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The Higgs Study of the 2HDM+S under LHC and precision measurement

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2HDM+singlet

$$V_{\rm 2HDM+S} = V_{\rm 2HDM} + V_{\rm S}.$$

Soft Z_2 Symmetry Breaking

$$\begin{aligned}
V_{\rm 2HDM} =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\
& + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
& + (\Phi_1^\dagger \Phi_2) \left(\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2) + \lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2) \right) + \text{h.c.}.
\end{aligned}$$

FCNC: Z_2 Symmetry

$$\begin{aligned}
V_{\rm S} =& m_S^2 S^\dagger S + \frac{m_S'^2}{2} (S^2 + \text{h.c.}) + \left(\frac{\mu_{S1}}{3!} S^3 + \frac{\mu_{S2}}{2} S (S^\dagger S) \right. \\
& \left. + S \left[\mu_{11} \Phi_1^\dagger \Phi_1 + \mu_{22} \Phi_2^\dagger \Phi_2 + \mu_{12} \Phi_1^\dagger \Phi_2 + \mu_{21} \Phi_2^\dagger \Phi_1 \right] + \text{h.c.} \right) \\
& + S^\dagger S \left(\lambda_1' \Phi_1^\dagger \Phi_1 + \lambda_2' \Phi_2^\dagger \Phi_2 - \lambda_3' \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) \\
& + \left[S^2 \left(\lambda_4' \Phi_1^\dagger \Phi_1 + \lambda_5' \Phi_2^\dagger \Phi_2 - \lambda_6' \Phi_1^\dagger \Phi_2 + \lambda_7' \Phi_2^\dagger \Phi_1 \right) + \text{h.c.} \right] \\
& + \left(\frac{\lambda_1''}{4!} S^4 + \frac{\lambda_2''}{3!} S^2 (S^\dagger S) + \text{h.c.} \right) + \frac{\lambda_3''}{4} (S^\dagger S)^2.
\end{aligned}$$

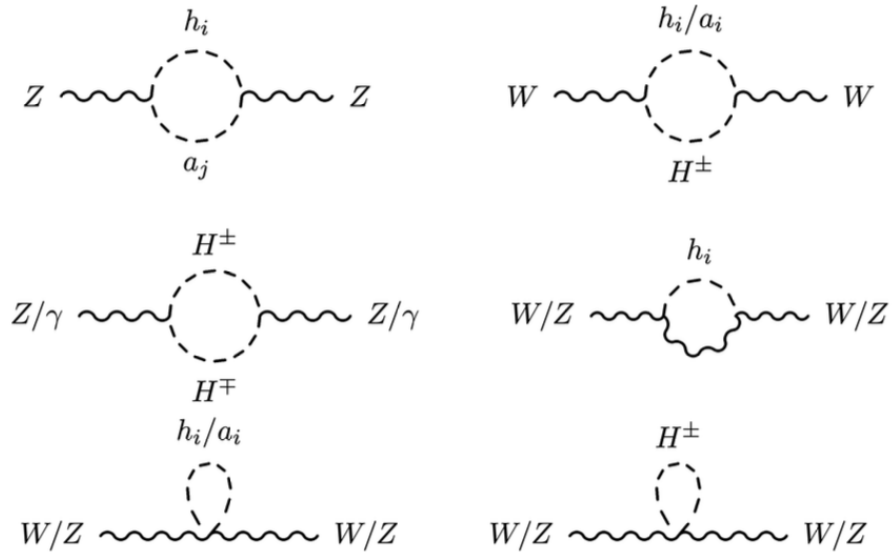
More symmetries

Models	Symmetries	Remaining dimensionful terms	Remaining quartic terms
U(1)[8]	$S \to e^{i\delta} S$	$m_{11}, m_{22}, m_{12}, m_S, m'_S$	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda'_1, \lambda'_2, \lambda''_3$
$\mathbb{Z}'_2$[4]	$S \to -S$	$m_{11}, m_{22}, m_{12}, m_S, m'_S$	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda'_1, \lambda'_2, \lambda''_1, \lambda''_3, \lambda'_4, \lambda'_5$
$\mathrm{U}(1)_{PQ}$ [59]	$S \to e^{\frac{i}{2}\alpha} S, \Phi_1 \to e^{ic_\beta^2 \alpha}\Phi_1$ $\Phi_2 \to e^{-is_\beta^2 \alpha}\Phi_2$	m_{11}, m_{22}, m_S	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda'_1, \lambda'_2, \lambda''_3, \lambda'_7$
$\mathbb{Z}_3$[7]	$S \to e^{-\frac{i2\pi}{3}} S, \Phi_2 \to e^{\frac{i2\pi}{3}}\Phi_2$	$m_{11}, m_{22}, m_{12}, m_S, \mu_{12}, \mu_{S1}$	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda'_1, \lambda'_2, \lambda''_3$

Table 1. Various symmetries considered in the literature on the 2HDM+S Higgs potential.

Z-pole measurements

- Nearly symmetry independent



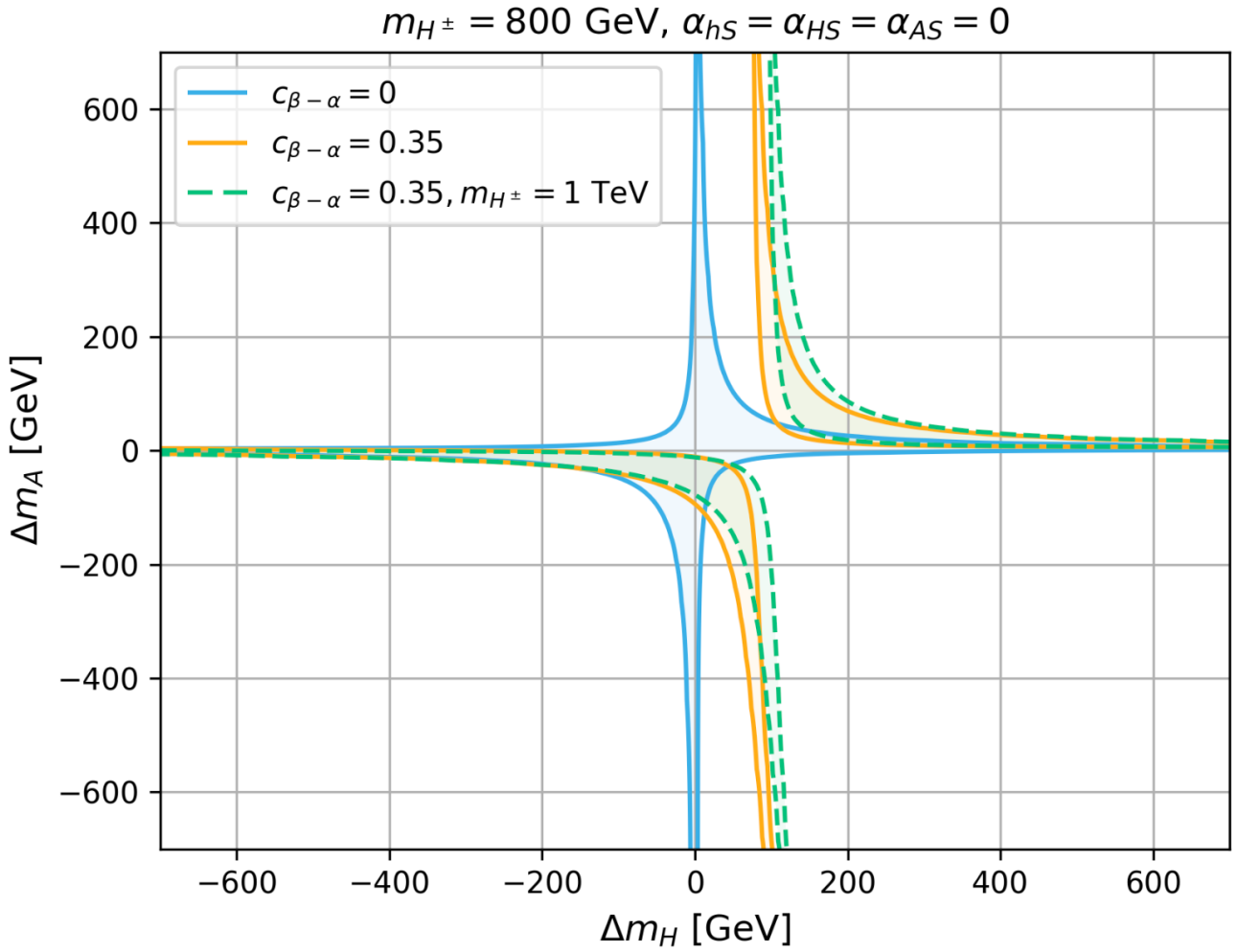
Benchmark Case		Fixed mixing angles	Variable mixing angles
Case-0	(2HDM alignment limit)	$c_{\beta-\alpha} = \alpha_{HS} = \alpha_{hS} = \alpha_{AS} = 0$	—
Case-I	(2HDM limit)	$\alpha_{HS} = \alpha_{hS} = \alpha_{AS} = 0$	$c_{\beta-\alpha}$
Case-II	(SSM limit)	$c_{\beta-\alpha} = \alpha_{HS} = \alpha_{AS} = 0$	α_{hS}
Case-III		$c_{\beta-\alpha} = \alpha_{hS} = \alpha_{AS} = 0$	α_{HS}
Case-IV		$c_{\beta-\alpha} = \alpha_{hS} = \alpha_{HS} = 0$	α_{AS}

$$\underbrace{m_h = 125\ \text{GeV},\ m_H,\ m_A,\ m_{H^\pm},\ \cos(\beta-\alpha),}_{\text{2HDM parameters}}\ \underbrace{m_{h_S},\ m_{A_S},\ \alpha_{HS},\ \alpha_{hS},\ \alpha_{AS}}_{\text{singlet parameters}}.$$

Case-I:

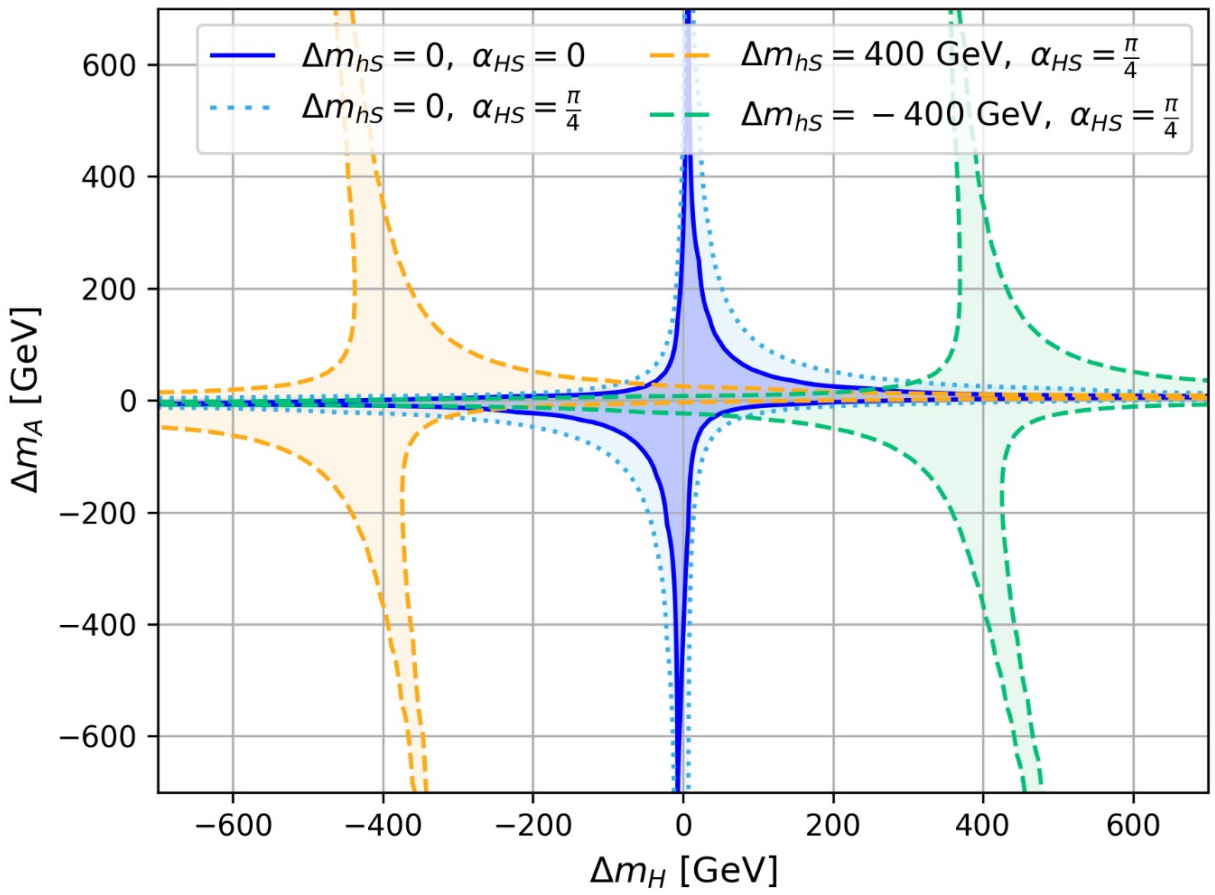
$$T_{\rm I} = T_0 + \Delta T_{\rm I}$$

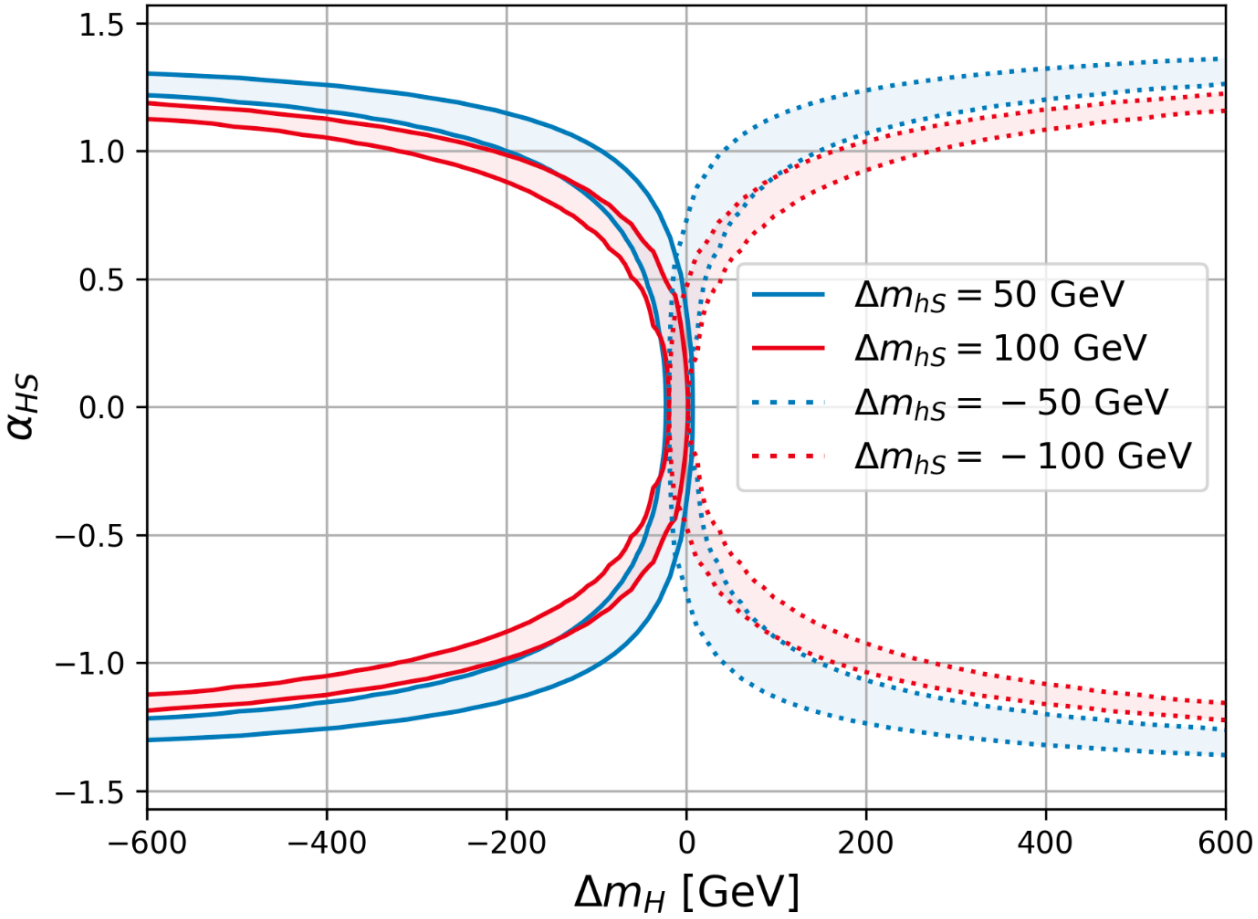
$$\Delta T_{\rm I} = \frac{c^2_{\beta-\alpha}}{16\pi s^2_W m^2_W}\{F(m^2_h, m^2_{H^\pm}) - F(m^2_h, m^2_A) - [F(m^2_H, m^2_{H^\pm}) - F(m^2_H, m^2_A)] - 3[F(m^2_h, m^2_Z) - F(m^2_h, m^2_{W^\pm})] + 3[F(m^2_H, m^2_Z) - F(m^2_H, m^2_{W^\pm})]\}.$$



Case-III:

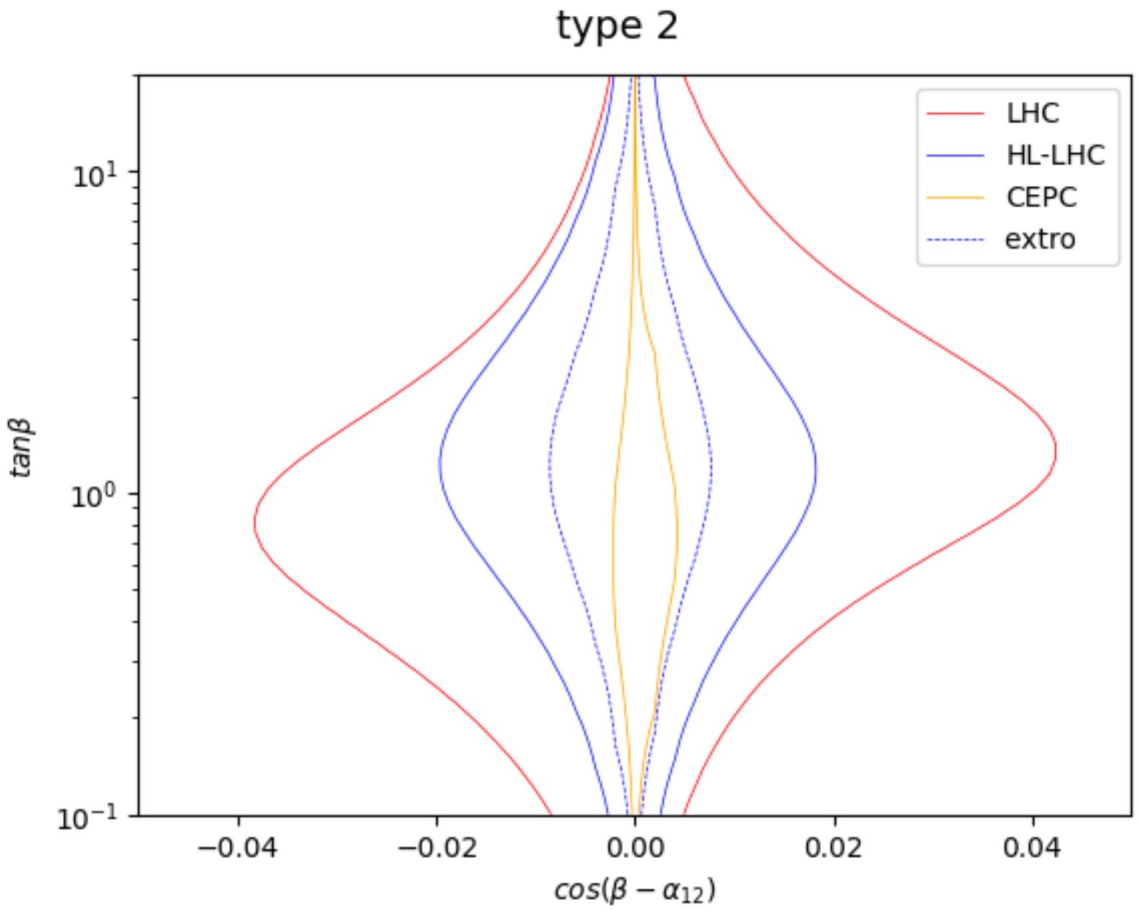
$$c^2_{\alpha_{HS}} m_H + s^2_{\alpha_{HS}} m_{h_S} = m_{H^\pm}, \quad \text{or } m_A = m_{H^\pm}.$$

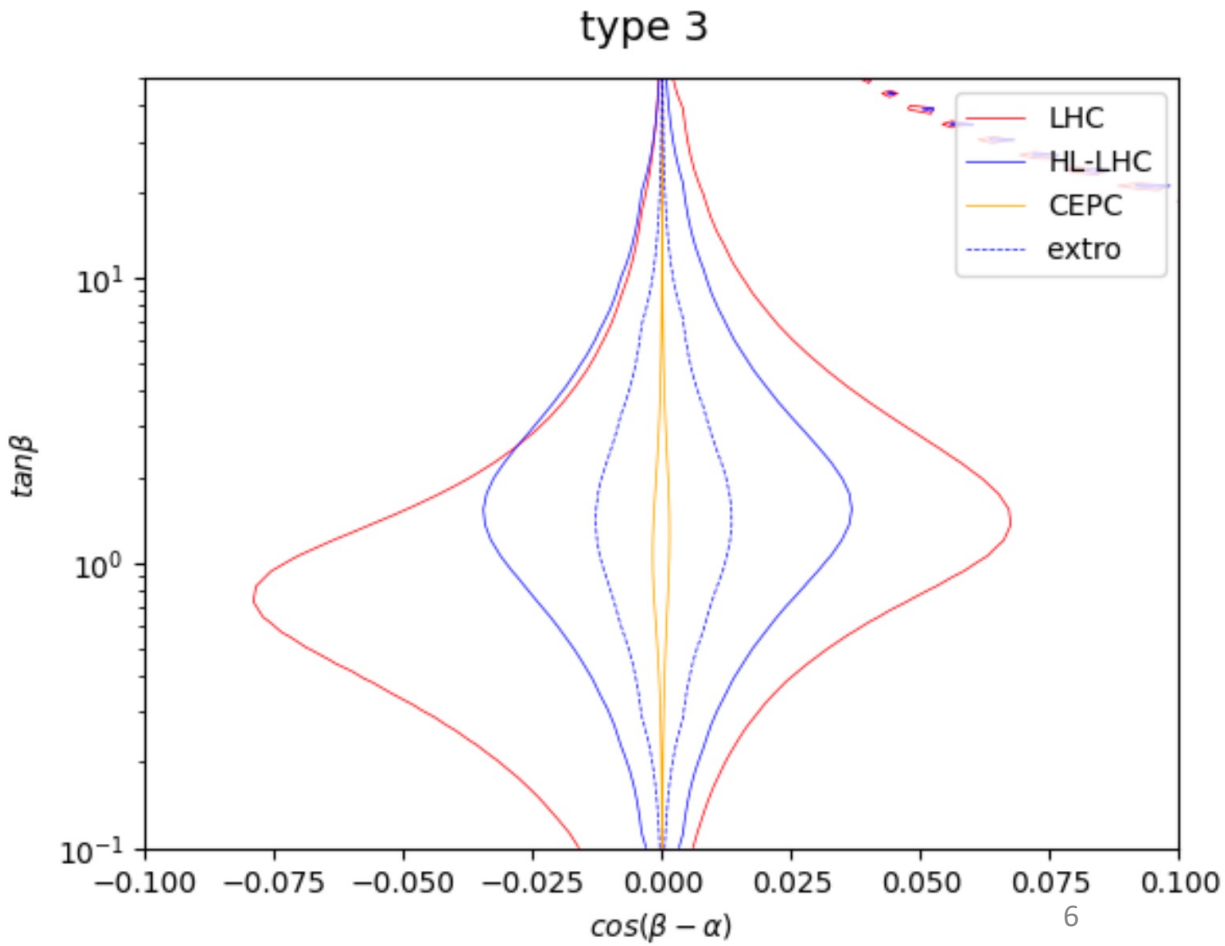




SM Higgs Study

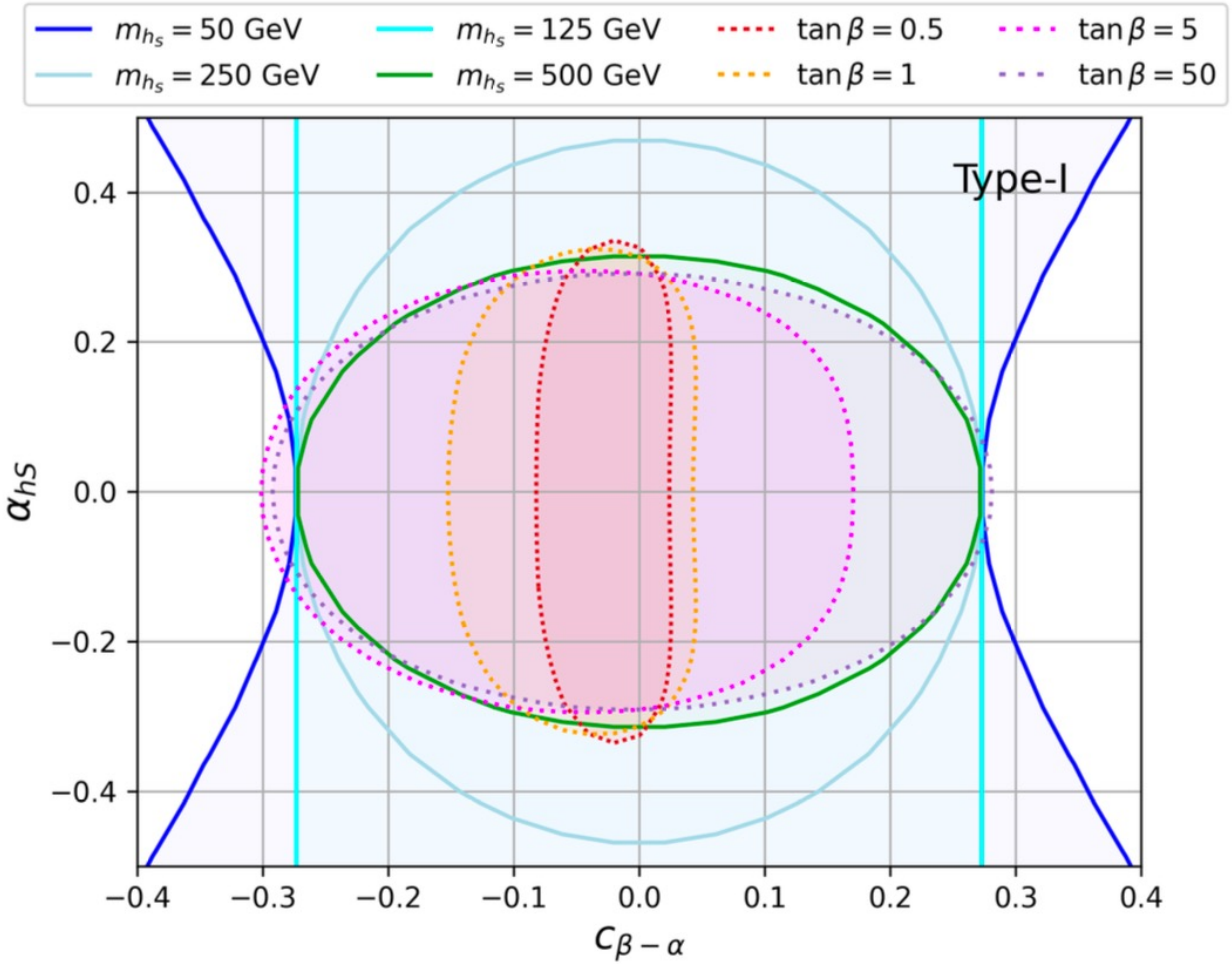
$$\Delta\sigma^{\text{HL-LHC}} = \Delta\sigma^{\text{LHC}} \times \sqrt{\frac{\mathcal{L}^{\text{LHC}}}{\mathcal{L}^{\text{HL-LHC}}}}$$

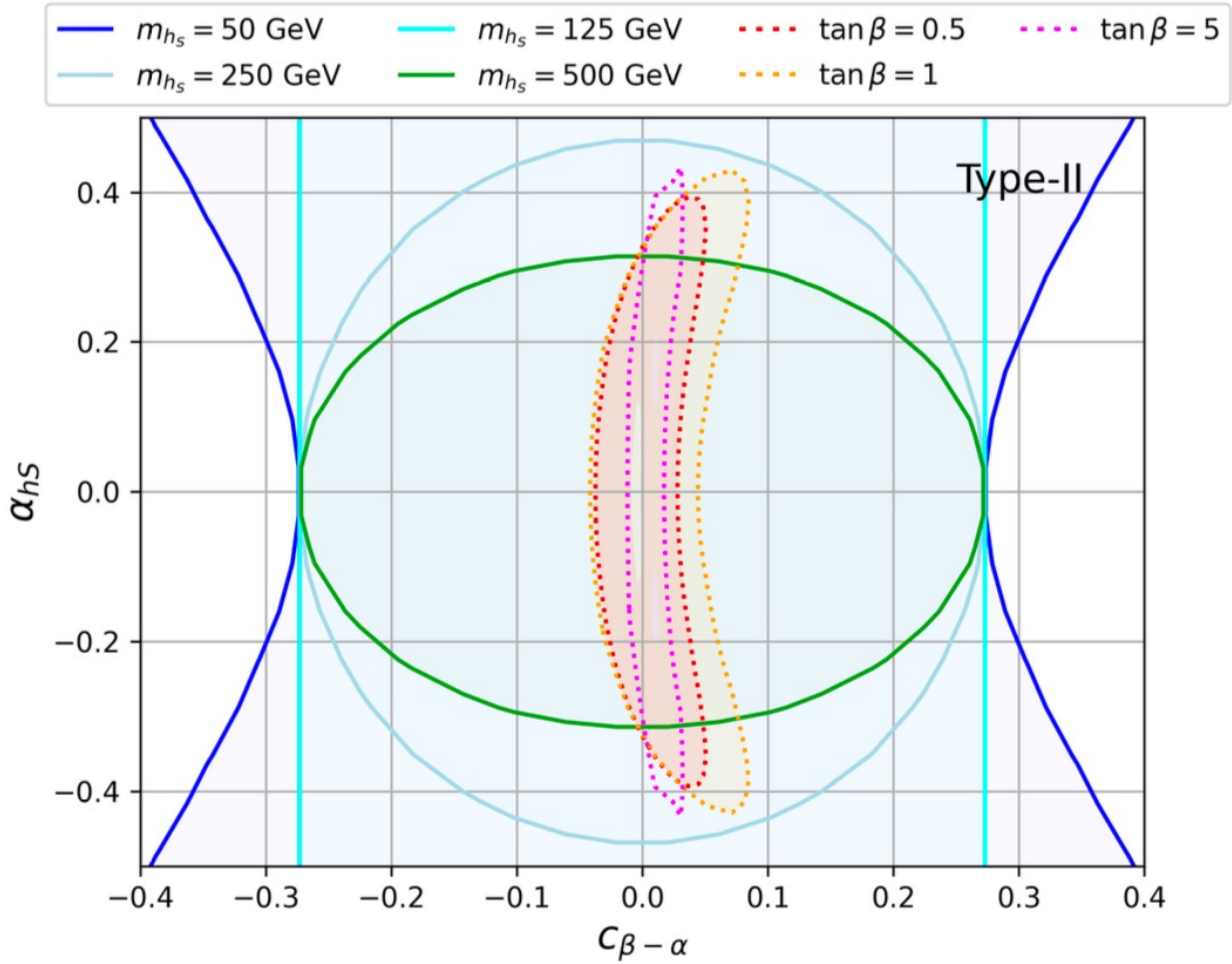




Electroweak and Higgs precision measurements

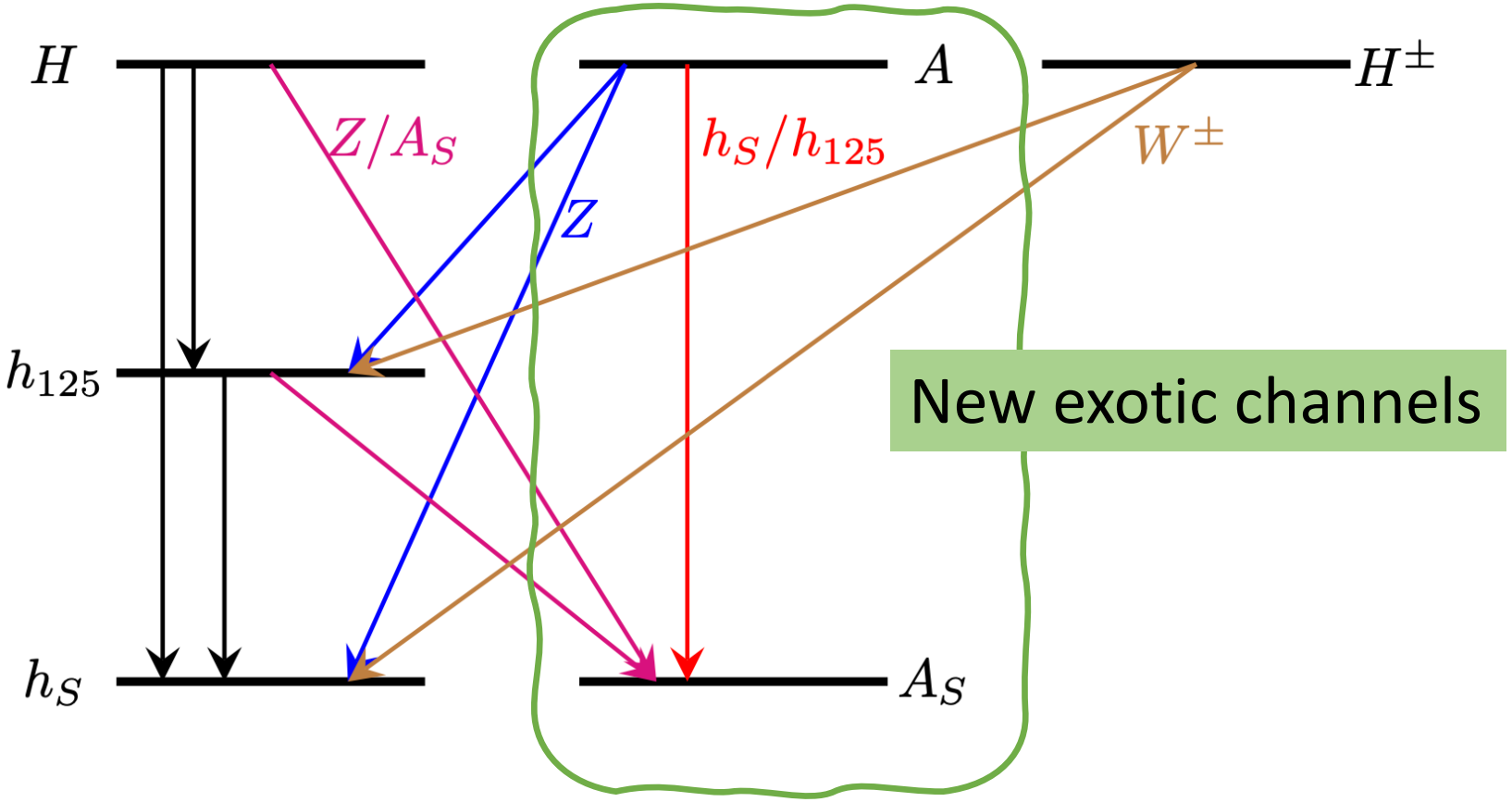
$$m_A = m_H = m_{H^\pm} = 800 \text{ GeV}, \text{ and } \alpha_{HS} = \alpha_{AS} = 0$$





2HDM+singlet : BSM Higgs sector

- The scenario with lighter singlet Higgs

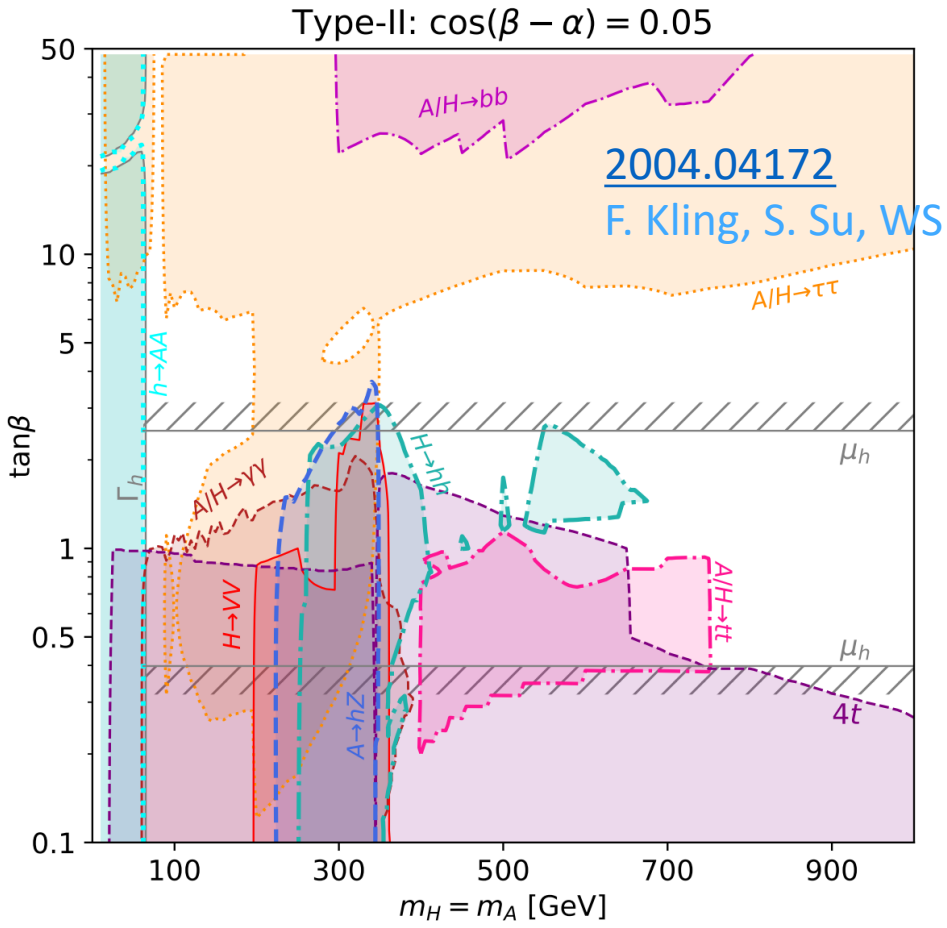


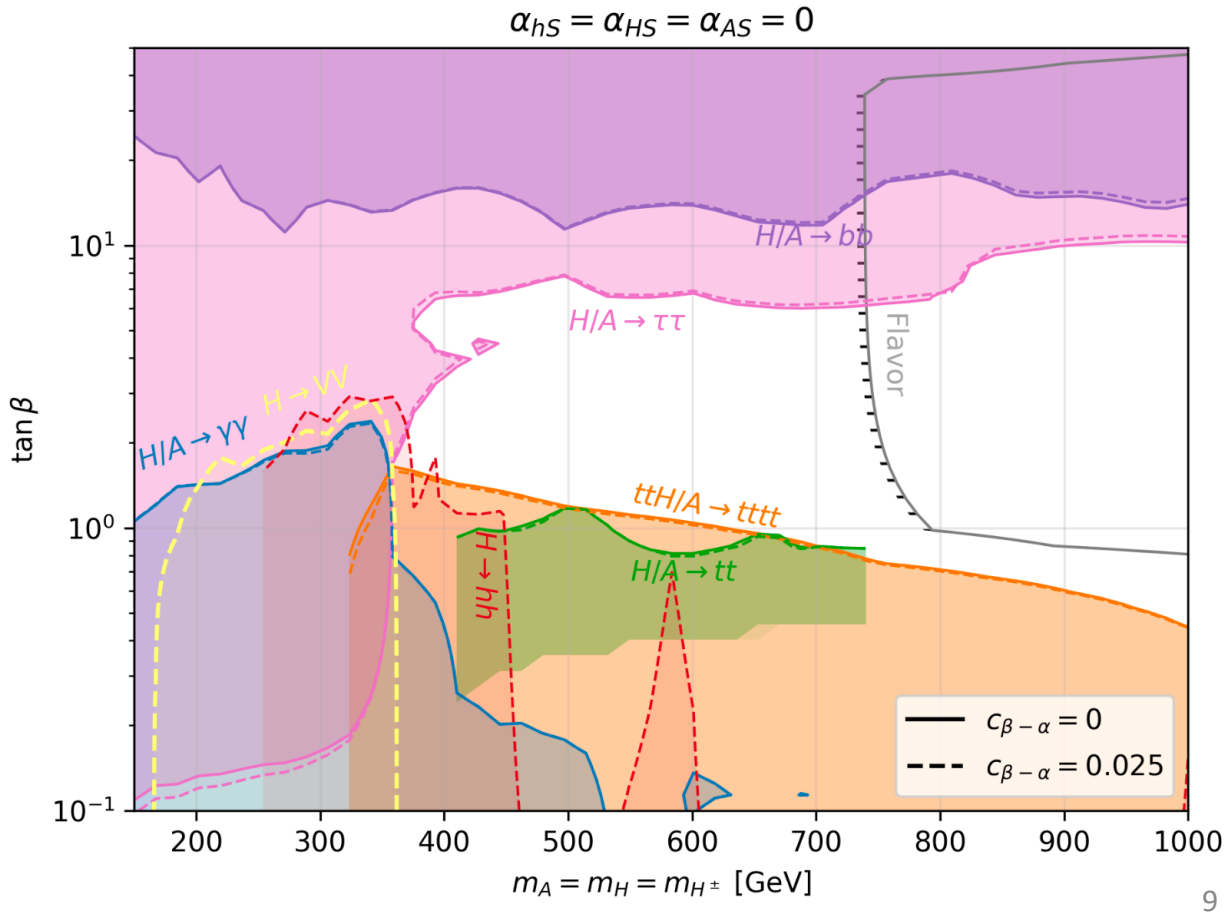
Well known results

2HDM Type-II

$$-\frac{\sin\beta}{\cos\alpha}-1=-\frac{1}{2}\cos^2(\beta-\alpha)-\cos(\beta-\alpha)\times\tan\beta$$

$$\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$





$\tan\beta$ - m_{h_i}

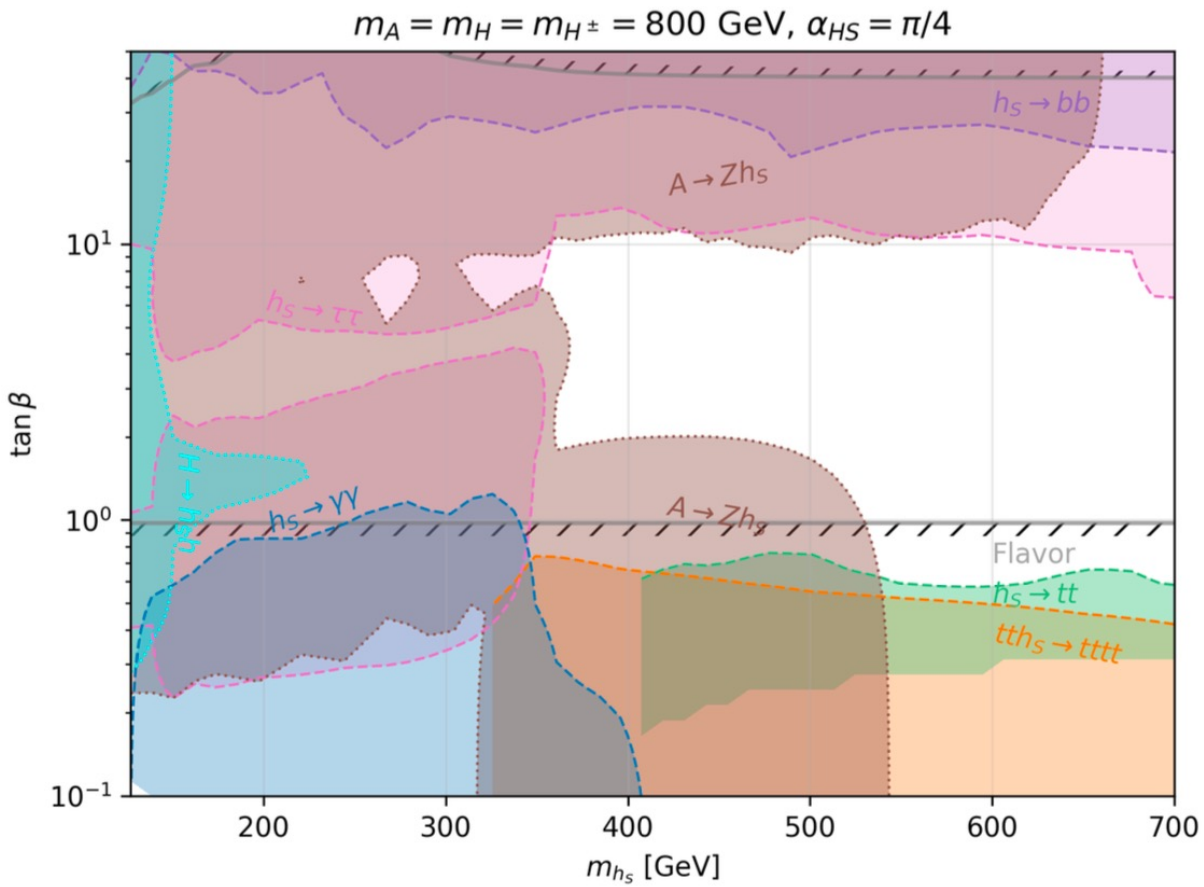
Phenomenological analyses

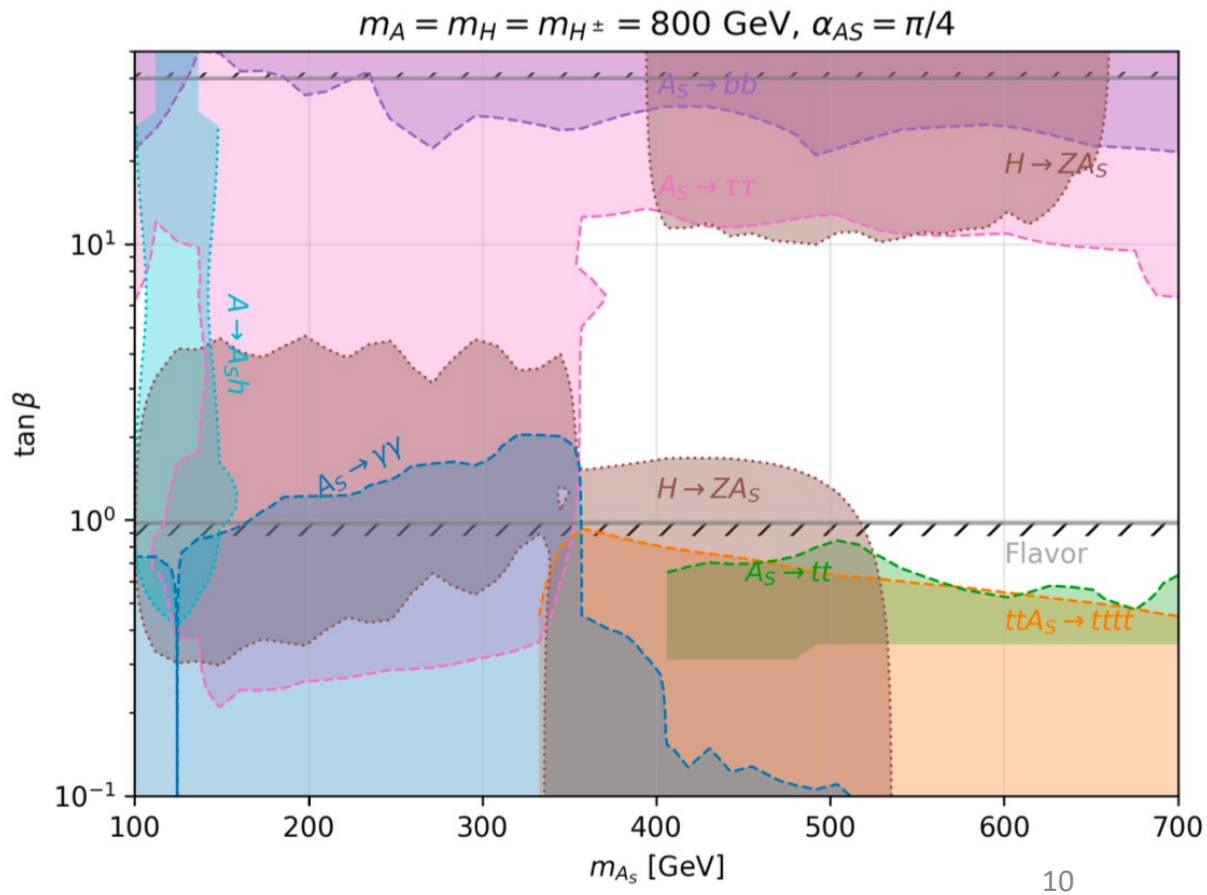
4.1 $\tan\beta$ - m_{h_i}

4.2 α_i - m_{h_i}

4.3 $\tan\beta$ - α_i

4.4 m_{h_i} - m_{h_j}

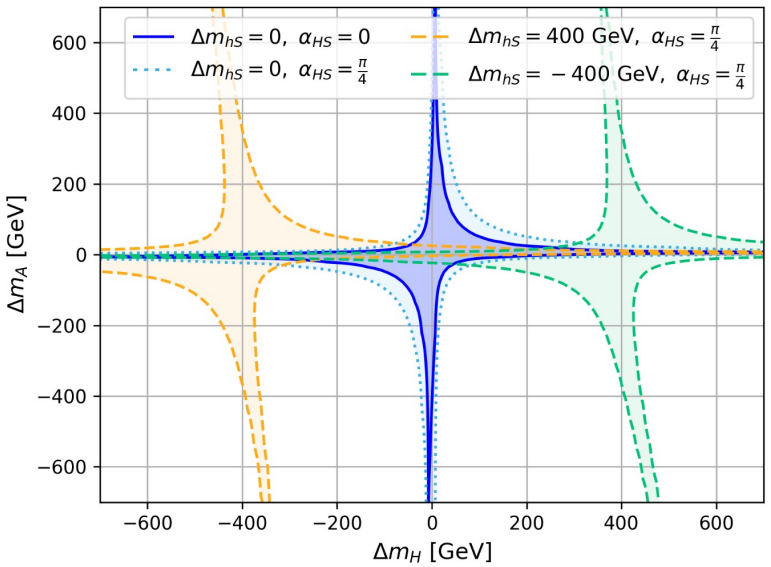


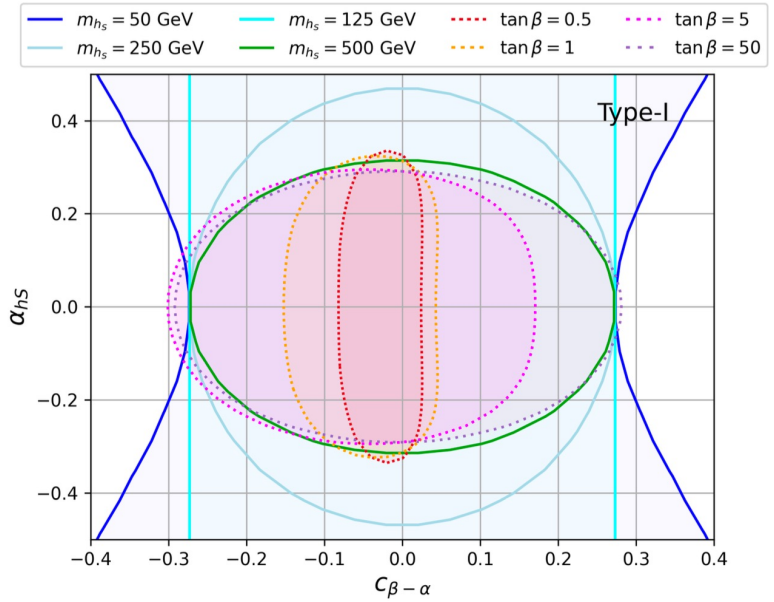


Summary

- Z – pole
- SM-like Higgs
- BSM Higgs

Benchmark Case		Fixed mixing angles	Variable mixing angles
Case-0	(2HDM alignment limit)	$c_{\beta-\alpha} = \alpha_{HS} = \alpha_{hS} = \alpha_{AS} = 0$	—
Case-I	(2HDM limit)	$\alpha_{HS} = \alpha_{hS} = \alpha_{AS} = 0$	$c_{\beta-\alpha}$
Case-II	(SSM limit)	$c_{\beta-\alpha} = \alpha_{HS} = \alpha_{AS} = 0$	α_{hS}
Case-III		$c_{\beta-\alpha} = \alpha_{hS} = \alpha_{AS} = 0$	α_{HS}
Case-IV		$c_{\beta-\alpha} = \alpha_{hS} = \alpha_{HS} = 0$	α_{AS}





Phenomenological analyses

4.1 $\tan\beta$ - m_{h_i}

4.2 α_i - m_{h_i}

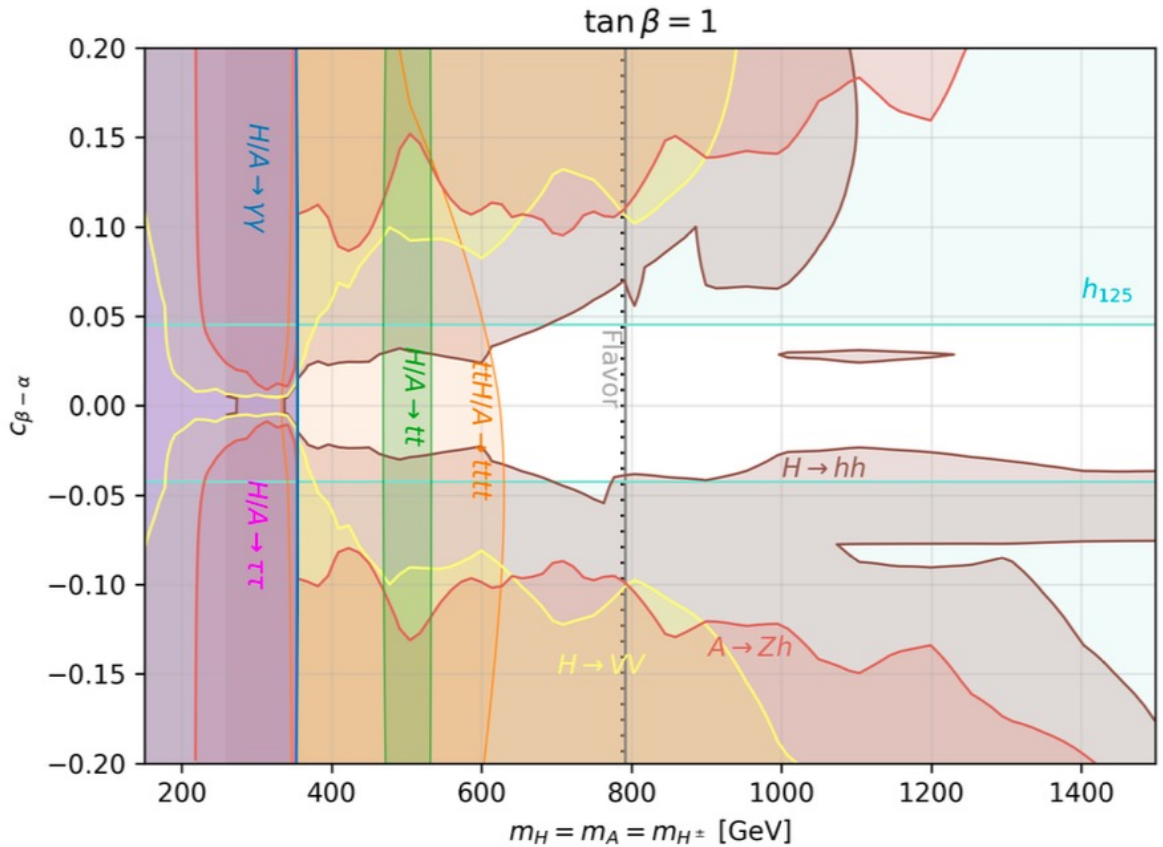
4.3 $\tan\beta$ - α_i

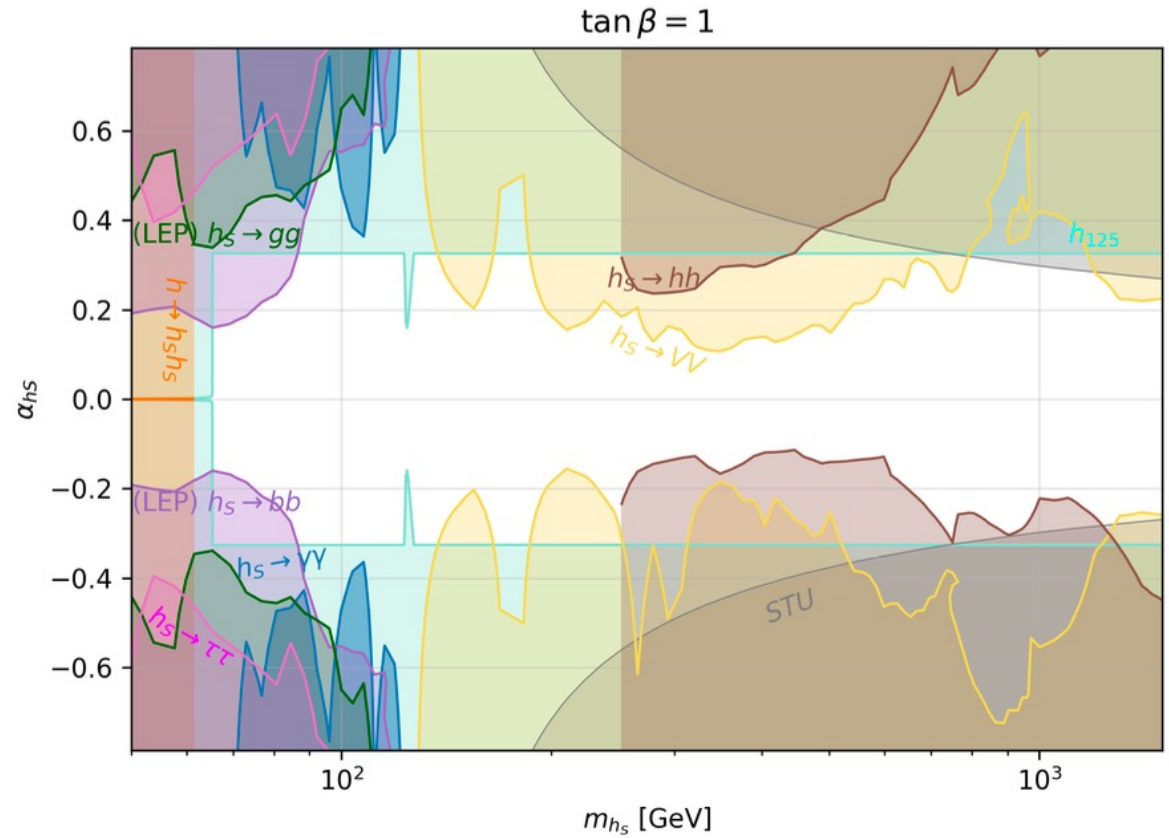
4.4 m_{h_i} - m_{h_j}

Thanks !

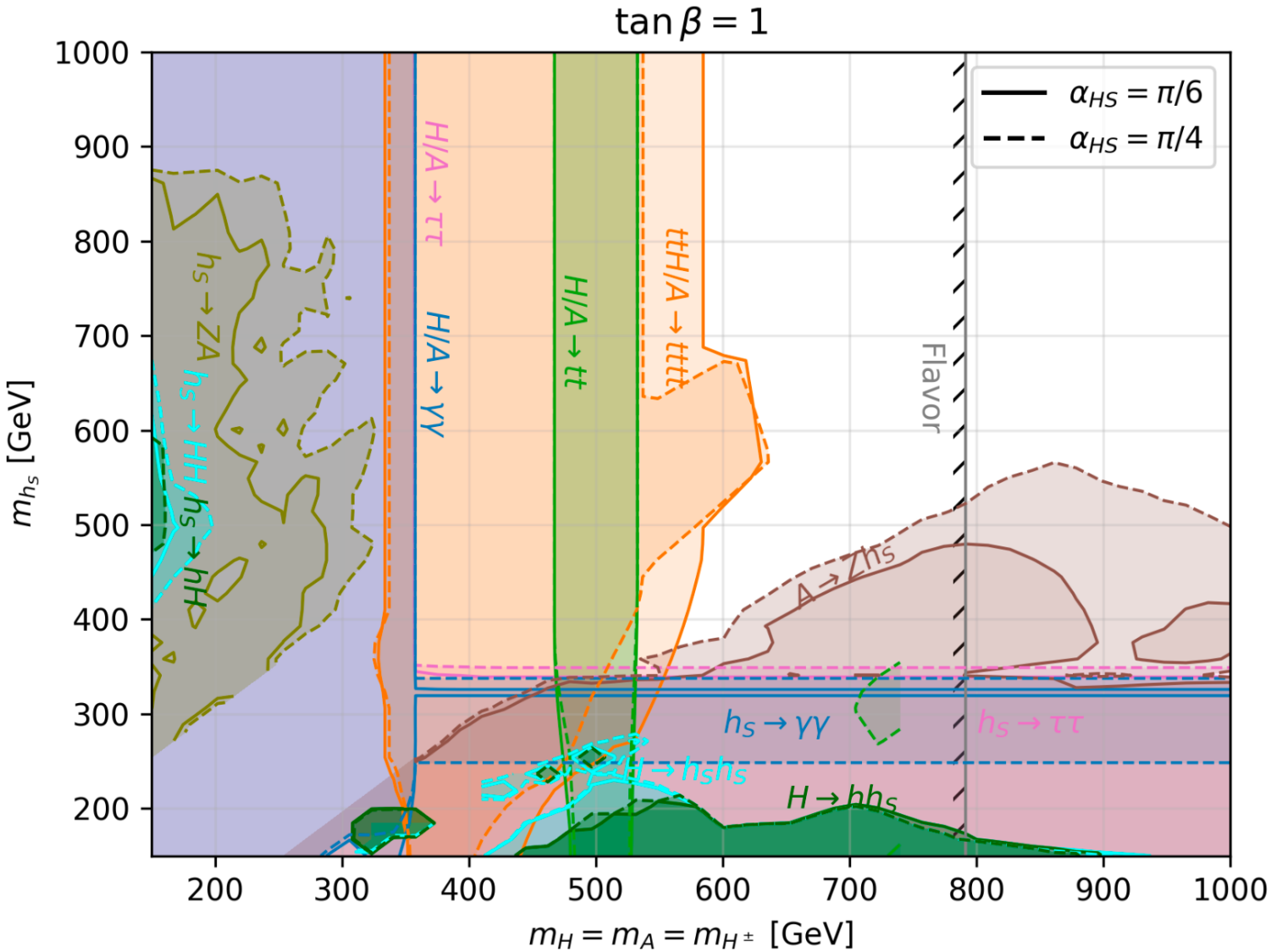
backup

α_i - m_{h_i}

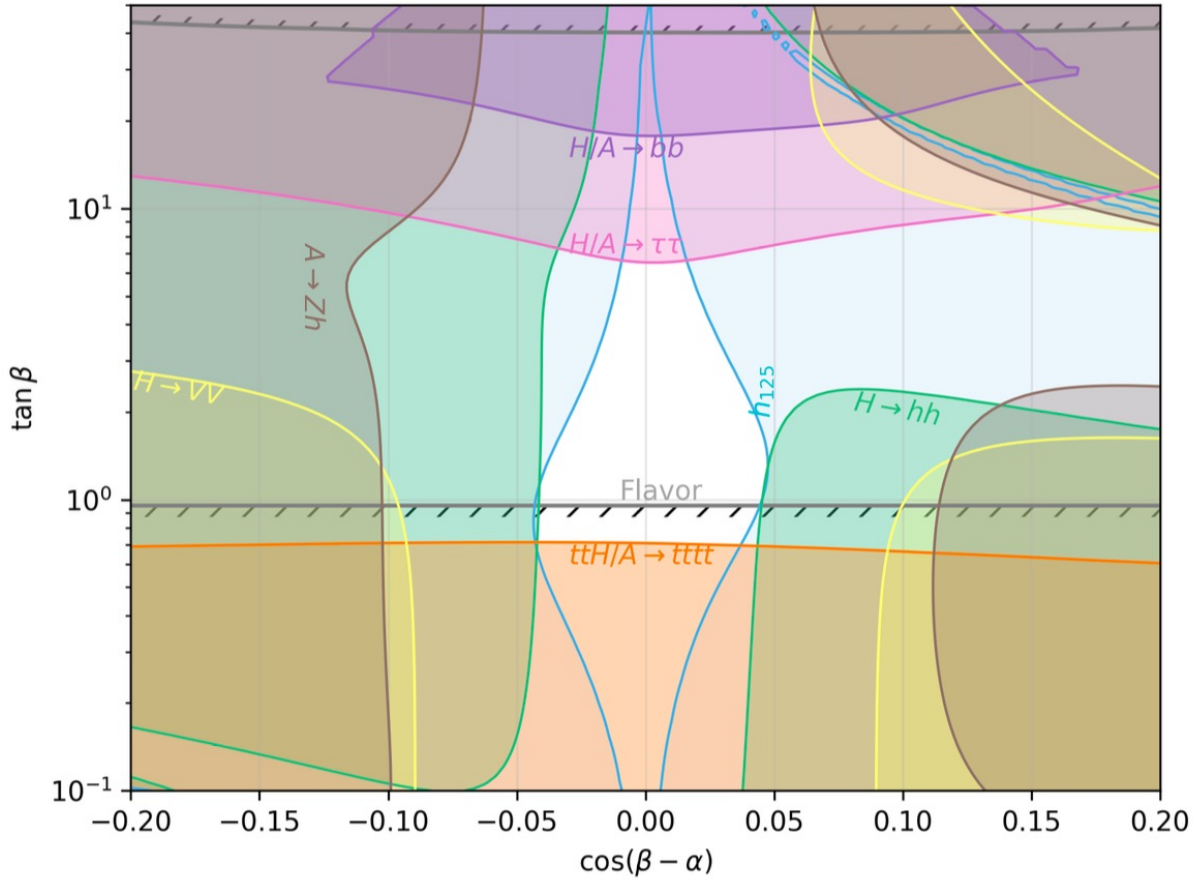

tan β = 1
H/A → γγ
H/A → ττ
H/A → tt
ttH/A → tttt
Flavor
h125
H → hh
H → VV
A → Zh
c_{β−α}
m_H = m_A = m_{H±} [GeV]

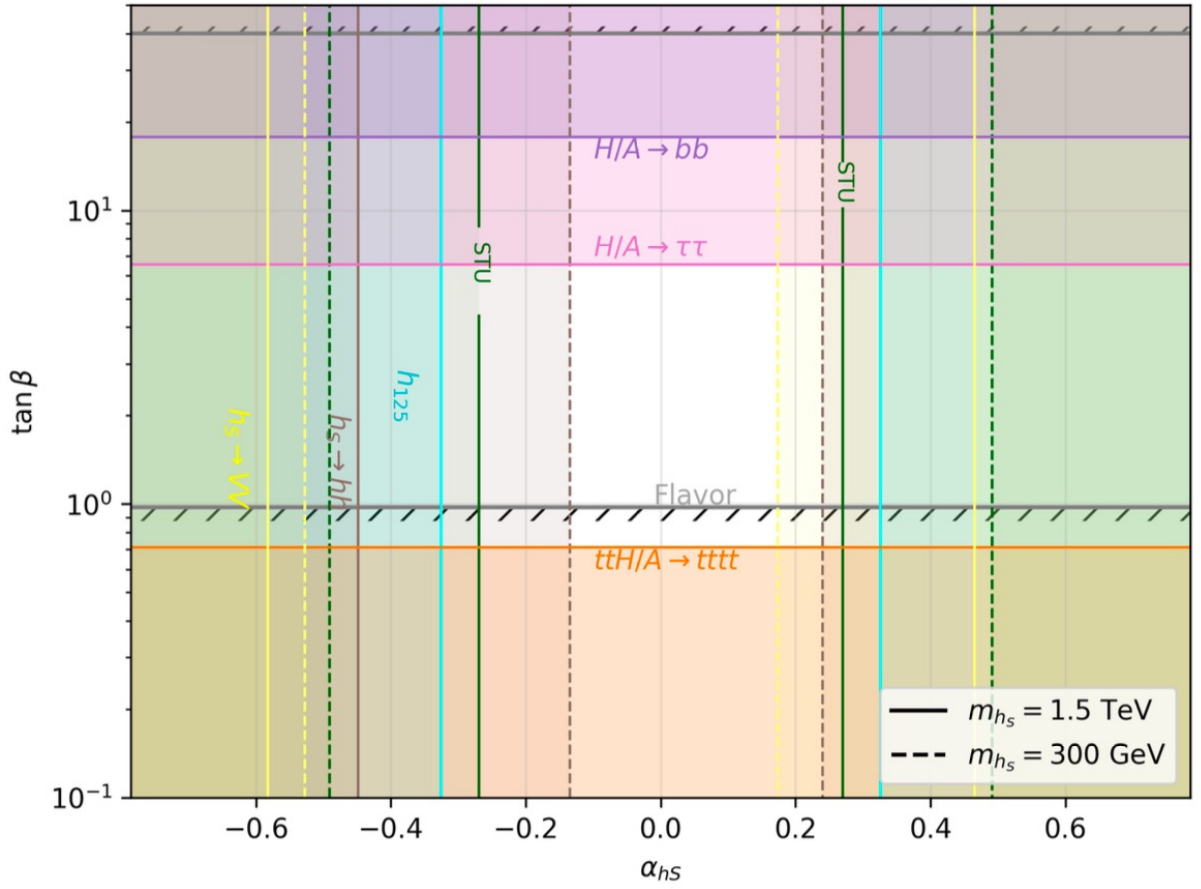

tan β = 1
(LEP) h_S → gg
h → h_S h_S
(LEP) h_S → bb
h_S → γγ
h_S → ττ
h_S → hh
h_S → VV
h125
STU
α_hS
m_{h_S} [GeV]

m_{h_i} - m_{h_j}


tan β = 1
$\alpha_{HS} = \pi/6$
$\alpha_{HS} = \pi/4$
$h_S \to ZA$
$h_S \to HH$
$h_S \to hh$
$H/A \to \tau\tau$
$H/A \to \gamma\gamma$
$H/A \to tt$
$ttH/A \to tttt$
Flavor
$A \to Zh_S$
$h_S \to \gamma\gamma$
$h_S \to \tau\tau$
$H \to h_S h_S$
$H \to hh_S$
m_{h_S} [GeV]
$m_H = m_A = m_{H^\pm}$ [GeV]
200
300
400
500
600
700
800
900
1000

tanbeta vs alphas





Brief plan： DM @ 2HDMS

- ✓ SUSY
- ✓ IDM
- ✓ 2HDM+ DM => 2HDMS

Current: Collider studies
Next step: Additional symmetry in need!

Models	Symmetries	Remaining dimensionful terms	Remaining quartic terms
U(1)[8]	$S \to e^{i\delta} S$	$m_{11}, m_{22}, m_{12}, m_S, m'_S$	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda'_1, \lambda'_2, \lambda''_3$
$\mathbb{Z}'_2$[4]	$S \to -S$	$m_{11}, m_{22}, m_{12}, m_S, m'_S$	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda'_1, \lambda'_2, \lambda''_1, \lambda''_3, \lambda'_4, \lambda'_5$
$U(1)_{PQ}$ [59]	$S \to e^{\frac{i}{2}\alpha} S, \Phi_1 \to e^{ic_\beta^2 \alpha}\Phi_1$ $\Phi_2 \to e^{-is_\beta^2 \alpha}\Phi_2$	m_{11}, m_{22}, m_S	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda'_1, \lambda'_2, \lambda''_3, \lambda'_7$
$\mathbb{Z}_3$[7]	$S \to e^{-\frac{i2\pi}{3}} S, \Phi_2 \to e^{\frac{i2\pi}{3}}\Phi_2$	$m_{11}, m_{22}, m_{12}, m_S, \mu_{12}, \mu_{S1}$	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda'_1, \lambda'_2, \lambda''_3$

Table 1. Various symmetries considered in the literature on the 2HDM+S Higgs potential.

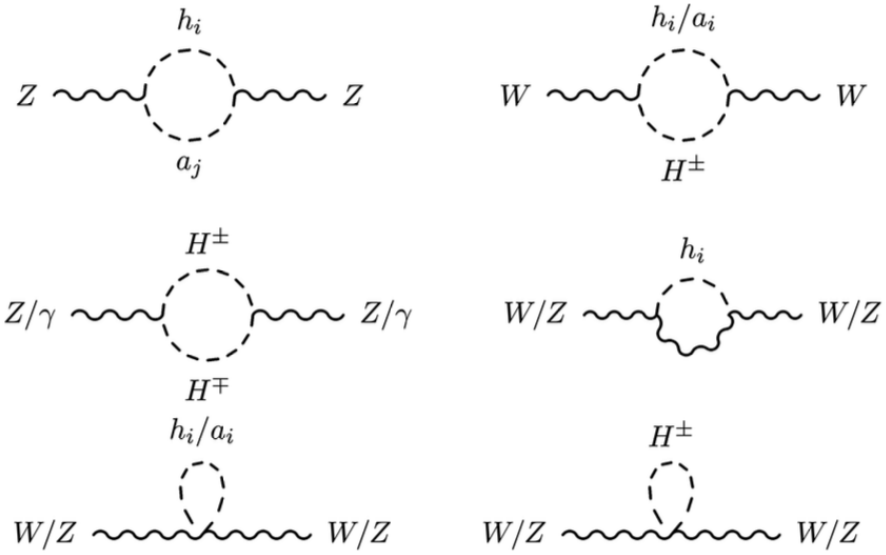
$$\Delta\sigma^{\text{HL-LHC}} = \Delta\sigma^{\text{LHC}} \times \sqrt{\frac{\mathcal{L}^{\text{LHC}}}{\mathcal{L}^{\text{HL-LHC}}}}$$

Higgs decay	production	LHC	HL-LHC extroplation	HL-LHC
$\gamma\gamma$	ggH	$1.07^{+0.12}_{-0.11}$	$1.07^{+0.026}_{-0.024}$	$1.00^{+0.04}_{-0.04}$
	VBF	$1.04^{+0.34}_{-0.31}$	$1.04^{+0.073}_{-0.066}$	$1.00^{+0.10}_{-0.09}$
	VH	$1.34^{+0.36}_{-0.33}$	$1.34^{+0.077}_{-0.071}$	$1.00^{+0.09}_{-0.09}$
	ttH	$1.35^{+0.34}_{-0.28}$	$1.35^{+0.073}_{-0.060}$	$1.00^{+0.08}_{-0.07}$
ZZ	ggH	$1.02^{+0.11}_{-0.10}$	$1.02^{+0.024}_{-0.021}$	$1.00^{+0.04}_{-0.04}$
	VBF	$0.50^{+0.44}_{-0.36}$	$0.50^{+0.094}_{-0.077}$	$1.00^{+0.12}_{-0.12}$
	VH	$1.56^{+1.99}_{-1.34}$	$1.56^{+0.425}_{-0.286}$	$1.00^{+0.19}_{-0.18}$
	ttH	$0.16^{+0.98}_{-0.16}$	$0.16^{+0.209}_{-0.034}$	$1.00^{+0.23}_{-0.20}$
WW	ggH	$0.92^{+0.11}_{-0.10}$	$0.92^{+0.024}_{-0.021}$	$1.00^{+0.05}_{-0.04}$
	VBF	$0.71^{+0.28}_{-0.25}$	$0.71^{+0.060}_{-0.054}$	$1.00^{+0.10}_{-0.09}$
$\tau\tau$	ggH	$0.97^{+0.20}_{-0.18}$	$0.97^{+0.043}_{-0.039}$	$1.00^{+0.12}_{-0.11}$
	VBF	$0.68^{+0.24}_{-0.23}$	$0.68^{+0.051}_{-0.049}$	$1.00^{+0.08}_{-0.08}$
bb	WH	combined $1.15^{+0.22}_{-0.20}$	$1.15^{+0.047}_{-0.043}$	$1.00^{+0.10}_{-0.10}$
	$qq \to ZH$			$1.00^{+0.12}_{-0.12}$
	$gg \to ZH$			$1.00^{+0.43}_{-0.43}$

Table 2. LHC precisions for Higgs boson measurements from CMS Collaboration Group and (extrapolated)HL-LHC precisions

Higgs gauge couplings for oblique parameters

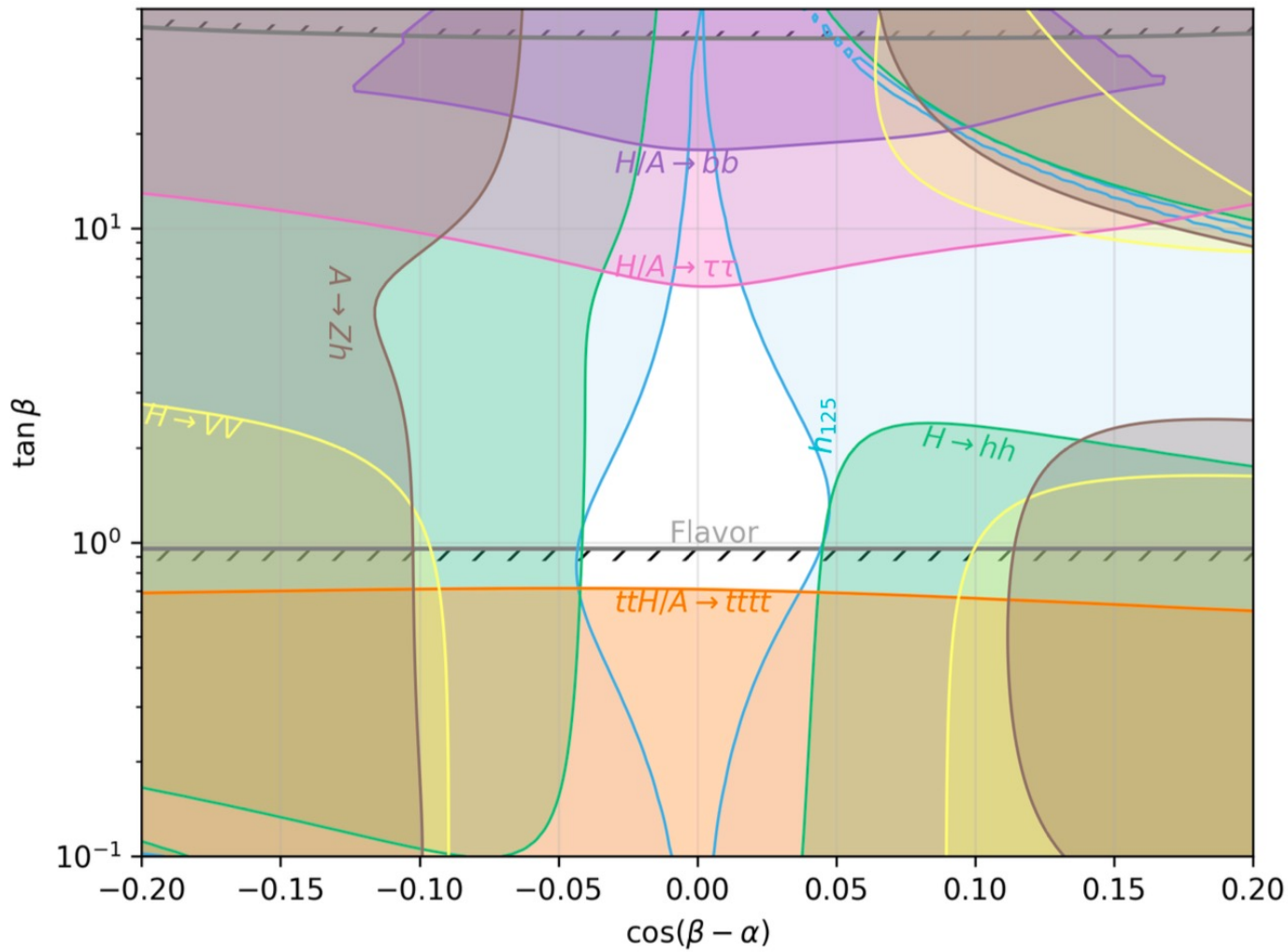
- For each case, only limited non-zero couplings



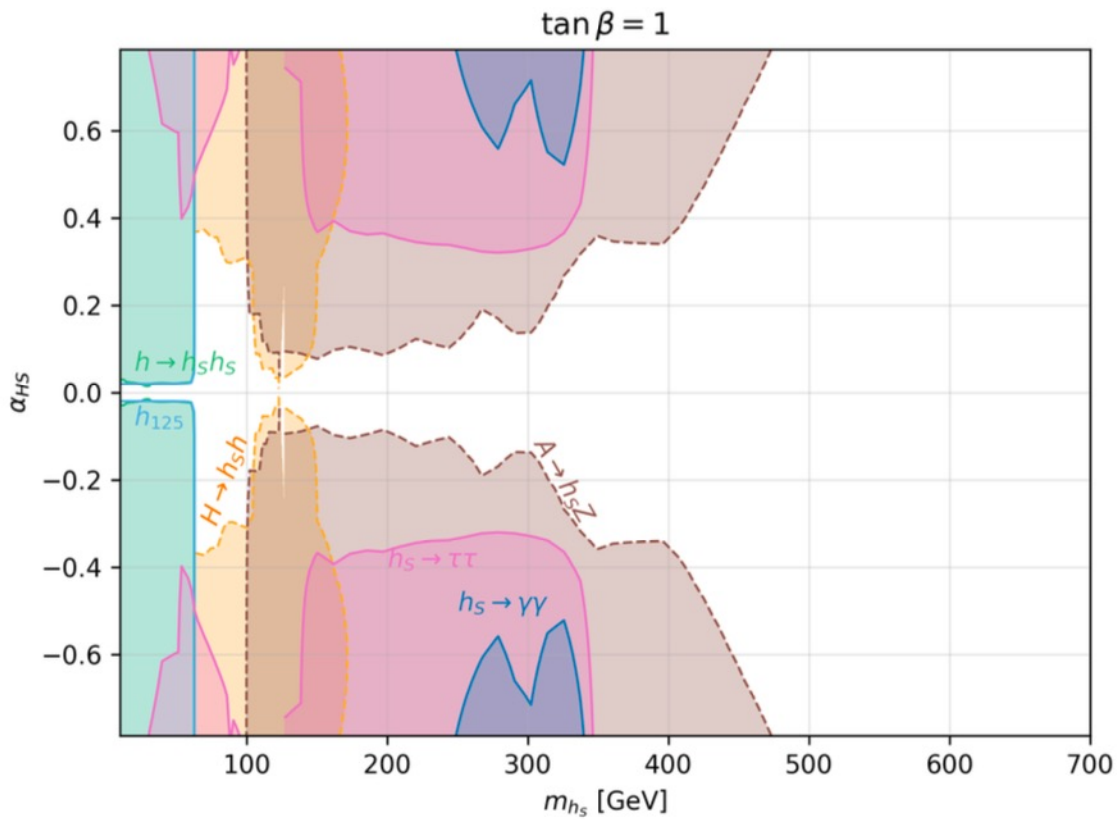
	Couplings	Case-0	Case-I	Case-II	Case-III	Case-IV
	$c_{h_iVV} = R_{i1}c_\beta + R_{i2}s_\beta$					
c_{HVV}	$c_{\beta-\alpha}c_{\alpha_{HS}}$	0	$c_{\beta-\alpha}$	0	0	0
c_{hVV}	$s_{\beta-\alpha}c_{\alpha_{hS}} - c_{\beta-\alpha}s_{\alpha_{HS}}s_{\alpha_{hS}}$	1	$s_{\beta-\alpha}$	$c_{\alpha_{hS}}$	1	1
c_{h_SVV}	$-s_{\beta-\alpha}s_{\alpha_{hS}} - c_{\beta-\alpha}s_{\alpha_{HS}}c_{\alpha_{hS}}$	0	0	$-s_{\alpha_{hS}}$	0	0
	$c_{a_ih_jZ} = R^A_{i1}R_{j1} + R^A_{i2}R_{j2}$					
c_{AHZ}	$-c_{\alpha_{AS}}c_{\alpha_{HS}}s_{\beta-\alpha}$	-1	$-s_{\beta-\alpha}$	-1	$-c_{\alpha_{HS}}$	$-c_{\alpha_{AS}}$
c_{AhZ}	$c_{\alpha_{AS}}\left(c_{\beta-\alpha}c_{\alpha_{hS}} + s_{\beta-\alpha}s_{\alpha_{HS}}s_{\alpha_{hS}}\right)$	0	$c_{\beta-\alpha}$	0	0	0
c_{Ah_SZ}	$-c_{\alpha_{AS}}\left(c_{\beta-\alpha}s_{\alpha_{hS}} - s_{\beta-\alpha}s_{\alpha_{HS}}c_{\alpha_{hS}}\right)$	0	0	0	$s_{\alpha_{HS}}$	0
c_{A_SHZ}	$s_{\alpha_{AS}}c_{\alpha_{HS}}s_{\beta-\alpha}$	0	0	0	0	$s_{\alpha_{AS}}$
c_{A_ShZ}	$-s_{\alpha_{AS}}\left(c_{\beta-\alpha}c_{\alpha_{hS}} + s_{\beta-\alpha}s_{\alpha_{HS}}s_{\alpha_{hS}}\right)$	0	0	0	0	0
$c_{A_Sh_SZ}$	$s_{\alpha_{AS}}\left(c_{\beta-\alpha}s_{\alpha_{hS}} - s_{\beta-\alpha}s_{\alpha_{HS}}c_{\alpha_{hS}}\right)$	0	0	0	0	0
	$c_{\phi_iH^\pm W^\mp} = R^\phi_{i2}c_\beta - R^\phi_{i1}s_\beta$					
$c_{HH^\pm W^\mp}$	$-ic_{\alpha_{HS}}s_{\beta-\alpha}$	-i	$-is_{\beta-\alpha}$	-i	$-ic_{\alpha_{HS}}$	-i
$c_{hH^\pm W^\mp}$	$i\left(c_{\beta-\alpha}c_{\alpha_{hS}} + s_{\beta-\alpha}s_{\alpha_{HS}}s_{\alpha_{hS}}\right)$	0	$ic_{\beta-\alpha}$	0	0	0
$c_{h_SH^\pm W^\mp}$	$-i\left(c_{\beta-\alpha}s_{\alpha_{hS}} - s_{\beta-\alpha}s_{\alpha_{HS}}c_{\alpha_{hS}}\right)$	0	0	0	$-is_{\alpha_{HS}}$	0
$c_{AH^\pm W^\mp}$	$c_{\alpha_{AS}}$	1	1	1	1	$c_{\alpha_{AS}}$
$c_{A_SH^\pm W^\mp}$	$-s_{\alpha_{AS}}$	0	0	0	0	$-s_{\alpha_{AS}}$
	$c_{\phi_i\phi_jVV} = R^\phi_{i1}R^\phi_{j1} + R^\phi_{i2}R^\phi_{j2}$					
c_{HHVV}	$c^2_{\alpha_{HS}}$	1	1	1	$c^2_{\alpha_{HS}}$	1
c_{hhVV}	$c^2_{\alpha_{hS}} + s^2_{\alpha_{HS}}s^2_{\alpha_{hS}}$	1	1	$c^2_{\alpha_{hS}}$	1	1
$c_{h_Sh_SVV}$	$c^2_{\alpha_{hS}}s^2_{\alpha_{HS}} + s^2_{\alpha_{hS}}$	0	0	$s^2_{\alpha_{hS}}$	$s^2_{\alpha_{HS}}$	0
c_{HhVV}	$-\frac{1}{2}s_{2\alpha_{HS}}s_{\alpha_{hS}}$	0	0	0	0	0
c_{Hh_SVV}	$-\frac{1}{2}s_{2\alpha_{HS}}c_{\alpha_{hS}}$	0	0	0	$-\frac{1}{2}s_{2\alpha_{HS}}$	0
c_{hh_SVV}	$-\frac{1}{2}c^2_{\alpha_{HS}}s_{2\alpha_{hS}}$	0	0	$-\frac{1}{2}s_{2\alpha_{hS}}$	0	0
c_{AAVV}	$c^2_{\alpha_{AS}}$	1	1	1	1	$c^2_{\alpha_{AS}}$
$c_{A_SA_SVV}$	$s^2_{\alpha_{AS}}$	0	0	0	0	$s^2_{\alpha_{AS}}$
c_{AA_SVV}	$-\frac{1}{2}s_{2\alpha_{AS}}$	0	0	0	0	$-\frac{1}{2}s_{2\alpha_{AS}}$
$c_{H^\pm H^\mp Z}$		1	1	1	1	1
$c_{H^\pm H^\mp\gamma}$		1	1	1	1	1
$c_{H^\pm H^\mp VV}$		1	1	1	1	1
Relavant mixing		—	H, h	h, h_S	H, h_S	A, A_S

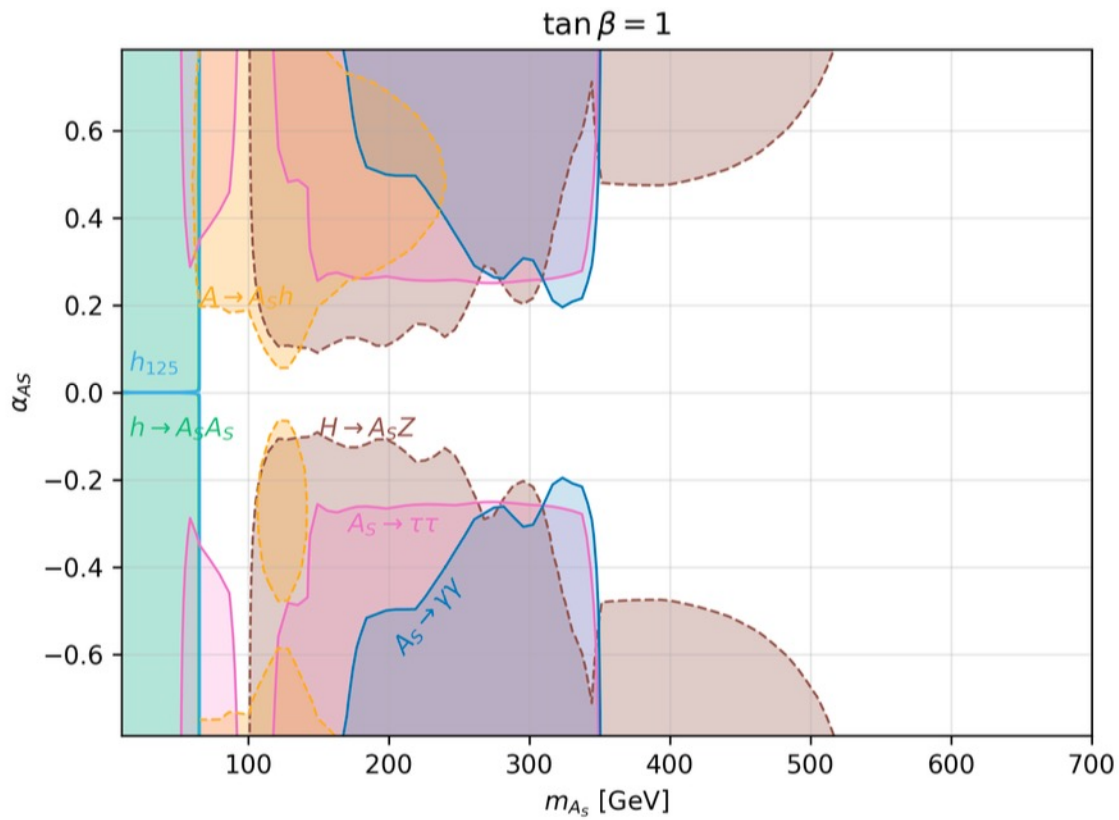
Table 2. The couplings between Higgs bosons and gauge bosons in 2HDM+S.

$\tan\beta$ - α_i

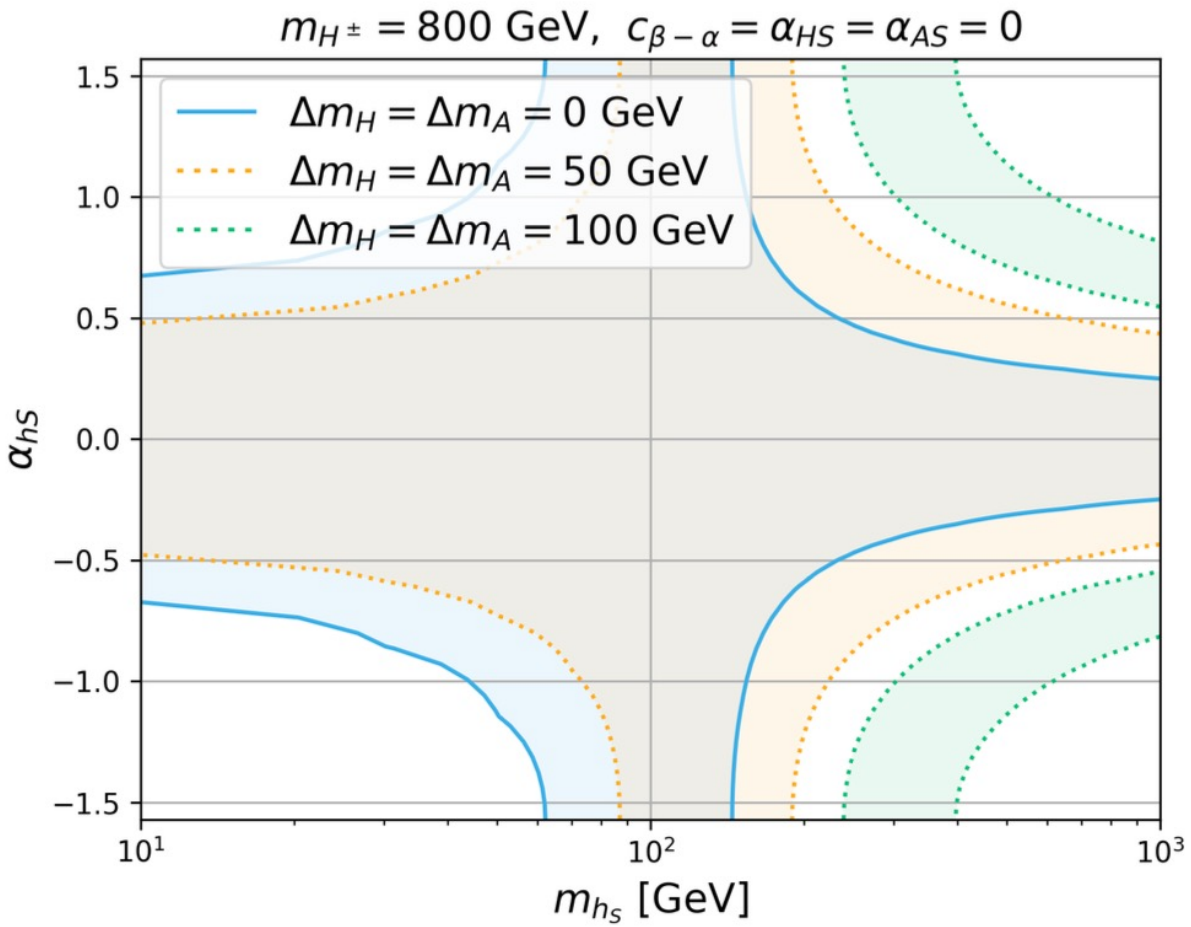


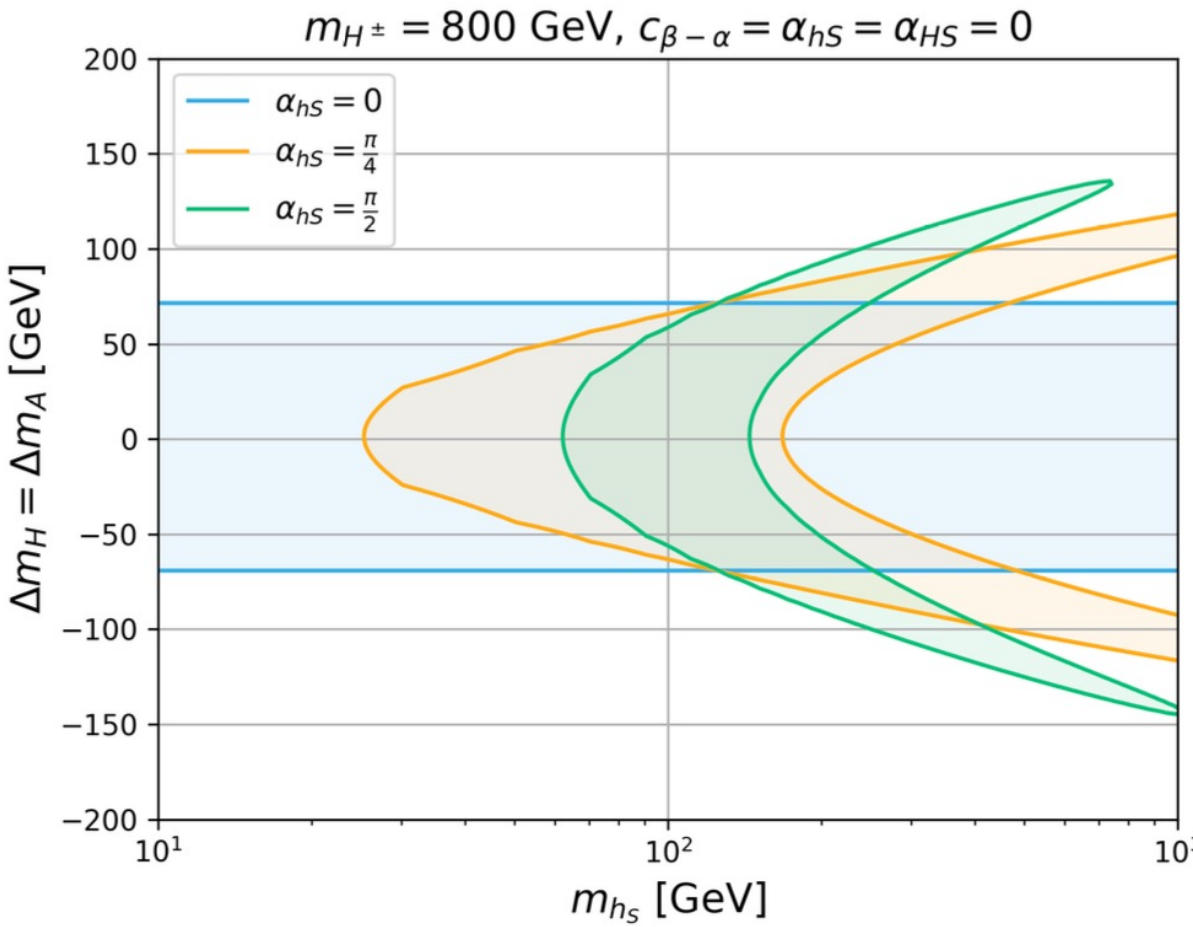
α_i - m_{h_i}


tan β = 1
α_HS
m_hs [GeV]
h → h_S h_S
h_125
H → h_S h
A → h_S Z
h_S → ττ
h_S → γγ

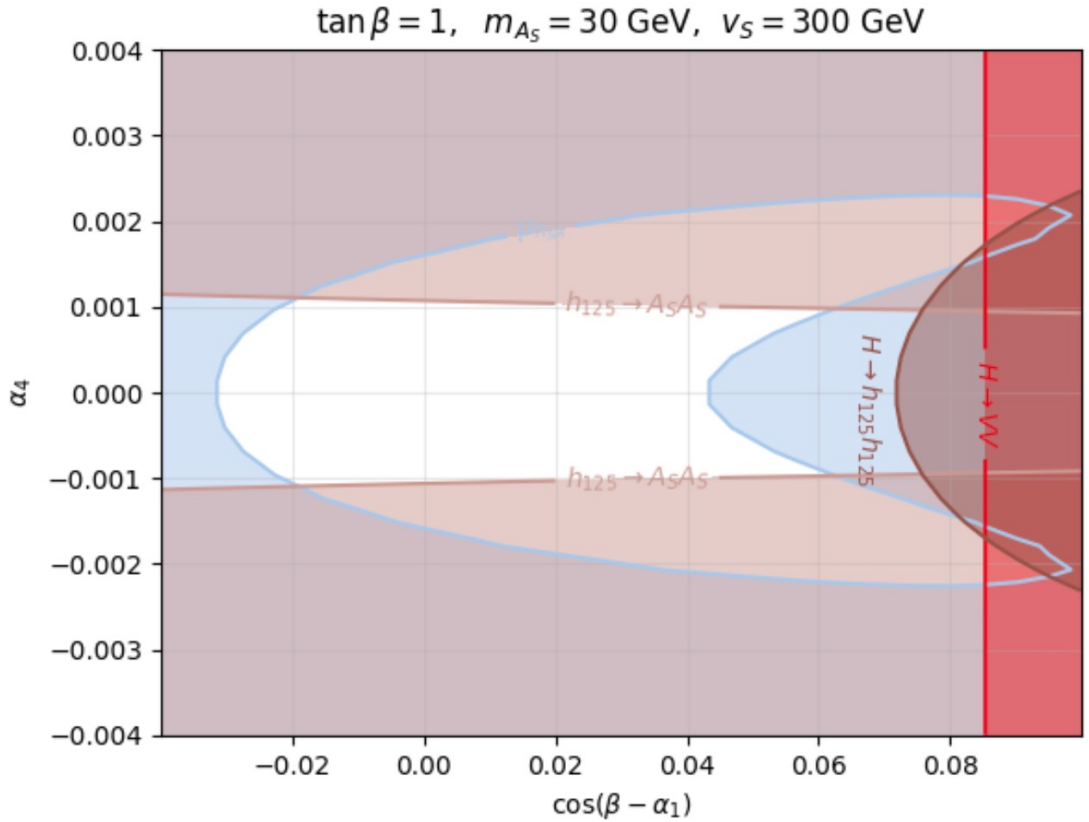

tan β = 1
α_AS
m_As [GeV]
A → A_S h
h_125
h → A_S A_S
H → A_S Z
A_S → ττ
A_S → γγ

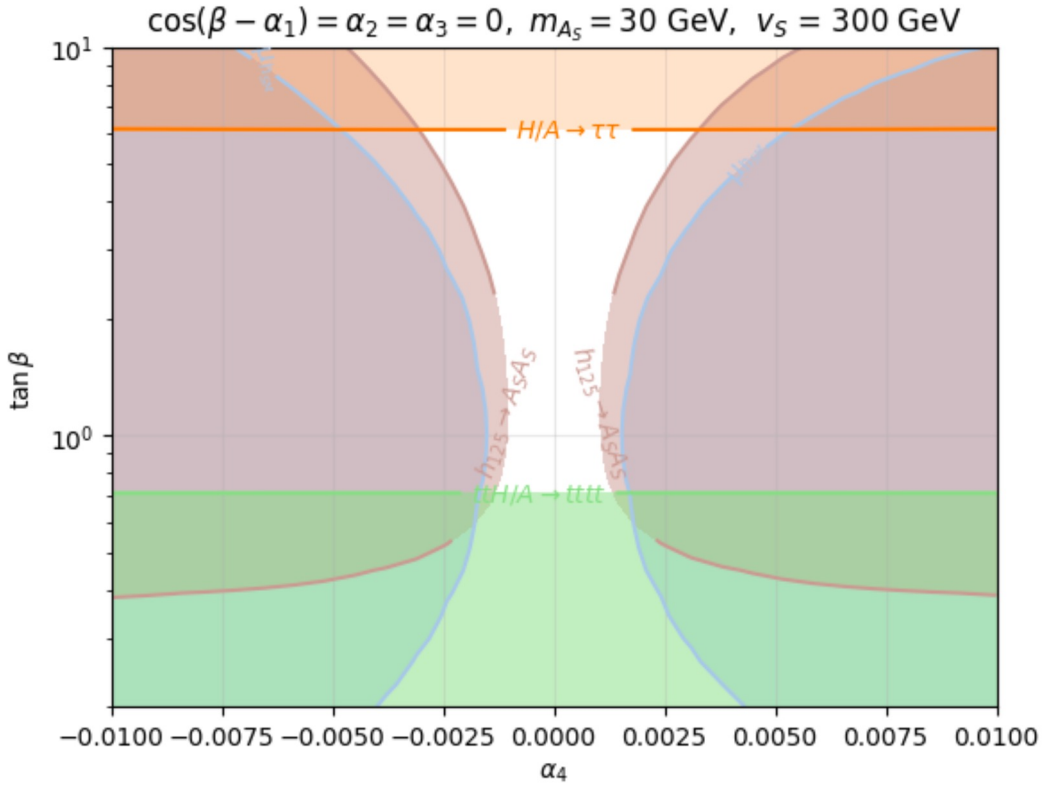
Results


$m_{H^\pm} = 800$ GeV, $c_{\beta-\alpha} = \alpha_{HS} = \alpha_{AS} = 0$
$\Delta m_H = \Delta m_A = 0$ GeV
$\Delta m_H = \Delta m_A = 50$ GeV
$\Delta m_H = \Delta m_A = 100$ GeV
α_{hS}
m_{h_S} [GeV]


$m_{H^\pm} = 800$ GeV, $c_{\beta-\alpha} = \alpha_{hS} = \alpha_{HS} = 0$
$\alpha_{hS} = 0$
$\alpha_{hS} = \frac{\pi}{4}$
$\alpha_{hS} = \frac{\pi}{2}$
$\Delta m_H = \Delta m_A$ [GeV]
m_{h_S} [GeV]

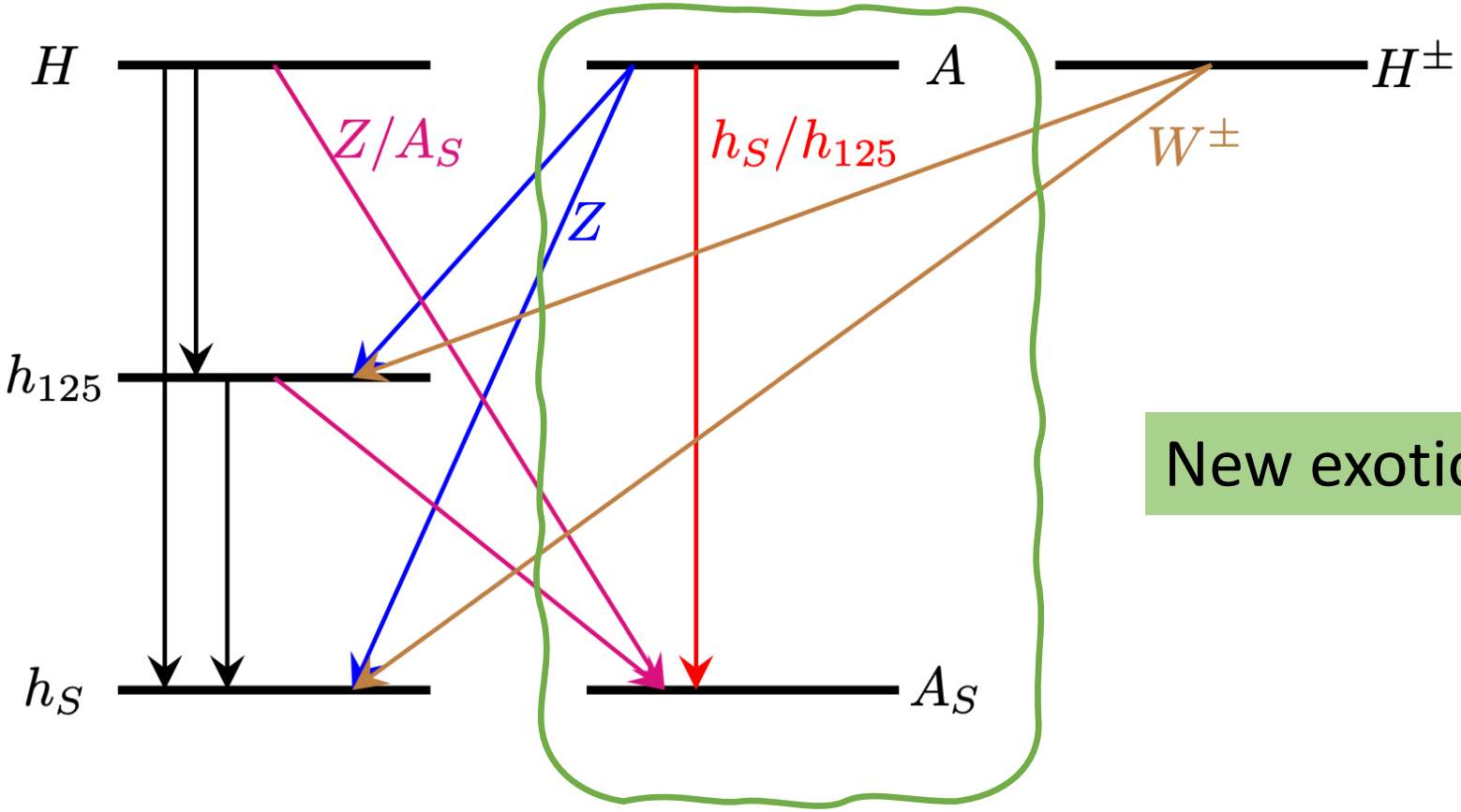
2HDM+singlet





2HDM+singlet

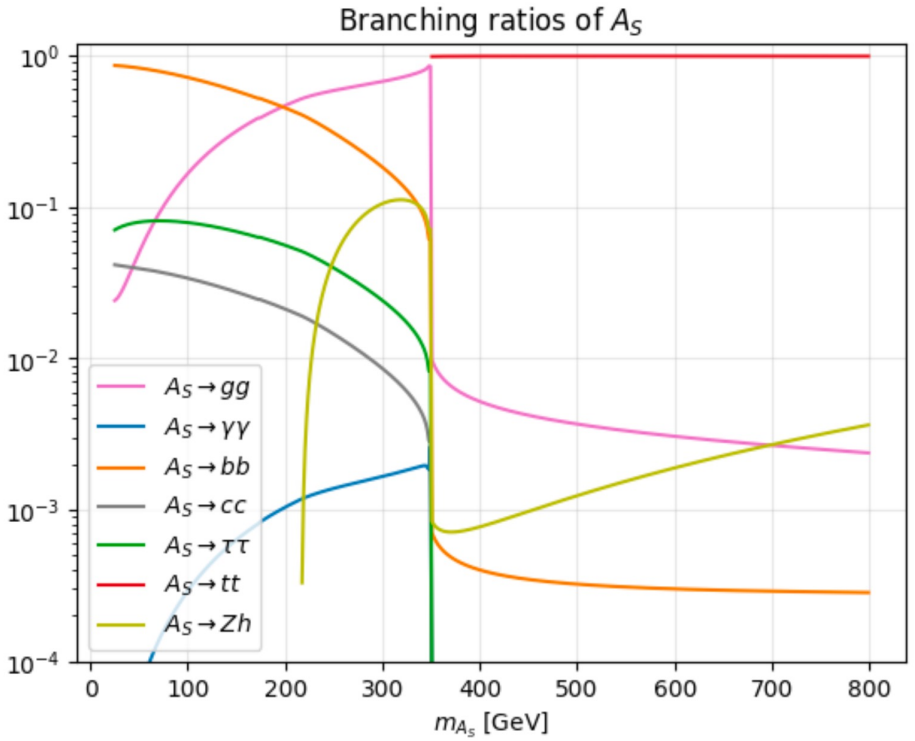
- The scenario with lighter singlet Higgs

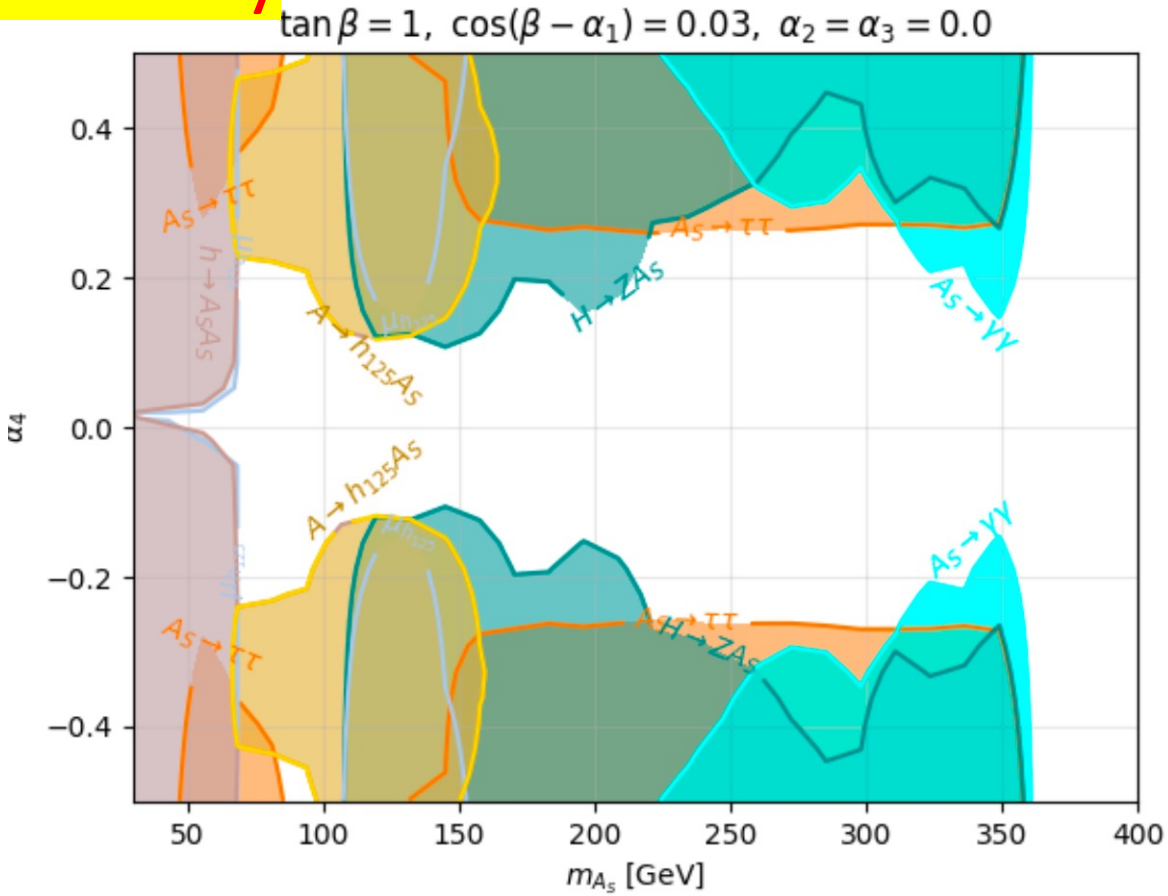


New exotic channels

Results : A_S

Preliminary





$$\alpha_4 = 0$$

2HDM+singlet

$$V_{\rm 2HDM+S} = V_{\rm 2HDM} + V_{\rm S}.$$

Soft Z_2 Symmetry Breaking

$$\begin{aligned}
V_{\rm 2HDM} =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\
& + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
& + (\Phi_1^\dagger \Phi_2) \left(\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2) + \lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2) \right) + \text{h.c.}.
\end{aligned}$$

FCNC: Z_2 Symmetry

$$\begin{aligned}
V_{\rm S} =& m_S^2 S^\dagger S + \frac{m_S'^2}{2} (S^2 + \text{h.c.}) + \left(\frac{\mu_{S1}}{3!} S^3 + \frac{\mu_{S2}}{2} S (S^\dagger S) \right. \\
& \left. + S \left[\mu_{11} \Phi_1^\dagger \Phi_1 + \mu_{22} \Phi_2^\dagger \Phi_2 + \mu_{12} \Phi_1^\dagger \Phi_2 + \mu_{21} \Phi_2^\dagger \Phi_1 \right] + \text{h.c.} \right) \\
& + S^\dagger S \left(\lambda_1' \Phi_1^\dagger \Phi_1 + \lambda_2' \Phi_2^\dagger \Phi_2 - \lambda_3' \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) \\
& + \left[S^2 \left(\lambda_4' \Phi_1^\dagger \Phi_1 + \lambda_5' \Phi_2^\dagger \Phi_2 - \lambda_6' \Phi_1^\dagger \Phi_2 + \lambda_7' \Phi_2^\dagger \Phi_1 \right) + \text{h.c.} \right] \\
& + \left(\frac{\lambda_1''}{4!} S^4 + \frac{\lambda_2''}{3!} S^2 (S^\dagger S) + \text{h.c.} \right) + \frac{\lambda_3''}{4} (S^\dagger S)^2.
\end{aligned}$$

2HDM+singlet

$$V_{\rm 2HDM+S} = V_{\rm 2HDM} + V_{\rm S}.$$

$$\begin{aligned}
V =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\
& + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} \left((\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right) \\
& + m_S^2 S^\dagger S + \frac{m_S'^2}{2} (S^2 + \text{h.c.}) + \left(\frac{\mu_{S1}}{3!} S^3 + \mu_{12} S \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) \\
& + S^\dagger S \left(\lambda_1' (\Phi_1^\dagger \Phi_1) + \lambda_2' (\Phi_2^\dagger \Phi_2) \right) + \left[S^2 \left(\lambda_4' (\Phi_1^\dagger \Phi_1) + \lambda_5' (\Phi_2^\dagger \Phi_2) \right) + \text{h.c.} \right] \\
& + \left(\frac{\lambda_1''}{4!} S^4 + \frac{\lambda_2''}{3!} S^2 (S^\dagger S) + \text{h.c.} \right) + \frac{\lambda_3''}{4} (S^\dagger S)^2 .
\end{aligned}$$

Models	Symmetries	
$\mathbb{Z}_2'$[11]	$S \to -S$	$\mu_{S1} = \mu_{12} = 0$
U(1)[17]	$S \to e^{i\delta} S$	$\lambda_1'' = \lambda_2'' = \lambda_4' = \lambda_5' = \mu_{S1} = \mu_{12} = 0$
$\mathbb{Z}_3$[18]	$\Phi_2 \to e^{i2\pi/3} \Phi_2,\ S \to e^{-2i\pi/3} S$	$\lambda_5 = m_S' = \lambda_1'' = \lambda_2'' = \lambda_4' = \lambda_5' = 0$

Table 1. Matching conditions to various singlet extended 2HDM