Strong and Weak CP in R-symmetric Supersymmetry

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with Parul Rastoggi and Neal Weiner, in progress
require highly suppressed off-diagonal squark mass matrix entries,

\[(\delta_{ij}^d)_{AB} \equiv \frac{(\delta \tilde{m}_{ij}^d)^2_{AB}}{\tilde{m}^2} \ll 1, \quad i \neq j, \quad A, B = L \text{ or } R\]

\(\Delta m_K\) is tightest CP conserving constraint. For \(\tilde{m} = 500 \text{ GeV}, m_{\tilde{g}} = 1 \text{ TeV}\)

\[\sqrt{|\text{Re}(\delta_{12}^d)_{LL}(\delta_{12}^d)_{RR}|} < 1.3 \times 10^{-3}\]

\(\epsilon_K\) is tightest constraint overall

\[\sqrt{|\text{Im}(\delta_{12}^d)_{LL}(\delta_{12}^d)_{RR}|} < 1.8 \times 10^{-4}\]

Ciuchini et al. '98
Some solutions to the flavor problem

Gravity mediation \( \Rightarrow \) squark non-universality,

quark/squark alignment, or non-abelian flavor symmetries can reduce off-diagonal squark masses \( \text{Nir, Seiberg; Dine, Leigh, AK;...} \)

Gauge mediation, Anomaly mediation, Gaugino mediation,....

\( \Rightarrow \) flavor universality

Dine, Nelson, Nir, Shirman; Randall, Sundrum; Giudice, Luty, Murayam, Rattazi; Kaplan, Kribs, Schmaltz; Chako, Luty, Nelson, Ponton;.....
Solutions to the Strong CP problem, $\bar{\theta} \lesssim 10^{-11}$

- Axion from a Peccei-Quinn $U(1)$ symmetry

- Strategies for obtaining $O(1)$ CKM phase and $\bar{\theta} = 0$ at tree-level
  \[ \bar{\theta} = \theta - \text{Arg det } M^u - \text{Arg det } M^d - 3\text{arg}m_{\tilde{g}} = 0 \]

- Spontaneous CP violation
  - Nelson-Barr
  - Hiller-Schmaltz

- Spontaneous P violation + supersymmetry, e.g., Dutta, Babu, Mohapatra
Spontaneous CP Violation: Nelson-Barr

- add vectorlike down (or up) quark pair \((D, \bar{D})\),
- SM singlet scalars \(N^i\) (2 or more).

New symmetries give quark mass matrix

\[
M_{LR}^d = \begin{pmatrix}
    m_d & 0 \\
    M_D \bar{a} & \mu
\end{pmatrix}, \quad m_{ij}^d = \lambda_{ij}^d < H^d >, \quad M_D \bar{a}_i = \gamma_{ij} < N^j >
\]

- \(N^i\) complex, break CP at large scale, e.g., \(M_D, \mu \sim M_{GUT}\)
- \(H^{u,d}\) real

\[\Rightarrow \det M^d \text{ real, } \bar{\theta} = 0 \text{ at tree-level.}\]

- SUSY non-renormalization eliminates potentially large \(\bar{\theta}\) contributions from heavy quarks and \(N^i\) in loops, which would need to be tuned away.
Spontaneous CP Violation: Hiller-Schmaltz

CKM phase at one-loop from wave function renormalization of quark fields:

\[ \mathcal{L}_{\text{kinetic}} = \bar{Q}i \not{D} Z Q + \bar{d}i \not{D} Z d + \bar{u}i \not{D} Z u \]
\[ \mathcal{L}_{\text{yukawa}} = \bar{Q}\hat{Y}_u H_u u + \bar{Q}\hat{Y}_d H_d d \]

\( \hat{Y}_{u,d} \) real due to CP

\( Z_i \) complex due to non-perturbative loops (need \( \delta Z \sim 1 \)) containing heavy superfields with complex masses, from spontaneous CPV at large \( M_{CP} \)

transformed \( Y_{u,d} \) in canonical basis are complex, but \( \text{arg} \det Y_{u,d} = 0 \)

\[ \Rightarrow \bar{\theta} = 0 \] at tree-level.

SUSY non-renormalization protects the quark masses from CP violating Yukawa vertex corrections containing the heavy fields
Constraints on SUSY breaking soft masses

- after integrating out heavy fields, squark mass-insertions generically lead to large $\bar{\theta}$ at one-loop in the spontaneous CP, and P violation set-ups

$$\text{arg det} M^q$$

$$\text{arg } m\bar{g}$$

- $\bar{\theta} \Rightarrow$ very tight bounds on non-degeneracy of squarks, non-proportionality of $A$-terms
  - Dine, Leigh, AK; Hiller, Schmaltz
  - e.g., in Nelson-Barr, Hiller-Schmaltz

$$\left(\frac{\delta\tilde{m}^d}{\tilde{m}}\right)^2_{LL} \frac{\tilde{m}^2}{\tilde{m}^2} \left(\frac{\delta\tilde{m}^d}{\tilde{m}}\right)^2_{RR} \frac{\tilde{m}^2}{\tilde{m}^2} < 10^{-13}, \quad \left(\frac{\delta\tilde{m}^d}{\tilde{m}}\right)^2_{LR} \frac{\tilde{m}^2}{\tilde{m}^2} \left(\frac{\delta\tilde{m}^d}{\tilde{m}}\right)^2_{RR} \frac{\tilde{m}^2}{\tilde{m}^2} < 10^{-11}$$

- Require flavor blind SUSY breaking, e.g., gauge mediation,...
  - $\Rightarrow$ MFV phenomenology
Supersymmetry with extended R-symmetry (MRSSM)

G. Kribbs, E. Poppitz, N. Weiner

- with superfield $U(1)_R$ charge assignments: Matter (+1), Higgs (0), Gauge (+1), $U(1)_R$ symmetry forbids

- $A$-terms, $\mu$-term $\Rightarrow$ no left-right squark mass insertions

- Majorana gaugino masses

no squark/gaugino - loop contributions to $\bar{\theta}$

natural framework for the $\text{arg det} M^q = 0$ strategy
gaugino, chargino masses

- add adjoint representation matter superfields $\phi_i \ (R = 0)$ for each gauge group.

- allows $R$-symmetric Dirac gaugino masses $m_i \lambda_i \psi_i$

- add copies $R_u, R_d \ (R = 2)$ of the Higgs superfields $H_u, H_d$

- allows generalized $\mu$-terms $\mu_u H_u R_u + \mu_d H_d R_d$
The Flavor Problem in the MRSSM

- no Majorana gaugino masses ⇒ SUSY meson mixing can be reduced by up to $O(10^5)$ compared to MSSM

- Dirac gauginos do not contribute to sfermion mass RGE’s
  ⇒ heavy gluino mass 3 -5 TeV, and lighter 300 – 500 GeV squarks are natural.
  ⇒ $O(10^2)$ suppression from $1/m_{	ilde{g}}^2$.

- integrating out a heavy Majorana gluino would give

$$\frac{1}{m_{\tilde{g}}} q\tilde{q}^* \tilde{q}^* \Rightarrow \frac{1}{m_{\tilde{g}}^2} \text{ in } \Delta M_K,..$$

with Dirac gluino left with

$$\frac{1}{m_{\tilde{g}}} \tilde{q} \gamma^\mu q\tilde{q}^* \partial_\mu q^* \Rightarrow \frac{1}{m_{\tilde{g}}^2} \frac{\tilde{m}_2^2}{m_{\tilde{g}}^2} \text{ in } \Delta M_K,.. \Rightarrow O(10^2) \text{ suppression from } \frac{\tilde{m}_2^2}{m_{\tilde{g}}^2}$$

- $O(10)$ suppression from different loop integrals
Remarkably weak constraints on squark flavor non-universality

- CP-conserving, $m_{\tilde{g}} = 3$ TeV, $\tilde{m} = 300$ (500) GeV

$$\Delta M_K : \sqrt{|\text{Re}(\delta_{12}^d)_{LL}(\delta_{12}^d)_{RR}|} < 0.15 \ (0.1)$$

$$\Delta M_D : \sqrt{|(\delta_{12}^u)_{LL}(\delta_{12}^u)_{RR}|} < 0.3 \ (0.2)$$

- no constraint for $B_d, B_s$

- $\Delta M_K$ bounds could be satisfied via radiative flavor-diagonal squark masses

- $\epsilon_K : \sqrt{|\text{Re}(\delta_{12}^d)_{LL}(\delta_{12}^d)_{RR}|} < 1.2 \times 10^{-2} \ (7.5 \times 10^{-3})$

- $O(10^2)$ weaker bound than in MSSM

- can a theory of CPV relax this to anarchic level of CP conserving bounds?

- negligible contributions to penguin $B_{d,s}, K, D$ decays
strong CP problem solved

add vectorlike up-quarks $U, \bar{U}$.

allows for suppression of weak phase entering $K - \bar{K}$-mixing.

original choice of vectorlike down quarks can not relax the $\epsilon_K$ bound

vectorlike up quarks $\Rightarrow$ CPV in $D$-mixing easily $O(10\%)$
A few details on the model scan

\[
M_{LR}^u = \begin{pmatrix}
m^u & 0 \\
M_U \bar{a} & \mu
\end{pmatrix}
\]

two physical phases, e.g., \( \bar{a} = (a_1, a_2 e^{i\phi_2}, a_3 e^{i\phi_3}) \)

scan \( \bar{a}, \frac{\mu}{M_U} \), squark mass matrices. Require

- central values of up quark masses, CKM magnitudes within 1 \( \sigma \),
  \[
  \frac{\Delta M_K}{\Delta M_K^{\exp}} \in [0.5, 1.5], \quad \frac{\Delta M_{B_{d,s}}}{\Delta M_{B_{d,s}}^{\exp}} \in [0.7, 1.3], \quad \frac{(\Delta M_{B_d}/\Delta M_{B_s})}{(\Delta M_{B_d}/\Delta M_{B_s})^{\exp}} \in [0.8, 1.2]
  \]

- \( \Delta M_{NP}^D < 2.2 \cdot 10^{-11} \) MeV (90\% c.l.), \( \frac{\epsilon_K}{\epsilon_K^{\exp}} \in [0.7, 1.3], \quad \frac{\sin 2\beta}{\sin 2\beta^{\exp}} \in [0.8, 1.2], \quad \alpha \in [75^\circ, 105^\circ] \)

- physical squark masses \( \in [250, 550] \) GeV

- find \( \frac{\mu}{M_U} \lesssim 10^{-2} \)
New Physics observables

- $D$-mixing,

$$\begin{align*}
R_{D}^{NP} &= \frac{M_{12}^{NP} \text{CKMD}}{|M_{12}^{\exp}|}, \\
\text{CKMD} &= \frac{V_{cs} V_{us}^{*}}{V_{cs}^{*} V_{us}}
\end{align*}$$

- $B_{d}$-mixing, $B_{s}$-mixing

$$\begin{align*}
\frac{M_{12}^{\text{total}}}{M_{12}^{\text{SM}}}, \\
\sin 2\beta_s &= \sin(\arg M_{12} \text{CKMBs}), \\
\text{CKMBs} &= \frac{V_{cb}^{*} V_{cs}}{V_{cb} V_{cs}^{*}}
\end{align*}$$

and similarly for $B_d$

- CKM factors insure phase reparametrization invariance of the observables.

$$\begin{align*}
\epsilon_K &\propto \text{Im}(M_{12} \text{CKMK}), \\
\text{CKMK} &= \frac{V_{us}^{*} V_{ud}}{V_{us} V_{ud}^{*}}
\end{align*}$$

Even though $M_{12}$ real in our basis (phases in $M^u$),
generally $\text{Im}(\text{CKMK}) \neq 0 \Rightarrow$ SUSY contributions to $\epsilon_K$. Similarly for $\sin 2\beta_{d,s}$
For $m_\tilde{g} = 3 \text{ TeV}$, generic scan
for $m_{\tilde{g}} = 3$ TeV new CPV in $B_s$-mixing is $O$(SM). At $m_{\tilde{g}} = 1.5$ TeV effects get interesting.

In general, the $\epsilon_K$ problem can be improved, but the squark degeneracy bound still tighter than for $\Delta M_K$, see CKMK plot.

If $\text{Im}(CKMK) \rightarrow 0$ then $\epsilon^{\text{susy}}_K \rightarrow 0$.

can be arranged if, due to flavor symmetry, weak phase $\phi_2$ can be rotated away e.g., the RH quarks $\bar{u}_1, \bar{u}_2$ only couple to same singlet $N^1$, $\bar{u}_3$ only couples to a second singlet, $N^2$
For $m_{\tilde{g}} = 3$ TeV, $\phi_2 = 0$ scan
Conclusion

- $U(1)_R$ symmetric SUSY is a natural framework for solving the strong CP problem

- By combining the MRSSM with Nelson-Barr can address the $\epsilon_K$ problem, and allow anarchic squark mass matrices

- Counterexample to the statement that O(TeV) New Physics requires a highly specialized flavor structure to evade FCNC’s

- the set-up links the strong CP problem with observable CPV in $D$-mixing

- all of the above should also hold for R-symmetric Hiller-Schmaltz, with wave function renormalization for the RH up quarks. Under investigation