Sizable D-term contribution as a signature of $E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model

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1.Introduction

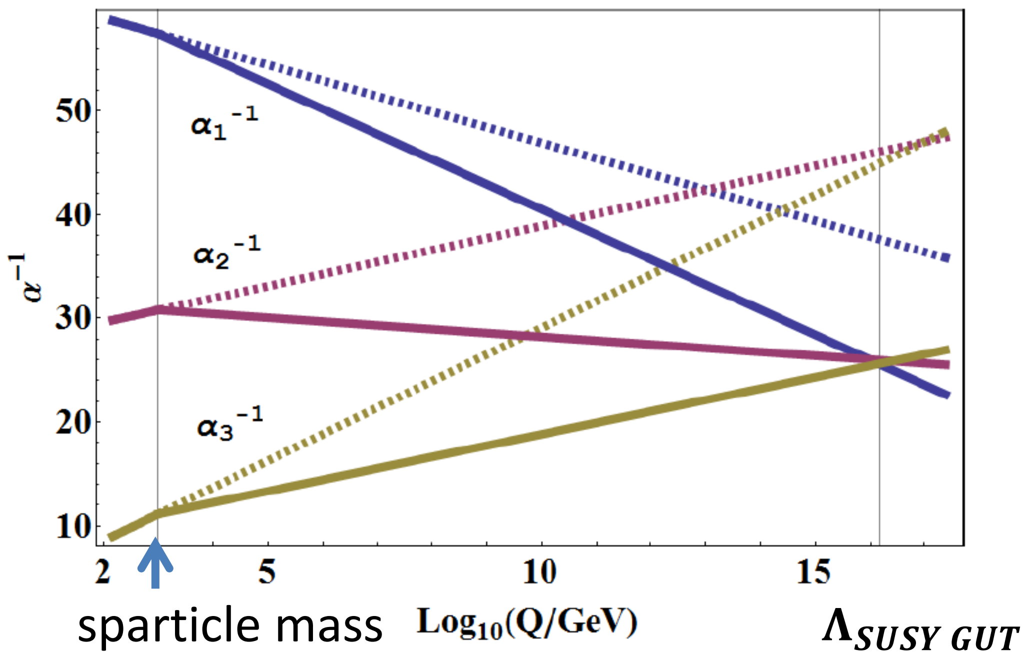
Advantages of SUSY GUT

two unifications
- gauge interactions
- particles (especially matters)

two supports
- gauge coupling unification
- quark and lepton masses and mixings

● unification of gauge interactions

SM gauge group G_{SM} is unified into grand unification group.



$\Lambda_{SUSY\ GUT} \sim 2 \times 10^{16}$ GeV

● unification of particles (especially matters)

$$SU(5) \to G_{SM} \equiv (SU(3)_C, SU(2)_L)_{U(1)_Y} \qquad \bar{\mathbf{5}} \longrightarrow d_R^c(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}} + l_L(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$$

$$\mathbf{10} \longrightarrow q_L(\mathbf{3},\mathbf{2})_{\frac{1}{6}} + u_R^c(\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}} + e_R^c(\mathbf{1},\mathbf{1})_1$$

10 SM matter induces stronger hierarchies for Yukawa coupling than $\bar{\mathbf{5}}$ SM matter.

$$\begin{pmatrix} \mathbf{10_1} \\ \mathbf{10_2} \\ \mathbf{10_3} \end{pmatrix} \Rightarrow \begin{pmatrix} \lambda^3 \\ \lambda^2 \\ 1 \end{pmatrix} \qquad \begin{pmatrix} \bar{\mathbf{5}}_\mathbf{1} \\ \bar{\mathbf{5}}_\mathbf{2} \\ \bar{\mathbf{5}}_\mathbf{3} \end{pmatrix} \Rightarrow \begin{pmatrix} \lambda^3 \\ \lambda^{2.5} \\ \lambda^2 \end{pmatrix} \qquad \lambda \sim 0.22$$

$$Y_{d,e} \mathbf{10} \cdot \bar{\mathbf{5}} \cdot \bar{\mathbf{5}}_{\boldsymbol{H}}$$

$$M_d = M_e^t = \lambda^2 \begin{array}{c} \\ \mathbf{10} \downarrow \end{array} \begin{array}{c} \xrightarrow{\quad \bar{\mathbf{5}} \quad} \\ \begin{pmatrix} \lambda^4 & \lambda^{3.5} & \lambda^3 \\ \lambda^3 & \lambda^{2.5} & \lambda^2 \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix} \end{array} \langle H_d \rangle$$

$$\psi_{Li} M_{ij} \psi_{Rj}^c = (L_\psi^\dagger \psi_L)_i (L_\psi^T M R_\psi)_{ij} (R_\psi^\dagger \psi_R^c)_j$$
$$= \psi'_{Li} M_{diag\, ij} \psi'^c_{Rj}$$

$\Rightarrow$ not only realistic quark and lepton mixings

L_ψ, R_ψ : diagonalizing matrix

$$U_{CKM} = L_u^\dagger L_d \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad U_{MNS} = L_\nu^\dagger L_e \sim \begin{pmatrix} 1 & \lambda^{0.5} & \lambda \\ \lambda^{0.5} & 1 & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix}$$

~ diagonalizing matrix for **10** SM matters ~ diagonalizing matrix for $\bar{\mathbf{5}}$ SM matters

but also realistic quark and lepton masses

Model identification

$$\Lambda_{GUT} = 10^{13-17}\ \mathrm{GeV} \gg \Lambda_{LHC} = 10^{3-4}\ \mathrm{GeV}$$

It is hard to identify models by accelerator directly.

Phenomenon to identify GUT model

- Nucleon decay
- D-term contribution to squark and slepton masses
- FCNC process

topic of this talk

In $E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT, we can expect

- sizable D-term contribution

as a signature of GUT model.

2. D-term contribution as a signature of GUT model

D-term contribution

larger rank gauge group breaks to smaller rank one

D-term contribution to squark and slepton masses

$$\Delta \tilde{m}_{\psi}^2 = \sum_I Q_I(\psi) D_I$$

D_I : squared gauge coupling × D-term

In $E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT there are four D-term contributions

- $E_6 \to SO(10) \times U(1)_{V'}$
- $SO(10) \to SU(5) \times U(1)_V$
- $SU(2)_F$ breaking
- $U(1)_A$ breaking

D_6 : D-term of $U(1)_{V'}$

D_{10} : D-term of $U(1)_V$

D_F : D-term of $U(1)_F$

D_A : D-term of $U(1)_A$

$Q_I(\psi)$: $U(1)$ charge of the field ψ

$U(1)_F$: Cartan part of $SU(2)_F$

rank of $SO(10)$ and E_6 gauge group $>$ rank of SM gauge group

⇒ D-term contribution is useful to identify GUT model

e. g. Kawamura, Tanaka (1994)

G_n	Scalar Masses
E_6	$m_{\tilde{d}}^2 = m_{\tilde{l}}^2$, $m_{\tilde{u}}^2 = m_{\tilde{q}}^2 = m_{\tilde{e}}^2$, $m_2^2 - m_1^2 = m_{\tilde{d}}^2 - m_{\tilde{u}}^2$

*In usual GUT model (without flavour symmetry), D-term contribution is flavour blind.

In $E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT

D-term contribution is not flavour blind.

- $SU(2)_F$ flavour symmetry
- special unification of matters to realize realistic quark and lepton masses and mixings

In $SU(5)$ GUT model we assume that $\mathbf{10}$ SM matter induces stronger hierarchies for Yukawa coupling than $\bar{\mathbf{5}}$ SM matter.

$$E_6 \supset SO(10) \supset SU(5)$$

$$\mathbf{27} \to \mathbf{16} + \mathbf{10} + \mathbf{1}$$

$$\mathbf{16} \to \underbrace{q_L(\mathbf{3},\mathbf{2})_{\frac{1}{6}} + u_R^c(\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}} + e_R^c(\mathbf{1},\mathbf{1})_1}_{\mathbf{10}} + \underbrace{d_R^c(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}} + l_L(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}}_{\bar{\mathbf{5}}} + \underbrace{\nu_R^c(\mathbf{1},\mathbf{1})_0}_{\mathbf{1}}$$

$$\mathbf{10} \to \underbrace{D_R^c(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}} + L_L(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}}_{\bar{\mathbf{5}}'} + \underbrace{\overline{D_R^c}(\mathbf{3},\mathbf{1})_{-\frac{1}{3}} + \overline{L_L}(\mathbf{1},\mathbf{2})_{\frac{1}{2}}}_{\mathbf{5}}$$

E_6	$\mathbf{27}$					
$SO(10)$	$\mathbf{16}$			$\mathbf{10}$		$\mathbf{1}$
$SU(5)$	$\mathbf{10}$	$\overline{\mathbf{5}}$	$\mathbf{1}$	$\overline{\mathbf{5}}$	$\mathbf{5}$	$\mathbf{1}$
$\Psi_1\ (\mathbf{27})$	u_L, d_L, u_R^c, e_R^c	e_L, ν_{eL}, d_R^c	ν_{eR}^c	μ_L, $\nu_{\mu L}$, s_R^c		N_{eR}^c
$\Psi_2\ (\mathbf{27})$	c_L, s_L, c_R^c, μ_R^c	τ_L, $\nu_{\tau L}$, b_R^c	$\nu_{\mu R}^c$			$N_{\mu R}^c$
$\Psi_3(\mathbf{27})$	t_L, b_L, t_R^c, τ_R^c		$\nu_{\tau R}^c$			$N_{\tau R}^c$

First generation matter

Second generation matter

Third generation matter

Right-handed neutrino

extra particle

Features of $E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT

Yukawa structure at GUT scale is restricted.

27 dimensional representation for matter : Ψ

$\Psi_a (a = 1,2)$: $SU(2)_F$ doublet for first- and second-generation matters

Ψ_3 : $SU(2)_F$ singlet for third-generation matters

- Realize realistic quark and lepton masses and mixings within restricted Yukawa structure
  $\Rightarrow$ 9 real parameters and 2 CP phases
- Suppress flavour Changing Neutral Current processes
  $\Rightarrow$ modified universality for squark and slepton masses

$$\tilde{m}_{\bar{5}}^2 \sim \begin{pmatrix} m_0^2 & & \\ & m_0^2 & \\ & & m_0^2 \end{pmatrix} \qquad \tilde{m}_{10}^2 \sim \begin{pmatrix} m_0^2 & & \\ & m_0^2 & \\ & & m_3^2 \end{pmatrix}$$

$m_0 \gg m_3$ In this work we add D-term contribution.

- Solve SUSY CP problem (Chromo-EDM constraint) by spontaneous CP violation mechanism $\Rightarrow$ real Y_u

Non flavour blind D-term contribution is dangerous.

⇐ SUSY FCNC problem

resent LHC result

- No SUSY signal
- 126 GeV Higgs

⇓

Natural SUSY scenario

- heavy stop mass to realize 126 GeV Higgs

(but near current experimental lower bound for naturalness)

- heavy squark and slepton mass to suppress SUSY FCNC processes ⇒ sizable D-term contribution

$$\tilde{m}^2_{\bar{5}} \sim \begin{pmatrix} m_0^2 & & \\ & m_0^2 & \\ & & m_0^2 \end{pmatrix} \qquad \tilde{m}^2_{10} \sim \begin{pmatrix} m_0^2 & & \\ & m_0^2 & \\ & & m_3^2 \end{pmatrix}$$

$$m_3 = O(1\mathrm{TeV}) \Rightarrow m_0 = O(10\mathrm{TeV})$$

$\frac{m_0}{m_3} \lesssim 5$ to realize positive stop mass

Arkani-Hamed and Murayama (1997)

squark and slepton masses including D-term contributions

$$\tilde{m}_{10}^2 = (m_0^2 + D_6 + D_{10} + D_F + 4D_A)\mathbf{1}_{3\times 3} + \begin{pmatrix} 0 & & \\ & -2D_F & \\ & & -D_F - \frac{5}{2}D_A + m_3^2 - m_0^2 \end{pmatrix} \equiv m_{10,0}^2 \mathbf{1}_{3\times 3} + \begin{pmatrix} 0 & & \\ & \Delta m_{10,2}^2 & \\ & & \Delta m_{10,3}^2 \end{pmatrix}$$

$$\tilde{m}_{\bar{5}}^2 = (m_0^2 + D_6 - 3D_{10} + D_F + 4D_A)\mathbf{1}_{3\times 3} + \begin{pmatrix} 0 & & \\ & -3D_6 + 5D_{10} & \\ & & -2D_F \end{pmatrix} \equiv m_{\bar{5},0}^2 \mathbf{1}_{3\times 3} + \begin{pmatrix} 0 & & \\ & \Delta m_{\bar{5},2}^2 & \\ & & \Delta m_{\bar{5},3}^2 \end{pmatrix}$$

$$\Delta m_{10,2}^2 = \Delta m_{\bar{5},3}^2$$

diagonalizing matrices

diagonalizing matrix for **10** matters

$$L_u \sim L_d \sim R_u \sim R_e \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

diagonalizing matrix for $\mathbf{\bar{5}}$ matters

$$L_e \sim L_\nu \sim R_d \sim \begin{pmatrix} 1 & \lambda^{0.5} & \lambda \\ \lambda^{0.5} & 1 & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix}$$

$$(\delta_{ij}^{\psi})_{\Gamma\Gamma} \equiv \frac{(U_{\psi_\Gamma}^\dagger \tilde{m}_{\psi_\Gamma}^2 U_{\psi_\Gamma})_{ij}}{m_{\tilde{\psi}}^2} \quad (\Gamma = L, R)$$

U : diagonalizing matrix

mass insertion parameter

Non flavour blind D-term contribution

flavour physics $\Rightarrow$ size of D-term contribution

$K^0 - \overline{K}^0$ mixing (ε_K parameter)

$$\sqrt{|\mathrm{Im}(\delta^d_{12})^2_{LL}|} < 2.9 \times 10^{-3} \left(\frac{m_{\tilde{d}}}{500\mathrm{GeV}}\right)$$

$$\sqrt{|\mathrm{Im}(\delta^d_{12})^2_{RR}|} < 2.9 \times 10^{-3} \left(\frac{m_{\tilde{d}}}{500\mathrm{GeV}}\right)$$

$$\sqrt{|\mathrm{Im}(\delta^d_{12})_{LL}(\delta^d_{12})_{RR}|} < 1.1 \times 10^{-4} \left(\frac{m_{\tilde{d}}}{500\mathrm{GeV}}\right)$$

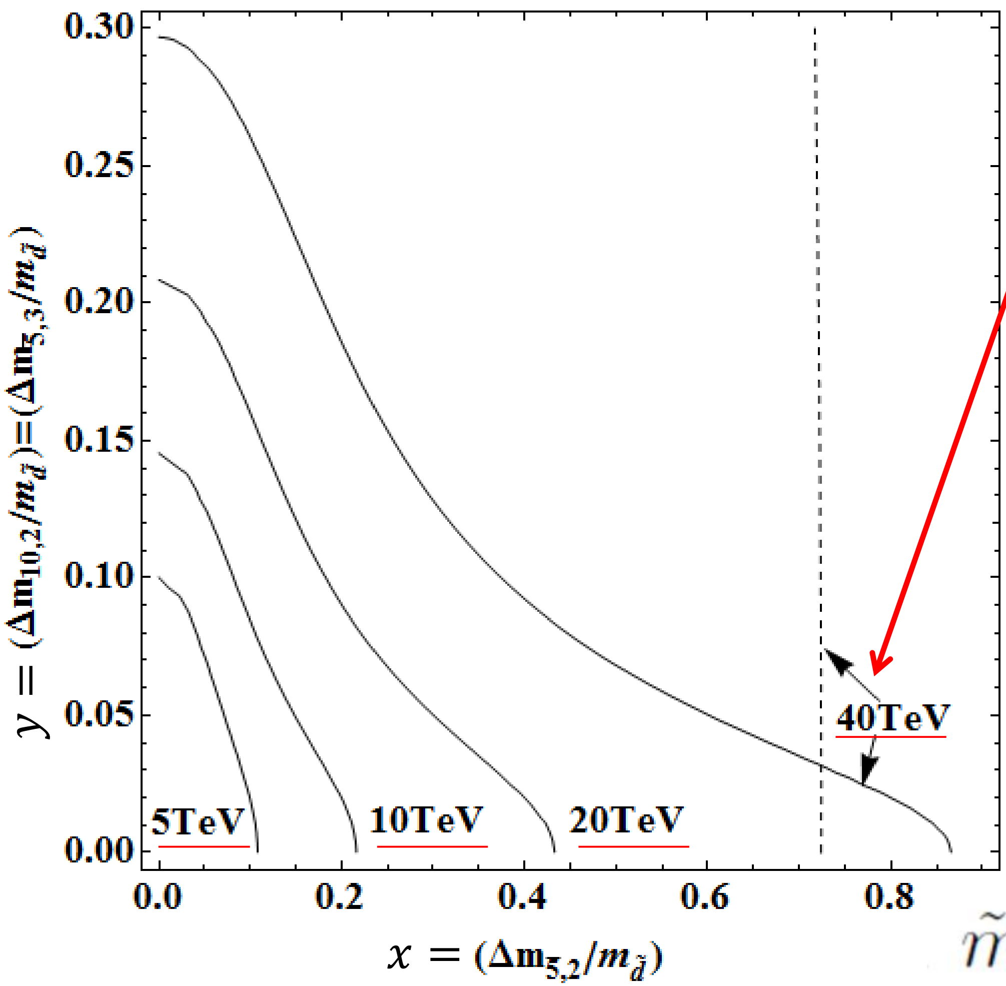
Ciuchini et al. (1998)

mass insertion parameter in this model

$$(\delta^d_{12})_{LL} \sim \left(\frac{2}{3} + i\frac{4}{27}\right)\left(\lambda\frac{\Delta m^2_{10,2}}{m^2_{\tilde{d}}} + \lambda^5\frac{\Delta m^2_{10,3}}{m^2_{\tilde{d}}}\right)$$

$$(\delta^d_{12})_{RR} \sim \frac{2}{3}(1+i)\left(\lambda^{0.5}\frac{\Delta m^2_{\bar{5},2}}{m^2_{\tilde{d}}} + \lambda^{1.5}\frac{\Delta m^2_{\bar{5},3}}{m^2_{\tilde{d}}}\right)$$

$\lambda \sim 0.22$



average down type squark mass : $m_{\tilde{d}}$

—— :constraint from

$$\sqrt{|\mathrm{Im}(\delta^d_{12})_{LL}(\delta^d_{12})_{RR}|}$$

········ :constraint from

$$\sqrt{|\mathrm{Im}(\delta^d_{12})^2_{RR}|}$$

$$\tilde{m}^2_{\bar{\mathbf{5}}_3} - \tilde{m}^2_{\bar{\mathbf{5}}_1} = \tilde{m}^2_{\mathbf{10}_2} - \tilde{m}^2_{\mathbf{10}_1}$$

Result 1

When $m_{\tilde{d}} = 10$ TeV

$$x \sim y \sim 0.1$$

= sizable D-term contribution

signature of $E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model in future experiments (100 TeV proton collider or muon collider)

Summary

Modified universality for squark and slepton masses is useful

$$\tilde{m}^2_{\bar{5}} \sim \begin{pmatrix} m_0^2 & & \\ & m_0^2 & \\ & & m_0^2 \end{pmatrix} \qquad \tilde{m}^2_{10} \sim \begin{pmatrix} m_0^2 & & \\ & m_0^2 & \\ & & m_3^2 \end{pmatrix}$$

to suppress Flavour Changing Neutral Current processes.

If

$$m_3 = O(1\mathrm{TeV}) \quad \text{and} \quad m_0 = O(10\mathrm{TeV})$$

it is possible to introduce sizable and flavour non blind D-term contributions.

As a result,

- D-term contribution to squark and slepton masses can be a signature of GUT model.

Future work

- FCNC processes

  B physics?

  chargino contribution for $b \to s + \gamma$?

- explicit calculation

$$(\delta^d_{12})_{LL} \simeq \left\{ -\left(\frac{2}{3}R^{dL}_{12} + \frac{4}{27}I^{dL}_{12}e^{i(2\rho-\delta)}\right)\lambda\frac{\Delta m^2_{10,2}}{m^2_{\tilde{d}}} \right.$$
$$\left. -R^{dL}_{23}\left(-\frac{1}{3}R^{dL}_{13} + \frac{2}{3}R^{dL}_{23}R^{dL}_{12} + \frac{4}{27}R^{dL}_{23}I^{dL}_{12}e^{i(2\rho-\delta)}\right)\lambda^5\frac{\Delta m^2_{10,3}}{m^2_{\tilde{d}}} \right\}$$

R, I : combination of nine $O(1)$ parameters

$$(\delta^d_{12})_{LL} \sim \left(\frac{2}{3} + i\frac{4}{27}\right)\left(\lambda\frac{\Delta m^2_{10,2}}{m^2_{\tilde{d}}} + \lambda^5\frac{\Delta m^2_{10,3}}{m^2_{\tilde{d}}}\right)$$

Back up

$$
Y_u = \begin{pmatrix} 0 & \frac{1}{3}d_q\lambda^5 & 0 \\ -\frac{1}{3}d_q\lambda^5 & c\lambda^4 & b\lambda^2 \\ 0 & b\lambda^2 & a \end{pmatrix}, \tag{6}
$$

$$
Y_d = \begin{pmatrix} -\left(\frac{(bg-af)^2}{ac-b^2}+g^2\right)\frac{\beta_H}{a}e^{i(2\rho-\delta)}\lambda^6 & -\frac{bg-af}{ac-b^2}\frac{2}{3}d_5\beta_H e^{i(\rho-\delta)}\lambda^{5.5} & \frac{1}{3}d_q\lambda^5 \\ \left(-\frac{d_q}{3}-\frac{bg-af}{ac-b^2}\frac{b\frac{2}{3}d_5}{g}\right)\lambda^5 & \left(f\beta_H e^{i(\rho-\delta)}-\frac{(\frac{2}{3}d_5)^2}{ac-b^2}\frac{ab}{g}e^{-i\rho}\right)\lambda^{4.5} & \frac{cg-bf}{g}\lambda^4 \\ -\frac{bg-af}{ac-b^2}\frac{a\frac{2}{3}d_5}{g}\lambda^3 & \left(g\beta_H e^{i(\rho-\delta)}-\frac{(\frac{2}{3}d_5)^2}{ac-b^2}\frac{a^2}{g}e^{-i\rho}\right)\lambda^{2.5} & \frac{bg-af}{g}\lambda^2 \end{pmatrix}, \tag{7}
$$

$$
Y_e = \begin{pmatrix} -\left(\frac{(bg-af)^2}{ac-b^2}+g^2\right)\frac{\beta_H}{a}e^{i(2\rho-\delta)}\lambda^6 & d_l\lambda^5 & 0 \\ 0 & f\beta_H e^{i(\rho-\delta)}\lambda^{4.5} & g\beta_H e^{i(\rho-\delta)}\lambda^{2.5} \\ -d_l\lambda^5 & \frac{cg-bf}{g}\lambda^4 & \frac{bg-af}{g}\lambda^2 \end{pmatrix}, \tag{8}
$$

$$L_u \sim \left(\begin{array}{ccc} 1 & \frac{1}{3}\lambda & 0 \\ \frac{1}{3}\lambda & 1 & \lambda^2 \\ \frac{1}{3}\lambda^3 & \lambda^2 & 1 \end{array} \right), R_u \sim \left(\begin{array}{ccc} 1 & \frac{1}{3}\lambda & 0 \\ \frac{1}{3}\lambda & 1 & \lambda^2 \\ \frac{1}{3}\lambda^3 & \lambda^2 & 1 \end{array} \right), \tag{20}$$

$$L_d \sim \left(\begin{array}{ccc} 1 & (\frac{2}{3}+i\frac{4}{27})\lambda & \frac{1}{3}\lambda^3 \\ (\frac{2}{3}+i\frac{4}{27})\lambda & 1 & \lambda^2 \\ (\frac{2}{3}+i\frac{4}{27})\lambda^3 & \lambda^2 & 1 \end{array} \right), R_d \sim \left(\begin{array}{ccc} 1 & \frac{2}{3}(1+i)\lambda^{0.5} & \frac{2}{3}\lambda \\ \frac{2}{3}(1+i)\lambda^{0.5} & 1 & (1+i)\lambda^{0.5} \\ \frac{2}{3}(1+i)\lambda & (1+i)\lambda^{0.5} & 1 \end{array} \right), \tag{21}$$

$$L_e \sim \left(\begin{array}{ccc} 1 & (1+i)\lambda^{0.5} & 0 \\ (1+i)\lambda^{0.5} & 1 & (1+i)\lambda^{0.5} \\ \lambda & (1+i)\lambda^{0.5} & 1 \end{array} \right), R_e \sim \left(\begin{array}{ccc} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{array} \right), \tag{22}$$