特定領域研究会 09.03.09

CEDM constraints on modified sfermion universality and spontaneous CP violation

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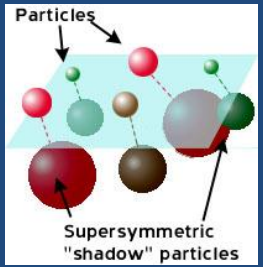
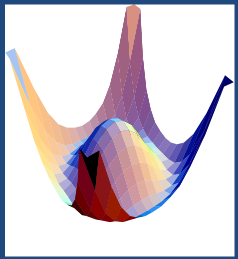
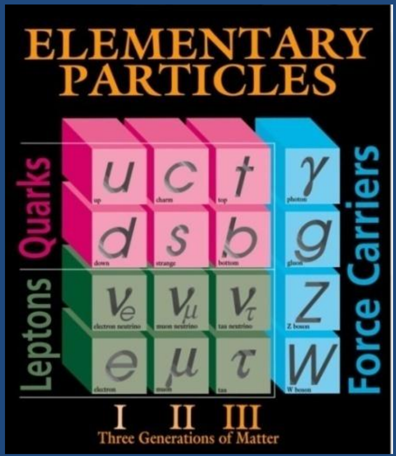
arXiv:0901.3400 [hep-ph]

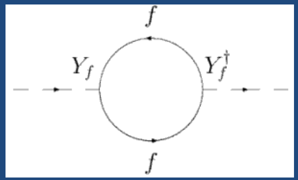
Low-energy supersymmetry

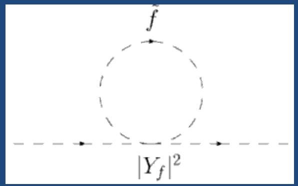


- naturalness and gauge hierarchy problem of the SM
- candidates for the dark matter
- Gauge coupling unification =>Grand Unified Theory







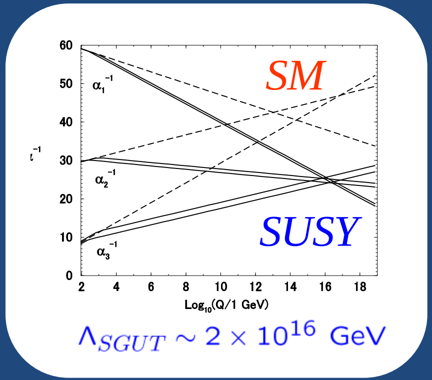


*SUSY must be broken

General soft SUSY breaking terms

new flavor mixing sources and

CP violating phases



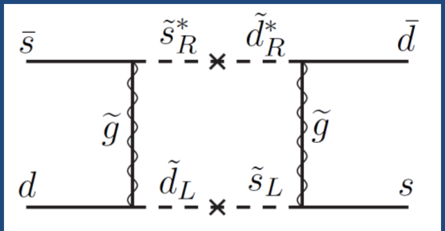
New flavor mixing and CP violating sources

$$\begin{pmatrix} \tilde{q}_{X1} \\ \tilde{q}_{X2} \\ \tilde{q}_{X3} \end{pmatrix}^{+} \begin{pmatrix} \tilde{m}^2_{\mathrm{XX}11} & \tilde{m}^2_{\mathrm{XX}12} & \tilde{m}^2_{\mathrm{XX}13} \\ \tilde{m}^2_{\mathrm{XX}21} & \tilde{m}^2_{\mathrm{XX}22} & \tilde{m}^2_{\mathrm{XX}23} \\ \tilde{m}^2_{\mathrm{XX}31} & \tilde{m}^2_{\mathrm{XX}32} & \tilde{m}^2_{\mathrm{XX}33} \end{pmatrix} \begin{pmatrix} \tilde{q}_{X1} \\ \tilde{q}_{X2} \\ \tilde{q}_{X3} \end{pmatrix} \qquad \tilde{D}_R^C (A_{\mathrm{d}} - Y_{\mathrm{d}} \mu \tan\beta) \tilde{D}_{\mathrm{L}} H_{\mathrm{d}}$$

$$(\delta^f_{XY})_{ij} = \frac{\tilde{m}^2_{\mathrm{fXYij}}}{\tilde{m}^2_{\mathrm{f}}} \qquad \mathrm{X, Y = L, R}$$

- SUSY flavor problem

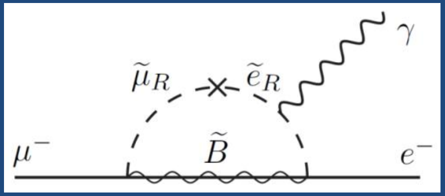
e.g., [Gabbiani et.al. '96]



Δm_K $\quad \sqrt{|\mathrm{Re}(\delta^{\mathrm{d}}_{\mathrm{LL}})_{12}(\delta^{\mathrm{d}}_{\mathrm{RR}})_{12}|} \le 2.8\times10^{-3}$

ε_K $\quad \sqrt{|\mathrm{Im}(\delta^{\mathrm{d}}_{\mathrm{LL}})_{12}(\delta^{\mathrm{d}}_{\mathrm{RR}})_{12}|} \le 2.2\times10^{-4}$

$m_{\tilde{q}} = 500\mathrm{GeV}$
$m_{\tilde{l}} = 100\mathrm{GeV}$
$x = 1$



μ->eγ $\quad |(\delta^{\mathrm{l}}_{\mathrm{LL}})_{12}| \le 7.7\times10^{-3}$

b->sγ $\quad |(\delta^{\mathrm{d}}_{\mathrm{LR}})_{23}| \le 1.6\times10^{-2}$

Universal & real (M, μ)

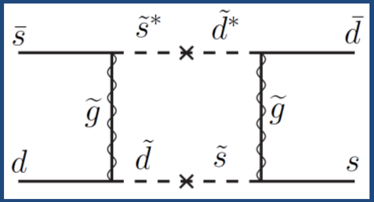
- SUSY CP problem

$$L = -\frac{i}{2} d_{\mathrm{f}} \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}$$

d_d $\quad |\mathrm{Im}(\delta^{\mathrm{d}}_{\mathrm{LR}})_{11}| \le 7.8\times10^{-7}$

d_e $\quad |\mathrm{Im}(\delta^{\mathrm{l}}_{\mathrm{LR}})_{11}| \le 8.5\times10^{-8}$

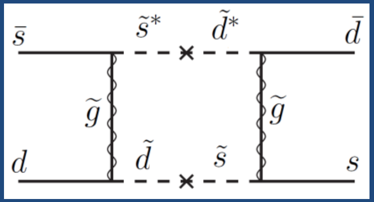
1–2 generations



Universality

$$\mathbf{10} = \{Q_i, U_R^C, E_R^C\},\ \bar{\mathbf{5}} = \{D_R^C, L\}$$

$$\tilde{m}^2_{\bar{5}^0} = \begin{pmatrix} \tilde{m}_0^2 & 0 & 0 \\ 0 & \tilde{m}_0^2 & 0 \\ 0 & 0 & \tilde{m}_0^2 \end{pmatrix} \quad \tilde{m}^2_{10} = \begin{pmatrix} \tilde{m}_0^2 & 0 & 0 \\ 0 & \tilde{m}_0^2 & 0 \\ 0 & 0 & \tilde{m}_0^2 \end{pmatrix}$$



Modified universality

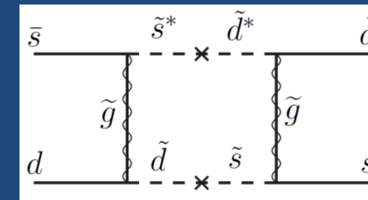
$$\mathbf{10} = \{Q_i, U_R^C, E_R^C\},\ \bar{\mathbf{5}} = \{D_R^C, L\}$$

$$\tilde{m}^2_{\bar{5}^0} = \begin{pmatrix} \tilde{m}_0^2 & 0 & 0 \\ 0 & \tilde{m}_0^2 & 0 \\ 0 & 0 & \tilde{m}_0^2 \end{pmatrix} \quad \tilde{m}^2_{10} = \begin{pmatrix} \tilde{m}_0^2 & 0 & 0 \\ 0 & \tilde{m}_0^2 & 0 \\ 0 & 0 & \underline{\tilde{m}_3^2} \end{pmatrix}$$

$$*\,\tilde{m}_0 \sim 1\text{TeV},\ \tilde{m}_3 \sim 500\text{GeV}$$

*If off-diagonal entries appear, it can be compensated by large m_0 w/o destabilizing the weak scale (cf. in case of Universality)

Modified universality



$$\mathbf{10}=\{Q_i,U_R^C,E_R^C\},\ \bar{\mathbf{5}}=\{D_R^C,L\}$$

$$\tilde{m}^2_{\bar{5}^0}=\begin{pmatrix}\tilde{m}_0^2 & 0 & 0\\ 0 & \tilde{m}_0^2 & 0\\ 0 & 0 & \tilde{m}_0^2\end{pmatrix} \qquad \tilde{m}^2_{10}=\begin{pmatrix}\tilde{m}_0^2 & 0 & 0\\ 0 & \tilde{m}_0^2 & 0\\ 0 & 0 & \tilde{m}_3^2\end{pmatrix}$$

$$+\ \Delta\tilde{m}^2\begin{pmatrix} & \lambda^5 & \lambda^3\\ \lambda^5 & & \lambda^2\\ \lambda^3 & \lambda^2 & \end{pmatrix}$$

KM like=>

$$*\Delta\tilde{m}=(\tilde{m}_3^2-\tilde{m}_0^2)$$

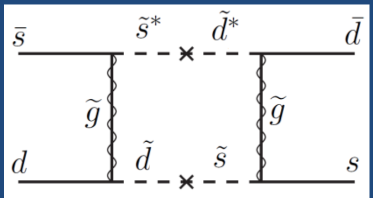
$$*\tilde{m}_0\sim 1\text{TeV},\ \tilde{m}_3\sim 500\text{GeV}$$

$$Y_U\sim\begin{pmatrix}\lambda^6 & \lambda^5 & \lambda^3\\ \lambda^5 & \lambda^4 & \lambda^2\\ \lambda^3 & \lambda^2 & 1\end{pmatrix} \Rightarrow \hat{Y}_U\sim\begin{pmatrix}\lambda^6 & & \\ & \lambda^4 & \\ & & 1\end{pmatrix}$$

$$V_L^U\sim\begin{pmatrix}1 & \lambda & \lambda^3\\ \lambda & 1 & \lambda^2\\ \lambda^3 & \lambda^2 & 1\end{pmatrix} \qquad V_R^U\sim\begin{pmatrix}1 & \lambda & \lambda^3\\ \lambda & 1 & \lambda^2\\ \lambda^3 & \lambda^2 & 1\end{pmatrix}$$

$$*\lambda=0.22$$

Modified universality



$$\mathbf{10} = \{Q_i, U_R^C, E_R^C\},\ \bar{\mathbf{5}} = \{D_R^C, L\}$$

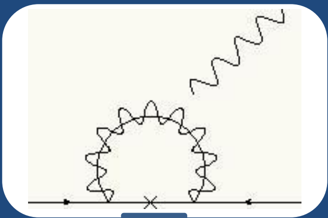
$$\tilde{m}^2_{\bar{5}^0} = \begin{pmatrix} \tilde{m}_0^2 & 0 & 0 \\ 0 & \tilde{m}_0^2 & 0 \\ 0 & 0 & \tilde{m}_0^2 \end{pmatrix} \qquad \tilde{m}^2_{10} = \begin{pmatrix} \tilde{m}_0^2 & 0 & 0 \\ 0 & \tilde{m}_0^2 & 0 \\ 0 & 0 & \tilde{m}_3^2 \end{pmatrix} + \Delta\tilde{m}^2 \begin{pmatrix} & \lambda^5 & \lambda^3 \\ \lambda^5 & & \lambda^2 \\ \lambda^3 & \lambda^2 & \end{pmatrix}$$

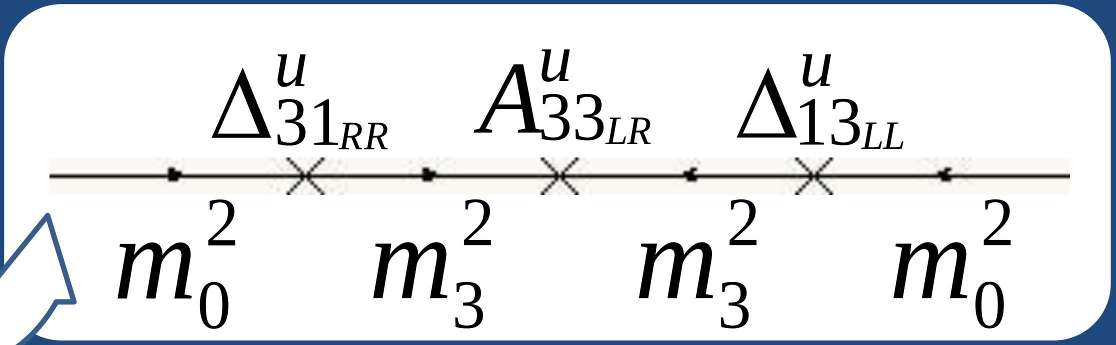
KM like=>

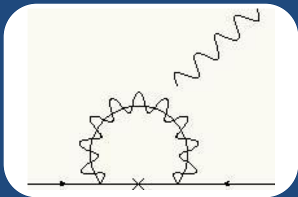
$$*\,\tilde{m}_0 \sim 1\text{TeV},\ \tilde{m}_3 \sim 500\text{GeV}$$

$$*\,\Delta\tilde{m} = (\tilde{m}_3^2 - \tilde{m}_0^2)$$

- Non-decoupling SUSY contribution to up quark (C)EDM contribution from 10_3



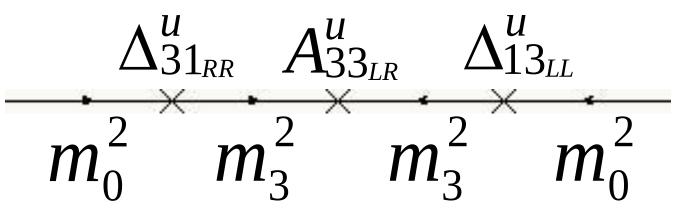




$$(\delta^f_{XY})_{ij} = \frac{\tilde{m}^2_{\mathrm{fXYij}}}{\tilde{m}^2_{\mathrm{f}}}$$

$$\Delta\tilde{m}^2 \begin{pmatrix} & \lambda^5 & \lambda^3 \\ \lambda^5 & & \lambda^2 \\ \lambda^3 & \lambda^2 & \end{pmatrix} \Rightarrow \delta_{\substack{LL \\ RR}} \sim \begin{pmatrix} & \lambda^5 & \lambda^3 \\ \lambda^5 & & \lambda^2 \\ \lambda^3 & \lambda^2 & \end{pmatrix}$$

- Non-decoupling contribution to up-quark CEDM



$$\sim \frac{M_3}{m_3^2} (\delta^u_{RR})_{31} (\delta^u_{LR})_{33} (\delta^u_{LL})_{13}$$

In general, the SCKM rotation matrices are Unitary

$$\mathrm{Im}[(\delta^u_{LL})_{13}(\delta^u_{RR})_{31}] \sim \lambda^6 \sim 10^{-4}$$

$$(\lambda = 0.22)$$

* experimental constraints

$$\mathrm{Im}[(\delta^u_{LL})_{13}(\delta^u_{RR})_{31}] < 9 \times 10^{-7}$$

[Hisano, Shimizu '04]

assuming $\mathrm{Im}(M_3, A_t) = 0, \mathrm{M}_3 = A_t = \mathrm{m}_3 = 500\mathrm{GeV}, \mathrm{m}_0 = 1\mathrm{TeV}$

$$(\mathrm{e}\,|\,\mathrm{d_n}\,| = 2.9 \times 10^{-26}\ \mathrm{e\,cm}\,[\mathrm{ILL}\ '06])$$

In order to satisfy this constraints w/o destabilizing the weak scale, we discuss

Real up-(s)quark sector

⇒The origin of CP violation

Spontaneous CP violation

– Origin of the CP violating phase
  - Yukawa coupling

=>flavor symmetry breaking

– Spontaneous CP violation

$$\left\langle F\bar{F}\right\rangle = e^{i\rho}\lambda^4$$

Assuming it is the only source of CP violating phase

- SU(2)$_F$ symmetric sector

M_i, μ, b :real

*advantage

- SU(2)$_F$ breaking sector

Y_f, A_f, m_f :complex

*E.g.,

	Ψ_a	Ψ_3	F_a	$\bar{F}^a$	H
$SU(2)$	2	1	2	$\bar{2}$	1

$$\begin{pmatrix} (\varepsilon^{ab}F_a\psi_b)^2 & \varepsilon^{ab}F_a\psi_b\bar{F}^c\psi_c & \varepsilon^{ab}F_a\psi_b\psi_3 \\ & (\bar{F}^a\psi_a)^2 & \bar{F}^a\psi_a\psi_3 \\ & & \psi_3\psi_3 \end{pmatrix} H$$

$$\left\langle F_a \right\rangle \sim \begin{pmatrix} 0 \\ VEV \end{pmatrix}, \quad \left\langle \bar{F}^a \right\rangle \sim \begin{pmatrix} 0 \\ VEV \end{pmatrix}$$

$$\Rightarrow \quad Y_{ij}\Psi_i\Psi_j H$$

Real up-(s)quark sector

$$\mathbf{27} = \mathbf{16}[\mathbf{10} + \bar{\mathbf{5}} + \mathbf{1}] + \mathbf{10}[\mathbf{5} + \bar{\mathbf{5}}'] + \mathbf{1}[\mathbf{1}]$$

[Ishiduki, SK, Maekawa, Sakurai '09]

$$W_{E_6} \supset Y^{H}_{ij} \mathbf{27}_i \mathbf{27}_j \mathbf{27}_H + Y^{C}_{ij} \mathbf{27}_i \mathbf{27}_j \mathbf{27}_C$$

real — complex

$$Hu = 5_H$$
$$Hd = \bar{5}'_H + \beta\lambda^{0.5}\bar{5}_C$$

*electron mass
CP phase

5bar mixing

$$\Rightarrow W_{SU(5)} \supset Y^{H}_{ij} 10_i 10_j 5_H + Y^{H}_{ij} 10_i \bar{5}_j \bar{5}'_H + Y^{C}_{ij} 10_i \bar{5}'_j \bar{5}_C$$

real — real — complex

$$Y_{U\,ij} \mathbf{10}_i \mathbf{10}_j \mathbf{5}_H + Y_{D,E\,ij} \mathbf{10}_i \bar{\mathbf{5}}^0_j \bar{\mathbf{5}}_H$$

real — complex

$$M_{5\bar{5}} \sim \begin{array}{c|cccccc} & \bar{5}'_1 & \bar{5}'_2 & \bar{5}'_3 & \bar{5}_1 & \bar{5}_2 & \bar{5}_3 \\ \hline 5_1 & \lambda^6 & \lambda^5 & \lambda^3 & \lambda^{6.5} & \lambda^{5.5} & \lambda^{3.5} \\ 5_2 & \lambda^5 & \lambda^4 & \lambda^2 & \lambda^{5.5} & \lambda^{4.5} & \lambda^{2.5} \\ 5_3 & \lambda^3 & \lambda^2 & 1 & \lambda^{3.5} & \lambda^{2.5} & \lambda^{0.5} \end{array}$$

E_6 SUSY GUT

[Bando, Kugo '99],
[Bando, Maekawa '01]
etc.

$$\mathbf{27} = \mathbf{16}[\mathbf{10} + \bar{\mathbf{5}} + \mathbf{1}] + \mathbf{10}[\mathbf{5} + \bar{\mathbf{5}}'] + \mathbf{1}[\mathbf{1}]$$

- Yukawa coupling

$$W_{E_6} \supset Y_H \Psi_i^{\mathbf{27}} \Psi_j^{\mathbf{27}} H^{\mathbf{27}} + Y_C \Psi_i^{\mathbf{27}} \Psi_j^{\mathbf{27}} C^{\mathbf{27}}$$

$$\supset Y \mathbf{16}_i \mathbf{16}_j \mathbf{10} + Y \mathbf{16}_i \mathbf{10}_j \mathbf{16}$$

$$\supset Y_{10} 10_i 10_j 5_H + Y_{\bar{5}} 10_i \bar{5}_j \bar{5}'_H + Y_{\bar{5}} 10_i \bar{5}'_j \bar{5}_C$$

Up-type (s)quark sector

$$Y_H, Y_C \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \Rightarrow Y_{\mathbf{10}} \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Down-type sector

$$\mathbf{27} = \mathbf{16}[\mathbf{10} + \bar{\mathbf{5}} + \mathbf{1}] + \mathbf{10}[\mathbf{5} + \bar{\mathbf{5}}'] + \mathbf{1}[\mathbf{1}]$$

- $W_{E_6} \supset Y_H \Psi_i^{\mathbf{27}} \Psi_j^{\mathbf{27}} H^{\mathbf{27}} + Y_C \Psi_i^{\mathbf{27}} \Psi_j^{\mathbf{27}} C^{\mathbf{27}}$

After GUT sym. breaking $E_6 \xrightarrow{\langle H^1 \rangle} SO(10) \xrightarrow{\langle C^{16} \rangle} SU(5)$

$$Y_H, Y_C \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\supset Y_H \mathbf{10}_i \mathbf{10}_j \langle \mathbf{1}_H \rangle + Y_C \mathbf{10}_i \mathbf{16}_j \langle \mathbf{16}_C \rangle$$

$$\supset Y_H \mathbf{5}_i \bar{\mathbf{5}}'_j \langle \mathbf{1}_H \rangle + Y_C \mathbf{5}_i \bar{\mathbf{5}}_j \langle \mathbf{1}_C \rangle$$

Massless modes originate from the 1st and 2nd gene.

$$M_{5\bar{5}} \sim \begin{array}{c} \\ 5_1 \\ 5_2 \\ 5_3 \end{array} \begin{array}{cccccc} \bar{5}'_1 & \bar{5}'_2 & \bar{5}'_3 & \bar{5}_1 & \bar{5}_2 & \bar{5}_3 \\ \lambda^6 & \lambda^5 & \lambda^3 & \lambda^{6.5} & \lambda^{5.5} & \lambda^{3.5} \\ \lambda^5 & \lambda^4 & \lambda^2 & \lambda^{5.5} & \lambda^{4.5} & \lambda^{2.5} \\ \lambda^3 & \lambda^2 & 1 & \lambda^{3.5} & \lambda^{2.5} & \lambda^{0.5} \end{array} \langle H \rangle$$

* Assuming

$\langle C \rangle / \langle H \rangle \sim \lambda^{0.5}$

Down-type sector

$$W_{E_6} \supset Y_H \Psi_i^{27} \Psi_j^{27} H^{27} + Y_C \Psi_i^{27} \Psi_j^{27} C^{27}$$

$$\supset Y \mathbf{16}_i \mathbf{16}_j \mathbf{10} + Y \mathbf{16}_i \mathbf{10}_j \mathbf{16}$$

$$\supset Y_{10} 10_i 10_j 5_H + Y_{\bar{5}} 10_i \bar{5}_j \bar{5}'_H + Y_{\bar{5}} 10_i \bar{5}'_j \bar{5}_C$$

$$\bar{5}_3 \sim \lambda^3 \bar{5}^0 (\bar{5}_1) + \lambda^2 \bar{5}^0 (\bar{5}_2) + \lambda^{2.5} \bar{5}^0 (\bar{5}'_1)$$

$$\begin{array}{c|ccc} & \bar{5}_1 & \bar{5}_2 & \bar{5}_3 \\ \hline 10_1 & \lambda^6 & \lambda^5 & \lambda^3 \\ 10_2 & \lambda^5 & \lambda^4 & \lambda^2 \\ 10_3 & \lambda^3 & \lambda^2 & 1 \end{array} \Rightarrow \begin{array}{c|ccc} & \bar{5}_1^0 & \bar{5}_2^0 & \bar{5}_3^0 \\ \hline 10_1 & \lambda^6 & \lambda^{5.5} & \lambda^5 \\ 10_2 & \lambda^5 & \lambda^{4.5} & \lambda^4 \\ 10_3 & \lambda^3 & \lambda^{2.5} & \lambda^2 \end{array}$$

*small tanβ

*large mixing

SU(2)$_F$ and SCPV

	Ψ_a	Ψ_3	F_a	$\bar{F}^a$	H	C	A
E_6	27	27	1	1	27	27	78
$SU(2)_H$	2	1	2	$\bar{2}$	1	1	1

$$\langle \bar{F} F \rangle \sim e^{i\rho} \lambda^4$$

$$\Rightarrow \langle F \rangle \sim \begin{pmatrix} 0 \\ e^{i\rho}\lambda^2 \end{pmatrix}, \quad \langle \bar{F} \rangle \sim \begin{pmatrix} 0 \\ \lambda^2 \end{pmatrix}$$

$$\mathrm{W}_{\mathrm{E}_6} \supset \mathrm{Y}^{\mathrm{H}}_{\mathrm{ij}} \mathbf{27}_i \mathbf{27}_j \mathbf{27}_H + \mathrm{Y}^{\mathrm{C}}_{\mathrm{ij}} \mathbf{27}_i \mathbf{27}_j \mathbf{27}_C$$

$$\begin{pmatrix} (F^a \psi_a)^2 & F^a \psi_a \bar{F}^b \psi_b & F^a \psi_a \psi_3 \\ & (\bar{F}^a \psi_a)^2 & \bar{F}^a \psi_a \psi_3 \\ & & \psi_3 \psi_3 \end{pmatrix} H, C \quad => \quad \mathrm{Y}_{\mathrm{H,C}} \sim \begin{pmatrix} e^{i2\rho}\lambda^6 & e^{i\rho}\lambda^5 & e^{i\rho}\lambda^3 \\ e^{i\rho}\lambda^5 & \lambda^4 & \lambda^2 \\ & \lambda^2 & 1 \end{pmatrix}$$

$$Y_u \sim (\frac{1}{3})^2 \lambda^6$$

Nontrivial discrete symmetry

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & (\bar{F}^a \psi_a)^2 & \bar{F}^a \psi_a \psi_3 \\ 0 & \psi_3 \bar{F}^a \psi_a & \psi_3 \psi_3 \end{pmatrix} H \quad => \quad \begin{pmatrix} 0 & \psi_a A \psi_a & 0 \\ \psi_a A \psi_a & (\bar{F}^a \psi_a)^2 & \bar{F}^a \psi_a \psi_3 \\ 0 & \psi_3 \bar{F}^a \psi_a & \psi_3 \psi_3 \end{pmatrix} H$$

$$* \varepsilon^{ab} \psi_a \psi_b = 0 \quad (\mathbf{27} \times \mathbf{27} = \overline{\mathbf{27}}_S + \overline{\mathbf{351}}_a + \overline{\mathbf{351}}_S)$$

Charge assignment

	F	$\bar{F}$	Ψ_a	Ψ_3	H	$\bar{H}$	C	$\bar{C}$	A
E_6	**1**	**1**	**27**	**27**	**27**	$\overline{\mathbf{27}}$	**27**	$\overline{\mathbf{27}}$	**78**
$SU(2)$	**2**	$\bar{\mathbf{2}}$	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Z_6	1	0	0	0	0	0	5	3	3

Top Yukawa
Up Yukawa
Real μ-,b-terms
DTS
DW-VEV
RB-mech
L[C^{16}] mixing

$$W_{E_6} \supset Y^{H}_{ij}(F,\bar{F})\mathbf{27}_i\mathbf{27}_j\mathbf{27}_H + Y^{C}_{ij}(F,\bar{F})\mathbf{27}_i\mathbf{27}_j\mathbf{27}_C$$

$$\begin{pmatrix} 0 & \psi_a A\psi_a & 0 \\ \psi_a A\psi_a & (\bar{F}^a\psi_a)^2 & \bar{F}^a\psi_a\psi_3 \\ 0 & \psi_3\bar{F}^a\psi_a & \psi_3\psi_3 \end{pmatrix} H \quad \begin{pmatrix} 0 & F^a\psi_a\bar{F}^b\psi_b & F^a\psi_a\psi_3 \\ \bar{F}^a\psi_a F^b\psi_b & 0 & 0 \\ \psi_3 F^a\psi_a & 0 & 0 \end{pmatrix} C$$

*O(1) coefficients (a, b, c, d, f, g) are assumed to be real

Yukawa couplings

$$\mathrm{H}d = 5_{\mathrm{H}} + \beta\lambda^{0.5}\,\overline{5}_{\mathrm{C}}$$

$$\mathrm{Y_U} = \begin{pmatrix} 0 & -d\lambda^5/2 & 0 \\ d\lambda^5/2 & c\lambda^4 & b\lambda^2 \\ 0 & b\lambda^2 & a \end{pmatrix}$$

real

complex

$$\mathrm{Y_D} = \begin{pmatrix} -\{(\frac{bg-af}{g})^2+1\}\frac{g}{a}g\beta e^{2i\rho}\lambda^6 & -\frac{bg-af}{g}\frac{d}{ac-b^2}g\beta e^{i\rho}\lambda^{5.5} & \frac{-1}{2}d\lambda^5 \\ (\frac{d}{2}-\frac{d}{ac-b^2}\frac{bg-af}{g}b)\lambda^5 & (-\frac{ad^2}{ac-b^2}\frac{b}{g}e^{-i\rho}+\beta f e^{i\rho})\lambda^{4.5} & (\frac{ac-b^2}{a}+\frac{bg-af}{g}\frac{b}{a})\lambda^4 \\ -\frac{ad}{ac-b^2}\frac{bg-af}{g}\lambda^3 & (-\frac{ad^2}{ac-b^2}\frac{a}{g}e^{-i\rho}+\beta g e^{i\rho})\lambda^{2.5} & \frac{bg-af}{g}\lambda^2 \end{pmatrix}$$

$$\mathrm{Y_E^T} = \begin{pmatrix} -\{(\frac{bg-af}{g})^2+1\}\frac{g}{a}g\beta e^{2i\rho}\lambda^6 & 0 & \frac{-3}{2}d\lambda^5 \\ \frac{3d}{2}\lambda^5 & \beta f e^{i\rho}\lambda^{4.5} & (\frac{ac-b^2}{a}+\frac{bg-af}{g}\frac{b}{a})\lambda^4 \\ 0 & \beta g e^{i\rho}\lambda^{2.5} & \frac{bg-af}{g}\lambda^2 \end{pmatrix}$$

Characteristic predictions

- CKM matrix elements

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^4 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$O(\lambda^4)$

$$V_{CKM} = \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = 0.2257^{+0.0009}_{-0.0010} \quad A = 0.814^{+0.021}_{-0.022}$$

$$\rho = 0.135^{+0.031}_{-0.016} \quad \eta = 0.349^{+0.015}_{-0.017}$$

[PDG ‘08]

- Tanβ

$$|\hat{Y}_{D33}\frac{V_{cb}}{\hat{Y}_{U22}}| = 1$$

$$\Rightarrow \tan\beta \sim 6$$

$$|\hat{Y}_{D33}\frac{V_{cb}}{\hat{Y}_{U22}}| \sim 1.7 \quad (\tan\beta = 10)$$

[Ross Serna ‘07]

$$\tan\beta \equiv \frac{Vu}{Vd}$$

$$\hat{Y}_D \propto \tan\beta$$

Numerical analysis

$$a = 0.4,\ b = -0.3,\ c = -0.2,\ d = 0.3,\ f = 0.1,\ g = 0.1,\ \beta = -5,\ \delta = \frac{\pi}{3}.$$

- As an example we took above O(1) coefficients and numerically derived the eigenvalues of Yukawa couplings, CKM matrix elements, and Jarlskog inv.

$$\begin{array}{lll} Y_t = 4(5) \times 10^{-1} & Y_b = 4(3) \times 10^{-2} & Y_\tau = 4(4) \times 10^{-2} \\ Y_c = 1(1) \times 10^{-3} & Y_s = 5(6) \times 10^{-4} & Y_\mu = 6(30) \times 10^{-4} \\ Y_u = 6(3) \times 10^{-6} & Y_d = 6(3) \times 10^{-5} & Y_e = 4(1) \times 10^{-5} \end{array}$$

$$|V_{CKM}| = \begin{pmatrix} 1 & 3(2) \times 10^{-1} & 3(4) \times 10^{-3} \\ 3(2) \times 10^{-1} & 1 & 3(4) \times 10^{-2} \\ 9(7) \times 10^{-3} & 3(4) \times 10^{-2} & 1 \end{pmatrix}$$

$$\text{Jarlskog Inv.} = 3(3) \times 10^{-5}$$

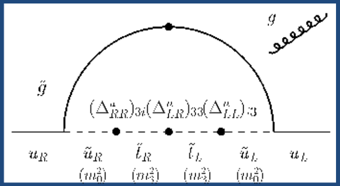
Model predictions and (Reference values)

[Ross Serna '07] (*3/5Ydi, 3/5Yei)

Up-quark CEDM

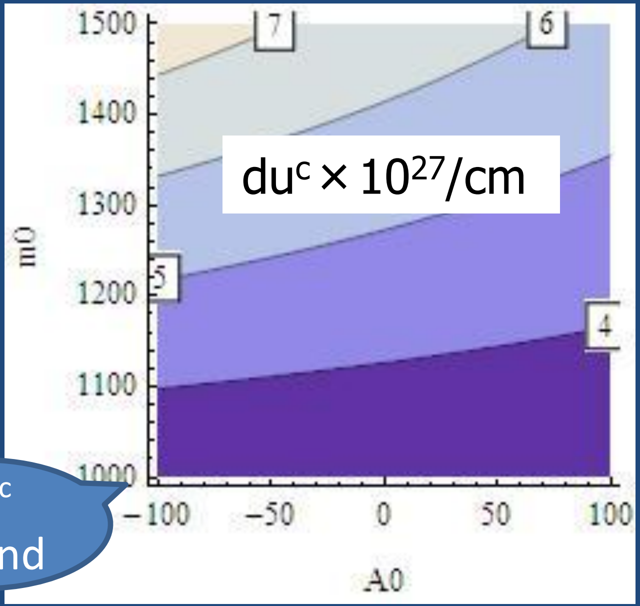
- RG effect : in Yu diagonal basis

$$Y_D = P V_{\rm CKM}^* \hat{Y}_D$$



$$\mathrm{Im}[(\mathbf{m}^2_{\tilde{Q}})_{i\neq j}] \simeq \frac{1}{16\pi^2}\ln(\frac{M_{GUT}}{M_{SUSY}})\mathrm{Im}[(P^* V_{\rm CKM}\hat{Y}_D^2 V_{\rm CKM}^\dagger P m^2_{\mathbf{10}} + h.c.)_{ij}]$$

$$\Rightarrow \mathrm{Im}[(\delta^u_{LL})_{13}] \sim \lambda\lambda^3\lambda^{2\times 1.5} \sim 10^{-5} \;\; (cf.\, \mathrm{Im}[(\delta^u_{LL})_{13}(\delta^u_{RR})_{31}] < 9\times 10^{-7})$$



dsc bound

$$M_{1/2} = 200\mathrm{GeV}, m_3 = 500\mathrm{GeV}$$
$$\tan\beta = 10, \mu = 200\mathrm{GeV}$$

Prediction $\times(\tan\beta/10)^2$

$$e|d_u^C| = \mathcal{O}(10^{-27})\mathrm{e\ cm}$$

Current exp. bound

$$e|d_u^C| = 1.8\times 10^{-26}\ \mathrm{e\ cm}$$

Future bound

(e|dD|~O(10^{-27}) e cm)

e|du^c|~O(10^{-28}) e cm

Summary

- Modified universality
  - non-decoupling SUSY contributions to up-quark (C)EDM
- real up-type (s)quark sector
  - Model of SCPV in the E_6*SU(2) SUSY GUT
    (universal 5bar soft mass, MNS mixing)

Realistic mass spectra, mixing angles and CP phase

Characteristic predictions: V_13 and Tanβ

RG effects: $e|d_u^c| \sim O(10^{-27})$ e cm