2HDM Fate after LHC8

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w/ J.F. Gunion, S. Kraml, B. Demount arXiv 1405.XXXX (appear soon)

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Outline

• 2HDM Snapshot

• Whether or not/How is the model parameter space constrained by
  A. Feed down effect
  B. Higher precision signal measurements

• Prospects at the LHC14/ILC
  • Triple Higgs coupling
  • Lightest Higgs h search and pseudoscalar A detection

• Conclusions
Whether or not it is the SM Higgs?

ATLAS
$m_H = 125.5$ GeV

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\mu$ (stat)</th>
<th>$\mu$ (sys)</th>
<th>$\mu$ (theo)</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H\to\gamma\gamma$</td>
<td>$1.55^{+0.33}_{-0.28}$</td>
<td>$0.23$</td>
<td>$-0.22$</td>
<td>$\pm 1\sigma$ on $\mu$</td>
</tr>
<tr>
<td>$H\to ZZ^*\to 4l$</td>
<td>$1.43^{+0.40}_{-0.35}$</td>
<td>$0.35$</td>
<td>$-0.32$</td>
<td></td>
</tr>
<tr>
<td>$H\to WW^*\to lv$</td>
<td>$0.99^{+0.31}_{-0.28}$</td>
<td>$0.20$</td>
<td>$-0.21$</td>
<td></td>
</tr>
<tr>
<td>Combined $H\to\gamma\gamma, ZZ^<em>, WW^</em>$</td>
<td>$1.33^{+0.21}_{-0.18}$</td>
<td>$0.13$</td>
<td>$-0.14$</td>
<td></td>
</tr>
</tbody>
</table>

CMS Preliminary
$m_H = 125.7$ GeV

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\sigma/\sigma_{SM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H\to bb$</td>
<td>$1.15 \pm 0.62$</td>
</tr>
<tr>
<td>$H\to \tau\tau$</td>
<td>$1.10 \pm 0.41$</td>
</tr>
<tr>
<td>$H\to \gamma\gamma$</td>
<td>$0.77 \pm 0.27$</td>
</tr>
<tr>
<td>$H\to WW$</td>
<td>$0.68 \pm 0.20$</td>
</tr>
<tr>
<td>$H\to ZZ$</td>
<td>$0.92 \pm 0.28$</td>
</tr>
</tbody>
</table>

Tevatron Run II, $L_{int} \leq 10$ fb$^{-1}$
$m_H = 125$ GeV/c$^2$
What's the naive extension?

**Two Higgs Doublet Model**

1. The simplest non-trivial extension on the Higgs sector beyond the SM.
   - Duplicate a complex $SU(2)_L$ Higgs doublet with the same hypercharge $Y = +1$.
   - More physical Higgs states.

2. Type II realized in the MSSM.

3. Existence of the charged Higgs boson $H^\pm$?
\[ \mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[ m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left\{ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right\} \]

The models we studied

1. **NO explicit \( \mathcal{CP} \) violation**: all \( \lambda_i \) and \( m_{12}^2 \) are assumed to be real.
2. **NO spontaneous \( \mathcal{CP} \) breaking**: take \( \xi = 0 \).
3. **"soft" \( Z_2 \) symmetry** (\( \Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow -\Phi_2 \)) breaking: \( m_{12}^2 \neq 0; \lambda_6 = \lambda_7 = 0 \).

**our inputs**: \( m_h, m_H, m_A, m_{H^+}, \tan \beta, \sin \alpha, m_{12}^2 \)

**Electroweak symmetry breaking**

\( \Phi_1 = \begin{pmatrix} \phi_1^+ \\ (\nu \cos \beta + \rho_1 + i \eta_1) / \sqrt{2} \end{pmatrix} \)

\( \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (e^{i \xi} \nu \sin \beta + \rho_2 + i \eta_2) / \sqrt{2} \end{pmatrix} \)

2 CP-even neutral scalars: \( h = -\rho_1 \sin \alpha + \rho_2 \cos \alpha \)
\( H = \rho_1 \cos \alpha + \rho_2 \sin \alpha \)

1 CP-odd neutral pseudoscalar: \( A = -\eta_1 \sin \beta + \eta_2 \cos \beta \)

2 charged scalars: \( H^\pm \)
2HDM Yukawa sector

\[ \mathcal{L} = y^1_{ij} \bar{\psi}_i \psi_j \Phi_1 + y^2_{ij} \bar{\psi}_i \psi_j \Phi_2 \]

We consider the Type I and Type II models, in which tree level FCNC are completely absent due to some symmetry.\(^1\)

<table>
<thead>
<tr>
<th>Model</th>
<th>(u^i_R)</th>
<th>(d^i_R)</th>
<th>(e^i_R)</th>
<th>Realization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>(\Phi_2)</td>
<td>(\Phi_2)</td>
<td>(\Phi_2)</td>
<td>(\Phi_1 \rightarrow -\Phi_1)</td>
</tr>
<tr>
<td>Type II</td>
<td>(\Phi_2)</td>
<td>(\Phi_1)</td>
<td>(\Phi_1)</td>
<td>(\Phi_1 \rightarrow -\Phi_1, d^i_R \rightarrow -d^i_R)</td>
</tr>
</tbody>
</table>

\[ \mathcal{L}^{2\text{HDM}}_{\text{Yukawa}} = -\sum_{f=u,d,\ell} \frac{m_f}{v} \left( C^h_f \bar{f} h + C^H_f \bar{f} f H - i C^A_f \bar{f} \gamma_5 f A \right) \]

\[ - \left\{ \frac{\sqrt{2} V_{ud}}{v} \bar{u} \left( m_u C^A_u P_L + m_d C^A_d P_R \right) dH^+ + \frac{\sqrt{2} m_\ell}{v} C^A_\ell \sqrt{L_R H^1} + \text{h.c.} \right\} \]

<table>
<thead>
<tr>
<th></th>
<th>(C^h_V)</th>
<th>(C^h_u)</th>
<th>(C^h_d,\ell)</th>
<th>(C^H_V)</th>
<th>(C^H_u)</th>
<th>(C^H_d,\ell)</th>
<th>(C^A_V)</th>
<th>(C^A_u)</th>
<th>(C^A_d,\ell)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>(\sin(\beta - \alpha))</td>
<td>(\cos \alpha \sin \beta)</td>
<td>(\cos \alpha \sin \beta)</td>
<td>(\cos(\beta - \alpha))</td>
<td>(\sin \alpha \sin \beta)</td>
<td>(\sin \alpha \sin \beta)</td>
<td>(0)</td>
<td>(\cot \beta)</td>
<td>(-\cot \beta)</td>
</tr>
<tr>
<td>Type II</td>
<td>(\sin(\beta - \alpha))</td>
<td>(\cos \alpha \sin \beta)</td>
<td>(-\sin \alpha \cos \beta)</td>
<td>(\cos(\beta - \alpha))</td>
<td>(\sin \alpha \sin \beta)</td>
<td>(\cos \alpha \cos \beta)</td>
<td>(0)</td>
<td>(\cot \beta)</td>
<td>(\tan \beta)</td>
</tr>
</tbody>
</table>

\[(C^h_V)^2 + (C^H_V)^2 + (C^A_V)^2 = 1\]

\(^1\) Paschos-Glashow-Weinberg theorem: if all fermions with the same quantum numbers couple to the same Higgs multiplet, then FCNC will be absent.
Our focus

1. $h \sim 125$ scenario: $m_h \in [123, 128]$ GeV , $m_H \in [128 \text{ GeV, } 2 \text{ TeV}]$ (Gunion’s talk)
2. $H \sim 125$ scenario: $m_H \in [123, 128]$ GeV , $m_h \in [12 \text{ GeV, } 123 \text{ GeV}]$

$$\alpha \in [-\pi/2, +\pi/2], \quad \tan \beta \in [0.5, 60]$$

$$m_A \in [5 \text{ GeV, } 2 \text{ TeV}], \quad m_{H^\pm} \in [m^*, 2 \text{ TeV}]$$

Points are retained only when “preLHC” constraints including are all satisfied.

preLHC:
- stability
- unitarity
- perturbatitivity
- EWK
- B-physics
- $(g-2)_\mu$
- LEP
Procedural details

Our focus

1. $h \sim 125$ scenario: $m_h \in [123, 128]$ GeV, $m_H \in [128 \text{ GeV, } 2 \text{ TeV}]$ (Gunion’s talk)
2. $H \sim 125$ scenario: $m_H \in [123, 128]$ GeV, $m_h \in [12 \text{ GeV, } 123 \text{ GeV}]

$\alpha \in [-\pi/2, +\pi/2]$,
$\tan \beta \in [0.5, 60]$

$m_A \in [5 \text{ GeV, } 900 \text{ GeV}]$, $m_{H\pm} \in [m^*, 900 \text{ GeV}]$

Points are retained only when “preLHC” constraints including are all satisfied.

preLHC:

- stability
- unitarity
- perturbatativity
- EWK
- B-physics
- $(g-2)_\mu$
- LEP
Current status

\[ \chi^2_Y = \begin{pmatrix} \mu_{ggF,Y} - \hat{\mu}_{ggF,Y} \\ \mu_{VBF,Y} - \hat{\mu}_{VBF,Y} \end{pmatrix}^T \begin{pmatrix} a_Y & b_Y \\ b_Y & c_Y \end{pmatrix} \begin{pmatrix} \mu_{ggF,Y} - \hat{\mu}_{ggF,Y} \\ \mu_{VBF,Y} - \hat{\mu}_{VBF,Y} \end{pmatrix} \]

\[ \chi = \sum_Y \chi^2_Y \]

What we consider ...

- **preLHC**: Stability, Unitarity, Perturbativity, STU, \(B\)-physics, \((g - 2)_\mu\), LEP
- **A limits**:
  - \(A \rightarrow ZZ(*) \rightarrow 4\ell\)
  - \(gg \rightarrow A \rightarrow \tau\tau\) and \(gg \rightarrow bbA\) with \(A \rightarrow \tau\tau\)
- **postLHC8**: additionally, \(\gamma\gamma\), \(ZZ\), \(WW\), \(bb\), \(\tau\tau\) signals for 125 GeV Higgs
Generally, for the heavy Higgs boson $H$ be SM like, $C_V^H = \cos(\beta - \alpha) \sim 1$.

However, there are two branches present in Type II model. In addition to the trivial one, the upper strip has $C_D^H \sim -1$, called “wrong-sign Yukawa coupling” (arXiv:1403.4736), extending the $C_V^H$ to $\sim 0.7$.

$\tan \beta \lesssim 1$ is eliminated by the $m_{H^\pm}$ bound.
An intriguing possibility?

- heavier scalars like H/A may already be indirectly observed at the LHC, not through their decays into gauge bosons or fermions, but rather through their chain decays into h.  
  Arhrib, Ferreira and Santos (2013)
An intriguing possibility?

- heavier scalars like $A$ may already be indirectly observed at the LHC, not through their decays into gauge bosons or fermions, but rather through their **chain decays** into $H$. 
Feed down (FD)

For heavier CP-even Higgs boson $H$, easier to access are $\mu_{gg}(ZZ)$ and $\mu_{VBF}(ZZ)$, about 0.2. This level of signal would eventually be accessible in light of a much smaller width.

We correct for the width difference by rescaling the observed limits on $\mu_{XH}$ by $f = \frac{v}{v_0}$.

$$\mu_{XH}^{FD} = \frac{\sum H \sigma_{XH} P_{FD}(H \to H + \text{anything})}{\sigma_{XH}}$$

$$P_{FD}(H \to H + \text{anything}) = 2P_{H,2H} + P_{H,1H}$$

$$\mu_{VH}^{FD} = \frac{\sigma_{ggFA} BR(A \to ZH)}{\sigma_{VH}}$$

2HDM fit (type I) $m_H = 125.5 \pm 2.5$ GeV

2HDM fit (type II) $m_H = 125.5 \pm 2.5$ GeV
Feed down (FD)

What amount of feed down is too large?

FDOK: $\mu_{ggFH+bbH}^{FD} \leq 0.1$  $\mu_{ZH}^{FD} \leq 0.3$

Low FD: $0.1 < \mu_{ggFH+bbH}^{FD} \leq 0.2$

$0.3 < \mu_{ZH}^{FD} \leq 0.5$

High FD: $\mu_{ggFH+bbH}^{FD} > 0.2$ $\mu_{ZH}^{FD} > 0.5$
For heavier CP-even Higgs boson $H$, easier to access are $\mu gg$ ($ZZ$) and $\mu VBF$ ($ZZ$), about 0.2. This level of signal would eventually accessible in light of much smaller width $\alpha$.

We correct for the width difference by rescaling the observed limits on $\mu \mathrm{BR}$ by $f = \frac{v^2}{u^2} H^2 + (4 \text{ GeV})^2 h_{SM}^2 + (4 \text{ GeV})^2$. 

CMS-PAS-13-025
FD happens at the value of large $\sin(\beta - \alpha)$, which is related to the HAZ coupling, and prefers small $\tan \beta$.

FD does NOT actually constrain the parameter space of the models.
H\sim 125-Higgs Signals @125

Type I
- not too much above 1 because that gluon fusion production cannot be much enhanced (universal up and down type couplings).
- \( \mu_{H}^{H}(ZZ) / \mu_{H}^{H}(\gamma\gamma) < 1 \) for enhanced \( \mu_{H}^{H}(\gamma\gamma) \) rate.

Type II
- easy realization of substantial enhancement.
- \( \mu_{gg}^{H}(ZZ) \) is strictly larger than \( \mu_{gg}^{H}(\gamma\gamma) \) for enhanced \( \mu_{gg}^{H}(\gamma\gamma) \) rate.
H~125-Higgs Signals @125

What happens if all measured signals converge to very SM?

For example, if the observed values of $\mu_{hX}^h(Y)$ all lie within $\pm15\%$, $\pm10\%$ and $\pm5\%$ of the SM prediction for the channels

$$(gg, \gamma\gamma), (gg, ZZ), (gg, \tau\tau),$$

$$(VBF, \gamma\gamma), (VBF, ZZ),$$

$$(VBF, \tau\tau) = (VH, bb), (ttH, bb)$$
<table>
<thead>
<tr>
<th></th>
<th>Inclusive (350 GeV)</th>
<th>ZH</th>
<th>ZH</th>
<th>1.4/3.0 TeV</th>
<th>ZH</th>
<th>ZH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>$2.6/3.0/-/%$</td>
<td>-/20/25/30%</td>
<td>-/1.7/-/%</td>
<td>-/1.7/-/%</td>
<td>-/2.3/1.4%</td>
<td>-/0.7/1.0%</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>$7/11/-/%$</td>
<td>-/19/25/30%</td>
<td>-/3.6/0/-/%</td>
<td>-/3.6/0/-/%</td>
<td>-/6.6/4.6/2.6%</td>
<td>-/6.2/3.1%</td>
</tr>
<tr>
<td>$H \rightarrow WW^{\pm}$</td>
<td>$1.2/1.8/-/%$</td>
<td>-/10/8/3.1%</td>
<td>-/2.5/0/-/%</td>
<td>-/2.5/0/-/%</td>
<td>-/4.6/2.6/1.6%</td>
<td>-/2.5/0/-/%</td>
</tr>
<tr>
<td>$H \rightarrow UVV$</td>
<td>$4.2/5.4/-/%$</td>
<td>-/3.0/2.5/1.6%</td>
<td>-/3.6/0/-/%</td>
<td>-/3.6/0/-/%</td>
<td>-/4.6/2.6/1.6%</td>
<td>-/2.5/0/-/%</td>
</tr>
<tr>
<td>$H \rightarrow \mu \mu$</td>
<td>$1.2/1.8/-/%$</td>
<td>-/2.0/3.0/1.0%</td>
<td>-/1.3/1.0/1%</td>
<td>-/1.3/1.0/1%</td>
<td>-/4.6/2.6/1.6%</td>
<td>-/2.5/0/-/%</td>
</tr>
</tbody>
</table>

**Table 1-13.** Expected relative precisions on the signal strengths of different Higgs decay final states as well as the 95% CL upper limit on the Higgs branching ratio to the invisible decay from the ZH search estimated by ATLAS and CMS. The ranges are not comparable between ATLAS and CMS. For ATLAS, they correspond to the cases with and without theoretical uncertainties while for CMS they represent two scenarios of systematic uncertainties.

<table>
<thead>
<tr>
<th></th>
<th>ZH</th>
<th>ZH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma \gamma$</td>
<td>$1.2/1.7/-/%$</td>
<td>-/2.3/1.4%</td>
</tr>
<tr>
<td>$Z Z^*$</td>
<td>$1.2/1.8/-/%$</td>
<td>-/2.5/0/-/%</td>
</tr>
<tr>
<td>$WW^{\pm}$</td>
<td>$1.2/1.8/-/%$</td>
<td>-/2.5/0/-/%</td>
</tr>
<tr>
<td>$UVV$</td>
<td>$1.2/1.8/-/%$</td>
<td>-/2.5/0/-/%</td>
</tr>
<tr>
<td>$\mu \mu$</td>
<td>$1.2/1.8/-/%$</td>
<td>-/2.5/0/-/%</td>
</tr>
</tbody>
</table>

**Future prospects**
H~125-Parameter @ higher precision

- Not unexpectedly, as increasingly precise agreement with the SM is imposed in the various final state channels one is quickly pushed to small $|\sin(\beta - \alpha)|$, but $\tan \beta$ remains unrestricted.

- SM±10% on each of the individual $\mu$’s will exclude the “wrong-sign” Yukawa region of the Type II model.

- If ±5% agreement with the SM can be verified in all the channels, then $m_H = 125.5$ GeV scenario will be eliminated in Type II and all but eliminated in Type I (due to the $H^\pm$ loop non-decoupling effect at large $m_{H^\pm}$).

**Fig. 20:** Constraints on the 2HDM of Type I and II in the $\sin(\beta - \alpha)$ versus $\tan \beta$ plane for $m_H \sim 125$. We show points that survive at the preLHC (grey), A-limits (green), postLHC8 (blue), SM ±5% (red), SM ±10% (dark green), and SM ±15% (cyan) levels.
Feed down vs. higher precision

For heavier CP-even Higgs boson $H$, easier to access are $\mu_{gg}(ZZ)$ and $\mu_{VBF}(ZZ)$, about 0.2. This level of signal would eventually accessible in light of much smaller width $a$.

We correct for the width difference by rescaling the observed limits on $\mu_{ggF+bb}$ by $f = \frac{v}{u}$.

In the signal strength measurements reduces the “danger” of FD contamination.
H~125-Triple H coupling

- Currently, a large deviation present.
- Tightly limited deviation if the signals become increasingly SM-like.
Other
Higgs bosons search at the LHC/ILC
H~125-lightest h detection

- For $m_h \lesssim 60$ GeV, one can require BR($H \rightarrow hh$) small enough to still allow the $H$ rates in the various channels to fit the 125.5 GeV signal at the LHC8.

- Can explain the LEP $\sim 2.3\sigma$ excess at $m_h \sim 98$ GeV in both the Type I and Type II models given current postLHC8 constraints on the $H$ properties. However, the Type I $\pm 5\%$ level and the Type II $\pm 10\%$ level would have a signal level that is not consistent with this LEP excess observed.
In Type I mA<60 GeV is possible but must have small BR(H->AA). For mA<100 GeV, tautau cross section are quite large.

LHC8 125 GeV Higgs data constrain the A mass <700 GeV in Type I and <625 GeV in Type II.

A large range of possible cross section value. In average, Type II tends to be substantially larger than Type I. The lowest cross values are really very small and would not allow A detection.
Conclusions

• The latest Higgs data from LHC clearly favors a fairly SM-like Higgs boson with mass of 125.5 GeV.

• There is consistent descriptions with the LHC8 Higgs signal in the both Type I and Type II 2HDMs in which the H is identified as the 125.5 GeV state.

• Feed down effect does not eliminate much parameter space and will be dramatically reduced if the higher precision in the signal measurement is verified in the future.

• The ratio $\frac{\mu_{gg}(ZZ)}{\mu_{gg}(\gamma\gamma)}$ might be a possible signature to examine the Type I and II 2HDM if the diphoton rate is confirmed to be very SM-like or a bit enhanced in the future.

• The A can be detected in many modes (except ZZ). In addition, there is good probability for viable signals for the lighter h. The opportunity of such detection is still ample even if the 125.5 GeV signals converge to very SM-like. Of course, the direct search associated with other (heavier) Higgs bosons is awaiting for LHC 14 run.
Next focus

1. low mass Higgs?

2. low mass DM?