A NEW PARADIGM: ROLE OF ELECTRON-POSITRON AND HADRON COLLIDERS

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Abstract

In 2012, a light scalar boson (denoted as H(125) in this paper) was discovered at the LHC. We explore the possible correlation between the lightness of H(125) and the smallness of CP-violation based on the Lee model, namely the spontaneous CP-violation two-Higgs-doublet-model. It is a new way to understand why H(125) is light. Based on this we propose that it is the much heavier scalar bosons, instead of the H(125), which need to be understood. This opens a new paradigm that one tries to understand the electro-weak symmetry breaking and CP violation. For the new paradigm, similar to many other physics beyond the standard model, one need both electron-positron and higher energy hadron collider, as well as the low energy experiments, in order to pin down the whole picture.

INTRODUCTION

The organizers of HF2014 invited me to give an overview on physics, especially the physics beyond the standard model (BSM), which can be investigated at Higgs Factories (HF). Since a new scalar (denoted as H(125) in this paper) was discovered in 2012, LHC is an obvious HF. For one hand, LHC can do much more in the future run, on the other hand, LHC precision is limited by its hadronic environment. Next generation electron-positron collider and higher energy hadron collider are under extensive discussion. One predominant example is the CEPC (circular electron and positron collider) with $\sqrt{s} = 240$ GeV or so, plus the possible update to super proton-proton collider (SPPC) with $\sqrt{s} = 50 - 100$ TeV or higher. It is quite natural to expect that CEPC can reach much higher precision that those of LHC, and SPPC can detect the much higher BSM scale than that of the LHC.

In principle, the whole BSM picture can usually be revealed via the combination efforts of LHC, CPEC/ILC, SPPC, FCC and other high energy colliders, as well as the low energy experiments which have certain unique opportunity, for example, CP violation and/or rare processes. There are numerous BSM, how to give the audience a relative global, objective and persuasive picture is a challenging task. In the end we decide to firstly give a brief overview on BSM motivations, then discuss a possible new paradigm as an example, which need high energy electron-positron and hadron colliders to pin down the whole picture.

MOTIVATION FOR BSM

The discovery of H(125) is revolutionary. For the fist time in the history of particle physics, we have a complete theory to describe the electro-weak and strong interactions. If the H(125) is really the SM one, as many people believe, SM can be applicable to a very high scale, much higher than the weak scale. However we also have many reasons that BSM should exist. In this section, the motivations for BSM are categorized into 4 classes.

Motivation(I): Test New Types of Interactions

In the SM, there are 3 types of interactions:

- Gauge interaction

- Yukwa interaction

- Higgs self interaction

Gauge interaction, which can describe the strong and electro-weak interactions excellently, is well-tested for most cases. The Yukawa interaction and Higgs self-interaction are new types of interactions, and which need to be checked in HF. In the SM Yukawa interaction is the origin of fermion mass, and induce the flavor changing processes. BSM can easily affect Yukawa interaction. For the Higgs self interaction in the SM, once Higgs boson mass is fixed, the triple h^3 and quartic h^4 interactions are also fixed. One motivation to measure the Higgs self couplings is related with electro-weak phase transition. In order to account for the matter dominant Universe, the Higgs self couplings are usually greatly altered. Another popular motivation is that Higgs potential might be more complicated than that in the SM. Therefore measuring the Higgs self interaction is the way to reconstruct the Higgs potential, though quite challenging.

Motivation (II): Account for Astrophysical Observations

There are several astrophysical observations (dark matter (DM), baryon asymmetry, and inflation) which may be related to BSM at O(TeV). There is not suitable DM candidate in the SM. In order to keep DM stable or pseudo-stable, one usually introduces new symmetry, and one popular example is the supersymmetry (SUSY). SUSY can provide a natural SM candidate is thought as one of its successes. In order to construct a complete theory, one likely

introduces more Higgs fields, for example in the supersymmetric model we have to introduce at least two Higgs doublets.

SM can't account for baryon asymmetry in the Universe, though the 3 Saharov conditions are fulfilled. If one insists on the electro-weak baryon-genesis, the Higgs couplings must be altered, which can be tested in HF. Another possible connection between baryon asymmetry and HF is the CP violation. New CP violation other than CKM matrix may be revealed in HF.

Motivation (III): Theoretical Ones

There are too many parameters in SM which could be reduced if we know what beneath the Higgs field(s). The introduction of scalar field brings some shortcomings to the theory, for example the naturalness issue. In order to make the theory natural, one has to introduce new strong interaction, new symmetry, or extra-dimension etc. There are many other theoretical issues, for example: what is the origin of P and CP violation, why are there 3 generations etc.

Last but not least, we don't include the gravity in the theory. HF may shed light on the nature of gravity, reveal hints for further knowledge on the space-time and quantum theory.

Motivation (IV): "Common Sense"

For the fundamental science, exploring the unknown and discovering the unexpected phenomena are the primary driving force for the progress. We call this as "common sense" motivation. To pursue the higher energy and smaller distance is the obvious next goal.

As the second "common sense" motivation, H(125) is special. Since the discovery of H(125) we have this new physical object which need the experimentalists to measure its properties as precisely as possible and discover possible deviations from the SM predictions.

SMALLNESS OF CP VIOLATION AND THE LIGHTNESS OF H(125)

A Story

In 2006, officials of both PRC and US signed a document which indicated that a joint workshop would be held in June 2007, in order to explore the possibility of parity spontaneous breaking at electron-positron colliders. In January 2007, a mini-workshop was organized by Prof. K.T. Chao and Prof. Y.P. Kuang in order to prepare for the workshop. I was invited to give a theoretical and experimental review on left-right symmetric models. During that time, the popular parity restoration models is left-right symmetric models. My personal impression on this model is that the scale is too high to electron-positron colliders, even for LHC, because the low energy measurements like $K_0 - \bar{K}_0$ mixing and direct search from Tevatron have put very strict limits on right-handed gauge bosons. After the mini-workshop, I realized that other parity restoration approaches, like mirror

models, might be tested at electron-positron collider and L-HC [1]. In fact the parity of weak interaction is maximally violated, while CP is a quite good approximate symmetry. This is one of reasons why the left-right symmetric models suffering so severe constraints. During the June workshop, the honorary chair of which is T.D. Lee, my impression on this topic kept the same.

In July 2012, the new scalar H(125) was discovered by ATLAS and CMS of the LHC, which surprised many theorists including me. In the SM, the discovery is not strange. However in the BSM, the scalar mass tends to be the BSM scale. We were thinking possible new mechanism to account for the new discovery. In the end of 2012, just before the celebration of 80's birthday of Prof. Kuang, I wrote the paper on the possible connection between the spontaneous CP violation and the mass of the new scalar [2, 3]. Some people concerned on the viability of the model. After more than one year, after checking all important measurements, we found [4] the model does viable and can be tested in the future LHC and electron-positron colliders. Meanwhile we began to think the possible implication for understanding electro-weak symmetry breaking and origin of CP violation.

Smallness of CP Violation

CP has been thought strict conserved after the discovery of P violation in 1957. However such situation did not last long, tiny CP violation was first discovered in neutral K-meson in 1964. Now all measured CP violated effects in neutral K- and B-meson, and charged B meson systems can be successfully accounted for by the CKM matrix, which is usually parameterized as the Wolfenstein formalism

$$
V_{\text{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \\ + \mathcal{O}(\lambda^4) \tag{1}
$$

In order to measure magnitude of CP violation independent on basis, the Jarlskog invariant [5][6] was introduced as

$$
J = A^2\lambda^6\eta = (2.96^{+0.20}_{-0.16}) \times 10^{-5}. \tag{2}
$$

The smallness of J means the smallness of CP-violation in the SM. In order to understand the smallness of CP violation, one has to go beyond the SM.

Lightness of H(125)

BSM is well motivated as we have discussed in the last section. BSM scale is usually pushed to a much higher value than that of weak interaction, given the great success of the SM. In such circumstance, the 125 GeV scalar boson is unnatural, i.e. the lightness of the new scalar must link to certain mechanism. It should be emphasized that the issue of the lightness of H(125) differs in the SM and the BSM. In the SM, the mass of Higgs boson is only a free parameter, and $m_H = 125$ GeV simply implies that the interactions are in the weak regime. However in some BSM

models there exists a light scalar naturally. We enumerate several examples, (1) in the minimal super-symmetric model (MSSM), the lightest Higgs boson mass should be less than 140GeV after including higher-order corrections; (2) in the little higgs models, a Higgs boson which is treated as a pseudo-Nambu-Goldstone boson must be light due to classical global symmetry and it acquires mass through quantum effects only; (3) the anomalous in scale invariance models can also generate a light Higgs boson; (4) the lightness of Higgs boson can intimately connect with the spontaneous CP violation. While the first three approaches base on the *conjectured* symmetry, the last one utilizes the *observed* approximate CP symmetry. Historically Lee proposed the spontaneous CP violation in 1973 [7] as an alternative way to induce CP violation. For the fourth approach, Lee's idea is extended to account for the lightness of the observed Higgs boson.

Lee Model

In order to analyze the connection between spontaneous CP violation and the Higgs boson mass, we begin with the description of Lee model [7] assuming that in the whole lagrangian there are no explicit CP-violated terms, which means all the CP-violated effects come from a complex vacuum.

For the Lee model, the interactions of scalar fields can be written as [7]

$$\mathcal{L} = (D_\mu \phi_1)(D^\mu \phi_1) + (D_\mu \phi_2)(D^\mu \phi_2) - V(\phi_1, \phi_2). \quad (3)$$

Here

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + R_1 + iI_1}{\sqrt{2}} \end{pmatrix}, \qquad \phi_1 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 e^{i\xi} + R_2 + iI_2}{\sqrt{2}} \end{pmatrix} \quad (4)$$

are the two Higgs doublets. We can see the ξ is the only source of CP violation. Here there are two vacuum expectation values v_1, v_2 and $v = \sqrt{v_1^2 + v_2^2} = 246\text{GeV}$ as usual. Defining $R(I)_{ij}$ as the real(imaginary) part of $\phi_i^\dagger \phi_j$, we can write a general potential as

$$
\begin{aligned}
V &= V_2 + V_4 \\
&= \mu_1^2 R_{11} + \mu_2^2 R_{22} \\
&\quad + \lambda_1 R_{11}^2 + \lambda_2 R_{11} R_{12} + \lambda_3 R_{11} R_{22} \\
&\quad + \lambda_4 R_{12}^2 + \lambda_5 R_{12} R_{22} + \lambda_6 R_{22}^2 + \lambda_7 I_{12}^2. \quad (5)
\end{aligned}
$$

We can also write the general Yukawa couplings as

$$
\begin{aligned}
\mathcal{L}_y &= -\bar{Q}_{Li}(Y_{1d}\phi_1 + Y_{2d}\phi_2)_{ij} D_{Rj} \\
&\quad - \bar{Q}_{Li}(Y_{1u}\tilde{\phi}_1 + Y_{2u}\tilde{\phi}_2)_{ij} U_{Rj}, \quad (6)
\end{aligned}
$$

in which $\tilde{\phi}_i = i\sigma_2 \phi_i^*$ and all Yukawa couplings are real.

After rotating away Goldstone mode, we can expand the neutral Higgs boson mass matrix $\tilde{m}$ in series of $t_\beta(s_\xi)$ as

$$\tilde{m} = \tilde{m}_0 + (t_\beta s_\xi)\tilde{m}_1 + (t_\beta s_\xi)^2 \tilde{m}_2 + \cdots \quad (7)$$

We found

$$\lim_{t_\beta s_\xi \to 0} \det(\tilde{m}) = \det(\tilde{m}_0) = 0 \quad (8)$$

which means a zero eigenvalue of $\tilde{m}_0$ thus there must be a light neutral scalar when $t_\beta s_\xi$ is small. To the leading order of $t_\beta s_\xi$, for the lightest scalar h, we have

$$
\begin{aligned}
m_h^2 &= \frac{v^2 t_\beta^2 s_\xi^2}{2}\left(\frac{(\tilde{m}_1)_{12}^2}{(\tilde{m}_0)_{22}} + \frac{(\tilde{m}_1)_{13}^2}{(\tilde{m}_0)_{33}} + (\tilde{m}_2)_{11} \right) \\
h &= I_2 + t_\beta s_\xi \left(\frac{(\tilde{m}_1)_{12}}{(\tilde{m}_0)_{22}}(c_\theta R_1 + s_\theta R_2) \right. \\
&\quad \left. + \frac{(\tilde{m}_1)_{13}}{(\tilde{m}_0)_{33}}(c_\theta R_2 - s_\theta R_1) - \frac{I_1}{t_\xi} \right), \quad (9)
\end{aligned}
$$

where $\theta = (1/2)\tan^{-1}(2\lambda_2/(4\lambda_1 - \lambda_4 + \lambda_7))$.

From the Yukawa couplings we will get the mass matrixes for fermions as

$$(M_U)_{ij} = \frac{v}{\sqrt{2}}(Y_{1u}c_\beta + Y_{2u}s_\beta e^{-i\xi})_{ij}, \quad (10)$$

$$(M_D)_{ij} = \frac{v}{\sqrt{2}}(Y_{1d}c_\beta + Y_{2d}s_\beta e^{i\xi})_{ij}. \quad (11)$$

We can always perform the diagonalization for $M_{U(D)}$ with matrixes $U(D)_L$ and $U(D)_R$ as

$$U_L M_U U_R^\dagger = diag\,(m_u, m_c, m_t), \quad (12)$$

$$D_L M_D D_R^\dagger = diag\,(m_d, m_s, m_b). \quad (13)$$

And $V_{\text{CKM}} = U_L D_L^\dagger$ is the CKM matrix.

We choose all the nine free parameters as nine observables in Higgs sector: masses of four scalars m_h, m_2, m_3 and $m_{H^\pm}$; vacuum expected values v_1, v_2, ξ and two mixing angles for neutral bosons. We choose them c_1 and c_2 defined as

$$\mathcal{L}_{h_i VV} = c_i h_i \left(\frac{2m_W^2}{v} W_\mu^+ W^{\mu-} + \frac{m_Z^2}{v} Z_\mu Z^\mu \right) \quad (14)$$

which just means the $h_i VV$ vertex strength comparing with that in SM. There is a sum rule $c_1^2 + c_2^2 + c_3^2 = 1$ due to spontaneous electro-weak symmetry broken, thus only two of the c_i are free.

In the scalar sector, for non-degenerate neutral Higgs bosons, a quantity $K = c_1 c_2 c_3$ measures the CP violation effects [8][9], while in Yukawa sector, the Jarlskog invariant J [6] measures that. In this scenario, to the leading order of $t_\beta s_\xi$, we have

$$K = c_1 c_2 c_3 = -s_\theta c_\theta (1 + \eta_1) t_\beta s_\xi \propto t_\beta s_\xi \quad (15)$$

In order to calculate J, we define matrix $\hat{C}$ as

$$\hat{C} \equiv \left[M_U M_U^\dagger, M_D M_D^\dagger \right]. \quad (16)$$

We can always choose a basis in which the diagonal elements of $\hat{C}$ are zero. Thus

$$
\begin{aligned}
\hat{C} &= \begin{pmatrix} 0 & C_3 & -C_2 \\ -C_3 & 0 & C_1 \\ C_2 & -C_1 & 0 \end{pmatrix} + i\begin{pmatrix} 0 & C_3^* & C_2^* \\ C_3^* & 0 & C_1^* \\ C_2^* & C_1^* & 0 \end{pmatrix} \\
&= \left(\text{Re}\hat{C} + i\text{Im}\hat{C} \right) \quad (17)
\end{aligned}
$$

It can be proved that [4]

$$J = \frac{\prod C_i \sum (C_i^*/C_i)}{\prod \left(m_{U_i}^2 - m_{U_j}^2\right) \prod \left(m_{D_i}^2 - m_{D_j}^2\right)} \propto t_\beta s_\xi. \quad (18)$$

According to the equations (15), (18), and (9), we propose that the lightness of the Higgs boson and the smallness of CP-violation effects could be correlated through small $t_\beta s_\xi$ since both the Higgs mass m_h and the quantities K and J to measure CP-violation effects are proportional to $t_\beta s_\xi$ at the small $t_\beta s_\xi$ limit.

A NEW PARADIGM

In the last section, the connection between small CP violation and H(125) is explored in the simplest spontaneous CP violation Lee model. Based on the above discussion, a new paradigm emerges. In the past studies, one tried to account for the lightness of the H(125). In the new paradigm, the mass of H(125) is due to the approximate CP symmetry and the extra scalar bosons can be much heavier, e.g. at O(TeV) even in the strong-coupled regime. This opens a new approach to understand the electro-weak symmetry breaking and the origin of CP violation. The schematic diagram is shown in Fig. 1. For the optimistic case (from the point view of experimentalists), the extra new scalars can be not so heavy. For this case, LHC has the good opportunity to discover them.
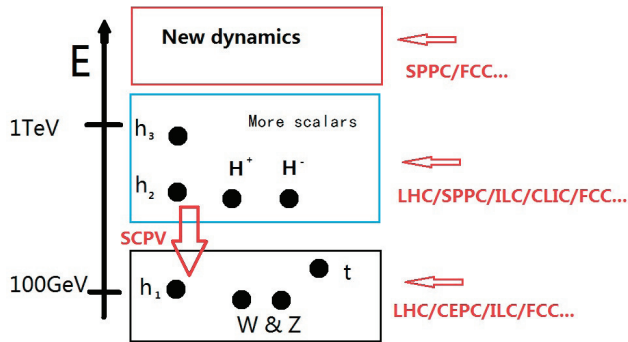

Figure 1: Schematic diagram for a new paradigm.

The generic feature of this new paradigm is summarized

- H(125) is not SM-like, instead H(125) is the CP mixing state

- There are other heavy neutral and charged Higgs bosons

- There are usually extra CP violation in scalar sector, besides CKM matrix, though they arise both from the complex vacuum

- The scale of the new mechanism for the complicated scalar sectors is higher.

PHENOMENOLOGY: ROLE OF ELECTRON-POSITRON AND HADARON COLLIDERS

Based on studies of Ref. [4], the Lee model is still viable confronting the high and low energy experiments. The next natural question is how to confirm/exclude this model at future facilities.

We treat the H(125) as the lightest neutral Higgs boson. If Lee model is true, the extra neutral and charged Higgs bosons should be discovered at high energy colliders. As the general rules, the lighter the extra Higgs bosons, the easier they can be produced. In order to confirm the Lee model, another possible signal can be the FCNC decay of the neural Higgs bosons which are unobservable small in the SM. Furthermore the CP properties of the Higgs boson are essential measurements, though it is a very challenging task.

As we have pointed out [4] that there is no SM limit in this scenario, thus it is always testable at the future colliders, such as LHC with $\sqrt{s} = 14$TeV, CEPC, ILC, or TLEP with $\sqrt{s} = (240 \sim 250)$TeV, even before the discovery of other neutral Higgs bosons and charged Higgs boson. The coupling between H(125) and other particle (especially $W^\pm$ and Z^0) are usually suppressed by the factor of $\mathcal{O}(t_\beta s_\xi)$. In the $b\bar{b}$ decay channel or any VBF, VH associated production channel, a significant suppression can be the first sign of this scenario. On the contrary if the signals become even more SM-like, this scenario will be disfavored.

For future LHC with $\sqrt{s} = 14$TeV, the signal strengths will be measured with an uncertainty of about 10% at the luminosity 300fb^{-1} [10][11]. These measurements can be used to constrain c_V (which is c_1 in the last section). A Higgs boson with $c_V \geq (0.6 \sim 0.7)$ is hardly to be pseudoscalar dominant thus if $c_V \leq (0.6 \sim 0.7)$ is excluded, we can say this scenario is excluded. So we can test this scenario by fitting the signal strengths. We list the estimating results in Tab. 1. It should be noted that the true abil-

Table 1: Abilities to test the scenario at $\sqrt{s} = 14$TeV LHC. Lower limit for the allowed c_V at 2σ and 3σ level are listed in the tables. For the up/down tables we assume all signal strengths are consistent with SM at $1\sigma/2\sigma$ level respectively.

Excluded level	2σ	3σ
300fb^{-1}	0.62	0.55
3000fb^{-1}	0.77	0.72
Excluded level	2σ	3σ
300fb^{-1}	0.53	0.45
3000fb^{-1}	0.7	0.65

ity to test this scenario depends strongly on the real signal strengths from future experiments.

At a HF with the e^+e^- initial state at $\sqrt{s} = (240 \sim 250)$GeV, the dominant production process for a Higgs bo-

son is associated with a Z^0 boson. Another important production process is through VBF. In this scenario it is suppressed by a factor c_1^2 thus this scenario can be excluded if the total cross section favors SM. For the total cross section, a measurement with $\mathcal{O}(10\%)$ uncertainty is accurate enough to distinguish the scenario we discussed in this paper and SM at 3σ or even 5σ significance. Such accuracy can be easily achieved at CEPC/ILC/TLEP.

For this new paradigm, the role of the higher energy hadron collider (like SPPC) is to probe the new dynamics which is responsible for the electro-weak symmetry breaking, origin of CP and/or P violation etc.

CONCLUSIONS AND DISCUSSIONS

In this paper, we explored the correlation between the lightness of Higgs boson and the smallness of CP-violation based on the Lee model, namely the spontaneous CP-violation two-Higgs-doublet-model. In this model, the mass of the lightest Higgs boson m_h as well as the quantities K and J are $\propto t_\beta s_\xi$ in the limit $t_\beta s_\xi \to 0$, namely the CP conservation limit. Here K and J are the measures for CP-violation effects in scalar and Yukawa sectors respectively. It is a new way to understand why the Higgs boson discovered at the LHC is light. Based on this possible connection, we proposed that H(125) is due to the approximate CP symmetry and there are extra heavier scalars. This opens a new paradigm that one tries to understand the electro-weak symmetry breaking and CP violation. For this new paradigm, one needs both electron-positron and higher energy hadron collider, as well as the low energy experiments, to pin down the whole picture. We emphasize that this final conclusion is also applicable to many other BSM as well, and which is one of the most important motivations to pursue the next generation colliders.

ACKNOWLEDGMENT

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