# Probing exotic Higgs sectors from the enhancement of the hVV coupling

Kei Yagyu（National Central Univ.）

*Shinya Kanemura, Mariko Kikuchi, and K.Y., PRD88, 015020*

*Cheng-Wei Chiang, An-Li Kuo, and K.Y., arXiv: 1307.7526*

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# Overview

☐ An observed new particle with 126 GeV at the LHC is consistent with the SM Higgs boson.

☐ Discovery of the SM-like Higgs boson does not necessarily mean that the SM is correct.

☐ The SM-like Higgs boson can also be explained in extended Higgs sectors.

☐ Extended Higgs sectors are often introduced in new physics models.

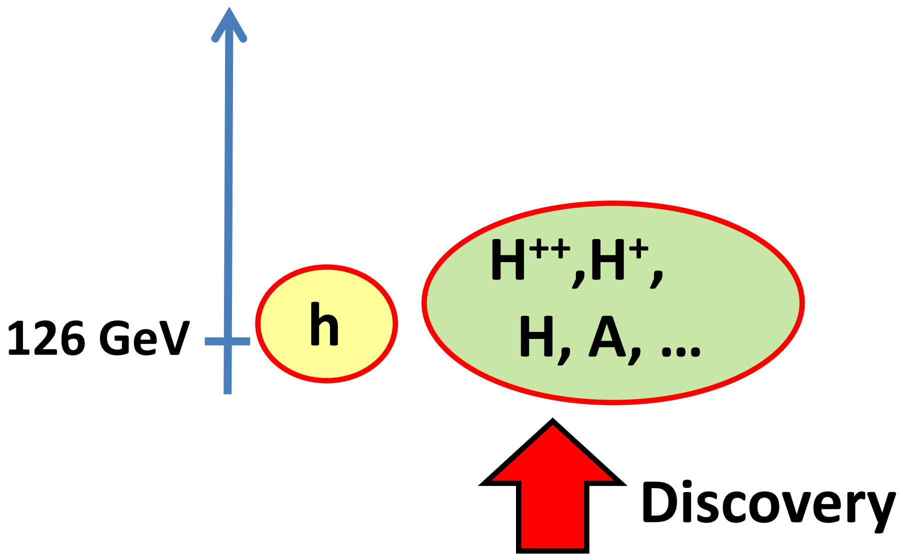
Determination of the true Higgs sector = Knowing new physics models

How can we determine the structure of the true Higgs sector?

# Testing extended Higgs sectors at colliders

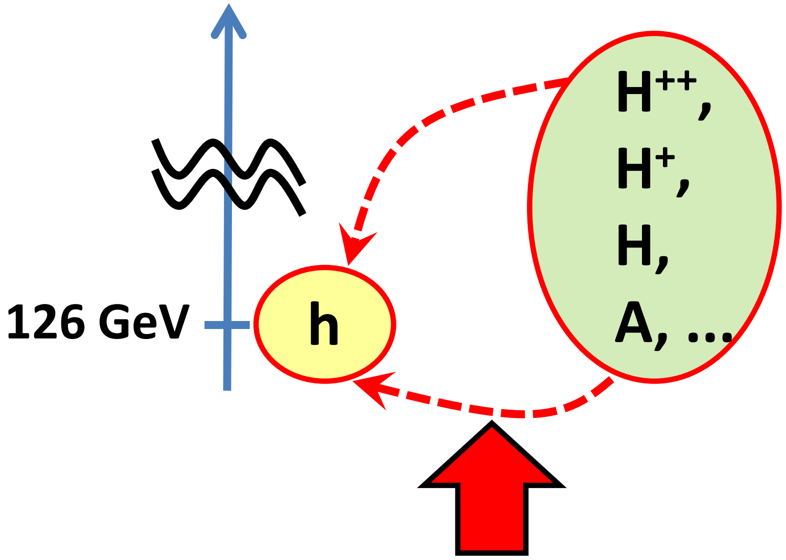
## 1. Direct way

-Discovery of extra Higgs bosons



## 2. Indirect way

-Precise measurements of the Higgs coupling constants.



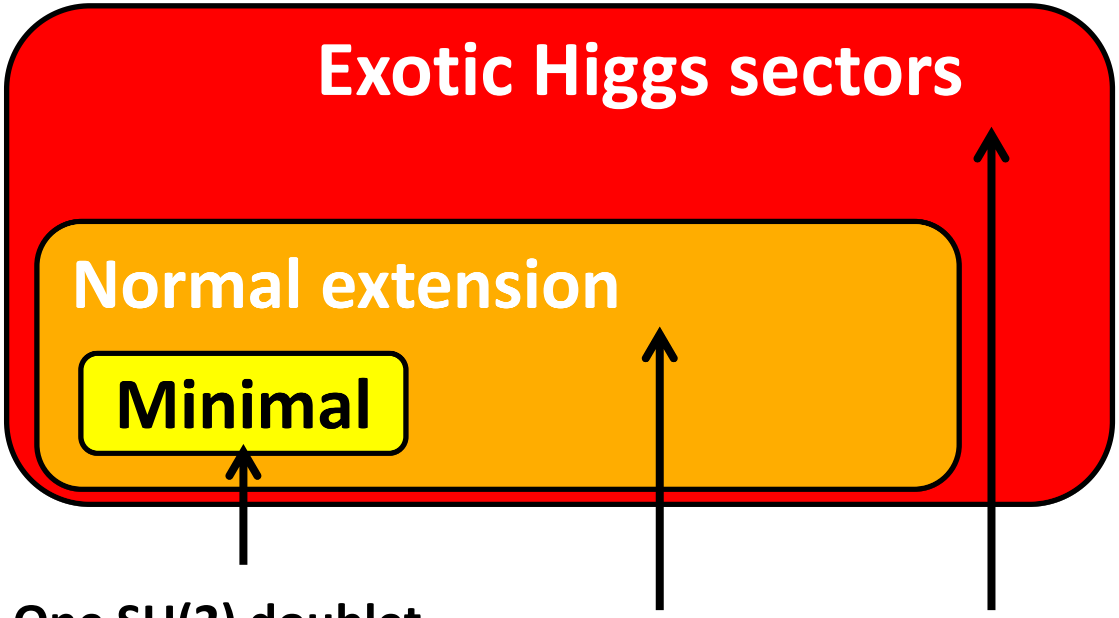
**Measuring effects on Higgs boson couplings**

Studying both ways is important to determine the structure of the Higgs sector.

# Exotic Higgs sectors

☐ In this talk, we focus on the Higgs sector with ***exotic scalar fields***.

☐ Exotic scalar fields are often introduced in neutrino mass models.



**Exotic Higgs sectors**

**Normal extension**

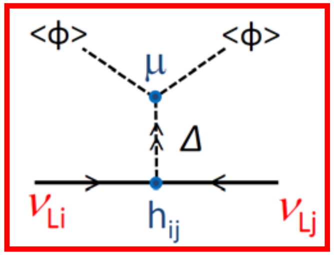
**Minimal**

**One SU(2) doublet**

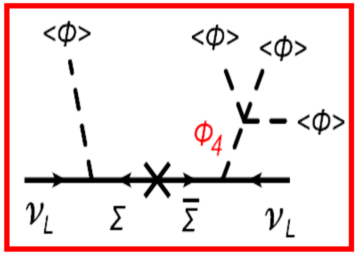
**Extra doublets and/or singlets**

**Extra triplets and/or larger than triplets**

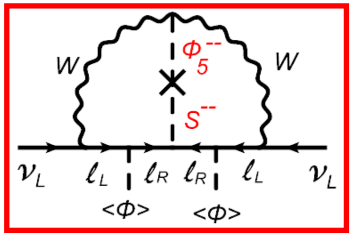
Ex.,



*Cheng, Li (1980); etc*



*Babu, Nandi and Tavartkiladze (2009)*



*Chen, Geng, Tsai (2012)*

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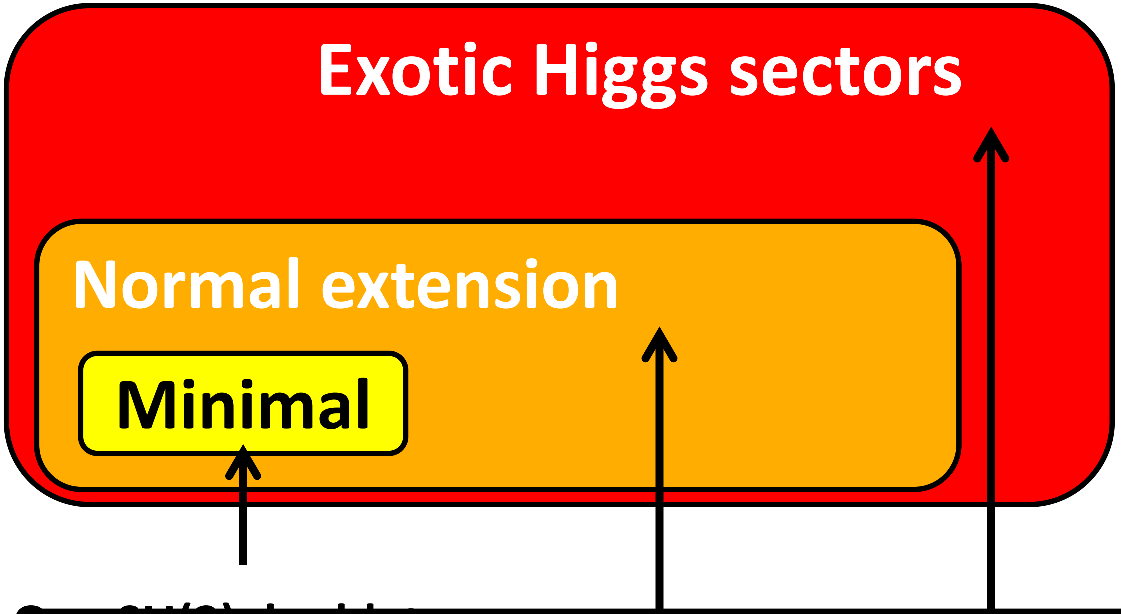

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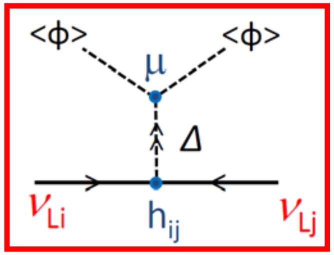

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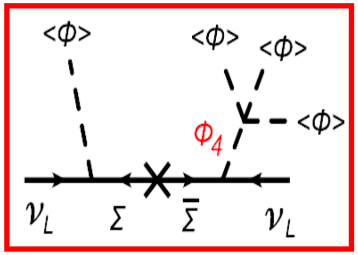

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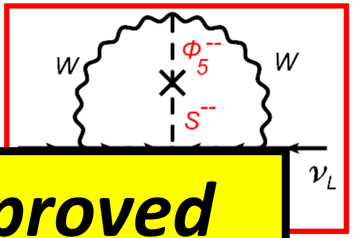

***We discuss how exotic Higgs sectors can be proved at collider experiments***

# Higgs boson couplings with gauge bosons

- ☐ In extended Higgs sectors, there is a sum rule for VEVs

$$\boxed{v_{\text{SM}}^2 = \sum_i \underline{2[T_i(T_i+1) - Y_i^2]} v_i^2}$$

$Y_i$ : hypercharge
$T_i$ : isospin
$v_i$ : VEV

Ex., **2[T(T+1)-Y^2] =**

$$\begin{cases} 1 & \text{for T=1/2, Y=1/2} \\ \mathbf{2} & \text{for T=1, Y=1 (complex triplet)} \\ \mathbf{4} & \text{for T=1, Y=0 (real triplet)} \\ \mathbf{16} & \text{for T=3, Y=2 (7-plet Higgs ), etc…} \end{cases}$$

*Hisano, Tusmura (2013), Kanemura, Kikuchi, KY (2013)*

- ☐ If the factor **2[T(T+1)-Y^2]** is larger than 1, it causes an enhanced hWW coupling compared to the SM value.

- ☐ The hZZ coupling can also be enhanced, if the factor **4Y^2** is larger than 1.

# Higgs boson couplings with gauge bosons

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Ex., **2[T(T+1)-Y^2] =**

- 1 for T=1/2, Y=1/2
- 2 for T=1, Y=1 (complex triplet)
- 4 for T=1, Y=0 (real triplet)
- 16 for T=3, Y=2 (7-plet Higgs ), etc…

*Hisano, Tusmura (2013), Kanemura, Kikuchi, KY (2013)*

- ☐ If the factor 2[T(T+1)-Y^2] is larger than 1, it causes an enhanced hWW coupling compared to the SM value.

***Measuring enhanced hVV couplings can be a probe of exotic Higgs sectors!***

*Georgi, Machacek (1985)*

# The Georgi-Machacek Model

☐ We focus on the Georgi-Machacek model as an example.
Higgs sector → Higgs doublet ϕ + complex triplet χ + real triplet ξ

☐ $SU(2)_L \times SU(2)_R$ form:

***$SU(2)_R$***

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ \phi^{-} & \phi^{0} \end{pmatrix} \qquad \Delta = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ \chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & \xi^{-} & \chi^{0} \end{pmatrix}$$

***$SU(2)_L$***

$$\Phi \rightarrow U_L \Phi U_R^{\dagger}$$

$$\Delta \rightarrow U_L \Delta U_R^{\dagger}$$

☐ If we take two triplet VEVs to be the same: $\langle\chi^0\rangle = \langle\xi^0\rangle = v_\Delta$

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- $SU(2)_L \times SU(2)_R$ form:

$$\langle \Phi \rangle = \begin{pmatrix} v_\phi & 0 \\ 0 & v_\phi \end{pmatrix} \quad \langle \Delta \rangle = \begin{pmatrix} v_\Delta & 0 & 0 \\ 0 & v_\Delta & 0 \\ 0 & 0 & v_\Delta \end{pmatrix}$$

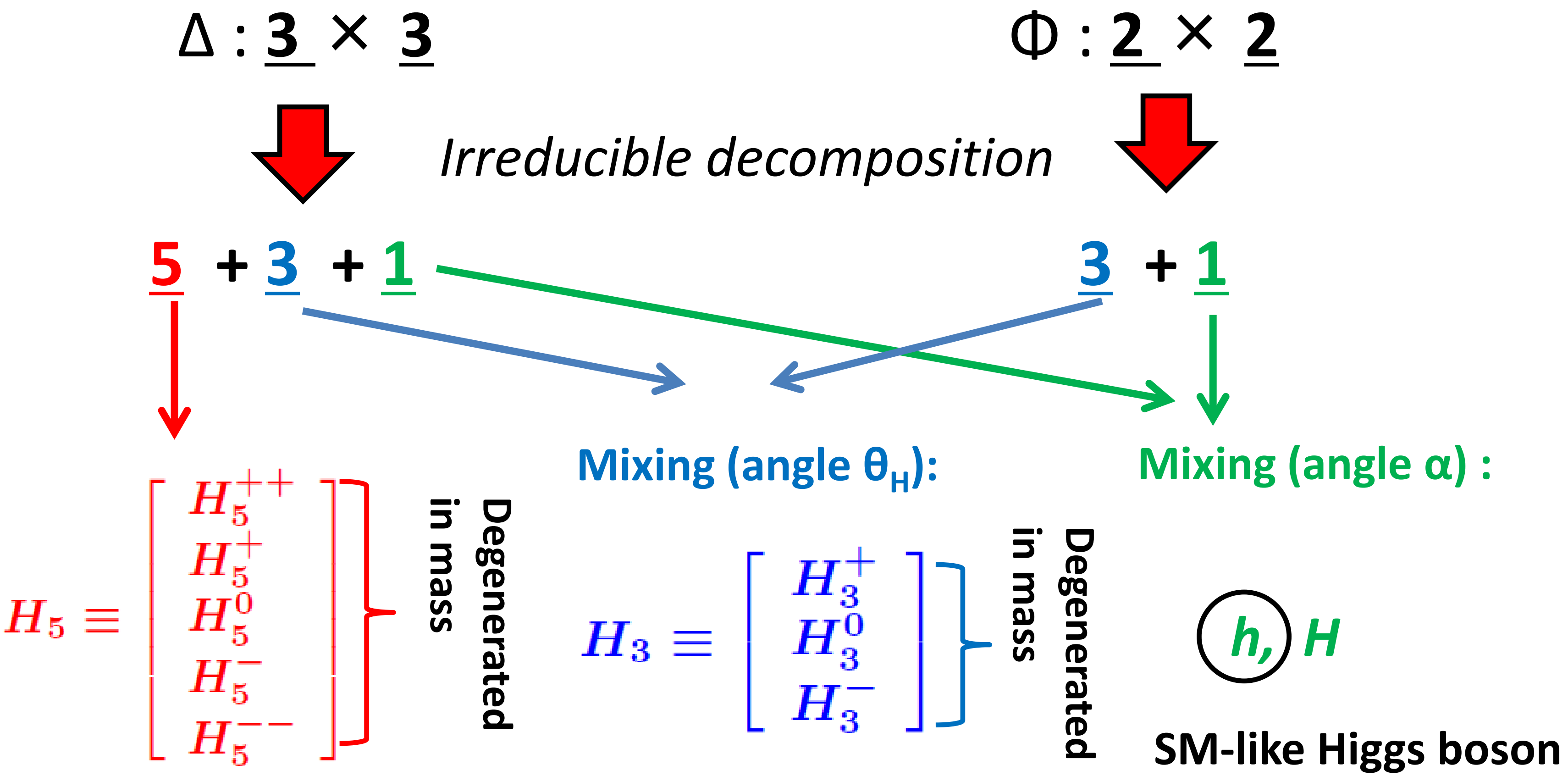
$$\langle \Phi \rangle \rightarrow U_V \langle \Phi \rangle U_V^\dagger$$

$$\langle \Delta \rangle \rightarrow U_V \langle \Delta \rangle U_V^\dagger$$

- If we take two triplet VEVs are the same: $\underline{\langle\chi^0\rangle = \langle\xi^0\rangle = v\Delta}$

**$SU(2)_L \times SU(2)_R$ → $SU(2)_V$ (Custodial Symmetry)**

# Decomposition



$\Delta : \underline{3} \times \underline{3}$

$\Phi : \underline{2} \times \underline{2}$

*Irreducible decomposition*

$\underline{5} + \underline{3} + \underline{1}$

$\underline{3} + \underline{1}$

**Mixing (angle $\theta_H$):**

**Mixing (angle α) :**

$$H_5 \equiv \begin{bmatrix} H_5^{++} \\ H_5^{+} \\ H_5^{0} \\ H_5^{-} \\ H_5^{--} \end{bmatrix}$$

**Degenerated in mass**

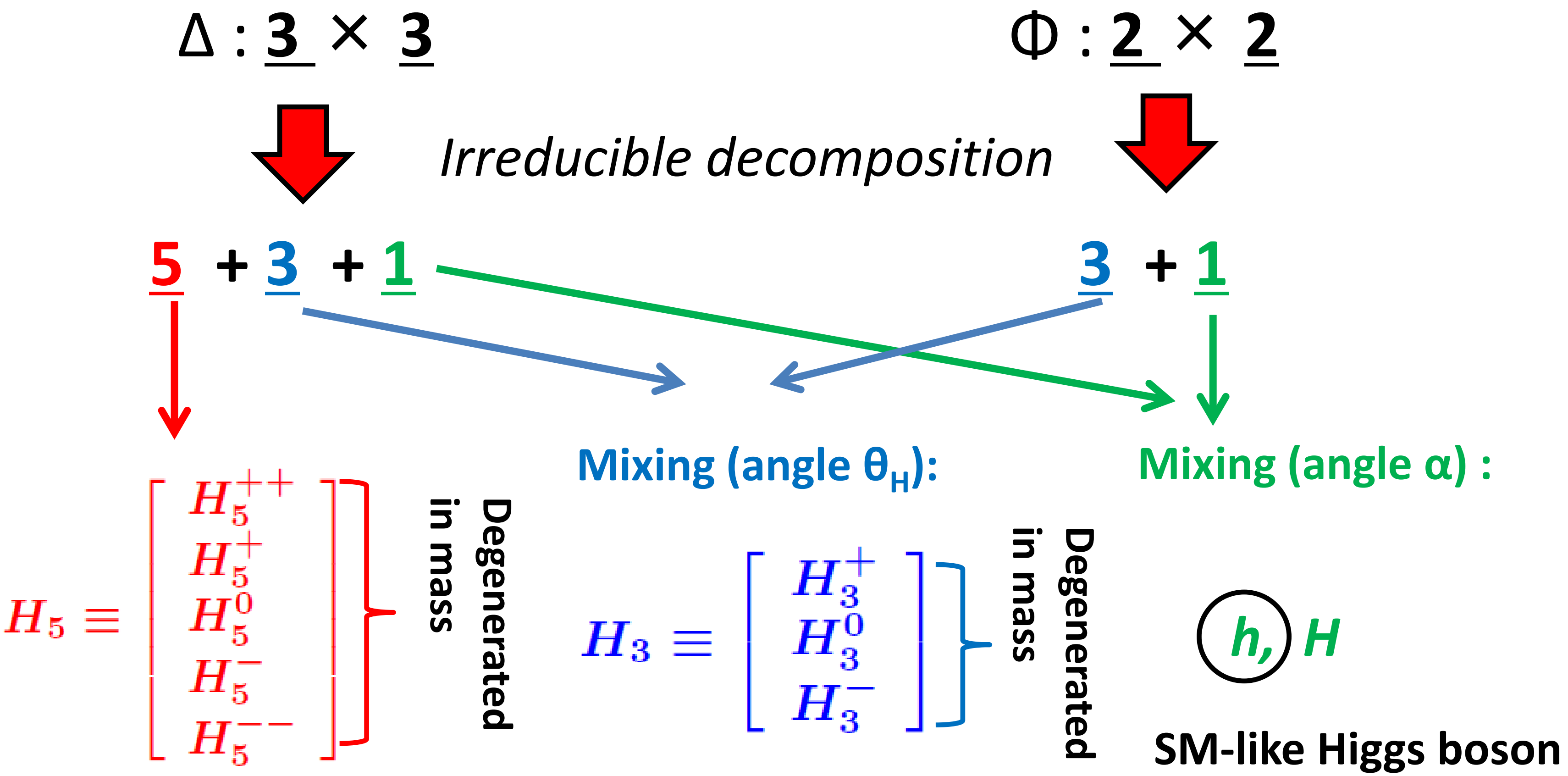
$$H_3 \equiv \begin{bmatrix} H_3^{+} \\ H_3^{0} \\ H_3^{-} \end{bmatrix}$$

**Degenerated in mass**

***h*, *H***

**SM-like Higgs boson**

# Decomposition



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**Degenerated in mass**

***h, H***

**SM-like Higgs boson**

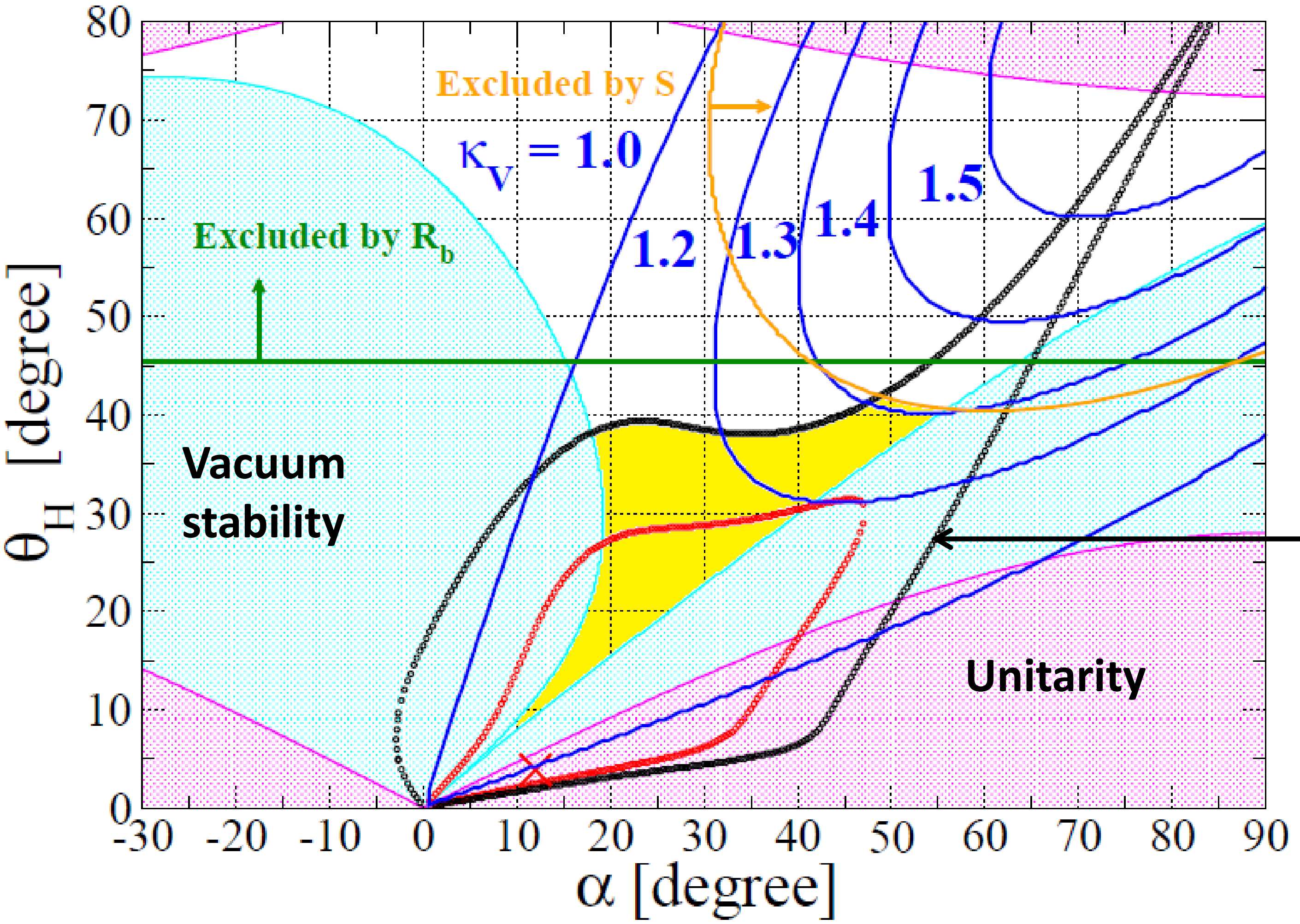
☐ The hVV and hff couplings are expressed as

$$\boxed{g_{hVV}^{\mathrm{GM}} = g_{hVV}^{\mathrm{SM}} \times \left( \cos\theta_H \cos\alpha + \frac{2}{3}\sqrt{6} \sin\theta_H \sin\alpha \right)}$$

$$\boxed{g_{hff}^{\mathrm{GM}} = g_{hff}^{\mathrm{SM}} \times \frac{\cos\alpha}{\cos\theta_H}}$$

# Allowed regions

All the triplet-like Higgs boson mass : 300 GeV



🟨 **Arrowed regions**

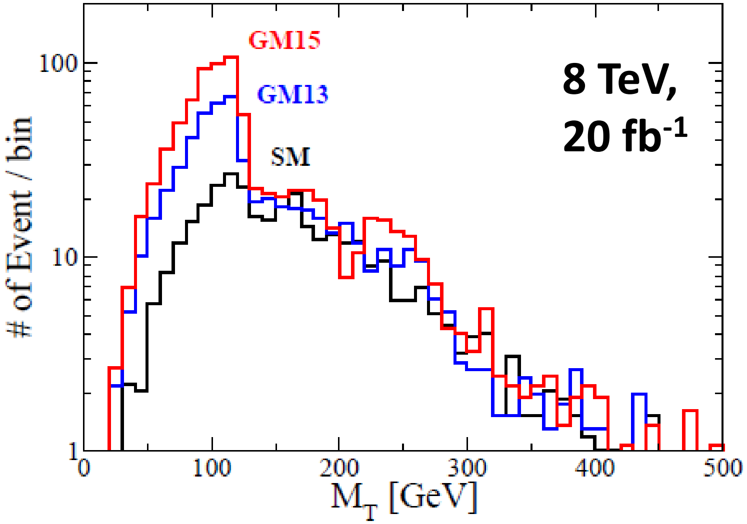
Consistent with the LHC data with 68% CL

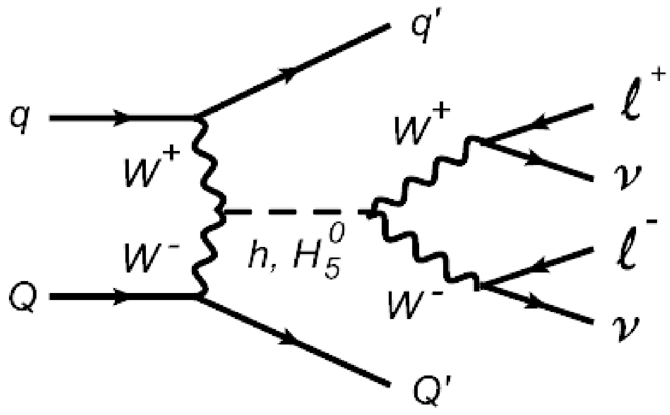
The hVV coupling can be 1.3 times larger than the SM prediction!

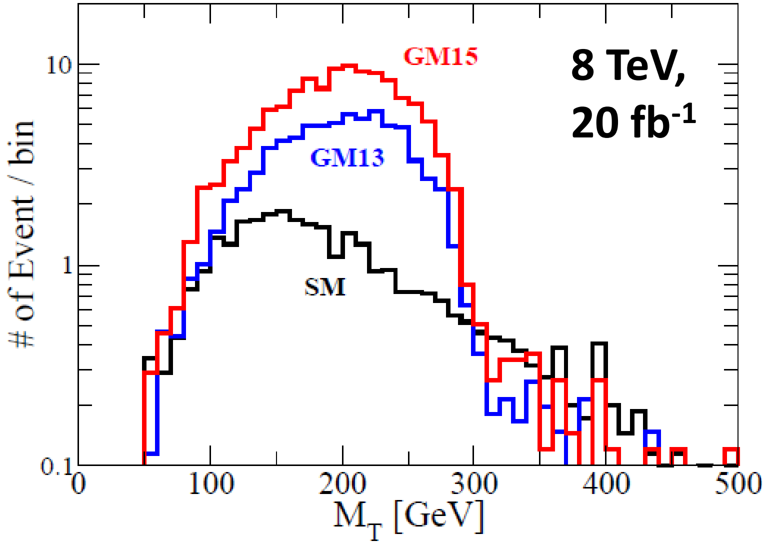
# Vector boson fusion processes

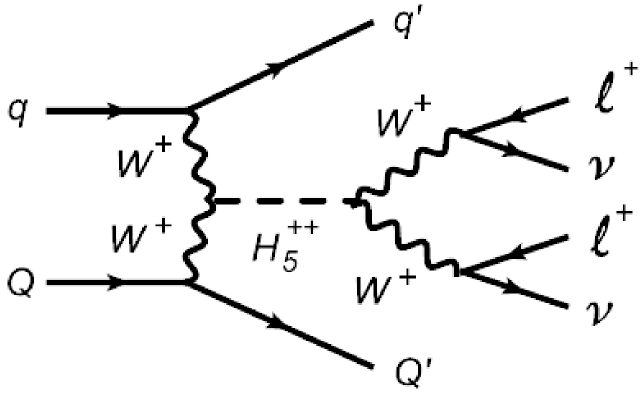
## Transverse mass distribution

GM13 (15): GM model with the hVV coupling being 1.3 (1.5) times larger than the SM prediction.



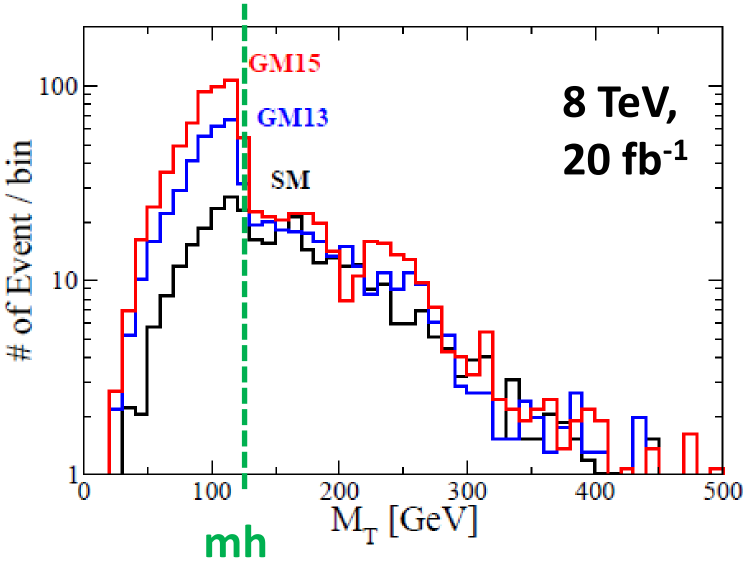






# Vector boson fusion processes

Transverse mass distribution



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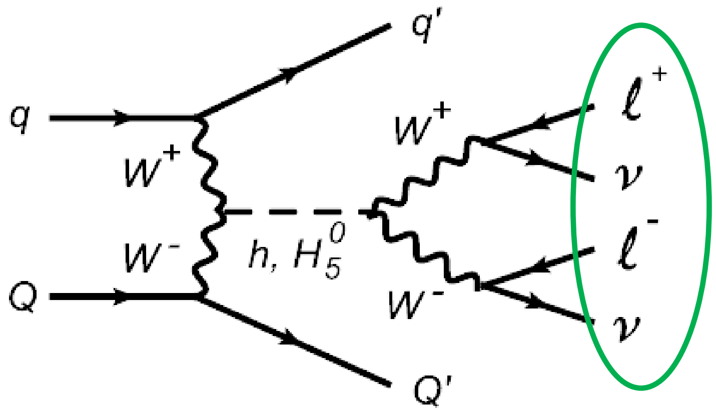
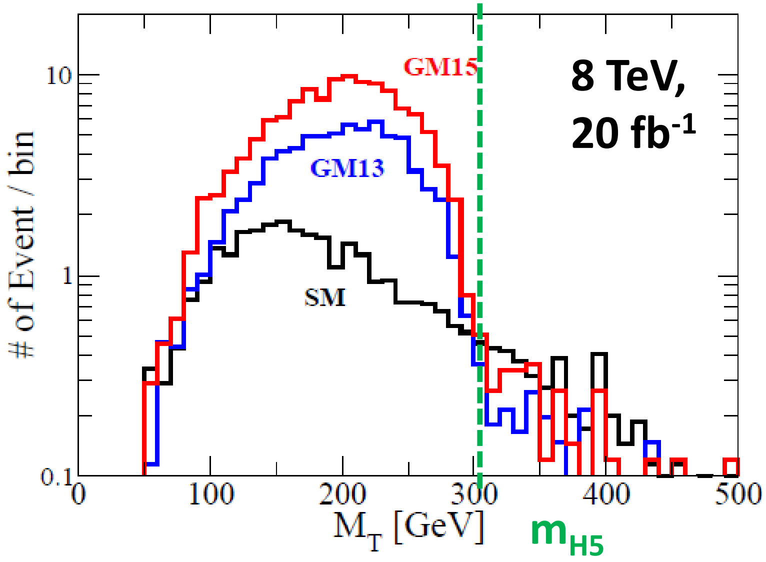
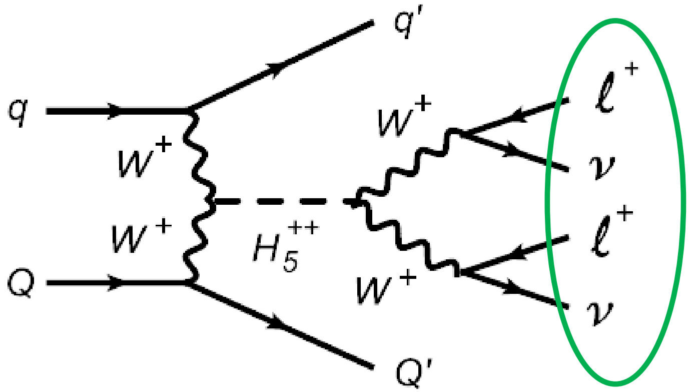






# Summary

- Measuring the enhancement of the **hVV** couplings can be a prove of **exotic Higgs sectors**.
- In the Georgi-Machacek model, the hVV coupling can be maximally **1.3 times** larger than the SM prediction.
- The **vector boson fusion process** is important to extract the enhanced hVV coupling and to detect extra Higgs bosons as well.

# 감사합니다!

# Cross section of VBF processes

| Mode | $jj'\ell^+\ell^-\not{E}_T$ | | | $jj'\ell^+\ell^+\not{E}_T$ | | | $jj'\ell^+\ell^+\ell^-\not{E}_T$ | | |
|---|---|---|---|---|---|---|---|---|---|
| Model | SM | GM13 | GM15 | SM | GM13 | GM15 | SM | GM13 | GM15 |
| Basic | 85 | 109 | 135 | 7.2 | 16 | 23 | 8.7 | 10 | 12 |
| | (203) | (260) | (322) | (17) | (39) | (57) | (18) | (22) | (26) |
| $\Delta\eta^{jj}$ | 18 | 29 | 42 | 1.7 | 7.6 | 12 | 2.0 | 3.0 | 3.9 |
| | (51) | (83) | (116) | (5.4) | (22) | (36) | (5.3) | (7.9) | (10.5) |

Basic cut:

$$p_T^\ell > 10 \quad \text{GeV}, \qquad p_T^j > 20 \quad \text{GeV},$$

$$|\eta^\ell| < 2.5, \qquad |\eta^j| < 5.0, \qquad \Delta R^{jj} > 0.4,$$

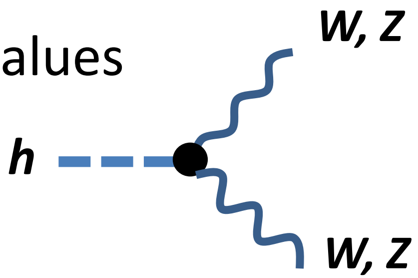
Rapidity gap cut:

$$\Delta\eta^{jj} \equiv |\eta^{j_1} - \eta^{j_2}| > 3.5$$

# Higgs boson couplings with gauge bosons

- Deviations in the hWW and hZZ couplings from the SM values can be defined as

$$g_{hVV} = g_{hVV}^{\mathrm{SM}} \times c_{hVV}$$



- In the general Higgs sector, $c_{hVV}$ factors are calculated by

$$\boxed{c_{hWW} = \frac{\sum_i 2v_i[T_i(T_i+1) - Y_i^2]R_{ih}}{v_{\mathrm{SM}}}}$$

$$\boxed{c_{hZZ} = \sum_i \frac{2Y_i^2 v_i R_{ih}}{\sqrt{\sum_j Y_j^2 v_j^2}}}$$

$Y_i$ : hypercharge
$T_i$ : isospin
$v_i$ : VEV

$R_{ih}$ : Mixing angles among CP-even Higgs bosons

***Model with multi-doublet structure***

→ $c_{hVV}$ are **smaller** than 1

***Model with exotic fields***

→ $c_{hVV}$ **can be larger** than 1

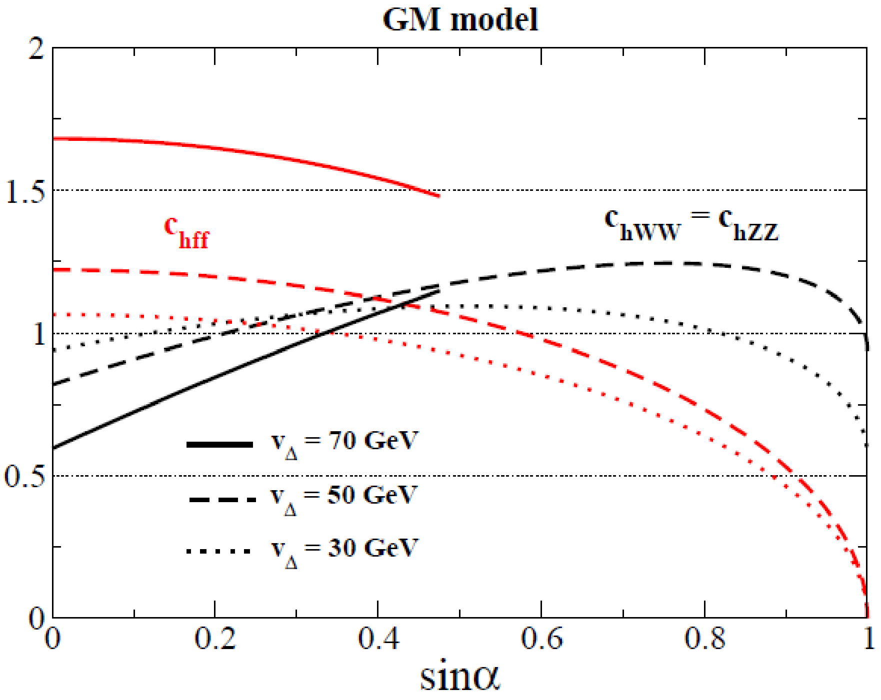
The Clebsh-Gordan coefficient $2[T(T+1)-Y^2]v$ and
the factor $4Y^2$ v from exotic fields are larger than those from the doublet.

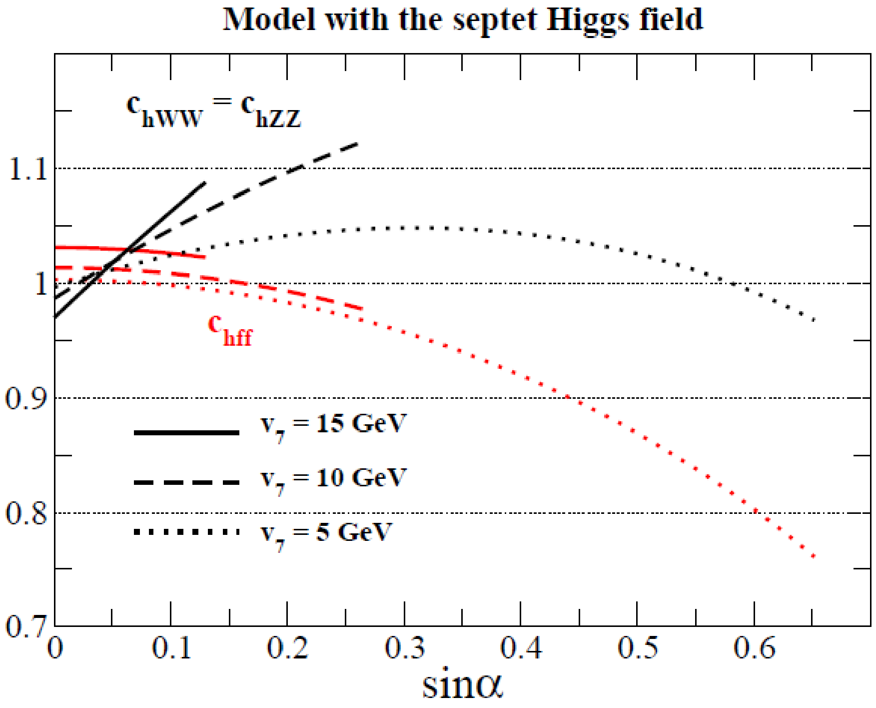
$$(\mathrm{GM13}):\ (\theta_H, \alpha) = (40^\circ, 55^\circ),$$

$$(\mathrm{GM15}):\ (\theta_H, \alpha) = (60^\circ, 70^\circ),$$

# Results in the GM model and HSM

*Kanemura, Kikuchi, KY (2013)*





**$c_{hVV}$ -1~ 30% (10%) is possible in the GM model (HSM) in the allowed regions by the EWPO.**

# S, T and U parameters

$$S = \frac{4 s_W^2 c_W^2}{\alpha_{\rm em}} \left[ \frac{\Pi^{\rm 1PI}_{\gamma\gamma}(m_Z^2) - \Pi^{\rm 1PI}_{\gamma\gamma}(0)}{m_Z^2} + \frac{c_W^2 - s_W^2}{c_W s_W} \frac{\Pi^{\rm 1PI}_{Z\gamma}(m_Z^2) - \Pi^{\rm 1PI}_{Z\gamma}(0)}{m_Z^2} - \frac{\Pi^{\rm 1PI}_{ZZ}(m_Z^2) - \Pi^{\rm 1PI}_{ZZ}(0)}{m_Z^2} \right],$$

$$T = \frac{1}{\alpha_{\rm em}} \left[ \frac{\Pi^{\rm 1PI}_{ZZ}(0)}{m_Z^2} - \frac{\Pi^{\rm 1PI}_{WW}(0)}{m_W^2} + \frac{2 s_W}{c_W} \frac{\Pi^{\rm 1PI}_{Z\gamma}(0)}{m_Z^2} + \frac{s_W^2}{c_W^2} \frac{\Pi^{\rm 1PI}_{\gamma\gamma}(0)}{m_Z^2} \right] + \delta T,$$

$$\begin{aligned} U = \frac{4 s_W^2}{\alpha_{\rm em}} \Bigg[ & s_W^2 \frac{\Pi^{\rm 1PI}_{\gamma\gamma}(m_Z^2) - \Pi^{\rm 1PI}_{\gamma\gamma}(0)}{m_Z^2} + 2 s_W c_W \frac{\Pi^{\rm 1PI}_{Z\gamma}(m_Z^2) - \Pi^{\rm 1PI}_{Z\gamma}(0)}{m_Z^2} + c_W^2 \frac{\Pi^{\rm 1PI}_{ZZ}(m_Z^2) - \Pi^{\rm 1PI}_{ZZ}(0)}{m_Z^2} \\ & - \frac{\Pi^{\rm 1PI}_{WW}(m_W^2) - \Pi^{\rm 1PI}_{WW}(0)}{m_W^2} \Bigg], \end{aligned}$$

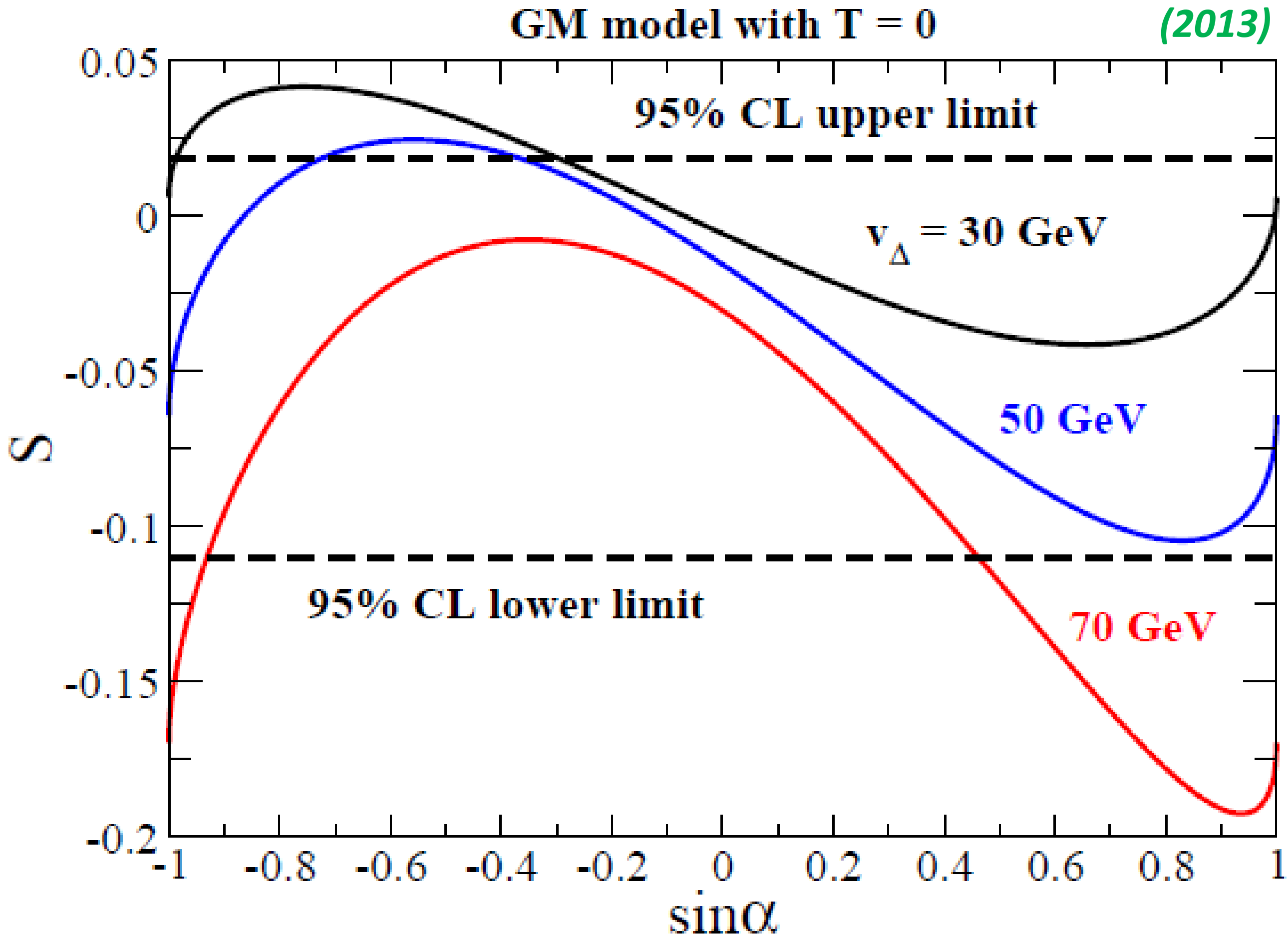
S = 0.05 ± 0.08 , T = 0.08 ± 0.07 by fixing U = 0
with mh(ref) = 126 GeV

# S parameter in the GM model with T=0

Gunion, Vega, Wudka (1991);
Englert, Re and Spannowsky (2013)

All the extra Higgs boson masses are taken to be 500 GeV.

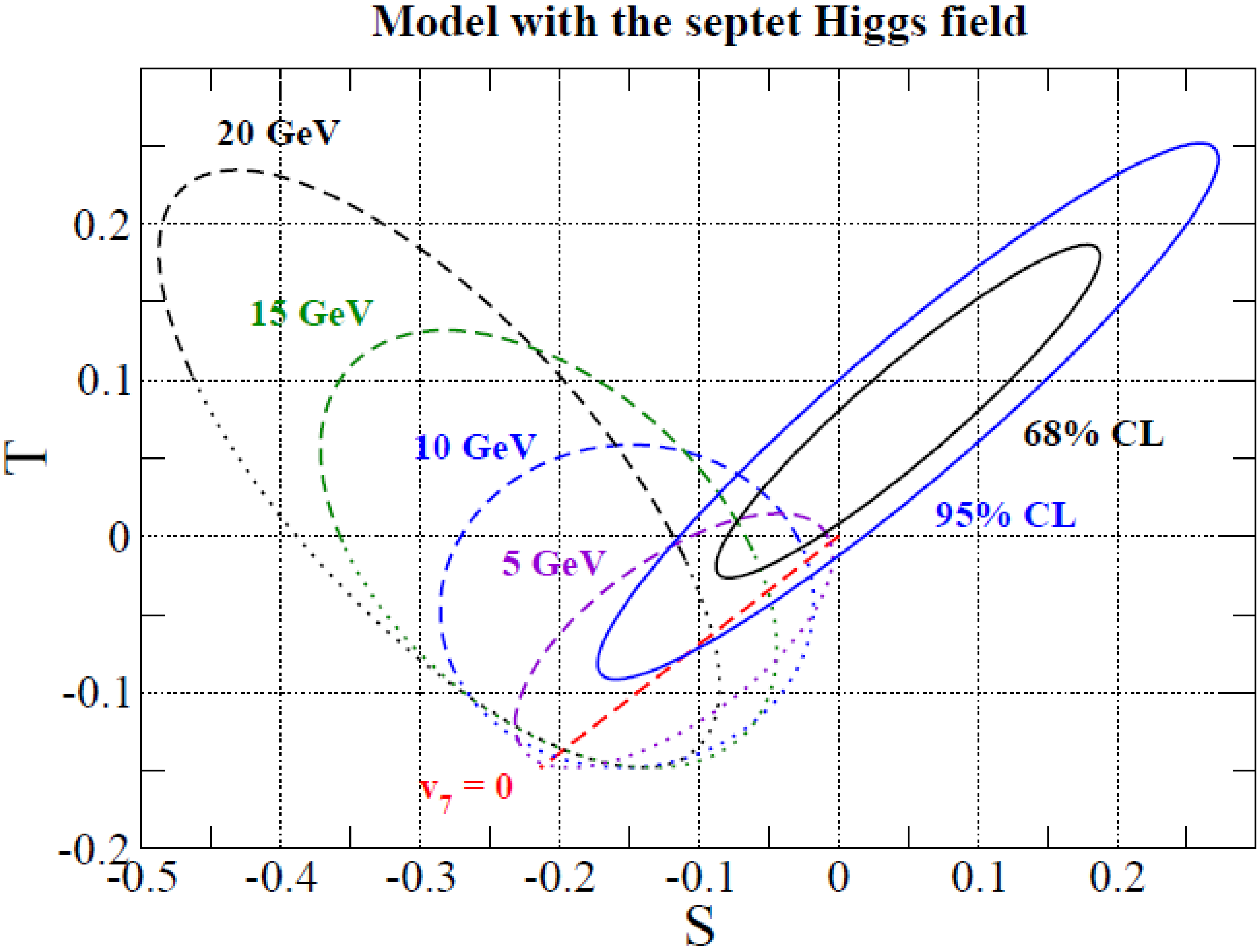
*Kanemura, Kikuchi, KY (2013)*



# S-T plot in the HTM

All the extra Higgs boson masses are taken to be 500 GeV.

*Kanemura, Kikuchi, KY (2013)*



# Four examples

We consider the following Higgs multiplets;

ϕ: (**2**, 1/2), χ: (**3**, 1), ξ: (**3**, 0), ϕ7: (**7**, 2).

1. Complex Higgs Triplet Model (cHTM)

   $\Phi + \chi$

2. Real Higgs Triplet Model (rHTM)

   $\Phi + \xi$

3. Georgi-Machacek (GM) Model

   $\Phi + \Delta\ (\chi + \xi)$

4. Higgs Septet Model (HSM)

   $\Phi + \phi_7$

$$\boldsymbol{\Phi} = \begin{pmatrix} \boldsymbol{\Phi}^{+} \\ \boldsymbol{\Phi}^{0} \end{pmatrix}$$

$$\chi = \begin{pmatrix} \chi^{++} \\ \chi^{+} \\ \chi^{0} \end{pmatrix}$$

$$\xi = \begin{pmatrix} \xi^{+} \\ \xi^{0} \\ \xi^{-} \end{pmatrix}$$

$$\boldsymbol{\Delta} = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ \chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & \xi^{-} & \chi^{0} \end{pmatrix}$$

$$\varphi_{\boldsymbol{7}} = \begin{pmatrix} \varphi_{\boldsymbol{7}}^{5+} \\ \varphi_{\boldsymbol{7}}^{4+} \\ \varphi_{\boldsymbol{7}}^{3+} \\ \varphi_{\boldsymbol{7}}^{++} \\ \varphi_{\boldsymbol{7}}^{+} \\ \varphi_{\boldsymbol{7}}^{0} \\ \varphi_{\boldsymbol{7}}^{-} \end{pmatrix}$$

# Four examples

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ϕ: (**2**, 1/2), χ: (**3**, 1), ξ: (**3**, 0), ϕ7: (**7**, 2).

**Charged (Neutral) Nambu-Goldstone bosons ($G^+$, $G^0$)**

1. Complex Higgs Triplet Model (cHTM)

Φ + χ

$$\begin{pmatrix} \Phi^+ \\ \chi^+ \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

$$\begin{pmatrix} \mathrm{Im}\Phi^0 \\ \mathrm{Im}\chi^0 \end{pmatrix} = \begin{pmatrix} c_{\beta'} & -s_{\beta'} \\ s_{\beta'} & c_{\beta'} \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

2. Real Higgs Triplet Model (rHTM)

Φ + ξ

$$\begin{pmatrix} \Phi^+ \\ \xi^+ \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

$$\mathbf{Im\Phi^0 = G^0}$$

3. Georgi-Machacek (GM) Model

Φ + Δ (χ + ξ)

$$\begin{pmatrix} \Phi^+ \\ \xi^+ \\ \chi^+ \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} c_\beta & -s_\beta & 0 \\ s_\beta & c_\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} G^+ \\ H_3^+ \\ H_5^+ \end{pmatrix}$$

$$\begin{pmatrix} \mathrm{Im}\Phi^0 \\ \mathrm{Im}\chi^0 \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

4. Higgs Septet Model (HSM)

Φ + ϕ$_7$

$$\begin{pmatrix} \Phi^+ \\ \varphi_7^+ \\ \bar{\varphi}_7^+ \end{pmatrix} = \begin{pmatrix} c_\beta & -\sqrt{\frac{5}{5+3c_\beta^2}}s_\beta & -\sqrt{\frac{3}{5+3c_\beta^2}}s_\beta c_\beta \\ \sqrt{\frac{5}{8}}s_\beta & \sqrt{\frac{8}{5+3c_\beta^2}}c_\beta & -\sqrt{\frac{15}{8(5+3c_\beta^2)}}s_\beta^2 \\ -\sqrt{\frac{3}{8}}s_\beta & 0 & -\sqrt{\frac{5+3c_\beta^2}{8}} \end{pmatrix} \begin{pmatrix} G^+ \\ H^+ \\ H'^+ \end{pmatrix}$$

$$\begin{pmatrix} \mathrm{Im}\Phi^0 \\ \mathrm{Im}\varphi_7^0 \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

# Four examples

We consider the following Higgs multiplets; ϕ: (**2**, 1/2), χ: (**3**, 1), ξ: (**3**, 0), $\phi_7$: (**7**, 2).

**Mixing angle among the CP-even states**

1. Complex Higgs Triplet Model (cHTM)

$\Phi + \chi$

$$\begin{pmatrix} \mathrm{Re}\Phi^0 \\ \mathrm{Re}\chi^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

2. Real Higgs Triplet Model (rHTM)

$\Phi + \xi$

$$\begin{pmatrix} \mathrm{Re}\Phi^0 \\ \xi^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

3. Georgi-Machacek (GM) Model

$\Phi + \Delta\ (\chi + \xi)$

$$\begin{pmatrix} \sqrt{2}\mathrm{Re}\Phi^0 \\ \xi^0 \\ \sqrt{2}\mathrm{Re}\chi^0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{3}} & -\sqrt{\frac{2}{3}} \\ 0 & \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \begin{pmatrix} c_\alpha & -s_\alpha & 0 \\ s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ H_1 \\ H_5 \end{pmatrix}$$

4. Higgs Septet Model (HSM)

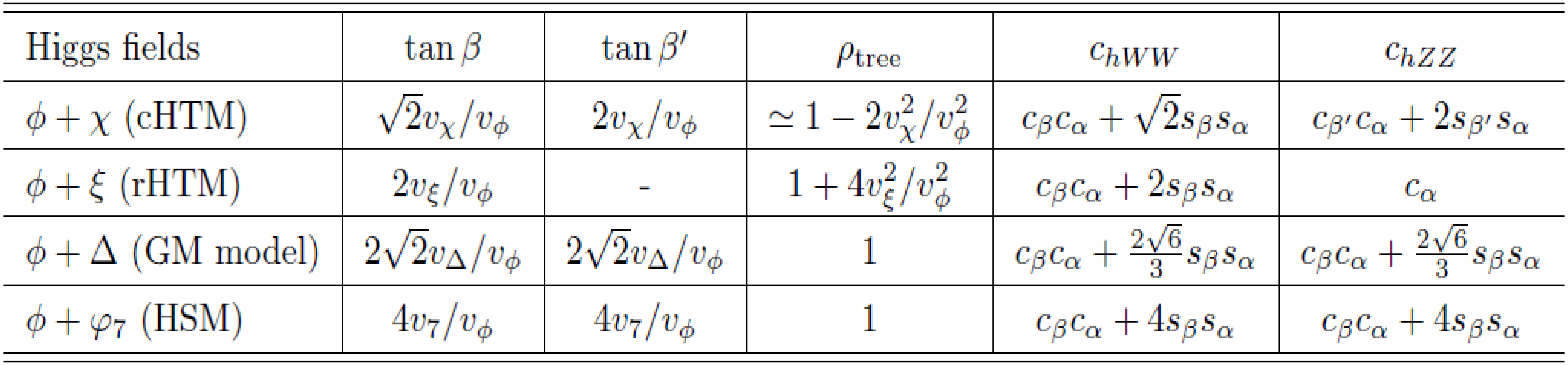
$\Phi + \phi_7$

$$\begin{pmatrix} \mathrm{Re}\Phi^0 \\ \mathrm{Re}\varphi_7^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

# hVV couplings in various ext. Higgs sectors

*Kanemura, Kikuchi, KY (2013)*

We list $c_{hVV}$ factors in the four models.



| Higgs fields | $\tan\beta$ | $\tan\beta'$ | $\rho_{\text{tree}}$ | $c_{hWW}$ | $c_{hZZ}$ |
|---|---|---|---|---|---|
| $\phi+\chi$ (cHTM) | $\sqrt{2}v_\chi/v_\phi$ | $2v_\chi/v_\phi$ | $\simeq 1-2v_\chi^2/v_\phi^2$ | $c_\beta c_\alpha+\sqrt{2}s_\beta s_\alpha$ | $c_{\beta'}c_\alpha+2s_{\beta'}s_\alpha$ |
| $\phi+\xi$ (rHTM) | $2v_\xi/v_\phi$ | - | $1+4v_\xi^2/v_\phi^2$ | $c_\beta c_\alpha+2s_\beta s_\alpha$ | $c_\alpha$ |
| $\phi+\Delta$ (GM model) | $2\sqrt{2}v_\Delta/v_\phi$ | $2\sqrt{2}v_\Delta/v_\phi$ | $1$ | $c_\beta c_\alpha+\frac{2\sqrt{6}}{3}s_\beta s_\alpha$ | $c_\beta c_\alpha+\frac{2\sqrt{6}}{3}s_\beta s_\alpha$ |
| $\phi+\varphi_7$ (HSM) | $4v_7/v_\phi$ | $4v_7/v_\phi$ | $1$ | $c_\beta c_\alpha+4s_\beta s_\alpha$ | $c_\beta c_\alpha+4s_\beta s_\alpha$ |