CP & SUSY breaking and E_6 GUT

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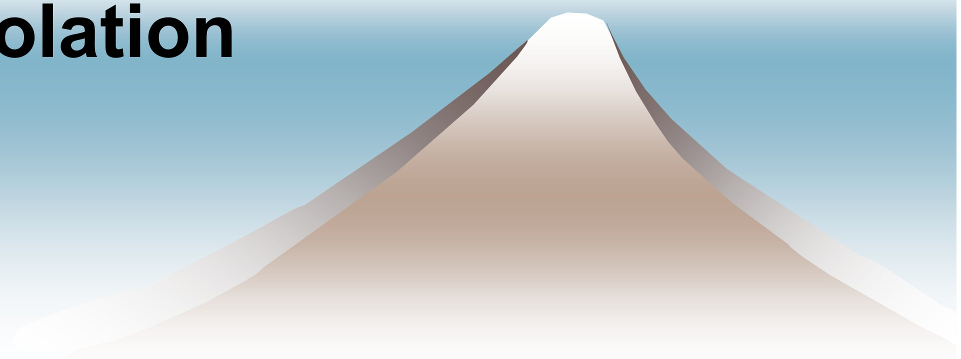
with S. Kim, A. Matsuzaki, K. Sakurai, T. Yoshikawa
M. Ishiduki

1. **SUSY GUT and Yukawa structures**
2. **E_6 Unification for Matter sector**
   - **Why are larger neutrino mixings?**
   - **Horizontal symmetry to solve SUSY flavor problem**
3. New **Prediction of E_6 GUT on FCNC**
4. New **Spontaneous CP violation**
5. **Summary**



Topics mensioned in this talk

- Quark&Lepton masses & mixings?

  SU(5) GUT with an assumption <- E6 GUT
- SUSY flavor problem

  E6+horizontal (family) symmetry

New
- Origin of CP violation(SUSY CP problem)

  Spontaneos CP violation in E6+horizontal

  KM phase &

  CEDM constraints (Hisano-Shimizu) OK!!

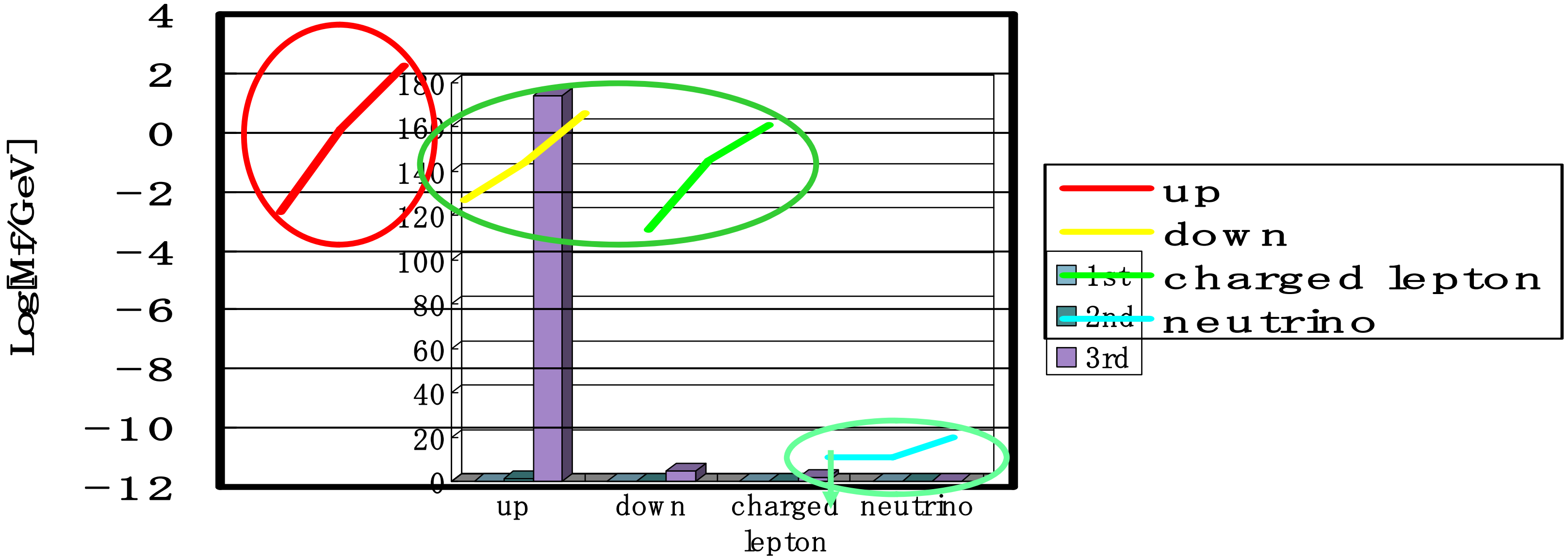
Quark&Lepton Masses & Mixings

SU(5) GUT with an assumption can explain these hierarchies

⇓

It may result in large FCNC in SUSY models

Masses & Mixings and GUT



u, c, t　　Strongest

Neutrinos　　Weakest

e, μ, τ　　Middle

d, s, b　　Middle

CKM　　small mixings

MNS　　large mixings

These can be naturally realized in SU(5) GUT!!

SU(5) SUSY GUT

Albright-Barr
Sato-Yanagida…

$$\mathbf{10} = (q, u_R^c, e_R^c) \qquad \bar{\mathbf{5}} = (d_R^c, l) \qquad \mathbf{1} = \nu_R^c$$

$$Y_u \mathbf{10_i 10_j 5}_H + Y_{(d,e)} \mathbf{10_i \bar{5}_j \bar{5}}_{\bar{H}} + \underbrace{Y_{\nu_D} \mathbf{\bar{5}_i 1_j 5}_H + M_{\nu_R} \mathbf{1_i 1_j}}_{\frac{Y_\nu}{M} \mathbf{\bar{5}_i \bar{5}_j 5}_H \mathbf{5}_H}$$

$$u \gg d, e \gg \nu$$

➡ $\mathbf{10_i}$ have stronger hierarchy than $\mathbf{\bar{5}_i}$

Stronger hierarchy leads to smaller mixings

➡ Quark mixings(CKM) $\ll$ Lepton mixing(MNS)

$\mathbf{10}_i(q_i)$ $\qquad$ $\bar{\mathbf{5}}_i(l_i)$

Mass hierarchy and mixings

- Stronger hierarchy leads to smaller mixings

$$\begin{pmatrix} (\epsilon^2) & \epsilon \\ \epsilon & 1 \end{pmatrix} \rightarrow 1, \epsilon^2$$

$$\begin{pmatrix} 1 & \epsilon \\ -\epsilon & 1 \end{pmatrix}$$

Stronger hierarchy ⟺ Smaller mixings

SU(5) SUSY GUT

$$\mathbf{10} = (q, u_R^c, e_R^c) \quad \bar{\mathbf{5}} = (d_R^c, l) \quad \mathbf{1} = \nu_R^c$$

$$Y_u \mathbf{10_i 10_j 5}_H + Y_{(d,e)} \mathbf{10_i \bar{5}_j \bar{5}}_{\bar{H}} + \underbrace{Y_{\nu_D} \mathbf{\bar{5}_i 1_j 5}_H + M_{\nu_R} \mathbf{1_i 1_j}}_{\frac{Y_\nu}{M} \mathbf{\bar{5}_i \bar{5}_j 5}_H \mathbf{5}_H}$$

$$u \gg d, e \gg \nu$$

⇒ $\mathbf{10_i}$ have stronger hierarchy than $\bar{\mathbf{5}}_\mathbf{i}$

Stronger hierarchy leads to smaller mixings

⇒ Quark mixings(CKM) $\ll$ Lepton mixing(MNS)

$\mathbf{10}_i(q_i)$ $\bar{\mathbf{5}}_i(l_i)$

Good agreement with masses & mixings

Large mixings and FCNC

- Even if universal sfermion masses at cutoff, radiative correction induces non-universality.

$$(\delta_{e_L})_{12} \rightarrow \mathrm{Br}(l_i \rightarrow l_j \gamma) \propto (V_L^\dagger \hat{Y}_{\nu_D}^2 V_L \tan\beta)^2$$

Borzumati-Masiero 85
Hisano-Moroi-Tobe-Yamaguchi-Yanagida Barbieri-Hall-Strumia 95

$$(\delta_{d_R})_{23} \rightarrow S_{K\phi}, \Delta M_{B_s}$$

Moroi 00 (SU(5))
Chang-Masiero-Murayama 02 (SO(10))

- Large mixings for $\bar{\mathbf{5}} = (d_R^c, l)$ $\quad V_L \sim V_{MNS}$
- SO(10) GUT relation $\quad Y_{\nu_D} \sim Y_u \sim Y_d$

⟺ Large $\tan\beta,\ Y_{\nu_D}$

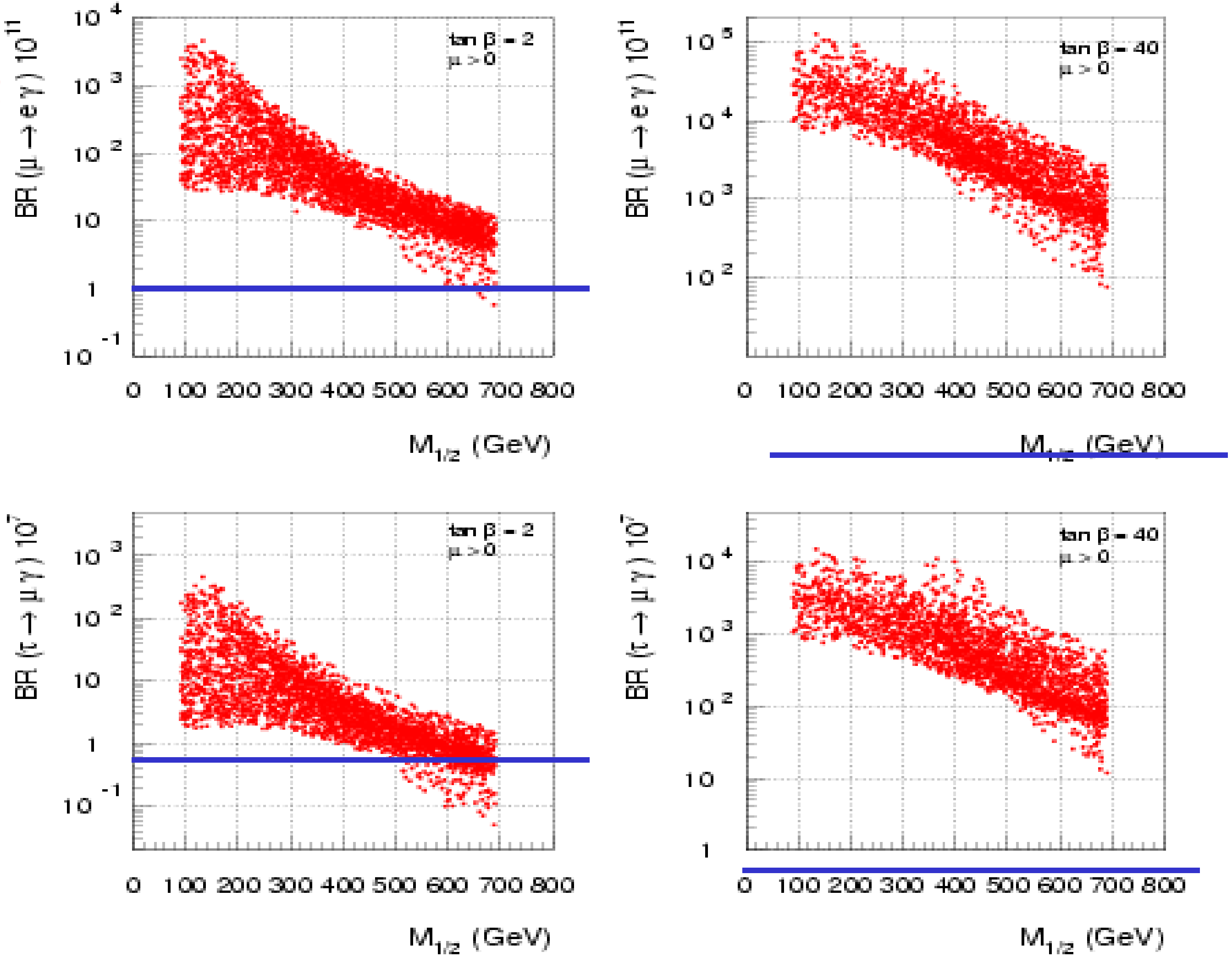
⇒ Large FCNC are expected.

Lepton Flavor Violation SO(10)

$$V_L \sim V_{MNS}$$

Masiero,Vempati,Vives 02

$$Y_{\nu_D} \sim Y_t$$



Constraints to $(\delta_{d_R})_{ij}$

- EDM of Hg (neutron) Hisano-Shimizu 03

$$\mathrm{Im}\ (\delta_{d_L})_{13}(\delta_{d_R})_{31} < 3(0.2) \times 10^{-3}$$

$$(\delta_{d_L})_{13} \sim 0.01 \rightarrow (\delta_{d_R})_{13} < 0.02$$

- Bs mixing CDF 06

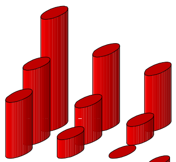
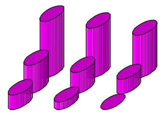
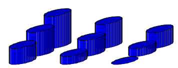
$$\sqrt{(\delta_{d_L})_{23}(\delta_{d_R})_{23}} < 0.02$$

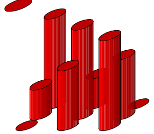
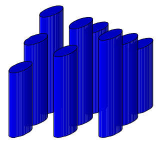
$$(\delta_{d_L})_{23} \sim 0.04 \rightarrow (\delta_{d_R})_{23} < 0.01$$

$$\tilde{m}_q \sim 500\ \mathrm{GeV}$$

1^{st} Summary & Questions

- SU(5) GUT is in good agreement with the hierarchies of quark & lepton masses and mixings.

$Y_u \sim$  $Y_{(d,e)} \sim$  $Y_\nu \sim$ 

$V_{CKM} \sim$  $V_{MNS} \sim$ 

$\mathbf{10_i}$ has stronger hierarchy than $\bar{\mathbf{5}}_\mathbf{i}$

- Suppressed FCNC & EDM $\rightarrow \delta_{\bar{\mathbf{5}}} \ll 1 \rightarrow Y_{\nu_D} \ll 1$

  SO(10) GUT relation $Y_{\nu_D} \sim Y_u \sim Y_d$ looks bad.
- More unification of quark and lepton ?
- Origin of the assumption?
- Origin of various Yukawa hierarchies ?

E6 GUT can answer these questions !

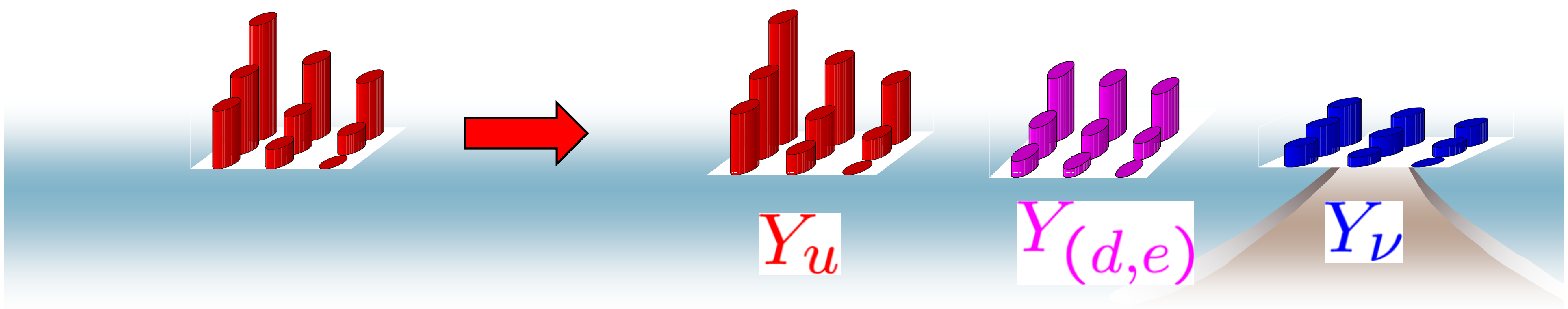
E6 GUT answers these questions

- More unification of quark and lepton ? Yes

  E6 $\supset$ SO(10) $\qquad \mathbf{27} = \mathbf{16} + \mathbf{10} + \mathbf{1}$

- Origin of the assumption ?
- Origin of various Yukawa hierarchies ?

  Various Yukawa hierarchies can be induced from one Yukawa hierarchy in E6 GUT.



E_6 unification

Guisey-Ramond-Sikivie, Aichiman-Stech, Shafi, Barbieri-Nanopoulos, Bando-Kugo,…

$$\mathbf{27}_i = \mathbf{16}_i[\mathbf{10}_i + \underbrace{\bar{\mathbf{5}}_i + \mathbf{1}_i] + \mathbf{10}_i[\mathbf{5}_i}_{\langle \mathbf{16}_C \rangle} + \underbrace{\bar{\mathbf{5}}_i}_{\langle \mathbf{1}_H \rangle}] + \mathbf{1}_i[\mathbf{1}_i]$$

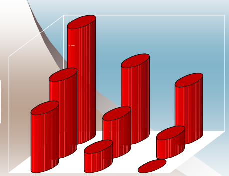
$(i = 1, 2, 3)$

Three of six $\bar{\mathbf{5}}$ become superheavy after the breaking

$$E_6 \xrightarrow[\langle \mathbf{1}_H \rangle]{} SO(10) \xrightarrow[\langle \mathbf{16}_C \rangle]{} SU(5) \qquad \langle \mathbf{1}_H \rangle \geq \langle \mathbf{16}_C \rangle$$

$$W = Y^H \mathbf{27}_i \mathbf{27}_j \langle \mathbf{27}_H \rangle + Y^C \mathbf{27}_i \mathbf{27}_j \langle \mathbf{27}_C \rangle$$

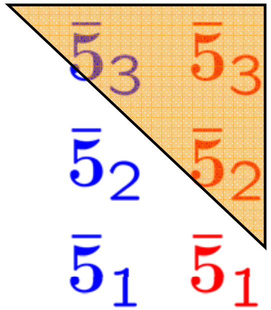
Once we fix $Y^H, Y^C, \langle \mathbf{27}_H \rangle, \langle \mathbf{27}_C \rangle$,
three light modes of six $\bar{\mathbf{5}}$ are determined.

We assume all Yukawa matrices $\sim$ 

Milder hierarchy for $\bar{\mathbf{5}}_i(l)$

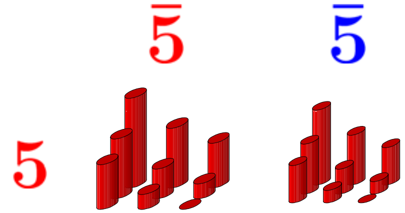
Bando-N.M. 01
N.M, T. Yamashita 02

- $\bar{\mathbf{5}}$ fields from $\mathbf{27}_3$ become superheavy.



Superheavy

unless $\langle \mathbf{27}_H \rangle >> \langle \mathbf{27}_C \rangle$



- Light modes $(\bar{\mathbf{5}}_1, \bar{\mathbf{5}}_1, \bar{\mathbf{5}}_2)$ have smaller Yukawa couplings and milder hierarchy than $(\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_3)$

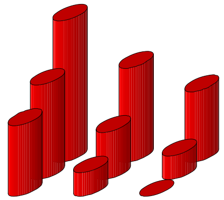
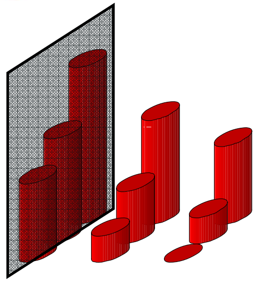
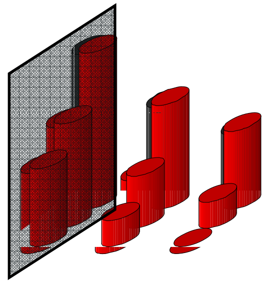
$$Y_{\nu_D}, Y_d << Y_u$$

- •Larger mixings in lepton sector than in quark sector.
- •Small $\tan\beta$
- •Small neutrino Dirac masses

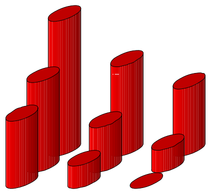
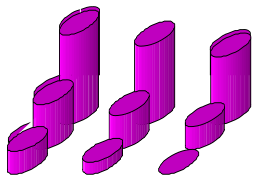
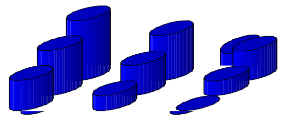
} Suppressed radiative LFV

How to obtain various Yukawas?

$$Y_u \mathbf{10_i 10_j 5}_H + Y_{(d,e)} \mathbf{10_i \bar{5}_j \bar{5}}_{\bar{H}} + Y_\nu \mathbf{\bar{5}_i \bar{5}_j 5}_H \mathbf{5}_H$$

$Y_u \sim$  $Y_{(d,e)} \sim$  $Y_\nu \sim$ 

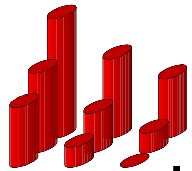
$$(\bar{\mathbf{5}}_1, \bar{\mathbf{5}}_2, \bar{\mathbf{5}}_3) \rightarrow (\bar{\mathbf{5}}_1, \bar{\mathbf{5}}'_1, \bar{\mathbf{5}}_2)$$

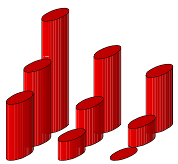
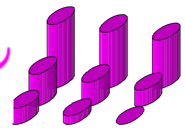
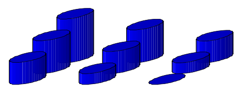
2nd Summary

- E_6 unification explains why the lepton sector has larger mixings than the quark sector.
- Suppressed radiative LFV

Small Y_{ν_D} Small $\tan\beta$

- A basic Yukawa hierarchy $Y \sim Y_u$ 

⇨ The other Yukawa hierarchies

$Y_u \sim$  $Y_{(d,e)} \sim$  $Y_\nu \sim$ 

Hierarchy of $\mathbf{10}_i$ is stronger than that of $\bar{\mathbf{5}}_i$

Three $\bar{\mathbf{5}}_\mathbf{i}$ come from the first 2 generation of $\mathbf{27}_1, \mathbf{27}_2$

SUSY flavor problem

- E6+horizontal (family) symmetry
- More structures for suppressing FCNC.

Horizontal Symmetry

Dine-Kagan-Leigh
Pomarol-Tommasini
Barbieri-Hall···

- •Origin of Yukawa hierarchy
- •Universal sfermion masses to suppress FCNC

$$\Phi_a, \Phi_3, H_u, H_d (\Phi = Q, U, D, L, E, N)$$

- The 1st 2 generation have universal sfermion masses.
- Large top Yukawa coupling

$$U(2)_H \longrightarrow U(1)_H \longrightarrow X$$

$$\langle \bar{F}^a \rangle / \Lambda \sim \epsilon \qquad \langle A^{ab} \rangle / \Lambda \sim \epsilon'$$

$$Y \sim \begin{pmatrix} 0 & \epsilon' & 0 \\ \epsilon' & \epsilon^2 & \epsilon \\ 0 & \epsilon & 1 \end{pmatrix} \qquad \tilde{m}_f^2 \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1+\epsilon^2 & \epsilon \\ 0 & \epsilon & O(1) \end{pmatrix} \tilde{m}_{\frac{3}{2}}^2$$

$$Y_u \sim Y_d \sim Y_e \sim Y_\nu ?$$

Not sufficient to suppress FCNC

Large neutrino mixings and FCNC

- The universal sfermion masses only for the 1st 2 generation $\bar{\mathbf{5}}$ do not suppress FCNC sufficiently

$$\delta_{\bar{\mathbf{5}}} - 1 \sim V_{\bar{\mathbf{5}}}^{\dagger} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a \end{pmatrix} V_{\bar{\mathbf{5}}} \sim a \begin{pmatrix} \lambda^2 & \lambda^{1.5} & \lambda \\ \lambda^{1.5} & \lambda & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix} \quad \lambda \sim 0.2$$

if $V_{\bar{\mathbf{5}}} \sim V_{MNS}$.

$\Updownarrow$ $a \sim O(1)$

$$|\mathrm{Im}(\delta_{d_R^c})_{12}| \leq 1.5 \times 10^{-3} \left(\frac{\tilde{m}_Q}{500\mathrm{GeV}}\right)$$

$$|(\delta_l)_{12}| \leq 4 \times 10^{-3} \left(\frac{\tilde{m}_l}{100\mathrm{GeV}}\right)^2$$

Universality for all three generations is required!

E_6 +horizontal symmetry

N.M. 02,04
N.M, T. Yamashita 04

- In E6 various Yukawa hierarchies are produced from one basic hierarchy from U(2) breaking.
- Unification of generations by $U(2)_H$ (or $U(3)_H$) realizes the universality of sfermion masses.

$$\Psi_a(\mathbf{27},\mathbf{2})+\Psi_3(\mathbf{27},\mathbf{1}) \qquad (a=1,2)$$

- A prediction for sfermion mass spectrum

$$m^2|\Psi_a(\mathbf{27},\mathbf{2})|^2 \qquad\qquad m_3^2|\Psi_3(\mathbf{27},\mathbf{1})|^2$$

Universal mass m: $\mathbf{10}_1, \mathbf{10}_2$, $\bar{\mathbf{5}}_1, \bar{\mathbf{5}}_2$

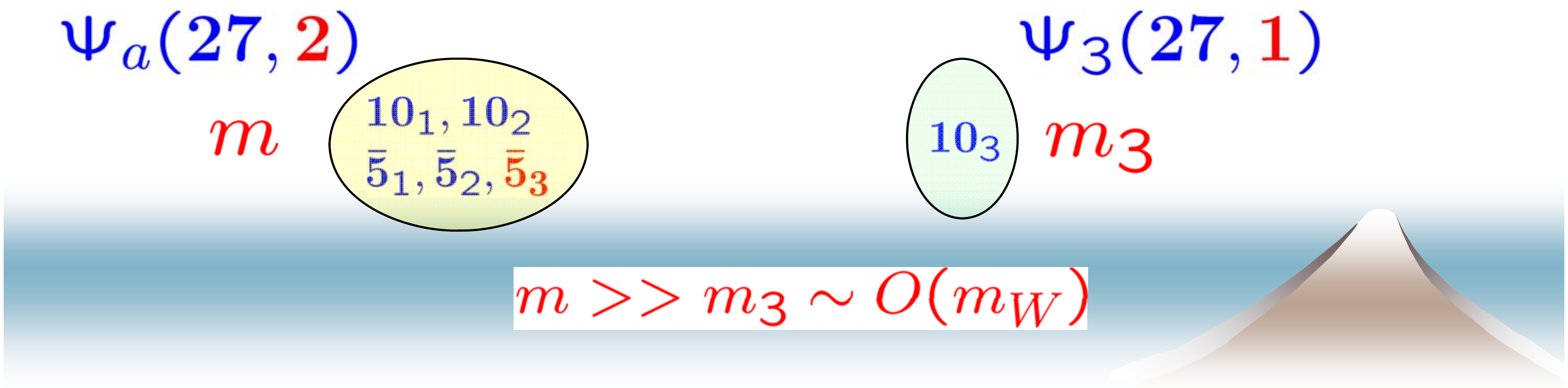
Different

Universal mass m_3: $\mathbf{10}_3$, $\bar{\mathbf{5}}_3$

- This shift makes this model consisitent with the present experiments.(Universal masses for $\bar{\mathbf{5}}_{\mathbf{i}}$)
- The 3rd generation FCNC can be large.(Testable)

Structures suppressing FCNC for $\bar{\mathbf{5}}_{\mathbf{i}}$

- Small Yukawa couplings
- Small $\tan\beta$
- Universal sfermion masses for $\bar{\mathbf{5}}_{\mathbf{i}}$
- m can increase without destabilizing the weak scale. (Effective SUSY)



How does FCNC processes take place in this model?

flavor violating ← $\mathbf{10}: \begin{pmatrix} m^2 & & \\ & m^2 & \\ & & m_3^2 \end{pmatrix}$

$\bar{\mathbf{5}}: \begin{pmatrix} m^2 & & \\ & m^2 & \\ & & m^2 \end{pmatrix}$ → No source of flavor violation

$\mathbf{10} :(Q,\ U_R^c,\ E_R^c)$

$\bar{\mathbf{5}} :(L,\ D_R^c)$

For example, for the right-handed charged slepton sector,

$$\tilde{e}_R^\dagger \begin{pmatrix} m^2 & & \\ & m^2 & \\ & & m_3^2 \end{pmatrix} \tilde{e}_R \rightarrow \tilde{e}_R^\dagger V^\dagger \begin{pmatrix} m^2 & & \\ & m^2 & \\ & & m_3^2 \end{pmatrix} V \tilde{e}_R = \tilde{e}_R^\dagger \tilde{m}_{\tilde{e}_R}^2 \tilde{e}_R$$

Since 10 contains Q, the form of unitary matrix V is CKM-like. We can parametrize it with Cabibbo angle λ.

$$V \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad \lambda = 0.22$$

$$\Delta m^2 = (m_3^2 - m^2)$$

$$\tilde{m}_{\tilde{e}_R}^2 = \tilde{m}_{\tilde{q}_L}^2 = \tilde{m}_{\tilde{u}_R}^2 = V^\dagger \begin{pmatrix} m^2 & & \\ & m^2 & \\ & & m_3^2 \end{pmatrix} V \sim \begin{pmatrix} m^2 & \Delta m^2 \lambda^5 & \Delta m^2 \lambda^3 \\ \Delta m^2 \lambda^5 & m^2 & \Delta m^2 \lambda^2 \\ \Delta m^3 \lambda^3 & \Delta m^2 \lambda^2 & m_3^2 \end{pmatrix}$$

Non universal SUSY breaking

- Universal sfermion masses for $\bar{\mathbf{5}}$ fields

$$\delta_{\bar{5}} \sim \delta_{d^c_R} \sim \delta_l \sim 0$$

- Non universaltiy for $\mathbf{10}$ fields

$$\delta_{10} \sim \delta_q \sim \delta_{u_R} \sim \delta_{e_R}$$

$$\sim V^\dagger_{CKM} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} V_{CKM} \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$V_q \sim V_{u_R} \sim V_{e_R} \sim V_{CKM}$$

- Weak scale stability requires $m_3^2 \sim O((100\text{GeV})^2)$
  but almost no constraint for m_0

Predictions of E6 GUT +horizontal symmetry

Kim-N.M.-Matsuzaki-Sakurai-Yoshikawa

m_3 must be around the weak scale, because of the stability of the weak scale, while m can be taken larger.

10: $\begin{pmatrix} m^2 & & \\ & m^2 & \\ & & m_3^2 \end{pmatrix}$ $\quad$ $\bar{\mathbf{5}}$: $\begin{pmatrix} m^2 & & \\ & m^2 & \\ & & m^2 \end{pmatrix}$

Non decoupling feature of this model (in lepton flavor violation)

$$\tilde{m}^2_{\tilde{e}_R} \sim \begin{pmatrix} m^2 & \Delta m^2\lambda^5 & \Delta m^2\lambda^3 \\ \Delta m^2\lambda^5 & m^2 & \Delta m^2\lambda^2 \\ \Delta m^3\lambda^3 & \Delta m^2\lambda^2 & m_3^2 \end{pmatrix}$$

$\lambda = 0.22$

$\Delta m^2 = (m_3^2 - m^2)$

- By picking up the 3-2 element, the size of τ→μ transition rate is order λ^2.

$\tau \to \mu\gamma$

$$\tilde{\tau}_R \; (\tilde{m}^2_{\tilde{e}_R})_{32} \; \tilde{\mu}_R \approx \frac{1}{m_3^2}\Delta m^2 \lambda^2 \frac{1}{m^2} \longrightarrow \frac{\lambda^2}{m_3^2}$$

- For μ→eγ, there are two passes to change the flavor μ→e. Both they are order λ^5.

$\mu \to e\gamma$

$$\tilde{\mu}_R \; (\tilde{m}^2_{\tilde{e}_R})_{21} \; \tilde{e}_R \approx \frac{1}{m^2}\Delta m^2 \lambda^5 \frac{1}{m^2} \longrightarrow 0$$

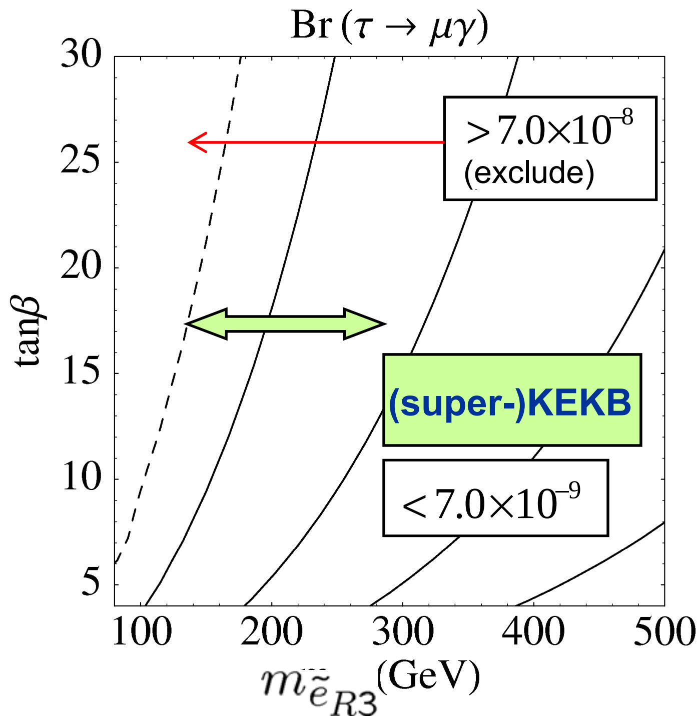
$$\tilde{\mu}_R \; (\tilde{m}^2_{\tilde{e}_R})_{23} \; \tilde{\tau}_R \; (\tilde{m}^2_{\tilde{e}_R})_{31} \; \tilde{e}_R \approx \frac{1}{m^2}\frac{(\Delta m^2)^2 \lambda^5}{m_3^2}\frac{1}{m^2} \longrightarrow \frac{\lambda^5}{m_3^2}$$

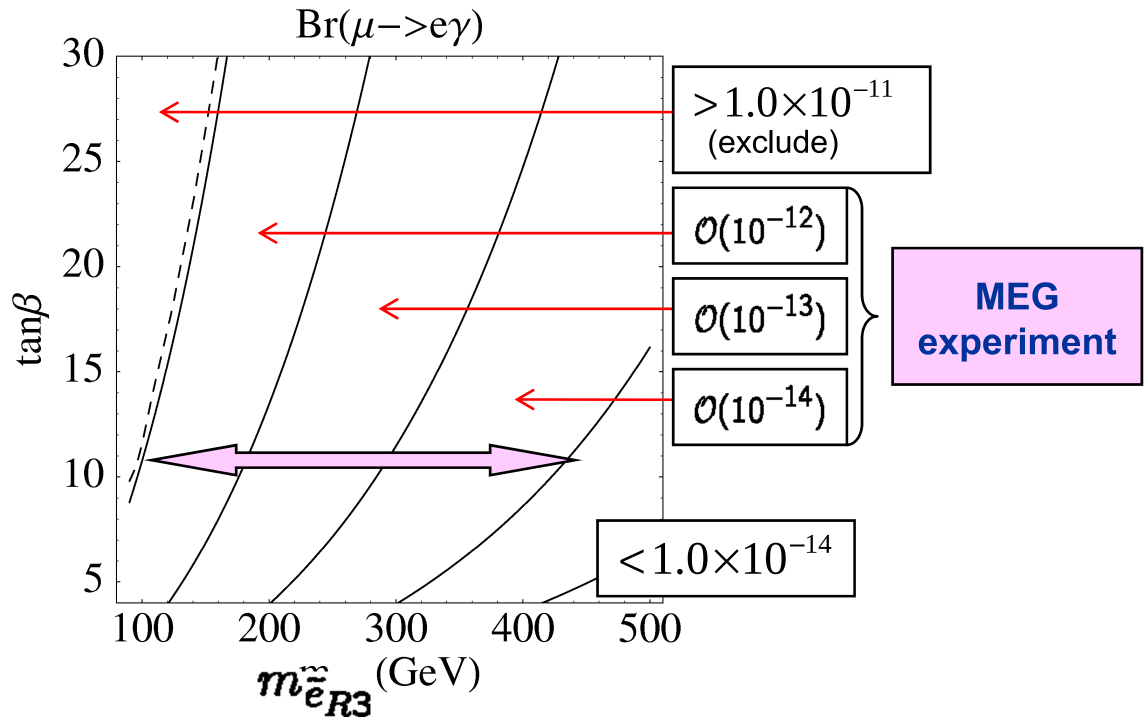
If we raise overall ~~SUSY~~ scale m …

$$m^2 \longrightarrow \infty$$

Propagator suppression from 1 or 2 generation becomes stronger, but mass difference Δm^2 increase. As a result, **both transition rate remain finite, and don't decouple!**

Can we discover the LFV at the future experiments?



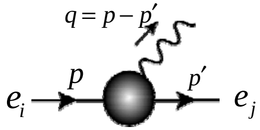


$$M_2 = 120\text{GeV}$$
$$\mu = 200\text{GeV}$$
$$m_{\tilde{e}_{R1,2}} = 600\text{GeV}$$

- τ→μγ ➡ Detectable, when tanβ is large and $m_{\tilde{e}_{R3}}$ <250GeV
- μ→eγ ➡ Detectable unless $m_{\tilde{e}_{R3}}$ <400GeV

This model says that final state lepton tends to be right-handed.

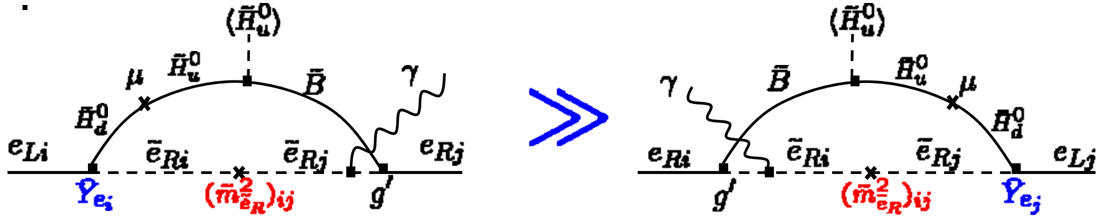
- Final state lepton has different chirality from initial one.



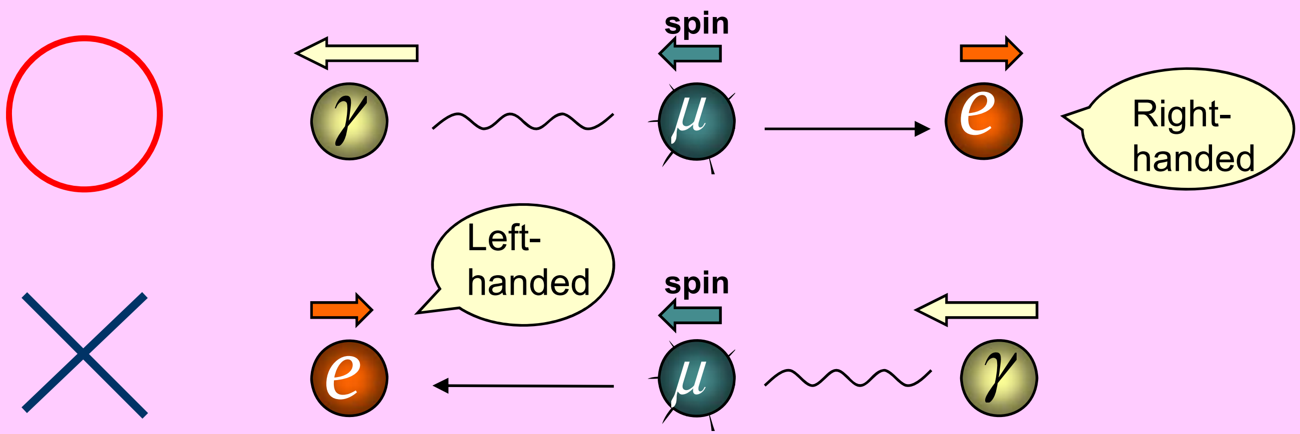
$$T = \epsilon^{*\mu}\bar{u}_i(p)\, i\sigma_{\mu\nu} q^{\nu} (A_L^{ij} P_L + A_R^{ij} P_R) u_j(p')$$

Opposite from MSSM+ν_R

- Intermediate state must be right-handed to pick up the $\tilde{m}^2_{\tilde{e}_R}$.



How can we see this feature experimentally?



It is possible to check this feature experimentally by measuring the angular distribution of final state lepton.

Predictions (Quark sector)

- The maginitudes are the same order as of $\tilde{m}^2_{\tilde{d}_L} = \tilde{m}^2_{\tilde{u}_L} = \tilde{m}^2_{\tilde{u}_R} \sim \begin{pmatrix} m^2 & \Delta m^2\lambda^5 & \Delta m^2\lambda^3 \\ \Delta m^2\lambda^5 & m^2 & \Delta m^2\lambda^2 \\ \Delta m^3\lambda^3 & \Delta m^2\lambda^2 & m_3^2 \end{pmatrix}$ the RGE effects in the universal mass case.
- New CP phases!!

  The CP violation in B meson system may be detectable.

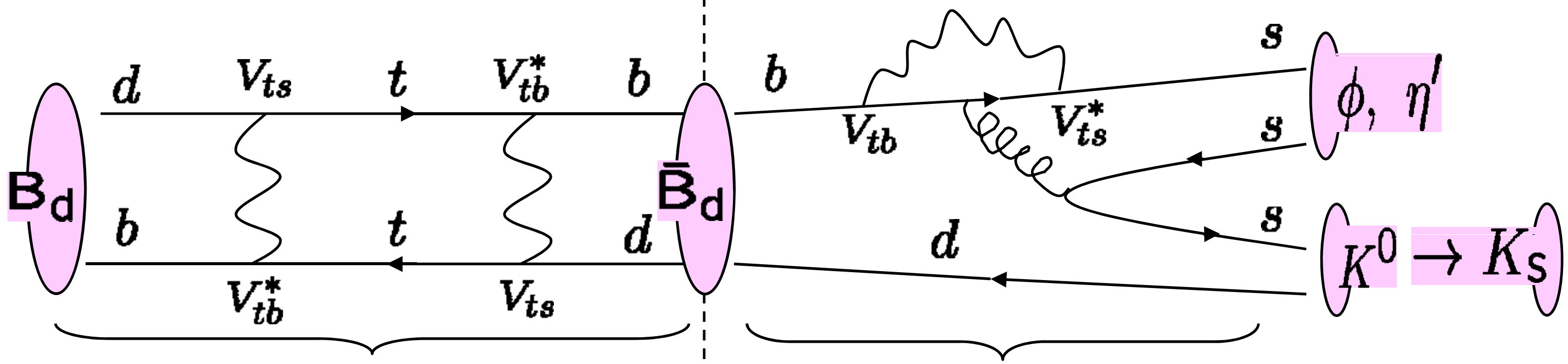
CP violation in B meson

	SM	E6	
$S_{B_s \to J/\Psi \phi}$	O(0.04)	O(0.006)	$(\delta_{d_R})_{23} \sim 0$
$\Delta S_{K\phi}, \Delta S_{K\eta'}$		<0.15	
$A_{CP}(b \to s\gamma)$	0.006	<0.01	$(\delta_{d_L})_{23} \sim \lambda^2$
$A_{CP}(B \to V\gamma)$		very small	$(\delta_{d_R})_{23} \sim 0$
$S_{B \to K_s \pi^0 \gamma}$		very small	

For $\tan\beta \sim 10$

$B_d \to \phi K_S, \eta' K_S$

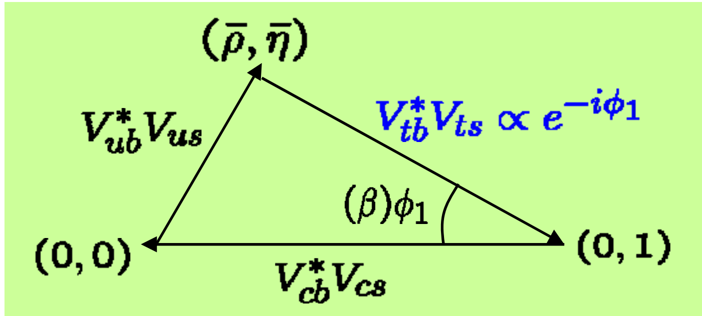
SM (we have already seen.) | Loop = SM + **NP**



$\langle \bar{B}_d | B_d \rangle \propto (V_{tb}^* V_{td})^2$

$\langle \phi K_S | \bar{B}_d \rangle \propto V_{tb} V_{ts}^* \simeq \textit{real}$ (in SM)

$$S_{\phi K_S} = \frac{2\mathrm{Im}\left[\sqrt{\frac{\langle \bar{B}_d | B_d \rangle^*}{\langle \bar{B}_d | B_d \rangle}}\frac{\langle \phi K_S | \bar{B}_d \rangle}{\langle \phi K_S | B_d \rangle}\right]}{1 + \left|\frac{\langle \phi K_S | \bar{B}_d \rangle}{\langle \phi K_S | B_d \rangle}\right|^2} = \mathrm{Im}\left[\frac{V_{tb} V_{td}^*}{V_{tb}^* V_{td}} \frac{\langle \phi K_S | \bar{B}_d \rangle}{\langle \phi K_S | B_d \rangle}\right]$$



$$= \mathrm{Im}\left[e^{2i\phi_1} \frac{\langle \phi K_S | \bar{B}_d \rangle}{\langle \phi K_S | B_d \rangle}\right] = \sin 2\phi_1 \, Re\left[\frac{\langle \phi K_S | \bar{B}_d \rangle}{\langle \phi K_S | B_d \rangle}\right] + \cos 2\phi_1 \mathrm{Im}\left[\frac{\langle \phi K_S | \bar{B}_d \rangle}{\langle \phi K_S | B_d \rangle}\right]$$

$\simeq \sin 2\phi_1 \simeq 0.68$ (in SM)

Numerical Estimation

We estimate $S_{\phi K_S}$ by using parameters R, that is ratio of SUSY and SM amplitude.

$$\frac{\langle \phi K_S | \bar{B}_d \rangle}{\langle \phi K_S | B_d \rangle} \simeq \frac{A^{SM}_{\phi K_s} + e^{-i\theta} |A^{SUSY}_{\phi K_s}|}{A^{SM}_{\phi K_s} + e^{i\theta} |A^{SUSY}_{\phi K_s}|} = \frac{1 + e^{-i\theta} R_{\phi K_s}}{1 + e^{i\theta} R_{\phi K_s}}$$

$$\left(R_{\phi K_s} \equiv \frac{|A^{SUSY}_{\phi K_s}|}{|A^{SM}_{\phi K_s}|} \ll 1 \right)$$

$$\simeq 1 - i2(\sin\theta) R_{\phi K_s}$$

(θ :SUSY phase)

$$S_{\phi K_S} = \sin 2\phi_1 Re\left[\frac{\langle \phi K_S | \bar{B}_d \rangle}{\langle \phi K_S | B_d \rangle}\right] + \cos 2\phi_1 \mathrm{Im}\left[\frac{\langle \phi K_S | \bar{B}_d \rangle}{\langle \phi K_S | B_d \rangle}\right]$$

$$\simeq \sin 2\phi_1 - \cos 2\phi_1 \cdot 2 \sin\theta R_{\phi K_s} \simeq 0.68 - 1.46 R_{\phi K_s} \sin\theta$$

(SM) (SUSY)

$$S_{\eta' K_S} \simeq 0.68 - 1.46 R_{\eta' K_s} \sin\theta$$

(SM) (SUSY)

SUSY contribution to $S_{\phi K_S}$ is linearly depend on R.

$B_d \rightarrow \phi Ks, \eta' Ks$

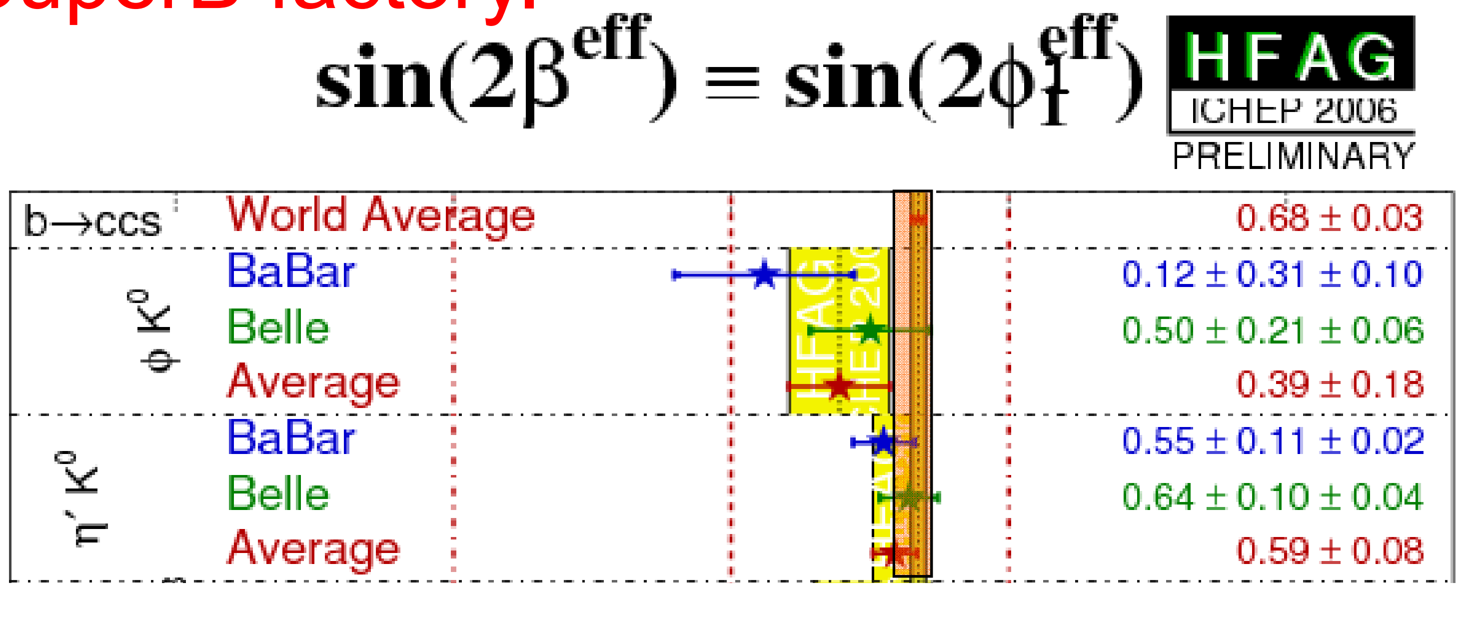
$\Delta S^{SUSY}_{\phi K_S}, \Delta S^{SUSY}_{\eta' K_S} \sim O(0.1)$ is possible.

Gluino contribution is decoupled.

Chargino contribution is not decoupled.

in the limit $m >> m_3$

O(0.1) deviation in B factory may be confirmed in SuperB factory.



Summary table of E6 predictions

	SM	E6	
$\mathrm{Br}(\mu \to e\gamma)$	~ 0	$10^{-11} - 10^{-14}$	◎
$\mathrm{Br}(\tau \to \mu\gamma)$	~ 0	$10^{-8} - 10^{-10}$	◎
$S_{B_s \to J/\Psi\phi}$	O(0.04)	O(0.006)	
$\Delta S_{K\phi}, \Delta S_{K\eta'}$		<0.15	△
$A_{CP}(b \to s\gamma)$	0.006	<0.01	
$A_{CP}(B \to V\gamma), S_{B \to K_s\pi^0\gamma}$		very small	

Discussions

- Strictly speaking, $\delta_{\bar{\mathbf{5}}} \neq 0$ $\delta_{LR} \neq 0$

  when $\cancel{U(2)}_H$ e.g.

$$\delta_{\bar{\mathbf{5}}} \sim \begin{pmatrix} \lambda^5 & \lambda^4 & \lambda^{3.5} \\ \lambda^4 & \lambda^3 & \lambda^{2.5} \\ \lambda^{3.5} & \lambda^{2.5} & \lambda^2 \end{pmatrix}$$

This can be consistent with the experiments,

but the predictions can be changed.

If we take $m_0 >> m_3$, this model dependent parts can be neglected.

No weak scale unstability!!

SUSY CP problem

Spontaneous CP violation by the VEV of F.

The severe constraints from CEDM are also satisfied because of real up-Yukawa couplings.

SUSY CP problem

- EDM constraints from 1 loop

$$\mu = |\mu| e^{i\delta_\mu},\ A = |A| e^{i\delta_A}$$

$$\delta_{\mu,A} < 10^{-2} \left(\frac{M_{SUSY}}{100\text{GeV}}\right)^2$$

- CEDM from Hg(neutron) even if $\delta_{\mu,A} = 0$

Hisano-Shimizu ‘04

$$\text{Im } (\delta_{d_L})_{13} (\delta_{d_R})_{31} < 3(0.2) \times 10^{-3}$$

$$\text{Im } (\delta_{u_L})_{23} (\delta_{u_R})_{32} < 3(0.2) \times 10^{-3} \quad \lambda^4 \sim 2 \times 10^{-3}$$

$$\text{Im } (\delta_{u_L})_{13} (\delta_{u_R})_{31} < 3(5) \times 10^{-5} \quad \lambda^6 \sim 10^{-4}$$

Contributions through stop loop are not decoupled.
Complex Yukawa couplings induce them generically.

Difficulties in CEDM constraints

- We usually assume complex Yukawa couplings to induce KM phase.
- Complex Yukawa couplings induce the complex $\delta_{u_L} \equiv U_{u_L} \tilde{m}^2_{u_L} U^\dagger_{u_L}$ generically.

  Then CEDM constraints become severe.

$$\mathrm{Im}\ (\delta_{u_L})_{23}(\delta_{u_R})_{32} < 3(0.2) \times 10^{-3}$$

$$\mathrm{Im}\ (\delta_{u_L})_{13}(\delta_{u_R})_{31} < 3(5) \times 10^{-5}$$

Spontaneos CP violation in E6 + $SU(2)_H(+U(1)_A)$

Ishiduki-Kim-N.M.-Sakurai

- Idea:

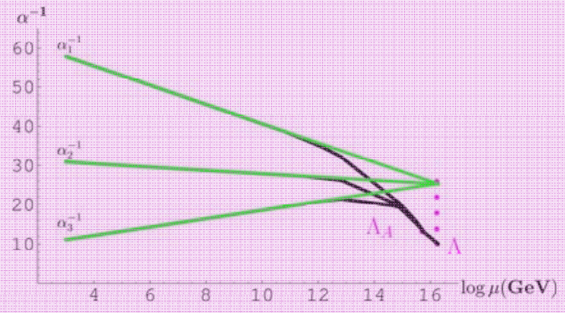
  1,If the Higgs F which breaks horizontal symmetry has complex phase, we can obtain complex Yukawa couplings, and KM phase.

  2, Naively the suppression $\langle \bar{F} F \rangle \sim \lambda^4$ can be expected for the phase of SUSY parameters.

Anomalous $U(1)_A$ GUT

N.M. 01, Bando-N.M. 01
N.M.-Yamashita 02

- Generic Interactions (Higher Dim. Op.)with O(1) Coefficients
  The symmetry define the theory
- Doublet-triplet splitting
- Suppressed Proton decay (dim. 5)
- Mass spectrum of Superheavy fields
- GUT scales and the other VEV scales
- Natural gauge coupling unification (miraculous cancellation!)
- Realistic quark&lepton masses and mixings (bi-large neutrino mixings)
- mu problem is solved



- To suppress the relative CP phase between μ and $B\mu$, non-trivial discrete charge must be imposed to F .

$$\langle \epsilon^{ab} F_a \rangle \Psi_b \sim \Psi_1 \qquad \langle \bar{F}^a \rangle \sim (0, v)$$

$$\langle \bar{F}^a \rangle \Psi_a \sim \Psi_2 \qquad \langle F_a \rangle \sim \begin{pmatrix} 0 \\ v e^{i\delta} \end{pmatrix}$$

A model with a discrete symmetry (Z_{12})

Bonus 1

- Real up-type Yukawa couplings ⇨ real $\delta_{u_L}, \delta_{u_R}$

  CEDM constraints can be satisfied.

- Complex down-type Yukawa couplings

  KM phase can be induced.

  $\langle F_a \rangle \sim \begin{pmatrix} 0 \\ v e^{i\delta} \end{pmatrix}$

- The point

  $Y^H(\not{F}, \bar{F})$: real, $H_u \sim 10_H$ $Y_u = Y^H$

  $Y^C(F, \bar{F})$: complex

  $H_d \sim 10_H + 10_C + 16_C$

$$W = Y^H 27_i 27_j \langle 27_H \rangle + Y^C 27_i 27_j \langle 27_C \rangle$$

A model with a discrete symmetry

- Bonus 2: small up quark mass is realized.

  Usually, to obtain the CKM matrix $V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$

$$Y_u = \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \Longrightarrow \begin{pmatrix} 0 & Q_{B-L}\lambda^5 & 0 \\ Q_{B-L}\lambda^5 & \lambda^4 & \lambda^2 \\ 0 & \lambda^2 & 1 \end{pmatrix}$$

$$\epsilon^{ab}\Psi_a\Psi_b H, \quad \epsilon^{ab}\Psi_a\langle A\rangle\Psi_b H$$

$$\langle\epsilon^{ab}F_a\rangle\Psi_b \sim \Psi_1$$

$$\langle A\rangle \propto Q_{B-L}$$

$$y_u \sim \lambda^6 \quad \Longrightarrow \left(\frac{1}{3}\right)^2 \lambda^6$$

Too large ➔ good value!

A model with a discrete symmetry

- Bonus 3?: # of O(1) parameters =10

  13 physical parameters

$$\Longrightarrow m_u, m_d, m_e, V_{CKM}$$

- One of the relations

$$m_b = m_\tau (1 + O(\lambda))$$

$$\begin{pmatrix} m_s = O(1) m_\mu \\ m_d = O(1) m_e \end{pmatrix}$$

A model with a discrete symmetry

- The discrete symmetry is consistent with the E6 Higgs sector which realizes doublet-triplet splitting and

$$H_u \sim 10_H$$
$$H_d \sim 10_H + 10_C + 16_C$$

- 16_C mixing is required to avoid massless electron in this model.

Summary

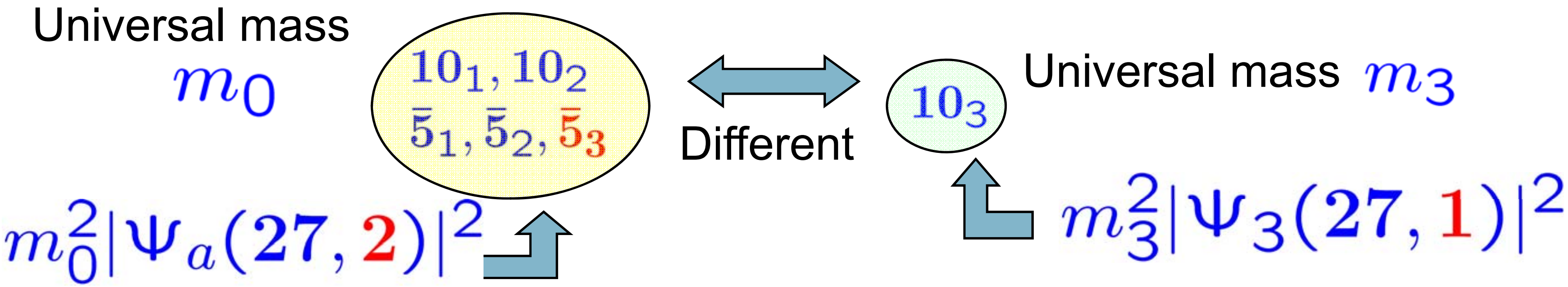
- In E_6 GUT, one basic hierarchy for Yukawa couplings results in various hierarchical structures for quarks and leptons including larger neutrino mixings.
- Horizontal symmetry can easily reproduce the basic hierarchy, and suppress FCNC naturally in E_6 GUT. (not in SO(10) GUT)
- Spontaneous CP violation solves SUSY CP problem(CEDM)
- The simpler unification of quarks and leptons explains the more questions.

$E_6 \quad 3 \times \mathbf{27}$ → larger neutrino mixings

$$E_6 \times \begin{cases} U(2)_H & 2(\mathbf{27}, \mathbf{2}+\mathbf{1}) \\ U(3)_H & 1(\mathbf{27}, \mathbf{3}) \end{cases}$$ → SUSY Flavor Problem, SUSY CP Problem

Summary

- Peculiar sfermion spectrum can be tested.



- $m_0 >> m_3$ without unstability of weak scale. FCNC of 3rd generation becomes larger.
- LFV ($\mu \to e_R\gamma, \tau \to \mu_R\gamma$) and CP violation in B ($B \to \phi K_s, \eta' K_s$ etc) may be detectable in future.
- Polarization of final lepton can test the GUT scenario.

Future work

- What is the signature in LHC?
- CP violation in neutrino oscillation?
- The origin of SUSY breaking? The mediation mechanism of SUSY breaking?
- Can the D term contribution be sufficiently small? $D_{SU(2)_H}$, D_{E_6}

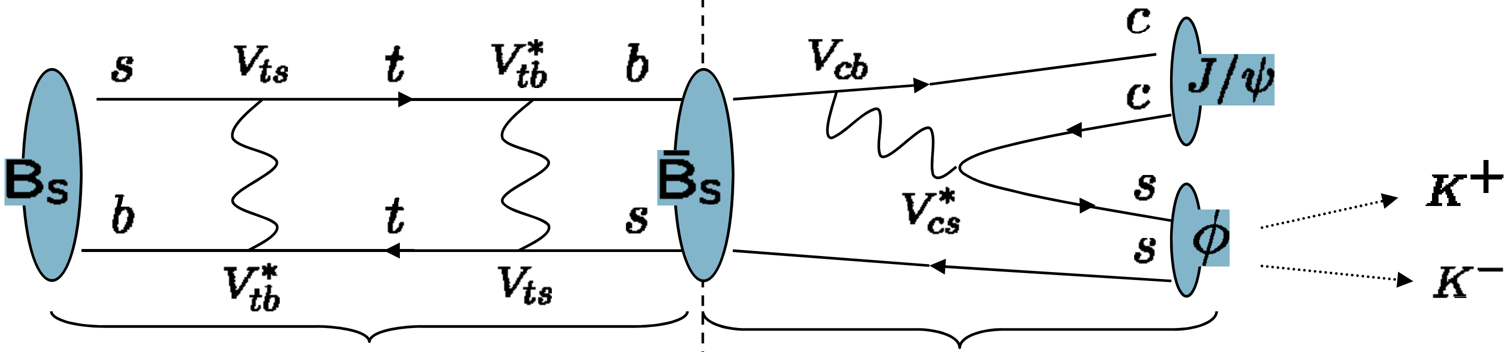
  Decoupling feature mildens the constraints

  Non-Abelian discrete symmetry?
- Cosmology?
- ….

$B_s \to J/\psi\phi$

- **Strategy**

Loop = SM + **NP** | Tree ~ SM



$\langle \bar{B}_s | B_s \rangle \propto (V_{tb}^* V_{ts})^2$ | $\langle \psi\phi | \bar{B}_s \rangle \propto V_{cb} V_{cs}^* \simeq$ *real*

Time dependent CP asym.

$$\frac{\Gamma[B_S(t) \to \psi\phi] - \Gamma[\bar{B}_S(t) \to \psi\phi]}{\Gamma[B_S(t) \to \psi\phi] + \Gamma[\bar{B}_S(t) \to \psi\phi]}$$

$$V_{tb} = 1 + \frac{1}{2}A^2\lambda^4 + \mathcal{O}(\lambda^6)$$

$$V_{ts} = -A\lambda^2 - i\eta A\lambda^4 + \cdots$$

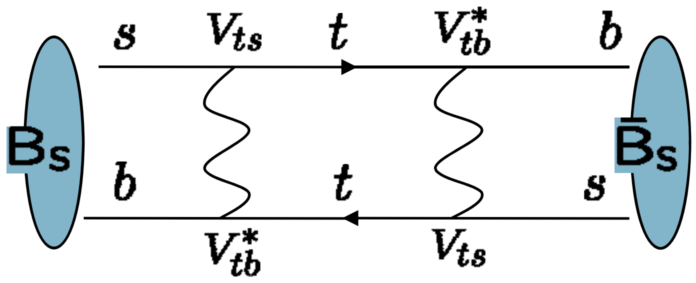
$$S_{\psi\phi} = \frac{2\mathrm{Im}\left[\sqrt{\frac{\langle \bar{B}_s|B_s\rangle^*}{\langle \bar{B}_s|B_s\rangle}}\frac{\langle \psi\phi|\bar{B}_s\rangle}{\langle \psi\phi|B_s\rangle}\right]}{1+\left|\frac{\langle \psi\phi|\bar{B}_s\rangle}{\langle \psi\phi|B_s\rangle}\right|^2} \simeq \mathrm{Im}\left[\frac{\langle B_s|\bar{B}_s\rangle^*}{\langle B_s|\bar{B}_s\rangle}\right] \simeq \mathrm{Im}\left[\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}\right] \simeq -\eta\lambda^2 = \mathcal{O}(10^{-2}) \ll 1$$

In SM, $S_{\psi\phi}$ is very small ! NP contribution may be dominant !

Naïve Estimation

$$\langle B_s|\bar{B}_s\rangle \simeq$$

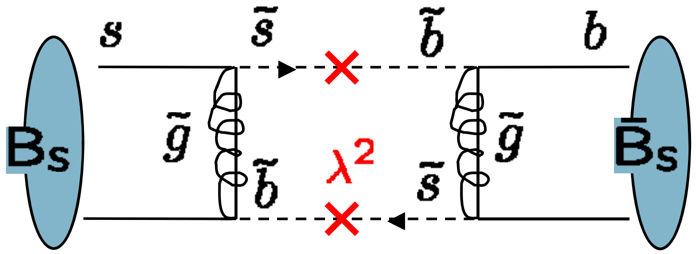
(SM)



$$\propto \frac{\alpha_W^2}{m_W^2}(A\lambda^2 + iA\eta\lambda^4)^2$$

+

(SUSY)



$$\propto \frac{\alpha_s^2}{m_{\tilde{q}}^2}\lambda^4$$

If λ^4 is pure imaginary…

$$S_{\psi\phi} \simeq \mathrm{Im}\left[\frac{\langle\bar{B}_s|B_s\rangle^*}{\langle\bar{B}_s|B_s\rangle}\right] \sim \frac{\frac{\alpha_s^2}{m_{\tilde{g}}^2}\lambda^4}{\frac{\alpha_W^2}{m_W^2}A^2\lambda^4} \simeq \frac{\alpha_s^2}{\alpha_W^2}\frac{m_W^2}{m_{\tilde{q}}^2} \sim 0.4 \;!!$$

$$\begin{pmatrix} \alpha_s \simeq 0.11 \\ \alpha_W \simeq 0.034 \\ m_{\tilde{q}} \sim 400\mathrm{GeV} \end{pmatrix}$$

Naively, it is expected that SUSY contribution make $S_{\psi\phi}$ 10 times larger than SM prediction !!

Numerical Estimation

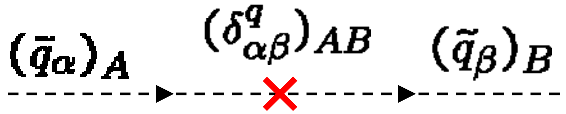
$$S_{\psi\phi} \simeq \mathcal{O}(0.04)$$ } (SM)

$(m_{\tilde{q}} = 380\text{GeV},\ m_{\tilde{g}} = 400\text{GeV})$

Khalil *et al.* ‘03

$$+2.65[(\delta_{23}^d)_{LL}^2 + (\delta_{23}^d)_{RR}^2] + 57.3[(\delta_{23}^d)_{LR}^2 + (\delta_{23}^d)_{RL}^2]$$
$$-90.3[(\delta_{23}^d)_{LR}(\delta_{23}^d)_{RL}] - 374[(\delta_{23}^d)_{LL}(\delta_{23}^d)_{RR}]$$ } (SUSY)

$$(\delta_{\alpha\beta}^q)_{AB} \equiv \frac{(m_{\tilde{q}}^2)_{\alpha\beta AB}}{m_{\tilde{q}}^2} \qquad (\alpha,\beta = 1,2,3) \quad (A,B = L,R)$$



In E_6 + Horizontal model

$$(\delta_{23}^d)_{LL} \simeq \lambda^2 \qquad (\delta_{23}^d)_{LR},\ (\delta_{23}^d)_{RR} \simeq 0$$

(SM) (SUSY)

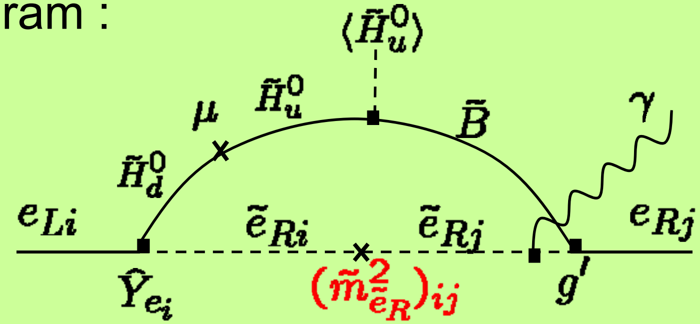
$$S_{\psi\phi} \simeq \mathcal{O}(0.04) + \mathcal{O}(0.006)$$

Actually, SUSY contribution is too tiny with compared to SM prediction.
It is difficult to observe it.

$$C_{SM} = \frac{\alpha_W^2}{m_W^2}(V_{tb}^* V_{ts})^2 \underbrace{S_0\left(\frac{m_t^2}{m_W^2}\right)}_{\mathcal{O}(1)} \qquad C_{SUSY} = -\frac{\alpha_s^2}{216 m_{\tilde{q}}^2}(\delta_{23}^d)_{LL}^2 \underbrace{\left[24\left(\frac{m_{\tilde{g}}}{m_{\tilde{q}}}\right)^2 f_6\left(\frac{m_{\tilde{g}}}{m_{\tilde{q}}}\right) + 66\tilde{f}_6\left(\frac{m_{\tilde{g}}}{m_{\tilde{q}}}\right)\right]}_{\mathcal{O}(1)}$$

Rough Estimation of the BRs

main diagram :



$$Br(l_i \to l_j \gamma) \sim \frac{1}{G_F^2} e(g')^2 \left| \frac{\tan\beta (m^2_{\tilde{e}_R})_{ij}}{m^4_{SUSY}} \right|^2 Br(l_i \to e\nu\bar{\nu})$$

$$\tilde{m}^2_{\tilde{e}_R} \sim \Delta m^2 \begin{pmatrix} 1 & \lambda^5 & \lambda^3 \\ \lambda^5 & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \mathcal{O}(1) \end{pmatrix}$$

$(m_{SUSY} = 200\,\text{GeV}, \quad \tan\beta = 5)$

$Br(\mu \to e\gamma) \sim 10^{-11}$ $\qquad$ $Br(\tau \to \mu\gamma) \sim 10^{-8}$

$(Br(\mu \to e\gamma)_{\text{exp.}} < 1.2 \times 10^{-11})$ $\qquad$ $(Br(\tau \to \mu\gamma)_{\text{exp.}} < 4.8 \times 10^{-8})$

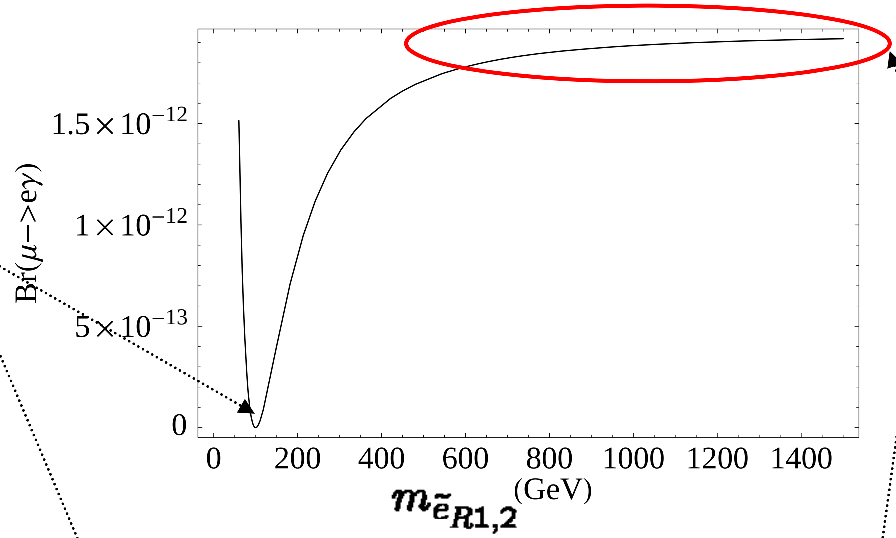
This model leads large LFV rate within reach of near future experiments.

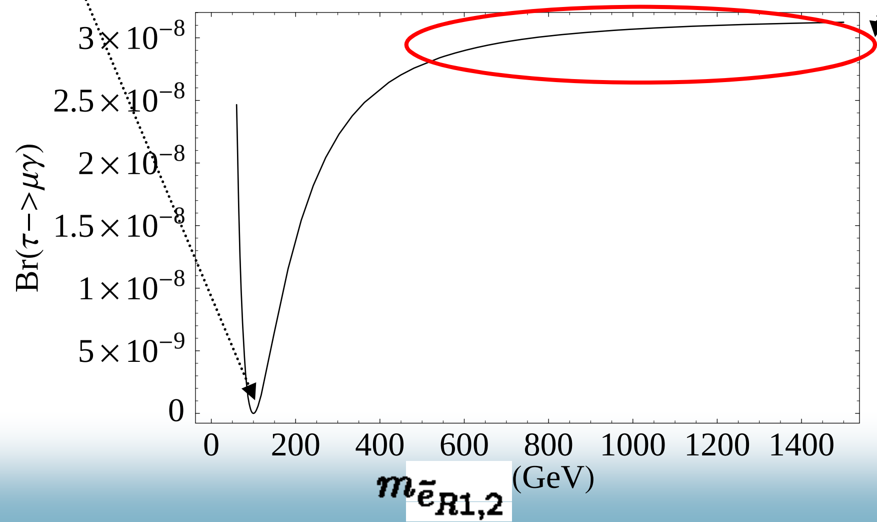
$m_{\tilde{e}_{R1,2}}$ dependence

At this point, m=m_3

$(\tilde{m}^2_{\tilde{e}_R})_{ij} \propto \Delta m^2 = (m_3^2 - m^2) = 0.$

There are no source of LFV.





In this reason, the BRs are no longer changed for $m_{\tilde{e}_{R1,2}}$.

BRs don't decouple as $m_{\tilde{e}_{R1,2}}$ becomes large.

These behavior are explained qualitatively already.

$$\tan\beta = 5$$
$$M_2 = 120\text{GeV}$$
$$\mu = 200\text{GeV}$$
$$m_{\tilde{e}_{R3}} = 100\text{GeV}$$

Branching Ratio is independent of $m_{\tilde{e}_{R1,2}}$ unless $m_{\tilde{e}_{R1,2}} < 600\text{GeV}$.

Quark sector

- Constraints from $B_s - \bar{B}_s$ mixing is OK.

$$(\delta_{d_L})_{23} < 0.2$$

$$\sqrt{(\delta_{d_L})_{23}\cancel{(\delta_{d_R})}_{23}} < 0.02$$

Khalil06

- EDM of Hg(neutron)

Hisano-Shimizu

$$\mathrm{Im}\ (\delta_{d_L})_{13}\cancel{(\delta_{d_R})}_{31} < 3(0.2)\times 10^{-3}$$ OK

$$\mathrm{Im}\ (\delta_{u_L})_{23}(\delta_{u_R})_{32} < 3(0.2)\times 10^{-3} \quad \lambda^4 \sim 2\times 10^{-3}$$

$$\mathrm{Im}\ (\delta_{u_L})_{13}(\delta_{u_R})_{31} < 3(5)\times 10^{-5} \quad \lambda^6 \sim 10^{-4}$$

A structure in E_6 explains

- the suppression of the radiative FCNC with unifing Yukawa $E_6 \supset SO(10)$
- why the mixings in lepton sector is larger.
- the various mass hierarchies in quark & lepton sector.

$$\frac{m_{ui}}{m_{uj}} >> \frac{m_{di}}{m_{dj}}, \frac{m_{ei}}{m_{ej}} >> \frac{m_{\nu i}}{m_{\nu j}} \qquad i < j$$

E_6 +horizontal symmetry

- A prediction for sfermion mass spectrum
  Universality of sfermion masses are
  partly realized.
- FCNC can be suppressed without special assumption for SUSY breaking sector.
- Non universality makes the 3rd generation FCNC larger than in the universal case.

Radiatively induced FCNC

$$\mathbf{10} = (q, u_R^c, e_R^c)$$
$$\bar{\mathbf{5}} = (d_R^c, l)$$
$$\mathbf{1} = \nu_R^c$$

$$\begin{aligned} W_Y &= (Y_u)_{ij}\mathbf{10}_i\mathbf{10}_j\bar{\mathbf{5}}_H + (Y_{(d,e)})_{ij}\mathbf{10}_i\bar{\mathbf{5}}_j\bar{\mathbf{5}}_{\bar{H}} \\ &+ (Y_{\nu_D})_{ij}\bar{\mathbf{5}}_i\mathbf{1}_j\mathbf{5}_H + (M_R)_{ij}\mathbf{1}_i\mathbf{1}_j \end{aligned}$$

- Even if universal sfermion masses at the cutoff, radiative correction induces the non-universality. Borzumati-Masiero 85 Hisano-Moroi-Tobe-Yamaguchi-Yanagida Barbieri-Hall-Strumia 95

$$\mathrm{Br}(l_i \to l_j \gamma) \propto (V_L^\dagger \hat{Y}_{\nu_D}^2 V_L \tan\beta)^2$$

- Large mixings $V_L \sim V_{MNS}$
- SO(10) GUT relations

$Y_{\nu_D} \sim Y_u \sim Y_d$ ⟺ $\tan\beta,\ Y_{\nu_D}$

⇨ too large LFV

Key Observation
to understand the different mixings

- SU(5) GUT Albright,Barr,Sato,Yanagida,Ramond,,,,

$$\mathbf{10} = (q, u_R^c, e_R^c) \qquad \bar{\mathbf{5}} = (d_R^c, l)$$

Quark mixings(CKM) ⟺ Mixings of $\mathbf{10}_i(q_i)$

⇑ ⇑

Lepton mixings(MNS) ⟺ Mixings of $\bar{\mathbf{5}}_i(l)$

⇒ $\mathbf{10}_i(q_i)$ have stronger hierarchy than $\bar{\mathbf{5}}_i(l)$

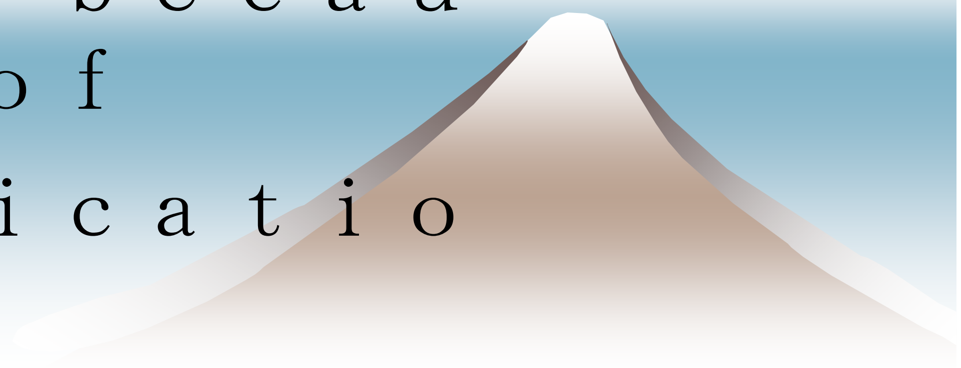
⇒ Y_u have stronger hierarchy than Y_d

$$Y_u \mathbf{10}_i \mathbf{10}_j \mathbf{5}_H + Y_d \mathbf{10}_i \bar{\mathbf{5}}_j \bar{\mathbf{5}}_{\bar{H}}$$

Next question

Why do $\bar{\mathbf{5}}_i(l)$ have milder hierarchy than $\mathbf{10}_i(q_i)$?

This is because of E_6 Unification



Unification of Yukawa hierarchies

Bando-N.M.
N.M.

All Yukawa couplings have the same hierarchical flavor structure.

⇨ Various hierarchies of quarks and leptons

Only one basic hierarchical flavor structure

(to realize Y_u) Not fix the origin.

An example

$$Y^H \sim Y^C \sim Y \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\left[\begin{pmatrix} 0 & \lambda^5 & 0 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ 0 & \lambda^2 & 1 \end{pmatrix}\right]$$

$\lambda \sim 0.22$

How to fix light modes of $\bar{\mathbf{5}}$?

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

$\langle \mathbf{1}_H \rangle$

$$M(\mathbf{5}, \bar{\mathbf{5}})/\langle \mathbf{1}_H \rangle \sim$$

	$\bar{\mathbf{5}}_1$	$\bar{\mathbf{5}}_2$	$\bar{\mathbf{5}}_3$	$\bar{\mathbf{5}}_1$	$\bar{\mathbf{5}}_2$	$\bar{\mathbf{5}}_3$
$\mathbf{5}_1$	λ^6	λ^5	λ^3	λ^{6+r}	λ^{5+r}	λ^{3+r}
$\mathbf{5}_2$	λ^5	λ^4	λ^2	λ^{5+r}	λ^{4+r}	λ^{2+r}
$\mathbf{5}_3$	λ^3	λ^2	1	λ^{3+r}	λ^{2+r}	λ^r

$$\lambda^r \equiv \frac{\langle \mathbf{27}_C \rangle}{\langle \mathbf{27}_H \rangle} \sim \lambda^{0.5}$$

Light modes $(\bar{\mathbf{5}}_1, \bar{\mathbf{5}}_1, \bar{\mathbf{5}}_2)$

SO(10) GUT relations

$$Y_d = Y_e^T = Y_u = Y_{\nu_D}$$

$$Y_u \sim \begin{array}{c} \\ \mathbf{10}_1 \\ \mathbf{10}_2 \\ \mathbf{10}_3 \end{array} \begin{array}{c} \begin{array}{ccc} \mathbf{10}_1 & \mathbf{10}_2 & \mathbf{10}_3 \end{array} \\ \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \end{array} \begin{array}{l} \big\}\lambda \\ \big\}\lambda^2 \end{array}
\qquad
Y_{\nu_D} \sim \begin{array}{c} \\ \bar{\mathbf{5}}_1 \\ \bar{\mathbf{5}}_1 \\ \bar{\mathbf{5}}_2 \end{array} \begin{array}{c} \begin{array}{ccc} \mathbf{1}_1 & \mathbf{1}_2 & \mathbf{1}_3 \end{array} \\ \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^{5.5} & \lambda^{4.5} & \lambda^{2.5} \\ \lambda^5 & \lambda^4 & \lambda^2 \end{pmatrix} \end{array} \begin{array}{l} \big]\lambda^{0.5} \\ \big]\lambda^{0.5} \end{array}$$

$$(\bar{\mathbf{5}}_1, \bar{\mathbf{5}}_1, \bar{\mathbf{5}}_2)$$

$$\bar{\mathbf{5}}_1 + \lambda^{\Delta}\bar{\mathbf{5}}_3 \quad (\Delta = 3 - r)$$

$$Y_d \sim Y_e^T \sim \begin{array}{c} \\ \mathbf{10}_1 \\ \mathbf{10}_2 \\ \mathbf{10}_3 \end{array} \begin{array}{c} \begin{array}{ccc} \bar{\mathbf{5}}_1 & \bar{\mathbf{5}}_1 & \bar{\mathbf{5}}_3 \end{array} \\ \begin{pmatrix} \lambda^6 & \lambda^{5.5} & \lambda^3 \\ \lambda^5 & \lambda^{4.5} & \lambda^2 \\ \lambda^3 & \lambda^{2.5} & 1 \end{pmatrix} \\ \underbrace{\quad}_{\lambda^{0.5}}\underbrace{\quad}_{\lambda^{0.5}} \end{array} \begin{array}{l} \big\}\lambda \\ \big\}\lambda^2 \end{array}$$

$$\lambda^r \equiv \frac{\langle \mathbf{27}_C \rangle}{\langle \mathbf{27}_\Phi \rangle} \sim \lambda^{0.5}$$

Small $\tan\beta$

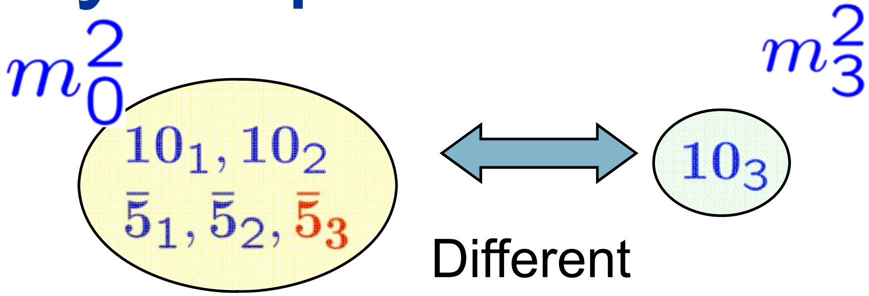
Small Y_{ν_D}

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}
\qquad
V_{MNS} \sim \begin{pmatrix} 1 & \lambda^{0.5} & \lambda \\ \lambda^{0.5} & 1 & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix}$$

E_6 GUT is

an interesting target of B factory

Weak scale stability requirement



- $m_3, M_{\frac{1}{2}}, m_H, \mu \sim O(100\text{GeV})$
- Not strong constraint

  for m_0 because of small Yukawa couplings
- If we take $m_0 >> m_3$, constraints from FCNC, EDM, g-2 etc. become much weaker.
- The little hierarchy problem?

  Natural parameters ⟹ ~~$m_h > 114.4$ GeV~~

  ⟹ Kim's talk