Multi-Higgs models. Perspectives for identification of wide set of models in future experiments at colliders in the SM-like scenario

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BASICS

1. Higgs boson h with mass 125 GeV is discovered at LHC

2. Its properties are close to those in minimal SM (SM)

– SM-like scenario is realized

This scenario does not ruled out extended Higgs sector, containing new neutral and charged scalars.

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

Non-minimal models for EWSB

1. Models in which non-zero v.e.v. is formed by Higgs doublets like in SM only. Other fields have no independent v.e.v.'s.

2. Models with alternative explanations or (and) additional mechanisms – with additional v.e.v.'s for some other fields – scalars, triplets, etc., little Higgs, orbifold, radion,...

I discuss only models of the first group

$$nHDM + p_2(HS_2M) + p_1(HS_1M)$$

(n fundamental weak isodoublets, p_2 complex weak isosinglets S_2 and p_1 real weak isosinglets S_1)

Examples

2HDM (since 1973) at some values of parameters

can explain CP violation, FCNC, etc

gives Dark Matter (Inert doublet Model – IDM) (without CP violation in Higgs sector and FCNC)

realizes Higgs sector of MSSM

$2HDM + 1(HS_2M)$ realizes Higgs sector of nMSSM
$3HDM$
gives Dark Matter (IDM) with CP violation and possible FCNC
gives asymmetric Dark Matter
$6HDM$ is used for some symmetry problems

The 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.

Lesson

In the general form these models are determined by huge number of constants. For example, 2HDM contains two fields with identical quantum numbers. Its description in terms of original fields or in terms of their linear superpositions are equivalent; this statement verbalizes the reparameterization (RPa) freedom of the model. This freedom means that the standard description of model contains irrelevant parameters like gauge fixing. All parameters of model can be expressed via measurable parameters – observables. The minimal set of observables for 2HDM contains 4 masses of scalars $M_\pm$, M_{1-3}, v.e.v. of Higgs field $v = 246$ GeV, two of three couplings $g(W^+W^-h_a)$, 3 triple Higgs couplings $g(H^+H^-h_a)$ and one quartic coupling $g(H^+H^-H^+H^-)$

We define relative couplings

$$\chi_a^P = \frac{g_a^P}{g_{SM}^P},, \qquad (P = W, Z, t, b, \tau, ...)$$

The models with charged Higgs bosons contain vertices $H_b^+ H_b^- h_a$ and $H_b^{\pm} W^{\mp} h_a$. For them, we define relative couplings

$$\chi_a^{H_b^{\pm} W^{\mp}} = \frac{g(H_b^{\pm} W^{\mp} h_a)}{M_W/v}; \quad \chi_a^{\pm b} = \frac{g(H_b^+ H_b^- h_a)}{2M_{\pm}^2/v}.$$

The neutrals h_a generally have no definite CP parity. Couplings χ_a^V and $\chi_a^{\pm b}$ are real due to Hermiticity of Lagrangian, while other couplings are generally complex. The $Re(\chi_a^f)$ and $Im(\chi_a^f)$ are responsible for the interaction of fermion f with CP-even and CP-odd components of h_a respectively.

Conditions for CP conservation

In the CP conserving case some of h_a are scalars, others are pseudoscalars.
In this case we have

$$(a)\ \boxed{\prod_a \chi_a^V = 0}, \quad (b)\ \boxed{\prod_a \chi_a^{\pm b} = 0}, \quad (c)\ \boxed{\left|\prod_a \chi_a^f\right| = \prod_a \left|\chi_a^f\right| \text{ for each fermion } f}.$$

(In the 2HDM with CP conservation we have $h_3 = A$ (pseudoscalar) and $\chi_3^V = 0$, $\chi_3^{\pm} = 0$, $Im(\chi_{2,1}^f) = 0$, $Re(\chi_3^f) = 0$. In this model the relationship (c) for fermions follows from the (a) – for gauge bosons.)

Sum rules

Some of them are known in CP conserving 2HDM with some definite forms of Yukawa interaction. All discussed Sum rules allow CP violation and arbitrary form of Yukawa interaction

- Sum rules for couplings of neutral Higgses h_a to vector bosons χ_V^a (real – due to Hermiticity of Hamiltonian) describe the fact that the masses of gauge bosons are given by Higgs mechanism of EWSB:

$$\sum_a (\chi_a^V)^2 = 1\,, \quad (V = W, Z)$$

valid for any $nHDM + p_2(HS_2M) + p_1(HS_1M)$ model.

(One can be $\chi_a^W = \chi_a^Z$ or $\chi_a^W \neq \chi_a^Z$).

- Sum rules for couplings χ_a^f of neutrals to separate fermion f (generally complex!)

$$\sum_a (\chi_a^f)^2 = 1$$

valid for $nHDM + p_2(HS_2M) + p_1(HS_1M)$ model, when Higgs singlets don't interact with fermions.

To prove this SR, we write general Yukawa interaction for given fermion (before EWSB) $L_Y^f = \sum_j g_j^f \bar{\psi}_f \phi_j^0 \psi_f$. Simple reparameterization $\phi_1'^0 = N g_1'^f \sum_j g_j^f \phi_j^0$ (N− normalization factor) transforms this Yukawa term to the form $L_Y^f = g_1'^f \bar{\psi}_f \phi_1'^0 \psi_f$. In this form Yukawa term coincides with that of $2HDMI$ or $2HDMII$, where such sum rules were proven earlier.

The relations between couplings χ_f^a for different fermions f vary for different forms of Yukawa interaction.

- 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)

$$|\chi_a^V|^2 + |\chi_a^{H^{\pm}W^{\mp}}|^2 = 1$$

valid for $2HDM + p_2(HS_2M) + p_1(HS_1M)$ model (e.g. nMSSM). These sum rules were proven for 2HDM by me and K. Kanishev (Phys. Rev. D, July 2015). This proof is naturally spread for models with additional Higgs singlets.

Our subsequent discussion is based on assumption that LHC data tell us that:

the SM-like scenario 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,

$$\varepsilon^P = |1 - |\chi^P_{exp}|^2| \ll 1, \qquad (P = V,\, f) \qquad .$$

The realization of SM-like scenario don't shoot the doors for realization of non-minimal Higgs models.

It is clear that successful experiments reduce ε_P and, consequently, the region of the allowed parameters of each non-minimal model.

No doubts that the SM-like scenario in the non-minimal model can occur if additional Higgs bosons are very heavy and are coupled only weakly with usual matter (decoupling limit). 15 years ago we (I.F.G., M. Krawczyk, P.Osland) found that, at finite (even high) precision of future experiments at LHC and at the planned linear e^+e^- collider even the simplest non-minimal model 2HDM with the special choice of the Yukawa interaction 2HDM-II (as in MSSM) allows several possible windows significantly differing from the decoupling limit and implementing the SM-like scenario. Naturally, such windows exist in other models as well. These very windows are studied now by many authors.

Consequences from SR's in the SM-like scenario

$\boxed{Discovered\ Higgs\ boson\ -\ h_1,\ other\ neutrals\ -\ h_a\ with\ a \geq 2.}$

1) $|\chi_a^V|^2 < \varepsilon^V \ll 1\,.$

2) $|\chi_a^{W^\pm H^\mp}|^2 \approx 1 \quad (a \geq 2),\ |\chi_1^{W^\pm H^\mp}|^2 \ll 1\,.$

3) The SR's for couplings to given fermions f $\sum\limits_{a\geq 2}(\chi_a^f)^2 \approx 0$ can be saturated by different ways, for example:

$$a) \qquad |\chi_a^t| < 1 \quad \text{for all} \quad h_a\,, \tag{1a}$$

$$b) \qquad (bI) \quad |\chi_a^t| \approx |\chi_a^b| \gg 1; \qquad (bII) \quad |\chi_a^t| \approx |1/\chi_a^b| \gg 1\,, \tag{1b}$$

$$c) \qquad |\chi_{a_2}^t| \approx |\chi_{a_1}^t| > 1\,, \quad \chi_{a_2}^t \approx i\chi_{a_1}^t \quad \text{for some } h_{a_1} \text{ and } h_{a_2}\,. \tag{1c}$$

Properties of neutral Higgses h_a

For definiteness $M_a > 150$ GeV, $|\chi_a^f| < 40$ for $f \neq t$,
invisible interactions with dark matter particles can be added.
We compare with would be Higgs of SM with the same mass, $_{SM}^{wb}$.

- **Decay channels and total width**.

The detection of h_a via $h_a \to WW$, ZZ is highly improbable.
At $M_a < 350$ GeV we have $\Gamma_a \ll \Gamma_{SM}^{wb}(M_a)$. The same is valid at $M_a > 350$ GeV in the case I-t for coupling to t. The main decay channel is $h_a \to b\bar{b}$ with huge background $\Rightarrow$ the detection of each h_a is a difficult problem.
At $M_a > 350$ GeV in the case II-t for coupling to t contribution of $t\bar{t}$ decay is enhanced so that one can be $\Gamma_a \gtrsim \Gamma_{SM}^{wb}(M_a)$. In this case one can hope to see h_a in $t\bar{t}$ mode.

Production of heavy Higgs through a gauge vertex

was until recently assumed to ensure the best signal/background ratio and the least inaccuracy in the measurement of its parameters: W fusion at the LHC, $e^+e^- \to Zh_a$ and $e^+e^- \to \nu\bar{\nu}h_a$ at the ILC, and $e\gamma \to \nu W^- h_a$, $\gamma\gamma \to W^+H^-h_a$ at the PLC (photon collider). In view of our SR's the experiments on the search for additional Higgs bosons at the LHC and linear collider in such processes cannot be successful, their cross sections are typically one order of value lower then those calculated for wbSM, having the same mass.

Gluon fusion

The Γ_a^{gg} is saturated by contribution of t-quark loop.

$$\sigma(gg \to h_a) = \sigma_{SM}^{(wb)}(gg \to h|M_a)\left[|Re(\chi_a^t)|^2 + |Im(\chi_a^t)|^2 \Phi^{(O/E)}(4M_t^2/M_a^2)\right].$$

$\Phi^{(O/E)}(r)$ – ratio of two well known loop integrals, defined for CP-odd and CP-even Higgs bosons respectively at $M_a = 300$ GeV we have $\Phi^{(O/E)}(r) \approx 2.7$. In the case a $\sigma(gg \to h_a) \ll \sigma_{SM}^{wb}(gg \to h(m_a))$. In the case b the $\sigma(gg \to h_a) > \sigma(gg \to h_{sM}^{wb}(M_a))$.

At $M_a < 350$ GeV for Yukawa sector similar to Model I one can hope to observe h_a as the narrow peak in the production of $\bar{b}b$ pairs:

Benchmark example for CP-even $\boldsymbol{h_2}$ with $\boldsymbol{M_2 = 300}$ GeV.

At this mass $\Gamma^{(wb)}_{SM,tot} = 8.4$ GeV, $BR^{(wb)}_{SM}(h \to b\bar{b}) \approx 0.0008$, $\Gamma^{(wb)}_{SM}(h \to gg) \approx 3.4$ MeV.

Let $|\chi^t_2| = |\chi^b_2| = 6$, $|\chi^V_2| = 0.2$. In this case

$\Gamma(h_2 \to b\bar{b}) = |\chi^b_2|^2 \cdot 7$ MeV ≈ 250 MeV,

$\Gamma(h_2 \to W^+W^-(ZZ)) = |\chi^V_2|^2 \cdot 8.4$ GeV ≈ 340 MeV,

$\Gamma(h_2 \to gg) = |\chi^t_2|^2 \cdot 3.4$ MeV ≈ 120 MeV.

It gives $\Gamma_2 \approx 0.7$ GeV with $BR(h_2 \to b\bar{b}) \approx 0.36$.

The cross section $\sigma(gg \to h_a \to \bar{b}b) \approx |\chi^t_a|^2 \sigma^{(wb)}_{SM}(gg \to h|M_a) BR(h_2 \to b\bar{b})$.

The possible CP odd admixture in h_2 increases result.

At $M_{a_1} > 350$ GeV, $M_{a_2} > 350$ GeV. Either two separated enhancements in $t\bar{t}$ production or even one enhancement (at $|M_{a_1} - M_{a_2}| \leq \Gamma_{a_1} + \Gamma_{a_2}$).

In the description of widths $h_a \to \gamma\gamma$, $h_a \to Z\gamma$ new information about vertices $H^+H^-h_a$ should be added. The knowledge of all masses and couplings χ_V^a don't limit values of these vertices.

Using of charged Higgs

(models $2HDM + p_2(HS_2M) + p_1(HS_1M)$).

We assume that masses $M_\pm$ are not extremely large and their observation has good signature.

• The partial width $\Gamma(H^+ \to W^+ h_1$ is small, while at $M_\pm > M_W + M_a$ the partial width $\Gamma(H^+ \to W^+ h^a$ is relatively large for $a \geq 2$.

• The production of Higgs boson h_1 in association with $H^\pm W^\mp$ is hardly observable.

• The search for Higgs bosons h_a can be successful in the following channels:

$q_1\bar{q}_2 \to H^+ h_a$, $q\bar{q} \to W^\mp H^\pm h_a$ at LHC,

$e\gamma \to \nu H^- h_a$, $e^+e^- \to H^\pm W^\mp h_a$ at ILC,

$\gamma\gamma \to H^\pm W^\mp h_a$ at PLC.

Certainly, ILC and PLC have advantages due to much better background conditions.