Signals of CP Violation Beyond the MSSM in Higgs Physics

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Based on arXiv:1107.3814 with Wolfgang Altmannshofer, Marcela Carena and Stefania Gori
Outline

- The Higgs sector in the MSSM and the Little Hierarchy Problem
  - Beyond the MSSM
- Additional sources of CP violation
  - CP violation beyond the MSSM
- Higgs Collider Phenomenology
- Closing Remarks
The MSSM

\[ W_{MSSM} = \mu \hat{H}_u \cdot \hat{H}_d + y_u^{ij} \hat{u}_i^c \hat{H}_u \cdot \hat{Q}_{Lj} - y_d^{ij} \hat{d}_i^c \hat{H}_d \cdot \hat{Q}_{Lj} - y_{\tau}^{ij} \hat{e}_i^c \hat{H}_d \cdot \hat{E}_{Lj} \]

What can it do:

- It is a solution to the “Hierarchy Problem”
- Light Higgs mimics SM Higgs in production and decay
- Bound on Higgs mass at tree-level proportional to gauge couplings

\[ M_{h^0} \leq M_Z \cos 2\beta \]
In the Higgs decoupling limit, the bound on the MSSM Higgs is the same as that of the SM Higgs from LEP→114 GeV

Need for large radiative corrections originating from SUSY particles... heavy stops above 1 TeV

Creates a fine tuning in the mass parameters since $m_{\tilde{t}}$ provides the cutoff for the quadratically divergent Higgs mass parameter

→Introduces a “Little Hierarchy problem”
Beyond the MSSM

- Effective Field theory with SUSY preserving and SUSY breaking dimension 5 operators

\[ W \supset \mu \hat{H}_u \hat{H}_d + \frac{\omega}{2M} (\hat{H}_u \hat{H}_d)^2 \]

NLO contributions arise from Kahler potential terms \( O\left(\frac{1}{M^2}\right) \) small for consistent effective field theory yet relevant
Beyond the MSSM

• Incorporate gauge singlets
  i.e. SMSSM (Delgado, Kolda, Olson, AP 2010):

\[ W_{\hat{S}} = (\lambda \hat{S} + \mu) \hat{H}_u \hat{H}_d + \frac{\mu_s}{2} \hat{S}^2 \]

\[ m_{h_0}^2 \approx m_Z^2 \cos^2 2\beta + \frac{2\lambda^2 v^2}{\mu_s} (2\mu \sin 2\beta - A_\lambda \sin^2 2\beta) \]
Hunting for additional sources of CP violation
Motivations for additional sources of CP violation

Standard Model has two sources of CP violation

1. CKM matrix: Constrained by unitarity
   - probed through the K and B meson systems

2. Arising from strong dynamics: \( L \supset \frac{\alpha_s}{8\pi} \Theta G \tilde{G} \)
   Constrained by neutron electric dipole moment (EDM)

Problem in reproducing CP violation from the baryon asymmetry in the universe (BAU)

\[
\frac{n_B}{n_\gamma} = (1.5 - 6.3) \times 10^{-10}
\]
CP violation in the MSSM Higgs sector

- Radiatively induced
- Phases may occur in $\mu, A_f, m_{1/2}$
- Mixing among CP-even and CP-odd Higgs

MSSM can be used as a model for electroweak baryogenesis to generate the BAU... However

- EWBG requires a light right handed stop... (strong 1st order phase transition)
- MSSM requires a large stop
  \[ \rightarrow \text{Fine tuning} \]
Beyond the MSSM with CP violation
CP violating BMSSM

Effective field theory approach:

• Leading higher dimensional operators added to MSSM Higgs sector

\[ W = W_{Yukawa} + \mu \hat{H}_u \hat{H}_d + \frac{w}{2M} (\hat{H}_u \hat{H}_d)^2 \]

• SUSY breaking term in the Lagrangian

\[ L \supset \alpha \frac{\omega m_s}{2M} (H_u H_d)^2 \]
CP violating BMSSM

Effective field theory approach:
- Leading higher dimensional operators added to MSSM Higgs sector

\[ W = W_{Yukawa} + \mu \hat{H}_u \hat{H}_d + \frac{w}{2M} (\hat{H}_u \hat{H}_d)^2 \]

- SUSY breaking term in the Lagrangian

\[ L \supset \alpha \frac{\omega m_s}{2M} (H_u H_d)^2 \]

\( \omega \) and \( \alpha \) are complex order one parameters; and \( m_s \) is the scale of the SUSY breaking terms of the BMSSM physics
At the renormalizable level, the tree level potential is given by:

\[
V_{\text{ren}} = V_{\text{MSSM}} + \left( \alpha \frac{\omega m_s}{2M} (H_u H_d)^2 - \frac{\omega \mu^*}{M} (H_u H_d)(H_u^\dagger H_u + H_d^\dagger H_d) + h.c. \right)
\]

\[
= (m_{H_u}^2 + |\mu|^2) H_u^\dagger H_u + (m_{H_d}^2 + |\mu|^2) H_d^\dagger H_d + (B \mu (H_u H_d) + h.c.)
\]

\[
+ \frac{g_2^2}{8c_W} (H_d^\dagger H_d)^2 + \frac{g_2^2}{8c_W} (H_u^\dagger H_u)^2 - \frac{g_2^2}{4c_W} (H_d^\dagger H_d)(H_u^\dagger H_u) + \frac{g_2^2}{2} (H_u^\dagger H_d)(H_d^\dagger H_u)
\]

\[
+ \left( \alpha \frac{\omega m_s}{2M} (H_u H_d)^2 - \frac{\omega \mu^*}{M} (H_u H_d)(H_u^\dagger H_u + H_d^\dagger H_d) + h.c. \right)
\]

- Parametrize the complex coefficients as

\[
\lambda_5 = |\lambda_5| e^{i\phi_5} \equiv \frac{\alpha \omega m_s}{M}
\]

\[
\lambda_6 = |\lambda_6| e^{i\phi_6} \equiv \frac{\omega \mu^*}{M}
\]
1/M operator in the Superpotential leads to additional non-renormalizable operators

\[ V_6 = \frac{\lambda_8}{M^2} (H_u H_d) (H_u^\dagger H_d^\dagger) (H_u^\dagger H_u) + \frac{\lambda_8'}{M^2} (H_u H_d) (H_u^\dagger H_d^\dagger) (H_d^\dagger H_d) \]

where \( \lambda_8 = |\omega|^2 \)

- Crucial in bounding potential from below
- At the \( 1/M^2 \), Kahler terms can be incorporated -> lead to larger Higgs masses

Carena, Kong, Ponton and Zurita
Electroweak Symmetry Breaking:

- The Higgs fields are parametrized as follow:

\[
H_u^T = e^{i\theta_u} (H_u^+, \frac{v_u + h_u + ia_u}{\sqrt{2}}) \quad H_d^T = e^{i\theta_d} (\frac{v_d + h_d + ia_d}{\sqrt{2}}, H_d^-)
\]

\[
v_u = v \sin \beta \\
v_d = v \cos \beta
\]

- Relative phase can be rotated away by a U(1) transformation and \( \theta = \theta_u + \theta_d \) is physical
where the third condition leads to:

\[ v^2 c_\beta s_\beta |\lambda_5| \sin(\phi_5 + 2\theta) + v^2 |\lambda_6| \sin(\phi_6 + \theta) - 2B\mu \sin \theta = 0 \]

Minimization conditions do not necessarily lead to a unique solution

Second mimima along D-flat direction

Metastability
Spectrum at tree-level

In the absence of CP violation we have:

\[
\begin{pmatrix}
    h \\
    H
\end{pmatrix} =
\begin{pmatrix}
    c_\alpha & -s_\alpha \\
    s_\alpha & c_\alpha
\end{pmatrix}
\begin{pmatrix}
    h_u \\
    h_d
\end{pmatrix},
\begin{pmatrix}
    G \\
    A
\end{pmatrix} =
\begin{pmatrix}
    s_\beta & -c_\beta \\
    c_\beta & s_\beta
\end{pmatrix}
\begin{pmatrix}
    a_u \\
    a_d
\end{pmatrix}
\]

- CP violation leads to scalar-pseudoscalar mixing:

\[
M^2_H = \begin{pmatrix}
    M^2_h & 0 & M^2_{hA} \\
    0 & M^2_H & M^2_{HA} \\
    M^2_{hA} & M^2_{HA} & M^2_A
\end{pmatrix}
\]

\[
M^2_{hA} = -\frac{v^2}{2} \left( c_{\beta+\alpha} |\lambda_5| \sin(\phi_5 + 2\theta) - 2s_{\beta-\alpha} |\lambda_6| \sin(\phi_6 + \theta) \right)
\]

\[
M^2_{HA} = -\frac{v^2}{2} \left( s_{\beta+\alpha} |\lambda_5| \sin(\phi_5 + 2\theta) - 2c_{\beta-\alpha} |\lambda_6| \sin(\phi_6 + \theta) \right)
\]
Spectrum at tree-level

\[
M^2_H = \begin{pmatrix}
M^2_h & 0 & M^2_{hA} \\
0 & M^2_H & M^2_{HA} \\
M^2_{hA} & M^2_{HA} & M^2_A
\end{pmatrix}
\]

- The mass matrix is diagonalized by an orthogonal matrix \( O_{ij} \) such that

\[
O^T M^2_H O = \text{diag}(M^2_{H1}, M^2_{H2}, M^2_{H3})
\]
Constraints arising from EDM’s

- Highly sensitive probes of CP violation
- Lead to tight constraints on new sources of CP violation

at 95% C.L:

\[ |d_n| < 3.5 \times 10^{-26} \text{ em} \]
\[ |d_{Tl}| < 1.1 \times 10^{-24} \text{ em} \]
\[ |d_{Hg}| < 2.9 \times 10^{-29} \text{ em} \]
Constraints arising from EDM's

- One loop EDMs mainly induced by phase of the Higgs vev

\[
\left\{ \frac{d \tilde{g}}{e}, \frac{d \tilde{g}}{d} \right\} \approx \frac{\alpha_s}{4\pi} m_d \text{ Im} \left[ e^{i\theta} \frac{t_\beta e^{i\epsilon_d t_\beta}}{1 + \epsilon_d t_\beta} \right] \frac{\mu M \tilde{g}}{\tilde{m}^4} \left\{ f_d(x_g), \tilde{f}_d(x_g) \right\}
\]

\[
d \tilde{H} / e \approx \frac{\alpha_2}{4\pi} m_e \text{ Im} \left[ e^{i\theta} \frac{t_\beta e^{i\epsilon_\ell t_\beta}}{1 + \epsilon_\ell t_\beta} \right] \frac{\mu M_2}{\tilde{m}^4} f_e(x_\mu, x_2)
\]

- \( \epsilon \) terms due to \( \tan \beta \) resummation from non-holomorphic corrections to down quark and electron Yukawa couplings
- One loop contributions are \( \tan \beta \) enhanced
Constraints arising from EDM's

- Two-loop contributions are due to Bar-Zee diagrams

\[ de^{(2)t}/e = \frac{\alpha_2 \alpha_{em}}{16\pi^2} \frac{4}{3} m_e \text{ Re} \left[ \frac{\tan \beta}{1 + \epsilon \ell t \beta} \right] \frac{m_i^2}{M_W^2} \]

\[ \times \sum_{i=1}^{3} \frac{1}{M_{H_i}^2} O_{3i} \left( \frac{s_\alpha}{s_\beta} O_{2i} + \frac{c_\alpha}{s_\beta} O_{1i} \right) f \left( \frac{m_i^2}{M_{H_i}^2} \right) \]

- Sensitive to mixing between scalar and pseudoscalar Higgs through \( O_{ij} \)
- Two-loop contributions can be as large as 1-loop contributions for relatively light Higgs masses
Bounds from the EDMs in the Argf $\alpha$ $\omega$ plane for two different values of $|\alpha| = p$, $o$. The remaining parameters are fixed to $\tan \beta = r$, $|\omega| = p$, $\mu = m$, $S = p$, $\mu E = \eta$, $\eta M = 1.5 T e V$.

The solid and dashed black lines correspond to the Thallium and Mercury EDMs respectively. The neutron EDM does not lead to constraints in the considered scenarios. The dotted blue lines indicate the values of the phase of the Higgs VEV $\theta$. In the red region the electroweak symmetry breaking vacuum is only a local minimum of the Higgs potential. In Fig. we show the constraints coming from the EDMs in the Argf $\omega$ $-\omega$ plane for two example scenarios with $\tan \beta = r$. We observe that the most stringent constraint comes from the Thallium EDM that is dominantly induced by the plloop chargino conl contribution to the electron EDM. From $r$ one expects that the allowed region therefore corresponds to small values of the phase of the Higgs VEV $\theta$ as it is also shown in Fig. where the values of $\theta$ are indicated in blue. In $r$ we neglected additional $p$/$M$ suppressed corrections that can be incorporated by replacing the Higgsino mass with an effective term $\mu = m_s = 150 150$, $M_{H^+} = 200$ GeV, $M = 1.5$ TeV.

Dashed blue lines correspond to different values of the phase of the Higgs vev.
Higgs Collider Phenomenology
LEP and Tevatron Bounds

- Worked with effective couplings normalized to SM

\[
\xi_{\gamma\gamma H_i}^2 = \frac{\Gamma(H_i \rightarrow \gamma\gamma)_{LO}}{\Gamma(H_i \rightarrow \gamma\gamma)_{LO}^{SM}}
\]

\[
\xi_{gg H_i}^2 = \frac{\Gamma(H_i \rightarrow gg)_{LO}}{\Gamma(H_i \rightarrow gg)_{LO}^{SM}} \approx \frac{\sigma(gg \rightarrow H_i)}{\sigma(gg \rightarrow H_i)^{SM}}
\]

5-20%

- Compatibility with LEP and Tevatron searches is checked using Higgsbounds

Bechtle, Brein, Heinemeyer, Werglein, Williams

- Incorporating also latest Tevatron exclusion

T. Aaltonen et al.  2011
Parameter Scan:

- Excluded by EDMs
- Excluded by LEP
- Excluded by Tevatron
- Allowed

\[ \tan \beta = 2, m_s = \mu = 150 \text{ GeV}, m_{\tilde{q}} = 800 \text{ GeV} \]

\[ \omega = (0.5 \to 2.) e^{-\frac{i}{5} \text{Arg}(\alpha)} \]

\[ M \in [1, 3] \text{ TeV} \]

\[ M_{H^\pm} \leq 350 \text{ GeV} \]
**Generic features of the Parameter Scan**

- **CP conserving**
- **CP violating**

**Figure 7:**

- **Left:** $gg \rightarrow H \rightarrow W+Higgs$ production cross sections times Higgs branching ratios into $WW$ normalized to the SM values.
- **Right:** $WW \rightarrow H \rightarrow Higgs$ production cross sections and Higgs branching ratios into $\tau\tau$ normalized to the SM values.

Orange points correspond to approximate CP conservation $m | \alpha |, \omega | < v_w$; green points correspond to the CP violating case $m | \alpha |, \omega | > v_w$. Only points allowed by LEP and Tevatron bounds on vacuum stability and EDMs are shown. See caption of Figure 6 for the details of the scan.

**Generic features of the Parameter Scan**

- **WW channel promising in both scenarios**
- **For masses below 140 GeV, $\sigma(gg \rightarrow H) \cdot BR(H \rightarrow WW)$ suppressed compared to SM, but may be possible to probe at Tevatron and LHC**
- **The $\tau\tau$ channel is slightly enhanced for wide range of masses... LHC not yet sensitive**
Generic features of the Parameter Scan

- **CP conserving**
- **CP violating**

- Heavier Higgs boson can be discovered in the WW channel

- Absence of a pure pseudoscalar... mixing even leads to sizable enhancement in the WW production cross section

- $\tau\tau$ channel enhanced with respect to SM for masses above 150 GeV where
  \[ \sigma(WW \rightarrow H_{2,3}) \cdot BR(H_{2,3} \rightarrow \tau\tau) \]
  are too small to allow for detection
CP violating scenarios: Benchmark points

Scenario A:

<table>
<thead>
<tr>
<th>Scenario III</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>$H_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{H_i}$ [GeV]</td>
<td>145</td>
<td>169</td>
<td>198</td>
</tr>
<tr>
<td>$\xi_{ZZH_i}^2$</td>
<td>0.94</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>$\xi_{ggH_i}^2$</td>
<td>0.68</td>
<td>0.59</td>
<td>0.53</td>
</tr>
<tr>
<td>BR($H_i \rightarrow bb$)</td>
<td>42% (23%)</td>
<td>59% (0.8%)</td>
<td>15% (0.2%)</td>
</tr>
<tr>
<td>BR($H_i \rightarrow WW$)</td>
<td>45% (60%)</td>
<td>31% (97%)</td>
<td>62% (74%)</td>
</tr>
<tr>
<td>BR($H_i \rightarrow ZZ$)</td>
<td>6% (8%)</td>
<td>0.7% (2.4%)</td>
<td>20% (26%)</td>
</tr>
<tr>
<td>BR($H_i \rightarrow \gamma\gamma \times 10^4$)</td>
<td>15 (17)</td>
<td>0.8 (1.6)</td>
<td>0.2 (0.5)</td>
</tr>
</tbody>
</table>

- All three neutral Higgs bosons have masses above 145 GeV with significant branching ratios into WW
- This scenario cannot be achieved in the MSSM
CP violating scenarios: Benchmark points

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<td>15 (17)</td>
</tr>
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</table>

- Scenario testable with 5fb$^{-1}$ of data at the LHC
CP violating scenarios: Benchmark points

Scenario B:

<table>
<thead>
<tr>
<th>Scenario II</th>
<th>$H_1$</th>
<th>$H_2$</th>
<th>$H_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{H_i}$ [GeV]</td>
<td>147</td>
<td>150</td>
<td>162</td>
</tr>
<tr>
<td>$\xi^2_{ZZH_i}$</td>
<td>0.62</td>
<td>0.32</td>
<td>0.06</td>
</tr>
<tr>
<td>$\xi^2_{ggH_i}$</td>
<td>0.41</td>
<td>0.53</td>
<td>0.39</td>
</tr>
<tr>
<td>BR($H_i \to bb$)</td>
<td>69% (22%)</td>
<td>72% (16%)</td>
<td>65% (2%)</td>
</tr>
<tr>
<td>BR($H_i \to WW$)</td>
<td>20% (63%)</td>
<td>17% (69%)</td>
<td>26% (94%)</td>
</tr>
<tr>
<td>BR($H_i \to ZZ$)</td>
<td>3% (8%)</td>
<td>2% (8%)</td>
<td>1% (3%)</td>
</tr>
<tr>
<td>BR($H_i \to \gamma\gamma$) $\times 10^4$</td>
<td>6 (16)</td>
<td>3 (13)</td>
<td>0.5 (4)</td>
</tr>
<tr>
<td>Sc. II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\alpha</td>
<td>$</td>
<td>0.8</td>
</tr>
<tr>
<td>$</td>
<td>\omega</td>
<td>$</td>
<td>1.6</td>
</tr>
<tr>
<td>$\text{Arg}(\alpha)$</td>
<td>$-2\pi/3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{Arg}(\omega)$</td>
<td>$\pi/20$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tan\beta$</td>
<td>3</td>
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</tr>
<tr>
<td>$M_{H^\pm}$ [GeV]</td>
<td>166</td>
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<td></td>
</tr>
<tr>
<td>$M$ [TeV]</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$ [GeV]</td>
<td>140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_S$ [GeV]</td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- All three neutral Higgs bosons have masses between 145 and 160 GeV decaying dominantly to $b\bar{b}$
- Strongly suppressed cross sections in the channel $gg \to H_i \to \gamma\gamma$
- Associated production with Higgs decays to $\tau\tau$ larger than SM but difficult to probe given the large Higgs masses
**CP violating scenarios: Benchmark points**

**Scenario B:**

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<td>$\text{BR}(H_i \rightarrow \gamma\gamma) \times 10^4$</td>
<td>6 (16)</td>
</tr>
</tbody>
</table>

- Might be probed with 5fb$^{-1}$ of data given lack of mass resolution... All three Higgs bosons appear as one
Closing Remarks

• Introduced two new dimension 5 operators to the MSSM and study their implications as a possible source of CP violation
  • Low $\tan\beta$ favorable with EDM constraints
  • Sizable couplings of Higgs bosons with weak gauge bosons
• BMSSM with CP violation leads to interesting signals in Higgs collider physics that will be probed very soon
  • Three Higgs bosons with significant branching ratios into WW
  • Three heavy Higgs bosons decaying primarily into $b\bar{b}$
Back-up Slides
**Constraints in the \( \mu - m_S \) plane from vacuum stability. The region within the blue, green, and red contour leads to an absolute stable electroweak vacuum for a charged Higgs mass of 150, 250, and 350 GeV. The NP scale \( M \) is fixed to 2 TeV, \( \tan \beta = 2 \), \( |\alpha| = |\omega| = 1 \).

However, one should keep in mind that the requirement of absolute vacuum stability is rather conservative. It would be sufficient to impose that the EW vacuum is metastable, provided that its lifetime is longer than the age of the universe. This possibility has been discussed in [1] in the context of the BMSSM without CP violation. Using simple analytic approximations for the bounce action [2], we checked that the viable parameter space indeed opens up to some extent if we allow for a metastable vacuum. However, to be conservative, we require always absolute stability of the vacuum in the discussion of the Higgs phenomenology.

**2.3 The Higgs Spectrum**

We now briefly review the effects of the higher dimensional operators introduced in the previous section and in particular of the new physics phases on the Higgs spectrum. In order to keep a clear comparison to the case without CP violation, we write the mass matrices of the neutral Higgs bosons in the basis that would diagonalize it in absence of new sources of CP violation:

\[
\begin{align*}
\tilde{h} & = \begin{pmatrix} c\alpha - s\alpha \\ s\alpha & c\alpha \end{pmatrix} \\
\tilde{H} & = \begin{pmatrix} c\beta - s\beta \\ s\beta & c\beta \end{pmatrix}
\end{align*}
\]

Plot corresponding to values for the charged Higgs mass of 150, 250, and 350 GeV.