E_6 Grand Unified Theory and Spontaneous CP Violation

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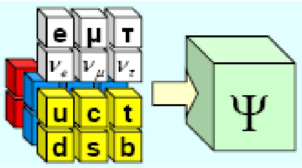
1. **Introduction**
2. **E_6 Grand Unified Theory**
3. **Horizontal Symmetry**
4. **Spontaneous CP Violation**
5. **Summary and Discussion**

Overview of this talk

- E_6 grand unified theory (GUT)

  Various hierarchies of quark and lepton masses and mixings can be explained. $(U_{e3}\sim\lambda)$

- E_6 GUT+non-Abelian horizontal symmetry



  The explanation is so natural that realistic Yukawa couplings can be realized after breaking the symmetries.

  Modified universal sfermion masses are predicted.

  1 $m_3 \ll m$ is interesting.

  a. light stop… weak scale stablity

  b. heavy sfermion…suppress FCNC, CP

  2. All FCNC are sufficiently suppressed.

  3. Several are within reach of future exp.

  4. No signal in LHC is consistent with light stop!

  5. New type of SUSY CP problem looks serious.

$$\tilde{m}_{10}{}^2 = \begin{pmatrix} m^2 & . & . \\ . & m^2 & . \\ . & . & m_3{}^2 \end{pmatrix},$$

$$\tilde{m}_{\bar{5}}{}^2 = \begin{pmatrix} m^2 & . & . \\ . & m^2 & . \\ . & . & m^2 \end{pmatrix}$$

Overview of this talk

- E_6 GUT+horizontal sym. with sp. CP violation (Discrete sym. is introduced.)

  Not only old type but also new type of SUSY CP problems can be solved.

  Several bonus (light up quark, $V_{ub}\sim\lambda^4$, predictive power)

  Examining the neutrino sector New!

  Same predictions as the usual E_6 GUT but non-trivial.

Introduction

Grand Unified Theories

2 Unifications

- Gauge Interactions

$$SU(5) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$$

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

- Matter

$$\boxed{Q \quad U_R^c \quad E_R^c} \; \boxed{D_R^c \quad L} \quad \boxed{N_R^c}$$

$$\mathbf{10} \quad + \quad \bar{\mathbf{5}} + \mathbf{1} \quad = \quad \mathbf{16}$$

Experimental supports for both unifications

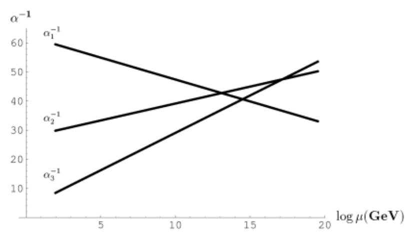
→ GUT is promising

Grand Unified Theories

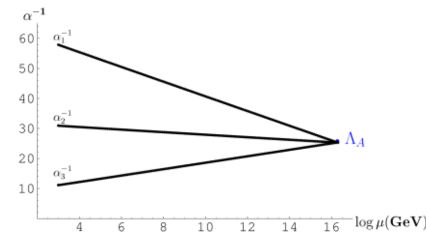
- Unification of gauge interactions

  quantitative evidence:

Non SUSY



SUSY GUT



- Unification of matters

  $(Y_u)_{ij}10_i10_j5_H + (Y_d)_{ij}10_i\bar{5}_j\bar{5}_H + (Y_\nu)_{ij}\bar{5}_i\bar{5}_j5_H5_H$

  qualitative evidence:

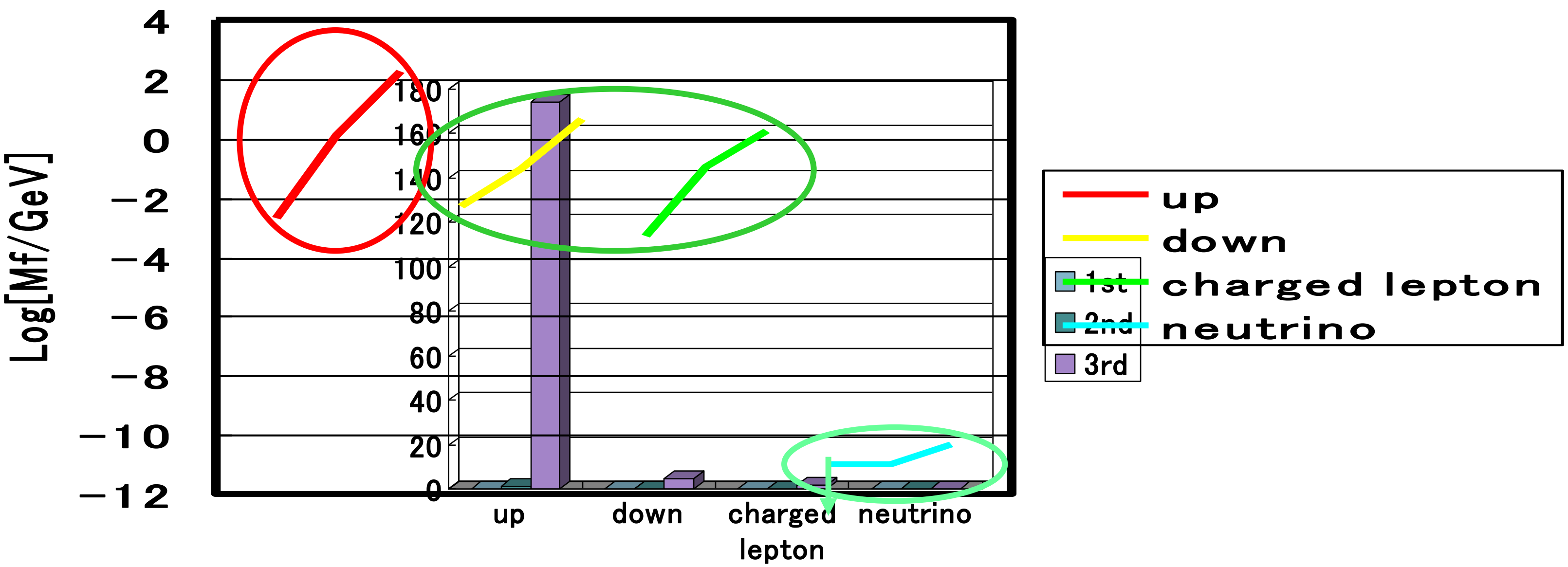
$10_i(Q_i)$ have stronger hierarchy than $\bar{5}_i(L)$

hierarchies of masses and mixings

lepton >>quark (in hierarchies for mixings)

ups >> downs, electrons >> neutrinos (in mass hierarchies)

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…

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

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

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

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

Stronger hierarchy leads to smaller mixings

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

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

Mass hierarchy and mixings

- Stronger hierarchy leads to smaller mixings

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

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

Stronger hierarchy $\Leftrightarrow$ Smaller mixings

SU(5) SUSY GUT

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

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

$\boxed{u \gg d, e \gg \nu}$

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

Stronger hierarchy leads to smaller mixings

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

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

Good agreement with masses & mixings

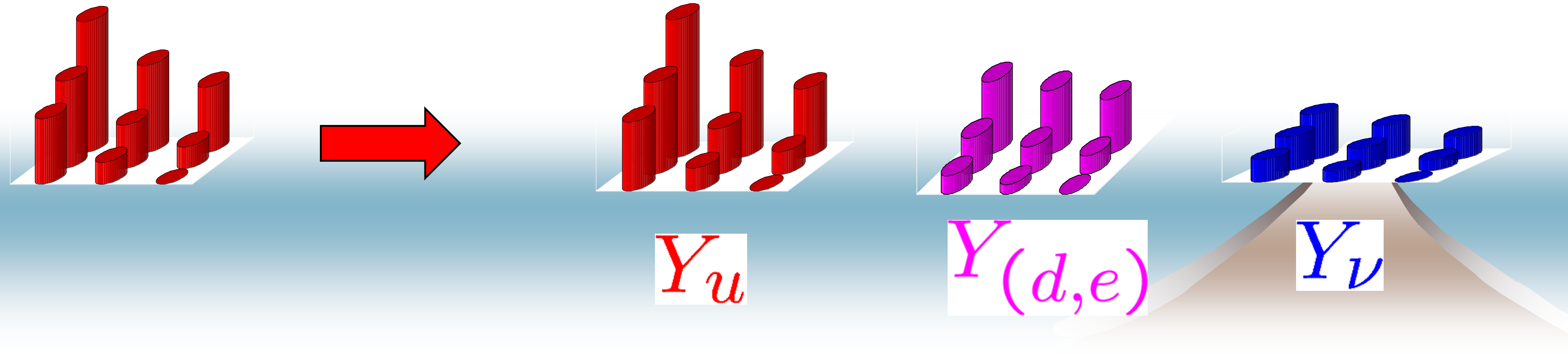
E_6 Grand Unified Theory

The assumption in SU(5) GUT

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

can be derived.

Various Yukawa hierarchies can be induced from one Yukawa hierarchy in E_6 GUT.



E_6 Unification

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

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

$(i = 1, 2, 3)$

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 $\bar{\mathbf{5}}_i(l)$

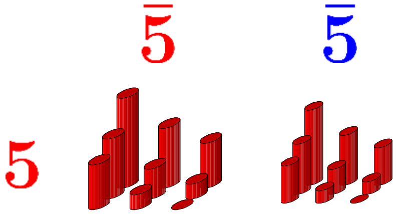
Bando-N.M. 01
N.M, T. Yamashita 02

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

$$\begin{matrix} & \bar{\mathbf{5}}_3 & \bar{\mathbf{5}}_3 \\ & \bar{\mathbf{5}}_2 & \bar{\mathbf{5}}_2 \\ & \bar{\mathbf{5}}_1 & \bar{\mathbf{5}}_1 \end{matrix}$$

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 $(\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_3)$

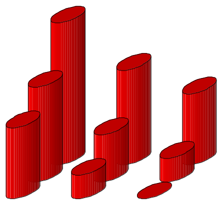
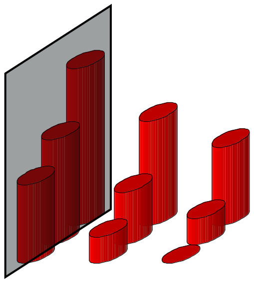
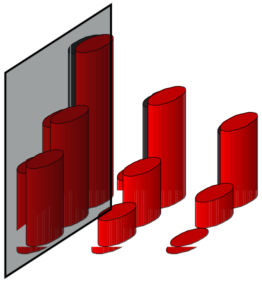
$$Y_{\nu_D}, Y_d << Y_u$$

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

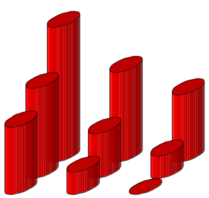
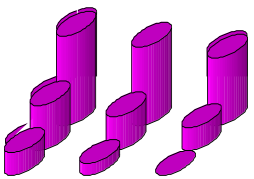
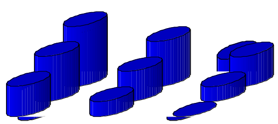
} Suppressed radiative LFV

How to obtain various Yukawas?

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

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

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

SO(10) GUT relations

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

$$Y_u \sim \begin{array}{c|ccc} & \mathbf{10}_1 & \mathbf{10}_2 & \mathbf{10}_3 \\ \hline \mathbf{10}_1 & \lambda^6 & \lambda^5 & \lambda^3 \\ \mathbf{10}_2 & \lambda^5 & \lambda^4 & \lambda^2 \\ \mathbf{10}_3 & \lambda^3 & \lambda^2 & 1 \end{array} \quad \begin{array}{l} \}\,\lambda \\ \}\,\lambda^2 \end{array}$$

$$Y_{\nu_D} \sim \begin{array}{c|ccc} & \mathbf{1}_1 & \mathbf{1}_2 & \mathbf{1}_3 \\ \hline \bar{\mathbf{5}}_1 & \lambda^6 & \lambda^5 & \lambda^3 \\ \bar{\mathbf{5}}_1 & \lambda^{5.5} & \lambda^{4.5} & \lambda^{2.5} \\ \bar{\mathbf{5}}_2 & \lambda^5 & \lambda^4 & \lambda^2 \end{array} \quad \begin{array}{l} \}\,\lambda^{0.5} \\ \}\,\lambda^{0.5} \end{array}$$

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

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

$$\underbrace{\quad\quad}_{\lambda^{0.5}} \underbrace{\quad\quad}_{\lambda^{0.5}}$$

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

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

Small $\tan\beta$

Small Y_{ν_D}

Large $U_{e3} \sim \lambda$

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

$$V_{MNS} \sim \begin{pmatrix} 1 & \lambda^{0.5} & \lambda \\ \lambda^{0.5} & 1 & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix}$$

Right-handed neutrinos

$$W = \frac{Y^{XY}}{\Lambda} \mathbf{27}_i \mathbf{27}_j \langle \overline{27}_X \rangle \langle \overline{27}_Y \rangle$$

$$X, Y = \bar{H}, \bar{C}$$

$$\Rightarrow \quad M_R = Y^{XY} \frac{\langle \overline{27}_X \rangle \langle \overline{27}_Y \rangle}{\Lambda}$$

- The same hierarchy $Y^{XY} \sim Y^H \sim Y^C$

$$M_\nu = Y_{\nu_D} M_R^{-1} Y_{\nu_D}^T \sim \begin{pmatrix} \lambda^2 & \lambda^{1.5} & \lambda \\ \lambda^{1.5} & \lambda & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix} \frac{\langle H_u \rangle^2 \Lambda}{\langle \mathbf{1}_H \rangle^2}$$

$$\frac{\Delta m^2_{solar}}{\Delta m^2_{atm}} \sim \frac{m^2_{\nu_\mu}}{m^2_{\nu_\tau}} \sim \lambda^2$$

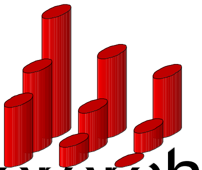
LMA for solar neutrino problem

1st Summary

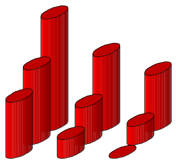
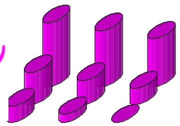
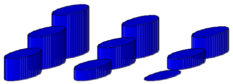
E_6 unification explains why the lepton sector has larger mixings than the quark sector.(Large $U_{e3} \sim \lambda$)

- Suppressed radiative LFV

Small Y_{ν_D} Small $\tan\beta$

- A basic Yukawa hierarchy $Y \sim Y_u$ 

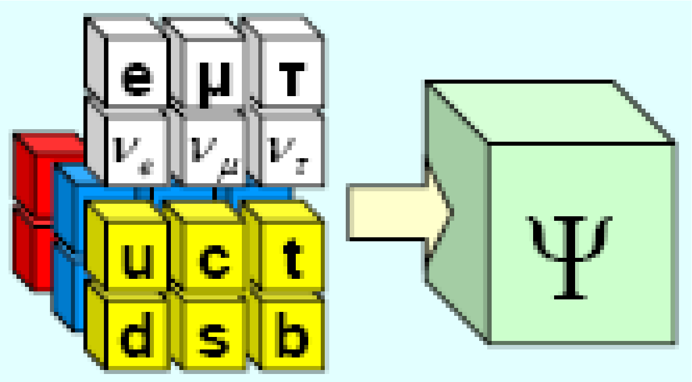
The other Yukawa hierarchies

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

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 $\mathbf{27}_1, \mathbf{27}_2$

Horizontal symmetry



All three generation quark and leptons can be unified into a single (or two) field(s)

By breaking the horizontal symmetry, realistic quark and lepton masses and mixings can be obtained.

Peculiar sfermion mass spectrum is predicted.

$$\tilde{m}_{10}{}^2 = \begin{pmatrix} m^2 & . & . \\ . & m^2 & . \\ . & . & m_3{}^2 \end{pmatrix}, \quad \tilde{m}_{\bar{5}}{}^2 = \begin{pmatrix} m^2 & . & . \\ . & m^2 & . \\ . & . & m^2 \end{pmatrix}$$

Horizontal Symmetry

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

- Origin of Yukawa hierarchy
- Semi-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

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

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

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

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

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

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

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

$$a \sim O(1)$$

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

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

Universality for all three generations is required!

E_6 unification solves these problems

N.M.02,04

- Various Yukawa hierarchies can be obtained from one basic hierarchy.

  Breaking $U(2)_H \underset{\lambda\Lambda}{\longrightarrow} SU(2)_H \underset{\lambda^2\Lambda}{\longrightarrow} X$

  gives the basic hierarchical structure.

- All the three light $\bar{\mathbf{5}}$ fields come from $\Psi(\mathbf{27}, \mathbf{2})$

  and therefore have universal sfermion masses.

  Important for suppressing FCNC sufficiently, because the mixings of $V_{\bar{\mathbf{5}}}$ are large.

Discussion

- Extension to $U(3)_H$ is straightforward. All three generation quarks and leptons are unified into a single multiplet $\mathbf{(27,3)}$
- If it is local, D term must be cared.
- Peculiar sfermion spectrum

$\Psi(\mathbf{27},\mathbf{2})$

$\mathbf{10}_1, \mathbf{10}_2$

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

Universal

Different

$\Psi(\mathbf{27},\mathbf{1})$

$\mathbf{10}_3$

Experiments

- Any mechanisms for the basic hierarchy.

  Extra dimension

  Stringy calculation

  Froggatt-Nielsen mechanism

  (Anomalous U(1))

- E_6 Higgs sector (Doublet-triplet splitting)

  Anomalous U(1) N.M.-Yamashita 02,03

  Generic interactions with O(1) coefficients.

  Orbifold breaking

$$E_6 \to SU(3)^3$$

2^{nd} 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.
- The simpler unification of quarks and leptons explains the more questions.

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

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

$\Rightarrow$ SUSY flavor problem

Predictions of E6 GUT +horizontal symmetry

Flavor physics : Kim-N.M.-Matsuzaki-Sakurai-Yoshikawa 06,08

LHC physics : Kim-N.M.-Nagao-Nojiri-Sakurai 09
Sakurai-Takayama 11

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 universal SUSY breaking

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

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

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

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

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

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

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

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)

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

m $\quad \mathbf{10}_1, \mathbf{10}_2 \quad \bar{\mathbf{5}}_1, \bar{\mathbf{5}}_2, \bar{\mathbf{5}}_3$ $\qquad$ $\mathbf{10}_3$ $\quad m_3$

$$m >> m_3 \sim O(m_W)$$

How does FCNC processes take place in this model?

flavor violating

No source of flavor violation

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

$\mathbf{10}\ :(Q,\ U_R^c,\ E_R^c)$ $\quad$ $\bar{5}\ :(L,\ D_R^c)$

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

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

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

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

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

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

Non 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

$\tau \to \mu\gamma$

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

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

$\mu \to e\gamma$

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

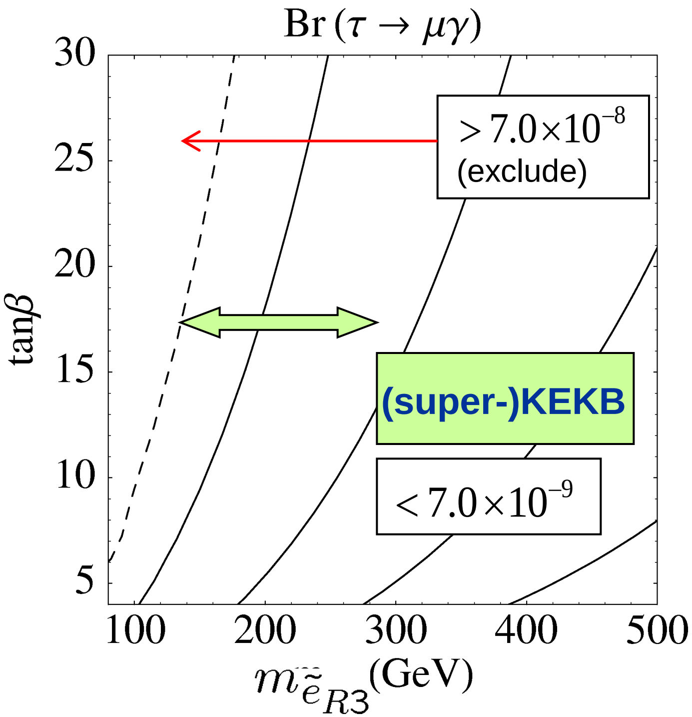
$$\tilde{\mu}_R \quad (\tilde{m}^2_{\tilde{e}_R})_{23} \quad \tilde{\tau}_R \quad (\tilde{m}^2_{\tilde{e}_R})_{31} \quad \tilde{e}_R \approx \frac{1}{m^2}\frac{(\Delta m^2)^2\lambda^5}{m_3^2}\frac{1}{m^2} \longrightarrow \frac{\lambda^5}{m_3^2}$$

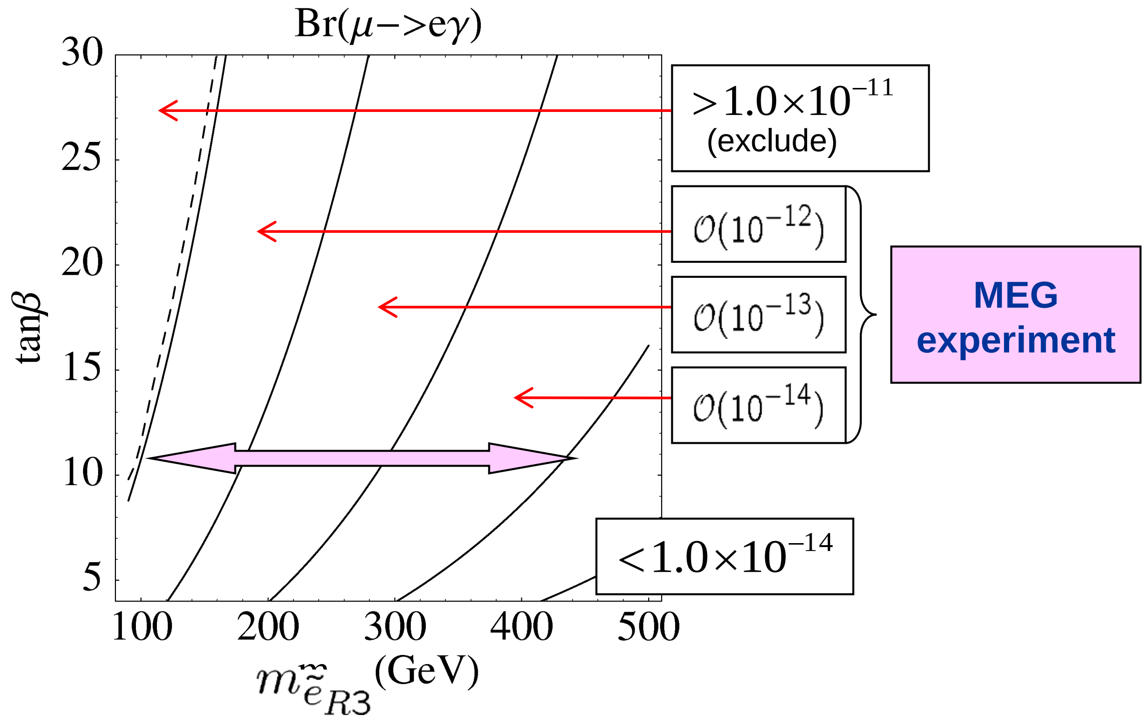
If we raise overall ~~SUSY~~ scale m …

$$\boxed{m^2 \longrightarrow \infty}$$

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?



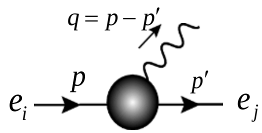


- $\tau \to \mu\gamma$ ➡ Detectable, when tanβ is large and $m_{\tilde{e}_{R3}}$<250GeV
- $\mu \to e\gamma$ ➡ Detectable if $m_{\tilde{e}_{R3}}$ <400GeV

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

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

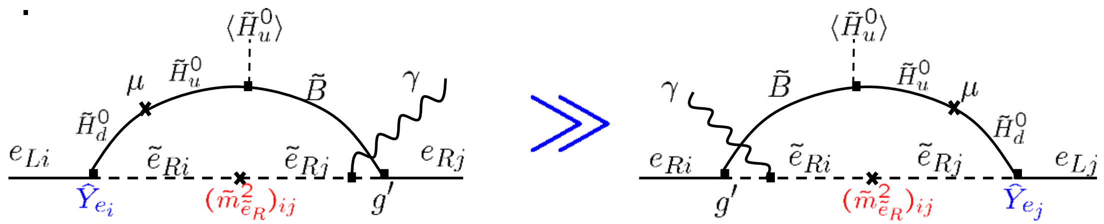
- Final state lepton has different chirality from initial one.



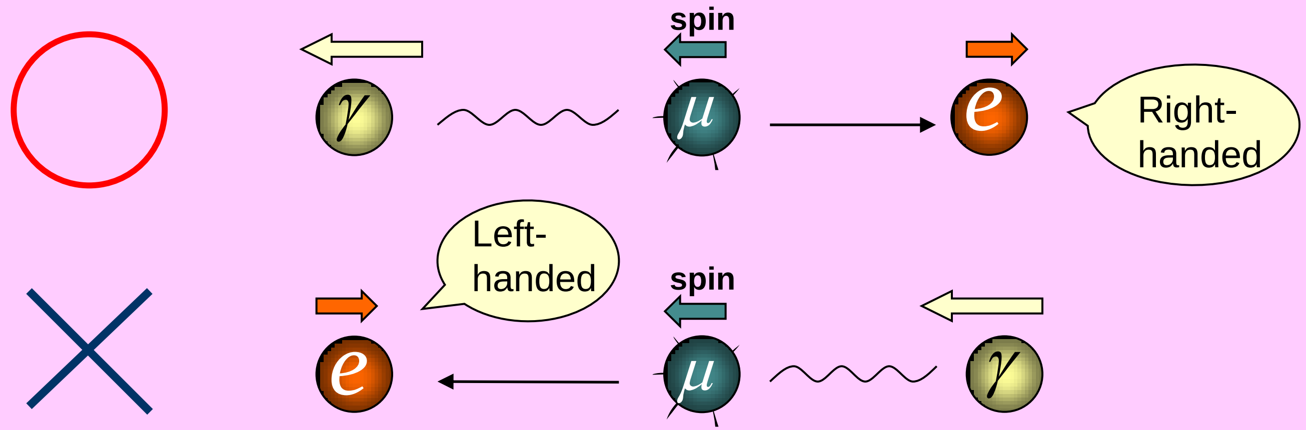
$$T = \epsilon^{*\mu}\bar{u}_i(p) i\sigma_{\mu\nu}q^\nu (A_L^{ij}P_L + A_R^{ij}P_R)u_j(p')$$

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 the RGE effects in the universal mass case.

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

- 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)
$\Delta S_{K\phi}, \Delta S_{K\eta'}$		<0.15
$A_{CP}(b \to s\gamma)$	0.006	<0.01
$A_{CP}(B \to V\gamma)$		very small
$S_{B \to K_s \pi^0 \gamma}$		very small

$(\delta_{d_R})_{23} \sim 0$

$(\delta_{d_L})_{23} \sim \lambda^2$

$(\delta_{d_R})_{23} \sim 0$

For $\tan\beta \sim 10$

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

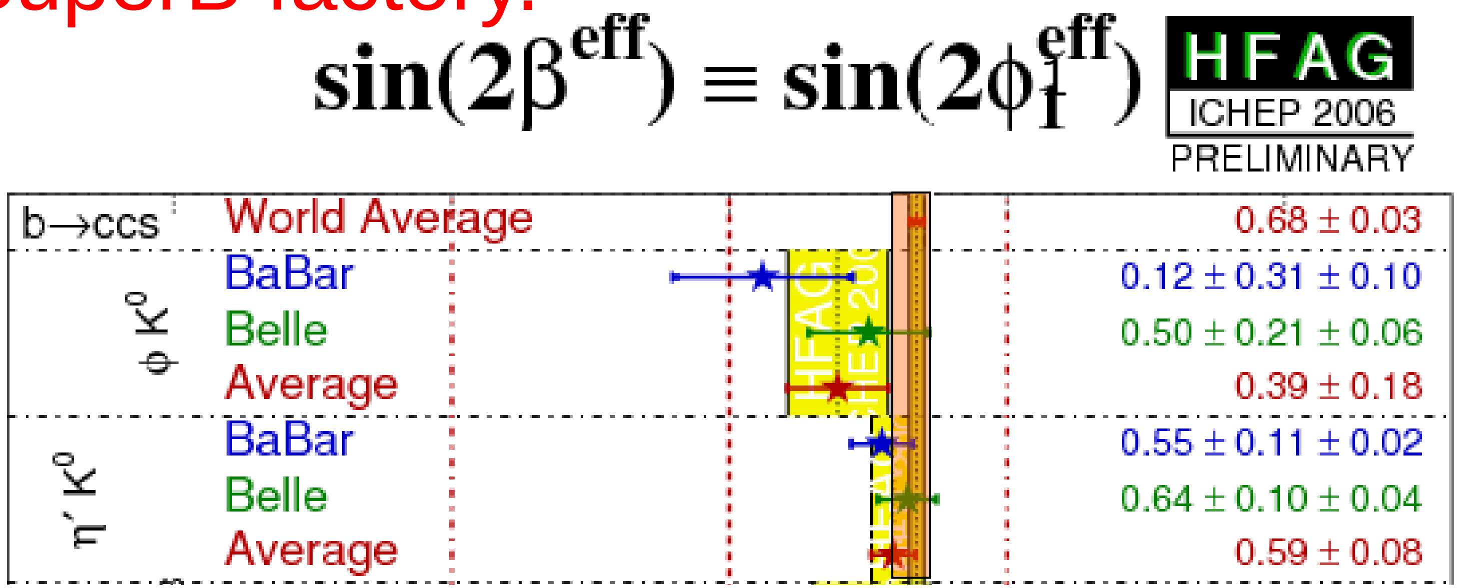
$\Delta S^{SUSY}_{\phi K_S}, \Delta S^{SUSY}_{\eta' K_S} \sim O(0.1)$ is possible.

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, $\delta_{\bar{\mathbf{5}}} \neq 0 \quad \delta_{LR} \neq 0$

  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 instability!!

LHC signatures

Kim-N.M.-Nagao-Nojiri-Sakurai 09
Sakurai-Takayama 11

- $m_0 >> m_3 \sim M_{1/2}$

  stop, sbottom, gluino…..light

  the other squark…… heavy

- production rate becomes lower

$$\boxed{p + p \to \tilde{g} + \tilde{g},} \; \tilde{g} + \tilde{q}, \tilde{q} + \bar{\tilde{q}}$$

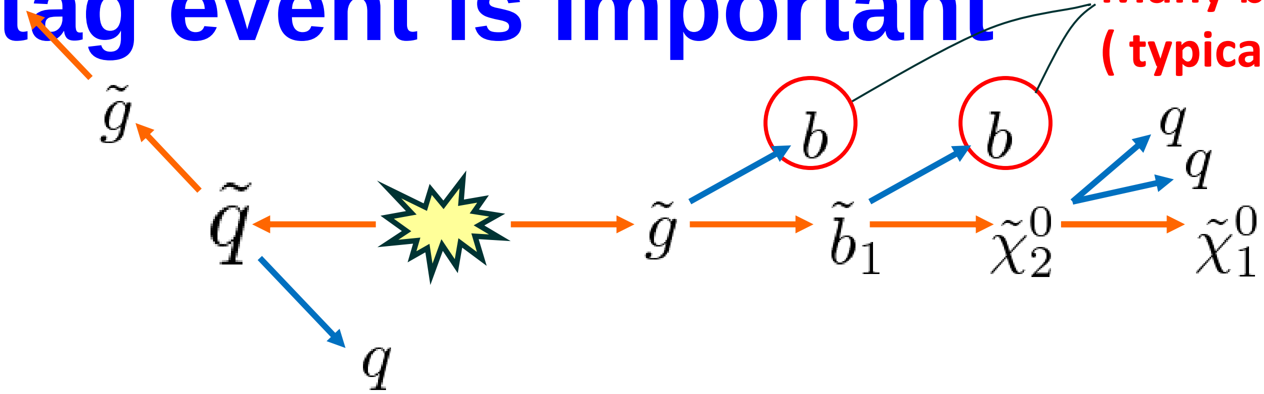
- Quark jets becomes softer.

$$\tilde{g} \to \tilde{t} + t(\to b + W)$$
$$\hookrightarrow \widetilde{W} + b$$
$$\hookrightarrow \widetilde{\chi_1} + W$$

$$\tilde{g} \to \tilde{b} + b$$
$$\hookrightarrow \widetilde{\chi_{1(2)}} + b$$
$$(\hookrightarrow \widetilde{\chi_1} + Z)$$

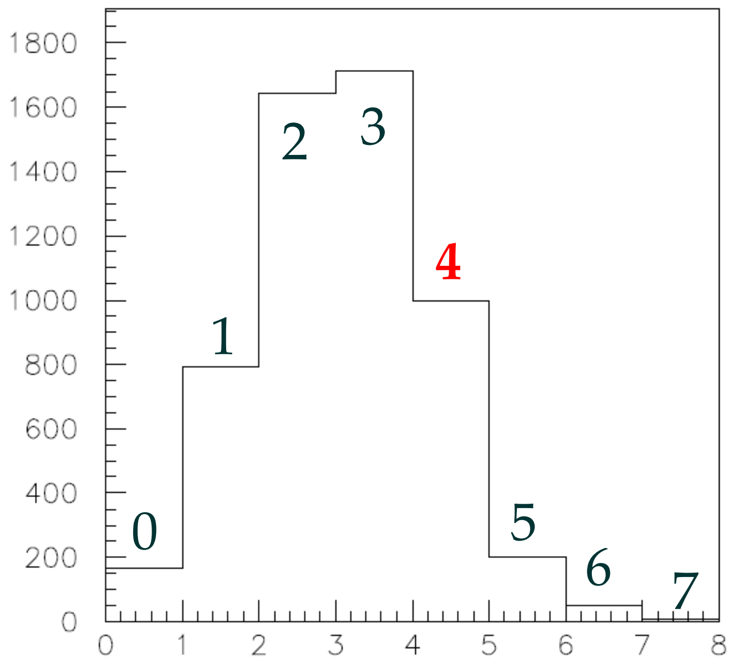
b-tag event is important

Many b jet
(typically 4)



distribution of *b* jet

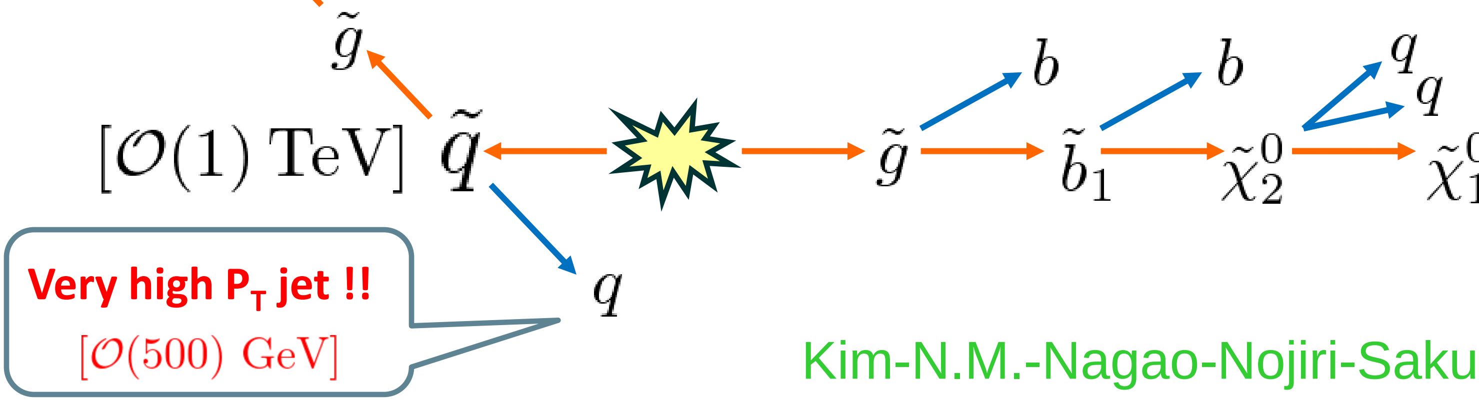
Kim-N.M.-Nagao-Nojiri-Sakurai 09



(*b* tagging efficiency 60%)

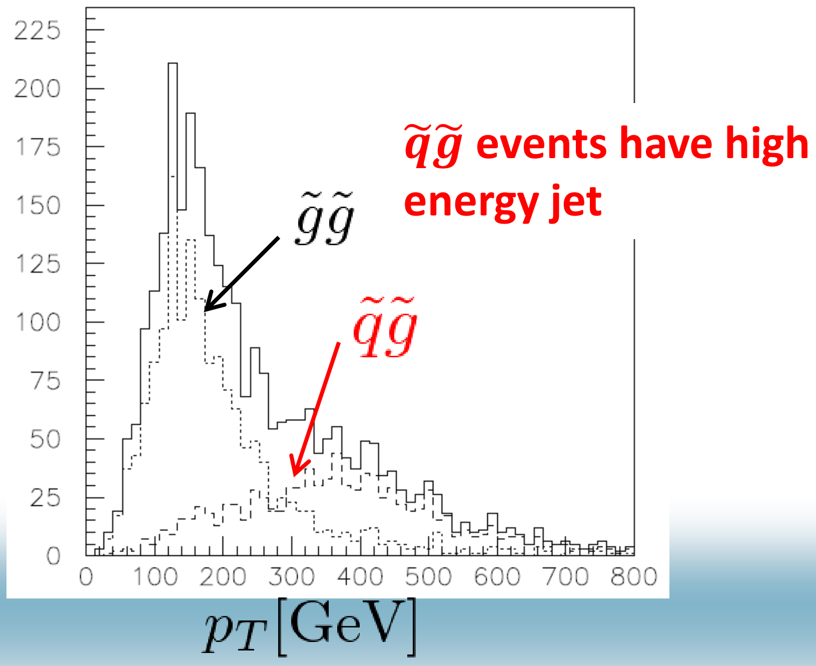
Roughly, it shows that only three generation fields are lighter than gluino

Highest P_T jet distribution

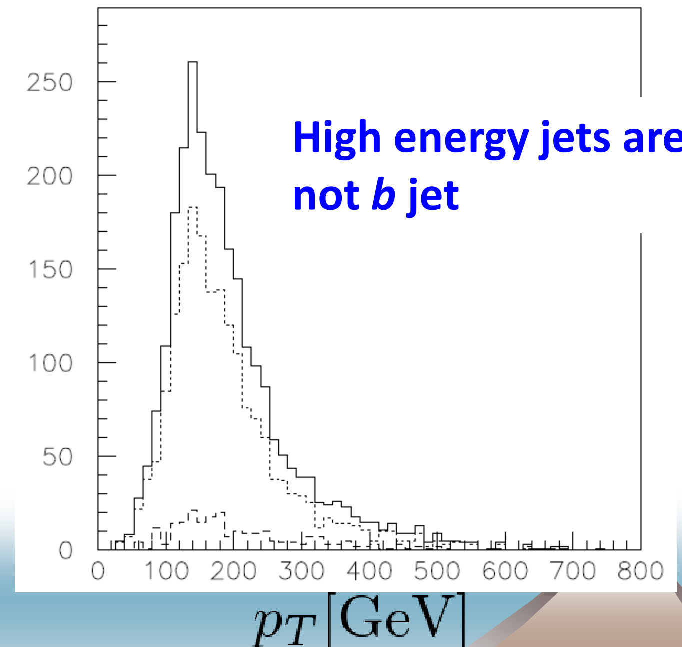


Kim-N.M.-Nagao-Nojiri-Sakurai 09

（Highest pT jet is not *b* jet ）



（Highest pT jet is *b* jet）



It shows that the first generation squark is much heavier than gluino.

7 TeV LHC with low luminosity

- b-tag+missing Et channels

  +no lepton

$$\tilde{g} \rightarrow \tilde{b} + {\color{red}b}$$

$$\hookrightarrow \widetilde{\chi_1} + {\color{red}b}$$

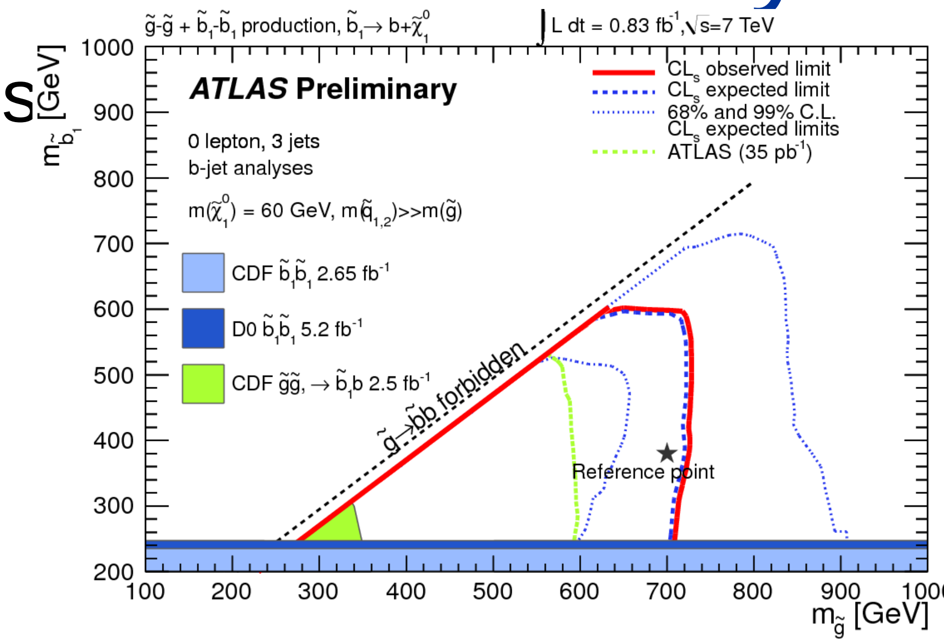
  +one lepton

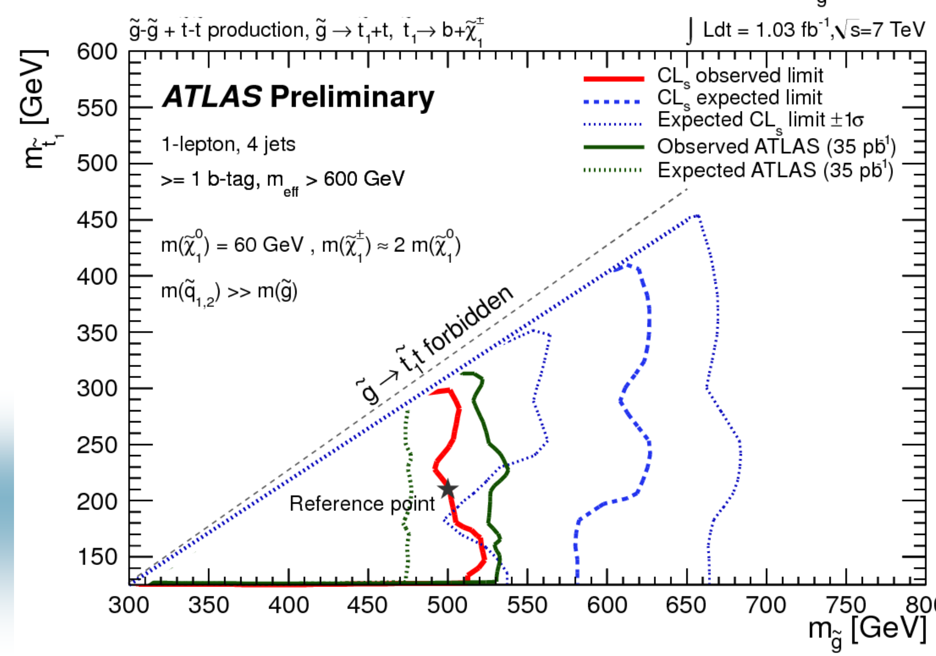
$$\tilde{g} \rightarrow \tilde{t} + t(\rightarrow {\color{red}b} + W)$$

$$\hookrightarrow \widetilde{W} + {\color{red}b} \qquad \hookrightarrow ({\color{red}l} + \nu)$$

$$\hookrightarrow \widetilde{\chi_1} + W$$

$$\hookrightarrow ({\color{red}l} + \nu)$$





7 TeV LHC with low luminosity

- b-tag+missing Et channels

  +no lepton

  $$\tilde{g} \to \tilde{b} + {\color{red} b}$$

  $$\hookrightarrow \widetilde{\chi_1} + {\color{red} b}$$

  +one lepton

  $$\tilde{g} \to \tilde{t} + t(\to {\color{red} b} + W)$$

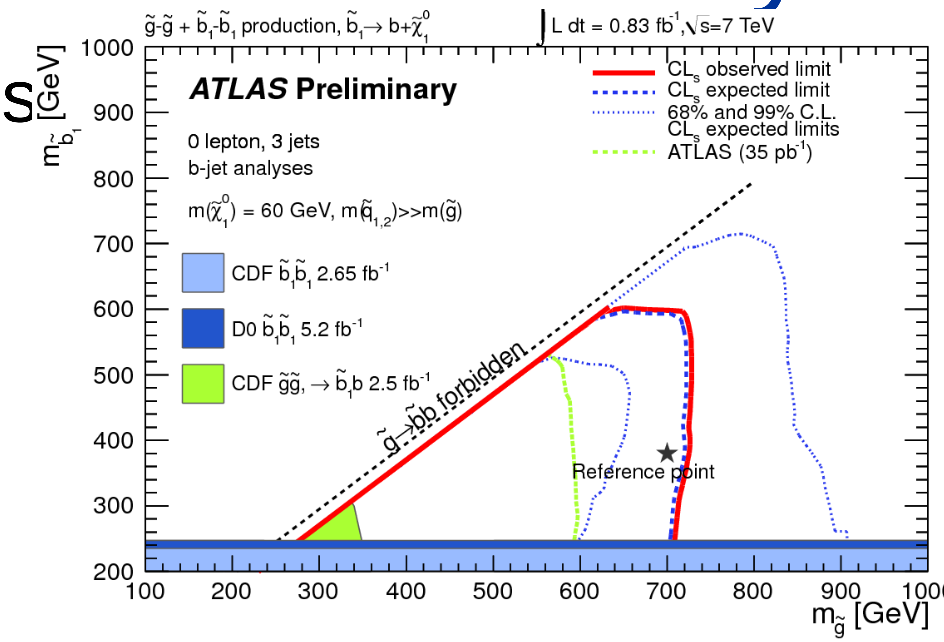
  $$\hookrightarrow \widetilde{W} + {\color{red} b} \qquad \hookrightarrow ({\color{red} l} + \nu)$$

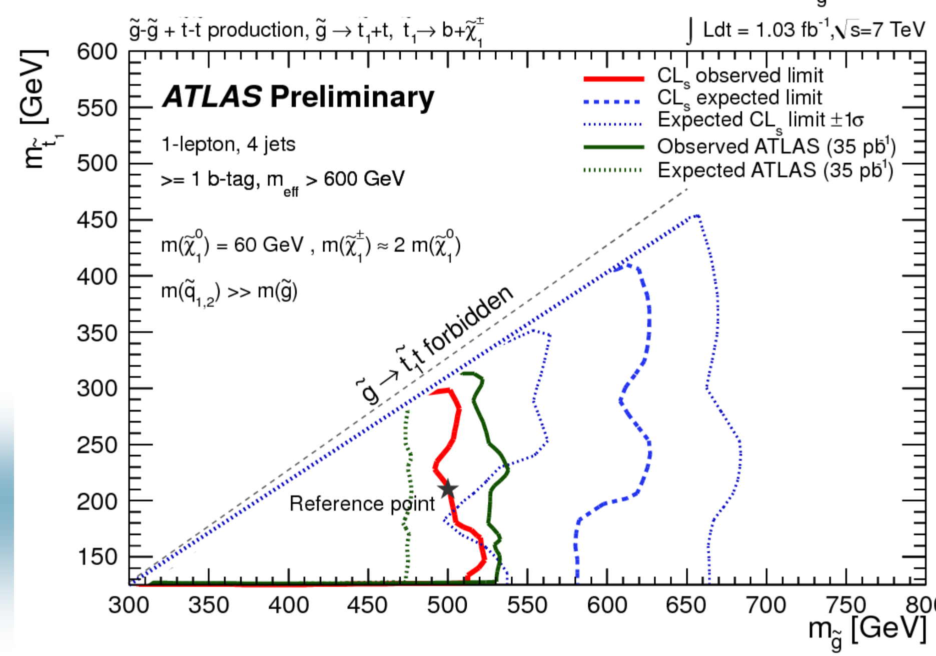
  $$\hookrightarrow \widetilde{\chi_1} + W$$

  $$\hookrightarrow ({\color{red} l} + \nu)$$

  1.2σ excess in both e and μ.

  Light stop may be appearing.





Spontaneous CP violation

Old and new type SUSY CP problems can be solved and several bonuses

SUSY CP Problem

- EDM constraints => Real SUSY parameters. Old type

$$\phi_{M_{1/2}}, \phi_\mu, \phi_B, \phi_A < 10^{-(2-3)}$$

μ problem is solved by anomalous U(1)

- Complex Yukawa couplings => CEDM New type

$$\mathrm{Im}((\delta^u_{LL})_{13}(\delta^u_{RR})_{31})) < 3 \times 10^{-7}$$

Hisano-Shimizu04
Griffith et.al.09

$$(\delta^u_{LL})_{13}(\delta^u_{RR})_{31} \sim \lambda^6 \sim 10^{-4}$$ in E6 GUT with SU(2)

$$\tilde{m}^2_{10} = \begin{pmatrix} m^2 & & \\ & m^2 & \\ & & m_3^2 \end{pmatrix} \qquad \delta^u_{LL} \equiv V_{10}\left(\frac{\tilde{m}^2_{10}}{m^2}\right)V^\dagger_{10} \sim \begin{pmatrix} 1 & \lambda^5 & \lambda^3 \\ \lambda^5 & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & O(1) \end{pmatrix}$$

$\lambda \sim 0.22$

Complex Yukawa => $V_{10} \sim V_{CKM}$ is complex generically

Additional (discrete) symmetry solves both problems

Decoupling features of SUSY CP problem

- EDM constraints from 1 loop

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

$$\delta_{\mu,A} < 10^{-(2-3)} \left(\frac{M_{SUSY}}{100\mathrm{GeV}}\right)^2$$

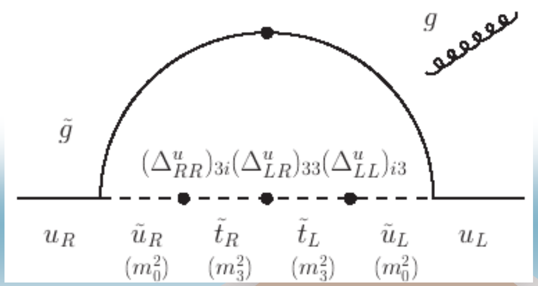
- CEDM from Hg(neutron) even if $\delta_{\mu,A} = 0$

Hisano-Shimizu '04

$$\mathrm{Im}\ (\delta_{d_L})_{13}(\delta_{d_R})_{31} < 8(24) \times 10^{-6}$$

$$\mathrm{Im}\ (\delta_{u_L})_{13}(\delta_{u_R})_{31} < 3(9) \times 10^{-7} \qquad \lambda^6 \sim 10^{-4}$$

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



Spontaneous CP violatoin in SU(2) model

- Doublets under SU(2) horizontal symmetry

$$\mathbf{27}_a, F_a, \bar{F}^a \qquad \langle \bar{F} \rangle \sim \begin{pmatrix} 0 \\ \bar{v} \end{pmatrix}, \quad \langle F \rangle \sim \begin{pmatrix} 0 \\ v e^{i\rho} \end{pmatrix}$$

$$\mathbf{27}_1 \sim \epsilon^{ab}\mathbf{27}_a\langle F_b \rangle \quad \mathbf{27}_2 \sim \mathbf{27}_a\langle \bar{F}^a \rangle \quad \mathbf{27}_3$$

$$W = (Y_H)_{ij}\mathbf{27}_i\mathbf{27}_j\mathbf{27}_H + (Y_C)_{ij}\mathbf{27}_i\mathbf{27}_j\mathbf{27}_C$$

$$\epsilon^{ab}\mathbf{27}_a\mathbf{78}_A\mathbf{27}_b\mathbf{27}_H(\cancel{\epsilon^{ab}\mathbf{27}_a\mathbf{27}_b\mathbf{27}_H}) \quad \langle \mathbf{78_A} \rangle = \mathbf{Q_{B-L}V}$$

$$\mathbf{27}_H = \mathbf{16}_H + \mathbf{10}_H + \langle \mathbf{1}_H \rangle \quad E_6 \to SO(10)$$

$$\mathbf{27}_C = \langle \mathbf{16}_H \rangle + \mathbf{10}_C + \mathbf{1}_C \quad SO(10) \to SU(5)$$

$$E_6 \text{ Higgs sector} \Rightarrow \begin{cases} H_u \sim \mathbf{10}_H \to Y_u = Y_H \\ (H_d \sim \mathbf{10}_H + \mathbf{16}_C) \end{cases}$$

Real μ and B require non-trivial discrete charge for F and $\mathbf{27}_C$.

A solution for μ problem

- Negative Higgs charges=> massless Higgs

  SUSY(holomorphic) zero mechanism
- SUSY breaking induces the non-vanishing VEV of superheavy positive charged singlet

$$W = SH_uH_d + \Lambda^2 S + \Lambda SZ$$

$$V_{SB} = A_{SHH} SH_uH_d + A_S \Lambda^2 S + \ldots$$

$$\langle S \rangle \sim \frac{A_S \Lambda^2}{M_S^2} \sim A_S$$

$$\mu \sim A_S \sim O(\tilde{m})$$

$$B\mu \sim A_{SHH} \langle S \rangle + F_S \sim O(\tilde{m}^2)$$

Additional discrete symmetry

$$W = SH_uH_d + \Lambda^2(1 + \bar{F}F)S + \Lambda SZ$$

$$V_{SB} = A_{SHH}SH_uH_d + A_S\Lambda^2 S + \ldots$$

$$\langle S\rangle \sim \frac{A_S\Lambda^2}{M_S^2} \sim A_S$$

$$\mu \sim A_S \sim O(\tilde{m})$$

Complex

$$B\mu \sim A_{SHH}\langle S\rangle + F_S \sim O(\tilde{m}^2)$$

Non trivial discrete charge for $\bar{F}F$ to forbid $S\bar{F}F$

What happens by the discrete symmetry?

$$W = (Y_H)_{ij}\mathbf{27}_i\mathbf{27}_j\mathbf{27}_H + (Y_C)_{ij}\mathbf{27}_i\mathbf{27}_j\mathbf{27}_C$$

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

$$\epsilon^{ab}\mathbf{27}_a\mathbf{78}_A\mathbf{27}_b\mathbf{27}_H \qquad \langle\mathbf{78_A}\rangle = \mathbf{Q_{B-L}V}$$

$$Y_C = \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & 0 & 0 \\ \lambda^3 & 0 & 0 \end{pmatrix} \Rightarrow \begin{pmatrix} 0 & \lambda^5 & \lambda^3 \\ \lambda^5 & 0 & 0 \\ \lambda^3 & 0 & 0 \end{pmatrix}$$ complex

SUSY zero mechanism

$\Rightarrow$ Y_u is real , Y_d is complex

$$\langle\bar{F}\rangle \sim \begin{pmatrix} 0 \\ \bar{v} \end{pmatrix}, \qquad \langle F\rangle \sim \begin{pmatrix} 0 \\ ve^{i\rho} \end{pmatrix}$$

A model with a discrete symmetry (Z_6)

Bonus 1

Ishiduki-Kim-N.M.-Sakurai09

- 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

$Y^H(\cancel{F}, \bar{F})$: real, $\quad H_u \sim 10_H \quad Y_u = Y^H$

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

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

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

A model with a discrete symmetry

- Bonus 2: small up quark mass is realized.

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

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

$$\boxed{\cancel{\epsilon^{ab}\Psi_a\Psi_b H}, \; \epsilon^{ab}\Psi_a \langle A \rangle \Psi_b H}$$

$$\langle \epsilon^{ab} F_a \rangle \Psi_b \sim \Psi_1 \qquad \langle A \rangle \propto Q_{B-L}$$

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

Too large ➔ good value!

A model with a discrete symmetry

- Bonus 3?: # of O(1) parameters =9-12

  13 physical parameters

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

- One of the relations

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

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

Interesting result(perturbation in λ)

- $V_{ub} \sim \lambda^4$ is obtained

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

$$V_{CKM} = \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda & 1 \end{pmatrix} \sim \lambda^4$$

$$A \sim 0.8, \rho, \eta \sim 0.2 - 0.4$$

This cancellation depends on the adjoint VEV. Kawase, N.M 10

(B factory measured the direction of GUT breaking?)

$$E_6 \rightarrow SO(10) \times U(1)_{V'}$$
$$E_6 \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_{V'}$$
$$E_6 \rightarrow SU(4) \times SU(2)_L \times U(1)_R \times U(1)_{V'}$$

- $|Y_b V_{cb}| = |Y_c| \rightarrow \tan\beta \sim 6$

Numerical calculation

Ishiduki-Kim-N.M.-Sakurai09

- O(1) coefficients(10 parameters)

$$a = 0.6, b = -0.5, c = -0.7, d_5 = -0.9$$

$$d_q = 0.4, d_l = -0.5, f = 1.5, g = -0.9$$

$$\beta_H = 0.9, \delta = 1.4$$

$$Y_t = 6(5) \times 10^{-1} \quad Y_b = 2(3) \times 10^{-2} \quad Y_\tau = 3(4) \times 10^{-2}$$

$$Y_c = 3(1) \times 10^{-3} \quad Y_s = 5(6) \times 10^{-4} \quad Y_\mu = 1(3) \times 10^{-3}$$

$$Y_u = 4(3) \times 10^{-6} \quad Y_d = 8(3) \times 10^{-5} \quad Y_e = 3(1) \times 10^{-5}$$

$$|V_{CKM}| = \begin{pmatrix} 1 & 2(2) \times 10^{-1} & 2(4) \times 10^{-3} \\ 2(2) \times 10^{-1} & 1 & 10(4) \times 10^{-2} \\ 20(7) \times 10^{-3} & 10(4) \times 10^{-2} & 1 \end{pmatrix}$$

$$J_{CP} = 1(3) \times 10^{-5}$$

Ref:Ross-Serna07 MSSM 2loop RGE

Heavy fields' contribution must be taken into account.

E6 Higgs sector

N.M.-Yamashita02
Ishiduki-Kim-N.M.-Sakurai 09

- E6 can be broken into the SM gauge group.
  1, Natural doublet-triplet splitting
  2, $H_u \sim \mathbf{10}_H$, $H_d \sim \mathbf{10}_H + \mathbf{16}_C$ is realized
  3, consistent with the discrete symmetry

	Ψ_a	Ψ_3	F_a	$\bar{F}^a$	H	$\bar{H}$	C	$\bar{C}$	C'	$\bar{C}'$	A	A'
E_6	$\mathbf{27}$	$\mathbf{27}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{27}$	$\overline{\mathbf{27}}$	$\mathbf{27}$	$\overline{\mathbf{27}}$	$\mathbf{27}$	$\overline{\mathbf{27}}$	$\mathbf{78}$	$\mathbf{78}$
$SU(2)_H$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\bar{\mathbf{2}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_A$	4	$\frac{3}{2}$	$-\frac{3}{2}$	$-\frac{5}{2}$	-3	2	-4	0	7	9	-1	4
Z_6	0	0	1	0	0	0	5	0	3	3	3	3

Neutrino sector

N.M.-Takayama 11

- $\bar{5}$ fields at the low energy are determined as 3 massless modes of this 3×6 matrix.

$$
\begin{array}{c}
. \\ 5_1 \\ 5_2 \\ 5_3
\end{array}
\begin{array}{c}
\begin{array}{cccccc}
\bar{5}_1{}' & \bar{5}_2{}' & \bar{5}_3{}' & \bar{5}_1 & \bar{5}_2 & \bar{5}_3
\end{array} \\
\left(\begin{array}{ccc|ccc}
0 & -Q_{B-L}\lambda^5 & 0 & 0 & \lambda^{5+r} & \lambda^{3+r} \\
Q_{B-L}\lambda^5 & \lambda^4 & \lambda^2 & \lambda^{5+r} & 0 & 0 \\
0 & \lambda^2 & 1 & \lambda^{3+r} & 0 & 0
\end{array}\right)\langle H\rangle
\end{array}
\qquad \lambda^r \equiv \frac{\langle C\rangle}{\langle H\rangle}
$$

- For lepton doublets, $\bar{5}_1{}'$ of three massless modes, $(\bar{5}_1, \bar{5}_1{}', \bar{5}_2)$, has no mixing with $\bar{5}_3$, because $Q_{B-L}=0$ for lepton doublets.
- Yukawa couplings of charged lepton in $\bar{5}_1{}'$can be obtained through $Y_C 16_i 10_1 16_C$
- Dirac neutrino Yukawa couplings of $\bar{5}_1{}'$ through $Y_H 1_i 10_1 10_H$ is vanishing because $Q_{B-L}=0$. $\longrightarrow m_{\nu_\mu}=0$ That's a problem.
- Fortunately, we have higher dimensional interactions

$$\epsilon^{ab}(\overline{27}_{\bar{H}}27_a)(27_b 27_H 27_H) \longrightarrow 1_2 10_1 10_H$$

We have many parameters on the right-handed neutrino masses.

Predictions on neutrino masses and mixings are the same as the usual E_6 GUT.

- $(\overline{27}_{\bar{H}}27_H)$ can couple with many interactions, but the effects are only for the neutrino sector in the model.

Discussion & Summary

- KM theory is naturally realized by spontaneous CP violation in E6 GUT with horizontal symmetry

  1, Real μ and B parameters are realized by introducing a discrete symmetry.

  2, The symmetry solves CEDM problem.

  $(Y_u)_{ij}$:real $(Y_d)_{ij}$:complex

  3, Predicted EDM induced by RGE effect is sizable.

  4, $V_{ub} \sim \lambda^3 \to \lambda^4, \quad |Y_c V_{bc}| = |Y_b| \to \tan\beta \sim 6$

  5, $Y_u \sim \lambda^6 \to \left(\frac{1}{3}\right)^2 \lambda^6$

  6, E6 Higgs sector consistent with the above scenario with natural realization of D-T splitting