What is the mass scale of the 2nd Higgs boson?

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Based on

S. Kanemura, K. Tsumura, KY, H. Yokoya, PRD90, 075001 (2014)

S. Moretti, and KY, PRD91, 055022 (2015)

29th, April, 2015

University College of London

LHC Run-I Tells Us

1. There exits one CP-even scalar boson

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

2. Its mass is about 125 GeV.

   → **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 **structure** of the Higgs sector?
  - the number of multiplets, representations, symmetries, ⋯

- What is the **relation** to the BSM phenomena?
  - Neutrino mass, dark matter, baryon number asymmetry, ⋯

Property of the Higgs sector can strongly depends on new physics scenarios.

→ Higgs is a probe of New Physics!!

Higgs as a Probe of New Physics

New Physics Beyond the SM

B-L models

Rad. ν-mass models

MSSM

CPV

Type-II seesaw

LR sym. models

Singlets

Doublets

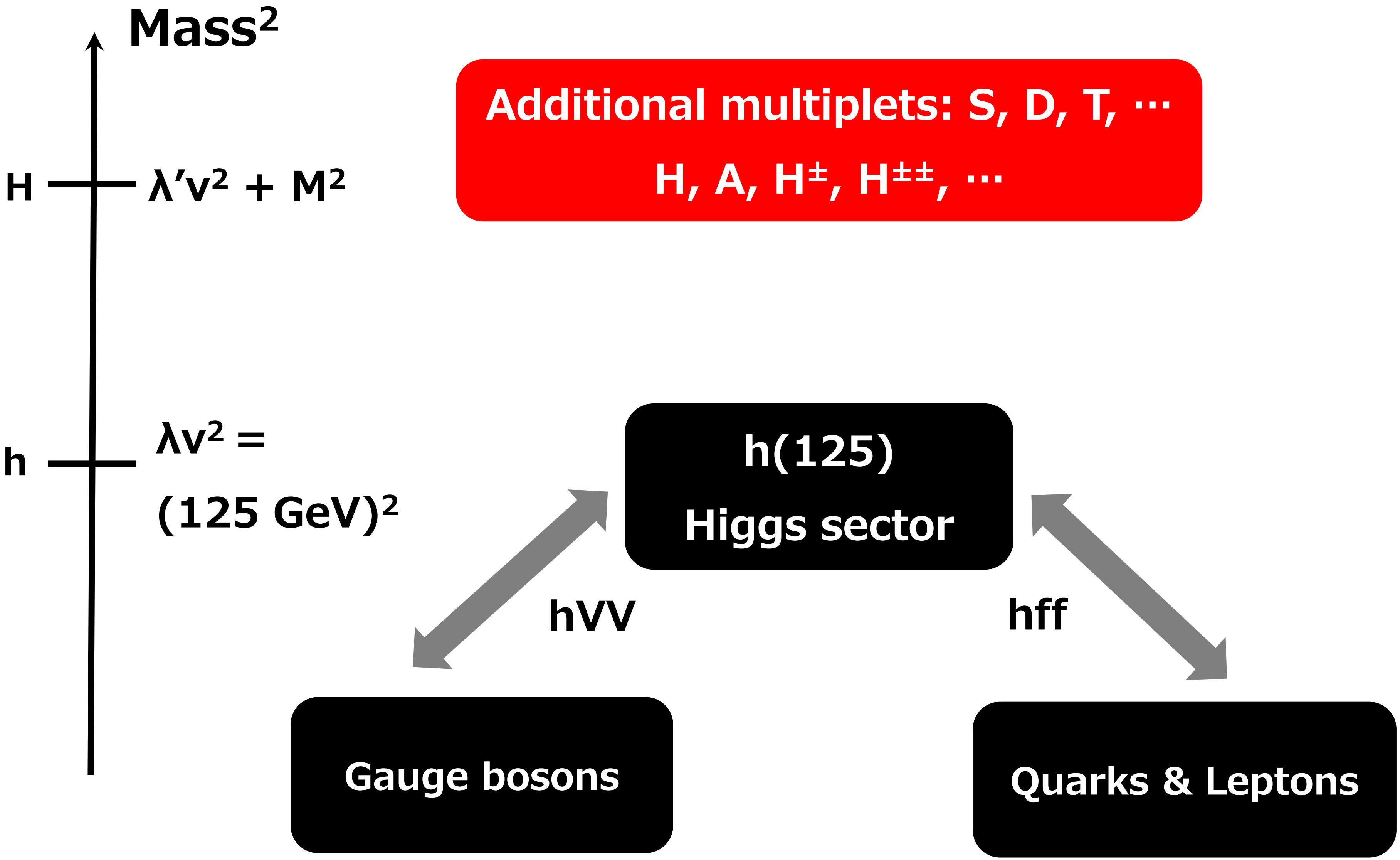
Triplets

+ Doublet ∋ h(125)

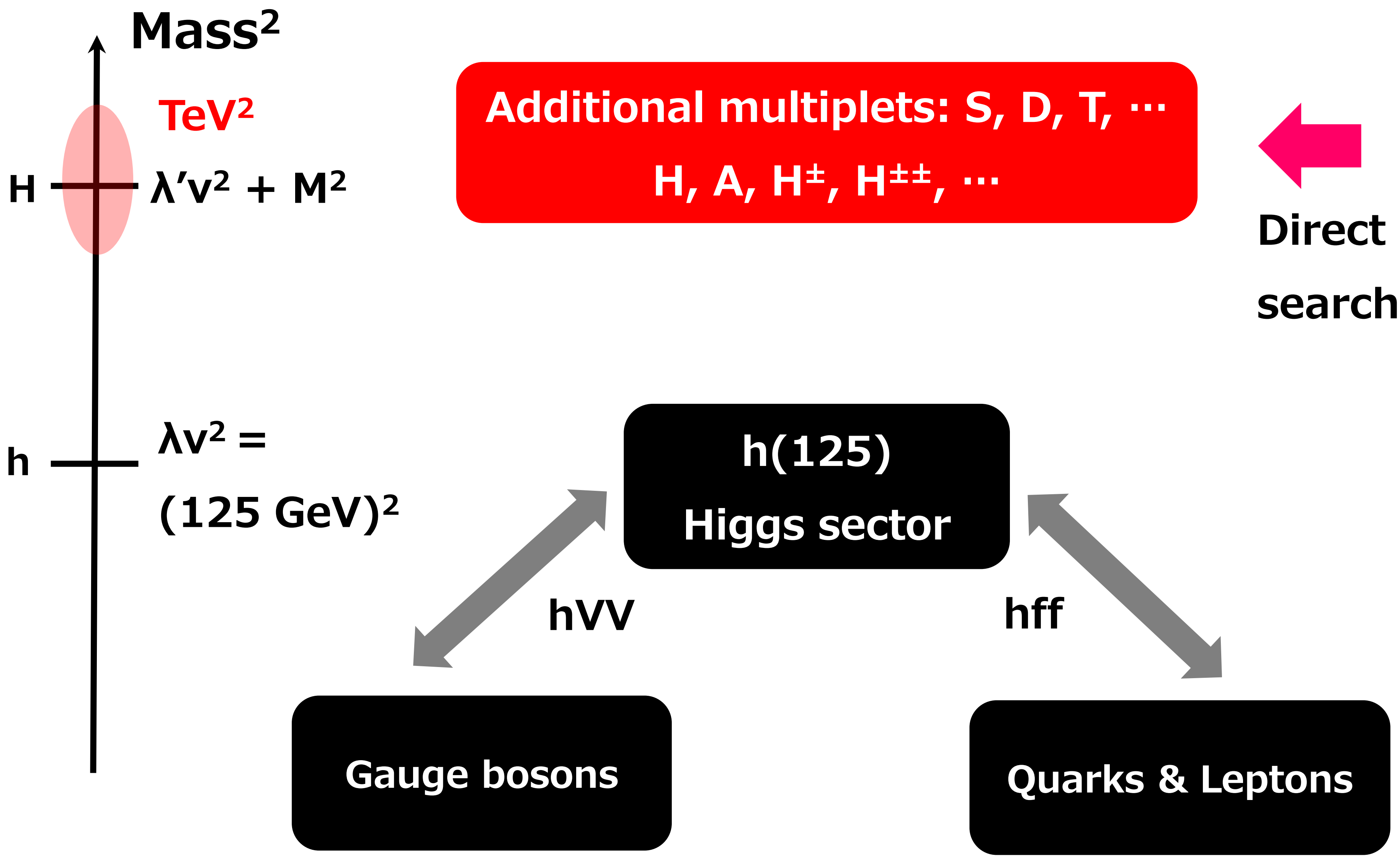
Non-minimal Higgs sectors

Bottom Up Approach!!

How can We Determine?



How can We Determine?



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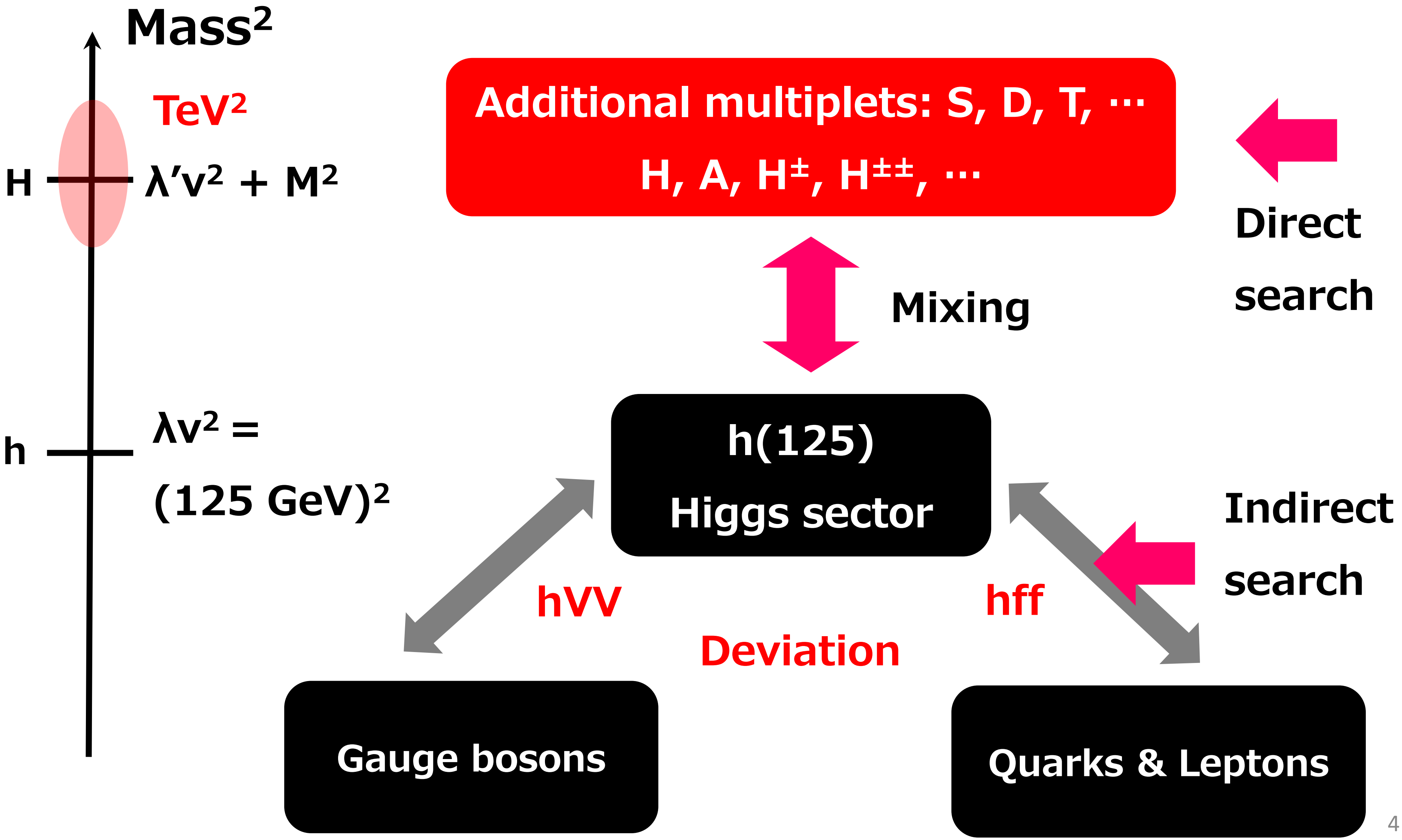
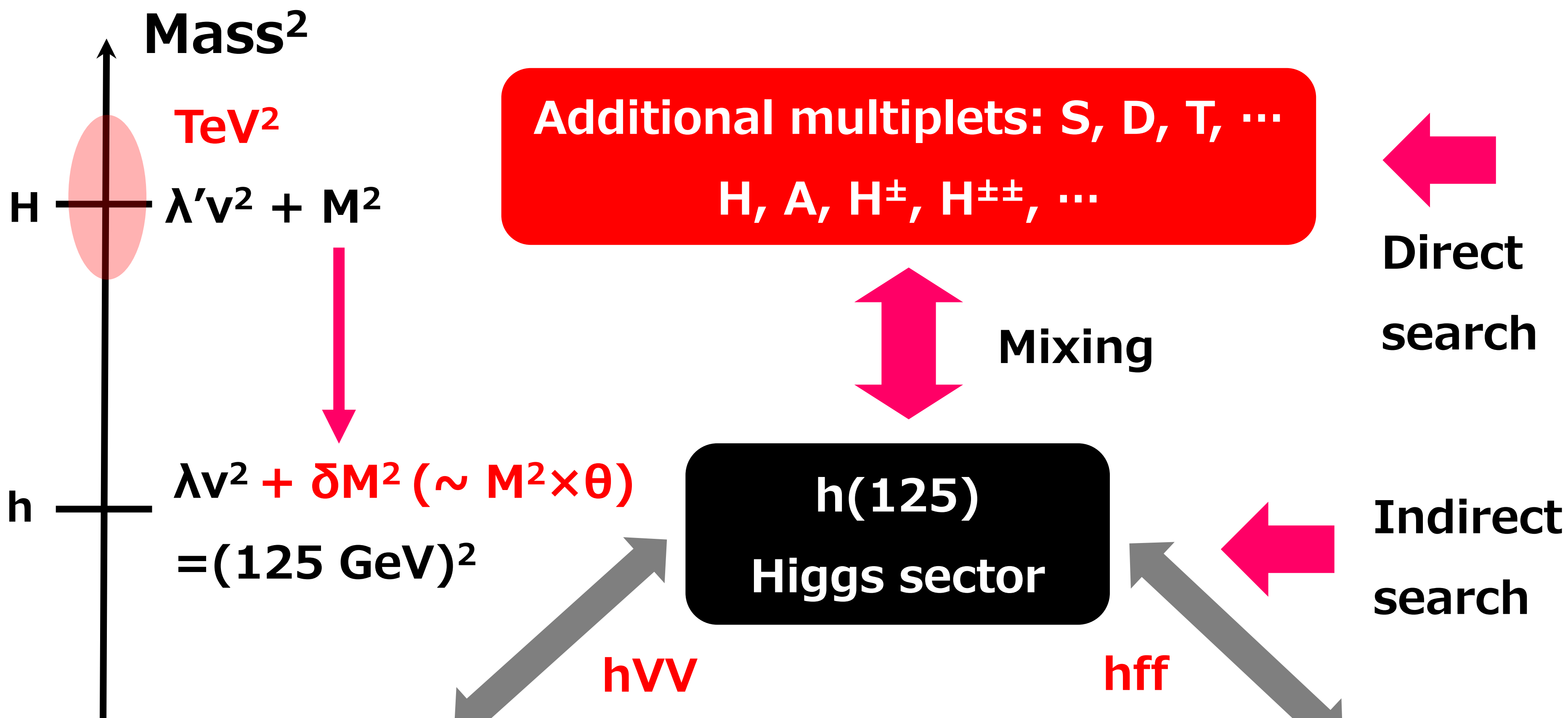


How can We Determine?



- 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 2nd Higgs mass!

In this talk, I discuss S-matrix unitarity to give the upper bound.

Contents

- Introduction
  - Relationship between Higgs coupling deviations & Higgs mass bound
- S matrix Unitarity and its application to Higgs mass bounds
  - SM, 2HDM, 3HDM
- Deviations in the SM-like Higgs boson couplings
- Summary

S matrix Unitarity

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

$$\Rightarrow \quad \sigma_{\rm tot} = \frac{1}{s}\,{\rm Im}\,\mathcal{M}(\theta = 0)$$

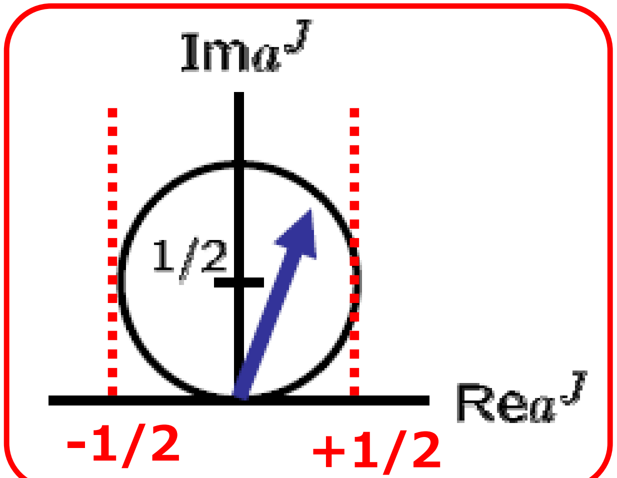
Using the partial wave expansion:

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

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→2 elastic scatterings.

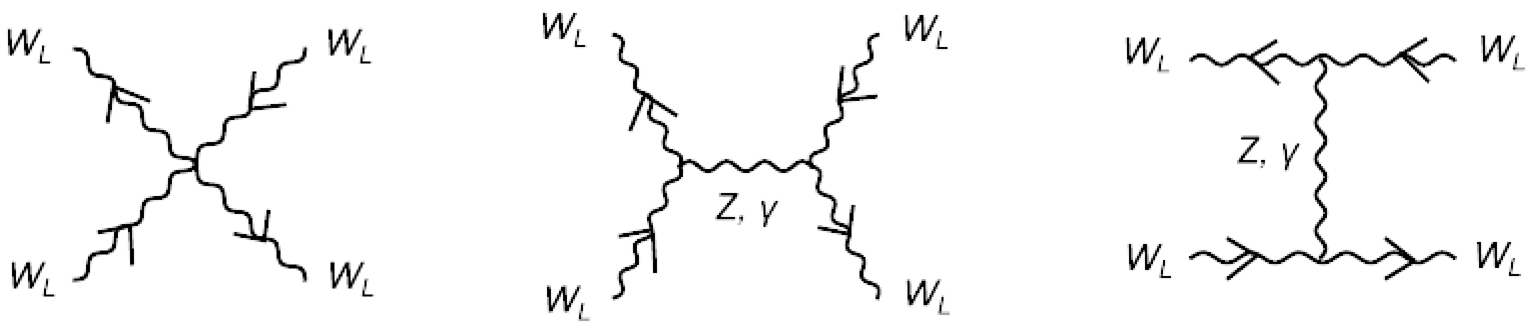


$$|\mathrm{Re}(a_J^{2\to 2})| < 1/2$$

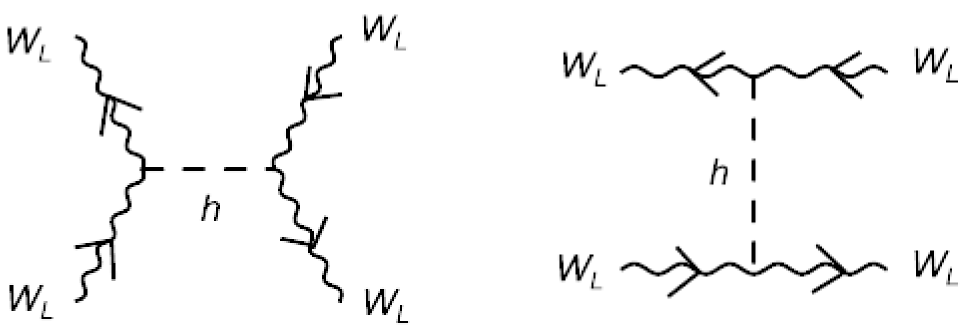
at the tree level.

$W_L^+W_L^- \to W_L^+W_L^-$ scattering in SM

Lee, Quigg, Thacker (1977)



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



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

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

$+ O(g^2)$

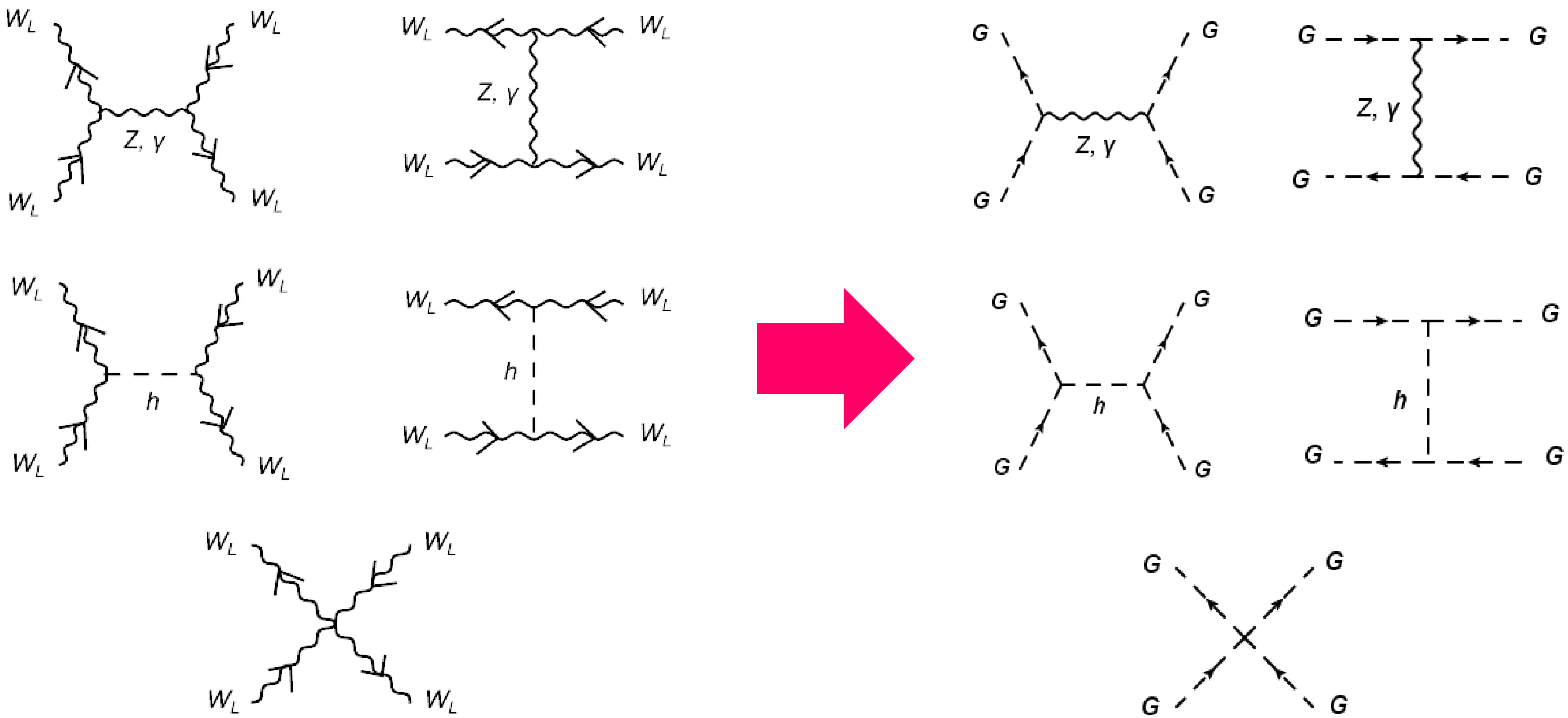
From $|a_0| < 1/2$, we get

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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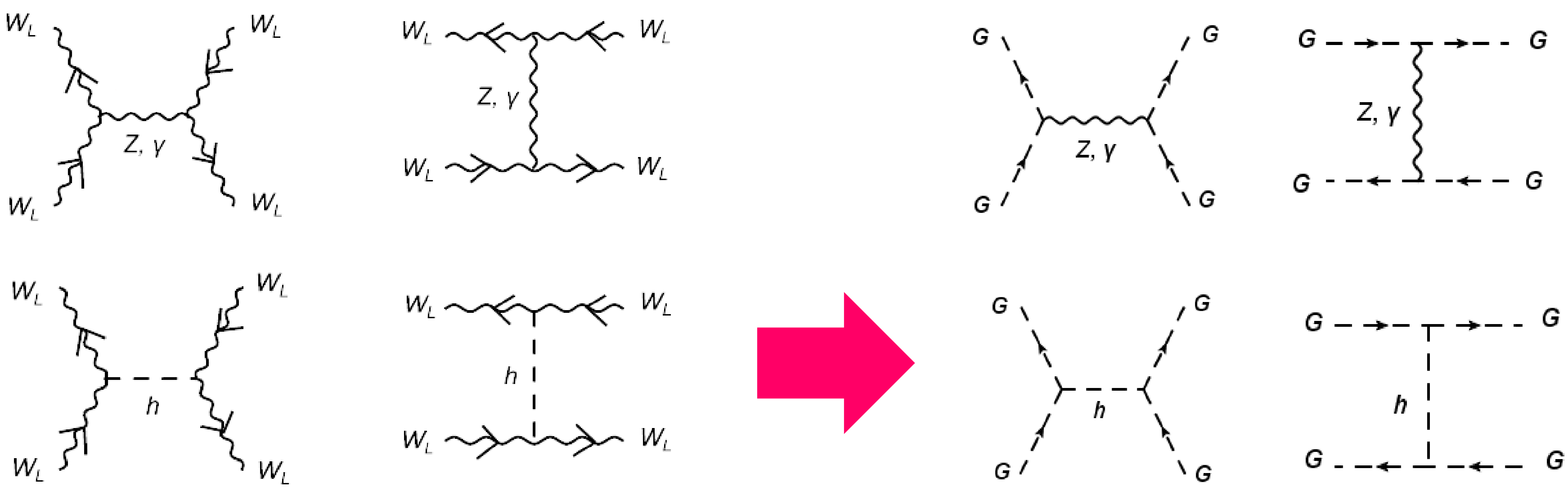
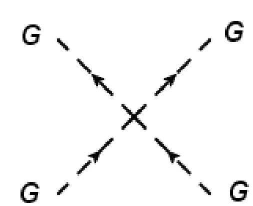


$$a_0 \xrightarrow[E\to\infty]{} \frac{\lambda}{4\pi}$$



Diagonalization of the S-wave matrix

- There are not only $W_L^+W_L^-$ state, but also Z_LZ_L, hh, Z_Lh (neutral), $W_L^\pm Z_L$, $W_L^\pm h$ (singly-charged) and $W_L^\pm W_L^\pm$ (doubly-charged) states.

Ginzburg, Ivanov (2003)

- In the $E\to\infty$ limit, we can classify all the orthogonal 2 body states by **T, T_3** and **Y**.

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

T=1 $\left\{ \begin{array}{ll} \phi^+\phi^+ & (T_3=1) \\ \phi^+\phi^0 & (T_3=0) \\ \phi^0\phi^0 & (T_3=-1) \end{array} \right\}$ $a_0=\lambda/8\pi$

T=0 Absent

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

$\left\{ \begin{array}{ll} \phi^+\phi^{0*} & (T_3=1) \\ \frac{\phi^+\phi^{0*}-\phi^+\phi^-}{\sqrt{2}} & (T_3=0) \\ \phi^-\phi^- & (T_3=-1) \end{array} \right\}$ $a_0=\lambda/8\pi$

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

From $|a_0^i| < 1/2 \to$ **mh < 712 GeV**

Application to the 2HDM

Let us consider the application of the unitarity bound to the 2HDM w/ a softly-broken Z_2 symmetry ($\Phi_1 \to +\Phi_1$, $\Phi_2 \to -\Phi_2$).

- Higgs doublets $\Phi_i = \begin{bmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(h_i + z_i + v_i) \end{bmatrix}$, (i =1, 2)

- Mass eigenstates

$$\begin{pmatrix} w_1^\pm \\ w_2^\pm \end{pmatrix} = R(\beta) \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}, \quad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = R(\beta) \begin{pmatrix} G^0 \\ A \end{pmatrix}, \quad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ h \end{pmatrix}$$

$$R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

Higgs potential in the 2HDM

- The Higgs potential under the softly-broken Z_2 sym. and CP-invariance

$$V = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2[\Phi_1^\dagger\Phi_2 + \text{h.c.}]$$
$$+\frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right]$$

- We have 8 parameters in the potential. They can be interpreted by

v (=246 GeV), m_h (=125 GeV),
m_H, m_A, m_{H+}, **sin(β-α), tanβ**, and **M^2** $M^2 = m_3^2/(\sin\beta\cos\beta)$

- Mass formulae with sin(β-α) ~1

$m_h^2 \sim \lambda v^2$, $m_\Phi^2 \sim M^2 + \lambda' v^2$

$\Phi = H^\pm, A, H$

S-wave amp. in 2HDM

Maalampi, Sirkka, Vilja (1991); Kanemura, Kubota, Takasugi (1993); Akeroyd, Arhrib, Naimi (2000); Ginzburg, Ivanov (2005)

- There are 14 neutral, 8 singly-charged and 3 doubly-charged states.
- The 2 body scalar states are classified
  in terms of Z_2 charge in addition to T, T_3 and Y.

$\Phi_1 \otimes \Phi_1$ (Y=1, Z_2 even)

T=1:

$$\begin{pmatrix} w_1^+ w_1^+ \\ w_2^+ w_2^+ \end{pmatrix} \quad (T_3=1)$$

$$\begin{pmatrix} w_1^+ \phi_1^0 \\ w_2^+ \phi_2^0 \end{pmatrix} \quad (T_3=0)$$

$$\begin{pmatrix} \phi_1^0 \phi_1^0 \\ \phi_2^0 \phi_2^0 \end{pmatrix} \quad (T_3=-1)$$

T = 0 Absent

$\Phi_1 \otimes \Phi_2$ (Y=1, Z_2 odd)

T=1:

$$w_1^+ w_2^+ \quad (T_3=1)$$

$$\frac{\phi_1^+ \phi_2^0 + \phi_1^0 \phi_2^+}{\sqrt{2}} \quad (T_3=0)$$

$$\phi_1^0 \phi_2^0 \quad (T_3=-1)$$

T = 0 $\quad \dfrac{\phi_1^+ \phi_2^0 - \phi_1^0 \phi_2^+}{\sqrt{2}}$

- In addition, there are (Y=0, Z_2 even) and (Y=0, Z_2 odd) states.

All the independent eigenvalues

Kanemura, Kubota, Takasugi (1993) [Diagonalized all the neutral channels]
Akeroyd, Arhrib, Naimi (2000) [Diagonalized all the singly-charged channels]
Ginzburg, Ivanov (2003) [Extended to the CPV 2HDM]

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

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

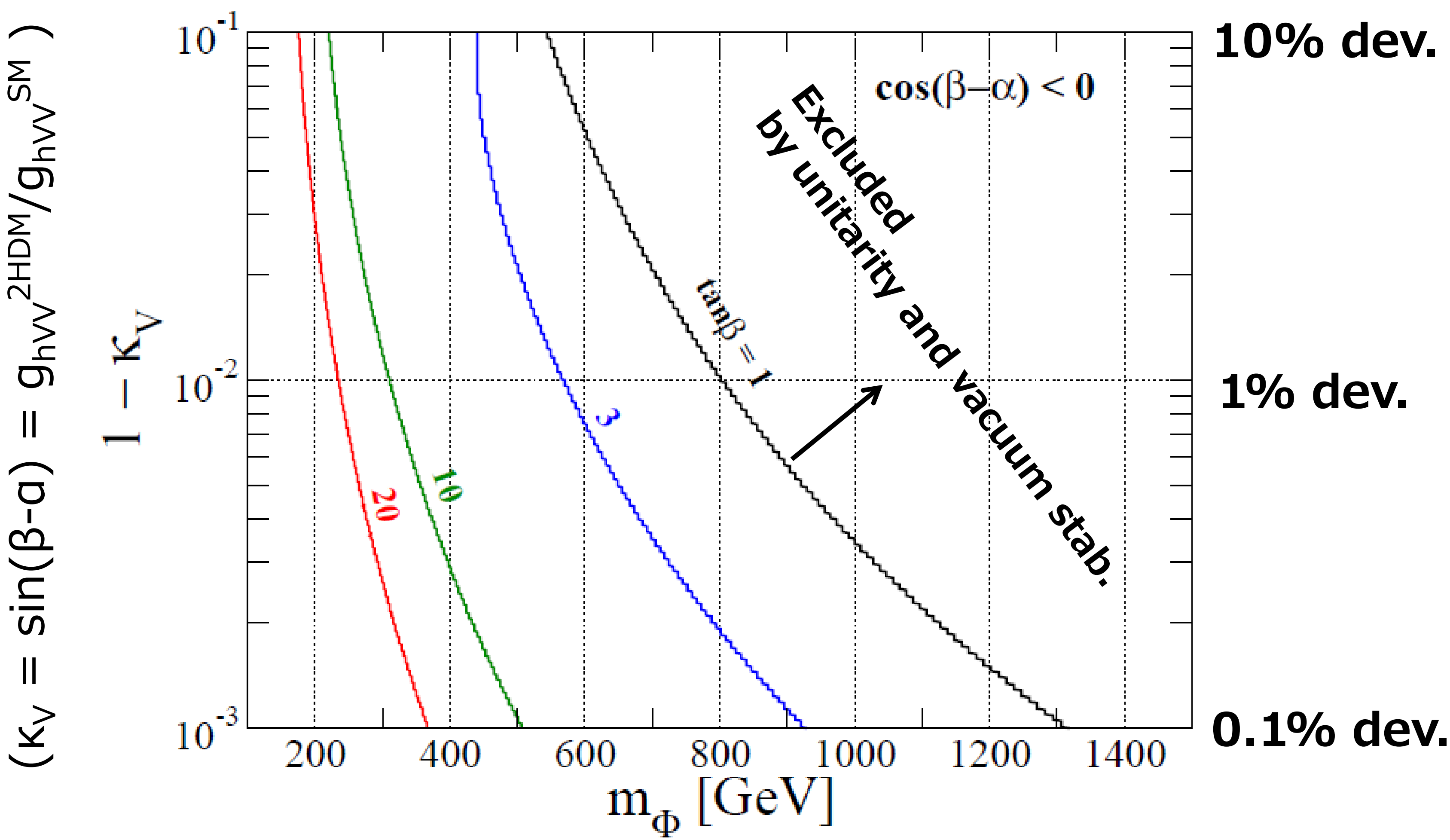
$$a^0_{3,\pm} = \frac{1}{32\pi}\left[(\lambda_1+\lambda_2) \pm \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2}\right],$$

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

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

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

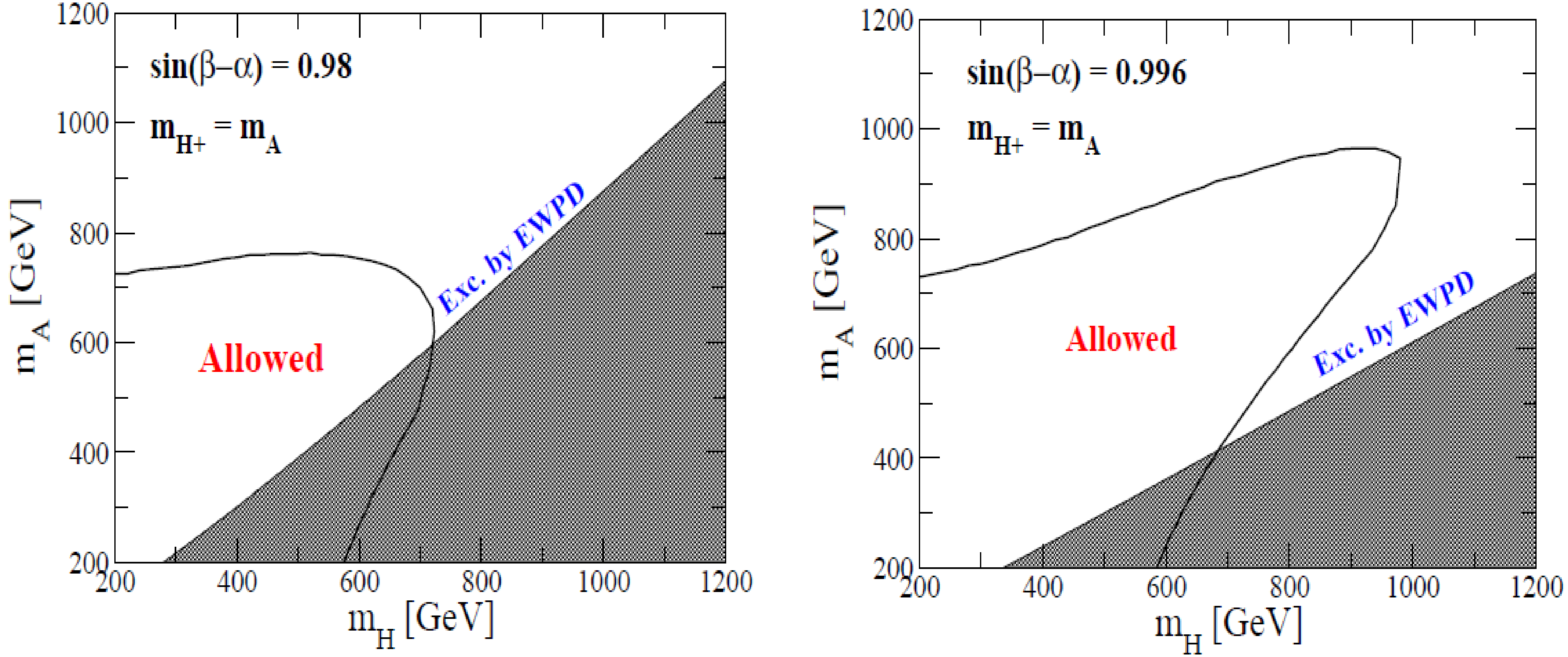
Upper lim. of the 2nd Higgs mass



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

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).

Application to the 3HDM

- There are several versions of 3HDM depending on a symmetry of the potential

Keus, King, Moretti, PRD91 (2015)

Grzadkowski, Ogreid, Osland, PRD80 (2009)

3HDM with Z_2 (exact, unbroken)× Z'_2 (softly-broken)

Φ_1 , Φ_2 (Z_2-even)

- Non-0 VEVs (Active)
- $H^\pm$, A, H, h (SM-like)
- No tree FCNC by Z_2'

Interaction

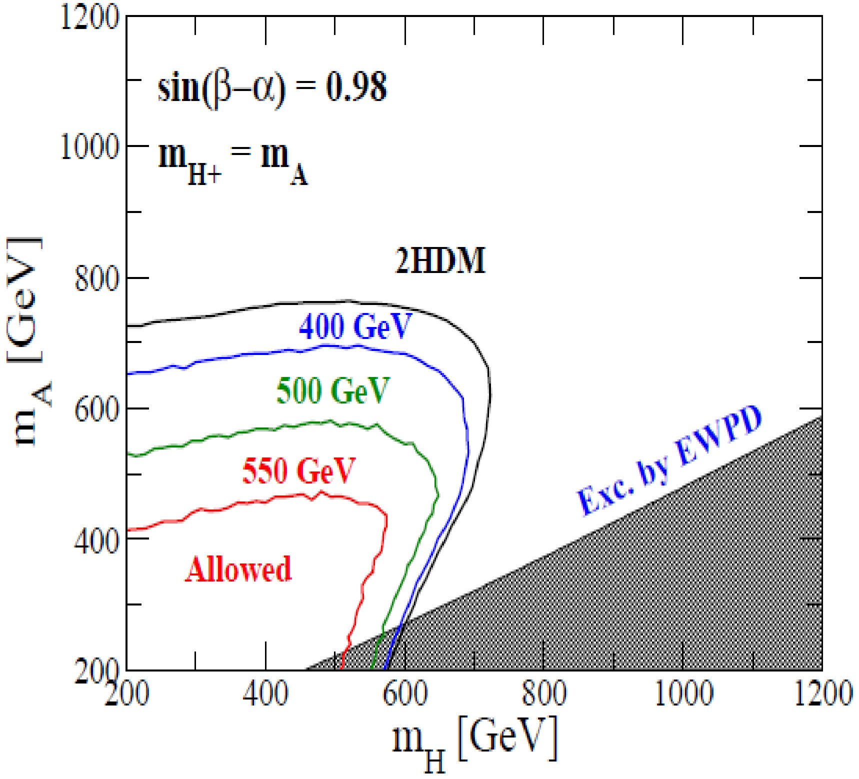
Φ_3 (Z_2-odd)

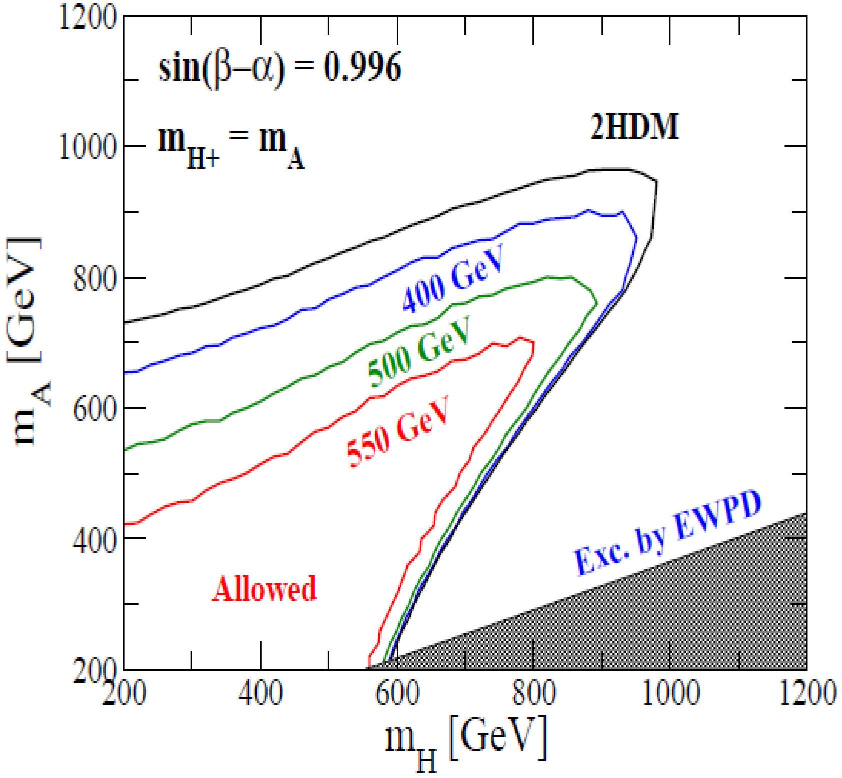
- No VEV (Inert)
- $H_3^\pm$, H_3^0, A_3^0
- Lightest one = DM

Via the interaction term, inert particles affect on the active sector.

Results

Moretti, KY, PRD91 (2015)





We take $m(H_3)$= mh/2 and

$m(A_3)$ = $m(H_3^{\pm})$=400, 500 and 550 GeV .

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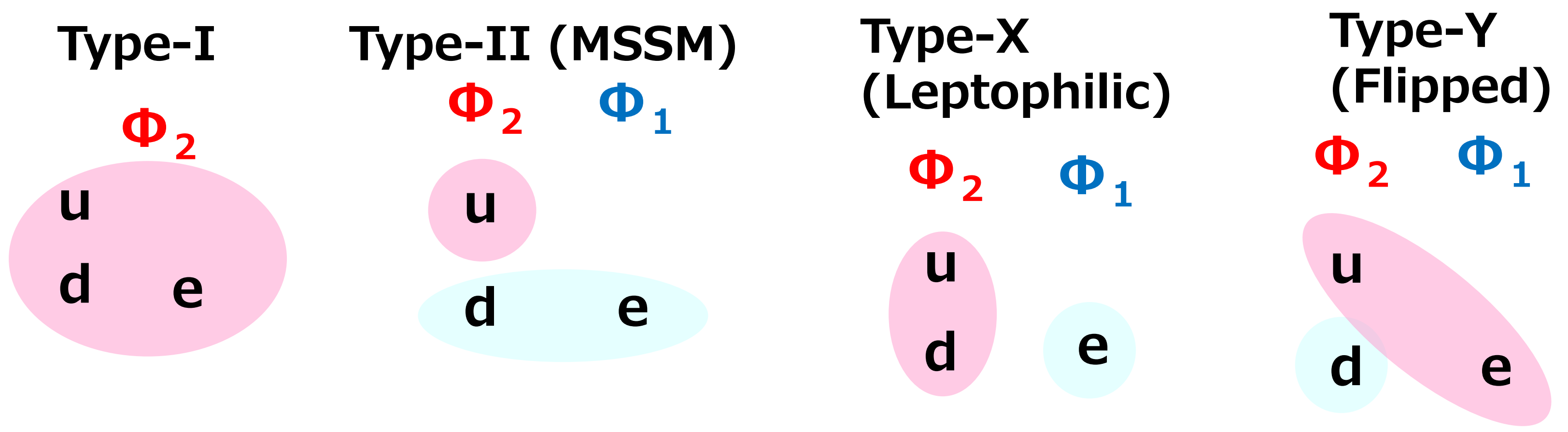
Yukawa Interactions

Under the Z_2 symmetry, the Yukawa interactions are given by

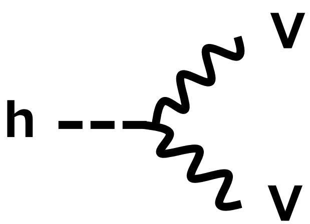
$$\mathcal{L}_Y = -Y_u \bar{Q}_L \Phi_u^c u_R - Y_d \bar{Q}_L \Phi_d d_R - Y_e \bar{L}_L \Phi_e e_R$$

Four independent types are allowed as follows

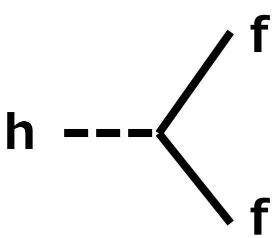
Barger, Hewett, Phillips, PRD41 (1990); Grossman, NPB426 (1994).



Higgs Boson Couplings



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



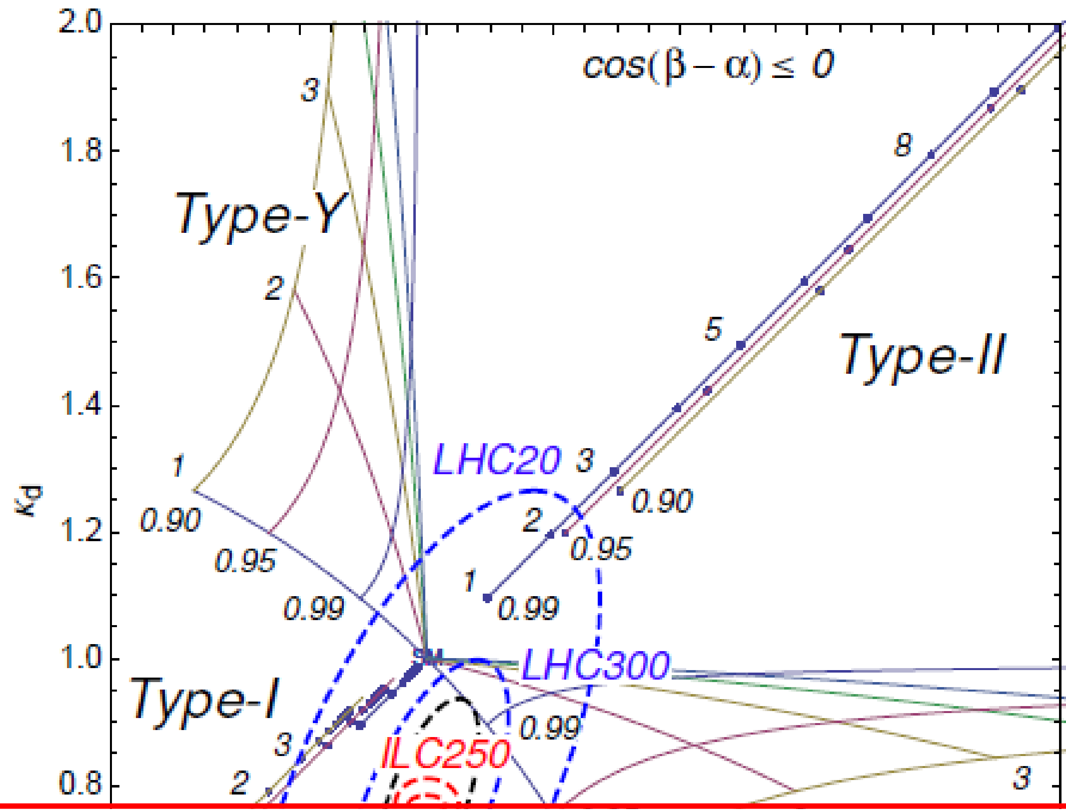
$= (\mathrm{SM}) \times [\sin(\beta-\alpha) + \xi_f \cos(\beta-\alpha)]$

	ξ_u	ξ_d	ξ_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.

κ_e VS κ_d

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



	ξ_d	ξ_e
Type-I	$\cot\beta$	$\cot\beta$
Type-II	$-\tan\beta$	$-\tan\beta$
Type-X	$\cot\beta$	$-\tan\beta$
Type-Y	$-\tan\beta$	$\cot\beta$

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

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

Summary

1. Bottom up approach

By the reconstruction of the Higgs sector, the direction of new physics can be clarified.

2. Non-zero mixing between h and extra Higgs bosons

Non-zero mixing between SM-like Higgs and extra Higgs bosons gives

an upper limit on masses of extra Higgs bosons and deviations in h couplings.

3. Unitarity bound

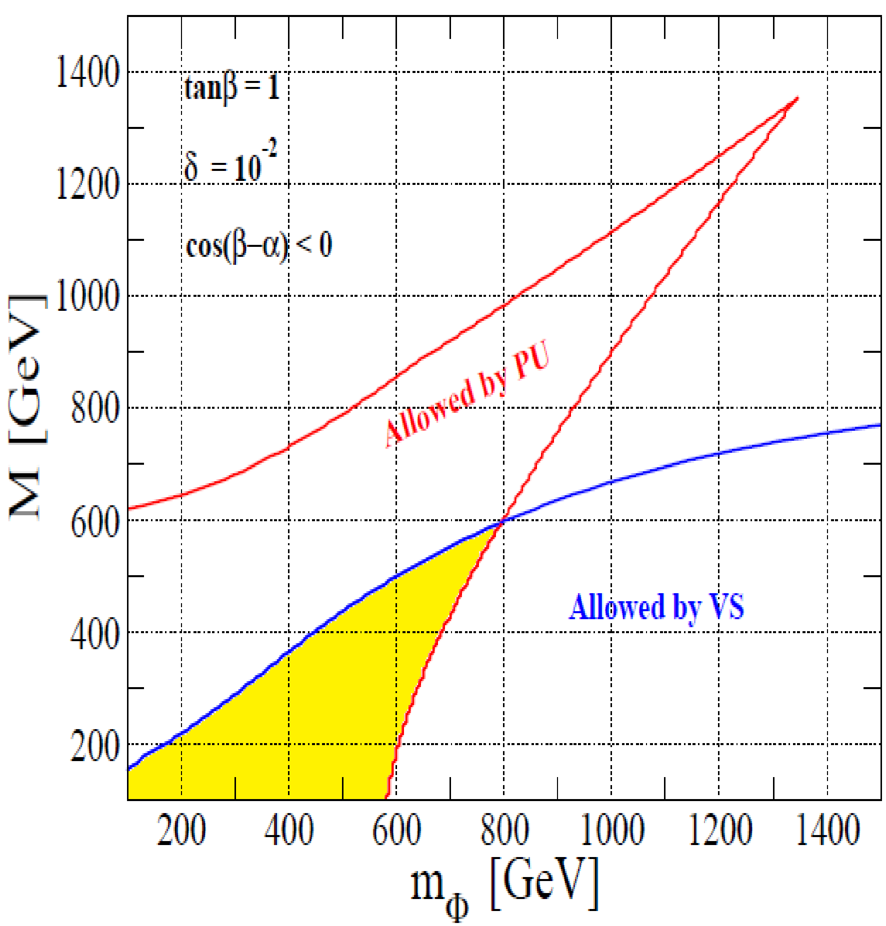
In the high-energy limit, only scalar quartic terms are related to the unitarity bound.

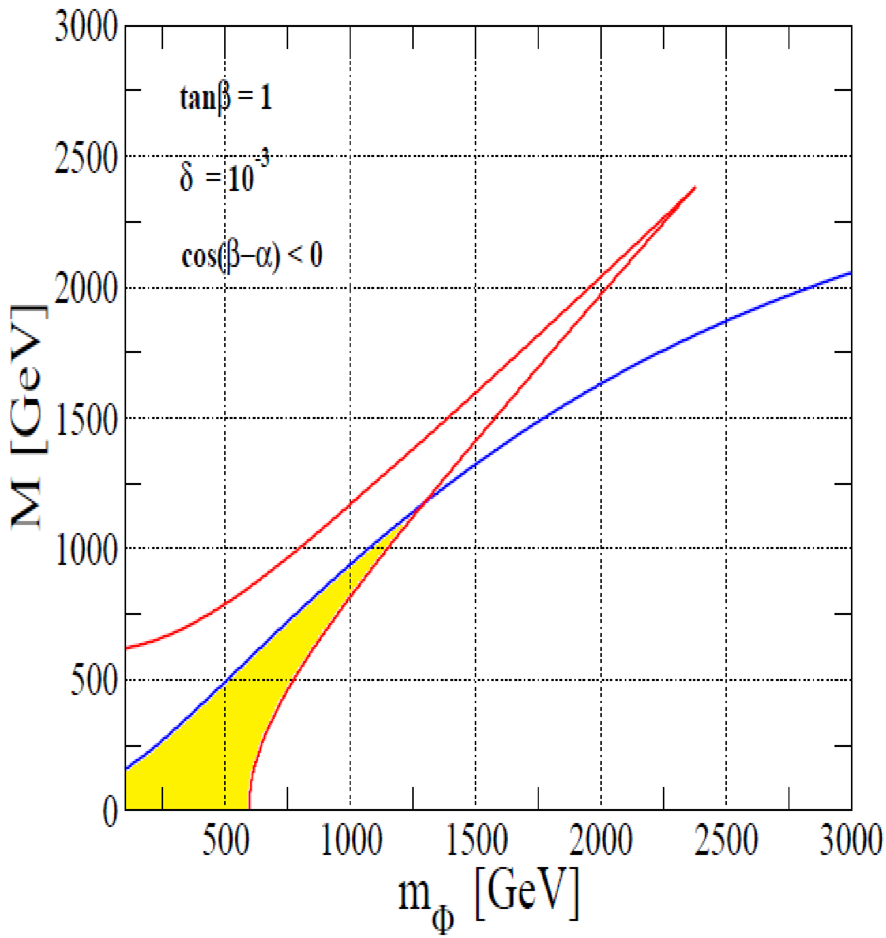
Larger deviations in hVV give stronger bounds on masses of extra Higgs bosons.

4. Fingerprinting the Higgs sector

From deviations in Yukawa couplings, we can discriminate the model type.

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-2014-009

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

CMS Collaboration, arXiv: 1412.8662 [hep-ex]

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

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
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%
κ_ℓ	$6-8\%$	$2-5\%$	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 ILC500** !

Higgs Potential in the 3HDM

Moretti, KY, PRD91 (2015)

Under $Z_2 \times Z_2'$, the most general Higgs potential is given by

$$V(\varphi_0,\varphi_1,\varphi_2) = \sum_{i=0,\dots 2} \mu_i^2 \varphi_i^\dagger \varphi_i + (\mu_{12}^2 \varphi_1^\dagger \varphi_2 + \mathrm{H.c.}) + \frac{1}{2}\sum_{i=0,\dots 2} \lambda_i (\varphi_i^\dagger \varphi_i)^2 + \lambda_3 (\varphi_1^\dagger \varphi_1)(\varphi_2^\dagger \varphi_2) + \lambda_4 |\varphi_1^\dagger \varphi_2|^2 + \frac{1}{2}[\lambda_5 (\varphi_1^\dagger \varphi_2)^2 + \mathrm{H.c.}] + \rho_1 (\varphi_1^\dagger \varphi_1)(\varphi_0^\dagger \varphi_0) + \rho_2 |\varphi_1^\dagger \varphi_0|^2 + \frac{1}{2}[\rho_3 (\varphi_1^\dagger \varphi_0)^2 + \mathrm{H.c.}] + \sigma_1 (\varphi_2^\dagger \varphi_2)(\varphi_0^\dagger \varphi_0) + \sigma_2 |\varphi_2^\dagger \varphi_0|^2 + \frac{1}{2}[\sigma_3 (\varphi_2^\dagger \varphi_0)^2 + \mathrm{H.c.}],$$

- There are totally 16 independent parameters.
- 8 of them correspond to 2HDM parameters.
- 3 of them correspond to the masses of inert scalar bosons.
- Remaining 5 are fixed as $\sigma_i = \rho_i$ (i=1,2,3), $\lambda_0 = 0$, $\rho_1 > 2|\rho_2|$.

All the independent eigenvalues

Moretti, KY, PRD91 (2015)

$$X_1 = \begin{pmatrix} 3\lambda_\eta & 2\rho_1+\rho_2 & 2\sigma_1+\sigma_2 \\ 2\rho_1+\rho_2 & 3\lambda_1 & 2\lambda_3+\lambda_4 \\ 2\sigma_1+\sigma_2 & 2\lambda_3+\lambda_4 & 3\lambda_2 \end{pmatrix}, \quad X_2 = \begin{pmatrix} \lambda_\eta & \rho_2 & \sigma_2 \\ \rho_2 & \lambda_1 & \lambda_4 \\ \sigma_2 & \lambda_4 & \lambda_2 \end{pmatrix}, \quad X_3 = \begin{pmatrix} \lambda_\eta & |\rho_3| & |\sigma_3| \\ |\rho_3| & \lambda_1 & |\lambda_5| \\ |\sigma_3| & |\lambda_5| & \lambda_2 \end{pmatrix},$$

$$y_1^\pm = \lambda_3 + 2\lambda_4 \pm 3|\lambda_5|,$$

$$y_2^\pm = \rho_1 + 2\rho_2 \pm 3|\rho_3|,$$

$$y_3^\pm = \sigma_1 + 2\sigma_2 \pm 3|\sigma_3|,$$

$$y_4^\pm = \lambda_3 \pm |\lambda_5|,$$

$$y_5^\pm = \rho_1 \pm |\rho_3|,$$

$$y_6^\pm = \sigma_1 \pm |\sigma_3|,$$

$$y_7^\pm = \lambda_3 \pm \lambda_4,$$

$$y_8^\pm = \rho_1 \pm \rho_2,$$

$$y_9^\pm = \sigma_1 \pm \sigma_2.$$

There are totally 27 independent eigenvalues.

Vacuum Stability

Grzadkowski, Ogreid, Osland, PRD80 (2009)

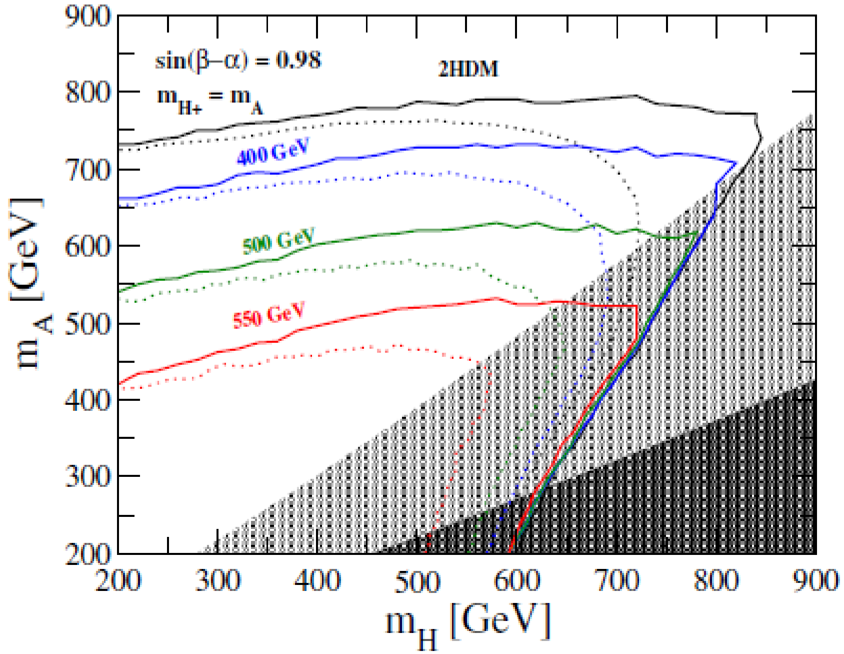
$$\lambda_\eta > 0, \quad \lambda_1 > 0, \quad \lambda_2 > 0,$$

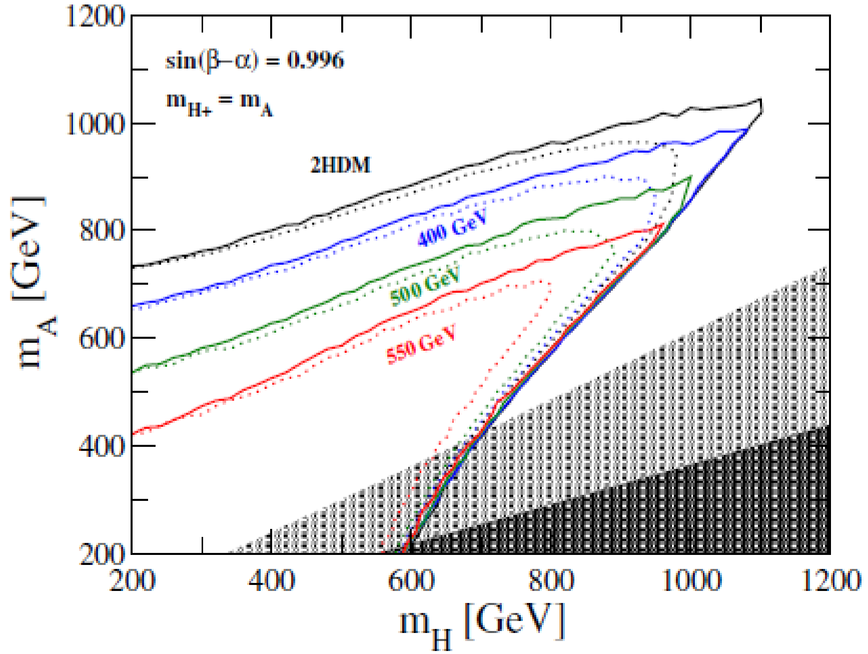
$$\sqrt{\lambda_1\lambda_2} + \bar{\lambda} > 0, \quad \sqrt{\lambda_\eta\lambda_1} + \bar{\rho} > 0, \quad \sqrt{\lambda_\eta\lambda_2} + \bar{\sigma} > 0,$$

$$\sqrt{\lambda_\eta}\bar{\lambda} + \sqrt{\lambda_1}\bar{\sigma} + \sqrt{\lambda_2}\bar{\rho} > 0 \ \text{ or } \ \lambda_\eta\bar{\lambda}^2 + \lambda_1\bar{\sigma}^2 + \lambda_2\bar{\rho}^2 - \lambda_\eta\lambda_1\lambda_2 - 2\bar{\lambda}\bar{\rho}\bar{\sigma} < 0,$$

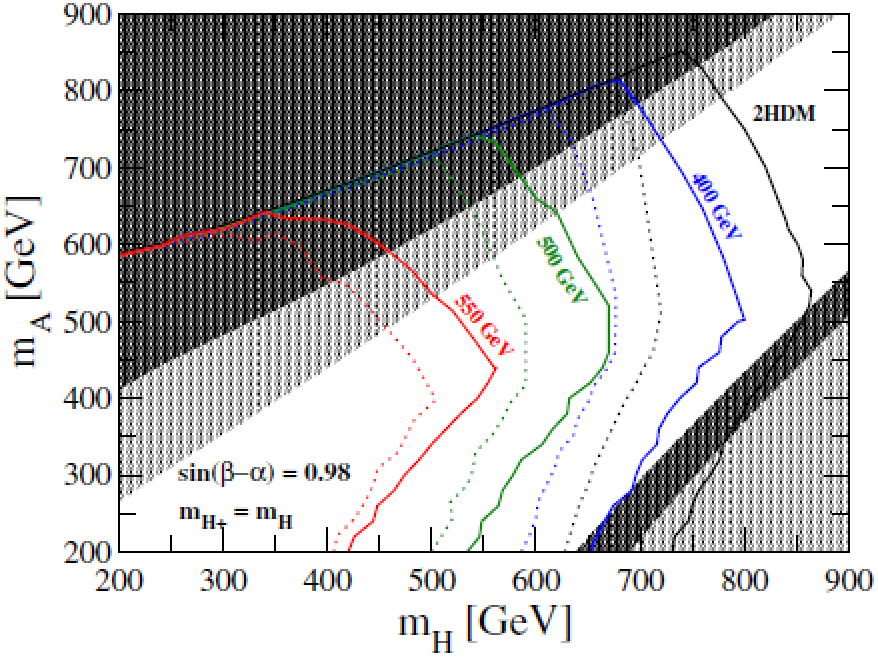
$$\bar{\lambda} = \lambda_3 + \mathrm{MIN}(0,\ \lambda_4 - |\lambda_5|), \quad \bar{\rho} = \rho_1 + \mathrm{MIN}(0,\ \rho_2 - |\rho_3|), \quad \bar{\sigma} = \sigma_1 + \mathrm{MIN}(0,\ \sigma_2 - |\sigma_3|)$$

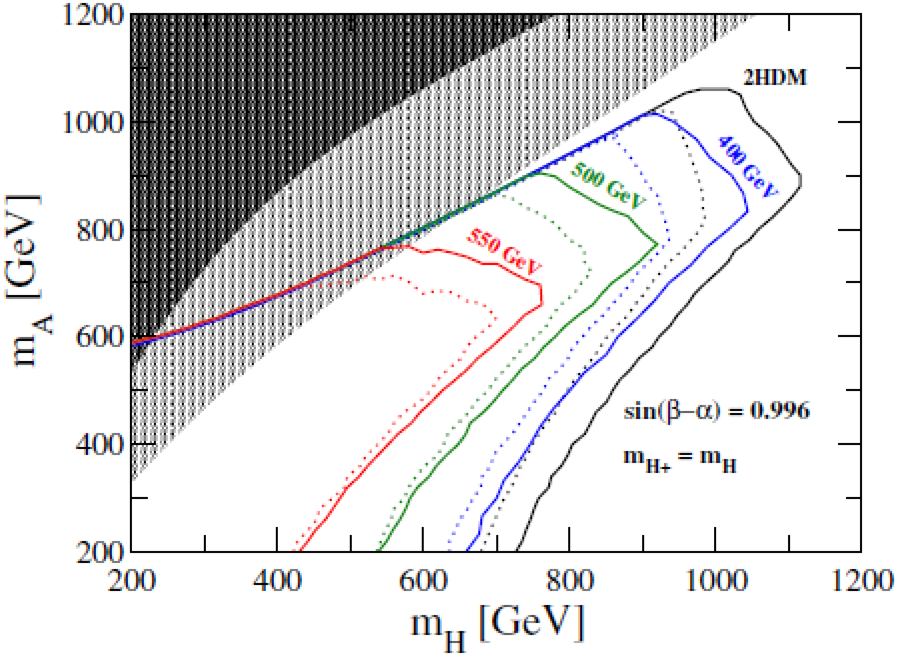
Tanβ Scanned Case





The case with $mH^{\pm} = mH$





Electroweak S and T parameters

Under $mH^{\pm} = mA$ and $mH_3^{\pm} = mA_3$, we have

$$\Delta S \simeq \frac{1}{12\pi}\left(-1 + \frac{m_H}{m_{H^\pm}} - 1 + \frac{m_{H_3}}{m_{H_3^\pm}}\right)$$