



Probing Higgs triplet models via the 125 GeV Higgs boson decays with radiative corrections

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* JHEP05(2026)136

* Paper in preparation



Talk Plan

1. Motivation
2. Complex and real Higgs triplet models
3. Constraints
4. One-loop calculations and renormalization
5. Numerical results for Higgs decays

Introduction

- Extended Higgs models are well-motivated for new physics phenomena and early Universe physics.

Φ (Doublet), S (Singlet), Δ (Triplet)

- $\Phi + S$ Scalar DM, EW phase transition
 - $\Phi + \Phi'$ MSSM, Neutrino mass, Scalar DM, EW phase transition, CPV
 - $\Phi + \Delta$ Neutrino mass, Scalar DM, EW phase transition, CPV
- The mechanism behind new physics can be closely connected to the Higgs sector structure.
- It is essentially important to determine the structure of the Higgs sector.

Higgs couplings as probes of New Physics

New physics effects appear in Higgs couplings.

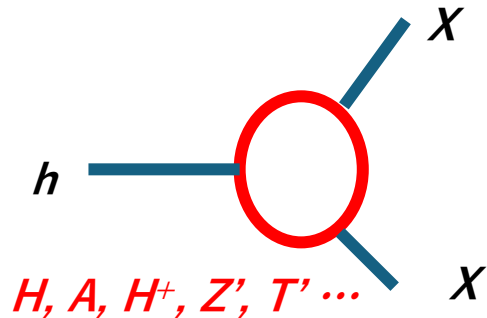
- Deviation at Tree level

① Field mixing $\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} h \\ H \end{pmatrix}$

② VEV mixing $\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = R(\beta) \begin{pmatrix} v \\ 0 \end{pmatrix}$

$$v = \sqrt{v_1^2 + v_2^2} \simeq 246 \text{ GeV}$$

- Loop corrections of new particles



- Higgs High Precision may allow us to detect deviations in Higgs couplings.
→ Indirect tests provide an important way to probe extended Higgs models.

Fortran program for **decay BRs** of **Higgs bosons** with **loop corrections** in **extended Higgs models**.

	Real Singlet	Softly broken Z2 2HDM (Type)	IDM	Complex Triplet	Real Triplet	SM
h_{125} -decays Couplings, BR, Γ	✓	✓	✓	New !!	New !!	✓
Heavy Higgs decays BR, Γ	✓	✓	✓			✓

Loop corrections : EW and scalar-NLO

QCD (NNLO, NLO) corrections (MS-bar scheme).

A. Djouadi, Phys. Rept., 457, 1 (2008),
B. M. Spira, Prog. Part. Nucl. Phys., 95, 98 (2017),
K. G. Chetyrkin, A. Kwiatkowski, Nucl. Phys., B461, 3 (1996)

- This framework can compare the predictions of different extended Higgs models consistently.
- We aim to discriminate the Higgs sector through comparison with precision measurements.

Models with an isospin triplet scalar

CHTM (Complex Higgs triplet model) : $\Phi + \Delta$ ($Y=1$)

RHTM (Real Higgs triplet model) : $\Phi + \Delta$ ($Y=0$)

- New physics

CHTM : Type-II seesaw, strongly EW phase transition Cheng, Li (1980), Mohapatra, Senjanovic(1981)

RHTM : Strongly EW phase transition Patel, Ramsey-Musolf (2013),
Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir (2019)

- Electroweak rho parameters $\rho_{\text{Tree}} = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \neq 1$

- Phenomenologically interesting processes in triplet models

- $H^+ \rightarrow WZ$ Asakawa, Kanemura, Kanzaki (2007), Kanemura, Yagyu, Yanase (2011)

- Characteristic deviations in hVV coupling $\rightarrow$ will explain later

Kanemura, Tsumura, Yagyu, Yokoya (2013)

Complex triplet model

	Φ	Δ
I	1/2	1
Y	1/2	1

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & \frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

$$\phi^0 = \frac{1}{\sqrt{2}}(\phi + v_\phi + i\chi)$$

$$\Delta^0 = \frac{1}{\sqrt{2}}(\delta + v_\Delta + i\eta)$$

$$\rho_{\text{Tree}} = \frac{v_\phi^2 + 2v_\Delta^2}{v_\phi^2 + 4v_\Delta^2} \neq 1$$

Constraints from ρ_{exp} $v_\Delta^2 \ll v_\phi^2$

$$\rho = 1.00031 \pm 0.00019 \quad (\text{PDG2024})$$

- Mass eigenstates

$$\begin{pmatrix} \phi^\pm \\ \Delta^\pm \end{pmatrix} = R(\beta) \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}, \quad \begin{pmatrix} \chi \\ \eta \end{pmatrix} = R(\beta') \begin{pmatrix} G^0 \\ A \end{pmatrix}, \quad \begin{pmatrix} \phi \\ \delta \end{pmatrix} = R(\alpha) \begin{pmatrix} h \\ H \end{pmatrix},$$

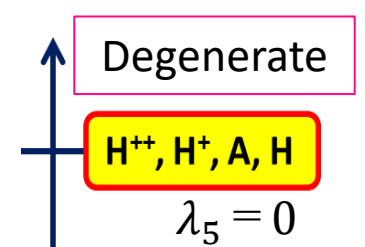
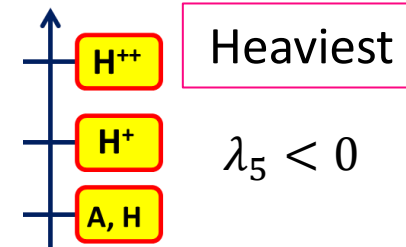
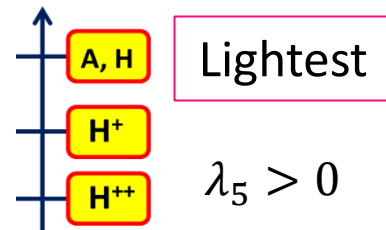
$$\left(\tan\beta = \frac{\sqrt{2}v_\Delta}{v_\phi}, \tan\beta' = \frac{2v_\Delta}{v_\phi} \right)$$

h
SM-like Higgs boson

$H^{\pm\pm}$ $H^\pm$ A H
triplet-like Higgs bosons

- Mass hierarchy

$$m_{H^{\pm\pm}}^2 - m_{H^\pm}^2 \cong m_{H^\pm}^2 - m_A^2 \cong -\frac{\lambda_5}{4}v^2$$



- Alignment

$$\sin\alpha \simeq \frac{v_\phi v_\Delta}{m_H^2 - m_h^2} \left[\frac{4m_{H^\pm}^2}{v_\phi^2 + 2v_\Delta^2} - \frac{2m_A^2}{v_\phi^2 + 4v_\Delta^2} - \lambda_4 \right]$$



$v_\Delta \rightarrow 0$: Alignment limit

Real triplet model

	Φ	Δ
I	1/2	1
Y	1/2	0

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \Delta = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^0 & \Delta^+ \\ \Delta^- & \Delta^0 \end{pmatrix}$$

$$\phi^0 = \frac{1}{\sqrt{2}}(\phi + v_\phi + i\chi)$$

$$\Delta^0 = (\delta + v_\Delta)$$

$$\rho_{\text{Tree}} = \frac{v_\phi^2 + 2v_\Delta^2}{v_\phi^2} \neq 1$$

Constraints from ρ_{exp} $v_\Delta^2 \ll v_\phi^2$

$$\rho = 1.00031 \pm 0.00019 \quad (\text{PDG2024})$$

- Mass eigenstates

$$\begin{pmatrix} \phi^\pm \\ \Delta^\pm \end{pmatrix} = R(\beta) \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}, \quad \begin{pmatrix} \phi \\ \delta \end{pmatrix} = R(\alpha) \begin{pmatrix} h \\ H \end{pmatrix},$$

h
SM-like Higgs boson

$H^\pm$ H
triplet-like Higgs bosons

$$\left(\tan\beta = -\frac{2v_\Delta}{v_\phi} \right)$$

- Mass difference

$$m_H^2 - m_{H^\pm}^2 = \left(\frac{\lambda_2}{2} + 2\lambda_1 - 4\lambda_3 \right) v_\Delta^2 + \dots \quad \text{Triplet Higgs bosons are almost degenerate.}$$

- Alignment

$$\sin\alpha \simeq \frac{2v_\phi v_\Delta (2\lambda_3 v_\Delta - \mu)}{2\lambda_1 v_\phi^2 v_\Delta - 2\lambda_2 v_\Delta^3 - \mu v_\phi^2}$$



$v_\Delta \rightarrow 0$: Alignment limit

Higgs couplings at tree level

$$\kappa_{hXX} = \frac{g_{hXX}}{g_{hZZ}^{SM}}$$

- hVV (hZZ , hWW) couplings

CHTM

$$\kappa_{hZZ}^{\text{CHTM}} = \frac{\cos \alpha \cos \beta' + 2 \sin \alpha \sin \beta'}{\sqrt{1 + \sin^2 \beta}} \quad \kappa_{hff}^{\text{CHTM}} = \frac{\cos \alpha}{\cos \beta}$$

$$\left(\tan \beta = \frac{\sqrt{2}v_{\Delta}}{v_{\phi}}, \tan \beta' = \frac{2v_{\Delta}}{v_{\phi}} \right)$$

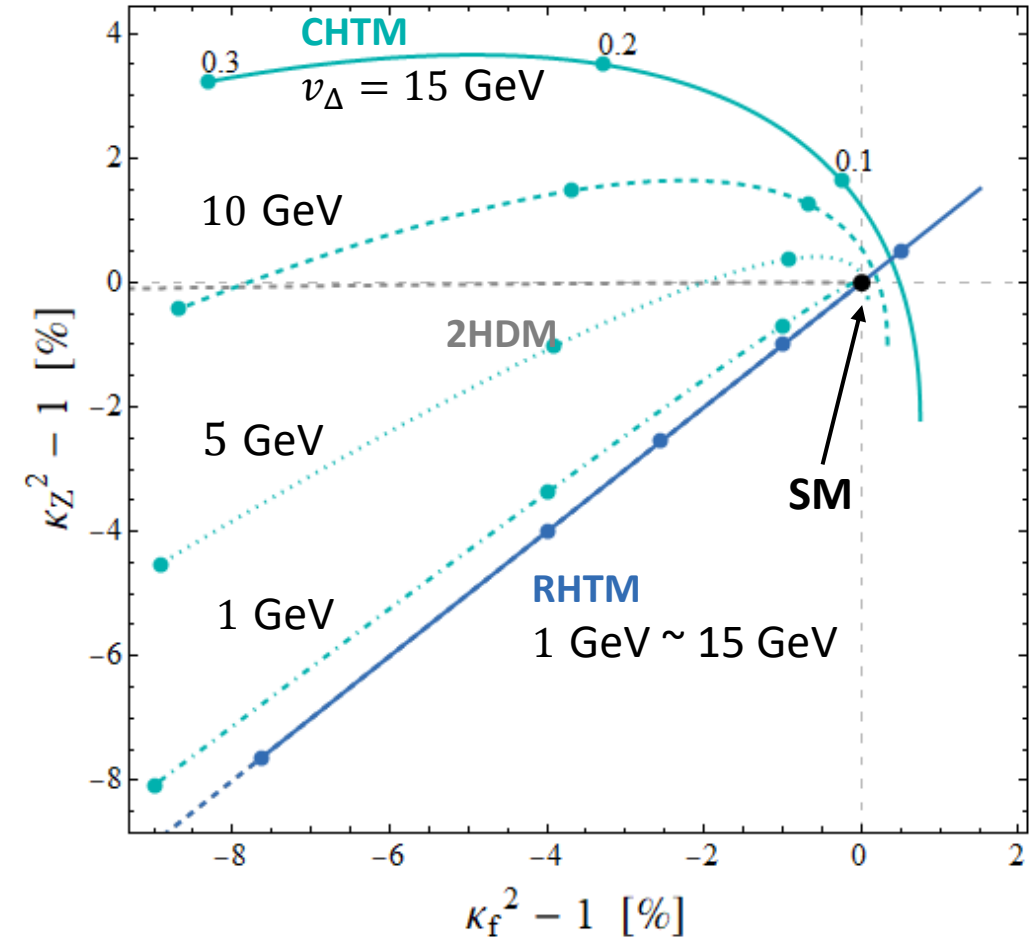
RHTM

$$\kappa_{hZZ}^{\text{RHTM}} = \kappa_{hff}^{\text{RHTM}} = \frac{\cos \alpha}{\cos \beta} \quad \left(\tan \beta = -\frac{2v_{\Delta}}{v_{\phi}} \right)$$

- A larger value of v_{Δ} leads to larger deviations in hZZ coupling in CHTM.

$$\kappa_{hZZ}^{\text{CHTM}} \simeq \cos \alpha + \frac{4v_{\Delta}}{v} \sin \alpha$$

$$\kappa_{hZZ}^{\text{RHTM}} = \kappa_{hff}^{\text{RHTM}} \simeq 1 + \mathcal{O}(v_{\Delta}^2/v^2)$$



Do the characteristic deviations pattern appear even with radiative correction?

One-loop calculations for 125 GeV Higgs decays

Calculation setup

- On-shell renormalization

Gauge dependence is removed by pinch technique

- One-loop corrected decay rates

$$\Gamma(h \rightarrow XX) = \Gamma_{LO}(h \rightarrow XX) \left(1 + \Delta_{EW}^{hXX} + \Delta_{QCD}^{hXX} \right)$$

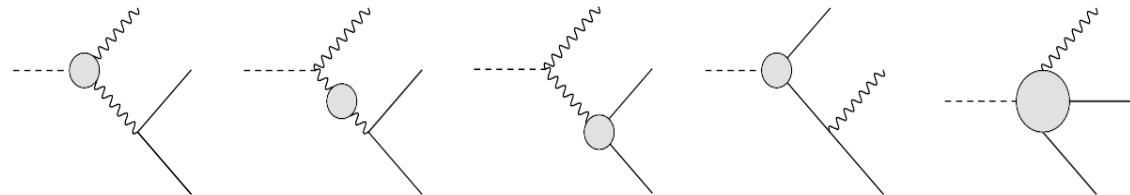
Aiko, Kanemura, MK, Sakurai, Taniguchi, Yagyu (2026)
Kanemura, Mawatari, MK, Sakurai, Yagyu (2019)

Δ_{EW}^{hXX}

$h \rightarrow ff, \quad h \rightarrow Vff, \quad hhh$

$h \rightarrow \gamma\gamma, \quad h \rightarrow Z\gamma, \quad h \rightarrow gg \text{ (EW-LO)}$

Ex). $h \rightarrow Vff$



Δ_{QCD}^{hXX}

MS-bar QCD corrections (NNLO)

A. Djouadi, *Phys. Rept.*, 457, 1 (2008)

Constraints (CHTM)

◆ EW precision observables

$$(m_W^{\text{rem}})^2 = \frac{m_Z^2 v^2}{2(v^2 + 2v_\Delta^2)} \left[1 + \sqrt{1 - \frac{4\pi\alpha_{\text{em}}(v^2 + 2v_\Delta^2)}{\sqrt{2} G_F m_Z^2 v^2 (1 - \Delta r)}} \right]$$

$$\Delta r \supset -\frac{1}{16\pi^2} \ln(m_{H^\pm} - m_H)^2 \quad \Rightarrow \quad \text{Larger } v_\Delta \text{ requires a larger mass splitting.}$$

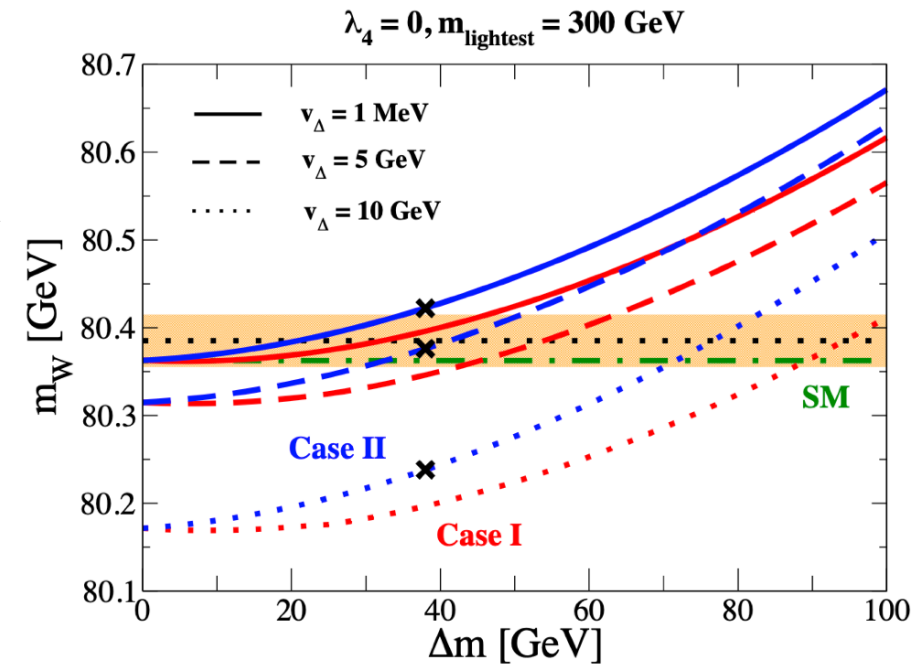
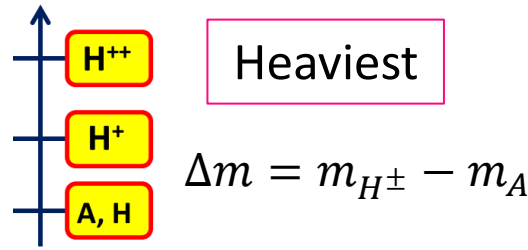
◆ $h \rightarrow \gamma\gamma$

$$\Gamma(h \rightarrow \gamma\gamma)_{\text{HTM}} = \left| \text{t-loop} + \text{w-loop} + \text{H}^{++}, \text{H}^+ \text{ loop} + \text{H}^{++}, \text{H}^+ \text{ triangle} \right|^2$$

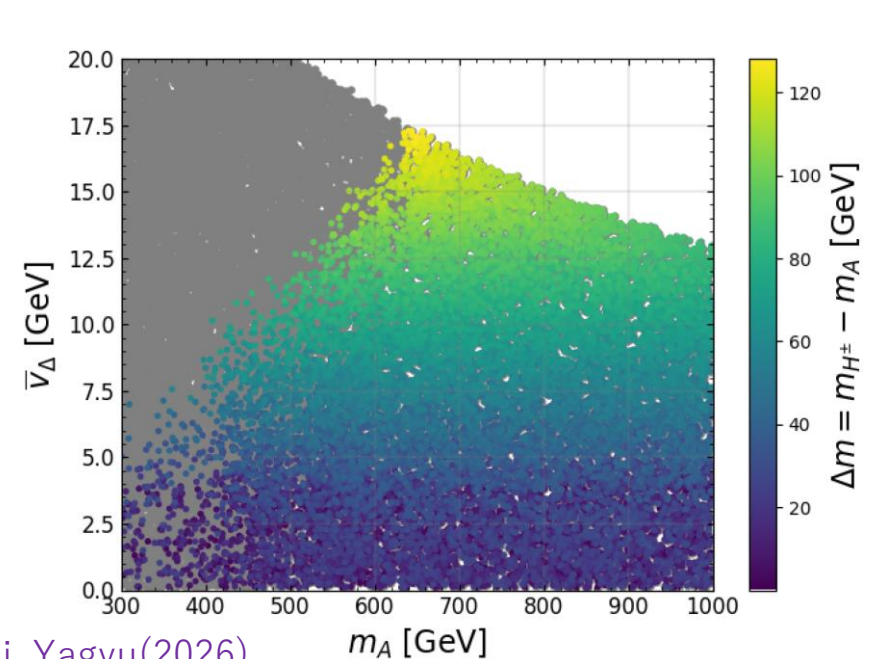
➡ LHC constraint ($|\Delta\mu_{\gamma\gamma}| < 0.18 (2\sigma)$) JHEP 07 (2023) 088
 $m_{H^\pm} \gtrsim 800 \text{ GeV}$ for $v_\Delta = 15 \text{ GeV}$

◆ Perturbative unitarity

Upper bound for $m_{H^{++}}$ $m_{H^\pm} \lesssim 900 \text{ GeV}$



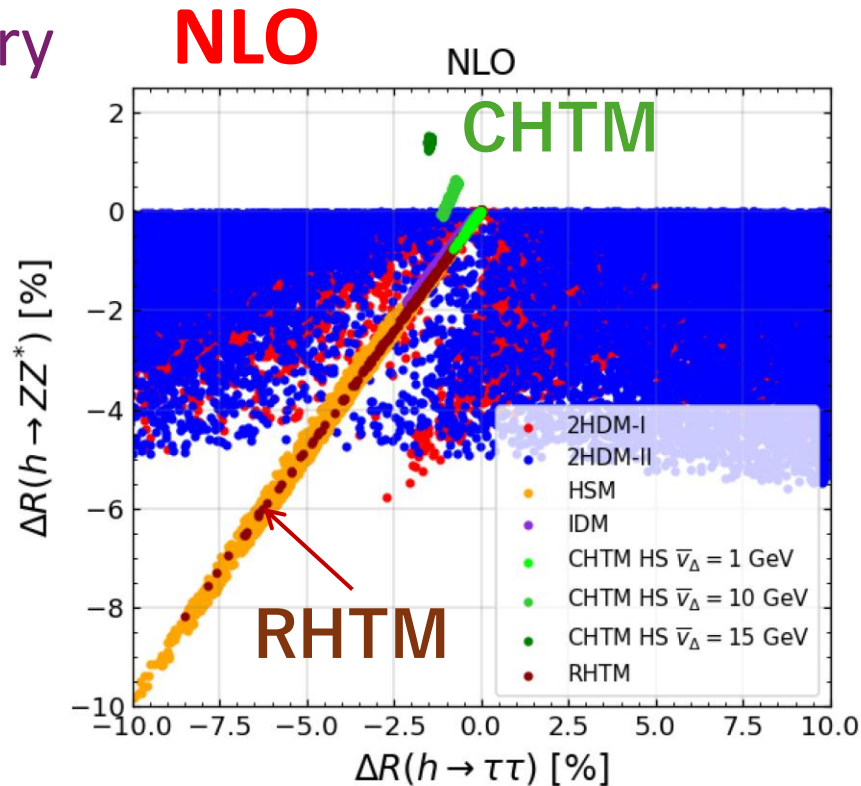
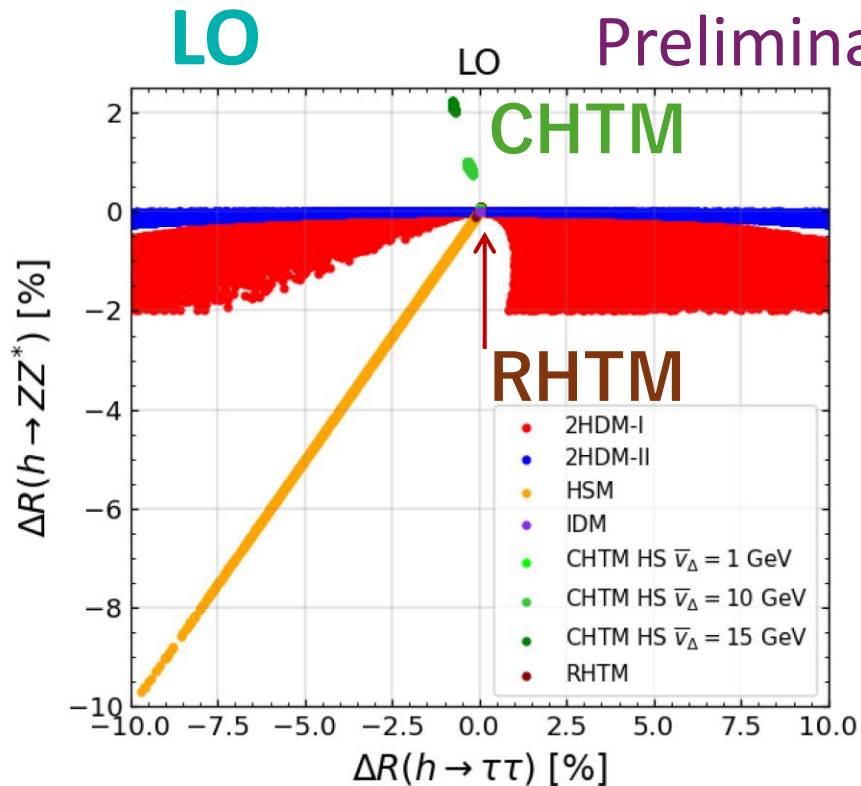
Aoki, Kanemura, MK, Yagyu (2012)



Aiko, Kanemura, MK, Sakurai, Taniguchi, Yagyu(2026)

$h \rightarrow ZZ^*$ and $h \rightarrow \tau\tau$ with NLO corr.

$$\Delta R[h \rightarrow XX] = \frac{\Gamma^{\text{HTM}}[h \rightarrow XX]}{\Gamma^{\text{SM}}[h \rightarrow XX]} - 1$$



CHTM

$$300 \text{ GeV} \leq m_A \leq 1 \text{ TeV},$$

$$0 \leq \Delta m \leq 150 \text{ GeV}$$

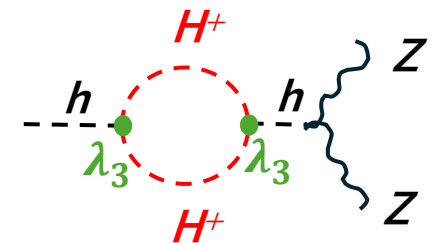
$$0 \leq \lambda_4 \leq 4\pi$$

RHTM

$$200 \text{ GeV} \leq m_{H^\pm} \leq 1 \text{ TeV},$$

$$0.1 \text{ GeV} \leq v_\Delta \leq 4 \text{ GeV}, (\leftarrow \text{EWPO})$$

$$0 \leq \lambda_2 \leq 4\pi, \quad -4\pi \leq \lambda_3 \leq 4\pi$$



$$\Delta R(h \rightarrow ZZ^*) \simeq -\frac{\lambda_3^2 v^2}{64\pi^2 m_{H^\pm}^2}$$

CHTM : Even at NLO, $\Gamma(h \rightarrow ZZ^*)$ can exceed the SM prediction.

RHTM : At LO, the deviation is negligible,

At NLO, can reach several percent due to non-decoupling loop effects of triplet Higgs.

NLO corrections make otherwise hidden new-physics effects visible.

$h \rightarrow ZZ^*$ and $h \rightarrow \gamma\gamma$

$$\Delta R[h \rightarrow XX] = \frac{\Gamma^{\text{HTM}}[h \rightarrow XX]}{\Gamma^{\text{SM}}[h \rightarrow XX]} - 1$$

Preliminary

CHTM

$h \rightarrow \gamma\gamma$ can be significantly deviated from SM.

$\Delta R(h \rightarrow \gamma\gamma) \simeq -20\%$ in $m_{H^{++}} > m_{H^+} > m_H$

$\Delta R(h \rightarrow \gamma\gamma) \simeq +10\%$ in $m_H > m_{H^+} > m_{H^{++}}$

RHTM

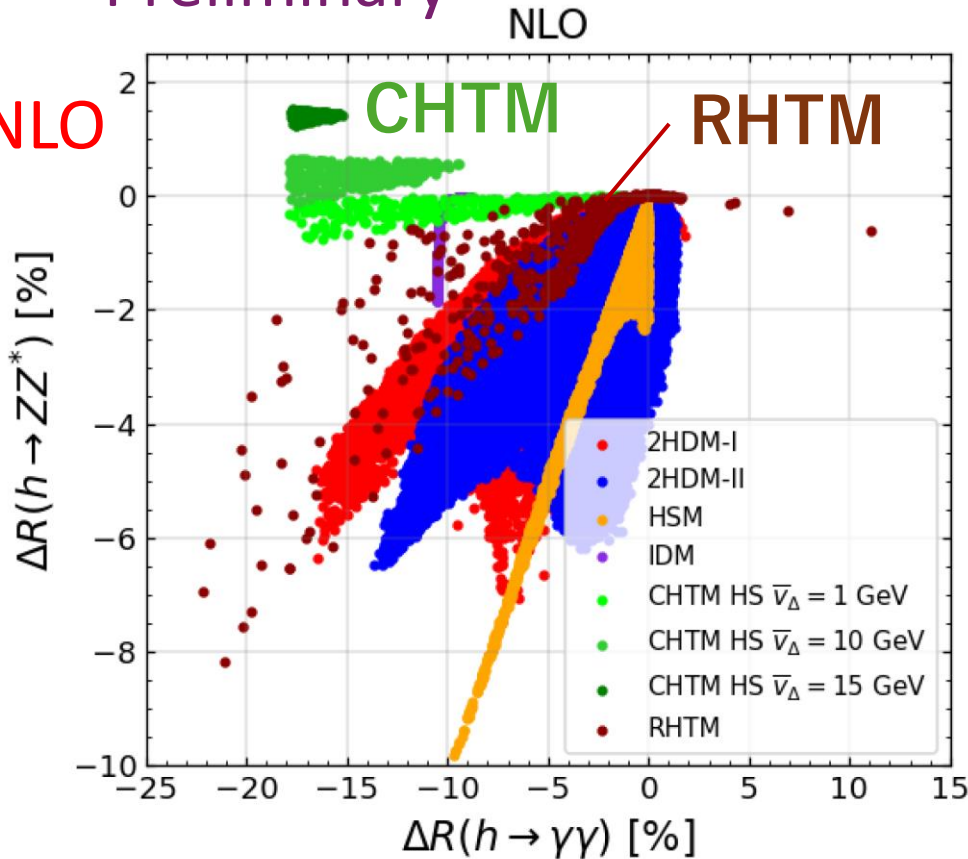
$-20\% < \Delta R(h \rightarrow \gamma\gamma) < +10\%$

Future measurements :

$\Gamma(h \rightarrow \gamma\gamma) \sim 2.6\%$ @ HL-LHC [2504.00672]

$\Gamma(h \rightarrow ZZ^*) \sim 0.5\%$ @ ILC250+550 [2503.19983]

$\Gamma(h \rightarrow \tau\tau) \sim 1.2\%$ @ ILC250+550



Both models : Expected to be distinguishable from other models through deviation patterns in certain parameter regions at future indirect test.

Summary

- Precision Higgs measurements provide indirect probes of extended Higgs sectors.
- CHTM and RHTM predict characteristic deviations in the hVV couplings.
- NLO corrections significantly modify the Higgs decay rates:
 - $h \rightarrow ZZ^*$ can exceed the SM prediction in the CHTM
 - Non-decoupling effects can generate a few-percent deviation in the RHTM.
- Correlations between $h \rightarrow ZZ^*$ and $h \rightarrow \gamma\gamma$ provide useful information for distinguishing Higgs triplet models from other extended Higgs models.
- These characteristic deviation patterns can be tested at the HL-LHC and future e^+e^- colliders.



$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} + \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & \frac{\Delta^+}{\sqrt{2}} \end{pmatrix} \quad \begin{aligned} \phi^0 &= \frac{1}{\sqrt{2}}(\phi + v_\phi + i\chi) \\ \Delta^0 &= \frac{1}{\sqrt{2}}(\delta + v_\Delta + i\eta) \end{aligned}$$

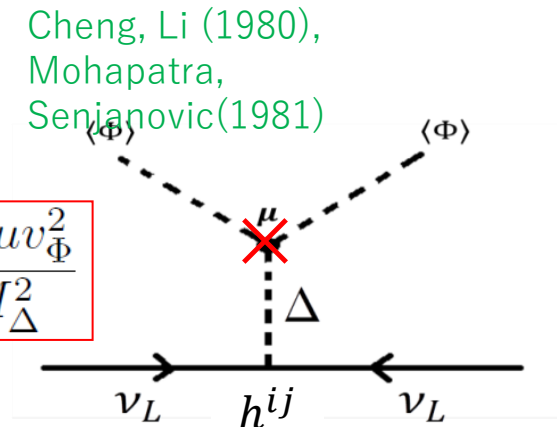
	SU(2) L	U(1) _Y
Φ	2	1/2
Δ	3	1

◆ Neutrino mass Type-II seesaw

$$\mathcal{L}_\nu = h_{ij} \overline{L}_L^i i\tau_2 \Delta L_L^j + hc$$

Majorana neutrino masses are generated via the LNV parameter μ .

$$M_\nu^{ij} = \frac{h^{ij} \mu v_\Phi^2}{M_\Delta^2}$$



◆ The rho parameter $\rho_{exp} \simeq 1.0008^{+0.0017}_{-0.0007}$

ρ is not equal to unity at tree.

We need to set $v_\Delta / v_\phi \ll 1$

$$\rho \equiv \frac{m_W^2}{\cos^2 \theta_W m_Z^2} = \frac{v_\phi^2 + 2v_\Delta^2}{v_\phi^2 + 4v_\Delta^2} \neq 1$$

v_ϕ : doublet
VEV
 v_Δ : triplet
VEV
 $v_\Delta \simeq 246$
GeV

Global symmetries

This potential respects additional global symmetries in some limits.

$$V_{Higgs} = m^2 \Phi^\dagger \Phi + M^2 \text{Tr}(\Delta^\dagger \Delta) + [\mu \Phi^T i\tau_2 \Delta^\dagger \Phi + h.c.] \\ + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 [\text{Tr}(\Delta^\dagger \Delta)]^2 + \lambda_3 \text{Tr}(\Delta^\dagger \Delta)^2 \\ + \lambda_4 (\Phi^\dagger \Phi) \text{Tr}(\Delta^\dagger \Delta) + \lambda_5 \Phi^\dagger \Delta \Delta^\dagger \Phi$$

- When the μ term is absent, there is the global U(1) symmetry in the potential. This symmetry conserves the lepton number.



Mass formula appear in this limit.

$$\xi \equiv m_{H^{++}}^2 - m_{H^+}^2 = m_{H^+}^2 - m_A^2, \\ \Delta m \equiv m_{H^+} - m_{\text{lightest}}, \quad \text{with} \quad m_H = m_A.$$

- When both the μ term and the λ_5 term are zero, an additional global SU(2) symmetry appears. This is the symmetry which rotate the doublet field and the triplet field with different angle.

In this case, all triplet-like Higgs bosons are degenerate in mass.



$$m_{H^{++}}^2 = m_{H^+}^2 = m_A^2 = m_H^2$$

Real triplet model

$$V(\Phi, \Delta) = m_\Phi^2 \Phi^\dagger \Phi + m_\Delta^2 \text{Tr}(\Delta^\dagger \Delta) + \mu \Phi^\dagger \Delta \Phi \\ + \frac{\lambda_1}{2} (\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2} [\text{Tr}(\Delta^\dagger \Delta)]^2 + \lambda_3 (\Phi^\dagger \Phi) \text{Tr}(\Delta^\dagger \Delta),$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v_\phi + \phi + iG^0) \end{pmatrix}, \quad \Delta = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^0 & \Delta^+ \\ \Delta^- & -\Delta^0 \end{pmatrix} \quad \text{with} \quad \Delta^0 = \frac{1}{\sqrt{2}}(v_\Delta + \delta),$$

$$\tan \beta = -\frac{2v_\Delta}{v_\phi}, \quad \tan 2\alpha = \frac{2\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2} = \frac{v_\phi}{v_\Delta} \frac{2\lambda_3 v_\Delta^2 - 4\mu v_\Delta}{\lambda_1 v_\phi^2 - \lambda_2 v_\Delta^2 - \mu v_\phi^2 / (4v_\Delta)}.$$



Renormalization

T. Blank, W. Hollik
(1998), S. Kanemura, K.
Yagyu (2012), P. H.
Chankowski, S. Pokorski,
J. Wagner, (2007); M. -C.
Chen, S. Dawson, C. B.
Jackson (2008).

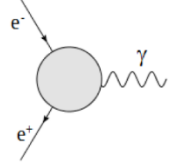
➤ The model with SM $\rho_{tree}=1$

- Lagrangian parameters $\dots g, g', v$
- Physical parameters $\dots m_W, m_Z, \sin\theta_W, G_F, \alpha_{em}$
- Renormalization conditions

On-shell condition

$$Re\Pi_{ZZ}(p^2)|_{p^2=m_Z^2} = 0, \quad \delta m_Z^2 = Re\Pi_{ZZ}^{1PI}(m_Z^2),$$

$$Re\Pi_{WW}(p^2)|_{p^2=m_W^2} = 0, \quad \delta m_W^2 = Re\Pi_{WW}^{1PI}(m_W^2),$$



$$\left. \right|_{p^2=0} = -ie\gamma^\mu$$

$$\frac{\delta\alpha_{em}}{\alpha_{em}} = \frac{d}{dp^2}\Pi_{\gamma\gamma}^{1PI}(p^2)|_{p^2=0} - \frac{2s_W}{c_W} \frac{\Pi_{\gamma Z}^{1PI}(0)}{m_Z^2}$$

➤ The model with HTM $\rho_{tree} \neq 1$

- Lagrangian parameters $\dots g, g', v, v_\Delta$
- Physical parameters $\dots m_W, m_Z, \sin\theta_W, G_F, \alpha_{em}$
- Renormalization conditions

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \neq 1$$

β' is a mixing
angle among
CP-odd scalar
field.

$\delta\beta'$ is
determined by

$$\sin^2\theta_W \neq 1 - \frac{m_W^2}{m_Z^2} \quad \Rightarrow \quad \frac{\delta s_W^2}{s_W^2} = \frac{c_W^2}{s_W^2} \left(\frac{\delta m_Z^2}{m_Z^2} - \frac{\delta m_W^2}{m_W^2} \right)$$

$$\cos\theta_W^2 = \frac{m_W^2}{m_Z^2} \frac{2}{(1 + \cos\beta'^2)}$$

$$\begin{aligned} \delta\bar{s}_W^2 &= -\delta\bar{c}_W^2 \\ &= \frac{2m_W^2}{m_Z^2(1 + c_{\beta'}^2)} \left(\frac{\delta m_Z^2}{m_Z^2} - \frac{\delta m_W^2}{m_W^2} - \frac{2s_{\beta'}c_{\beta'}}{(1 + c_{\beta'}^2)} \delta\beta' \right) \end{aligned}$$

$$\left. \Pi_{AG^0}(p^2) \right|_{p^2=m_A^2, 0} = 0$$

Renormalization in EW

➤ Parameters ; $m_W, m_Z, \sin\theta_W, G_F, \alpha_{em}$

➤ Relation ; $G_F = \frac{\pi\alpha_{em}}{\sqrt{2}m_W^2\sin\theta_W}$, $\cos^2\theta_W = \frac{2m_W^2}{m_Z^2(1+\cos^2\beta')}$

➤ Input parameters ; $m_W, m_Z, \alpha_{em}, \sin\theta_W$
 $\Rightarrow \beta'$ (mixing angle among the CP-odd scalar field)

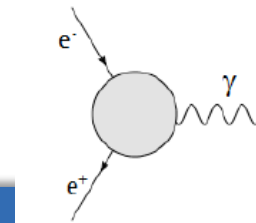
➤ Parameter shift ; $m_W^2 \rightarrow m_W^2 + \delta m_W^2$,
 $m_Z^2 \rightarrow m_Z^2 + \delta m_Z^2$,
 $\alpha_{em} \rightarrow \alpha_{em} + \delta\alpha_{em}$,
 $\sin^2\theta_W \rightarrow \sin^2\theta_W + \delta\sin^2\theta_W$

➤ Renormalization conditions ;

$$\text{Re}\hat{\Pi}_{WW}[m_W^2] = 0, \quad \rightarrow \delta m_W^2 \quad \text{Re}\hat{\Pi}_{ZZ}[m_Z^2] = 0, \quad \rightarrow \delta m_Z^2,$$

$$\hat{\Gamma}_\mu^{\gamma ee}[q^2 = 0, \not{p}_1 = \not{p}_2 = m_e] = ie\gamma_\mu,$$

$$\rightarrow \delta\alpha_{em},$$



Renormalization in Higgs potential

➤ Higgs potential

(α : Mixing angle among CP- even Higgs bosons,
 β : Mixing angle among charged Higgs bosons)

- Parameters . . . $v, \alpha, \beta, \beta', m_{H^{\pm\pm}}, m_{H^{\pm}}, m_A, m_H, m$

➤ Counter-terms

$\delta v, \delta \alpha, \delta \beta, \delta \beta', \delta m_{H^{\pm\pm}}^2, \delta m_{H^{\pm}}^2, \delta m_A^2, \delta m_h^2, \delta m_H^2$

Tadpole : $\delta T_\phi, \delta T_\Delta,$

Wave function renormalization : $\delta Z_h, \delta Z_H, \delta Z_A, \delta Z_{G0}, \delta Z_{H^+}, \delta Z_{G^+}, \delta Z_{H^{\pm\pm}}, \delta C_{hH}, \delta C_{AG0}, \delta C_{H^+G^+}$

➤ Renormalization conditions

$$\delta m_\phi^2 \quad . . . \quad \Pi_{\phi\phi}[m_\phi^2] = 0, \quad \Pi_{\phi\phi}[p^2]_{v^2} = \frac{m_W^2 \sin^2 \theta_W}{\pi^2 \alpha_{em}},$$

$\delta v \quad . . .$ Renormalizations in the gauge sector,  $\frac{\delta v}{v} = \frac{1}{2} \left(\frac{\delta m_W^2}{m_W^2} - \frac{\delta \alpha_{em}}{\alpha_{em}} + \frac{\delta \bar{s}_W^2}{\bar{s}_W^2} \right)$

$\delta \alpha \quad . . . \quad \Pi_{Hh}[m_h^2] = 0, \Pi_{Hh}[m_H^2] = 0,$ No mixing on-shell

$\delta \beta' \quad . . . \quad \Pi_{AG}[m_A^2] = 0, \Pi_{AG}[m_G^2] = 0,$ No mixing on-shell

$\delta \beta \quad . . . \quad \delta \beta = \frac{1 + s_\beta^2}{\sqrt{2}} \delta \beta',$  $\tan \beta = \frac{\sqrt{2} v_\Delta}{v_\phi}, \quad \tan \beta' = \frac{2 v_\Delta}{v_\phi},$

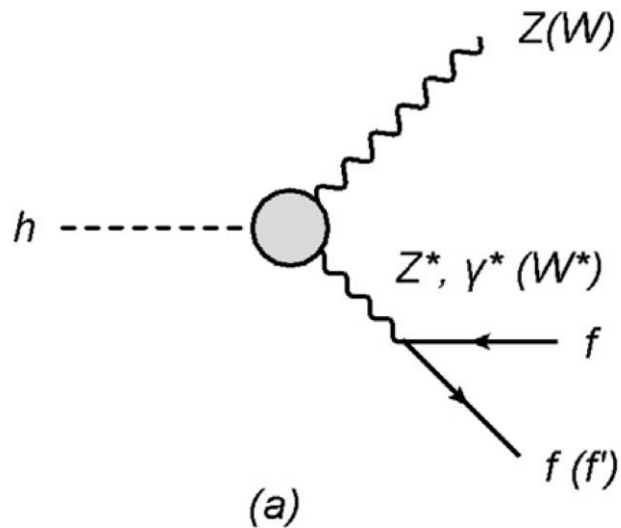
NLO calculations

$$\Gamma(h \rightarrow XX) = \Gamma_{LO}(h \rightarrow XX) \left(1 + \Delta_{EW}^{hXX} + \Delta_{QCD}^{hXX} \right)$$

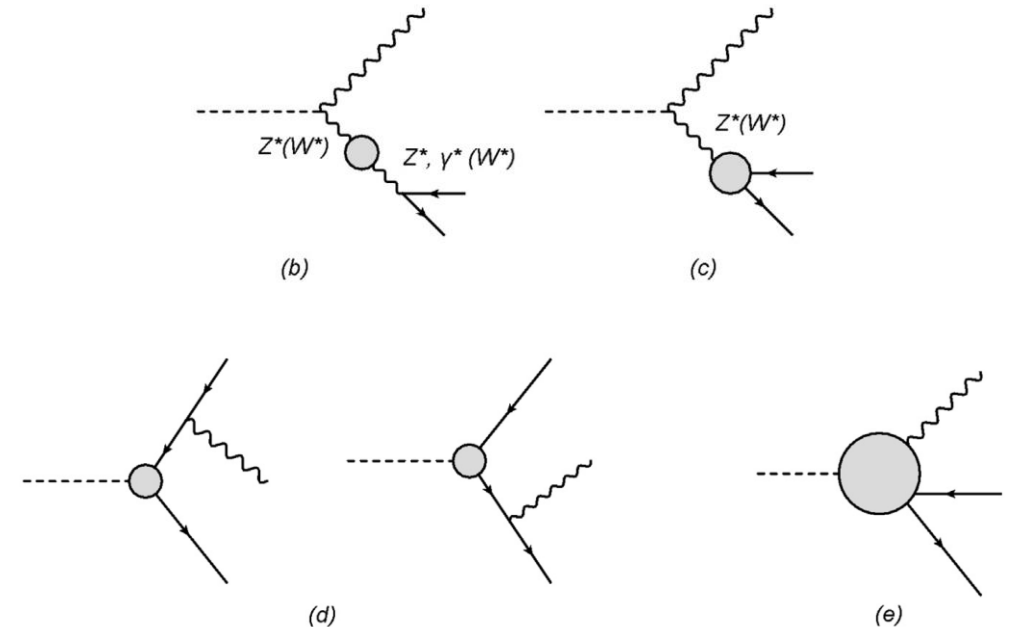
Δ_{EW}^{hXX}

$h \rightarrow ZZ^* \rightarrow Zff$

Renormalized hVV coupling



Other EW corrections



We have to calculate renormalized hXX couplings.

Alignment in Higgs Physics

- What is the “alignment”? → Modifications of the h_{125} properties from the SM predictions.
- Numerical definition → Deviations in h_{125} -couplings = mixing angle parameter (Tree level)

➤ Field mixing

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} h \\ H \end{pmatrix}$$

➤ VEV mixing

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = R(\beta) \begin{pmatrix} v \\ 0 \end{pmatrix} \quad v \simeq 246 \text{ GeV}$$

$$\sum_i h_i \text{ --- } \begin{array}{c} \text{ } \\ \text{ } \end{array} \begin{array}{c} \text{ } \\ \text{ } \end{array} \begin{array}{c} W \\ W \end{array} = g_{hWW}^{SM} \times \text{mixing angles parameter} \xrightarrow{\text{Mixing parameter} \Rightarrow 1} \text{Alignment limit} \quad g_{hVV}^{SM}$$

(Note: The diagram shows a dashed line from h_i and a solid line from v_i meeting at a vertex from which two wavy lines labeled W emerge.)

Mixing angles = “Alignmentness”
[degree of alignment]

Yukawa interaction

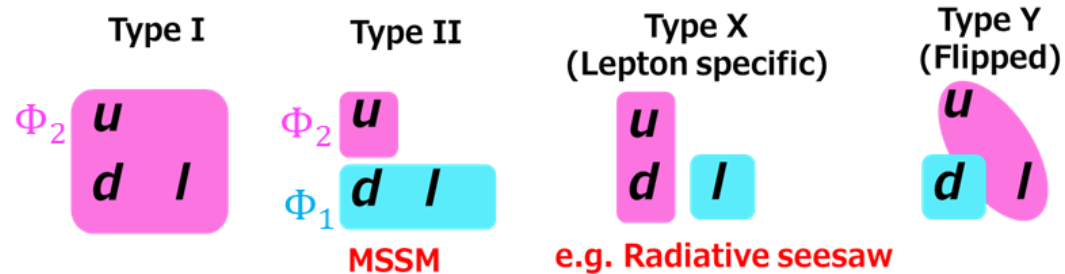
- 2HDMs with the softly broken Z_2 symmetry as an example.

$$\Phi_1 \rightarrow + \Phi_1$$

$$\Phi_2 \rightarrow - \Phi_2$$

Can avoid FCNC.

4 types of Yukawa interactions $\Rightarrow$



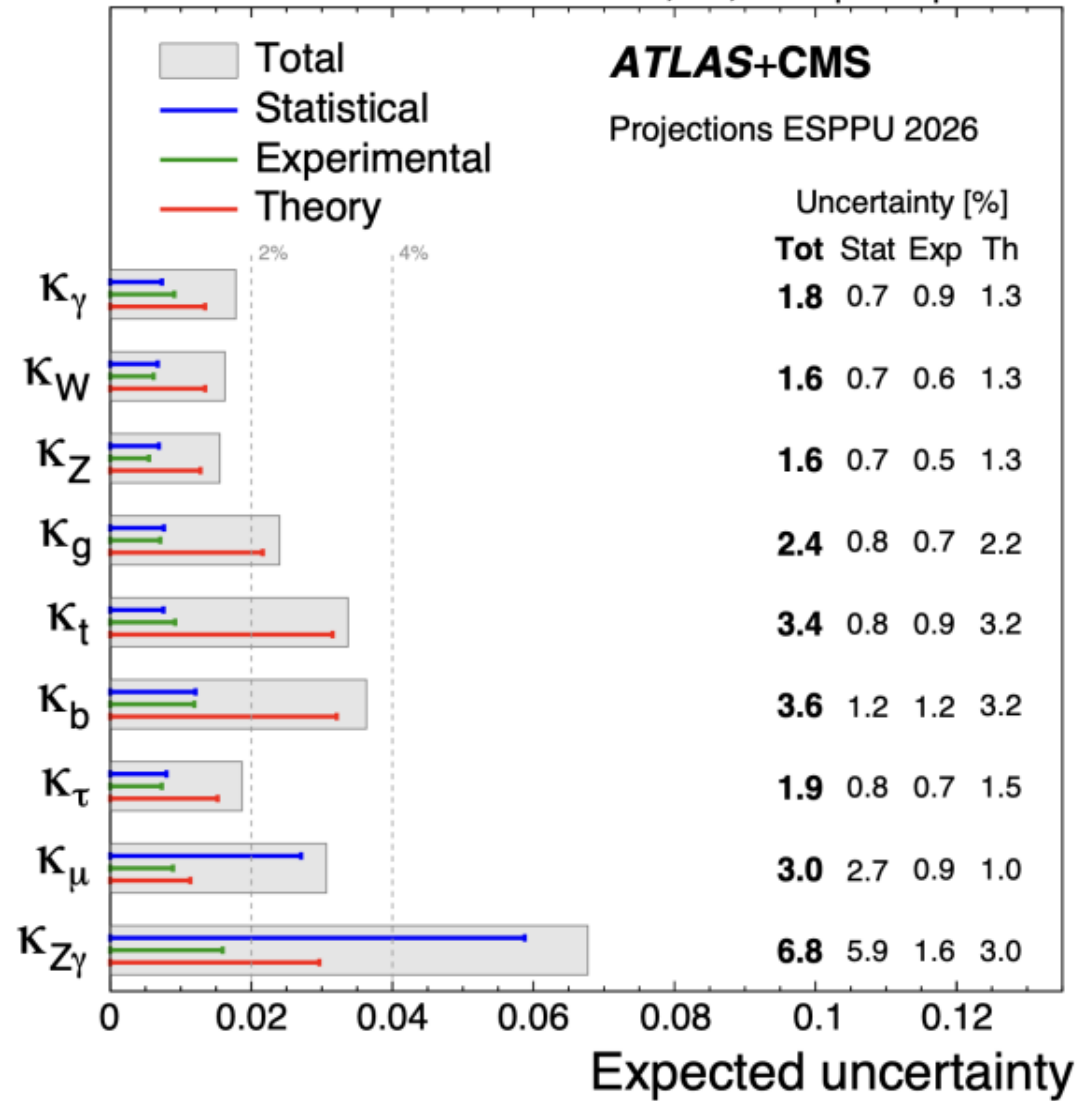
Yukawa couplings

$$\kappa_f^h = \sin(\beta - \alpha) + \zeta_f \cos(\beta - \alpha)$$

The form of κ_f^h depends on the Higgs field that couples to the fermion.

	ζ_u	ζ_d	ζ_e
Type-I	$\cot \beta$	$\cot \beta$	$\cot \beta$
Type-II	$\cot \beta$	$-\tan \beta$	$-\tan \beta$
Type-X (lepton specific)	$\cot \beta$	$\cot \beta$	$-\tan \beta$
Type-Y (flipped)	$\cot \beta$	$-\tan \beta$	$\cot \beta$

$\sqrt{s} = 14 \text{ TeV}$, S2, 3 ab^{-1} per experiment



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Expected Higgs coupling precisions

@ FCC-ee

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	—	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$ \kappa_s $ (%)	—	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	—	0.78	0.69
$\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$	$1.9 \times 10^{-2} *$	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$	$4 \times 10^{-2} *$	6.8×10^{-3}	6.7×10^{-3}

2504.00672 [hep-ex]

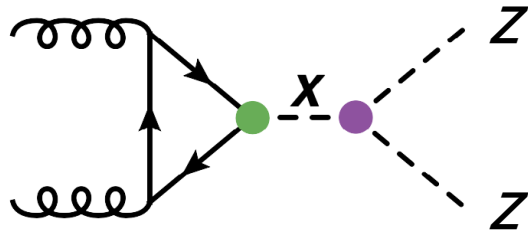
@ LCF(ILC)

	LCF, L[ab ⁻¹]	250 GeV 3, pol.	250 + 550 GeV 3+4, pol.	250 + 550 GeV 3+8, pol.
Higgs couplings				
$g(Hb\bar{b})$		0.72	0.46	0.38
$g(Hc\bar{c})$		1.45	1.04	0.87
$g(Hgg)$		1.31	0.86	0.70
$g(H\tau\tau)$		0.83	0.61	0.53
$g(HWW)$		0.34	0.24	0.22
$g(HZZ)$		0.34	0.24	0.22
$g(H\gamma\gamma)$		1.02	0.98	0.94
$g(H\gamma Z)$		7.51	5.75	5.41
$g(H\mu\mu)$		3.87	3.68	3.53
Higgs widths				
total width		1.39	0.97	0.85
width to invisible (95%CL)		0.36	0.33	0.31
width to unclassified (95%CL)		1.53	1.23	1.11

2503.19983 [hep-ex]

How to search at colliders

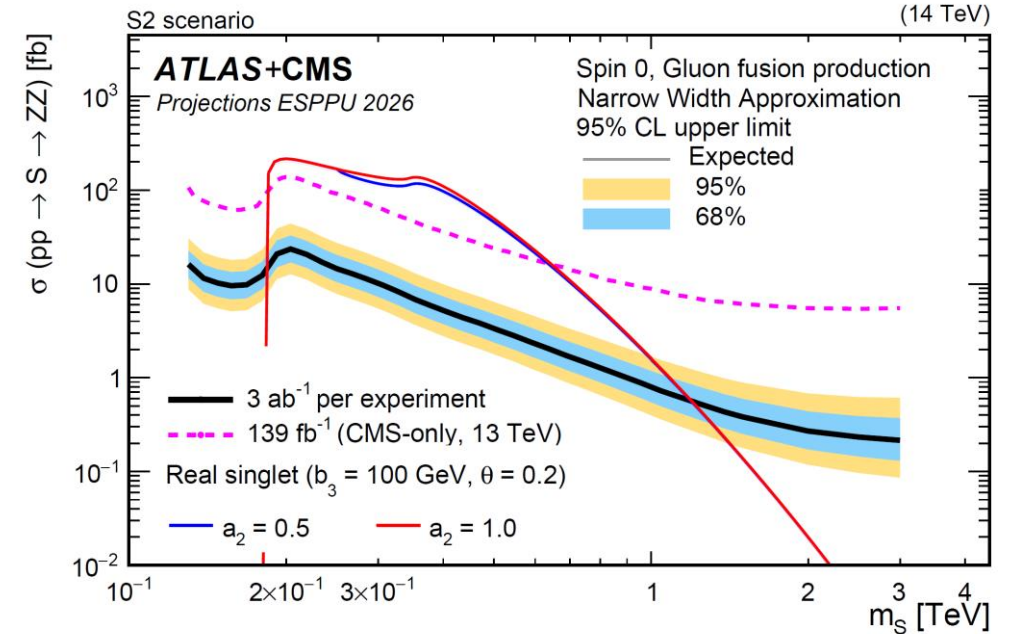
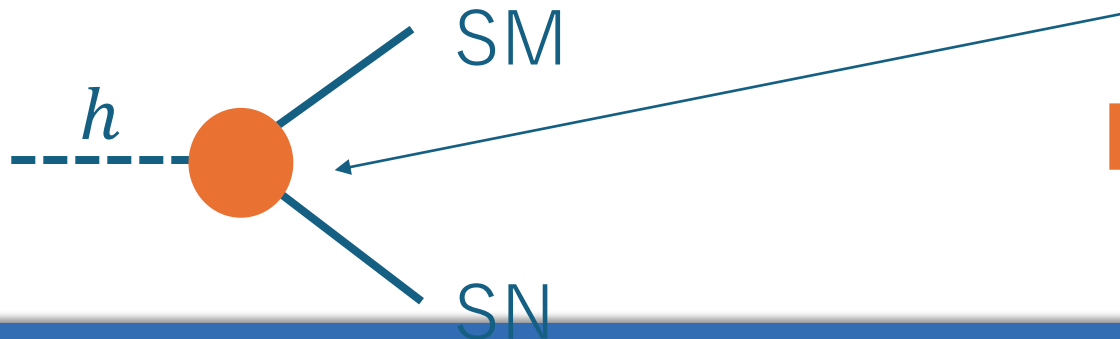
Direct searches of heavy Higgs



Indirect test by h -precision

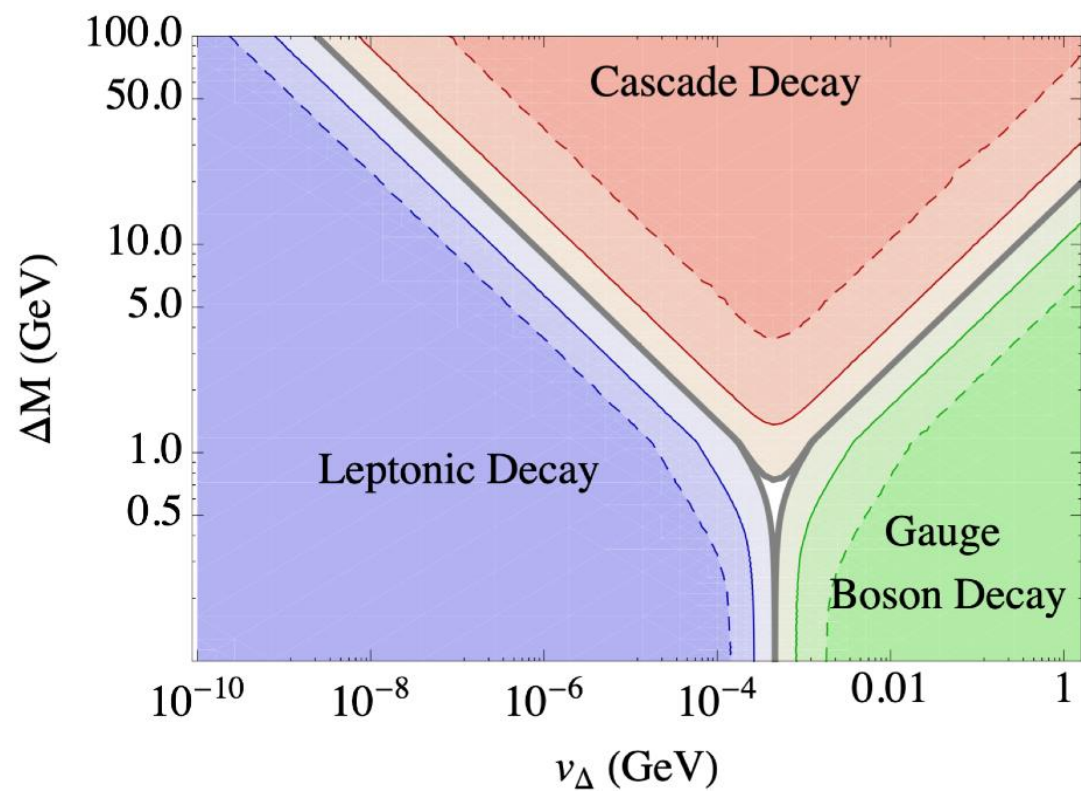
In SM : couplings $\propto$ masses

Deviations from the SM predictions = New physics effects

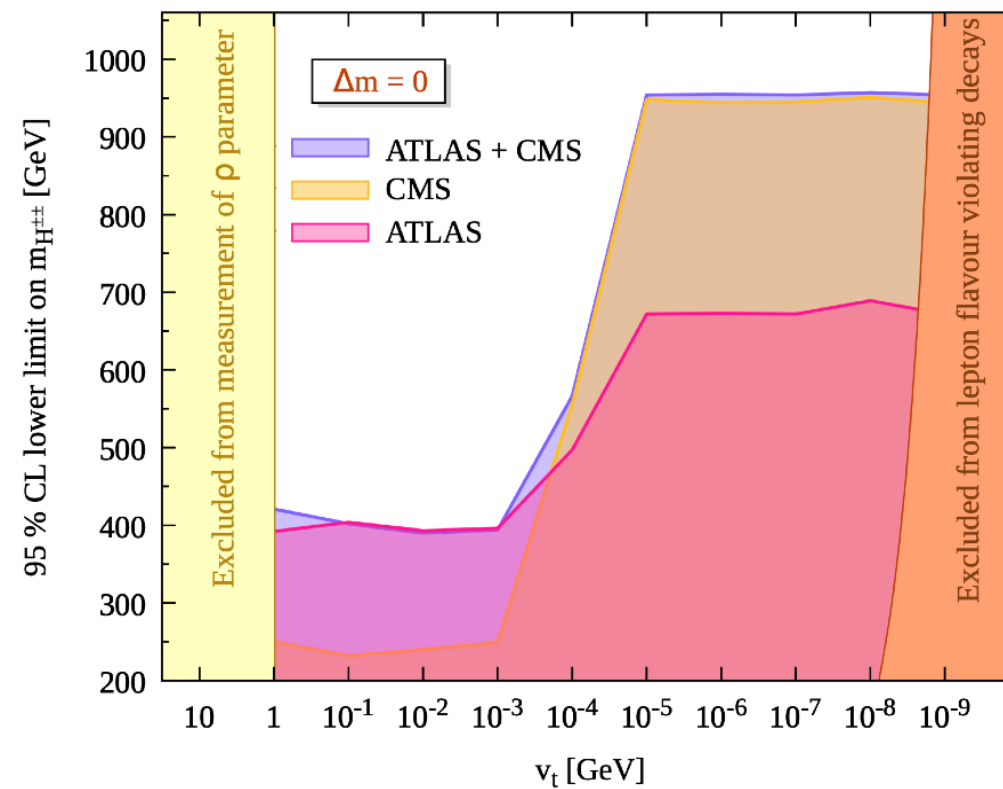


2504.00672 [hep-ex]

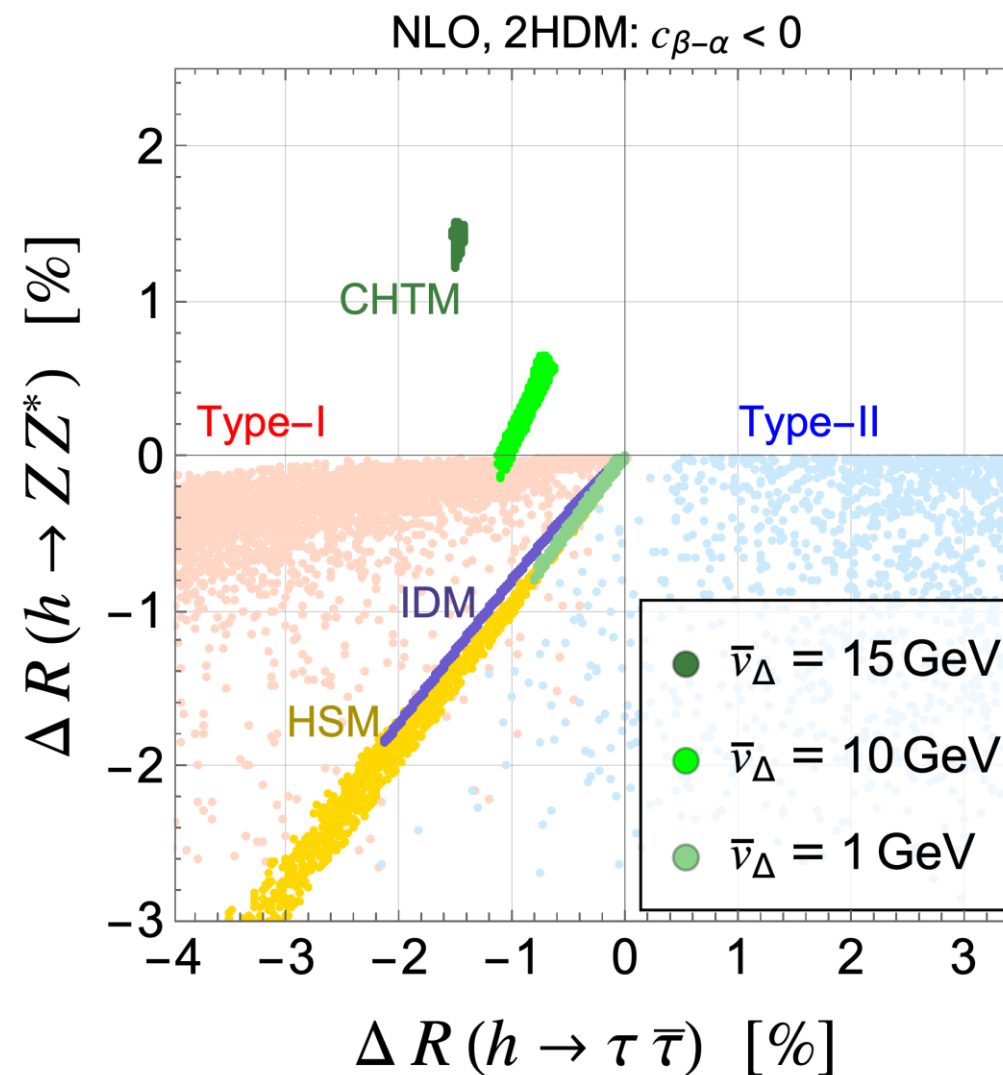
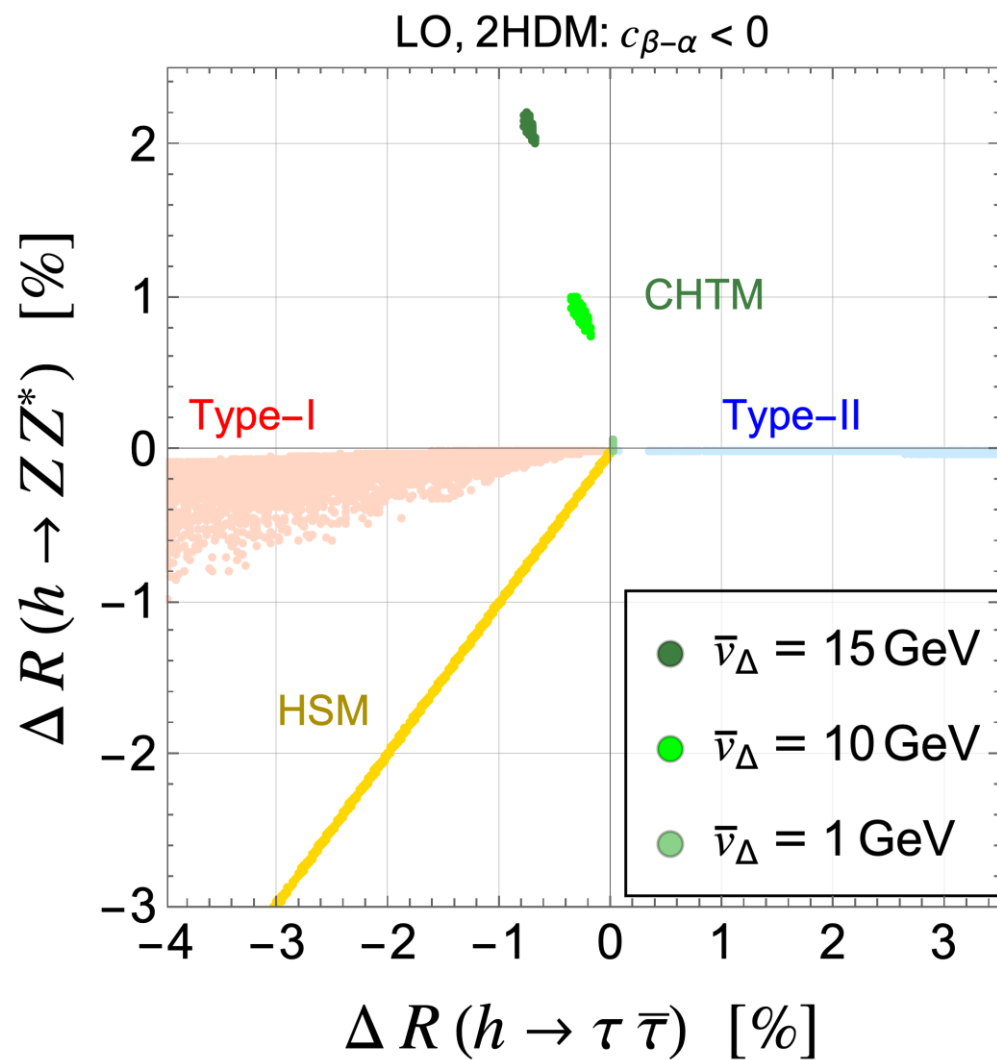
Precision measurements of h
Higgs factory !!

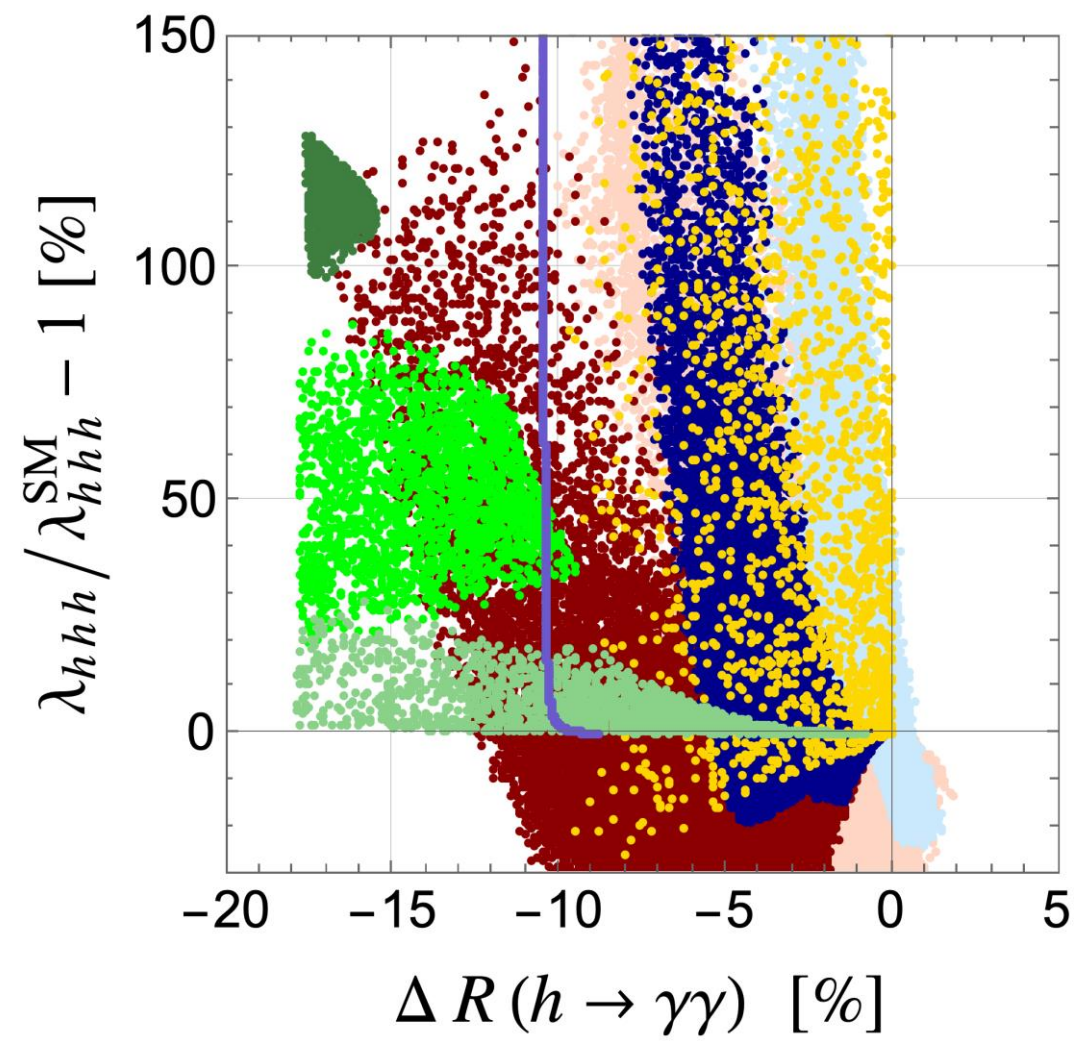


[Melfo, Nemevšek, et.al., PRD85 (2012)]



[Ashanujjaman, Ghosh, JHEP 03 (2022)]





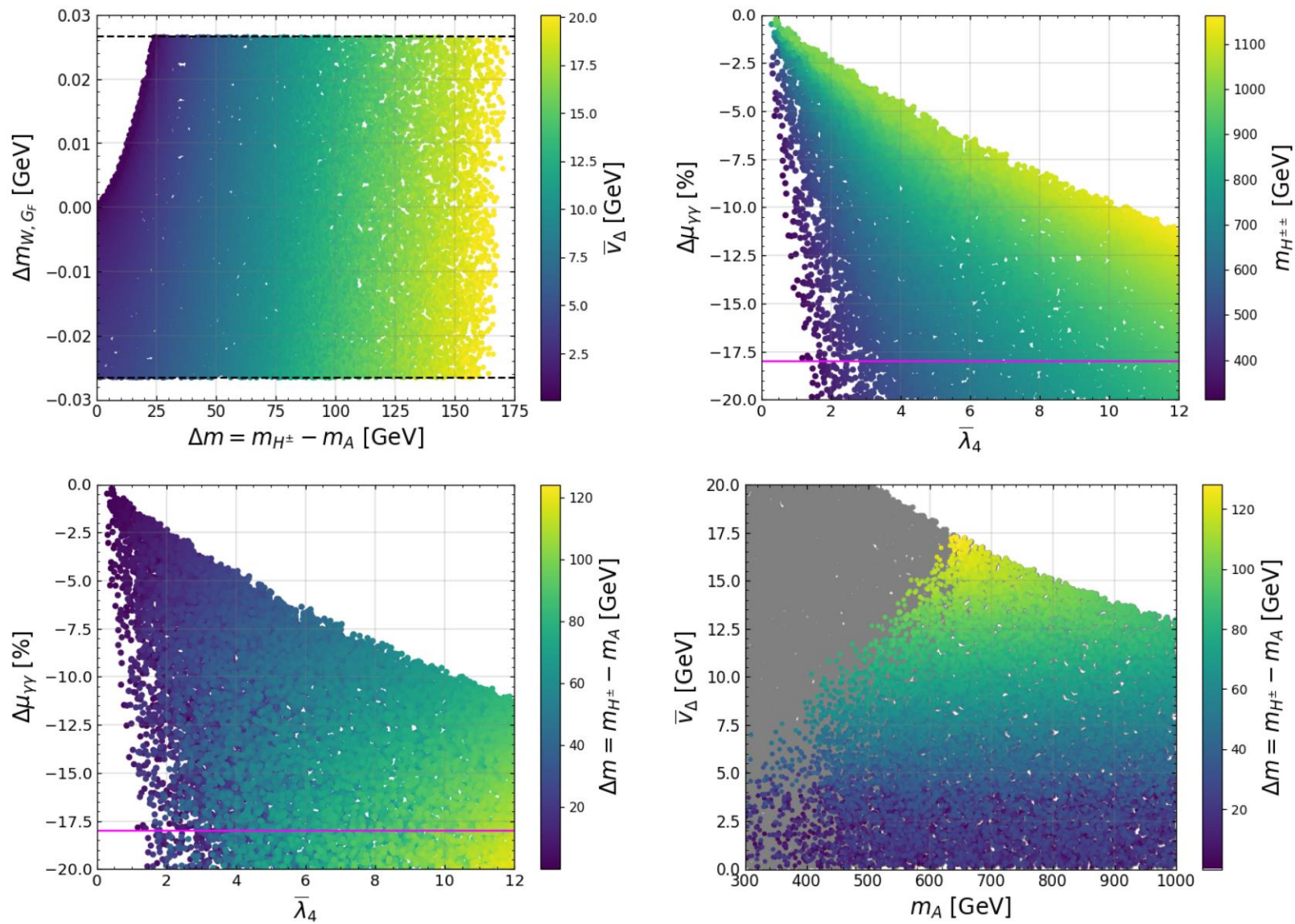
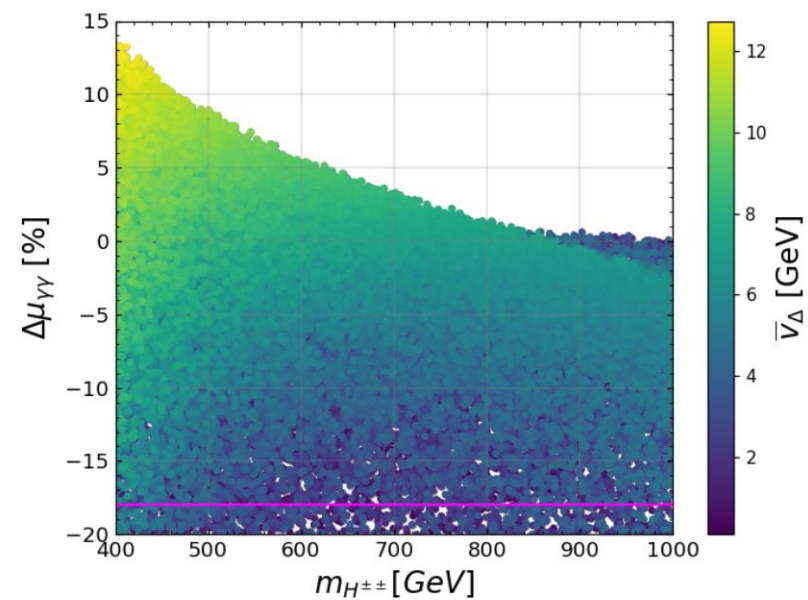
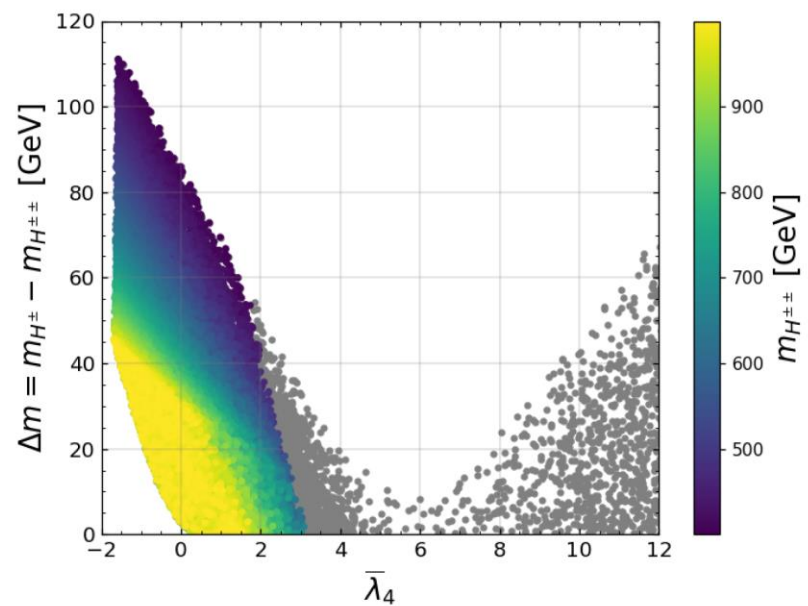
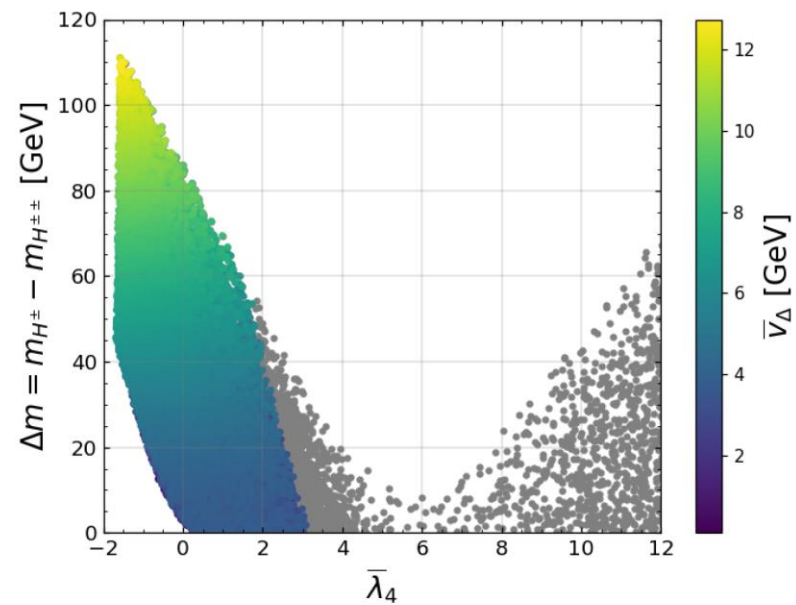
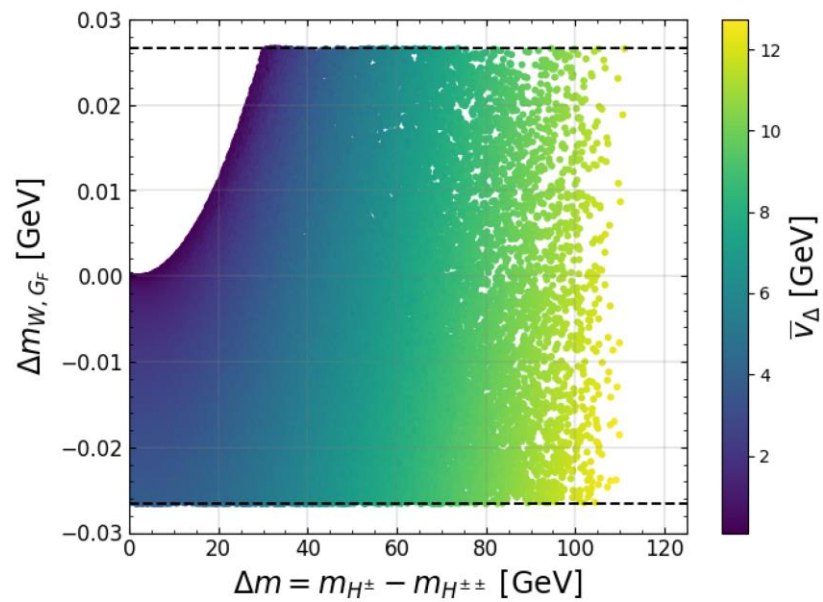


Figure 9: Predictions for $\Delta m_{W,G_F}$ (upper left) and $\Delta\mu_{\gamma\gamma}$ (upper right and lower left), together with the allowed parameter points (lower right) in the HS.



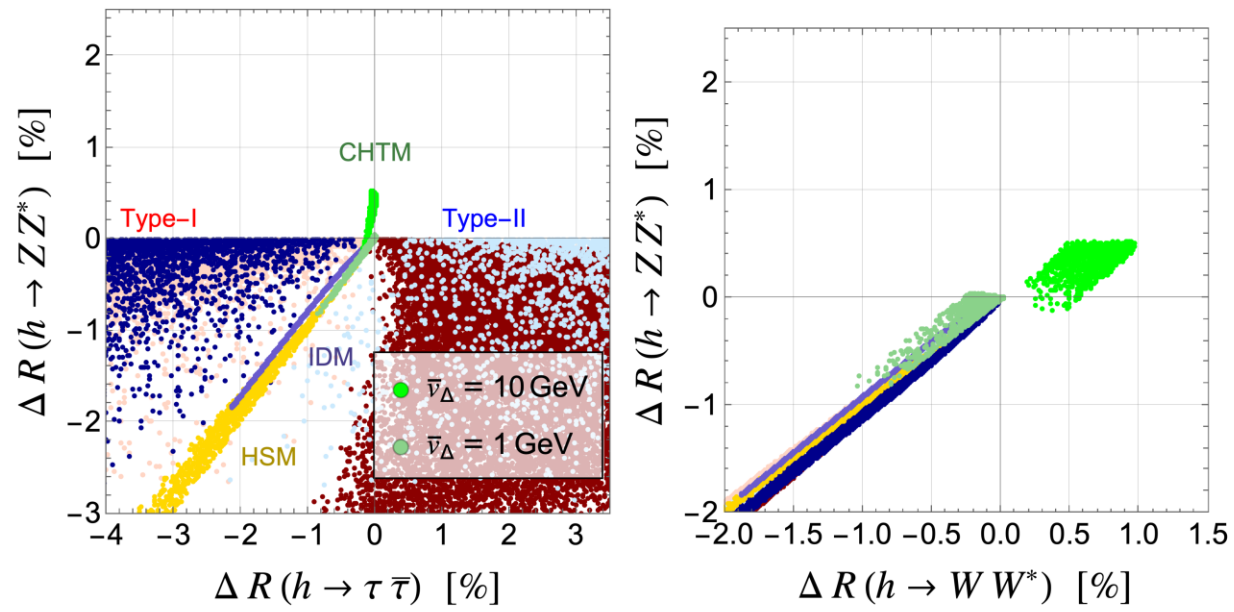
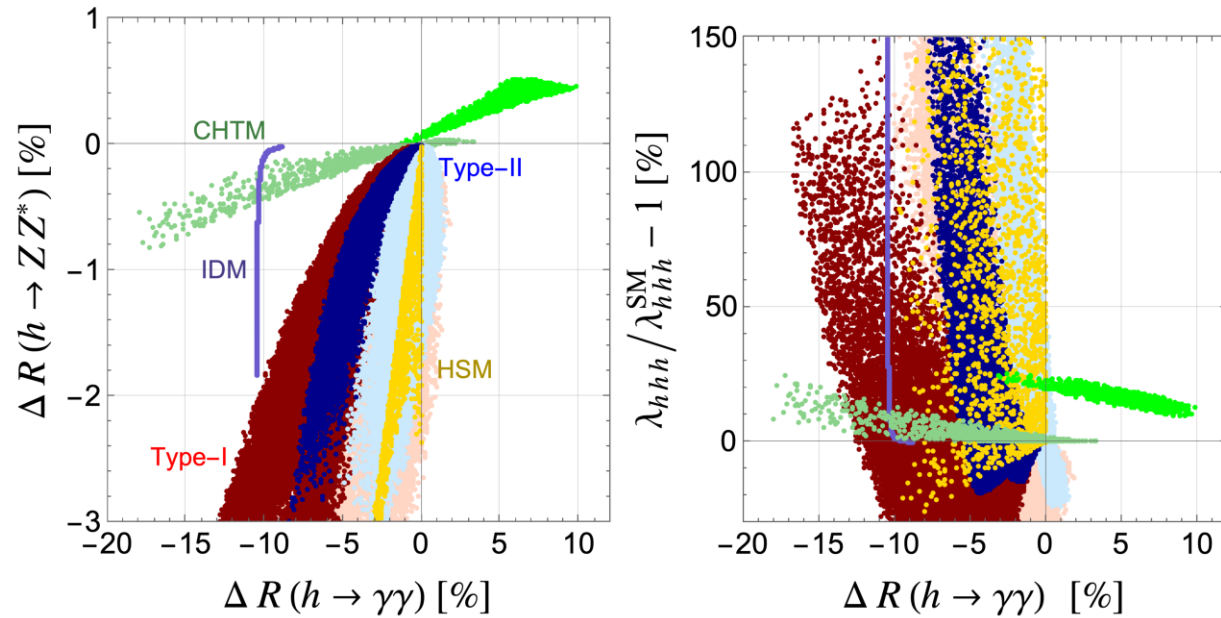


Figure 16: Correlations for the deviations in the decay rates in the LS. The color code is the same as that in the HS.



Renormalization

◆ $\rho = 1$ (SM, Two Higgs Doublet Model)

- Independent parameters m_W, m_Z, α_{em}
- Need 3 Renormalization conditions

$$\text{Re}\Pi_{ZZ}(p^2)|_{p^2=m_Z^2} = 0, \quad \text{Re}\Pi_{WW}(p^2)|_{p^2=m_W^2} = 0, \quad \hat{\Gamma}_\mu^{\gamma ee}[q^2 = 0, \not{p}_1 = \not{p}_2 = m_e] = ie\gamma_\mu,$$

◆ $\rho \neq 1$ (HTMs)

- Independent parameters $m_W, m_Z, \alpha_{em}, \theta_W$
- An additional condition is required

$\delta\theta_W$: determined by β' renormalization (CP-odd scalar-field renormalization).

$$\cos\theta_W^2 = \frac{2m_W^2}{m_Z^2(1 + \cos\beta'^2)} \quad \Rightarrow \quad \begin{aligned} \delta\bar{s}_W^2 &= -\delta\bar{c}_W^2 \\ &= \frac{2m_W^2}{m_Z^2(1 + c_{\beta'}^2)} \left(\frac{\delta m_Z^2}{m_Z^2} - \frac{\delta m_W^2}{m_W^2} - \frac{2s_{\beta'}c_{\beta'}}{(1 + c_{\beta'}^2)}\delta\beta' \right) \end{aligned}$$

T. Blank, W. Hollik (1998), S. Kanemura, K. Yagyu (2012), P. H. Chankowski, S. Pokorski, J. Wagner, (2007); M. -C. Chen, S. Dawson, C. B. Jackson (2008),), M. Aoki, S. Kanemura, MK, K. Yagyu (2012)

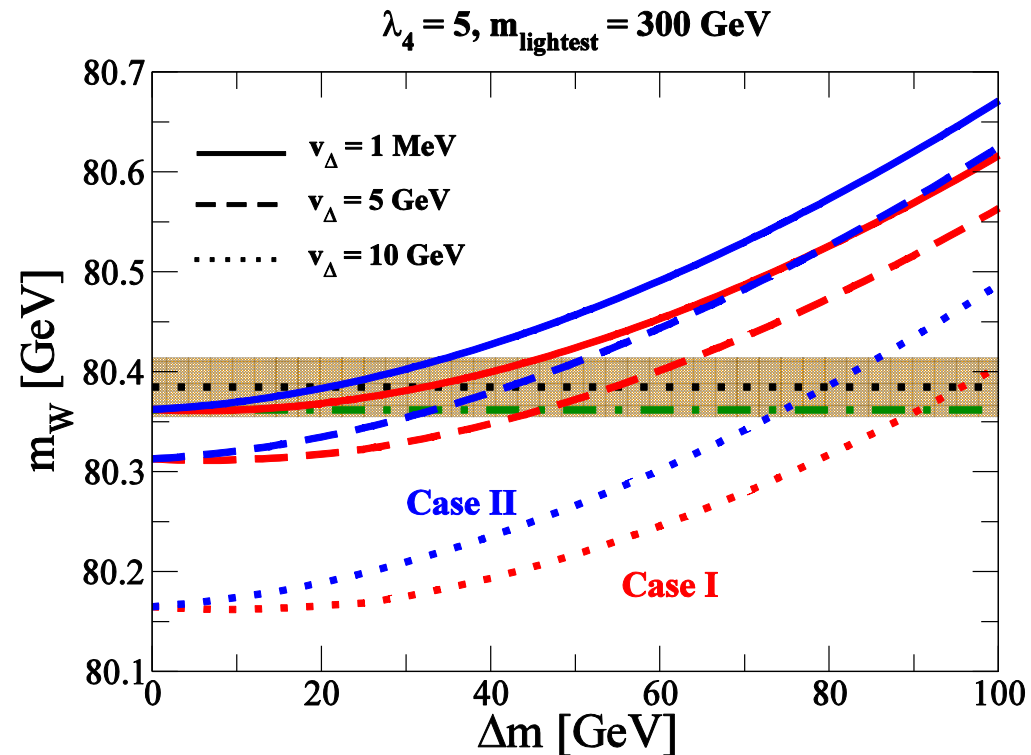
Renormalized EW parameters

$$\Delta r = \frac{\delta \alpha_{em}}{\alpha_{em}} - \frac{\delta G_F}{G_F} - \frac{\delta m_W^2}{m_W^2} - \frac{\delta \bar{s}_W^2}{\bar{s}_W^2}$$

➤ Input

$$\begin{aligned} \alpha_{em}^{-1} &= 137.035989, & \Delta \alpha_{ferm} &= 0.06635, \\ G_F &= 1.16637 \times 10^{-5} \text{ GeV}^{-2}, & m_Z &= 91.1876 \text{ GeV}, \\ \alpha_s &= 0.118, & m_t &= 173.5 \text{ GeV}, \\ m_b &= 4.7 \text{ GeV}, & m_h &= 126 \text{ GeV}, \end{aligned} \quad (86)$$

$$\lambda_4 = 0, m_{lightest} = 300 \text{ GeV}$$



	Case-I	Case-II
$v_\Delta \lesssim 1 \text{ GeV}$	$0 \lesssim \Delta m \lesssim 50 \text{ GeV}$	$0 \lesssim \Delta m \lesssim 30 \text{ GeV}$
$v_\Delta = 5 \text{ GeV}$	$40 \text{ GeV} \lesssim \Delta m \lesssim 60 \text{ GeV}$	$30 \text{ GeV} \lesssim \Delta m \lesssim 50 \text{ GeV}$
$v_\Delta = 10 \text{ GeV}$	$85 \text{ GeV} \lesssim \Delta m \lesssim 100 \text{ GeV}$	$70 \text{ GeV} \lesssim \Delta m \lesssim 85 \text{ GeV}$

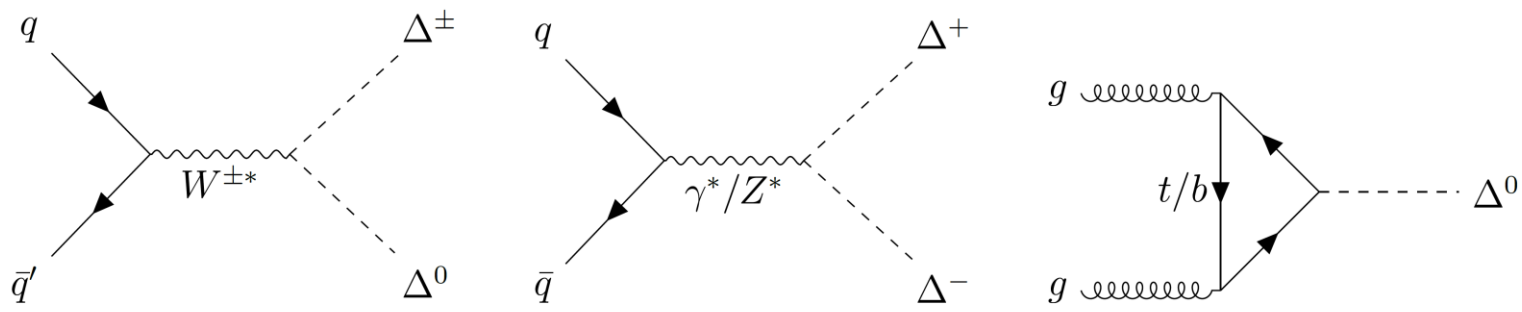


Figure 1. Example Feynman diagrams showing the production of the triplet-like Higgs at the LHC: Drell-Yan (left and middle) and ggF (right).

