Delicious Supersymmetry:

Removing the flavor problem with an R-Symmetry

G.Kribs, E.Poppitz, NW, arXiv:0712.2038

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KITP Conference: Anticipating the LHC

June 4, 2008

Our perspective on flavor at the weak scale

*Could there be new states at the weak scale that couple to flavor and show essentially no flavor alignment?**

Minimal flavor violation (Chivukula & Georgi, 1987; Hall and Randall 1990; D'Ambrosio, Giudice, Isidori & Strumia 2002; Buras, Gambino, Gorbahn, Jäger & Silvestrini 2001; Ali & London 1999)

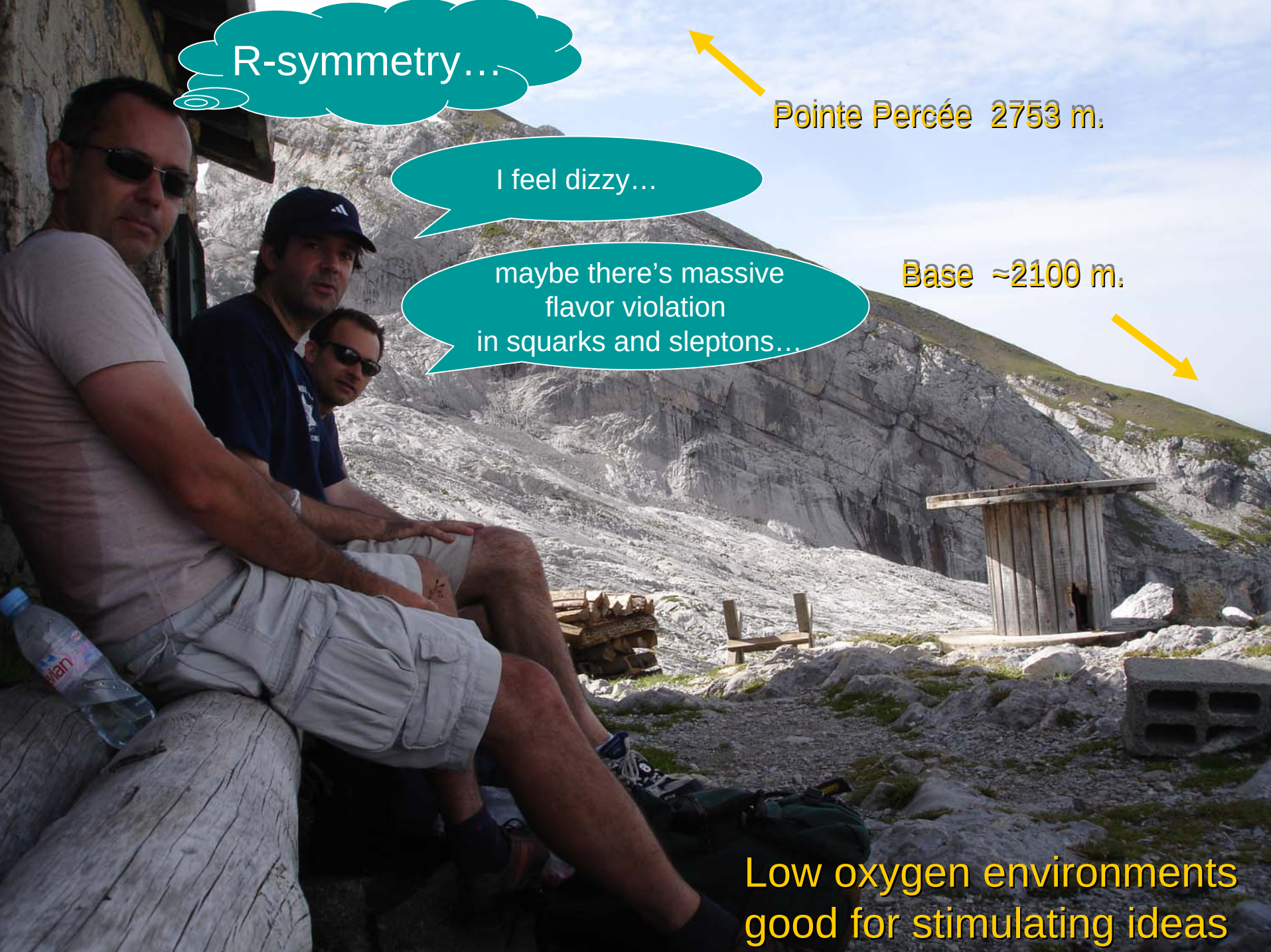
Next-to-minimal flavor violation (Ligeti, Papucci, Perez 2006; Agashe, Papucci, Perez, Pirjol 2005)

*and be consistent with experiment

Can there be a rich flavor structure accessible at the LHC?

- Yes!

  If supersymmetry is extended to contain an extended R-symmetry (i.e., larger than R-parity) one can have highly mixed, highly non-degenerate squarks and sleptons at a few hundred GeV


R-symmetry…
I feel dizzy…
maybe there's massive flavor violation in squarks and sleptons…
Pointe Percée 2753 m.
Base ~2100 m.
Low oxygen environments good for stimulating ideas

The SUSY flavor problem

$M^2_{\text{sfermion}} \sim$

How do you make these zero? (and similarly for A-terms?)

Solving the flavor problem

- All attempts to solve the SUSY flavor problem rely on suppressing off-diagonal elements of the squark and slepton mass matrices
  - Flavor Universality at high scale (Dimopoulos & Georgi)
  - Gauge mediation (Dine, Nelson, Nir, Shirman)
  - Anomaly mediation (Randall, Sundrum; Giudice, Luty, Murayama, Rattazzi)
  - Gaugino mediation (Kaplan, Kribs, Schmaltz ; Chacko, Luty, Nelson, Ponton)
  - "Mirage" mediation (Choi, Jeong, Okumura)
  - Gaugino-assisted anomaly mediation (Kaplan & Kribs)
  - Flavor symmetries/alignment (multiple; Nir & Seiberg)
  - Nelson-Strassler models (Nelson & Strassler) and AdS duals
- Alternatives: large flavor violation, but push 1st/2nd gen squarks to 200 TeV, 20 TeV w/ 10% tuning (effective SUSY; Cohen ,Kaplan & Nelson)
- Consequence: either minor FV or large flavor violation must be pushed into the multi-TeV regime
- Problem much weaker in R-symmetric SUSY

R-Symmetry in SUSY

- Can extend R-parity to continuous $U(1)_R$
  - "Superpartner number"
- Dynamical SUSY breaking requires an R-symmetry (Nelson & Seiberg)
  - MSSM requires R-breaking
  - Explicit R-breaking while maintaining SUSY breaking a challenge for DSB
- Can we extend phenomenological SUSY to have a full $U(1)_R$?

What breaks R-symmetry in MSSM?

- Three things
  - A-terms
  - Majorana gaugino masses
  - μ-term

A-terms and μ-terms

$$\int d^2\theta \lambda_{ij} Q U H_u \supset \lambda_{ij} \bar{q} u h_u$$

R charge 2 R charge 0

$$\longrightarrow \quad \lambda_{ij} \tilde{q} \tilde{u} h_u$$ R charge 2

A terms in the presence of superpotential Yukawas Violate R-symmetry

μ and B_μ

- Similar story to A-terms

$$\int d^2\mu H_u H_d \supset \mu \bar{H}_u H_d$$

R charge 2 R charge 0

$\rightarrow$ $B_\mu h_u h_d$

R charge 2

Keep this one (to generate h_d vev)

Scalar terms with same structure as superpotential terms violate R-symmetry

Gaugino masses

$$\int d^2\theta X W_\alpha W^\alpha$$

Gaugino mass ($\langle X \rangle = \theta^2 F$)

$$+ \int d^2\theta W_\alpha W^\alpha$$

Gaugino kinetic term

$\Rightarrow$X is complete singlet

$\Rightarrow F_x$ carries R-charge 2

Constructing an R-symmetric theory: A terms

- Step one: no A-terms

easy enough…

Constructing an R-symmetric theory: μ term

- Add extra Higgs doublets, $R_{u,d}$ with R-charge 2

$$\int d^2\theta \mu_u H_u R_u + \mu_d H_d R_d$$

Can still have $B_\mu h_u h_d$ as usual

Constructing an R-symmetric theory: gaugino masses

- Problem was Majorana nature of gaugino masses
  - Gauginos carry R-charge 1

- Dirac gauginos can carry conserved continuous quantum numbers

  (Polchinski & Susskind 1982, Hall & Randall 1991, Dine & MacIntire 1993, Fox, Nelson, NW 2002…, Scherk-Schwarz theories)

$$\frac{1}{M}\int d^2\theta W'_\alpha W_i^\alpha A^i$$

Polchinski & Susskind ‘82;
Dine & Macintire ‘93;
Fox, Nelson, NW ‘02

- Generates Dirac gaugino masses
- Generates new scalar couplings
- Gives scalar (not pseudoscalar) mass twice that of the gaugino

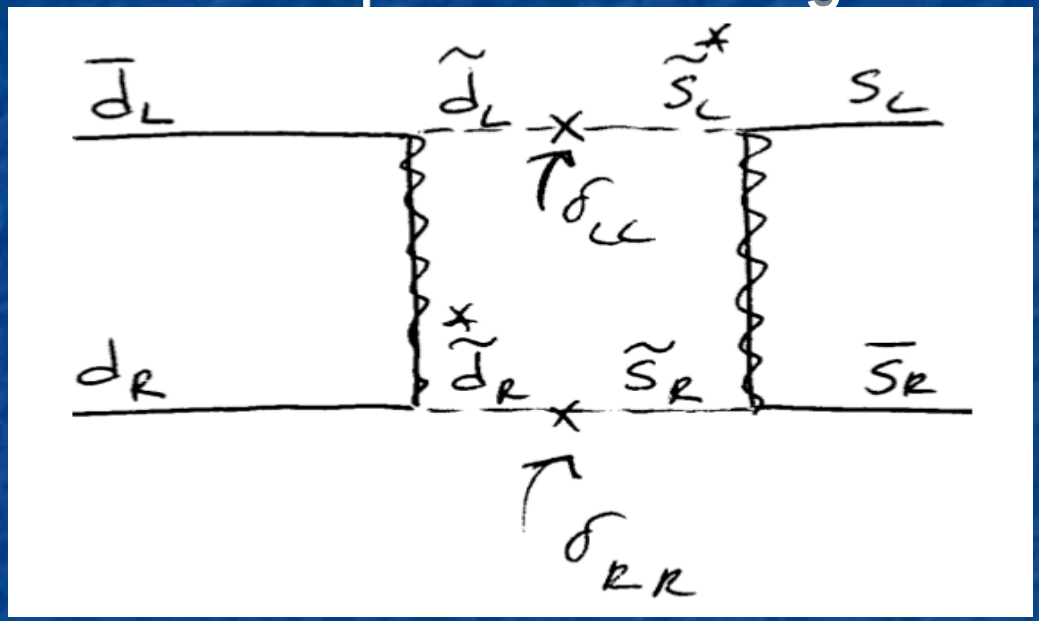
Note: gauginos now fill out N=2 multiplet,
“gauge extended model”

R-symmetric summary

- We can construct an R-symmetric theory using the three independent ingredients (MRSSM)
  - No A-terms
  - Modified Higgs sector (μ term)
  - Dirac gauginos
- Claim: in such a theory, the flavor problem can be nearly absent

Flavor in the MRSSM

- Case in point: box diagram contributions to Δm_K



Generates dim 6 operator

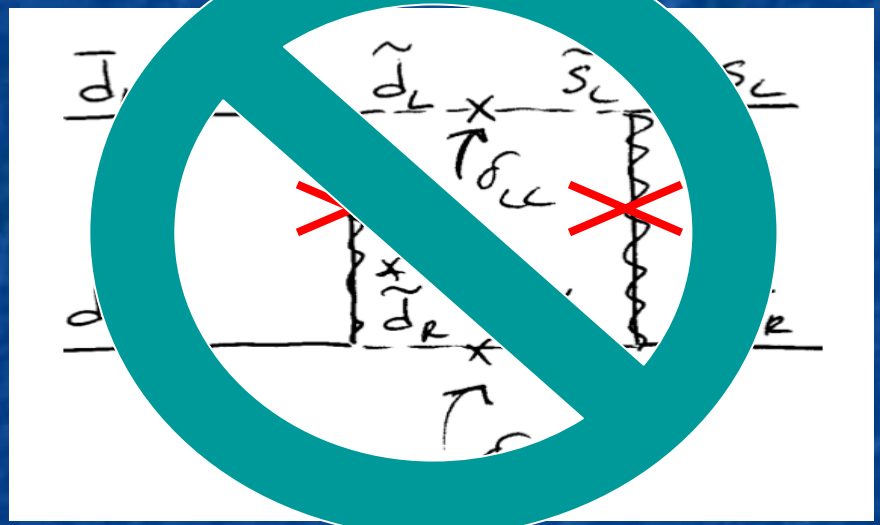
$$\frac{\alpha_s^2 \delta^2}{M^2} (\bar{d}s)^2$$

$$\delta = \frac{\tilde{m}_{ds}^2}{\tilde{m}^2}$$

If $m_{squark}=m_{gluino}=500$ GeV, and $\delta=1$
=> 10^6 times too large

Where do we get a 10^6?

- First, note diagram is two pieces, one with helicity flips, and one without



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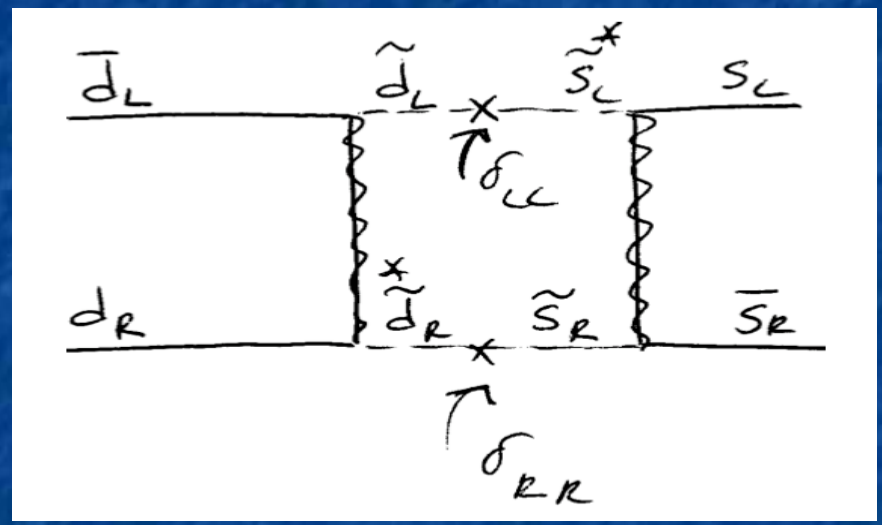


1/10

For similar masses $m_{squark} \sim m_{gluino}$, factor of 10 difference

With Dirac gauginos, helicity flips take you to uncoupled RH state

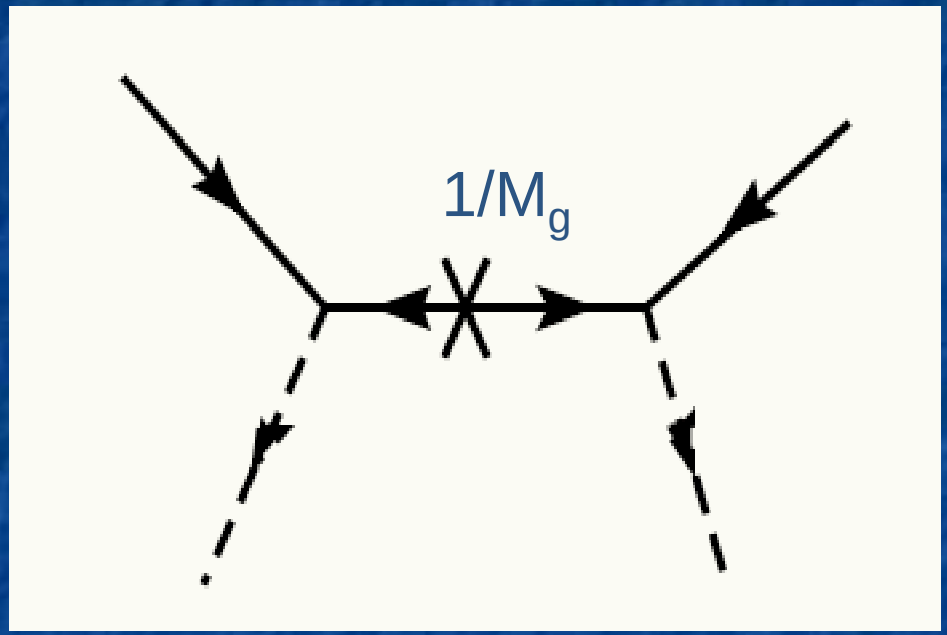
Heavy gauginos

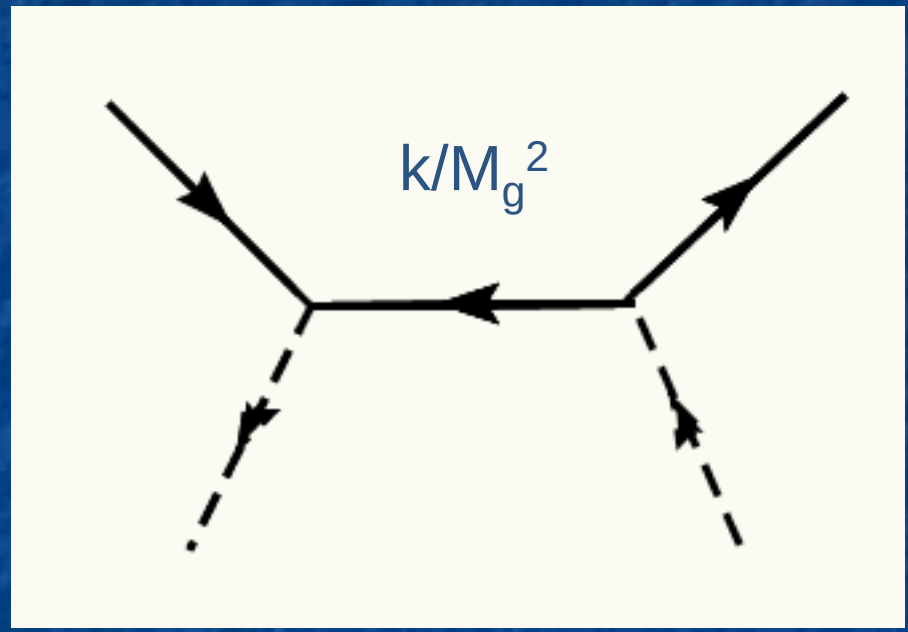
- Unlike Majorana gauginos, Dirac gauginos do not contribute to RGEs of sfermion masses
  - => natural to have gauginos heavier by $(4\pi/\alpha)^{1/2}$~10
- Thus few hundred GeV squarks natural with few TeV gauginos

$$\frac{\alpha_s^2 \delta^2}{m_{\tilde{g}}^2} (\bar{d}s)^2$$

1/10 x 1/(10)^2=1/(10)^3

Effective operators



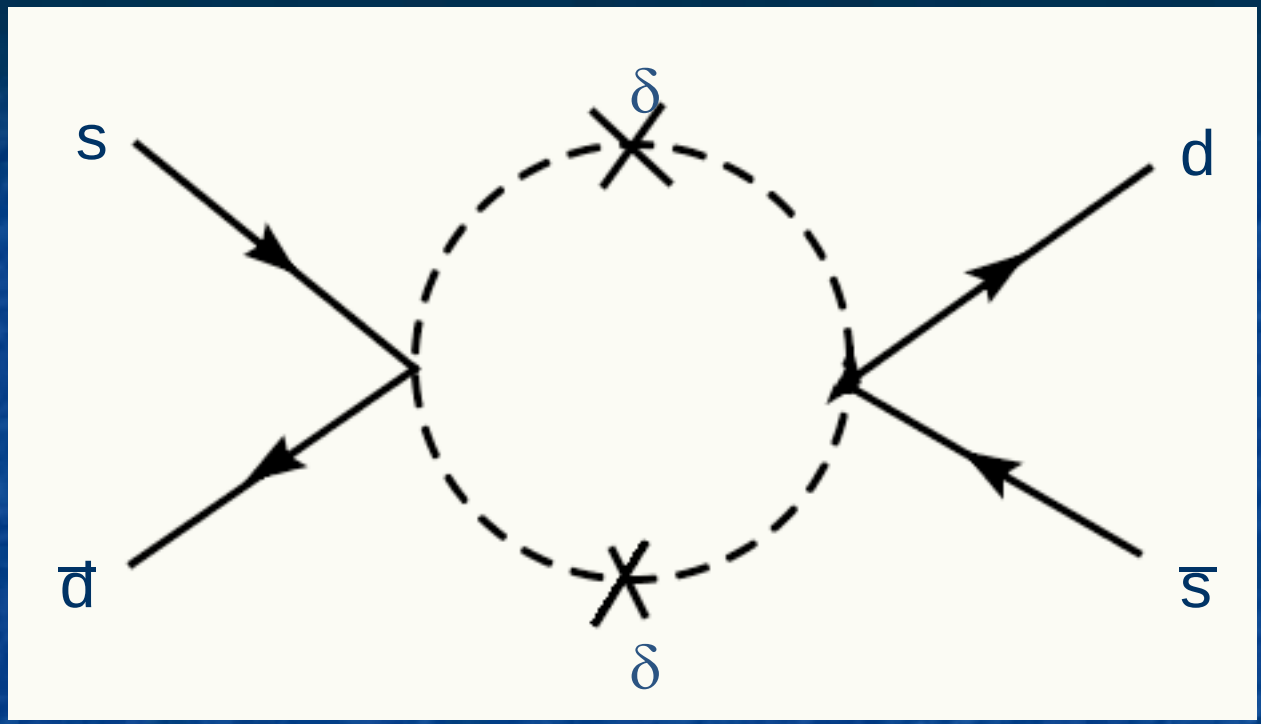


Dim 5 operator

$$\frac{1}{M} qq\tilde{q}^* \tilde{q}^*$$

Dim 6 operator

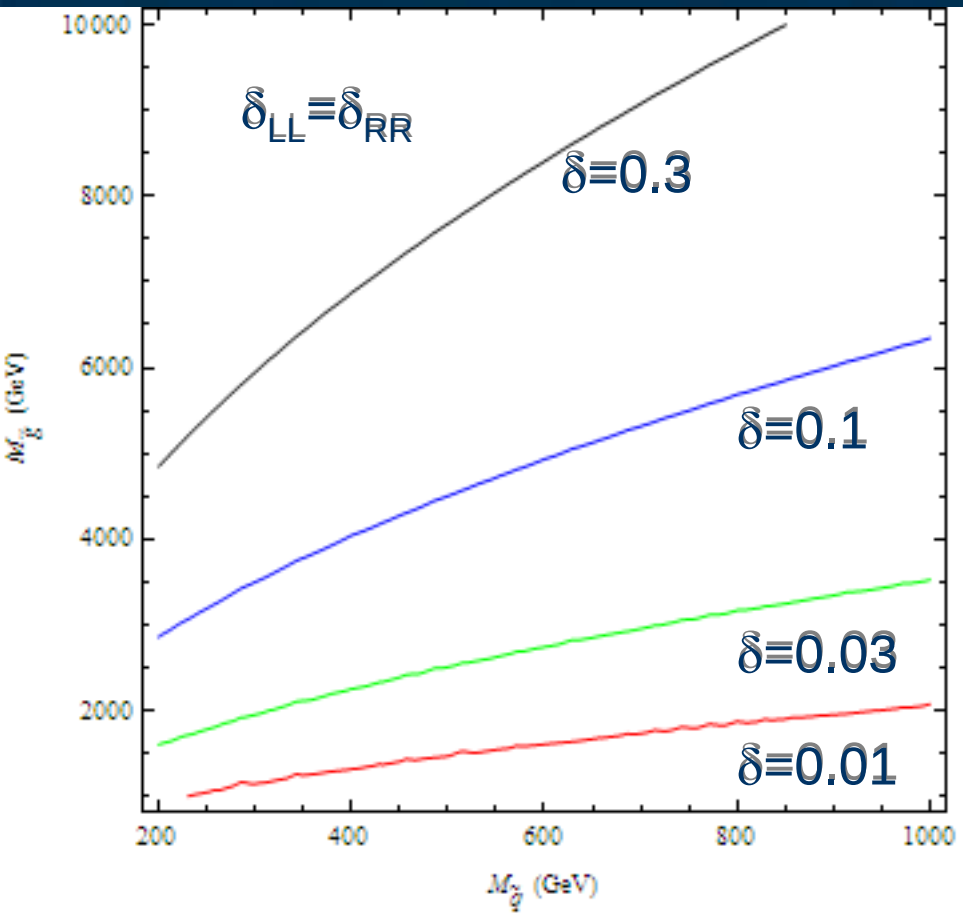
$$\frac{1}{M^2} \bar{q}\gamma_\mu q\tilde{q}^* \partial^\mu \tilde{q}$$

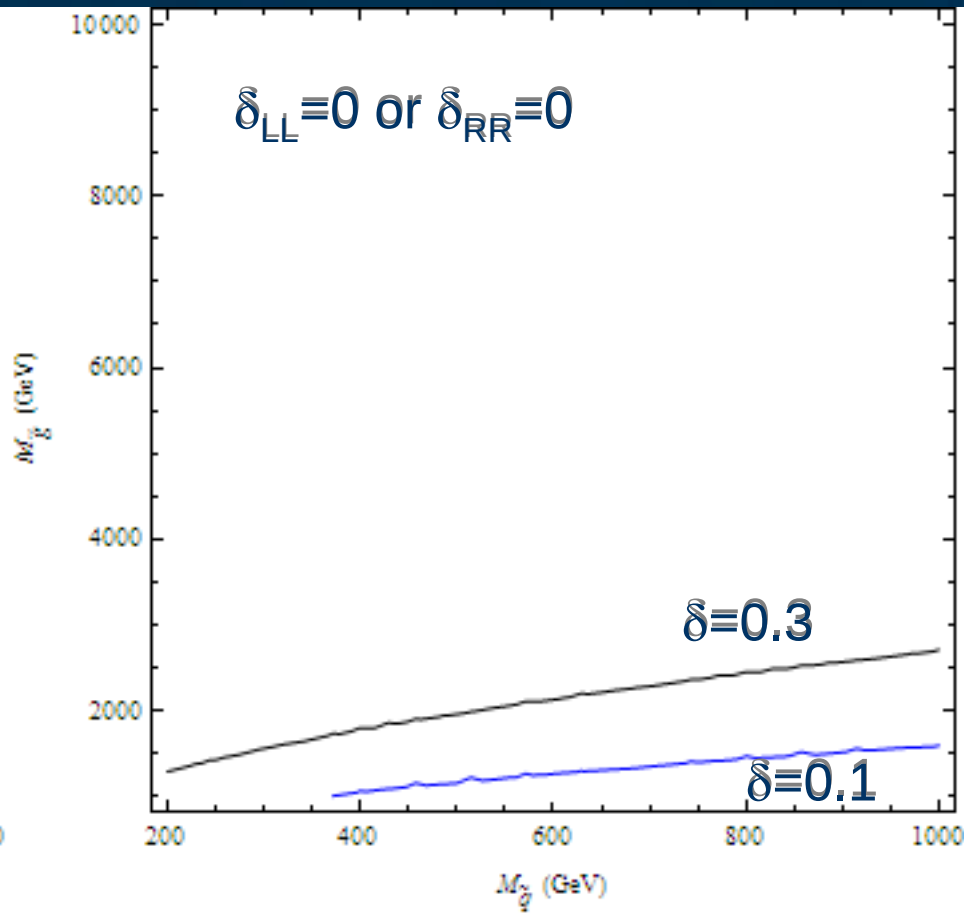


- Dominated by $k \sim m_{squark}$
- Leads to additional $m^2_{squark} / m^2_{gaugino} \sim 10^{-2}$ suppression

So $1/10^5$ in total

Limits from Δm_k

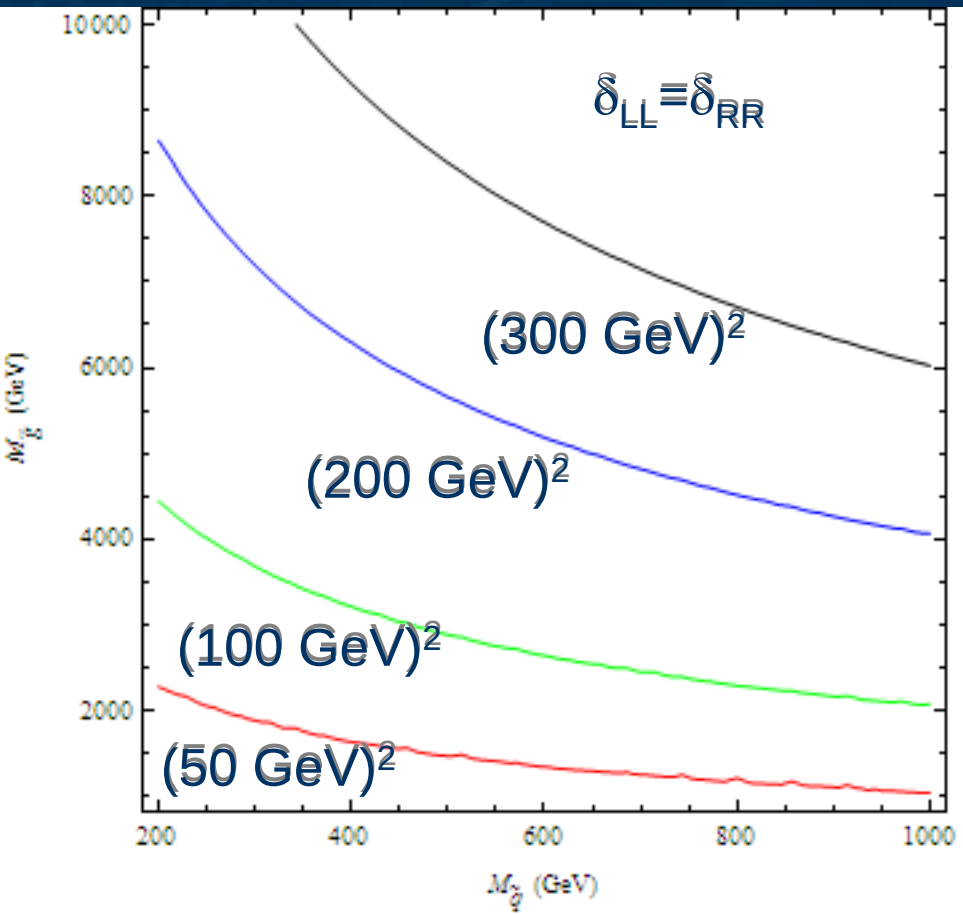


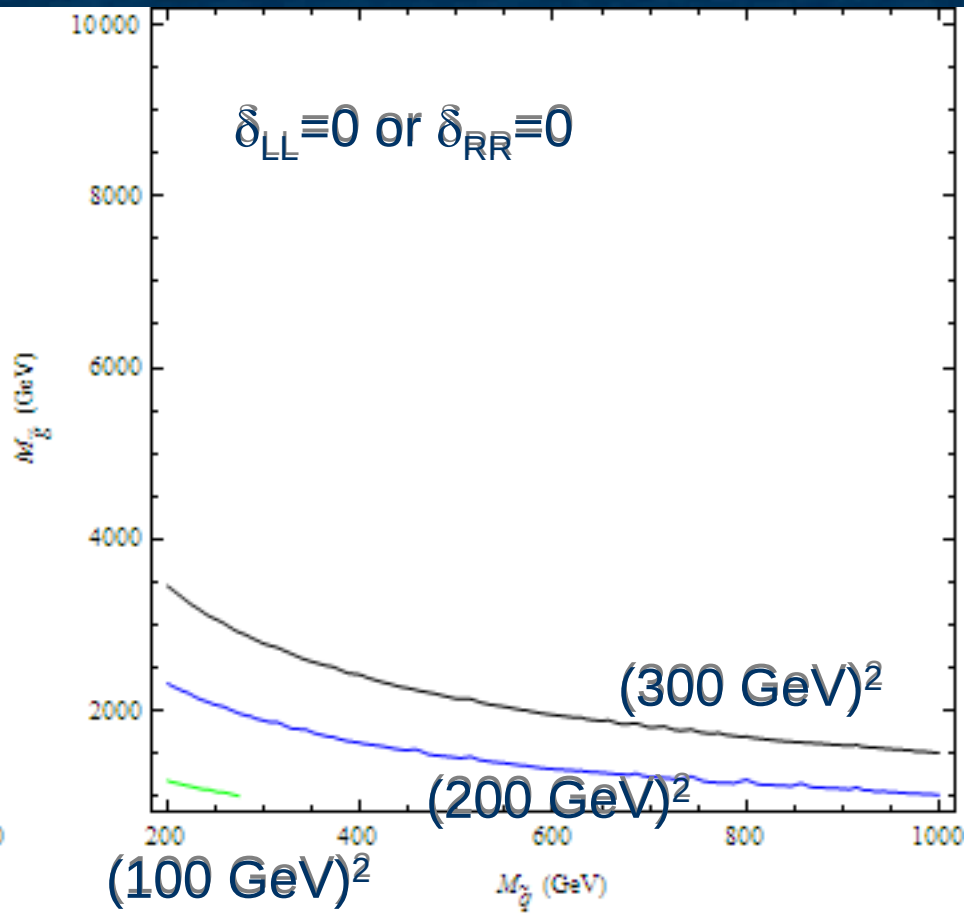


Limits *including* LO QCD corrections (Blechman & Ng arXiv:0803.3811) - cannot simply apply Bagger, Matchev, Zhang (LO) or Ciuchini et al (NLO) in SUSY because of dim 6 vs dim 5 ops

(Plots courtesy Siew-Phang Ng)

Can easily have $(100\ \text{GeV})^2$ - (300 GeV)^2 soft masses masses on top of flavor diagonal radiative masses





More natural than equivalent MSSM theory with similar mass squarks because no large logarithm

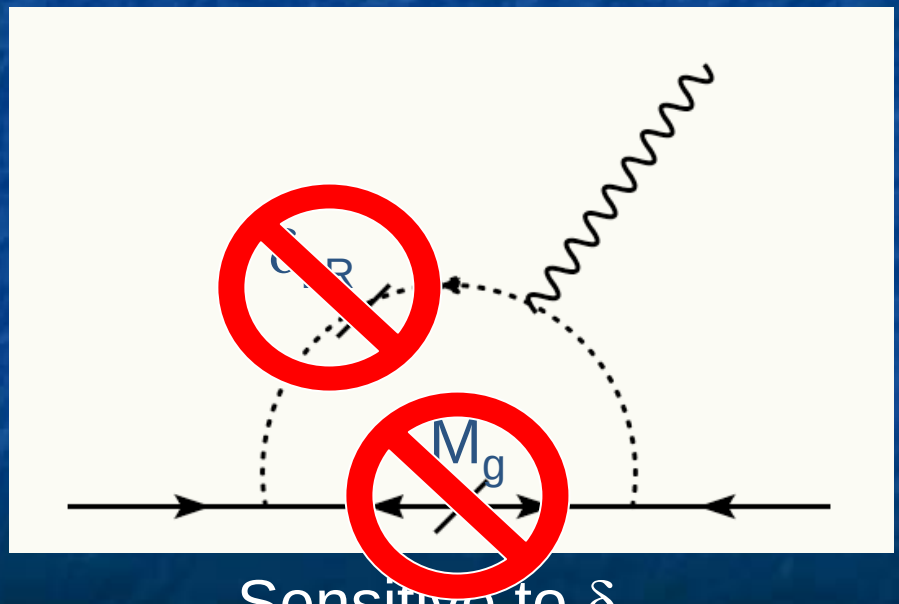
(Plots courtesy Siew-Phang Ng)

No strong constraints from mixing

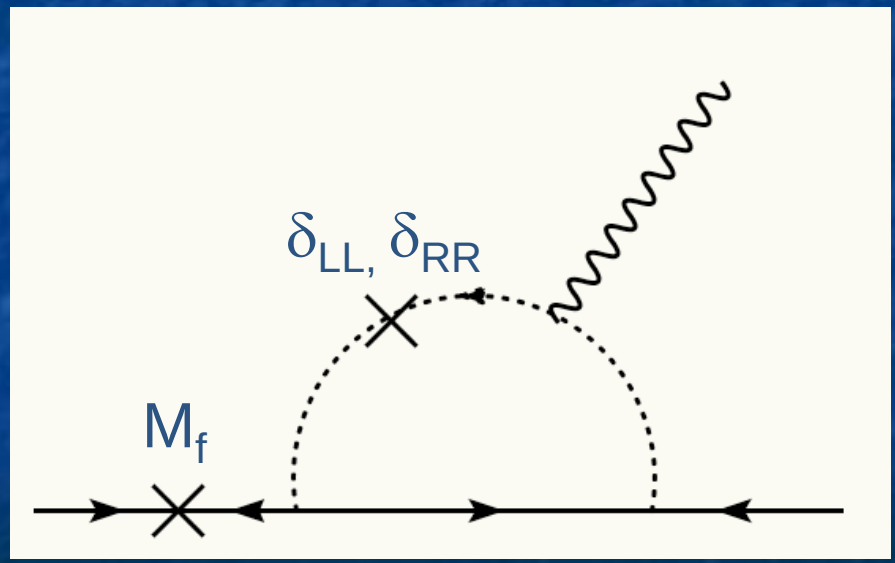
- B,D,K mixing all yield weak constraints
  - (B,D much weaker than K)
- ε_k needs additional 10^{-2} suppression
  - Small d_{LL} or d_{RR} (~$(30\ \text{GeV})^2$ with 8TeV/600Gev)
  - Real soft masses
  - Spontaneous CP (a la Nelson-Barr or Hiller-Schmaltz) via up sector (in prog, Kagan, Rastogi, NW)

Radiative ΔF=1

$$\bar{f}_L \sigma^{\mu\nu} f_R F_{\mu\nu}$$

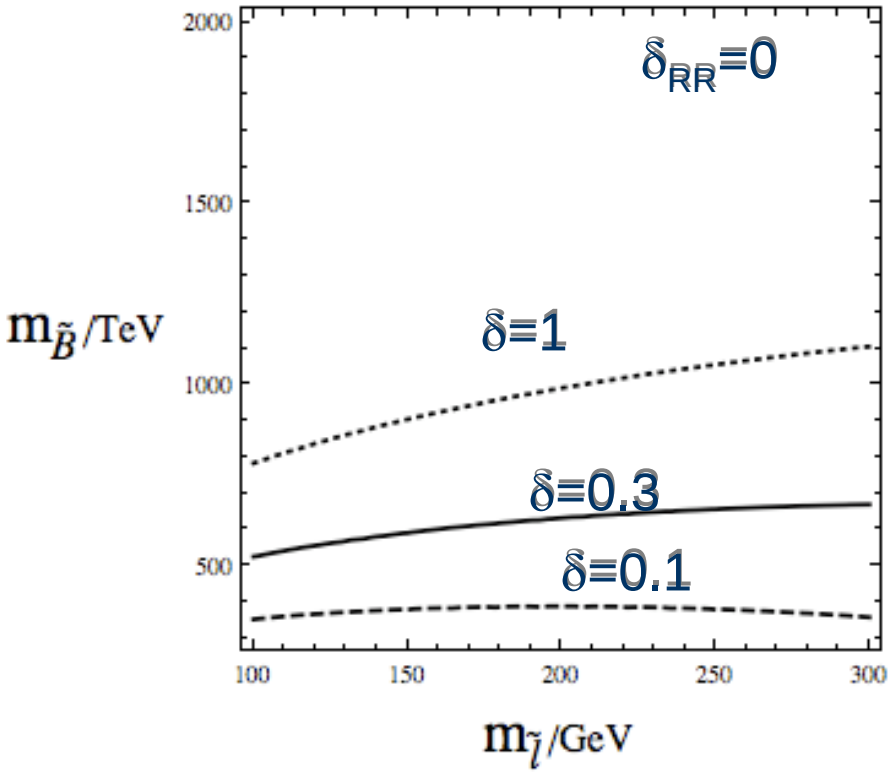


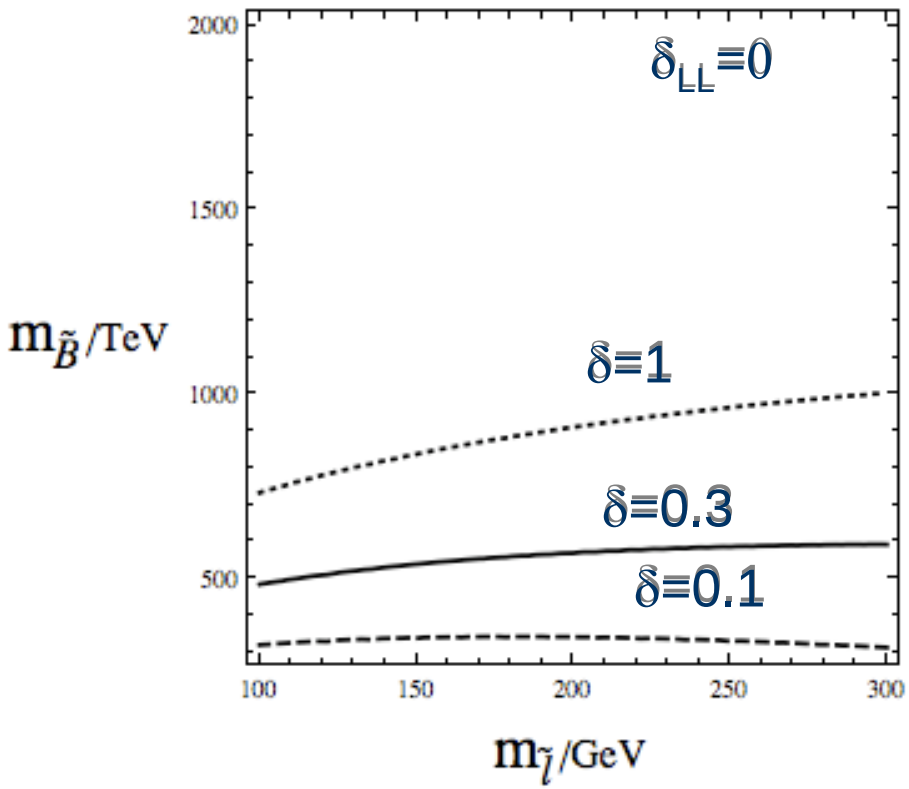
Sensitive to δ_{LR}



Sensitive to δ_{LL}, δ_{RR}

μ -> e γ





(assuming mB=mW/2)

- Heavy gauginos, no triple flip diagrams
- b->s γ, τ-> μ γ, τ-> e γ safe

Flavor Summary

- The new MFV: Massive Flavor Violation
- The presence of an R-symmetry in SUSY, coupled with heavy gauginos allows significant flavor violation

Consequences

Broad spectra

$\tilde{u}_R^3$ — 800 GeV

$\tilde{q}_L^3$ — 700 GeV

$\tilde{q}_L^2$ — 675 GeV

$\tilde{q}_L^1$ — 600 GeV

$\tilde{d}_R^3$ — 600 GeV

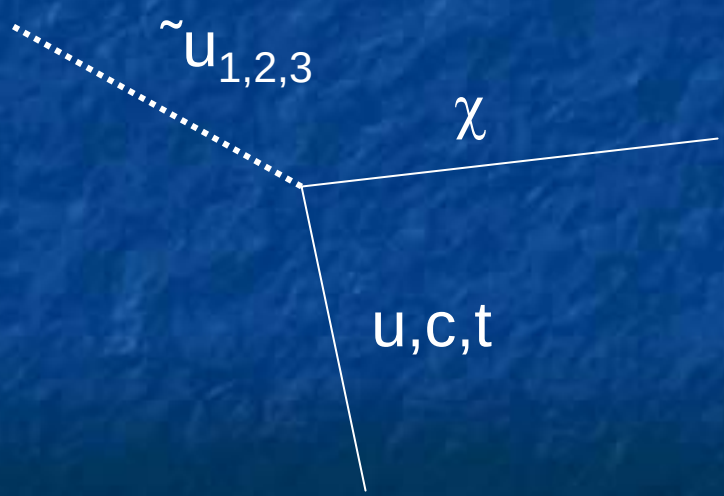
$\tilde{u}_R^2$ — 575 GeV

$\tilde{u}_R^1$ — 525 GeV

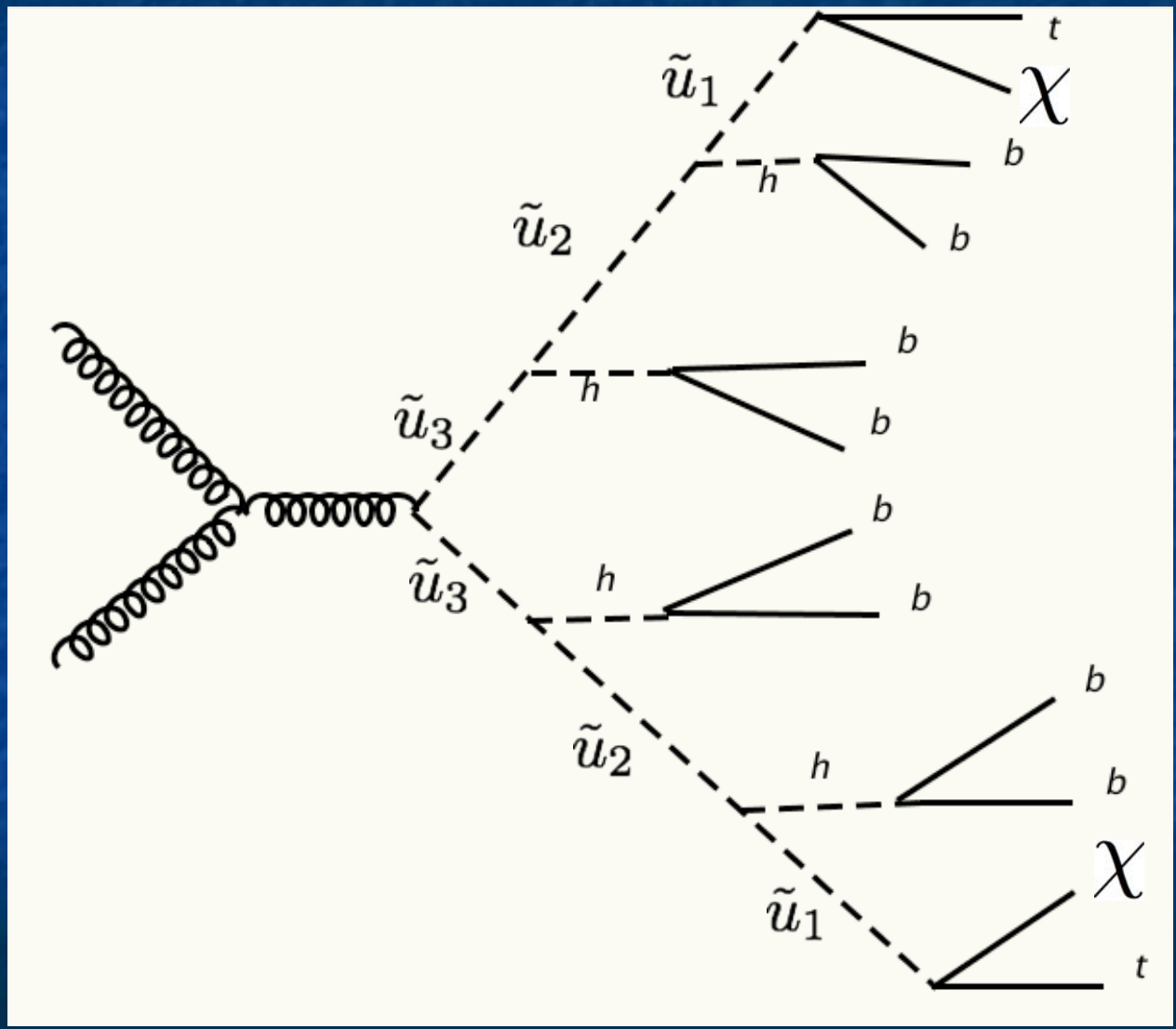
$\tilde{d}_L^2$ — 475 GeV

$\tilde{d}_L^1$ — 425 GeV

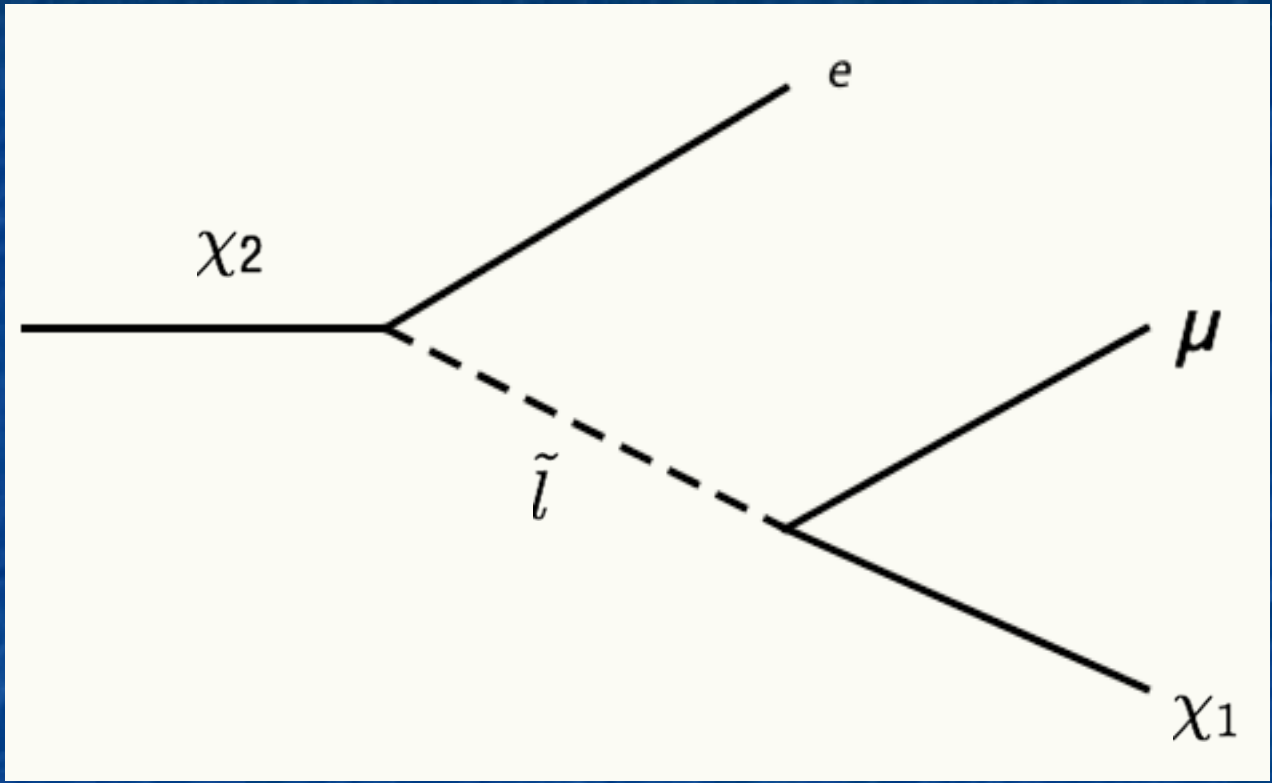
No characteristic decay, because they're all "top" squarks, "bottom" squarks



New cascades



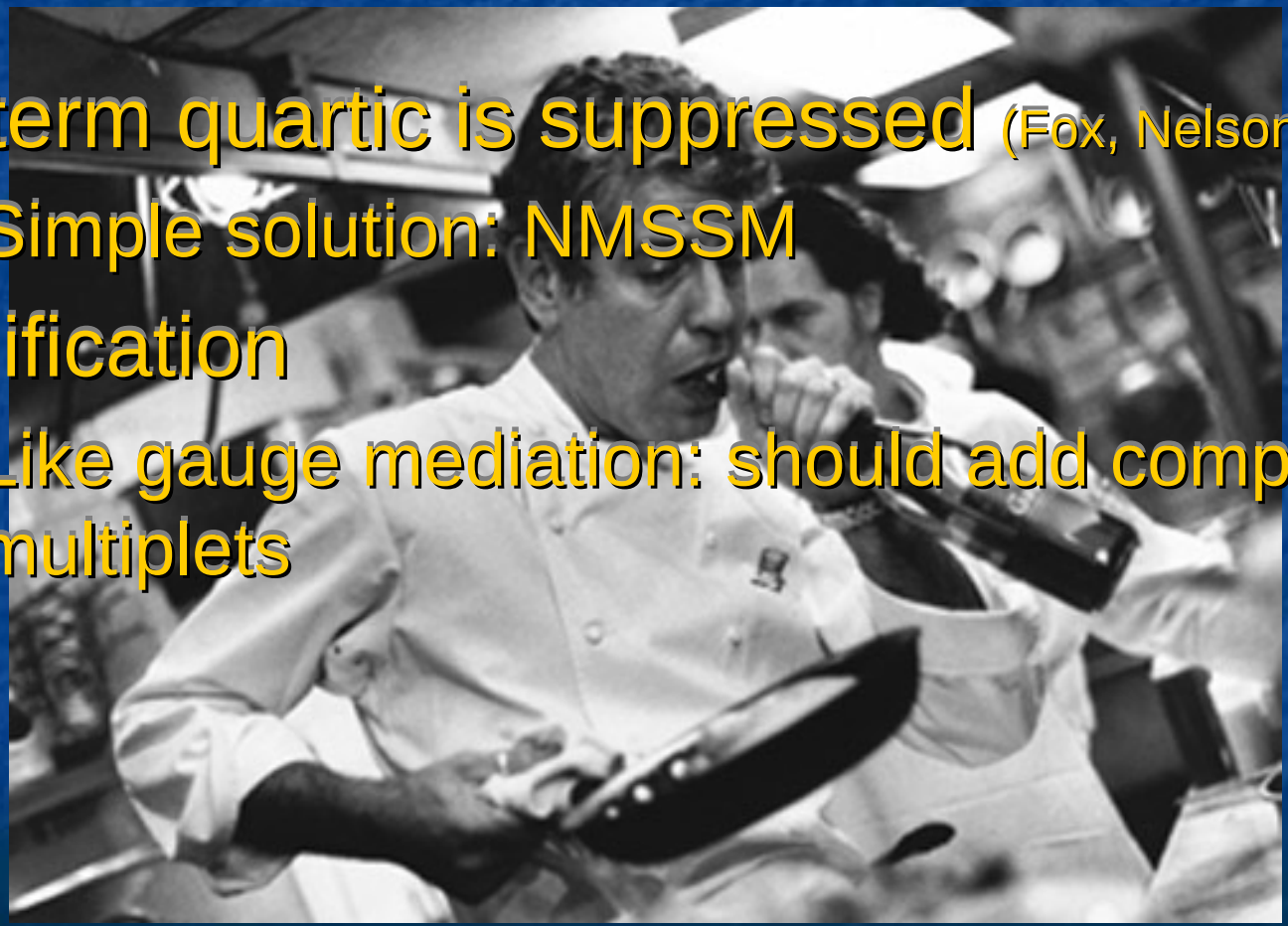
Flavor violating edges



Can’t use flavor subtraction

Should be able to see these things - but need to figure out how to tease the FV out of the signal

What goes on in the kitchen…



- D-term quartic is suppressed (Fox, Nelson, NW)
  - Simple solution: NMSSM
- Unification
  - Like gauge mediation: should add complete multiplets

New possibilities for flavor at < TeV

- *New proposal for addressing flavor in supersymmetry*
  - *Similar in field content to GMSB*
  - *Dramatically different phenomenology*
  - *Important to think about how to see FV*
- *Many issues to address*
  - *LHC phenomenology (Kribs & Roy in progress)*
  - *General structures, Higgs mass, naturalness (Blechman, Kaplan, Luty, NW in progress)*
  - *CP violation (Kagan, Rastogi, NW, in progress)*
  - *Dark Matter (Chang, Kribs, Tucker-Smith, NW, in progress)*
  - *Neutrino masses (Kumar, NW, in progress)*
  - *…*
- *Hoping for a feast of new data from the LHC!*