Spontaneous CP-violation in the Simplest Little Higgs Model

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Y.-N. Mao, Phys. Rev. D 97, 075031 (2018).

Motivation and Introduction

- This is a connection between little Higgs mechanism and CP-violation;
- Little Higgs is one popular mechanism to solve the little hierarchy problem;
- The Simplest Little Higgs (SLH) model has the minimal extended scalar sector: only one additional scalar comparing with the standard model (SM);
- As a special composite model, scalars appear as pseudo-Goldstone bosons, thus the Higgs boson is naturally light;
- CP-violation (CPV) was discovered in 1964 in K-sector [J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964)];
- All discovered CPV effects can be successfully explained by the K-M mechanism;

- However, new CPV sources are still required, for example, to try to understand the puzzle of matter-antimatter asymmetry, etc.;

- Besides this, new CPV is also a type of physics beyond the SM (BSM);

- As a possibility, CPV in BSM physics may appear from the "scalar sector", like in some weak coupled models— of course it can also appear in weak or Yukawa sector;

- In this talk, we choose a variation of the SLH model as an example, to discuss how CPV can be generated from the scalar sector in a composite model;

- We also show the importance of vector-scalar interaction in testing CPV in the scalar sector, which is also a theoretical motivation for future colliders.

Model Construction

- In such models, a global symmetry breaks at a scale $f \gg v = 246$ GeV, and electroweak symmetry breaking (EWSB) is dominantly generated through quantum correction [CW potential, S. R. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973)];
- For the SLH model, a global symmetry breaking $[SU(3) \times U(1)]^2 \to [SU(2) \times U(1)]^2$ happens at scale f, and the gauge group is enlarged to $SU(3) \times U(1)$ [D. E. Kaplan and M. Schmaltz, JHEP10, 039 (2003)];
- 10 Goldstone bosons are generated, and 8 of which are eaten by massive gauge bosons;
- Two physical Goldstone bosons are left— in the CP-conserving case, one is a SM-like Higgs boson (H), and the other is a pseudoscalar (η);

- Two scalar triplets $\Phi_{1,2}$ are nonlinear realized as

$$\Phi_1 = \mathrm{e}^{\mathrm{i}\Theta'}\mathrm{e}^{\mathrm{i}t_\beta\Theta}\begin{pmatrix}\mathbf{0}_{1\times 2}\\ fc_\beta\end{pmatrix}, \qquad \Phi_2 = \mathrm{e}^{\mathrm{i}\Theta'}\mathrm{e}^{-\mathrm{i}\Theta/t_\beta}\begin{pmatrix}\mathbf{0}_{1\times 2}\\ fs_\beta\end{pmatrix};$$

- The matrix fields Θ and Θ' are

$$\Theta \equiv \frac{1}{f}\left(\frac{\eta\mathbb{I}_{3\times 3}}{\sqrt{2}} + \begin{pmatrix}\mathbf{0}_{2\times 2} & \phi\\ \phi^\dagger & 0\end{pmatrix}\right), \qquad \Theta' \equiv \frac{1}{f}\left(\frac{G'\mathbb{I}_{3\times 3}}{\sqrt{2}} + \begin{pmatrix}\mathbf{0}_{2\times 2} & \varphi\\ \varphi^\dagger & 0\end{pmatrix}\right);$$

- $\phi \equiv \left((v_h + h - \mathrm{i}G)/\sqrt{2}, G^-\right)^T$ and $\varphi \equiv (y^0, x^-)^T \sim$ are SU(2) doublet, in which $\phi \sim$ the usual Higgs doublet, η and G' are SU(2) singlets, in which $\eta \sim$ the pseudoscalar;

- Define $\kappa \equiv v/f$ from now on, $v_h/v \sim 1 + \mathcal{O}(\kappa^2)$.

- Covariant Derivation Lagrangian: $\mathcal{L} \supset (D_\mu \Phi_1)^\dagger (D^\mu \Phi_1) + (D_\mu \Phi_2)^\dagger (D^\mu \Phi_2)$;

- $D_\mu \equiv \partial_\mu - \mathrm{i} g \mathbb{G}_\mu$, θ_W is the EW-mixing angle, and $\theta_X \equiv \arctan(t_W/\sqrt{3})$,

$$\mathbb{G}_\mu \equiv \begin{pmatrix} \frac{1}{2c_W} Z + \frac{1-3s_X^2}{2\sqrt{3}c_X} Z' & \frac{1}{\sqrt{2}} W^+ & \frac{1}{\sqrt{2}} Y^0 \\ \frac{1}{\sqrt{2}} W^- & -s_W A - \frac{c_{2W}}{2c_W} Z + \frac{1-3s_X^2}{2\sqrt{3}c_X} Z' & \frac{1}{\sqrt{2}} X^- \\ \frac{1}{\sqrt{2}} \bar{Y}^0 & \frac{1}{\sqrt{2}} X^+ & -\frac{1}{\sqrt{3}c_X} Z' \end{pmatrix}_\mu$$

  is the gauge field matrix to the leading order of κ;

- Mass spectrum to the leading order of κ:

$$m_A = 0, \quad m_W = \frac{gv}{2}, \quad m_Z = \frac{gv}{2c_W}, \quad m_X = m_Y = \frac{gf}{\sqrt{2}}, \quad m_{Z'} = \frac{2gf}{\sqrt{6}c_X};$$

- $W^\pm$ and $X^\pm$ mix with each other at $\mathcal{O}(\kappa^3)$;

- In the basis (Z, Z', Y^2) where $Y^2 \equiv \mathrm{i}\left(\bar{Y}^0 - Y^0\right)/\sqrt{2}$, the mass matrix $\mathbb{M}_V^2$ is not diagonal which means further mixing between (Z, Z', Y^2);

- It can be diagonalized through an orthogonal matrix $\mathbb{R}$ as $\mathbb{R}\mathbb{M}_V^2\mathbb{R}^T = m_p^2\delta_{pq}$;

- Mass correction of neutral massive gauge boson:

$$\delta m_Z^2 = -\delta m_{Z'}^2 = \frac{g^2 v^2 c_{2W}^2 \kappa^2}{32 c_W^6}, \quad \text{and} \quad \delta m_Y^2 = 0.$$

Updated Formalism

- Kinetic terms: $\mathcal{L}_\mathrm{k} = \frac{1}{2}\left(\partial_\mu h \partial^\mu h + \partial_\mu y^1 \partial^\mu y^1 + \mathbb{K}_{ij} \partial_\mu G_i \partial^\mu G_j\right)$;

- $G_{i,j}$ runs over (η, G, G', y^2) and $y^1 \equiv (y^0 + \bar{y}^0)/\sqrt{2}$, $y^2 \equiv \mathrm{i}(\bar{y}^0 - y^0)/\sqrt{2}$;

- After EWSB ($v_h \neq 0$), $\mathbb{K} \neq \mathbb{I}_{4\times 4}$ which means the CP-odd scalar sector is not canonically-normalized, thus we must perform further diagonalization [see also S.-P. He, Y.-N. Mao, C. Zhang, and S.-H. Zhu, Phys. Rev. D 97, 075005 (2018)];

- Two-point transitions $\mathbb{F}_{pi} V_p^\mu \partial_\mu G_i$ should also be canceled by gauge-fixing term;

- Canonically-normalized basis: $\left(\tilde{\eta}, \tilde{G}_p\right) = \left(\eta/\sqrt{(\mathbb{K}^{-1})_{11}}, (\mathbb{R}\mathbb{F})_{pi} G_i / m_p\right)$ where $\tilde{G}_p$ are the corresponding Goldstone of $\tilde{V}_p$, and $\sqrt{(\mathbb{K}^{-1})_{11}} = c_\alpha^{-1}$ with $\alpha \equiv \sqrt{2}\kappa/s_{2\beta}$.

Yukawa Interactions

- Fermions doublets must be enlarged to triplets due to the extension of gauge group;

- Choose "anomaly-free" embedding [O. C. W. Kong, arXiv: hep-ph/0307250; J. Korean Phys. Soc. 45, S404 (2004); Phys. Rev. D 70, 075021 (2004)], fermion triplets are:

$$L = (\nu_L, \ell_L, \mathrm{i}N_L)^T\,, Q_1 = (d_L, -u_L, \mathrm{i}D_L)^T\,, Q_2 = (s_L, -c_L, \mathrm{i}S_L)^T\,, Q_3 = (t_L, b_L, \mathrm{i}T_L)^T\,;$$

- The Lagrangian of the Yukawa interactions:

$$\begin{aligned}\mathcal{L}_{\mathrm{Y}} \;=\; & \mathrm{i}\left(\lambda^a_{d,n}\bar{d}^a_{R,n}\Phi_1^T + \lambda^b_{d,n}\bar{d}^b_{R,n}\Phi_2^T\right)Q_n - \mathrm{i}\frac{\lambda_u^{jk}}{f}\bar{u}_{R,j}\det\left(\Phi_1^*, \Phi_2^*, Q_k\right) \\ & +\mathrm{i}\left(\lambda^a_t\bar{u}^a_{R,3}\Phi_1^\dagger + \lambda^b_t\bar{u}^b_{R,3}\Phi_2^\dagger\right)Q_3 - \mathrm{i}\frac{\lambda_{b,j}}{f}\bar{d}_{R,j}\det\left(\Phi_1, \Phi_2, Q_3\right) \\ & +\mathrm{i}\lambda_{N,j}\bar{N}_{R,j}\Phi_2^\dagger L_j - \mathrm{i}\frac{\lambda_\ell^{jk}}{f}\bar{\ell}_{R,j}\det\left(\Phi_1, \Phi_2, L_k\right) + \mathrm{H.c.}\end{aligned}$$

- $d_{R,j}$ runs over $(d, D, s, S, b)_R$ and $u_{R,j}$ runs over $(u, c, t, T)_R$.

- Fermion mass [F. del Águila, J. I. Illana, and M. D. Jenkins, JHEP03, 080 (2011)]:

$$m_{N,j} = \lambda_{N,j} f s_\beta, \quad m_{\nu,j} = 0, \quad m_{\ell,j} = \frac{v}{\sqrt{2}} y_{\ell,j}, \quad m_{u/c} = \frac{v}{\sqrt{2}} y_{u/c} \quad m_b = \frac{v}{\sqrt{2}} \lambda_{b,3};$$

$$m_{Q=T/D/S} = \sqrt{\left|\lambda_q^a c_\beta\right|^2 + \left|\lambda_q^b s_\beta\right|^2} f, \quad m_{q=t/d/s} = \frac{\left|\lambda_q^a \lambda_q^b\right|}{\sqrt{\left|\lambda_q^a c_\beta\right|^2 + \left|\lambda_q^b s_\beta\right|^2}} \frac{v}{\sqrt{2}} = \frac{\lambda_q v}{\sqrt{2}};$$

- $y_{\ell,j}$ are eigenvalues of λ_ℓ^{jk} and $y_{u/c}$ are eigenvalues of λ_u^{jk};

- Mass mixing (right-handed θ_R and left-handed θ_L):

$$s_{2\theta_{R,q}} = \frac{\sqrt{2} m_q f}{m_Q v} s_{2\beta}, \quad |\theta_{L,q}| = \left| \frac{c_{2\theta_{R,q}} + c_{2\beta}}{\sqrt{2} s_{2\beta}} \kappa \right|, \quad \theta_{L,\nu} = \frac{\kappa}{\sqrt{2} t_\beta};$$

- Left-handed mixing must be suppressed by v/f.

Potential and Spontaneous CP-violation

- We should use the continuum effective field theory framework [H. Georgi, Ann. Rev. Nucl. Part. Sci. 43, 209 (1993)] in which the UV-divergences are absorbed by the counter-terms, thus no dependence on UV-cutoff Λ survives;

- After calculating the CW potential,

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

- If we remove the first bracket, η remains massless, we also add the red term to generate CPV; the coefficients in the last bracket are [K. Cheung, S.-P. He, Y.-N. Mao, C. Zhang, and Y. Zhou, Phys. Rev. D 97, 115001 (2018)]:

$$\begin{aligned}\Delta_A &\equiv \frac{3}{16\pi^2}\left(\lambda_t^4\ln\frac{m_T^2}{m_t^2} - \frac{g^4}{8}\ln\frac{m_X^2}{m_W^2} - \frac{g^4}{16c_W^4}\ln\frac{m_{Z'}^2}{m_Z^2}\right),\\ A &\equiv \frac{3}{16\pi^2}\left(\lambda_t^4 - \frac{g^4}{8} - \frac{g^4}{16c_W^4}\right).\end{aligned}$$

- If μ and ϵ are both nonzero, generally there may be a relative phase between them;
- When such a phase vanishes, CP-symmetry is good in the Lagrangian level;
- The vacuum condition: $\partial V/\partial h = \partial V/\partial \eta = 0$;
- The condition including η shows $v_\eta \equiv \langle \eta \rangle = 0$ becomes unstable if $\mu^2 < |2\epsilon f^2 s_{2\beta} c_\alpha|$;
- Thus $v_\eta = \pm \frac{f s_{2\beta}}{\sqrt{2}} \arccos\left(\frac{\mu^2}{2\epsilon f^2 s_{2\beta} c_\alpha}\right) \longrightarrow$ Spontaneous CPV is generated;
- In such scenario, all CPV effects comes from the complex vacuum [such idea was proposed by Lee, see T. D. Lee, Phys. Rev. D 8, 1226 (1973)].

- Define $\xi \equiv \sqrt{2}v_\eta/(f s_{2\beta})$, the other condition gives $\lambda = 2\epsilon + (\Delta_A - A)\kappa^2(\alpha/s_\alpha)$;

- Choose field redefinition $\eta \to \bar{\eta} \equiv \tilde{\eta} - \langle\tilde{\eta}\rangle$, the mass term

$$\mathcal{L}_{\rm m} = \frac{1}{2}\,(h,\bar{\eta})\,M_S^2 \begin{pmatrix} h \\ \bar{\eta} \end{pmatrix} = \frac{1}{2}\,(h,\bar{\eta}) \begin{pmatrix} M_{hh}^2 & 2\epsilon f^2 s_{2\xi} s_\alpha \\ 2\epsilon f^2 s_{2\xi} s_\alpha & 4\epsilon f^2 s_\xi^2 \end{pmatrix} \begin{pmatrix} h \\ \bar{\eta} \end{pmatrix},$$

  with matrix element $M_{hh}^2 = 4\epsilon f^2 c_\xi^2 s_\alpha^2 + ((3 - 2\alpha/t_{2\alpha})\Delta_A - (5 - 2\alpha/t_{2\alpha})A)\,v^2$;

- Nonzero off-diagonal element in M_S^2 means the mass eigenstates are CP-mixing states;

- We parameterize the mixing as

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} h \\ \bar{\eta} \end{pmatrix};$$

- The mass eigenvalues are

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

- the mixing angle satisfies

$$t_{2\theta} = \frac{4\epsilon f^2 s_{2\xi} s_\alpha}{4\epsilon f^2 s_\xi^2 - M_{hh}^2};$$

- h_1 is the 125 GeV SM-like Higgs boson and h_2 is the extra scalar;

- $s_\theta \ll 1$ thus $M_{hh}^2 = m_1^2 c_\theta^2 + m_2^2 s_\theta^2 \sim m_1^2$.

Some Interactions Including Scalars

A. Coefficients of Vector-Scalar-Scalar Type Vertices

(Calculate to the leading order of κ)

Vertex	Coefficient
$Z_\mu(h_2\partial^\mu h_1 - h_1\partial^\mu h_2)$	$-g\kappa^3/(4\sqrt{2}c_W^3 t_{2\beta})$
$Z'_\mu(h_2\partial^\mu h_1 - h_1\partial^\mu h_2)$	$-\sqrt{2/3}g\kappa/(c_X t_{2\beta})$
$Y_\mu^2(h_2\partial^\mu h_1 - h_1\partial^\mu h_2)$	$g/2$

*The red result is different from that in previous papers.

B. Coefficients of Vector-Vector-Scalar Type Vertices

(Calculate to the leading order of κ)

Vertex	$S = h_1$	$S = h_2$
$SW^+W^-(= -SX^+X^-)$	$g^2 v c_\theta / 2$	$g^2 v s_\theta / 2$
$SZZ(= -SZ'Z')$	$g^2 v c_\theta / (2c_W)^2$	$g^2 v s_\theta / (2c_W)^2$
SZZ'	$g^2 v c_{2W} c_\theta / (2\sqrt{3} c_W^3 c_X)$	$g^2 v c_{2W} s_\theta / (2\sqrt{3} c_W^3 c_X)$
SZY^2	$g^2 v \kappa c_\theta / (\sqrt{2} c_W t_{2\beta})$	$g^2 v \kappa s_\theta / (\sqrt{2} c_W t_{2\beta})$
$SZ'Y^2$	$-g^2 v \kappa c_\theta / (\sqrt{6} c_W^2 c_X t_{2\beta})$	$-g^2 v \kappa s_\theta / (\sqrt{6} c_W^2 c_X t_{2\beta})$
$SY^0 \bar{Y}^0$	0	0

C. Coefficients of Yukawa Type Vertices

(Calculate to the leading order of κ)

Vertex	$S = h_1$	$S = h_2$
$-\frac{m_f}{v} S \bar{f}_L f_R$ $(f{=}u,c,b,\ell,\nu)$	c_θ	s_θ
$-\frac{m_f}{v} S \bar{q}_L q_R$ $(q{=}t,d,s)$	$c_\theta - \mathrm{i}\delta_q s_\theta \kappa\zeta$	$s_\theta + \mathrm{i}\delta_q c_\theta \kappa\zeta$
$-\frac{m_Q}{f} S \bar{Q}_L Q_R$ $(Q{=}T,D,S)$	$-\frac{c_\theta \kappa}{2}\left(\frac{s_{2\theta_{R,q}}}{s_{2\beta}}\right)^2 + \mathrm{i}\delta_Q s_\theta \zeta$	$\frac{s_\theta \kappa}{2}\left(\frac{s_{2\theta_{R,q}}}{s_{2\beta}}\right)^2 - \mathrm{i}\delta_Q c_\theta \zeta$
$-\frac{m_Q}{f} S \bar{q}_R Q_L$	$\delta_Q \frac{c_\theta m_q}{\sqrt{2} m_Q} \frac{c_{2\theta_{R,q}} - c_{2\beta}}{s_{2\beta}} - \mathrm{i} s_\theta \frac{m_q f}{m_Q v}$	$\delta_Q \frac{s_\theta m_q}{\sqrt{2} m_Q} \frac{c_{2\theta_{R,q}} - c_{2\beta}}{s_{2\beta}} + \mathrm{i} c_\theta \frac{m_q f}{m_Q v}$
$-\frac{m_Q}{f} S \bar{q}_L Q_R$	$\delta_Q c_\theta \zeta - \mathrm{i} s_\theta \kappa \left(\zeta^2 + \frac{1}{2}\right)$	$\delta_Q s_\theta \zeta + \mathrm{i} c_\theta \kappa \left(\zeta^2 + \frac{1}{2}\right)$

Red parts are different from those in previous papers, $\delta_{q(Q)} = +1$ for $q(Q) = t(T)$ and $\delta_{q(Q)} = -1$ for $q(Q) = d(D), s(S)$, $\zeta \equiv (c_{2\theta_{R,q}} + c_{2\beta})/(\sqrt{2} s_{2\beta}) \sim \theta_{L,q}/\kappa$.

D. Pure Triple Scalar Interactions

Effective Lagrangian:

$$\mathcal{L} \supset -\frac{1}{2} f \left(\lambda_{122} h_1 h_2^2 + \lambda_{211} h_2 h_1^2 \right) ;$$

The Coefficients:

$$\begin{aligned}
\lambda_{122} &= c_\theta s_\theta^2 \lambda_0 + s_\theta (2 - 3 s_\theta^2) \frac{\sqrt{2} \epsilon s_{2\xi} (3 c_{2\alpha} - 1)}{s_{2\beta} c_\alpha} \\
&\quad + c_\theta (1 - 3 s_\theta^2) \frac{2\sqrt{2} \epsilon t_\alpha (3 c_{2\xi} - 1)}{s_{2\beta}} - c_\theta^2 s_\theta \frac{6\sqrt{2} \epsilon s_{2\xi}}{c_\alpha s_{2\beta}} \\
\lambda_{211} &= c_\theta^2 s_\theta \lambda_0 + c_\theta (1 - 3 s_\theta^2) \frac{\sqrt{2} \epsilon s_{2\xi} (3 c_{2\alpha} - 1)}{s_{2\beta} c_\alpha} \\
&\quad - s_\theta (2 - 3 s_\theta^2) \frac{2\sqrt{2} \epsilon t_\alpha (3 c_{2\xi} - 1)}{s_{2\beta}} + c_\theta s_\theta^2 \frac{6\sqrt{2} \epsilon s_{2\xi}}{c_\alpha s_{2\beta}} ;
\end{aligned}$$

where $\lambda_0 = (6\Delta_A - 16A)\kappa + 8(\Delta_A - A)\kappa^3 / s_{2\beta}^2 + 6\sqrt{2}\epsilon c_\xi^2 s_{2\alpha} / s_{2\beta}$.

Theoretical and Experimental Constraints

- Perturbation unitarity of Goldstone bosons scattering;
- Mass relation from the scalar potential;
- Direct (and indirect) bound on the global symmetry breaking scale f;
- Direct searches on h_2 from LEP and LHC;
- Higgs signal strengths fit and rare decay constraints from LHC;
- Electric dipole moment (EDM) of electron, neutron, (or heavy atoms).

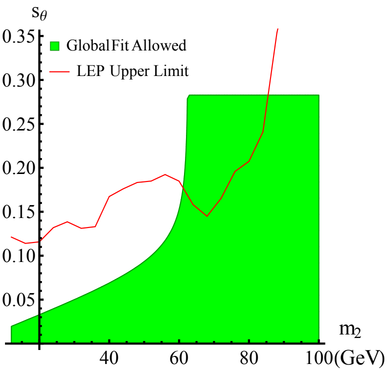
A. Bounds on f

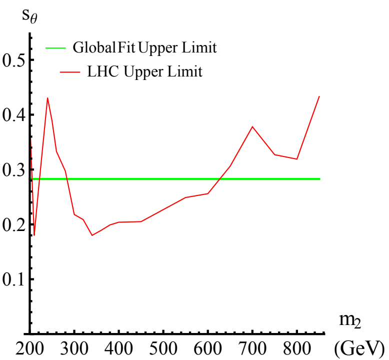
- Lower bound: direct search of Z' [CMS Collaboration, CMS-PAS-EXO-18-006], it gives a strict lower bound $f \gtrsim 8$ TeV (corresponding to $m_{Z'} \gtrsim 4.5$ TeV), it is stricter than the indirect results which comes from the EW oblique parameters (S and T);

- Upper bound: Goldstone scattering unitarity [K. Cheung, S.-P. He, Y.-N. Mao, C. Zhang, and Y. Zhou, Phys. Rev. D 97, 115001 (2018)], UV-cutoff $\Lambda \lesssim \sqrt{8\pi} f c_\beta \Rightarrow f \lesssim 85$ TeV and $t_\beta \lesssim 8.9$;

- In the last step, we assumed all particles to appear below the UV-cutoff, $m_{Z'}, m_Q < \Lambda$.

B. Bounds on s_θ





- Up: low m_2 region; Down: high m_2 region;
- Green line or region comes from Higgs strength global fit [CMS Collaboration, CMS-PAS-HIG-17-031];
- Higgs rare decay sets strict constraint on s_θ if $m_2 < m_1/2$, for example, $s_\theta \lesssim (0.03{-}0.15)$, but not sensitive to other parameters, like f or β;
- Red lines come from LEP [LEP Higgs Working Group, Phys. Lett. B 565, 61 (2003)] and LHC [ATLAS Collaboration, ATLAS-CONF-2017-058] direct searches;
- In large m_2 region, $s_\theta \lesssim (0.2 - 0.3)$ in most region.

C. Bounds on m_T

- Useful relation: $M_{hh}^2 = m_1^2 c_\theta^2 + m_2^2 s_\theta^2$;
- Numerical results ($8\ \text{TeV} \lesssim f \lesssim 85\ \text{TeV}$):

Light m_2 Scenario ($m_2 < m_1$)	$12\ \text{TeV} \lesssim m_T \lesssim 18\ \text{TeV}$
Heavy m_2 Scenario ($m_2 > m_1$)	$17\ \text{TeV} \lesssim m_T \lesssim 24\ \text{TeV}$

- m_T appears logarithmically in the potential, overlaps occur in the allowed region in the table above because of f;
- Different from the CP-conserving case in which $m_T \sim (2-18)$ TeV [K. Cheung, S.-P. He, Y.-N. Mao, C. Zhang, and Y. Zhou, Phys. Rev. D 97, 115001 (2018)].

D. Bounds from EDM

- EDM effective interaction

$$\mathcal{L} \supset -\frac{\mathrm{i}d_f}{2}\bar{f}\sigma^{\mu\nu}\gamma^5 f F_{\mu\nu} \longrightarrow (d/S)\vec{S}\cdot\vec{E} \longrightarrow \mathrm{CPV};$$

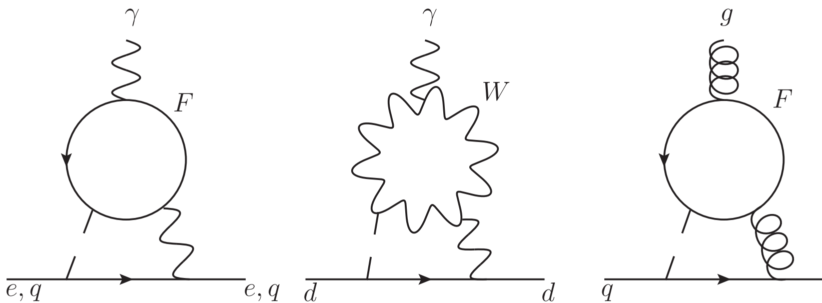
- Current 90% C.L. Limits on d_e, d_n [ACME Collaboration, Science 343, 269 (2014); C. Baker *et al.*, Phys. Rev. Lett. 97, 131801 (2006); J. M. Pendlebury *et al.*, Phys. Rev. D 92, 092003 (2015).]

$$|d_e| < 8.7\times 10^{-29}\ e\cdot\mathrm{cm}, \qquad |d_n| < 3.0\times 10^{-26}\ e\cdot\mathrm{cm};$$

- In new physics models, EDM may be generated at one- or two-loop levels;

- Thus all models containing new CPV sources must face the EDM constraints;

- In the model discussed here, EDM is dominantly generated at two-loop level [known as the Barr-Zee diagram S. M. Barr and A. Zee, Phys. Rev. Lett. 65, 21 (1990); Phys. Rev. Lett. 65, 2920(E) (1990)]:



- In this model, the EDM constraints are not strict (for example, for the whole region $m_2 \sim (20 - 600)$ GeV, $s_\theta \sim 0.1$ and $f \gtrsim 8$ TeV is allowed by electron EDM measurement. Neutron and heavy atoms' EDM set weaker constraints).

Collider Test on CP-violation in the Scalar Sector

- The main idea is to use three kinds of tree-level vertices: CP-properties analysis

$h_1\,VV$	$h_2\,VV$	$h_1\,h_2\,V$
$+$	$+$	$+?\ -?$
		$-?\ +?$

- If all the three types of vertices exist, CP-violation can be confirmed [G. Li, Y.-N. Mao, C. Zhang, and S.-H. Zhu, Phys. Rev. D 95, 035015 (2017)]

- For the first two vertices, we can choose $V = W$ or Z (recent results about h_1 couplings to gauge bosons showed that h_1VV vertex is already discovered);

- For the last vertex, however, as discussed above, Zh_1h_2 coupling is suppressed by κ^3 [S.-P. He, Y.-N. Mao, C. Zhang, and S.-H. Zhu, Phys. Rev. D 97, 075005 (2018)] that we must get help from heavy gauge bosons, such as Z'.

Channels Candidates

- For light h_2, we can choose $e^+e^- \to Z^* \to Zh_2$ or $e^+e^- \to Z^* \to Zh_1(h_1 \to Z^{(*)}h_2)$ at future high luminosity Higgs factories;

- For heavy h_2, we can choose $pp \to h_2 \to WW/ZZ$ at pp colliders, if m_2 is not too large (for example, ~ 1 TeV), LHC is enough;

- To measure $Z'h_1h_2$-vertex, LHC is not enough since its $\sqrt{s}$ is only $(13-14)$ TeV, we need a larger pp collider to measure this process;

- What is the role of $Y^0(\bar{Y}^0)$? There is no suppression in $Y^0h_1h_2$-vertex.

Conclusions and Discussions

- We proposed how spontaneous CPV can be generated in the SLH (through adding a $(\Phi_1^\dagger\Phi_2)^2$ term);
- The model is still alive, but facing strict constraints, especially direct Z' search (constrain f) and Higgs global fit (constrain s_θ, especially in light h_2 region);
- EDM constraints are not strict comparing with other constraints in this model;
- $f \sim (8-85)$ TeV is the same as the CP-conserving SLH model;
- The m_T allowed region in SLH model with CPV is quite different from the CP-conserving scenario, due to the modification of M_{hh}^2 ($m_h^2 \to m_1^2 c_\theta^2 + m_2^2 s_\theta^2$);

- We showed the importance of vector-vector-scalar and vector-scalar-scalar type of vertices in searching for CPV effects in the scalar sector;

- To test h_2VV-vertex, for light h_2, Zh_2 associated production or $h_1 \to Zh_2$ cascade decay at future e^+e^- collider are preferred;

- While for heavy h_2, it's better to choose $h_2 \to WW/ZZ$ channels at hadron colliders;

- To test h_1h_2V-vertex, we must turn to Z' for help since h_1h_2Z-vertex is suppressed by κ^3 (which is different from the early results on this vertex);

- Both nonzero vertices can help to confirm CPV in the scalar sector.

End

- References are hyper-links thus you can click them directly through the webpage;
- By the way, I'm sorry that I changed my title and abstract a bit comparing with the first submitted version, because recently I found something wrong in the solution to strong CP problem in this model, thus I must remove this part from my talk;
- Collaborators on this topic are welcome, my email: maoyn@ihep.ac.cn;

Thank you!