 2HDMs with a $\mathbb{Z}_2$ symmetry that sets $m_{12}^2 = 0$ in some basis, 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 where $Y_2 \gg v$ (such that $m^2_{2.3} \gg m^2_1$). But the alignment limit ($Z_6 \ll 1$) is still possible.

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 $s_{\beta-\alpha} \equiv \sin(\beta - \alpha)$.

In the decoupling limit ($m_H \gg m_h$) or in the alignment limit ($Z_6 \ll 1$),

$$c_{\beta-\alpha} \simeq -\frac{Z_6 v^2}{m_H^2 - m_h^2} \ll 1\,.$$

The neutral Higgs masses are: $m_h^2 \simeq Z_1 v^2$ and $m_{H,A}^2 \simeq Y_2 + \frac{1}{2}(Z_3 + Z_4 \pm Z_5)v^2$.

2HDM couplings of the SM-like Higgs boson h normalized to those of the SM Higgs boson, in the decoupling/alignment limit. The scalar Higgs potential is taken to be CP-conserving.

Higgs interaction	2HDM coupling	decoupling/alignment limit
$hW^+W^-\,,\,hZZ$	$s_{\beta-\alpha}$	$1 - \frac{1}{2}c_{\beta-\alpha}^2$
hhh		$1 + 3(Z_6/Z_1)c_{\beta-\alpha}$
$hhhh$		$1 + 4(Z_6/Z_1)c_{\beta-\alpha}$
$h\overline{D}D$	$s_{\beta-\alpha}\mathbb{1} + c_{\beta-\alpha}\rho_R^D$	$\mathbb{1} + c_{\beta-\alpha}\rho_R^D$
$ih\overline{D}\gamma_5 D$	$-c_{\beta-\alpha}\rho_I^D$	$-c_{\beta-\alpha}\rho_I^D$
$h\overline{U}U$	$s_{\beta-\alpha}\mathbb{1} + c_{\beta-\alpha}\rho_R^U$	$\mathbb{1} + c_{\beta-\alpha}\rho_R^U$
$ih\overline{U}\gamma_5 U$	$c_{\beta-\alpha}\rho_I^U$	$c_{\beta-\alpha}\rho_I^U$

2HDM couplings of the other neutral Higgs bosons normalized to those of the SM Higgs boson, in the decoupling/alignment limit. The scalar Higgs potential is taken to be CP-conserving. In the convention of $Z_6 > 0$, we identify $H \equiv -h_2$ and $A \equiv h_3$.

Higgs interaction	2HDM coupling	decoupling/alignment limit
HW^+W^-, HZZ	$c_{\beta-\alpha}$	$c_{\beta-\alpha}$
$H\overline{D}D$	$c_{\beta-\alpha}\mathbb{1} - s_{\beta-\alpha}\rho_R^D - s_{12}s_{13}\rho_I^D$	$c_{\beta-\alpha}\mathbb{1} - \rho_R^D$
$iH\overline{D}\gamma_5 D$	$s_{\beta-\alpha}\rho_I^D - s_{12}s_{13}\rho_R^D$	ρ_I^D
$H\overline{U}U$	$c_{\beta-\alpha}\mathbb{1} - s_{\beta-\alpha}\rho_R^U$	$c_{\beta-\alpha}\mathbb{1} - \rho_R^U$
$iH\overline{U}\gamma_5 U$	$-s_{\beta-\alpha}\rho_I^U$	$-\rho_I^U$
AW^+W^-, AZZ	0	0
$h_3\overline{D}D$	ρ_I^D	ρ_I^D
$iA\overline{D}\gamma_5 D$	ρ_R^D	ρ_R^D
$A\overline{U}U$	ρ_I^U	ρ_I^U
$iA\overline{U}\gamma_5 U$	$-\rho_R^U$	$-\rho_R^U$

Constraining the Higgs-fermion Yukawa couplings

To avoid Higgs-mediated tree-level FCNCs, the ρ^Q must be very close to 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: $\rho_R^D = \rho_R^U = \mathbb{1}\cot\beta\,, \qquad \rho_I^D = \rho_I^U = 0.$

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

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

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

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

Case study: The MSSM Higgs sector

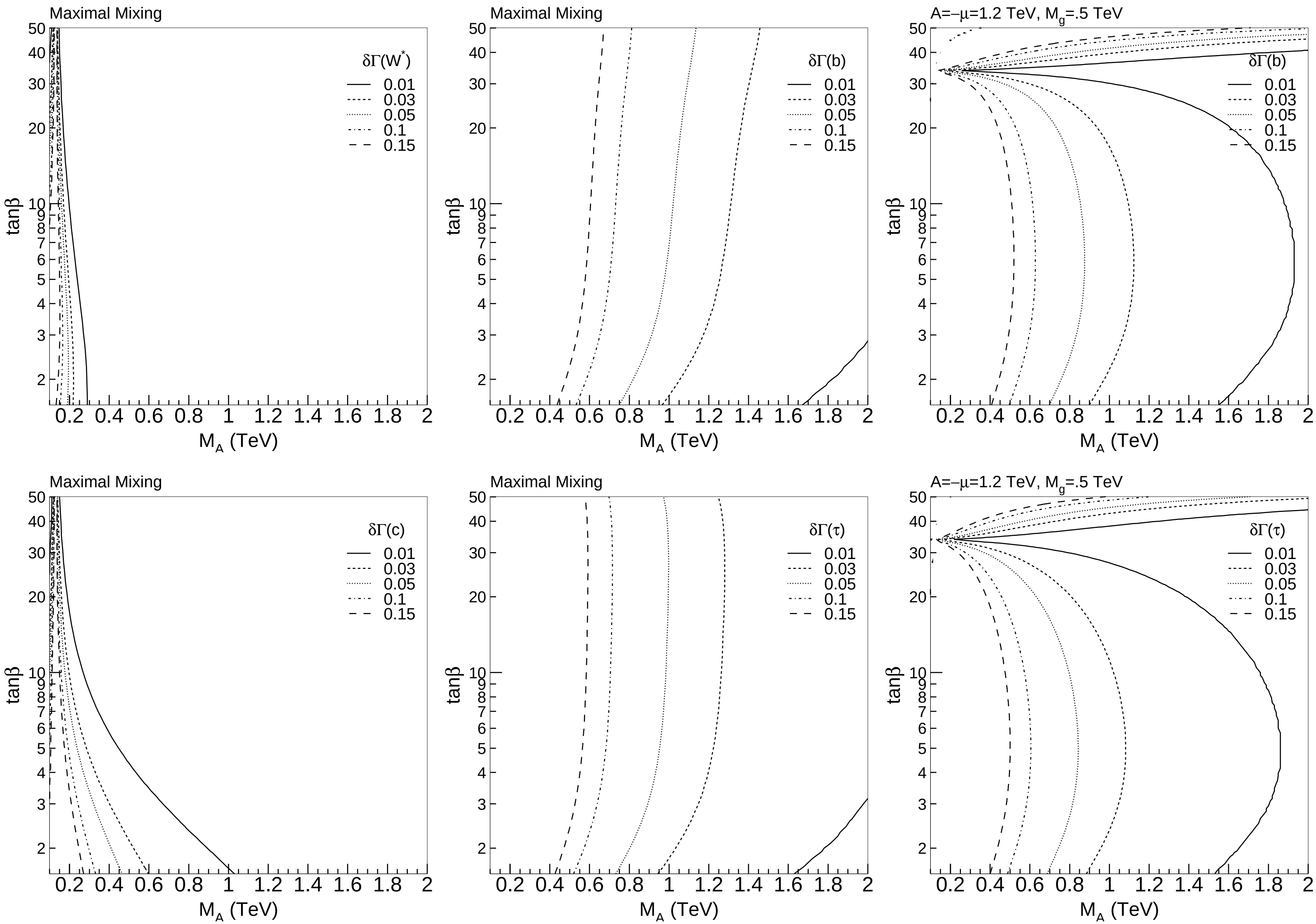
In the MSSM, supersymmetry constrains the scalar Higgs potential:

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

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

In addition, supersymmetry imposes Type-II Higgs-fermion Yukawa interactions.

- 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).
- Due to $\tan\beta$-enhanced radiative corrections, SUSY parameter regions exist in which $Z_6 \simeq 0$ (for a particular value of $\tan\beta$), corresponding to the alignment limit.



Deviations of Higgs partial widths from their SM values in two different MSSM scenarios (Carena, Haber, Logan and Mrenna).

What if the SM-like Higgs boson is the heavier one?

Can we identify the CP-even H as the SM-like Higgs boson? In this case $c_{\beta-\alpha} \simeq 1$ and $s_{\beta-\alpha} \ll 1$. This cannot be achieved in the (heavy mass) decoupling limit, but it can be achieved in the alignment limit ($Z_6 \ll 1$), where

$$s_{\beta-\alpha} \simeq -\frac{Z_6 v^2}{m_H^2 - m_h^2} \ll 1\,.$$

The corresponding neutral Higgs masses are:

$$\begin{aligned} m_H^2 &= Z_1 v^2\,, \\ m_{h,A}^2 &= Y_2 + \tfrac{1}{2}(Z_3 + Z_4 \pm Z_5)v^2\,. \end{aligned}$$

Note that in order to have $m_h < m_H$, the following relation must be satisfied,

$$Z_1 v^2 > Y_2 + \tfrac{1}{2}(Z_3 + Z_4 + Z_5)v^2\,.$$

A SM-like Higgs boson in magnitude but not sign?

Higgs interaction	2HDM coupling	decoupling/alignment limit
$hW^+W^-\,, hZZ$	$s_{\beta-\alpha}$	$1-\frac{1}{2}c^2_{\beta-\alpha}$
$h\overline{D}D$	$s_{\beta-\alpha}\mathbb{1}+c_{\beta-\alpha}\rho^D_R$	$\mathbb{1}+c_{\beta-\alpha}\rho^D_R$
$h\overline{U}U$	$s_{\beta-\alpha}\mathbb{1}+c_{\beta-\alpha}\rho^U_R$	$\mathbb{1}+c_{\beta-\alpha}\rho^U_R$

Is it possible to have either $c_{\beta-\alpha}\rho^D_R\simeq -2$ and/or $c_{\beta-\alpha}\rho^U_R\simeq -2$, in which case the $h\overline{D}D$ and/or $h\overline{U}U$ couplings would be SM-like in magnitude but opposite in sign? In the Type-II 2HDM, we have $\rho^D_R=-\mathbb{1}\tan\beta$ and $\rho^U_R=\mathbb{1}\cot\beta$. So, at large $\tan\beta$ it is conceivable that $c_{\beta-\alpha}\ll 1$ but

$$\tan\beta\simeq\frac{2}{c_{\beta-\alpha}}\gg 1\,,$$

which reverses the sign of the $h\overline{D}D$ coupling. To reverse the sign of the $h\overline{U}U$ coupling requires $\cot\beta\gg 1$ leading to an uncomfortably large $h\bar{t}t$ coupling.

Note that with moderately large $\tan\beta$, it is possible to have non-SM-like $h\overline{D}D$ couplings close to the decoupling/alignment limits.

Ingredients for CP-conserving 2HDM benchmarks

Given the observation of a SM-like Higgs boson at the LHC, we propose to use this information in the search for states of an extended Higgs sector. For example, consider the Type I or Type II 2HDM. To implement the required Higgs-fermion Yukawa couplings, we impose a $\mathbb{Z}_2$ symmetry on the dimension-four interactions of the Higgs Lagrangian in some basis $\{\Phi_1\,,\,\Phi_2\}$. With respect to this basis, we can define $\tan\beta=\langle\Phi_2^0\rangle/\langle\Phi_1^0\rangle$. The existence of this $\mathbb{Z}_2$ symmetry imposes the following constraint on the Higgs basis scalar potential parameters:

$$(Z_6+Z_7)(Z_2-Z_1)(Z_1+Z_2-2Z_{345})+(Z_6-Z_7)\left[(Z_2-Z_1)^2-4(Z_6+Z_7)^2\right]=0\,,$$

where $Z_{345}\equiv Z_3+Z_4+Z_5$. The parameter β is also determined (by convention, $0\leq\beta\leq\frac{1}{2}\pi$),

$$\tan 2\beta=\frac{2(Z_6+Z_7)}{Z_2-Z_1}\,.$$

The case of $Z_1=Z_2$ and $Z_6=-Z_7$ must be treated separately [example: the MSSM Higgs sector]. In this case, a $\mathbb{Z}_2$ symmetry governing the quartic terms of the scalar potential is automatically present, and the corresponding value of β is determined from the following equation,

$$(Z_1-Z_{345})\tan 2\beta+2Z_6(1-\tan^2 2\beta)=0\,.$$

Case 1: Identify h with the observed Higgs boson, with $m_h \simeq 126$ GeV.

1. Choose $c_{\beta-\alpha} \ll 1$ to give SM-like hVV couplings.

2. Z_1 is determined by
$$Z_1 v^2 = m_h^2 - Z_6 v^2 \frac{c_{\beta-\alpha}}{s_{\beta-\alpha}}$$

3. Z_2 is determined in terms of β, Z_6 and Z_7

4. Imposing the $\mathbb{Z}_2$ symmetry, Z_{345} is determined in terms of Z_1, Z_2, Z_6, Z_7.

5. Scan in the couplings Z_4, Z_5, Z_6 and Z_7 [where $Z_6 > 0$ and $s_{\beta-\alpha}c_{\beta-\alpha} < 0$ by convention], consistent with unitarity bounds on the Z_i (roughly, $|Z_i| \lesssim 2\pi$).

The masses m_H, m_A and $m_{H^\pm}$ are determined by:

$$m_H^2 = m_h^2 - \frac{Z_6 v^2}{s_{\beta-\alpha}c_{\beta-\alpha}}, \qquad m_A^2 = m_H^2 + \left[\frac{c_{\beta-\alpha}}{s_{\beta-\alpha}} Z_6 - Z_5\right] v^2,$$
$$m_{H^\pm}^2 = m_A^2 - \tfrac{1}{2}(Z_4 - Z_5)v^2.$$

Case 2: Identify H with the observed Higgs boson, with $m_H \simeq 126$ GeV.

1. Choose $s_{\beta-\alpha} \ll 1$ to give SM-like HVV couplings.

2. Z_1 is determined by

$$Z_1 v^2 = m_H^2 + Z_6 v^2 \frac{s_{\beta-\alpha}}{c_{\beta-\alpha}}$$

3. Z_2 is determined in terms of β, Z_6 and Z_7

4. Imposing the $\mathbb{Z}_2$ symmetry, Z_{345} is determined in terms of Z_1, Z_2, Z_6, Z_7.

5. Scan in the couplings Z_4, Z_5, Z_6 and Z_7 [where $Z_6 > 0$ and $s_{\beta-\alpha}c_{\beta-\alpha} < 0$ by convention], consistent with the unitarity bounds on the Z_i. Choose a value for $Z_6/s_{\beta-\alpha}$ such that $m_h^2 > 0$ consistent with the LEP Higgs bounds. The masses m_h, m_A and $m_{H^\pm}$ are determined by:

$$m_h^2 = m_H^2 + \frac{Z_6 v^2}{s_{\beta-\alpha}c_{\beta-\alpha}}, \qquad m_A^2 = m_H^2 + \left[\frac{c_{\beta-\alpha}}{s_{\beta-\alpha}} Z_6 - Z_5\right] v^2,$$

$$m_{H^\pm}^2 = m_A^2 - \tfrac{1}{2}(Z_4 - Z_5)v^2.$$

Phenomenological consequence of the decoupling/alignment limit

Assume that h is identified with $h(126)$.

1. WW, ZZ, Zh couplings to H and and A are either suppressed or absent.

2. In the Type-II 2HDM, H and A couplings to down-type fermions are $\tan\beta$-enhanced in the decoupling/alignment 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

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

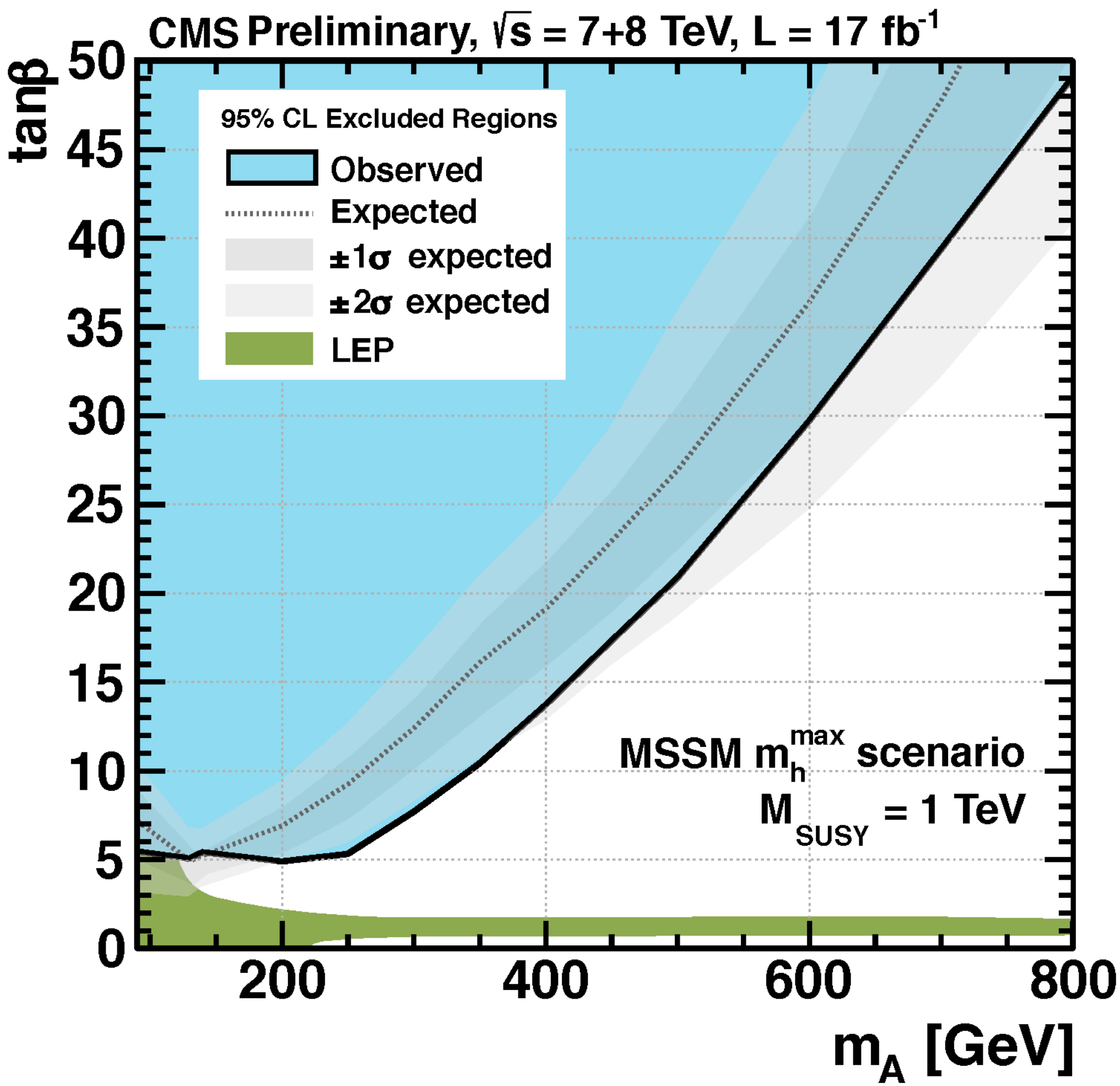
In contrast, the H and A couplings to both up-type and down-type fermions in Type-I models are $\tan\beta$ suppressed.

3. In the alignment limit, the squared-masses of the additional Higgs scalar states can be of order $Z_i v^2$, i.e. not significantly larger than the squared mass of $h(126)$. At large $\tan\beta$, the neutral states are most visible via production in association with $b\bar{b}$ followed by the decay into $b\bar{b}$ and/or $\tau^+\tau^-$. The charged Higgs boson can appear in top decays if kinematically allowed.

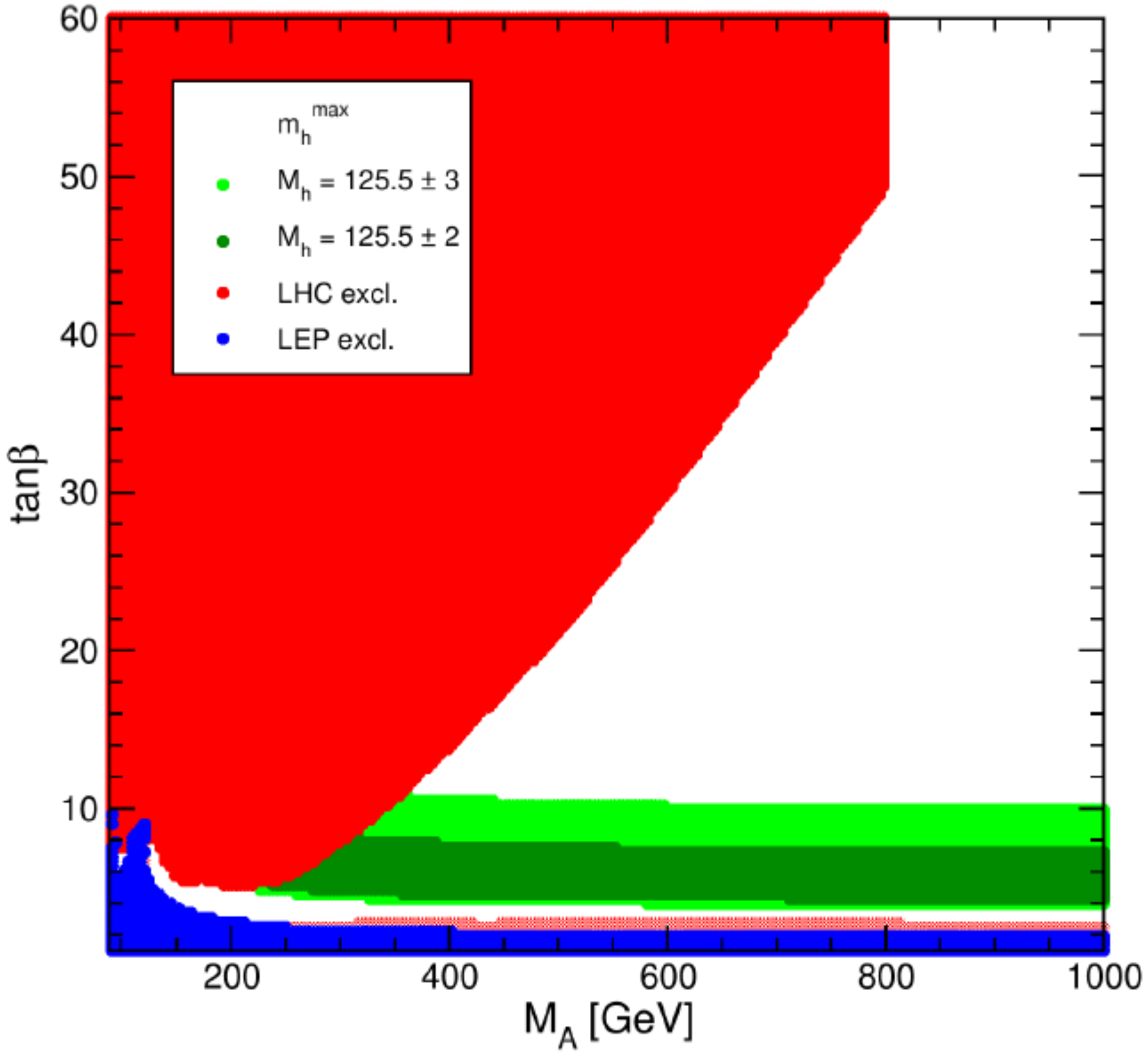
4. In the decoupling limit, the additional Higgs scalar states are significantly heavier than $h(126)$. The production of the neutral Higgs states in association with $b\bar{b}$ or the charged Higgs boson in association with the top quark is a viable discovery mode for large enough $\tan\beta$. At smaller values of $\tan\beta$, discovery of the additional Higgs scalars is difficult (the infamous LHC wedge region), although the production of H via gluon-gluon fusion followed by $H \to hh$ provides a possible signature for discovery.

$$g_{Hhh} \simeq v\big[3Z_6 - c_{\beta-\alpha}(3Z_1 + 2Z_{345})\big] .$$

The MSSM Higgs sector---approaching the decoupling limit?



If you also impose the constraint of the observed Higgs mass, the lower bound on m_A is raised above 200 GeV, which is approaching the Higgs decoupling regime.



Taken from M. Carena et al., arXiv:1302.7033

Beyond the 2HDM—surprises in the hVV couplings

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 $g_{h_iVV} \leq g_{h_{\rm SM}VV}$ for all i. 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:

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

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

$H_1^{\prime\,0}$ 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 gm_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. This can occur in either the decoupling and/or the alignment limits.
3. To explore the decoupling/alignment limits of the 2HDM, the framework of the Higgs basis is particularly useful as it isolates the physical couplings of the model in an elegant way.
4. In the absence of significant deviations from the SM predictions for the couplings of $h(126)$, one can begin to exploit the decoupling/alignment limits in more detail in phenomenological Higgs studies.
5. The decoupling/alignment regimes of the 2HDM provides challenges for LHC searches due to the suppressed couplings of the non-minimal Higgs states to VV ($V = W$ or Z).
6. Extended Higgs sectors beyond the 2HDM can yield unsuppressed VV couplings to the non-minimal Higgs states consistent with a SM-like $h(126)$.