FeynRules Implementation of 4th_Generation_Complex_CKM

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Abstract

We describe the implementation of the 4th_Generation_Complex_CKM model using the FeynRules package.

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1 Introduction

We describe the implementation of the 4th_Generation_Complex_CKM model using the FeynRules [1] package.

2 Gauge Symmetries

The gauge group of this model is

$$U1Y \times SU2L \times SU3C. \tag{1}$$

Details of these gauge groups can be found in Table 1.

Group	Abelian	Gauge Boson	Coupling Constant	Charge	Structure Constant	Symmetric Tensor	Reps	Defs
U1Y	T	B	g1	Y				
SU2L	F	Wi	gw		Eps		$FSU2L_{k,k}$	FSU2L[a$_, b$_, c$_] → -I Eps[a$, b$,
SU3C	F	G	gs		f	dSUN	$T_{i,i}$	FSU3C[a$_, b$_, c$_] → -I f[a$, b$, c
							$FSU3C_{a,a}$	

Table 1: Details of gauge groups.

The definitions of the indices can be found in Table 2.

Index	Symbol	Range
Generation	f	1-3
QuarkGeneration	q	1-4
Colour	i	1-3
Gluon	a	1-8
SU2W	k	1-3

Table 2: Definition of the indices.

3 Fields

In this section, we describe the field content of our model implementation.

3.1 Vector Fields

In this subsection, we describe the vector fields of our model. The details of the physical vectors can be found in Table 3.

Class	SC	I	FI	QN	Mem	M	W	PDG
A	T				A	0	0	22
Z	T				Z	MZ= 91.188	WZ= 2.4414	23
W	F			$Q = 1$	W	MW= Internal	WW= 2.0476	24
G	T	a			G	0	0	21

Table 3: Details of physical vector fields. The headers are as follows: SC = self conjugate, I = indices, FI = flavor index, QN = quantum numbers, Mem = members, M = mass, W = width, and PDG = particle data group number.

The details of the unphysical vectors can be found in Table 4.

Class	SC	I	FI	QN	Mem	Definitions
Wi	T	k	k		Wi	$\text{Wi}_{\mu,1} \to \frac{W_\mu + W_\mu{}^\dagger}{\sqrt{2}}$ $\text{Wi}_{\mu,2} \to -\frac{i\left(-W_\mu + W_\mu{}^\dagger\right)}{\sqrt{2}}$ $\text{Wi}_{\mu,3} \to s_w A_\mu + c_w Z_\mu$
B	T				B	$B_\mu \to c_w A_\mu - s_w Z_\mu$

Table 4: Details of unphysical vector fields. The headers are as follows: SC = self conjugate, I = indices, FI = flavor index, QN = quantum numbers, and Mem = members.

3.2 Fermion Fields

In this subsection, we describe the fermion fields of our model. The details of the physical fermions can be found in Table 5.

3.3 Scalar Fields

In this subsection, we describe the scalar fields of our model. The details of the physical scalars can be found in Table 6.

3.4 Ghost Fields

In this subsection, we describe the ghost fields of our model. The details of the physical ghosts can be found in Table 7. The details of the unphysical ghosts can be found in Table 8.

Class	SC	I	FI	QN	Mem	M	W	PDG
vl	F	f	f	$LeptonNumber = 1$				
					ve			12
					vm			14
					vt			16
l	F	f	f	$Q = -1$		Ml		
				$LeptonNumber = 1$	e	Me= 0.000511		11
					m	MM= 0.10566		13
					tt	MTA= 1.777		15
uq	F	q, i	q	$Q = 2/3$		Mu		
					u	MU= 0.00255	0	2
					c	MC= 1.42	0	4
					t	MT= 172	WT= 1.4516	6
					tp	MTp= 700	WTp= 14.109	8
dq	F	q, i	q	$Q = -1/3$		Md		
					d	MD= 0.00504	0	1
					s	MS= 0.104	0	3
					b	MB= 4.7	0	5
					bp	MBp= 500	WBp= 0.28454	7

Table 5: Details of physical fermion fields. The headers are as follows: SC = self conjugate, I = indices, FI = flavor index, QN = quantum numbers, Mem = members, M = mass, W = width, and PDG = particle data group number.

Class	SC	I	FI	QN	Mem	M	W	PDG
H	T				H	MH= 120	WH= 0.00575309	25
phi	T				phi	MZ= 91.188	Wphi	250
phi2	F			$Q = 1$	phi2	MW= Internal	Wphi2	251

Table 6: Details of physical scalar fields. The headers are as follows: SC = self conjugate, I = indices, FI = flavor index, QN = quantum numbers, Mem = members, M = mass, W = width, and PDG = particle data group number.

Class	SC	I	FI	QN	Mem	M	W	PDG
ghA	F			$GhostNumber = 1$	ghA	0		
ghZ	F			$GhostNumber = 1$	ghZ	MZ= 91.188		
ghWp	F			$Q = 1$	ghWp	MW= Internal		
				$GhostNumber = 1$				
ghWm	F			$Q = -1$	ghWm	MW= Internal		
				$GhostNumber = 1$				
ghG	F	a		$GhostNumber = 1$	ghG	0		

Table 7: Details of physical ghost fields. The headers are as follows: SC = self conjugate, I = indices, FI = flavor index, QN = quantum numbers, Mem = members, M = mass, W = width, and PDG = particle data group number.

Class	SC	I	FI	QN	Mem	Definitions
ghWi	F	k	k		ghWi	$\mathrm{ghWi}_1 \to \frac{\mathrm{ghWm}+\mathrm{ghWp}}{\sqrt{2}}$ $\mathrm{ghWi}_2 \to -\frac{i(\mathrm{ghWm}-\mathrm{ghWp})}{\sqrt{2}}$ $\mathrm{ghWi}_3 \to c_w \mathrm{ghZ} + \mathrm{ghA} s_w$
ghB	F				ghB	$\mathrm{ghB} \to c_w \mathrm{ghA} - \mathrm{ghZ} s_w$

Table 8: Details of unphysical ghost fields. The headers are as follows: SC = self conjugate, I = indices, FI = flavor index, QN = quantum numbers, and Mem = members.

4 Lagrangian

In this section, we describe the Lagrangian of our model implementation.

4.1 L_1

$$-\frac{1}{4}\left(-\partial_\nu\left[B_\mu\right]+\partial_\mu\left[B_\nu\right]\right)^2-$$
$$\frac{1}{4}\left(-\partial_\nu\left[G_{\mu,\mathrm{a1}}\right]+\partial_\mu\left[G_{\nu,\mathrm{a1}}\right]+g_s f_{\mathrm{a1,a2,a3}}G_{\mu,\mathrm{a2}}G_{\nu,\mathrm{a3}}\right)\left(-\partial_\nu\left[G_{\mu,\mathrm{a1}}\right]+\partial_\mu\left[G_{\nu,\mathrm{a1}}\right]+g_s f_{\mathrm{a1,a4,a5}}G_{\mu,\mathrm{a4}}G_{\nu,\mathrm{a5}}\right)-$$
$$\frac{1}{4}\left(-\partial_\nu\left[\mathrm{Wi}_{\mu,\mathrm{i1}}\right]+\partial_\mu\left[\mathrm{Wi}_{\nu,\mathrm{i1}}\right]+g_w\epsilon_{\mathrm{i1,i2,i3}}\mathrm{Wi}_{\mu,\mathrm{i2}}\mathrm{Wi}_{\nu,\mathrm{i3}}\right)\left(-\partial_\nu\left[\mathrm{Wi}_{\mu,\mathrm{i1}}\right]+\partial_\mu\left[\mathrm{Wi}_{\nu,\mathrm{i1}}\right]+g_w\epsilon_{\mathrm{i1,i4,i5}}\mathrm{Wi}_{\mu,\mathrm{i4}}\mathrm{Wi}_{\nu,\mathrm{i5}}\right)$$

4.2 L_2

$$\mu^2\left(\mathrm{phi2phi2}^\dagger+\frac{1}{2}(H-i\phi+v)(H+i\phi+v)\right)-\left(\mathrm{phi2phi2}^\dagger+\frac{1}{2}(H-i\phi+v)(H+i\phi+v)\right)^2\lambda+$$
$$\left(-\frac{ie\mathrm{phi2}B_\mu}{2c_w}+\partial_\mu[\mathrm{phi2}]+\frac{e\left(\frac{(H+i\phi+v)(\mathrm{Wi}_{\mu,1}-i\mathrm{Wi}_{\mu,2})}{\sqrt{2}}-i\mathrm{phi2}\mathrm{Wi}_{\mu,3}\right)}{2s_w}\right)\left(\frac{ie\mathrm{phi2}^\dagger B_\mu}{2c_w}+\partial_\mu\left[\mathrm{phi2}^\dagger\right]+\frac{e\left(\frac{(H-i\phi+v)(\mathrm{Wi}_{\mu,1}+i\mathrm{Wi}_{\mu,2})}{\sqrt{2}}+i\mathrm{phi2}^\dagger\mathrm{Wi}_{\mu,3}\right)}{2s_w}\right)+$$
$$\left(\frac{e(H-i\phi+v)B_\mu}{2\sqrt{2}c_w}-\frac{i(\partial_\mu[H]-i\partial_\mu[\phi])}{\sqrt{2}}+\frac{e\left(i\mathrm{phi2}^\dagger(\mathrm{Wi}_{\mu,1}-i\mathrm{Wi}_{\mu,2})-\frac{(H-i\phi+v)\mathrm{Wi}_{\mu,3}}{\sqrt{2}}\right)}{2s_w}\right)\left(\frac{e(H+i\phi+v)B_\mu}{2\sqrt{2}c_w}+\frac{i(\partial_\mu[H]+i\partial_\mu[\phi])}{\sqrt{2}}+\frac{e\left(-i\mathrm{phi2}(\mathrm{Wi}_{\mu,1}+i\mathrm{Wi}_{\mu,2})-\right.}{2s_w}\right.$$

4.3 L_3

$$i\bar{\mathrm{dq}}.\gamma^\mu.\partial_\mu[\mathrm{dq}]+i\bar{l}.\gamma^\mu.\partial_\mu[l]+i\bar{\mathrm{uq}}.\gamma^\mu.\partial_\mu[\mathrm{uq}]+i\bar{\mathrm{vl}}.\gamma^\mu.\partial_\mu[\mathrm{vl}]+\frac{eB_\mu\bar{\mathrm{dq}}.\gamma^\mu.P_-.\mathrm{dq}}{6c_w}-\frac{eB_\mu\bar{\mathrm{dq}}.\gamma^\mu.P_+.\mathrm{dq}}{3c_w}-\frac{eB_\mu\bar{l}.\gamma^\mu.P_-.l}{2c_w}-\frac{eB_\mu\bar{l}.\gamma^\mu.P_+.l}{c_w}+$$
$$\frac{eB_\mu\bar{\mathrm{uq}}.\gamma^\mu.P_-.\mathrm{uq}}{6c_w}+\frac{2eB_\mu\bar{\mathrm{uq}}.\gamma^\mu.P_+.\mathrm{uq}}{3c_w}-\frac{eB_\mu\bar{\mathrm{vl}}.\gamma^\mu.P_-.\mathrm{vl}}{2c_w}+g_s\left(\bar{\mathrm{dq}}.T^a.\gamma^\mu.\mathrm{dq}+\bar{\mathrm{uq}}.T^a.\gamma^\mu.\mathrm{uq}\right)G_{\mu,a}+$$
$$\frac{e\left(\sqrt{2}\bar{\mathrm{vl}}.\gamma^\mu.P_-.lW_\mu+\sqrt{2}\bar{\mathrm{uq}}.\mathrm{CKM}.\gamma^\mu.P_-.\mathrm{dq}W_\mu+\sqrt{2}\bar{l}.\gamma^\mu.P_-.\mathrm{vl}{W_\mu}^\dagger+\sqrt{2}\bar{\mathrm{dq}}.\mathrm{CKM}^\dagger.\gamma^\mu.P_-.\mathrm{uq}{W_\mu}^\dagger-\bar{\mathrm{dq}}.\gamma^\mu.P_-.\mathrm{dq}\mathrm{Wi}_{\mu,3}-\bar{l}.\gamma^\mu.P_-.l\mathrm{Wi}_{\mu,3}+\bar{\mathrm{uq}}.\gamma^\mu.P_-.\mathrm{uq}\mathrm{Wi}_{\mu,3}+\bar{\mathrm{vl}}.\right.}{2s_w}$$

4.4 L_4

$$i\mathrm{phi2CKM}_{\mathrm{n\$990,m\$990}}\bar{\mathrm{uq}}_{\mathrm{s\$990,n\$990,i\$990}}.\mathrm{dq}_{\mathrm{r\$990,m\$990,i\$990}}P_{+\mathrm{s\$990,r\$990}}{y^d}_{\mathrm{m\$990}}-$$
$$i\mathrm{phi2}^\dagger\mathrm{CKM}_{\mathrm{n\$991,m\$991}}{}^*\bar{\mathrm{dq}}_{\mathrm{r\$992,m\$991,i\$991}}.\mathrm{uq}_{\mathrm{r\$993,n\$991,i\$991}}P_{-\mathrm{r\$992,r\$993}}{y^d}_{\mathrm{m\$991}}-$$
$$\frac{(H+i\phi+v)\bar{\mathrm{dq}}_{\mathrm{s\$990,n\$990,i\$990}}.\mathrm{dq}_{\mathrm{r\$990,n\$990,i\$990}}P_{+\mathrm{s\$990,r\$990}}{y^d}_{\mathrm{n\$990}}}{\sqrt{2}}-\frac{(H-i\phi+v)\bar{\mathrm{dq}}_{\mathrm{r\$994,n\$991,i\$991}}.\mathrm{dq}_{\mathrm{r\$995,n\$991,i\$991}}P_{-\mathrm{r\$994,r\$995}}{y^d}_{\mathrm{n\$991}}}{\sqrt{2}}-$$
$$\frac{(H+i\phi+v)\bar{l}_{\mathrm{s\$990,n\$990}}.l_{\mathrm{r\$990,n\$990}}P_{+\mathrm{s\$990,r\$990}}{y^l}_{\mathrm{n\$990}}}{\sqrt{2}}+i\mathrm{phi2}\bar{\mathrm{vl}}_{\mathrm{s\$990,n\$990}}.l_{\mathrm{r\$990,n\$990}}P_{+\mathrm{s\$990,r\$990}}{y^l}_{\mathrm{n\$990}}-$$
$$\frac{(H-i\phi+v)\bar{l}_{\mathrm{r\$996,n\$991}}.l_{\mathrm{r\$997,n\$991}}P_{-\mathrm{r\$996,r\$997}}{y^l}_{\mathrm{n\$991}}}{\sqrt{2}}-i\mathrm{phi2}^\dagger\bar{l}_{\mathrm{r\$998,n\$991}}.\mathrm{vl}_{\mathrm{r\$999,n\$991}}P_{-\mathrm{r\$998,r\$999}}{y^l}_{\mathrm{n\$991}}+$$
$$i\mathrm{phi2}^\dagger\mathrm{CKM}_{\mathrm{m\$990,n\$990}}{}^*\bar{\mathrm{dq}}_{\mathrm{s\$990,n\$990,i\$990}}.\mathrm{uq}_{\mathrm{r\$990,m\$990,i\$990}}P_{+\mathrm{s\$990,r\$990}}{y^u}_{\mathrm{m\$990}}-$$
$$i\mathrm{phi2CKM}_{\mathrm{m\$991,n\$991}}\bar{\mathrm{uq}}_{\mathrm{r\$1000,m\$991,i\$991}}.\mathrm{dq}_{\mathrm{r\$1001,n\$991,i\$991}}P_{-\mathrm{r\$1000,r\$1001}}{y^u}_{\mathrm{m\$991}}-$$
$$\frac{(H-i\phi+v)\bar{\mathrm{uq}}_{\mathrm{s\$990,n\$990,i\$990}}.\mathrm{uq}_{\mathrm{r\$990,n\$990,i\$990}}P_{+\mathrm{s\$990,r\$990}}{y^u}_{\mathrm{n\$990}}}{\sqrt{2}}-\frac{(H+i\phi+v)\bar{\mathrm{uq}}_{\mathrm{r\$1002,n\$991,i\$991}}.\mathrm{uq}_{\mathrm{r\$1003,n\$991,i\$991}}P_{-\mathrm{r\$1002,r\$1003}}{y^u}_{\mathrm{n\$991}}}{\sqrt{2}}$$

4.5 L_5

$$-\mathrm{ghB}^\dagger.\partial_\mu\left[\partial_\mu[\mathrm{ghB}]\right]-\frac{eM_W\left((H-i\phi+v)\mathrm{ghWm}^\dagger.\mathrm{ghWm}+(H+i\phi+v)\mathrm{ghWp}^\dagger.\mathrm{ghWp}\right)}{2s_w}-$$
$$\frac{eM_W\left(i\mathrm{phi2}^\dagger\left(2c_ws_w\mathrm{ghWm}^\dagger.\mathrm{ghA}+\left({c_w}^2-{s_w}^2\right)\mathrm{ghWm}^\dagger.\mathrm{ghZ}\right)-i\mathrm{phi2}\left(2c_ws_w\mathrm{ghWp}^\dagger.\mathrm{ghA}+\left({c_w}^2-{s_w}^2\right)\mathrm{ghWp}^\dagger.\mathrm{ghZ}\right)\right)}{2c_ws_w}-$$
$$\frac{ie\mathrm{MZ}\left(\mathrm{phi2ghZ}^\dagger.\mathrm{ghWm}-\mathrm{phi2}^\dagger\mathrm{ghZ}^\dagger.\mathrm{ghWp}\right)}{2s_w}-\frac{e\mathrm{MZ}(H+v)\mathrm{ghZ}^\dagger.\mathrm{ghZ}}{2c_ws_w}-$$
$$g_s\mathrm{ghG}_a{}^\dagger.\left(\frac{\partial_\mu[\partial_\mu[\mathrm{ghG}_a]]}{g_s}+f_{a,\mathrm{a2\$1004,a3\$1004}}\left(\partial_\mu\left[\mathrm{ghG}_{\mathrm{a3\$1004}}\right]G_{\mu,\mathrm{a2\$1004}}+\partial_\mu\left[G_{\mu,\mathrm{a2\$1004}}\right]\mathrm{ghG}_{\mathrm{a3\$1004}}\right)\right)-$$
$$\mathrm{ghWi}_a{}^\dagger.\left(\partial_\mu\left[\partial_\mu\left[\mathrm{ghWi}_a\right]\right]+\frac{e\epsilon_{a,\mathrm{i2\$1005,i3\$1005}}\left(\partial_\mu\left[\mathrm{Wi}_{\mu,\mathrm{i2\$1005}}\right]\mathrm{ghWi}_{\mathrm{i3\$1005}}+\partial_\mu\left[\mathrm{ghWi}_{\mathrm{i3\$1005}}\right]\mathrm{Wi}_{\mu,\mathrm{i2\$1005}}\right)}{s_w}\right)$$

5 Parameters

In this section, we describe the parameters of our model implementation.

5.1 External Parameters

In this subsection, we describe the external parameters of our model. The details of the external parameters can be found in Tables 9, 10.

P	C	I	V	D	PN	BN	OB	IO	Description
αEWM1	F		127.9		aEWM1	SMINPUTS		QED, -2	Inverse of the electroweak coupling constant
G_f	F		0.0000116639			SMINPUTS		QED, 2	Fermi constant
α_s	F		0.1172		aS	SMINPUTS		QCD, 2	Strong coupling constant at the Z pole.
ymc	F		0.			YUKAWA	4		Charm Yukawa mass
ymb	F		4.7			YUKAWA	5		Bottom Yukawa mass
ymbp	F		500.			YUKAWA	7		Bottom-prime Yukawa mass
ymt	F		174.3			YUKAWA	6		Top Yukawa mass
ymtp	F		700.			YUKAWA	8		Top-prime Yukawa mass
ymtau	F		1.777			YUKAWA	15		Tau Yukawa mass
RCKM	F	q, q	$\mathrm{RCKM}_{1,1} \to 1.$			RCKM			Real Part of the CKM matrix
			$\mathrm{RCKM}_{1,2} \to 0.$						
			$\mathrm{RCKM}_{1,3} \to 0.$						
			$\mathrm{RCKM}_{1,4} \to 0.$						
			$\mathrm{RCKM}_{2,1} \to 0.$						
			$\mathrm{RCKM}_{2,2} \to 0.99995$						
			$\mathrm{RCKM}_{2,3} \to 0.$						
			$\mathrm{RCKM}_{2,4} \to 0.01$						
			$\mathrm{RCKM}_{3,1} \to 0.$						
			$\mathrm{RCKM}_{3,2} \to -0.001$						
			$\mathrm{RCKM}_{3,3} \to 0.995$						
			$\mathrm{RCKM}_{3,4} \to 0.1$						
			$\mathrm{RCKM}_{4,1} \to 0.$						
			$\mathrm{RCKM}_{4,2} \to -0.01$						
			$\mathrm{RCKM}_{4,3} \to -0.1$						
			$\mathrm{RCKM}_{4,4} \to 0.99495$						
ICKM	F	q, q	$\mathrm{ICKM}_{1,1} \to 0.$			ICKM			Imaginary Part of the CKM matrix
			$\mathrm{ICKM}_{1,2} \to 0.$						
			$\mathrm{ICKM}_{1,3} \to 0.$						
			$\mathrm{ICKM}_{1,4} \to 0.$						
			$\mathrm{ICKM}_{2,1} \to 0.$						
			$\mathrm{ICKM}_{2,2} \to 0.$						
			$\mathrm{ICKM}_{2,3} \to 0.$						
			$\mathrm{ICKM}_{2,4} \to 0.$						
			$\mathrm{ICKM}_{3,1} \to 0.$						
			$\mathrm{ICKM}_{3,2} \to 0.$						
			$\mathrm{ICKM}_{3,3} \to 0.$						
			$\mathrm{ICKM}_{3,4} \to 0.$						
			$\mathrm{ICKM}_{4,1} \to 0.$						
			$\mathrm{ICKM}_{4,2} \to 0.$						

Table 9: Details of external parameters. The headers are as follows: P = parameter, C = complex, I = indices, V = value, D = definition, PN = parameter name, BN = block name, OB = order block, and IO = interaction order.

P	C	I	V	D	PN	BN	OB	IO	Description
			$\mathrm{ICKM}_{4,3} \to 0.$ $\mathrm{ICKM}_{4,4} \to 0.$						

Table 10: Details of external parameters. The headers are as follows: P = parameter, C = complex, I = indices, V = value, D = definition, PN = parameter name, BN = block name, OB = order block, and IO = interaction order.

5.2 Internal Parameters

In this subsection, we describe the internal parameters of our model. The details of the internal parameters can be found in Tables 11, 12. The values and definitions of the internal parameters will be written below.

P	C	I	V	NV	D	PN	IO	Description
α_{EW}	F		Eq. 2	0.00781861		aEW	QED, 2	Electroweak coupling contant
M_W	F		Eq. 3	79.8252				W mass
sw2	F		Eq. 4	0.23369				Squared Sin of the Weinberg angle
e	F		Eq. 5	0.313451			QED, 1	Electric coupling constant
c_w	F		Eq. 6	0.875391				Cos of the Weinberg angle
s_w	F		Eq. 7	0.483415				Sin of the Weinberg angle
g_w	F		Eq. 8	0.648409			QED, 1	Weak coupling constant
g_1	F		Eq. 9	0.35807			QED, 1	U(1)Y coupling constant
g_s	F		Eq. 10	1.21358		G	QCD, 1	Strong coupling constant
v	F		Eq. 11	246.218			QED, -1	Higgs VEV
λ	F		Eq. 12	0.118766		lam	QED, 2	Higgs quartic coupling
μ	F		Eq. 13	84.8528				Coefficient of the quadratic piece of the Higgs potential
yl	F	f	Eq. 14	${y^l}_1 \to 0.$ ${y^l}_2 \to 0.$ ${y^l}_3 \to 0.0102066$		${y^l}_1 \to$ ye ${y^l}_2 \to$ ym ${y^l}_3 \to$ ytau	QED, 1	Lepton Yukawa coupling
yu	F	q	Eq. 15	${y^u}_1 \to 0.$ ${y^u}_2 \to 0.$ ${y^u}_3 \to 1.00113$ ${y^u}_4 \to 4.02061$		${y^u}_1 \to$ yup ${y^u}_2 \to$ yc ${y^u}_3 \to$ yt ${y^u}_4 \to$ ytp	QED, 1	U-quark Yukawa coupling
yd	F	q	Eq. 16	${y^d}_1 \to 0.$ ${y^d}_2 \to 0.$ ${y^d}_3 \to 0.0269956$ ${y^d}_4 \to 2.87187$		${y^d}_1 \to$ ydo ${y^d}_2 \to$ ys ${y^d}_3 \to$ yb ${y^d}_4 \to$ ybp	QED, 1	D-quark Yukawa coupling
CKM	F	q, q	Eq. 17	$\mathrm{CKM}_{1,1} \to 1. + 0.I$ $\mathrm{CKM}_{1,2} \to 0. + 0.I$ $\mathrm{CKM}_{1,3} \to 0. + 0.I$ $\mathrm{CKM}_{1,4} \to 0. + 0.I$ $\mathrm{CKM}_{2,1} \to 0. + 0.I$ $\mathrm{CKM}_{2,2} \to 0.99995 + 0.I$ $\mathrm{CKM}_{2,3} \to 0. + 0.I$ $\mathrm{CKM}_{2,4} \to 0.01 + 0.I$				CKM-Matrix

Table 11: Details of internal parameters. The headers are as follows: P = parameter, C = complex, I = Indices, V = value, NV = numerical value, D = definition, PN = parameter name, and IO = interaction order.

$$\alpha_{\mathrm{EW}} = \frac{1}{\alpha\mathrm{EWM1}} \tag{2}$$

$$M_W = \sqrt{\frac{\mathrm{MZ}^2}{2} + \sqrt{\frac{\mathrm{MZ}^4}{4} - \frac{\mathrm{MZ}^2 \pi \alpha_{\mathrm{EW}}}{\sqrt{2} G_f}}} \tag{3}$$

P	C	I	V	NV	D	PN	IO	Description
				$\mathrm{CKM}_{3,1} \to 0. + 0.I$ $\mathrm{CKM}_{3,2} \to -0.001 + 0.I$ $\mathrm{CKM}_{3,3} \to 0.995 + 0.I$ $\mathrm{CKM}_{3,4} \to 0.1 + 0.I$ $\mathrm{CKM}_{4,1} \to 0. + 0.I$ $\mathrm{CKM}_{4,2} \to -0.01 + 0.I$ $\mathrm{CKM}_{4,3} \to -0.1 + 0.I$ $\mathrm{CKM}_{4,4} \to 0.99495 + 0.I$				

Table 12: Details of internal parameters. The headers are as follows: P = parameter, C = complex, I = Indices, V = value, NV = numerical value, D = definition, PN = parameter name, and IO = interaction order.

$$\mathrm{sw2} = 1 - \frac{{M_W}^2}{\mathrm{MZ}^2} \tag{4}$$

$$e = 2\sqrt{\pi}\sqrt{\alpha_{\mathrm{EW}}} \tag{5}$$

$$c_w = \sqrt{1 - \mathrm{sw2}} \tag{6}$$

$$s_w = \sqrt{\mathrm{sw2}} \tag{7}$$

$$g_w = \frac{e}{s_w} \tag{8}$$

$$g_1 = \frac{e}{c_w} \tag{9}$$

$$g_s = 2\sqrt{\pi}\sqrt{\alpha_s} \tag{10}$$

$$v = \frac{2M_W s_w}{e} \tag{11}$$

$$\lambda = \frac{\mathrm{MH}^2}{2v^2} \tag{12}$$

$$\mu = \sqrt{v^2\lambda} \tag{13}$$

$$\begin{aligned} {y^l}_1 &= 0 \\ {y^l}_2 &= 0 \\ {y^l}_3 &= \frac{\sqrt{2}\mathrm{ymtau}}{v} \end{aligned} \tag{14}$$

$$\begin{aligned} {y^u}_1 &= 0 \\ {y^u}_2 &= \frac{\sqrt{2}\mathrm{ymc}}{v} \\ {y^u}_3 &= \frac{\sqrt{2}\mathrm{ymt}}{v} \\ {y^u}_4 &= \frac{\sqrt{2}\mathrm{ymtp}}{v} \end{aligned} \tag{15}$$

$$\begin{aligned} {y^d}_1 &= 0 \\ {y^d}_2 &= 0 \\ {y^d}_3 &= \frac{\sqrt{2}\mathrm{ymb}}{v} \\ {y^d}_4 &= \frac{\sqrt{2}\mathrm{ymbp}}{v} \end{aligned} \tag{16}$$

$$\mathrm{CKM}_{i,j} = i\mathrm{ICKM}_{i,j} + \mathrm{RCKM}_{i,j} \tag{17}$$

6 Vertices

In this section, we describe the vertices of our model implementation.

6.1 V_1

$$\begin{pmatrix} H & 1 \\ H & 2 \\ H & 3 \\ H & 4 \end{pmatrix} \qquad -6i\lambda$$

$$\begin{pmatrix} H & 1 \\ H & 2 \\ H & 3 \end{pmatrix} \qquad -6iv\lambda$$

$$\begin{pmatrix} G & 1 \\ G & 2 \\ G & 3 \end{pmatrix} \qquad g_s f_{\mathrm{a}_1,\mathrm{a}_2,\mathrm{a}_3} {\mathrm{p}_1}^{\mu_3} \eta_{\mu_1,\mu_2} - g_s f_{\mathrm{a}_1,\mathrm{a}_2,\mathrm{a}_3} {\mathrm{p}_2}^{\mu_3} \eta_{\mu_1,\mu_2} - g_s f_{\mathrm{a}_1,\mathrm{a}_2,\mathrm{a}_3} {\mathrm{p}_1}^{\mu_2} \eta_{\mu_1,\mu_3} + g_s f_{\mathrm{a}_1,\mathrm{a}_2,\mathrm{a}_3} {\mathrm{p}_3}^{\mu_2} \eta_{\mu_1,\mu_3} + g_s f_{\mathrm{a}_1,\mathrm{a}_2,\mathrm{a}_3} {\mathrm{p}_2}^{\mu_1} \eta_{\mu_2,\mu_3} - g_s f_{\mathrm{a}_1,\mathrm{a}_2,\mathrm{a}_3} {\mathrm{p}_3}^{\mu_1} \eta_{\mu_2,\mu_3}$$

$$\begin{pmatrix} G & 1 \\ G & 2 \\ G & 3 \\ G & 4 \end{pmatrix} \qquad i{g_s}^2 f_{\mathrm{a}_1,\mathrm{a}_3,\mathrm{a1}} f_{\mathrm{a}_2,\mathrm{a}_4,\mathrm{a1}} \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} + i{g_s}^2 f_{\mathrm{a}_1,\mathrm{a}_2,\mathrm{a1}} f_{\mathrm{a}_3,\mathrm{a}_4,\mathrm{a1}} \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} + i{g_s}^2 f_{\mathrm{a}_1,\mathrm{a}_4,\mathrm{a1}} f_{\mathrm{a}_2,\mathrm{a}_3,\mathrm{a1}} \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} - i{g_s}^2 f_{\mathrm{a}_1,\mathrm{a}_2,\mathrm{a1}} f_{\mathrm{a}_3,\mathrm{a}_4,\mathrm{a1}} \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} - i{g_s}^2 f_{\mathrm{a}_1,\mathrm{a}_4,\mathrm{a1}} f_{\mathrm{a}_2,\mathrm{a}_3,\mathrm{a1}} \eta_{\mu_1,\mu_2} \eta_{\mu_3,\mu_4} - i{g_s}^2 f_{\mathrm{a}_1,\mathrm{a}_3,\mathrm{a1}} f_{\mathrm{a}_2,\mathrm{a}_4,\mathrm{a1}} \eta_{\mu_1,\mu_2} \eta_{\mu_3,\mu_4}$$

$$\begin{pmatrix} \mathrm{dq} & 1 \\ \bar{\mathrm{dq}} & 2 \\ G & 3 \end{pmatrix} \qquad i g_s {\gamma_{\mathrm{s}_2,\mathrm{s}_1}}^{\mu_3} \delta_{\mathrm{q}_1,\mathrm{q}_2} {T_{\mathrm{i}_2,\mathrm{i}_1}}^{\mathrm{a}_3}$$

$$\begin{pmatrix} G & 1 \\ \mathrm{uq} & 2 \\ \bar{\mathrm{uq}} & 3 \end{pmatrix} \qquad i g_s {\gamma_{\mathrm{s}_3,\mathrm{s}_2}}^{\mu_1} \delta_{\mathrm{q}_2,\mathrm{q}_3} {T_{\mathrm{i}_3,\mathrm{i}_2}}^{\mathrm{a}_1}$$

$$\begin{pmatrix} A & 1 \\ W & 2 \\ W^\dagger & 3 \end{pmatrix} \qquad -i g_w s_w {\mathrm{p}_1}^{\mu_3} \eta_{\mu_1,\mu_2} + i g_w s_w {\mathrm{p}_2}^{\mu_3} \eta_{\mu_1,\mu_2} + i g_w s_w {\mathrm{p}_1}^{\mu_2} \eta_{\mu_1,\mu_3} - i g_w s_w {\mathrm{p}_3}^{\mu_2} \eta_{\mu_1,\mu_3} - i g_w s_w {\mathrm{p}_2}^{\mu_1} \eta_{\mu_2,\mu_3} + i g_w s_w {\mathrm{p}_3}^{\mu_1} \eta_{\mu_2,\mu_3}$$

$$\begin{pmatrix} H & 1 \\ H & 2 \\ W & 3 \\ W^\dagger & 4 \end{pmatrix} \qquad \frac{ie^2 \eta_{\mu_3,\mu_4}}{2{s_w}^2}$$

$$\begin{pmatrix} H & 1 \\ W & 2 \\ W^\dagger & 3 \end{pmatrix} \qquad \frac{ie^2 v \eta_{\mu_2,\mu_3}}{2{s_w}^2}$$

$$\begin{pmatrix} A & 1 \\ A & 2 \\ W & 3 \\ W^\dagger & 4 \end{pmatrix} \qquad i{g_w}^2{s_w}^2 \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} + i{g_w}^2{s_w}^2 \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} - 2i{g_w}^2{s_w}^2 \eta_{\mu_1,\mu_2} \eta_{\mu_3,\mu_4}$$

$$\begin{pmatrix} W & 1 \\ W^\dagger & 2 \\ Z & 3 \end{pmatrix} \qquad -i c_w g_w {\mathrm{p}_1}^{\mu_3} \eta_{\mu_1,\mu_2} + i c_w g_w {\mathrm{p}_2}^{\mu_3} \eta_{\mu_1,\mu_2} + i c_w g_w {\mathrm{p}_1}^{\mu_2} \eta_{\mu_1,\mu_3} - i c_w g_w {\mathrm{p}_3}^{\mu_2} \eta_{\mu_1,\mu_3} - i c_w g_w {\mathrm{p}_2}^{\mu_1} \eta_{\mu_2,\mu_3} + i c_w g_w {\mathrm{p}_3}^{\mu_1} \eta_{\mu_2,\mu_3}$$

$$\begin{pmatrix} W & 1 \\ W & 2 \\ W^\dagger & 3 \\ W^\dagger & 4 \end{pmatrix} \qquad -i{g_w}^2 \eta_{\mu_1,\mu_4} \eta_{\mu_2,\mu_3} - i{g_w}^2 \eta_{\mu_1,\mu_3} \eta_{\mu_2,\mu_4} + 2i{g_w}^2 \eta_{\mu_1,\mu_2} \eta_{\mu_3,\mu_4}$$

$$\begin{pmatrix} \mathrm{dq} & 1 \\ \bar{\mathrm{dq}} & 2 \\ H & 3 \end{pmatrix} \qquad -\frac{i\delta_{\mathrm{i}_1,\mathrm{i}_2}\delta_{\mathrm{q}_1,\mathrm{q}_2}\delta_{\mathrm{s}_2,\mathrm{s}_1}{y^d}_{\mathrm{q}_1}}{\sqrt{2}}$$

$$\begin{pmatrix} H & 1 \\ l & 2 \\ \bar{l} & 3 \end{pmatrix} \qquad -\frac{i\delta_{\mathrm{f}_2,\mathrm{f}_3}\delta_{\mathrm{s}_3,\mathrm{s}_2}{y^l}_{\mathrm{f}_2}}{\sqrt{2}}$$

$$\begin{pmatrix} H & 1 \\ \mathrm{uq} & 2 \\ \bar{\mathrm{uq}} & 3 \end{pmatrix} \qquad -\frac{i\delta_{\mathrm{i}_2,\mathrm{i}_3}\delta_{\mathrm{q}_2,\mathrm{q}_3}\delta_{\mathrm{s}_3,\mathrm{s}_2}{y^u}_{\mathrm{q}_2}}{\sqrt{2}}$$

$$\begin{pmatrix} A & 1 \\ W & 2 \\ W^\dagger & 3 \\ Z & 4 \end{pmatrix} \qquad -2ic_w{g_w}^2s_w\eta_{\mu_1,\mu_4}\eta_{\mu_2,\mu_3}+ic_w{g_w}^2s_w\eta_{\mu_1,\mu_3}\eta_{\mu_2,\mu_4}+ic_w{g_w}^2s_w\eta_{\mu_1,\mu_2}\eta_{\mu_3,\mu_4}$$

$$\begin{pmatrix} H & 1 \\ H & 2 \\ Z & 3 \\ Z & 4 \end{pmatrix} \qquad ie^2\eta_{\mu_3,\mu_4}+\frac{i{c_w}^2e^2\eta_{\mu_3,\mu_4}}{2{s_w}^2}+\frac{ie^2{s_w}^2\eta_{\mu_3,\mu_4}}{2{c_w}^2}$$

$$\begin{pmatrix} H & 1 \\ Z & 2 \\ Z & 3 \end{pmatrix} \qquad ie^2v\eta_{\mu_2,\mu_3}+\frac{i{c_w}^2e^2v\eta_{\mu_2,\mu_3}}{2{s_w}^2}+\frac{ie^2{s_w}^2v\eta_{\mu_2,\mu_3}}{2{c_w}^2}$$

$$\begin{pmatrix} W & 1 \\ W^\dagger & 2 \\ Z & 3 \\ Z & 4 \end{pmatrix} \qquad i{c_w}^2{g_w}^2\eta_{\mu_1,\mu_4}\eta_{\mu_2,\mu_3}+i{c_w}^2{g_w}^2\eta_{\mu_1,\mu_3}\eta_{\mu_2,\mu_4}-2i{c_w}^2{g_w}^2\eta_{\mu_1,\mu_2}\eta_{\mu_3,\mu_4}$$

$$\begin{pmatrix} A & 1 \\ \mathrm{dq} & 2 \\ \bar{\mathrm{dq}} & 3 \end{pmatrix} \qquad -\frac{1}{3}ie{\gamma_{\mathrm{s}_3,\mathrm{s}_2}}^{\mu_1}\delta_{\mathrm{i}_2,\mathrm{i}_3}\delta_{\mathrm{q}_2,\mathrm{q}_3}$$

$$\begin{pmatrix} A & 1 \\ l & 2 \\ \bar{l} & 3 \end{pmatrix} \qquad -ie{\gamma_{\mathrm{s}_3,\mathrm{s}_2}}^{\mu_1}\delta_{\mathrm{f}_2,\mathrm{f}_3}$$

$$\begin{pmatrix} A & 1 \\ \mathrm{uq} & 2 \\ \bar{\mathrm{uq}} & 3 \end{pmatrix} \qquad \frac{2}{3}ie{\gamma_{\mathrm{s}_3,\mathrm{s}_2}}^{\mu_1}\delta_{\mathrm{i}_2,\mathrm{i}_3}\delta_{\mathrm{q}_2,\mathrm{q}_3}$$

$$\begin{pmatrix} l & 1 \\ \bar{\mathrm{vl}} & 2 \\ W & 3 \end{pmatrix} \qquad \frac{ie\delta_{\mathrm{f}_1,\mathrm{f}_2}\gamma^{\mu_3}.P_{-\mathrm{s}_2,\mathrm{s}_1}}{\sqrt{2}s_w}$$

$$\begin{pmatrix} \mathrm{dq} & 1 \\ \bar{\mathrm{uq}} & 2 \\ W & 3 \end{pmatrix} \qquad \frac{ie\mathrm{CKM}_{\mathrm{q}_2,\mathrm{q}_1}\delta_{\mathrm{i}_1,\mathrm{i}_2}\gamma^{\mu_3}.P_{-\mathrm{s}_2,\mathrm{s}_1}}{\sqrt{2}s_w}$$

$$\begin{pmatrix} \bar{l} & 1 \\ \mathrm{vl} & 2 \\ W^\dagger & 3 \end{pmatrix} \qquad \frac{ie\delta_{\mathrm{f}_1,\mathrm{f}_2}\gamma^{\mu_3}.P_{-\mathrm{s}_1,\mathrm{s}_2}}{\sqrt{2}s_w}$$

$$\begin{pmatrix} \bar{\text{dq}} & 1 \\ \text{uq} & 2 \\ W^{\dagger} & 3 \end{pmatrix} \qquad \frac{ie\text{CKM}_{\text{q}_2,\text{q}_1}{}^{*}\delta_{\text{i}_1,\text{i}_2}\gamma^{\mu_3}.P_{-\text{s}_1,\text{s}_2}}{\sqrt{2}s_w}$$

$$\begin{pmatrix} \text{dq} & 1 \\ \bar{\text{dq}} & 2 \\ Z & 3 \end{pmatrix} \qquad -\frac{ic_w e\delta_{\text{i}_1,\text{i}_2}\delta_{\text{q}_1,\text{q}_2}\gamma^{\mu_3}.P_{-\text{s}_2,\text{s}_1}}{2s_w} - \frac{ies_w\delta_{\text{i}_1,\text{i}_2}\delta_{\text{q}_1,\text{q}_2}\gamma^{\mu_3}.P_{-\text{s}_2,\text{s}_1}}{6c_w} + \frac{ies_w\delta_{\text{i}_1,\text{i}_2}\delta_{\text{q}_1,\text{q}_2}\gamma^{\mu_3}.P_{+\text{s}_2,\text{s}_1}}{3c_w}$$

$$\begin{pmatrix} l & 1 \\ \bar{l} & 2 \\ Z & 3 \end{pmatrix} \qquad -\frac{ic_w e\delta_{\text{f}_1,\text{f}_2}\gamma^{\mu_3}.P_{-\text{s}_2,\text{s}_1}}{2s_w} + \frac{ies_w\delta_{\text{f}_1,\text{f}_2}\gamma^{\mu_3}.P_{-\text{s}_2,\text{s}_1}}{2c_w} + \frac{ies_w\delta_{\text{f}_1,\text{f}_2}\gamma^{\mu_3}.P_{+\text{s}_2,\text{s}_1}}{c_w}$$

$$\begin{pmatrix} \text{uq} & 1 \\ \bar{\text{uq}} & 2 \\ Z & 3 \end{pmatrix} \qquad \frac{ic_w e\delta_{\text{i}_1,\text{i}_2}\delta_{\text{q}_1,\text{q}_2}\gamma^{\mu_3}.P_{-\text{s}_2,\text{s}_1}}{2s_w} - \frac{ies_w\delta_{\text{i}_1,\text{i}_2}\delta_{\text{q}_1,\text{q}_2}\gamma^{\mu_3}.P_{-\text{s}_2,\text{s}_1}}{6c_w} - \frac{2ies_w\delta_{\text{i}_1,\text{i}_2}\delta_{\text{q}_1,\text{q}_2}\gamma^{\mu_3}.P_{+\text{s}_2,\text{s}_1}}{3c_w}$$

$$\begin{pmatrix} \text{vl} & 1 \\ \bar{\text{vl}} & 2 \\ Z & 3 \end{pmatrix} \qquad \frac{ic_w e\delta_{\text{f}_1,\text{f}_2}\gamma^{\mu_3}.P_{-\text{s}_2,\text{s}_1}}{2s_w} + \frac{ies_w\delta_{\text{f}_1,\text{f}_2}\gamma^{\mu_3}.P_{-\text{s}_2,\text{s}_1}}{2c_w}$$

References

[1] N. D. Christensen and C. Duhr, arXiv:0806.4194 [hep-ph].