Benchmark Suggestions - 2HDM+S

SB, Nausheen Shah [1904.10810]

Sebastian Baum

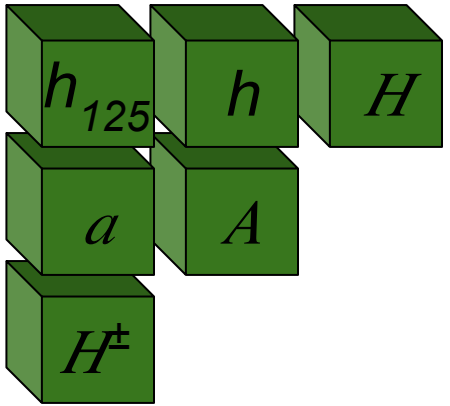
Oskar Klein Centre for Cosmoparticle Physics
Stockholm University

2HDM+S

[SB, Shah '18 (1808.02667)]

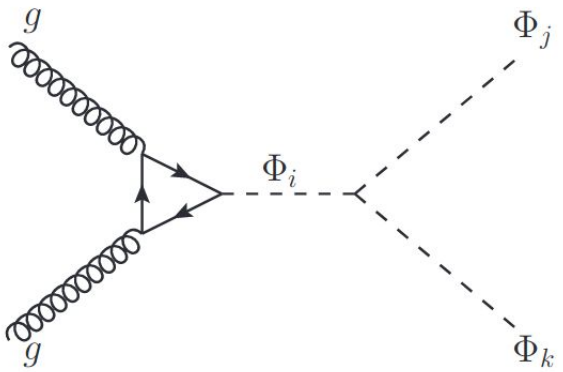
- 2 Higgs doublets + 1 complex singlet

  (= NMSSM Higgs sector without SUSY relations)
- 6 physical states after EW symmetry breaking
- Parameterize model in Higgs basis
- Neutral physical states:



$$h_i = \{h_{125}, h, H\}$$
$$= S^{\mathrm{SM}}_{h_i} H^{\mathrm{SM}} + S^{\mathrm{NSM}}_{h_i} H^{\mathrm{NSM}} + S^{\mathrm{S}}_{h_i} H^{\mathrm{S}}$$

$$a_i = \{a, A\}$$
$$= P^{\mathrm{NSM}}_{a_i} A^{\mathrm{NSM}} + P^{\mathrm{S}}_{a_i} A^{\mathrm{S}}$$



27 free parameters:

[SB, Shah '18 (1808.02667)]

6 physical masses:

$$m_{h_{125}}\,, \quad m_h\,, \quad m_H\,, \quad m_a\,, \quad m_A\,, \quad m_{H^\pm}$$

4 mixing angles:

$$S^{\mathrm{NSM}}_{h_{125}}\,, \quad S^{\mathrm{S}}_{h_{125}}\,, \quad S^{\mathrm{S}}_{H}\,, \quad P^{\mathrm{S}}_{A}$$

3 vacuum expectation values:

$$v\,, \quad \tan\beta\,, \quad v_S$$

10 independent trilinear couplings:

$$g_{H^{\mathrm{SM}}H^{\mathrm{NSM}}H^{\mathrm{NSM}}}, \quad g_{H^{\mathrm{SM}}H^{\mathrm{S}}H^{\mathrm{S}}}, \quad g_{H^{\mathrm{SM}}A^{\mathrm{S}}A^{\mathrm{S}}},$$
$$g_{H^{\mathrm{NSM}}H^{\mathrm{NSM}}H^{\mathrm{NSM}}}, \quad g_{H^{\mathrm{NSM}}H^{\mathrm{NSM}}H^{\mathrm{S}}}, \quad g_{H^{\mathrm{NSM}}H^{\mathrm{S}}H^{\mathrm{S}}}, \quad g_{H^{\mathrm{NSM}}A^{\mathrm{S}}A^{\mathrm{S}}},$$
$$g_{H^{\mathrm{S}}H^{\mathrm{S}}H^{\mathrm{S}}}, \quad g_{H^{\mathrm{S}}A^{\mathrm{NSM}}A^{\mathrm{S}}}, \quad g_{H^{\mathrm{S}}A^{\mathrm{S}}A^{\mathrm{S}}}$$

4 independent quartic couplings:

$$\lambda_{H^{\mathrm{NSM}}H^{\mathrm{NSM}}H^{\mathrm{S}}H^{\mathrm{S}}}, \quad \lambda_{H^{\mathrm{NSM}}H^{\mathrm{NSM}}A^{\mathrm{S}}A^{\mathrm{S}}}, \quad \lambda_{H^{\mathrm{S}}H^{\mathrm{S}}A^{\mathrm{S}}A^{\mathrm{S}}}, \quad \lambda_{A^{\mathrm{S}}A^{\mathrm{S}}A^{\mathrm{S}}A^{\mathrm{S}}}$$

27 free parameters:

[SB, Shah '18 (1808.02667)]

6 physical masses:

$$m_{h_{125}}\,, \quad m_h\,, \quad m_H\,, \quad m_a\,, \quad m_A\,, \quad m_{H^\pm}$$

4 mixing angles:

$$S^{\rm NSM}_{h_{125}}\,, \quad S^{\rm S}_{h_{125}}\,, \quad S^{\rm S}_{H}\,, \quad P^{\rm S}_{A}$$

3 vacuum expectation values:

$$v\,, \quad \tan\beta\,, \quad v_S$$

10 independent trilinear couplings:

$$g_{H^{\rm SM}H^{\rm NSM}H^{\rm NSM}}\,, \quad g_{H^{\rm SM}H^{\rm S}H^{\rm S}}\,, \quad g_{H^{\rm SM}A^{\rm S}A^{\rm S}}\,,$$
$$g_{H^{\rm NSM}H^{\rm NSM}H^{\rm NSM}}\,, \quad g_{H^{\rm NSM}H^{\rm NSM}H^{\rm S}}\,, \quad g_{H^{\rm NSM}H^{\rm S}H^{\rm S}}\,, \quad g_{H^{\rm NSM}A^{\rm S}A^{\rm S}}\,,$$
$$g_{H^{\rm S}H^{\rm S}H^{\rm S}}\,, \quad g_{H^{\rm S}A^{\rm NSM}A^{\rm S}}\,, \quad g_{H^{\rm S}A^{\rm S}A^{\rm S}}$$

4 independent quartic couplings:

$$\lambda_{H^{\rm NSM}H^{\rm NSM}H^{\rm S}H^{\rm S}}\,, \quad \lambda_{H^{\rm NSM}H^{\rm NSM}A^{\rm S}A^{\rm S}}\,, \quad \lambda_{H^{\rm S}H^{\rm S}A^{\rm S}A^{\rm S}}\,, \quad \lambda_{A^{\rm S}A^{\rm S}A^{\rm S}A^{\rm S}}$$

Resonant double Higgs production

- $H \to h_{125} h_{125}$ suppressed by alignment:

$$
\begin{aligned}
g_{h_{125}h_{125}H} \sim\ & (S^{\mathrm{SM}}_{h_{125}})^2 S^{\mathrm{NSM}}_{H} g_{H^{\mathrm{SM}}H^{\mathrm{SM}}H^{\mathrm{NSM}}} + (S^{\mathrm{SM}}_{h_{125}})^2 S^{\mathrm{S}}_{H} g_{H^{\mathrm{SM}}H^{\mathrm{SM}}H^{\mathrm{S}}} \\
& - S^{\mathrm{SM}}_{h_{125}} S^{\mathrm{NSM}}_{h_{125}} \left[S^{\mathrm{SM}}_{h_{125}} g_{H^{\mathrm{SM}}H^{\mathrm{SM}}H^{\mathrm{SM}}} - 2 S^{\mathrm{NSM}}_{H} g_{H^{\mathrm{SM}}H^{\mathrm{NSM}}H^{\mathrm{NSM}}} \right] \\
& + 2 S^{\mathrm{SM}}_{h_{125}} \left[\left(S^{\mathrm{NSM}}_{h_{125}} S^{\mathrm{S}}_{H} + S^{\mathrm{S}}_{h_{125}} S^{\mathrm{NSM}}_{H} \right) g_{H^{\mathrm{SM}}H^{\mathrm{NSM}}H^{\mathrm{S}}} + S^{\mathrm{S}}_{h_{125}} S^{\mathrm{S}}_{H} g_{H^{\mathrm{SM}}H^{\mathrm{S}}H^{\mathrm{S}}} \right] .
\end{aligned}
$$

- $(H \to h_{125} h)$ and $(A \to h_{125} a)$ mainly controlled by masses & mixing angle:

$$
\begin{aligned}
g_{h_{125}Hh} &= \frac{S^{\mathrm{NSM}}_{H} S^{\mathrm{S}}_{H}}{\sqrt{2}v} \left\{ \left[1 - 2 (S^{\mathrm{S}}_{H})^2 \right] \left(m_H^2 - m_h^2 \right) + \sqrt{2} v \ \widetilde{g}_H \right\} , \\
g_{h_{125}Aa} &= \frac{P^{\mathrm{NSM}}_{A} P^{\mathrm{S}}_{A}}{\sqrt{2}v} \left\{ \left[1 - 2 (P^{\mathrm{S}}_{A})^2 \right] \left(m_A^2 - m_a^2 \right) + \sqrt{2} v \ \widetilde{g}_A \right\} .
\end{aligned}
$$

- $(H \to hh)$, $(H \to aa)$, and $(A \to ha)$ mainly controlled by masses and free trilinears

Z-phobic benchmarks

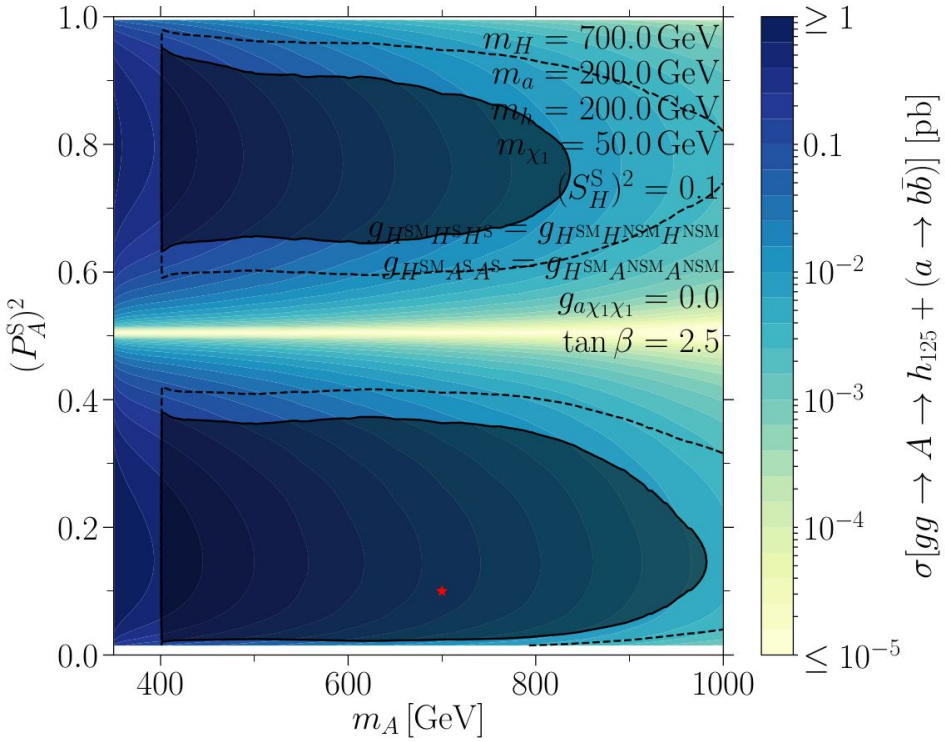
- Choose $\{(S_H^{\mathrm{S}})^2, (P_A^{\mathrm{S}})^2\} \ll 1$ to suppress ($\Phi_i \to Z\,\Phi_j$) decays
- Assume perfect alignment (simplifies parameter space, little impact on BRs)

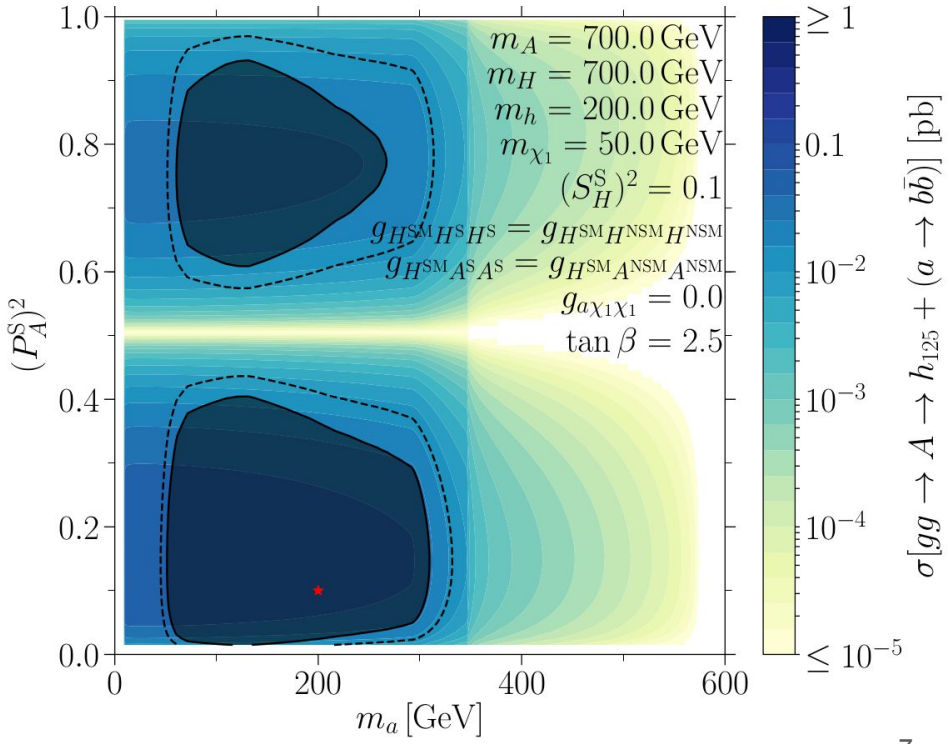
Z-Phobic	Visible ($2b$)	Invisible ($\not{E}_T$)	Double Singlet
m_H [GeV]		700	
m_A [GeV]		700	
m_h [GeV]		200	
m_a [GeV]		200	
m_χ [GeV]		50	
$\tan\beta$		2.5	
$(S_H^{\mathrm{S}})^2$		0.1	
$(P_A^{\mathrm{S}})^2$		0.1	
$g_{\Phi_i\chi_1\chi_1}$	0	2.5	–
$g_{H^{\mathrm{NSM}}H^{\mathrm{S}}H^{\mathrm{S}}}$ [GeV]		0	174
$g_{H^{\mathrm{NSM}}A^{\mathrm{S}}A^{\mathrm{S}}}$ [GeV]		0	174
$g_{A^{\mathrm{NSM}}H^{\mathrm{NSM}}H^{\mathrm{S}}}$ [GeV]		0	174

Z-phobic benchmarks: h_{125}+ ($h/a \rightarrow$ visible)

$A \rightarrow h_{125}\, a \rightarrow bbbb$

Reach: [Ellwanger, Rodriguez-Vazquez '17]

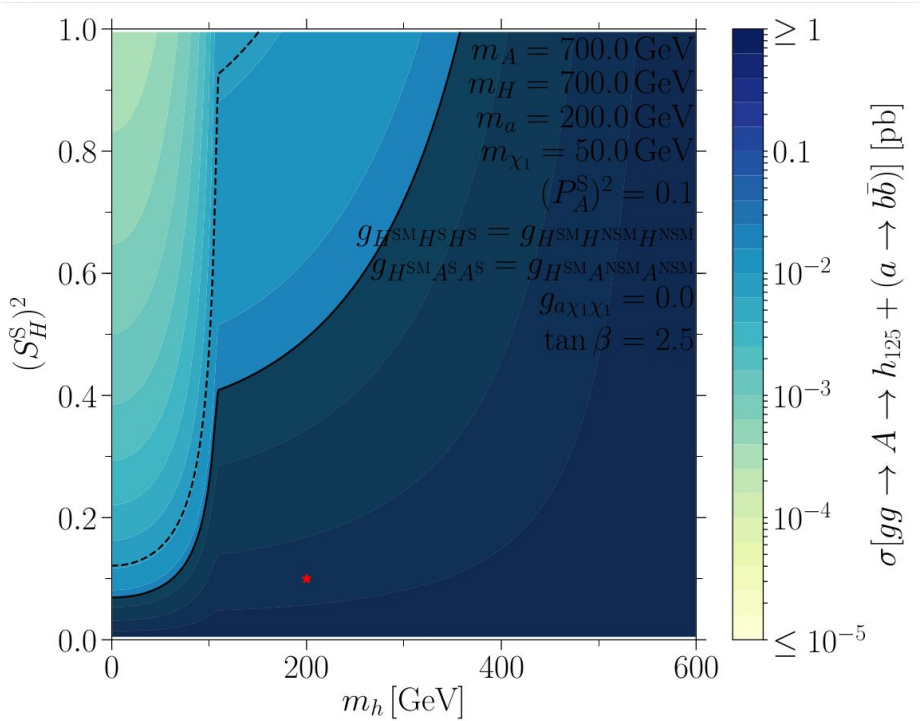




Z-phobic benchmarks: h_{125}+ ($h/a \rightarrow$ visible)

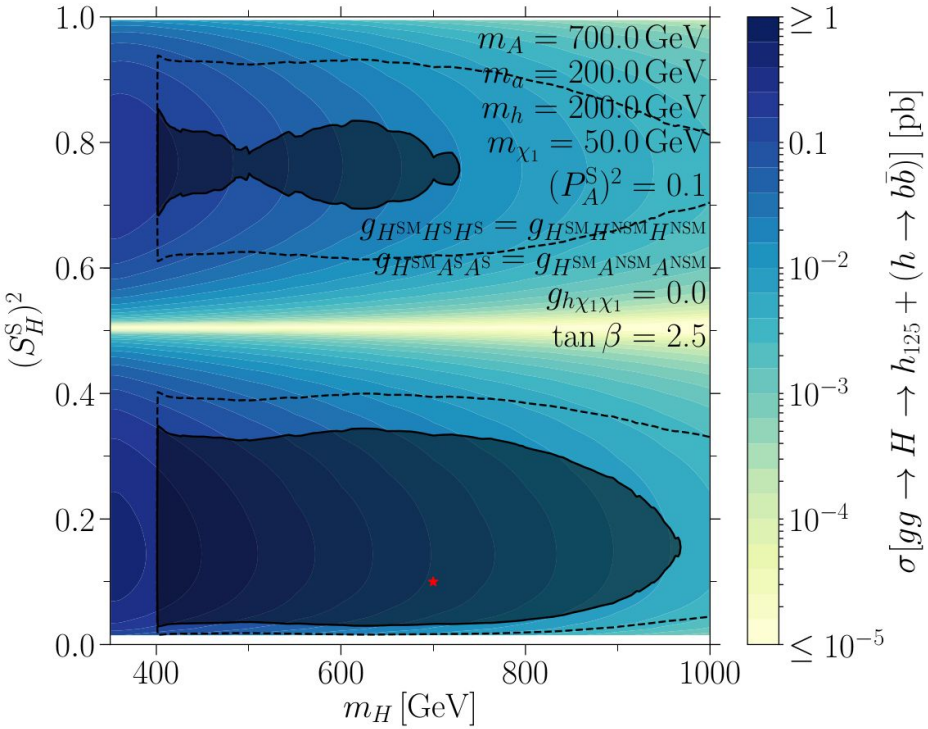
$A \rightarrow h_{125}\, a \rightarrow bbbb$

Reach: [Ellwanger, Rodriguez-Vazquez '17]

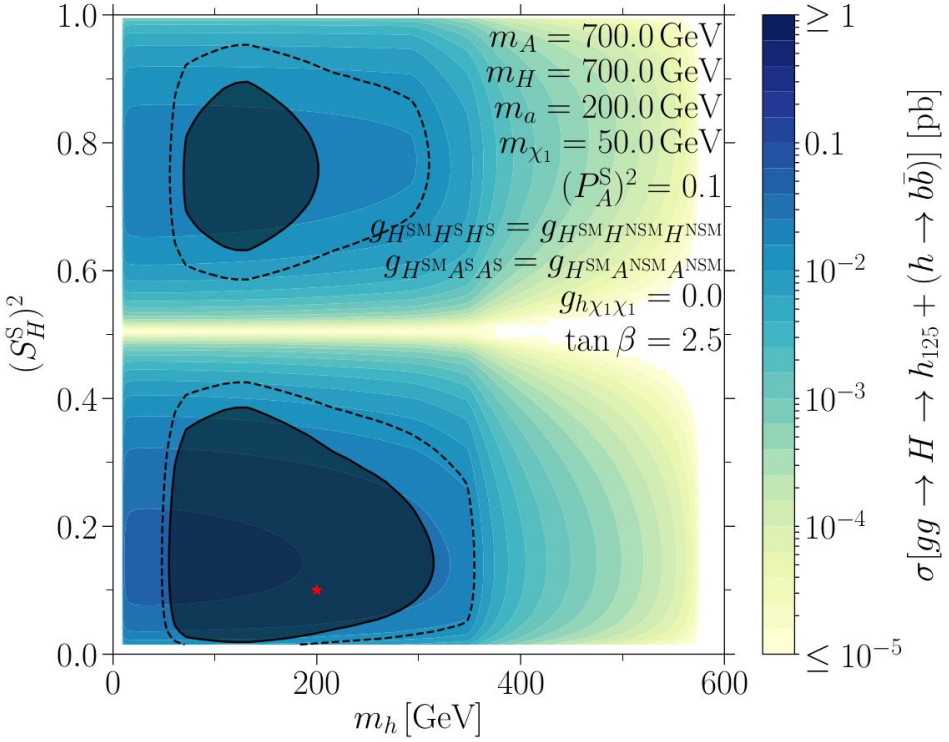


Z-phobic benchmarks: h_{125}+ ($h/a \rightarrow$ visible)

$H \rightarrow h_{125}\, h \rightarrow bbbb$



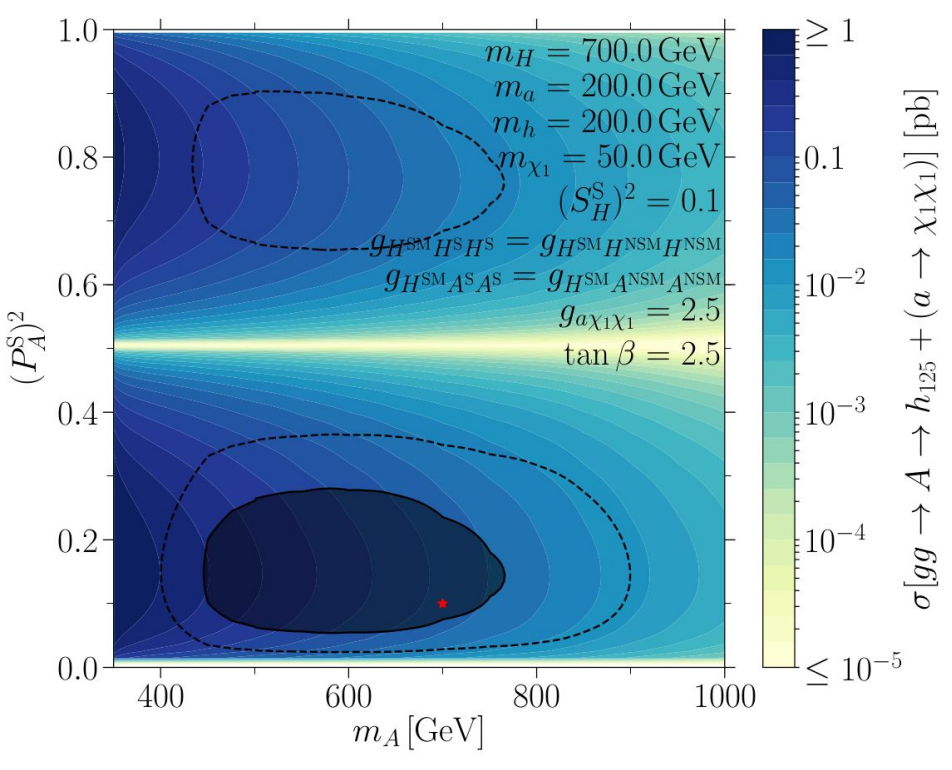
Reach: [Ellwanger, Rodriguez-Vazquez '17]

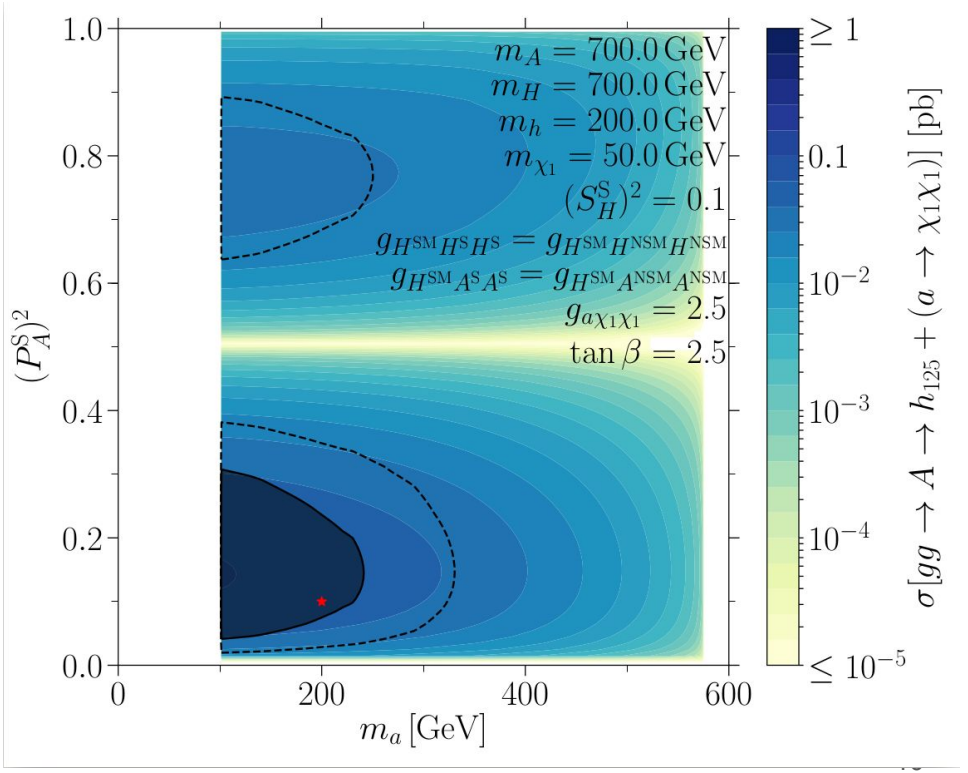


Z-phobic benchmarks: h_{125}+ ($h/a \to$ invisible)

$A \to h_{125}\, a \to \gamma\gamma\, \chi\chi$

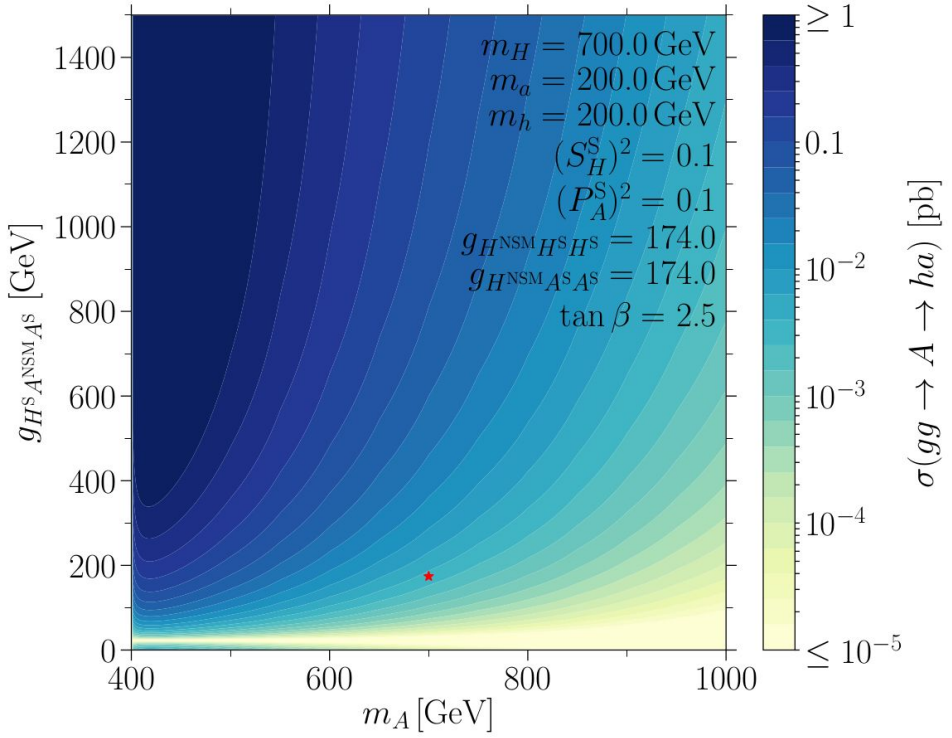
Reach: [SB, Freese, Shah, Shakya '17]



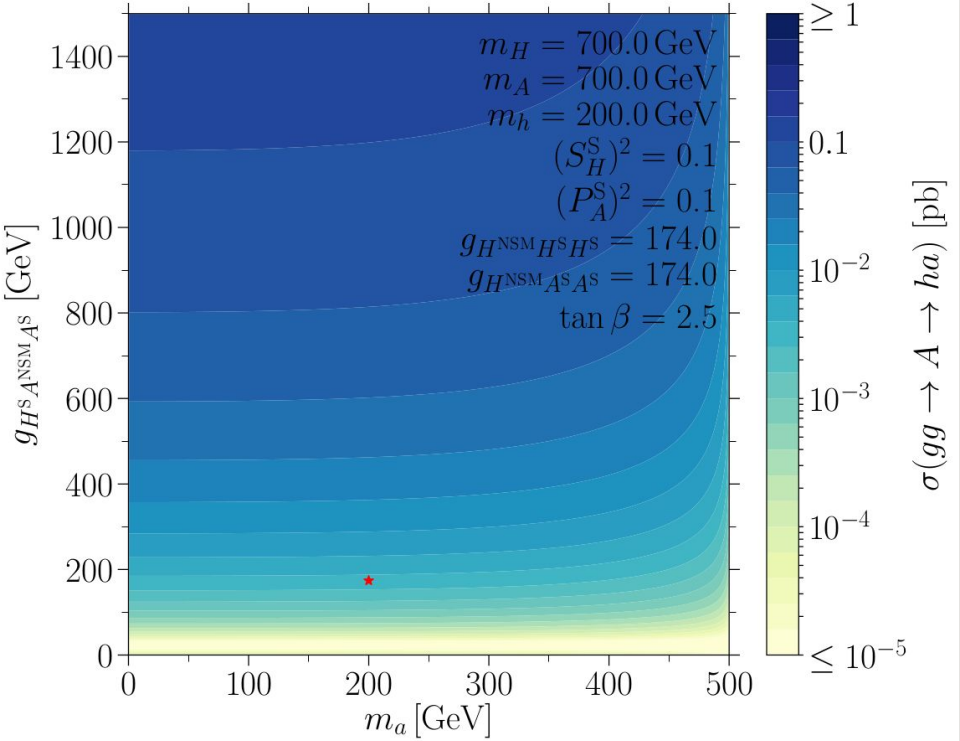


Z-phobic benchmarks: ($H \to hh$), ($H \to aa$), ($A \to ha$)

Example: $A \to h\,a$



No Reach available



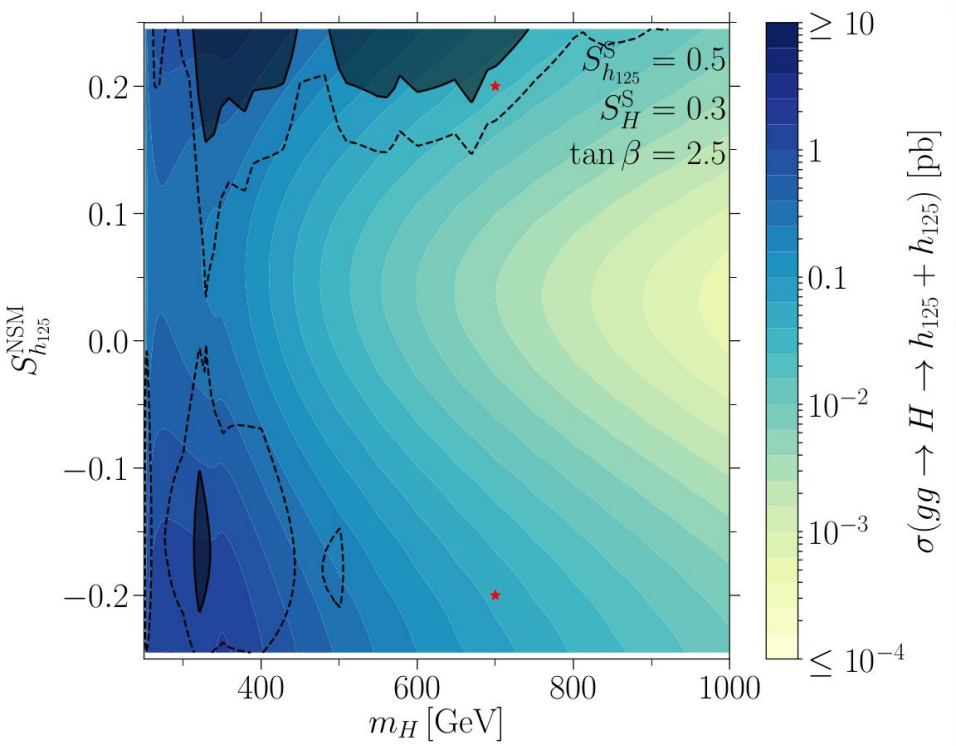
Max Misalignment Scenario: $H \to h_{125}h_{125}$

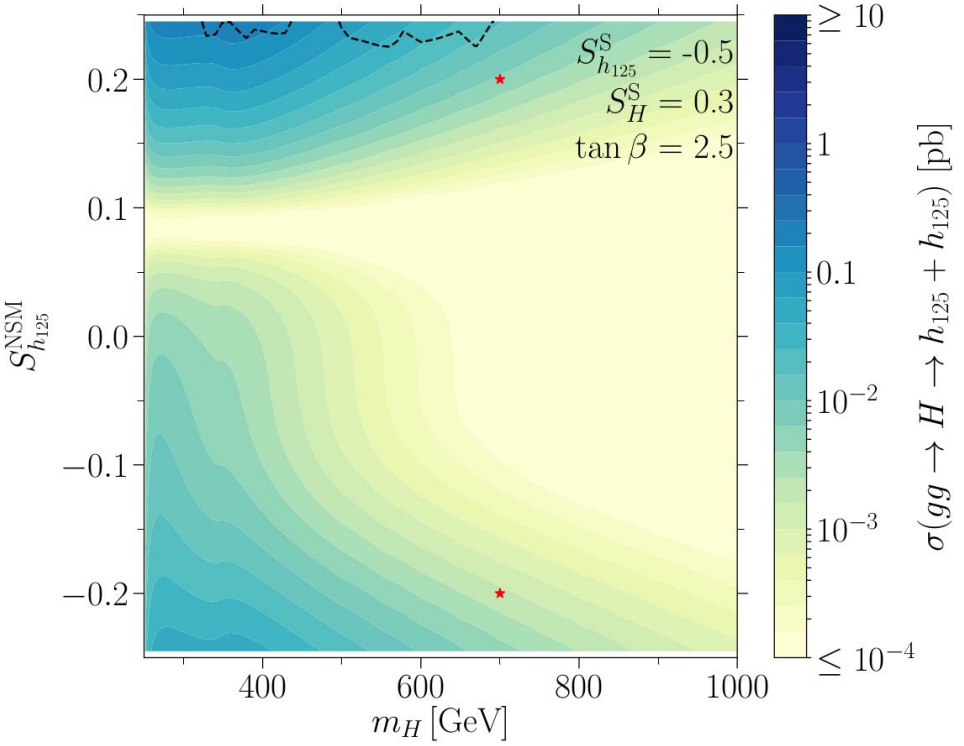
- BR($H \to h_{125}h_{125}$) vanishes for alignment
- Assume ~maximal misalignment allowed by data
- Forbid ($H \to hh$) , ($H \to aa$) and ($H \to Za$) by appropriate choice of masses

m_H [GeV]	700			
m_A [GeV]	1000			
m_h [GeV]	$m_H - 100$ GeV $= 600$			
m_a [GeV]	950			
$S^{\mathrm{NSM}}_{h_{125}}$	0.2	0.2	−0.2	−0.2
$S^{\mathrm{S}}_{h_{125}}$	0.5	−0.5	0.5	−0.5
S^{S}_{H}	0.3			
$g_{H^{\mathrm{SM}}H^{\mathrm{SM}}H^{\mathrm{SM}}} = 3\mathcal{M}^2_{S,11}/\sqrt{2}v$ [GeV]	1800	1400	1400	1800
$g_{H^{\mathrm{SM}}H^{\mathrm{SM}}H^{\mathrm{NSM}}} = 3\mathcal{M}^2_{S,12}/\sqrt{2}v$ [GeV]	1500	480	−480	−1500
$g_{H^{\mathrm{SM}}H^{\mathrm{SM}}H^{\mathrm{S}}} = \mathcal{M}^2_{S,13}/\sqrt{2}v$ [GeV]	340	−680	680	−340
$g_{H^{\mathrm{SM}}H^{\mathrm{NSM}}H^{\mathrm{S}}} = \mathcal{M}^2_{S,23}/\sqrt{2}v$ [GeV]	−560	−370	−370	−560
$\sigma(ggH)$ [pb]	0.96	0.018	0.36	0.097
$\mathrm{BR}(H \to h_{125}h_{125})$	0.032	0.35	0.15	0.016
$\mathrm{BR}(H \to ZZ)$	0.23	0.20	0.13	0.31
$\mathrm{BR}(H \to WW)$	0.46	0.40	0.26	0.63

Max Misalignment Scenario: $H \rightarrow h_{125}h_{125}$

Compare to current CMS/ATLAS limits in *bbbb, bbγγ* final states





Conclusions

- ($\Phi_i \to h_{125}\,\Phi_j$) most promising?
  - Large cross sections up to $\sigma(gg \to \Phi_i \to h_{125}\,\Phi_j)$ ~ 100 fb
  - Presence of h_{125} with known mass and BR's allows the tagging of events
- ($\Phi_i \to \Phi_j \Phi_k$) needs work!
  - Large cross sections comparable to, or even larger, than ($\Phi_i \to h_{125}\,\Phi_j$)
  - Experimentally more difficult (maybe j=k is easier?), no sensitivity estimates available…
- ($\Phi_i \to h_{125}\,h_{125}$) accessible in best-case scenario of ~ max misalignment and suitable mass spectrum
  - Could be complementary to direct h_{125} precision measurements