CP & FLAVOUR

BEYOND THE S.M. (SUSY)

1) WHY SUSY ?

2) THE PROBLEMS WITH SUSY

3) APPROACHES

4) THE BOTTOM-UP APPROACH i.e. M.I.A.

5) THE TOP-DOWN APPROACH
e.g. 'TEXTURES' THAT ALLOW $\delta_{CKM} = 0$

6) THE "FUNDAMENTAL" APPROACH
e.g. BREAKING CP AT STRING LEVEL

CHARMING - STRANGE
APPROACH ?

$$\delta_{CKM} = \frac{\pi}{3} \cdot \frac{\pi}{4}$$

1 WHY STUDY SUSY ?

a) HIERARCHY PROBLEM
UNIFICATION EVIDENCE
LOW MASS HIGGS

b) STRING THEORY LIKES IT

c) BARYOGENESIS REQUIRES SOME BSM CP.

d) NO UNDERSTANDING OF FLAVOUR + CP ANYWAY.
- LOOK FOR IT IN 'HIGHER' THEORY.

2 SUSY NOT FUNDAMENTAL ENOUGH !

PROBLEMS: ARBITRARY SUSY DOESN'T LOOK LIKE EXPERIMENT

MSSM:
$$W_{MSSM} = h_{U_{ij}} Q_i H_2 U_j^c + h_{D_{ij}} Q_i H_1 D_j^c + h_{E_{ij}} L_i H_1 E_j + \mu H_1 H_2$$

ADD SUSY BREAKING

$$\begin{aligned} \delta \mathcal{L} = \; & - m_{ij}^2 \, \phi^i \phi^{*j} \\ & + A_{U_{ij}} h_{U_{ij}} \tilde{q}_L^i h_2 \tilde{u}_R^{*j} \\ & + A_{D_{ij}} h_{D_{ij}} \tilde{q}_L^i h_1 \tilde{d}_R^{*j} \\ & + A_{E_{ij}} h_{E_{ij}} \tilde{l}_L^i h_1 \tilde{e}_R^{*j} \\ & + B\mu \, h_1 h_2 \end{aligned}$$

143 PARAMETERS !

APPROACHES

1) FIND GENERAL LIMITS FROM EXPT ON $\widetilde{\text{SUSY}}$
(BOTTOM UP) $\Downarrow$
i.e. MASS INSERTION APPROX

2) ASSUME A FORM OF $\widetilde{\text{SUSY}}$ "MOTIVATED" BY SUGRA, STRINGS ETC.
(TOP DOWN) $\Downarrow$ $\Rightarrow$ D-BRANE "MODELS"
e.g. "Constrained" MSSM

3) TRY TO DERIVE $\widetilde{\text{SUSY}}$ FROM FIRST PRINCIPLES AND ALSO FLAVOUR + $\cancel{CP}$, EITHER IN SUGRA OR STRINGS
("FUNDAMENTAL") $\Downarrow$
e.g. CP IS GAUGE SYMMETRY IN STRINGS !

THE BOTTOM UP APPROACH

- MASS INSERTION APPROX – CONSTRAINTS ON GENERAL SUSY MODELS (gabbiani et al)

e.g. DOWNS ARE DIAGONAL (DM_K)

$$h_{D_{ij}} = \frac{\mathrm{Diag}(m_d, m_s, m_b)}{V_D}$$

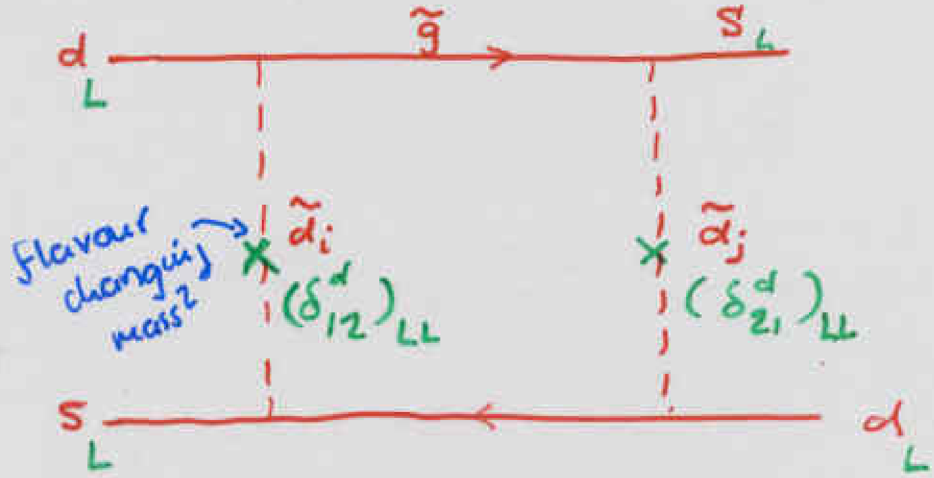
$$\tilde{m}^2_{d_{ij}} = \begin{pmatrix} \begin{bmatrix} \tilde{m}^2_{11} & \Delta_{12} & \Delta_{13} \\ \Delta_{21} & \tilde{m}^2_{22} & \Delta_{23} \\ \Delta_{31} & \Delta_{32} & \tilde{m}^2_{33} \end{bmatrix}_{LL} & \begin{bmatrix} \Delta_{ab_{LR}} \end{bmatrix} \\ \begin{bmatrix} \Delta_{ab_{RL}} \end{bmatrix} & \begin{bmatrix} \tilde{m}^2_{11} & \Delta_{12} & \Delta_{13} \\ \Delta_{21} & \tilde{m}^2_{22} & \Delta_{23} \\ \Delta_{31} & \Delta_{32} & \tilde{m}^2_{33} \end{bmatrix}_{RR} \end{pmatrix}$$

$$\Delta_{.} \ll \tilde{m}^2_{ii}$$

$$(\tilde{m}^2_{ii} - \tilde{m}^2_{jj})_{LL} \ll (\tilde{m}^2_{ii} + \tilde{m}^2_{jj})_{LL}$$ AND SAME FOR RR.

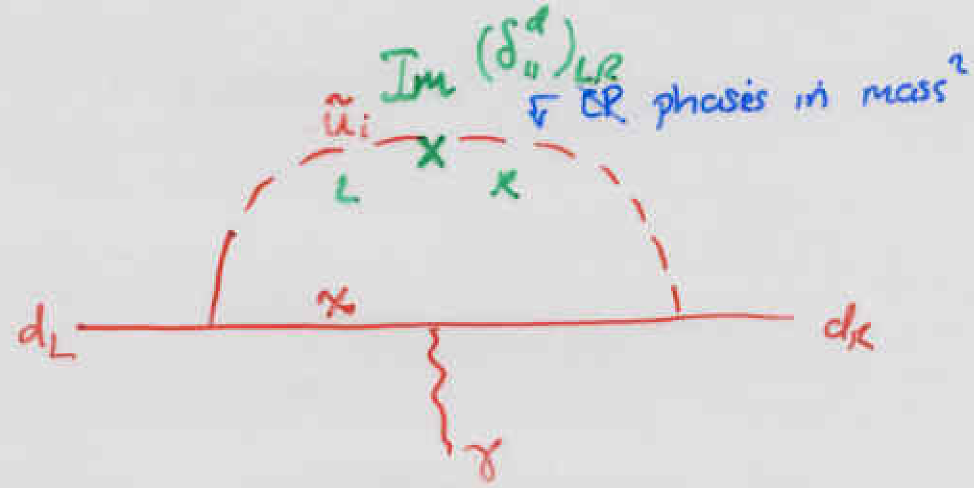
DEFINE $\delta = \dfrac{\Delta}{\tilde{m}^2}$

SUSY FLAVOUR PROBLEM:



$\Delta M_{K\,SUSY}$

SUSY CP PROBLEM:



nEDM, eEDM, h_gEDM

EXPT ALWAYS SATISFIED IF ALL PHASES (INCLUDING δ_{CKM}) SMALL $\lesssim 10^{-2}$

"APPROXIMATE CP" – CAN STILL WORK (Eyal, Nir)
IF DEMOCRATIC YUKAWAS + FLAVOUR NON-UNIVERSALITY
(Branco, Gomez, Khalil, Teixeira)

e.g. if $\tilde{m}_{\tilde{q}LL} = \tilde{m}_{\tilde{q}RR} = 500$ GeV $\quad m_{\tilde{\chi}} = 100$ GeV

Δm_K	$(\delta^d_{12})_{LL} < 4 \cdot 10^{-2}$	$(\delta^d_{12})_{LR} < 4 \cdot 10^{-3}$
Δm_{B_d}	$(\delta^d_{13})_{LL} < 10^{-1}$	$(\delta^d_{13})_{LR} < 3 \cdot 10^{-2}$
Δm_D	$(\delta^u_{12})_{LL} < 10^{-1}$	$(\delta^u_{12})_{LR} < 3 \cdot 10^{-2}$
$b \to s\gamma$	$(\delta^d_{23})_{LL}$ No Bound	$(\delta^d_{23})_{LR} < 10^{-2}$
$\mu \to e\gamma$	$(\delta^l_{12})_{LL} < 8 \cdot 10^{-3}$	$(\delta^l_{12})_{LR} < 2 \cdot 10^{-6}$
$\tau \to \mu\gamma$	$(\delta_{23})_{LL}$ No Bound	$(\delta^l_{23})_{LR} < 2 \cdot 10^{-2}$

CP VIOLATING PROCESSES :

ε

$$\sqrt{\mathrm{Im}\,(\delta^d_{12})^2_{LL}} < 3.10^{-3}$$

$$\sqrt{\mathrm{Im}\,(\delta^d_{12})^2_{LR}} < 3.10^{-4}$$

ε'

$$|\,\mathrm{Im}\,(\delta^d_{12})_{LL}\,| < 5.10^{-1}$$

$$|\,\mathrm{Im}\,(\delta_{12})_{LR}\,| < 2.10^{-5}$$

Hg EDM

$$\mathrm{Im}\,(\delta^{d,u}_{11})_{LR} < 10^{-(7\to 8)}$$

(Olin, Pospelov, Riobon) (SAA, Khalil, Lebedev)

$a_{J/\psi K_S} \Rightarrow \sin 2\beta_{eff} = 0.79 \pm 0.1$

$$\mathrm{Im}\,(\delta^d_{13})_{LL} < 3.10^{-1}$$

$$\mathrm{Im}\,(\delta^d_{13})_{LR} < 7.4.\,10^{-2}$$

(NLO From Becirevic et al hep/ph/0112303)

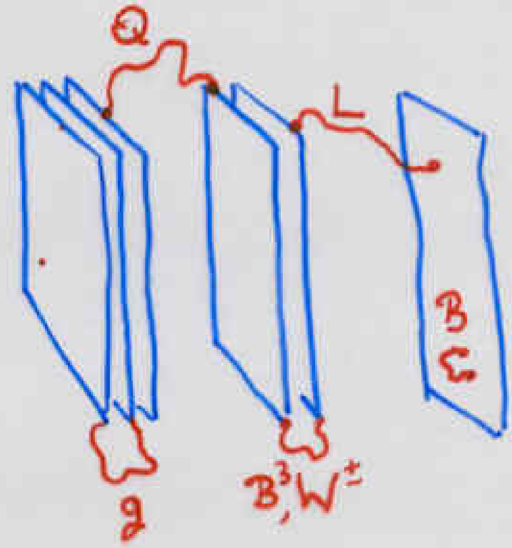
THE TOP DOWN APPROACH

BEGIN WITH A SUSY "TEXTURE" AND SEE IF IT LOOKS LIKE EXPT.

e.g. • CMSSM – CHOOSE DEGENERATE SUSY
gives contributions ~ 20% (Barth + 6
hep-ph/0112179)

e.g D-BRANE MODELS

SCHEMATICALLY ...



CAN HAVE

$$A_{ij} = \begin{bmatrix} a & a & a \\ b & b & b \\ c & c & c \end{bmatrix}$$

COULD THERE BE NO CP IN δ_{CKM}?

$$A = \begin{bmatrix} a & a & a \\ b & b & b \\ c & c & c \end{bmatrix}$$ REDUCES EDM's

$$\left[A_{ij} h_{ij\,\mathrm{diag}}\right]_{11} = \left(\begin{bmatrix} a & & \\ & b & \\ & & c \end{bmatrix} \cdot h\right)_{11}$$

1st gen mass

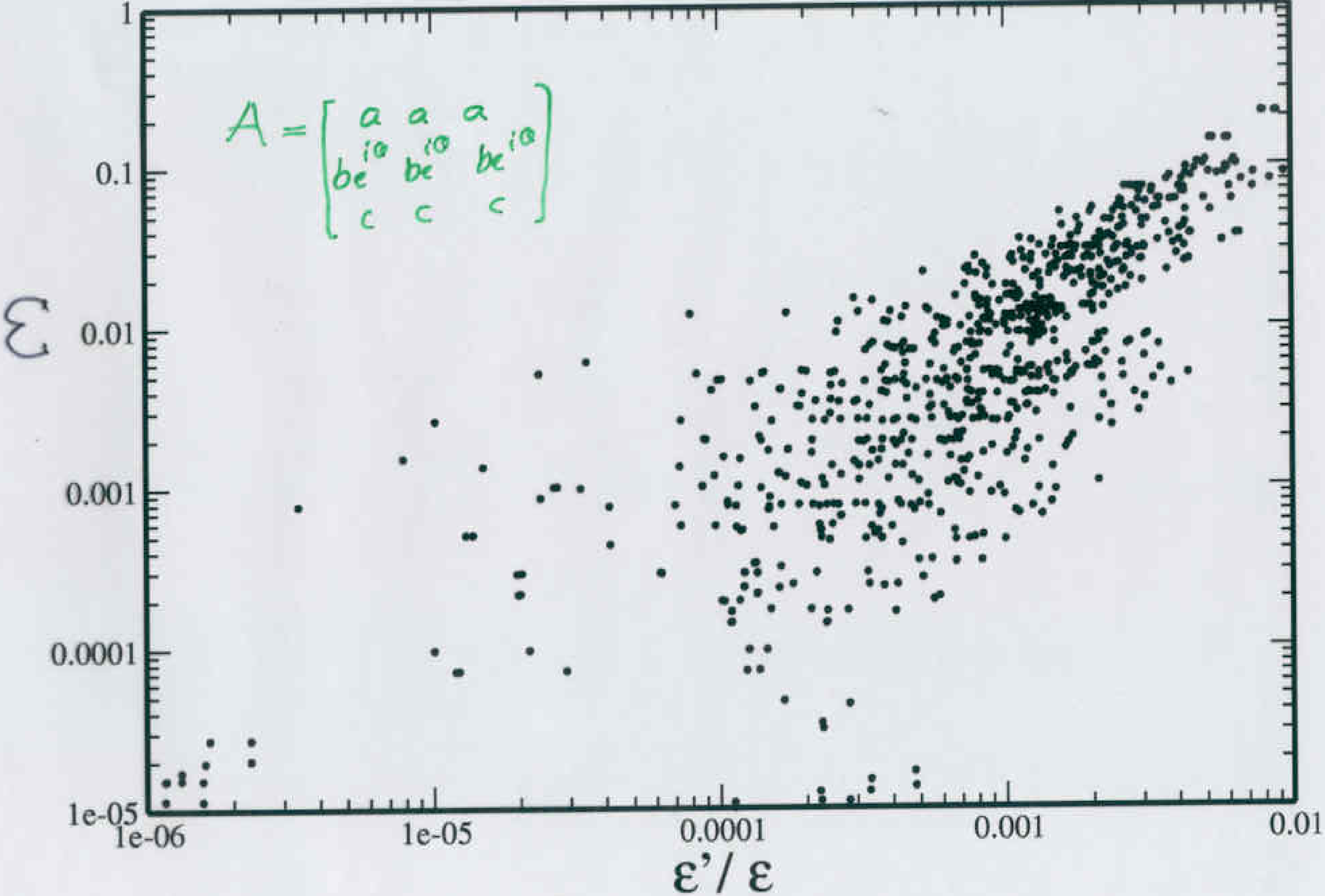
EDM's SMALL IF a AND c HAVE SMALL PHASE.

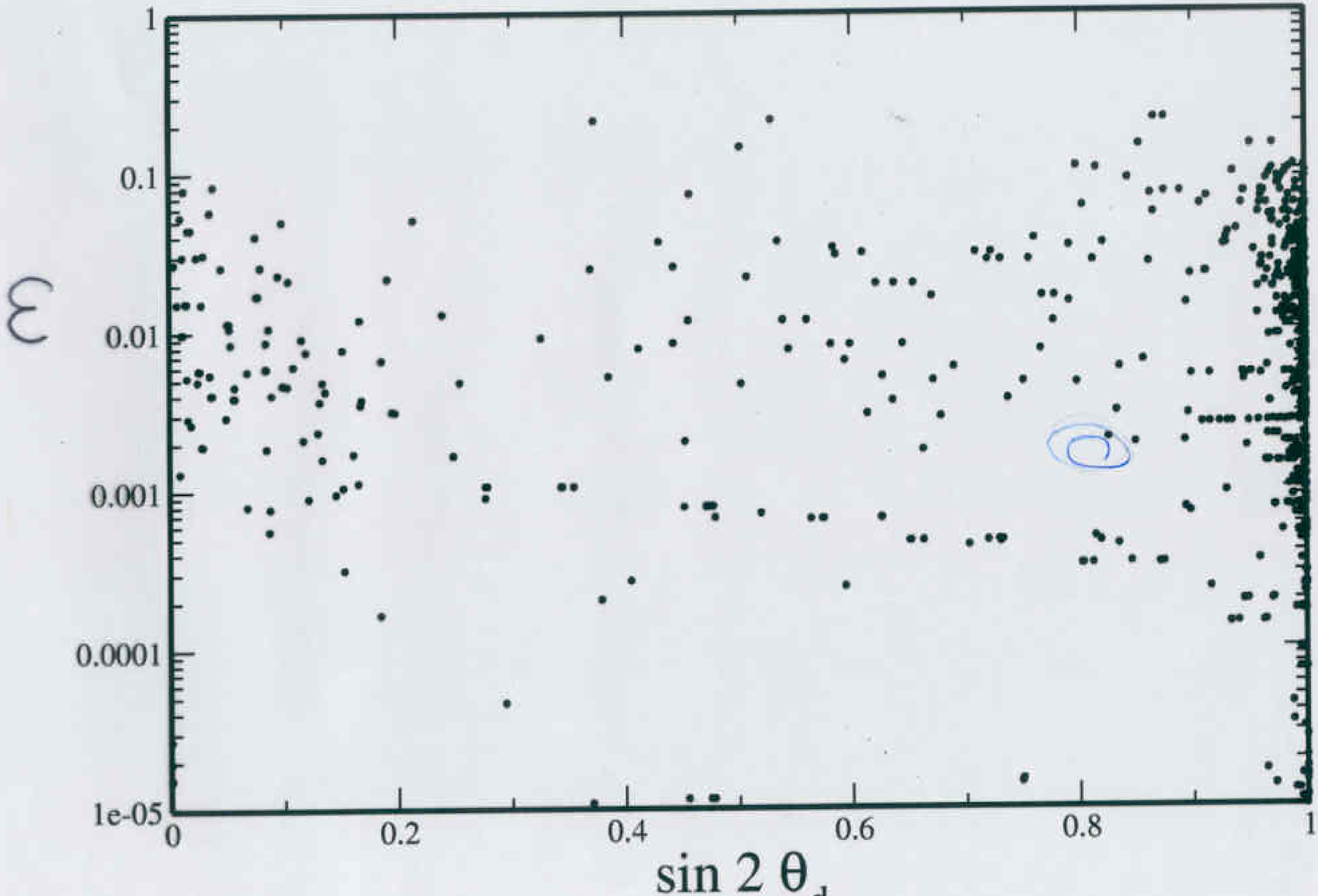
$\underbrace{\text{PHASE ON } b}_{\text{NOT APPROXIMATE CP}}$ CAN GIVE LARGE $\sin 2\beta_{\mathrm{eff}}$

(S.A.A. S. Khalil)

$h_d = V^T \frac{m_{d\,diag}}{v_1} V \qquad h_u = V^T K^T \frac{m_{u\,diag}}{v_2} K V$

$$A = \begin{bmatrix} a & a & a \\ be^{i\theta} & be^{i\theta} & be^{i\theta} \\ c & c & c \end{bmatrix}$$





ε
1
0.1
0.01
0.001
0.0001
1e-05
0
0.2
0.4
0.6
0.8
1
sin 2 θ_d

"FUNDAMENTAL" APPROACH

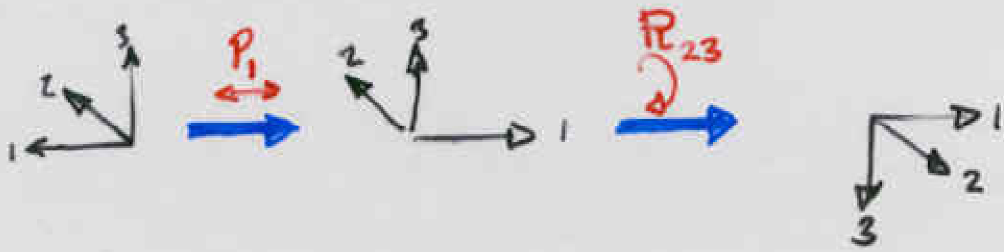
TRY TO LEARN SOMETHING ABOUT CP FROM E.G STRING THEORY

CP as a gauge Symmetry

4D parity: $(x_1\ x_2\ x_3) \to (-x_1\ x_2\ x_3)$

$$\equiv (-x_1\ -x_2\ -x_3)$$

why?



In a 10-D theory can reverse orientation of compact space and 4-D space

call $z_1 = ix_4 + x_7$

$z_2 = ix_5 + x_8$

$z_3 = ix_6 + x_9$

$M^{i\pi\Omega}$ s = 3

4 total

$x^\mu,\ Z_i \to x_\mu,\ Z_i^*$

P C

CP is a Lorentz rotation in Strings

Dine
Leigh
MacIntyre

BREAKING CP WITH DISCRETE TORSION

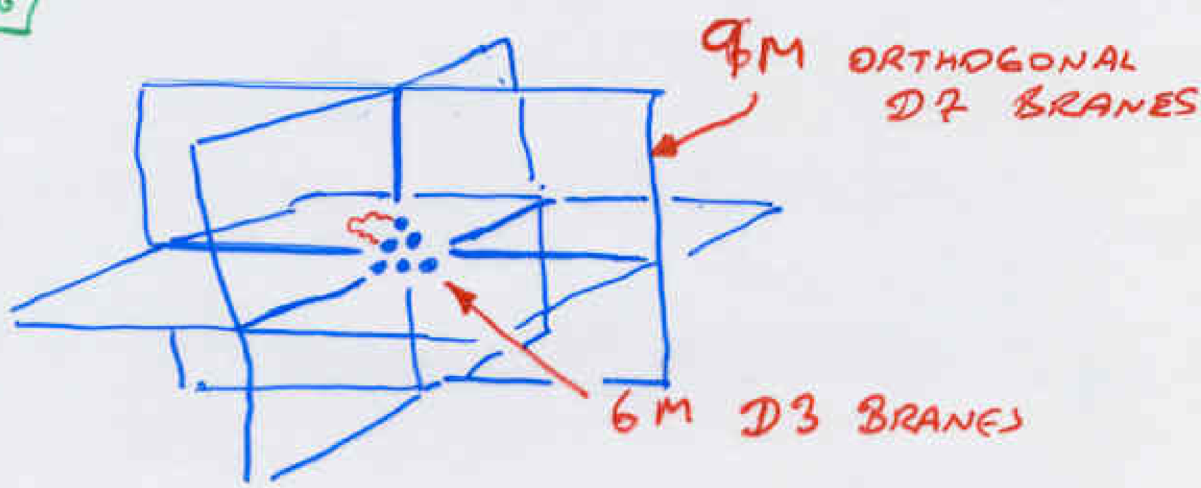
(SAA, Olsen)

$$M_4 \times K_6$$

BEGIN WITH MODEL WITH MSSM-LIKE SPECTRUM AT $\mathbb{Z}_3 \times \mathbb{Z}_M \times \mathbb{Z}_M$ ORBIFOLD FIXED POINT

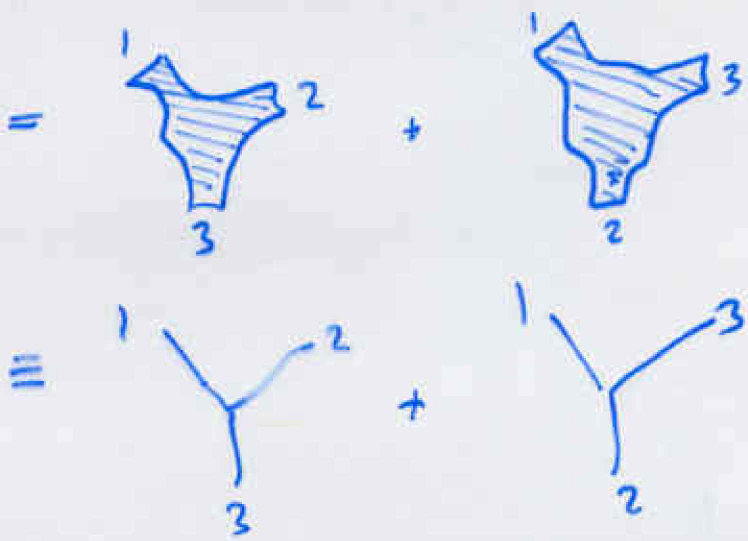
(Aldazabal Ibanez, Quevedo, Uranga)

K_6



CONFIGURATION ALLOWS NON-ZERO $\langle B_{ij} \rangle$

CALCULATE $W =$



CP VIOLATING PHASES FROM DISCRETE TORSION...

$$W = \frac{1}{2}\varepsilon_{abc}\,\mathrm{tr}\left[\varphi^a\varphi^b\varphi^c + -\epsilon\,\varphi^b\varphi^a\varphi^c\right]$$

Under $\hat{CP}$ we have $\left(x^\mu, Z^a \to x_\mu, Z^{a*}\right)$

$$\begin{aligned} \{ z^a, \psi^a, F^a \} &\to \{ z^{a*}, \bar{\psi}^a, F^{*a} \} \\ \theta, \bar\theta &\to \bar\theta, \theta \\ \epsilon &\longrightarrow \epsilon \end{aligned}$$

$$\int d^2\theta\, W + \int d^2\bar\theta\, \bar{W} \to \int d^2\bar\theta\, \bar{W}_{cp} + \int d^2\theta\, W_{cp}$$

$$W_{cp} = \varepsilon_{abc}\,\mathrm{tr}\left[\varphi^a\varphi^b\varphi^c + -\varepsilon^*\varphi^b\varphi^a\varphi^c\right]$$

generally $\quad W_{cp} \neq W$

CKM PREDICTIONS (WITH SIMPLE ANSATZ FOR MODULI)

One free parameter $\sin\theta_{12} = \lambda = 0.22$

predictions ... $\sin\theta_{23} = \sqrt{\frac{m_c}{m_t}}$

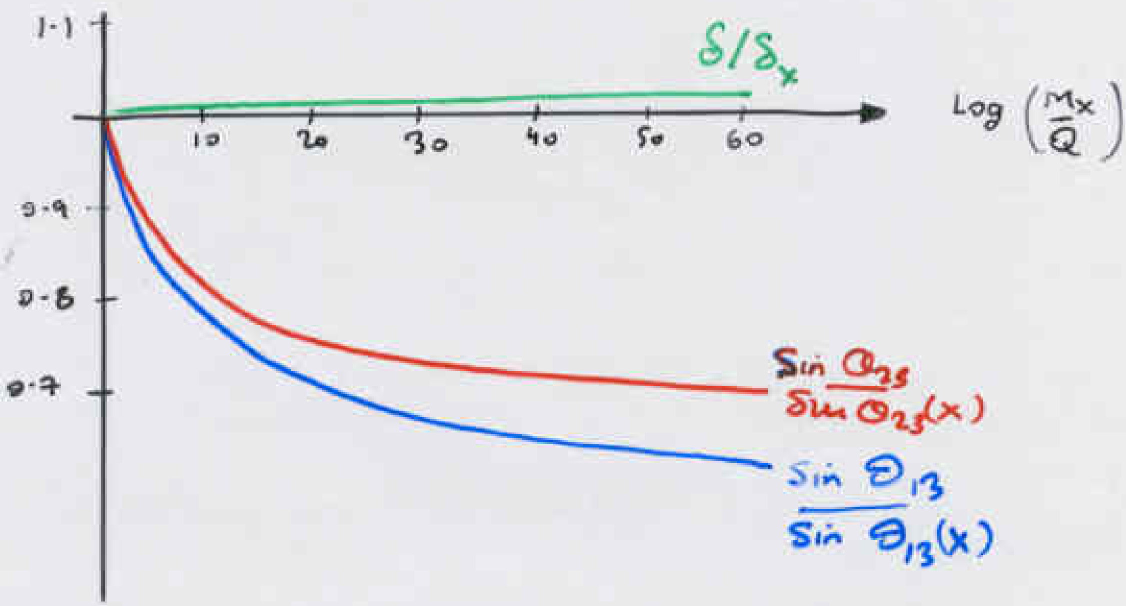
$$\sin\theta_{13} = \lambda\sqrt{\frac{m_c}{m_t}}$$

$$\delta = \pi/3,\ \pi/4,\ \pi/M$$

$\sin\theta_{13}$	0.018	0.002 → 0.005
$\sin\theta_{23}$	0.08	0.037 → 0.043
δ	60°, 45°	30° → 70° (unitarity)

HOW THE CKM MATRIX RUNS

$\lambda_t = 5$ at m_X.



Can only reasonably get 30% suppression

SUMMARY

1) B-PHYSICS TESTING SUSY

2) BUT STILL FREEDOM. (e.g. $\delta_{CKM} = 0$)

3) DIFFERENT APPROACHES ARE COMPLEMENTARY

4) POSSIBILITY OF TESTING FUNDAMENTAL THEORY.
(e.g. $\delta_{CKM} \approx \frac{\pi}{3}$ MAY INDICATE UNDERLYING ORBIFOLD)