Thoughts on 2HDM Benchmarks

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LHC Higgs cross section working group
WG3/Extended scalars
2015-02-24
LHC analyses of 2HDM

- Interpretation of 125 GeV coupling measurements
  
  ATLAS-CONF-2014-010

- Genuine 2HDM searches

- Model sensitivity:
  \( \text{BR}(H \rightarrow hh) \) depends on full model
  SM \( h \rightarrow \gamma\gamma \) sensitive to \( H^+H^-h \)
Idea of Benchmarks

- Like probably most theorists, I favor keeping experimental searches as model-independent as possible.

- Still, in many situations it also makes sense to consider specific models.

- The role of benchmarks is to:
  - Motivate experimental searches to exploit all channels
  - Improve search strategies using model-specific information
  - Combine different channels to improve sensitivity
  - Define unambiguous and complete sets of parameters to be able to consider relevant model constraints
  - Enable calculations of higher-order corrections
  - Provide language to compare exp <-> exp and exp <-> th
The Higgs basis

Among the 2HDM basis choices, there is one special case: the Higgs basis, where only one of the doublets acquires a vev:

\[ H_1 = \cos \beta \Phi_1 + \sin \beta \Phi_2 \quad \langle H_1^0 \rangle = \frac{v}{\sqrt{2}} \quad \langle H_2^0 \rangle = 0 \]

\[ H_2 = -\sin \beta \Phi_1 + \cos \beta \Phi_2 \]

\[ V = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] \]

\[ + \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \frac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \]

\[ + \left\{ \frac{1}{2} Z_5 (H_1^\dagger H_2)^2 + [Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2)] H_1^\dagger H_2 + \text{h.c.} \right\}, \]

Soft \(Z_2\)-breaking condition (existence of basis with \(\lambda_6 = \lambda_7 = 0\)):

\[ (Z_1 - Z_2) \left[ Z_1 Z_7 + Z_2 Z_6 - Z_{345} Z_{67} \right] + 2 Z_{67}^2 (Z_6 - Z_7) = 0 \]
2HDM Hybrid basis

H.E. Haber, OS [to appear]

- Even with restrictions to CP conservation and soft $Z_2$ (Types) there remains seven free parameters in the 2HDM:
  \[ \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{12}^2, \tan \beta \]
  or
  \[ m_h, m_H, m_A, m_{H^\pm}, \sin(\beta - \alpha), m_{12}^2, \tan \beta \]
  or

- Hybrid basis: \[ m_h, m_H, \cos(\beta - \alpha), \tan \beta, Z_4, Z_5, Z_7 \]

  \[ m_H > m_h \]
  \[ 0 < \beta < \pi/2 \quad 0 \leq \sin(\beta - \alpha) \leq 1 \]

- “Type” condition on the Yukawa couplings implicit
  $Z_2$ symmetry manifest ($\lambda_6 = \lambda_7 = 0$) in basis with specified $\tan \beta$
Mass relations in hybrid basis

- Remaining masses fixed by the quartic Higgs basis couplings:

\[ m_A^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 - Z_5 v^2 \]
\[ m_{H^\pm}^2 = m_A^2 - \frac{1}{2} (Z_4 - Z_5) v^2 \]

\( Z_7 \) enters only in triple/quartic scalar interactions

- Theoretical constraints:

\[ |Z_i| \lesssim \mathcal{O}(1) \]

- Practical to use hybrid basis to find theoretically allowed regions of 2HDM parameter space.

Predictions presented in terms of physical parameters.
Overview of scenarios

H.E. Haber, OS [to appear]

- **Scenario A**
  “Standard” scenario with lightest Higgs at 125 GeV
  \[ M_h = 125 \text{ GeV} < M_H < M_A = M_{H^+}. \]
  Useful for H searches in standard modes and H -> h h

- **Scenario B**
  “Inverted” scenario with heavy CP-even Higgs at 125 GeV
  \[ M_h < M_H = 125 \text{ GeV} < M_A = M_{H^+}. \]
  Useful for h searches.

- **Scenario C**
  Overlapping CP-even and CP-odd Higgses at 125 GeV
  \[ M_h = M_A = 125 \text{ GeV} < M_H = M_{H^+}. \]
  Test sensitivity to mixed CP.
Overview of scenarios

H.E. Haber, OS [to appear]

- **Scenario D**
  “Inverted” scenario with heavy CP-even Higgs having non-SM cascade decays, e.g. $H \rightarrow A \ Z$, $H \rightarrow H^+ W^-$. $M_A/M_{H^+} < M_H$.

- **Scenario E**
  Scenario with heavy CP-odd / charged Higgs in cascades $A \rightarrow H^+ W^-$ or $H^+ \rightarrow A W^+$.

- **Scenario F**
  $h$ with SM-like couplings to up-type fermions and vector bosons, but flipped sign of coupling to down-type fermions.

- **Scenario G**
  “MSSM”-like (mass-degenerate) scenario for heavy Higgs bosons $M_h = 125 \text{ GeV} < M_H = M_A = M_{H^+}$, decoupling as $M >> v$. 

2HDMC (2-Higgs Doublet Model Calculator)

- Public, object-oriented C++ code implementing calculations for the general (CP-conserving) 2HDM in different parametrizations

  D. Eriksson (Ericsson), OS (Stockholm), J. Rathsman (Lund)
  \[0902.0851\]
  http://2hdmc.hepforge.org

- First released in 2009, current public version is 1.6.5

- Predictions for all benchmark scenarios of branching ratios and LHC cross sections – link to SusHi

  R. Harlander, S. Liebler, H. Mantler, [1212.3249]

- Part of XSWG interim recommendations for the 2HDM

  R. Harlander, M. Muhlleitner, J. Rathsman, M. Spira, OS [1312.5571]
Example: Scenario G (MSSM-like)

- Start from MSSM tree-level values for the Higgs potential

\[
\begin{align*}
\lambda_1 &= \lambda_2 = \frac{g^2 + g'^2}{4}, \\
\lambda_3 &= \frac{g^2 - g'^2}{4}, \\
\lambda_4 &= -\frac{g^2}{2}, \\
\lambda_5 &= \lambda_6 = \lambda_7 = 0. \\
\end{align*}
\]

\[
m_{12}^2 = \frac{1}{2} m_A^2 \sin 2\beta
\]

- Assume dominant radiative corrections to the (2,2) element of the CP-even Higgs mass matrix is due to \(\lambda_2\).

Define:

\[
\lambda_2 \rightarrow \lambda_2 + \delta
\]

Use measured value of \(m_h\) as input to fix \(\delta\). Input parameters:

\[
m_A, \tan \beta, m_h
\]

- Phenomenology similar to “hMSSM” approach

A. Djouadi, et al [1307.5205], [1502.05653]
Most MSSM-like scenario (Type-II)

Excluded by direct searches (HiggsBounds)

Fit to light h rates (HiggsSignals)

- $\Delta \chi^2 < 11.8$
- $\Delta \chi^2 < 5.99$
- $\Delta \chi^2 < 2.30$
Less MSSM-like scenario (Type-I)

Excluded by direct searches (HiggsBounds)

Fit to light h rates (HiggsSignals)

- $\Delta \chi^2 < 11.8$
- $\Delta \chi^2 < 5.99$
- $\Delta \chi^2 < 2.30$
Backup
The general two-Higgs-doublet Model (2HDM)

- Two complex SU(2) doublets \((Y=1)\): \(\Phi_1, \Phi_2\)

- Scalar potential:

\[
V_{2\text{HDM}} = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - \left[ m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]
+ \frac{1}{2} \lambda_1 |\Phi_1|^4 + \frac{1}{2} \lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 \left( \Phi_1^\dagger \Phi_2 \right) \left( \Phi_2^\dagger \Phi_1 \right)
+ \left\{ \frac{1}{2} \lambda_5 \left( \Phi_1^\dagger \Phi_2 \right)^2 + \left[ \lambda_6 \left( \Phi_1^\dagger \Phi_1 \right) + \lambda_7 \left( \Phi_2^\dagger \Phi_2 \right) \right] \left( \Phi_1^\dagger \Phi_2 \right) + \text{h.c.} \right\}
\]

- Complex phases on \(\lambda_5, \lambda_6, \lambda_7\) and \(m_{12}\) can give rise to tree-level CP-violation (restricted by data). This talk: CP conservation.

- Reparameterization invariance: \(\Phi_a = U_{ab} \Phi_b \quad (a = 1, 2)\)

Review: [arXiv:1106.0034]
The general two-Higgs-doublet Model (2HDM)

- Introducing an explicit basis in \((\Phi_1, \Phi_2)\) space:
  \[
  \tan \beta = \frac{v_2}{v_1} \\
  \Phi_1 = \frac{1}{\sqrt{2}} \left( \begin{array}{c}
  \sqrt{2} \left( G^+ \cos \beta - H^+ \sin \beta \right) \\
  v \cos \beta - h \sin \alpha + H \cos \alpha + i \left( G^0 \cos \beta - A \sin \beta \right)
  \end{array} \right) \\
  \Phi_2 = \frac{1}{\sqrt{2}} \left( \begin{array}{c}
  \sqrt{2} \left( G^+ \sin \beta + H^+ \cos \beta \right) \\
  v \sin \beta + h \cos \alpha + H \sin \alpha + i \left( G^0 \sin \beta + A \cos \beta \right)
  \end{array} \right)
  \]

- Five physical Higgs states following EWSB:
  Two CP-even Higgs bosons: \(h, H\)
  \(m_{h} < m_{H}\), mixing angle \(\alpha\)
  One CP-odd Higgs boson: \(A\)
  One charged Higgs pair: \(H^{\pm}\)
Higgs Couplings

- Couplings to vector bosons determined by mixing angle

\[
g_{hVV} = \sin(\beta - \alpha) \quad \frac{g_{hVV}}{g_{hVV}^{\text{SM}}} = \cos(\beta - \alpha) \quad g_{AVV} = 0
\]

SM-like Higgs \(\sin(\beta - \alpha) \rightarrow 1\) possible with or without decoupling

- 2HDM Yukawa couplings in arbitrary basis

\[
-\mathcal{L}_Y = \frac{1}{\sqrt{2}} \bar{D} \left[ \kappa^D s_{\beta-\alpha} + \rho^D c_{\beta-\alpha} \right] Dh + \frac{1}{\sqrt{2}} \bar{D} \left[ \kappa^D c_{\beta-\alpha} - \rho^D s_{\beta-\alpha} \right] DH + \frac{i}{\sqrt{2}} \bar{D} \gamma_5 \rho^D DA
\]
\[
+ \frac{1}{\sqrt{2}} \bar{U} \left[ \kappa^U s_{\beta-\alpha} + \rho^U c_{\beta-\alpha} \right] Uh + \frac{1}{\sqrt{2}} \bar{U} \left[ \kappa^U c_{\beta-\alpha} - \rho^U s_{\beta-\alpha} \right] UH - \frac{i}{\sqrt{2}} \bar{U} \gamma_5 \rho^U UA
\]
\[
+ \frac{1}{\sqrt{2}} \bar{L} \left[ \kappa^L s_{\beta-\alpha} + \rho^L c_{\beta-\alpha} \right] Lh + \frac{1}{\sqrt{2}} \bar{L} \left[ \kappa^L c_{\beta-\alpha} - \rho^L s_{\beta-\alpha} \right] LH + \frac{i}{\sqrt{2}} \bar{L} \gamma_5 \rho^L LA
\]
\[
+ \left[ \bar{U} (V_{\text{CKM}} \rho^D P_R - \rho^U V_{\text{CKM}} P_L) DH^+ + \bar{\nu} \rho^L P_R LH^+ + \text{h.c.} \right].
\]


- If \(\rho^F\) and \(\kappa^F\) are not simultaneously diagonal the Higgs sector mediates tree-level FCNC (\(\rightarrow\) strongly restricted from data)
Absence of tree-level FCNC $\rightarrow$ 2HDM Types

- To get rid of these FCNC naturally, implement a (softly broken) $Z_2$ symmetry $\rightarrow$ 2HDM Types depending on fermion $Z_2$ charges

$$\rho_F \propto \kappa_F = \frac{\sqrt{2}}{v} M_F$$

<table>
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<th>Type</th>
<th>$U_R$</th>
<th>$D_R$</th>
<th>$L_R$</th>
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<th>$\rho^D$</th>
<th>$\rho^L$</th>
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<td>+</td>
<td>+</td>
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<td>$\kappa^U \cot \beta$</td>
<td>$\kappa^D \cot \beta$</td>
<td>$-\kappa^L \tan \beta$</td>
</tr>
</tbody>
</table>

Type III = Type Y = “Flipped”  Type IV = Type X = “Lepton-spec.”

- Promotes $\tan \beta$ to a physical parameter (basis with $\lambda_6 = \lambda_7 = 0$)

- MSSM: Type-II couplings at tree level, broken by $\Delta_b$ corrections
From Hybrid basis to Higgs basis

- Higgs basis condition for soft $Z_2$-breaking:

$$ (Z_1 - Z_2) \left[ Z_1 Z_7 + Z_2 Z_6 - Z_{345} Z_{67} \right] + 2 Z_{67}^2 (Z_6 - Z_7) = 0 $$

- Preferred basis in which soft $Z_2$-breaking is manifest:

$$ \tan 2\beta = \pm \frac{|Z_6| + \epsilon_6 \epsilon_7 |Z_7|}{Z_2 - Z_1} $$

- Remaining quartic couplings (in the Higgs basis) determine the CP-odd and charged Higgs masses:

$$ m_A^2 = m_H^2 s_{\beta - \alpha}^2 + m_h^2 c_{\beta - \alpha}^2 - Z_5 v^2 $$

$$ m_{H^\pm}^2 = m_A^2 - \frac{1}{2} (Z_4 - Z_5) v^2 $$
Alignment and Decoupling

- Assuming that the lightest 2HDM state (h) is the 125 GeV Higgs, SM-like couplings are obtained for $\cos(\beta - \alpha) \approx 0$

- Without approximation, the following relation holds:

$$\sin(\beta - \alpha) \cos(\beta - \alpha) = -\frac{Z_6 v^2}{m_H^2 - m_h^2}$$

- Two ways in which the 2HDM can mimic the SM:

  Alignment: $Z_6 \rightarrow 0$ (independent of $m_H$)

  Decoupling: $m_H \gg v$ (independently of $Z_6$)

  -> Measuring SM-like Higgs does not necessarily imply $m_H \gg v$
Scenario A

“Standard” scenario with lightest Higgs at 125 GeV
$M_h = 125 \text{ GeV} < M_H < M_A = M_{H^+}.$

$Z_4 = Z_5 = -2 \quad Z_7 = 0$
Theoretical constraints restricts coupling space

- As before, S-matrix unitarity and positivity of Higgs potential:
  
  \[ Z_i \sim \mathcal{O}(1) \]

  Ex: \( M_h = 125 \text{ GeV} < M_H < M_A = M_{H^+} \) \( (Z_4 = Z_5 < -2, Z_7 = 0) \)

- Allowed parameter region tends towards SM \( (c_{\beta-\alpha} \rightarrow 0) \) at high \( \tan \beta \), positive values of \( c_{\beta-\alpha} \) preferred for \( \tan \beta > 1 \)
Scenario A: Lightest 2HDM Higgs@125 GeV

- $\chi^2$ fit of light Higgs signal rates with HiggsSignals
  
  $M_H = 500 \text{ GeV} < M_A = M_{H^\pm}$

- Type-I

- Type-II couplings much more restricted around alignment, in particular for high $\tan \beta$. Exception: flipped-sign scenario (F)

Ferreira, Haber, Gunion, Santos, [1403.4736]
Scenario A (Type-I): Light Higgs rates

- $R_{Z\gamma}^h$: $0.7 - 1.3$
- $R_{\gamma\gamma}^h$: $0.8 - 1.2$
- $R_{\tau\tau}^h$: $0.9 - 1.1$
- $R_{bb}^h$ (VH): $0.7 - 1.3$
Scenario A (Type-II): Light Higgs rates

- Allowed region driven by total width (h -> bb)

![Graphs showing allowed regions for h -> bb](image-url)
The experimentally favored region is driven by the total h width, which in turns follow closely the coupling to b quarks

\[ \frac{g_{hdd}}{g_{SM}^{hdd}} = \sin(\beta - \alpha) - \tan \beta \cos(\beta - \alpha) \]
Type-II: Heavy Higgs production

- Since the H must have suppressed couplings to gauge bosons, only \( gg \to H \) and \( b \bar{b} \to H \) (at high \( \tan \beta \))
Type-II: H decays to fermions

- Fermions dominate when $h$ becomes SM-like, $c_{\beta-\alpha} \rightarrow 0$
- Complementarity between up- and down-type modes typical of Type-II

$m_H = 500$ GeV

$\text{BR}(H \rightarrow bb)$

$\text{BR}(H \rightarrow \tau\tau)$

$\text{BR}(H \rightarrow tt)$
Type-II: H decays to bosons

- Bosonic modes become important away from $c_{\beta-\alpha} = 0$
- Difficult to have appreciable rate in region allowed by 125 GeV measurements (for Type-II)
Type-II: The allowed parameter space

- Applying theory constraints and rates of 125 GeV Higgs within 20% of SM

\[ R_{tt}^H = \frac{\sigma(gg \rightarrow H) \times \text{BR}(H \rightarrow tt)}{[\sigma(gg \rightarrow H) \times \text{BR}(H \rightarrow tt)]_{SM}} \]
Scenario A: Type-II Benchmark

- 1D Benchmark can be defined by choosing fixed values for $c_{\beta-\alpha}$ and $\tan \beta$ inside allowed region, Ex: $\cos(\beta-\alpha) = 0.01$, $\tan \beta = 1.5$

- Maximizes production and decay to $tt$
- Total $H$ width remains relatively small, $\Gamma_H/\Gamma_{SM} < 0.1$
Scenario A: Type-I Benchmark

- For Type-I, larger deviations from SM in the coupling to vector bosons is allowed. Ex: \(\cos(\beta-\alpha) = 0.05, \tan \beta = 3\)

- Sizeable branching ratios to bosonic final states, total width small
Without perturbativity constraint \(H \rightarrow hh\), grows without control
Total rates for LHC-13

Type-II: $c_{\beta-\alpha} = 0.01$, $\tan \beta = 1.5$
Total rates for LHC-13

Type-I: $c_{\beta-\alpha} = 0.05$, $\tan \beta = 3$
Scenario B

“Inverted” scenario with heavy CP-even Higgs at 125 GeV
$M_h < M_H = 125 \text{ GeV} < M_A = M_{H^+}$. Useful for light h searches.
Scenario B

- “Inverted” scenario with lightest Higgs below 125 GeV, second CP-even Higgs, H, as the SM-like Higgs at 125 $M_h < M_H = 125\,\text{GeV} < M_A = M_{H^+}$ ($M_{H^+}$ above 350 GeV for Type-II)

Constraints from LEP/Tevatron/LHC (gray). Below 90 GeV only allowed solution is alignment of heavy Higgs: $|c_{\beta-\alpha}| \rightarrow 1$

In Type-II also LHC constraints at higher $\tan\beta$ for $m_h > 90\,\text{GeV}$. 
Scenario B (Type-I): Decays

- Fix the remaining free parameter $c_{\beta-\alpha}$ to ensure $H$ SM-like, get predictions for varying $M_h$

Type-I: $\tan \beta = 1.5$, $c_{\beta-\alpha} = 0.99$, $M_H = 125.5$ GeV

- $gg \rightarrow h$ cross section can be factor $\sim 2$ lower than SM. $A \rightarrow hZ$?
Scenario C

Overlapping CP-even and CP-odd Higgses @ 125 GeV

\[ M_h = M_A = 125 \text{ GeV} < M_H = M_{H^+} \]

\[ Z_5 = \frac{m^2_H - m^2_h}{v^2} \sin^2 \beta - \alpha \]

\[ Z_4 = -Z_5 - 2 \frac{m^2_H - m^2_h}{v^2} \cos^2 \beta - \alpha \]

\[ Z_7 = -Z_5 \]
Scenario C: Degenerate states

- Our framework is CP-conserving, but Scenario C can “emulate” a CP-admixture for the signal in some channels:

  - $h/A \rightarrow \gamma\gamma$ (inclusive) – $A$ contribution exists, $O(\%)$ – interesting?
  - $h/A \rightarrow WW/ZZ$ (inclusive) – no tree-level $A$ coupling
  - $h/A \rightarrow bb$ (VH) – no tree-level $A$ coupling (inclusive/ttH - yes)
  - $h/A \rightarrow \tau\tau$ (inclusive) – similar $h/A$ contributions possible

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\caption{Type-I}
\end{figure}

\begin{itemize}
\item $0.7 – 1.3$
\item $0.8 – 1.2$
\item $0.9 – 1.1$
\end{itemize}
Scenario C: h/A production

- Total cross section dominated by SM-like h for high tan β (Yukawa decoupling in Type-I)
Inclusive $\tau\tau$ signal composition

\[
R_{\tau\tau}^{h/A} = \frac{\sigma(pp \to h/A) \times \text{BR}(h/A \to \tau\tau)}{\sigma(pp \to H_{SM}) \times \text{BR}(H_{SM} \to \tau\tau)}
\]

- The currently allowed value for the $\tau\tau$ rate (within errors) could easily accommodate for a large CP-odd contribution
Scenario C (Type-II): $\tau\tau$ composition

- Larger variation in $h$ rate from BR($h \rightarrow \tau\tau$) (non-zero $c_{\beta-\alpha}$)
  Relative contribution of CP-odd Higgs always above 35%

- Low/high $\tan\beta$ in principle excluded from direct searches / rates
  Define benchmark at minimum of combined rate
Charged Higgs

- Interesting component of all models with multiple Higgs doublets, mass related to neutral scalars through SU(2) (custodial) symmetry

- Fewer signatures to consider (if neutral Higgs channels closed)

\[ M_{H^\pm} < m_t \quad \text{and} \quad M_{H^\pm} > m_t \]
2HDM interpretation of Charged Higgs searches

F. Mahmoudi, OS
Low-energy constraints

F. Mahmoudi, OS, [to appear]
Model predictions for the LHC

- Two bundles of codes provide complete 2HDM predictions of cross sections + branching ratios, including available higher-order (mostly QCD) corrections

**SusHi + 2HDMC**
Harlander, Mantler, Liebler, [1212.3249]
Eriksson, Rathsman, OS, [0902.0851]

**HIGLU+HDECAY**

LHC Higgs Cross Section Working Group
Interim recommendations for the evaluation of Higgs production cross sections and branching ratios at the LHC in the Two-Higgs-Doublet Model

R. Harlander\(^1\), M. Mühlleitner\(^2\), J. Rathsman\(^3\), M. Spira\(^4\), O. Stål\(^5\)

[LHCHXSWG-2013-001], [1312.5571]
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