Spontaneous CP-violation in the Simplest Little Higgs Model

Ying-nan Mao[*]

Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan 300
E-mail: ynmao@cts.nthu.edu.tw, maoyn@ihep.ac.cn

We proposed how spontaneous CP-violation can be generated in the simplest little Higgs model in this talk. Comparing with the original paper, both formalism and phenomenology are updated. The model is still alive facing the collider and electric dipole moment (EDM) measurements. Strictest constraint comes from LHC Z' direct search, which leads to $f \gtrsim 8$ TeV. Higgs measurements also set strict constraint on the scalar mixing angle, if the Higgs rare decay channel is open. EDM measurements still set weak constraints for this model, even after the recent ACME updated measurement on electron's EDM. In this talk, we also discussed the test of CP-violation in the scalar sector, through the interactions between scalars and gauge bosons.

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[*]Speaker.

1. Introduction

Little Higgs mechanism [1] was proposed to solve the "little hierarchy" problem. As an example, the simplest little Higgs (SLH) model [2] contains the minimal extended scalar sector. In the standard model (SM), complex CKM matrix is the only source of CP-violation. It is successful to explain all discovered CP-violation effects [3]. However, there may be other CP-violation sources, especially in the scalar sector. The speaker had proposed the possibility of spontaneous CP-violation in the SLH model [4] with the new SLH formalism [5], as an example of the connection between CP-violation and little Higgs mechanism. In this talk, we introduce its realization together with the updated formalism and phenomenology.

2. Formalism

In the SLH model, a global symmetry breaking $[\mathrm{SU}(3) \times \mathrm{U}(1)]^2 \to [\mathrm{SU}(2) \times \mathrm{U}(1)]^2$ happens at a scale $f \gg v = 246$ GeV. The gauge group is also extended to $\mathrm{SU}(3) \times \mathrm{U}(1)$, which means there are five extra heavy gauge bosons at scale f. Two scalar triplets are nonlinear realized as [6]

$$\Phi_1 = \mathrm{e}^{\mathrm{i}\frac{\Theta'}{f}} \mathrm{e}^{\mathrm{i}\frac{t_\beta \Theta}{f}} \left(0,0,fc_\beta\right)^T, \quad \Phi_2 = \mathrm{e}^{\mathrm{i}\frac{\Theta'}{f}} \mathrm{e}^{-\mathrm{i}\frac{\Theta}{ft_\beta}} \left(0,0,fs_\beta\right)^T. \tag{2.1}$$

We denote $s_\alpha \equiv \sin\alpha, c_\alpha \equiv \cos\alpha, t_\alpha \equiv \tan\alpha$ as usual. The matrix fields are

$$\Theta \equiv \frac{\eta}{\sqrt{2}} + \begin{pmatrix} \mathbf{0}_{2\times2} & \phi \\ \phi^\dagger & 0 \end{pmatrix}, \quad \Theta' \equiv \frac{\zeta}{\sqrt{2}} + \begin{pmatrix} \mathbf{0}_{2\times2} & \varphi \\ \varphi^\dagger & 0 \end{pmatrix}. \tag{2.2}$$

SM singlets η, ζ and doublets $\phi \equiv ((v+h-\mathrm{i}\chi)/\sqrt{2}, G^-)^T, \varphi \equiv ((\sigma-\mathrm{i}\omega)/\sqrt{2}, x^-)^T$ are all pseudo-Goldstone bosons, but only two of which are physical. ϕ is the usual Higgs doublet and thus h is the physical Higgs boson. We should also perform further canonically-normalization [5] in the CP-odd scalar sector, and after which another physical field is proportional to η, as expected.

In fermion sector, all doublets should also be enlarged to triplets. For example, for the third generation quark, we need another SM singlet heavy quark T as the partner of t. The Yukawa interaction is constructed based on the "anomaly-free embedding" [6, 7]. Electro-weak symmetry breaking (EWSB) is mainly induced by quantum correction. To one-loop level, the scalar potential which may induce CP-violation in this model is [4, 5, 6, 8, 9]

$$V = \left[-\mu^2 \Phi_1^\dagger \Phi_2 + \varepsilon \left(\Phi_1^\dagger \Phi_2\right)^2 + \mathrm{H.c.}\right] + \lambda \left|\Phi_1^\dagger \Phi_2\right|^2 + \left[\Delta_A + A\left(\ln\frac{v^2}{2\phi^\dagger\phi} - \frac{1}{2}\right)\right]. \tag{2.3}$$

The coefficients in the last term are [5]

$$\Delta_A = \frac{3}{16\pi^2}\left(\lambda_t^4 \ln\frac{m_T^2}{m_t^2} - \frac{g^4}{8}\ln\frac{m_X^2}{m_W^2} - \frac{g^4}{16c_W^4}\ln\frac{m_{Z'}^2}{m_Z^2}\right), \quad A = \frac{3}{16\pi^2}\left(\lambda_t^4 - \frac{g^4}{8} - \frac{g^4}{16c_W^4}\right), \tag{2.4}$$

with $\lambda_t \equiv \sqrt{2}m_t/v$. X and Z' are charged and neutral heavy gauge bosons respectively. Here we used the continuum effective field theory (CEFT) framework [10] in which the dependence on the UV-cutoff Λ is canceled during renormalization, as shown in [5]. Define $\kappa \equiv v/f$ and $\alpha \equiv \sqrt{2}\kappa/s_{2\beta}$, when both $\mu, \varepsilon \neq 0$ and $\mu^2 < |2\varepsilon f^2 s_{2\beta}c_\alpha|$, η would acquire a nonzero VEV $v_\eta =$

$f\xi s_{2\beta}/\sqrt{2}$ where $\xi \equiv \arccos\left(\frac{\mu^2}{2\varepsilon f^2 s_{2\beta}c_\alpha}\right)$. That means spontaneous CP-violation occurs. From the potential, we have $\lambda = 2\varepsilon + (\Delta_A - A)\kappa^2(\alpha/s_\alpha)$.

Both scalars become CP-mixing states, we denote them as $h_{1,2}$, the mass mixing has the form

$$h_1 \equiv c_\theta h - s_\theta \eta, \quad h_2 \equiv s_\theta h + c_\theta \eta, \tag{2.5}$$

where the mixing angle satisfies $t_{2\theta} = \frac{4\varepsilon f^2 s_{2\xi}s_\alpha}{4\varepsilon f^2 s_\xi^2 - M_{hh}^2}$. The masses are

$$m_{1,2}^2 = \frac{M_{hh}^2 + 4\varepsilon f^2 s_\xi^2}{2} \pm \left(\frac{M_{hh}^2 - 4\varepsilon f^2 s_\xi^2}{2}c_{2\theta} - 2\varepsilon f^2 s_{2\xi}s_\alpha s_{2\theta}\right), \tag{2.6}$$

where M_{hh}^2 is the mass matrix element $-\left.\frac{\partial^2 V}{\partial h^2}\right|_{h=\eta=0} = 4\varepsilon f^2 c_\xi^2 s_\alpha^2 + v^2\left[\left(3 - \frac{2\alpha}{t_{2\alpha}}\right)\Delta_A - \left(5 - \frac{2\alpha}{t_{2\alpha}}\right)A\right] = m_1^2 c_\theta^2 + m_2^2 s_\theta^2 \simeq m_1^2$. Here we chose $|\theta| \ll 1$ thus h_1 is the SM-like scalar.

The $h_1 h_2 h_2$ trilinear interaction can be parameterized as $\mathscr{L} \supset -\lambda_I f h_1 h_2^2/2$, in which

$$\lambda_I = c_\theta s_\theta^2 \lambda_0 + s_\theta(2 - 3s_\theta^2)\frac{\sqrt{2}\varepsilon s_{2\xi}(3c_{2\alpha} - 1)}{s_{2\beta}c_\alpha} + c_\theta(1 - 3s_\theta^2)\frac{2\sqrt{2}\varepsilon t_\alpha(3c_{2\xi} - 1)}{s_{2\beta}} - c_\theta^2 s_\theta\frac{6\sqrt{2}\varepsilon s_{2\xi}}{c_\alpha s_{2\beta}}, \tag{2.7}$$

with $\lambda_0 \equiv 2(3\Delta_A - 8A)\kappa + 8(\Delta_A - A)\kappa^3/s_{2\beta}^2 + 6\sqrt{2}\varepsilon c_\xi^2 s_{2\alpha}/s_{2\beta}$. When $m_2 < m_1/2$, such a vertex can lead to $h_1 \to 2h_2$ rare decay, which will face strict constraint from Higgs measurements.

3. Phenomenology

Facing many experimental constraints, the model is still alive. First, through direct search of Z' at LHC [11], we obtained a 95% C.L. lower limit $f \gtrsim 8$ TeV. Its upper limit is about $f \lesssim 85$ TeV [5], which is the same as the CP-conserving case based on Goldstone scattering unitarity analysis [5]. The bounds on s_θ mainly come from the Higgs signal strengths fit, LEP and LHC [12] direct searches. When $m_2 \lesssim m_1/2$, strict constraint comes from the bound for $h_1 \to 2h_2$ rare decay channel. For light m_2 with a mass around $(15 - 60)$ GeV, we have $|s_\theta| \lesssim (0.03 - 0.15)$; while for large $m_2(\gtrsim m_1/2)$, we have $s_\theta \lesssim (0.15 - 0.3)$ [4]. With the updated CEFT formalism, we also obtained 12 TeV $\lesssim m_T \lesssim 24$ TeV in this model. As a model with extra CP-violation source, there must be constraints from electric dipole moments (EDM) [13]. In this model, this constraint is not very strict, even after the recent updated measurement of electron EDM [13]. For $|s_\theta| \sim (0.1 - 0.2)$ and $f \gtrsim 8$ TeV, it is allowed for $m_2 \sim (20 - 500)$ GeV. Constraints from neutron and heavy atoms' EDM set weaker constraints comparing with electron EDM.

To test the CP-violation in the scalar sector, we just need to confirm both h_2VV and h_1h_2V vertices together (where V denotes a massive gauge boson, and h_1VV vertices have already been confirmed at LHC), based on the CP properties' analysis [14]. For h_2VV vertices, we can test it at a Higgs or Z factory for light h_2 scenario, or at a hadron collider for heavy h_2 scenario. For h_1h_2V vertices, we need the help of Z' since the Zh_1h_2 vertex is suppressed by κ^3 [5], while the $Z'h_1h_2$ vertex is only suppressed by κ. This is one of the motivations for future colliders.

4. Summary

In this talk, we discussed how spontaneous CP-violation can be generated in the simplest little Higgs model. Comparing with the original paper, we updated both its formalism and phenomenology. The formalism is based on CEFT in the scalar potential, together with a canonically-normalization in the scalar kinetic part. The model is still allowed by data, facing the constraints from colliders and EDM. The most strict constraint for the model is $f \gtrsim 8$ TeV, which comes from LHC direct Z' search. For $m_2 < m_1/2$, s_θ also face strict constraint from $h_1 \to 2h_2$ rare decay. We also discussed the test of CP-violation in the scalar sector. The idea is to confirm both h_2VV and h_1h_2V type vertices at future colliders.

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