H_{125} pair-production via mass-degenerate heavy scalars in the N2HDM

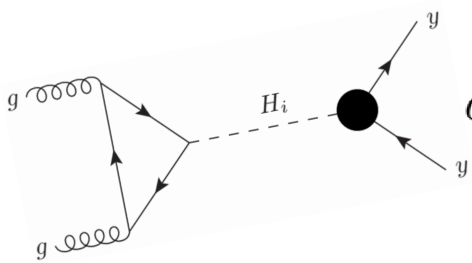
Shoaib Munir
EAIFR, Kigali

LHC WG3 Extended Scalars Meeting, *Cyberspace*

July 06, 2021

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

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

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

$$\Im\mathrm{m}\hat{\Pi}_{ij}^{H_2}(s) = \frac{v^2}{16\pi} \frac{S_{ij}}{2} g_{H_i H_2 H_2} g_{H_j H_2 H_2} \sqrt{1 - 4\frac{m_{H_2}^2}{\hat{s}}}\, \Theta\Big(s - 4m_{H_2}^2\Big)$$

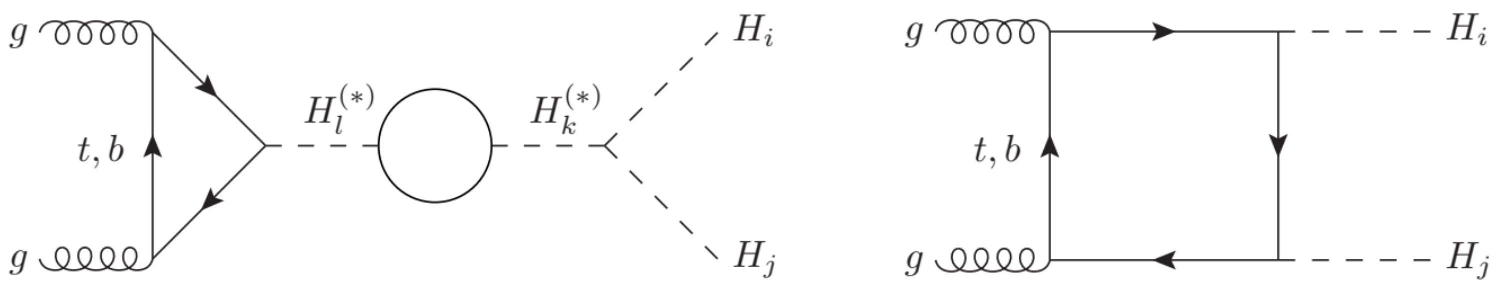
should appear in the amplitude, which becomes

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

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

Pair-production of the SM Higgs boson

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:

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

Including NLO corrections (NNLO also available)

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

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

... in the NMSSM

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

Z_3-invariant

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

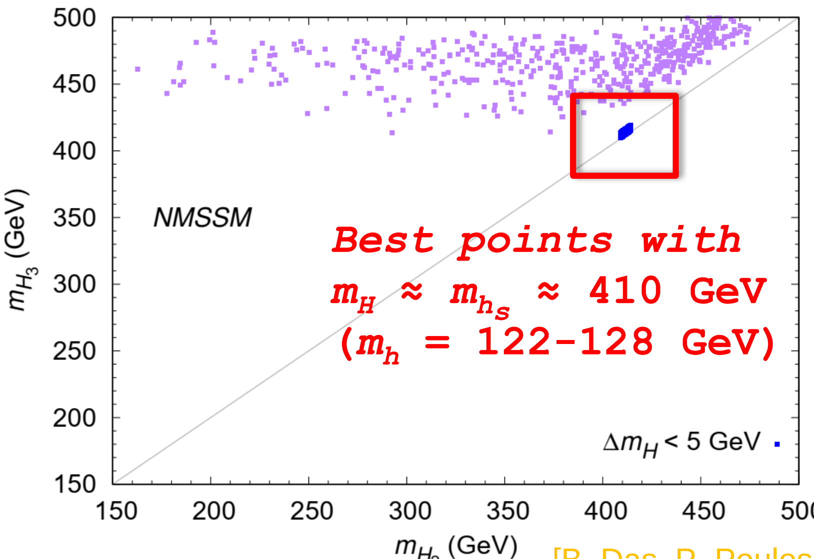
$$\boxed{\textbf{EWSB} \Rightarrow \mu_{\rm eff} \equiv \lambda \langle \widehat{S} \rangle = \lambda v_s}$$

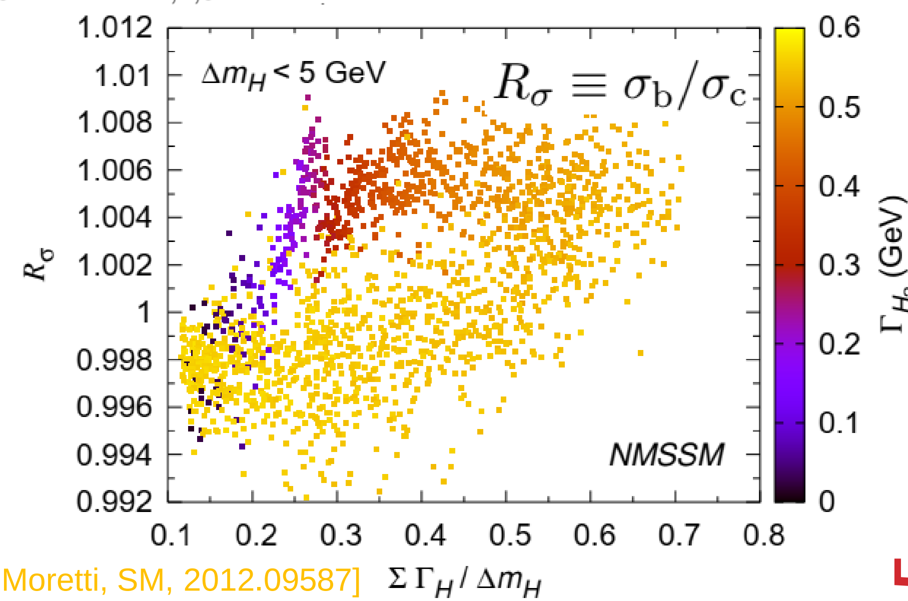
- **5 neutral Higgs bosons: h, h_s, H, a_s, A**

We scanned the NMSSM parameter space for $m_H \approx m_{h_s}$

A_0 (GeV)	$-5000 - 0$
$\mu_{\rm eff}$ (GeV)	$100 - 1000$
$\tan\beta$	$1 - 40$
λ	$0.001 - 0.7$
κ	$0.001 - 0.7$
m_P (GeV)	$100 - 1000$
m_A (GeV)	$100 - 1000$

$$M_{Q_{1,2,3}} = M_{U_{1,2,3}} = M_{D_{1,2,3}} = 3\,\text{TeV}$$





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

... and in the Next-to-2HDM

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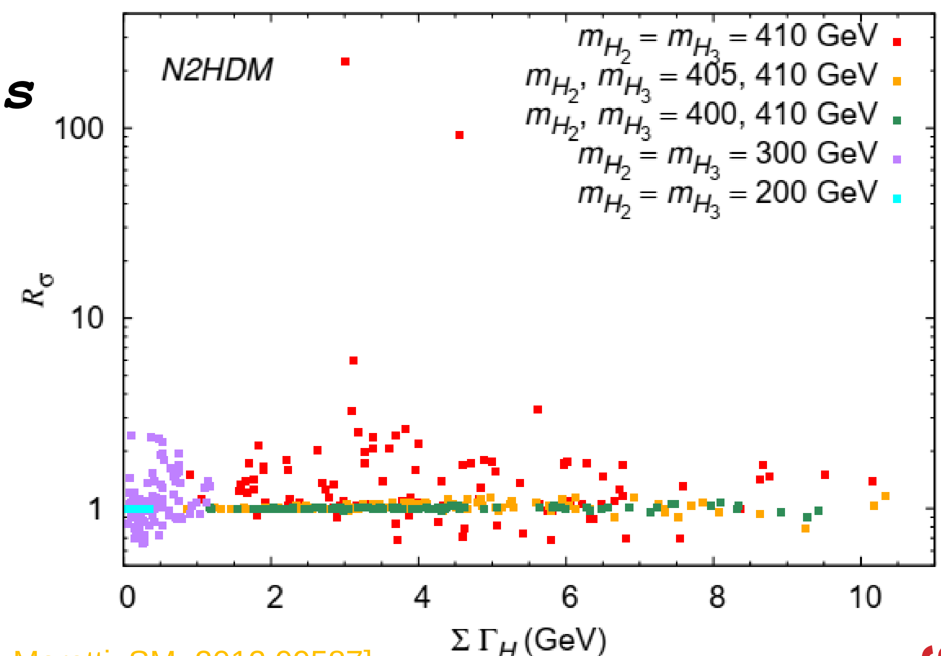
Real-singlet-extension of the 2-Higgs-doublet model

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

$$\boxed{S = v_S + S_R}$$

- Physical masses of the three neutral Higgs bosons can be 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



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

N2HDM benchmark points

We extracted six BPs from the $m_H = m_{h_s} = 410$ GeV scan
- allows direct comparison with the 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

We investigated the propagator interference effects between two heavy mass-degenerate scalars in the pair-production of the H_{125} at the 14 TeV LHC

- *In the NMSSM, strongly constrained Higgs boson widths limit these effects*
- *In the N2HDM, for some parameter configurations the propagator interference can suppress the cross section by orders of magnitude*


THANK YOU!
MURAKOZE!

Backup

$g_{H_2 t\bar{t}}$

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