Constraints from flavor and electroweak physics in little-Higgs scenario with 2HDM structure

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Based on N. Kumar and S. Sadhukhan, Phys. Rev. D 103, 055011 [arXiv:2007.15626]

Motivation

- **Little Higgs and Composite Higgs scenario**: Enhanced gauge symmetries are systematically broken, to emerge the Higgs as a pNGB. The extended scalar sector manifests from the Goldstone bosons and unbroken symmetry does contain the SM $SU(2) \times U(1)$.

- The low energy effective theory ($\sim$ TeV) of the little-Higgs model with $SU(6)/Sp(6)$, as proposed by Low, Skiba and Smith (LSS), exhibits a two-Higgs doublet model (2HDM) structure.
- The symmetry dictates interesting Yukawa patterns$\rightarrow$ non-trivial fermion couplings with both of the Higgs doublets, 2HDM structure with no 'ad-hoc' assumption.
- The couplings induce FCNC, which get constraints from flavor physics observables, precision measurements and LHC data.
- The effective 2HDM is studied in terms of the model parameters.

Little Higgs model, $SU(6)/Sp(6)$

Low,Skiba and Smith, Phys.Rev.D66,072001

$35 - 21 = 14$ NGB's (π^a) are contained in $\Sigma = e^{[i\pi^a X^a/f]}\langle\Sigma\rangle$, where $\langle\Sigma\rangle$ is the anti-symmetric condensate and X^a's are the broken generator.

Particle Content:

SM Fermions, W, Z + 2HDM like scalar sector(h, H, $H^{\pm}$, A)

+ Vectorlike fermions: doublets (Q', Q'^c), up type singlets (t'', t''^c), down type singlets (b'' and b''^c)

+heavy vector-boson states (W', B')

SU(6) symmetry is broken explicitly by the gauge and Yukawa couplings in multiple steps: termed as *collective symmetry breaking*.

$$\mathcal{L}_{Yuk} = y_1 f \begin{pmatrix} Q' & t'' & (i\sigma^2 Q)^T & 0 \end{pmatrix} (\Sigma)^* \begin{pmatrix} 0 \\ t^c \end{pmatrix} + y_2 f \begin{pmatrix} 0 & 0 & Q^T & 0 \end{pmatrix} (\Sigma) \begin{pmatrix} i\sigma^2 Q'^c \\ t''^c \\ 0 \\ b''^c \end{pmatrix}$$
$$- i y_{1b} f \begin{pmatrix} 0 & 0 & Q^T & 0 \end{pmatrix} (\Sigma) \begin{pmatrix} 0 \\ 0 \\ 0 \\ b^c \end{pmatrix} + i y_{2b} f \begin{pmatrix} 0 & 0 & (i\sigma_2 Q)^T & 0 \end{pmatrix} (\Sigma)^* \begin{pmatrix} 0 \\ b^c \\ 0 \\ 0 \end{pmatrix} + \text{.h.c. .} \qquad ($$

Little Higgs model, $SU(6)/Sp(6)$

Mass diagonalization of "f" dependent terms

$$\mathcal{L}^{\rm mass} \supset \begin{pmatrix} t_0 & t_1 & t_2 \end{pmatrix} \begin{pmatrix} \mathcal{M}^t_{11} & 0 & \mathcal{M}^t_{13} \\ \mathcal{M}^t_{21} & \mathcal{M}^t_{22} & \mathcal{M}^t_{23} \\ 0 & 0 & -\mathcal{M}^t_{33} \end{pmatrix} \begin{pmatrix} t^c_0 \\ t^c_1 \\ t^c_2 \end{pmatrix} + \begin{pmatrix} b_0 & b_1 & b_2 \end{pmatrix} \begin{pmatrix} \mathcal{M}^b_{11} & 0 & \mathcal{M}^b_{13} \\ \mathcal{M}^b_{21} & \mathcal{M}^b_{22} & \mathcal{M}^b_{23} \\ 0 & 0 & \mathcal{M}^b_{33} \end{pmatrix} \begin{pmatrix} b^c_0 \\ b^c_1 \\ b^c_2 \end{pmatrix} +$$

After the field redefinitions, the new mass matrix entries $\mathcal{M}^{t,b}_{ij}$ are,

$$\begin{aligned}
\mathcal{M}^t_{11} &= \frac{y_1(y_3y_4v_1 + y_2y_3v_2 - y_2y_4v_2)}{\sqrt{y}_{14}\sqrt{y}_{23}\sqrt{2}}\,, \qquad \mathcal{M}^t_{13} = \frac{(y_1^2y_3v_1 - y_2y_3y_4v_2 - y_1^2y_2v_2)}{\sqrt{y}_{14}\sqrt{y}_{23}\sqrt{2}}\,, \\
\mathcal{M}^t_{21} &= \frac{y_1(y_2y_4v_1 + y_2^2v_2 + y_3y_4v_2)}{\sqrt{y}_{14}\sqrt{y}_{23}\sqrt{2}}\,, \qquad \mathcal{M}^t_{23} = \frac{(y_1^2y_2v_1 - y_2^2y_4v_2 + y_1^2y_3v_2)}{\sqrt{y}_{14}\sqrt{y}_{23}\sqrt{2}}\,, \\
\mathcal{M}^t_{33} &= -f\sqrt{y}_{14}\,, \qquad \mathcal{M}^t_{22} = f\sqrt{y}_{23}\,, \\
\mathcal{M}^b_{11} &= c_{23}y_{ib}\frac{v_i}{\sqrt{2}}\,, \qquad \mathcal{M}^b_{13} = y_2\frac{v_1}{\sqrt{2}}\,, \qquad \mathcal{M}^b_{33} = y_5 f\,, \\
\mathcal{M}^b_{21} &= y_{ib}\frac{v_i}{\sqrt{2}}s_{23}\,, \qquad \mathcal{M}^b_{23} = -y_2\frac{v_2}{\sqrt{2}}s_{23}, \quad \mathcal{M}^b_{22} = \sqrt{y}_{23}f,
\end{aligned}$$

where $\sqrt{y}_{14} \equiv \sqrt{y_1^2 + y_4^2}$, $\sqrt{y}_{23} \equiv \sqrt{y_2^2 + y_3^2}$.

Yukawa Couplings in LSS model

Bi-orthogonal transformation of v_i dependent terms,

$$R_L \mathcal{M}^t_{ij} R_R^T \equiv (\mathcal{M}^t_{ij})_D$$
$$(t_0 \;\; t_1 \;\; t_2)^T = R_L^T (T_2 \;\; T_1 \;\; t)^T$$
$$(t_0^c \;\; t_1^c \;\; t_2^c)^T = R_R^T (T_2^c \;\; T_1^c \;\; t^c)^T,$$

$$\mathcal{L}_h^{\mathrm{Yuk}} \supset \frac{h}{\sqrt{2}} [y_{00} t_0 t_0^c + y_{01} t_0 t_1^c + y_{10} t_1 t_0^c + y_{11} t_1 t_1^c] + h.c.$$

$$y_{htt} = [y_{00} (R_L)_{31} (R_R)_{31} + y_{01} (R_L)_{31} (R_R)_{32} + \ldots\ldots..]$$

$$\mathcal{L}_{H^\pm tb} \supset V_{tb} \frac{1}{v} H^+ \bar{t} \left(y_{H^\pm t_L b_R} m_t P_R + y_{H^\pm t_R b_L} m_b P_L \right) b + h.c.$$

$$y_{H^\pm t_L b_R} = [f(y_1, y_2..)(R_L)_{31} + f(y_{1b}, y_{2b}..)(R_L)_{32}];$$
$$y_{H^\pm t_R b_L} = [f(y_1, y_2..)(R_R)_{31} + f(y_1, y_2..)(R_R)_{32}]$$

y_{ii}, $R_{L/R}$ are functions of LSS model parameters,

$$y_1,\ y_2,\ y_3,\ y_4,\ y_5,\ y_{1b},\ y_{2b},\ f,\ M,\ (c,\ c',\ g_1,\ g_1')$$

Effective 2HDM

The scalar potential is generated in one loop,
$\mathcal{V}_{LSS} = m_1^2|\phi_1|^2 + m_2^2|\phi_2|^2 + (b^2\phi_1^T \cdot \phi_2 + \mathrm{h.c.}) + \lambda_5'|\phi_1^T \cdot \phi_2|^2$

Masses of all particles are obtained in terms of model parameters,

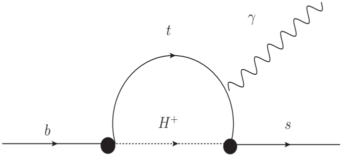
$$M_H^{\pm},\ M_A,\ M_h,\ M_H,\ M_{Ti},\ M_{Bi},\ M_{W'},\ M_{B'}$$

ref. to:

N. Kumar and S. Sadhukhan, Phys.Rev.D103,055011
Low,Skiba and Smith, Phys.Rev.D66,072001
S.Gopalakrishna, T.S.Mukherjee and S.Sadhukhan, Phys.Rev.D94,015034

$B \to X_s\gamma$

The charged Higgs contributes additionally in the flavor observables. Contribution of other scalars are small.



$$\delta C_{7,8} = \left[\frac{y^2_{H^\pm t_L b_R}}{3} F^{(1)}_{7,8}(x) - y_{H^\pm t_L b_R} y_{H^\pm t_R b_L} F^{(2)}_{7,8}(x) \right]$$

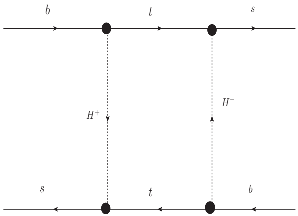
Observables	SM value	Experimental value
$\mathrm{Br}(B \to X_s\gamma)$	$(3.36 \pm 0.23) \times 10^{-4}$	$(3.32 \pm 0.16) \times 10^{-4}$

$$-0.063 \leq \delta C_7 + 0.242\ \delta C_8 \leq 0.073$$

2HDM: destructive interference

LSS eff2HDM: Destructive and constructive both

Neutral B-meson mixing



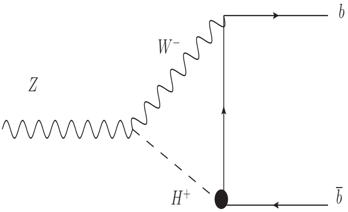
$$\Delta m_q = \frac{G_F^2}{24\pi^2}(V_{tq}V_{tb}^*)^2\ \eta_B\ m_B\ m_t\ f_{Bq}^2\ I_{tot}(x_W, x_H, x_H)$$

$$I_{\rm tot} = I_{WW}(x_W) + y^4_{H^\pm t_L b_R} I_{HH}(x_H, x_H) + 2y^2_{H^\pm t_L b_R} I_{WH}(x_W, x_H)$$

Observables	SM value	Experimental value
Δm_{B_s}	$(17.757 \pm 0.021)\ \mathrm{ps}^{-1}$	$(18.3 \pm 2.7)\ \mathrm{ps}^{-1}$

$$0.067 \leq \frac{\Delta m_{B_s}}{\Delta m_{B_s}^{SM}} \leq 1.265$$

$Zb\bar{b}$ vertex



$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}$$

Observable	SM value	Experimental value
R_b	0.21581 ± 0.00011	0.21629 ± 0.00066

$$-0.00086 \leq \delta R_b \leq 0.00182$$

Scan A: Flavor and EW observables

We analyse three differnet FCNC scenario,

$$\begin{aligned} \text{Case I:} &\quad y_{1b} \neq 0,\ y_{2b} \neq 0, \\ \text{Case II:} &\quad y_{1b} = 0,\ y_{2b} \neq 0, \\ \text{Case III:} &\quad y_{1b} \neq 0,\ y_{2b} = 0. \end{aligned}$$

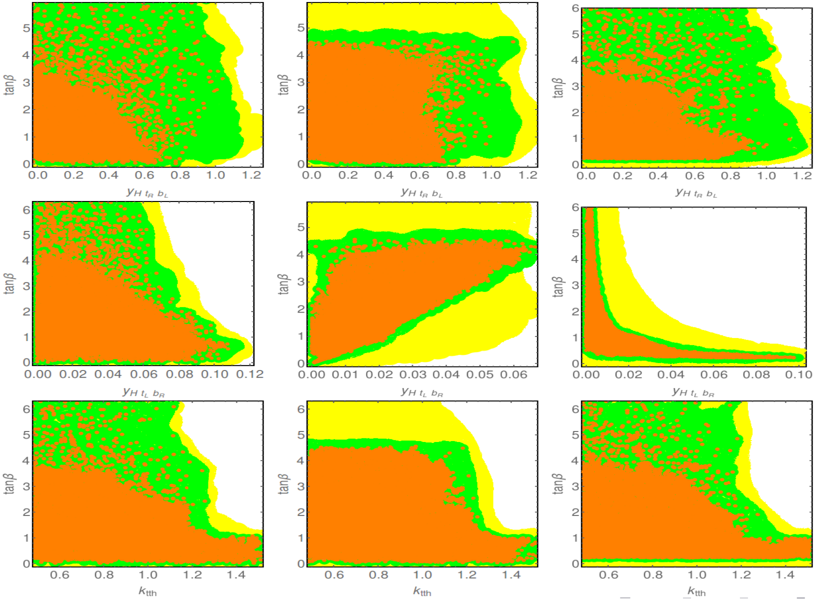
Parameter	Value
y_i(i=1....5), c, c_1, g_1, g_1'	$\mathcal{O}(1)$
y_{1b}, y_{2b}	≤ 0.10
f	≤ 2 TeV
M	≤ 3 TeV
VEV	246 GeV

$m^2_{1,2} > 0$, $(m_1^2 m_2^2 - b^4) < 0$ and b^2 is real

S and T parameters are kept well within limit by keeping the new gauge degrees of freedom in the heavier side.

Scan A: Result

LSS Model, $B \to X_s\gamma$, Other Flavor

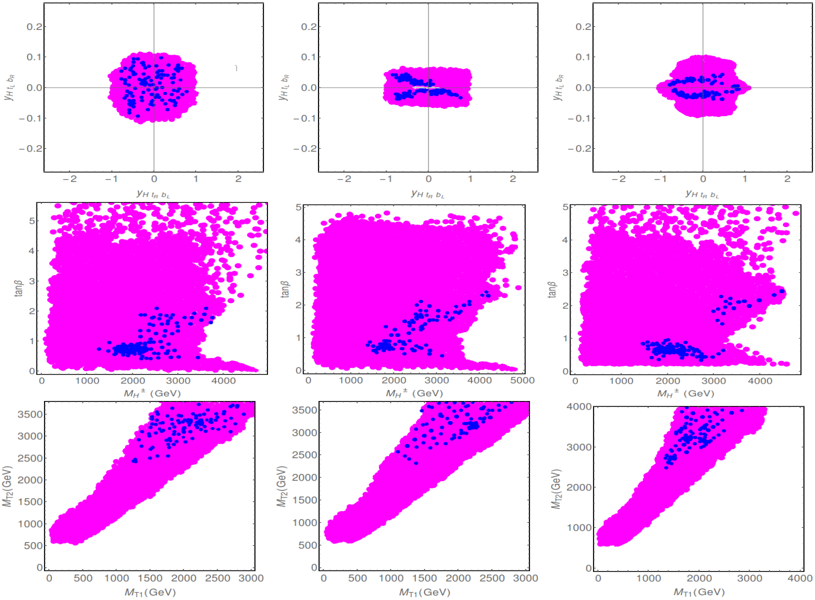


Scan B: LHC observables

Quantity	Constraints
$\lvert\sin(\beta-\alpha)\rvert$	~ 1
k_{tth}	$0.7 - 1.4$
$m_t(\overline{MS})$	$(156, 170)$ GeV
m_h	$(123, 127)$ GeV
m_b	$(3, 5)$ GeV
$m_H^{\pm}$	$> m_t$
$m_B,\ m_T$	> 1.4 TeV

Scan B: Result

Flavor and EW(A), LHC(B)



Conclusion

- From the flavor data and $Zb\bar{b}$, we find that the charged Higgs mass is relaxed with $\tan\beta$ being restricted to $0.5 - 5$, whereas the charged Higgs mass is pushed to larger than 1 TeV along with $\tan\beta$ being further restricted to < 3 when the LHC bounds are incorporated.
- Very narrow $\tan\beta$ range compared to general 2HDM, due to the predictive nature of the Yukawa sector in the LSS model, where the Higgs, top mass and top Yukawa couplings are fixed in terms of strong sector parameters of the LSS model.
- Charged Higgs mass limit is strong, $m_H^{\pm} > 1.2$ TeV.
- Composite Higgs Model with same group structure needs detailed study.