

# FeynRules Implementation of Higgs\_Effective\_Couplings

N. Christensen \*

Michigan State University

C. Duhr †

Universite catholique de Louvain (CP3)

April 3, 2011

## Abstract

We describe the implementation of the Higgs\_Effective\_Couplings model using the FeynRules package.

## Contents

<b>1</b>	<b>Introduction</b>	<b>2</b>
<b>2</b>	<b>Gauge Symmetries</b>	<b>2</b>
<b>3</b>	<b>Fields</b>	<b>3</b>
3.1	Vector Fields . . . . .	3
3.2	Fermion Fields . . . . .	3
3.3	Scalar Fields . . . . .	3
3.4	Ghost Fields . . . . .	3
<b>4</b>	<b>Lagrangian</b>	<b>6</b>
4.1	$L_1$ . . . . .	6
4.2	$L_2$ . . . . .	6
4.3	$L_3$ . . . . .	6
4.4	$L_4$ . . . . .	6
4.5	$L_5$ . . . . .	6
4.6	$L_6$ . . . . .	6
<b>5</b>	<b>Parameters</b>	<b>7</b>
5.1	External Parameters . . . . .	7
5.2	Internal Parameters . . . . .	8

## List of Tables

1	Gauge Groups . . . . .	2
2	Indices . . . . .	2
3	Physical Vector Fields . . . . .	3
4	Unphysical Vector Fields . . . . .	3
5	Physical Fermion Fields . . . . .	4
6	Physical Scalar Fields . . . . .	4
7	Physical Ghost Fields . . . . .	4
8	Unphysical Ghost Fields . . . . .	5
9	External Parameters . . . . .	7
10	Internal Parameters . . . . .	8
11	Internal Parameters . . . . .	9

---

\*email: neil@pa.msu.edu

†email: claude.duhr@uclouvain.be

# 1 Introduction

We describe the implementation of the Higgs\_Effective\_Couplings 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		$FSU2L_{k,k}$	$FSU2L[a\$, b\$, c\$] \rightarrow -I \text{Eps}[a\$, b\$, c\$]$
SU3C	F	G	gs		f	dSUN	$T_{i,i}$ $FSU3C_{a,a}$	$FSU3C[a\$, b\$, c\$] \rightarrow -I f[a\$, b\$, c\$]$

Table 1: Details of gauge groups.

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

Index	Symbol	Range
Generation	f	1-3
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= 91.1876	WZ= 2.4952	23
W	F			$Q = 1$	W	MW= Internal	WW= 2.085	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	$Wi_{\mu,1} \rightarrow \frac{W_{\mu} + W_{\mu}^{\dagger}}{\sqrt{2}}$ $Wi_{\mu,2} \rightarrow -\frac{i(-W_{\mu} + W_{\mu}^{\dagger})}{\sqrt{2}}$ $Wi_{\mu,3} \rightarrow s_w A_{\mu} + c_w Z_{\mu}$
B	T				B	$B_{\mu} \rightarrow c_w A_{\mu} - s_w Z_{\mu}$

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	$Q = -1$ $LeptonNumber = 1$	e	MI Me= 0.000511		11
					m	MM= 0.10566		13
					tt	MTA= 1.777		15
uq	F	f, i	f	$Q = 2/3$	u	Mu MU= 0.00255	0	2
					c	MC= 1.42	0	4
					t	MT= 172	WT= 1.50834	6
dq	F	f, i	f	$Q = -1/3$	d	Md MD= 0.00504		1
					s	MS= 0.101		3
					b	MB= 4.7		5

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= 91.1876	Wphi	250
phi2	F			$Q = 1$	phi2	MW= Internal	Wphi2	251
h1	T				h1	MP= 120	WH1= 0.00575309	

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= 91.1876		
ghWp	F			$Q = 1$	ghWp	MW= Internal		
ghWm	F			$GhostNumber = 1$ $Q = -1$	ghWm	MW= Internal		
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	$\text{ghWi}_1 \rightarrow \frac{\text{ghWm} + \text{ghWp}}{\sqrt{2}}$ $\text{ghWi}_2 \rightarrow -\frac{i(\text{ghWm} - \text{ghWp})}{\sqrt{2}}$ $\text{ghWi}_3 \rightarrow c_w \text{ghZ} + \text{ghA}_{s_w}$
ghB	F				ghB	$\text{ghB} \rightarrow c_w \text{ghA} - \text{ghZ}_{s_w}$

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 $L_1$

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

### 4.2 $L_2$

$$\bar{d}q_\mu \gamma^\mu \cdot \partial_\mu [dq] + i \bar{l} \cdot \gamma^\mu \cdot \partial_\mu [l] + i \bar{u}q_\mu \gamma^\mu \cdot \partial_\mu [uq] + i \bar{v}l_\mu \gamma^\mu \cdot \partial_\mu [vl] + \frac{e B_\mu \bar{d}q_\mu \gamma^\mu \cdot P_- \cdot dq}{6c_w} - \frac{e B_\mu \bar{d}q_\mu \gamma^\mu \cdot P_+ \cdot dq}{3c_w} - \frac{e B_\mu \bar{l} \cdot \gamma^\mu \cdot P_- \cdot l}{2c_w} - \frac{e B_\mu \bar{l} \cdot \gamma^\mu \cdot P_+ \cdot l}{c_w} + \frac{e B_\mu \bar{u}q_\mu \gamma^\mu \cdot P_- \cdot uq}{6c_w} + \frac{2e B_\mu \bar{u}q_\mu \gamma^\mu \cdot P_+ \cdot uq}{3c_w} - \frac{e B_\mu \bar{v}l_\mu \gamma^\mu \cdot P_- \cdot vl}{2c_w} + g_s \left( \bar{d}q \cdot T^a \cdot \gamma^\mu \cdot dq + \bar{u}q \cdot T^a \cdot \gamma^\mu \cdot uq \right) G_{\mu,a} + \frac{e \left( \sqrt{2} \bar{v}l_\mu \gamma^\mu \cdot P_- \cdot l W_\mu + \sqrt{2} \bar{u}q \cdot \text{CKM} \cdot \gamma^\mu \cdot P_- \cdot dq W_\mu + \sqrt{2} \bar{l} \cdot \gamma^\mu \cdot P_- \cdot vl W_\mu^\dagger + \sqrt{2} \bar{d}q \cdot \text{CKM}^\dagger \cdot \gamma^\mu \cdot P_- \cdot uq W_\mu^\dagger - \bar{d}q \cdot \gamma^\mu \cdot P_- \cdot dq W_{\mu,3} - \bar{l} \cdot \gamma^\mu \cdot P_- \cdot l W_{\mu,3} + \bar{u}q \cdot \gamma^\mu \cdot P_- \cdot uq W_{\mu,3} + \bar{v}l \cdot \gamma^\mu \cdot P_- \cdot vl W_{\mu,3} \right)}{2s_w}$$

### 4.3 $L_3$

$$\mu^2 (\text{phi}2\text{phi}2^\dagger + \frac{1}{2}(H - i\phi + v)(H + i\phi + v)) - (\text{phi}2\text{phi}2^\dagger + \frac{1}{2}(H - i\phi + v)(H + i\phi + v))^2 \lambda + \left( -\frac{i e \text{phi}2 B_\mu}{2c_w} + \partial_\mu [\text{phi}2] + \frac{e \left( \frac{(H+i\phi+v)(W_{i\mu,1} - iW_{i\mu,2})}{\sqrt{2}} - i\text{phi}2 W_{i\mu,3} \right)}{2s_w} \right) \left( \frac{i e \text{phi}2^\dagger B_\mu}{2c_w} + \partial_\mu [\text{phi}2^\dagger] + \frac{e \left( \frac{(H-i\phi+v)(W_{i\mu,1} + iW_{i\mu,2})}{\sqrt{2}} + i\text{phi}2^\dagger W_{i\mu,3} \right)}{2s_w} \right) + \left( \frac{e(H-i\phi+v)B_\mu}{2\sqrt{2}c_w} - \frac{i(\partial_\mu [H] - i\partial_\mu [\phi])}{\sqrt{2}} + \frac{e(i\text{phi}2^\dagger (W_{i\mu,1} - iW_{i\mu,2}) - \frac{(H-i\phi+v)W_{i\mu,3}}{\sqrt{2}})}{2s_w} \right) \left( \frac{e(H+i\phi+v)B_\mu}{2\sqrt{2}c_w} + \frac{i(\partial_\mu [H] + i\partial_\mu [\phi])}{\sqrt{2}} + \frac{e(-i\text{phi}2 (W_{i\mu,1} + iW_{i\mu,2}) - \frac{(H-i\phi+v)W_{i\mu,3}}{\sqrt{2}})}{2s_w} \right)$$

### 4.4 $L_4$

$$i\text{phi}2\text{CKM}_{n\$1129,m\$1129} \bar{u}q_{s\$1129,n\$1129,i\$1129} \cdot dq_{r\$1129,m\$1129,i\$1129} P_{+s\$1129,r\$1129} y^d_{m\$1129} - i\text{phi}2^\dagger \text{CKM}_{n\$1130,m\$1130} \bar{d}q_{r\$1131,m\$1130,i\$1130} \cdot uq_{r\$1132,n\$1130,i\$1130} P_{-r\$1131,r\$1132} y^d_{m\$1130} - \frac{(H+i\phi+v) \bar{d}q_{s\$1129,n\$1129,i\$1129} \cdot dq_{r\$1129,n\$1129,i\$1129} P_{+s\$1129,r\$1129} y^d_{n\$1129}}{\sqrt{2}} - \frac{(H-i\phi+v) \bar{d}q_{r\$1133,n\$1130,i\$1130} \cdot dq_{r\$1134,n\$1130,i\$1130} P_{-r\$1133,r\$1134} y^d_{n\$1130}}{\sqrt{2}} - \frac{(H+i\phi+v) \bar{l}_{s\$1129,n\$1129} \cdot l_{r\$1129,n\$1129} P_{+s\$1129,r\$1129} y^l_{n\$1129}}{\sqrt{2}} + i\text{phi}2 \bar{v}_{s\$1129,n\$1129} \cdot l_{r\$1129,n\$1129} P_{+s\$1129,r\$1129} y^l_{n\$1129} - \frac{(H-i\phi+v) \bar{l}_{r\$1135,n\$1130} \cdot l_{r\$1136,n\$1130} P_{-r\$1135,r\$1136} y^l_{n\$1130}}{\sqrt{2}} - i\text{phi}2^\dagger \bar{l}_{r\$1137,n\$1130} \cdot v_{r\$1138,n\$1130} P_{-r\$1137,r\$1138} y^l_{n\$1130} + i\text{phi}2^\dagger \text{CKM}_{m\$1129,n\$1129} \bar{d}q_{s\$1129,n\$1129,i\$1129} \cdot uq_{r\$1129,m\$1129,i\$1129} P_{+s\$1129,r\$1129} y^u_{m\$1129} - i\text{phi}2 \text{CKM}_{m\$1130,n\$1130} \bar{u}q_{r\$1139,m\$1130,i\$1130} \cdot dq_{r\$1140,n\$1130,i\$1130} P_{-r\$1139,r\$1140} y^u_{m\$1130} - \frac{(H-i\phi+v) \bar{u}q_{s\$1129,n\$1129,i\$1129} \cdot uq_{r\$1129,n\$1129,i\$1129} P_{+s\$1129,r\$1129} y^u_{n\$1129}}{\sqrt{2}} - \frac{(H+i\phi+v) \bar{u}q_{r\$1141,n\$1130,i\$1130} \cdot uq_{r\$1142,n\$1130,i\$1130} P_{-r\$1141,r\$1142} y^u_{n\$1130}}{\sqrt{2}}$$

### 4.5 $L_5$

$$-\frac{1}{4} A_H H (-\partial_\nu [A_\mu] + \partial_\mu [A_\nu])^2 - \frac{1}{4} G_H H (-\partial_\nu [G_{\mu,b}] + \partial_\mu [G_{\nu,b}] + g_s f_{b,bb\$1143,cc\$1143} G_{\mu,bb\$1143} G_{\nu,cc\$1143}) (-\partial_\nu [G_{\mu,b}] + \partial_\mu [G_{\nu,b}] + g_s f_{b,bb\$1144,cc\$1144} G_{\mu,bb\$1144} G_{\nu,cc\$1144} + g_s f_{b,bb\$1145,cc\$1145} G_{\mu,bb\$1145} G_{\nu,cc\$1145})$$

### 4.6 $L_6$

$$-\frac{1}{8} G_h h_1 \epsilon_{\mu,\nu,xx\$1146,yy\$1146} (-\partial_\nu [G_{\mu,a}] + \partial_\mu [G_{\nu,a}] + g_s f_{a,bb\$1145,cc\$1145} G_{\mu,bb\$1145} G_{\nu,cc\$1145}) (-\partial_{yy\$1146} [G_{xx\$1146,a}] + \partial_{xx\$1146} [G_{yy\$1146,a}])$$

## 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

P	C	I	V	D	PN	BN	OB	IO	Description
$\alpha_{\text{EWM1}}$	F		127.9		aEWM1	SMINPUTS		QED, -2	Inverse of the electroweak coupling constant
$G_f$	F		0.0000116637			SMINPUTS		QED, 2	Fermi constant
$\alpha_s$	F		0.1184		aS	SMINPUTS		QCD, 2	Strong coupling constant at the Z pole.
y <sub>mdo</sub>	F		0.			YUKAWA	1		Down Yukawa mass
y <sub>mup</sub>	F		0.			YUKAWA	2		Up Yukawa mass
y <sub>ms</sub>	F		0.			YUKAWA	3		Strange Yukawa mass
y <sub>mc</sub>	F		0.			YUKAWA	4		Charm Yukawa mass
y <sub>mb</sub>	F		4.7			YUKAWA	5		Bottom Yukawa mass
y <sub>mt</sub>	F		172.			YUKAWA	6		Top Yukawa mass
y <sub>me</sub>	F		0.			YUKAWA	11		Electron Yukawa mass
y <sub>mm</sub>	F		0.			YUKAWA	13		Muon Yukawa mass
y <sub>mtau</sub>	F		1.777			YUKAWA	15		Tau Yukawa mass
$\theta_c$	F		0.227736			CKMBLOCK			Cabibbo angle

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.

Table 9.

## 5.2 Internal Parameters

In this subsection, we describe the internal parameters of our model. The details of the internal parameters can be found

P	C	I	V	NV	D	PN	IO	Description
$\alpha_{EW}$	F		Eq. 2	0.00781861		aEW	QED, 2	Electroweak coupling constant
$M_W$	F		Eq. 3	79.8244				W mass
sw2	F		Eq. 4	0.233699				Squared Sin of the Weinberg angle
$e$	F		Eq. 5	0.313451			QED, 1	Electric coupling constant
$c_w$	F		Eq. 6	0.875386				Cos of the Weinberg angle
$s_w$	F		Eq. 7	0.483424				Sin of the Weinberg angle
$g_w$	F		Eq. 8	0.648397			QED, 1	Weak coupling constant
$g_1$	F		Eq. 9	0.358072			QED, 1	U(1)Y coupling constant
$g_s$	F		Eq. 10	1.21978		$G$	QCD, 1	Strong coupling constant
$v$	F		Eq. 11	246.221			QED, -1	Higgs VEV
$\lambda$	F		Eq. 12	0.118764		lam	QED, 2	Higgs quartic coupling
$\mu$	F		Eq. 13	84.8528				Coefficient of the quadratic piece of the Higgs potential
yl	F	f	Eq. 14	$y^l_1 \rightarrow 0.$ $y^l_2 \rightarrow 0.$ $y^l_3 \rightarrow 0.0102065$		$y^l_1 \rightarrow ye$ $y^l_2 \rightarrow ym$ $y^l_3 \rightarrow ytau$	QED, 1	Lepton Yukawa coupling
yu	F	f	Eq. 15	$y^u_1 \rightarrow 0.$ $y^u_2 \rightarrow 0.$ $y^u_3 \rightarrow 0.987914$		$y^u_1 \rightarrow yup$ $y^u_2 \rightarrow yc$ $y^u_3 \rightarrow yt$	QED, 1	U-quark Yukawa coupling
yd	F	f	Eq. 16	$y^d_1 \rightarrow 0.$ $y^d_2 \rightarrow 0.$ $y^d_3 \rightarrow 0.0269953$		$y^d_1 \rightarrow ydo$ $y^d_2 \rightarrow ys$ $y^d_3 \rightarrow yb$	QED, 1	D-quark Yukawa coupling
CKM	F	f, f	Eq. 17	CKM <sub>1,1</sub> $\rightarrow$ 0.97418 CKM <sub>1,2</sub> $\rightarrow$ 0.225773 CKM <sub>1,3</sub> $\rightarrow$ 0. CKM <sub>2,1</sub> $\rightarrow$ -0.225773 CKM <sub>2,2</sub> $\rightarrow$ 0.97418 CKM <sub>2,3</sub> $\rightarrow$ 0. CKM <sub>3,1</sub> $\rightarrow$ 0. CKM <sub>3,2</sub> $\rightarrow$ 0. CKM <sub>3,3</sub> $\rightarrow$ 1.				CKM-Matrix

Table 10: 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.

in Tables 10, 11. The values and definitions of the internal parameters will be written below.

$$\alpha_{EW} = \frac{1}{\alpha_{EWM1}} \quad (2)$$

$$M_W = \sqrt{\frac{MZ^2}{2} + \sqrt{\frac{MZ^4}{4} - \frac{MZ^2\pi\alpha_{EW}}{\sqrt{2}G_f}}} \quad (3)$$

$$sw2 = 1 - \frac{M_W^2}{MZ^2} \quad (4)$$



P	C	I	V	NV	D	PN	IO	Description
$A_H$	F		Eq. 18	0.0000321323			HIW, 1	
$G_H$	F		Eq. 19	-0.0000525471			HIG, 1	
$G_h$	F		Eq. 20	-0.0000798544			HIG, 1	

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.

$$e = 2\sqrt{\pi}\sqrt{\alpha_{EW}} \quad (5)$$

$$c_w = \sqrt{1 - s_w^2} \quad (6)$$

$$s_w = \sqrt{s_w^2} \quad (7)$$

$$g_w = \frac{e}{s_w} \quad (8)$$

$$g_1 = \frac{e}{c_w} \quad (9)$$

$$g_s = 2\sqrt{\pi}\sqrt{\alpha_s} \quad (10)$$

$$v = \frac{2M_W s_w}{e} \quad (11)$$

$$\lambda = \frac{MH^2}{2v^2} \quad (12)$$

$$\mu = \sqrt{v^2 \lambda} \quad (13)$$

$$\begin{aligned} y^l_1 &= \frac{\sqrt{2}y_{me}}{v} \\ y^l_2 &= \frac{\sqrt{2}y_{mm}}{v} \\ y^l_3 &= \frac{\sqrt{2}y_{m\tau}}{v} \end{aligned} \quad (14)$$

$$\begin{aligned} y^u_1 &= \frac{\sqrt{2}y_{m\mu p}}{v} \\ y^u_2 &= \frac{\sqrt{2}y_{mc}}{v} \\ y^u_3 &= \frac{\sqrt{2}y_{mt}}{v} \end{aligned} \quad (15)$$

$$\begin{aligned} y^d_1 &= \frac{\sqrt{2}y_{mdo}}{v} \\ y^d_2 &= \frac{\sqrt{2}y_{ms}}{v} \\ y^d_3 &= \frac{\sqrt{2}y_{mb}}{v} \end{aligned} \quad (16)$$

$$\begin{aligned} \text{CKM}_{1,1} &= \text{Cos}[\theta_c] \\ \text{CKM}_{1,2} &= \text{Sin}[\theta_c] \\ \text{CKM}_{1,3} &= 0 \\ \text{CKM}_{2,1} &= -\text{Sin}[\theta_c] \\ \text{CKM}_{2,2} &= \text{Cos}[\theta_c] \\ \text{CKM}_{2,3} &= 0 \\ \text{CKM}_{3,1} &= 0 \\ \text{CKM}_{3,2} &= 0 \\ \text{CKM}_{3,3} &= 1 \end{aligned} \quad (17)$$

$$A_H = \frac{47e^2 \left( 1 - \frac{2MH^4}{987MT^4} - \frac{14MH^2}{705MT^2} + \frac{213MH^{12}}{26346320M_W^{12}} + \frac{5MH^{10}}{119756M_W^{10}} + \frac{41MH^8}{180950M_W^8} + \frac{87MH^6}{65800M_W^6} + \frac{57MH^4}{6580M_W^4} + \frac{33MH^2}{470M_W^2} \right)}{72\pi^2 v} \quad (18)$$

$$G_H = -\frac{g_s^2 \left( 1 + \frac{13MH^6}{16800MT^6} + \frac{MH^4}{168MT^4} + \frac{7MH^2}{120MT^2} \right)}{12\pi^2 v} \quad (19)$$

$$G_h = -\frac{g_s^2 \left( 1 + \frac{MH^6}{560MT^6} + \frac{MH^4}{90MT^4} + \frac{MH^2}{12MT^2} \right)}{8\pi^2 v} \quad (20)$$

## 6 Vertices

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

### 6.1 $V_1$

$$\begin{aligned}
 & \begin{pmatrix} H & 1 \\ H & 2 \\ H & 3 \\ H & 4 \end{pmatrix} && -6i\lambda \\
 & \begin{pmatrix} H & 1 \\ H & 2 \\ \phi & 3 \\ \phi & 4 \end{pmatrix} && -2i\lambda \\
 & \begin{pmatrix} \phi & 1 \\ \phi & 2 \\ \phi & 3 \\ \phi & 4 \end{pmatrix} && -6i\lambda \\
 & \begin{pmatrix} H & 1 \\ H & 2 \\ \text{phi2} & 3 \\ \text{phi2}^\dagger & 4 \end{pmatrix} && -2i\lambda \\
 & \begin{pmatrix} \phi & 1 \\ \phi & 2 \\ \text{phi2} & 3 \\ \text{phi2}^\dagger & 4 \end{pmatrix} && -2i\lambda \\
 & \begin{pmatrix} \text{phi2} & 1 \\ \text{phi2} & 2 \\ \text{phi2}^\dagger & 3 \\ \text{phi2}^\dagger & 4 \end{pmatrix} && -4i\lambda \\
 & \begin{pmatrix} H & 1 \\ H & 2 \\ H & 3 \end{pmatrix} && -6i\nu\lambda \\
 & \begin{pmatrix} H & 1 \\ \phi & 2 \\ \phi & 3 \end{pmatrix} && -2i\nu\lambda \\
 & \begin{pmatrix} H & 1 \\ \text{phi2} & 2 \\ \text{phi2}^\dagger & 3 \end{pmatrix} && -2i\nu\lambda \\
 & \begin{pmatrix} A & 1 \\ A & 2 \\ \text{phi2} & 3 \\ \text{phi2}^\dagger & 4 \end{pmatrix} && 2ie^2\eta_{\mu_1,\mu_2} \\
 & \begin{pmatrix} A & 1 \\ \text{phi2} & 2 \\ \text{phi2}^\dagger & 3 \end{pmatrix} && ie p_2^{\mu_1} - ie p_3^{\mu_1}
 \end{aligned}$$

$$\begin{aligned}
\begin{pmatrix} A & 1 \\ A & 2 \\ H & 3 \end{pmatrix} & -iA_{HP_1}{}^{\mu_2} p_2^{\mu_1} + iA_H \eta_{\mu_1, \mu_2} p_1 \cdot p_2 \\
\begin{pmatrix} G & 1 \\ G & 2 \\ H & 3 \end{pmatrix} & -iG_{HP_1}{}^{\mu_2} p_2^{\mu_1} \delta_{a_1, a_2} + iG_H \delta_{a_1, a_2} \eta_{\mu_1, \mu_2} p_1 \cdot p_2 \\
\begin{pmatrix} \text{gh}A^\dagger & 1 \\ \text{gh}W_m & 2 \\ W & 3 \end{pmatrix} & iep_2^{\mu_3} + iep_3^{\mu_3} \\
\begin{pmatrix} \text{gh}A^\dagger & 1 \\ \text{gh}W_p & 2 \\ W^\dagger & 3 \end{pmatrix} & -iep_2^{\mu_3} - iep_3^{\mu_3} \\
\begin{pmatrix} \text{gh}W_m^\dagger & 1 \\ \text{gh}A & 2 \\ \text{phi}2^\dagger & 3 \end{pmatrix} & eM_W \\
\begin{pmatrix} \text{gh}W_m^\dagger & 1 \\ \text{gh}A & 2 \\ W^\dagger & 3 \end{pmatrix} & iep_2^{\mu_3} + iep_3^{\mu_3} \\
\begin{pmatrix} \text{gh}W_m^\dagger & 1 \\ \text{gh}W_m & 2 \\ H & 3 \end{pmatrix} & -\frac{ieM_W}{2s_w} \\
\begin{pmatrix} \text{gh}W_m^\dagger & 1 \\ \text{gh}W_m & 2 \\ \phi & 3 \end{pmatrix} & -\frac{eM_W}{2s_w} \\
\begin{pmatrix} A & 1 \\ \text{gh}W_m^\dagger & 2 \\ \text{gh}W_m & 3 \end{pmatrix} & -iep_1^{\mu_1} - iep_3^{\mu_1} \\
\begin{pmatrix} \text{gh}W_m^\dagger & 1 \\ \text{gh}W_m & 2 \\ Z & 3 \end{pmatrix} & -\frac{ic_w ep_2^{\mu_3}}{s_w} - \frac{ic_w ep_3^{\mu_3}}{s_w} \\
\begin{pmatrix} \text{gh}W_m^\dagger & 1 \\ \text{gh}Z & 2 \\ \text{phi}2^\dagger & 3 \end{pmatrix} & \frac{c_w eM_W}{2s_w} - \frac{eM_W s_w}{2c_w} \\
\begin{pmatrix} \text{gh}W_m^\dagger & 1 \\ \text{gh}Z & 2 \\ W^\dagger & 3 \end{pmatrix} & \frac{ic_w ep_2^{\mu_3}}{s_w} + \frac{ic_w ep_3^{\mu_3}}{s_w} \\
\begin{pmatrix} \text{gh}W_p^\dagger & 1 \\ \text{gh}A & 2 \\ \text{phi}2 & 3 \end{pmatrix} & -eM_W
\end{aligned}$$

$$\begin{aligned}
\begin{pmatrix} \text{ghWp}^\dagger & 1 \\ \text{ghA} & 2 \\ W & 3 \end{pmatrix} & -iep_2^{\mu_3} - iep_3^{\mu_3} \\
\begin{pmatrix} \text{ghWp}^\dagger & 1 \\ \text{ghWp} & 2 \\ H & 3 \end{pmatrix} & -\frac{ieM_W}{2s_w} \\
\begin{pmatrix} \text{ghWp}^\dagger & 1 \\ \text{ghWp} & 2 \\ \phi & 3 \end{pmatrix} & \frac{eM_W}{2s_w} \\
\begin{pmatrix} A & 1 \\ \text{ghWp}^\dagger & 2 \\ \text{ghWp} & 3 \end{pmatrix} & iep_1^{\mu_1} + iep_3^{\mu_1} \\
\begin{pmatrix} \text{ghWp}^\dagger & 1 \\ \text{ghWp} & 2 \\ Z & 3 \end{pmatrix} & \frac{ic_w ep_2^{\mu_3}}{s_w} + \frac{ic_w ep_3^{\mu_3}}{s_w} \\
\begin{pmatrix} \text{ghWp}^\dagger & 1 \\ \text{ghZ} & 2 \\ \text{phi2} & 3 \end{pmatrix} & -\frac{c_w eM_W}{2s_w} + \frac{eM_W s_w}{2c_w} \\
\begin{pmatrix} \text{ghWp}^\dagger & 1 \\ \text{ghZ} & 2 \\ W & 3 \end{pmatrix} & -\frac{ic_w ep_2^{\mu_3}}{s_w} - \frac{ic_w ep_3^{\mu_3}}{s_w} \\
\begin{pmatrix} \text{ghZ}^\dagger & 1 \\ \text{ghWm} & 2 \\ \text{phi2} & 3 \end{pmatrix} & \frac{eMZ}{2s_w} \\
\begin{pmatrix} \text{ghZ}^\dagger & 1 \\ \text{ghWm} & 2 \\ W & 3 \end{pmatrix} & \frac{ic_w ep_2^{\mu_3}}{s_w} + \frac{ic_w ep_3^{\mu_3}}{s_w} \\
\begin{pmatrix} \text{ghZ}^\dagger & 1 \\ \text{ghWp} & 2 \\ \text{phi2}^\dagger & 3 \end{pmatrix} & -\frac{eMZ}{2s_w} \\
\begin{pmatrix} \text{ghZ}^\dagger & 1 \\ \text{ghWp} & 2 \\ W^\dagger & 3 \end{pmatrix} & -\frac{ic_w ep_2^{\mu_3}}{s_w} - \frac{ic_w ep_3^{\mu_3}}{s_w} \\
\begin{pmatrix} \text{ghZ}^\dagger & 1 \\ \text{ghZ} & 2 \\ H & 3 \end{pmatrix} & -\frac{ieMZ}{2c_w s_w} \\
\begin{pmatrix} G & 1 \\ G & 2 \\ \text{h1} & 3 \end{pmatrix} & \frac{1}{8}iG_h \epsilon_{\mu_1, \mu_2, \alpha 1, \beta 1} p_1^{\beta 1} p_2^{\alpha 1} \delta_{a_1, a_2} + \frac{1}{8}iG_h \epsilon_{\mu_1, \mu_2, \alpha 1, \delta 1} p_1^{\delta 1} p_2^{\alpha 1} \delta_{a_1, a_2} - \frac{1}{8}iG_h \epsilon_{\mu_1, \mu_2, \alpha 1, \beta 1} p_1^{\alpha 1} p_2^{\beta 1} \delta_{a_1, a_2} - \\
& \frac{1}{8}iG_h \epsilon_{\mu_1, \mu_2, \gamma 1, \beta 1} p_1^{\gamma 1} p_2^{\beta 1} \delta_{a_1, a_2} + \frac{1}{8}iG_h \epsilon_{\mu_1, \mu_2, \gamma 1, \beta 1} p_1^{\beta 1} p_2^{\gamma 1} \delta_{a_1, a_2} + \frac{1}{8}iG_h \epsilon_{\mu_1, \mu_2, \gamma 1, \delta 1} p_1^{\delta 1} p_2^{\gamma 1} \delta_{a_1, a_2} - \\
& \frac{1}{8}iG_h \epsilon_{\mu_1, \mu_2, \alpha 1, \delta 1} p_1^{\alpha 1} p_2^{\delta 1} \delta_{a_1, a_2} - \frac{1}{8}iG_h \epsilon_{\mu_1, \mu_2, \gamma 1, \delta 1} p_1^{\gamma 1} p_2^{\delta 1} \delta_{a_1, a_2}
\end{aligned}$$

$$\begin{aligned}
& \begin{pmatrix} G & 1 \\ \text{ghG}^\dagger & 2 \\ \text{ghG} & 3 \end{pmatrix} & g_s f_{a_1, a_2, a_3} P_1^{\mu_1} + g_s f_{a_1, a_2, a_3} P_3^{\mu_1} \\
& \begin{pmatrix} G & 1 \\ G & 2 \\ G & 3 \end{pmatrix} & g_s f_{a_1, a_2, a_3} P_1^{\mu_3} \eta_{\mu_1, \mu_2} - g_s f_{a_1, a_2, a_3} P_2^{\mu_3} \eta_{\mu_1, \mu_2} - g_s f_{a_1, a_2, a_3} P_1^{\mu_2} \eta_{\mu_1, \mu_3} + g_s f_{a_1, a_2, a_3} P_3^{\mu_2} \eta_{\mu_1, \mu_3} + \\
& & g_s f_{a_1, a_2, a_3} P_2^{\mu_1} \eta_{\mu_2, \mu_3} - g_s f_{a_1, a_2, a_3} P_3^{\mu_1} \eta_{\mu_2, \mu_3} \\
& \begin{pmatrix} G & 1 \\ G & 2 \\ G & 3 \\ G & 4 \end{pmatrix} & i g_s^2 f_{a_1, a_3, a_1} f_{a_2, a_4, a_1} \eta_{\mu_1, \mu_4} \eta_{\mu_2, \mu_3} + i g_s^2 f_{a_1, a_2, a_1} f_{a_3, a_4, a_1} \eta_{\mu_1, \mu_4} \eta_{\mu_2, \mu_3} + i g_s^2 f_{a_1, a_4, a_1} f_{a_2, a_3, a_1} \eta_{\mu_1, \mu_3} \eta_{\mu_2, \mu_4} - \\
& & i g_s^2 f_{a_1, a_2, a_1} f_{a_3, a_4, a_1} \eta_{\mu_1, \mu_3} \eta_{\mu_2, \mu_4} - i g_s^2 f_{a_1, a_4, a_1} f_{a_2, a_3, a_1} \eta_{\mu_1, \mu_2} \eta_{\mu_3, \mu_4} - i g_s^2 f_{a_1, a_3, a_1} f_{a_2, a_4, a_1} \eta_{\mu_1, \mu_2} \eta_{\mu_3, \mu_4} \\
& \begin{pmatrix} G & 1 \\ G & 2 \\ G & 3 \\ H & 4 \end{pmatrix} & G_H g_s f_{a_1, a_2, a_3} P_1^{\mu_3} \eta_{\mu_1, \mu_2} - G_H g_s f_{a_1, a_2, a_3} P_2^{\mu_3} \eta_{\mu_1, \mu_2} - G_H g_s f_{a_1, a_2, a_3} P_1^{\mu_2} \eta_{\mu_1, \mu_3} + \\
& & G_H g_s f_{a_1, a_2, a_3} P_3^{\mu_2} \eta_{\mu_1, \mu_3} + G_H g_s f_{a_1, a_2, a_3} P_2^{\mu_1} \eta_{\mu_2, \mu_3} - G_H g_s f_{a_1, a_2, a_3} P_3^{\mu_1} \eta_{\mu_2, \mu_3} \\
& \begin{pmatrix} G & 1 \\ G & 2 \\ G & 3 \\ G & 4 \\ H & 5 \end{pmatrix} & i G_H g_s^2 f_{a_1, a_3, a_1} f_{a_2, a_4, a_1} \eta_{\mu_1, \mu_4} \eta_{\mu_2, \mu_3} + i G_H g_s^2 f_{a_1, a_2, a_1} f_{a_3, a_4, a_1} \eta_{\mu_1, \mu_4} \eta_{\mu_2, \mu_3} + \\
& & i G_H g_s^2 f_{a_1, a_4, a_1} f_{a_2, a_3, a_1} \eta_{\mu_1, \mu_3} \eta_{\mu_2, \mu_4} - i G_H g_s^2 f_{a_1, a_2, a_1} f_{a_3, a_4, a_1} \eta_{\mu_1, \mu_3} \eta_{\mu_2, \mu_4} - \\
& & i G_H g_s^2 f_{a_1, a_4, a_1} f_{a_2, a_3, a_1} \eta_{\mu_1, \mu_2} \eta_{\mu_3, \mu_4} - i G_H g_s^2 f_{a_1, a_3, a_1} f_{a_2, a_4, a_1} \eta_{\mu_1, \mu_2} \eta_{\mu_3, \mu_4} \\
& \begin{pmatrix} G & 1 \\ G & 2 \\ G & 3 \\ \text{h1} & 4 \end{pmatrix} & \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \alpha_1} f_{a_1, a_2, a_3} P_1^{\alpha_1} + \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \beta_1} f_{a_1, a_2, a_3} P_1^{\beta_1} + \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \gamma_1} f_{a_1, a_2, a_3} P_1^{\gamma_1} + \\
& & \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \delta_1} f_{a_1, a_2, a_3} P_1^{\delta_1} + \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \alpha_1} f_{a_1, a_2, a_3} P_2^{\alpha_1} + \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \beta_1} f_{a_1, a_2, a_3} P_2^{\beta_1} + \\
& & \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \gamma_1} f_{a_1, a_2, a_3} P_2^{\gamma_1} + \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \delta_1} f_{a_1, a_2, a_3} P_2^{\delta_1} + \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \alpha_1} f_{a_1, a_2, a_3} P_3^{\alpha_1} + \\
& & \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \beta_1} f_{a_1, a_2, a_3} P_3^{\beta_1} + \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \gamma_1} f_{a_1, a_2, a_3} P_3^{\gamma_1} + \frac{1}{4} G_h g_s \epsilon_{\mu_1, \mu_2, \mu_3, \delta_1} f_{a_1, a_2, a_3} P_3^{\delta_1} \\
& \begin{pmatrix} G & 1 \\ G & 2 \\ G & 3 \\ G & 4 \\ \text{h1} & 5 \end{pmatrix} & -i G_h g_s^2 \epsilon_{\mu_1, \mu_2, \mu_3, \mu_4} f_{a_1, a_4, a_1} f_{a_2, a_3, a_1} + i G_h g_s^2 \epsilon_{\mu_1, \mu_2, \mu_3, \mu_4} f_{a_1, a_3, a_1} f_{a_2, a_4, a_1} - \\
& & i G_h g_s^2 \epsilon_{\mu_1, \mu_2, \mu_3, \mu_4} f_{a_1, a_2, a_1} f_{a_3, a_4, a_1} \\
& \begin{pmatrix} \text{dq} & 1 \\ \bar{\text{dq}} & 2 \\ G & 3 \end{pmatrix} & i g_s \gamma_{s_2, s_1}^{\mu_3} \delta_{f_1, f_2} T_{i_2, i_1}^{a_3} \\
& \begin{pmatrix} G & 1 \\ \text{uq} & 2 \\ \bar{\text{uq}} & 3 \end{pmatrix} & i g_s \gamma_{s_3, s_2}^{\mu_1} \delta_{f_2, f_3} T_{i_3, i_2}^{a_1} \\
& \begin{pmatrix} A & 1 \\ H & 2 \\ \text{phi}2^\dagger & 3 \\ W & 4 \end{pmatrix} & -\frac{e^2 \eta_{\mu_1, \mu_4}}{2s_w} \\
& \begin{pmatrix} A & 1 \\ \phi & 2 \\ \text{phi}2^\dagger & 3 \\ W & 4 \end{pmatrix} & -\frac{i e^2 \eta_{\mu_1, \mu_4}}{2s_w} \\
& \begin{pmatrix} A & 1 \\ \text{phi}2^\dagger & 2 \\ W & 3 \end{pmatrix} & -\frac{e^2 v \eta_{\mu_1, \mu_3}}{2s_w}
\end{aligned}$$

$$\begin{aligned}
& \begin{pmatrix} H & 1 \\ \text{phi}2^\dagger & 2 \\ W & 3 \end{pmatrix} & -\frac{e\mathbf{p}_1^{\mu_3}}{2s_w} + \frac{e\mathbf{p}_2^{\mu_3}}{2s_w} \\
& \begin{pmatrix} \phi & 1 \\ \text{phi}2^\dagger & 2 \\ W & 3 \end{pmatrix} & -\frac{ie\mathbf{p}_1^{\mu_3}}{2s_w} + \frac{ie\mathbf{p}_2^{\mu_3}}{2s_w} \\
& \begin{pmatrix} A & 1 \\ W & 2 \\ W^\dagger & 3 \end{pmatrix} & -ig_w s_w \mathbf{p}_1^{\mu_3} \eta_{\mu_1, \mu_2} + ig_w s_w \mathbf{p}_2^{\mu_3} \eta_{\mu_1, \mu_2} + ig_w s_w \mathbf{p}_1^{\mu_2} \eta_{\mu_1, \mu_3} - ig_w s_w \mathbf{p}_3^{\mu_2} \eta_{\mu_1, \mu_3} - ig_w s_w \mathbf{p}_2^{\mu_1} \eta_{\mu_2, \mu_3} + ig_w s_w \mathbf{p}_3^{\mu_1} \eta_{\mu_2, \mu_3} \\
& \begin{pmatrix} A & 1 \\ H & 2 \\ \text{phi}2 & 3 \\ W^\dagger & 4 \end{pmatrix} & \frac{e^2 \eta_{\mu_1, \mu_4}}{2s_w} \\
& \begin{pmatrix} A & 1 \\ \phi & 2 \\ \text{phi}2 & 3 \\ W^\dagger & 4 \end{pmatrix} & -\frac{ie^2 \eta_{\mu_1, \mu_4}}{2s_w} \\
& \begin{pmatrix} A & 1 \\ \text{phi}2 & 2 \\ W^\dagger & 3 \end{pmatrix} & \frac{e^2 v \eta_{\mu_1, \mu_3}}{2s_w} \\
& \begin{pmatrix} H & 1 \\ \text{phi}2 & 2 \\ W^\dagger & 3 \end{pmatrix} & -\frac{e\mathbf{p}_1^{\mu_3}}{2s_w} + \frac{e\mathbf{p}_2^{\mu_3}}{2s_w} \\
& \begin{pmatrix} \phi & 1 \\ \text{phi}2 & 2 \\ W^\dagger & 3 \end{pmatrix} & \frac{ie\mathbf{p}_1^{\mu_3}}{2s_w} - \frac{ie\mathbf{p}_2^{\mu_3}}{2s_w} \\
& \begin{pmatrix} H & 1 \\ H & 2 \\ W & 3 \\ W^\dagger & 4 \end{pmatrix} & \frac{ie^2 \eta_{\mu_3, \mu_4}}{2s_w^2} \\
& \begin{pmatrix} \phi & 1 \\ \phi & 2 \\ W & 3 \\ W^\dagger & 4 \end{pmatrix} & \frac{ie^2 \eta_{\mu_3, \mu_4}}{2s_w^2} \\
& \begin{pmatrix} \text{phi}2 & 1 \\ \text{phi}2^\dagger & 2 \\ W & 3 \\ W^\dagger & 4 \end{pmatrix} & \frac{ie^2 \eta_{\mu_3, \mu_4}}{2s_w^2} \\
& \begin{pmatrix} H & 1 \\ W & 2 \\ W^\dagger & 3 \end{pmatrix} & \frac{ie^2 v \eta_{\mu_2, \mu_3}}{2s_w^2} \\
& \begin{pmatrix} A & 1 \\ A & 2 \\ W & 3 \\ W^\dagger & 4 \end{pmatrix} & ig_w^2 s_w^2 \eta_{\mu_1, \mu_4} \eta_{\mu_2, \mu_3} + ig_w^2 s_w^2 \eta_{\mu_1, \mu_3} \eta_{\mu_2, \mu_4} - 2ig_w^2 s_w^2 \eta_{\mu_1, \mu_2} \eta_{\mu_3, \mu_4}
\end{aligned}$$

$$\begin{aligned}
& \begin{pmatrix} W & 1 \\ W^\dagger & 2 \\ Z & 3 \end{pmatrix} & -i c_w g_w P_1^{\mu_3} \eta_{\mu_1, \mu_2} + i c_w g_w P_2^{\mu_3} \eta_{\mu_1, \mu_2} + i c_w g_w P_1^{\mu_2} \eta_{\mu_1, \mu_3} - i c_w g_w P_3^{\mu_2} \eta_{\mu_1, \mu_3} - i c_w g_w P_2^{\mu_1} \eta_{\mu_2, \mu_3} + i c_w g_w P_3^{\mu_1} \eta_{\mu_2, \mu_3} \\
& \begin{pmatrix} W & 1 \\ W & 2 \\ W^\dagger & 3 \\ W^\dagger & 4 \end{pmatrix} & -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} dq & 1 \\ \text{phi}2 & 2 \\ \bar{u}q & 3 \end{pmatrix} & -\text{CKM}_{f_3, f_1} \delta_{i_1, i_3} P_{+s_3, s_1} y_{f_1}^d + \text{CKM}_{f_3, f_1} \delta_{i_1, i_3} P_{-s_3, s_1} y_{f_3}^u \\
& \begin{pmatrix} \bar{d}q & 1 \\ \text{phi}2^\dagger & 2 \\ uq & 3 \end{pmatrix} & \text{CKM}_{f_3, f_1}^* \delta_{i_1, i_3} P_{-s_1, s_3} y_{f_1}^d - \text{CKM}_{f_3, f_1}^* \delta_{i_1, i_3} P_{+s_1, s_3} y_{f_3}^u \\
& \begin{pmatrix} dq & 1 \\ \bar{d}q & 2 \\ H & 3 \end{pmatrix} & -\frac{i \delta_{i_1, i_2} \delta_{f_1, f_2} \delta_{s_2, s_1} y_{f_1}^d}{\sqrt{2}} \\
& \begin{pmatrix} dq & 1 \\ \bar{d}q & 2 \\ \phi & 3 \end{pmatrix} & \frac{\gamma_{s_2, s_1}^5 \delta_{i_1, i_2} \delta_{f_1, f_2} y_{f_1}^d}{\sqrt{2}} \\
& \begin{pmatrix} H & 1 \\ l & 2 \\ \bar{l} & 3 \end{pmatrix} & -\frac{i \delta_{f_2, f_3} \delta_{s_3, s_2} y_{f_2}^l}{\sqrt{2}} \\
& \begin{pmatrix} l & 1 \\ \bar{l} & 2 \\ \phi & 3 \end{pmatrix} & \frac{\gamma_{s_2, s_1}^5 \delta_{f_1, f_2} y_{f_1}^l}{\sqrt{2}} \\
& \begin{pmatrix} l & 1 \\ \text{phi}2 & 2 \\ \bar{\nu}l & 3 \end{pmatrix} & -\delta_{f_1, f_3} P_{+s_3, s_1} y_{f_1}^l \\
& \begin{pmatrix} \bar{l} & 1 \\ \text{phi}2^\dagger & 2 \\ \nu l & 3 \end{pmatrix} & \delta_{f_1, f_3} P_{-s_1, s_3} y_{f_1}^l \\
& \begin{pmatrix} H & 1 \\ uq & 2 \\ \bar{u}q & 3 \end{pmatrix} & -\frac{i \delta_{i_2, i_3} \delta_{f_2, f_3} \delta_{s_3, s_2} y_{f_2}^u}{\sqrt{2}} \\
& \begin{pmatrix} \phi & 1 \\ uq & 2 \\ \bar{u}q & 3 \end{pmatrix} & -\frac{\gamma_{s_3, s_2}^5 \delta_{i_2, i_3} \delta_{f_2, f_3} y_{f_2}^u}{\sqrt{2}} \\
& \begin{pmatrix} A & 1 \\ \text{phi}2 & 2 \\ \text{phi}2^\dagger & 3 \\ Z & 4 \end{pmatrix} & \frac{i c_w e^2 \eta_{\mu_1, \mu_4}}{s_w} - \frac{i e^2 s_w \eta_{\mu_1, \mu_4}}{c_w} \\
& \begin{pmatrix} H & 1 \\ \phi & 2 \\ Z & 3 \end{pmatrix} & -\frac{c_w e P_1^{\mu_3}}{2s_w} - \frac{e s_w P_1^{\mu_3}}{2c_w} + \frac{c_w e P_2^{\mu_3}}{2s_w} + \frac{e s_w P_2^{\mu_3}}{2c_w}
\end{aligned}$$



$$\begin{aligned}
& \begin{pmatrix} \text{phi2} & 1 \\ \text{phi2}^\dagger & 2 \\ Z & 3 \end{pmatrix} & \frac{ic_w e p_1^{\mu_3}}{2s_w} - \frac{ies_w p_1^{\mu_3}}{2c_w} - \frac{ic_w e p_2^{\mu_3}}{2s_w} + \frac{ies_w p_2^{\mu_3}}{2c_w} \\
& \begin{pmatrix} H & 1 \\ \text{phi2}^\dagger & 2 \\ W & 3 \\ Z & 4 \end{pmatrix} & \frac{e^2 \eta_{\mu_3, \mu_4}}{2c_w} \\
& \begin{pmatrix} \phi & 1 \\ \text{phi2}^\dagger & 2 \\ W & 3 \\ Z & 4 \end{pmatrix} & \frac{ie^2 \eta_{\mu_3, \mu_4}}{2c_w} \\
& \begin{pmatrix} \text{phi2}^\dagger & 1 \\ W & 2 \\ Z & 3 \end{pmatrix} & \frac{e^2 v \eta_{\mu_2, \mu_3}}{2c_w} \\
& \begin{pmatrix} H & 1 \\ \text{phi2} & 2 \\ W^\dagger & 3 \\ Z & 4 \end{pmatrix} & -\frac{e^2 \eta_{\mu_3, \mu_4}}{2c_w} \\
& \begin{pmatrix} \phi & 1 \\ \text{phi2} & 2 \\ W^\dagger & 3 \\ Z & 4 \end{pmatrix} & \frac{ie^2 \eta_{\mu_3, \mu_4}}{2c_w} \\
& \begin{pmatrix} \text{phi2} & 1 \\ W^\dagger & 2 \\ Z & 3 \end{pmatrix} & -\frac{e^2 v \eta_{\mu_2, \mu_3}}{2c_w} \\
& \begin{pmatrix} A & 1 \\ W & 2 \\ W^\dagger & 3 \\ Z & 4 \end{pmatrix} & -2ic_w g_w^2 s_w \eta_{\mu_1, \mu_4} \eta_{\mu_2, \mu_3} + ic_w g_w^2 s_w \eta_{\mu_1, \mu_3} \eta_{\mu_2, \mu_4} + ic_w g_w^2 s_w \eta_{\mu_1, \mu_2} \eta_{\mu_3, \mu_4} \\
& \begin{pmatrix} H & 1 \\ H & 2 \\ Z & 3 \\ Z & 4 \end{pmatrix} & ie^2 \eta_{\mu_3, \mu_4} + \frac{ic_w^2 e^2 \eta_{\mu_3, \mu_4}}{2s_w^2} + \frac{ie^2 s_w^2 \eta_{\mu_3, \mu_4}}{2c_w^2} \\
& \begin{pmatrix} \phi & 1 \\ \phi & 2 \\ Z & 3 \\ Z & 4 \end{pmatrix} & ie^2 \eta_{\mu_3, \mu_4} + \frac{ic_w^2 e^2 \eta_{\mu_3, \mu_4}}{2s_w^2} + \frac{ie^2 s_w^2 \eta_{\mu_3, \mu_4}}{2c_w^2} \\
& \begin{pmatrix} \text{phi2} & 1 \\ \text{phi2}^\dagger & 2 \\ Z & 3 \\ Z & 4 \end{pmatrix} & -ie^2 \eta_{\mu_3, \mu_4} + \frac{ic_w^2 e^2 \eta_{\mu_3, \mu_4}}{2s_w^2} + \frac{ie^2 s_w^2 \eta_{\mu_3, \mu_4}}{2c_w^2} \\
& \begin{pmatrix} H & 1 \\ Z & 2 \\ Z & 3 \end{pmatrix} & ie^2 v \eta_{\mu_2, \mu_3} + \frac{ic_w^2 e^2 v \eta_{\mu_2, \mu_3}}{2s_w^2} + \frac{ie^2 s_w^2 v \eta_{\mu_2, \mu_3}}{2c_w^2}
\end{aligned}$$

$\begin{pmatrix} W & 1 \\ W^\dagger & 2 \\ Z & 3 \\ Z & 4 \end{pmatrix}$	$ic_w^2 g_w^2 \eta_{\mu_1, \mu_4} \eta_{\mu_2, \mu_3} + ic_w^2 g_w^2 \eta_{\mu_1, \mu_3} \eta_{\mu_2, \mu_4} - 2ic_w^2 g_w^2 \eta_{\mu_1, \mu_2} \eta_{\mu_3, \mu_4}$
$\begin{pmatrix} A & 1 \\ dq & 2 \\ \bar{dq} & 3 \end{pmatrix}$	$-\frac{1}{3}ie\gamma_{s_3, s_2}^{\mu_1} \delta_{i_2, i_3} \delta_{f_2, f_3}$
$\begin{pmatrix} A & 1 \\ l & 2 \\ \bar{l} & 3 \end{pmatrix}$	$-ie\gamma_{s_3, s_2}^{\mu_1} \delta_{f_2, f_3}$
$\begin{pmatrix} A & 1 \\ uq & 2 \\ \bar{uq} & 3 \end{pmatrix}$	$\frac{2}{3}ie\gamma_{s_3, s_2}^{\mu_1} \delta_{i_2, i_3} \delta_{f_2, f_3}$
$\begin{pmatrix} l & 1 \\ \bar{vl} & 2 \\ W & 3 \end{pmatrix}$	$\frac{ie\delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{-s_2, s_1}}{\sqrt{2}s_w}$
$\begin{pmatrix} dq & 1 \\ \bar{uq} & 2 \\ W & 3 \end{pmatrix}$	$\frac{ieCKM_{f_2, f_1} \delta_{i_1, i_2} \gamma^{\mu_3} \cdot P_{-s_2, s_1}}{\sqrt{2}s_w}$
$\begin{pmatrix} \bar{l} & 1 \\ vl & 2 \\ W^\dagger & 3 \end{pmatrix}$	$\frac{ie\delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{-s_1, s_2}}{\sqrt{2}s_w}$
$\begin{pmatrix} \bar{dq} & 1 \\ uq & 2 \\ W^\dagger & 3 \end{pmatrix}$	$\frac{ieCKM_{f_2, f_1}^* \delta_{i_1, i_2} \gamma^{\mu_3} \cdot P_{-s_1, s_2}}{\sqrt{2}s_w}$
$\begin{pmatrix} dq & 1 \\ \bar{dq} & 2 \\ Z & 3 \end{pmatrix}$	$-\frac{ic_w e \delta_{i_1, i_2} \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{-s_2, s_1}}{2s_w} - \frac{ies_w \delta_{i_1, i_2} \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{-s_2, s_1}}{6c_w} + \frac{ies_w \delta_{i_1, i_2} \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{+s_2, s_1}}{3c_w}$
$\begin{pmatrix} l & 1 \\ \bar{l} & 2 \\ Z & 3 \end{pmatrix}$	$-\frac{ic_w e \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{-s_2, s_1}}{2s_w} + \frac{ies_w \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{-s_2, s_1}}{2c_w} + \frac{ies_w \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{+s_2, s_1}}{c_w}$
$\begin{pmatrix} uq & 1 \\ \bar{uq} & 2 \\ Z & 3 \end{pmatrix}$	$\frac{ic_w e \delta_{i_1, i_2} \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{-s_2, s_1}}{2s_w} - \frac{ies_w \delta_{i_1, i_2} \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{-s_2, s_1}}{6c_w} - \frac{2ies_w \delta_{i_1, i_2} \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{+s_2, s_1}}{3c_w}$
$\begin{pmatrix} vl & 1 \\ \bar{vl} & 2 \\ Z & 3 \end{pmatrix}$	$\frac{ic_w e \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{-s_2, s_1}}{2s_w} + \frac{ies_w \delta_{f_1, f_2} \gamma^{\mu_3} \cdot P_{-s_2, s_1}}{2c_w}$

## References

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