ICTP—East African Institute
for Fundamental Research

Mass-degeneracies in extended Higgs sectors

Shoaib Munir
EAIFR, Kigali

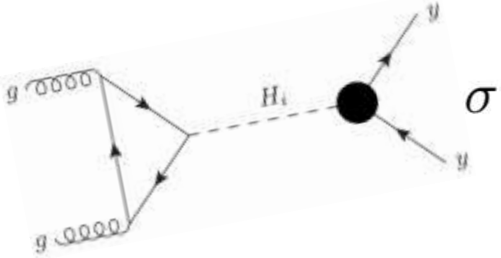
partner
institute

BSM-2021, Cyberspace
April 01, 2021

United Nations
Educational, Scientific and
Cultural Organization

The gluon-fusion process

Consider the production of a yy pair in the gluon-fusion process via a single Higgs boson at the LHC



$$\sigma(pp \to yy) = \int_0^1 d\tau \int_\tau^1 \frac{dx_1}{x_1} \frac{g(x_1)g(\tau/x_1)}{1024\pi\hat{s}^3} \left|\mathcal{A}_{gg\to H\to yy}\right|^2$$

$$\hat{s} = x_1 x_2 s \implies \tau \equiv \frac{s}{s} = x_1 x_2$$

The amplitude for the process is defined as

$$\mathcal{A} = \mathcal{M}_P \frac{1}{\hat{s} - M_H^2 + i\Im\mathrm{m}\hat{\Pi}_H(\hat{s})} \mathcal{M}_{D^{yy}}$$

Using the narrow-width approximation,

$$\left|\frac{1}{\hat{s} - M_H^2 + iM_H\Gamma_H}\right|^2 \to \frac{\pi}{M_H\Gamma_H}\delta(\hat{s} - M_H^2)$$

the cross-section expression can be factorised as

$$\sigma(pp \to yy) \implies \sigma(pp \to H) \times \mathrm{BR}(H \to yy)$$

Two (or more) Higgs bosons

If, instead, two Higgs bosons contribute to the production, the complete propagator matrix

$$\mathcal{D}(\hat{s}) = \hat{s}\begin{pmatrix} \hat{s} - m^2_{H_1} + i\Im\mathrm{m}\hat{\Pi}_{11}(\hat{s}) & i\Im\mathrm{m}\hat{\Pi}_{12}(\hat{s}) \\ i\Im\mathrm{m}\hat{\Pi}_{21}(\hat{s}) & \hat{s} - m^2_{H_2} + i\Im\mathrm{m}\hat{\Pi}_{22}(\hat{s}) \end{pmatrix}^{-1}$$

with generalised self-energies given, e.g., as

$$\Im\mathrm{m}\hat{\Pi}^{H_2}_{ij}(s) = \frac{v^2}{16\pi}\frac{S_{ij}}{2} g_{H_iH_2H_2} g_{H_jH_2H_2} \sqrt{1 - 4\frac{m^2_{H_2}}{\hat{s}}}\;\Theta\left(s - 4m^2_{H_2}\right)$$

should appear in the amplitude, which becomes

$$\mathcal{A} = \sum_{i,j=1,2} \mathcal{M}_{P_i}\mathcal{D}_{ij}(\hat{s})\mathcal{M}_{D^{yy}_j}$$

'Interference' can be sizeable if the magnitude of the off-diagonal terms is comparable to the mass-splitting (indicator: $\Gamma_1 + \Gamma_2 \sim \Delta m_{12}$)

The Next-to-MSSM

Add a singlet superfield to address the `μ-problem' of the Minimal Supersymmetric Standard Model:

$$W_{\rm NMSSM} = \widehat{U}^C \mathbf{h}_u \widehat{Q}\widehat{H}_u + \widehat{D}^C \mathbf{h}_d \widehat{H}_d \widehat{Q} + \widehat{E}^C \mathbf{h}_e \widehat{H}_d \widehat{L} + \cancel{\mu \widehat{H}_u \widehat{H}_d} + \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

Z_3-invariant

$$\boxed{\textbf{EWSB} \Rightarrow \mu_{\rm eff} \equiv \lambda\langle\widehat{S}\rangle = \lambda v_s}$$

$$H_d^0 = \begin{pmatrix} v_d + H_{dR} + iH_{dI} \\ H_d^- \end{pmatrix}, \quad H_u^0 = \begin{pmatrix} H_u^+ \\ v_u + H_{uR} + iH_{uI} \end{pmatrix}, \quad S = v_S + S_R + iS_I$$

- 5 neutral Higgs bosons:

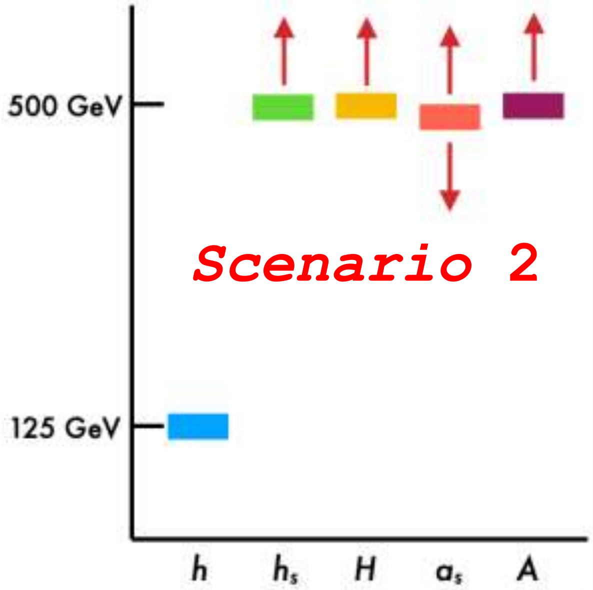
h, h_s, H, a_s, and A

$\tan\beta \equiv v_u/v_d$

λ~0.5, tanβ~2 lead to large singlet-doublet mixing

$$\Rightarrow \boxed{M_{h,h_s} \simeq 125\,\text{GeV}}$$

Scenario 1



Scenario 2

Scenario 1 - $m_h \approx m_{h_s} \approx 125$ GeV

Define for cross section computations:

Case 1: $$\left|\mathcal{A}_{gg\to\gamma\gamma}\right|^2 = \sum_{i=1-3}\left|\mathcal{M}_{P_i\lambda}\frac{1}{\hat{s}-M_{H_i}^2+i\Im\mathrm{m}\hat{\Pi}_{H_i}(\hat{s})}\mathcal{M}_{D_i^{\gamma\gamma}}\right|^2$$

Case 2: $$\left|\mathcal{A}_{gg\to\gamma\gamma}\right|^2 = \left|\sum_{i=1-3}\mathcal{M}_{P_i\lambda}\mathcal{D}_{ii}(\hat{s})\mathcal{M}_{D_i^{\gamma\gamma}}\right|^2$$

Case 3: $$\left|\mathcal{A}_{gg\to\gamma\gamma}\right|^2 = \left|\sum_{i,j=1-3}\mathcal{M}_{P_i\lambda}\mathcal{D}_{ij}(\hat{s})\mathcal{M}_{D_j^{\gamma\gamma}}\right|^2$$

Relevant constraints: [B. Das, P. Poulose, S. Moretti, SM, 1704.02941]

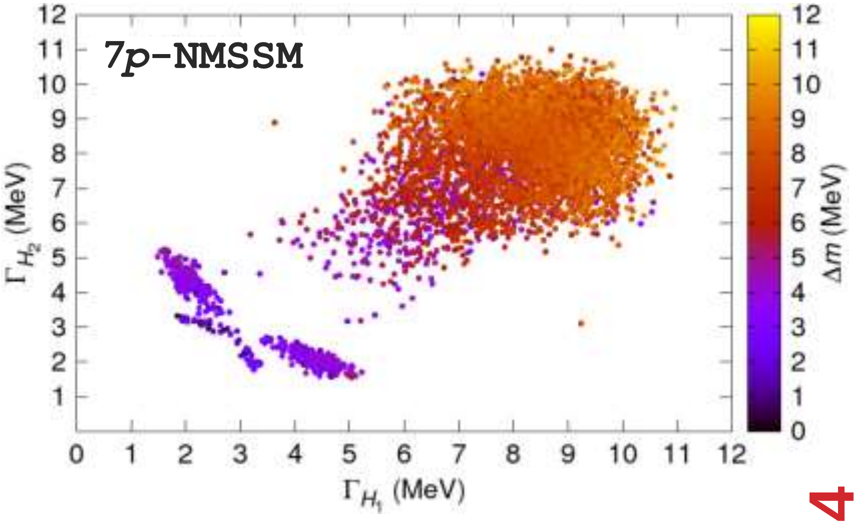
$\Gamma_{125} < 41$ MeV from fits to the LHC signal rate measurements

[CMS-PAS-Higgs-16-033]

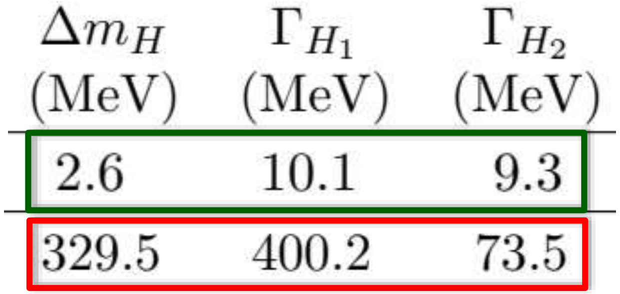
Measurements of the fiducial cross section for $H_{125} \longrightarrow \gamma\gamma$:

$43.2 \pm 14.9 \pm 4.9$ fb [CMS-PAS-Higgs-16-020]

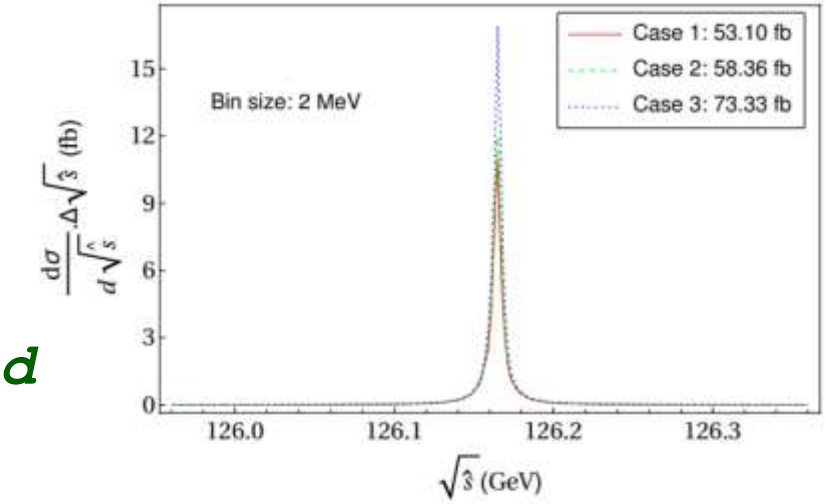
69^{+18}_{-22} fb [ATLAS-CONF-2016-067]



Benchmark points

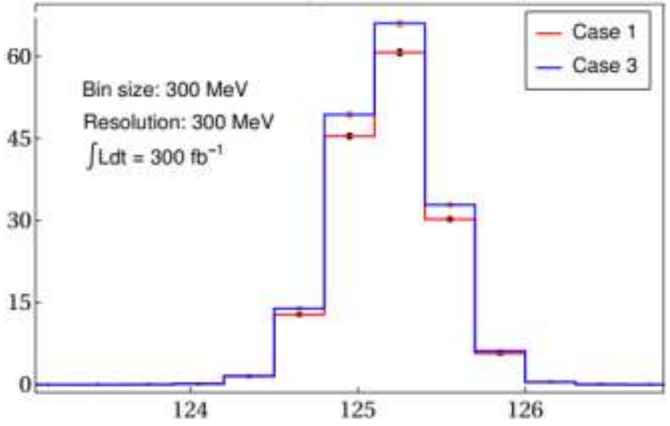


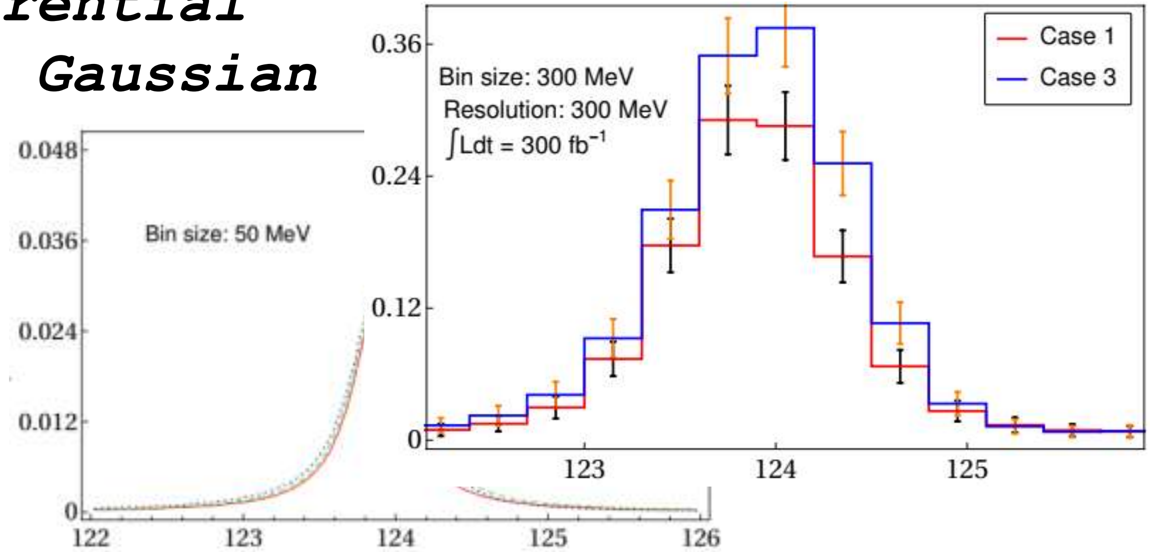
Δm_H (MeV)	Γ_{H_1} (MeV)	Γ_{H_2} (MeV)
2.6	10.1	9.3
329.5	400.2	73.5



(NNLO) Cross section enhanced by ~40% for $\Gamma_1 + \Gamma_2 >> \Delta m_{12}$

Convolute the differential distribution with a Gaussian

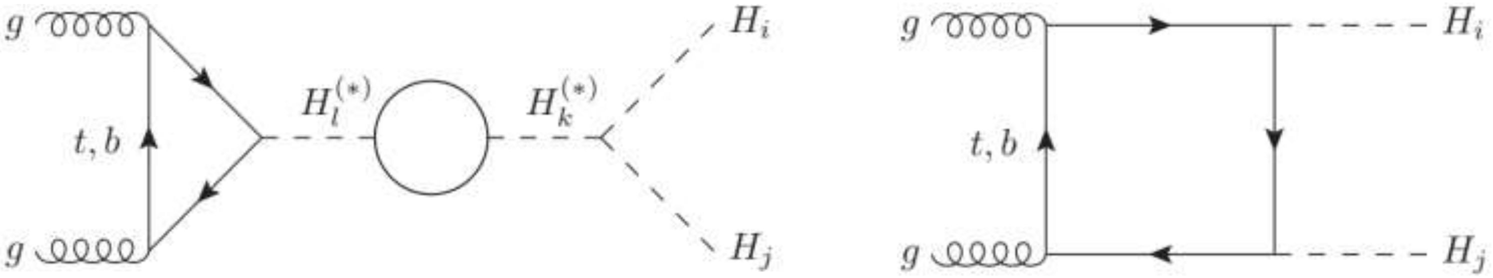




Distribution shapes mutually distinguishable only for $\Gamma_{125} >> 41$ MeV

Scenario 2 - $m_H \approx m_{h_s} >> 125$ GeV

Two main contributions at the leading order,



with amplitude-squared of the process given as

$$\left|\mathcal{A}_{gg\to H_iH_j}\right|^2 = \left|C_\triangle F_\triangle + C_\Box F_\Box\right|^2 + \left|C_\Box G_\Box\right|^2 \qquad C_\Box = \sum_q g_{H_i\bar{q}q} g_{H_j\bar{q}q}$$

[T. Plehn, M. Spira, P. M. Zerwas, 9603205]

Define and compute:

$$\sigma_{\rm b} \sim C_\triangle^{\rm diag} \equiv \sum_{l=1}^{3} \mathcal{D}_{ll}(\hat{s}) \lambda_{H_iH_jH_l} \qquad \sigma_{\rm c} \sim C_\triangle^{\rm full} \equiv \sum_{k,l=1}^{3} \mathcal{D}_{kl}(\hat{s}) \lambda_{H_iH_jH_k}$$

Including NLO corrections (NNLO also available)

$$\Delta\sigma = \Delta\sigma_{\rm virt} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{\bar{q}q}$$

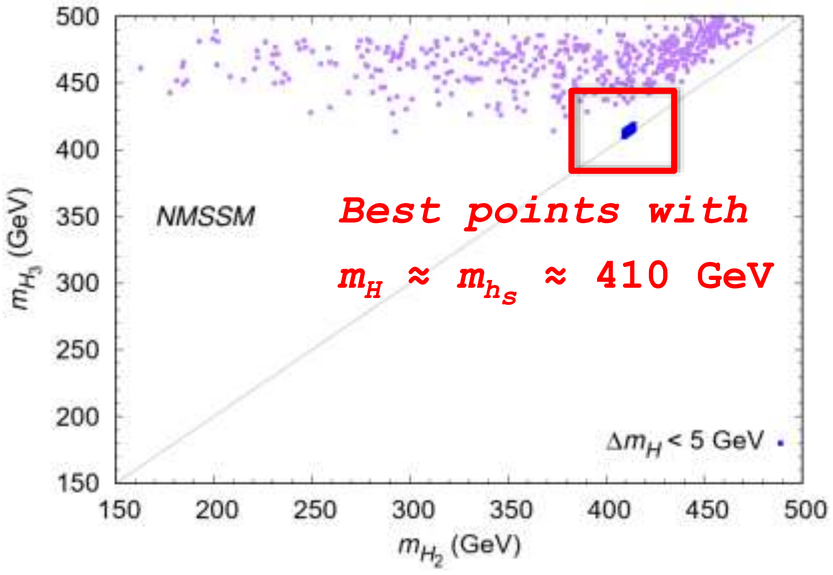
[S. Dawson, S. Dittmaier, M. Spira, 9805244]

… in the NMSSM

Squarks O(1) TeV; $\Gamma_1 + \Gamma_2 > \Delta m_{12}$ condition never satisfied

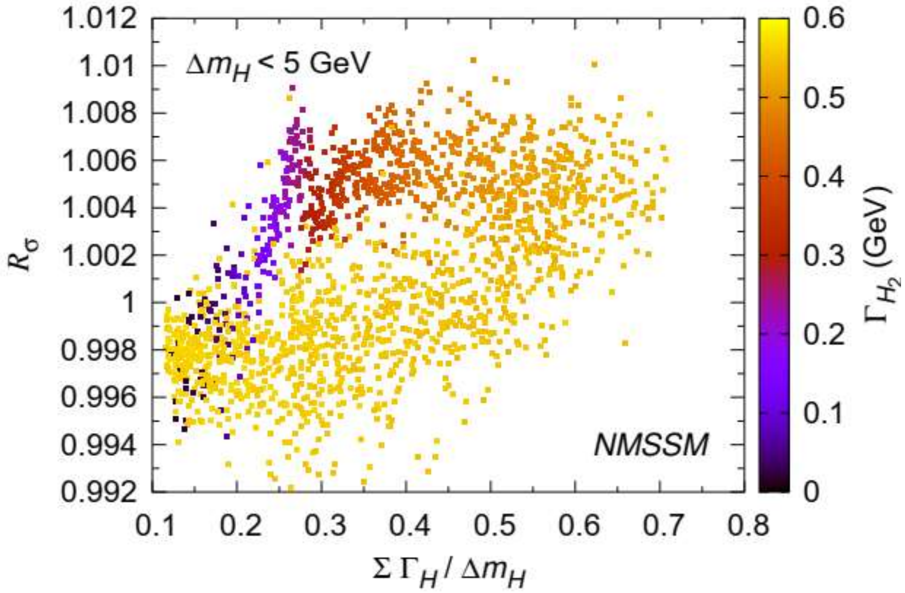
➡ *contribution to σ from off-diagonal propagator terms never exceeds ~1%*

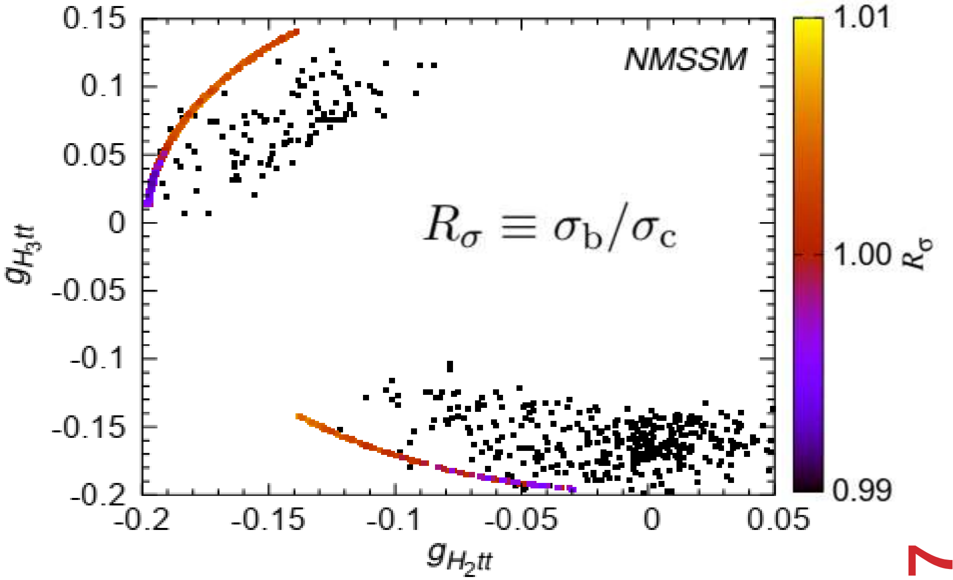
Maximal dependence on the strengths and relative signs of the two top-Yukawas



Best points with $m_H \approx m_{h_s} \approx 410$ GeV

[B. Das, P. Poulose, S. Moretti, SM, 2012.09587]





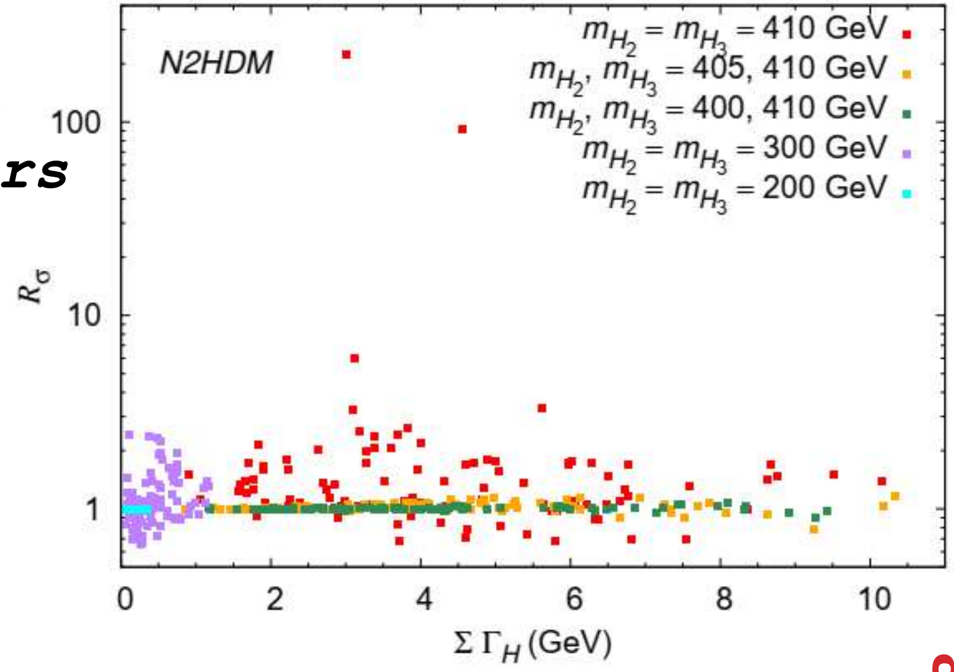
… in the Next-to-2HDM

Singlet-extension of the 2 Higgs-doublet-model

$$
\begin{aligned}
V_{\mathrm{N2HDM}} &= m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 - m_{12}^2\left(H_u^\dagger H_d + \mathrm{h.c.}\right) + \frac{\lambda_1}{2}\left(H_u^\dagger H_u\right)^2 + \frac{\lambda_2}{2}\left(H_d^\dagger H_d\right)^2 \\
&+ \lambda_3\left(H_u^\dagger H_u\right)\left(H_d^\dagger H_d\right) + \lambda_4\left(H_u^\dagger H_d\right)\left(H_d^\dagger H_u\right) + \frac{\lambda_5}{2}\left\{\left(H_u^\dagger H_d\right)^2 + \mathrm{h.c.}\right\} \\
&+ \frac{m_S^2}{2}S^2 + \frac{\lambda_6}{8}S^4 + \frac{\lambda_7}{2}\left(H_u^\dagger H_u\right)S^2 + \frac{\lambda_S}{2}\left(H_d^\dagger H_d\right)S^2,
\end{aligned}
$$

Physical masses of the 3 neutral Higgs scalars (h, h_s, H) are input parameters

- We scanned the Type-II N2HDM parameter space, fixing m_h to 125 GeV and $m_H \approx m_{h_s}$ to several different test values

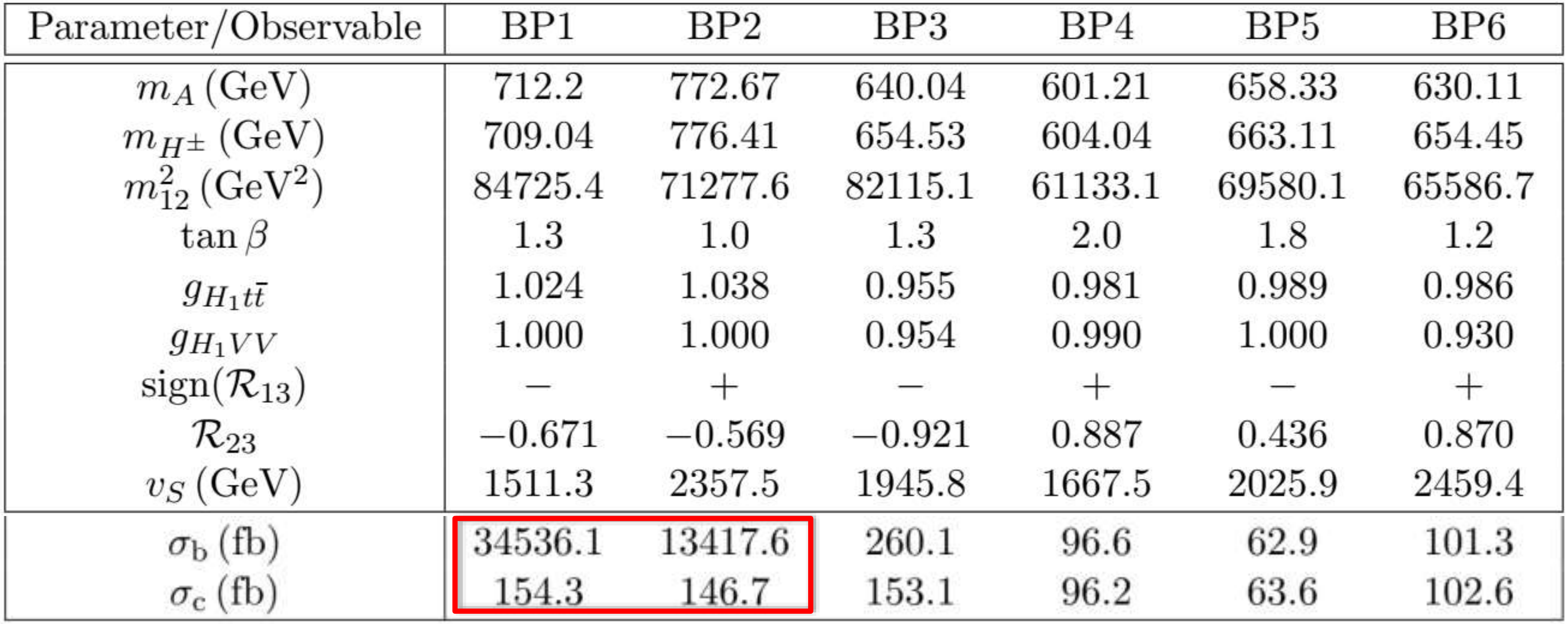


N2HDM benchmark points

We extracted six BPs from the $m_H = m_{h_s} = 410$ GeV scan

- allows direct comparison with NMSSM

- largest observed total widths, since H and h_s can decay into top-antitop pairs



Parameter/Observable	BP1	BP2	BP3	BP4	BP5	BP6
m_A (GeV)	712.2	772.67	640.04	601.21	658.33	630.11
$m_{H^\pm}$ (GeV)	709.04	776.41	654.53	604.04	663.11	654.45
m_{12}^2 (GeV^2)	84725.4	71277.6	82115.1	61133.1	69580.1	65586.7
$\tan\beta$	1.3	1.0	1.3	2.0	1.8	1.2
$g_{H_1 t\bar{t}}$	1.024	1.038	0.955	0.981	0.989	0.986
$g_{H_1 VV}$	1.000	1.000	0.954	0.990	1.000	0.930
sign($\mathcal{R}_{13}$)	$-$	$+$	$-$	$+$	$-$	$+$
$\mathcal{R}_{23}$	-0.671	-0.569	-0.921	0.887	0.436	0.870
v_S (GeV)	1511.3	2357.5	1945.8	1667.5	2025.9	2459.4
σ_b (fb)	34536.1	13417.6	260.1	96.6	62.9	101.3
σ_c (fb)	154.3	146.7	153.1	96.2	63.6	102.6

Negative interference reduces the total cross section by two orders of magnitude!

Summary and outlook

We investigated whether propagator interference effects can help disentangle two mass-degenerate Higgs bosons produced at the 14 TeV LHC

- ***In the NMSSM, strongly constrained Higgs boson widths prove to be limiting factors***
- ***In the N2HDM, the cross section for the pair production of the H_{125} can get suppressed by orders of magnitude due to these effects***

Moving forward, we plan to

- ***analyse how the Higgs propagator interference manifests itself in dark matter (co-)annihilation***
- ***develop a general formalism for exploring such effects in various sectors of BSM physics***

THANK YOU!

MURAKOZE!