$$L_L \equiv \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \qquad Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad j,k = 1 \sim 3$$

	T	T^3	Y	$Q = T^3 + \frac{Y}{2}$
ν_L	$1/2$	$1/2$	-1	0
ℓ_L		$-1/2$		-1
ν_R	0	0	0	0
ℓ_R	0	0	-2	-1

	T	T^3	Y	Q
u_L	$1/2$	$1/2$	$1/3$	$2/3$
d_L		$-1/2$		$-1/3$
u_R	0	0	$4/3$	$2/3$
d_R	0	0	$-2/3$	$-1/3$

$$\Phi(x) \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = e^{i\left\{ g\frac{\tau^l}{2}\chi^l(x) + g'\frac{Y_H}{2}\eta(x) \right\}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \phi(x) \end{pmatrix}$$

	T	T^3	Y	Q
ϕ^+	$1/2$	$1/2$	1	1
ϕ^0		$-1/2$		0

$$\tilde{\Phi}(x) \equiv i\tau^2 \Phi^*(x)$$

$$\left[\frac{\tau^l}{2}, \frac{\tau^m}{2}\right] = i\epsilon_{lmn}\frac{\tau^n}{2} \qquad l,m,n = 1 \sim 3 \qquad \left[\frac{\lambda^a}{2}, \frac{\lambda^b}{2}\right] = i\, f_{abc}\frac{\lambda^c}{2} \qquad a,b,c = 1 \sim 8$$

$$\mathcal{L} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}^{\rm kin}_{\rm lepton} + \mathcal{L}^{\rm mass}_{\rm lepton} + \mathcal{L}^{\rm kin}_{\rm quark} + \mathcal{L}^{\rm mass}_{\rm quark}$$

$$\begin{aligned} \mathcal{L}_{\rm gauge} = & -\frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \frac{1}{4}(\partial_\mu A^l_\nu - \partial_\nu A^l_\mu - g\epsilon_{lmn}A^m_\mu A^n_\nu)^2 \\ & -\frac{1}{4}\left(\partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g_s\, f_{abc} G^b_\mu G^c_\nu\right)^2 \end{aligned}$$

$$\mathcal{L}_{\rm Higgs} = \left| \left(i\partial_\mu - g'\frac{1}{2}Y_H B_\mu - g\frac{\tau^l}{2}A^l_\mu \right)\Phi \right|^2 + \mu^2 \Phi^\dagger\Phi - \frac{\lambda}{2}(\Phi^\dagger\Phi)^2$$

$$\mathcal{L}^{\rm kin}_{\rm lepton} = \bar{L}^j_L \gamma^\mu \left[i\partial_\mu - g'\frac{Y_{\ell L}}{2}B_\mu - g\frac{\tau^l}{2}A^l_\mu \right] L^j_L + \bar{\ell}^j_R \gamma^\mu \left[i\partial_\mu - g'\frac{Y_{\ell R}}{2}B_\mu \right] \ell^j_R + \bar{\nu}^j_R \gamma^\mu i\partial_\mu \nu^j_R$$

$$\begin{aligned} \mathcal{L}^{\rm mass}_{\rm lepton} = & -(\bar{L}'^j_L \Phi) Y_\ell^{jk} \ell'^k_R - (\bar{L}'^j_L \tilde{\Phi}) Y_\nu^{jk} \nu'^k_R + h.c. \\ = & -y^j_\ell (\bar{L}^j_L \Phi) \ell^j_R - y^j_\nu [(\bar{L}_L U_\nu)^j \tilde{\Phi}] \nu^j_R + h.c. \end{aligned}$$

$$V_{\ell L}\, Y_\ell V^\dagger_{\ell R} \equiv {\rm diag}(y^j_\ell) \qquad V_{\nu L}\, Y_\nu V^\dagger_{\nu R} \equiv {\rm diag}(y^j_\nu) \qquad V_{\ell L} V^\dagger_{\nu L} \equiv U_\nu$$

$$L^j_L \equiv V^{jk}_{\ell L} L'^k_L \qquad \ell^j_R \equiv V^{jk}_{\ell R} \ell'^k_R \qquad \nu^j_R \equiv V^{jk}_{\ell R} \nu'^k_R$$

$$\begin{aligned} \mathcal{L}^{\rm kin}_{\rm quark} = & \ \bar{Q}^j_L \gamma^\mu \left[i\partial_\mu - g'\frac{Y_{QL}}{2}B_\mu - g\frac{\tau^l}{2}A^l_\mu - g_s\frac{\lambda^a}{2}G^a_\mu \right] Q^j_L \\ & + \bar{u}^j_R \gamma^\mu \left[i\partial_\mu - g'\frac{Y_{uR}}{2}B_\mu - g_s\frac{\lambda^a}{2}G^a_\mu \right] u^j_R + \bar{d}^j_R \gamma^\mu \left[i\partial_\mu - g'\frac{Y_{dR}}{2}B_\mu - g_s\frac{\lambda^a}{2}G^a_\mu \right] d^j_R \end{aligned}$$

$$\begin{aligned} \mathcal{L}^{\rm mass}_{\rm quark} = & -(\bar{Q}'^j_L \Phi) Y_d^{jk} d'^k_R - (\bar{Q}'^j_L \tilde{\Phi}) Y_u^{jk} u'^k_R + h.c. \\ = & -y^j_d [(\bar{Q}_L U_d)^j \Phi] d^j_R - y^j_u (\bar{Q}^j_L \tilde{\Phi}) u^j_R + h.c. \end{aligned}$$

$$V_{uL}\, Y_u V^\dagger_{uR} \equiv {\rm diag}(y^j_u) \qquad V_{dL}\, Y_d V^\dagger_{dR} \equiv {\rm diag}(y^j_d) \qquad V_{uL} V^\dagger_{dL} \equiv U_d$$

$$Q^j_L \equiv V^{jk}_{uL} Q'^k_L \qquad u^j_R \equiv V^{jk}_{uR} u'^k_R \qquad d^j_R \equiv V^{jk}_{uR} d'^k_R$$

$$\Phi(x)\to\frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+\phi(x)\end{pmatrix}\qquad \tilde{\Phi}(x)\to\frac{1}{\sqrt{2}}\begin{pmatrix}v+\phi(x)\\ 0\end{pmatrix}\qquad V(\Phi)\equiv-\mu^2\Phi^\dagger\Phi+\frac{\lambda}{2}(\Phi^\dagger\Phi)^2$$

$$\cos\theta_W\equiv\frac{g}{\sqrt{g^2+g'^2}}\qquad \sin\theta_W\equiv\frac{g'}{\sqrt{g^2+g'^2}}\qquad e\equiv\frac{g\,g'}{\sqrt{g^2+g'^2}}=g\sin\theta_W=g'\cos\theta_W$$

$$\frac{v}{\sqrt{2}}=\frac{\mu}{\sqrt{\lambda}}\qquad m\equiv\sqrt{2}\mu\qquad M_W\equiv\frac{g\,v}{2}\qquad M_Z\equiv\frac{1}{2}\sqrt{g^2+g'^2}\,v=\frac{M_W}{\cos\theta_W}$$

$$\begin{pmatrix}Z_\mu\\ A_\mu\end{pmatrix}\equiv\begin{pmatrix}\cos\theta_W & -\sin\theta_W\\ \sin\theta_W & \cos\theta_W\end{pmatrix}\begin{pmatrix}A^3_\mu\\ B_\mu\end{pmatrix}\qquad \sin^2\theta_W\approx 0.23$$

$$W_\mu\equiv\frac{1}{\sqrt{2}}(A^1_\mu-iA^2_\mu)\qquad F^A_{\mu\nu}\equiv\partial_\mu A_\nu-\partial_\nu A_\mu\qquad F^Z_{\mu\nu}\equiv\partial_\mu Z_\nu-\partial_\nu Z_\mu$$

$$\mathcal{D}_\mu W_\nu\equiv(\partial_\mu+igA^3_\mu)W_\nu=(\partial_\mu+i\,eA_\mu+ig\cos\theta_W Z_\mu)W_\nu$$

$$m^j_f\equiv\frac{y^j_f v}{\sqrt{2}}\qquad y^j_f=\sqrt{2}\,\frac{m^j_f}{v}=g\,\frac{m^j_f}{\sqrt{2}M_W}\qquad \text{where}\quad f=\ell,\nu,u,d$$

$$\nu^j\equiv U^{jk}_\nu\hat{\nu}^k\ (U_\nu\text{: PMNS matrix})\qquad d^j\equiv U^{jk}_d\hat{d}^k\ (U_d\text{: CKM matrix})$$

$$J^\mu\equiv\frac{1}{2}\bar{\ell}^j\gamma^\mu(1-\gamma^5)\nu^j+\frac{1}{2}\bar{d}^j\gamma^\mu(1-\gamma^5)u^j=\frac{1}{2}\bar{\ell}^j\gamma^\mu(1-\gamma^5)U^{jk}_\nu\hat{\nu}^k+\frac{1}{2}U^{jk*}_d\bar{\hat{d}}^k\gamma^\mu(1-\gamma^5)u^j$$

$$J^\mu_{\rm EM}\equiv(-)\bar{\ell}^j\gamma^\mu\ell^j+\left(\frac{2}{3}\right)\bar{u}^j\gamma^\mu u^j+\left(-\frac{1}{3}\right)\bar{d}^j\gamma^\mu d^j$$

$$J^{3\mu}\equiv\frac{1}{4}\bar{\nu}^j\gamma^\mu(1-\gamma^5)\nu^j-\frac{1}{4}\bar{\ell}^j\gamma^\mu(1-\gamma^5)\ell^j+\frac{1}{4}\bar{u}^j\gamma^\mu(1-\gamma^5)u^j-\frac{1}{4}\bar{d}^j\gamma^\mu(1-\gamma^5)d^j$$

$$J^\mu_Z\equiv J^{3\mu}-\sin^2\theta_W J^\mu_{\rm EM}$$

$$\begin{aligned}\mathcal{L}_{\rm gauge}=\ &-\frac{1}{4}F^A_{\mu\nu}F^{A\mu\nu}-\frac{1}{4}F^Z_{\mu\nu}F^{Z\mu\nu}-\frac{1}{2}(\mathcal{D}_\mu W_\nu-\mathcal{D}_\nu W_\mu)^\dagger(\mathcal{D}^\mu W^\nu-\mathcal{D}^\nu W^\mu)\\ &+i(e\,F^A_{\mu\nu}+g\cos\theta_W F^Z_{\mu\nu})W^{\dagger\mu}W^\nu+\frac{g^2}{2}(|W_\mu W^\mu|^2-|W_\mu W^\nu|^2)\\ &-\frac{1}{4}(\partial_\mu G^a_\nu-\partial_\nu G^a_\mu-g_s\,f_{abc}\,G^b_\mu\,G^c_\nu)^2\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\rm Higgs}=\ &M^2_W W^\dagger_\mu W^\mu+\frac{1}{2}M^2_Z Z^2_\mu+\left(g\,M_W\phi+\frac{g^2}{4}\phi^2\right)\left(W^\dagger_\mu W^\mu+\frac{1}{2\cos^2\theta_W}Z^2_\mu\right)\\ &+\frac{1}{2}[(\partial_\mu\phi)^2-m^2\phi^2]-\frac{m\sqrt{\lambda}}{2}\phi^3-\frac{\lambda}{8}\phi^4-V\left(\frac{v}{\sqrt{2}}\right)\end{aligned}$$

$$\mathcal{L}^{\rm kin}_{\rm lepton}=\bar{\ell}^j i\not{\partial}\ell^j+\bar{\nu}^j i\not{\partial}\nu^j+\mathcal{L}^{\rm (lepton)}_{\rm EWint}$$

$$\mathcal{L}^{\rm mass}_{\rm lepton}=-\left(m^j_\ell+\frac{y^j_\ell}{\sqrt{2}}\phi\right)\bar{\ell}^j\ell^j-\left(m^j_\nu+\frac{y^j_\nu}{\sqrt{2}}\phi\right)\bar{\hat{\nu}}^j\hat{\nu}^j$$

$$\mathcal{L}^{\rm kin}_{\rm quark}=\bar{u}^j i\not{\partial}u^j+\bar{d}^j i\not{\partial}d^j-g_s\bar{u}^j\gamma^\mu\frac{\lambda^a}{2}u^j G^a_\mu-g_s\bar{d}^j\gamma^\mu\frac{\lambda^a}{2}d^j G^a_\mu+\mathcal{L}^{\rm (quark)}_{\rm EWint}$$

$$\mathcal{L}^{\rm mass}_{\rm quark}=-\left(m^j_d+\frac{y^j_d}{\sqrt{2}}\phi\right)\bar{\hat{d}}^j\hat{d}^j-\left(m^j_u+\frac{y^j_u}{\sqrt{2}}\phi\right)\bar{u}^j u^j$$

$$\mathcal{L}_{\rm EWint}=-\frac{g}{\sqrt{2}}(J^{\mu\dagger}W_\mu+J^\mu W^\dagger_\mu)-e\,J^\mu_{\rm EM}A_\mu-\frac{g}{\cos\theta_W}J^\mu_Z Z_\mu$$

$$\left(-i\frac{g}{\sqrt{2}}\right)^2 J^\dagger_\mu\frac{i(-g^{\mu\nu}+p^\mu p^\nu/M^2_W)}{p^2-M^2_W}J_\nu\ \overset{p^2\ll M^2_W}{\longrightarrow}-i\frac{4G}{\sqrt{2}}J^\dagger_\mu J^\mu\qquad \frac{G}{\sqrt{2}}=\frac{g^2}{8M^2_W}=\frac{1}{2v^2}$$