# Connection between the 2$^{nd}$ Higgs boson mass and a deviation in h(125) couplings

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Based on

S. Moretti, and KY, PRD91, 055022 (2015) [arXiv:1501.06544]

S. Kanemura, and KY, PLB751, 289-296 (2015) [arXiv:1509.06060]

Scalars2015, 6th, Dec, 2015

U of Warsaw

# LHC Run-I Tells Us

1. There exits one CP-even scalar boson

   $\rightarrow$ **At least 4 d.o.f. of scalar state (3 NGBs and h)**

2. Its mass is about 125 GeV.

   $\rightarrow$ **Consistent w/ EW precision tests**

3. It was observed from ZZ, $\gamma\gamma$, WW and $\tau^+\tau^-$.

   $\rightarrow$ **hVV/hff couplings**

4. The combined signal strength is consistent w/ the SM Higgs.

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   → **At least 4 d.o.f. of scalar state (3 NGBs and h)**

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   → **Consistent w/ EW precision tests**

- This suggests that there is **at least** one isospin doublet scalar field.
- The SM Higgs sector is the minimal realization.

# Questions for the Higgs Sector

- What is the identity of the Higgs boson?
  - elementary or composite?
- Are there any relations to the BSM phenomena?
  - Neutrino mass, dark matter, baryon number asymmetry, ⋯
- What is the structure of the Higgs sector?
  - Number of multiplets and their representations, symmetries

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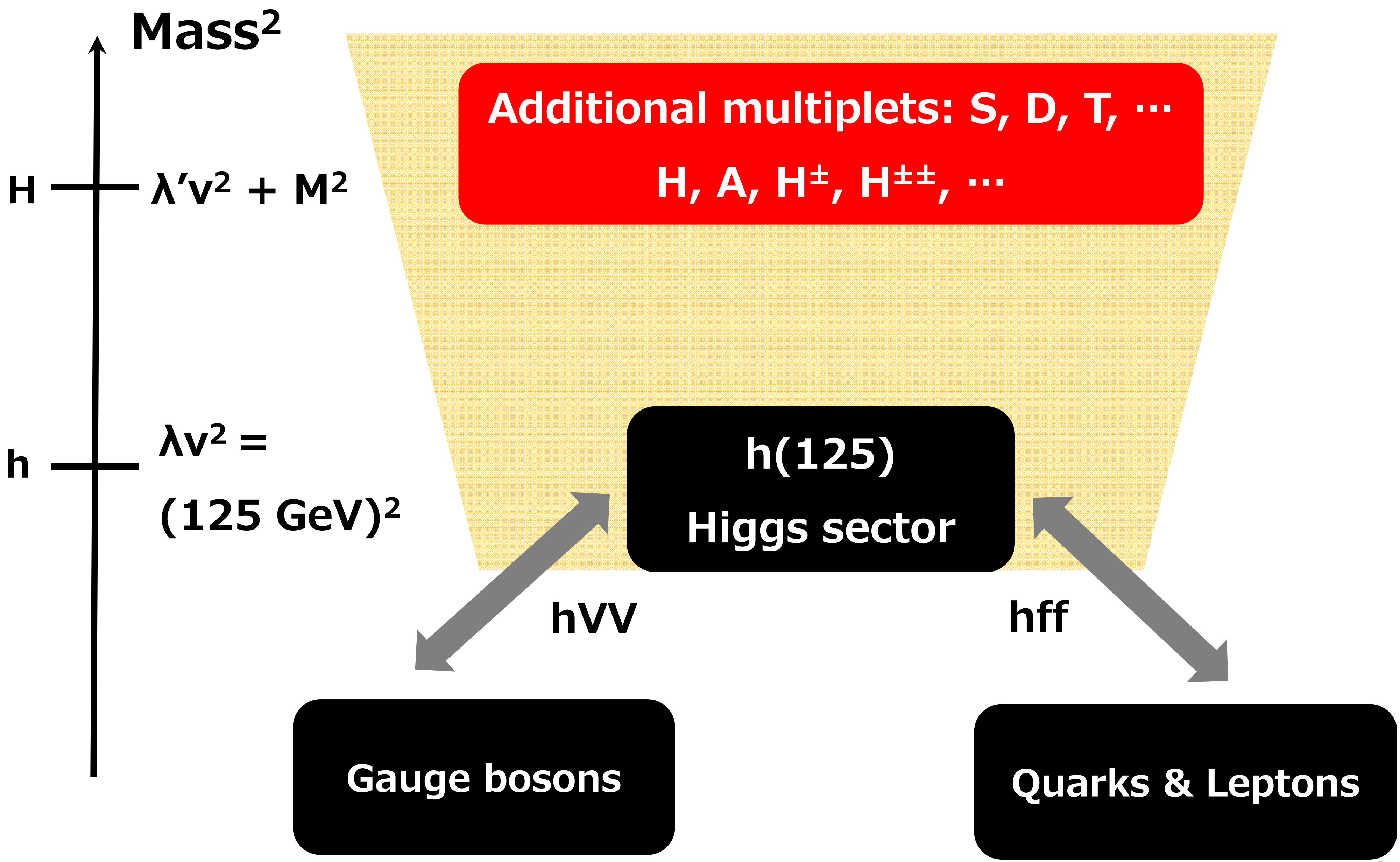
  - Number of multiplets and their representations, symmetries

Property of the Higgs sector can strongly depend on NP scenarios.

$\rightarrow$ Higgs is a probe of New Physics!!

# How can We Determine?



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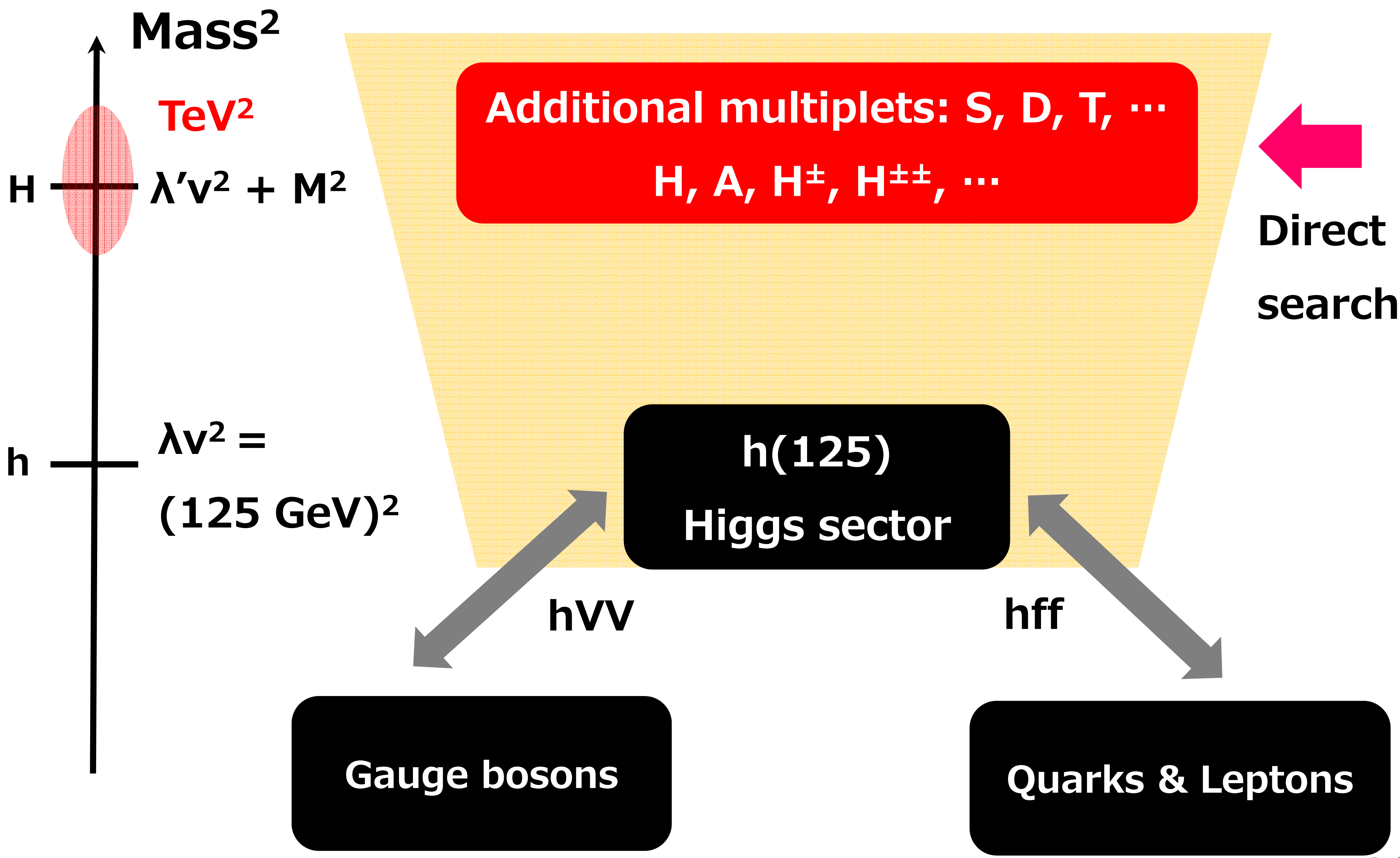

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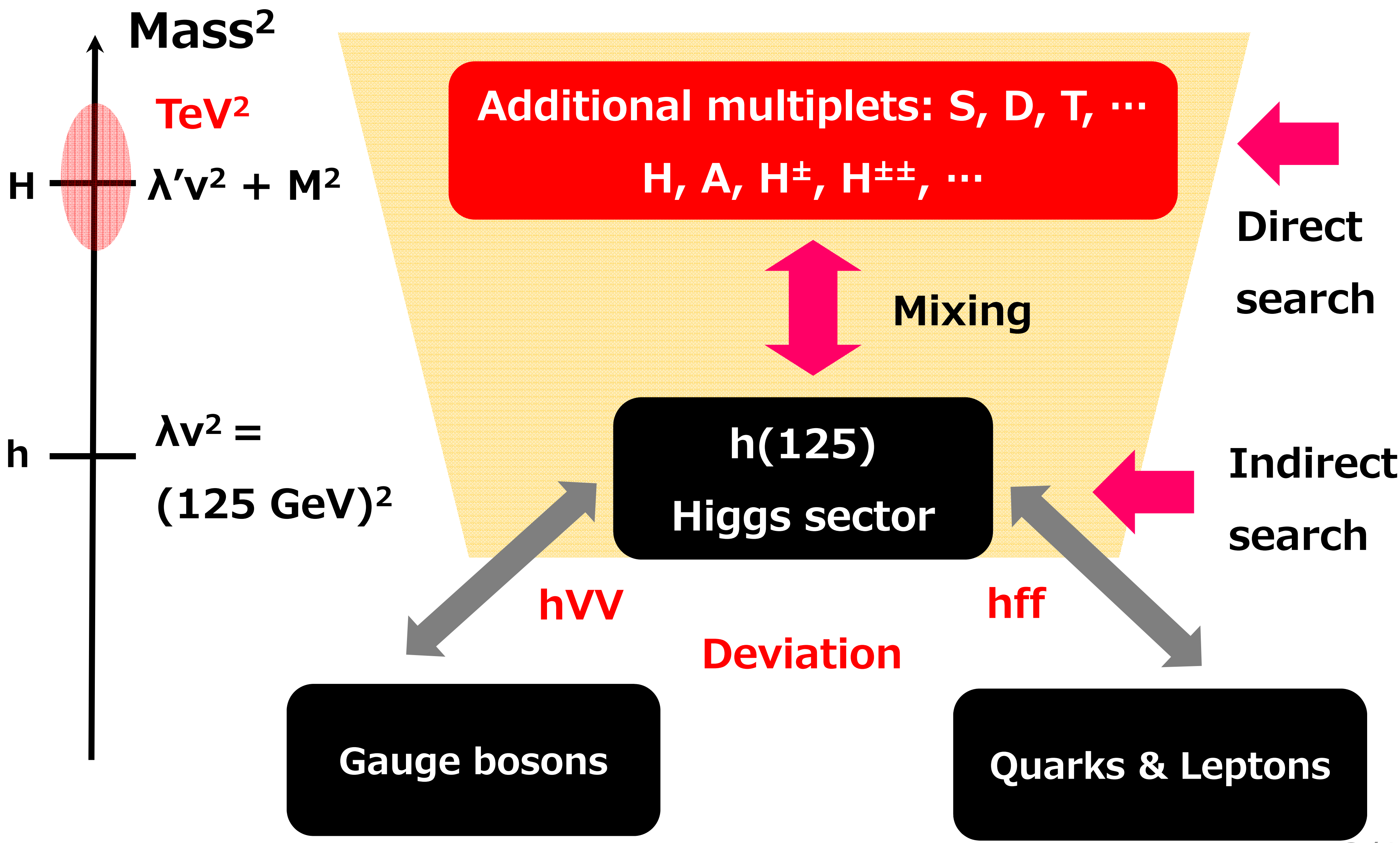

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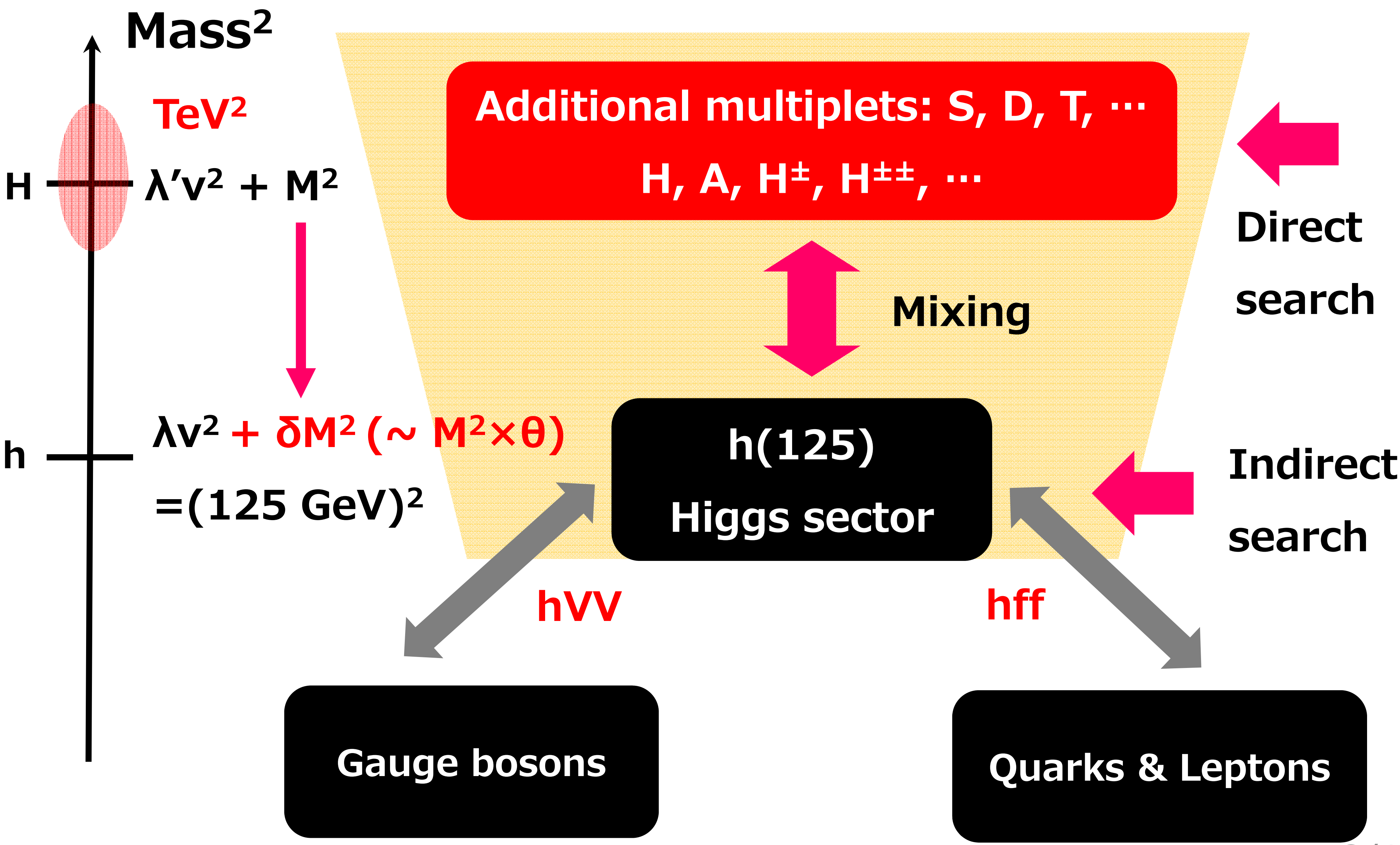

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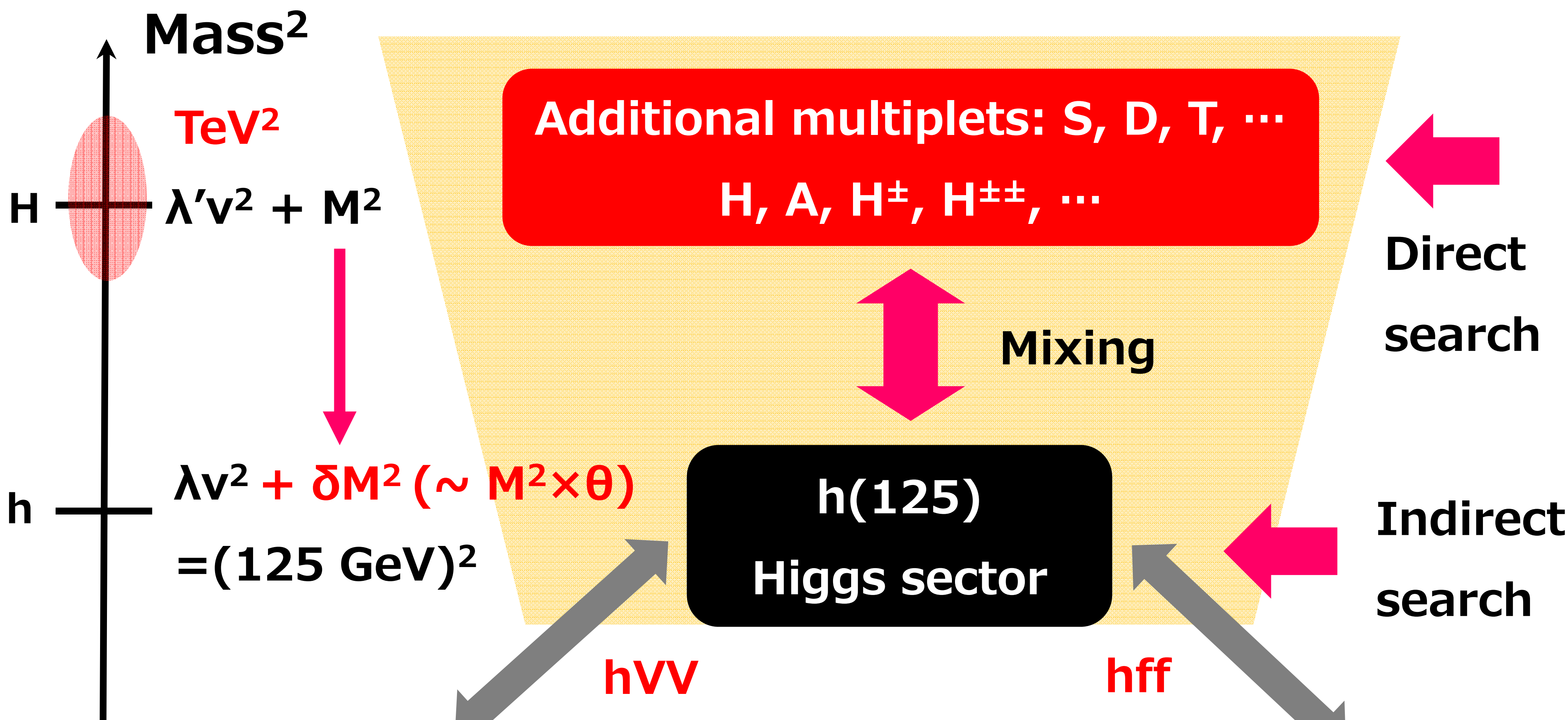


- When $M^2 \gg v^2$ and $\theta \neq 0 \Rightarrow |\lambda| \gg 1$

  $\Rightarrow$ This must break perturbativity of the theory.

# Implication of non-zero mixing

Non-zero mixing between h and extra Higgs bosons

**Higgs coupling deviations**

and

**Upper limit on the 2$^{nd}$ Higgs mass!**

I discuss the relation between the h coupling dev. and

the upper limit on the 2nd Higgs mass from S-matrix unitarity.

# Contents

# Two Higgs doublet models (2HDMs)

- Many of new physics models introduce the second doublet

  (e.g., MSSM, CPV, Neutrino mass models, ⋯)

- Naturally we obtain $\rho_{\mathrm{tree}} = 1$.

- Good to learn typical feature of non-minimal Higgs sectors.

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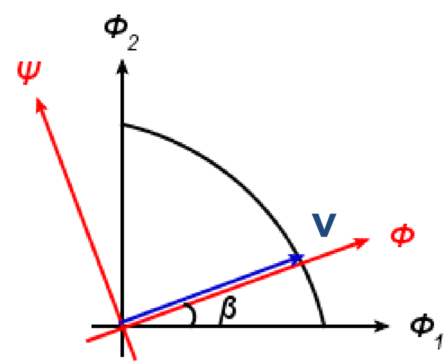
**Higgs Basis** $\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Psi \end{pmatrix}$ ($\tan\beta = v_2/v_1$)




**NG bosons**

**Charged Higgs**

$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h_1' + v + iG^0) \end{bmatrix} \qquad \Psi = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + ih_3') \end{bmatrix}$$

**Neutral Higgses**

# Most general Higgs potential

- The most general Higgs potential under the $SU(2)_L \times U(1)_Y$ symmetry

$$
\begin{aligned}
V(\Phi_1, \Phi_2) = {} & m_1|\Phi_1|^2 + m_2|\Phi_2|^2 - [m_3^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}] \\
& + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\
& + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\right] + \left[\lambda_6|\Phi_1|^2(\Phi_1^\dagger\Phi_2) + \mathrm{h.c.}\right] + \left[\lambda_7|\Phi_2|^2(\Phi_1^\dagger\Phi_2) + \mathrm{h.c.}\right]
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$$+\lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2$$
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- Two VEVs are taken to be real without loss of generality.

*Ginzburg, Krawczyk, PRD72 (2175)*

$$e^{i\rho_1}v_1 \to v_1, \quad e^{i\rho_2}v_2 \to v_2$$

(Rephasing invariance)

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(Rephasing invariance)

- Number of parameters

= 14 (in potential) + 2 (VEVs) -3 (stationary conditions) = 13

$$\lambda_{1-4},\ \lambda_{5-7}^R,\ \lambda_{5-7}^I,\ v,\ \tan\beta,\ \mathrm{Re}\, m_3^2 (= M^2 s_\beta c_\beta)$$

# Mass Matrix for neutral Higgs bosons

$$V_{\rm mass} = \frac{1}{2}(h'_1, h'_2, h'_3)\begin{pmatrix} M_{11}^2 & M_{12}^2 & M_{13}^2 \\ M_{12}^2 & M_{22}^2 & M_{23}^2 \\ M_{13}^2 & M_{23}^2 & M_{33}^2 \end{pmatrix}\begin{pmatrix} h'_1 \\ h'_2 \\ h'_3 \end{pmatrix}$$

$$= \frac{1}{2}(H_1, H_2, H_3)\,{\rm diag}(m_{H_1}^2,\ m_{H_2}^2,\ m_{H_3}^2)\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} \quad (m_{H_1}^2 \leq m_{H_2}^2 \leq m_{H_3}^2)$$

We identify $H_1$ (=h) as the discovered Higgs boson and $m_{H1}$ = 125 GeV.

| Matrix element | Dependence |
|---|---|
| $M_{11}^2$, $M_{12}^2$ | $\lambda_{1\text{-}4}$, $\lambda_{5\text{-}7}^R$, $\tan\beta$ |
| $M_{22}^2$, $M_{33}^2$ | $\lambda_{1\text{-}4}$, $\lambda_{5\text{-}7}^R$, $\tan\beta$, $M^2$ |
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CPC limit : $\lambda_{5\text{-}7}^I \to 0$

[$M_{13}^2$, $M_{23}^2 \to 0$]

Decoupling limit : $M^2 \to \infty$

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We identify $H_1$ (=h) as the discovered Higgs boson and $m_{H1}$ = 125 GeV.

$$\tilde{m}_h^2 = s_{\beta-\tilde{\alpha}}^2 M_{11}^2 + c_{\beta-\tilde{\alpha}}^2 M_{22}^2 - 2 s_{\beta-\tilde{\alpha}} c_{\beta-\tilde{\alpha}} M_{12}^2$$

$$\tilde{m}_H^2 = c_{\beta-\tilde{\alpha}}^2 M_{11}^2 + s_{\beta-\tilde{\alpha}}^2 M_{22}^2 + 2 s_{\beta-\tilde{\alpha}} c_{\beta-\tilde{\alpha}} M_{12}^2$$

$$\tilde{m}_A^2 = M_{33}^2$$

$$\tan 2(\beta - \tilde{\alpha}) = \frac{2M_{12}^2}{M_{22}^2 - M_{11}^2}$$

CPC limit : $\lambda_{5\text{-}7}^{I} \to 0$

[$M_{13}^2$, $M_{23}^2 \to 0$]

Decoupling limit : $M^2 \to \infty$

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$$v,\ \tilde{m}_h^2,\ \tilde{m}_H^2,\ \tilde{m}_A^2,\ m_{H\pm}^2,\ \tan\beta,\ \sin(\beta-\tilde{\alpha}),\ M^2,\ |\lambda_{6,7}|,\ \theta_{5,6,7}$$

# Mass Matrix for neutral Higgs bosons

Advantages: Good to see the impact of imaginary part of the parameters

Good to discuss physics in the CPC or SM-like regime.

Alternatives: ( $\tilde{m}_h,\ \tilde{m}_H,\ \tilde{m}_A,\ \tilde{\alpha},\ \lambda_5^I$ ) $\rightarrow$ ( $\alpha_1,\ \alpha_2,\ \alpha_3,\ m_{H_1},\ m_{H_2}$ )

*Kaffas, Khater, Ogreid, Osland, NPB775 (2177)*

*Arhrib, Christova, Eberl, Ginina, JHEP04 (2011)*

*Barroso, Ferreira, Santos, Silva, PRD86 (2012)*

$$\tilde{m}_h^2 = s^2_{\beta-\tilde{\alpha}} M^2_{11} + c^2_{\beta-\tilde{\alpha}} M^2_{22} - 2 s_{\beta-\tilde{\alpha}} c_{\beta-\tilde{\alpha}} M^2_{12}$$

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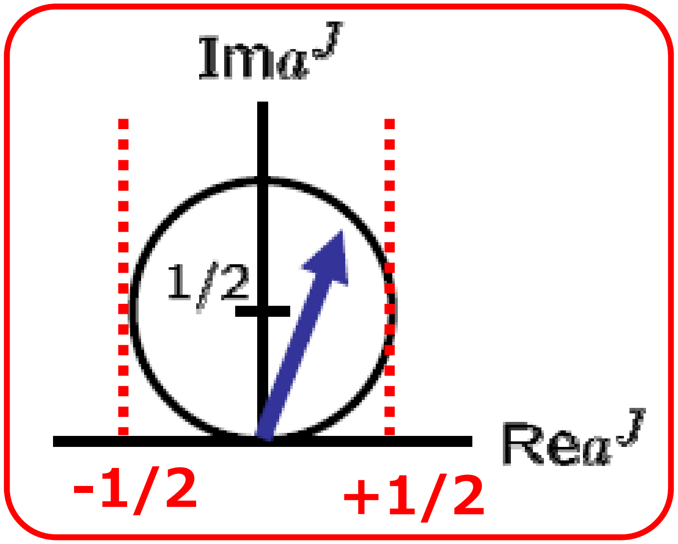
# S matrix Unitarity

*See E. Yildirim's talk about composite 2HDM*

S matrix unitarity: $S^\dagger S = S S^\dagger = 1$

$$\sigma_{\text{tot}} = \frac{1}{s} \mathrm{Im}\, \mathcal{M}(\theta = 0)$$




Using the partial wave expansion:

$$\mathcal{M} = 16\pi \sum_{J=0}^{\infty} (2J+1) P_J(\cos\theta) a_J$$

we obtain

$$\mathrm{Re}(a_J^{2\to 2})^2 + [\mathrm{Im}(a_J^{2\to 2}) - 1/2]^2 = (1/2)^2$$

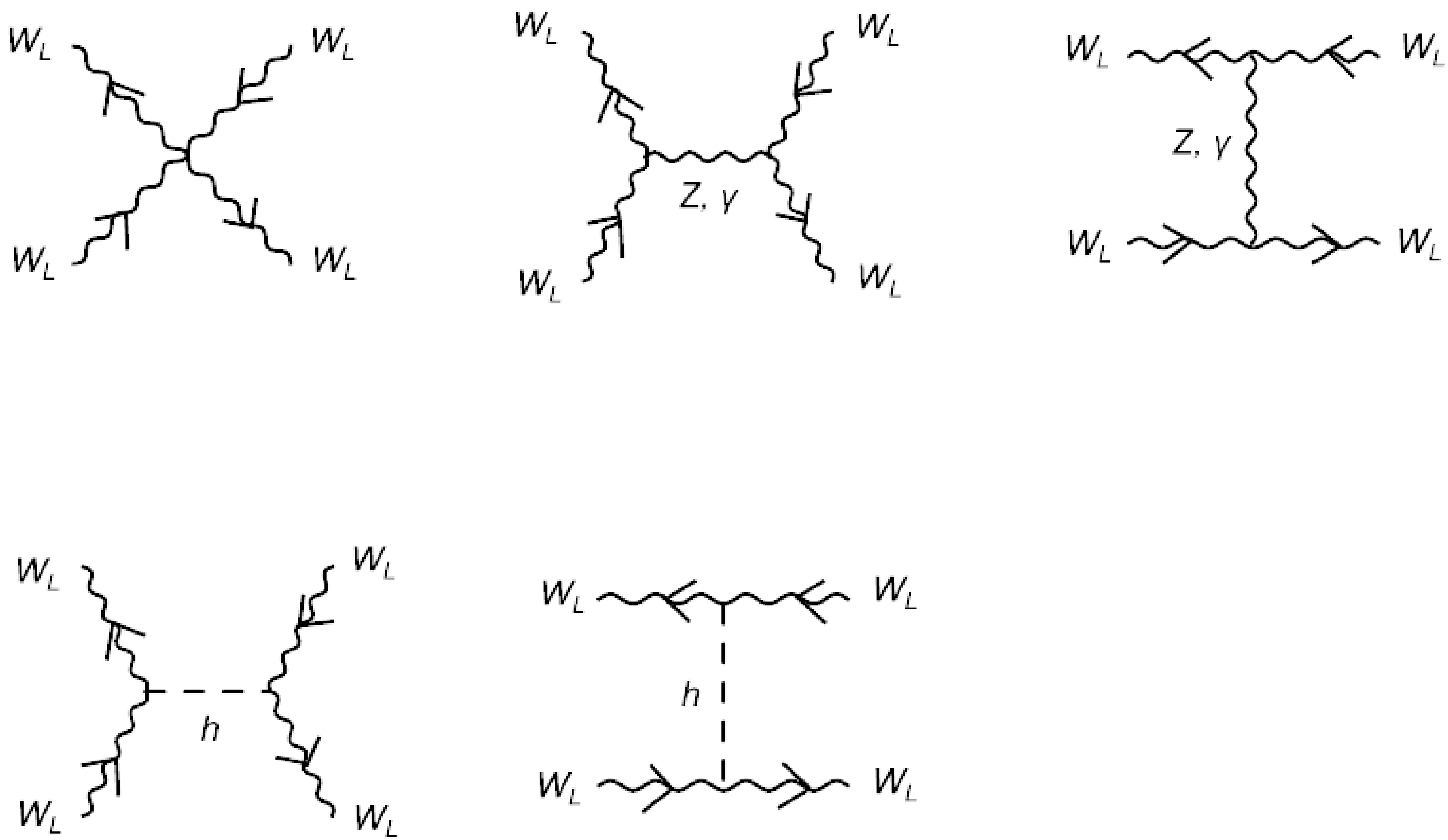
for $2 \to 2$ elastic scatterings.

Perturbative unitarity bound:

$$\boxed{|\mathrm{Re}(a_J^{2\to 2})| < 1/2}$$

# $W_L^+W_L^- \rightarrow W_L^+W_L^-$ scattering in SM

*Lee, Quigg, Thacker (1977)*



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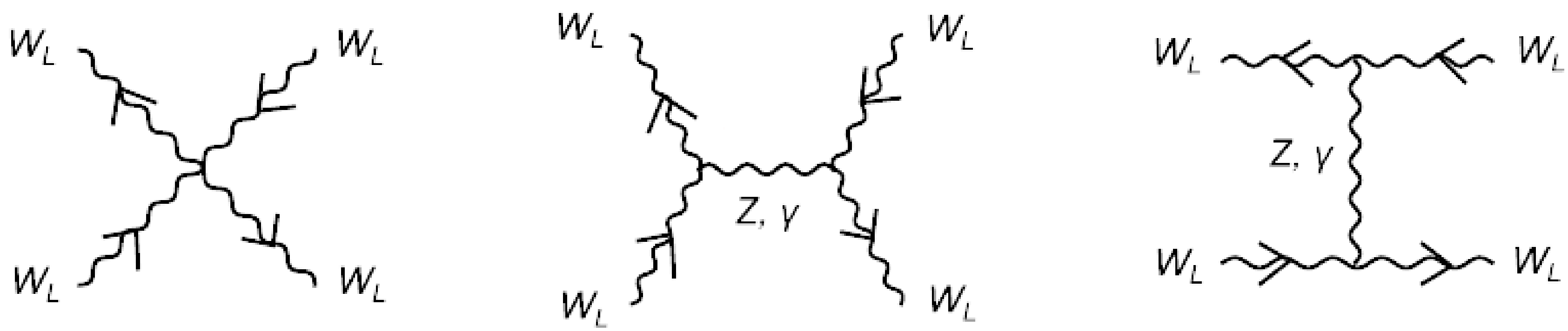
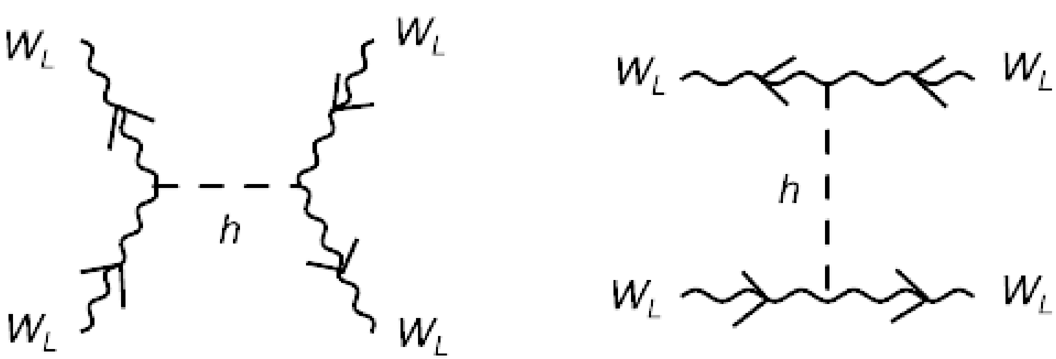



$$a_0 \sim a\, E^2 + O(E^0)$$




$$a_0 \sim -a\, E^2 + O(E^0)$$

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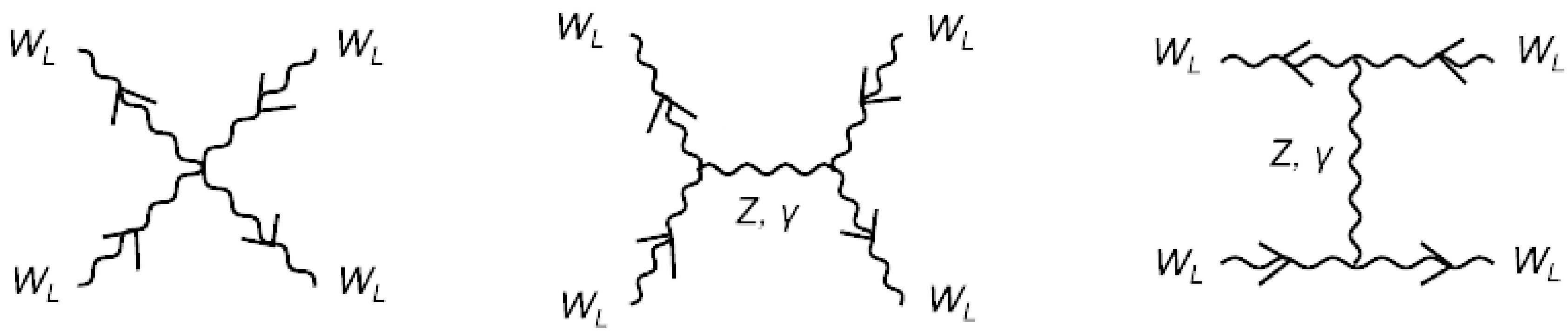
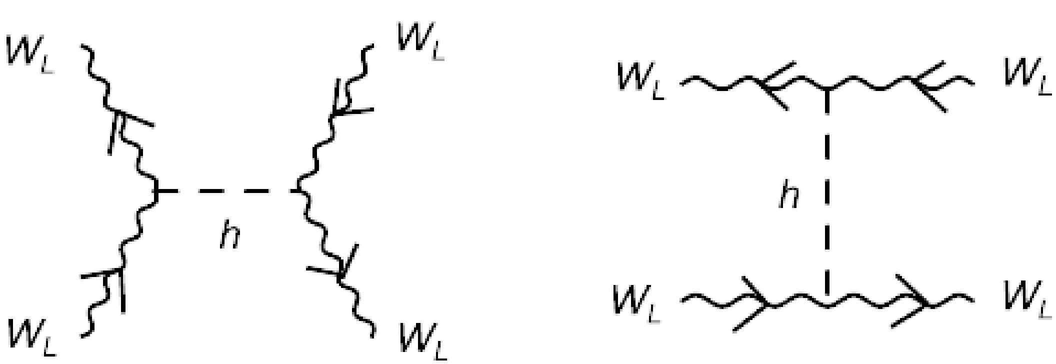



**$a_0 \sim \cancel{a\, E^2} + O(E^0)$**




**$a_0 \sim -\cancel{a\, E^2} + O(E^0)$**

$$a_0 \sim \frac{m_h^2}{8\pi v^2} \left(= \frac{\lambda}{4\pi}\right)$$

$+ O(g^2)$

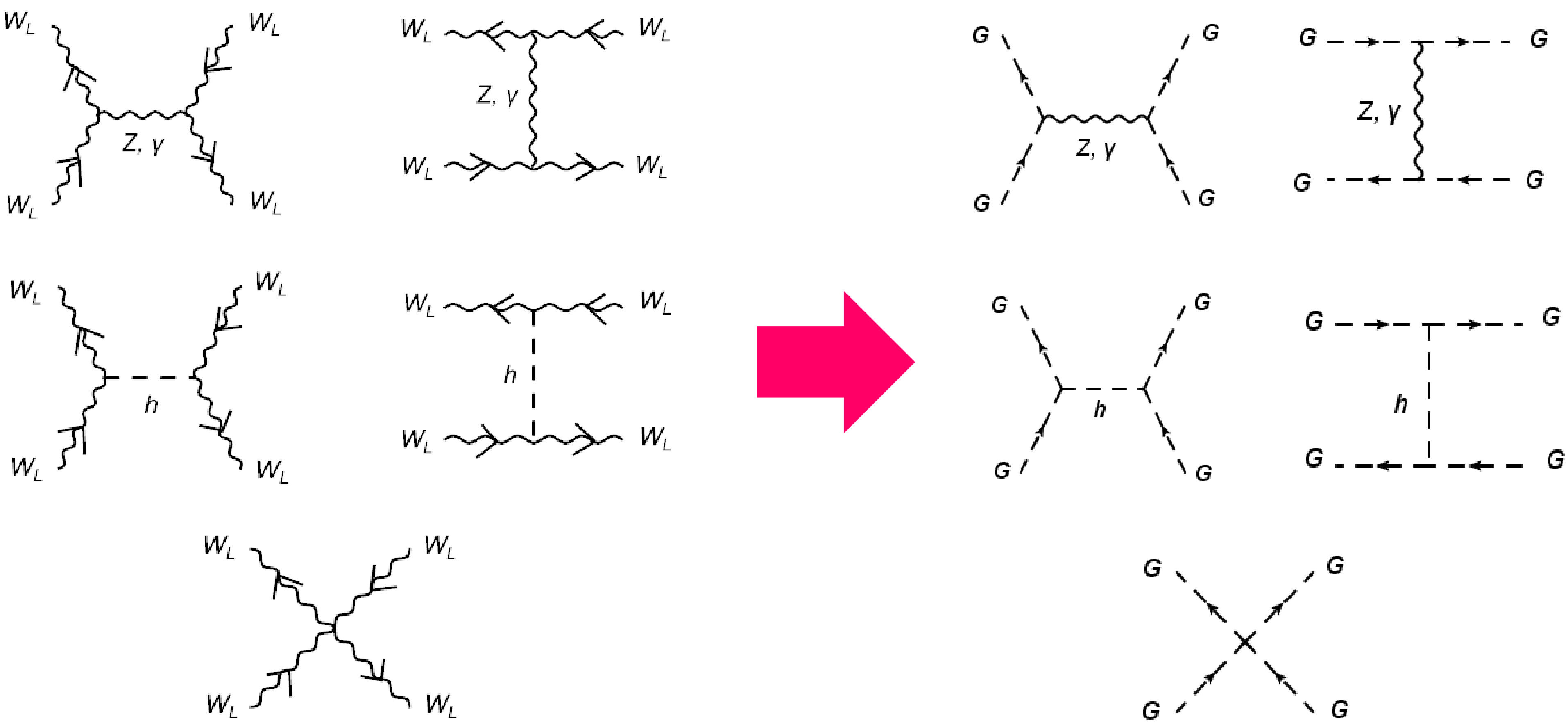
From $|a_0| < 1/2$ , we get

**mh < 870 GeV**

# Equivalence Theorem

*Cornwall, Levin, Tiktopoulos (1974)*

In the high energy limit, we can replace $W_L^{\pm}$, $Z_L^0$ by $G^{\pm}$, $G^0$ .



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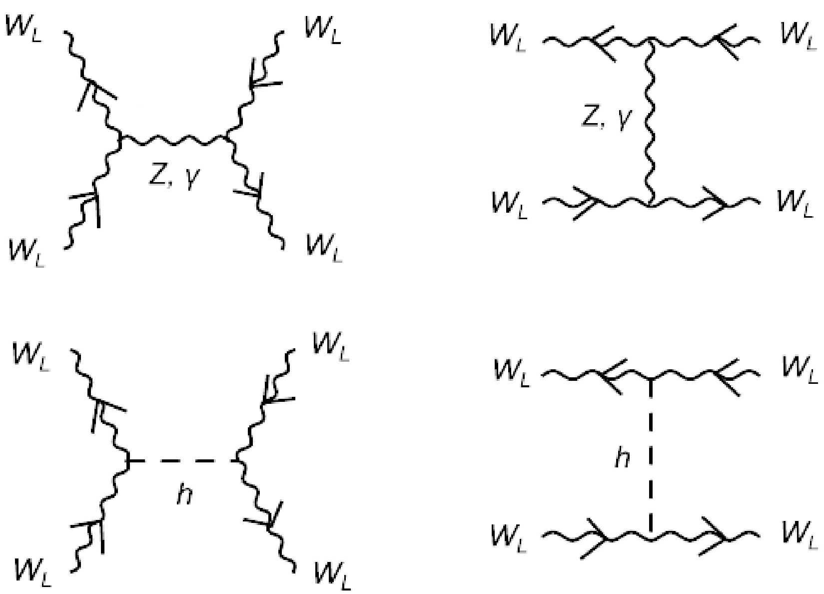
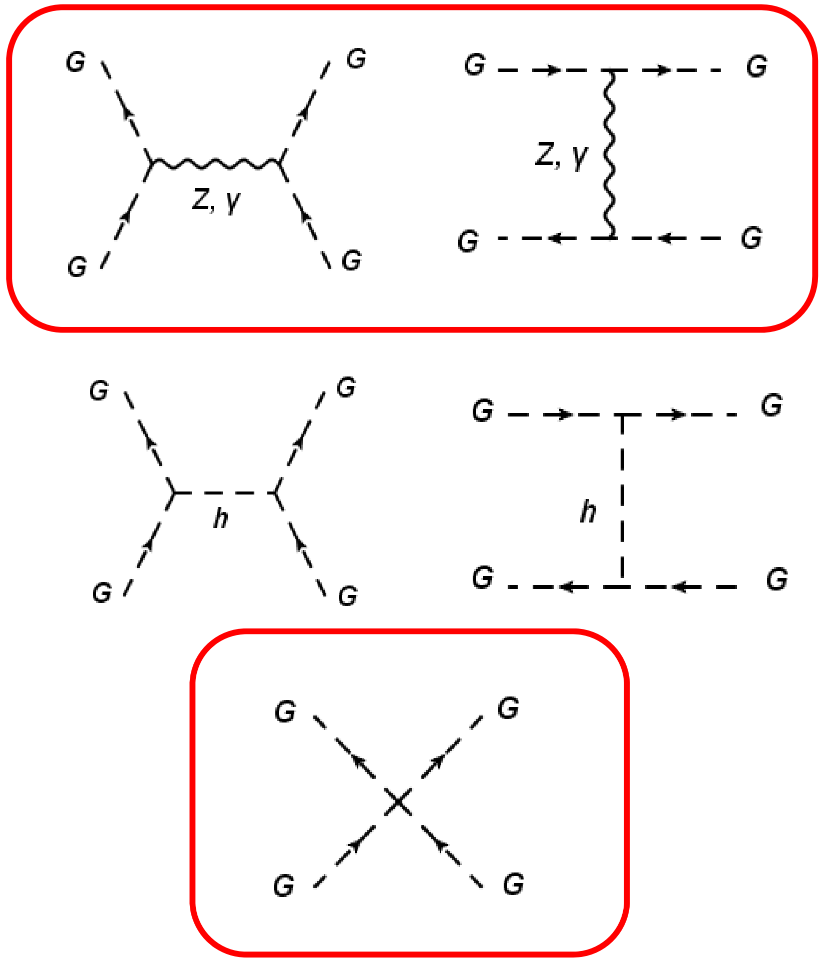



$O(g^2)$




$$\boxed{a_0 \xrightarrow[E\to\infty]{} \frac{\lambda}{4\pi}}$$

# Diagonalization of S-wave matrix

- There are the other neutral channels other than $W_L^+ W_L^-$, i.e., $Z_L Z_L$, hh and $Z_L h$.
- At a high-energy, all the scattering channels can be classified by **I, $I_3$** and **Y.**

*Ginzburg, Ivanov (2003)*

**$\Phi \otimes \Phi$ (Y=1)**

$$
\mathrm{I}=1 \quad \left\{ \begin{bmatrix} \phi^+\phi^+ & (\mathrm{I}_3=1) \\ \phi^+\phi^0 & (\mathrm{I}_3=0) \\ \phi^0\,\phi^0 & (\mathrm{I}_3=-1) \end{bmatrix} \right\} \quad a_0=\lambda/8\pi
$$

$\mathrm{I}=0$ Absent

**$\Phi \otimes \Phi^c$ (Y=0)**

$$
\left\{ \begin{bmatrix} \phi^+\phi^{0*} & (\mathrm{I}_3=1) \\ \dfrac{\phi^0\phi^{0*}-\phi^+\phi^-}{\sqrt{2}} & (\mathrm{I}_3=0) \\ \phi^0\phi^- & (\mathrm{I}_3=-1) \end{bmatrix} \right\} \quad a_0= \lambda/8\pi
$$

$$
\frac{\phi^+\phi^{0*}+\phi^+\phi^-}{\sqrt{2}} \qquad \mathbf{a_0= 3\lambda/8\pi}
$$

The stronger constraint : **mh < 712 GeV** is obtained by the diagonalization.

# Diagonalization in 2HDM

*Kanemura, Kubota, Takasugi (1993)*
*Akeroyd, Arhrib, Naimi (2170)*
*Ginzburg, Ivanov (2175)*
*Kanemura, KY(2015)*

- There are 14 neutral, 8 singly-charged and 3 doubly-charged channels.

$$\boxed{G^+G^-,\ \frac{G^0G^0}{\sqrt{2}},\ \frac{hh}{\sqrt{2}},\ hG^0,\ H^+H^-,\ \frac{AA}{\sqrt{2}},\ \frac{HH}{\sqrt{2}},\ HA,\ hH,\ G^0A,\ hA,\ HG^0,\ G^+H^-,\ H^+G^-}$$

$$\Rightarrow \quad a_0^0 = \begin{pmatrix} X_{4\times 4} & 0 & 0 & 0 \\ 0 & Y_{4\times 4} & 0 & 0 \\ 0 & 0 & Z_{3\times 3} & 0 \\ 0 & 0 & 0 & Z_{3\times 3} \end{pmatrix}$$

$$X_{4\times 4} = \begin{pmatrix} 3\lambda_1 & 2\lambda_3+\lambda_4 & 3\sqrt{2}\lambda_6^R & 3\sqrt{2}\lambda_6^I \\ 2\lambda_3+\lambda_4 & 3\lambda_2 & 3\sqrt{2}\lambda_7^R & 3\sqrt{2}\lambda_7^I \\ 3\sqrt{2}\lambda_6^R & 3\sqrt{2}\lambda_7^R & \lambda_3+2\lambda_4+3\lambda_5^R & 3\lambda_5^I \\ 3\sqrt{2}\lambda_6^I & 3\sqrt{2}\lambda_7^I & 3\lambda_5^I & \lambda_3+2\lambda_4-3\lambda_5^R \end{pmatrix}$$

# Diagonalization in 2HDM

Kanemura, Kubota, Takasugi (1993)
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$$G^+G^-,\ \frac{G^0G^0}{\sqrt{2}},\ \frac{hh}{\sqrt{2}},\ hG^0,\ H^+H^-,\ \frac{AA}{\sqrt{2}},\ \frac{HH}{\sqrt{2}},\ HA,\ hH,\ G^0A,\ hA,\ HG^0,\ G^+H^-,\ H^+G^-$$

(Y, I, I$_3$) = (0,0,0)

(0,1,0)

$$a_0^0 = \begin{pmatrix} \boxed{X_{4\times4}} & 0 & 0 & 0 \\ 0 & \boxed{Y_{4\times4}} & 0 & 0 \\ 0 & 0 & Z_{3\times3} & 0 \\ 0 & 0 & 0 & Z_{3\times3} \end{pmatrix}$$

$$\frac{\phi_i^0\phi_j^{0*} + \phi_k^+\phi_\ell^-}{\sqrt{2}}$$ (i,j,k,l) = (1,2)

(1,1,-1)

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# Diagonalization in 2HDM+CPC

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**(Y, I, $I_3$) = (0,0,0)**

**(0,1,0)**

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$$X_{4\times4} = \begin{pmatrix} 3\lambda_1 & 2\lambda_3+\lambda_4 & 3\sqrt{2}\lambda_6^R & 0 \\ 2\lambda_3+\lambda_4 & 3\lambda_2 & 3\sqrt{2}\lambda_7^R & 0 \\ 3\sqrt{2}\lambda_6^R & 3\sqrt{2}\lambda_7^R & \lambda_3+2\lambda_4+3\lambda_5^R & 0 \\ 0 & 0 & 0 & \lambda_3+2\lambda_4-3\lambda_5^R \end{pmatrix}$$

# Diagonalization in 2HDM+CPC+$Z_2$

- There are 14 neutral, 8 singly-charged and 3 doubly-charged channels.

$$G^+G^-,\ \frac{G^0G^0}{\sqrt{2}},\ \frac{hh}{\sqrt{2}},\ hG^0,\ H^+H^-,\ \frac{AA}{\sqrt{2}},\ \frac{HH}{\sqrt{2}},\ HA,\ hH,\ G^0A,\ hA,\ HG^0,\ G^+H^-,\ H^+G^-$$

**(Y, I, $I_3$) = (0,0,0)**

**(0,1,0)**

$$a_0^0 = \begin{pmatrix} \boxed{X_{4\times4}} & 0 & 0 & 0 \\ 0 & \boxed{Y_{4\times4}} & 0 & 0 \\ 0 & 0 & Z_{3\times3} & 0 \\ 0 & 0 & 0 & Z_{3\times3} \end{pmatrix}$$

$$\frac{\phi_i^0\phi_j^{0*} + \phi_k^+\phi_\ell^-}{\sqrt{2}}$$ (i,j,k,l) = (1,2)

**(1,1,-1)**

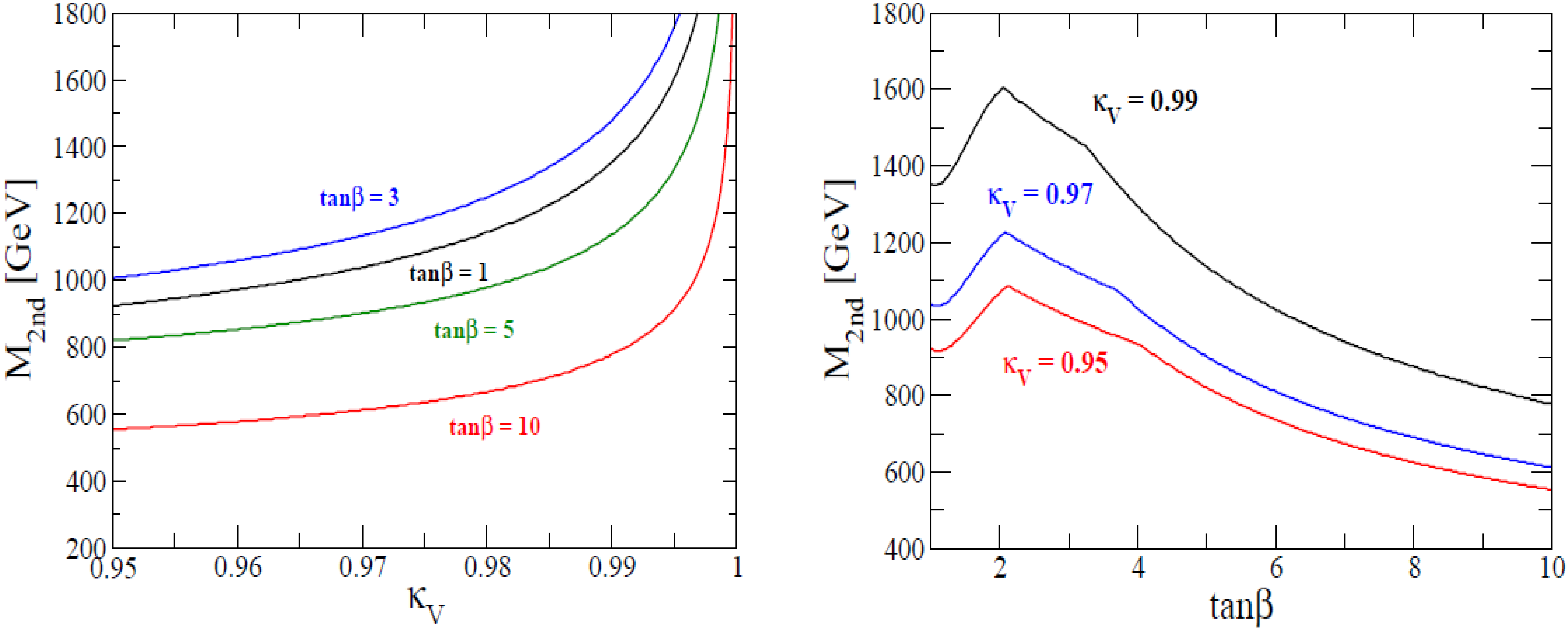
$$X_{4\times4} = \begin{pmatrix} 3\lambda_1 & 2\lambda_3+\lambda_4 & 0 & 0 \\ 2\lambda_3+\lambda_4 & 3\lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3+2\lambda_4+3\lambda_5^R & 0 \\ 0 & 0 & 0 & \lambda_3+2\lambda_4-3\lambda_5^R \end{pmatrix}$$

# $Z_2$ symmetric and CPC case

$M^2$: scanned

$\kappa_V \coloneqq g_{hVV}/g_{hVV}(SM) = \sin(\beta-\alpha)$

$M_{2nd} \coloneqq m_{H+} (= m_A = m_H)$




- We obtain the upper limit on $M_{2nd}$ as long as $\kappa_V \neq 1$.
- The bound tends to be stronger for larger $1-\kappa_V$ and tanβ (>2).

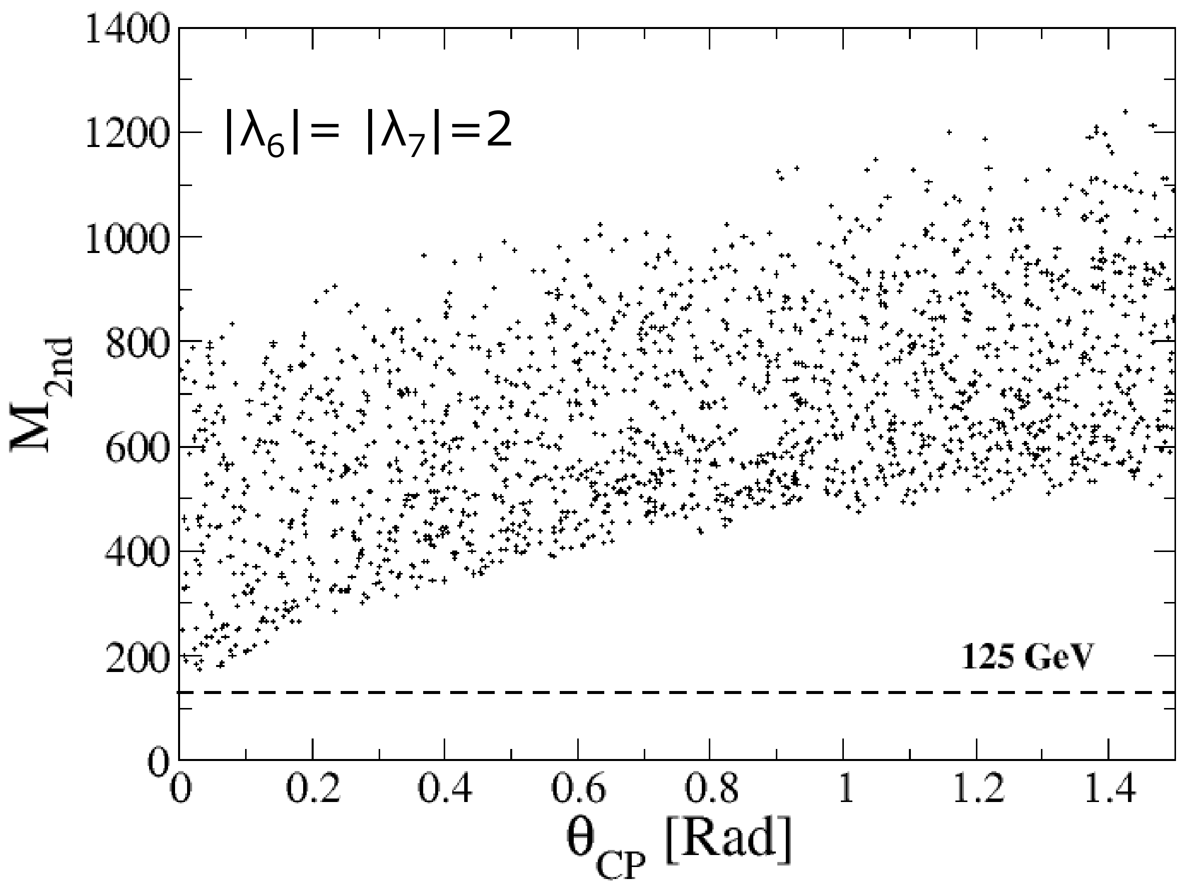
*Kanemura, KY, PLB751 (2015)*

# General case

$M(= m_{H+} = \tilde{m}_A = \tilde{m}_H)$, $\sin(\beta-\tilde{\alpha})$ scanned

$\theta_{CP} \coloneqq \theta_5 \ (= \theta_6 = \theta_7)$

$M_{2nd} \coloneqq \mathrm{Min}(m_{H+}, m_{H2}, m_{H3})$




**$0.97 < \kappa_V < 0.99$**

- The lower limit also appears in the CPV case.

Kanemura, KY, PLB751 (2015)

# General case

$M(= m_{H+} = \tilde{m}_A = \tilde{m}_H)$, $\sin(\beta-\tilde{\alpha})$ scanned

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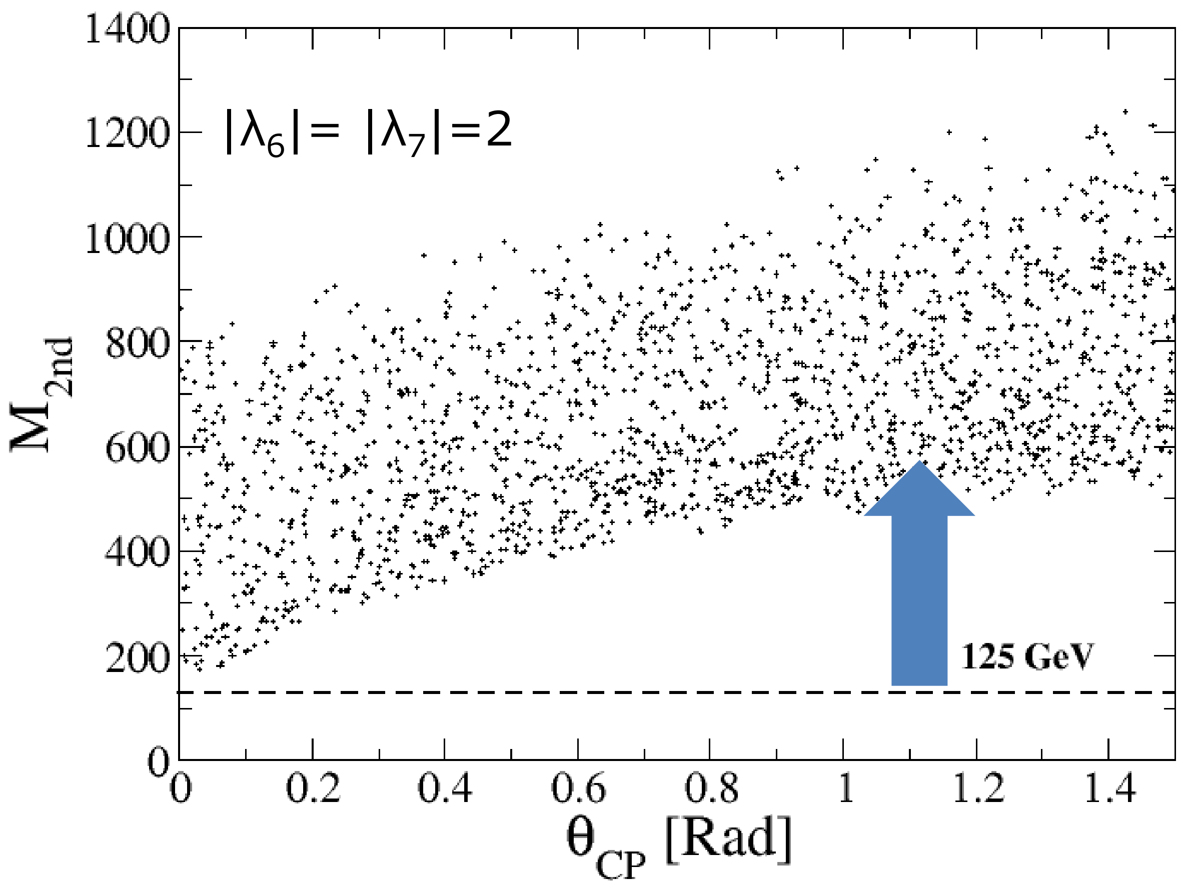
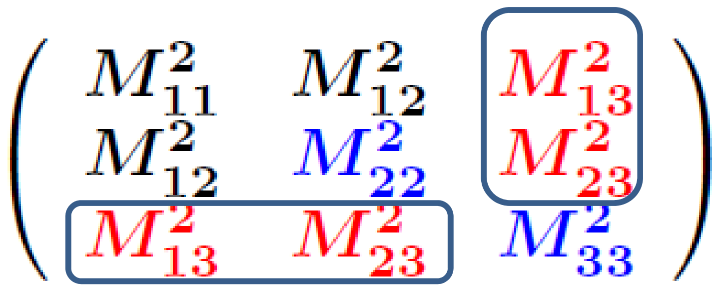



**0.97 < $\kappa_V$ < 0.99**




- The lower limit also appears in the CPV case.

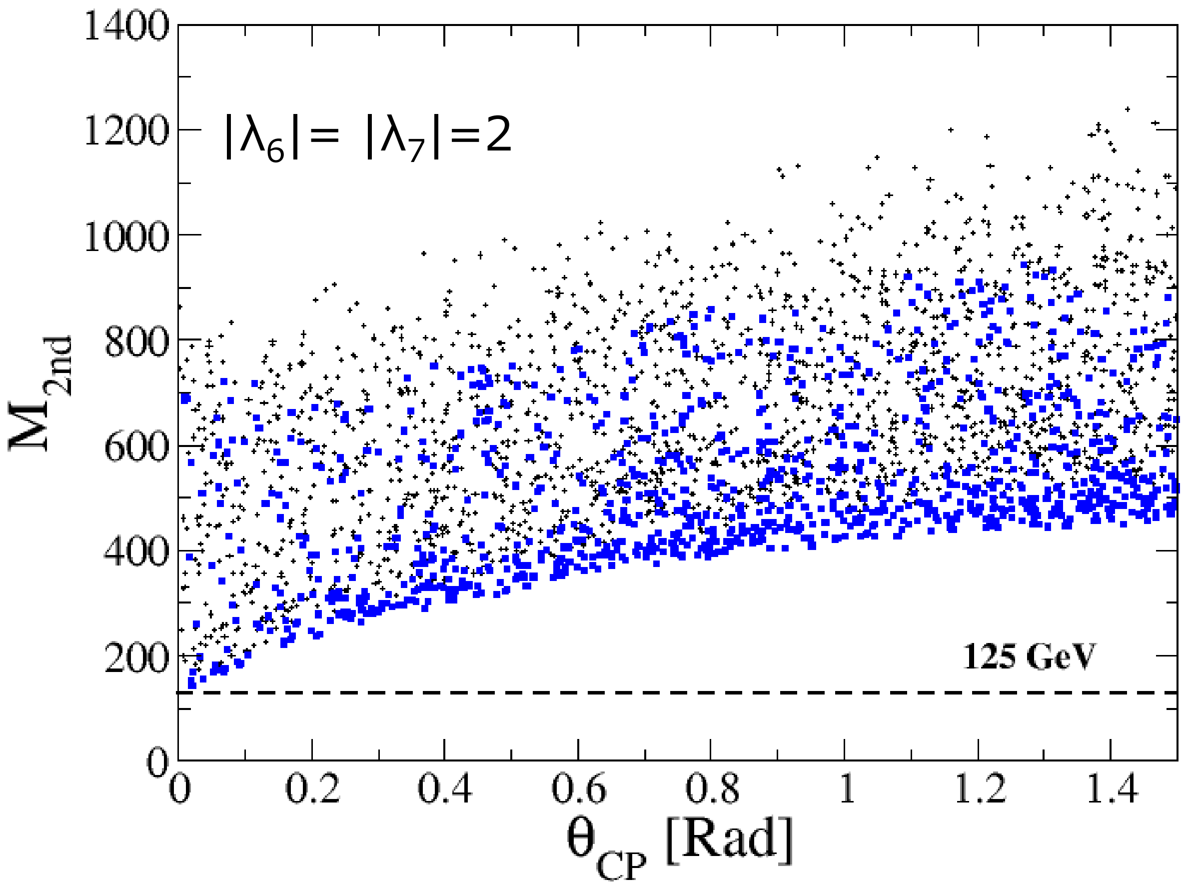
*Kanemura, KY, PLB751 (2015)*

# General case

$M(= m_{H+} = \tilde{m}_A = \tilde{m}_H)$, $\sin(\beta\text{-}\tilde{\alpha})$ scanned

$\theta_{CP} \coloneqq \theta_5 \ (= \theta_6 = \theta_7)$

$M_{2nd} \coloneqq \mathrm{Min}(m_{H+}, m_{H2}, m_{H3})$




**$0.97 < \kappa_V < 0.99$**

**$0.95 < \kappa_V < 0.97$**

- ☐ The lower limit also appears in the CPV case.

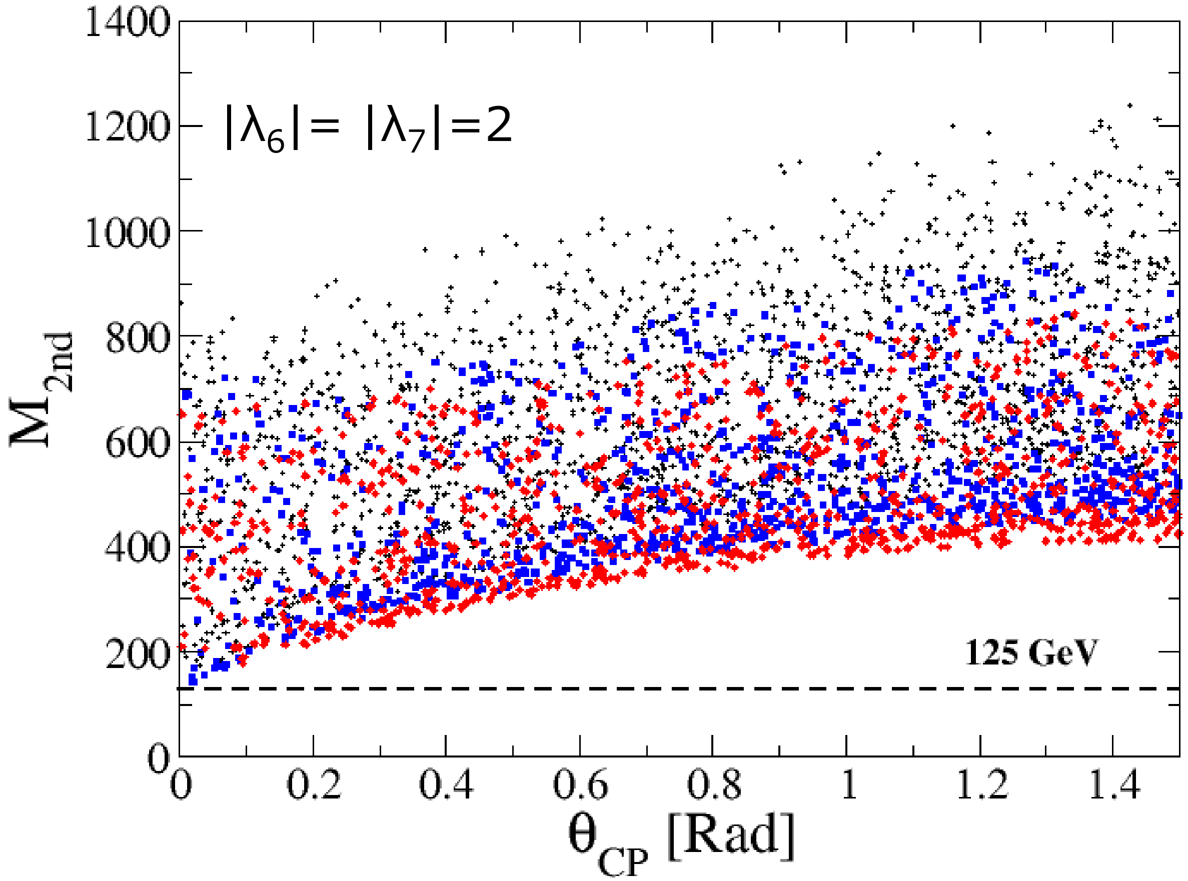
# General case

Kanemura, KY, PLB751 (2015)

$M (= m_{H+} = \tilde{m}_A = \tilde{m}_H)$, $\sin(\beta-\tilde{\alpha})$ scanned

$\theta_{CP} \coloneqq \theta_5 \; (= \theta_6 \; = \theta_7)$

$M_{2nd} \coloneqq \mathrm{Min}(m_{H+}, m_{H2}, m_{H3})$




**$0.97 < \kappa_V < 0.99$**

**$0.95 < \kappa_V < 0.97$**

**$0.93 < \kappa_V < 0.95$**

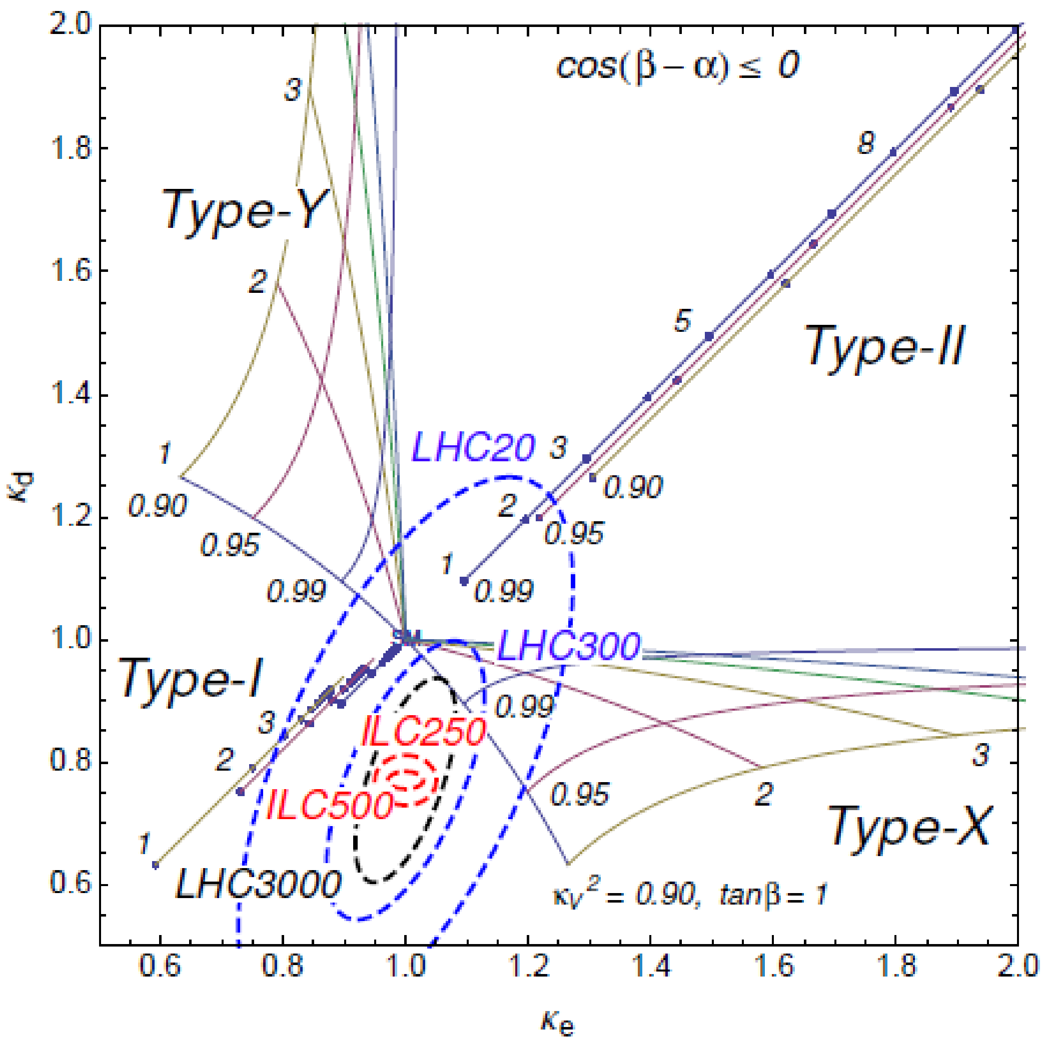
- ☐ The lower limit also appears in the CPV case.
- ☐ A larger deviation gives a stronger upper limit.

See M. Kikuchi's talk about rad. corrections

# Fingerprinting the Higgs sectors

Kanemura, Tsumura, KY, Yokoya, PRD90 (2014)

$Z_2$ symmetric and CPC case



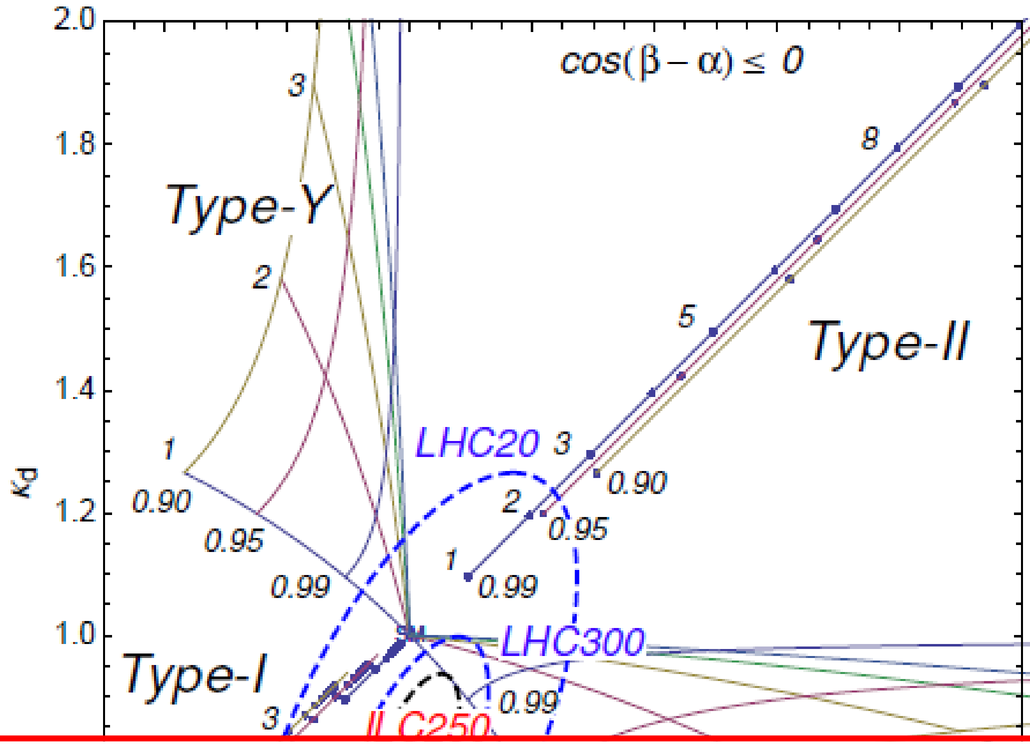

| | $\xi_d$ | $\xi_e$ |
|---|---|---|
| Type-I | cotβ | cotβ |
| Type-II | -tanβ | -tanβ |
| Type-X | cotβ | -tanβ |
| Type-Y | -tanβ | cotβ |

$$\kappa_f = \sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha)$$

# Fingerprinting the Higgs sectors

*Kanemura, Tsumura, KY, Yokoya, PRD90 (2014)*

$Z_2$ symmetric and CPC case




| | $\xi_d$ | $\xi_e$ |
|---|---|---|
| Type-I | cotβ | cotβ |
| Type-II | -tanβ | -tanβ |
| Type-X | cotβ | -tanβ |
| Type-Y | -tanβ | cotβ |

$$\kappa_f = \sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha)$$

The structure of the Higgs sector can be determined from the measurements of hVV and hff couplings!

# Summary

**Non-zero deviation in the hVV coupling gives us**

1. the upper limit on the mass of the 2$^{nd}$ Higgs bosons (or a NP scale)

   from **perturbative unitarity**

2. possibility of **fingerprinting** of the Higgs sector

   Four types of Yukawa interactions in the 2HDM (related to the NP scenarios)

   can be separated by looking at the pattern of deviations in hff couplings.

**Precise measurements of the Higgs boson couplings**

**provide us the great hint of New Physics scenarios!**

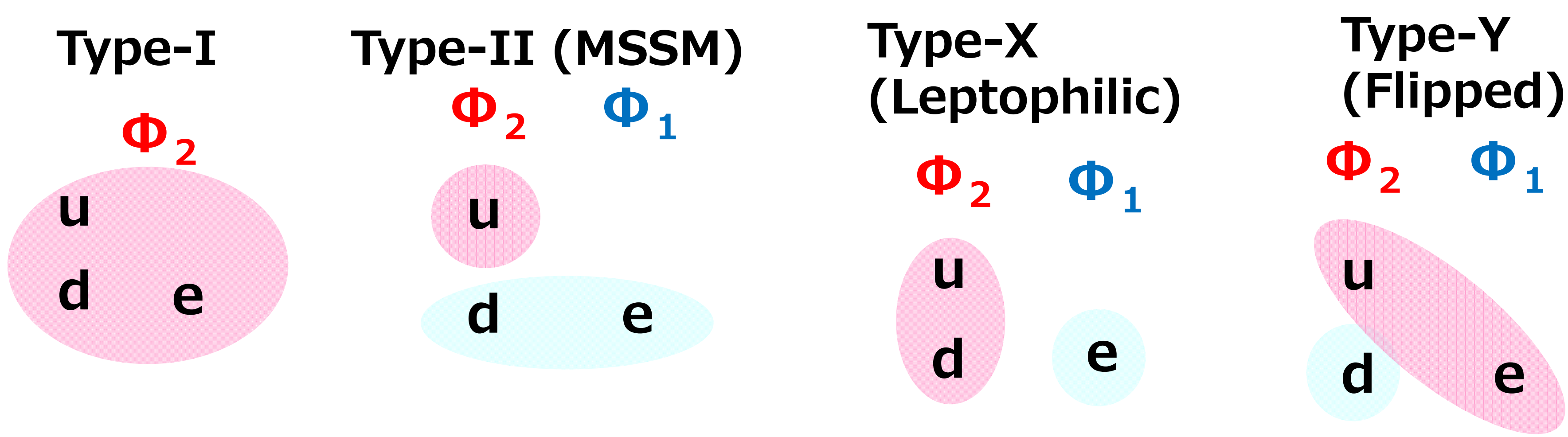
# Yukawa Interactions

Under the $Z_2$ symmetry, the Yukawa interactions are given by

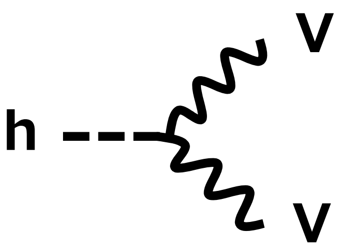
$$\mathcal{L}_Y = -Y_u \bar{Q}_L \Phi_u^c u_R - Y_d \bar{Q}_L \Phi_d d_R - Y_e \bar{L}_L \Phi_e e_R$$

Four independent types are allowed as follows

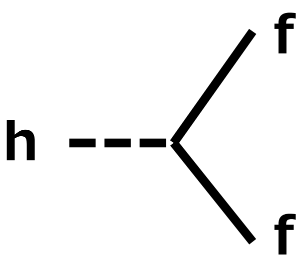
*Barger, Hewett, Phillips, PRD41 (1990); Grossman, NPB426 (1994).*



# Higgs Boson Couplings (CPC+$Z_2$ case)




$$= (\mathrm{SM}) \times \sin(\beta-\alpha)$$




$$= (\mathrm{SM}) \times [\sin(\beta-\alpha)+\xi_f \cos(\beta-\alpha)]$$

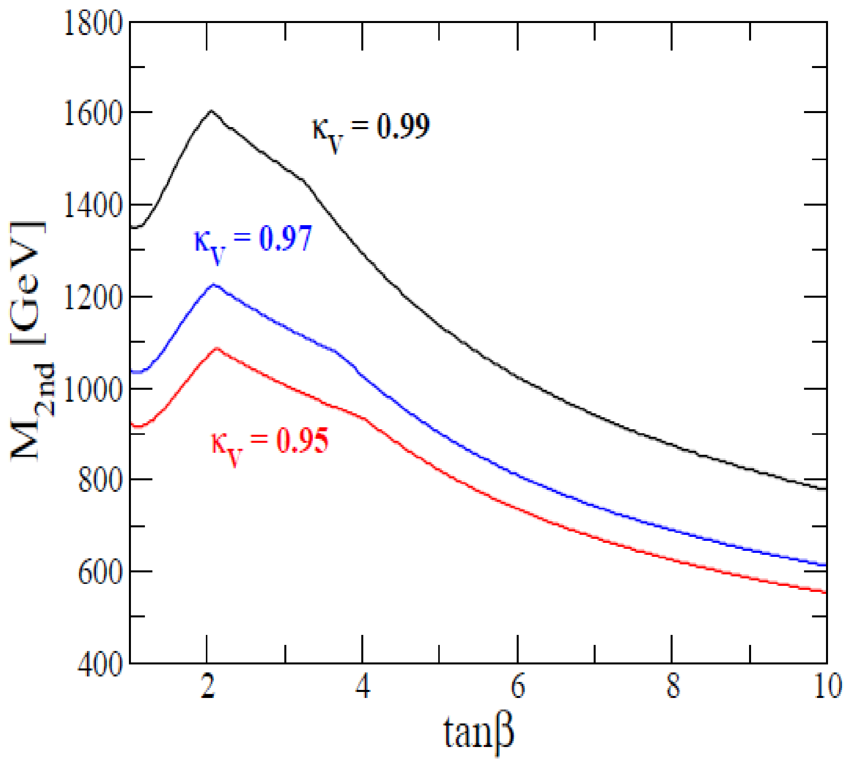
| | $\xi_u$ | $\xi_d$ | $\xi_e$ |
|---|---|---|---|
| Type-I | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ |
| Type-II | $\cot\beta$ | $-\tan\beta$ | $-\tan\beta$ |
| Type-X | $\cot\beta$ | $\cot\beta$ | $-\tan\beta$ |
| Type-Y | $\cot\beta$ | $-\tan\beta$ | $\cot\beta$ |

When $\sin(\beta-\alpha) \neq 1$, both hVV and hff couplings deviate from the SM predictions.

# Tanβ dependence

$$a^0_{1,\pm} = \frac{1}{32\pi}\left[3(\lambda_1+\lambda_2) \pm \sqrt{9(\lambda_1-\lambda_2)^2 + 4(2\lambda_3+\lambda_4)^2}\right]$$

Under sin(β-α) ~ 1 and $M_{2nd} \gg m_h$




$$\lambda_1 v^2 \simeq (M^2_{\rm 2nd} s^2_{\beta-\alpha} - M^2)\tan^2\beta + 2M^2_{\rm 2nd} s_{\beta-\alpha}c_{\beta-\alpha}\tan\beta$$

$$\lambda_2 v^2 \simeq (M^2_{\rm 2nd} s^2_{\beta-\alpha} - M^2)\cot^2\beta - 2M^2_{\rm 2nd} s_{\beta-\alpha}c_{\beta-\alpha}\cot\beta$$

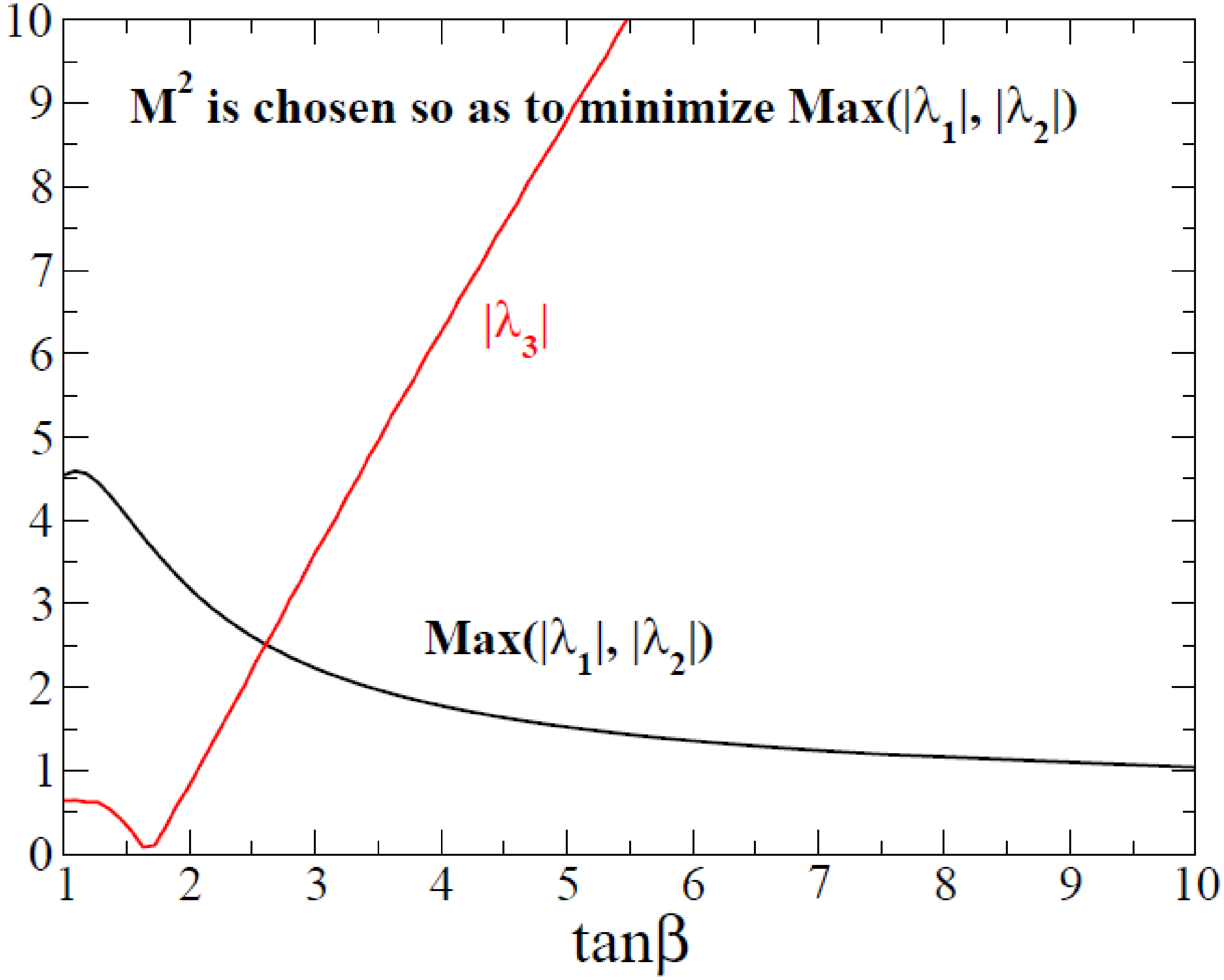
$$\lambda_3 v^2 \simeq M^2_{\rm 2nd}[(\tan\beta - \cot\beta)s_{\beta-\alpha}c_{\beta-\alpha} + 1] - M^2$$

$$\lambda_4 v^2 = \underline{M^2 - M^2_{\rm 2nd}}$$

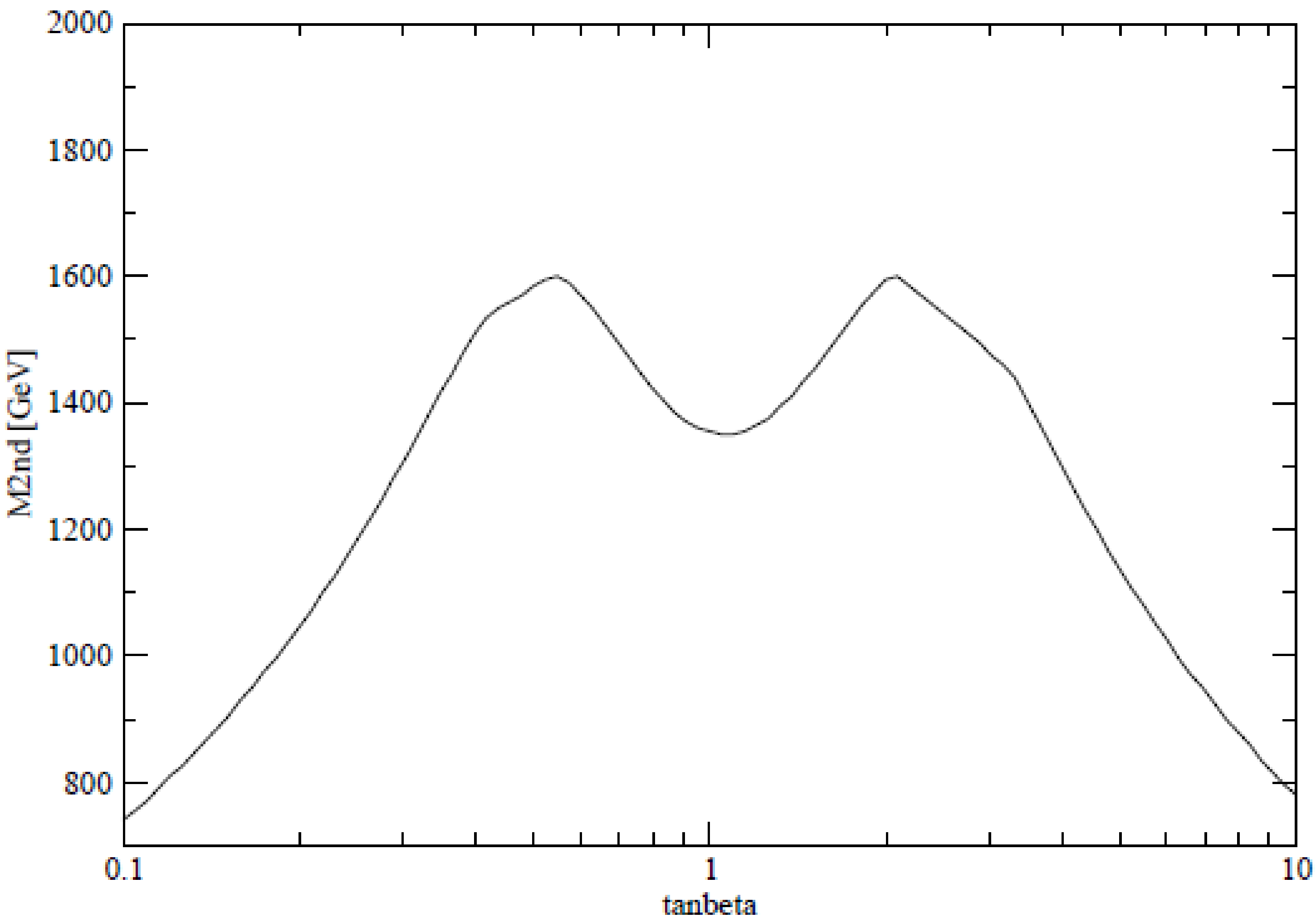
At a fixed value of M ($\simeq M_{2nd}$) to minimize Max($\lambda_1$, $\lambda_2$),
A value of λ3 and Max($\lambda_1$, $\lambda_2$) is increase (decrease) as tanβ becomes larger, and at tanβ ~ 2, these two values are crossed.

# Tanβ dependence

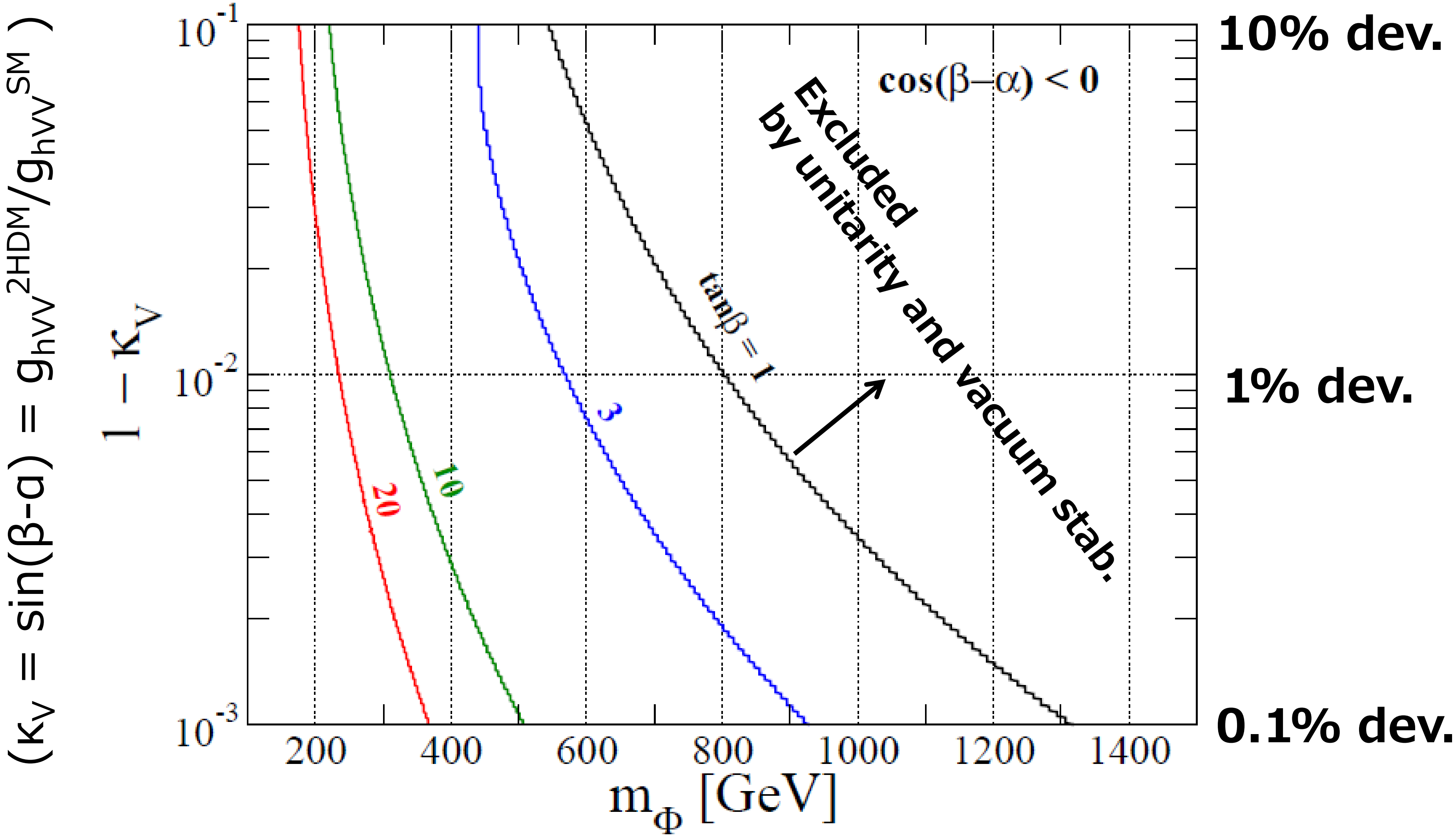
$\sin(\beta\text{-}\alpha) = 0.99$, $M_{2nd} = 1170$ GeV



# Tanβ dependence

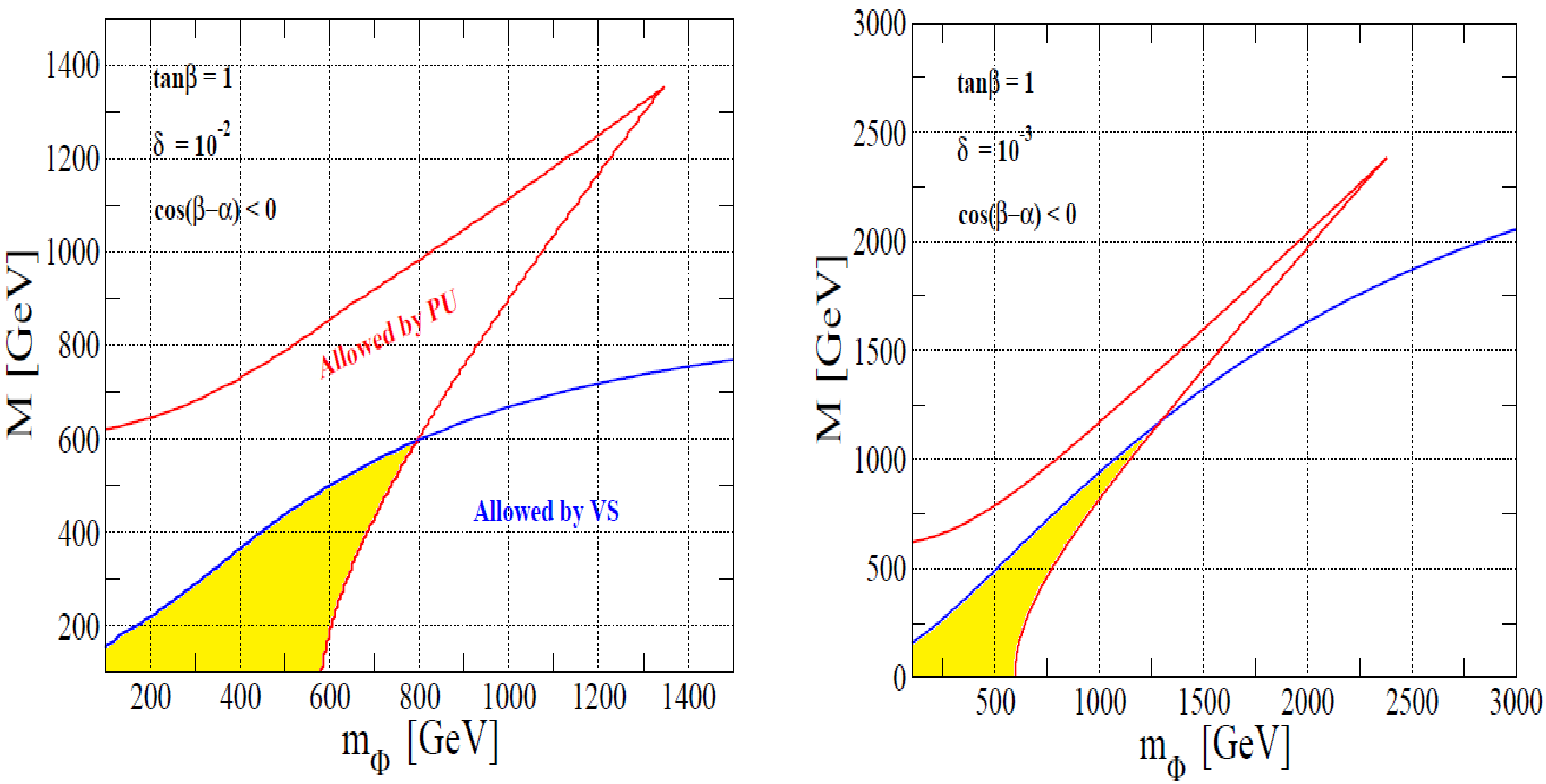


# Upper lim. of the 2nd Higgs mass




$(m_\Phi = m_{H+} = m_A = m_H)$

# Unitarity & Vacuum stability bounds



# h Coupling Measurements (Current)

- Scaling factors: $\kappa_X = g_{hXX}^{exp}/g_{hXX}^{SM}$

*Heinemeyer, Mariotti, Passarino, Tanaka, arXiv:1307.1347 [hep-ph]*

- 2 parameter fit ($\kappa_V = \kappa_Z = \kappa_W,\ \kappa_F = \kappa_t = \kappa_b = \kappa_\tau$)

*ATLAS Collaboration, ATLAS-CONF-2014-179*

$$\boxed{\kappa_V = 1.15 \pm 0.08, \quad \kappa_F = 0.99^{+0.08}_{-0.15}, \quad \text{ATLAS}}$$

*CMS Collaboration, arXiv: 1412.8662 [hep-ex]*

$$\boxed{\kappa_V = 1.01 \pm 0.07, \quad \kappa_F = 0.87^{+0.14}_{-0.13}, \quad \text{CMS}}$$

# h Coupling Measurements (Future)

*Snowmass Higgs Working Group Report, arXiv: 1310.8361 [hep-ex]*

| Facility | LHC | HL-LHC | ILC500 | ILC500-up | ILC1000 | ILC1000-up |
|---|---|---|---|---|---|---|
| $\sqrt{s}$ (GeV) | 14,000 | 14,000 | 250/500 | 250/500 | 250/500/1000 | 250/500/1000 |
| $\int \mathcal{L}dt$ ($\mathrm{fb}^{-1}$) | 300/expt | 3000/expt | 250+500 | 1150+1600 | 250+500+1000 | 1150+1600+2500 |
| $\kappa_\gamma$ | $5-7\%$ | $2-5\%$ | 8.3% | 4.4% | 3.8% | 2.3% |
| $\kappa_g$ | $6-8\%$ | $3-5\%$ | 2.0% | 1.1% | 1.1% | 0.67% |
| $\kappa_W$ | $4-6\%$ | $2-5\%$ | 0.39% | 0.21% | 0.21% | 0.2% |
| $\kappa_Z$ | $4-6\%$ | $2-4\%$ | 0.49% | 0.24% | 0.50% | 0.3% |
| $\kappa_\ell$ | $6-8\%$ | $2-5\%$ | 1.9% | 0.98% | 1.3% | 0.72% |
| $\kappa_d = \kappa_b$ | $10-13\%$ | $4-7\%$ | 0.93% | 0.60% | 0.51% | 0.4% |
| $\kappa_u = \kappa_t$ | $14-15\%$ | $7-10\%$ | 2.5% | 1.3% | 1.3% | 0.9% |

The Higgs boson couplings can be measured with the accuracy of **a few% at HL-LHC** and **O(1)% or better than 1% at ILC517** !

# Eigenvalues of S-wave matrix w/ $Z_2$

*Kanemura, Kubota, Takasugi (1993)* *[Diagonalized all the neutral channels]*
*Akeroyd, Arhrib, Naimi (2170)* *[Diagonalized all the singly-charged channels]*
*Ginzburg, Ivanov (2173)* *[Extended to the CPV 2HDM]*
*Kanemura, KY(2015)* *[Extended to the most general 2HDM]*

$$a^0_{1,\pm} = \frac{1}{32\pi}\left[3(\lambda_1+\lambda_2) \pm \sqrt{9(\lambda_1-\lambda_2)^2+4(2\lambda_3+\lambda_4)^2}\right],$$

$$a^0_{2,\pm} = \frac{1}{32\pi}\left[(\lambda_1+\lambda_2) \pm \sqrt{(\lambda_1-\lambda_2)^2+4\lambda_4^2}\right],$$

$$a^0_{3,\pm} = \frac{1}{32\pi}\left[(\lambda_1+\lambda_2) \pm \sqrt{(\lambda_1-\lambda_2)^2+4\lambda_5^2}\right],$$

$$a^0_{4,\pm} = \frac{1}{16\pi}(\lambda_3+2\lambda_4 \pm 3\lambda_5),$$

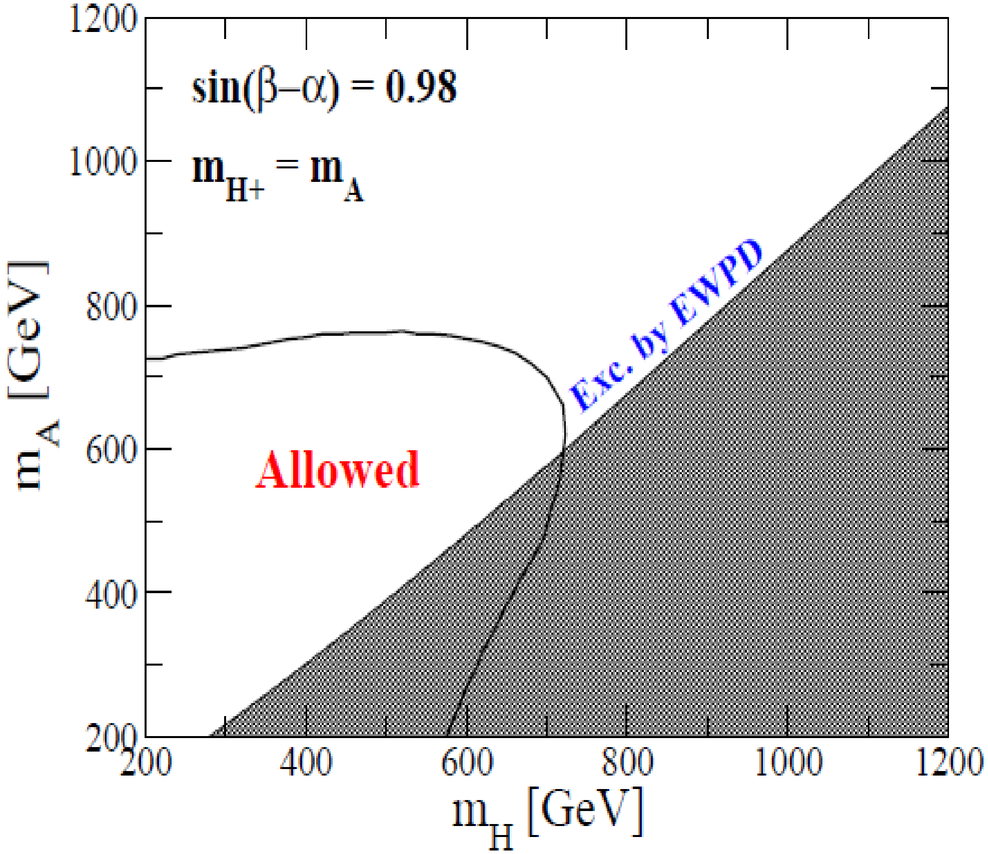
$$a^0_{5,\pm} = \frac{1}{16\pi}(\lambda_3 \pm \lambda_4),$$

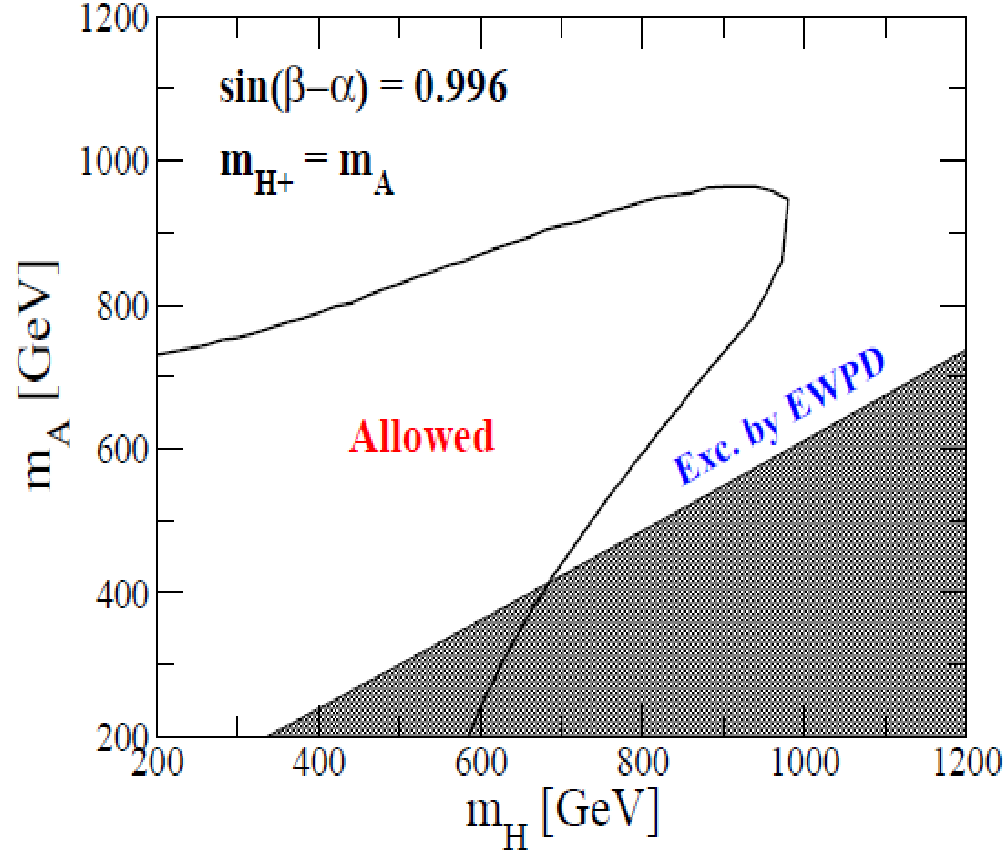
$$a^0_{6,\pm} = \frac{1}{16\pi}(\lambda_3 \pm \lambda_5).$$

- All the $\lambda$ couplings are translated into the physical parameters, so that the unitarity bound gives bound on masses of Higgs bosons and mixing angles.

# Constraint on the $m_A$ vs $m_H$ plane

*Moretti, KY, PRD91 (2015)*




- Bound on mH and mA is correlated .
- Stronger constraint is obtained in the case with larger 1-sin(β-α).