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Higgs physics as a proble of new physics

S. Kanemura
Department of Physics, University of Toyama - Toyama 930-8555, Japan

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Summary. — The discovery of the Higgs boson at the LHC has opened the door to clarifying the mechanism of electroweak symmetry breaking and the origin of particle masses. The Higgs sector in the SM is the simplest possible one but is not based on a fundamental theoretical principle, so that there is also the possibility of non-minimal Higgs sectors. While the standard model is not in contradiction with current LHC data within the errors, many extended Higgs sectors can also reproduce these data. An extended Higgs sector often appears in new physics models beyond the standard model, so that this allows to determine new physics from the Higgs sector. In this talk, we discuss various aspects of extended Higgs sectors, in particular their phenomenological properties and testability at future experiments, as the International Linear Collider.

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1. – Introduction

Why is the Higgs boson important? The Higgs field couples to all the particles in the standard model (SM). The Higgs field obtains the vacuum expectation value (VEV) v by electroweak symmetry breaking (EWSB), triggered by some unknown dynamics. The weak gauge bosons become massive due to the consequence of the Higgs mechanism. All the quarks and the charged leptons get masses via the Yukawa interactions by the replacement of the Higgs field by v. Even neutrinos (although this is physics beyond the SM) can have their tiny masses through dimension five operators or neutrino Yukawa couplings after the Higgs boson obtains v. The Higgs field is indeed the origin of mass.

It is also known that the Higgs field is necessary to stabilize the unitarity of partial wave amplitudes of elastic scatterings of longitudinally polarized weak bosons such as $W_L^+W_L^- \to W_L^+W_L^-$ at high energies. Without the Higgs field the S-wave amplitude $a^0(W_L^+W_L^- \to W_L^+W_L^-)$ blows up at high energies $a^0 \sim G_F s/(8\pi\sqrt{2})$ where G_F is the Fermi constant and $\sqrt{s}$ is the collision energy, and the unitarity is broken at a TeV scale. The introduction of the Higgs field cancels such a behavior, and a^0 is a constant at high energies; $a^0 \sim -G_F m_h^2/(4\pi\sqrt{2})$, where m_h is the mass of the Higgs boson. Therefore, the Higgs field is necessary to save unitarity. The condition that the perturbative calculation does not break unitarity gives the upper bound such as $m_h < 1\,\text{TeV}$ [1].

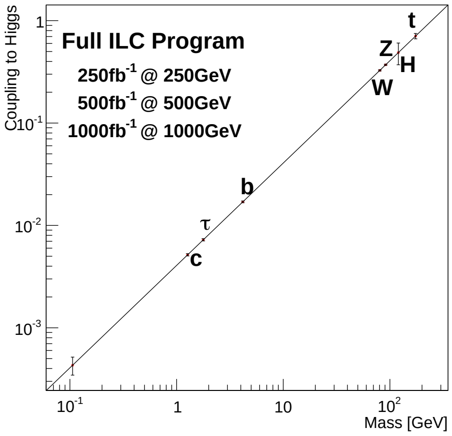

Fig. 1. – Relation between the mass and the coupling with the Higgs boson in the standard model. The expected error precision in the full ILC program is also indicated [2].

There is no theoretical principle to determine the structure of the Higgs sector within the SM. One isospin doublet scalar field Φ is simply introduced as the minimum form in the SM. Under renormalizability, its potential can be uniquely written as

$$V(\Phi) = +\mu^2|\Phi|^2 + \lambda|\Phi|^4. \tag{1}$$

By putting an assumption of $\mu^2 < 0$ and $\lambda > 0$, the shape of the potential becomes like a Mexican hat, and the electroweak symmetry is spontaneously broken at the vacuum $\langle\Phi\rangle = (0, v/\sqrt{2})^T$, where $v \simeq 246\,\text{GeV}$. Consequently, all SM particles but photons and gluons obtain masses from the unique VEV v. In fig. 1, the universal relation between couplings and masses is shown.

The SM gives a simple description for EWSB. However, the following questions are in order. Why is it the minimal form? How we obtain $\mu^2 < 0$? What is the origin of the Higgs force λ? Now that a Higgs boson has been found with the mass of about 125 GeV, the time has come to consider these questions more seriously.

2. – Extended Higgs sectors and new physics models

As there is no principle in the SM Higgs sector, there are many possibilities for non-minimal Higgs sectors. Notice that while the current LHC data do not contradict the predictions in the SM, most of the extended Higgs sectors can also satisfy current data as well. These extended Higgs sectors are sometimes introduced to solve the problems beyond the SM such as baryogenesis, dark matter and tiny neutrino masses. Each scenario does have a specific Higgs sector.

It is also well known that the introduction of the elementary scalar field is problematic, predicting the quadratic divergence in the radiative correction to the mass. Such quadratic divergence causes the hierarchy problem. There have been many scenarios proposed to solve this problem such as Supersymmetry, Dynamical Symmetry Breaking, Extra dimensions and so on. Many of the models based on these new paradigms predict specific Higgs sectors in their low energy effective theories.

Therefore, to determine the Higgs sector by experiments is essentially important not only to clarify the mechanism of EWSB but also as a window to new physics beyond the SM. The discovery of the 125 GeV Higgs boson at the LHC is surely a great step for determination of the structure of the Higgs sector. From the detailed study of the Higgs sector, we can determine the model of new physics.

What kind of extended Higgs sectors we can consider? As the SM Higgs sector does not contradict the current data within the errors, we may think that there is at least one isospin doublet field. An extended Higgs sector can contain additional isospin multiplets to the doublet of the SM. In principle, there can be infinite kinds of extended Higgs sectors. As a simple example, we may consider models with one additional singlet field, one additional doublet field, one additional triplet field and so on. These extended Higgs sectors can receive constraints from the current data of many experiments including those for the electroweak rho parameter and for flavor changing neutral currents (FCNCs).

The rho parameter for a Higgs sector with N multiplets is given at the tree level by

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_i \left\{4T_i(T_i+1) - Y_i^2\right\} |v_i|^2 c_i}{\sum_i 2Y_i^2 |v_i|^2}\,, \tag{2}$$

where T_i and Y_i ($i = 1, \ldots, N$) are isospin and hyper charges of the i-th multiplet ($Q_i = T_i + Y_i/2$), and $c_i = 1/2$ for real fields ($Y_i = 0$) and 1 for completx fields. The data shows $\rho = 1.0004^{+0.0003}_{-0.0004}$ [3]. It is found that Higgs sectors with additional doublets $(T_i, Y_i) = (1/2, 1)$ (and singlets) predict $\rho = 1$ at the tree level, like the SM Higgs sector. Hence, multi-doublet extensions would be regarded as natural extensions. On the other hand, the introduction of higher representation fields except for the septet field causes deviations in the rho parameter from unity at the tree level. For example, in the model with a triplet field $\Delta(1,2)$ with the VEV v_Δ, $\rho \sim 1 - 2(v_\Delta/v)^2$ is given, so that a tuning $(v_\Delta/v)^2 \ll 1$ is required to satisfy the data. Thus such models are relatively exotic.

It is well known that the multi-Higgs structure receives a severe constraint from the results of FCNC experiments. FCNC processes such as $K^0 \to \mu^+\mu^-$ and B^0-$\bar{B}^0$ are strongly suppressed [3]. In the SM with a doublet Higgs field, the suppression of FCNC processes is perfectly explained by the GIM mechanism [4]. In multi Higgs doublet models where multiple Higgs doublets couple to one quark or charged lepton, Higgs boson mediated FCNC can easily occur. In order to avoid FCNC, it is required that Higgs bosons have different quantum numbers [5].

3. – Two-Higgs doublet model

Let us discuss the two-Higgs doublet model (2HDM) with Φ_1 and Φ_2, the minimal extension with multi-doublet structure. For avoiding FCNC, a softly-broken discrete symmetry under $\Phi_1 \to +\Phi_1$ and $\Phi_2 \to -\Phi_2$ is imposed [5]. The Higgs potential is then given by

$$\begin{aligned} V = {} & +\mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 - \mu_3^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\ & +\lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\left\{\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right\}. \end{aligned} \tag{3}$$

The doublet fields are parameterized as

$$\Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix} \qquad (i = 1, 2), \tag{4}$$

TABLE I. – *Four types of Yukawa interaction in the* 2HDM.

	Φ_1	Φ_2	u_R^i	d_R^i	e_R^i	Q_L^i, L_L^i
Type I	$+$	$-$	$-$	$-$	$-$	$+$
Type II	$+$	$-$	$-$	$+$	$+$	$+$
Type X	$+$	$-$	$-$	$-$	$+$	$+$
Type Y	$+$	$-$	$-$	$+$	$-$	$+$

where vacuum expectation values v_1 and v_2 are expressed by v ($\simeq 246\,\text{GeV}$) and $\tan\beta$ by $v^2 = v_1^2 + v_2^2$ and $\tan\beta = v_2/v_1$. The mass matrix of the CP-even scalars is diagonalized by introducing the mixing angle α, and two mass eigenstates h and H are obtained. The mass matrices of CP-odd and charged scalars are diagonalized by β, and physical mass eigenstates A and $H^\pm$ are obtained, respectively. Their masses are given in the decoupling regime ($M \gg v$) by

$$\begin{aligned}
(5)\qquad m_h^2 &= \left(\lambda_1\cos^4\beta + \lambda_2\sin^4\beta + \frac{1}{2}(\lambda_3+\lambda_4+\lambda_5)\sin^2 2\beta\right) v^2 + \mathcal{O}\left(\frac{v^2}{M^2}\right),\\
m_H^2 &= M^2 + (\lambda_1+\lambda_2-2(\lambda_3+\lambda_4+\lambda_5))\sin^2\beta\cos^2\beta\, v^2 + \mathcal{O}\left(\frac{v^2}{M^2}\right),\\
m_{H^\pm}^2 &= M^2 - \frac{\lambda_4+\lambda_5}{2}v^2, \qquad m_A^2 = M^2 - \lambda_5 v^2,
\end{aligned}$$

where M ($= \sqrt{\mu_3^2/\sin\beta\cos\beta}$) represents the soft breaking scale of the discrete symmetry.

Under the discrete symmetry, there are four possible charge assignments for quarks and charged leptons in table. I [6]. In Type I, all the quarks and charged leptons obtain their masses from Φ_1. In Type II, Φ_1 gives masses to down-type quarks and charged leptons, while Φ_2 does to the up-type quarks. In Type X, Φ_1 gives mass to the quarks and Φ_2 does to charged leptons. The rest possibly is called as Type Y. The phenomenology for the difference among types of Yukawa interactions have been studied in refs. [7,8] There are two possibilities to explain the current data which show SM-like. When $M^2 \gg v^2$, the additional Higgs bosons are as heavy as $\sqrt{M^2}$, and only h stays at the electroweak scale behaving as the SM-like Higgs boson. The effective Lagrangian is

$$(6)\qquad \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{O}\left(\frac{v^2}{M^2}\right).$$

Another case is $\sqrt{M^2} \sim v$. In the limit where the hWW coupling takes the same value as the SM prediction $\sin(\beta-\alpha) = 1$, all the Yukawa couplings with h takes the SM values, and HWW is negligible. In this case, h behaves as the SM-like Higgs boson. When $\sin(\beta-\alpha)$ is slightly smaller than unity, the couplings hVV ($V = W, Z$), $hff(f = t, b, c, \ldots)$ deviate from the SM predictions depending on type of Yukawa interaction. By detecting the pattern of the deviation in each Higgs boson coupling, we can distinguish the type of Yukawa coupling in the 2HDMs.

4. – Fingerprinting of models with future precision data at the ILC

In 2015, the LHC experiment will restart with the highest energy 14 TeV. Extra Higgs bosons in extended Higgs sectors can be discovered as long as their masses are not

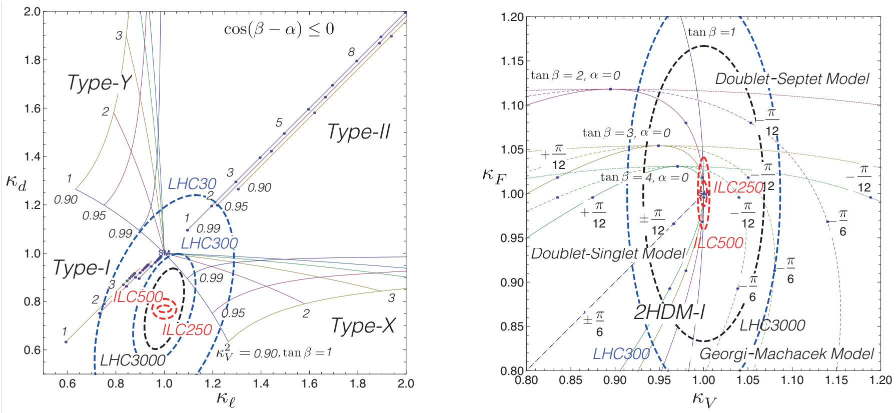

Fig. 2. – Left: The scaling factors in 2HDM with four types of Yukawa interactions. Right: The scaling factors in models with universal Yukawa couplings. The current LHC bounds and the expected LHC and ILC sensitivities are also shown at the 68.27% CL. For details, see the text and ref. [11]

too large as compared to the electroweak scale. On the other hand, at the International Linear Collider (ILC) [2], these extended Higgs sectors can also be tested by accurately measuring the coupling constants with the discovered Higgs bosons h. In non-minimal Higgs models, the relation in fig. 1 does not hold, so that we can test the SM by using this relation. This is complementary with the direct searches at the LHC.

The gauge couplings and Yukawa interactions of h are given by

$$\mathcal{L}^{\text{int}} = +\kappa_W \frac{2m_W^2}{v} hW^{+\mu}W_\mu^- + \kappa_Z \frac{m_Z^2}{v} hZ^\mu Z_\mu - \sum_f \kappa_f \frac{m_f}{v} \overline{f} f h + \dots, \tag{7}$$

where κ_V ($V = W$ and Z) and κ_f ($f = t, b, c, \dots$) are the scaling factors measuring the deviation from the SM predictions. In the SM, we have $\kappa_V = \kappa_f = 1$.

In the 2HDM, κ_V are given by $\kappa_V = \sin(\beta - \alpha)$, while those for the Yukawa interactions are given depending on the type of Yukawa interaction [7]. For the SM-like limit $\kappa_V = 1$, all the scaling factors κ_f become unity. In fig. 2 (left), the scale factors κ_f in the 2HDM with the softly-broken symmetry are shown on the κ_ℓ-κ_d plane for various values of $\tan\beta$ and κ_V ($= \sin(\beta - \alpha)$). The points and the dashed curves denote changes of $\tan\beta$ by steps of one. κ_V ($= \kappa_W = \kappa_Z$) is taken as $\kappa_V^2 = 0.99, 0.95$ and 0.90. The current LHC constraints as well as the expected LHC and ILC sensitivities for κ_d and κ_ℓ are also shown at the 68.27% Confidence Level (CL). For the current LHC constraints (LHC30), we take the numbers from the universal fit in eq. (18) of ref. [9]. For the future LHC sensitivities (LHC300 and LHC3000), the expectation numbers are taken from the Scenario 1 in table. 1 of ref. [10]. The central values and the correlations are assumed to be the same as in LHC30. The ILC sensitivities are taken from table. 2.6 in ref. [2]. The same central value without correlation is assumed for the ILC sensitivity curves. For more details see ref. [11], and for some revisions see ref. [12]. The analysis including radiative corrections has been done recently [13].

Precision measurements for the couplings of the SM-like Higgs boson h at the ILC can also discriminate exotic Higgs sectors. In a model with mixing of h with a singlet

Higgs field, we have a universal suppression on the coupling constants, $\kappa_F = \kappa_V = \cos\theta$ with θ being the mixing angle between the doublet field and the singlet field. However, $\kappa_F \neq \kappa_V$ is predicted in more complicated Higgs sectors such as the 2HDM, the Georgi-Machacek model [14] and the doublet-septet model [15]. Notice that in exotic models with higher representation scalar fields such as the Georgi-Machacek model and doublet-septet model, κ_V can be greater than 1. This can be a signature of exotic Higgs sectors. In fig. 2 (right), the predictions for the scale factors of the universal Yukawa coupling κ_F and the gauge coupling κ_V are plotted in exotic Higgs sectors for each set of mixing angles. The current LHC bounds, expected LHC and ILC sensitivities for κ_F and κ_V are also shown at the 68.27% CL. Therefore, exotic Higgs sectors can be discriminated by measuring κ_V and κ_F precisely. For details, see ref. [11, 12].

5. – Conclusion

Extended Higgs sectors appear in new physics models beyond the SM. We can explore new physics from the structure of the Higgs sector. The Higgs sector can be determined by precisely measuring the properties of h at the LHC and the ILC. In particular, using high ability of the ILC for measuring the Higgs boson couplings, we can discriminate extended Higgs sectors, and consequently narrow down the new physics models.

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