The electroweak precision constraints of the 2HDM+S

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Brief Introduction： 2HDMS

- ✓ Electroweak precision
- ✓ Higgs precision
- ✓ Direct searches
- ✓ …

2HDMS

$$\Phi_1 = \begin{pmatrix} \chi_1^+ \\ \frac{\rho_1 + i\eta_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \chi_2^+ \\ \frac{\rho_2 + i\eta_2}{\sqrt{2}} \end{pmatrix}, \qquad S = \frac{\rho_S + i\eta_S}{\sqrt{2}},$$

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

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

2HDM+singlet

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\alpha_{hS}} & s_{\alpha_{hS}} \\ 0 & -s_{\alpha_{hS}} & c_{\alpha_{hS}} \end{pmatrix} \begin{pmatrix} c_{\alpha_{HS}} & 0 & s_{\alpha_{HS}} \\ 0 & 1 & 0 \\ -s_{\alpha_{HS}} & 0 & c_{\alpha_{HS}} \end{pmatrix} \begin{pmatrix} c_{\alpha} & s_{\alpha} & 0 \\ -s_{\alpha} & c_{\alpha} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

SM – singlet

Non-SM – singlet

Doublet mixing

SM limit of 2HDMS

$$\cos(\beta - \alpha_1) = 0, \ \alpha_3 = 0.$$

$$R^A = \begin{pmatrix} c_{\alpha_{AS}} & s_{\alpha_{AS}} \\ -s_{\alpha_{AS}} & c_{\alpha_{AS}} \end{pmatrix}$$

A - A_S

2HDM limit of 2HDMS

$$\alpha_2 = \alpha_3 = \alpha_4 = 0$$

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

Electroweak Precision: Oblique

- Only relevant to boson couplings

$h_i VV,\ h_i a_j Z,$
$h_i/a_i H^{\pm} W^{\mp}$
$Z/\gamma H^{\pm} H^{\mp}$

$H^{\pm} H^{\mp} VV$
$h_i h_i VV,\ a_i a_i VV$

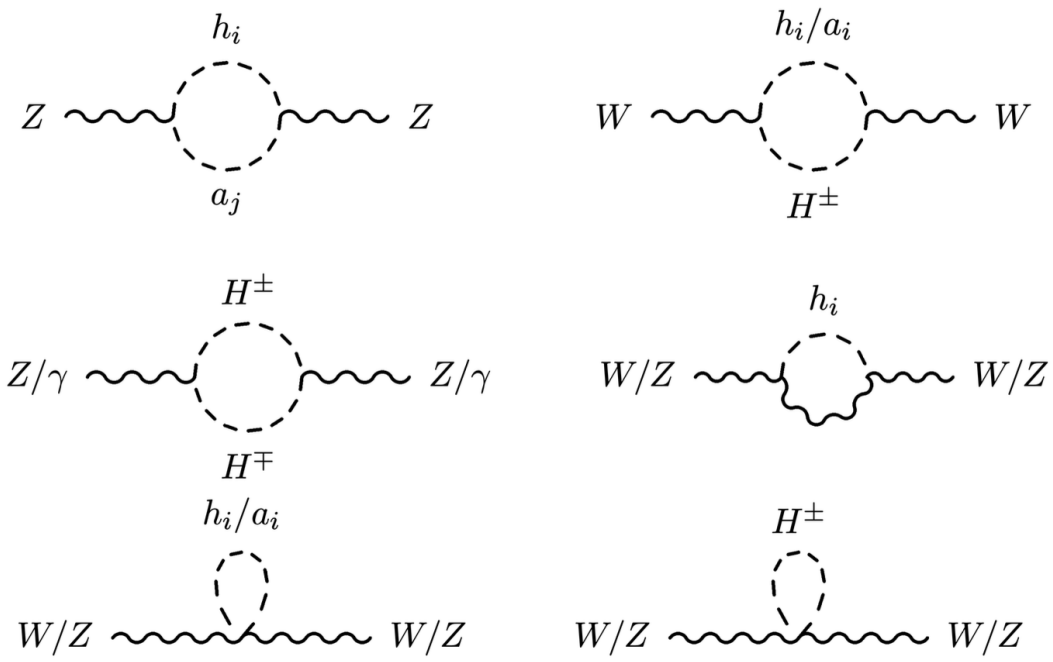


Figure 1. Feynman diagrams that contribute to the self energy of the SM gauge bosons.

Electroweak Precision

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}

Table 1. Five benchmark cases for the mixing angles configuration.

- Only relevant to boson 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

Case-0 & Case-I

$$T_0 = \frac{1}{16\pi s_W^2 m_W^2}[F(m_{H^\pm}^2, m_H^2) - F(m_A^2, m_H^2) + F(m_{H^\pm}^2, m_A^2)],$$

$$S_0 = \frac{1}{24\pi}[(2s_W^2 - 1)^2 G(m_{H^\pm}^2, m_{H^\pm}^2, m_Z^2) + G(m_A^2, m_H^2, m_Z^2) + \ln\left(\frac{m_H^2}{m_{H^\pm}^2}\right) + \ln\left(\frac{m_A^2}{m_{H^\pm}^2}\right)]$$

2HDM alignment limit

2HDM limit

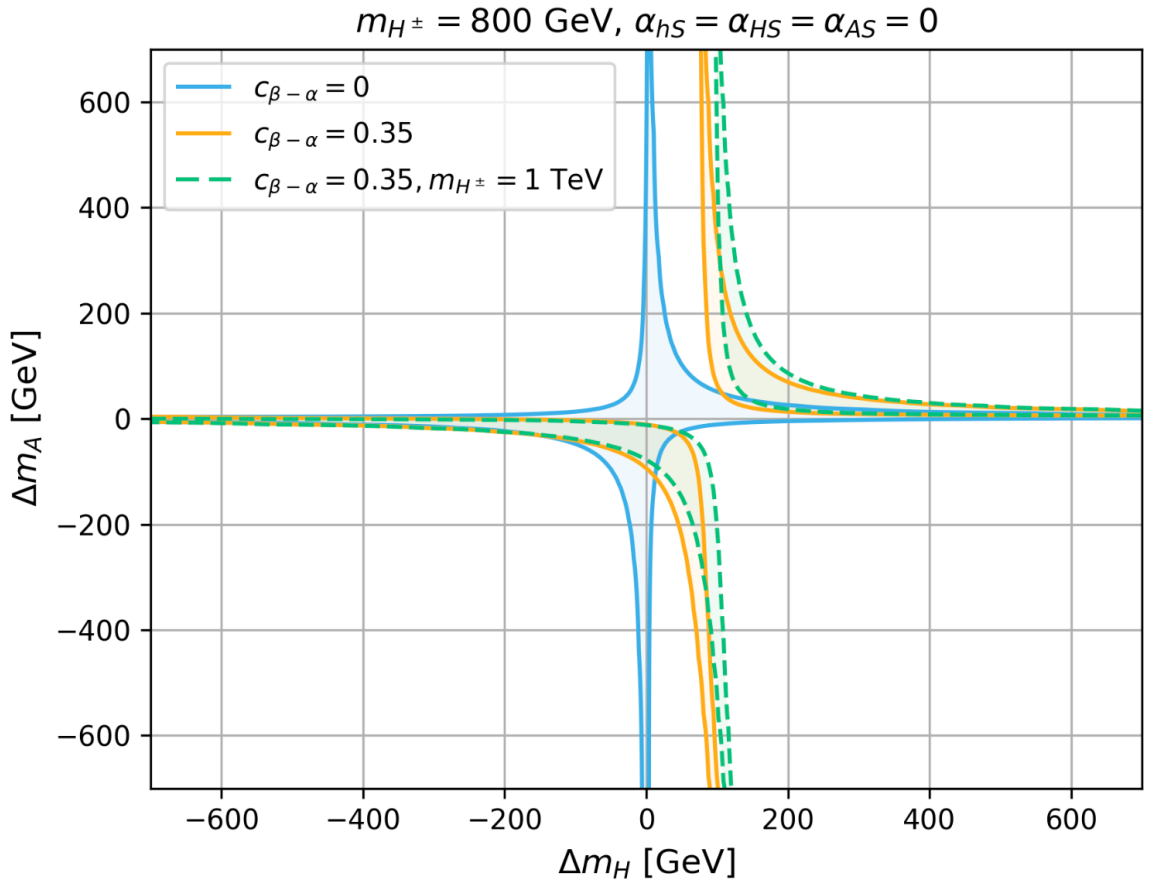
$$\alpha_{hS} = \alpha_{HS} = \alpha_{AS} = 0$$

$$\Delta m_H = m_H - m_{H^\pm},$$

$$\Delta m_{h_S} = m_{h_S} - m_{H^\pm},$$

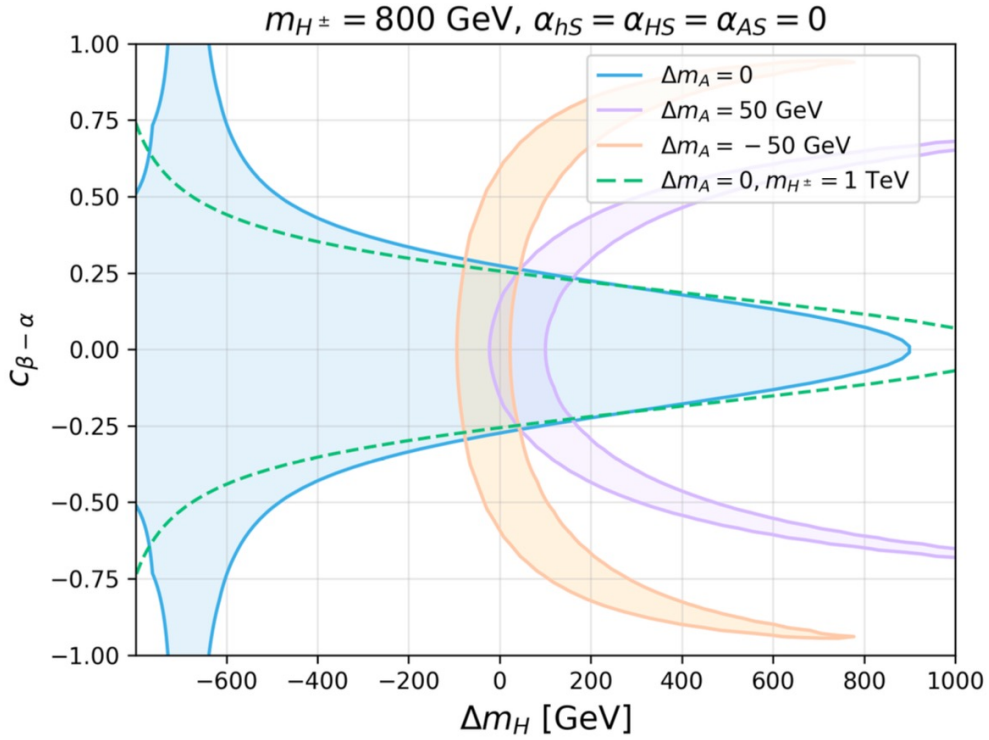
$$\Delta m_A = m_A - m_{H^\pm},$$

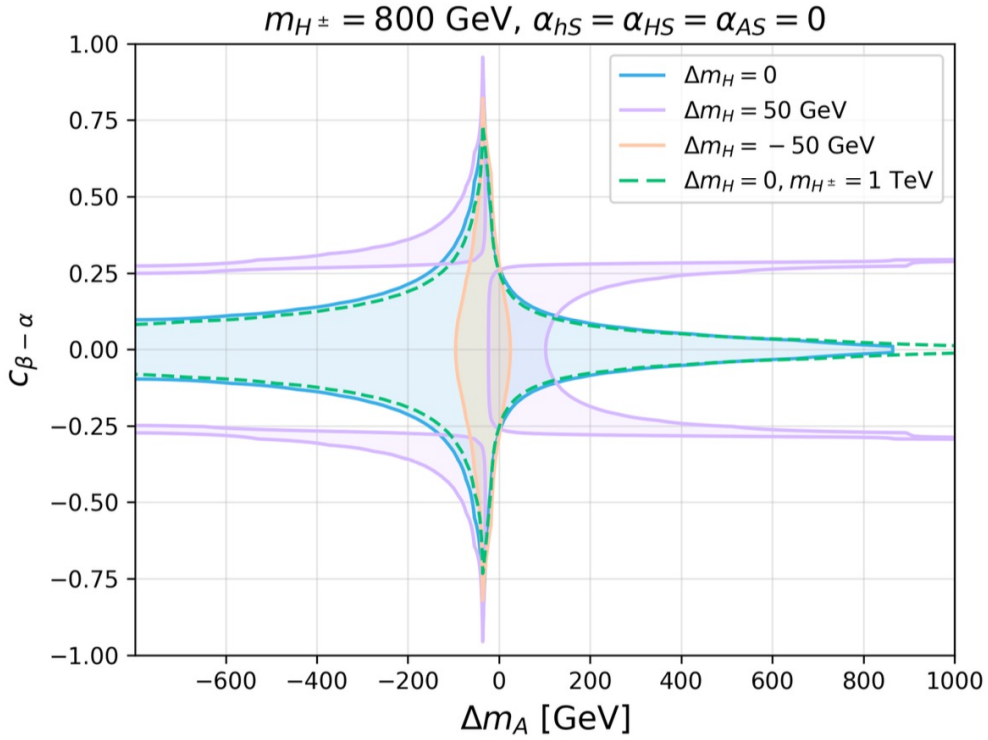
$$\Delta m_{A_S} = m_{A_S} - m_{H^\pm}.$$



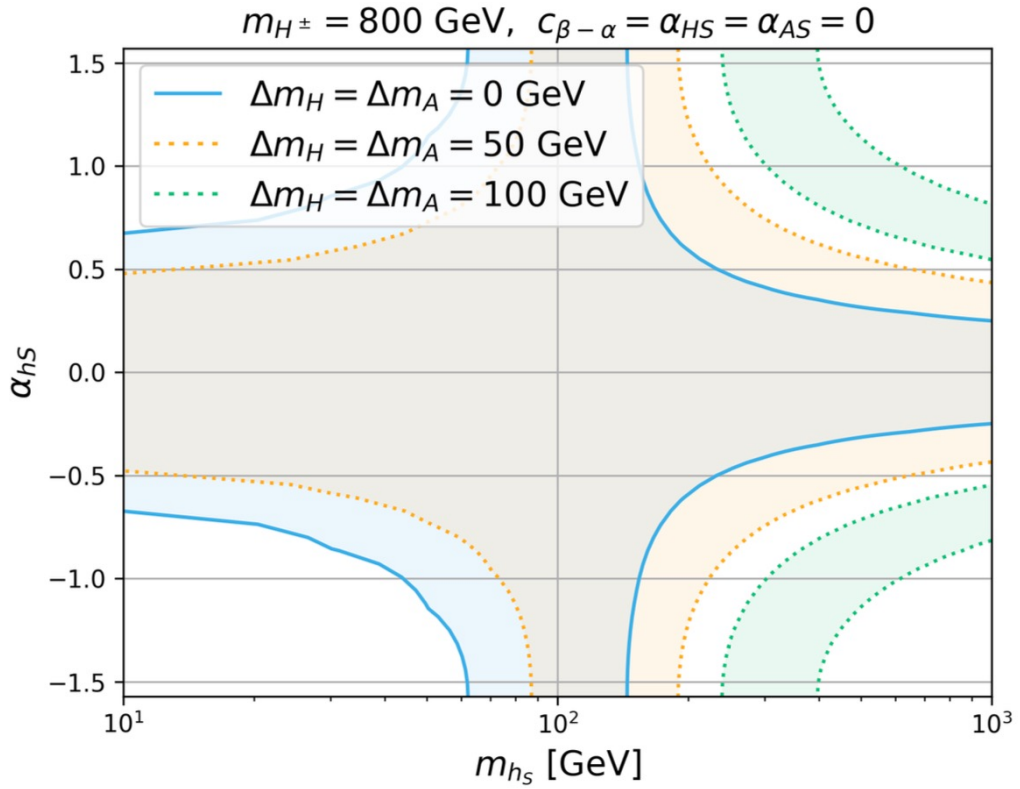
Case-0 & Case-I

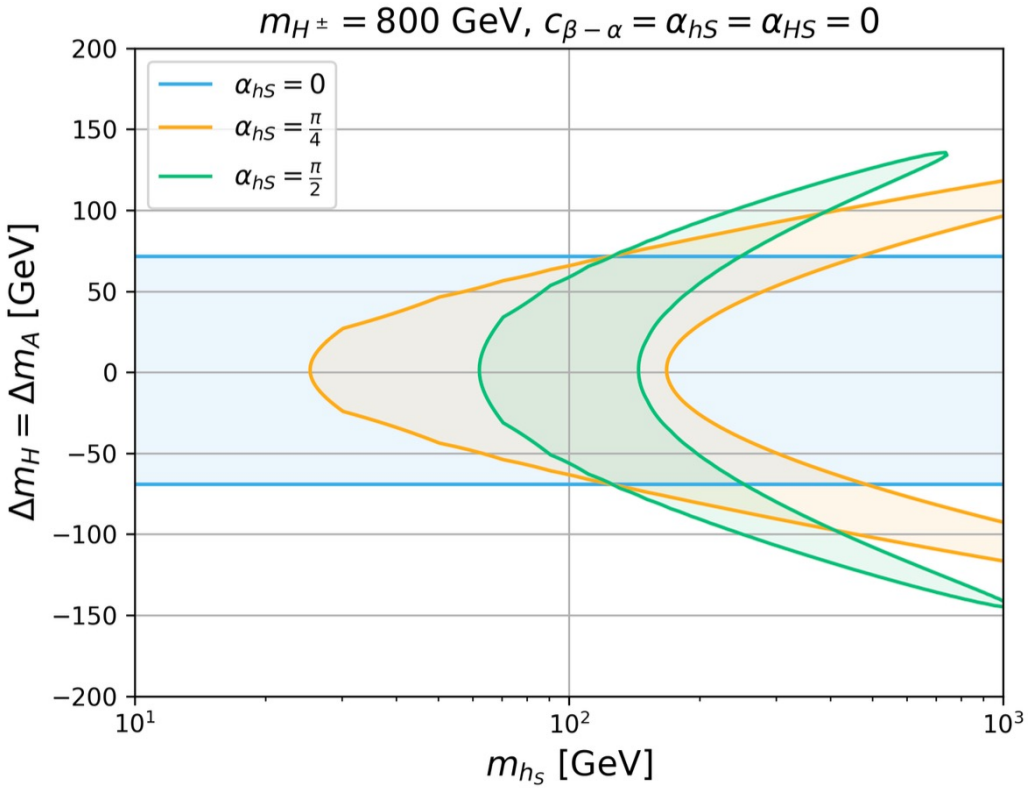
upper limit of Δm_H or Δm_A



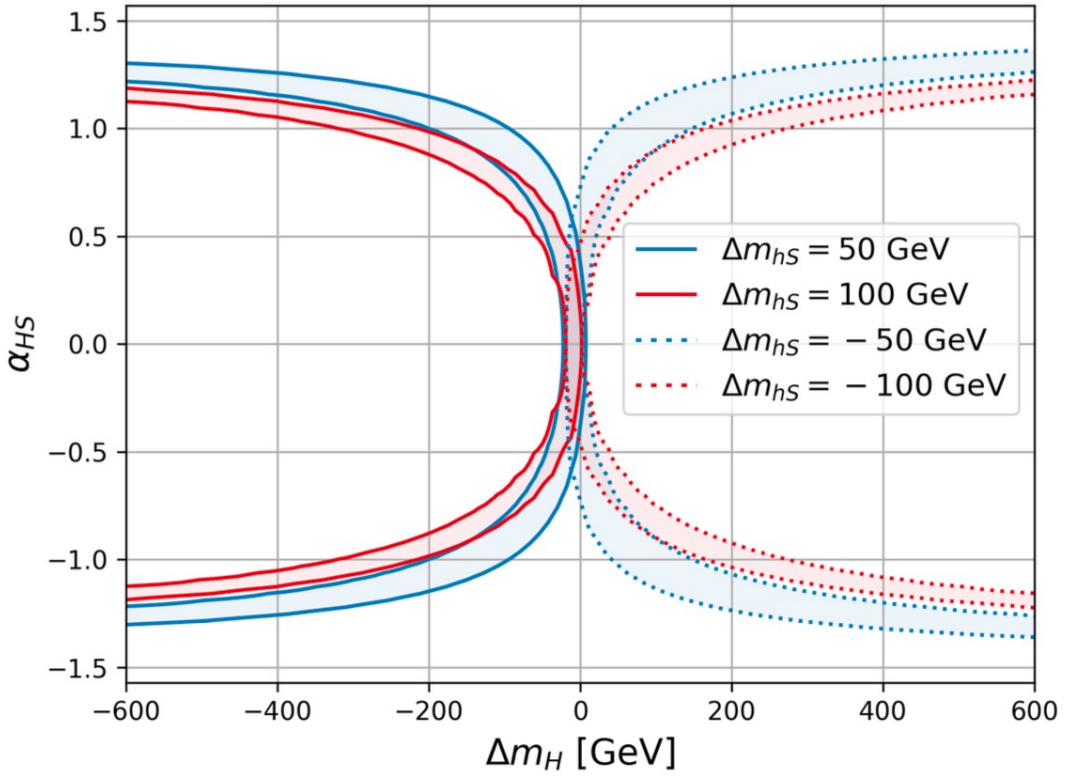


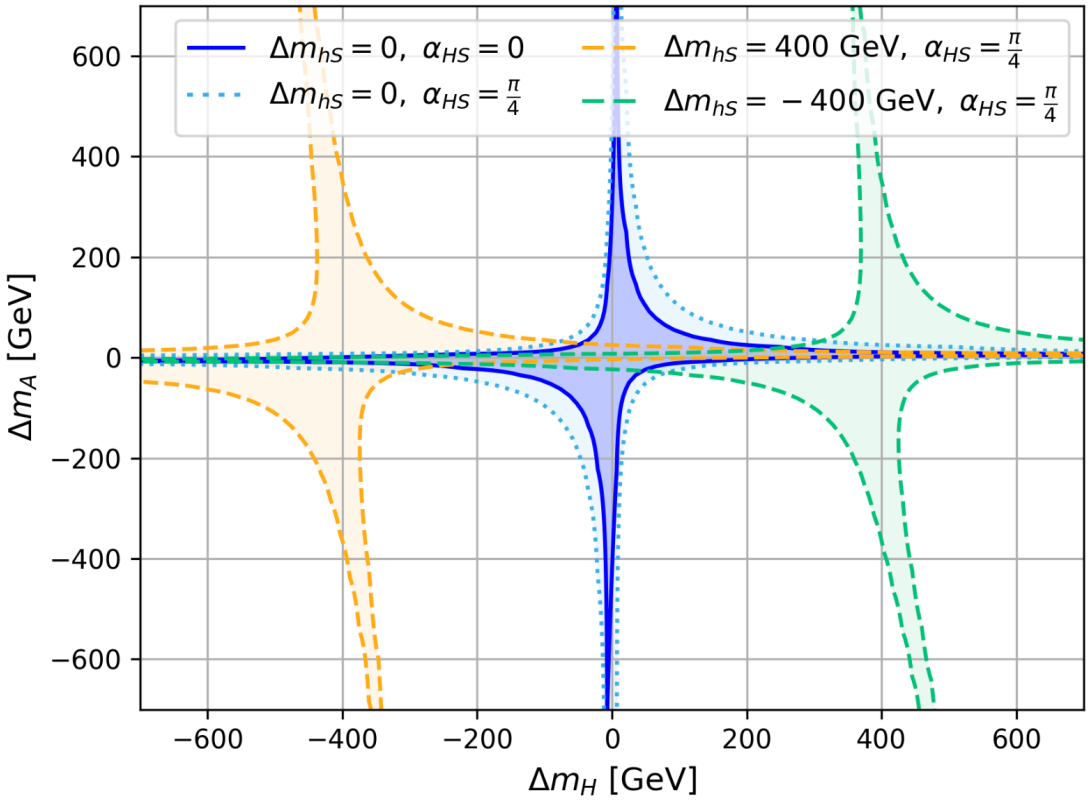
Case-II: $\alpha_{hS} \neq 0$ and $c_{\beta-\alpha} = \alpha_{HS} = \alpha_{AS} = 0$





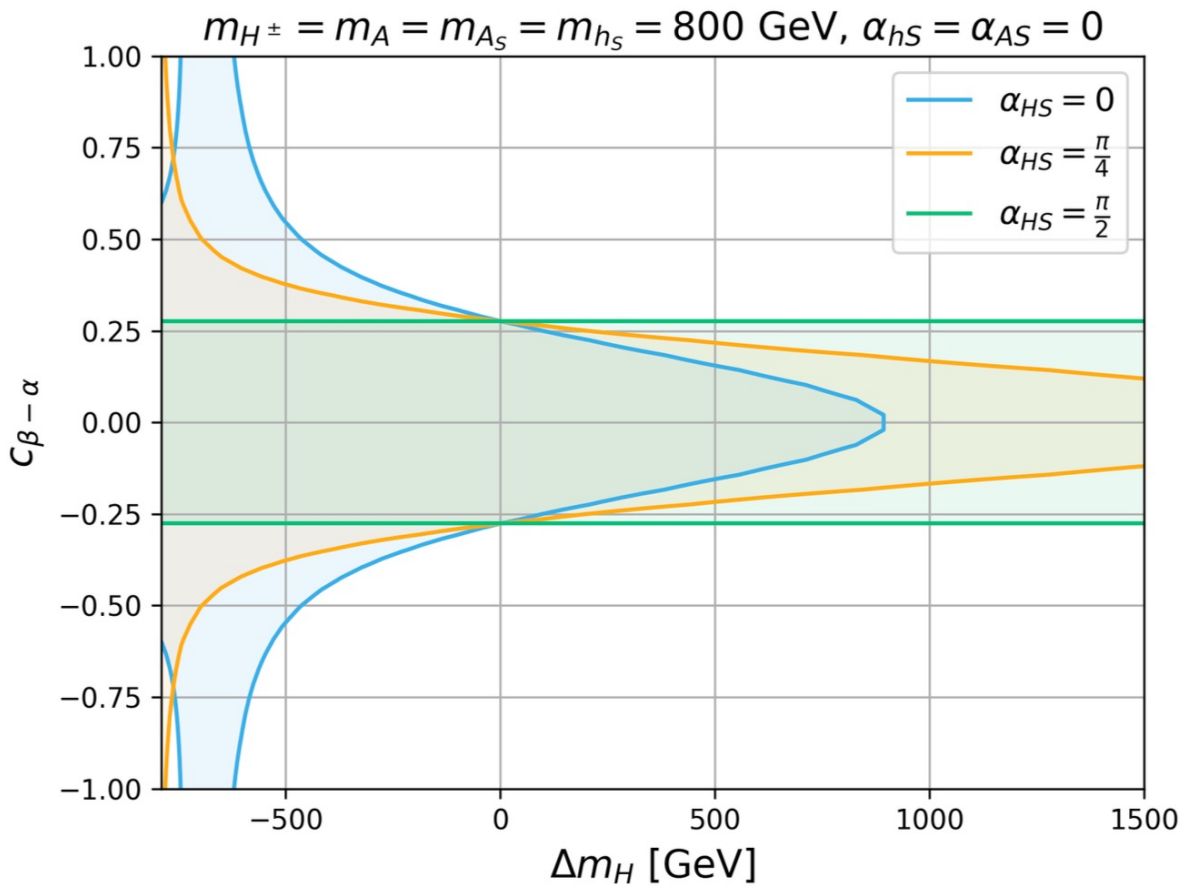
Case-III : $\alpha_{HS} \neq 0$ & Case-IV: $\alpha_{AS} \neq 0$

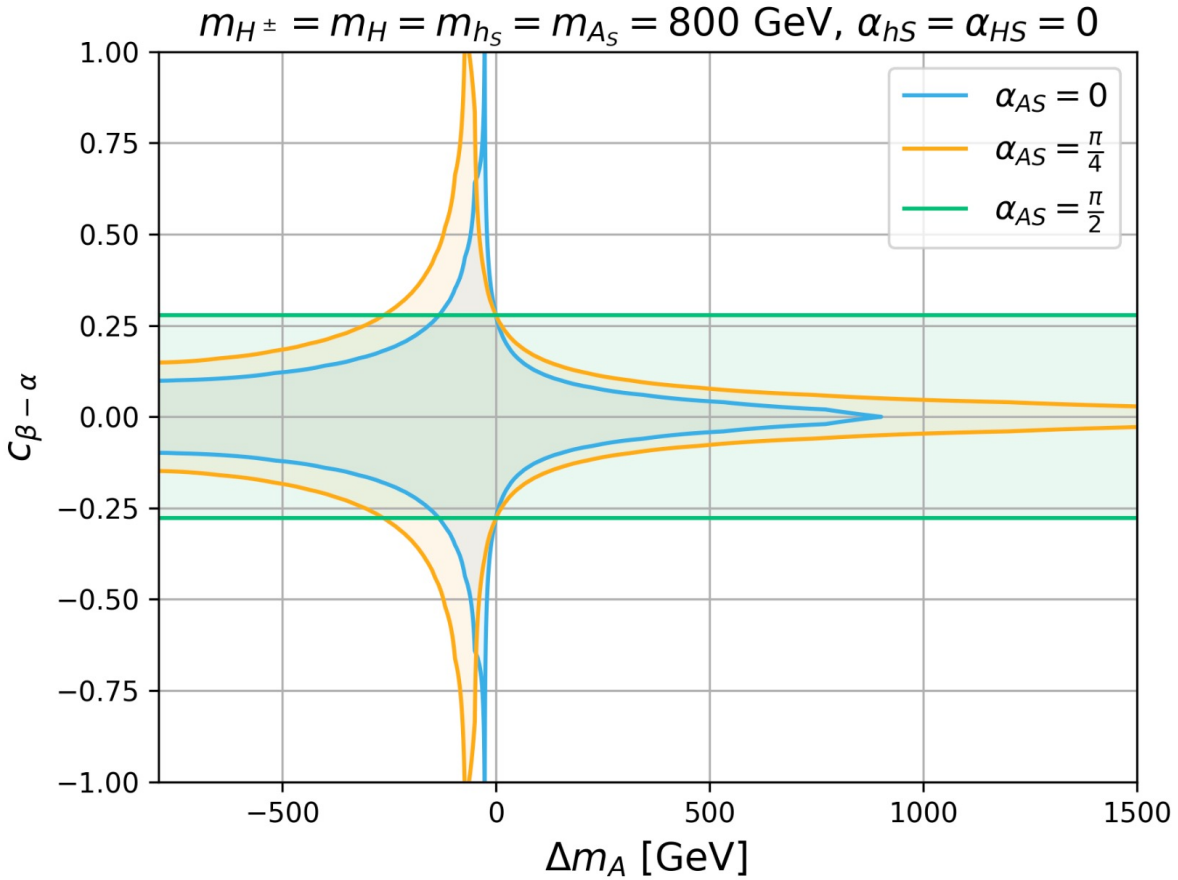




$$c^2_{\alpha_{HS}} m_H + s^2_{\alpha_{HS}} m_{h_S} = m_{H^\pm}, \quad \text{or } m_A = m_{H^\pm}.$$

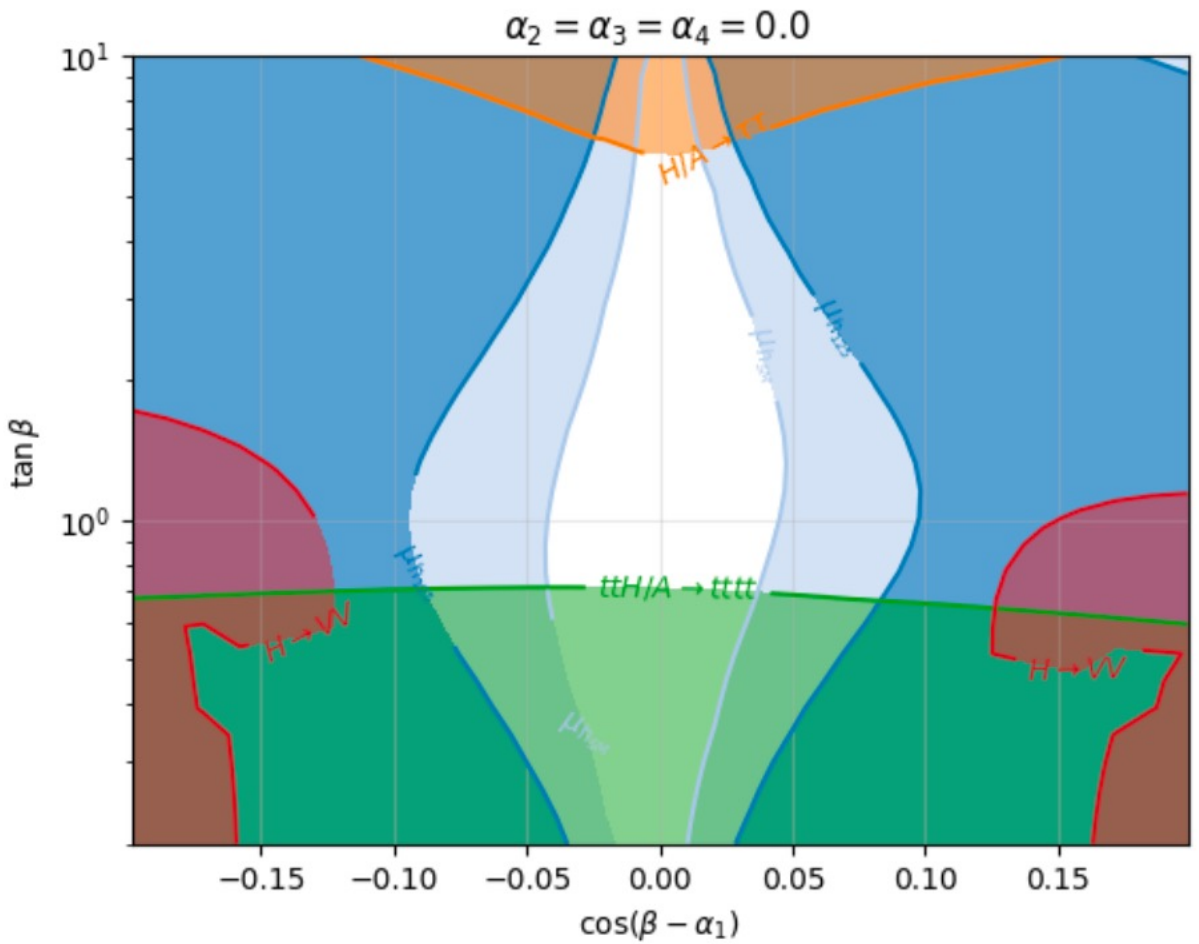
Beyond the alignment limit

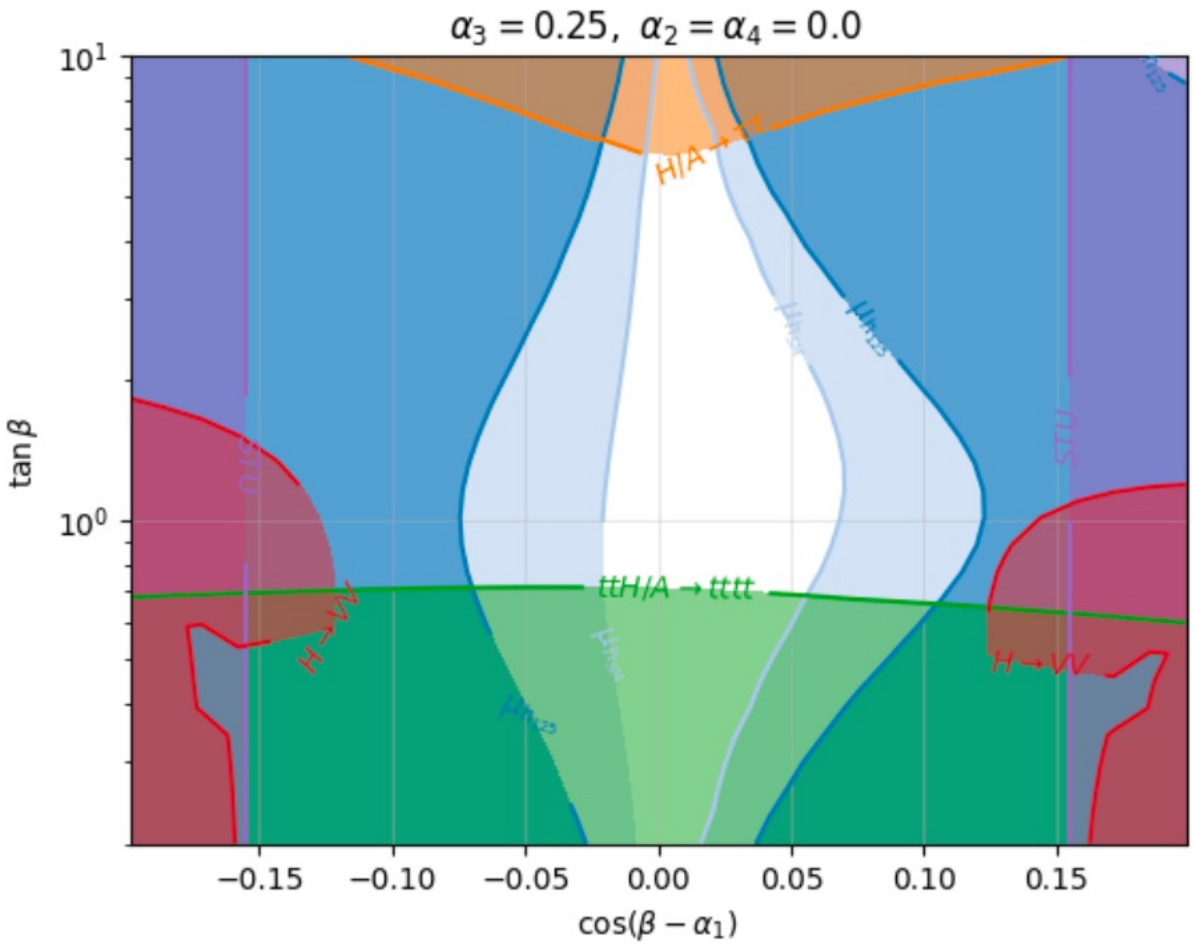




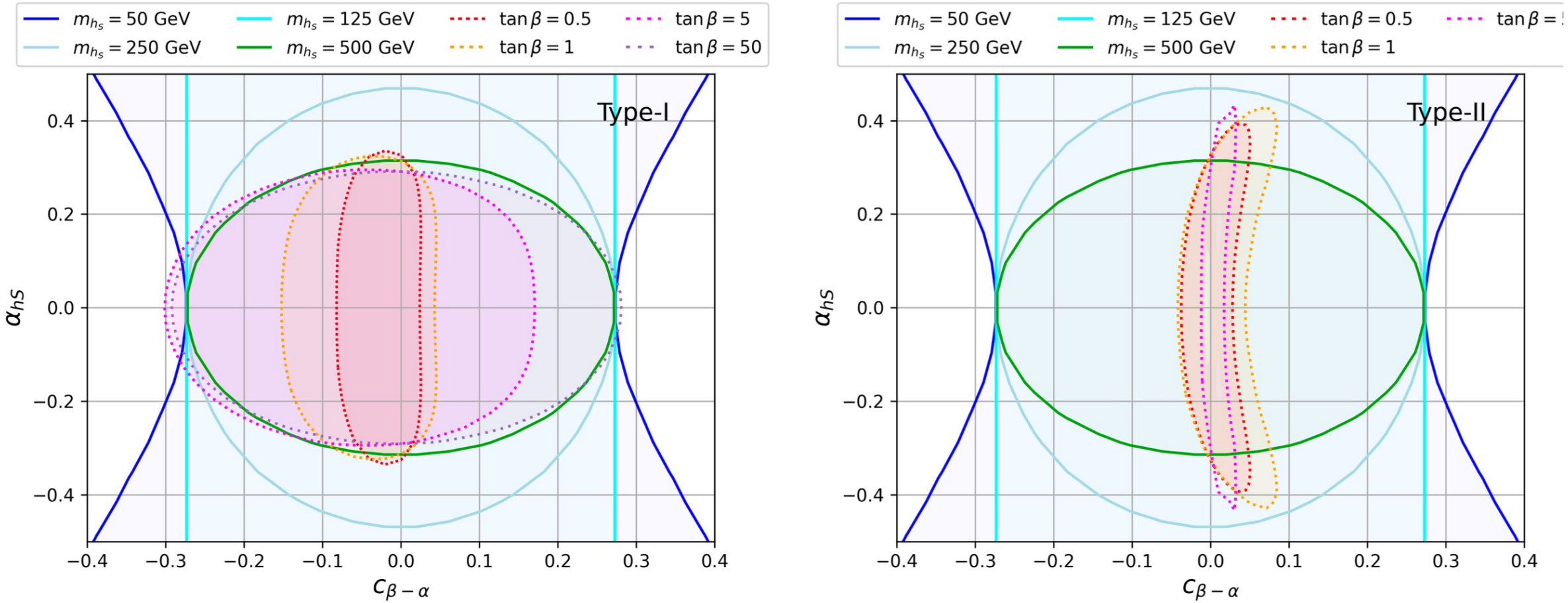
2HDMS: Higgs precision

$$m_{h_S} = m_{a_S} = 1500 \text{ GeV}$$

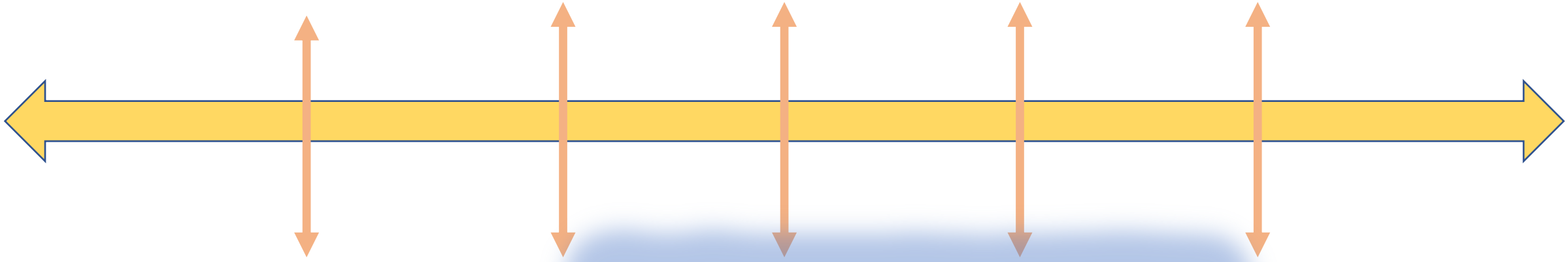




Electroweak + Higgs precision



2HDMS @ direct search



Mass hierarchy

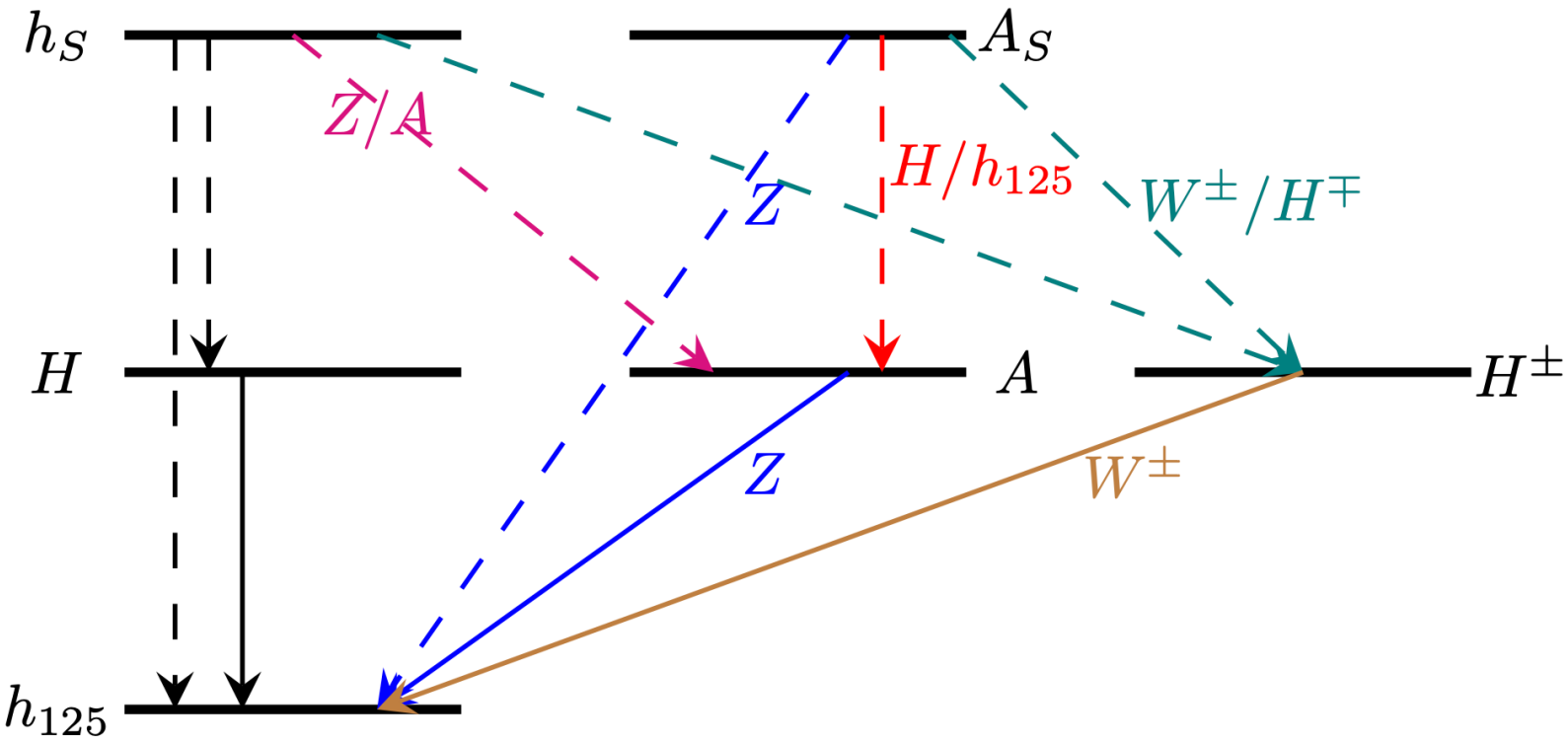
- $m_{h_S} < 0.1$ GeV
- 0.1 GeV$< m_{h_S} <$ 10 GeV
- 10 GeV $< m_{h_S} <$ 62.5 GeV
- 62.5 GeV $< m_{h_S} <$ 1 TeV
- 1 TeV $< m_{h_S} <$ 10TeV
- 10 TeV $< m_{h_S}$

LHC era

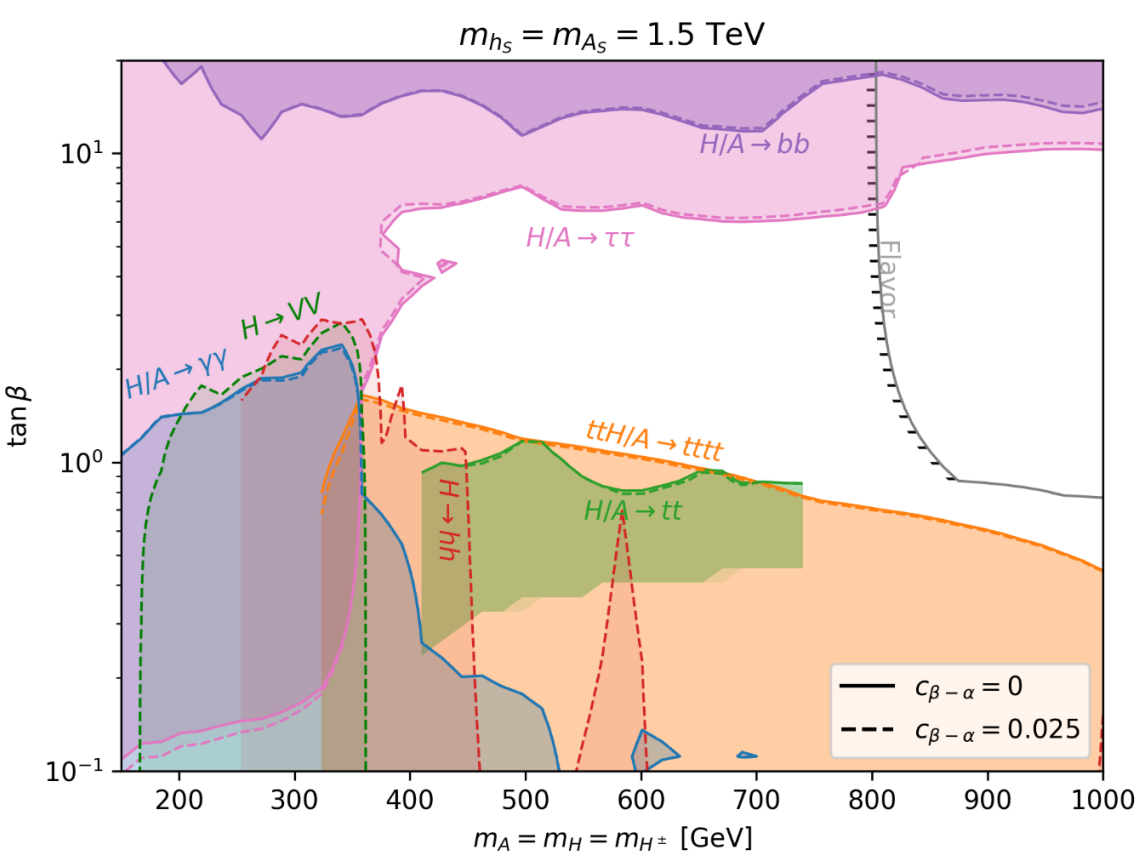
2HDMS: Higgs sector

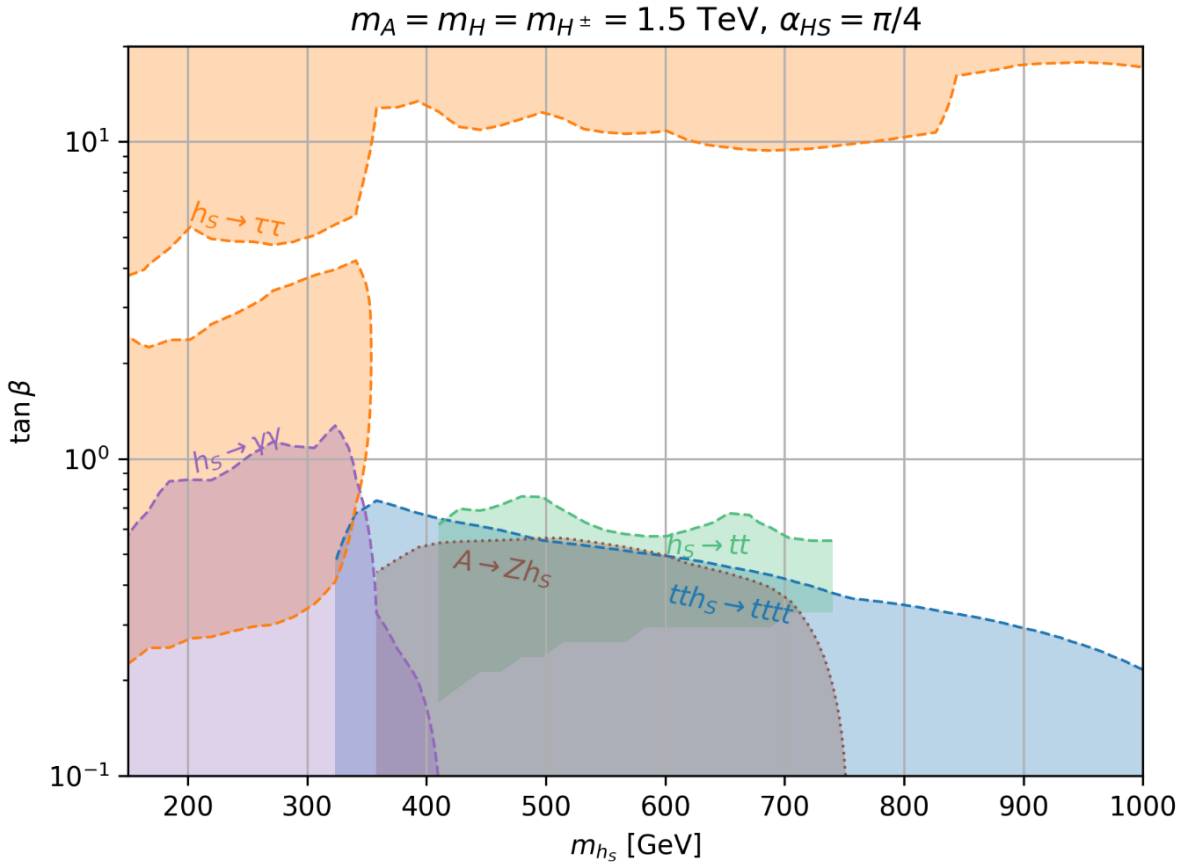
- The scenario with heavier singlet Higgs

Type-II like 2HDMS



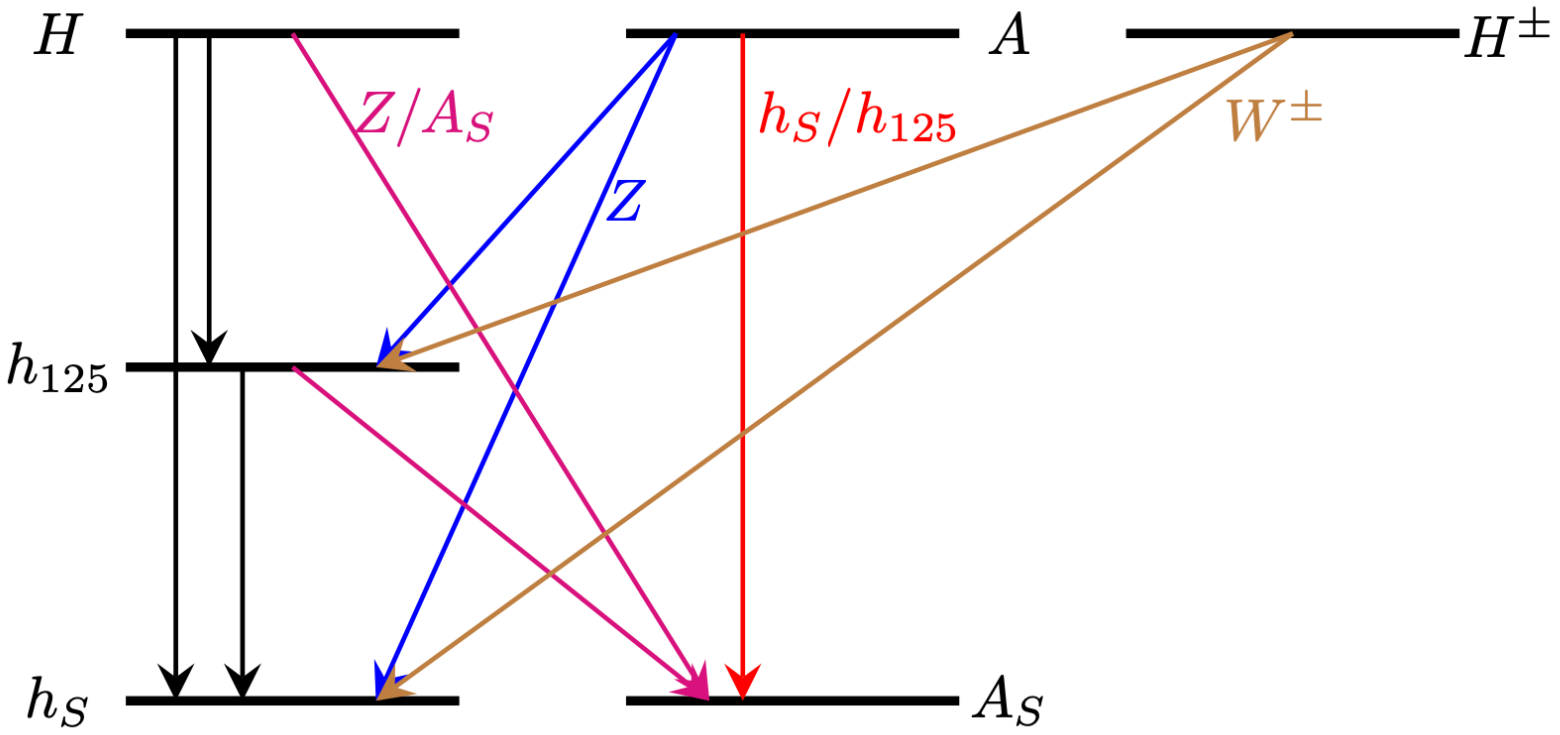
2HDMS


$m_{h_S} = m_{A_S} = 1.5$ TeV
$H/A \to bb$
$H/A \to \tau\tau$
Flavor
$H \to VV$
$H/A \to \gamma\gamma$
$ttH/A \to tttt$
$H \to hh$
$H/A \to tt$
$c_{\beta-\alpha} = 0$
$c_{\beta-\alpha} = 0.025$
$\tan\beta$
$m_A = m_H = m_{H^\pm}$ [GeV]


$m_A = m_H = m_{H^\pm} = 1.5$ TeV, $\alpha_{HS} = \pi/4$
$h_S \to \tau\tau$
$h_S \to \gamma\gamma$
$h_S \to tt$
$A \to Zh_S$
$tth_S \to tttt$
$\tan\beta$
m_{h_S} [GeV]

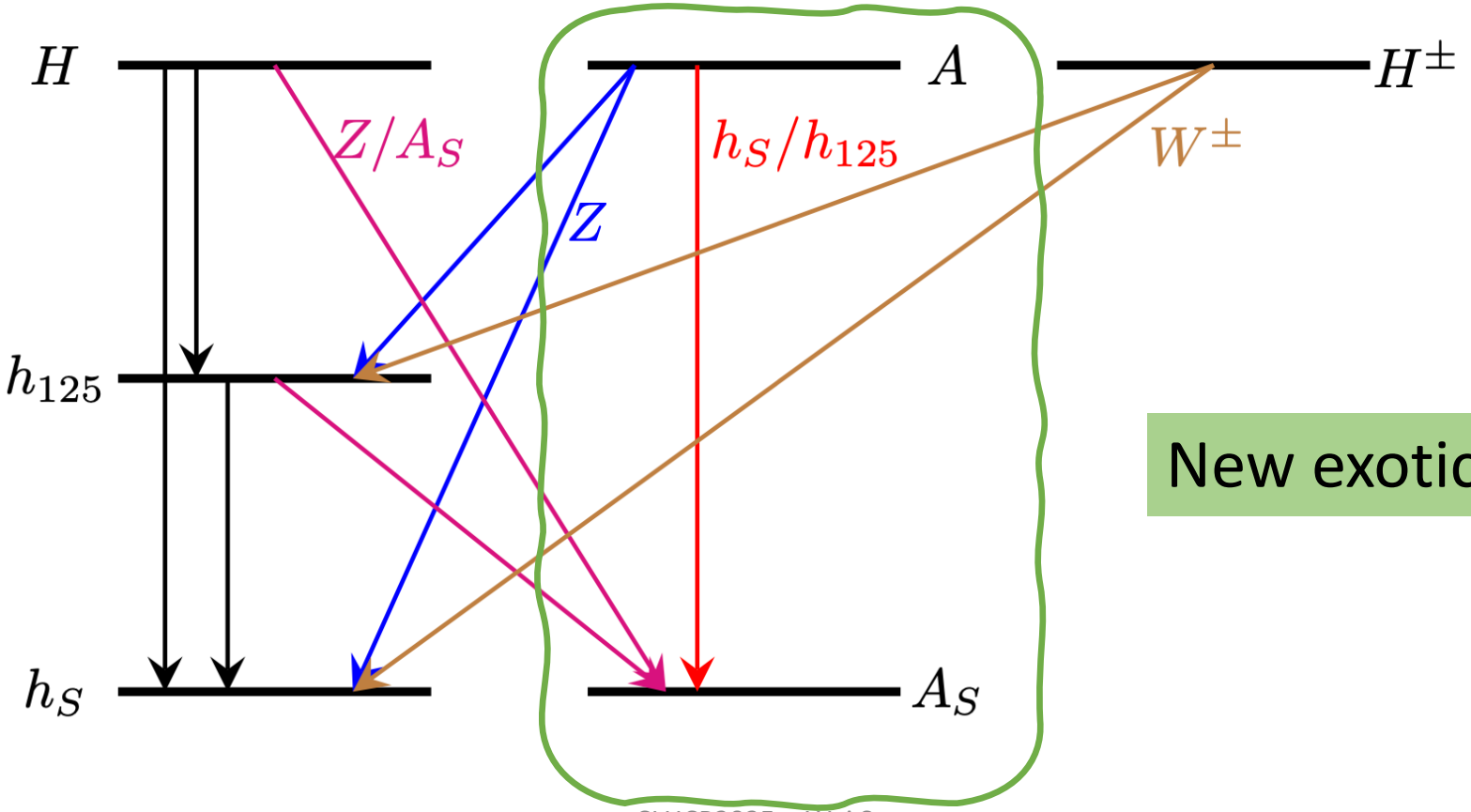
2HDMS

- The scenario with lighter singlet Higgs



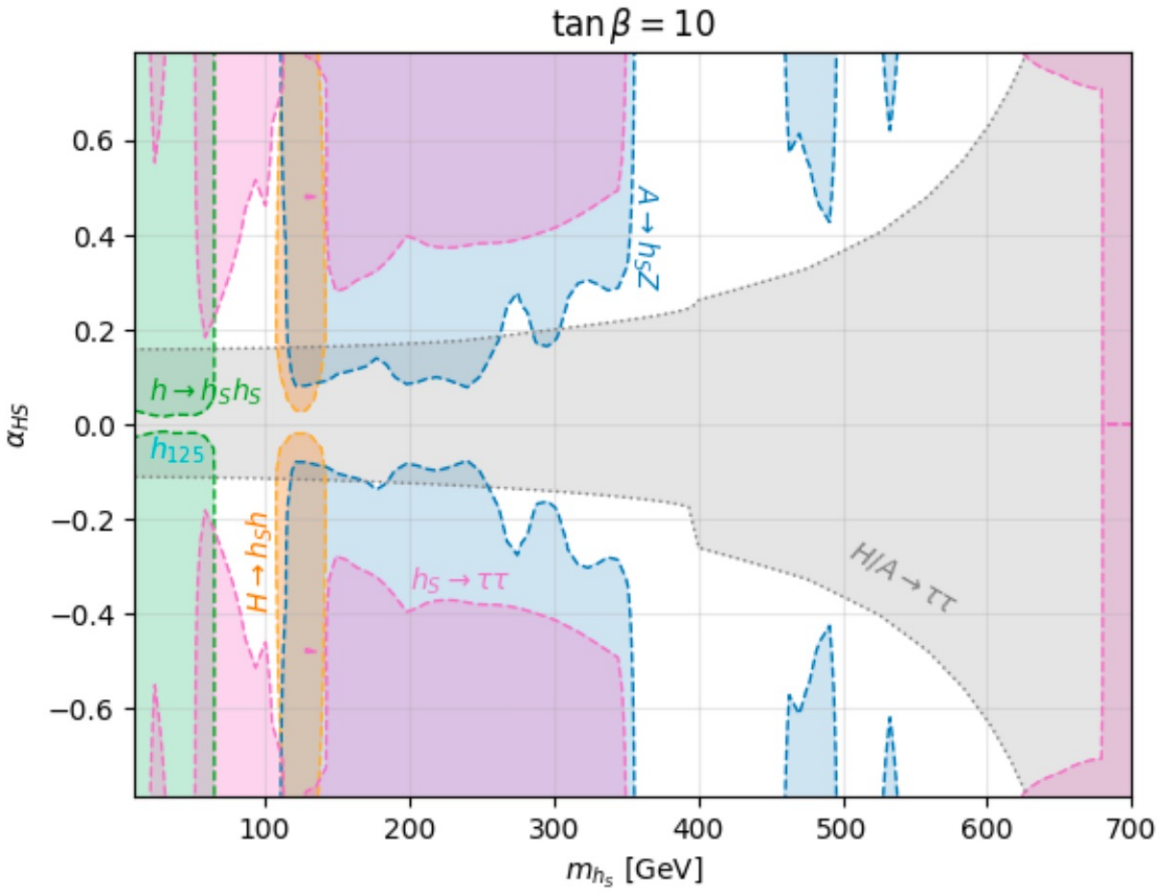
2HDMS: A_S and h_S

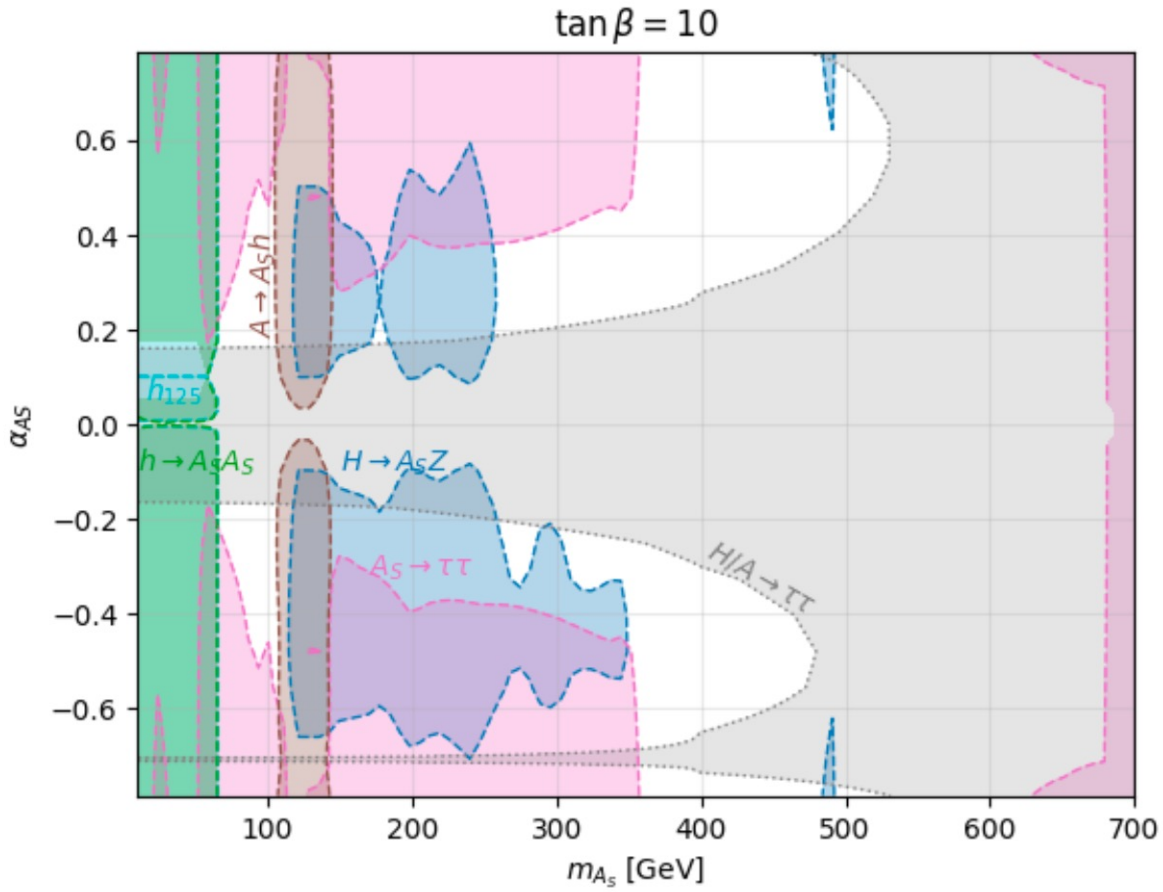
- The scenario with lighter singlet Higgs



New exotic channels

2HDMS： A_S and h_S





Conclusion

- ✓ Electroweak precision
- ✓ Higgs precision
- ✓ Direct searches
- ✓ …

Electroweak Precision

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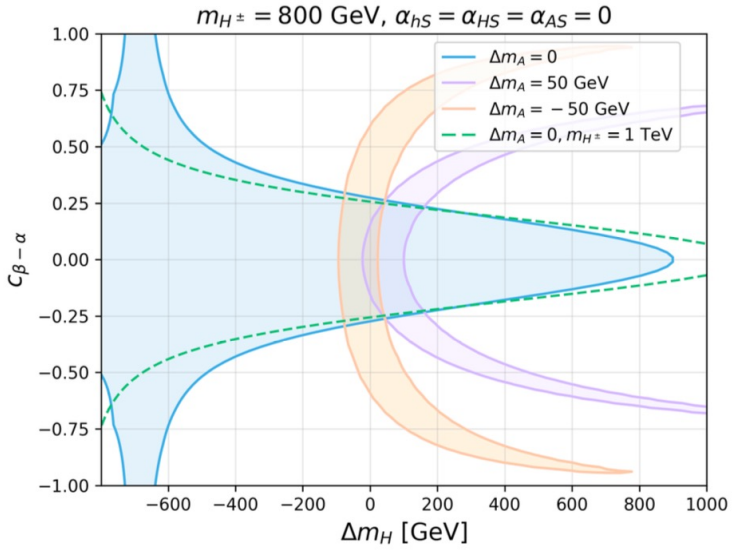
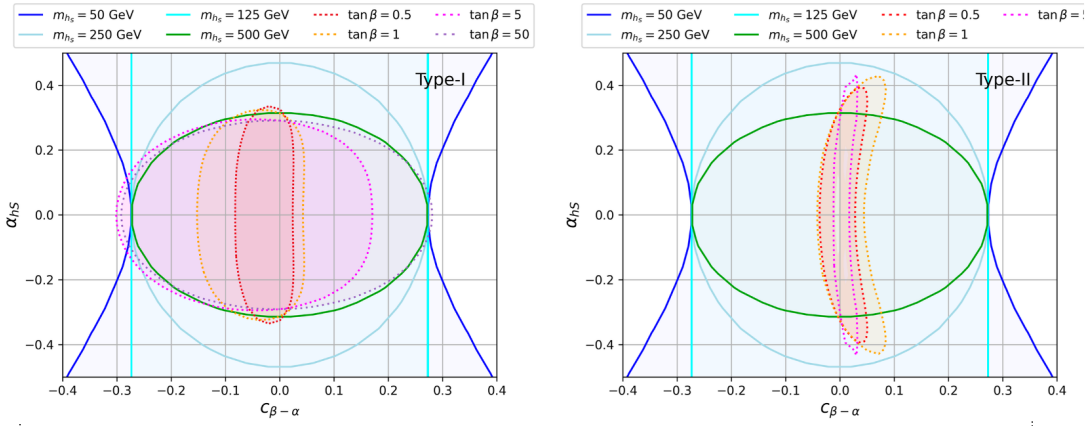
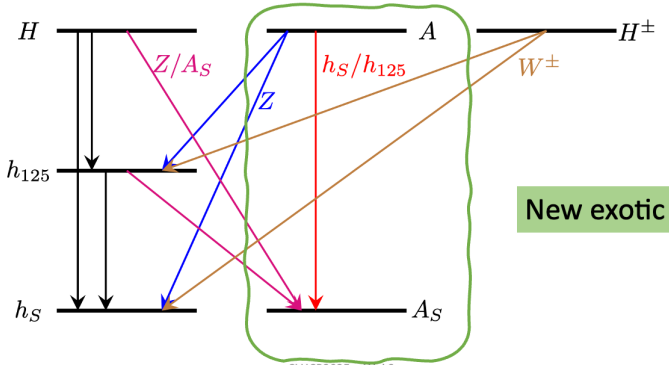


Electroweak + Higgs precision



2HDMS: A_S and h_S

- The scenario with lighter singlet Higgs



New exotic channels