The Electroweak precision observables of the 2HDM+S

Cheng Li

in collaboration with Shufang Su and Wei Su

Higgs potential 2024

中山大學 理学院
SCHOOL OF SCIENCE, SUN YAT-SEN UNIVERSITY

Introduction

- The 2HDM+S can accommodate the 95 GeV excess at LHC and LEP, the Dark Matter candidate, as well as match to the NMSSM at low energy scale
- The singlet field of 2HDM+S could potentially lead to different impact on W and Z bosons self energy (i.e. STU observables) compared to the 2HDM
- We can disentangled the 3×3 mixing system of CP-even sector in the 2HDM+S 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 2HDM+S

The 2HDM + Singlet extension [S. Baum et al. 18']

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

Yields three neutral CP-even Higgs (h, H and h_S), two neutral CP-odd Higgs (A and A_S) and one charged Higgs $H^{\pm}$

Models	Symmetries	New features
U(1) [X.M, Jiang et al, 19']	$S \to e^{i\delta} S$	pNG dark matter
$\mathbb{Z}_2'$ [J. Dutta et al, 23']	$S \to -S$	Dark matter (pseudoscalar)
$\mathbb{Z}_3$ [S. Heinemeyer et al, 21']	$\Phi_2 \to e^{i2\pi/3}\Phi_2$	NMSSM structure

The electroweak observables only depend on the Higgs bosons masses and couplings, which are independent on the explicit symmetry structures of the Higgs potential.

The 2HDM+S in the mass eigenstate

The CP-even fields mix and generate three scalar Higgs

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

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

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\alpha_{hS}} & s_{\alpha_{hS}} \\ 0 & -s_{\alpha_{hS}} & c_{\alpha_{hS}} \end{pmatrix} \begin{pmatrix} c_{\alpha_{HS}} & 0 & s_{\alpha_{HS}} \\ 0 & 1 & 0 \\ -s_{\alpha_{HS}} & 0 & c_{\alpha_{HS}} \end{pmatrix} \begin{pmatrix} c_\alpha & s_\alpha & 0 \\ -s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

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

$$\begin{pmatrix} 1 & 0 \quad 0 \\ 0 & \\ 0 & R^A \end{pmatrix} \begin{pmatrix} c_\beta & s_\beta & 0 \\ -s_\beta & c_\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_S \end{pmatrix} = \begin{pmatrix} G^0 \\ A \\ A_S \end{pmatrix}, \qquad R^A = \begin{pmatrix} c_{\alpha_{AS}} & s_{\alpha_{AS}} \\ -s_{\alpha_{AS}} & c_{\alpha_{AS}} \end{pmatrix}, \tag{4}$$

The 2HDM+S 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

$$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ m_{h_S},\ m_{A_S},\ c_{\beta-\alpha},\ \alpha_{hS},\ \alpha_{HS},\ \alpha_{AS} \tag{5}$$

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
$c_{A h_S Z}$	$-c_{\alpha_{AS}} \left(c_{\beta-\alpha} s_{\alpha_{hS}} - s_{\beta-\alpha} s_{\alpha_{HS}} c_{\alpha_{hS}} \right)$	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

The electroweak precision observables STU are defined by the self-energy of the W and Z bosons. [E. Peskin et al, 92']

$$\alpha(m_Z)T = \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}, \tag{6}$$

$$\frac{\alpha(m_Z)}{4s_W^2 c_W^2} S = \frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} - \frac{c_W^2 - s_W^2}{s_W c_W}\frac{\Pi_{Z\gamma}(m_Z^2)}{m_Z^2} - \frac{\Pi_{\gamma\gamma}(m_Z^2)}{m_Z^2}, \tag{7}$$

$$\frac{\alpha(m_Z)}{4s_W^2}(S+U) = \frac{\Pi_{WW}(m_W^2) - \Pi_{WW}(0)}{m_W^2} - \frac{c_W}{s_W}\frac{\Pi_{Z\gamma}(m_Z^2)}{m_Z^2} - \frac{\Pi_{\gamma\gamma}(m_Z^2)}{m_Z^2}, \tag{8}$$

The experimental measurement of STU observables [PDG 23']

$$\begin{array}{ccc} S^{\rm exp} = -0.02 \pm 0.10, & T^{\rm exp} = 0.03 \pm 0.12, & U^{\rm exp} = 0.01 \pm 0.11, \\ \mathrm{corr}(S,T) = +0.92, & \mathrm{corr}(S,U) = -0.80, & \mathrm{corr}(T,U) = -0.93. \end{array}$$

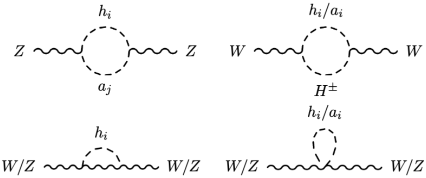
Determine the limit by fitting to the experimental values

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

where

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

The STU observables in 2HDM+S



[W. Grimus et al. 08']

$$T = \frac{1}{16\pi s_W^2 m_W^2}\Bigg[\sum_i^3 |c_{h_i H^\pm W^\mp}|^2 F(m_{H^\pm}^2, m_{h_i}^2) + \sum_i^2 |c_{a_i H^\pm W^\mp}|^2 F(m_{H^\pm}^2, m_{a_i}^2) - \sum_{i,j} |c_{a_i h_j Z}|^2 F(m_{a_i}^2, m_{h_j}^2)$$
$$+ 3\sum_i^3 |c_{h_i VV}|^2 \left(F(m_Z^2, m_{h_i}^2) - F(m_W^2, m_{h_i}^2)\right) - 3\left(F(m_Z^2, m_h^2) - F(m_W^2, m_h^2)\right)\Bigg], \quad (11)$$

$$S = \frac{1}{24\pi}\Bigg[(2s_W^2 - 1)^2 G(m_{H^\pm}^2, m_{H^\pm}^2, m_Z^2) + \sum_{i,j} |c_{a_i h_j Z}|^2 G(m_{a_i}^2, m_{h_j}^2, m_Z^2) - 2\ln(m_{H^\pm}^2) - \ln(m_h^2)$$
$$+ \sum_i^3 c_{h_i h_i VV} \ln(m_{h_i}^2) + \sum_i^2 c_{a_i a_i VV} \ln(m_{a_i}^2) + \sum_i |c_{h_i VV}|^2 \hat{G}(m_{h_i}^2, m_Z^2) - \hat{G}(m_h^2, m_Z^2)\Bigg], \quad (12)$$

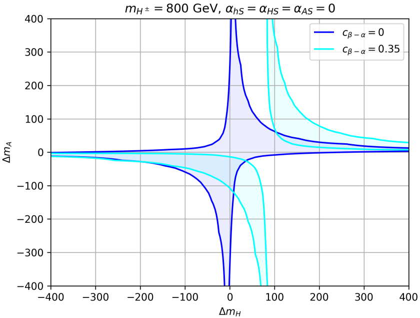
- The U observable does not get significant effect from this model
- The T observable usually play the dominant role of STU constraint

2HDM limit (Case-I)

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

For convenience, we define the mass splittings

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

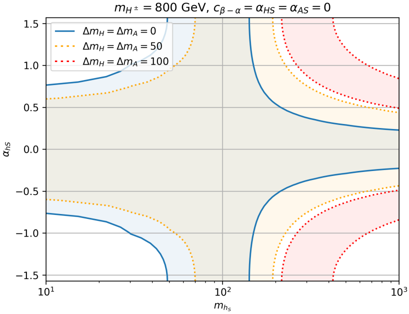


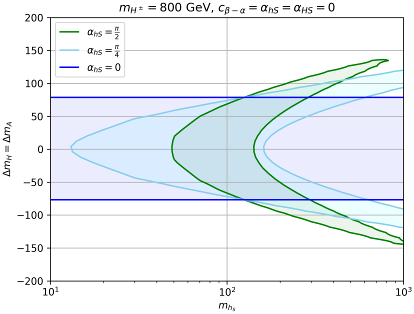
$$T_0 = \frac{1}{16\pi s_W^2 m_W^2}[F(m_{H^\pm}^2, m_H^2) - F(m_A^2, m_H^2) + F(m_{H^\pm}^2, m_A^2)] \quad (13)$$

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

SSM limit (Case-II)

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



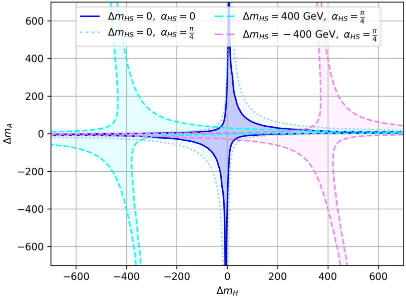


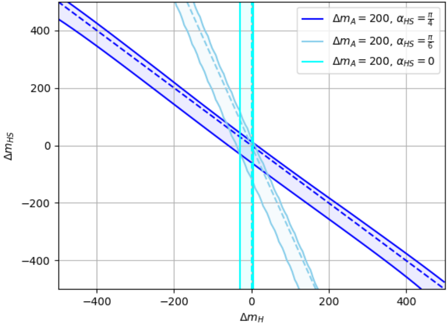
$$T = \frac{1}{16\pi s_W^2 m_W^2} 3 s_{\alpha_{hS}}^2 \left[F(m_Z^2, m_{h_S}^2) - F(m_W^2, m_{h_S}^2) - F(m_Z^2, m_{h_{125}}^2) + F(m_W^2, m_{h_{125}}^2) \right] + T_0 \tag{14}$$

- 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

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



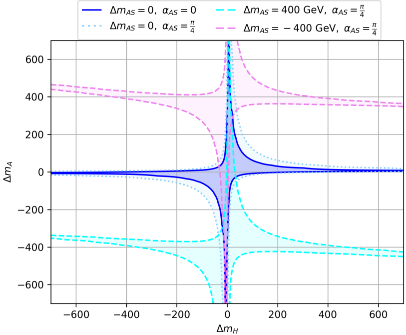


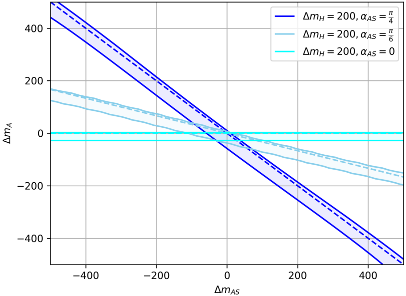
$$c^2_{\alpha_{HS}} m_H + s^2_{\alpha_{HS}} m_{h_S} = m_{H^\pm} \tag{15}$$

- 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. (15) ensures that the STU constraints can be fulfilled for arbitrary α_{HS}, when $\Delta m_A = \neq 0$.

Case-IV

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



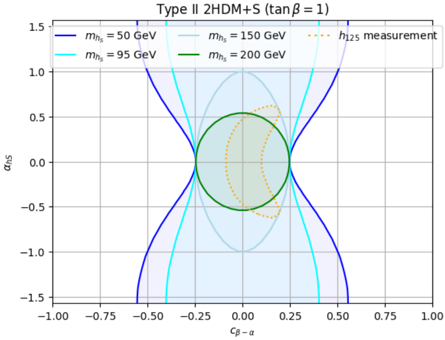


$$c^2_{\alpha_{AS}} m_A + s^2_{\alpha_{AS}} m_{A_S} = m_{H^\pm} . \quad (16)$$

- 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. (16) 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.

Summary

Conclusions

- We disentangle and extract the effect of each mixing angles in the 2HDM+S, 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 as well as the cosmological effect. (In proceeding)
- Distinguish the 2HDM and 2HDM+S with higher precision of STU observables at potential future colliders (CEPC, etc.)

Thank you!

Back up

The general form of the Higgs potential

$$
\begin{aligned}
V_{\mathrm{2HDM}} = {} & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\
& + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left(\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\right).
\end{aligned} \tag{17}
$$

$$
\begin{aligned}
V_{\mathrm{S}} = {} & m_S^2 S^\dagger S + \frac{m_S'^2}{2}(S^2 + \mathrm{h.c.}) + \left(\frac{\lambda_1''}{4!}S^4 + \frac{\lambda_2''}{3!}S^2(S^\dagger S) + \mathrm{h.c.}\right) + \frac{\lambda_3''}{4}(S^\dagger S)^2 \\
& + \Big[S^\dagger S\left(\lambda_1'\Phi_1^\dagger\Phi_1 + \lambda_2'\Phi_2^\dagger\Phi_2 + \lambda_3'\Phi_1^\dagger\Phi_2\right) + S^2\left(\lambda_4'\Phi_1^\dagger\Phi_1 + \lambda_5'\Phi_2^\dagger\Phi_2 + \lambda_6'\Phi_1^\dagger\Phi_2 + \lambda_7'\Phi_2^\dagger\Phi_1\right) \\
& + \frac{\mu_{S1}}{3!}S^3 + \frac{\mu_{S2}}{2}S(S^\dagger S) + S\left(\mu_{11}\Phi_1^\dagger\Phi_1 + \mu_{22}\Phi_2^\dagger\Phi_2 + \mu_{12}\Phi_1^\dagger\Phi_2 + \mu_{21}\Phi_2^\dagger\Phi_1\right) + \mathrm{h.c.}\Big]
\end{aligned} \tag{18}
$$

Backup

The *STU* constraints in 2HDM+S beyond the alignment limit