Sum rules for multi Higgs models and opportunities of future experiments, Triple Higgs in 2HDM

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Higgs mechanism of EWSB can be realized in both well known minimal model (SM) and with more complex non-minimal Higgs sector.

These non-minimal models contain new scalar particles – new Higgs bosons, neutral h_a with masses M_a and widths Γ_a, just as charged $H_b^{\pm}$ with masses $M_{\pm}^b$ and widths $\Gamma_{\pm}^b$.

Necessary step in the discovery of such model is observation of these additional Higgses.

For any model we define relative couplings

$$\chi_P^a = \frac{g_P^a}{g_P^{SM}} \qquad (P = W, Z, t, b, \tau, ...)$$

Besides, for models with single charged Higgs we define

$$\chi_{H^\pm W^\mp}^a = \frac{g(H^\pm W^\mp h_a)}{M_W/v} \qquad (v = 246 GeV)$$

Couplings χ_W^a, χ_Z^a are real. Other couplings χ can be complex.

Sum rules

- Sum rules for couplings of neutral Higgses h_a to vector bosons χ_V^a (real quantities)

$$\text{I.} \quad \sum_a (\chi_V^a)^2 = 1$$

valid for any Higgs model (with additional doublets, singlets, triplets, independent on CP conservation). These sum rules describe only the fact that the masses of gauge bosons are given by Higgs mechanism of EWSB. (One can be $\chi_W^a = \chi_Z^a$ or $\chi_W^a \neq \chi_Z^a$).
(For particular case of 2HDM these sum rules were proven by many authors.)

- Sum rules for couplings $\chi_f^{(a)}$ of neutrals to separate fermion f (generally complex!)

$$\text{II.}\quad \sum_a (\chi_f^a)^2 = 1$$

valid for Higgs models $nHDM + p(HSnM)$, with arbitrary number n of Higgs doublets plus p Higgs singlets, when latter don't interact with fermions.

For separate variants of 2HDM with specific forms of Yukawa interaction such sum rules were proven by many authors.

To prove our extension of applicability, we write general Yukawa interaction for given fermion (before EWSB) $L_Y^f = \sum_j g_j^f \bar{\psi}_f \phi_j \psi_f$. Simple reparameterization $\phi'_1 = N g_1'^f \sum_j g_j^f \phi_j$ (N− normalization factor) transforms this Yukawa term to the form $L_Y^f = g_1'^f \bar{\psi}_f \phi'_1 \psi_f$. In this form Yukawa term coincides with that of $2HDMI$ or $2HDMII$, where these sum rules were proven earlier.

The relations between couplings χ_f^a for different fermions f vary for different forms of Yukawa interaction. We don't discuss them.

- Sum rules for couplings $H^{\pm}W^{\mp}h_a$ of neutral Higgs boson h_a to charged Higgs boson $H^{\pm}$ and vector boson $W^{\pm}$ (generally complex)

$$\textbf{III.}\quad |\chi_V^a|^2 + |\chi_{H^{\pm}W^{\mp}}^a|^2 = 1$$

valid for any model with 2 Higgs doublets and arbitrary number p of Higgs singlets $2HDM + p(HSnM)$ (e.g. nMSSM). These sum rules were proven for 2HDM by me and K. Kanishev (in preparation). This proof is naturally spread for models with additional Higgs singlets.

Experimental situation

Based on LHC data, we believe:

The SM-like situation is realized:

1) One Higgs boson h has mass $M_h \approx 126$ GeV

2) Its couplings to gauge bosons V and fermions f are close to the SM expectations,

$$1 - |\chi_V^{exp}|^2 \ll 1, \qquad |\chi_{t,b}^{exp}|^2 \approx 1 \qquad .$$

In the extended models we denote discovered Higgs boson as h_1, for other neutrals h_a we have $a \geq 2$.

Important: realization of SM-like situation don't shoot the doors for realization of non-minimal Higgs models.

First conclusions for SM-like situation

Some of conclusions presented here were obtained earlier in particular models with some benchmark parameters (often only for CP conserving case). The problem about general situation was unclear. Below I present general results for large group of models with arbitrary parameters, allowing SM-like situation.

- In any Higgs model we have $|\chi_V^a| \ll 1$.
- In $2HDM + p(HSnM)$ we have $|\chi^1_{H^\pm W^\mp}| \ll 1$ and $|\chi^{a\geq 2}_{H^\pm W^\mp}| \approx 1$.
- In $nHDM + p(HSnM)$ for separate fermion f we have $\sum \chi_f^{a\geq 2} \ll 1$.

Physical picture

- **New neutral Higgs widths and decay channels**.

At $M_h > 150$ GeV due to Sum Rule I for Higgses h_a at $a \geq 2$ contributions of decays $h_a \to WW, ZZ$ are smaller than those in SM. $\Longrightarrow$

observation of h_a via decay $h_a \to WW, ZZ$ become difficult problem.

At $M_a < 350$ GeV total widths Γ_a are generally small with main decay channel $h_a \to b\bar{b}$, having huge background, e.g. in gluon fusion.

At $M_a > 350$ GeV decay $h_a \to t\bar{t}$ can be either weak or strong (depending on form of Yukawa sector). The observation of this decay in gluon fusion looks difficult due to strong background. In the case of enhanced decay $h_a \to t\bar{t}$ for some a there is at least one more neutral h_b with enhanced coupling $h_b t\bar{t}$ (like H and A with $M_H \approx M_A$ in CP conserving 2HDM-II). If $M_b > 350$ GeV, properties of h_a and h_b are similar. At $M_b < 350$ GeV boson h_b is hardly observable.

• The production of CP-even Higgs via gauge vertex was considered as the channel, allowing to obtain the best S/B ratio and the best precision in the measuring of Higgs properties.

At LHC that are processes like W-fusion.

At ILC that are processes $e^+e^- \to Zh$, $e^+e^- \to \nu\nu W^* W^* \to \nu\nu h$.

Cross sections of all these processes are much smaller than those anticipated for would be SM Higgs boson of similar mass. These observation are at least difficult.

Using of charged Higgs.

Sum rules III show that the success in the search for new neutral Higgses h_a can be expected in processes involving the charged Higgs.
1. Discovery of $H^\pm$ in association with h_1 (like $\to W^+ \to H^+ h_1$) is hardly probable.
2. Perspective processes at $a > 1$ (after discovery $H^\pm$)
the discovery of h_a in the processes like
$q\bar{q} \to H^\pm h_a W^\mp$, $q_1\bar{q}_2 \to H^+ h_a$ $q_1\bar{q}_2 \to W^\pm \to h_a H^\pm$, $q\bar{q} \to h_a h_b$ at LHC,
$e^+e^- \to H^\pm h_a W^\mp$, $e^+e^- \to W^+ W^- h_a$ at ILC,
$\gamma\gamma \to H^+ W^- h_a$, $e\gamma \to \nu W^* \to \nu H^- h_a$ at PLC.

One more point.
Triple Higgs coupling in 2HDM

In the paper of Kanishev and myself (in preparation) we express all parameters of most general 2HDM via measurable quantities – 3 masses M_a, $M_{\pm}$, v.e.v. $v = 246$ GeV, couplings χ_V^a, and couplings $H^+H^-h_a$, $H^+H^-H^+H^-$ (latter are related to parameters Λ_3, Λ_7 and Λ_2 in Higgs basis).

In the SM we have $g(hhh) = 3M_h^2/v$. In 2HDM

$$g(h_1h_1h_1) = 3\frac{M_1^2}{v}\chi_V^1 \chi_{hhh}^{111}$$

$$\chi_{hhh}^{111} = 1 + \left(1 - (\chi_V^1)^2\right)\left[\left(1 + 2(\chi_V^1)^2\right) + \sum_{b\neq 1} 2\frac{M_b^2}{M_1^2}(\chi_V^b)^2 + \right.$$
$$\left. + \frac{(v^2\Lambda_3 - 2M_\pm^2)}{M_1^2} + \frac{v^2 Re(\Lambda_7^* \chi_{W^\mp H^\pm}^1)}{M_1^2 \chi_V^1}\right].$$

In the SM-like situation $\chi_V^1 \approx 1$ and $|\chi_{H^\pm W^\mp}^1/\chi_V^1| \ll 1$.
Therefore at reasonable values of parameters (with any Yukawa sector)

$$\chi_{hhh}^{111} \approx 1$$

(Similar result was obtained earlier for the CP conserving case).
The significant deviation of this coupling from SM value will be clear signal of either very heavy new Higgses (TeV's) or large value of parameter Λ_3 – strong interaction in Higgs sector.

Thank you