Flavor in supersymmetry with an extended R-symmetry

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Pointe Percée 2753 m.

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

or not enough oxygen?

inspiration from above

base ~ 2100 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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• 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:
\[
\delta_{ij} = \frac{m_{ij}}{|m_i|^2}
\]

most favorable (least constrained) case occurs

\[
i f \quad \delta_{\ell\ell} = \delta_{\ell'} = 0
\]

then, for “natural” ~ 500 GeV squark and gauginos

\[
\Delta M_{\nu\nu} < 10^{-6} \text{ eV}
\]

implies

\[
|\delta_{\ell\ell}| < 6 \times 10^{-2}
\]
the "supersymmetric flavor problem" - small numbers below need explanation:

\[ |\tilde{d}_L \cdot \tilde{s}^c_R| < 2 \times 10^{-3} \]

\[ |\tilde{d}_L \cdot \tilde{d}_R| < 10^{-3} \]

for general nondegeneracy, we also have:

\[ \sim \frac{1}{m^2} |\sigma_{LR}|^2 \tilde{d}_L \cdot \tilde{s}^c_R \tilde{s}^c_R \tilde{d}_R \tilde{s}^c_L \]

\[ \sim \frac{1}{m^2} |\sigma_{LR}| \tilde{d}_L \cdot \tilde{d}_L \tilde{s}^c_R \tilde{s}^c_R \tilde{d}_R \tilde{s}^c_L \]
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 \( \frac{\partial \Gamma}{\partial \mu^2_{1/2}} \) vertices to get Delta(S)=2 transition

finite loop dominated by IR \( \sim m_{\text{squark}} \) momenta:
explain the "miracles" at work: in Dirac gaugino (R) case,

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

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

\[
\sim \frac{1}{m_c^2} \left( \frac{\omega_c}{\omega_{1/2}} \right)^4 \bar{d}_c \cdot \bar{d}_c \quad s_c \cdot s_c \quad |\delta_c|^2
\]

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

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

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

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

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

\[ \Delta(S) = \frac{1}{m_o^2} \left( \frac{\omega_o}{\omega_{1/2}} \right)^4 \bar{d}_L \bar{d}_L \bar{s}_L \bar{s}_L \{ \delta \xi \}^2 \]

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

e.g.: 

\[ \Delta M_{kk'} \sim 10^{-2} \text{ eV} \gg 10^{-6} \text{ eV} \quad (\sim \text{the measured value}) \]

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 $\frac{\partial F}{\partial \bar{w}_{1/2}}$ vertices to get Delta(S)=2 transition

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

\[
\begin{align*}
\text{finite loop dominated by IR } & \sim m_{\text{squark}} \\
\text{momenta:} & \\
\end{align*}
\]

now, recall that a generic weak-strength/weak-cutoff Delta(S)=2 contribution,
e.g.:

\[
\begin{align*}
\text{gives } & \Delta M_{\kappa \bar{\kappa}} \sim 10^{-2} \text{ eV} \gg 10^{-6} \text{ eV} \\
\end{align*}
\]

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

we also have “miracle” #2: with Dirac gauginos, \(\frac{\omega_o}{\omega_{1/2}} \sim \frac{1}{10}\) is natural
“miracle” #2: with Dirac gauginos, $\frac{\omega_0}{\omega_{1/2}} \sim \frac{1}{10}$ is natural

Dirac gauginos have N=2 vector multiplet structure:

\[
\begin{pmatrix}
\lambda^a \\
\phi^a \\
\end{pmatrix}
\]

Dirac gaugino mass from D-term supersymmetry breaking spurion: $m_D\omega_0 \lambda^a \phi^a$

via operator: $\int d^2 \theta \left( \Theta^a \lambda^a \right) \omega^2 \phi$  

realizing “supersoft” supersymmetry breaking  

“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...

how about Delta(F)=1?  

Kribs, EP, Weiner

**LL only**

$\delta LL=1$

$m_{\tilde{g}}$/TeV vs $m_{\tilde{q}}$/GeV

- 0.1
- 0.3

**LL=RR**

$\delta LL=\delta RR=1$

$m_{\tilde{g}}$/TeV vs $m_{\tilde{q}}$/GeV

- 0.03
- 0.1
- 0.3

cf. MSSM: squarks, gluinos $>500$ TeV for $\delta LL=1$!
before describing limits, note that the R-symmetry of the Dirac gauginos can be \textbf{beneficially} promoted to an exact symmetry of the MSSM --- "$\text{MRSSM}$"...

\textit{why?}

- because the vast majority of supersymmetric flavor problems arise from \textit{R-violation}

\textbf{R-violating} Majorana masses and mu-term: allow chirality flip on gaugino/higgsino lines

\textbf{R-violating} A-terms allow LR scalar mass mixing

\textit{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 suppresed photino mass....

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

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

usual R-charges of MSSM superfields:

\[
R = 2 \quad \text{superpotential} \\
1 \quad W_\alpha \text{ super field strength (and gaugino)} \\
1 \quad Q,u,d,L,e \\
0 \quad H_u,H_d \quad \text{R-symmetric Higgsino masses} \\
\]

\(-\) Dirac gaugino masses for all gauginos - require adjoint chiral fields with supersoft operator
\(-\) 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 - *a priori* one more phase than in MSSM
- however, all 1- and 2-loop EDMs require A-, mu-, or Majorana insertions - *absent here!*
  
  *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 mu’ terms can be “rephased” without consequence

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

  *spontaneous CP violation *a la* Barr-Nelson or Hiller-Schmaltz can be incorporated naturally as both mechanisms require significant flavor violation to work*  

  Weiner et al in progress
\[ b \to s\gamma \quad \text{and} \quad \mu \to e\gamma: \]
- 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 \( \delta_{\ell\ell} \) insertions, absent here

only (smaller) contributions with external line helicity flip or gaugino-Higgsino (both Dirac) mixing

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

Kribs, EP, Weiner

cf. MSSM: for \( \delta < 0.007 \)

\[ m_{\tilde{B}}/\text{GeV} \]

\[ m_{\tilde{L}}/\text{GeV} \]

... MEG experiment?
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

Hamzaoui, Pospelov, Toharia 1998
Rough Spectrum

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

*[The only exception is $\epsilon_k$ that requires $\text{Im}[^{\delta_{LL_2}}_{\delta_{RR_2}}] < 0.01$; 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 \_\_\_d \_\_d \_d \_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, Krasnikov1997 + ...
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...