# Effective theory for universal seesaw model, FCNC and CP violation

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13-16 Sep.2022, KAON 2022, OSAKA UNIV.

Abstract We study the quark sector of the universal seesaw model with $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times U(1)$ symmetry. The model incorporates seesaw mechanism using the vector-like quarks. The purpose of the research is to study the model with the effective theory and FCNC for Z boson is derived.

## 1 The Lagrangian of the model

The model is based on $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)$. The two SU(2) doublet Higgs fields are introduced so that $\phi_L$ for $\mathrm{SU}(2)_L$ doublet and $\phi_R$ for $\mathrm{SU}(2)_R$. They repectively break $\mathrm{SU}(2)_L$ and $\mathrm{SU}(2)_R$ with their vevs satisfying $v_R \gg v_L$. The ordinary quarks $\psi_L(\psi_R)$ are also $\mathrm{SU}(2)_L$ $(\mathrm{SU}(2)_R)$ doublets. The six vector-like quarks $(U_1 \sim U_3, D_1 \sim D_3)$ are also introduced and the Lagrangian is,

$$\begin{aligned}
\mathcal{L}_{doublet} &= \sum_{i=1}^{3} \overline{\psi_{Li}}(i\partial\!\!\!/ - g_L W\!\!\!/_L - g_1'\frac{1}{6}B\!\!\!/_1)\psi_{Li} + (L \to R) \\
\mathcal{L}_{vlq} &= \sum_{I=1}^{3} \overline{U_I}(i\partial\!\!\!/ - g_1' B\!\!\!/_1 \frac{2}{3} - M_{U_I})U_I \\
&+ \sum_{I=1}^{3} \overline{D_I}(i\partial\!\!\!/ + g_1' B\!\!\!/_1 \frac{1}{3} - M_{D_I})D_I \\
\mathcal{L}_{vlq-doublet} &= -y^u_{LiJ}\overline{\psi_{iL}}\tilde{\phi}_L U_{JR} - y^u_{RiJ}\overline{\psi_{iR}}\tilde{\phi}_R U_{JL} - h.c. \\
&- y^d_{LiJ}\overline{\psi_{iL}}\phi_L D_{JR} - y^d_{RiJ}\overline{\psi_{iR}}\phi_R D_{JL} - h.c..
\end{aligned}$$

After the symmetry breaking of $\mathrm{SU}(2)_L\times \mathrm{SU}(2)_R\times \mathrm{U}(1)$, the mixing of the neutral gauge bosons is given by the product of the three orthogonal rotation matrices,

$$\begin{pmatrix} W^3_{L\mu} \\ B_{1\mu} \\ W^3_{R\mu} \end{pmatrix} = O_{23}(\theta_{W_R})O_{12}(-\theta_W)O_{13}(\theta_{13}) \begin{pmatrix} Z_\mu \\ A_\mu \\ Z'_\mu \end{pmatrix}$$

$$\tan\theta_{W_R} = \frac{g_1}{g_R}\tan\theta_W = \frac{g'}{g_L}\tan 2\theta_{13} = \frac{\sin^2\theta_{W_R}\sin 2\theta_{W_R} v_L^2}{\sin\theta_W v_R^2}$$

$$e = g'\cos\theta_W = g_1\cos\theta_{W_R}\cos\theta_W.$$

Z neutral current is given as,

$$\begin{aligned}
\mathcal{L}_Z &= -\frac{e}{2\sin 2\theta_W}(\overline{u^i_L}\gamma_\mu u^i_L - \overline{d^i_L}\gamma_\mu d^i_L)Z^\mu \\
&\times(\cos\theta_{13} + \tan\theta_{W_R}\sin\theta_W\sin\theta_{13}) \\
&- \frac{g_R}{2\cos\theta_{W_R}}(\overline{u^i_R}\gamma_\mu u^i_R - \overline{d^i_R}\gamma_\mu d^i_R)Z^\mu \sin\theta_{13}.
\end{aligned}$$

## 2 The mass matrix and FCNC

We integrate the five VLQ $(U_1 \sim U_2, D_1 \sim D_3)$ with their masses being larger than $v_R$. We assume $M_{U_3} \ll v_R$ and $U_3$ is not integrated. Then the theory is written in terms of four up-type quarks, three down type-quarks, two massive neutral gauge bosons $Z$ and $Z'$, two charged gauge bosons etc. Ignoring the operator suppressed by $\frac{v_L^2, v_R^2}{M_{vlq}^2}$, one obtains the following 4 by 4 up-type quark mass matrix.

$$\mathcal{L}_{\mathrm{uptypemass}} = -\begin{pmatrix}\overline{u}_L & U_{L3}\end{pmatrix}\mathcal{M}_u \begin{pmatrix} u_R \\ U_{R3}\end{pmatrix}$$

$$\mathcal{M}_u = \begin{pmatrix} -\sum_{I=1}^{2}\frac{\mathbf{y}^u_{LI}\mathbf{y}^{u\dagger}_{RI}v_L v_R}{2M_{UI}} & \frac{\mathbf{y}^u_{L3}v_L}{\sqrt{2}} \\ \frac{\mathbf{y}^{u\dagger}_{R3}v_R}{\sqrt{2}} & M_{U_3}\end{pmatrix}.$$

The up-type quark matrix is diagonalized by the 4 by 4 bi-unitary transformation $V_L^u, W_R^u$ with the additional U(2) rotations $v^u$ and $w^u_R$ for the lighter two generation sector.

$$v^{u\dagger}V_L^{u\dagger}\mathcal{M}_u W_R^u w_R^u = \begin{pmatrix} m_u & 0 & 0 & 0 \\ 0 & m_c & 0 & 0 \\ 0 & 0 & \frac{|\mathbf{y}^u_{L3}|v_L}{\sqrt{2}}\cos\theta & \simeq 0 \\ 0 & 0 & 0 & M_4\end{pmatrix}$$

$$M_4 = \sqrt{M_{U3}^2 + \frac{\mathbf{y}^{u\dagger}_{R3}\mathbf{y}^u_{R3}v_R^2}{2}} \simeq \frac{|\mathbf{y}^u_{R3}|v_R}{\sqrt{2}}, \sin\theta = \frac{M_{U_3}}{M_4} = O(\frac{v_L}{v_R}).$$

If we rewrite the up type right-handed weak isospin current with the mass eigenstates,

$$\begin{aligned}
\sum_{i=1}^{3}\overline{u^i_R}\gamma_\mu u^i_R &= -\sin\theta\cos\theta(\overline{t_R}\gamma_\mu U_{4R} + \overline{U_{4R}}\gamma_\mu t_{4R}) \\
&+\overline{u_R}\gamma_\mu u_R + \overline{c_R}\gamma_\mu c_R + \sin^2\theta\overline{t_R}\gamma_\mu t_R + \cos^2\theta\overline{U_{4R}}\gamma_\mu U_{4R},
\end{aligned}$$

The FCNC between $t_R$ and $U_{4R}$ is consistent with the full theory analysis [1].

## 3 Conclusion

We investigated the effective theory of the universal seesaw model with the three generation VLQ. The effective field theory includes four up-type quarks in addtion to the three down-type quarks. The tree level Z FCNC between the right-handed top quark and the fourth generation up-type quark occurs.

## References

[1] T. Morozumi, T. Satou, M. N. Rebelo and M. Tanimoto, Phys. Lett. B **410**, 233-240 (1997).