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

Shoaib Munir*
(*KIAS, Seoul*)

HPNP 2017, Toyama
March 02, 2017

**in collaboration with* B. Das, S. Moretti and P. Poulose, ArXiv:1703.xxxxx

Coupled system of two ~125 GeV Higgs bosons in the (complex) NMSSM

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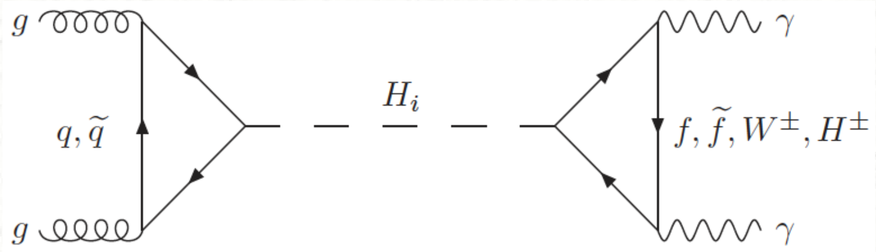
Outline

- 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

$gg \rightarrow H \rightarrow \gamma\gamma$ at the LHC



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

Applying the narrow width approximation,

$$|D_{ii}(\hat{s})|^2 = \left| \frac{1}{\hat{s} - m^2_{H_i} + i m_{H_i}\Gamma_{H_i}} \right|^2 \rightarrow \frac{\pi}{m_{H_i}\Gamma_{H_i}} \delta(\hat{s} - m^2_{H_i})$$

[E. Fuchs, S. Thewes ,G. Weiglein 0411.4652]

simplifies the expression for the partonic cross section

$$\hat{\sigma}(gg \rightarrow H \rightarrow \gamma\gamma) = \frac{1}{1024\pi\hat{s}} \sum_{i=1-5} \left(\sum_{\lambda=\pm} |\mathcal{M}_{P_i\lambda}|^2 \times \frac{\pi}{m_{H_i}\Gamma_{H_i}} \delta(\hat{s} - m^2_{H_i}) \times \sum_{\sigma=\pm} |\mathcal{M}_{D_i\sigma}|^2 \right)$$

$M\gamma\gamma = 125$ GeV

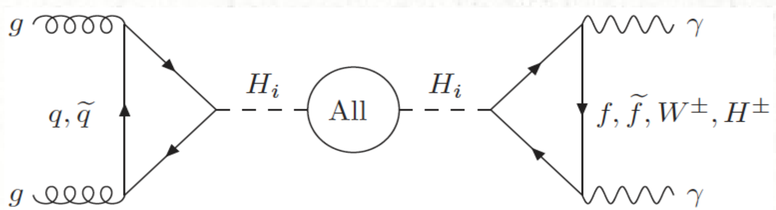
Two (or more) Higgs bosons near 125 GeV can undergo quantum interference due to loop effects, e.g.,

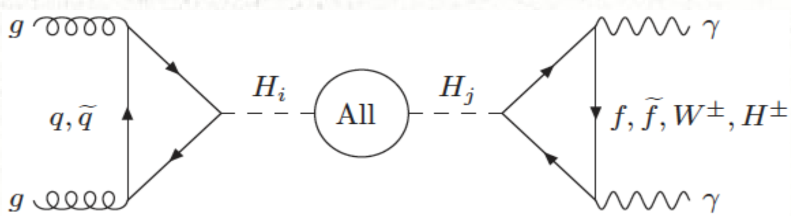
$$\Im\mathrm{m}\widehat{\Pi}^{HH}_{ij}(s) = \frac{v^2}{16\pi} \sum_{k\geq l=1,2,3} \frac{S_{ij;kl}}{1+\delta_{kl}} g_{H_iH_kH_l} g_{H_jH_kH_l} \lambda^{1/2}(1, \kappa_{H_k}, \kappa_{H_l})\, \Theta\left(s - (M_{H_k}+M_{H_l})^2\right)$$

[J. Ellis, J. S. Lee, A. Pilaftsis, 0404167]

The full propagator matrix needs to be taken into account

$$D(\hat{s}) = \hat{s} \begin{pmatrix} \hat{s} - M^2_{H_1} + i\Im\mathrm{m}\widehat{\Pi}_{11}(\hat{s}) & & \\ & \hat{s} - M^2_{H_2} + i\Im\mathrm{m}\widehat{\Pi}_{22}(\hat{s}) & \\ & & \hat{s} - M^2_{H_3} + i\Im\mathrm{m}\widehat{\Pi}_{33}(\hat{s}) \end{pmatrix}^{-1}$$





$$\frac{d\sigma^{\gamma\gamma}_{pp}}{d\sqrt{\hat{s}}} = \int_\tau^1 \frac{2\sqrt{\hat{s}}}{s} \frac{dx_1}{x_1} \frac{g(x_1)g(\hat{s}/sx_1)}{1024\pi\hat{s}^3} \sum_{i,j=1-5} \left\{ \sum_{\lambda=\pm} |\mathcal{M}_{P_i\lambda}|^2 \, |D_{ij}(\hat{s})|^2 \sum_{\sigma=\pm} |\mathcal{M}_{D_j\sigma}|^2 \right\}$$

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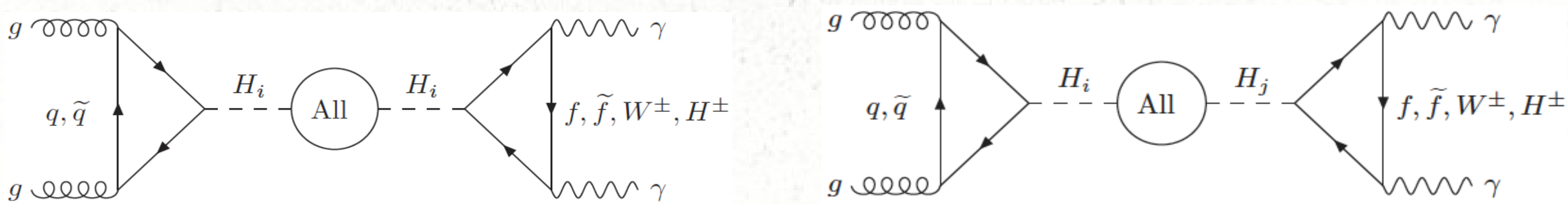

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Coupled system of Higgs bosons

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

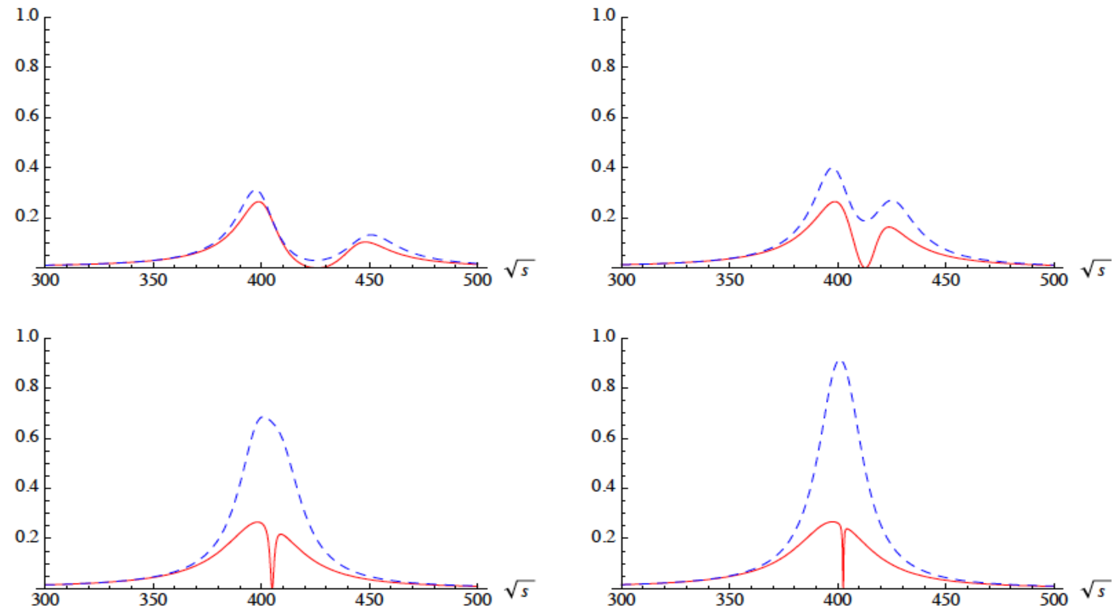


Figure 1: Plots of the production cross section (in arbitrary units) of two nearby Higgses decaying into gauge boson pairs for the naive Breit-Wigner (blue-dashed) and exact mixing (red-solid). The mass of the first resonance is fixed to 400 GeV, the splitting respectively 50, 25, 10 and 5 GeV and $\alpha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

But two ~125 GeV neutral Higgs bosons difficult in

- MSSM: SM-like *h* ⟶ other Higgs bosons heavy
- 2HDMs: Strong electroweak precision constraints

The Next-to-Minimal Supersymmetric SM

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

$$W_{\rm NMSSM} = h_u \,\widehat{Q} \cdot \widehat{H}_u \,\widehat{U}_R^c \,+\, h_d \,\widehat{H}_d \cdot \widehat{Q} \,\widehat{D}_R^c \,+\, h_e \,\widehat{H}_d \cdot \widehat{L} \,\widehat{E}_R^c \,+\, \lambda \widehat{S} \widehat{H}_u \cdot \widehat{H}_d \,+\, \frac{\kappa}{3}\,\widehat{S}^3$$

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

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

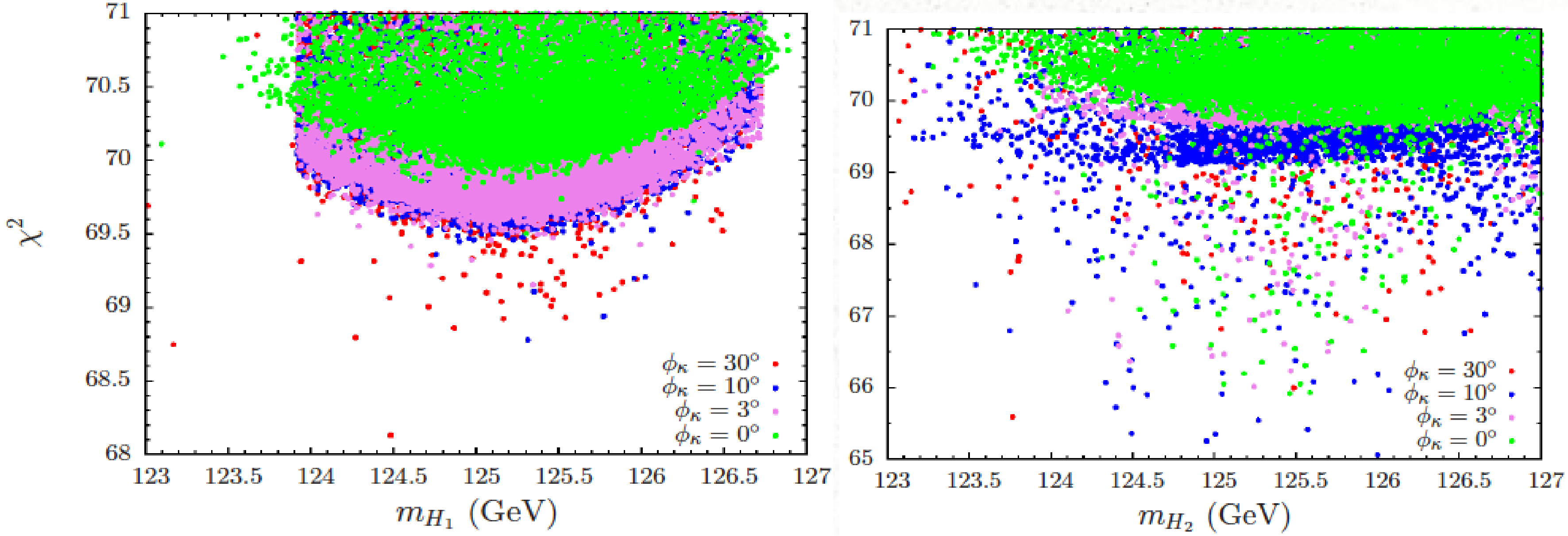
- The singlet-like pseudoscalar can be near 125 GeV also

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

Fit to the 7-8 TeV LHC data

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

Total number of observables: 81



[S. Moretti, SM, 1505.00545]

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

$$\mathcal{M}_0^2 = \left(\begin{array}{c|c} \mathcal{M}_S^2 & \\ \hline & \mathcal{M}_P^2 \end{array}\right)$$

$$\downarrow$$

$$D_H(\hat{s}) = \hat{s}\begin{pmatrix} \mathrm{m}_{11} & i\mathfrak{Im}\hat{\Pi}_{12}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{13}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{14}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{15}(\hat{s}) \\ i\mathfrak{Im}\hat{\Pi}_{21}(\hat{s}) & \mathrm{m}_{22} & i\mathfrak{Im}\hat{\Pi}_{23}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{24}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{25}(\hat{s}) \\ i\mathfrak{Im}\hat{\Pi}_{31}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{32}(\hat{s}) & \mathrm{m}_{33} & i\mathfrak{Im}\hat{\Pi}_{34}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{35}(\hat{s}) \\ i\mathfrak{Im}\hat{\Pi}_{41}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{42}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{43}(\hat{s}) & \mathrm{m}_{44} & i\mathfrak{Im}\hat{\Pi}_{45}(\hat{s}) \\ i\mathfrak{Im}\hat{\Pi}_{51}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{52}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{53}(\hat{s}) & i\mathfrak{Im}\hat{\Pi}_{54}(\hat{s}) & \mathrm{m}_{55} \end{pmatrix}^{-1}$$

Higgs propagator matrix in the NMSSM

5x5 Higgs mass matrix after isolating the Goldstone boson

$$\mathcal{M}_0^2 = \left(\begin{array}{c|c} \mathcal{M}_S^2 & \mathcal{M}_{SP}^2 \\ \hline (\mathcal{M}_{SP}^2)^T & \mathcal{M}_P^2 \end{array} \right)$$

Non-zero complex phases

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

Parameter space scans

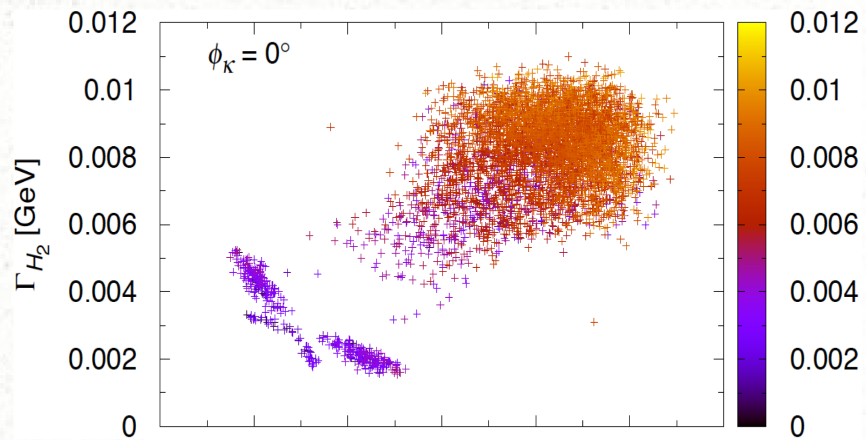
$$M_0 \equiv M_{Q_{1,2,3}} = M_{U_{1,2,3}} = M_{D_{1,2,3}} = M_{L_{1,2,3}} = M_{E_{1,2,3}}\,,$$

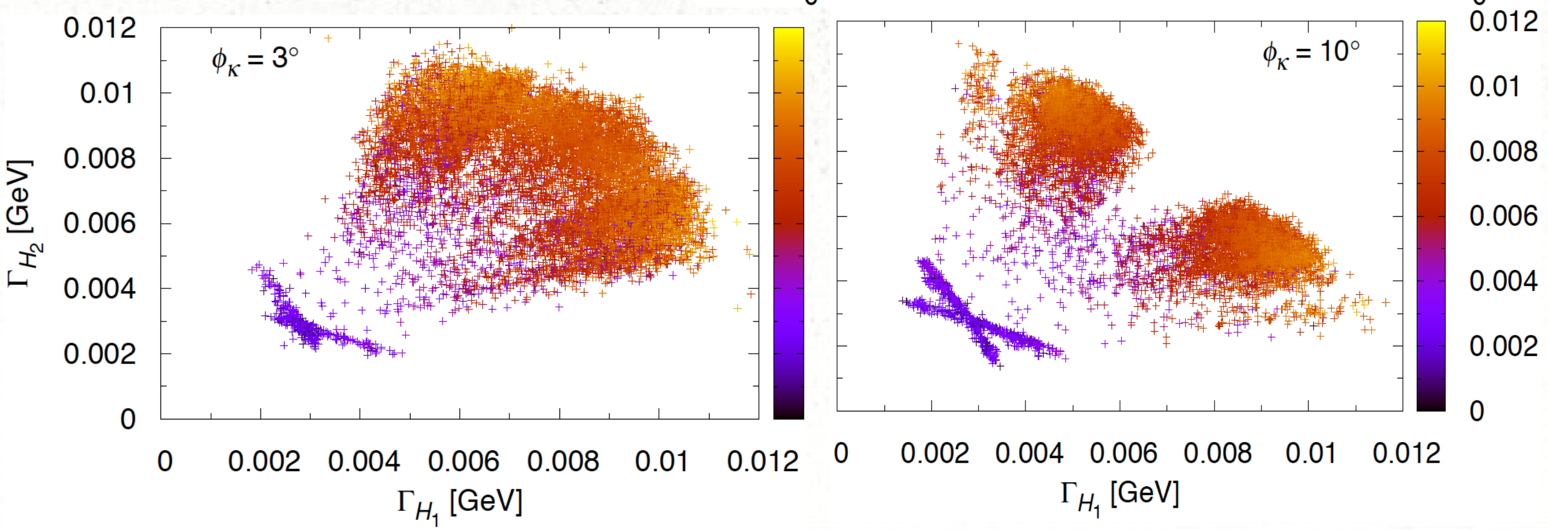
$$M_{1/2} \equiv 2M_1 = M_2\,,$$

$$A_0 \equiv A_{\tilde{t}} = A_{\tilde{b}} = A_{\tilde{\tau}}$$

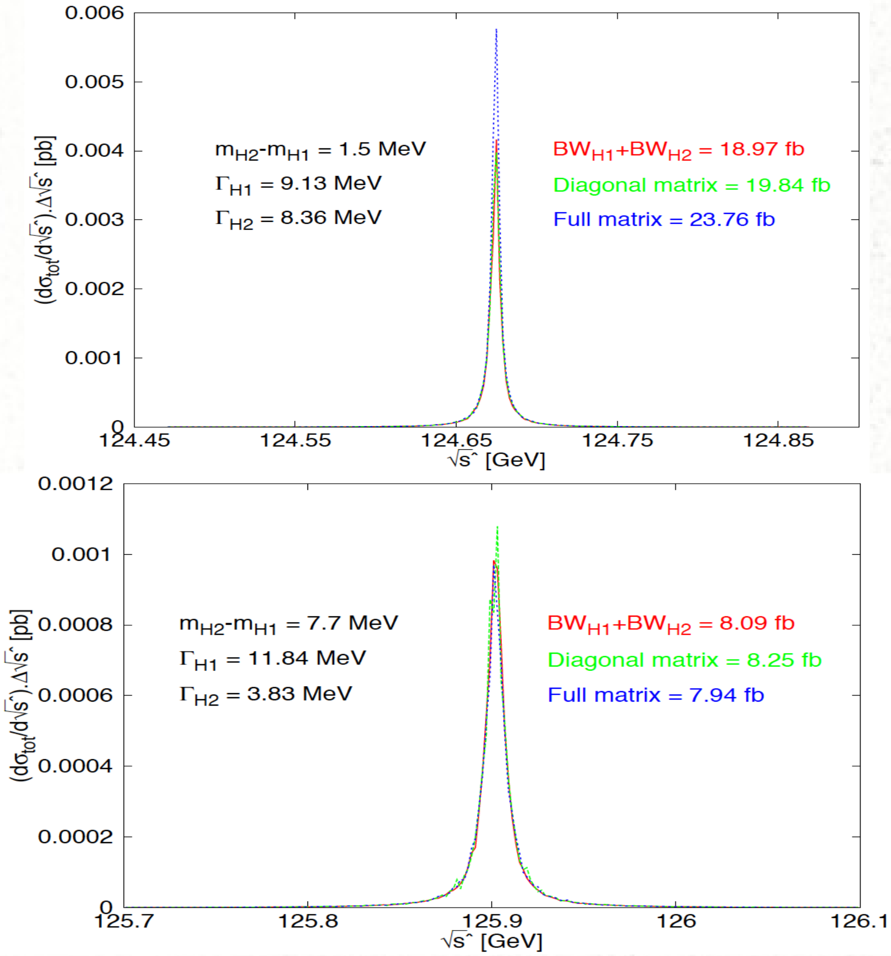
Parameter	Scanned range
M_0 (GeV)	800 – 2000
$M_{1/2}$ (GeV)	100 – 500
A_0 (GeV)	−3000 – 0
$\tan\beta$	2 – 8
$\lvert\lambda\rvert$	0.58 – 0.7
$\lvert\kappa\rvert$	0.3 – 0.6
$\mu_{\rm eff}$ (GeV)	100 – 200
$\lvert A_\lambda\rvert$ (GeV)	200 – 1000
$\lvert A_\kappa\rvert$ (GeV)	−300 – 0

$$\Delta m_{H_2-H_1} < \Gamma_{H_1} \text{ and/or } \Gamma_{H_2}$$





Interference effects

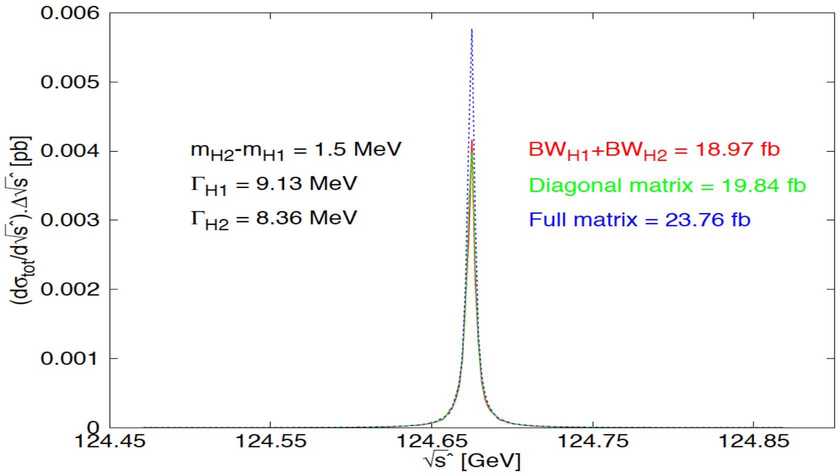


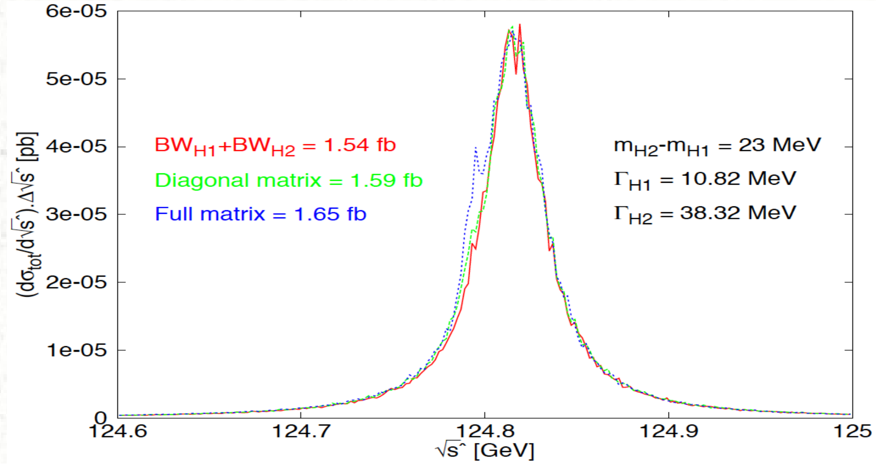
$\Gamma_{h_{SM}} < 13$ MeV

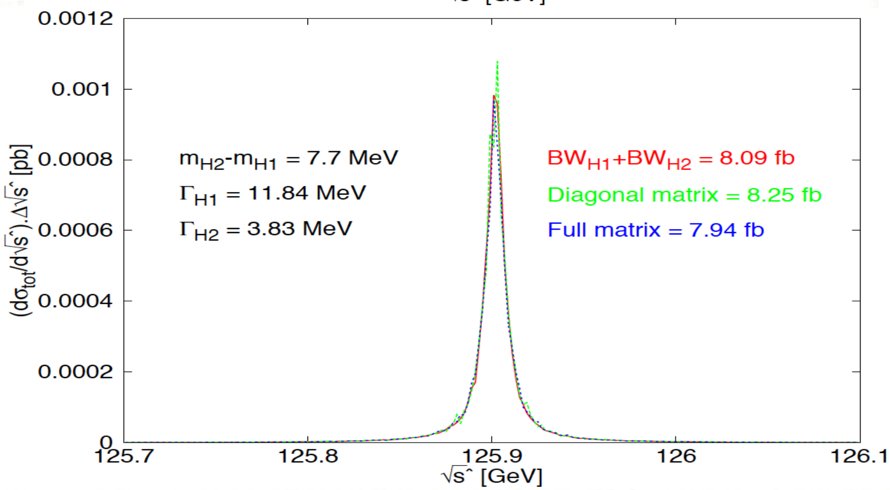
[CMS Collaboration,1605.02329]

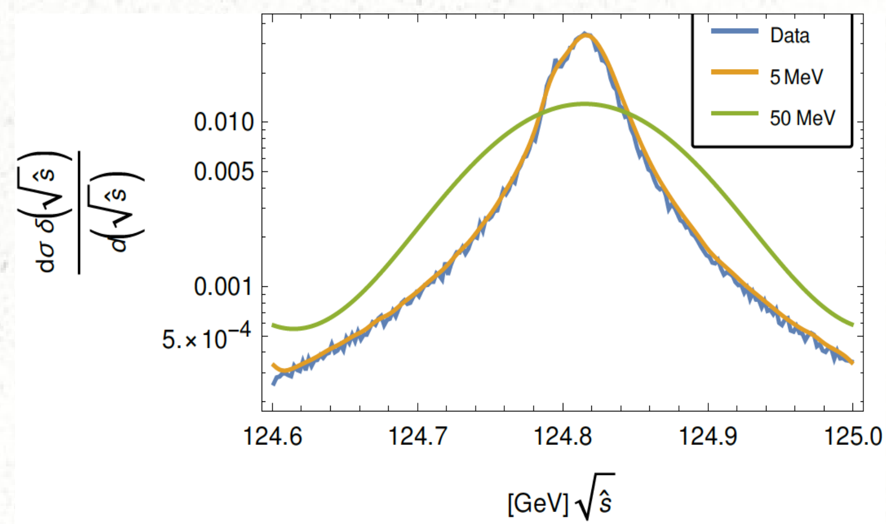
[B. Das, S. Moretti, SM, P. Poulose, 1703.xxxxx]

Interference effects









$\Gamma_{h_{SM}} < 13$ MeV

[CMS Collaboration,1605.02329]

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