

# 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: ‘ $\mu$ -problem’

$$W_{\text{MSSM}} = h_u \hat{Q} \cdot \hat{H}_u \hat{U}_R^c + h_d \hat{H}_d \cdot \hat{Q} \hat{D}_R^c + h_e \hat{H}_d \cdot \hat{L} \hat{E}_R^c + \mu \hat{H}_u \cdot \hat{H}_d$$

- Higgs boson@LHC  $\rightarrow$  Large  $A_t$

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2} \left[ \ln \left( \frac{M_{\text{SUSY}}^2}{m_t^2} \right) + \frac{X_t^2}{M_{\text{SUSY}}^2} \left( 1 - \frac{X_t^2}{12M_{\text{SUSY}}^2} \right) \right]$$

- SUSY@LHC: Large  $M_{\text{SUSY}}$ , fine-tuning reintroduced!

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2$$

- $\sim 122$  new parameters!

➤ pMSSM:  $\sim 25$  SUSY parameters

➤ GUT-universality – CMSSM: only 4 SUSY parameters

$\rightarrow$  severely constrained / fine-tuned

# The NMSSM

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

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

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

- 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

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

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

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

$$\mathcal{M}_{SP}^2 =$$

$$0$$

$$\begin{aligned} \mathcal{R} &= |\lambda||\kappa| \cos(\phi'_\lambda - \phi'_\kappa), & \mathcal{I} &= |\lambda||\kappa| \sin(\phi'_\lambda - \phi'_\kappa), \\ R_\lambda &= \frac{|\lambda||A_\lambda|}{\sqrt{2}} \cos(\phi'_\lambda + \phi_{A_\lambda}), & R_\kappa &= \frac{|\kappa||A_\kappa|}{\sqrt{2}} \cos(\phi'_\kappa + \phi_{A_\kappa}) \end{aligned}$$

For real  $\lambda, \kappa$  (and  $A_\lambda, A_\kappa$ )

# $\sim 125$ GeV scalar Higgs boson(s)

Masses of the two lightest scalars (for large-ish  $\tan\beta$ )

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

- $\lambda, \kappa \rightarrow 0$ :  $H_1$  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

$$\rightarrow H_2 \sim 125 \text{ GeV}: \sigma_{\gamma\gamma}(H_2) > \sigma_{\gamma\gamma}(H_{SM})$$

[U. Ellwanger, 1112.3548]

$$\rightarrow H_1, H_2 \sim 125 \text{ GeV}: \sigma_{\gamma\gamma}(H_1+H_2) > \sigma_{\gamma\gamma}(H_{SM})$$

[J. F. Gunion, Y. Jiang, S. Kraml, 1207.1545]

# A ~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!

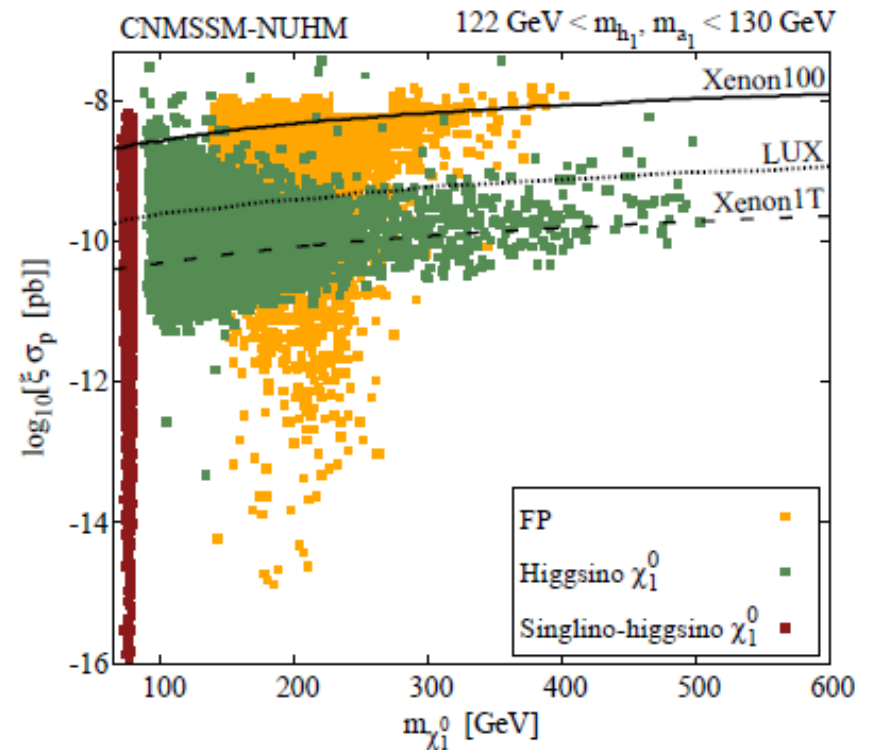
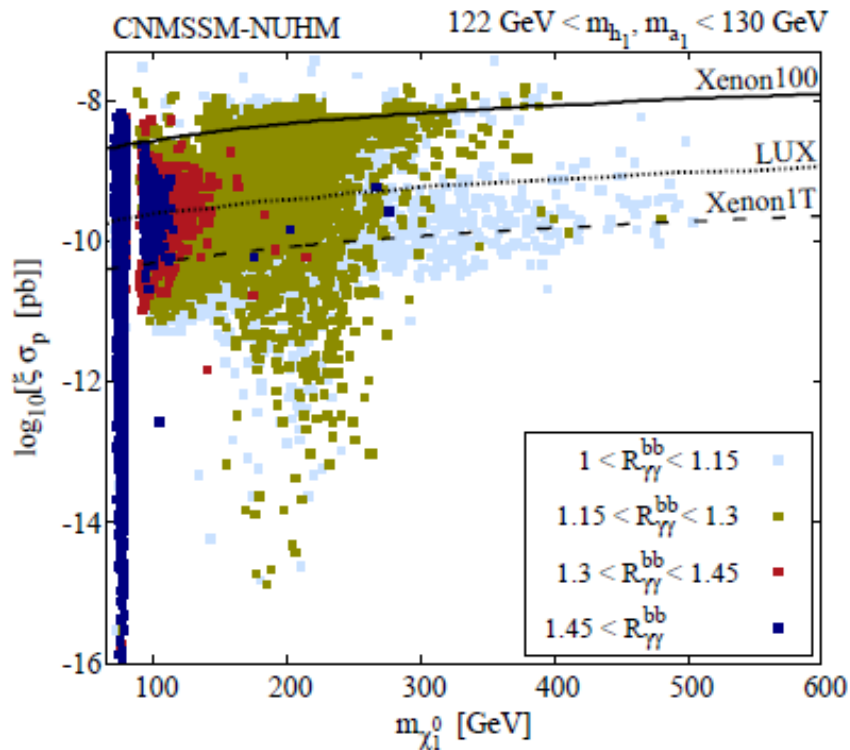
$$R_{\gamma\gamma}^Y(\text{obs}) = R_{\gamma\gamma}^Y(h_1) + R_{\gamma\gamma}^Y(a_1) \simeq 1 + R_{\gamma\gamma}^Y(a_1);$$

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

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

# 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

$$\lambda \equiv |\lambda|e^{i\varphi_\lambda} \text{ and } \kappa \equiv |\kappa|e^{i\varphi_\kappa} \quad \longrightarrow \quad M_0^2 = \begin{pmatrix} M_S^2 & M_{SP}^2 \\ (M_{SP}^2)^T & M_P^2 \end{pmatrix}$$

- Diagonalization of  $\mathcal{M}_0 \rightarrow$  Higgs couplings contain  $O_{ai}$

$$(H_1, H_2, H_3, H_4, H_5, H_6)_a^T = O_{ai} (H_{dR}, H_{uR}, S_R, H_{dL}, H_{uL}, S_L)_i^T$$

- Beyond the Born approximation, phases induced by

$$\widetilde{\mathcal{M}}_t^2 = \begin{pmatrix} M_{\tilde{Q}_3}^2 + m_t^2 + \cos 2\beta M_Z^2 \left(\frac{1}{2} - \frac{2}{3}s_W^2\right) & h_t^* v_u (|A_t| e^{-i(\theta+\phi_{A_t})} - \frac{|\lambda|v_S}{\sqrt{2}} e^{i\phi'_\lambda \cot \beta}) / \sqrt{2} \\ h_t v_u (|A_t| e^{i(\theta+\phi_{A_t})} - \frac{|\lambda|v_S}{\sqrt{2}} e^{-i\phi'_\lambda \cot \beta}) / \sqrt{2} & M_{\tilde{U}_3}^2 + m_t^2 + \cos 2\beta M_Z^2 Q_t s_W^2 \end{pmatrix}$$

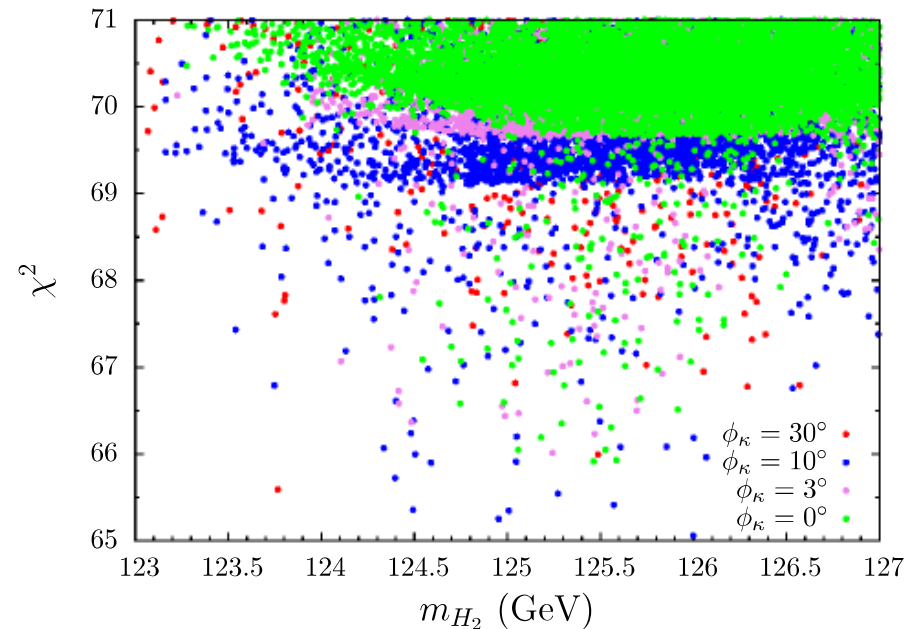
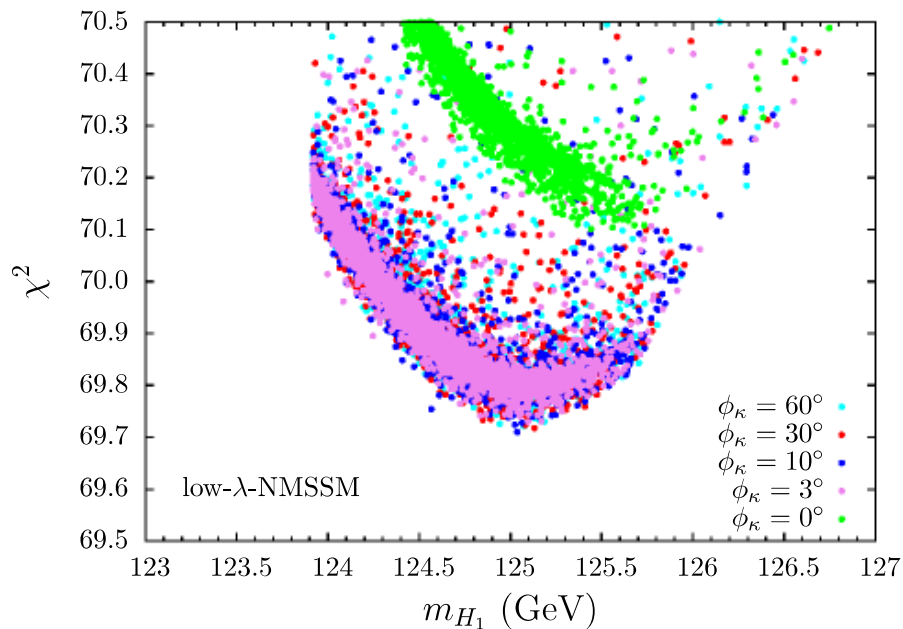
$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -m_Z \cos \beta s_W & m_Z \sin \beta s_W & 0 \\ M_2 & m_Z \cos \beta c_W & -m_Z \sin \beta c_W & 0 & 0 \\ 0 & -\frac{|\lambda|v_S}{\sqrt{2}} e^{i\phi'_\lambda} & -\frac{|\lambda|v_S \beta}{\sqrt{2}} e^{i\phi'_\lambda} & 0 & -\frac{|\lambda|v \cos \beta}{\sqrt{2}} e^{i\phi'_\lambda} \\ 0 & 0 & -\frac{|\lambda|v \cos \beta}{\sqrt{2}} e^{i\phi'_\lambda} & \sqrt{2}|\kappa|v_S e^{i\phi'_\kappa} & 0 \end{pmatrix} \quad \mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2}M_W \cos \beta \\ \sqrt{2}M_W \sin \beta & \frac{|\lambda|v_S}{\sqrt{2}} e^{i\phi'_\lambda} \end{pmatrix}$$

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



[S. Moretti, SM, 1505.00545]

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  $\sim \left| \begin{array}{c} g \text{ } \overbrace{\text{ } }^{\text{ } } \\ q, \tilde{q} \\ g \text{ } \underbrace{\text{ } }^{\text{ } } \end{array} \rightarrow H_1 \right|^2 \times \frac{\left| \begin{array}{c} \text{ } \xrightarrow{H_1} \text{ } \\ f, \tilde{f}, W^\pm, H^\pm \\ \text{ } \end{array} \right|^2}{\text{Total width}}$

Finite width effects:  $\left| \begin{array}{c} g \text{ } \overbrace{\text{ } }^{\text{ } } \\ q, \tilde{q} \\ g \text{ } \underbrace{\text{ } }^{\text{ } } \end{array} \rightarrow H_i \text{ } \text{All} \text{ } H_j \rightarrow \begin{array}{c} \text{ } \xrightarrow{H_j} \text{ } \\ f, \tilde{f}, W^\pm, H^\pm \\ \text{ } \end{array} \right|^2$

$\text{ } \text{ } \text{ } \sim D(\hat{s}) = \hat{s} \begin{pmatrix} \hat{s} - M_{H_1}^2 + i\Im m\hat{\Pi}_{11}(\hat{s}) & i\Im m\hat{\Pi}_{12}(\hat{s}) & i\Im m\hat{\Pi}_{13}(\hat{s}) \\ i\Im m\hat{\Pi}_{21}(\hat{s}) & \hat{s} - M_{H_2}^2 + i\Im m\hat{\Pi}_{22}(\hat{s}) & i\Im m\hat{\Pi}_{23}(\hat{s}) \\ i\Im m\hat{\Pi}_{31}(\hat{s}) & i\Im m\hat{\Pi}_{32}(\hat{s}) & \hat{s} - M_{H_3}^2 + i\Im m\hat{\Pi}_{33}(\hat{s}) \end{pmatrix}^{-1}$

With, e.g.,

$$\Im m\hat{\Pi}_{ij}^{\tilde{f}\tilde{f}}(s) = \frac{v^2}{16\pi} \sum_{f=b,t,\tau} \sum_{k,l=1,2} N_C^f g_{H_i \tilde{f}_k^* \tilde{f}_l} g_{H_j \tilde{f}_k^* \tilde{f}_l}^* \lambda^{1/2}(1, \kappa_{\tilde{f}_k}, \kappa_{\tilde{f}_l}) \Theta(s - (M_{\tilde{f}_k} + M_{\tilde{f}_l})^2)$$

[J. Ellis, J. S. Lee, A. Pilaftsis, hep-ph/0404167]

# $VV$ production with two-Higgs propagator

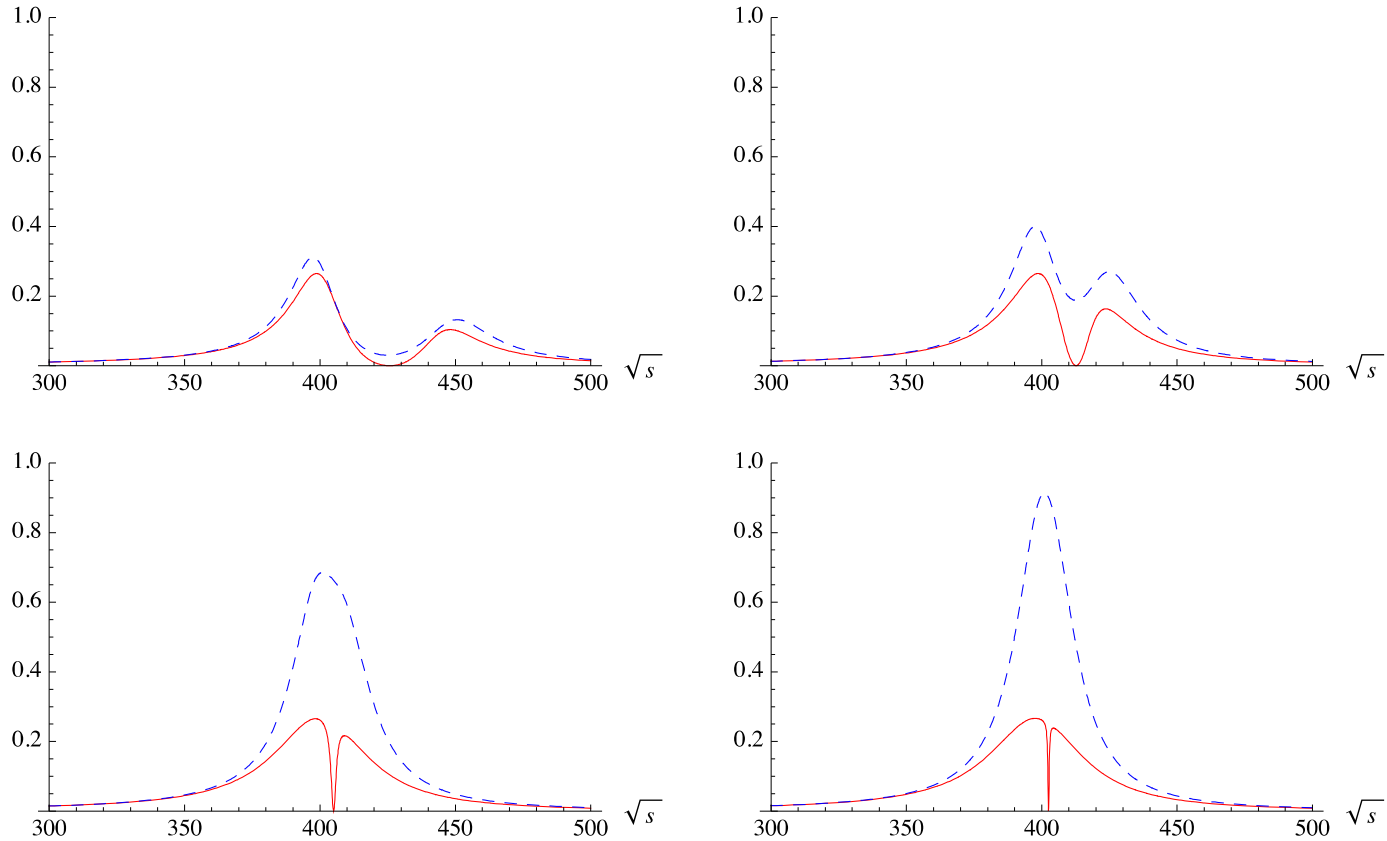


Figure 1: Plots of the production cross section (in arbitrary units) of two nearby Higgses decaying into gauge boson pairs for the naive Breit-Wigner (blue-dashed) and exact mixing (red-solid). The mass of the first resonance is fixed to 400 GeV, the splitting respectively 50, 25, 10 and 5 GeV and  $\alpha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

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

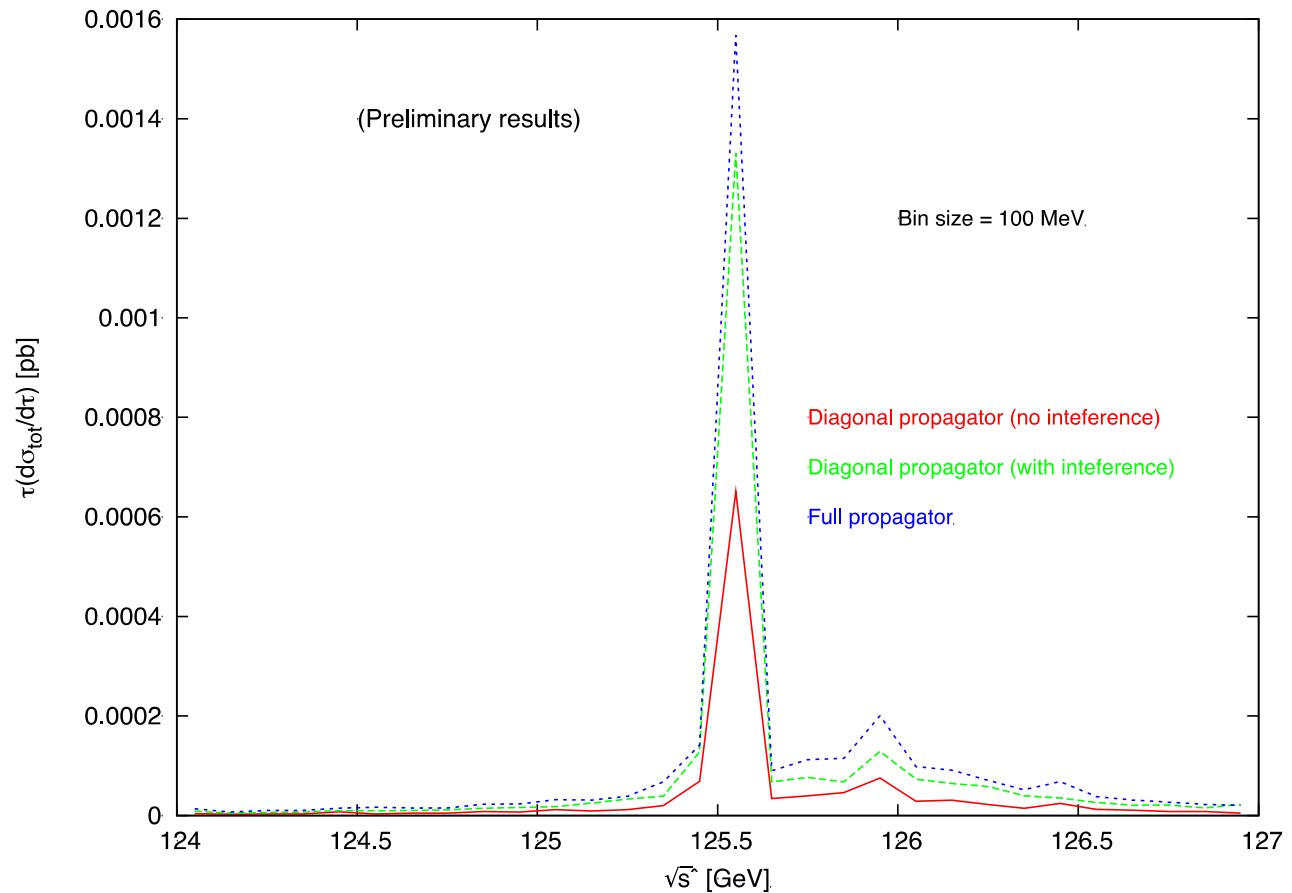
# Sample cNMSSM point

$$gg \rightarrow X \rightarrow \gamma\gamma$$

- $M_{H1} = 125.55$  GeV
- $M_{H2} = 125.9$  GeV
- $\Gamma_{H1} = 0.0042$  GeV
- $\Gamma_{H2} = 0.4496$  GeV

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

[J. Baglio *et al*, 1312.4788]



two BWs  $\rightarrow$  0.84 fb

Total  $\sigma$ : with interference: 1.64 fb

full propagator: 1.99 fb

[B. Das, S. Moretti, SM, P. Poulose, 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!