New physics effects on the hZZ and hhh vertices

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3. October 2003 at 2nd LC Physics Study Group Meeting

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I. Introduction

The Higgs boson $\Longrightarrow$ yet to be confirmed

m_h: free in the SM

- **Theoretical bounds:**

$$140 \lesssim m_h^{\mathsf{SM}} \lesssim 175 \ \textbf{GeV for } \Lambda = 10^{19} \ \textbf{GeV}$$

(In MSSM, $m_h < 120$-130 GeV)

- **Experimental bounds:**

LEP data: 114 GeV $< m_h < 196$ GeV (SM)

h will be discovered at Tevatron, LHC

$\Downarrow$

Once a Higgs boson (h) is found,
a precision study of Higgs couplings
hVV, $h\bar{f}f$, hhh
is done at a Linear Collider (LC)

Higgs coupling measurements at LC

ACFA Report
TESLA TDR

- **Higgs-gauge coupling** g_{hWW}, g_{hZZ}

  $\Rightarrow$ **Higgs Mechanism**

  $\sigma(e^+e^- \to Zh)$, $\sigma(e^+e^- \to \bar{\nu}\nu h)$ $\Rightarrow \mathcal{O}(1\%)$

- **Yukawa coupling** Y_f

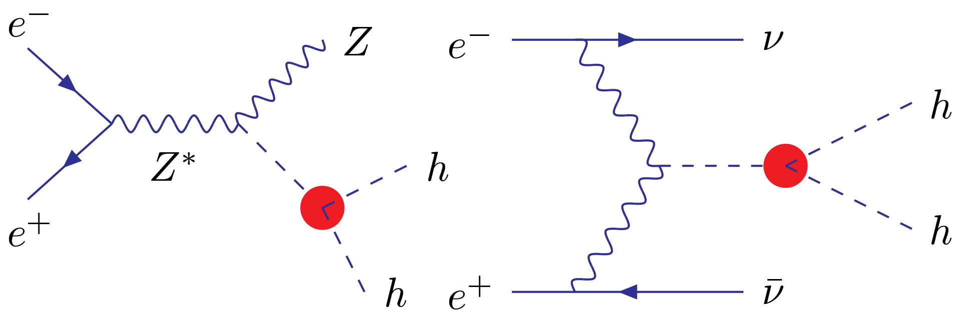
  $\Rightarrow$ **Mass Generation of Matter**

  $B(h \to \bar{f}f') \Rightarrow \mathcal{O}(1\%)$

- **Higgs self-coupling** λ_{hhh}

  $\Rightarrow$ **Dynamics of Higgs sector**

Double Higgs production



λ_{hhh} **can be measured by** $\mathcal{O}(10-20\%)$ **accuracy**

LC: $\sqrt{s} = 0.5 - 1.5$ TeV, $\mathcal{L} = 1ab^{-1}$

Battaglia et al, ACFA Higgs WG

The potential for precision measurement at a LC motivates us to study radiative corrections.

$\Delta^{\mathsf{Exp}} g_{hVV}/g_{hVV} = \mathcal{O}(1\%)$
$\Delta^{\mathsf{Exp}} \lambda_{hhh}/\lambda_{hhh} = \mathcal{O}(10-20\%)$

Leading top-loop contribution in the SM

- hVV **coupling**

$$M_{hVV}^{\mu\nu} = M_1\, g^{\mu\nu} + M_2\, p_1^{\nu} p_2^{\mu} + M_3\, i\epsilon^{\mu\nu\rho\sigma} p_{1\rho} p_{2\sigma}$$

$$g_{hZZ} \equiv M_1 = \frac{2m_Z^2}{v}\left(1 - \frac{5N_c m_t^2}{96\pi^2 v^2} + \cdots\right),$$

loop effects $\sim$ 1%

- hhh **coupling**

$$\lambda_{hhh} \sim \frac{3m_h^2}{v}\left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right)$$

loop effects $\sim$ 10%

A m_t^4 term appears in the renormalized λ_{hhh}.

The corrections are comparable to the measurement accuracy
$\Rightarrow$ How about new physics effects?

Probe of new physics via Higgs sector

New Physics

- Naturalness

  SUSY, Dynamical EW breaking, Little Higgs, Extra D ......

- EW baryogenesis
- Neutrino mass
- Top-bottom mass hierarchy

$$\Downarrow$$

Low-energy Effective Theory

Extended Higgs sectors
with additional doublets, singlets, $\cdots$

$$\Downarrow$$

Extra Higgs scalars $H^{\pm}$, A, ...

$\Rightarrow$ different prediction to hVV, $h\bar{f}f$ and hhh.

$$\Downarrow$$

We can determine direction of new physics
by a detailed study of the Higgs masses and couplings

Property of extra scalars (H, $H^{\pm}$, A, ...)
in extended Higgs sectors

SM like Higgs boson (h) mass

$m_h^2 \sim \lambda v^2$, **VEV:** v **($\simeq 246$ GeV)**

Extra Higgs boson masses

$$\left.\begin{array}{c} m_H \\ m_{H^\pm} \\ m_A \\ \cdots\cdots \end{array}\right\} \sim \quad \lambda_i v^2 + M^2$$

In this talk:

We evaluate
the one-loop corrected hZZ and hhh vertices
in the two-Higgs doublet model (THDM).

THDM

- Simplest extension of the SM Higgs sector
- Typical aspects of extended Higgs sectors motivated by various new physcis scenarios

How much can the deviation from
the SM prediction be substantial
under theoretical and experimental constraints?

The two Higgs doublet model (THDM)

- THDM with a softly-broken discrete symmetry:

$$(\Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2)$$
$\Rightarrow$ Natural FCNC suppression

Yukawa interaction (Model I, II):

$$\mathcal{L}_{\mathrm{I}} = -y_D \overline{Q}_L \Phi_1 b_R - y_U \bar{t}_R \Phi_1^\dagger Q_L + (h.c.).$$
$$\mathcal{L}_{\mathrm{II}} = -y_D \overline{Q}_L \Phi_1 b_R - y_U \bar{t}_R \Phi_2^\dagger Q_L + (h.c.).$$

Higgs potential:

$$V_{\mathrm{THDM}} = +m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - \underline{m_3^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right)}$$
$$+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2$$
$$+\lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + (\mathrm{h.c.})\right]$$

Φ_1 and Φ_2 $\Rightarrow$ $h,\ H,\quad A^0,\ H^\pm$ $\oplus$ 3 Goldstone bosons

$\uparrow$ $\quad\uparrow$ $\quad\uparrow$charged

CPeven CPodd

8 parameters : $\Rightarrow \{m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \alpha,\ \beta,\ v,\ M_{\text{soft}}\ \}$

v (VEV) $\simeq 246$ GeV, $\tan\beta\ (= \langle\Phi_2\rangle/\langle\Phi_1\rangle)$

α: mixing angle between h and H

$M_{\text{soft}}\ \ (= \frac{m_3}{\sqrt{\cos\beta\sin\beta}})$: soft-breaking scale of the discrete symm.

- Masses of physical Higgs bosons:

$$
\begin{aligned}
m_h^2 &= v^2\left(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + \frac{\lambda}{2}\sin^2 2\beta\right) + \mathcal{O}(\frac{v^2}{M_{\text{soft}}^2}), \\
m_H^2 &= M_{\text{soft}}^2 + v^2(\lambda_1 + \lambda_2 - 2\lambda)\sin^2\beta\cos^2\beta + \mathcal{O}(\frac{v^2}{M_{\text{soft}}^2}), \\
m_{H^\pm}^2 &= M_{\text{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2}v^2, \\
m_A^2 &= M_{\text{soft}}^2 - \lambda_5 v^2.
\end{aligned}
$$

M_{soft}: soft breaking scale

of the discrete symmetry

- M_{soft} determines decoupling/non-decoupling property of heavy Higgs bosons ($\Phi = A, H^\pm$ or H)

$$\boxed{m_\Phi^2 = M_{\text{soft}}^2 + \lambda_i v^2}$$

Decoupling: for $m_\Phi^2 \sim M_{\text{soft}}^2$ ($M_{\text{soft}}^2 \gg \lambda v^2$)

Loop-effects of $H, A, H^\pm$ decouple

(Decoupling Theorem)

Non-Decoupling: for $m_\Phi^2 \sim \lambda_i v^2$ ($M_{\text{soft}}^2 \lesssim \lambda v^2$)

m_Φ^n terms in the renormalized low energy observables

(similar to the top effects: $m_t^2 = y_t^2 v^2$)

The tree-level coupling constants

THDM

$$
\begin{aligned}
g_{hZZ}^{\text{tree}} &= +\frac{2m_Z^2}{v}\sin(\beta-\alpha) \\
\lambda_{hhh}^{\text{tree}} &= -\frac{3}{2v\sin 2\beta}\left[\{\cos(3\alpha-\beta)+3\cos(\beta+\alpha)\}\, m_h^2\right. \\
&\qquad \left. -4\cos^2(\alpha-\beta)\cos(\alpha+\beta)M_{\text{soft}}^2\right]
\end{aligned}
$$

- $\alpha \to \beta - \pi/2$ (Decoupling Limit)

$$
g_{hZZ}^{\text{tree}} \to g_{hZZ}^{\text{tree}}(\text{SM}) = \frac{2m_Z^2}{v},
$$

$$
\lambda_{hhh}^{\text{tree}} \to \lambda_{hZZ}^{\text{tree}}(\text{SM}) = \frac{3m_h^2}{v}
$$

Loop correction is essentially important!

- $\alpha \neq \beta - \pi/2$

The tree-level deviation from the SM prediction appears.

$\boxed{\text{Tree-Level Deviation vs Loop Correction}}$

One-loop effects on g_{hZZ} and λ_{hhh}

- Contributions of heavy quarks and Higgs bosons
- Renormalization: On-shell scheme

The leading 1-loop contribution
in Decoupling Limit ($\alpha \to \beta - \pi/2$)

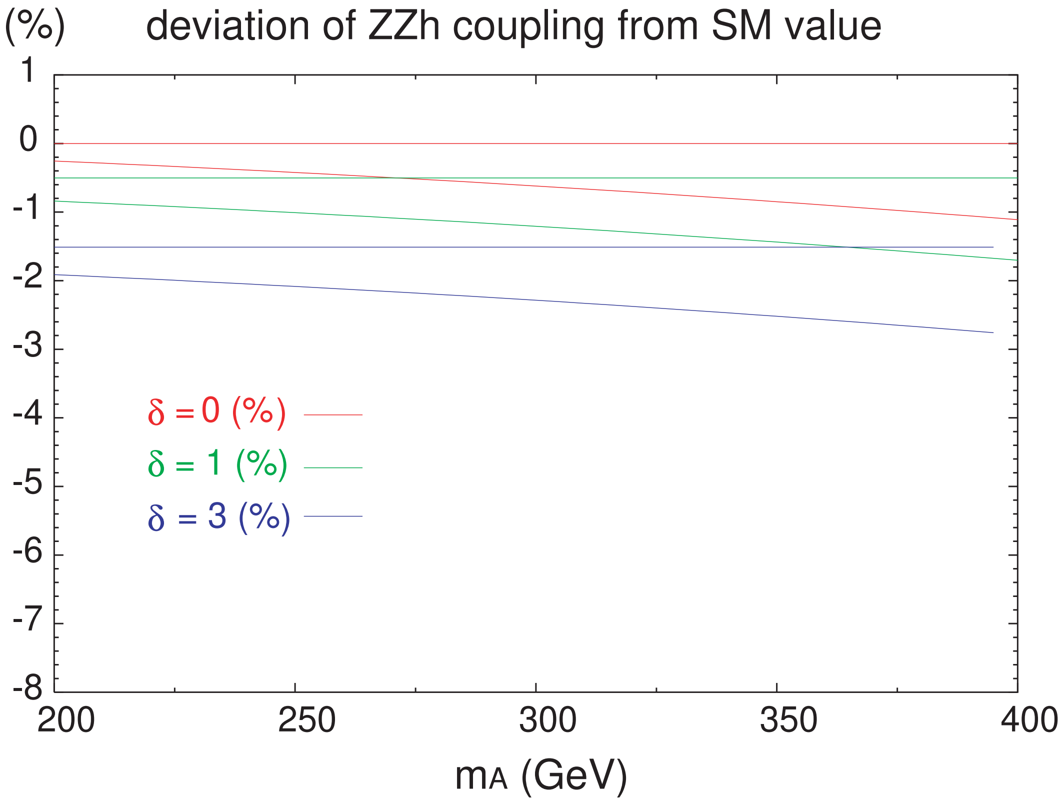
$$g_{hZZ}^{\text{loop}} = \frac{2m_Z^2}{v}\left[1 - \frac{1}{16\pi^2}\left\{\frac{5}{6}\frac{N_c m_t^2}{v^2} + \frac{2}{3}\frac{m_\Phi^2}{v^2}\left(1 - \frac{M_{\text{soft}}^2}{m_\Phi^2}\right)^2\right\}\right]$$

$$\lambda_{hhh}^{\text{loop}} = -\frac{3m_h^2}{v}\left[1 + \frac{1}{16\pi^2}\left\{ -\frac{16}{3}\frac{N_c m_t^4}{v^2 m_h^2} + \frac{16}{3}\frac{m_\Phi^4}{m_h^2 v^2}\left(1 - \frac{M_{\text{soft}}^2}{m_\Phi^2}\right)^3\right\}\right]$$

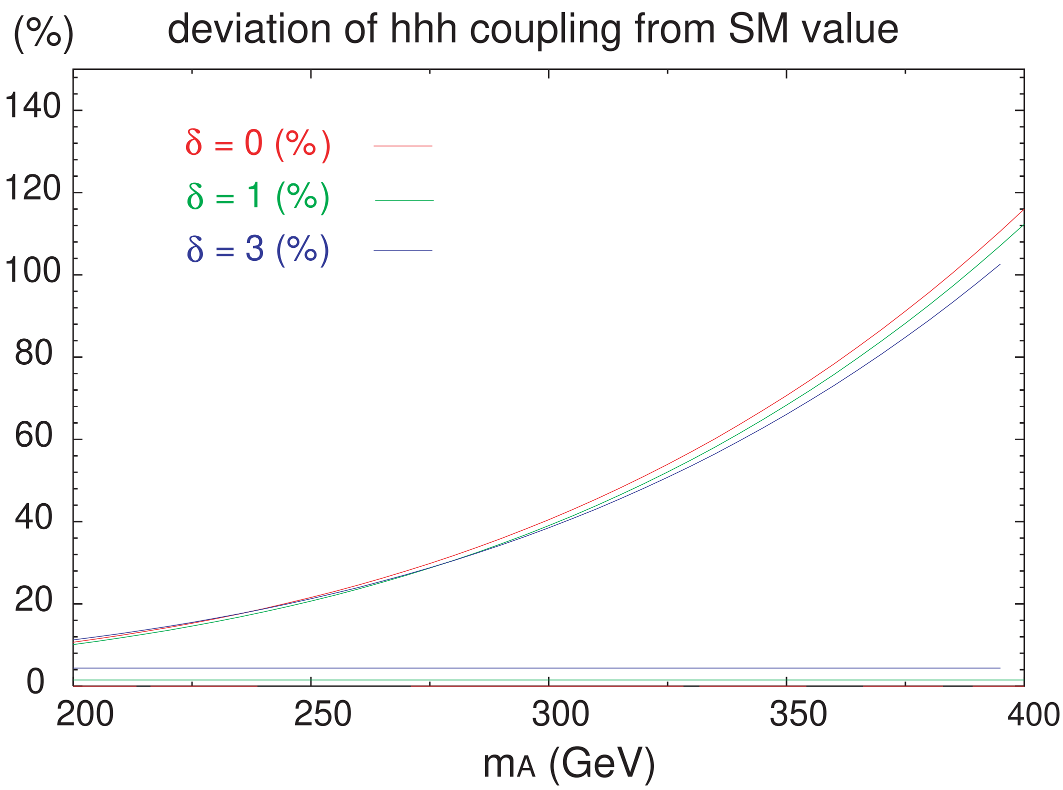
In $\lambda_{hhh}^{\text{loop}}$, $\mathcal{O}(m_\Phi^4)$ ($\Phi = H, A, H^+$) terms appear
with a suppression factor

$$m_\Phi^4\left(1 - \frac{M_{\text{soft}}^2}{m_\Phi^2}\right)^3 \to \begin{cases} \dfrac{\lambda_i v^2}{m_\Phi^2}, \quad (m_\Phi^2 \sim M_{\text{soft}}^2), \\ \qquad (\text{decoupling for } m_\Phi \to \infty) \\ m_\Phi^4, \quad (m_\Phi^2 \sim \lambda_i v^2), \\ \qquad (\text{non-decoupling effect}) \end{cases}$$

Non-decoupling Effects



hZZ coupling
Deviation
from the SM
$\sim 1\%$



hhh coupling
Deviation
from the SM
$\sim$ 30-100%
due to
the m_A^4 term

$\delta \equiv 1 - \sin^2(\alpha - \beta)$

$M_{\mathsf{soft}} = 0,\ \tan\beta = 1,\ m_A = m_H = m_{H^\pm}$

Scan Analysis

Free Parameters in the THDM:

$\tan\beta$, m_H, $m_{H^\pm}$, m_A, M_{soft}.

for fixed m_h, and $\delta \equiv 1 - \sin^2(\alpha - \beta)$.

Searching allowed region of the deviation from the SM in the hZZ and hhh vertices,

under the constraint from

- Perturbative unitarity

$$|a^0(W_L^+W_L^- \to W_L^+W_L^-)| < \xi, \quad (\xi = 1/4)$$

for 15 channels $W_L^+W_L^-$, Z_LZ_L, Z_Lh, hh, hH, ...

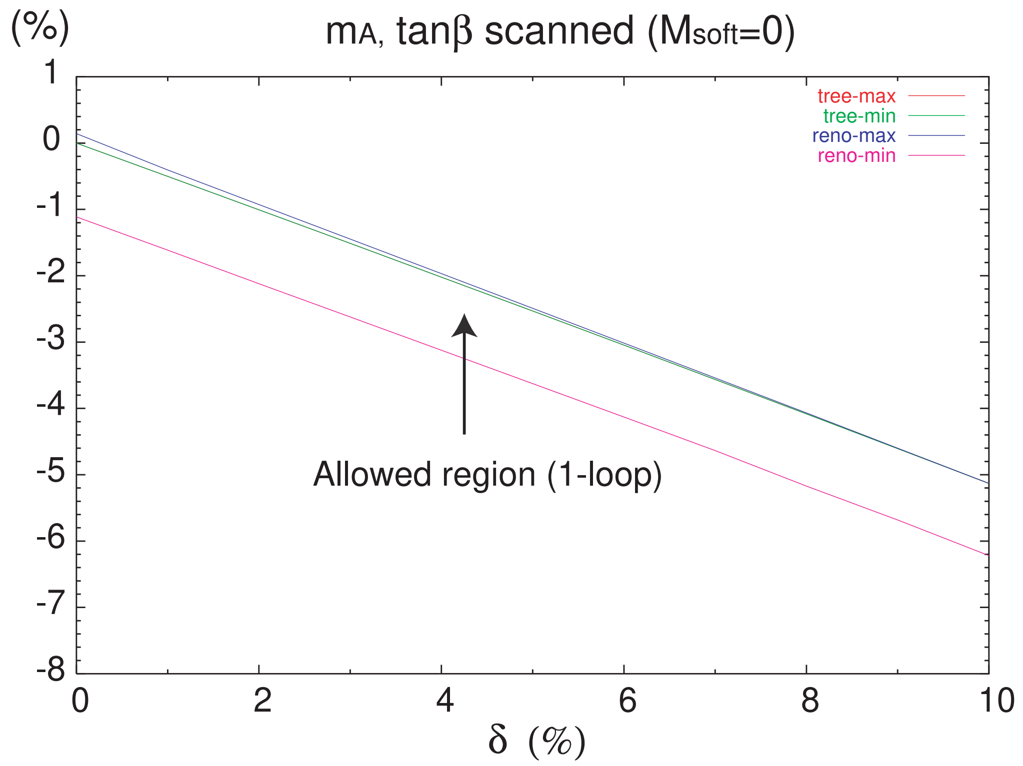
- Vacuum Stability

$$V_{\text{eff}}(\langle\Phi_1\rangle, \langle\Phi_2\rangle) \geq 0 \text{ for } \langle\Phi_i\rangle \to \infty.$$

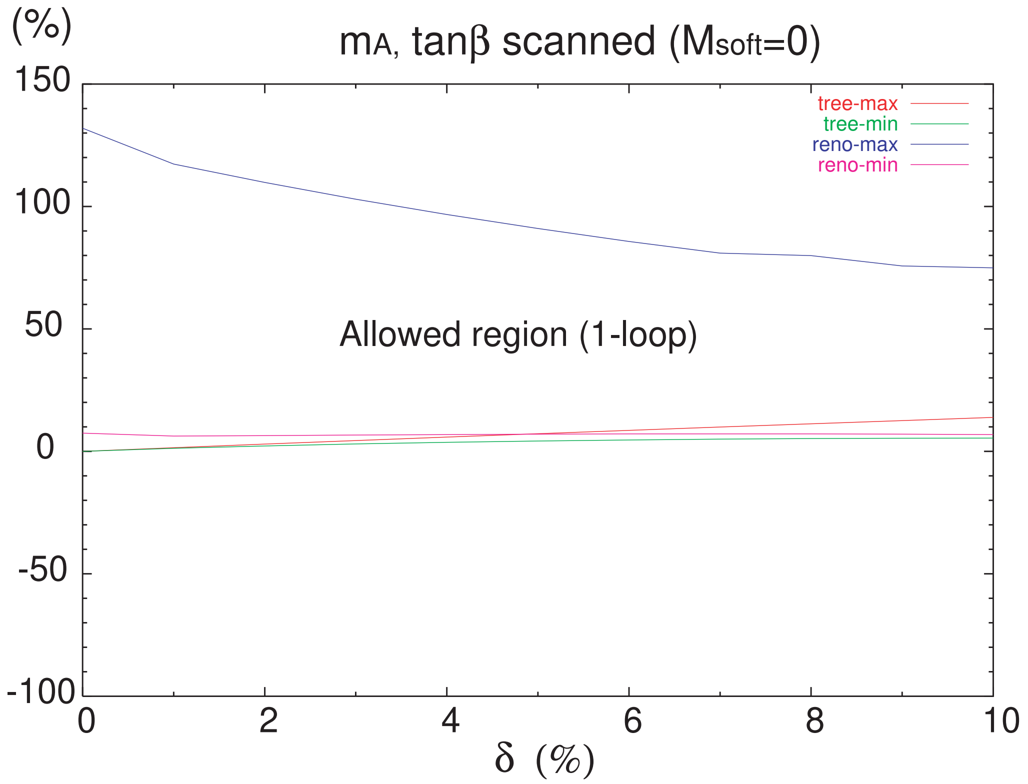
- LEP Precision Data:

Constraint on the (S,T,U) parameters

Allowed Region ($M_{\text{soft}} = 0$)



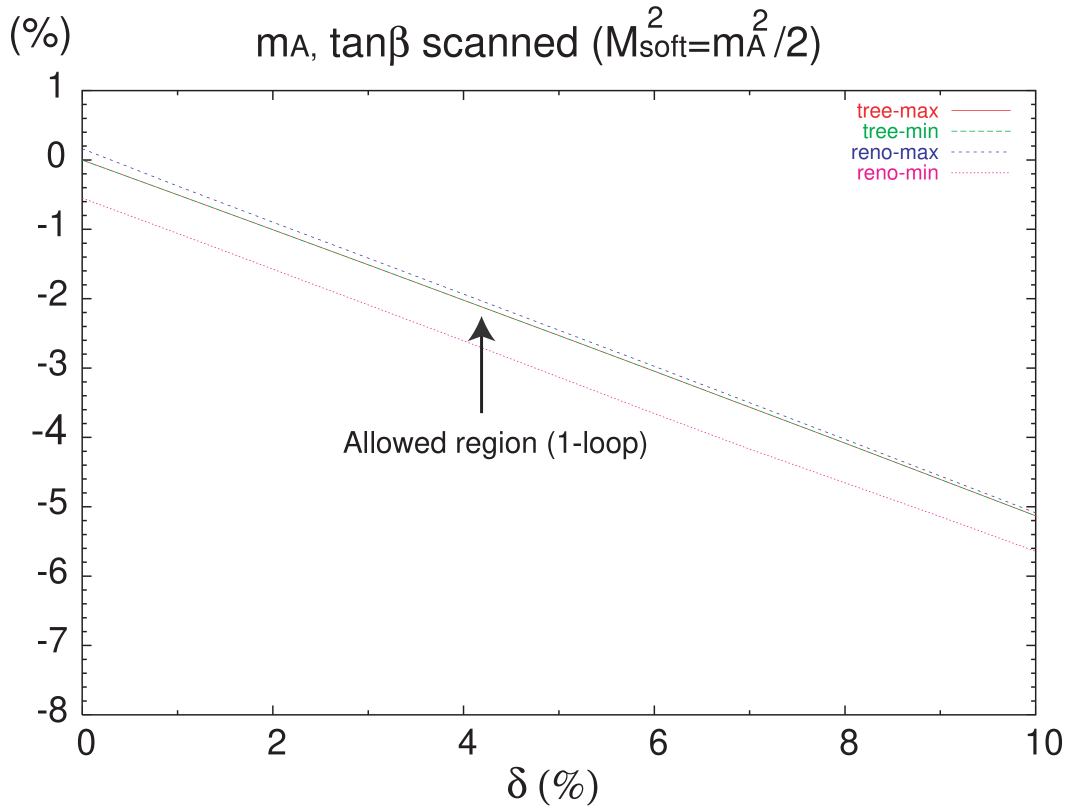
hZZ coupling
Deviation
from the SM
$\sim 1\%$

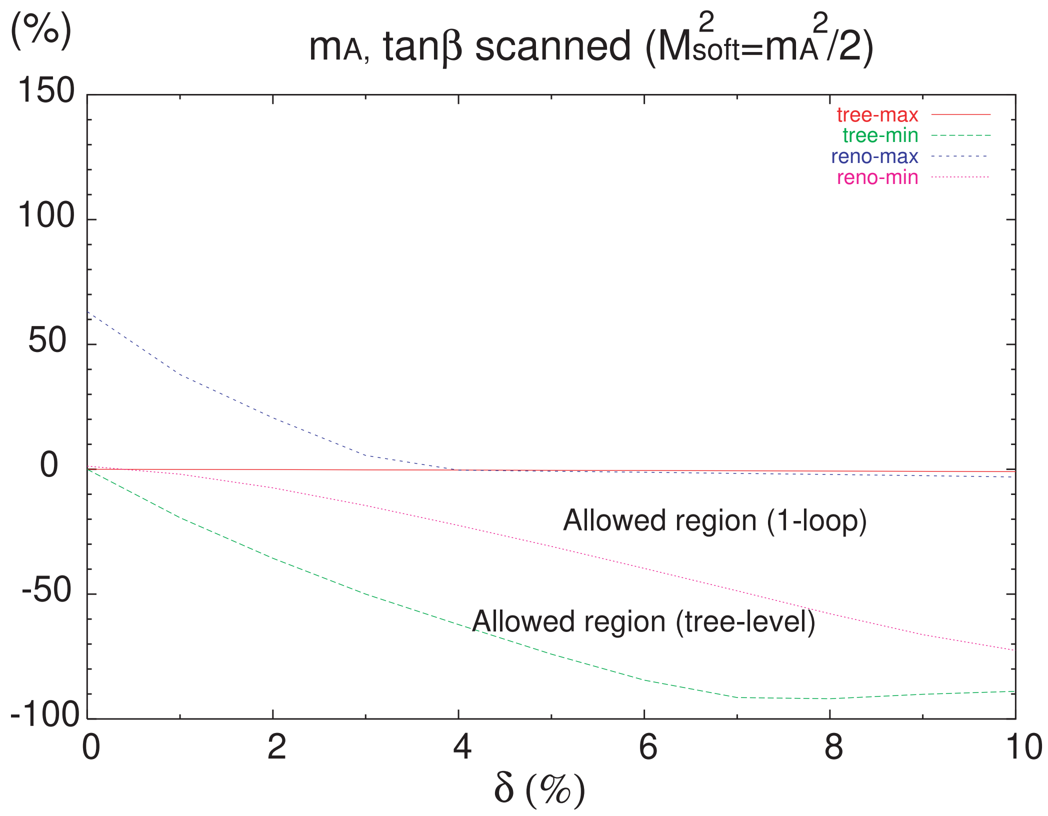


hhh coupling
Deviation
from the SM
$\lesssim$ 50-100%
due to
the m_A^4 term

$\delta \equiv 1 - \sin^2(\alpha - \beta)$

Allowed Region ($M_{\text{soft}} = m_A/\sqrt{2}$)





$$\delta \equiv 1 - \sin^2(\alpha - \beta)$$

Summary

One-loop effective couplings of hZZ and hhh in the SM and the THDM

Scan Analysis:

- hZZ: deviation from the SM

  One-loop $\mathcal{O}(m_A^2)$ contribution $(\sim 1\%)$
  $\oplus$ Tree-level difference when $\delta = 1 - \sin^2(\alpha - \beta) \neq 0$

- hhh: deviation from the SM

  One-loop $\mathcal{O}(m_A^4)$ contribution $\lesssim 50\text{-}100\%$
  $\oplus$ Tree-level difference when $\delta \neq 0$

Even when the hZZ measurement is consistent with the SM by $\mathcal{O}(1)$ %, hhh can deviate from the SM by $\sim 30\text{-}100$ % due to the non-decoupling effects of heavy Higgs bosons

Such deviation can be tested at a Linear Collider