Two Higgs bosons near 125 GeV in the complex NMSSM

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Outline

- Beyond minimal SUSY: The Next-to-MSSM
- Two scalars near 125 GeV in the NMSSM
- A scalar and a pseudoscalar near 125 GeV
- NMSSM with complex Higgs sector
- Beyond the Breit-Wigner approach: `coupled-channel’ Higgs boson propagator
- Conclusions
Why beyond the MSSM?

- Superpotential not conformal invariant: `μ-problem`
  \[ W_{\text{MSSM}} = h_u \hat{Q} \cdot \hat{H}_u \hat{U}_R^c + h_d \hat{H}_d \cdot \hat{Q} \hat{D}_R^c + h_e \hat{H}_d \cdot \hat{\bar{L}} \hat{E}_R^c + \mu \hat{H}_u \cdot \hat{H}_d \]

- Higgs boson@LHC -> Large \( A_t \)
  \[ \Delta m_h^2 = \frac{3m_t^4}{4\pi^2v^2} \left[ \ln \left( \frac{M_{\text{SUSY}}^2}{m_t^2} \right) + \frac{X_t^2}{M_{\text{SUSY}}^2} \left( 1 - \frac{X_t^2}{12M_{\text{SUSY}}^2} \right) \right] \]

- SUSY@LHC: Large \( M_{\text{SUSY}} \), fine-tuning reintroduced!
  \[ \frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^d) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \]

- ~ 122 new parameters!
  - pMSSM: ~ 25 SUSY parameters
  - GUT-universality – CMSSM: only 4 SUSY parameters
    -> severely constrained / fine-tuned
The NMSSM

Add a Higgs singlet superfield $\hat{S}$

$$ W_{\text{NMSSM}} = \text{MSSM Yukawa terms} + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{K}{3} \hat{S}^3 $$

EWSB $\rightarrow \mu_{\text{eff}} = \lambda v_S$

- 5 new parameters: $\lambda, \kappa, A_\lambda, A_\kappa, v_S$
- 5 neutral Higgs bosons, 5 neutralinos
- Enhanced tree-level mass of SM-like Higgs boson

$$ m_{H_{\text{SM}}}^2 \simeq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2 v^2}{\kappa^2} \left[ \lambda - \sin 2\beta \left( \kappa + \frac{A_\lambda}{2s} \right) \right]^2 $$

Reduced fine-tuning!
The (real) Higgs sector

- Tree-level mass matrix

\[ M^2_0 = \begin{pmatrix} M^2_S & M^2_{SP} \\ (M^2_{SP})^T & M^2_P \end{pmatrix} \]

\[ \mathcal{M}^2_{S,11} = \frac{g^2}{2} v_d^2 + \left( R_\lambda + \frac{R_s}{2} \right) s \tan \beta \]
\[ \mathcal{M}^2_{S,12} = (\mathcal{M}^2_S)_{21} = \left( -\frac{g_1^2 + g_2^2}{4} + |\lambda|^2 \right) v_d v_u - \left( R_\lambda + \frac{R_s}{2} \right) s, \]
\[ \mathcal{M}^2_{S,22} = \frac{g^2}{2} v_u^2 + \left( R_\lambda + \frac{R_s}{2} \right) \frac{s}{\tan \beta}, \]
\[ \mathcal{M}^2_{S,33} = R_\lambda \frac{v_d v_u}{s} + 2|\kappa|^2 s^2 + R_\kappa s, \]
\[ \mathcal{M}^2_{S,13} = (\mathcal{M}^2_S)_{31} = -R_\lambda v_u + |\lambda|^2 v_d s - R_\kappa v_u s, \]
\[ \mathcal{M}^2_{S,23} = (\mathcal{M}^2_S)_{32} = -R_\lambda v_d + |\lambda|^2 v_u s - R_\kappa v_d s. \]

\[ \mathcal{M}^2_P = \begin{pmatrix} (R_\lambda + R_s/2)s \tan \beta & (R_\lambda + R_s/2)s & (R_\lambda - R_s) v_u \\ (R_\lambda + R_s/2)s & (R_\lambda + R_s/2)s \cot \beta & (R_\lambda - R_s) v_d \\ (R_\lambda - R_s) v_u & (R_\lambda - R_s) v_d & R_\lambda \frac{v_d v_u}{s} + 2R_v_d v_u - 3R_\kappa s \end{pmatrix} \]

\[ \mathcal{M}^2_{SP} = 0 \]

For real \( \lambda, \kappa \) (and \( A_\lambda, A_\kappa \))
~125 GeV scalar Higgs boson(s)
Masses of the two lightest scalars (for large-ish $\tan\beta$)

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

- $\lambda, \kappa \to 0$: $H_1$ almost SM-like (maximally fine-tuned)
- $\lambda \sim 0.1, \tan\beta \sim 10$: $H_1$ still quite SM-like

[M. Badziak, M. Olechowski, S. Pokorski, 1304.5437]

- $\lambda \sim 0.5 - 0.7, \tan\beta \sim 2 - 6$: two possibilities
  - $H_2 \sim 125$ GeV: $\sigma_{\gamma\gamma}(H_2) > \sigma_{\gamma\gamma}(H_{SM})$
    [U. Ellwanger, 1112.3548]
  - $H_1, H_2 \sim 125$ GeV: $\sigma_{\gamma\gamma}(H_1 + H_2) > \sigma_{\gamma\gamma}(H_{SM})$
    [J. F. Gunion, Y. Jiang, S. Kraml, 1207.1545]
A $\sim$125 GeV pseudoscalar

The singlet-like pseudoscalar can be very light

$$m_{A_1}^2 \simeq \lambda (A_\lambda + 4\kappa s) \frac{v^2 \sin 2\beta}{2s} - 3\kappa s A_\kappa - \frac{M_{P,12}^4}{M_{P,11}^2}$$

- Light (higgsino) charginos $\rightarrow$ large $A_1\gamma\gamma$ coupling

$$C_{a_1}(\gamma\gamma) \simeq \lambda \times \frac{130 \text{ GeV}}{m_{\chi_1^\pm}}$$

Discrepancy between the $\gamma\gamma$ and ZZ signal rates!

$$R_{\gamma\gamma}^Y(\text{obs}) = R_{\gamma\gamma}^Y(h_1) + R_{\gamma\gamma}^Y(a_1) \simeq 1 + R_{\gamma\gamma}^Y(a_1);$$

$$R_{WW/ZZ}^Y(\text{obs}) = R_{WW/ZZ}^Y(h_1) \simeq 1$$

$$R_{\gamma\gamma}(a_1) \simeq \left| \frac{(A_\lambda^{\text{SUSY}} - 2\kappa s)v}{\mu(A_\lambda^{\text{SUSY}} + \kappa s)} \right|^2 \lambda^4 \left( \frac{130 \text{ GeV}}{m_{\chi_1^\pm}} \right)^2 \left( \frac{1}{\Gamma_{\text{total}}^{a_1}/\Gamma_{\text{total}}^{h_{\text{SM}}}} \right)$$
Parameter space regions

Three consistent regions found, defined by $\chi_1$ composition

[SM, L. Roszkowski, S. Trojanowski, 1305.0591]

Upper limit on $m_{\chi^\pm}$!
The complex NMSSM

- CP-violation necessary for baryon asymmetry of the Universe
- Contrary to the MSSM, Higgs sector CPV possible at tree-level

\[ \lambda \equiv |\lambda|e^{i\phi_\lambda} \quad \text{and} \quad \kappa \equiv |\kappa|e^{i\phi_\kappa} \]

\[ M_0^2 = \begin{pmatrix} M_{S}^2 & M_{SP}^2 \\ (M_{SP}^2)^T & M_{P}^2 \end{pmatrix} \]

- Diagonalization of \( \mathcal{M}_o \) -> Higgs couplings contain \( O_{ai} \)

\[ (H_1, H_2, H_3, H_4, H_5, H_6)^T = O_{ai} (H_d R, H_u R, S_R, H_d l, H_u l, S_l)^T \]

- Beyond the Born approximation, phases induced by

\[
\begin{align*}
\widetilde{M}_t^2 &= \begin{pmatrix} M_{Q_3}^2 + m_t^2 + \cos 2\beta M_Z^2 \left( \frac{1}{2} - \frac{2}{3} s_W^2 \right) h_t v_u (|A_t| e^{-i(\theta + \phi_A t)} - |\lambda| v s e^{i\phi_\lambda} \cot \beta) / \sqrt{2} \\ h_t v_u (|A_t| e^{i(\theta + \phi_A t)} - |\lambda| v s e^{i\phi_\lambda} \cot \beta) / \sqrt{2} \\ M_{U_3}^2 + m_t^2 + \cos 2\beta M_Z^2 Q_t s_W^2 \end{pmatrix} \\
M_N &= \begin{pmatrix} M_1 & 0 & -m_Z \cos \beta s_W & m_Z \sin \beta s_W & 0 \\ 0 & M_2 & m_Z \cos \beta c_W & -m_Z \sin \beta c_W & 0 \\ -m_Z \cos \beta s_W & m_Z \sin \beta c_W & 0 & -|\lambda| v s e^{i\phi_\lambda} \frac{\beta}{2} & 0 \\ -|\lambda| v s e^{i\phi_\lambda} \frac{\beta}{2} & 0 & -|\lambda| v \cos \beta e^{i\phi_\lambda} \frac{\beta}{2} & 0 & \sqrt{2} |\kappa| v_S e^{i\phi_\kappa} \frac{\beta}{2} \\ \sqrt{2} |\kappa| v_S e^{i\phi_\kappa} \frac{\beta}{2} & 0 & -|\lambda| v \cos \beta e^{i\phi_\lambda} \frac{\beta}{2} & 0 & 0 \\ \sqrt{2} |\kappa| v_S e^{i\phi_\kappa} \frac{\beta}{2} & 0 & -|\lambda| v \cos \beta e^{i\phi_\lambda} \frac{\beta}{2} & 0 & 0 \\ \sqrt{2} |\kappa| v_S e^{i\phi_\kappa} \frac{\beta}{2} & 0 & -|\lambda| v \cos \beta e^{i\phi_\lambda} \frac{\beta}{2} & 0 & 0 \\ \sqrt{2} |\kappa| v_S e^{i\phi_\kappa} \frac{\beta}{2} & 0 & -|\lambda| v \cos \beta e^{i\phi_\lambda} \frac{\beta}{2} & 0 & 0 \\ \sqrt{2} |\kappa| v_S e^{i\phi_\kappa} \frac{\beta}{2} & 0 & -|\lambda| v \cos \beta e^{i\phi_\lambda} \frac{\beta}{2} & 0 & 0 \\ \sqrt{2} |\kappa| v_S e^{i\phi_\kappa} \frac{\beta}{2} & 0 & -|\lambda| v \cos \beta e^{i\phi_\lambda} \frac{\beta}{2} & 0 & 0 \\ \sqrt{2} |\kappa| v_S e^{i\phi_\kappa} \frac{\beta}{2} & 0 & -|\lambda| v \cos \beta e^{i\phi_\lambda} \frac{\beta}{2} & 0 & 0 \\ \sqrt{2} |\kappa| v_S e^{i\phi_\kappa} \frac{\beta}{2} & 0 & -|\lambda| v \cos \beta e^{i\phi_\lambda} \frac{\beta}{2} & 0 & 0 \\ \sqrt{2} |\kappa| v_S e^{i\phi_\kappa} \frac{\beta}{2} & 0 & -|\lambda| v \cos \beta e^{i\phi_\lambda} \frac{\beta}{2} & 0 & 0 \end{pmatrix} \\
\mathcal{M}_C &= \begin{pmatrix} M_2 & \sqrt{2} M_W \cos \beta \\ \sqrt{2} M_W \sin \beta & |\lambda| v s e^{i\phi_\lambda} \frac{\beta}{2} \end{pmatrix}
\end{align*}
\]

Tightly constrained by fermion EDMs!
Fit to 7-8 TeV LHC Higgs boson data

With HiggsSignals [Bechtle et al., 1305.1933]

- Total number of observable: 81

Some points with both $H_1$ and $H_2 \sim 125$ GeV give a better fit, especially for a non-zero CPV phase!
Coupled-channel analysis

Cross section in NWA ~

Finite width effects:

\[ \mathcal{D}(\hat{s}) = \hat{s} \left[ \hat{s} - M_{H_1}^2 + i \text{Im} \hat{\Pi}_{11}(\hat{s}) \right] \left[ \hat{s} - M_{H_2}^2 + i \text{Im} \hat{\Pi}_{22}(\hat{s}) \right] \left[ \hat{s} - M_{H_3}^2 + i \text{Im} \hat{\Pi}_{33}(\hat{s}) \right] \]

With, e.g.,

\[ \text{Im} \hat{\Pi}_{ij}(\hat{s}) = \frac{\sqrt{2}}{16\pi} \sum_{f=b,t,\tau} \sum_{k,l=1,2} N_c g_{H_i f_k^* f_l} g_{H_j f_k^* f_l}^* \lambda^{1/2}(1, k_{f_k}, k_{f_l}) \Theta(\hat{s} - (M_{f_k} + M_{f_l})^2) \]

[J. Ellis, J. S. Lee, A. Pilaftsis, hep-ph/0404167]
VV production with two-Higgs propagator

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 $\alpha = \pi/4$.

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

\[ gg \rightarrow X \rightarrow \gamma \gamma \]

- \( M_{H1} = 125.55 \text{ GeV} \)
- \( M_{H2} = 125.9 \text{ GeV} \)
- \( \Gamma_{H1} = 0.0042 \text{ GeV} \)
- \( \Gamma_{H2} = 0.4496 \text{ GeV} \)

Mass spectrum and \( \Pi \)'s calculated using the public program NMSSMCalc

[J. Baglio \textit{et al}, 1312.4788]

\[ gg \rightarrow X \rightarrow \gamma \gamma \]

- Two BWs \( \rightarrow 0.84 \text{ fb} \)
- Total \( \sigma \): with interference: 1.64 fb
  - Full propagator: 1.99 fb

[B. Das, S. Moretti, SM, P. Pouluse, Work in progress]
Conclusions & Outlook

• The NMSSM Higgs sector contains interesting scenarios that are precluded in the MSSM
• Two scalars, as well as a scalar-pseudoscalar pair, possible near 125 GeV
• With complex Higgs sector couplings, the five physical Higgs bosons are CP-mixed states
• Important to consider the full propagator when the mass difference between the two Higgs bosons is comparable to their widths
Thank you!