

# Effects of Extra Yukawa Couplings and Alignment

Mariko Kikuchi  
(National Taiwan University)

Collaborator:  
Wei-Shu Hou (National Taiwan University)

Accepted by PRD [arXiv : 1704.03788]

EPS2017@Venice, Italy, 2017/07/07

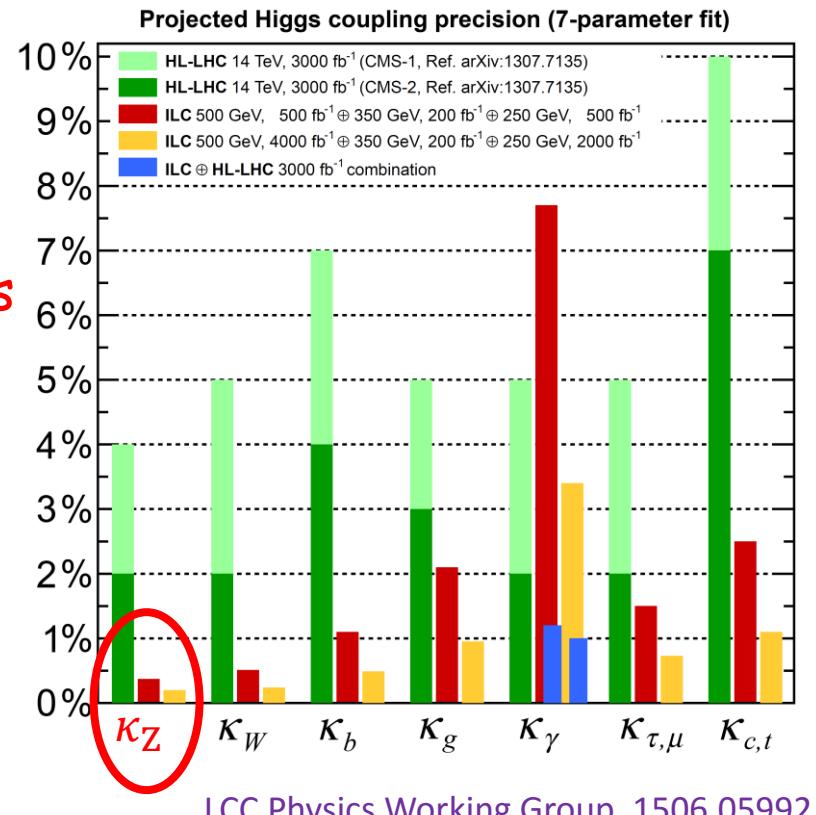
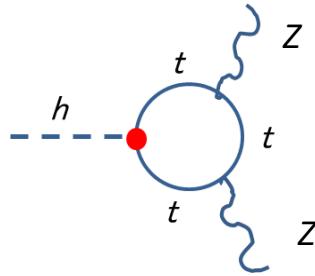
# Introduction

- Iso-doublet exists. → Extension to Two Higgs doublets is natural
- 2HDM-II (2HDM with discrete symm.)
  - Motivated by SUSY  
→ So far, there is no indication of SUSY particles @ LHC
  - Tree level Flavor Changing Neutral Couplings are forbidden by **discrete sym.**  
 $\mathcal{L}_Y = -\bar{Q}_{L,i}(\kappa_{ij}\Phi_1 + \cancel{\rho_{ij}}\Phi_2)f_{R,j} + h.c.$       Glashow-Weinberg, '77  
→ *ad hoc*  $Z_2$  symm. "**artificially**" restricts Y-matrices too much.
- In general 2HDM,  $\bar{f}_i \cancel{\rho_{ij}} \Phi_2 f_j$  interaction appears

It is important to determine the form of additional Yukawa interactions ( $\rho_{ij}$ ) not by *ad hoc* symmetry, but by experiments (bottom up) !!

# In my talk

- Explore extra Yukawa couplings using hZZ measurement
- Calculate EW radiative corrections to hZZ in General 2HDM



- Properties of radiative corrections
- Future precision measurements can explore larger parameter space
- Summary

# General 2HDM

- General Higgs potential

$$V = \mu_{11}^2 |\Phi|^2 + \mu_{22}^2 |\Phi'|^2 - (\mu_{12}^2 \Phi^\dagger \Phi' + h.c.) + \frac{\eta_1}{2} |\Phi|^4 + \frac{\eta_2}{2} |\Phi'|^4 + \eta_3 |\Phi|^2 |\Phi'|^2 \\ + \eta_4 |\Phi^\dagger \Phi'|^2 + \left\{ \frac{\eta_5}{2} (\Phi^\dagger \Phi')^2 + (\eta_6 |\Phi|^2 + \eta_7 |\Phi'|^2) (\Phi^\dagger \Phi') + h.c. \right\},$$

- Basis

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(\phi_1 + v + i G^0) \end{pmatrix} \quad \Phi' = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\phi_2 + i A) \end{pmatrix} \quad v \simeq 246 \text{ GeV}$$

- Mass eigenstates

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos \gamma & -\sin \gamma \\ \sin \gamma & \cos \gamma \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

In 2HDM-II case,  
 $\gamma \rightarrow \beta - \alpha$

- Alignment limit :  $\sin(-\gamma) \rightarrow 1$

- Decoupling limit ;  $\varepsilon \equiv v^2/m_{H, A, H^\pm}^2 \ll 1,$

$$\sin(-\gamma) = 1 - \frac{1}{2} \left( \frac{\eta_6 v^2}{m_H^2} \right)^2 + \mathcal{O}(\varepsilon^3)$$

Decoupling limit is the special case  
of alignment limit.

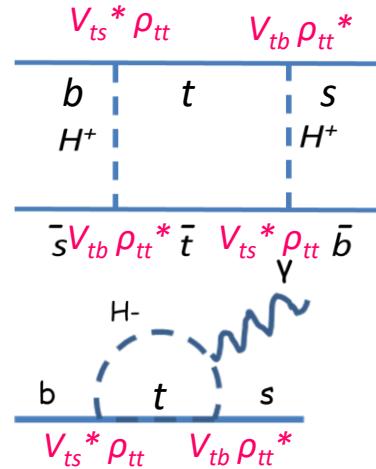
# Yukawa interaction

$$\mathcal{L}_y = -\bar{Q}_{L,i} (\kappa_{ij} \tilde{\Phi} + \rho_{ij} \widetilde{\Phi'}) u_{R,j} + h.c. + (\text{down quark part}) + (\text{lepton part})$$

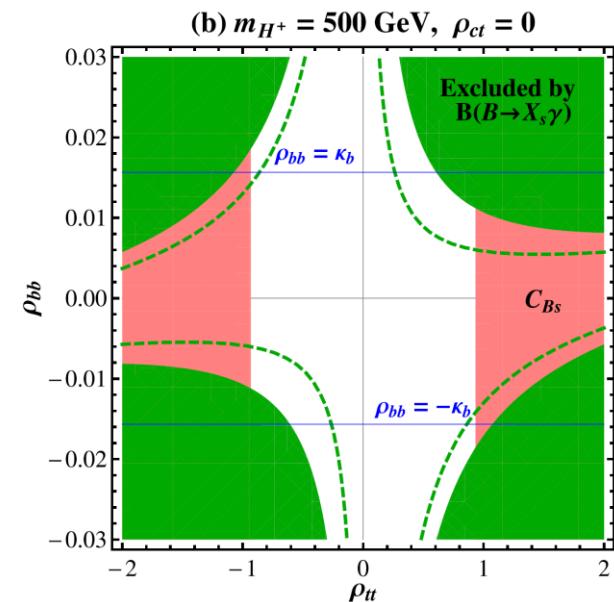
- $\kappa_{ij}$  → Diagonalized mass matrix of fermion  $\kappa_{ii} = \frac{\sqrt{2}m_i}{v}, \kappa_{ij} = 0 \ (i \neq j)$
- $\rho_{ij}$  can have non-diagonal components  
 $\rho_{ij} \ (i \neq j)$  cause FCN processes  
 (FCN processes including  $\rho_{tc}$  are interesting processes ( $t \rightarrow ch$ ). )
- Some components are still allowed to be  $O(1)$ .

$\rho_{tt}$        $B_{d,s}$  mixing

$B \rightarrow X_s \gamma$



If  $\rho_{bb} \approx 0, \rho_{ct} \approx 0$ ,  $\rho_{tt}$  can be  $O(1)$ .



Altunkaynak, Hou, Kao,  
Kohda, McCoy (2015)

# In our numerical calculations

$$\Gamma_{hZZ}^{\text{2HDM}}[p_1^2, p_2^2, q^2] = \text{---} \begin{array}{c} q \\ \diagdown \\ \text{---} \end{array} \text{---} \begin{array}{c} p_1 \\ \diagup \\ \text{---} \end{array} + \text{---} \begin{array}{c} p_2 \\ \diagdown \\ \text{---} \end{array} = \text{---} \begin{array}{c} \text{Tree} \\ \diagup \\ \text{---} \end{array} + \text{---} \begin{array}{c} \text{1-loop vertex} \\ \text{corrections} \\ \diagup \\ \text{---} \end{array} + \text{---} \begin{array}{c} \text{Counter terms} \\ \diagup \\ \text{---} \end{array}$$

We numerically evaluate renormalized scaling factor of  $hZZ$ .

$$\text{Renormalized scaling factor} ; \kappa_V \equiv \frac{\Gamma_{hVV}^{\text{2HDM}} \left[ (m_h + m_V)^2, m_V^2, m_h^2 \right]}{\Gamma_{hVV}^{\text{SM}} \left[ (m_h + m_V)^2, m_V^2, m_h^2 \right]}$$

$$\Delta\kappa_V \equiv \kappa_V - 1$$

# Properties of one-loop $hZZ$

Approximate formula in  $\varepsilon \equiv v^2/m_{H,A,H^\pm}^2 \ll 1$  limit  $\rightarrow \sin(-\gamma) \rightarrow 1$

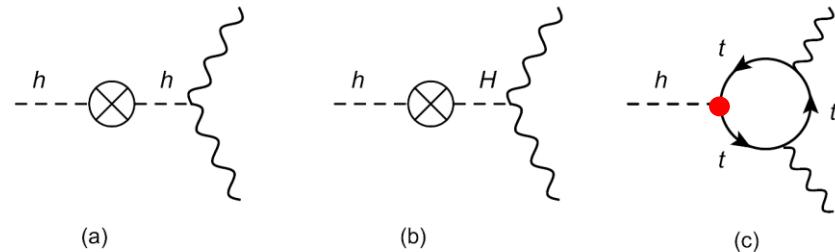
$$\kappa_Z \simeq \sin(-\gamma) \quad \xleftarrow{\text{Tree contribution}}$$

$$- \frac{1}{6} \frac{1}{16\pi^2} \sum_{\varphi=H,A,H^\pm} c_\varphi \frac{m_\varphi^2}{v^2} \left(1 - \frac{\mu_{22}^2}{m_\varphi^2}\right)^2 \quad \xleftarrow{\text{Bosonic loop contribution}}$$

$$+ \frac{\sqrt{2}N_t^c}{16\pi^2} \frac{m_t}{v} \rho_{tt} \cos \gamma \left\{ (2 - \ln[m_H^2]) - \left[ B_0[m_h^2; m_t, m_t] - 4m_t^2 \frac{d}{dp^2} B_0[p^2; m_t, m_t] \Big|_{p^2=m_h^2} \right] \right.$$

$$\left. + 2 \sin^2(-\gamma) [(v_f^2 + a_f^2)P_1 - (v_f^2 - a_f^2)P_2] \right\} \quad \xleftarrow{\textcolor{red}{\rho_{tt} (\sim O(1)) \text{ contribution}}}$$

Dominant contribution in fermionic loop



$\rho_{ij}$  ( $i \neq j$ ) cont.; subdominant

because they have higher power of  $\cos \gamma$  suppression

$\rho_{ii}$  (except  $i=t$ ) cont.; subdominant

because they are suppressed by  $m_f/v$

# Sign of loop contributions

Approximate formula in  $\varepsilon \equiv v^2/m_{H, A, H^\pm}^2 \ll 1$  limit

$$\begin{aligned} \kappa_Z \simeq \sin(-\gamma) &\quad \xleftarrow{\hspace{1cm}} \text{Tree contribution} \\ -\frac{1}{6} \frac{1}{16\pi^2} \sum_{\varphi=H,A,H^\pm} c_\varphi \frac{m_\varphi^2}{v^2} \left(1 - \frac{\mu_{22}^2}{m_\varphi^2}\right)^2 &\quad \xleftarrow{\hspace{1cm}} \text{Bosonic loop contribution} \\ + \frac{\sqrt{2}N_t^c}{16\pi^2} \frac{m_t}{v} \rho_{tt} \cos \gamma \left\{ (2 - \ln[m_H^2]) - \left[ B_0[m_h^2; m_t, m_t] - 4m_t^2 \frac{d}{dp^2} B_0[p^2; m_t, m_t] \Big|_{p^2=m_h^2} \right] \right. \\ \left. + 2 \sin^2(-\gamma) [(v_f^2 + a_f^2)P_1 - (v_f^2 - a_f^2)P_2] \right\} &\quad \xleftarrow{\hspace{1cm}} \text{Top } \rho_{tt} \text{ contribution} \end{aligned}$$

## Sign of loop contributions

$$\begin{aligned} \Delta_{\text{loop}} &\equiv \kappa_Z - \sin(-\gamma) \\ &\simeq \Delta_{\text{loop}}^{\text{bosonic}} + \Delta_{\text{loop}}^{\rho_{tt}} \\ &\text{Negative } \downarrow \end{aligned}$$

Depend on sign of  $\rho_{tt} \cos \gamma$

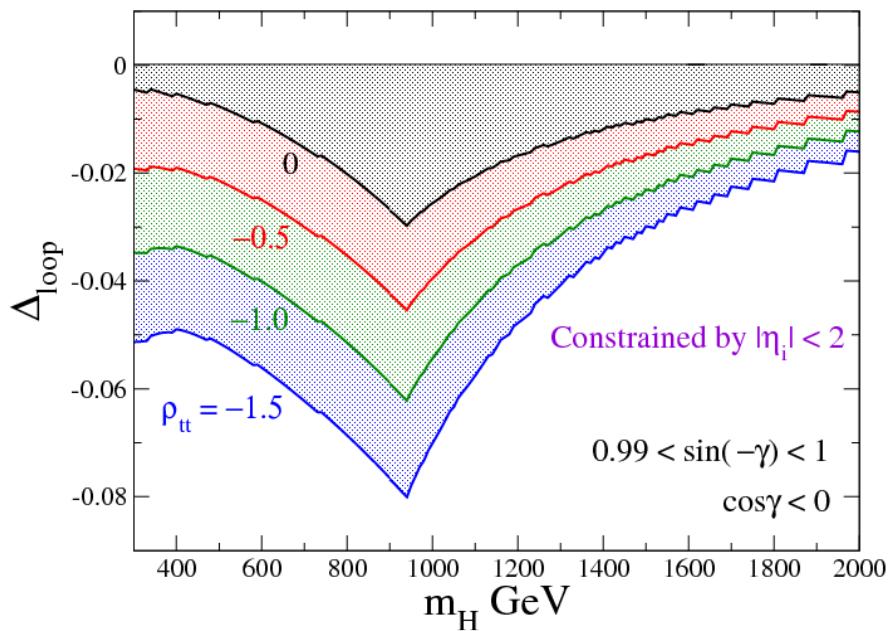
- $\rho_{tt} \cos \gamma > 0$  : Negative  $\downarrow$
- $\rho_{tt} \cos \gamma < 0$  : Positive  $\uparrow$

If  $\rho_{tt} \cos \gamma < 0$ ,  $\Delta_{\text{loop}}^{\text{bosonic}}$  and  $\Delta_{\text{loop}}^{\rho_{tt}}$  can cancel out each other, so that  $\kappa_Z \simeq 1$

# $\Delta_{\text{loop}}$

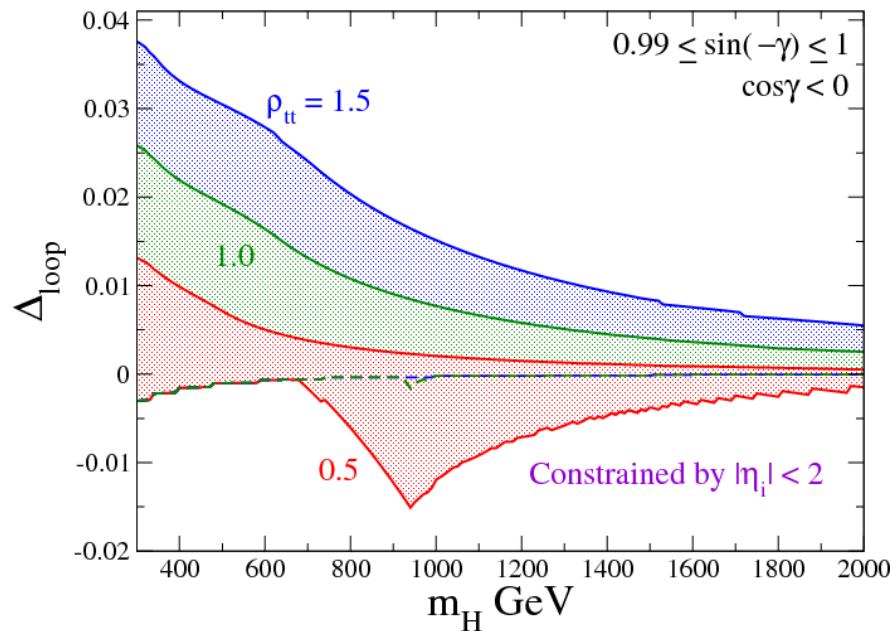
$\rho_{tt} \cos \gamma > 0$

$$\Delta_{\text{loop}} \simeq \Delta_{\text{loop}}^{\text{bosonic}}(\downarrow) + \Delta_{\text{loop}}^{\rho_{tt}}(\downarrow)$$



$\rho_{tt} \cos \gamma < 0$

$$\Delta_{\text{loop}} \simeq \Delta_{\text{loop}}^{\text{bosonic}}(\downarrow) + \Delta_{\text{loop}}^{\rho_{tt}}(\uparrow)$$



- $\Delta_{\text{loop}}$  is always negative

- Total loop effect can increase hZZ by  $\rho_{tt}$  effect.

$\Delta_{\text{loop}}$  decouples in large mass limit.

# $\rho_{tt}$ dependence of $\Delta\kappa_Z$ (Illustration)

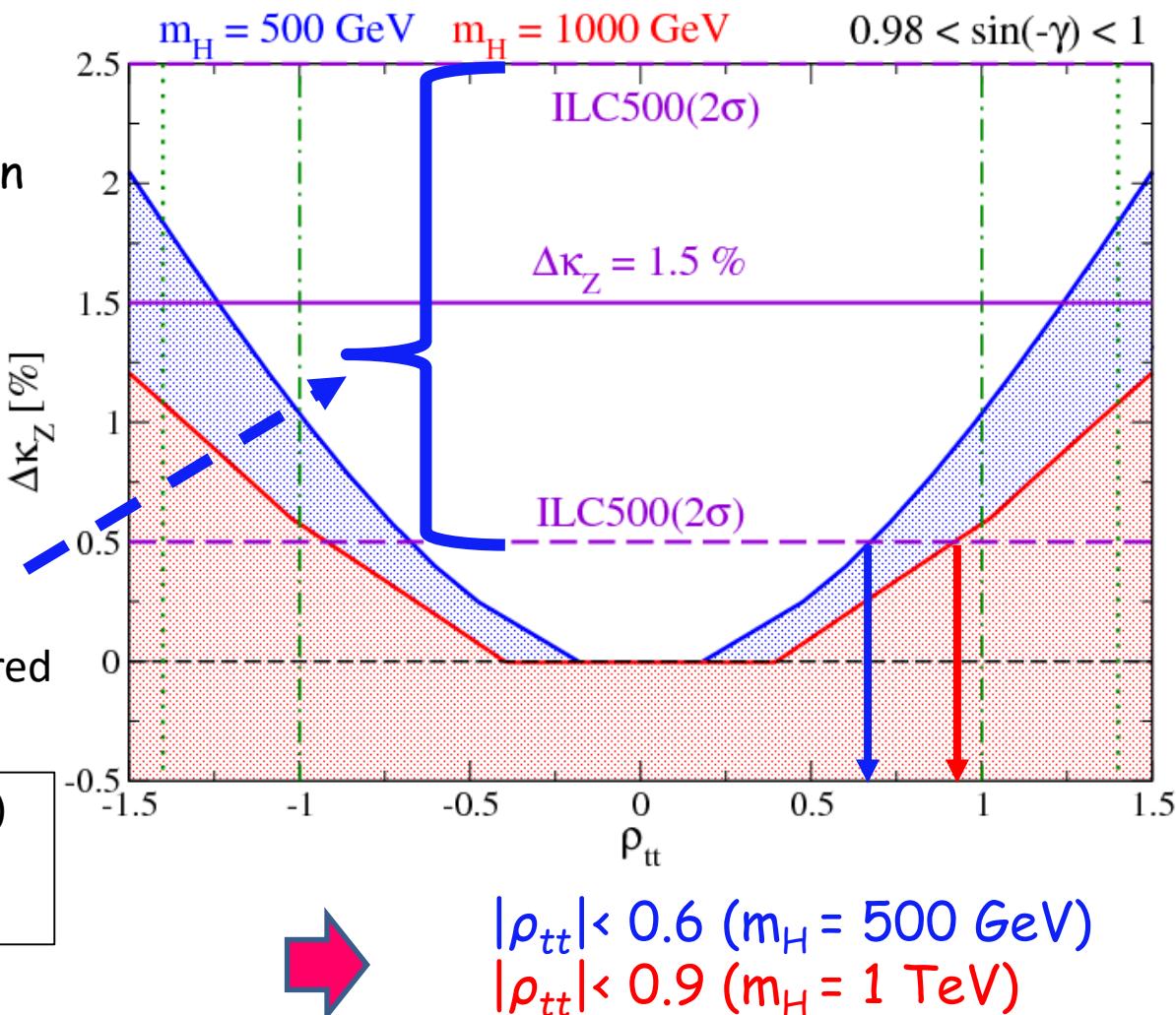
Positive deviation in  $hZZ$  can be realized by  $\Delta_{\text{loop}}^{\rho_{tt}}$

Suppose that the  $\Delta\kappa_Z$  is measured at center value **+1.5%** at ILC

Measurement uncertainties ( $1\sigma$ )

HL-LHC : 2 %

ILC (250+500) : 0.5%



It can be a probe of  $\rho_{tt}$  in general 2HDM

# Summary

- In General 2HDM, extra Yukawa  $\rho_{tt}$  is still allowed to be  $O(1)$
- Explore  $\rho_{tt}$  effect in precision measurement of  $hZZ$   
⇒ Calculate  $hZZ$  by on-shell renormalization
- $\rho_{tt}$  loop effect can cancel against bosonic loop effect for  $\rho_{tt} \cos \gamma < 0$   
⇒ Only  $\rho_{tt}$  loop can increase  $hZZ$  from SM

Can probe  $\rho_{tt}$  coupling in General 2HDM

# Extra !

Alignment w/o decoupling  
 $(|\cos\gamma| \ll 1, m_{H,A,H^+} \sim 500\text{GeV})$   
naturally emerges in General 2HDM !

[arXiv:1706.07694](https://arxiv.org/abs/1706.07694)

Thank you !



# Counter terms

Parameter shift ;  $m_\phi^2 \rightarrow m_\phi^2 + \delta m_\phi^2$ , ( $\phi = h, H, A$ , and  $H^\pm$ ),  
 $\gamma \rightarrow \gamma + \delta\gamma$ ,  $v \rightarrow v + \delta v$ ,  $\mu_{22}^2 \rightarrow \mu_{22}^2 + \delta\mu_{22}^2$ ,  
 $\eta_2 \rightarrow \eta_2 + \delta\eta_2$ ,  $\eta_7 \rightarrow \eta_7 + \delta\eta_7$ . 9

Field shift ;  $\binom{H}{h} \rightarrow \begin{pmatrix} 1 + \delta Z_H & \delta C_{Hh} + \delta\gamma \\ \delta C_{hh} - \delta\gamma & 1 + \delta Z_h \end{pmatrix} \binom{H}{h}$  12

Tadpole shift ;  $T_{\phi_1} \rightarrow T_{\phi_1} + \delta T_{\phi_1}$   $T_{\phi_2} \rightarrow T_{\phi_2} + \delta T_{\phi_2}$  2

**9(parameters) + 2(Tadpole) + 6(fields) + 6(field mixing) = 23**

---

$$\Gamma_{hZZ}^{Tree} hZ^\mu Z^\nu = \frac{2m_Z^2}{v} \sin(-\gamma) hZ^\mu Z^\nu$$

$$\rightarrow \frac{2m_Z^2}{v} \sin(-\gamma) \left( 1 + \underbrace{\frac{\delta m_Z^2}{m_Z^2} - \frac{\delta v}{v} + \delta Z_Z + \frac{1}{2}\delta Z_h + \frac{\cos\gamma}{\sin(-\gamma)} \delta C_{Hh}}_{\text{Counter term formula of } hZZ} \right) hZ^\mu Z^\nu$$

Counter term formula of  $hZZ$

# Renormalization conditions

## ■ On shell conditions

$$\delta T_h \quad \text{---} \Big|_{p^2=m_h^2} = 0 \quad \delta T_h = -T_h^{1PI}[0]$$

$$\delta m_h^2 \quad \Pi_{hh}(m_h^2) = 0 \quad \delta m_h^2 = \frac{s_\gamma^2}{v} \delta T_1 - \frac{2s_\gamma c_\gamma}{v} \delta T_2 + \Pi_{hh}^{1PI}[m_h^2],$$

$$\delta Z_h \quad \frac{d}{dp^2} \Pi_{hh}(m_h^2) = 1 \quad \delta Z_h = -\frac{d}{dp^2} \Pi_{hh}^{1PI}(m_h^2)$$

$$\begin{aligned} \delta C_{Hh} & \quad \Pi_{hH}(m_h^2) = \Pi_{hH}(m_H^2) = 0 \\ \delta C_{hH} & \quad \delta C_{Hh} = \frac{1}{m_H^2 - m_h^2} (\Pi_{hH}^{1PI}[m_h^2] - \Pi_{hH}^{1PI}[m_H^2]) \end{aligned}$$

$\delta v$   $\delta Z_Z$ ; Determined by renormalization in gauge sector

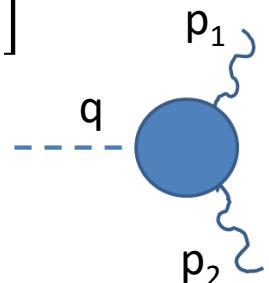
# In our numerical calculations

Renormalized scaling factor

$$\kappa_V \equiv \frac{\Gamma_{hVV}^{2HDM} \left[ (m_h + m_V)^2, m_V^2, m_h^2 \right]}{\Gamma_{hVV}^{SM} \left[ (m_h + m_V)^2, m_V^2, m_h^2 \right]}$$

## ● Parameter set

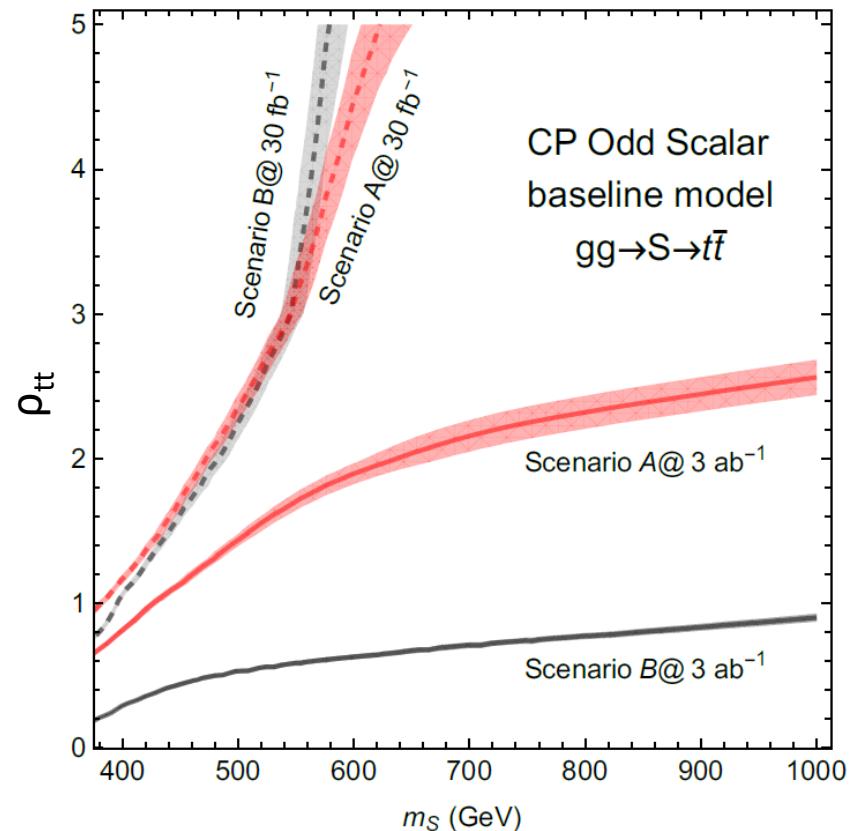
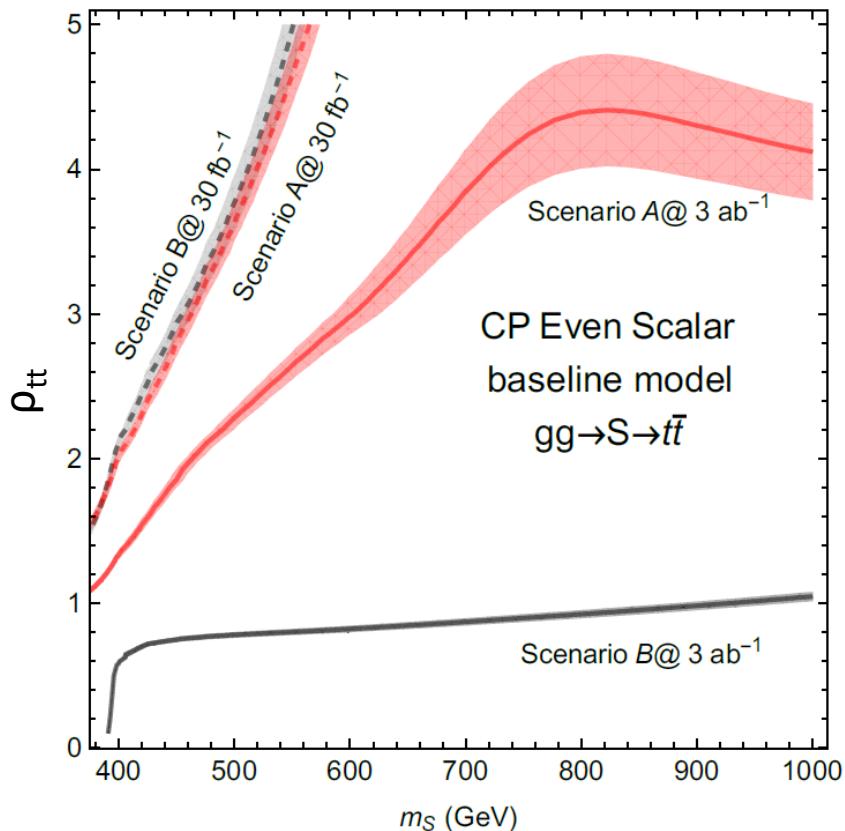
- $\rho_{cc} = \rho_{uu} = \rho_{bb} = \rho_{ss} = \rho_{dd} = 0$ ,  $\rho_{ij} = 0$  ( $i \neq j$ )
- $m_H = m_A = m_{H^\pm}$



## ● Constraints

- Perturbativity bound on  $\eta_i$ :  $|\eta_i| < 2$
- Vacuum stability bound on Higgs potential

# Heavy scalars searches in $t\bar{t}$ channel @ LHC



Carena, Liu (2016)

# LHC Run-I data of $\kappa$

$\kappa_Z$	$1.00_{-0.08}$
$\kappa_W$	$0.90^{+0.09}_{-0.09}$
$\kappa_t$	$1.42^{+0.23}_{-0.22}$
$\kappa_\tau$	$0.87^{+0.12}_{-0.11}$
$\kappa_b$	$0.57^{+0.16}_{-0.16}$
$\kappa_g$	$0.81^{+0.13}_{-0.10}$
$\kappa_\gamma$	$0.90^{+0.10}_{-0.09}$
$\text{BR}_{\text{BSM}}$	$0.00^{+0.16}$

# Z2 symmetry model limit

Basis :  $\Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + iz_i) \end{pmatrix}$   $\tan \beta = \frac{v_2}{v_1}$

## ■ Top Yukawa interaction

$$\begin{aligned} \mathcal{L}_t = & -\bar{t}_L \left\{ \frac{m_t}{v} (s_{\beta-\alpha} - \tan \beta c_{\beta-\alpha}) + \frac{\eta_t}{\sqrt{2}} c_{\beta-\alpha} (s_\beta \tan \beta + c_\beta) \right\} h t_R \\ & - \bar{t}_L \left\{ \frac{m_t}{v} (c_{\beta-\alpha} + \tan \beta s_{\beta-\alpha}) - \frac{\eta_t}{\sqrt{2}} s_{\beta-\alpha} (s_\beta \tan \beta + c_\beta) \right\} H t_R + h.c. + \dots . \end{aligned}$$

$Z_2$  symmetry model limit ;  $\eta_t \rightarrow 0$

$$\mathcal{L}_t = -\bar{t}_L \frac{m_t}{v} (s_{\beta-\alpha} - \tan \beta c_{\beta-\alpha}) h t_R - \bar{t}_L \frac{m_t}{v} (c_{\beta-\alpha} + \tan \beta s_{\beta-\alpha}) H t_R + h.c. + \dots .$$

# $\beta 0$ basis

Basis :  $\Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + iz_i) \end{pmatrix}$   $\tan \beta = \frac{v_2}{v_1}$

## ■ Top Yukawa interaction

$$\begin{aligned} \mathcal{L}_t = & -\bar{t}_L \left\{ \frac{m_t}{v} (s_{\beta-\alpha} - \tan \beta c_{\beta-\alpha}) + \frac{\eta_t}{\sqrt{2}} c_{\beta-\alpha} (s_\beta \tan \beta + c_\beta) \right\} h t_R \\ & - \bar{t}_L \left\{ \frac{m_t}{v} (c_{\beta-\alpha} + \tan \beta s_{\beta-\alpha}) - \frac{\eta_t}{\sqrt{2}} s_{\beta-\alpha} (s_\beta \tan \beta + c_\beta) \right\} H t_R + h.c. + \dots \end{aligned}$$

## ■ $\beta 0$ basis limit : $\beta \rightarrow 0$

$$\mathcal{L}_t = -\bar{t}_L \left\{ \frac{m_t}{v} s_{-\alpha} + \frac{\eta_t}{\sqrt{2}} c_{-\alpha} \right\} h t_R - \bar{t}_L \left\{ \frac{m_t}{v} c_{-\alpha} - \frac{\eta_t}{\sqrt{2}} s_{-\alpha} \right\} H t_R + h.c. + \dots$$

The change by the shift  $\beta \rightarrow \beta' = \beta + \Delta\beta$  can be absorbed by reparameterization ;

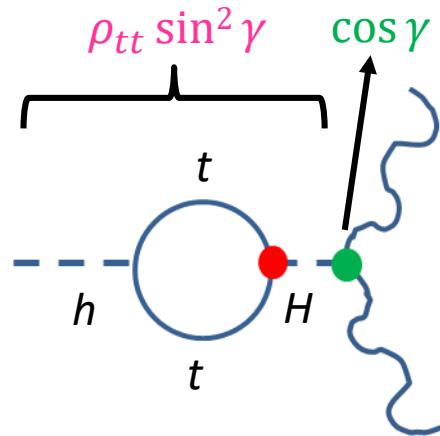
$$\alpha \rightarrow \alpha' = +\alpha + \Delta\beta, \quad \eta_t \rightarrow \eta'_t = \eta_t \frac{c_\beta + s_\beta \tan \beta}{c_{\beta+\Delta\beta} + s_{\beta+\Delta\beta} \tan(\beta + \Delta\beta)}.$$

We can take  $\beta=0$  without loss of generality.

# Important contributions

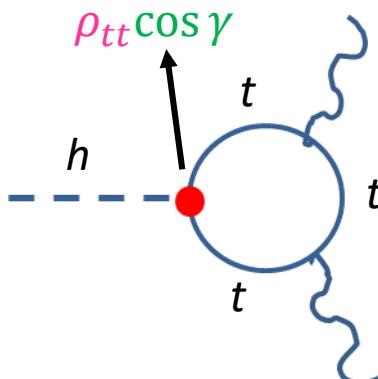
Factor that suppresses the effect of new physics :  $\cos \gamma$

In the SM like limit :  $\cos \gamma \rightarrow 0$



$$\rho_{tt} \sin^2 \gamma \cos \gamma$$

One suppression factor



$$\rho_{tt} \cos \gamma$$

One suppression factor