Coupled system of two ~750 GeV Higgs bosons in the (complex) NMSSM

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HPNP 2017, Toyama
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Coupled system of two ~125 GeV Higgs bosons in the (complex) NMSSM

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Outline

- Di-photon via the Higgs boson at the LHC
- Narrow width approximation, and beyond
- The NMSSM
- Two Higgs bosons near 125 GeV
- Interference effects from high mass-degeneracy
- Conclusions
Applying the narrow width approximation,

\[
|\mathcal{M}|^2 = \sum_{\lambda,\sigma=\pm} \mathcal{M}_{P\lambda}^* \mathcal{M}_{P\lambda} |D_H(\hat{s})|^2 \mathcal{M}_{D\sigma}^* \mathcal{M}_{D\sigma}
\]

simplifies the expression for the partonic cross section

\[
\hat{\sigma}(gg \rightarrow H \rightarrow \gamma\gamma) = \frac{1}{1024\pi\hat{s}} \sum_{i=1-5} \left( \sum_{\lambda=\pm} |\mathcal{M}_{P\lambda}|^2 \times \frac{\pi}{m_{H_i}\Gamma_{H_i}} \delta(\hat{s} - m_{H_i}^2) \times \sum_{\sigma=\pm} |\mathcal{M}_{D\sigma}|^2 \right)
\]
Two (or more) Higgs bosons near 125 GeV can undergo quantum interference due to loop effects, e.g.,

$$\sum_{i,j} \langle s \mid \hat{D}_{ij}(s) \rangle = \frac{v^2}{16\pi} \sum_{k \geq l=1,2,3} S_{ij;kl} g_{H_iH_k} g_{H_jH_k} \frac{\lambda^{1/2}(1, \kappa_{H_k}, \kappa_{H_l}) \Theta(s - (M_{H_k} + M_{H_l})^2)}{1 + \delta_{kl}}$$

The full propagator matrix needs to be taken into account

$$D(s) = \hat{s} \begin{pmatrix} \hat{s} - M_{H_1}^2 + i\Im \Pi_{11}(s) \\ \hat{s} - M_{H_2}^2 + i\Im \Pi_{22}(s) \\ \hat{s} - M_{H_3}^2 + i\Im \Pi_{33}(s) \end{pmatrix}^{-1}$$

$$\frac{d\sigma_{pp}}{d\sqrt{s}} = \int_\tau^1 \frac{2\sqrt{s}}{s} dx_1 g(x_1) g(s/sx_1) \frac{1024\pi s^3}{M_{P,\lambda}} \sum_{i,j=1-5} \sum_{\lambda=\pm} |\mathcal{M}_{P,\lambda}|^2 |D_{ij}(s)|^2 \sum_{\sigma=\pm} |\mathcal{M}_{D_{ij}}|^2$$
Two (or more) Higgs bosons near 125 GeV can undergo quantum interference due to loop effects, e.g.,

\[ \Im m \hat{\Pi}_{ij}^{HH}(s) = \frac{v^2}{16\pi} \sum_{k \geq l=1,2,3} \frac{S_{ij,kl}}{1 + \delta_{kl}} g_{H_i H_k H_l} g_{H_j H_k H_l} \lambda^{1/2}(1, \kappa_{H_k}, \kappa_{H_l}) \Theta \left( s - (M_{H_k} + M_{H_l})^2 \right) \]

The full propagator matrix needs to be taken into account

The differential cross section is given by

\[ \frac{d\sigma_{pp}^{\gamma\gamma}}{d\sqrt{s}} = \int_0^1 \frac{d^3x_1}{s} \frac{g(x_1)g(\hat{s}/sx_1)}{1024\pi \hat{s}^3} \sum_{i,j=1-5} \left\{ \sum_{\lambda=\pm} |M_{P_{i\lambda}}|^2 |D_{ij}(\hat{s})|^2 \sum_{\sigma=\pm} |M_{D_{j\sigma}}|^2 \right\} \]
Coupled system of Higgs bosons

[G. Cacciapaglia, A. Deandrea, S. De Curtis, 0906.3417]

But two $\sim125$ GeV neutral Higgs bosons difficult in

- MSSM: SM-like $h$ $\rightarrow$ other Higgs bosons heavy
- 2HDMs: Strong electroweak precision constraints

Figure 1: Plots of the production cross section (in arbitrary units) of two nearby Higgses decaying into gauge boson pairs for the naive Breit-Wigner (blue-dashed) and exact mixing (red-solid). The mass of the first resonance is fixed to 400 GeV, the splitting respectively 50, 25, 10 and 5 GeV and $\alpha = \pi/4$. 
The Next-to-Minimal Supersymmetric SM

The two Higgs doublets of the MSSM augmented by an additional Higgs singlet superfield

\[ W_{\text{NMSSM}} = h_u \hat{Q} \cdot \hat{H}_u \hat{U}_R^c + h_d \hat{H}_d \cdot \hat{Q} \hat{D}_R^c + h_e \hat{H}_d \cdot \hat{L} \hat{E}_R^c + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 \]

- 5 neutral Higgs bosons in total: three scalars \( H_{1-3} \) and two pseudoscalars \( A_{1,2} \) in the CP-conserving limit
- The two lightest CP-even states can be mass degenerate

\[ m_{h_{1,2}}^2 \approx \frac{1}{2} \left\{ M_Z^2 + 4(\kappa s)^2 + \kappa s A_\kappa \mp \sqrt{[M_Z^2 - 4(\kappa s)^2 - \kappa s A_\kappa]^2 + 4\lambda^2 v^2 [2\lambda s - (A_\lambda + \kappa s) \sin 2\beta]^2} \right\} \]

- The singlet-like pseudoscalar can be near 125 GeV also

\[ m_{A_1}^2 \approx \lambda (A_\lambda + 4\kappa s) \frac{v^2 \sin 2\beta}{2s} - 3\kappa s A_\kappa - \frac{M_{P,12}^4}{M_{P,11}^2} \]
**Fit to the 7-8 TeV LHC data**

Performed using HiggsSignals [P. Bechtle et al., 1305.1933]

Total number of observables: 81

Some points with both $H_1$ and $H_2$ near 125 GeV give a better fit, especially for a non-zero CPV phase!
Higgs propagator matrix in the NMSSM

5x5 Higgs mass matrix after isolating the Goldstone boson

\[
\mathcal{M}_0^2 = \begin{pmatrix}
\mathcal{M}_S^2 \\
\hline
\mathcal{M}_P^2
\end{pmatrix}
\]

\[
D_H(\hat{s}) = \hat{s} \begin{pmatrix}
m_{11} & i\hat{\Im}m\hat{\Pi}_{12}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{13}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{14}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{15}(\hat{s}) \\
i\hat{\Im}m\hat{\Pi}_{21}(\hat{s}) & m_{22} & i\hat{\Im}m\hat{\Pi}_{23}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{24}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{25}(\hat{s}) \\
i\hat{\Im}m\hat{\Pi}_{31}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{32}(\hat{s}) & m_{33} & i\hat{\Im}m\hat{\Pi}_{34}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{35}(\hat{s}) \\
i\hat{\Im}m\hat{\Pi}_{41}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{42}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{43}(\hat{s}) & m_{44} & i\hat{\Im}m\hat{\Pi}_{45}(\hat{s}) \\
i\hat{\Im}m\hat{\Pi}_{51}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{52}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{53}(\hat{s}) & i\hat{\Im}m\hat{\Pi}_{54}(\hat{s}) & m_{55}
\end{pmatrix}^{-1}
\]
Higgs propagator matrix in the NMSSM

5x5 Higgs mass matrix after isolating the Goldstone boson

$$M_0^2 = \begin{pmatrix}
M_S^2 & M_{SP}^2 \\
M_{SP}^2 & M_P^2
\end{pmatrix}$$

Non-zero complex phases

$$D_H(\hat{s}) = \hat{s}^{-1}$$

$$\begin{pmatrix}
m_{11} & i\Im\hat{\Pi}_{12}(\hat{s}) & i\Im\hat{\Pi}_{13}(\hat{s}) & i\Im\hat{\Pi}_{14}(\hat{s}) & i\Im\hat{\Pi}_{15}(\hat{s}) \\
i\Im\hat{\Pi}_{21}(\hat{s}) & m_{22} & i\Im\hat{\Pi}_{23}(\hat{s}) & i\Im\hat{\Pi}_{24}(\hat{s}) & i\Im\hat{\Pi}_{25}(\hat{s}) \\
i\Im\hat{\Pi}_{31}(\hat{s}) & i\Im\hat{\Pi}_{32}(\hat{s}) & m_{33} & i\Im\hat{\Pi}_{34}(\hat{s}) & i\Im\hat{\Pi}_{35}(\hat{s}) \\
i\Im\hat{\Pi}_{41}(\hat{s}) & i\Im\hat{\Pi}_{42}(\hat{s}) & i\Im\hat{\Pi}_{43}(\hat{s}) & m_{44} & i\Im\hat{\Pi}_{45}(\hat{s}) \\
i\Im\hat{\Pi}_{51}(\hat{s}) & i\Im\hat{\Pi}_{52}(\hat{s}) & i\Im\hat{\Pi}_{53}(\hat{s}) & i\Im\hat{\Pi}_{54}(\hat{s}) & m_{55}
\end{pmatrix}$$
Parameter space scans

\[ M_0 \equiv M_{Q_{1,2,3}} = M_{U_{1,2,3}} = M_{D_{1,2,3}} = M_{L_{1,2,3}} = M_{E_{1,2,3}}, \]
\[ M_{1/2} = 2M_1 = M_2, \]
\[ A_0 \equiv A^\chi = A^\tilde{b} = A^\tilde{\tau}, \]
\[ \Delta m_{H_2-H_1} < \Gamma_{H_1} \text{ and/or } \Gamma_{H_2} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scanned range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_0 ) (GeV)</td>
<td>800 – 2000</td>
</tr>
<tr>
<td>( M_{1/2} ) (GeV)</td>
<td>100 – 500</td>
</tr>
<tr>
<td>( A_0 ) (GeV)</td>
<td>(-3000 – 0)</td>
</tr>
<tr>
<td>( \tan \beta )</td>
<td>2 – 8</td>
</tr>
<tr>
<td>(</td>
<td>\lambda</td>
</tr>
<tr>
<td>(</td>
<td>\kappa</td>
</tr>
<tr>
<td>( \mu_{\text{eff}} ) (GeV)</td>
<td>100 – 200</td>
</tr>
<tr>
<td>(</td>
<td>A_\lambda</td>
</tr>
<tr>
<td>(</td>
<td>A_\kappa</td>
</tr>
</tbody>
</table>

\[ \phi_\kappa = 0^\circ \]

\[ \phi_\kappa = 3^\circ \]

\[ \phi_\kappa = 10^\circ \]
Interference effects

\[ \Gamma_{h_{\text{SM}}} < 13 \text{ MeV} \]

[CMS Collaboration, 1605.02329]

[B. Das, S. Moretti, SM, P. Poulouse, 1703.xxxxx]
Interference effects

\[ \Gamma_{h_{\text{SM}}} < 13 \text{ MeV} \]

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Convolution with a Gaussian

[B. Das, S. Moretti, SM, P. Poulose, 1703.xxxxx]
Conclusions and outlook

- Two Higgs bosons near 125 GeV possible in the NMSSM – may not have been resolved independently
- For very strong mass-degeneracy, quantum interference effects can become sizable – contributing by up to 30% in the total cross section
- Certain parameter choices give negative interference also
- Due to the narrow widths of the two 125 GeV Higgs bosons, these effects are not probable with the LHC mass resolution
- For the heavier Higgs bosons they can be more crucial and also accessible… analysis underway