Flavor in supersymmetry with an extended R-symmetry

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...hmmm... extended R-symmetry...

or not enough oxygen?

inspiration from above

base ~ 2100 m.

Pointe Percée 2753 m.

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Oregon, Toronto, and New York U.
the LHC is turning on soon ... what do we expect?

Standard Model is incomplete -
perhaps supersymmetry - the assumption of this talk

supersymmetry “doubles” the particle spectrum

but supersymmetry is broken

>100 “soft” supersymmetry-breaking parameters:
squark and slepton masses, gaugino masses, A-terms...

generic values of superparticle masses - e.g., nondegenerate
squarks and sleptons are excluded by precision measurements
K-Kbar mixing still strongest constraint

- the “supersymmetric flavor problem”
who fixes the soft parameters?

- usually assume flavor blind mechanism of generating soft parameters
  (of “mediating” supersymmetry breaking)
  gauge mediation, anomaly mediation, gaugino mediation, mirage...

- or decouple flavor violation - as in “more minimal supersymmetry”

- flavor symmetries may solve problem - must be nonabelian
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an exciting and different possibility is to have large flavor violation in superpartner sector, but be “shielded” from its effects in low-energy experiments

• turns out this is possible in a simple extension of the MSSM by postulating an enhanced R-symmetry - call it the “MRSSM”
  
  • will explain the “miracles” at work
  
  • new signatures at the LHC detailed study Kribs, Roy in progress
    new possibilities for dark matter e.g., Weiner et al in progress
    new avenues for model building e.g., Fox, E.P. in progress

• most importantly if this is true we will know soon!
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Outline/Summary/Conclusions:

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  • most importantly if this is true we will know soon!
to explain the “miracles” at work - first recall constraints in squark nondegeneracy from $\Delta(S) = 2$: $\delta_{ij} = \frac{M_{ij}}{|m_o|^2}$

most favorable (least constrained) case occurs if $\delta_{eR} = \delta_{\tilde{e}_L} = 0$

two-component notation: undotted R-handed fermions are antiparticles

then, for “natural” $\sim 500$ GeV squark and gauginos $\Delta M_{\nu\tilde{\nu}} < 10^{-6}$ eV

implies $|\delta_{\tilde{e}_L}| < 6 \times 10^{-2}$
for general nondegeneracy, we also have:

\[ \sim \frac{1}{m_0^2} \delta_{LR} \bar{d}_c \bar{s}_R \bar{s}_L d_L \]

\[ \sim \frac{1}{m_0^2} |\delta_{LR}|^2 \bar{d}_c \bar{s}_R d_L \bar{s}_L \]

\[ \sim \frac{1}{m_0^2} \delta_{LR}^2 \bar{d}_c \bar{d}_c \bar{s}_L \bar{s}_R \bar{s}_L \bar{s}_R \]

the **supersymmetric flavor problem** - small numbers below need explanation:

\[ \sqrt{|\delta_{LR} \delta_{RR}|} < 2 \times 10^{-3} \]

\[ \sqrt{|\delta_{UL} \delta_{RR}|} < 10^{-3} \]

detailed bounds in e.g., Gabbiani Masiero, 1989 + ...
explain the “miracles” at work -
Dirac (R) vs Majorana (no R) gauginos?

consider the box diagram in the gauginos heavier than squarks limit:

- Majorana dim-5 operator R-violating

- Dirac dim-6 operator R-preserving
explain the "miracles" at work: in Dirac gaugino \((R)\) case,

contract two \(\frac{\partial}{\partial \omega_{1/2}^2}\) vertices to get \(\Delta(S)=2\) transition

finite loop dominated by \(\text{IR} \sim m_{\text{squark}}\) momenta:

\[
\sim \frac{1}{m_c^2} \left( \frac{\omega_c}{\omega_{1/2}} \right)^4 \bar{d}_c \bar{d}_c \bar{s}_c s_c |\delta_{Lc}|^2
\]
explain the “miracles” at work: in Dirac gaugino (R) case,

contract two $\frac{\partial^R}{\partial \mu^2}$ vertices to get $\Delta(S)=2$ transition

finite loop dominated by $\text{IR} \sim m_{\text{squark}}$ momenta:

\[
\frac{1}{\mu^2} \left( \frac{\mu_0}{\mu_{1/2}} \right)^4 \bar{d}_L \cdot \bar{d}_L \delta_{L_L}^2 \delta_{\bar{L}_R}^2
\]

now, recall that a generic weak-strength/weak-cutoff $\Delta(S)=2$ contribution,

e.g.:

\[
\Delta \sim (\bar{d}_s)(\bar{d}_s) \frac{G_F^2 \Lambda_{uv}^2}{16 \pi^2} \text{ with } \Lambda_{uv} \sim \frac{1}{\sqrt{G_F}}
\]

gives $\Delta M_{k\bar{k}} \sim 10^{-2} \text{ eV} \gg 10^{-6} \text{ eV}$ (\sim the measured value)
explain the “miracles” at work: in Dirac gaugino (R) case,

contract two $\frac{\partial^4}{\omega_{1/2}^2}$ vertices to get $\Delta(S)=2$ transition

finite loop dominated by $\text{IR} \sim m_{\text{squark}}$ momenta:

\[ \sim \frac{1}{m_o^2} \left( \frac{\omega_o}{\omega_{1/2}} \right)^4 \bar{d}_L \bar{d}_L \bar{s}_L \bar{s}_L |\delta_{LL}|^2 \]

now, recall that a generic weak-strength/weak-cutoff $\Delta(S)=2$ contribution,

\[ \sim (\bar{d}s) (\bar{d}s) \frac{G_F^2 \Lambda_{\text{IR}}^2}{16 \pi^2} \] with \[ \Lambda_{\text{UV}} \sim \frac{1}{\sqrt{G_F}} \]

gives $\Delta m_{K}\bar{K} \sim 10^{-2} \text{eV} \gg 10^{-6} \text{eV}$ (~the measured value)

so, we have “miracle” #1: if $\left( \frac{\omega_o}{\omega_{1/2}} \right)^4 \sim 10^{-4}$ for Dirac gluinos nondegenerate squarks compatible with K-Kbar mixing
explain the “miracles” at work: in Dirac gaugino (R) case,

contract two \( \frac{d^4}{\omega_{1/2}^2} \) vertices to get \( \Delta(S)=2 \) transition

finite loop dominated by \( \text{IR} \sim m_{\text{squark}} \) momenta:

\[
\begin{align*}
&\sum_{i} \frac{1}{m_i^2} \left( \frac{w_0}{\omega_{1/2}} \right)^4 \bar{d}_c \bar{d}_c \ s_c \ s_c \ |\delta_{cL}|^2
\end{align*}
\]

now, recall that a generic weak-strength/weak-cutoff \( \Delta(S)=2 \) contribution,

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\text{e.g.:} & \quad \sum_{i} \frac{1}{m_i^2} \left( \frac{w_0}{\omega_{1/2}} \right)^4 \bar{d}_c \bar{d}_c \ s_c \ s_c \ |\delta_{cL}|^2
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with \( \Lambda_{uV} \sim \frac{1}{G_F} \)

gives \( \Delta m_{K\bar{K}} \sim 10^{-2} \text{eV} \gg 10^{-6} \text{eV} \) (~the measured value)

so, we have “miracle” #1: if \( \left( \frac{w_0}{\omega_{1/2}} \right)^4 \sim 10^{-4} \) for Dirac gluinos nondegenerate squarks compatible with K-Kbar mixing

we also have “miracle” #2: with Dirac gauginos, \( \frac{w_0}{\omega_{1/2}} \sim \frac{1}{10} \) is natural
"miracle" #2: with Dirac gauginos, \( \frac{\mu_0}{\mu_{1/2}} \sim \frac{1}{10} \) is natural

Dirac gauginos have N=2 vector multiplet structure:

\[
\begin{array}{c}
\omega \\
\lambda \\
\Phi \\
\end{array}
\]

Dirac gaugino mass from D-term supersymmetry breaking spurion: \( \left[ \Theta^a \phi^a \right] \) or \( \bar{D}^2 D^\alpha \theta^4 m_D \)

via operator: \( \int d^2 \theta \left[ \Theta^a \phi^a \right] W^a \phi^a \) Polchinski, Susskind, 1985

realizing "supersoft" supersymmetry breaking Fox, Nelson, Weiner, 2002

"supersoft" - as can be seen in many ways, e.g., at one loop due to N=2 structure - finite, instead of log-divergent contribution of gaugino mass to scalar mass: \( \delta m_0^2 \sim \frac{m_D^2}{16\pi^2} \)

more details on spectra: Blechman, Kaplan, Weiner..., in progress

thus, the "miracles" at play, due to "supersoft"/Dirac nature

= weak K-Kbar constraints

(weaker ones from B_d, and even less from B_s oscill.)
how weak are the K-Kbar constraints, really?

R-symmetric model has no LR mixing (from A- or mu- term), so bounds on LL and RR only

LO QCD corrections recently computed yielding 2x stronger constraints (Blechman, Ng, 2008)

from same plot, since $\epsilon_K$ down by $6 \times 10^{-3}$ - phases in squark masses should be small (or even exact CP) or else invoke moderate degeneracy...

cf. MSSM: squarks, gluinos >500 TeV for delta=1!

how about Delta(F)=1? -
before describing limits, note that the R-symmetry of the Dirac gauginos can be **beneficially** promoted to an exact symmetry of the MSSM --- “**MRSSM**”...

**why?**

- because the vast majority of supersymmetric flavor problems arise from R-violation

  *R-violating* Majorana masses and mu-term: allow chirality flip on gaugino/higgsino lines

  *R-violating* A-terms allow LR scalar mass mixing

  *Hall and Randall (1990)* constructed an R-symmetric model and discovered the suppression of EDMs; as written their model is ruled out by LEP: \( m_{\text{wino}} = m_W \), one-loop suppressed photino mass....

- many (metastable) vacua with broken supersymmetry preserve R (or a discrete subgroup)...

**our proposal:** \( U(1) \) or \( Z_{2n}, n>1 \) **exact R-symmetry**

Kribs, EP, Weiner
our proposal: $U(1)$ or $Z_{2n, n>1}$ exact R-symmetry

usual R-charges of MSSM superfields:

$R = 2$ superpotential

1 $W_\alpha$ super field strength (and gaugino) - Dirac gaugino masses for all gauginos - require adjoint chiral fields with supersoft operator
1 $Q, u, d, L, e$
0 $H_u, H_d$ - R-symmetric Higgsino masses - require two additional Higgs doublets of $R=2$: $R_u$ and $R_d$ - $R_u$, $R_d$ do not couple to matter

the “MRSSM”

- no Majorana gaugino/higgsino masses
- $\Delta L = 2$ Majorana neutrino mass allowed (dim-5)
- no dim-5 proton decay, no $\Delta B = 1$ and $\Delta L = 1$
- no mu-term, instead two mu’ terms: $\int d^2 \theta \mu_u H_u R_u + \mu_d H_d R_d$
- B-mu term is allowed
- no LR scalar mass mixing through A- or mu- terms
benefits?

\[ \Delta(F) = 2: \]
- as explained

EDMs:
- counting of phases beyond flavor sector - \emph{a priori} one more phase than in MSSM
- however, all 1- and 2-loop EDMs require A-, mu-, or Majorana insertions - \emph{absent here!}

\textit{while MSSM electron and neutron EDMs require phases as small as < 0.001 for O(100) GeV supersymmetric mass...}

- leading neutron EDM in “MRSSM” arises through the Weinberg operator, yields no significant constraint on flavor-diagonal phases

essentially, Dirac gaugino mass and \textquoteleft mu’ terms can be “rephased” without consequence

strong-CP:
- needs a solution as in MSSM ...

\textit{spontaneous CP violation a la Barr-Nelson or Hiller-Schmaltz can be incorporated naturally as both mechanisms require significant flavor violation to work} \quad Weiner et al in progress
$b \rightarrow s\gamma$ and $\mu \rightarrow e\gamma$:

- both involve a helicity flip in diagram
- but for Dirac gauginos, opposite helicity state (chiral adjoint) has no coupling to matter

in MSSM, most constrained are $\delta_{eL}$ insertions, absent here only (smaller) contributions with

external line helicity flip or gaugino-Higgsino (both Dirac) mixing

Contours of $\delta$ where $BR_{\mu\rightarrow e\gamma} = 1.2 \times 10^{-11}$ for $\delta_{LL} = \delta$, $\delta_{RR} = 0$, $m\tilde{B} = m\tilde{W}/2$.

Kribs, EP, Weiner

$0 < \delta < 0.007$
large tan(beta) flavor violation:

in MSSM, up-type Higgs can couple to down-type quarks at one loop -

- this coupling can be the leading source of flavor violation at large tan(beta);
  in mixing as well as decays, i.e. $B \rightarrow \mu\mu$

- in MRSSM, absent - require mu- and Majorana- or A-term insertions

  PQ symmetry forbidding up-Higgs coupling to down quarks broken only by
  dim-2 B-mu term, no dim-3 mu-term contribution as in MSSM

hence, modified Higgs sector in “MRSSM” addresses large tan(beta) flavor problems as well
Rough Spectrum

10 TeV

1 TeV

100 GeV

Squark and slepton mass matrices completely arbitrary in size and phase*!

Dirac gluino and Wino heavy.

New particles: color octet, weak triplet scalars
R_u,R_d scalars and fermions

...a 'pre-QCD corrections' slide stolen from Graham Kribs - in reality, for not-too-heavy, e.g., not >10 TeV but only a few TeV, gluinos ~ 30% nondegeneracy allowed

*[The only exception is \( \epsilon_k \) that requires \( \text{Im}[\delta_{LL12}\delta_{RR12}] < 0.01 \); so that, e.g., no more than 0.1 phase is permitted in LL and RR]
possible signatures at the LHC?

apart from seeing the new adjoint/$R_U, R_D$ (R-charge 2 higgses) states charged under SM gauge group

Dirac nature of gauginos - no like-sign dilepton (signature of Majorana gauginos)
however, gauginos may be too heavy for pair production at LHC

signals of flavor nondegeneracy - e.g. single top production via squarks

detailed study needed
- G. Kribs, T. Roy, in progress

similarly, slepton production with unlike flavor final states
studied in the past, e.g. Bityukov, Krasnikov 1997 + ...
some obvious issues I didn’t go into...

not the usual unification - but SU(3)$^3$ naturally fits

where does it come from? -
for example, can be realized in R-symmetric
supersymmetry-breaking vacua

$U(1)_Y$ “adjoint” (= SM singlet) tadpole?
- discrete symmetry easy to incorporate

supergravity R-breaking effects
- must be small, or absent...

note that all these are UV...
...while staying in the IR, we

- found that much of flavor violation in supersymmetry is tied to R-violation
- showed that an R-symmetric extension of the MSSM:
  - allows for significant flavor non-degeneracy among squarks and leptons
  - opens the door for more model building...
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... the near future will tell how the pieces fit together...