The Electroweak precision observables of the 2HDMS

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Introduction

- The 2HDMS can accommodate the 95 GeV excess at LHC and LEP, as well as match to the NMSSM at low energy scale
- The singlet field of 2HDMS could potentially lead to different effect on STU observables as the 2HDM
- We can disentangled the 3×3 mixing system of CP-even sector in the 2HDMS and analyze the singlet field impacts in the four fundamental cases
- We can explore the STU constraint on the singlet Higgs masses and the singlet mixing angles.

The 2HDMS

The 2HDM + Singlet extension [S. Heinemeyer et al. 21']

$$\Phi_1 = \begin{pmatrix} \chi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \chi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}, \qquad S = v_S + \rho_S + i\eta_S, \tag{1}$$

One of the possible Higgs potential ($\mathbb{Z}_3$ symmetry)

$$\begin{aligned} V =& m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ &+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) - m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.} \\ &+ m_S^2 S^\dagger S + \lambda_1'(S^\dagger S)(\Phi_1^\dagger\Phi_1) + \lambda_2'(S^\dagger S)(\Phi_2^\dagger\Phi_2) \\ &+ \frac{\lambda_3''}{4}(S^\dagger S)^2 + \left(\frac{\mu_{S1}}{6}S^3 + \mu_{12}S\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right) \end{aligned} \tag{2}$$

The 2HDMS in the mass eigenstate

The CP-even fields mix and generate three scalar Higgs

$$R\begin{pmatrix}\rho_1\\ \rho_2\\ \rho_S\end{pmatrix}=\begin{pmatrix}H\\ h\\ h_S\end{pmatrix},\qquad RM_S^2R^T=\mathrm{diag}\{m_H^2,m_h^2,m_{h_S}^2\}. \tag{3}$$

We fix the order of eigenvalues and the R matrix is given by the following configuration

$$R=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{\alpha_{hS}} & s_{\alpha_{hS}}\\ 0 & -s_{\alpha_{hS}} & c_{\alpha_{hS}}\end{pmatrix}\begin{pmatrix}c_{\alpha_{HS}} & 0 & s_{\alpha_{HS}}\\ 0 & 1 & 0\\ -s_{\alpha_{HS}} & 0 & c_{\alpha_{HS}}\end{pmatrix}\begin{pmatrix}c_\alpha & s_\alpha & 0\\ -s_\alpha & c_\alpha & 0\\ 0 & 0 & 1\end{pmatrix} \tag{4}$$

The CP-odd fields mix and generate one goldstone boson and two pseudoscalar Higgs

$$\begin{pmatrix}1 & 0 & 0\\ 0 & \multicolumn{2}{c}{\multirow{2}{*}{R^A}}\\ 0 & & \end{pmatrix}\begin{pmatrix}c_\beta & s_\beta & 0\\ -s_\beta & c_\beta & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\eta_1\\ \eta_2\\ \eta_S\end{pmatrix}=\begin{pmatrix}G^0\\ A\\ A_S\end{pmatrix},\qquad R^A=\begin{pmatrix}c_{\alpha_{AS}} & s_{\alpha_{AS}}\\ -s_{\alpha_{AS}} & c_{\alpha_{AS}}\end{pmatrix}, \tag{5}$$

The 2HDMS in the mass eigenstate

The input parameters of the mass eigenstate

$$\underbrace{\tan\beta,\ m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \alpha}_{\text{2HDM parameters}}\ \underbrace{v_S,\ m_{h_S},\ m_{A_S},\ \alpha_{HS},\ \alpha_{hS},\ \alpha_{AS}}_{\text{singlet parameters}}.$$

The six Higgs bosons mass and four mixing angles are relevant for the STU observables, since STU is independent on $\tan\beta$, v_S and the Yukawa type

$$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ m_{h_S},\ m_{A_S},\ c_{\beta-\alpha},\ \alpha_{hS},\ \alpha_{HS},\ \alpha_{AS} \tag{6}$$

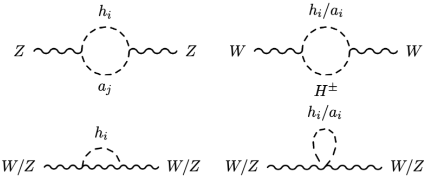
The fundamental scenarios

Case 0	(2HDM alignment limit)	$c_{\beta-\alpha} = \alpha_{HS} = \alpha_{hS} = \alpha_{AS} = 0$	
Case I	(2HDM limit)	$\alpha_{HS} = \alpha_{hS} = \alpha_{AS} = 0$	$c_{\beta-\alpha} \neq 0$
Case II	(SSM limit)	$c_{\beta-\alpha} = \alpha_{HS} = \alpha_{AS} = 0$	$\alpha_{hS} \neq 0$
Case III		$c_{\beta-\alpha} = \alpha_{hS} = \alpha_{AS} = 0$	$\alpha_{HS} \neq 0$
Case IV		$c_{\beta-\alpha} = \alpha_{hS} = \alpha_{HS} = 0$	$\alpha_{AS} \neq 0$

The Higgs to gauge bosons couplings

		0	I	II	III	IV
	$c_{h_i VV} = R_{i1} c_\beta + R_{i2} s_\beta$					
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
$c_{h_S VV}$	$-s_{\beta-\alpha} s_{\alpha_{hS}} - c_{\beta-\alpha} s_{\alpha_{HS}} c_{\alpha_{hS}}$	0	0	$-s_{\alpha_{hS}}$	0	0
	$c_{A_i H_j Z} = R^A_{i1} R_{j1} + R^A_{i2} R_{j2}$					
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
$c_{Ah_S Z}$	$-c_{\alpha_{AS}} \left(c_{\beta-\alpha} s_{\alpha_{hS}} - s_{\beta-\alpha} s_{\alpha_{HS}} c_{\alpha_{hS}} \right)$	0	0	0	$s_{\alpha_{HS}}$	0
$c_{A_S HZ}$	$s_{\alpha_{AS}} c_{\alpha_{HS}} s_{\beta-\alpha}$	0	0	0	0	$s_{\alpha_{AS}}$
$c_{A_S hZ}$	$-s_{\alpha_{AS}} \left(c_{\beta-\alpha} c_{\alpha_{hS}} + s_{\beta-\alpha} s_{\alpha_{HS}} s_{\alpha_{hS}} \right)$	0	0	0	0	0
$c_{A_S h_S Z}$	$s_{\alpha_{AS}} \left(c_{\beta-\alpha} s_{\alpha_{hS}} - s_{\beta-\alpha} s_{\alpha_{HS}} c_{\alpha_{hS}} \right)$	0	0	0	0	0
	$c_{\phi_i H^\pm W^\mp} = R^\phi_{i2} c_\beta - R^\phi_{i1} s_\beta$					
$c_{HH^\pm W^\mp}$	$-i c_{\alpha_{HS}} s_{\beta-\alpha}$	-i	$-i s_{\beta-\alpha}$	-i	$-i c_{\alpha_{HS}}$	-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	$i c_{\beta-\alpha}$	0	0	0
$c_{h_S H^\pm W^\mp}$	$-i \left(c_{\beta-\alpha} s_{\alpha_{hS}} - s_{\beta-\alpha} s_{\alpha_{HS}} c_{\alpha_{hS}} \right)$	0	0	0	$-i s_{\alpha_{HS}}$	0
$c_{AH^\pm W^\mp}$	$c_{\alpha_{AS}}$	1	1	1	1	$c_{\alpha_{AS}}$
$c_{A_S H^\pm W^\mp}$	$-s_{\alpha_{AS}}$	0	0	0	0	$-s_{\alpha_{AS}}$

The *STU* observables in 2HDMS



[W. Grimus et al. 08']

$$T = \frac{1}{16\pi s_W^2 m_W^2}\left[\sum_i^3 |c_{h_i H^\pm W^\mp}|^2 F(m_{H^\pm}^2, m_{h_i}^2) + \sum_i^2 |c_{a_i H^\pm W^\mp}|^2 F(m_{H^\pm}^2, m_{a_i}^2) - \sum_{i,j} |c_{a_i h_j Z}|^2 F(m_{a_i}^2, m_{h_j}^2) \right.$$
$$\left. + 3\sum_i^3 |c_{h_i VV}|^2 \left(F(m_Z^2, m_{h_i}^2) - F(m_W^2, m_{h_i}^2)\right) - 3\left(F(m_Z^2, m_h^2) - F(m_W^2, m_h^2)\right)\right], \quad (7)$$

$$S = \frac{1}{24\pi}\left[(2s_W^2 - 1)^2 G(m_{H^\pm}^2, m_{H^\pm}^2, m_Z^2) + \sum_{i,j} |c_{a_i h_j Z}|^2 G(m_{a_i}^2, m_{h_j}^2, m_Z^2) - 2\ln(m_{H^\pm}^2) - \ln(m_h^2) \right.$$
$$\left. + \sum_i^3 c_{h_i h_i VV} \ln(m_{h_i}^2) + \sum_i^2 c_{a_i a_i VV} \ln(m_{a_i}^2) + \sum_i |c_{h_i VV}|^2 \hat{G}(m_{h_i}^2, m_Z^2) - \hat{G}(m_h^2, m_Z^2)\right], \quad (8)$$

- The *U* observable does not get significant effect from this model
- The *T* observable usually play the dominant role of *STU* constraint

The STU observables

The experimental measurement of STU observables [J. Haller et. al 18']

$$\begin{aligned} S^{\rm exp} &= 0.04 \pm 0.11, & T^{\rm exp} &= 0.09 \pm 0.14, & U^{\rm exp} &= -0.02 \pm 0.11, \\ {\rm corr}(S,T) &= +0.92, & {\rm corr}(S,U) &= -0.68, & {\rm corr}(T,U) &= -0.87. \end{aligned}$$

Determine the limit by fitting to the experimental values

$$\chi^2_{STU} = \begin{pmatrix} S - S^{\rm exp} & T - T^{\rm exp} & U - U^{\rm exp} \end{pmatrix} \cdot \mathbf{cov}^{-1} \cdot \begin{pmatrix} S - S^{\rm exp} \\ T - T^{\rm exp} \\ U - U^{\rm exp} \end{pmatrix} < 5.99, \tag{9}$$

where

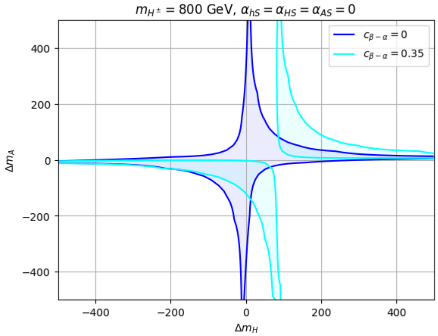
$$\mathbf{cov} = \begin{pmatrix} \Delta_S^2 & {\rm corr}(S,T)\Delta_S\Delta_T & {\rm corr}(S,U)\Delta_S\Delta_U \\ {\rm corr}(S,T)\Delta_S\Delta_T & \Delta_T^2 & {\rm corr}(T,U)\Delta_T\Delta_U \\ {\rm corr}(S,U)\Delta_S\Delta_U & {\rm corr}(T,U)\Delta_T\Delta_U & \Delta_U^2 \end{pmatrix}, \tag{10}$$

2HDM limit (Case-I)

$c_{\beta-\alpha} \neq 0$, $\alpha_{hS} = \alpha_{HS} = \alpha_{AS} = 0$

For convenience, we define the mass splittings

$$\Delta m_H = m_H - m_H^{\pm}, \qquad \Delta m_A = m_A - m_H^{\pm},$$
$$\Delta m_{HS} = m_{h_S} - m_H^{\pm}, \qquad \Delta m_{AS} = m_{A_S} - m_H^{\pm},$$

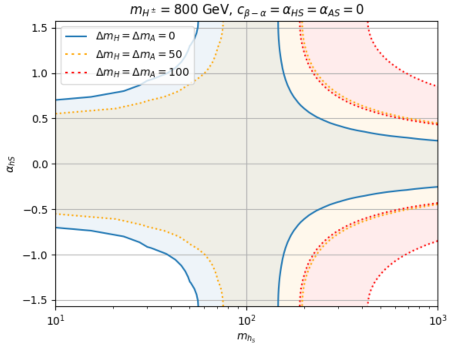


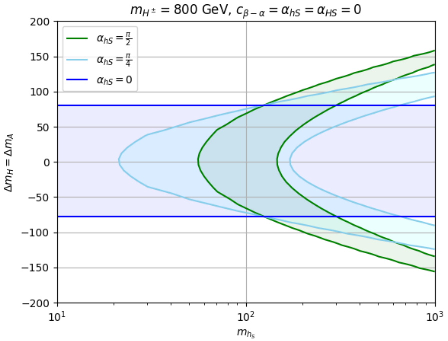
$$T_0 = \frac{1}{16\pi s_W^2 m_W^2}[F(m_{H^\pm}^2, m_H^2) - F(m_A^2, m_H^2) + F(m_{H^\pm}^2, m_A^2)] \tag{11}$$

- The *STU* observables behave basically the same as the 2HDM in this case

SSM limit (Case-II)

$\alpha_{hS} \neq 0,\ c_{\beta-\alpha} = \alpha_{HS} = \alpha_{AS} = 0$



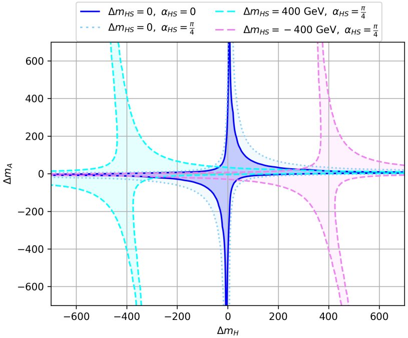


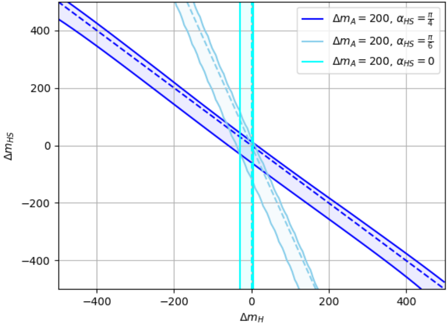
$$T = \frac{1}{16\pi s_W^2 m_W^2} 3 s_{\alpha_{hS}}^2 \left[F(m_Z^2, m_{h_S}^2) - F(m_W^2, m_{h_S}^2) - F(m_Z^2, m_{h_{125}}^2) + F(m_W^2, m_{h_{125}}^2) \right] + T_0 \tag{12}$$

- The STU constraints would be weak when m_{h_S} close to 125 GeV
- For $\Delta m_H = \Delta m_A \gtrsim 80$ GeV, the $\alpha_{hS} = 0$ would be excluded while the non-zero α_{hS} can compensate the STU value for $m_{h_S} > 125$ GeV

Case-III

$\alpha_{HS} \neq 0,\ c_{\beta-\alpha} = \alpha_{hS} = \alpha_{AS} = 0$



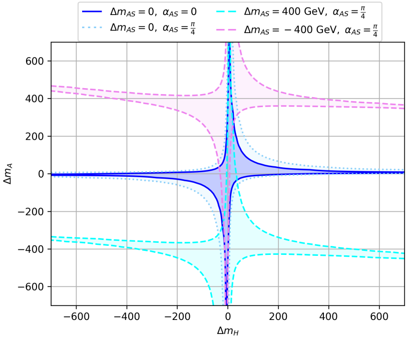


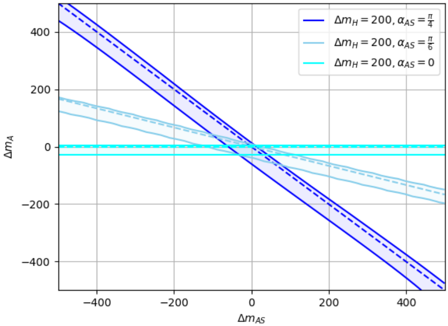
$$c_{\alpha_{HS}}^2 m_H + s_{\alpha_{HS}}^2 m_{h_S} = m_{H^\pm} \tag{13}$$

- The *STU* allowed region would be shifted by α_{HS} and Δm_{HS}, while the constraints can be always allowed when $\Delta m_A = 0$.
- The mass relation Eq. (13) ensures that the *STU* constraints can be fulfilled for arbitrary α_{HS}, when $\Delta m_A =\neq 0$.

Case-IV

$\alpha_{AS} \neq 0,\ c_{\beta-\alpha} = \alpha_{hS} = \alpha_{HS} = 0$



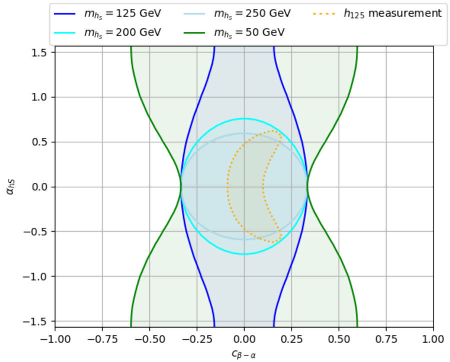


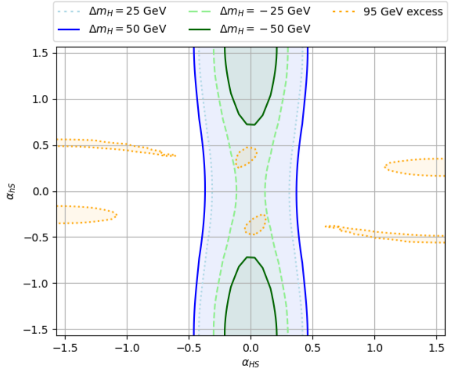
$$c^2_{\alpha_{AS}} m_A + s^2_{\alpha_{AS}} m_{A_S} = m_{H^\pm}\,. \tag{14}$$

- The *STU* allowed region would be shifted by α_{AS} and Δm_{AS}, while the constraints can be always allowed when $\Delta m_H = 0$.
- The mass relation Eq. (14) ensures that the *STU* constraints can be fulfilled for arbitrary α_{AS}, when $\Delta m_H \neq 0$.

Specific scenarios

We choose the type-II Yukawa couplings as the example, and set $\tan\beta = 1$ and $m_{H^\pm} = 800$





- The heavier h_S would yield a stronger STU bound on $c_{\beta-\alpha}$ vs α_{hS} plane, and can be more restrict than the h_{125} precision measurement (HiggsSignals) limit.
- The 95 GeV excess would disfavor the region of $\Delta m_H < 0$ by STU constraints, when $\Delta m_A = -100$ GeV.

Summary

Conclusions

- We disentangle and extract the effect of each mixing angles in the 2HDMS, and set up four fundamental cases.
- The *STU* properties of case I ($c_{\beta-\alpha} \neq 0$ and $\alpha_{hS} = \alpha_{HS} = \alpha_{AS} = 0$) is identical to the 2HDM.
- The *STU* properties of case II ($\alpha_{hS} \neq 0$ and $c_{\beta-\alpha} = \alpha_{HS} = \alpha_{AS} = 0$) mainly depends on the mass difference between m_{h_S} and $m_{h_{125}}$
- In case III ($\alpha_{HS} \neq 0$ and $c_{\beta-\alpha} = \alpha_{hS} = \alpha_{AS} = 0$), the *STU* constraints can be fulfilled when the mass relation $c^2_{\alpha_{HS}} m_H + s^2_{\alpha_{HS}} m_{h_S} = m_{H^\pm}$ is satisfied
- In case IV ($\alpha_{AS} \neq 0$ and $c_{\beta-\alpha} = \alpha_{hS} = \alpha_{HS} = 0$), the *STU* constraints can be fulfilled when the mass relation $c^2_{\alpha_{AS}} m_A + s^2_{\alpha_{AS}} m_{A_S} = m_{H^\pm}$ is satisfied

Outlook

- Interplay with others collider searches constraints. (In proceeding)
- Interplay with the theoretical constraints as well as the cosmological effect.

Backup

The STU constraints in 2HDMS beyond the alignment limit