UC Davis
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Supersymmetric Flavor Problem, R Symmetry, and the LHC

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Flavor in Supersymmetry?

Let me first establish notation by briefly discussing flavor in the SM.

Flavor in SM

Flavor originates in the Yukawa couplings:

$$Y^u_{ij}\, Q_i H \bar{u}_j + Y^d_{ij}\, Q_i H^\dagger \bar{d}_j + Y^e_{ij}\, L_i H^\dagger \bar{e}_j$$

The Y's are arbitrary complex 3x3 matrices in flavor space.

Inserting the vev for the Higgs:

$$\begin{pmatrix} u_1 & u_2 & u_3 \end{pmatrix} \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & Y^u & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} v \begin{pmatrix} \bar{u}_1 \\ \bar{u}_2 \\ \bar{u}_3 \end{pmatrix}$$

$$\begin{pmatrix} d_1 & d_2 & d_3 \end{pmatrix} \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & Y^d & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} v \begin{pmatrix} \bar{d}_1 \\ \bar{d}_2 \\ \bar{d}_3 \end{pmatrix}$$

Do the standard diagonalization,

$$Y^u \rightarrow U^T Y^u \bar{U}$$

$$Y^d \rightarrow D^T Y^d \bar{D}$$

rotating the quarks, to obtain, e.g.,

$$(d \;\; s \;\; b) \begin{pmatrix} \lambda_d v & 0 & 0 \\ 0 & \lambda_s v & 0 \\ 0 & 0 & \lambda_b v \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

leaving the only residual in the weak interactions:

$$u^\dagger \gamma^\mu d \rightarrow u^\dagger \underbrace{U^\dagger D}_{V_{\rm CKM}} \gamma^\mu d$$

Flavor in Supersymmetry

In minimal weak-scale SUSY, there is a plethora of soft breaking parameters that also "know" about flavor:

$$\tilde{Q}_i^\dagger m^2_{Q\,ij} \tilde{Q}_j + \tilde{\bar{u}}_i^\dagger m^2_{u\,ij} \tilde{\bar{u}}_j + \ldots$$

squark,slepton (mass)^2 matrices

$$A^u_{ij} \tilde{Q}_i \tilde{H}_u \tilde{\bar{u}}_j + A^d_{ij} \tilde{Q}_i \tilde{H}_d^\dagger \tilde{\bar{d}}_j + A^e_{ij} \tilde{L}_i \tilde{H}_d^\dagger \tilde{\bar{e}}_j$$

scalar trilinear couplings

After rotating superfields to remove Y^u Y^d Y^e, these mass parameters remain, in general,

$$m^2_{Q_{ij}} = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$$

"LL" mixing

$$m^2_{d_{ij}} = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$$

"RR" mixing

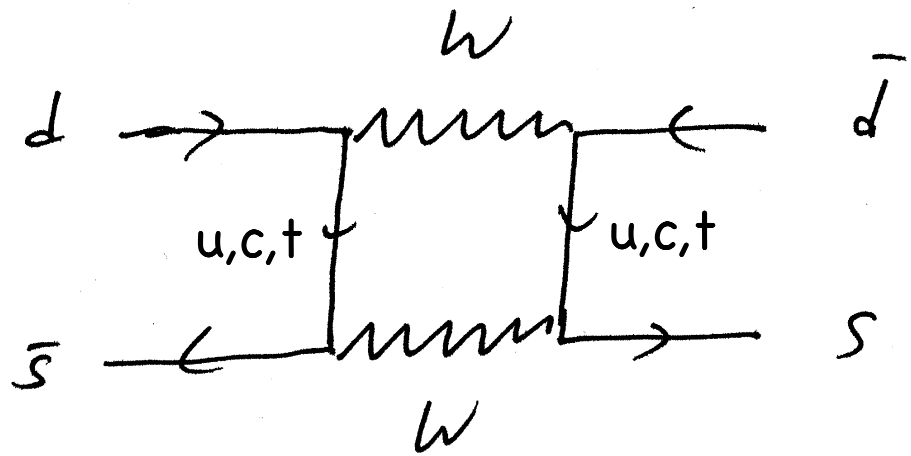
$$A^d_{ij} = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$$

"LR" mixing

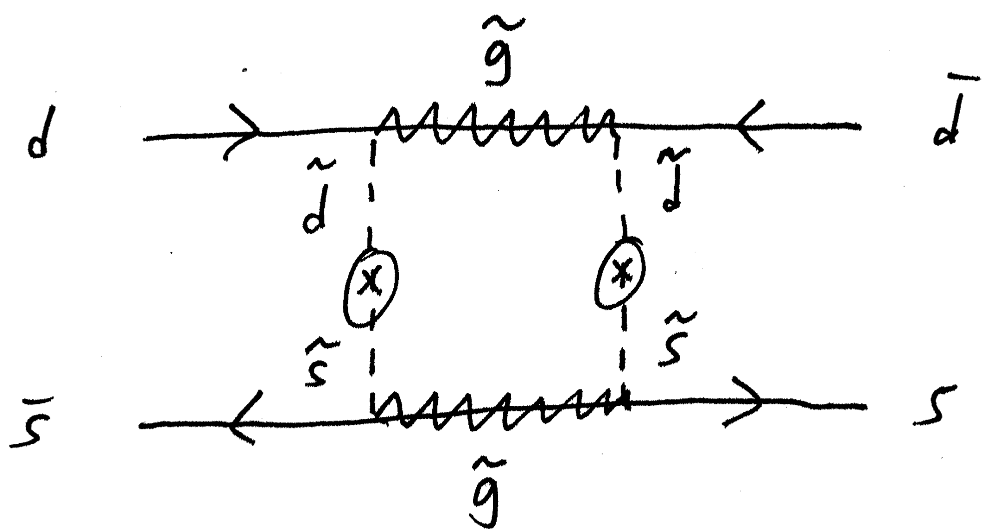
Not diagonal in flavor space.

Supersymmetric Flavor Problem

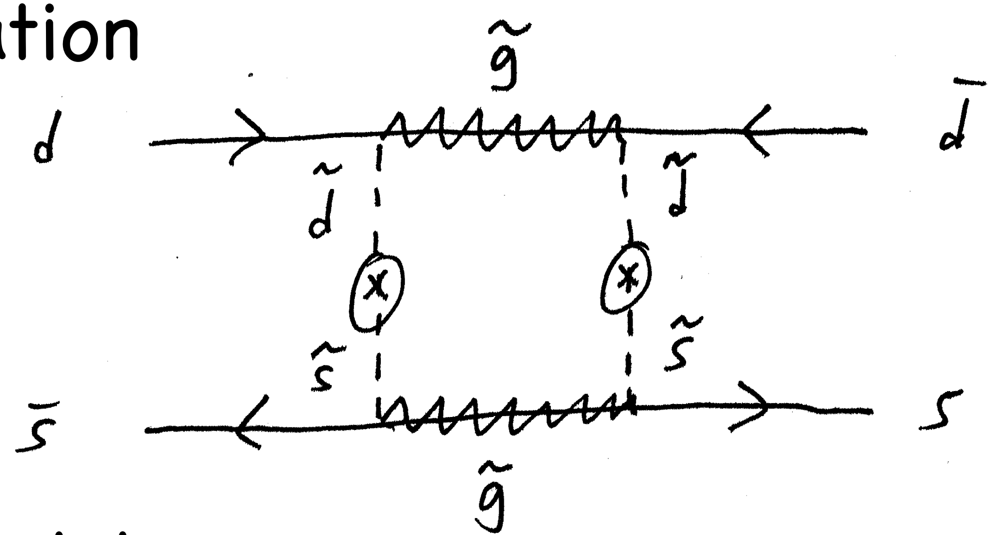
For example, K^0-$\overline{K}^0$ mixing



Has contributions from superpartner loops



The contribution



is proportional to

$$\Delta m_K \propto \alpha_s^2 \left(\frac{\tilde{m}^2_{12}}{\tilde{m}^2_q}\right)^2 \frac{1}{M^2_{\tilde{g}}}$$

Putting in the numbers...

$$\delta_{12} \equiv \frac{\tilde{m}^2_{12}}{\tilde{m}^2_q} < 0.06 \rightarrow 10^{-3} \quad \left\{ \begin{array}{l} \tilde{m}_q = 500\,\mathrm{GeV} \\ M_{\tilde{g}} = 500\,\mathrm{GeV} \end{array} \right.$$

(range depending on “LL”, “RR”, or “LR” mixings)

B^0–$\overline{B}^0$ mixing

SUSY flavor problem extends beyond (12) mixing...

$$\Delta m_B \propto \alpha_s^2 \left(\frac{\tilde{m}_{13}^2}{\tilde{m}_q^2} \right)^2 \frac{1}{M_{\tilde{g}}^2}$$

Putting in the numbers...

$$\delta_{13} \equiv \frac{\tilde{m}_{13}^2}{\tilde{m}_q^2} < 0.1 \to 0.02 \left\{ \begin{array}{l} \tilde{m}_q = 500 GeV \\ M_{\tilde{g}} = 500 GeV \end{array} \right.$$

(range depending on "LL", "RR", or "LR" mixings)

Many Flavor Problems

Horrendous problems also with:

- LFV (μ->eγ; τ->$\mu\gamma$)
- ϵ'/ϵ
- ϵ_K [Im(Δm_K)]
- b->sγ
- flavor at large tan β (e.g., B -> $\mu\mu$)

As well as serious related problems with:

- contributions to EDMs of e,n,Hg...
- proton decay through dim-5 (QQQL, ...)

Naive supersymmetrization of the Standard Model (MSSM + flavor-arbitrary) is completely ruled out by existing FCNC constraints unless sparticles are extremely heavy -- far beyond what the LHC can find.

Is there a mechanism to ensure that the SUSY contributions to FCNC are sufficiently small?

15 Years of Model Building...

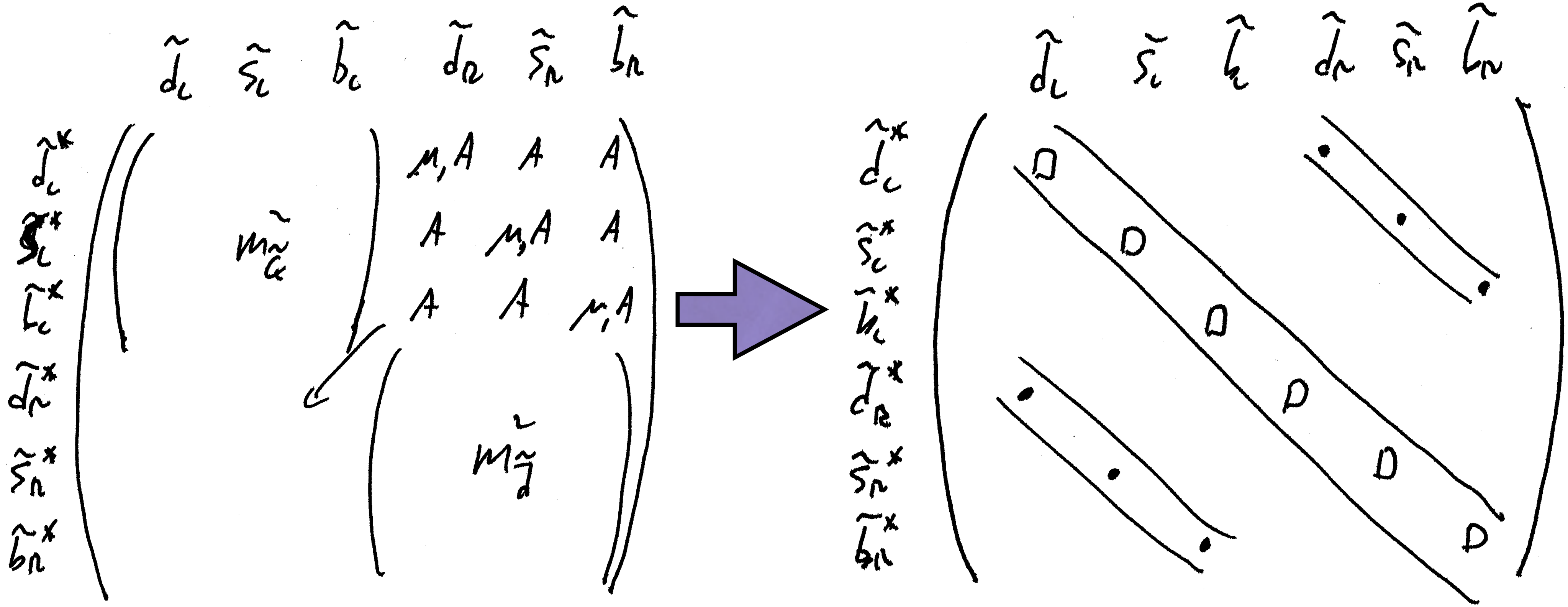
Gauge Mediation (1980s-1990s)
- complicated models; messenger/matter mixing;
- μ-term; unification?; dark matter?

Anomaly Mediation (1998)
- sequestering; μ-term;
- slepton $(\text{mass})^2$ negative

Gaugino Mediation (1999)
- sequestering; μ-term

... and many others ...

…have attempted to justify:



The "lore" is that SUSY breaking must be flavor-blind.

R Symmetry

N=1 Supersymmetry contains $U(1)_R$ symmetry

In terms of the superspace coordinates:

$$\theta \quad \longrightarrow \quad e^{i\alpha}\theta$$
$$\bar{\theta} \quad \longrightarrow \quad e^{-i\alpha}\bar{\theta}$$

A general superfield (quark, lepton, Higgs)

$$\Phi = \phi + \sqrt{2}\theta\psi + \theta^2 F$$

with charge "R" under $U(1)_R$ transforms as

$$\begin{aligned} e^{iR\alpha}\Phi &= (e^{iR\alpha}\phi) \\ &\quad + \sqrt{2}\theta(e^{i(R-1)\alpha}\psi) \\ &\quad + \theta^2(e^{i(R-2)\alpha}F) \end{aligned}$$

R symmetry transforms a scalar and fermion differently. It smells like R-parity (but it's not).

R charges of MSSM

$$\mathcal{L} = \int d^2\theta \, W[\Phi] + h.c. + \int d^2\theta d^2\bar{\theta} K[\Phi, \Phi^\dagger]$$

2 superpotential

1 W_α super field strength (and gaugino)

1 Q,u,d,L,e

0 H_u,H_d

R symmetry and SUSY Breaking

The simplest model of (global) supersymmetry breaking, the O'Raifeartaigh model, preserves $U(1)_R$,

$$W = \mu^2 X + c_{ij} X \Phi_i \Phi_j + m_{ij} \Phi_i \Phi_j$$

For suitable choices of c_{ij} and m_{ij}, $\langle F_X \rangle$ nonzero, spontaneously breaking SUSY.

Since $R[X]=2$, then $R[F_X]=0$,
$\langle F_X \rangle$ preserves R symmetry.

Metastable SUSY Breaking

Intriligator, Seiberg, Shih (2006-7) realized that a wide class of supersymmetric theories have metastable SUSY breaking vacua.

The low energy descriptions appear as variations of O'Raifeartaigh models.

Generically the metastable local SUSY breaking minimum has an accidential continous R-symmetry.

Dine, Feng, Silverstein (2006) showed explicit examples where the R symmetry breaks, but to a larger discrete subgroup Z_{2N}.

The “Problem” of R Symmetry

Gaugino Mass versus R Symmetry

Unbroken R symmetry historically was considered a problem.

The phenomenological issue is generating gaugino masses. Usually this is done:

$$\int d^2\theta \, \frac{X}{M_{\rm Pl}} W_\alpha W^\alpha \;\to\; \frac{F_X}{M_{\rm Pl}} \lambda\lambda + h.c.$$

resulting in a Majorana mass for the gauginos.

But this violates the R symmetry since R[λλ]=2.

Dirac Gaugino Masses

Fox, Nelson, Weiner (2002) emphasized that gauginos could acquire Dirac masses through a different type of operator:

$$\int d^2\theta \, \frac{W'_\alpha}{M_{\rm Pl}} W^\alpha \Phi \;\rightarrow\; \frac{D}{M_{\rm Pl}} \lambda\psi + h.c.$$

where the gauge fermion is paired up with the fermionic component of Φ [adjoint under SM].

Here, supersymmetry breaking arises from a D-term [such as hidden sector U(1)′].

GK, Poppitz, Weiner:

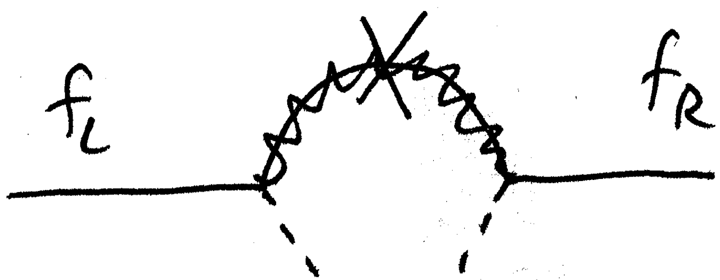
We realized:

The vast majority of the supersymmetric flavor problem arises from R violating interactions.

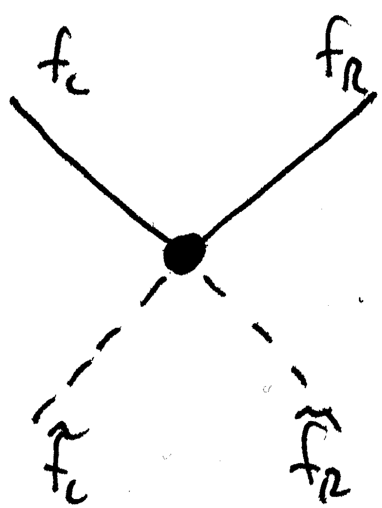
What violates R symmetry in MSSM?

Majorana masses, A-terms, and μ-term. They allow:

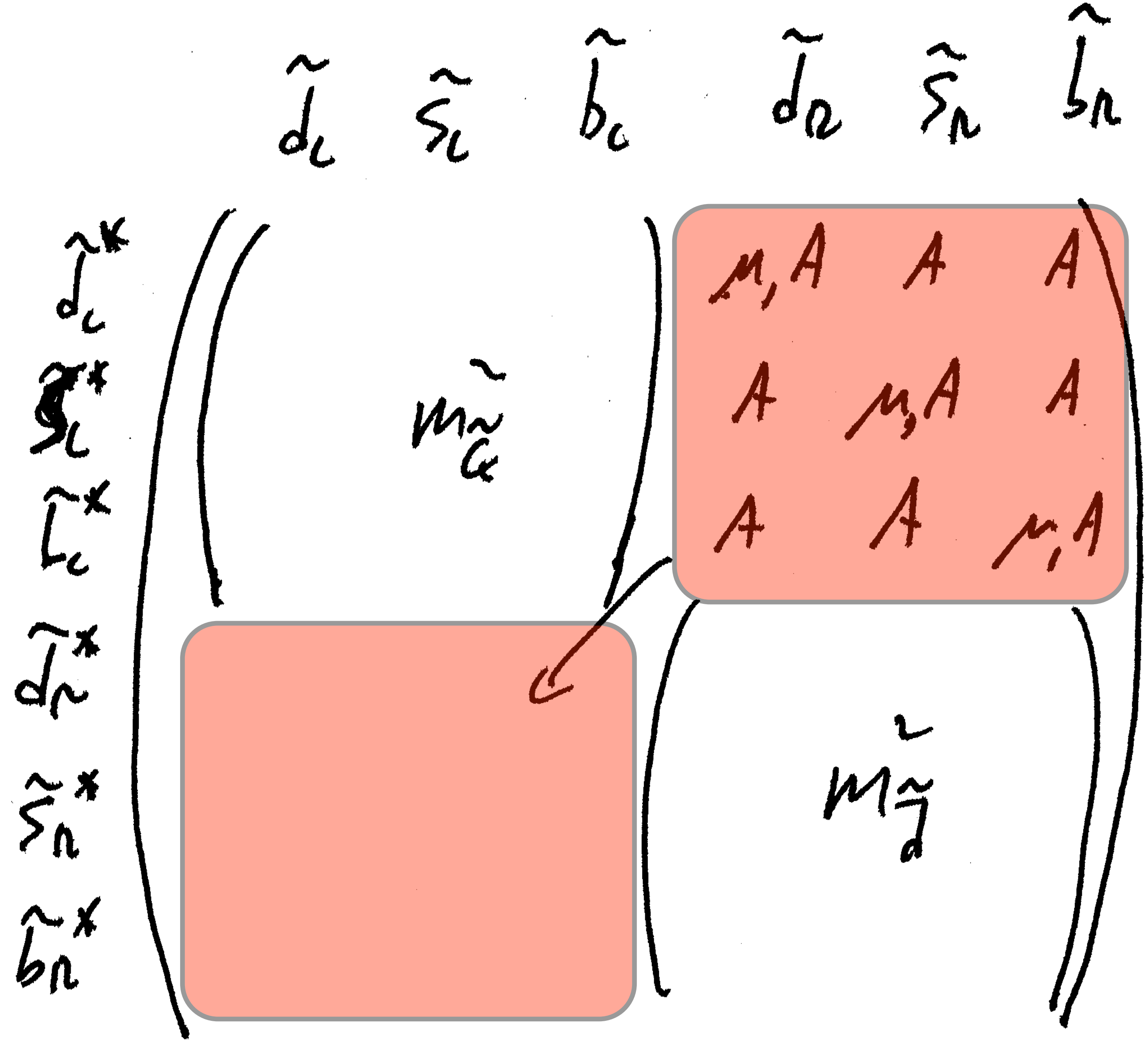
(1) chirality flip on gaugino/Higgsino lines:



(2) effective dim-5 operators suppressed by $1/M_g$ or $1/\mu$:



(3) LR scalar mass mixing:



R Symmetric SUSY

Hall-Randall (1990)

Proposed a weak-scale model with R symmetry.

They had:

- gluino Dirac mass (chiral adjoint added)
- no μ-term
- m(Wino) = m_W (paired with charged Higgsino)
- m(Zino) = m_Z (paired with neutral Higgsino)
- m(photino) = one-loop suppressed; top-stop loop pairing photino with other neutral Higgsino.

Discovered the suppression of EDMs.

Alas, this model as written is ruled out by LEP II.

Our Proposal:

Replace the MSSM with an R symmetric supersymmetric weak-scale model.

[Could be continous $U(1)_R$ or discrete subgroup Z_{2N} (N>=2)]

We have: R symmetric Dirac gaugino masses for all gauginos; R symmetric Higgsino masses.

Dirac gaugino masses

Require additional fields:

$$\Phi_{\tilde{g}} \qquad (\mathbf{8}, \mathbf{1}, 0)$$

$$\Phi_{\tilde{W}} \qquad (\mathbf{1}, \mathbf{3}, 0) \qquad R[\Phi_i] = 0$$

$$\Phi_{\tilde{B}} \qquad (\mathbf{1}, \mathbf{1}, 0)$$

Coupled to a SUSY breaking spurion $W'_\alpha = D\theta_\alpha$

$$\int d^2\theta \, \frac{W'_\alpha}{M_{\mathrm{Pl}}} W^\alpha \Phi \rightarrow \underbrace{\frac{D}{M_{\mathrm{Pl}}}}_{m_D} \lambda\psi + h.c.$$

R symmetric μ-terms

Require additional fields:

$$R_u \qquad (\mathbf{1}, \mathbf{2}, -1/2) \qquad R[R_u] = 2$$

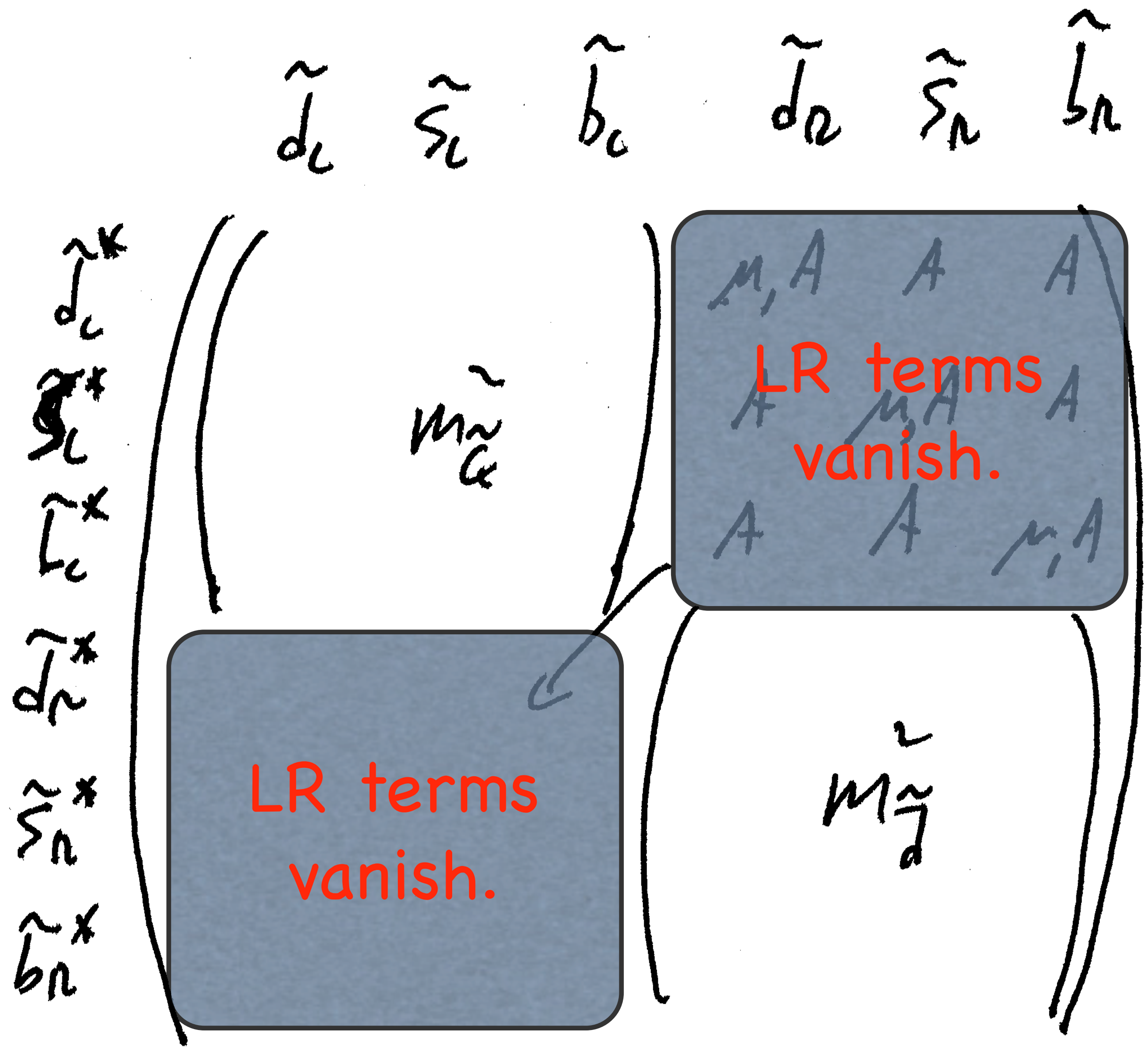
$$R_d \qquad (\mathbf{1}, \mathbf{2}, +1/2) \qquad R[R_d] = 2$$

Coupled to the Higgs in an R-symmetric way:

$$\mathcal{L} = \int d^2\theta \, \mu_u H_u R_u + \mu_d H_d R_d$$

Since just H_u,H_d couple to matter, their (mass)^2 are naturally driven negative, leading to R-symmetric EWSB.

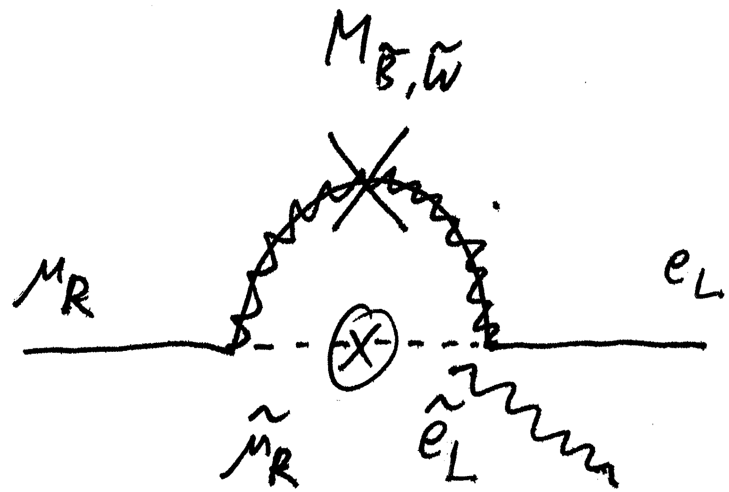
R symmetric scalar masses: LR absent!



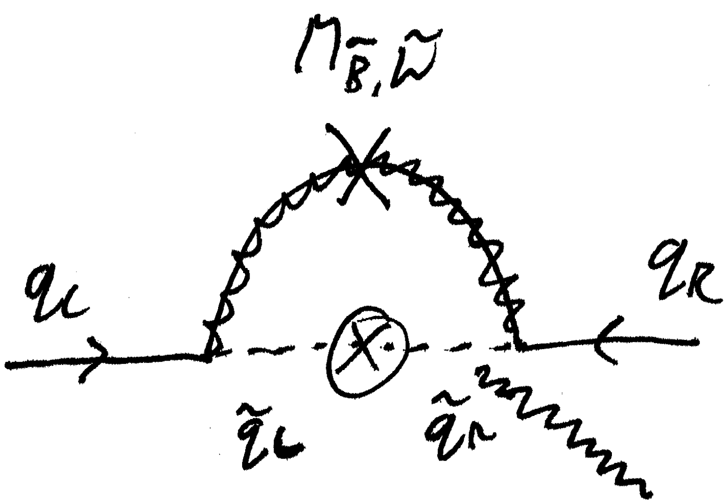
Consequences

Absence of LR scalar mass mixing dramatically weakens many bounds and kills whole classes of problems:

LFV LR mixing diagrams killed.



SUSY EDMs with μ or M_g insertions killed.



Heavy Gauginos

Dirac gaugino masses can be naturally heavier than squark masses by about a factor of 4π.

This is because the operator

$$\int d^2\theta \, \frac{W'_\alpha}{M_{\rm Pl}} W^\alpha \Phi \;\rightarrow\; \frac{D}{M_{\rm Pl}} \lambda\psi + h.c.$$

leads to a one-loop finite (not log enhanced) contribution to scalar $(\text{mass})^2$ "supersoft"

Supersoft

$$\int d^4\theta \frac{W'_\alpha W'^\alpha (W'_\beta W'^\beta)^\dagger}{M^6} Q^\dagger Q$$

Writing $m_D = D/M$, this yields scalar masses

$$\frac{m_D^4}{M^2} \tilde{Q}^\dagger \tilde{Q}$$

This is $1/M^2$, i.e., no counterterm needed, and hence D-term induces finite contribution to scalars.

Heavy Dirac and No Dim-5

As contributions to flavor-violating observables scale as $(m_q/M_g)^n$ for "n" Majorana mass insertions; get additional $(m_q/M_g)^n$ for Dirac mass totaling $(m_q/M_g)^{2n}$.

This provides a significant additional suppression to non-zero flavor observables.

K^0–$\overline{K}^0$ mixing: MSSM

$$\delta_{12} \equiv \frac{\tilde{m}^2_{12}}{\tilde{m}^2_q} < 0.06 \rightarrow 10^{-3} \quad \begin{cases} \tilde{m}_q = 500\,\mathrm{GeV} \\ M_{\tilde{g}} = 500\,\mathrm{GeV} \end{cases}$$

In the limit of large squark masses

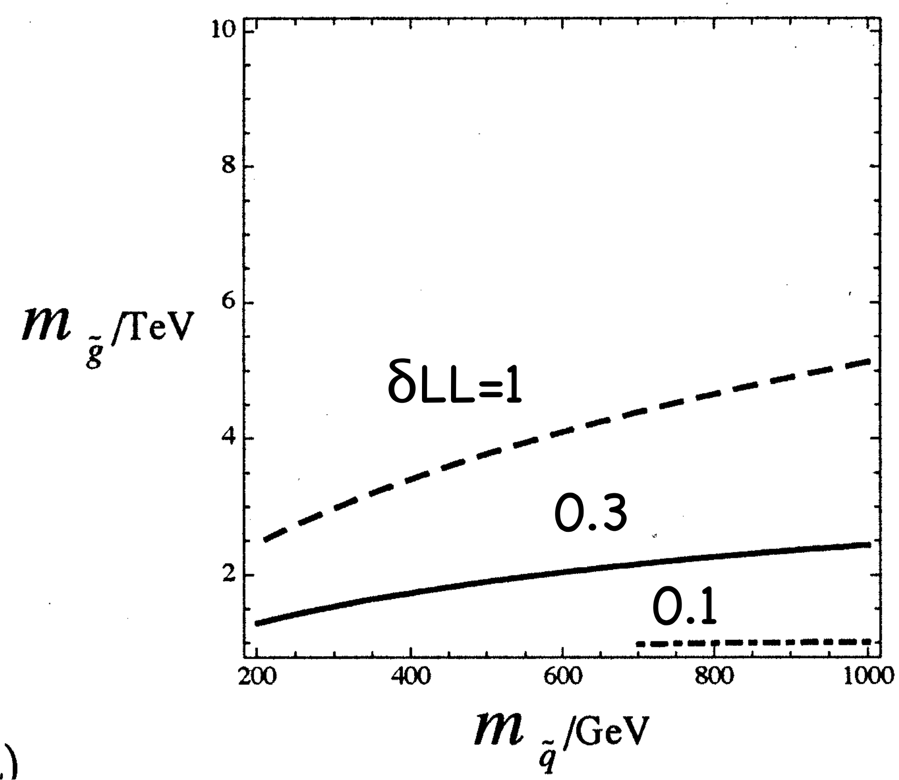
$$\Delta m_K \propto \alpha_s^2 \delta_{12}^2 \frac{1}{m^2_{\tilde{q}}}$$

which implies that δ=1 is allowed only if m_q > 8 TeV (LL only) to 500 TeV (LLRR; LR)

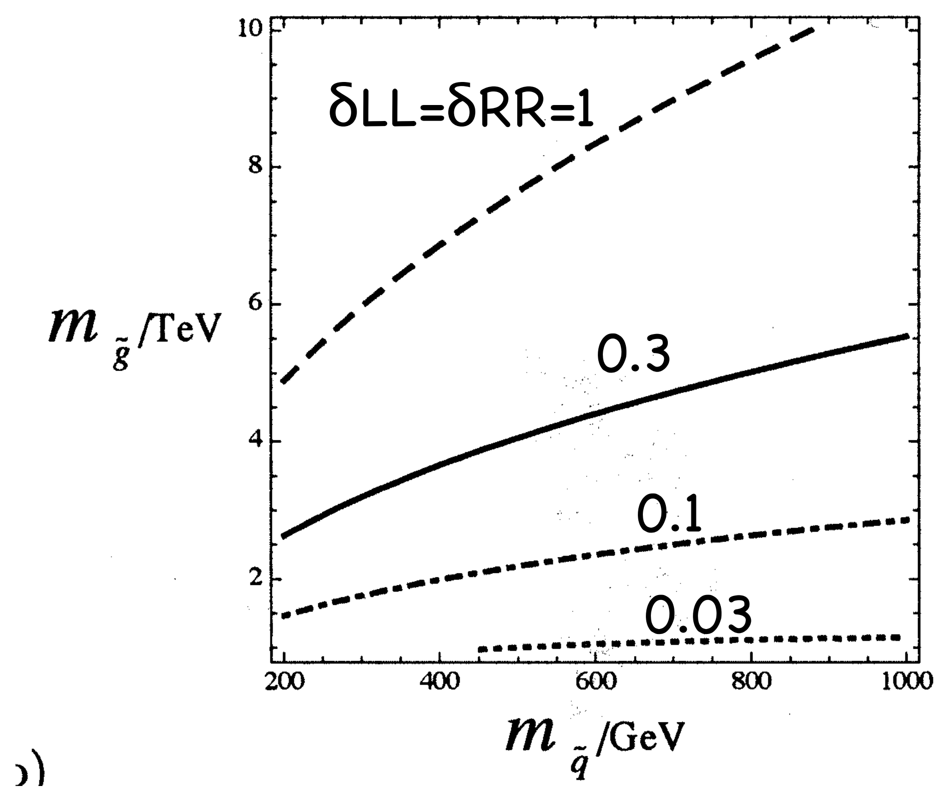
K^0–$\bar{K}^0$ mixing: R symmetric

LR mixing: no bounds.

LL only



LL=RR



ϵ/ϵ'

MSSM: severe bounds:

$$|\mathrm{Im}(\delta_{12})| \quad < \quad \begin{cases} 0.5 & LL \\ 2 \times 10^{-5} & LR \end{cases}$$

R symmetric: no LR; essentially no bound.

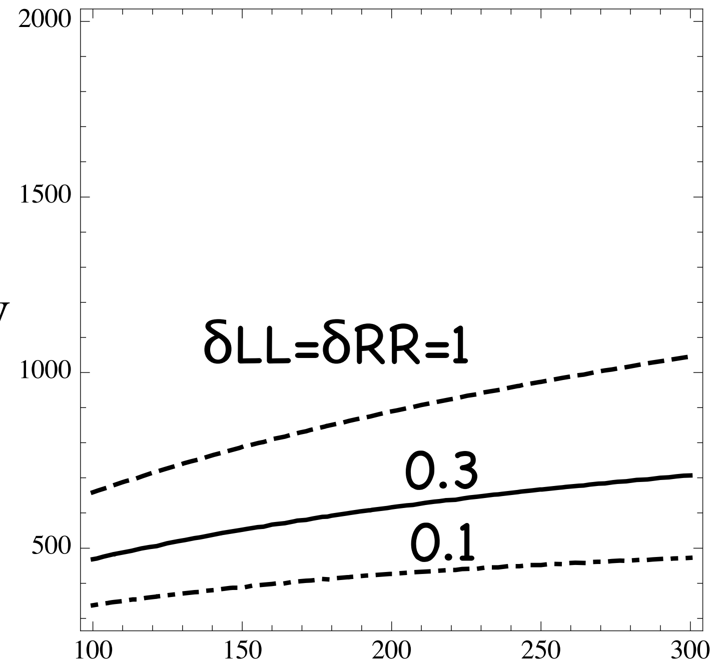
μ->eγ

MSSM: severe bounds:

$$|\delta_{12}| \quad < \quad \begin{cases} 7.7 \times 10^{-3} & LL \\ 1.7 \times 10^{-6} & LR \end{cases}$$

R symmetric: no LR mixing.

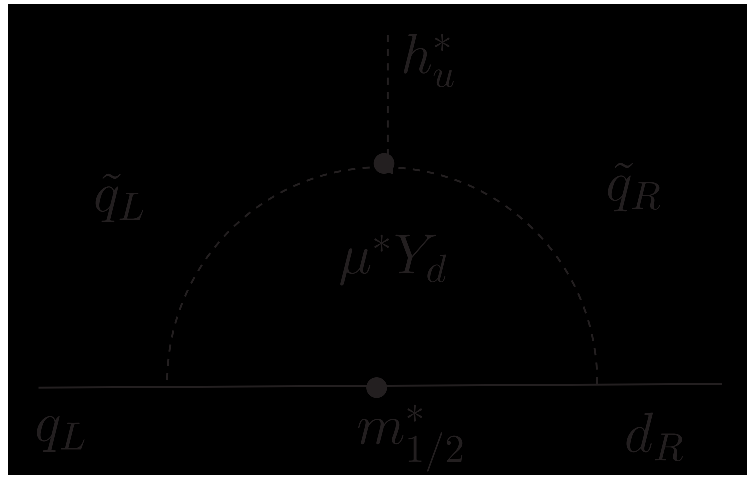
$$\frac{m_{\tilde{W}}}{2} = \mathrm{m}_{\tilde{B}}/\mathrm{GeV}$$



$\mathrm{m}_{\tilde{l}}/\mathrm{GeV}$

Large tan β

Through gaugino mass and μ-term, diagrams such as



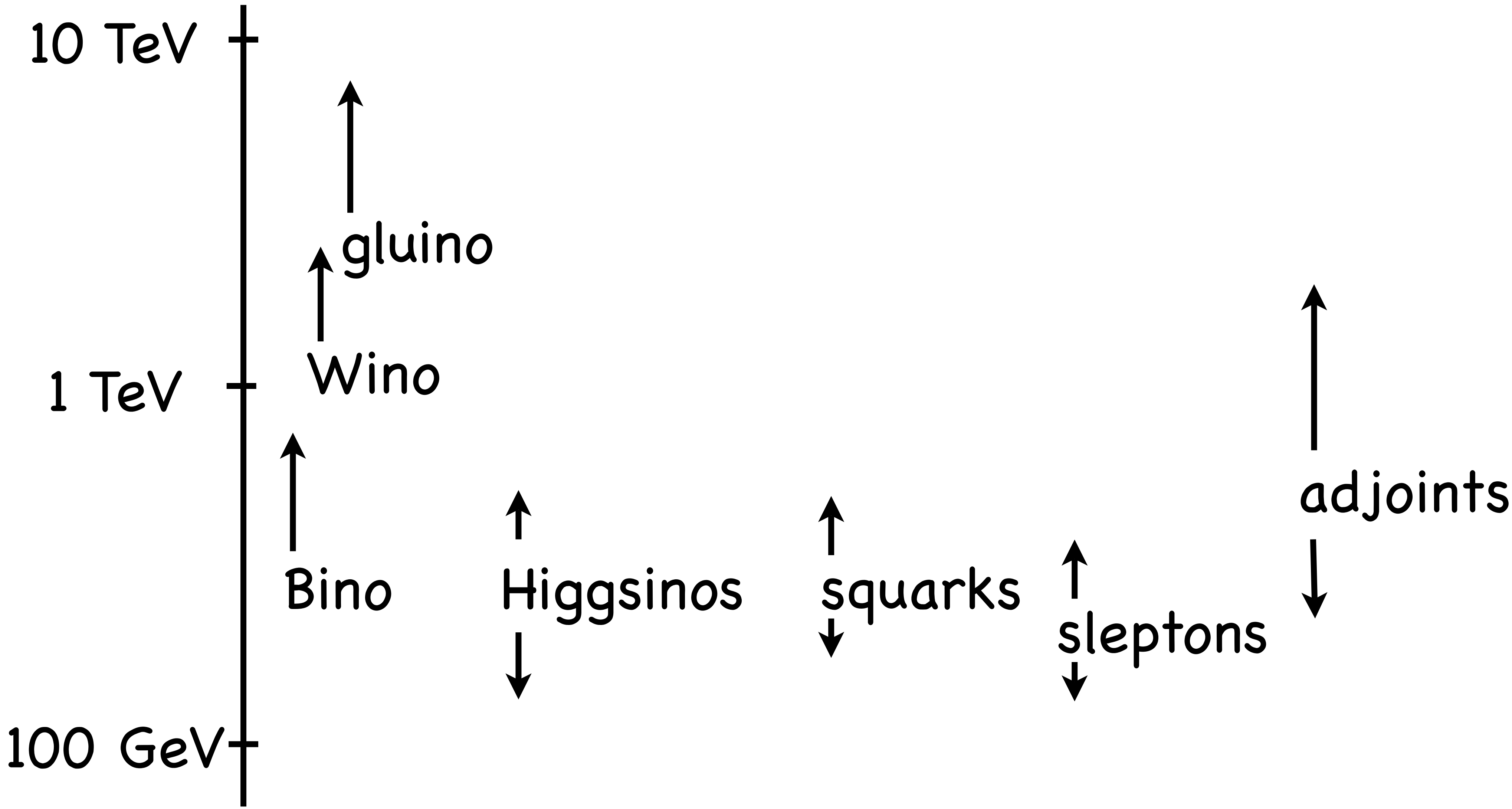
integrating out a heavy gluino leads to an interaction of up-type Higgs to down-type quarks. These lead to tan β enhanced contributions to B -> μμ, etc.

No such large tan β effects in R symmetric model.

Phenomenology

(Sketch)

Rough Spectrum



Features

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

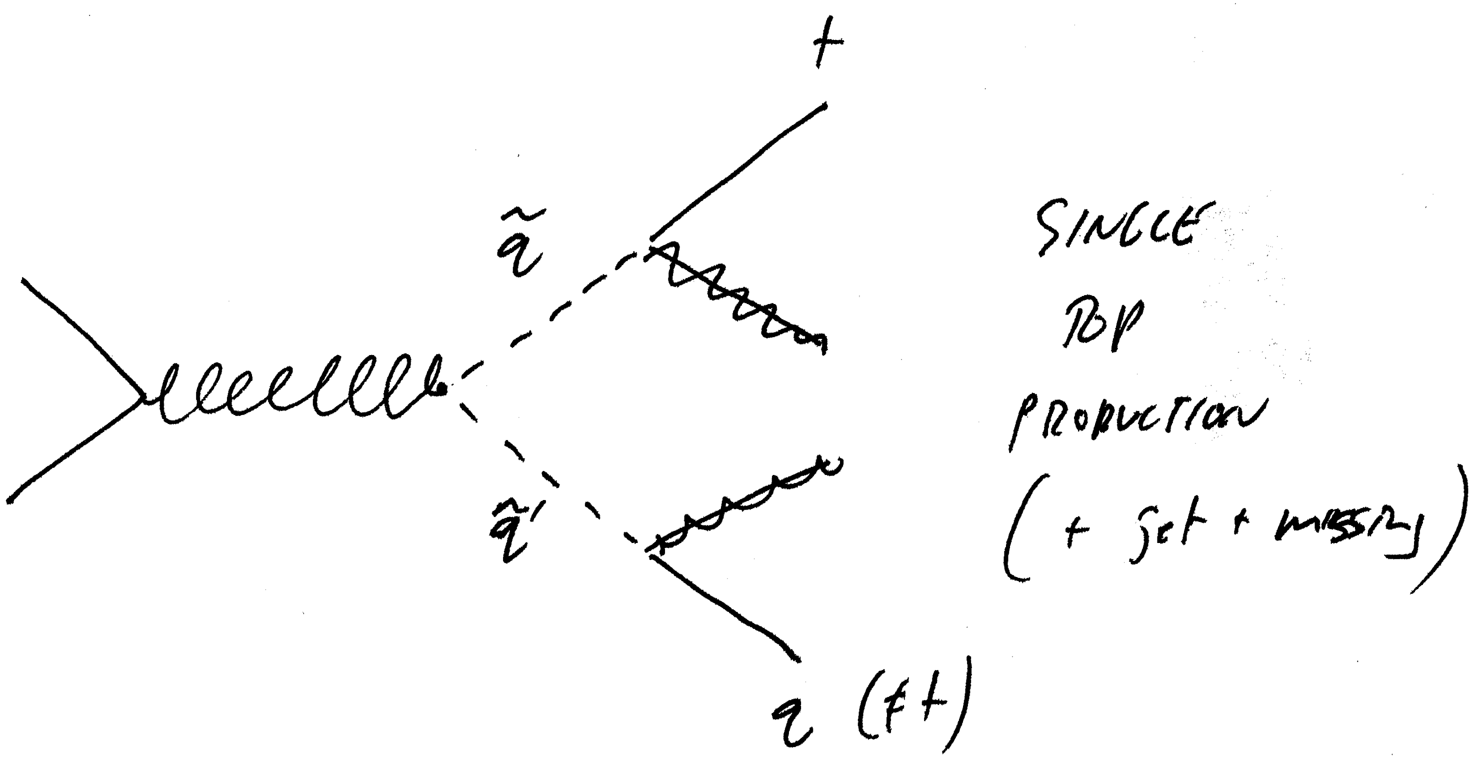
Dirac gluino and Wino heavy.

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

*[The only exception is ϵ_K that requires $\mathrm{Im}[\delta_{LL12}\delta_{RR12}] < 0.01$; so that, e.g., no more than 0.1 phase is permitted in LL and RR]

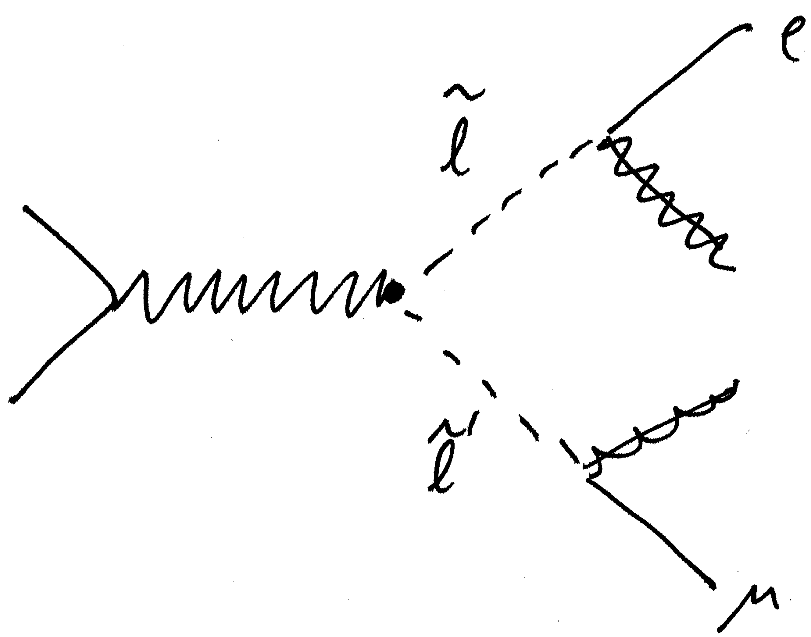
Squark Flavor Violation

Squark production with maximal flavor violation in decay:



Slepton Flavor Violation

More extensively studied in literature; one mode is:



SLEPTON PRODUCTION W/ UNLIKE FLAVOR FINAL STATES

Another is $\chi_2 \to \chi_1\ l\ l'$; this mode is likely harder given the Wino mass.

Open Questions

- What is lightest SUSY particle?
  Higgsino? Bino? Singlino (NMSSM)? dark matter...
- Which SUSY flavor violation can be found at LHC?
- Higgs mass? (chiral adjoint scalars heavy or NMSSM)
- Gauge Coupling Unification?
  $SU(3)_c \times SU(3)_L \times SU(3)_R/Z_3$?
- D-terms slightly larger than F-terms?
- continuous, approximate or discrete R symmetry?
  explicit model...
- supergravity issues
  (cancellation of CC usually done by small explicit
  R symmetry breaking, leads to gravitino mass, etc.)

Summary

FCNC is the strongest indirect constraint on supersymmetry.

The "lore" that SUSY breaking masses must be flavor-blind is wrong.

Much of the SUSY-induced flavor-violation arises as a result of R symmetry violation.

The R symmetric model permits O(1) flavor violation in squark and slepton masses (and raises mass of gauginos) -- dramatically affects the phenomenology of SUSY at LHC!