The 2HDM in light of the recent LHC results

KEK

16 February 2012

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The 2HDM potential

\[
V(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2} \lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}]
\]

\[\phi_1 \rightarrow \phi_1 \quad \phi_2 \rightarrow -\phi_2\]

“Normal” vacuum (CP conserving and non charge breaking)

\[
\begin{pmatrix} <\Phi_1>_N \\ <\Phi_2>_N \end{pmatrix} = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \quad \begin{pmatrix} 0 \\ v_2 \end{pmatrix}
\]

8 + 2 parameters - 2 are fixed by the minimum conditions and one by the W mass \(v^2 = v_1^2 + v_2^2\). The remaining 7 are

\[
m_h, m_H, m_A, m_{H\pm}, \tan\beta, \sin\alpha \quad M^2 = \frac{m_{12}^2}{\sin\beta \cos\beta}
\]
The 2HDM Lagrangian

- Couplings that involve gauge bosons
  \[ \sin(\beta - \alpha) \]

- Couplings that involve fermions

We extend the Z\(_2\) symmetry to the fermions -
4 independent Yukawa Lagrangians

4 models with no FCNC at tree-level

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\(\text{III} = \text{I}' = \text{Y} = \text{Flipped}\)
\(\text{IV} = \text{II}' = \text{X} = \text{Leptonic}\)

\[ \sin \alpha, \tan \beta \]
The data - Higgs results LHC@7TeV

- 2.8 standard deviations (126.5 GeV)
- LEE significance is 1.5 standard deviations

- 3.1 standard deviations (124 GeV)
- LEE significance is 1.9 standard deviations
Higgs results LHC@7TeV

• What do we “know”?

\[
\frac{\sigma^{2HDM}(pp \rightarrow h) \cdot BR^{2HDM}(h \rightarrow \gamma\gamma)}{\sigma^{SM}(pp \rightarrow h) \cdot BR^{SM}(h \rightarrow \gamma\gamma)} \approx 1
\]

regarding production and decay to $\gamma\gamma$ ($VV$)

2HDM is similar to the SM

\[
\frac{\sigma^{2HDM}(pp \rightarrow h) \cdot BR^{2HDM}(h \rightarrow VV)}{\sigma^{SM}(pp \rightarrow h) \cdot BR^{SM}(h \rightarrow VV)} \approx 1
\]

• What will data on new channels tell us?

\[
\frac{\sigma^{2HDM}(pp \rightarrow h) \cdot BR^{2HDM}(h \rightarrow \bar{b}b)}{\sigma^{SM}(pp \rightarrow h) \cdot BR^{SM}(h \rightarrow \bar{b}b)}
\]

how important are future searches for 2HDM?

\[
\frac{\sigma^{2HDM}(pp \rightarrow h) \cdot BR^{2HDM}(h \rightarrow \tau^+\tau^-)}{\sigma^{SM}(pp \rightarrow h) \cdot BR^{SM}(h \rightarrow \tau^+\tau^-)}
\]
The Constraints
**INDIRECT BOUNDS**

All models

\[ Z \to b\bar{b} \quad B_q\bar{B}_q \quad \tan\beta > 1 \]

\[ \rho = \frac{M_W^2}{M_Z^2 c_W^2} = 1 \]

- \( m_A = m_{H^0} \)
- \( \sin(\beta - \alpha) = 1 \Rightarrow m_{H^0} = m_H \)
- \( \sin(\beta - \alpha) = 0 \Rightarrow m_{H^0} = m_h \)

\[ |\delta\rho| \lesssim 10^{-3} \]

**Compact spectrum**

Used in all calculations presented.
**INDIRECT BOUNDS** B factories

\[ B \rightarrow X_s \gamma \]

**Models II and Y**  
\[ X_iY_i = 1 \]

**Models I and X**  
\[ X_iY_i = 1/\tan^2 \beta \]

\[ \mathcal{L}_Y^\pm = (2\sqrt{2}G_F)^{1/2} \sum_{i=2}^{\text{\text{n}}} (X_iU_{LV}M_D D_R + Y_i \overline{U}_{RM} U V D_L + Z_i \overline{N}_{LM} E E_R) H_i^+ + \text{h.c.} \]

\[ \text{BR}(b \rightarrow s\gamma) = C|\eta_2 + G_W(x_t) + (|Y|^2/3)G_W(y_t) + (XY^*)G_H(y_t)|^2, \]

**Models II and Y**  
\[ m_{H^\pm} \gtrsim 300 \text{ GeV} \]

**Models I and X**  
\[ \tan \beta > 1 \]

Best available bound on the charged Higgs mass

\[ m_{H^\pm} = 100 \text{ GeV} \]
h or H?

• All results will be presented in the \((\tan\beta; \sin\alpha)\) plane.

  • We started with 7 parameters.

• One of the CP-even Higgs mass is “known” (125 GeV).

• The other CP-even Higgs mass is either irrelevant or benchmarks will be discussed.

• \(m_{H^\pm} = m_A = 600\ \text{GeV}\) (relevant only \(h\) to \(\gamma\gamma\) due to charged Higgs loop).

  • \(M = m_{H^\pm} = m_A\) or \(M = 0\).
Is it the light CP-even (h)?

\begin{align*}
\frac{\sigma^{2HDM}(pp \rightarrow h) \, BR^{2HDM}(h \rightarrow \gamma\gamma)}{\sigma^{SM}(pp \rightarrow h) \, BR^{SM}(h \rightarrow \gamma\gamma)}
\end{align*}

In the quark sector sector I = LS and the cross section ratio is just \( \frac{\cos^2 \alpha}{\sin^2 \beta} \).

In Model I the ratio never reaches \( 2^{\ast} \text{SM} \).

When \( \sin \alpha \approx \pm 1 \) the Higgs becomes fermiophobic and therefore it is not produced in gluon fusion.

In LS as the total width grows with \( \tan \beta \) (due to \( h \rightarrow \tau \tau \)) the allowed region to fit the Higgs shrinks. Again no \( 2^{\ast} \text{SM} \).
Is it the light CP-even?

Again, in the quark sector sector II = F
But now the ratio is not just a factor.

The contributions of the b-quark become important and even dominant for large tanβ for both production and decay. This completely changes the picture: we can be above but also below the SM prediction.

For these models, the region of parameter space where we get a number of events close to SM, is more likely to be in the region of small sinα especially for large tanβ.
Is it the light CP-even?

A few events have also been detected in $h \rightarrow WW + ZZ$.

Does this information help improving the constraint in the $(\tan \beta; \sin \alpha)$ plane?

Model I and LS - the ratio is never much bigger than 1. Information about this decay is unlikely to prove useful in further constraining the parameter space; but a substantial enhancement would imply physics beyond the 2HDM.

Model II and F - irrelevant unless huge enhancement happens...
Is it the light CP-even?

We have also analysed the decay $h \rightarrow bb$. For the type I model one sees relatively little variation over much of parameter space. For the type II model, there is a much larger variation. However, if one restricts the parameter space to that allowed by the signal, then the variation is fairly small. The same happens in the LS and F models.
Is it the light CP-even?

For the LS model the $\tau\tau$ channel gives dramatically different constraints in the ($\tan\beta$; $\sin\alpha$) plane. If one can limit the rate for $h$ to $\tau\tau$ down to less than twice the SM rate, then the parameter space will be much more severely restricted than implied by other processes.
**Is it the light CP-even?**

- Data is consistent with the Higgs detected being the lightest CP-even scalar of a 2HDM in all four models.

- With the data to be collected this year and even combining all searches (channels) we will not be able to identify or exclude models unless:

  a) Number of gamma events is much above/below SM

  b) Number of WW/ZZ events is much above/below SM.

  c) Indication of the LS model would be an enhancement in $h$ to $\tau\tau$
Is it the heavy CP-even?

• Hints for a 125 GeV state decaying into two photons. In the context of 2HDMs: h, H or A?

• We now focus on the heavier CP-even scalar, H.

• The lightest scalar h should have, thus far, evaded detection.

• The combined requirements on H and h place stringent limits on the parameter space. We will consider two qualitatively distinct cases.

• Case 1: $m_h = 105$ GeV and $m_H = 125$ GeV, thus precluding the decay H to hh.

• Case 2: $m_h = 50$ GeV and $m_H = 125$ GeV, implying that H to hh is kinematically allowed.
Is it the heavy CP-even?

- LEP experiments searched for associated production of a light Higgs up to masses around 115 GeV.

- In 2HDMs, rates with $hVV$ couplings ($V = Z; W$) are suppressed by $\sin^2(\beta - \alpha)$, which the LEP data constrains to lie below 0.2 for $m_h = 105 \text{ GeV}$.

- This implies a very stringent constraint on the $(\sin \alpha; \tan \beta)$ plane, shown for $m_h = 105 \text{ GeV}$ (light yellow shaded areas).

- For $m_h = 50 \text{ GeV}$, $\sin^2(\beta - \alpha) < 0.04$ leads to even smaller allowed regions, shown in as dark red areas.

The LEP constraints forces $\sin \alpha$ to be close to ±1, with a severe impact on the observability of the lightest Higgs.
Is it the heavy CP-even?

- **Case 1:** $m_h = 105$ GeV, $m_H = 125$ GeV.

- The decay of the heavy Higgs has to lie very close to its SM value. SM/2 is excluded. This is consistent with its detectability in this channel at the LHC.

- For the light Higgs all values above SM/2 are excluded and therefore for this scenario the lightest Higgs decay into two photons will not be seen at LHC in the near future.
Is it the heavy CP-even?

- An interesting situation for type I 2HDM arises in the decays into $bb$.
- We find that $H$ can decay into $bb$, with SM or with SM/2 ratios, in a small region close to $(\sin\alpha; \tan\beta) = (0.7; 2)$.
- This is the same region in which $h$ to $bb$ could have a rate close to the SM one. The same conclusions hold for $H$ to $\tau\tau$ and $h$ to $\tau\tau$.
- This raises the interesting possibility that the decays into $bb$ and $\tau\tau$ could be sensitive to both the heavy and the light Higgs scalars, while only $H$ can be seen in the $\gamma\gamma$ and $VV$ channel at the LHC.
Is it the heavy CP-even?

- In model type II and Flipped both the decays to two photons and to $VV$ are similar to type I – the only difference is that values of $2\times\text{SM}$ or larger, can be reached. Again $h$ is undetectable in the decays to gauge bosons.

- But the situation may improve with respect to the type I model, concerning $bb$. We see that both $H$ to $bb$ and $h$ to $bb$ could occur at rates twice the SM rate, for $\sin\alpha > 0.8$ and $\tan\beta > 13$.

- Similar behavior is seen in $\tau\tau$. 

Is it the heavy CP-even?

- Next we consider the LS model. As in the type I model, $h$ to two photons is unobservably small, while $H$ may be detected.

- Unlike model I, we see that the decays of both $h$ and $H$ into $\tau^+\tau^-$ could be substantially larger than in the SM. Also, they prefer to be close to $\sin\alpha = \pm 1$.

- The decays into $b\bar{b}$ have features similar to those for model I. In particular, detection of $H$ to $b\bar{b}$ at SM rates is possible for large $\sin\alpha$ and any value for $\tan\beta$, but simultaneous detection of $h$ to $b\bar{b}$ around SM rates is only possible for low values of $\tan\beta$. 
Is it the heavy CP-even?

- Case 2: $m_h = 50$ GeV and $m_H = 125$ GeV, implying that $H$ to $hh$ is kinematically allowed.

- When $H$ to $hh$ is opened, all other branching ratios are much suppressed and, in particular, $H$ could not even be seen in the $\gamma\gamma$ channel. This violates our working hypothesis that current LHC hints correspond indeed to $H$ to $\gamma\gamma$. As a result, we are interested in regions where $\lambda_{Hhh}$ is close to zero.

\[
\lambda_{Hhh} \propto \frac{\cos (\beta - \alpha)}{\sin (2\beta)} \left( m_H^2 + 2m_h^2 \right) \sin (2\alpha) \left[ 1 - x \left( \frac{3}{\sin (2\beta)} - \frac{1}{\sin (2\alpha)} \right) \right]
\]

- a) Exact Z2: $m_{12} = 0$.
- b) Softly broken Z2: $m_{12} \neq 0$. 

\[
x = \frac{2m_{12}^2}{m_H^2 + 2m_h^2}
\]
Is it the heavy CP-even?

- If $m_{12} = 0 \lambda_{Hhh}$ is close to zero when $\sin \alpha = \pm 1$ or $0$ but only $\sin \alpha = \pm 1$ are consistent with the LEP bounds (shown in yellow).

- Only close to $\sin \alpha = \pm 1$ $H$ may be visible in $H$ to $\gamma \gamma$ or in any other channel other than $H$ to $hh$. This a necessary but not a sufficient condition.

- Similar conclusions for the remaining models.

- The results are approximately the same for $H$ to $VV$.

- Regarding $bb$ and $\tau \tau$: $H$ might be seen in both decays for type I; it might be seen in $bb$ but not in $\tau \tau$ for LS; it might be seen in $\tau \tau$ but not in $bb$ for the Flipped; and it will not be seen in either for the type II model.
Is it the heavy CP-even?

• If $m_{12} = 0$, the $\sin \alpha = \pm 1$ constraint also has a very strong impact on the detectability of the light scalar $h$.

• To avoid the LEP bound, $h$ is close to gaugephobic. Thus, it cannot be seen in $VV$, regardless of the specific 2HDM considered.

• We have checked that $h$ to $\gamma \gamma$ and $h$ to $bb$ is undetectable, while $h$ to $\tau \tau$ is only detectable in the LS model.

• Notice that, in the scenario $m_H = 125$ GeV, $m_h = 50$ GeV, and $m_{12} = 0$, the LS model has a very interesting prediction: $H$ may be seen in $\gamma \gamma$, $VV$, and $bb$ at rates around the SM value, but it will not show up in $\tau \tau$, while $h$ exhibits exactly the opposite features.
Is it the heavy CP-even?

\[
\frac{2m_{12}^2}{m_H^2 + 2m_h^2} = \frac{\sin(2\alpha) \sin(2\beta)}{3\sin(2\alpha) - \sin(2\beta)}
\]

- Lines in the (\(\sin\alpha; \tan\beta\)) plane where \(\lambda_{Hhh}\) vanishes. A judicious choice of \(m_{12}\) guarantees that \(H\) to \(\gamma\gamma\) is not swamped by \(H\) to \(hh\).

- If \(m_{12} \neq 0\) we might have \(H\) to \(\gamma\gamma\) at levels consistent with LHC hints in regions away from \(\sin\alpha = \pm 1\).

- This is shown as a scatter plot drawn for the type II model (similar for all other models) and for random choices of \(m_{12}\). One can now cover almost the entire LEP allowed region.

- In this case, the phenomenology is very similar to the \(m_h = 105 \text{ GeV}\) case.
Is it the heavy CP-even?

- **Case 1:** $m_h = 105$ GeV, $m_H = 125$ GeV.

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Is it the heavy CP-even?

- Case 2 a) $m_h = 50$ GeV and $m_H = 125$ GeV, $m_{12} = 0$.

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The experimental searches on $h$ to $\tau\tau$ already allow us to set bounds on the 2HDM parameter space.

Type II and LS are the most constrained models due to the large cross section and branching ratio into $\tau\tau$. Note that in LS, the allowed regions close to $\sin\alpha = \pm1$ are not compatible with $h$ being detected in $\gamma\gamma$ at rates close to the SM rates.

No bounds on models I and Flipped because either cross section or branching ratio into $\tau\tau$ is too small.
Conclusions

• In a CP-conserving 2HDM with a softly broken Z2 symmetry, both $h$ and $H$ scalars are consistent with the LHC results presented so far.

• More luminosity will probably tell us if the number of $\gamma \gamma$ and VV events is consistent with the SM predictions. A large difference in either $\gamma \gamma$ or VV may be explained by a 2HDM.

• Bounds derived from experimental searches on $h$ to $\tau \tau$ and $h$ to $b\bar{b}$ may help clarify which types of 2HDM’s are allowed (or at least constrain the parameter space).
Workshop on Multi-Higgs Models
28-31 August 2012
Lisbon - Portugal

This Workshop brings together those interested in the theory and phenomenology of Multi-Higgs models. The program is designed to include talks given by some of the leading experts in the field, and also ample time for discussions and collaboration between researchers. A particular emphasis will be placed on identifying those features of the models which are testable at the LHC.

For registration and/or to propose a talk, send an email to:
ferreira@cii.fc.ul.pt

Web Page: http://www.ciul.ul.pt/~2hdmwork/

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M. Krawczyk
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Theoretical

Remaining parameters are fixed by the theoretical constraints - tree-level vacuum stability (potential is bounded from below at tree-level) and perturbative unitarity.
Is it the heavy \textit{CP}-even?

- In all four models, decays \( h \) to \( \gamma\gamma \), \( WW \) and \( ZZ \) will be unobservable.

- \( H \) to \( hh \) is kinematically inaccessible. Type I: decays of \( h \) and \( H \) into \( bb \) and \( \tau\tau \) can both be observed at a rate similar to SM. Type II and Flipped: decays can both occur at rates twice that of the SM. In LS one can have a huge enhancement in the \( H \) to \( \tau\tau \) and \( h \) to \( \tau\tau \) rates.

- \( H \) to \( hh \) is kinematically allowed, and will generally be large.

  If \( m_{12} = 0 \), \( \sin\alpha = \pm 1 \) - \( h \) to \( \gamma\gamma \), \( VV \) and \( bb \) is undetectable, while \( h \) to \( \tau\tau \) is only detectable in the LS model.

  If \( m_{12} \neq 0 \), the region of parameter-space in which the \( \lambda_{Hhh} \) coupling is suppressed is substantially expanded, and can cover most of the LEP-allowed region (similar results as for case I).