united nations
educational, scientific
and cultural
organization

international atomic
energy agency

the
abdus salam
international centre for theoretical physics

SMR.1317 - 20

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

SUSY GRAND UNIFICATION AND CP VIOLATION

Lecture III

J.C. PATI
Department of Physics
University of Maryland
College Park, MD 20742
USA

Please note: These are preliminary notes intended for internal distribution only.

I. Preliminary Remarks

① Experimental Situation (3 Major Results)

A) $\nu_\mu - \nu_\tau$ (ν_x) Oscillation (SuperK)

$$\left.\begin{array}{l}\delta m^2_{\nu_\mu - \nu_\tau} \approx (10^{-2} - 10^{-3})\,eV^2 \\ \sin^2 2\Theta^{osc}_{\nu_\mu \nu_\tau} \approx 0.9 - 1\end{array}\right\} \Rightarrow \text{PHYSICS BEYOND THE SM.}$$

B) $Re(\epsilon'/\epsilon) = \left\{\begin{array}{l}(20.7 \pm 2.6)\times 10^{-4}\ (\text{KTeV}) \\ (15.6 \pm 2.3)\times 10^{-4}\ (\text{NA48})\end{array}\right\} \Rightarrow$ Direct $\cancel{CP}$

C) $(B_d, \bar{B}_d) \to J/\psi + K_S$

$$a_{B\bar{B}} = \left\{\begin{array}{ll}.79\,^{+.41}_{-.44} & (\text{CDF}) \\ .34 \pm .20 \pm .05 & (\text{BaBar}) \\ .58\,^{+.32}_{-.34}\,^{+.09}_{-.10} & (\text{Belle})\end{array}\right.$$

Average $= .48 \pm .16$

$\Rightarrow$ Very likely $\cancel{CP}$ in B-System

Std. CKM $\approx 0.72 \pm .10$

② Selecting The Route To Higher Unification

1. Family multiplet structure : (Y_W, Q_{em})

   All 16 in one multiplet $\Rightarrow$ G(224)/SO(10)

2. Coupling Unification $\Rightarrow$ SUSY SU(5), SO(10), String-G(224).

3. ν-oscillation : $m(\nu_\tau) \sim 1/20$ eV (Super K)

4. Some Intriguing Features of Fermion Masses & Mixings

   $m_b^0 \approx m_\tau^0$; $m(\nu_\tau)^0_{Dirac} \approx m_t^0 \Leftrightarrow$ SU(4)-Color.

   V_{bc} Small $\longleftrightarrow$ $\nu_\mu - \nu_\tau$ osc. angle Large

5. Lepto/Baryogenesis $\longrightarrow$ B-L

All of these not only favor grand unification but in fact select out a particular route to such unification based on SUSY, SU(4)-Color & L-R symmetry $\Downarrow$

String-G(224) or SO(10)

Main Result

Find an intriguing link between atmospheric ~~ν-oscillation~~ & CP violation within SUSY Grand Unification

Flavor-changing & SUSY $\not{CP}$ $\xleftrightarrow[]{K^0-\overline{K^0},\ B^0-\overline{B^0}}$ Entirely Through Fermion Mass-Matrix

Enhanced because

$$\boxed{\begin{array}{ll} a) & \text{MSSM} \longrightarrow SO(10) \text{ or String-}G(224) \\ \& \quad b) & \nu_\mu - \nu_\tau \text{ oscill. angle Large} \end{array}}$$

$\Downarrow$

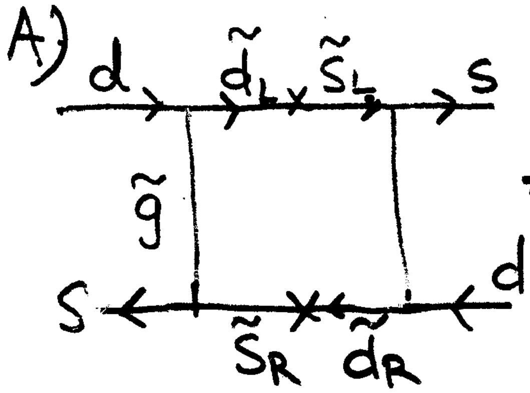
Even if flavor-viol only through Yukawa matrix

$$\left[\varepsilon_K,\ \varepsilon'_K,\ \text{Asym}\,(B\text{-}\overline{B} \to J/\psi + K_s)\right]_{SUSY}$$

$\sim$ Large departures from Standard CKM.

③ SUSY $\not{CP}$

A)



$\Rightarrow$ Potentially Large FCNC
CP-conserving (Δm_K) &
CP Violating (ε_K, ε'_K)
⊕ Generically Large $(edm)_{n,e}$

Smallness of ε_K, ε'_K etc. Need
- sufficient squark degen /and/or small mixings or small phases

$\Bigg\}$ WHY?

B) 2 Classes of Models of SUSY Breaking

Intermed. Squark Degen (ISD)

$$r^{(0)}_{ij} \equiv \frac{\tilde{m}_i^{(0)2} - \tilde{m}_j^{(0)2}}{\tilde{m}^2} \approx 10^{-2} \left(\text{String/GUT scale}\right)$$

Examples

- Anomalous $U(1)_A$ D-Term (Family Universal) + Supergravity (Non-Universal)

$\Downarrow$

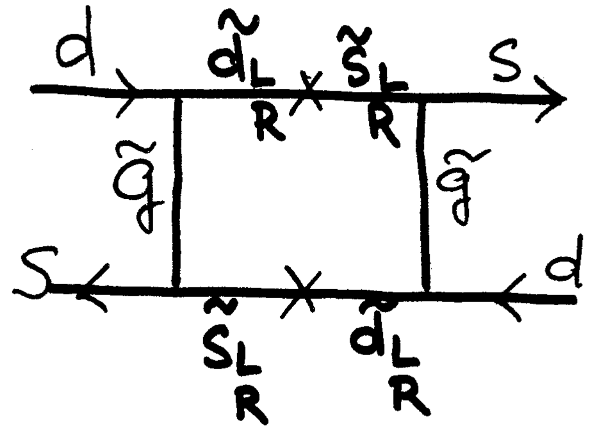
- Combined $U(1)_A$ + dilaton $\langle F_S \rangle \neq 0$ + Supergravity

Extreme Sq. Degen (ESD)

$$r^{(0)}_{ij} \lesssim 10^{-5}$$

- Supergravity + Flavor symm.
- Gauge Med.
- Gaugino Med. SUSY Br.
- Anomaly Med. SUSY Br.

III SUSY FCNC AMPLITUDES: EXPTL. LIMITS



$$\mathrm{Amp}(K^0-\bar{K}^0) \propto \alpha_s^2 \left[\Delta_{LL}^2 (\text{coeff}) + \Delta_{RR}^2 (\text{coeff}) + (\Delta_{LL})(\Delta_{RR}) (\text{coeff}) \right]$$

$$\Delta_{LL} = \frac{\tilde{d}_L \times \tilde{s}_L}{} \quad ; \quad \Delta_{RR} = \frac{\tilde{d}_R \times \tilde{s}_R}{}$$

Δ_{LL} & Δ_{RR} depend on squark and quark mass-matrices in <u>SUSY-Basis</u>,

<u>SUSY-Basis</u>: $\begin{cases} \text{quarks in physical basis //} \\ \text{gluino interactions flavor-diagonal} \end{cases}$

References:

Gabbiani et al Nuc. Phys. (1996)

Bagger et al Phys. Lett (1997)

$\boxed{\text{Ciuchini et al} \rightarrow \text{hep-ph/9808328 (1998).}}$

Hall, Kostelecky, Raby Nuc. Phys. (1986).

Transforming from gauge to SUSY-Basis

Quark Mass Matrix $\boxed{\overline{D}^0_L} M^0_d D^0_R \longrightarrow \overline{D}_L M^{Diag}_d D_R$; $D^0_L = \begin{pmatrix} d^0 \\ s^0 \\ b^0 \end{pmatrix}_L$

$$\underset{\text{PHYSICAL}}{D_{L,R}} = U^d_{L,R} \underset{\text{GAUGE BASIS}}{D^{(0)}_{L,R}} \quad ; \quad \boxed{U^d_L M^0_d (U^d_R)^{-1} = M^{Diag}_d}$$

Instructive to consider only 1st 2 Families

$$U^d_{L,R} = e^{i\zeta_{L,R}} \begin{bmatrix} \cos\theta_d \, e^{i\alpha} & \sin\theta_d \, e^{-i\delta} \\ -\sin\theta_d \, e^{i\delta} & \cos\theta_d \, e^{-i\alpha} \end{bmatrix}_{L,R}$$

$$\Downarrow$$

$$U^d_L \begin{array}{c} \begin{array}{cc} \tilde{d}^{(0)}_L & \tilde{s}^{(0)}_L \end{array} \\ \begin{bmatrix} m^{(0)\,2}_1 & \Delta^{(0)}_{12} \\ \Delta^{(0)*}_{12} & m^{(0)\,2}_2 \end{bmatrix} \end{array} (U^d_L)^{-1} = \begin{array}{cc} & \begin{array}{cc} \tilde{d}_L & \tilde{s}_L \end{array} \\ \begin{array}{c} \tilde{d}^*_L \\ \tilde{s}^*_L \end{array} & \begin{bmatrix} m^2_1 & \Delta_{12} \\ \Delta^*_{12} & m^2_2 \end{bmatrix} \end{array}$$

GAUGE BASIS $\longrightarrow$ SUSY Basis

$$\boxed{\tilde{D}_{L,R} = U^d_{L,R} \tilde{D}^{(0)}_{L,R}}$$

$$\boxed{(\Delta_{12})_{\substack{LL \\ RR}} = \Big[\left(m^{(0)\,2}_2 - m^{(0)\,2}_1\right) c_d \, s_d \, e^{i(\delta-\alpha)} + c^2_d |\Delta^0_{12}| \, e^{i(2\alpha+\phi_{12})} \left\{ 1 - \tan^2\theta_d \, e^{-2i(\alpha+\delta+\phi_{12})} \right\} \Big]_{\substack{LL \\ RR}}}$$

$c_d = \cos\theta_d$; $s_d = \sin\theta_d$

$$(\Delta_{12})_{\substack{LL\\RR}} = \Big[\left(m_2^{(0)^2} - m_1^{(0)^2}\right) c_d s_d \, e^{i(\delta-\alpha)} + c_d^2 \, |\Delta_{12}^0| \, e^{i(2\alpha+\phi_{12})} \left\{ 1 - \tan^2\theta_d \, e^{-2i(\alpha+\delta+\phi_{12})} \right\} \Big]_{LL/RR}$$

Note even if $\Delta_{12}^0 = 0$, 1st term exists for ISD; phase determined by quark mass matrix

Exptl. Constraints

Ciuchini et al (98)
QCD (NLO) + Lattice

Re K^0-$\bar{K}^0$

$$\left| \mathrm{Re}\,(\Delta_{12})_{LL}(\Delta_{12})_{RR}/\tilde{m}^4 \right| \lesssim 0.8\times10^{-6} \left(\tilde{m}/500\,\mathrm{GeV}\right)^2$$

$$\left| \mathrm{Re}\,(\Delta_{12})^2_{LL}/\tilde{m}^4 \right| \lesssim (0.5-2)\times10^{-3} (\rho)^2$$

Im K^0-$\bar{K}^0$

$$\boxed{\left| \mathrm{Im}(\Delta_{12})_{LL}(\Delta_{12})_{RR}/\tilde{m}^4 \right| \lesssim 1.5 \times10^{-8} (\rho^2)}$$

$$\left| \mathrm{Im}\,(\Delta_{12})^2_{LL}/\tilde{m}^4 \right| \lesssim (1-4)\times10^{-6} \rho^2$$

For $x \equiv m^2_{\tilde{g}}/m^2_{\tilde{q}} = 0.5$

Most stringent constraint satisfied if

$$\boxed{\begin{array}{l} \text{(i) } r^{\Delta(0)} \equiv \Delta_{12}^0/\tilde{m}^2 < 10^{-4}\rho \\ \text{(ii) } \phi_{LR}^{\mathrm{eff}} = \left|(\delta_L-\alpha_L)+(\delta_R-\alpha_R)\right| \lesssim 0.4\times10^{-2}\rho^2 \end{array}}$$

with $r_{12}^{m(0)} \equiv \left|m_1^{(0)2} - m_2^{(0)2}\right|/\tilde{m}^2 \approx 10^{-2}$ (ISD).

Thus for Intermed. Squark degen: $r^{m(0)} \approx 10^{-2}$
need to understand why;

Ⓐ $r_{ij}^{\Delta(0)} \equiv \Delta_{ij}^{(0)}/\tilde{m}^2 < 10^{-4}$

Ⓑ $\Phi_{eff}^{\tilde{d}\tilde{s}} = |(\delta_L - \alpha_L) + (\delta_R - \alpha_R)| \lesssim .4 \times 10^{-2} \rho^2$

Soln to Ⓐ

Flavor symmetries, suggested by a Class of Explicit String Solns.

Soln to Ⓑ

The Problem takes a different Complexion in the presence of 3 Families

$\Updownarrow$

NATURAL Soln. in the Context of L-R Gauge Symmetry & Hierarchical Realistic Fermion Mass matrix in the Context of G(224) / SO(10)

Solns. To String Theory (Free Fermionic Construction)
A set of Boundary Conditions

$$\downarrow$$

$$(N=1 \text{ SUSY}) \times [\mathcal{G} = SU(5)\times U(1) \text{ or } G(224) \text{ or } G(2213), \ldots] \times \boxed{G_{Flavor}} \times G_{Hidden}$$

(3 chiral Families + Higgs + A Host of massless states (mixed charges) + Hidden Matter)

A Concrete Soln $\quad \downarrow \quad$ e.g. Faraggi (92)

$$\{G(2213) = [SU(2)_L \times (I_{3R}) \times (B-L) \times SU(3)^c]\} \times \{U(1)^6\} \times G_H$$

$$\downarrow$$

$U(1)^6 \rightarrow$ One one anomalous $U(1)_A$ + Non-Anomalous $U(1)_\alpha$

$$\downarrow$$

$$D_A = [K_A + \Sigma Q_A^K |\chi_K|^2 + \underset{\substack{\uparrow \\ \text{Fayet-Iliopoulos Term}}}{\xi}]$$

$$D_\alpha = [K_\alpha + \Sigma Q_\alpha^K |\chi_K|^2]$$

SUSY Preserved if, $\boxed{\langle D_A \rangle = \langle D_\alpha \rangle = 0; F_i = 0}$

Dine, Seiberg, Witten // Atick, Sen, Dixon //

$$\boxed{\xi = \frac{g^2 \, Tr Q_A}{192\pi^2} M_{Pl}^2} \qquad M_{Pl} = 2\times 10^{18} \text{ GeV}$$

$\boxed{\text{Typically } Tr Q_A \approx 50\text{-}100}$

$$\approx 10^{-2} M_{Pl}^2 \; (>0)$$

15

IV String-Flavor Symmetries & Suppression of $r_{12}^{\Delta(0)} = \Delta^0_{12}(\tilde{d}_{L(R)} \to \tilde{s}_{L(R)})/\tilde{m}^2 < 10^{-4}$

A Flavor symm. distinguishing e versus μ-Families would Forbid Δ^0_{12}.

How good is the forbiddeness? Flavor Symm. Breaking?

Flavor Symmetries do arise in string solns.

For Concreteness, consider a class of string-solns. (semi-realistic) A. Faraggi (93) Faraggi, JCP (97)

$\to$ 3 Families : $G_{st} = [SU(2)_L \times I_{3R} \times (B-L) \times SU(3)^c] \times \boxed{U(1)^6} \times \ldots$

Flavor symm

	Q_1	Q_2	Q_3	$Q_{12} = Q_1 - Q_2$	$Q_\psi = Q_1 + Q_2 - 2Q_3$	$Q_A = Q_1 + Q_2 + Q_3$
$\tau(\underset{\sim}{16})$	$1/2$	0	0	$1/2$	$1/2$	$1/2$
$\mu(\underset{\sim}{16})$	0	$1/2$	0	$-1/2$	$1/2$	$1/2$
$e(\underset{\sim}{16})$	0	0	$1/2$	0	-1	$1/2$

$\therefore \boxed{\tilde{d}_L \tilde{s}_L^+}$ has $\boxed{Q_\psi = -3/2 \; ; \; Q_{12} = +1/2}$

Faraggi, JCP, Nucl. Phys. (98)

SUSY Breaking Through $U(1)_A$ in string solns.

$$D_A = \left[K_A - |\Phi_{45}|^2 + |\bar{\Phi}_{45}|^2 + \cdots \xi_A\right]$$

$$D_{12} = \left[K_{12} + \sum Q^i_{12}\ |\phi^i|^2\right]$$

$$D_{123} = \left[K_{123} + \sum Q^i_{123}\ |\phi^i|^2\right.$$

SUSY Preserved if $m(\Phi_A, \Phi_{\bar{A}}) = 0$

$$\{\Phi_{45}, \langle\Phi_1\rangle, \langle\Phi_2\rangle \cdots\} = O(\sqrt{\xi}) \approx M_{st}/(10 \text{ to } 20)$$

$\downarrow$

SUSY Pres. with $F_i, D_\alpha = 0$

But if $W \supset m\,\Phi_{45}\,\bar{\Phi}_{45}$ $(m \neq 0)$

$\Rightarrow$ SUSY Broken, Found m is generated:

$$m \sim \left(\frac{\langle\Phi_i\rangle}{M_{st}}\right)^4 \frac{\langle T\bar{T}\rangle}{M_{st}} \sim (\tfrac{1}{2} - 50)\,\text{TeV}$$

$\Uparrow$

m is suppressed compared to string scale by $U(1)^6$.

$\Rightarrow$ THUS A NATURAL REASON WHY

$$\boxed{M_{SUSY} \sim 10^{-15} M_{Pl}}$$

16

$U(1)^6$ break by VEV's of a set of fields

$$\{\langle\Phi_a\rangle\} \sim \mathcal{O}(\sqrt{\xi}) \approx M_{st}/(10 \text{ to } 20)$$

$\rightarrow$ Cancel Fayet-Iliopoulos term ξ, Keeping $F_i, D_\alpha = 0$

Dine, Seiberg, Witten // Attick, Dixon, Sen

Choice of set $\{\langle\Phi_a\rangle\}$ not unique

$\tilde{d}^0_L - \tilde{s}^0_L$ mixing $(\text{mass})^2 \longrightarrow$ Kahler Potential.

$$\int d^4\theta \, (q^0_{d_L} q^{0\dagger}_{s_L})\left(\frac{\chi\chi^\dagger}{M_{Pl}^2}\right)\sum_{m,n} a^{mn}_{ij} \left(\Phi_i/M_{Pl}\right)^m \left(\Phi_j^\dagger/M_{Pl}\right)^n$$

$$(F_\chi \neq 0)$$

Can verify that owing to $U(1)^6$ flavor symm, no such term can arise at least for $(m+n) \lesssim 5$ // $\langle\Phi_i/M_{Pl}\rangle \sim \frac{1}{10}$; $\frac{|F_\chi|^2}{M_{Pl}^2} \sim 10^{-2}\tilde{m}^2$

$$\Rightarrow \boxed{r^{\Delta(0)}_{12} \lesssim 10^{-7}} \quad \left(\underline{\text{regardless of choice of } \{\langle\Phi_a\rangle\}}\right).$$

Likewise, $\tilde{d}_R - \tilde{s}_R$, $\tilde{d}_L - \tilde{b}_L$, $\tilde{d}_R - \tilde{b}_R$, $\tilde{s}_L \leftrightarrow \tilde{b}_L$, $\tilde{s}_R \leftrightarrow \tilde{b}_R$ and chirality flipping $\tilde{d}_L \leftrightarrow \tilde{s}_R$, $\tilde{d}_R \leftrightarrow \tilde{s}_L$ $\rightarrow$ Extremely tiny or Zero, near String or GUT-scale.

Although no particular string soln can be taken seriously at present, flavor symm. arise rather generically ....

Same Flavor symmetries $U(1)^6$

ensure → 1) proton longevity (Suppress $d=5$ / $d=4$) JCP ('98)

2) $\boxed{A\text{-terms} = 0}$ at string/GUT scale

Non-Univ. Piece

Induced radiatively by Yukawa Couplings.

3) Hier. Yukawa Couplings (Faraggi 93-94)

Assume true ground state possesses flavor Symm as above which <u>strongly suppress</u> squark-mixing in <u>gauge basis</u> (Chirality Preserving & Flipping)

$$\boxed{\tilde{q}^{i(0)}_{\substack{L\\R}} \leftrightarrow \tilde{q}^{j(0)}_{\substack{L\\R}}} \; ; \; \boxed{\tilde{q}^{i(0)}_{L} \rightarrow \tilde{q}^{j(0)}_{R}} \rightarrow \text{"0"}$$

String/GUT scale

→ $\boxed{\text{ENORMOUS REDUCTION OF PARAMETERS}}$

→ Barring Possible small diagonal mass-splittings $\sim 10^{-2}$ (ISD), SUSY Breaking is Flavor-preserving

⇓

STUDY SUSY $\cancel{CP}$ In This class of models.

B. Complexification : CP Violation

- Expect parameters $\eta, \varepsilon, \sigma$ etc. to be in general complex
- Complexification would preserve the successes of the scheme, if, for example,

Keep real parts within (say) 20% of values given above, preserving relative signs of real parts (e.g. $\mathrm{Re}\,\varepsilon < 0$, $\mathrm{Re}\,\eta > 0$, $\mathrm{Re}\,\sigma > 0$) and phases ~ (1/10 − 1/3) (say)

$$\eta \pm \varepsilon \to |\eta \pm \varepsilon| \quad \text{etc.}$$

Example of a complex set

Real	Complex
$\sigma = 0.11$	$\sigma = 0.1 - 0.012\,i$
$\epsilon = -0.095$	$\epsilon = -0.0954$
$\eta = 0.151$	$\eta \simeq 0.12 - \boxed{0.05\,i}$
$\eta' \simeq 4 \times 10^{-3}$	$\eta' \simeq 3 \times 10^{-3}$

Fit & successes of predictions preserved.

$\therefore$ Take Gross pattern seriously, allowing parameters to have sizable phases.

Minimal Higgs ($45_H, 16_H, \overline{16}_H, 10_H \parallel S, S'$)

$$\mathcal{L}_{yuk} = h_{33}\, 16_3\, 16_3\, 10_H \quad \Rightarrow \quad \begin{array}{l} m_b^0 \approx m_\tau^0 \\ m_t^0 \approx (m_{\nu_\tau}^0)_{Dirac} \end{array}$$

$$1 \leftarrow h_{33}$$

$$\sigma \leftarrow + h_{23}\, 16_2\, 16_3\, 10_H (S/M) \quad \rightarrow \text{SYMM. Mixing}$$

$$\varepsilon \leftarrow + a_{23}\, 16_2\, 16_3\, 10_H \cdot \underset{\propto B-L}{45_H}/M \quad \Rightarrow \begin{array}{l} \text{ANTI SYM} \\ m_\mu^0 \neq m_s^0 \end{array}$$

$$\hat{\eta} \leftarrow + g_{23}\, 16_2\, 16_3\, 16_H^{(d)} \cdot 16_H/M \quad \Rightarrow \text{CKM} \neq 1\!\!1$$

$$U = \begin{array}{cc} c & t \end{array} \quad U = \begin{pmatrix} 0 & \varepsilon+\sigma \\ -\varepsilon+\sigma & 1 \end{pmatrix} m_U^{(0)} \; ; \; D = \begin{pmatrix} 0 & \varepsilon+\eta \\ -\varepsilon+\eta & 1 \end{pmatrix} m_D^0 \quad \begin{array}{cc} s & b \end{array}$$

$$N_{Dirac} = \begin{pmatrix} 0 & -3\varepsilon+\sigma \\ 3\varepsilon+\sigma & 1 \end{pmatrix} m_U^0 \quad (\nu_\mu, \nu_\tau) \; ; \; L = \begin{pmatrix} 0 & -3\varepsilon+\eta \\ 3\varepsilon+\eta & 1 \end{pmatrix} m_D^0 \quad (\mu, \tau)$$

Note quark $\rightarrow$ Lepton Correlation

$$\varepsilon \rightarrow -3\varepsilon \; ; \; \sigma \rightarrow \sigma \, , \; \eta \rightarrow \eta \, , \; 1 \rightarrow 1$$

Up $\rightarrow$ down correlation

$$\varepsilon \rightarrow \varepsilon \, , \; 1 \rightarrow 1 \, , \; \sigma \rightarrow \eta = \hat{\eta} + \sigma$$

$$m_U^0 \rightarrow m_D^0$$

Dirac Masses (3 Families)

$$U = \begin{pmatrix} 0 & \epsilon' & 0 \\ -\epsilon' & 0 & \epsilon+\sigma \\ 0 & -\epsilon+\sigma & 1 \end{pmatrix} m_U^0 \; ; \; D = \begin{pmatrix} 0 & \epsilon'+\eta' & 0 \\ -\epsilon'+\eta' & 0 & \epsilon+\eta \\ 0 & \epsilon+\eta & 1 \end{pmatrix} m_D^0$$

$$N = \begin{pmatrix} 0 & -3\epsilon' & 0 \\ 3\epsilon' & 0 & -3\epsilon+\sigma \\ 0 & 3\epsilon+\sigma & 1 \end{pmatrix} m_U^0 \; ; \; L = \begin{pmatrix} 0 & \epsilon'+\eta' & 0 \\ -\epsilon'+\eta' & 0 & -3\epsilon+\eta \\ 0 & +3\epsilon+\eta & 1 \end{pmatrix} \times m_D^0$$

---

2 New param (ϵ', η'), but 5 new Observables just in (q, ℓ) System $\Rightarrow$ 3 New predictions for (q,ℓ) // With $\epsilon' = 0$ $\rightarrow m_u \rightarrow 0$

ν Majorana Masses

$$M_R^\nu = \begin{pmatrix} z & 0 & \omega \\ 0 & 0 & y \\ \omega & y & 1 \end{pmatrix} M_R$$

Saw before,

$M_R \approx (1/2 - 1) \times 10^{15}$ GeV

Expect $y \sim 1/10$

---

4 Fermion Masses & Mixings Within a G(224) / SO(10) Framework

Babu, JCP, Wilczek (99)

Predictions	Obs. Values
1) $m_b(M_X) \approx m_\tau(M_X) \Rightarrow m_b^{Phys} \approx 4.7\,\mathrm{GeV}$	4.5 GeV
2) $(m_{\nu_\tau})^{Dirac}(M_X) \approx m_t(M_X) \Rightarrow \boxed{m(\nu_L^\tau) \sim 1/20\,\mathrm{eV}}$ SU(4)-color	$(1/15 - 1/30)\,\mathrm{eV}$
3) $V_{cb} \approx 0.043$ $\Updownarrow$	$0.040 \pm .002$
4) $\sin^2 2\Theta^{osc}_{\nu_\mu \nu_\tau} \approx \boxed{0.85-0.96}$	$(0.9 - 1.0)$
5) $\Theta_{cabibbo} \approx 0.22$	0.21
6) $m_d \approx 8\,\mathrm{MeV}$	$9 \pm 2\,\mathrm{MeV}$
7) $V_{ub}/V_{cb} \approx 0.07$	$0.09 \pm .02$
8) $\nu_e - \nu_\mu$ — Small Angle MSW (Generic)	Disfavored (2σ)
$\nu_e - \nu_\mu$ — Large " " Possible	Somewhat Favored

All Seven Good to Within 10% !

All Correlated with the Group Theory of G(224) / SO(10)

Consider a Complex Hierarchical Mass Matrix

$$M_u = \begin{array}{c|ccc} & u_R & c_R & t_R \\ \hline \bar{u}_L & 0 & \epsilon' & 0 \\ \bar{c}_L & -\epsilon' & \zeta_{22} & \sigma+\epsilon \\ \bar{t}_L & 0 & \sigma-\epsilon & 1 \end{array} \; M_u^0 \; ; \quad M_d = \begin{array}{ccc} d_R & s_R & b_R \\ \hline 0 & \eta'+\epsilon' & 0 \\ \eta'-\epsilon' & \zeta_{22} & \eta+\epsilon \\ 0 & \eta-\epsilon & 1 \end{array} \times M_d^0$$

$$|\epsilon, \eta, \sigma| \sim O(1/10), \quad \eta' \approx (3 \text{ to } 4) \times 10^{-3}$$

$$|\zeta_{22}| \lesssim |\eta^2 - \epsilon^2| \; ; \; |\epsilon'| \sim 10^{-4} \sim 1/30 \, |\eta'|$$

Diagonalize & Choose phases so that V_{CKM} has Wolfenstein form (V_{ub}, V_{td} Complex, Rest $\approx$ Real)

$$M_d^{Diag} = (X_L^d)^\dagger M_d (X_R^d)$$

$$M_u^{Diag} = (X_L^u)^\dagger M_u (X_R^u)$$

$$
X_L^d \approx \begin{bmatrix} e^{-i\phi_{\eta-\varepsilon}} & \left|\frac{\eta'}{X_d}\right| e^{-i(\phi_{\eta-\varepsilon}+\zeta_{us})} & \eta' |\eta-\varepsilon|\, e^{i(\zeta_{33}^d-\phi_{\eta-\varepsilon})} \\ -|\eta'/X_d|\, e^{i\phi_{\eta+\varepsilon}} & e^{i(\phi_{\eta+\varepsilon}+\phi_{2d}-\zeta_{us})} & |\eta+\varepsilon|\, e^{i(\phi_{\eta+\varepsilon}+\zeta_{33}^d)} \\ |\eta'/X_d|\, e^{i(\phi_{2d})} |\varepsilon+\eta| - \eta' |\eta-\varepsilon| & -|\eta+\varepsilon|\, e^{i(\phi_{2d}-\zeta_{us})} & e^{i\zeta_{33}^d} \end{bmatrix}
$$

$$
X_R^d \approx \begin{bmatrix} e^{i(\phi_{\eta+\varepsilon}+\phi_{2d})} & \left|\frac{\eta'}{X_d}\right| e^{i(\phi_{\eta+\varepsilon}+\phi_{2d}-\zeta_{us})} & \eta' |\eta+\varepsilon|\, e^{i(\phi_{\eta+\varepsilon}+\zeta_{33}^d)} \\ -\left|\frac{\eta'}{X_d}\right| e^{-i\phi_{\eta-\varepsilon}} & e^{-i(\phi_{\eta-\varepsilon}+\zeta_{us})} & |\eta-\varepsilon|\, e^{-i(\phi_{\eta-\varepsilon}-\zeta_{33}^d)} \\ |\eta'/X_d|\, |\eta-\varepsilon| & -|\eta-\varepsilon|\, e^{-i\zeta_{us}} & e^{i\zeta_{33}^d} \end{bmatrix}
$$

$$\phi_{\eta\pm\varepsilon} \equiv \arg(\eta\pm\varepsilon)$$

$$X_d \equiv -|\varepsilon^2-\eta^2| + |\zeta_{2d}|\, e^{-i(\phi_{\eta+\varepsilon}+\phi_{\eta-\varepsilon}-\phi_{\zeta_{2d}})}$$

$$\phi_{2d} \equiv \arg X_d$$

ζ_{us}, ζ_{33}^d determined by η, ε etc.

Similarly, $X_{L,R}^u$ $(\eta\to\sigma,\ \eta'\to 0)$

The CKM elements in Wolfenstein-Basis

$$V_{ud} \approx V_{cs} \approx V_{tb} \approx 1$$

$$V_{us} \approx \left| |\eta'/x_d| - |\varepsilon'/x_u| e^{i\Omega} \right| \approx -V_{cd}$$

$$V_{cb} \approx \left| e^{i(\gamma - \phi_{2u})} \left\{ |\eta+\varepsilon| - |\sigma+\varepsilon| e^{i(\phi_{\sigma+\varepsilon} - \phi_{\eta+\varepsilon})} \right\} \right|$$

$$\approx -V_{ts}$$

$$V_{ub} \approx \Big[\eta' |\eta-\varepsilon| - |\varepsilon'/x_u| \, |\eta+\varepsilon| e^{i(\gamma - \phi_{2u})} + |\varepsilon'/x_u| \, |\sigma+\varepsilon| \, e^{i(\phi_{2u} - \delta)} \Big] \times$$

$$\times \, e^{i[\Omega(1+\beta_\Omega) - \zeta_{cb}]}$$

$$V_{td} \approx \Big[|\eta'/x_d| \, e^{i(\phi_{2d} + \delta)} \times$$

$$\times \left\{ |\varepsilon+\eta| - |\sigma+\varepsilon| e^{i(\phi_{\eta+\varepsilon} - \phi_{\sigma+\varepsilon})} \right\} - \eta' |\eta-\varepsilon| e^{i\delta} \Big]$$

$$\times \, e^{-i[\Omega(1+\beta_\Omega) - \zeta_{cb} + \delta]} .$$

ϕ_{2d}, ϕ_{2u}, δ, Ω, ζ_{cb}, γ known in terms of $\eta, \varepsilon, \sigma, \eta', \varepsilon'$ etc.

From V_{ub}, V_{td} $\rightarrow$ Get η_W, ρ_W.

Wolfenstein

$$
V_{CKM} \approx \begin{array}{c c}
 & \begin{array}{ccc} d & s & b \end{array} \\
\begin{array}{c} u \\ c \\ t \end{array} &
\left[\begin{array}{c|c|c}
1-\lambda^2/2 & \lambda & A\lambda^3(\rho_W - i\eta_W) \\ \hline
-\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \hline
A\lambda^3(1-\rho_W - i\eta_W) & -A\lambda^2 & 1
\end{array}\right]
\end{array}
$$

$$\lambda \approx \sin\theta_c \approx 0.22$$

A Few Sample Fits

A

η_{Real} & ε opposite sign to make $\nu_\mu \nu_\tau$ osc. angle large

$$\boxed{\begin{array}{ll} \eta = 0.12 - 0.05\,i \; ; & \sigma = 0.1 - 0.012\,i \\ \varepsilon = -0.0954 \; ; & \eta' = 4\times 10^{-3} \end{array}}$$

$$\varepsilon' = 1.47\times 10^{-4}\, e^{i\pi/7} \;, \quad \zeta_{2u} = 1.25\times 10^{-3}\, e^{i\pi/4}$$

$$\zeta_{2d} = 4\times 10^{-3}\, e^{i\pi/2}$$

$$m_{\tau,\mu,e} \approx [1.77\overset{*}{7}, 0.1076 ; 3.6\times 10^{-4}]\,\mathrm{GeV}$$

$$m_{b,s,d} \approx [5 , 0.139 , 7.7\times 10^{-3}]\,\mathrm{GeV}$$

$$m_{t,c,u} \approx [16\overset{*}{7} , 1.327 , 3.6\times 10^{-3}]\,\mathrm{GeV}$$

$$\boxed{\begin{array}{ll} V_{us} = 0.20 \; ; & V_{ub} = 0.003 \\ V_{cb} = 0.044 \; ; & V_{td} \simeq 0.112 \end{array}}$$

All masses & CKM elements good to 10%.

$$\boxed{\eta_W = 0.197 \;, \quad \rho_W = -0.245}$$

SUSY $\Delta F = 2$ Amplitudes depend on other phas

$$\boxed{(\phi_{2u}, \phi_{2d}, \zeta^d_{33}) \approx (154.1^\circ, 176.8^\circ, 183^\circ)}$$

Fit B Same $(\eta, \sigma, \varepsilon, \eta')$ as in Fit Ⓐ

$$\boxed{\begin{aligned} \zeta_{2d} &= 4\times10^{-3}\, e^{i\pi(150/180)}, \quad \zeta_{2u} = 0.25\times10^{-3}\, e^{i\pi/9} \\ \varepsilon' &= 1.54\times10^{-4}\, e^{i\pi/4} \end{aligned}}$$

Similar fit to that of Fit A

Main Changes

$V_{us} = 0.2169$; $V_{ub} \simeq 0.0034$

$m_c = 1180$ MeV ; $m_u = 102$ MeV

$$\boxed{\eta_W = 0.293 \quad ; \quad \rho_W = -0.187}$$

Other relevant phases.

$$(\varphi_{2u}, \varphi_{2d}, \zeta^d_{33}) = (174.4, \underline{\underline{-169}}, \underline{\underline{-159.6}})^\circ$$

Other Fits Retain success of Fermion masses & Mixings,

letting η_W vary typically between 0.1 to 0.3

& $(\varphi_{2u}, \varphi_{2d}, \zeta^d_{33})$ as well.

VIII SUSY Flavor Violation: 3 Sources of Enhancement

① Embedding of MSSM into SO(10)/G(224)

Assume ISD or ESD arise at a scale M_S between M_{GUT} & M_{st} : $M_S \sim (5 \text{ to } 20) M_{GUT}$ (say)?

$M_S \sim M_{st} \longrightarrow$ Extreme or Interm. degen

$h_t\, 16_3\, 16_3\, \boxed{10_H} \Longrightarrow$ e.g. $h_t\, \tilde{\bar{t}}_R\, \tilde{\bar{b}}_R\, \acute{H}_c(3^*c)$

$(2,2,1)_H + (1,1,6)_H$

Mix with $\boxed{16d}$

$\Rightarrow$ In SO(10), $\exists$ heavy color-triplets + a Heavy doublet with masses $\sim M_{GUT} \rightarrow$ Large Yuk. Coupling third Family

$M_{H_c} \sim M_{GUT}$

$$\Delta\hat{m}^2_{\tilde{b}_R} = \Delta\hat{m}^2_{\tilde{b}_L} = -30\, m_0^2 \left(\frac{h_t^2}{4\pi}\right) \ln\left(M_S/M_{H_c}\right)$$

18 from triplets
12 from doublets

$10\,(1/3 \text{ to } 3)$

$\boxed{\xi \approx 1/2 \text{ to } 1.4}$

$$\approx -(m_0^2/4)\,(1/2 \text{ to } 1.4)$$

$\Rightarrow$ Large splitting between $(\tilde{b}_L, \tilde{b}_R)$ vs. $(\tilde{d}, \tilde{s})_{L,R}$ at GUT-scale, even if $\tilde{b} = \tilde{s} = \tilde{d}$ at M_S

ONLY DUE TO EMBEDDING OF MSSM $\rightarrow$ SO(10)

② Flavor Viol. Through RG Running: $M_{GUT} \to m_W$, Suppression of $\tilde{b}_L$ mass in MSSM

$$h_t \quad \tilde{b}_L \quad \tilde{t}_R \quad \boxed{H_u}$$ Light MSSM doublet

$$\left(\Delta m^2_{\tilde{b}_L}\right)' \approx -3.2\, m_0^2 \eta_y + 2.3\, A_0\, m_{1/2} \eta_y (1-\eta_y)$$
$$- A_0^2 \eta_y (1-\eta_y) + m_{1/2}^2 (3\eta_y^2 - 7\eta_y)$$ (For simplicity Assume Universality)

$$\eta_y \equiv \left(\frac{m_t}{v \sin\beta}\right)^2 (1/1.21) \approx 0.836 \quad (\tan\beta = 3)$$

$$m_{\tilde{g}} \approx 3 m_{1/2} \quad ; (m^2_{sq})_{1,2} \approx m_0^2 + 7 m_{1/2}^2$$

$\Rightarrow$ At EW scale,

Not including shift at GUT scale $\leftarrow$ $$\left(\frac{m^2_{\tilde{b}_L} - m^2_{sq}}{m^2_{sq}}\right)'_{M_{GUT}\to M_{EW}} \approx \begin{pmatrix} -0.38 \\ -0.25 \end{pmatrix} \begin{matrix} \to x = \frac{m^2_{\tilde{g}}}{m^2_{sq}} = 0.3 \\ \to x = 1 \end{matrix}$$

$\downarrow$

Again a large source of Flavor-Violation Within MSSM.

③ Enhancement of RH Mixing Angles

$\Leftrightarrow$ $\boxed{\text{Largeness of } \mu\text{-}\tau \leftrightarrow \nu_\mu \nu_\tau \text{ oscil. Angle}}$

$$\left(\frac{\Delta m^2_{\tilde{b}_R}}{m^2_{sq}}\right)\left[\left(\tilde{b}_R^* \, \tilde{b}_R\right)\right] \longrightarrow (X^d_R)^\dagger_{13}\, (X^d_R)^*_{32}\; \underbrace{\tilde{d}_R\, \tilde{S}_R^*}_{\text{SUSY Basis}}$$

$$\underbrace{\underbrace{\left(\frac{\eta'}{x}\right)}_{1/5}\underbrace{\left(|\eta-\varepsilon|\right)}_{1/4}} \qquad \underbrace{\left(-\underbrace{|\eta-\varepsilon|}_{1/4}\right)}$$

Compare with $(V_{td})_L \approx 10^{-2}$;

η & ε have opposite signs so that V_{bc} suppressed, but $\Theta_{\mu\tau} \to \Theta^{osc}_{\nu_\mu \nu_\tau}$ Enhanced.

$\boxed{\text{SUSY } \cancel{CP} \longleftrightarrow \nu_\mu \nu_\tau \text{ oscillation}}$

$\Rightarrow$ Large Enhancement of $(\Delta_{RR})_{ij}$

$$V_{cb} = \left| \sqrt{m_s/m_b}\,\sqrt{\frac{\eta+\varepsilon}{\eta-\varepsilon}} + \quad \right|$$

η, ε opposite sign $\to$ suppressed

$$\Theta_{\mu\tau} = \sqrt{\frac{m_\mu}{m_\tau}}\,\sqrt{\frac{\eta-3\varepsilon}{\eta+3\varepsilon}} \longrightarrow \text{ENHANCED.}$$

Squark Transition Masses at GUT-Scale

$$\hat{\delta}^{12}_{LL}(M_{GUT}) \simeq e^{-i\phi_{td}}\Big[(m_1^{(0)2}-m_2^{(0)2})/m_{sq}^2\, |\eta'/x_d|$$
$$+(\Delta m^2_{\tilde{b}_L}/m^2_{sq})\left(-|\eta'/x_d||\epsilon+\eta|^2+\eta'|\epsilon^2-\eta^2|\, e^{i\phi_{2d}}\right)\Big]$$
$$\approx\Big[(2\times10^{-3})\frac{\kappa_I}{ISD} \pm 10^{-5}(\xi)\, e^{i\phi_{2d}}\Big]\left(\frac{m_0^2}{m_{sq}^2}\right)e^{-i\phi_{td}}$$

$$\hat{\delta}^{12}_{RR}(M_{GUT}) \simeq e^{-i\phi_{td}}\Big[\Big\{ (m_1^{(0)2}-m_2^{(0)2})/m_{sq}^2\, |\eta'/x_d| \xrightarrow{\text{ENHANCEMENT}}$$
$$+(\Delta m^2_{\tilde{b}_R}/m^2_{sq})\left(-|\eta'/x_d||\epsilon-\eta|^2+\eta'|\epsilon^2-\eta^2|\, e^{-i\phi_{2d}}\right)\Big\}\Big]$$
$$\approx\Big[(2\times10^{-3})\frac{\kappa_I}{ISD} \pm 3\xi\times10^{-3} \mp 10^{-5}\,\xi\, e^{-i\phi_{2d}}\Big]\left(\frac{m_0^2}{m_{sq}^2}\right)e^{-i\phi_{td}}$$

$$\hat{\delta}^{13}_{LL} \approx (\Delta m^2_{\tilde{b}_L}/m^2_{sq})\Big[-\eta'|-\epsilon+\eta|\, e^{i\zeta^d_{33}}+|\eta'/x_d||\epsilon+\eta|\, e^{i(\zeta^d_{33}-\phi_{2d})}\Big]$$
$$\approx\Big[(2.5\,\xi)\times10^{-4}\, e^{i\zeta^d_{33}} - (2.5\,\xi)\times10^{-3}\, e^{i(\zeta^d_{33}-\phi_{2d})}\Big]\left(\frac{m_0^2}{m_{sq}^2}\right)$$

$$\hat{\delta}^{13}_{RR} \approx (\Delta m^2_{\tilde{b}_R}/m^2_{sq})\Big[-\eta'|\eta+\epsilon|\, e^{i(\zeta^d_{33}-\phi_{2d})}+\overbrace{|\eta'/x_d||\eta-\epsilon|}^{\text{ENHANCEMENT}}\, e^{i\zeta^d_{33}}\Big]$$
$$\approx\Big[(5\xi\times10^{-5})\, e^{i(\zeta^d_{33}-\phi_{2d})} - (1.25\,\xi)\times10^{-2}\, e^{i\zeta^d_{33}}\Big]\left(\frac{m_0^2}{m_{sq}^2}\right)$$

$$\hat{\delta}^{23}_{LL} \approx (\Delta m^2_{\tilde{b}_L}/m^2_{sq})\left(-|\eta+\epsilon|\, e^{i(\zeta^d_{33}-\phi_{2d}+\phi_{td})}\right) \approx \Big[1.25\xi\times10^{-2}\, e^{i(\zeta^d_{33}-\phi_{2d}+\phi_{td})}\Big]\times(m_0^2/m_{sq}^2)$$

$$\hat{\delta}^{23}_{RR} \approx \left(\frac{\Delta m^2_{\tilde{b}_R}}{m^2_{sq}}\right)\Big(-\underbrace{|\eta-\epsilon|}_{\text{ENHANCEMENT}}\, e^{i(\zeta^d_{33}+\phi_{td})}\Big) \approx \Big[6.2\times10^{-3}\xi\, e^{i(\zeta^d_{33}+\phi_{td})}\Big]\left(\frac{m_0^2}{m_{sq}^2}\right)$$

MSSM Running from M_{GUT} to m_W

$h_t(\tilde{b}_L \tilde{\bar{t}}_R H_u) \rightarrow$ significant supp. of $\tilde{b}_L$ mass

Not shared by $\tilde{b}_R, (\tilde{d}, \tilde{s})_{L,R}$

$$\Delta\mathcal{L} = -\Delta m_L'^2 \, \tilde{b}_L'^* \tilde{b}_L'$$

$$\boxed{\tilde{b}_L' = V_{td}\,\tilde{d}_L + V_{ts}\,\tilde{s}_L + V_{tb}\,\tilde{b}_L}$$

SUSY Partners of physical (d_L, s_L, b_L)

$$\Delta m_L'^2 = -3/2\, m_0^2 \eta_t + 2.3 A_0 \eta_t (1-\eta_t) - \cancel{A_0^2(\;)} + m_{1/2}^2 (3\eta_t^2 - 7\eta_t)$$

$$\eta_t \equiv h_t/h_f = (m_t/v\sin\beta)^2 \left(\frac{1}{1.21}\right) \approx 0.836 \quad (\tan\beta = 3)$$

$$\Downarrow$$

$$\boxed{\left(\Delta m_L'^2 / m_{sq}^2\right) \approx (-0.36)\,(1 \text{ to } .8) \quad (\text{for } x = .3 \text{ to } .6)}$$

$$\Downarrow$$

$$\left(\delta'_{ij}\right) = \left(\frac{\Delta m_L'^2}{m_{sq}^2}\right)\left(V_{td}^* V_{ts}, \rightarrow (\tilde{d}^* \tilde{s} \rightarrow K^0 \leftrightarrow \overline{K^0})\right)$$

12 ------> $V_{td}^* V_{ts}$

13 ------> $V_{td}^* V_{tb} \rightarrow (\tilde{d}^* \tilde{b}) \rightarrow B_d - \overline{B}_d)$

23 ------> $V_{ts}^* V_{tb} \rightarrow (\tilde{s}^* \tilde{b}) \rightarrow B_s - \overline{B}_s)$

Net

$$\boxed{\begin{aligned} \delta_{LL}^{ij} &= \hat{\delta}_{LL}^{ij} + \delta_{LL}'^{ij} \\ \delta_{RR}^{ij} &= \hat{\delta}_{RR}^{ij} \end{aligned}}$$

$K^0 - \overline{K^0}$

$$\left(m_1^{(0)2} - m_2^{(0)2}\right)/m_{sq}^2 \equiv 10^{-2} \kappa_{ISD} \text{ (For ISD)}$$

$$\kappa_{ISD} \approx 2 \text{ to } 1/3 \text{ (say)}$$

$$\mathrm{Re}\,\delta_{LL}^{12}\delta_{RR}^{12} \approx \begin{cases} (10^{-6}\kappa_{ISD})(1/2 \text{ to } 1)\cos^2\phi_{td} & \text{ISD} \\ (10^{-6})(1/6 \text{ to } 1)\cos^2\phi_{td} & \text{ESD} \end{cases}$$

$$\mathrm{Im}\,\delta_{LL}^{12}\delta_{RR}^{12} \approx \begin{cases} (7\times 10^{-8}\kappa_{ISD})(\sin\phi_{td}/1/8) & \text{ISD} \\ \text{Need } \kappa_{ISD} \approx 1/2 - 1/3 & \\ (3.5-7)\times 10^{-8}\,(\sin\phi_{td}/(1/8)) & \text{ESD} \\ \text{Need } m_{\tilde{q}} \gtrsim 800\,\text{GeV}. & \end{cases}$$

$\Downarrow$

Thus Conclude $(\Delta m_K)_{susy}$ & $(\varepsilon_K)_{susy}$ (will see $(\varepsilon'_K)_{susy}$ as well) Comparable to observed Values. Need good lattice Calculation to distinguish.

$B_d - \bar{B}_d$

$$\mathrm{Re}\,\delta^{13}_{LL}\delta^{13}_{RR} \approx (-10^{-4})\,(\underbrace{\rho_X^2 \approx 1/4 \text{ to } 1/2}_{1/3})(\underbrace{\xi^2 \approx 1/4 \text{ to } 2}_{1})$$

median $\approx -3 \times 10^{-5}$ (ISD & ESD)

$$\mathrm{Im}\,\delta^{13}_{LL}\delta^{13}_{RR} \approx (-2.1 \times 10^{-5})\,(\rho_X^2\,\xi^2)$$

median $\approx -(2/3) \times 10^{-5}$ (ISD & ESD)

$$\Downarrow$$

$(\Delta m_{B_d}) \rightarrow \mathrm{Re}\,A(B_d - \bar{B}_d)_{SUSY} \sim 1/5\ \mathrm{Re}\,A(B_d - \bar{B}_d)_{obs}$

$$\boxed{\frac{\mathrm{Im}\,A(B_d - \bar{B}_d)_{SUSY}}{\mathrm{Im}\,A(B_d - \bar{B}_d)^{Std}_{CKM}} \approx -(1/2 \text{ to } 1/4)\,(1/3 / \eta_W)}$$

would significantly alter $\underline{a(B_d - \bar{B}_d \rightarrow J/\psi + K_S)}$

B_s-$\bar{B}_s$

$$\left.\begin{array}{l} \mathrm{Re}\,\delta^{23}_{LL}\,\delta^{23}_{RR} \approx (14 \text{ to } 4)\times 10^{-4} \\ \mathrm{Im}\,\delta^{23}_{LL}\,\delta^{23}_{RR} \approx (4 \text{ to } 1)\times 10^{-4} \end{array}\right\}.$$

Need $\mathrm{Re}\,A_{B_s} \sim 10^{-3}$ $\leftrightarrow$ to compare with SM contrib

$$\boxed{a^{J/\psi K_S}_{B_s\bar{B}_s} \approx 0.7 \text{ to } 0.2}$$

Embedded MSSM with ν_μ-ν_τ

$\updownarrow$

Stand. Model $= 0$!

unembedded MSSM with flavor viol only in Yukawa ≈ 0 !

ε_K'

$$\frac{dA_{33}}{dt} = \frac{h_t}{16\pi^2}\left(63\, g^2 M_\lambda\right)$$

$$A_{33}(M_X) = \frac{63}{16\pi^2}\left(1/\sqrt{2}\right)\left(1/2\right)\ln\left(M_S/M_{GUT}\right)$$

$$\simeq (0.6)\left(\ln(M_S/M_G)/2\right)$$

$$A_{\bar{\tilde{d}}_L \tilde{s}_R} = A_{33}\,(X^d_R)_{32}\,(X^d_L)^*_{31}$$

$$(1-|\varepsilon+\eta|)\quad\left[(\eta'/x)|\varepsilon+\eta|\, e^{-i\phi_{22}} - \eta'|1-\varepsilon+\eta|\right]$$

$$A_{\bar{\tilde{d}}_R \tilde{s}_L} = A_{33}\,(X^d_R)^*_{31}\,(X^d_L)_{32}$$

$$\Downarrow$$

$$\varepsilon' \propto \left(A_{\bar{\tilde{d}}_L \tilde{s}_R} - A_{\bar{\tilde{d}}_R \tilde{s}_L}\right)$$

$$(\delta_{12})_{LR} - (\delta_{12})_{RL} \simeq (-2.8\times 10^{-3})\sin\phi_{22}\times$$

$$\times\left(M_\lambda v_d/m^2_{sq}\right)$$

$$\simeq (1 \text{ to } 3)\times 10^{-4}\,\sin\phi_{22}$$

Need $\simeq 10^{-5}$ To be important

To Conclude

① Embedding of MSSM into G(224)/SO(10)

AND

② Understanding of Largeness of ν_μ-ν_τ osc. angle

$\updownarrow$

$$\boxed{\text{Should clearly have visible effects on } \epsilon_K,\ a_{B\bar{B}}^{J\psi+K_S} \text{ \& very likely } \epsilon'_K}$$

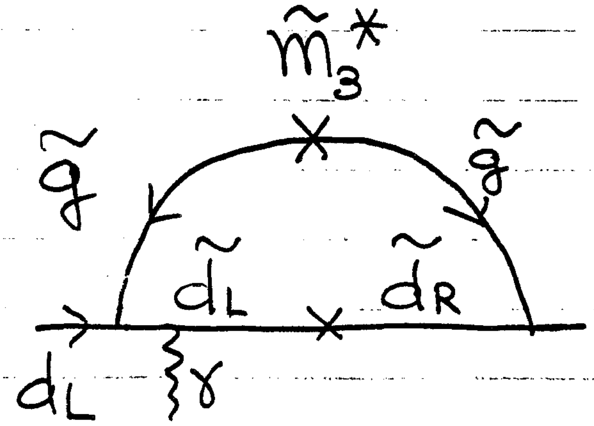
Without the enhancements due to ① & ②, SUSY $\cancel{CP}$ effects would be too small to be detected.

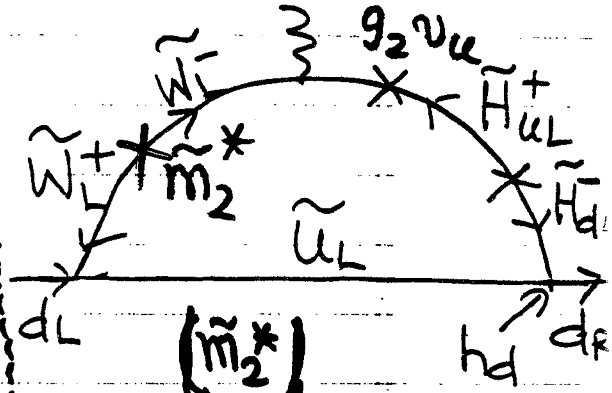
(E) EDM (n, e)

$d_n < 1.1 \times 10^{-25}$ ecm

$d_e < 6 \times 10^{-27}$ ecm

NEUTRON $\quad d^n = \frac{1}{3}(4d^d - d^u)$





$$\propto \frac{m_d\left(|A_d|\sin\xi_A + |\mu|\tan\beta \sin\xi_\mu\right)\overset{(\tilde m_3^*)}{M_1(x)}}{(m_{\tilde d})^4} \quad \Bigg| \quad \propto \frac{\overset{(\tilde m_2^*)}{m_d}\left(|\mu|\tan\beta \sin\xi_\mu\right)}{(m_{\tilde u}^2)\max(m_{\tilde W}^2, m_{\tilde H}^2)}$$

Comparable

$\boxed{\text{Ibrahim \& Nath}}$

For our case: ① $m_0 \gtrsim m_{1/2}$

$$A_0(M_{st}) \simeq 0 \Rightarrow \operatorname{Arg} A_d(m_Z) \simeq \operatorname{Arg} m_{1/2}$$

$$\Rightarrow \boxed{\xi_A \simeq 0}$$

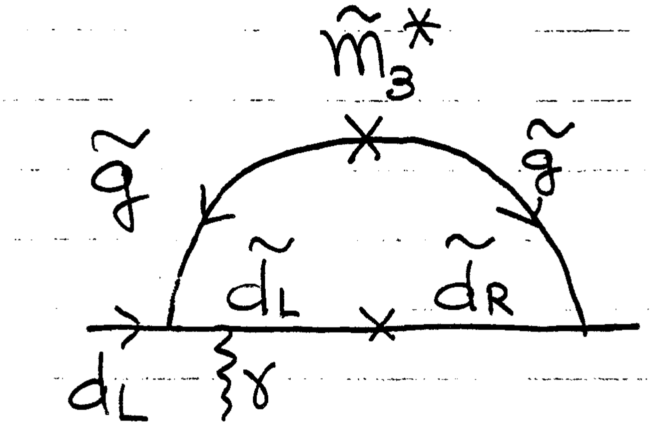
Only New Phase in μ-term.

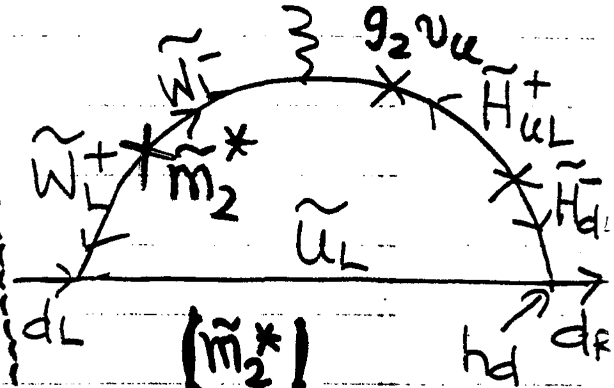
(E) EDM (n, e)

$d_n < 1.1 \times 10^{-25}$ ecm

$d_e < 6 \times 10^{-27}$ ecm

NEUTRON $\quad d^n = \frac{1}{3}(4d^d - d^u)$





$$\propto \frac{m_d\left(|A_d|\sin\underline{\underline{\xi_A}} + |\mu|\tan\beta\sin\underline{\underline{\xi_\mu}}\right)\overset{\{\tilde{m}_3^*\}}{M_1(x)}}{(m_{\tilde{d}})^4} \qquad \propto \frac{m_d\overset{\{\tilde{m}_2^*\}}{}\left(|\mu|\tan\beta\sin\xi_\mu\right)}{(m_{\tilde{u}}^2)\max(m_{\tilde{W}}^2, m_{\tilde{H}}^2)}$$

Comparable

$\boxed{\text{Ibrahim \& Nath}}$

For our case: ① $m_0 \gtrsim m_{1/2}$

$A_0(M_{St}) \simeq 0 \Rightarrow \mathrm{Arg}\,A_d(m_Z) \simeq \mathrm{Arg}\,m_{1/2}$

$\Rightarrow \boxed{\xi_A \simeq 0}$

Only New Phase in μ-term.

From $d_n < 1.1 \times 10^{-25}$ ecm (expt)

$\tan\beta \approx 2\text{-}4$	$\sin\xi_{eff}$
$m_0 = 500$ GeV, $m_{1/2} = 70$ GeV $\Downarrow$ $m_{\tilde g} \approx 210$ GeV	$\lesssim 1/15$
$m_0 = 800$ GeV, $m_{1/2} \approx 100$ GeV $\downarrow$ $m_{\tilde g} \simeq 300$ GeV	$\lesssim 1/10$
$m_0 \simeq 1$ TeV, $m_{1/2} \simeq 100$ GeV	$\lesssim 1/8$
$m_0 = 1.2$ TeV, $m_{1/2} = 135$ GeV $m_{\tilde g} = 400$ GeV	$\lesssim 1/5$

Thus for $m_0 \gtrsim 700$ GeV, $m_{1/2} \sim (70-500)$ GeV and $\tan\beta \simeq 2-5$, (edm)$_{neutron}$-limits are satisfied for natural phases $\lesssim 1/6$.

Assuming no apriori reason for phases to be $< 1/10$ and $m_0 \lesssim 1$ TeV (natural-ness "Fine-Tuning")

$\boxed{\text{expect } d_n \text{ to show above } 10^{-26} \text{ ecm level and also } d_e \text{ to show above } 10^{-27} \text{ ecm.}}$

$(edm)_{electron}$

Following Ibrahim & Nath for our case

- $\boxed{\text{Chargino} \gg \text{Neutralino Contribution} \sim (\tilde{B}, \tilde{W}_3)}$

$$d^e_{chargino} \approx \underbrace{(1 \text{ to } 2)}_{(m_0 = 1\text{ TeV to } 700\text{ GeV})}(10^{-26}\, ecm) \tan\beta \,[|C_1| - |C_2|] \sin\phi$$

$(m_0 = 1$ TeV to 700 GeV

$m_{1/2} \simeq 120$ GeV

$\tan\beta \approx \underline{\underline{2 - 5}}$

$|C_1| \approx (1)$, $|C_2|$: $(\mathcal{O}(1) < 1)$ → (Take 1/2)

$$(d_e)_{expt} < 6 \cdot \times 10^{-27}\ ecm$$

$$\Rightarrow \sin\phi \lesssim \left(\frac{1}{1.5} - \frac{1}{3}\right)(1/\tan\beta)$$

$$\lesssim \left(\frac{1}{3} - \frac{1}{6}\right) \quad (\tan\beta = 2)$$

$$\lesssim \left(\frac{1}{7.5} - \frac{1}{15}\right) \quad (\tan\beta = 5)$$

∴ **Both d_e and d_n - limits can be satisfied with "natural phases" for $m_0 \gtrsim 700$ GeV, $m_{1/2} \approx (100 - 500)$ GeV, $\tan\beta \lesssim 4$ ⟶ should be seen soon.**

Thus, would expect both to show with factor 10 improvement on present limits.

Note, for $\tan\beta \lesssim 20$, ϵ_{SUSY} gives a stronger constraint on phase than d_e, d_n.

$\mu \to e\gamma$ (Most sensitive part $\propto \underline{\tilde{\mu}_L \times \tilde{e}_R}$)

ϵ' (" " $\propto \underline{\tilde{d}_L \times \tilde{s}_R}$)

Can show these Flavor-changing chirality-flipping $(\text{mass})^2$ vanish in SUSY Basis.

SUSY contrib from (LL) & (RR)-contrib fully compatible with current limits.