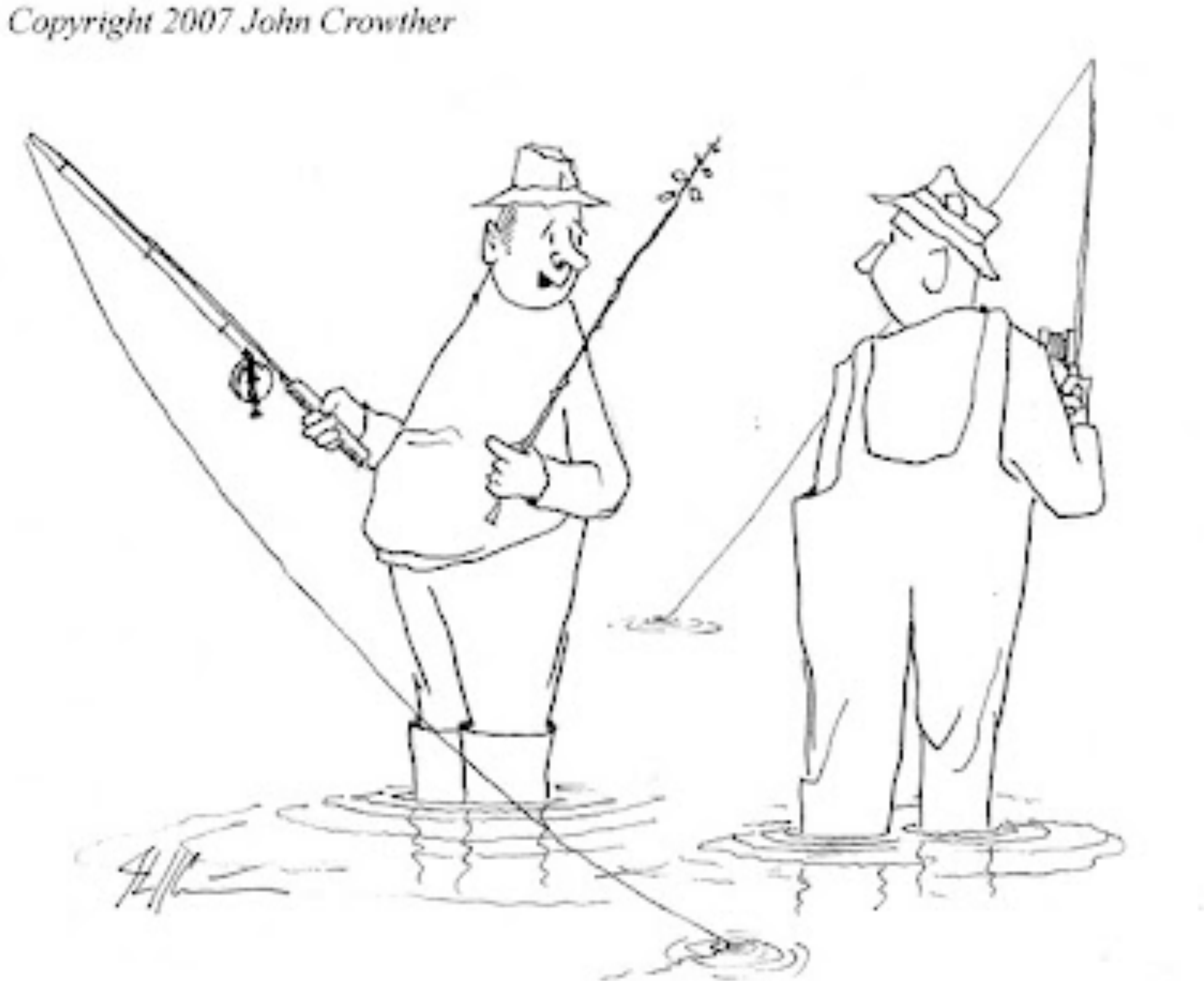
Extra Dimensions

or

Other Exciting Stuff

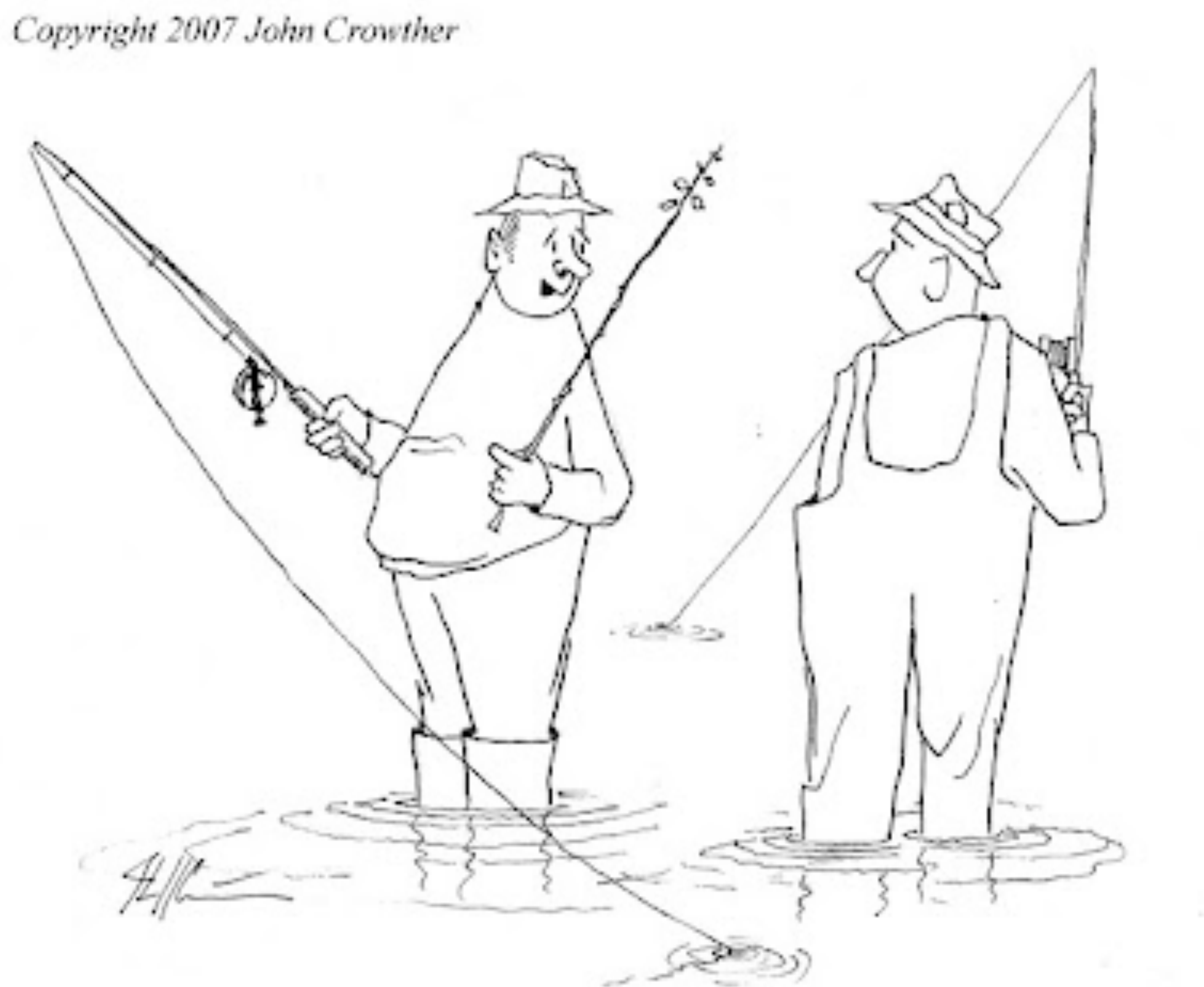


"It's the old bait and switch, but to tell you the truth it's the first time I've tried it. I understand the bait, but I have no idea what to do with the switch."

Extra Dimensions

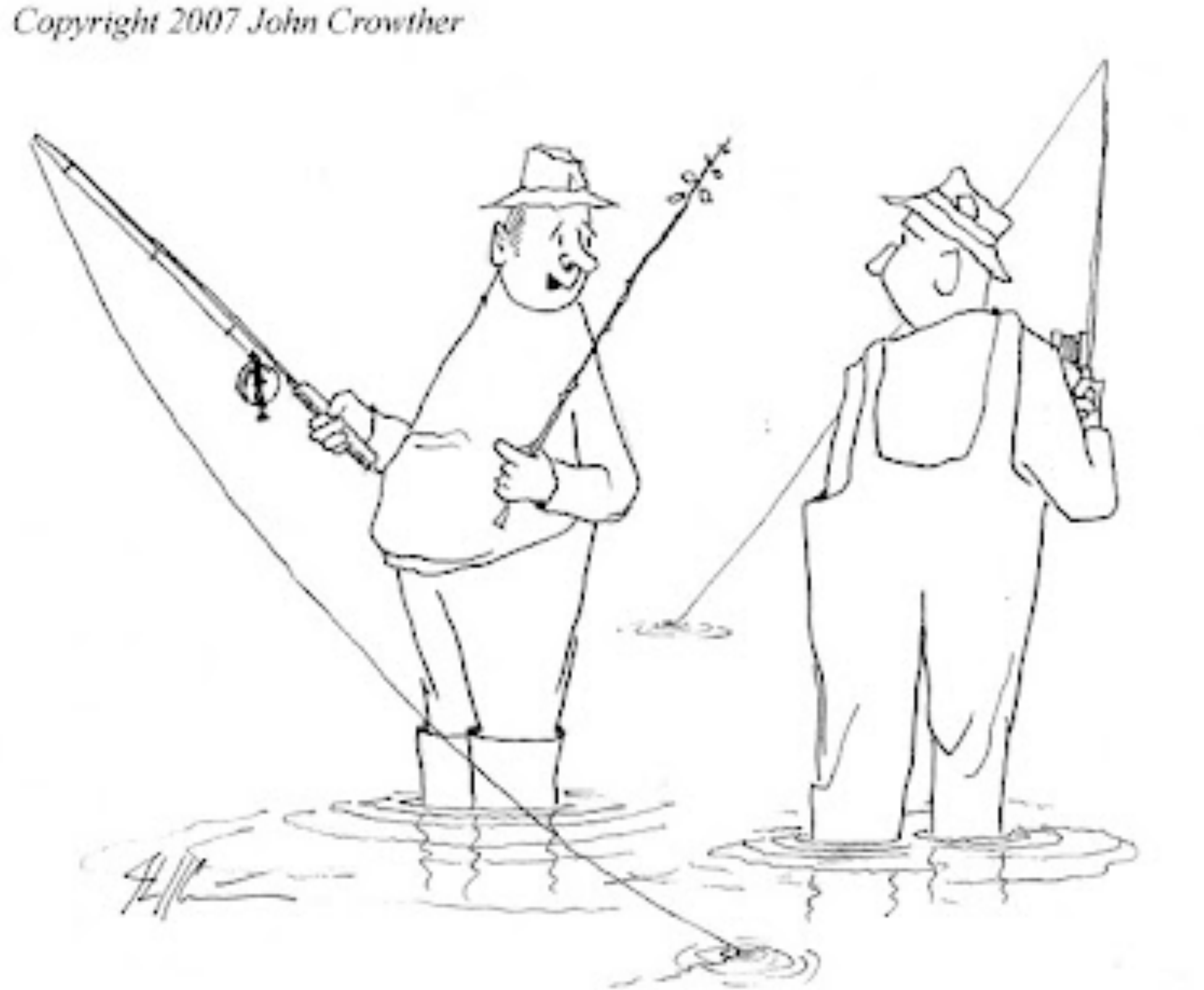
or

Other Exciting Stuff



"It's the old bait and switch, but to tell you the truth it's the first time I've tried it. I understand the bait, but I have no idea what to do with the switch."

Other Exciting Stuff



"It's the old bait and switch, but to tell you the truth it's the first time I've tried it. I understand the bait, but I have no idea what to do with the switch."

Flavor in Supersymmetry

Interlude: Flavor in the Standard Model

Flavor originates in the Yukawa couplings:

$$Y_{ij}^u \, Q_i H \bar{u}_j + Y_{ij}^d \, Q_i H^\dagger \bar{d}_j + Y_{ij}^e \, L_i H^\dagger \bar{e}_j$$

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

Inserting the vevs for the Higgs:

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

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

These masses are not yet diagonal, until...

Perform global rotations on the fields, shifts

$$Y^u \to U^T Y^u \bar{U}$$
$$Y^d \to D^T Y^d \bar{D}$$

which diagonalizes the fermion mass matrices:

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

leaving the only residual in the weak interactions:

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

Flavor in Supersymmetry

In the MSSM, there is a plethora of soft breaking parameters that also "know" about flavor:

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

squark,slepton (mass)^2 matrices

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

scalar trilinear couplings

After rotating superfields to remove Yu Yd Ye, these mass parameters remain, in general,

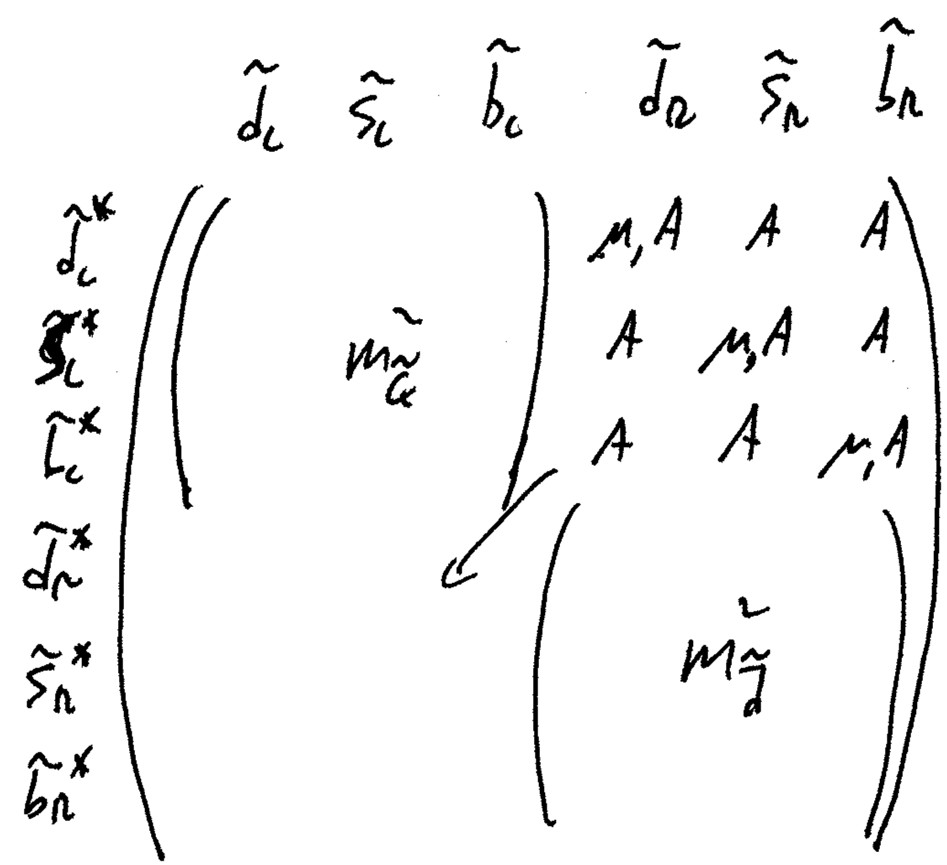
$$m^2_{Q_{ij}} = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$$ “LL” mixing

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

General 6x6 squark mass matrix:



Squarks and Sleptons

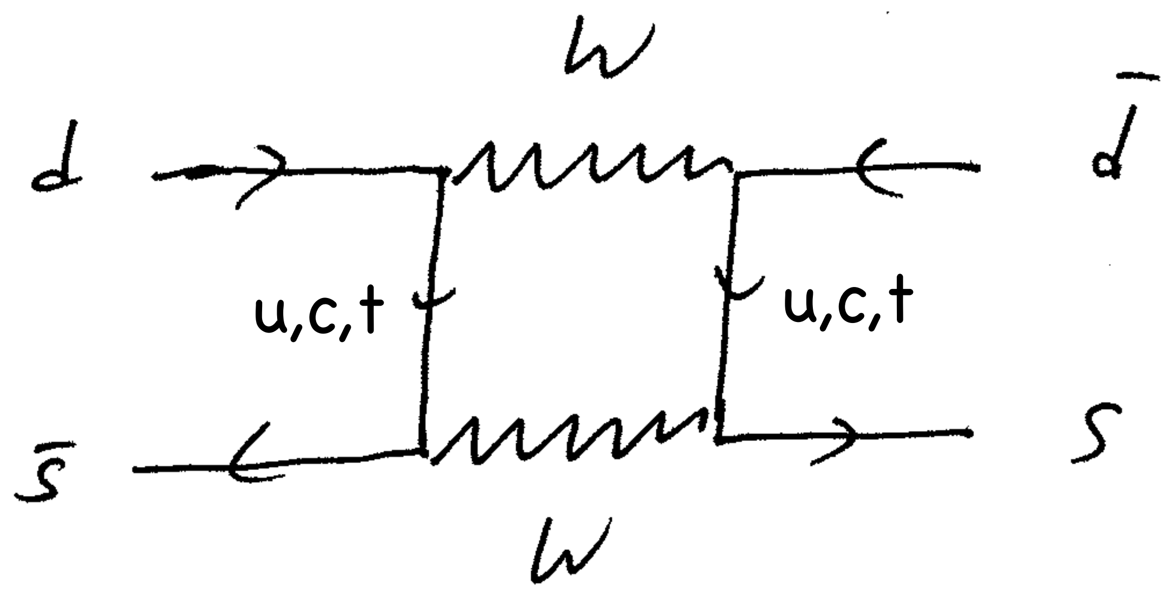
To treat these in complete generality, we would have to take into account arbitrary mixing. So the mass eigenstates would be obtained by diagonalizing:

- a 6×6 (mass)^2 matrix for up-type squarks ($\widetilde{u}_L, \widetilde{c}_L, \widetilde{t}_L, \widetilde{u}_R, \widetilde{c}_R, \widetilde{t}_R$),
- a 6×6 (mass)^2 matrix for down-type squarks ($\widetilde{d}_L, \widetilde{s}_L, \widetilde{b}_L, \widetilde{d}_R, \widetilde{s}_R, \widetilde{b}_R$),
- a 6×6 (mass)^2 matrix for charged sleptons ($\widetilde{e}_L, \widetilde{\mu}_L, \widetilde{\tau}_L, \widetilde{e}_R, \widetilde{\mu}_R, \widetilde{\tau}_R$),
- a 3×3 (mass)^2 matrix for sneutrinos ($\widetilde{\nu}_e, \widetilde{\nu}_\mu, \widetilde{\nu}_\tau$)

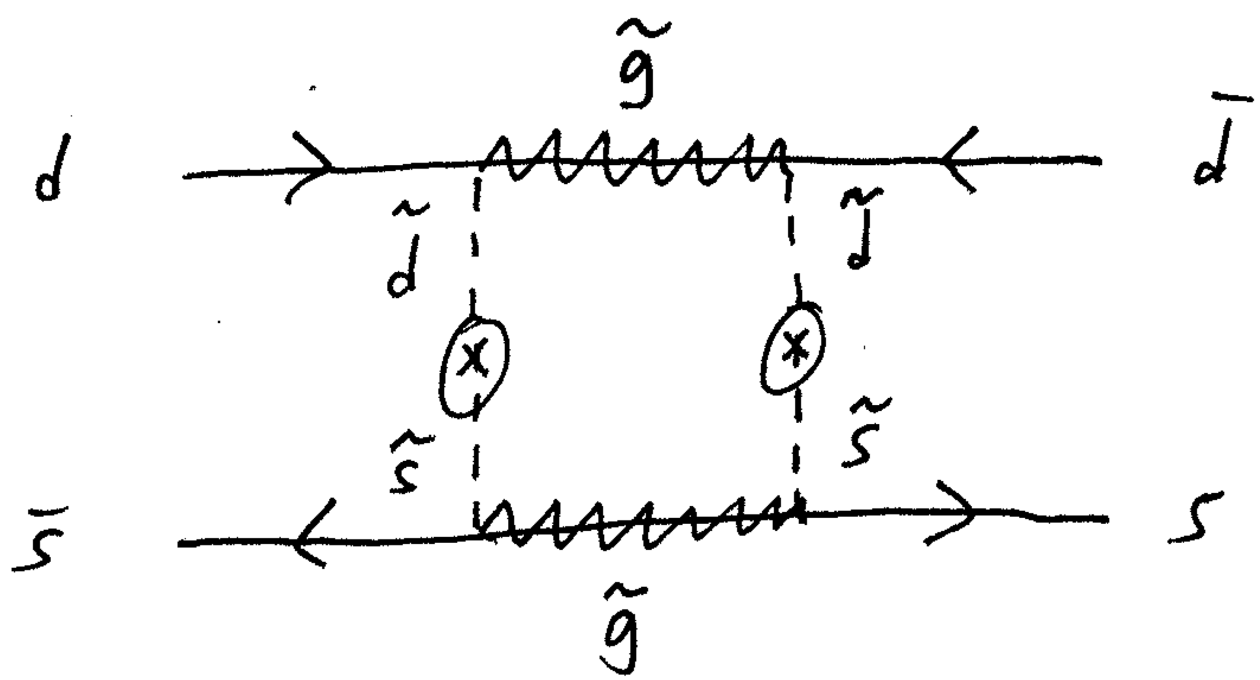
This potential large mixing among the squark and slepton gauge eigenstates has dramatic consequences for flavor physics.

This is a phenomenological disaster:

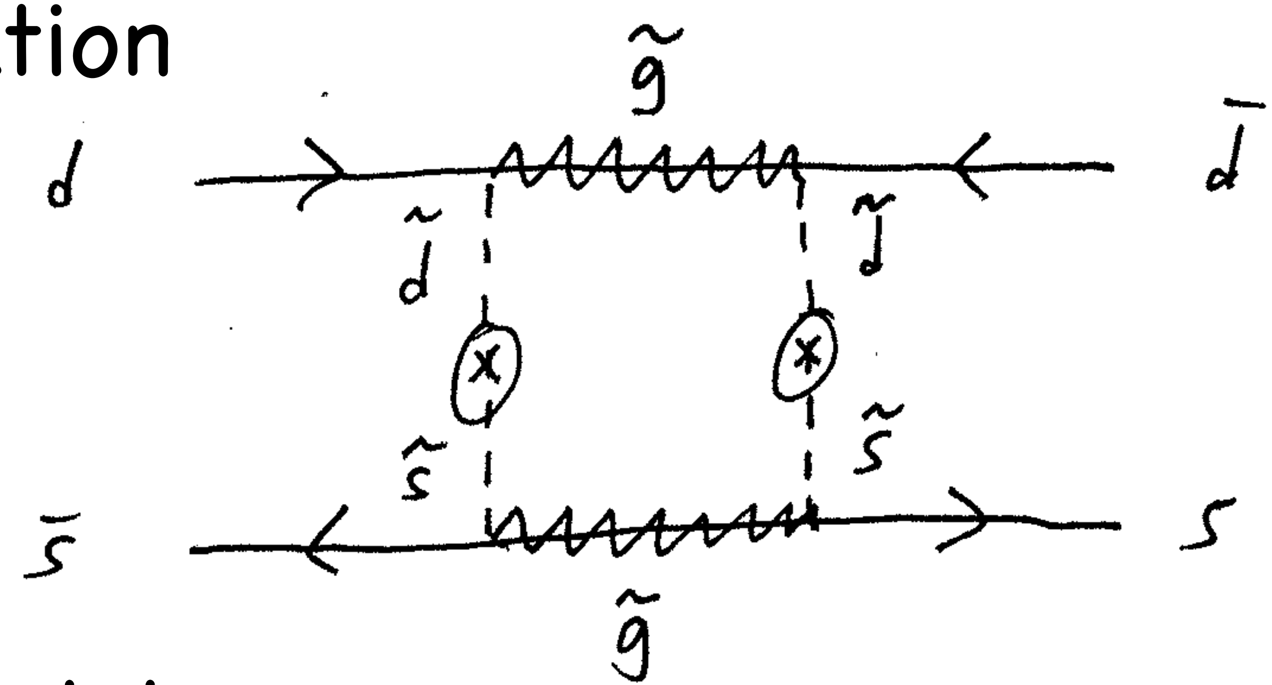
For example, K^0–$\bar{K}^0$ mixing



Has contributions from superpartner loops



The contribution



is proportional to

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

Putting in the numbers...

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

(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)

SUSY Flavor "Problem"

Sflavor highly constrained by:
- $K-\bar{K}$, $B-\bar{B}$, $D-\bar{D}$ mixing
- LFV ($\mu \to e\gamma$; $\tau \to \mu\gamma$)
- ε'/ε
- ε_K [$\mathrm{Im}(\Delta m_K)$]
- $b \to s\gamma$
- flavor at large $\tan\beta$ (e.g., $B \to \mu\mu$)

As well as serious related problems with:
- contributions to EDMs of e,n,Hg...
- proton decay through dim-5 (QQQL, ...)

Sflavor...

The MSSM + flavor-arbitrary soft breaking is completely ruled out by existing FCNC constraints unless sparticles are extremely heavy...

(Far beyond what the LHC can find.)

Flavor-blind Paradigm ("mSUGRA")

If

$$\tilde{m}^2_{ij} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tilde{m}^2_0 \quad , \quad A_{ij} = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix} A_0$$

Then, for example,

$$\tilde{Q}^\dagger_i \tilde{m}^2_{ij} \tilde{Q}_j \to \tilde{Q}^\dagger_i L^\dagger (\tilde{m}^2) L \tilde{Q}_j \to \tilde{m}^2_0 \tilde{Q}^\dagger_i \tilde{Q}_i$$

or put simply,

sflavor = flavor

Decades of Model Building...

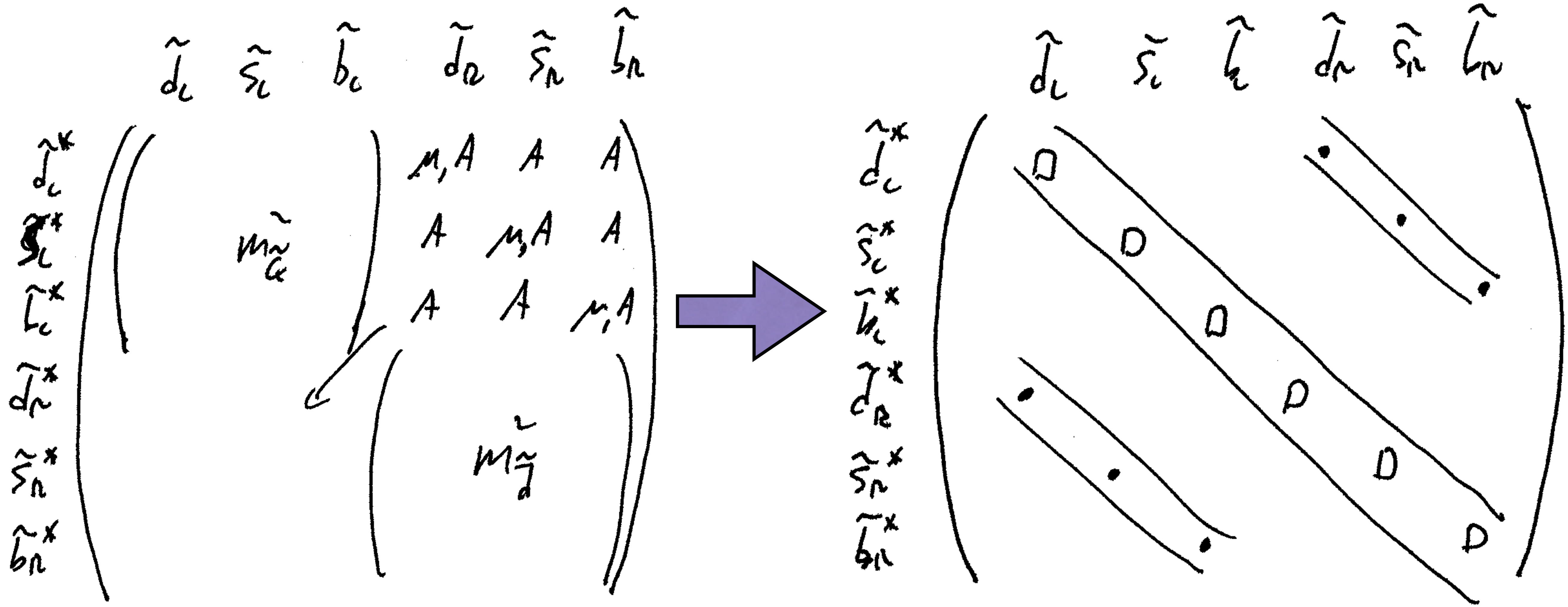
Gauge Mediation (1980s–1990s)

Anomaly Mediation (1998)

Gaugino Mediation (1999)

... and many others ...

Have attempted to justify the "lore":



e.g., mSUGRA, SPS points, ... assume flavor universality.

Much of the supersymmetric flavor problem can be attributed to interactions that violate the supersymmetric "R symmetry".

GK, Poppitz, Weiner [2007]

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

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

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

R charges of MSSM

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

Required:

2 superpotential

1 W_α super field strength (and gaugino)

For Yukawas:

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}.

What violates R symmetry of MSSM?

Majorana gaugino masses

μ/B_μ-term (one or the other; take μ-term)

A-terms

Unbroken R symmetry historically considered a problem.

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

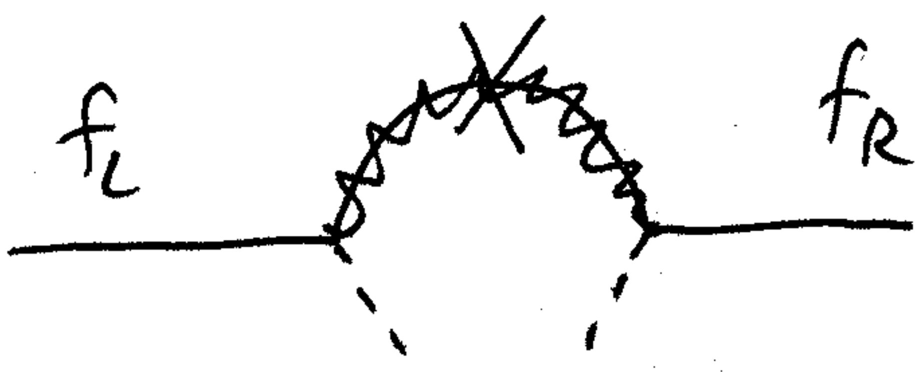
$$\int d^2\theta \, \frac{X}{M_{\rm Pl}} W_\alpha W^\alpha \rightarrow \frac{F_X}{M_{\rm Pl}} \lambda\lambda + h.c.$$

resulting in a Majorana mass for the gauginos.

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

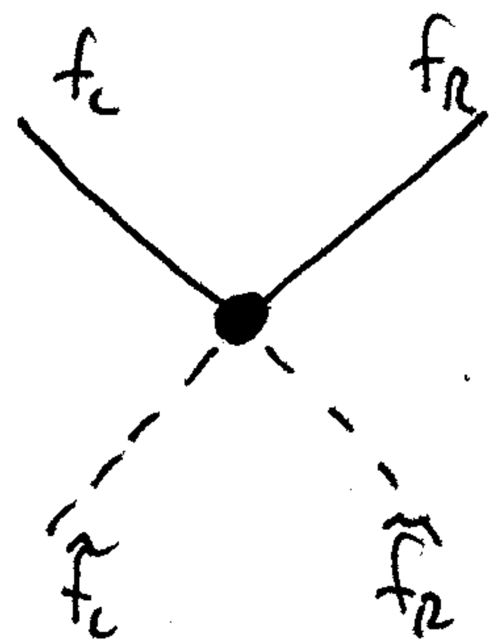
What do Majorana masses do?

Majorana masses and μ-term allow chirality flip on gaugino/Higgsino lines:



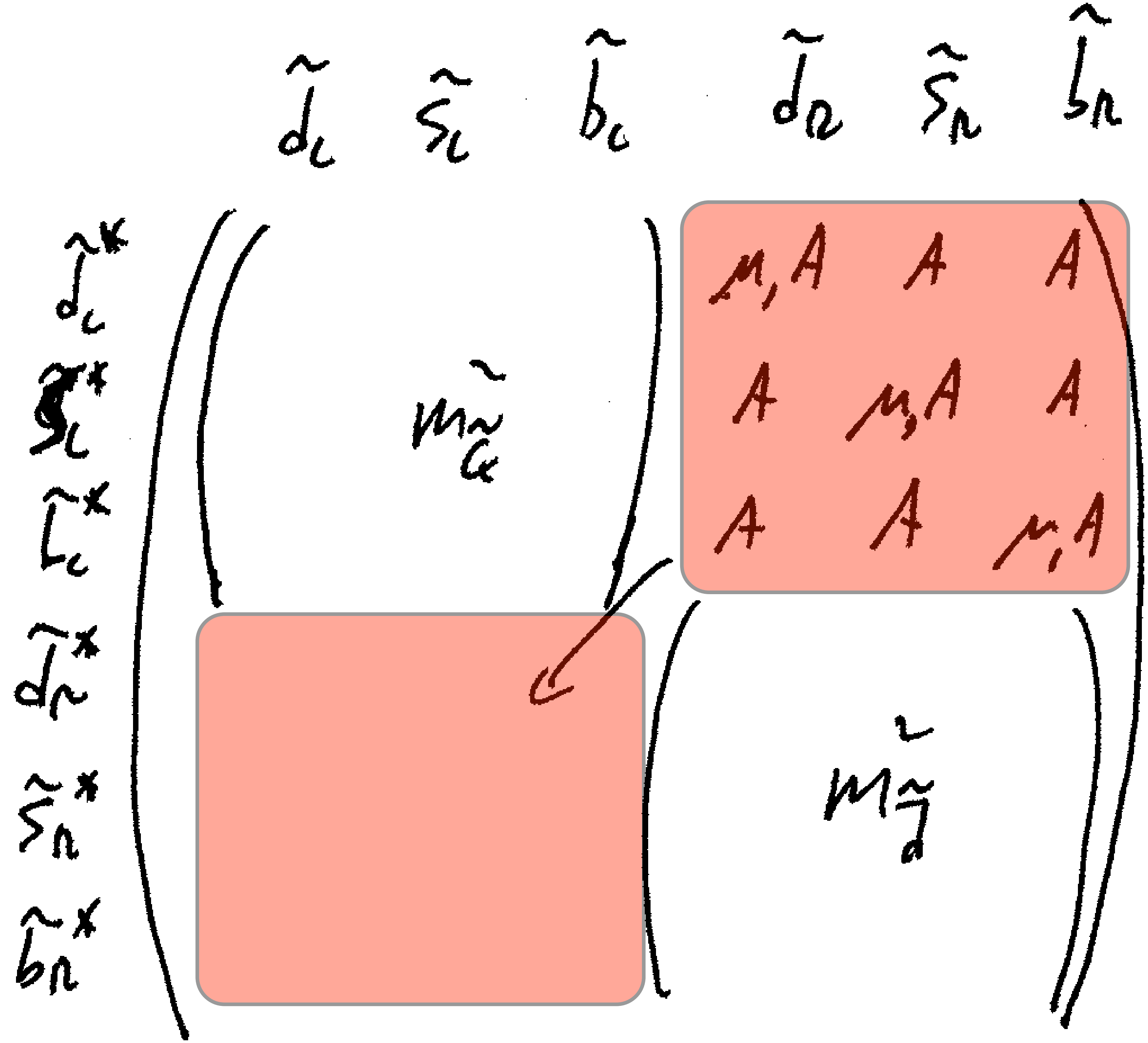
The SM, by contrast, can flip external fermion chirality only through a fermion mass insertion.

If the Majorana mass or μ-term is heavy, integrating it out leads to dim-5 operators suppressed by $1/M_g$ or $1/\mu$:



Integrating out the weak interactions of the SM, by contrast, leads to dim-6 operators (Fermi interaction!)

A-terms allow flavor-violating left-right mixing:



Building R-Symmetric SUSY

Early attempt: 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 proposed is ruled out by LEP II.

Our Idea:

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

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

Step (1): 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 $W'_\alpha = D\theta_\alpha$

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

Step (2): R symmetric μ-terms

Require additional fields:

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

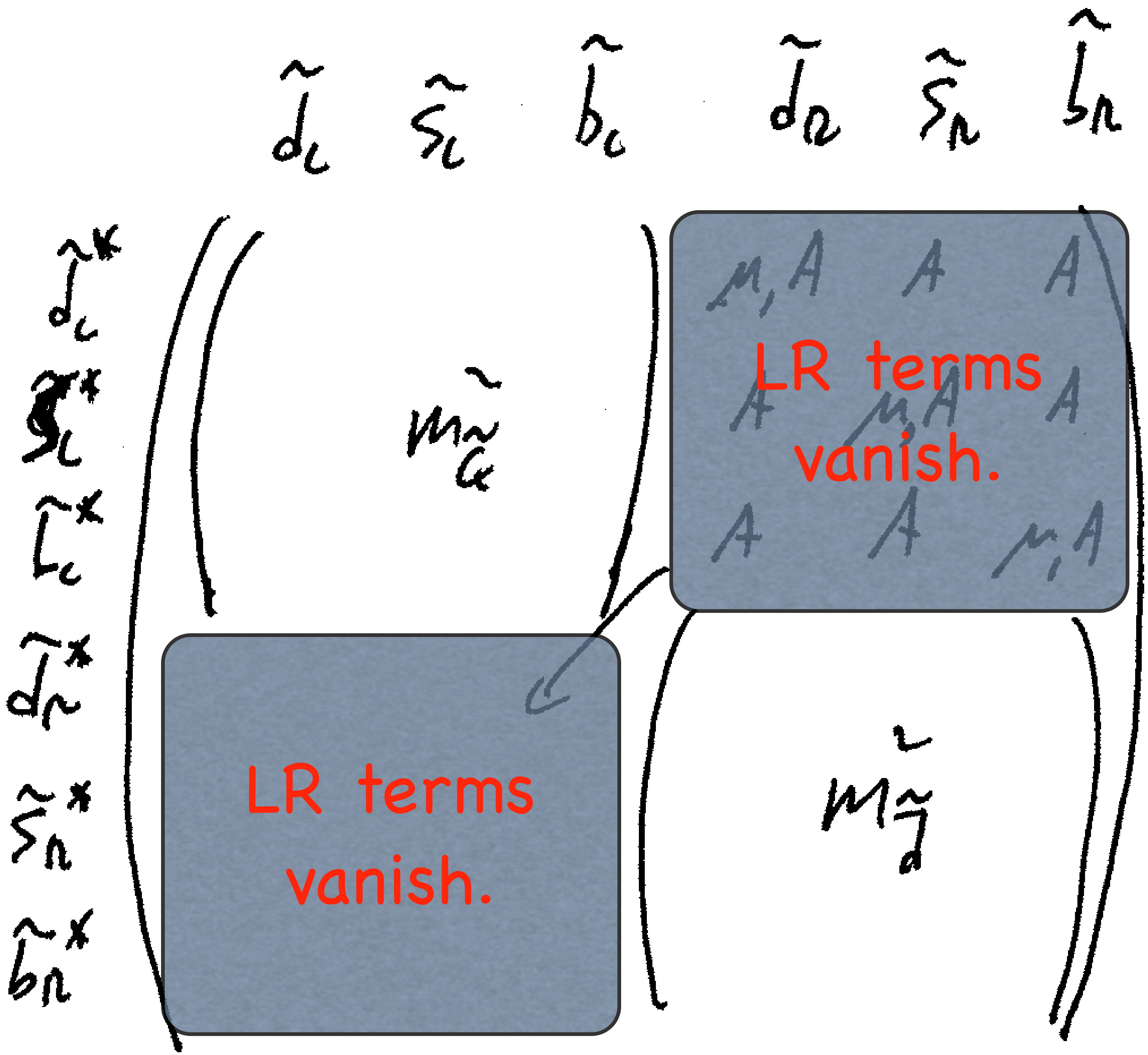
$$R_d \qquad (\mathbf{1}, \mathbf{2}, +1/2) \qquad R[R_d] = 2$$

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.

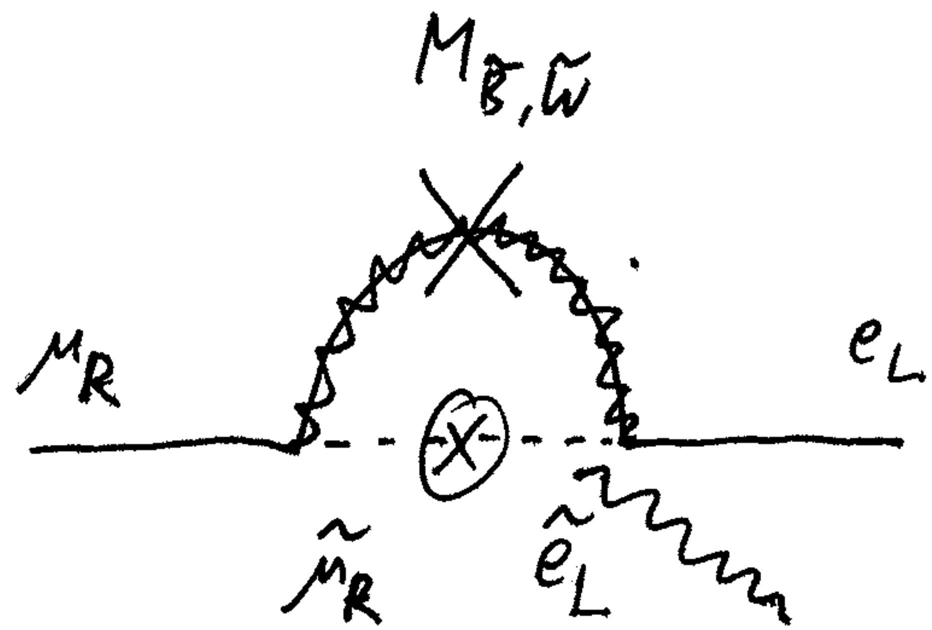
Step (3): Toss out A-terms (R violating!)



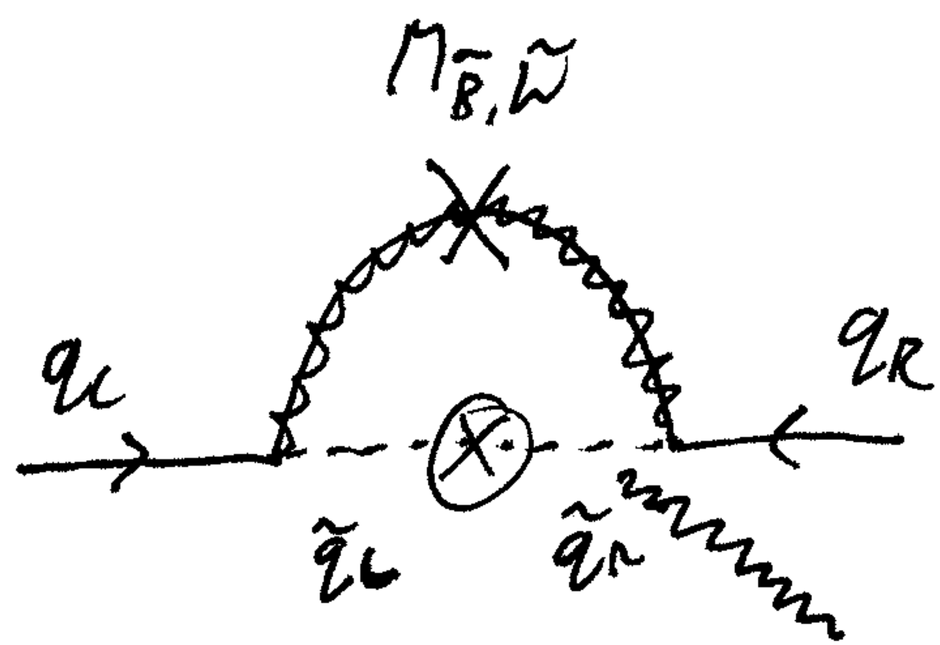
Consequences

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 5-10.

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

Fox, Nelson, Weiner

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

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 => No Dim-5

Given that the gluino can be made naturally heavier that the squarks, an additional suppression to flavor-violating observables can be realized with R-symmetry:

Integrating out heavy (Dirac) gauginos leads to dimension-6, not dimension-5 operators.

A modest (few to 4π) hierarchy thus leads to a suppression of $1/(\text{few})^2$ to $1/(4\pi)^2$ compared with the MSSM.

K^0–$\overline{K}^0$ mixing: MSSM

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

In the limit of large squark masses

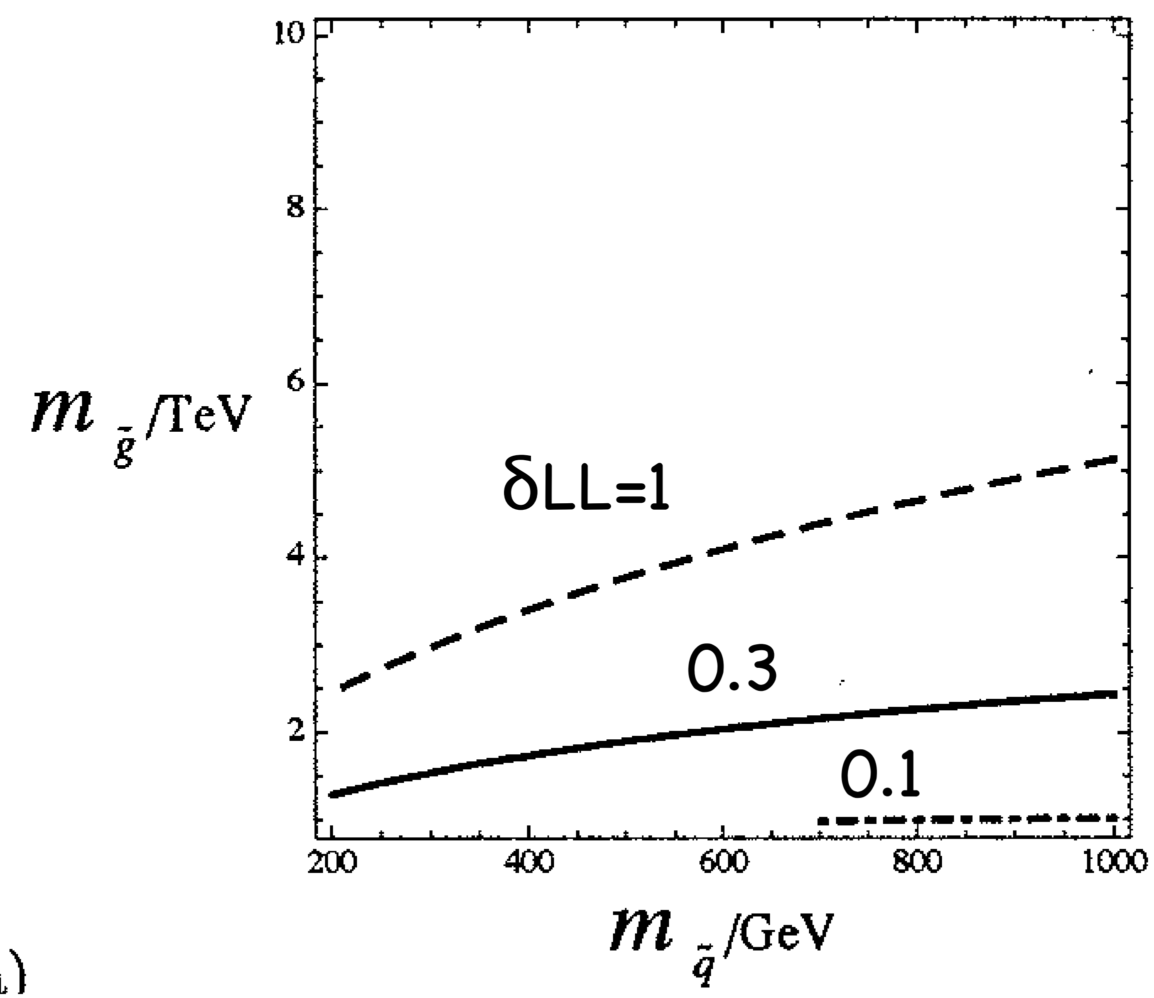
$$\Delta m_K \propto \alpha_s^2 \delta_{12}^2 \frac{1}{m^2_{\tilde{q}}}$$

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

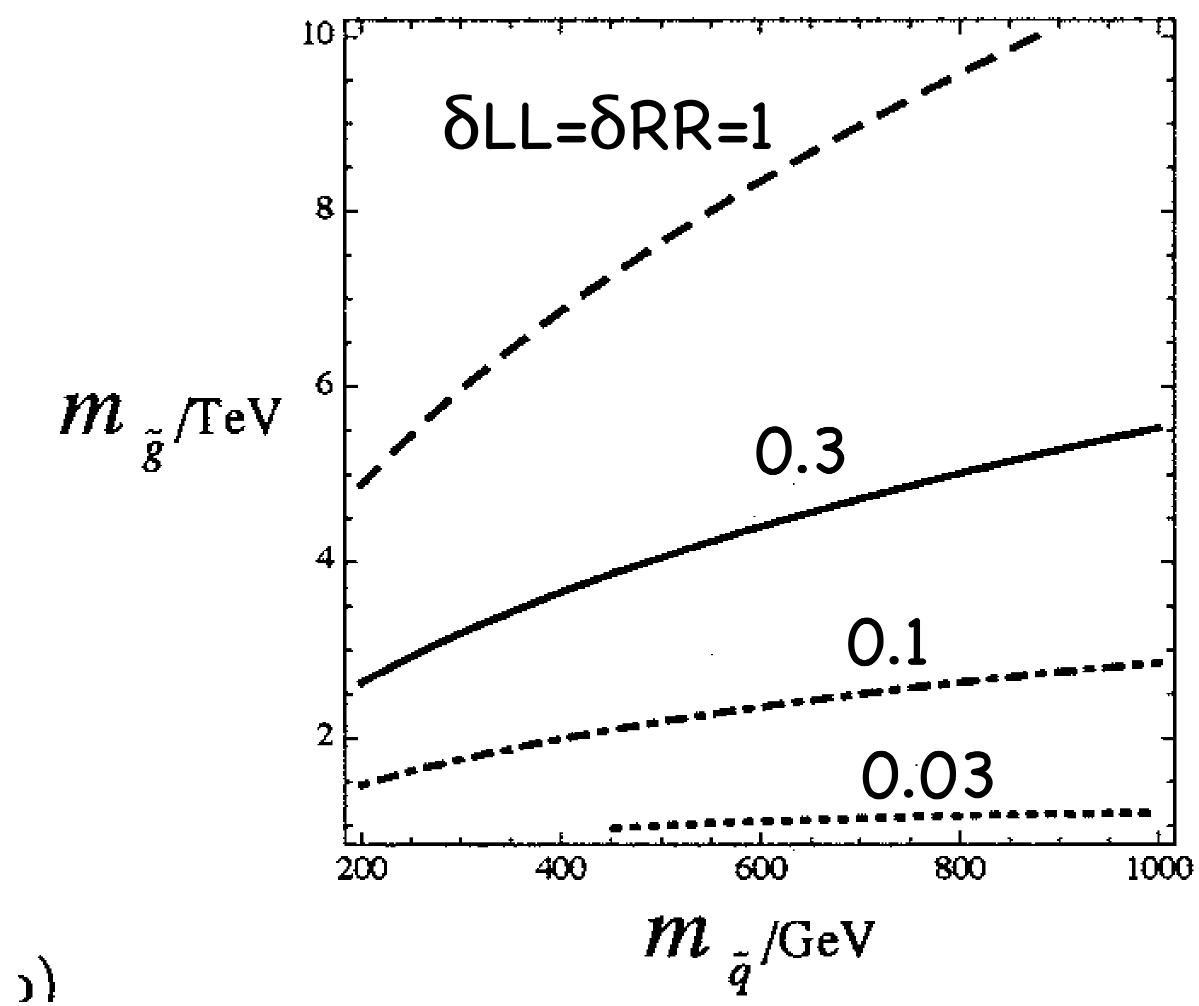
K^0–$\bar{K}^0$ mixing: R symmetric

LR mixing: no bounds.

LL only



LL=RR



Blechmann-Ng recently found QCD corrections worsen these bounds by factor of 3.

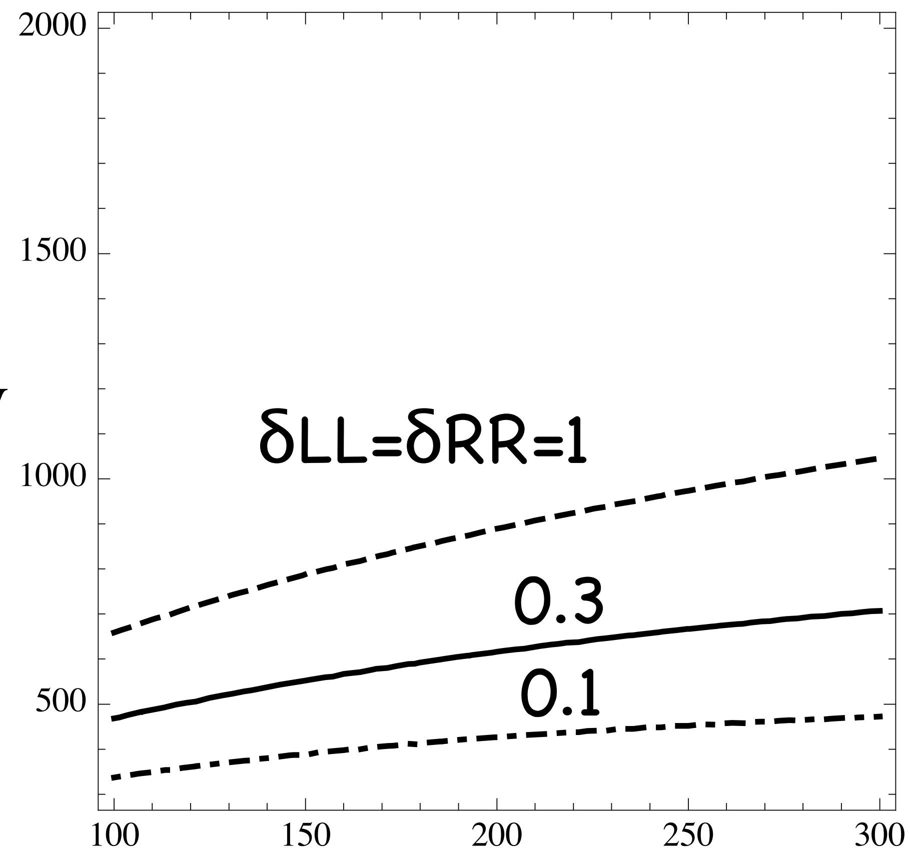
μ->eγ

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.

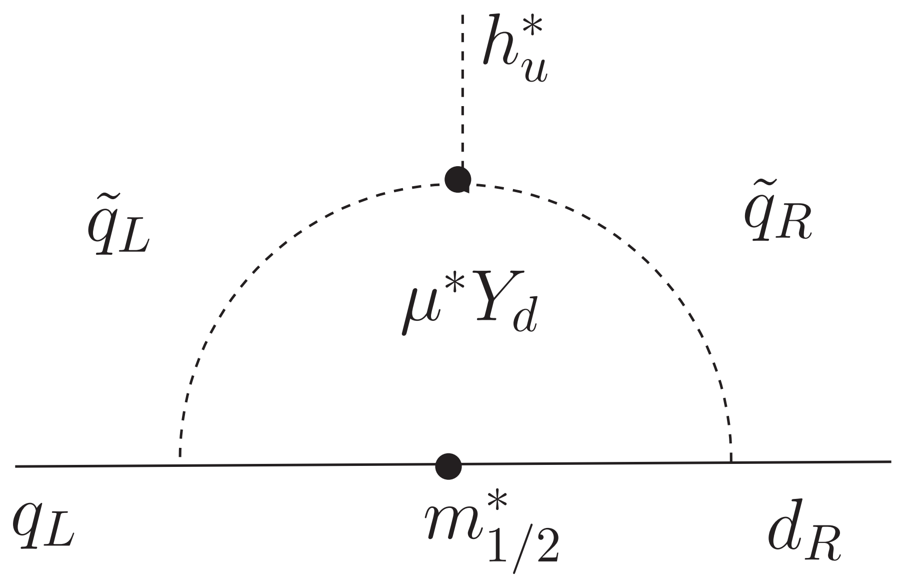
$$\frac{m_{\tilde{W}}}{2} = \mathrm{m}_{\tilde{B}}/\mathrm{GeV}$$



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

Large tan β

MSSM: Through gaugino mass and μ-term, get:

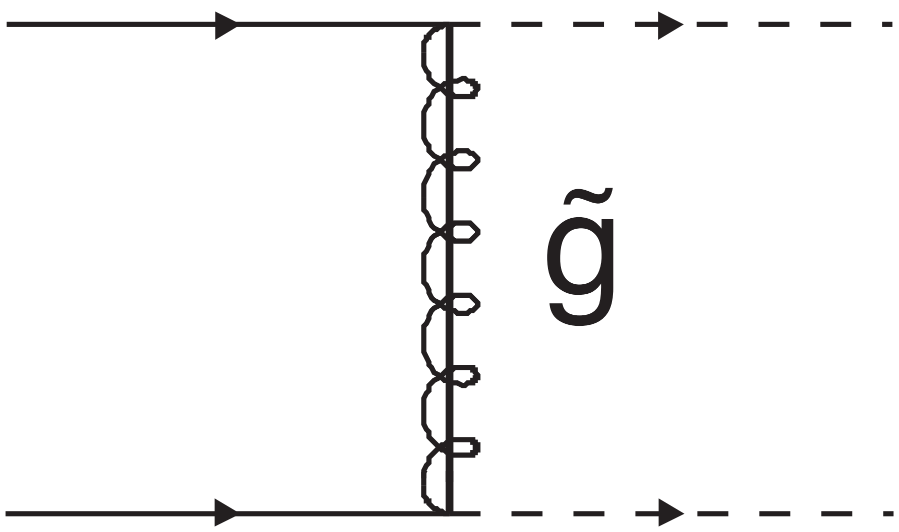


integrating out a heavy gluino leads to an interaction of up-type Higgs to down-type quarks. These lead to tan β enhanced contributions to B -> μμ, etc.

R-symmetric: Such large tan β effects are absent (need R-violating μ-term and Majorana mass).

Phenomenology

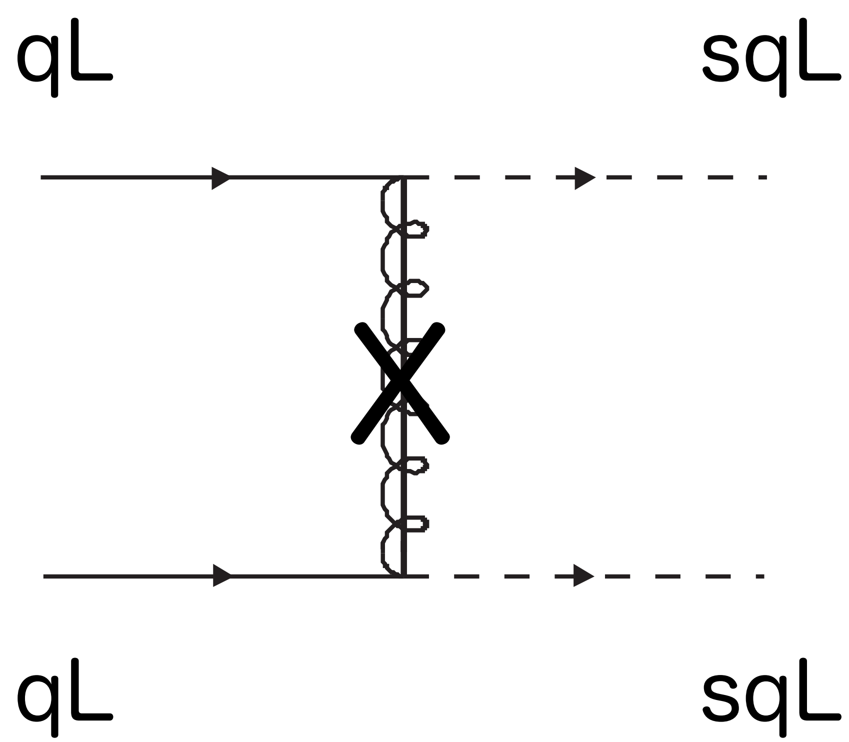
Squark Production



Gluino exchange diagrams
ought to dominate
LHC production of
(1st generation) squarks

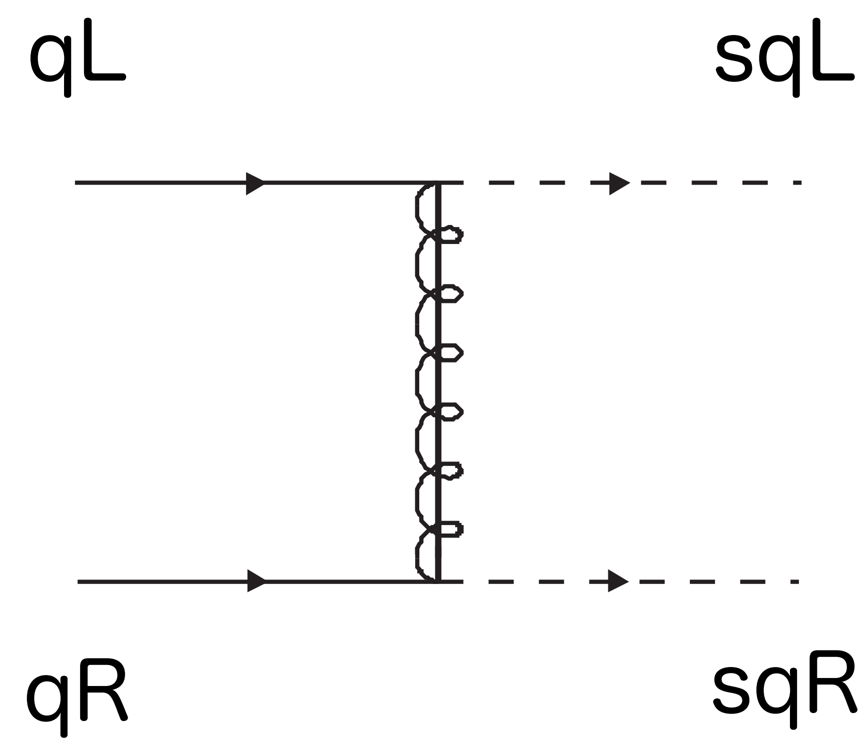
But for heavier gluino...

Majorana versus Dirac



Requires Majorana mass insertion. Scales as

$1/M$

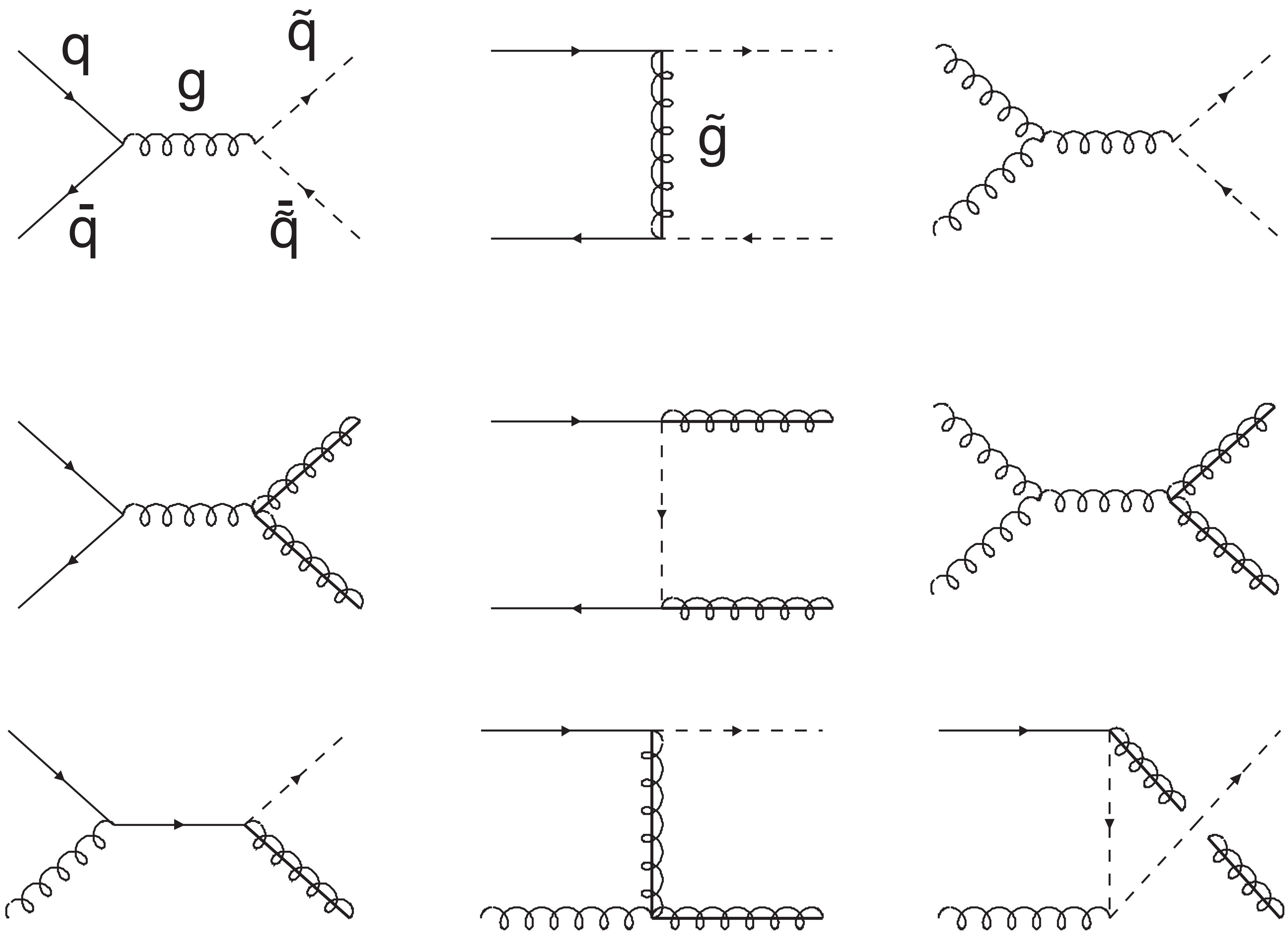


Dirac and Majorana. Scales as

$|p|/M^2$

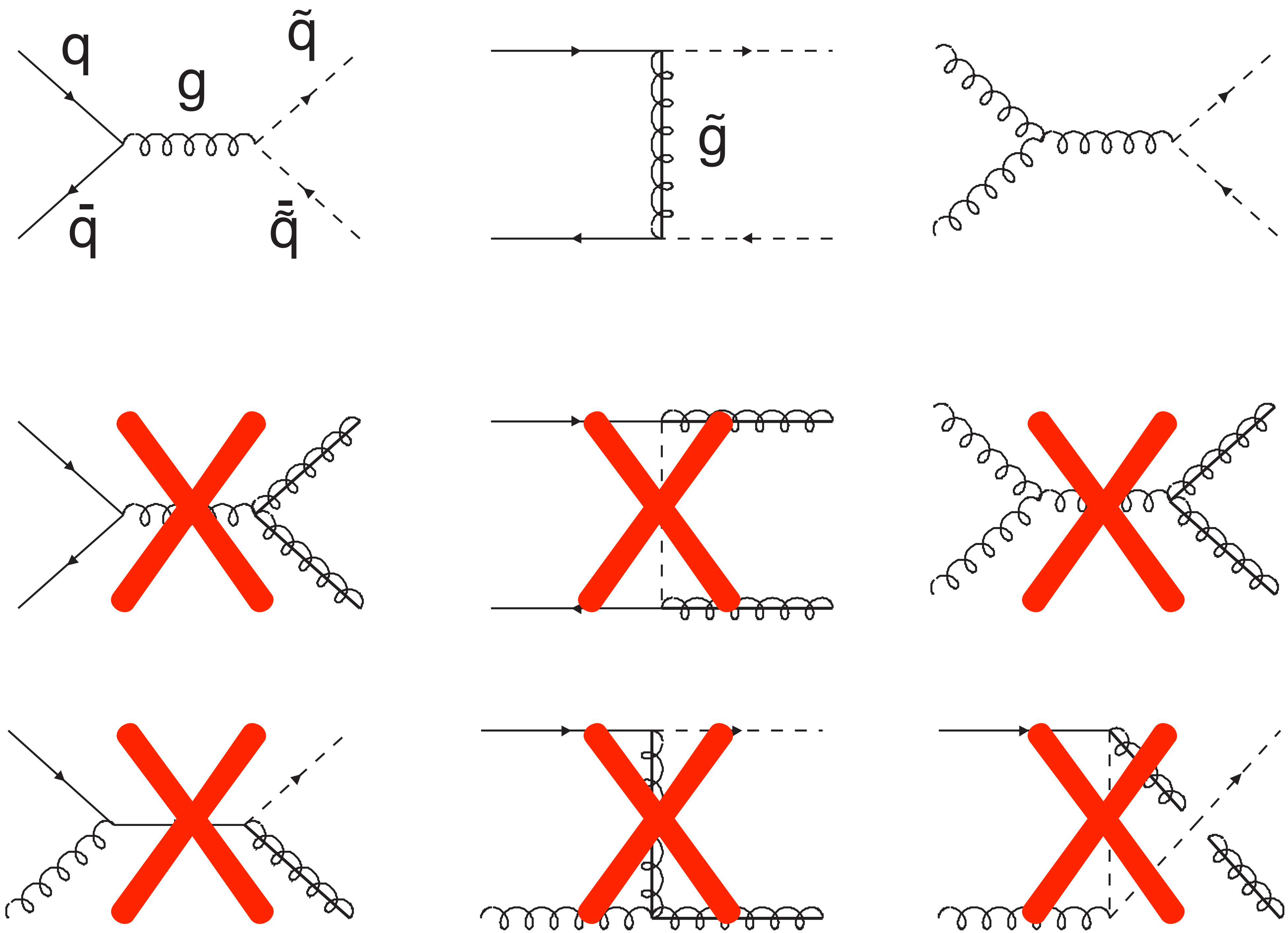
Suppressed

Squark and/or gluino production (LO)

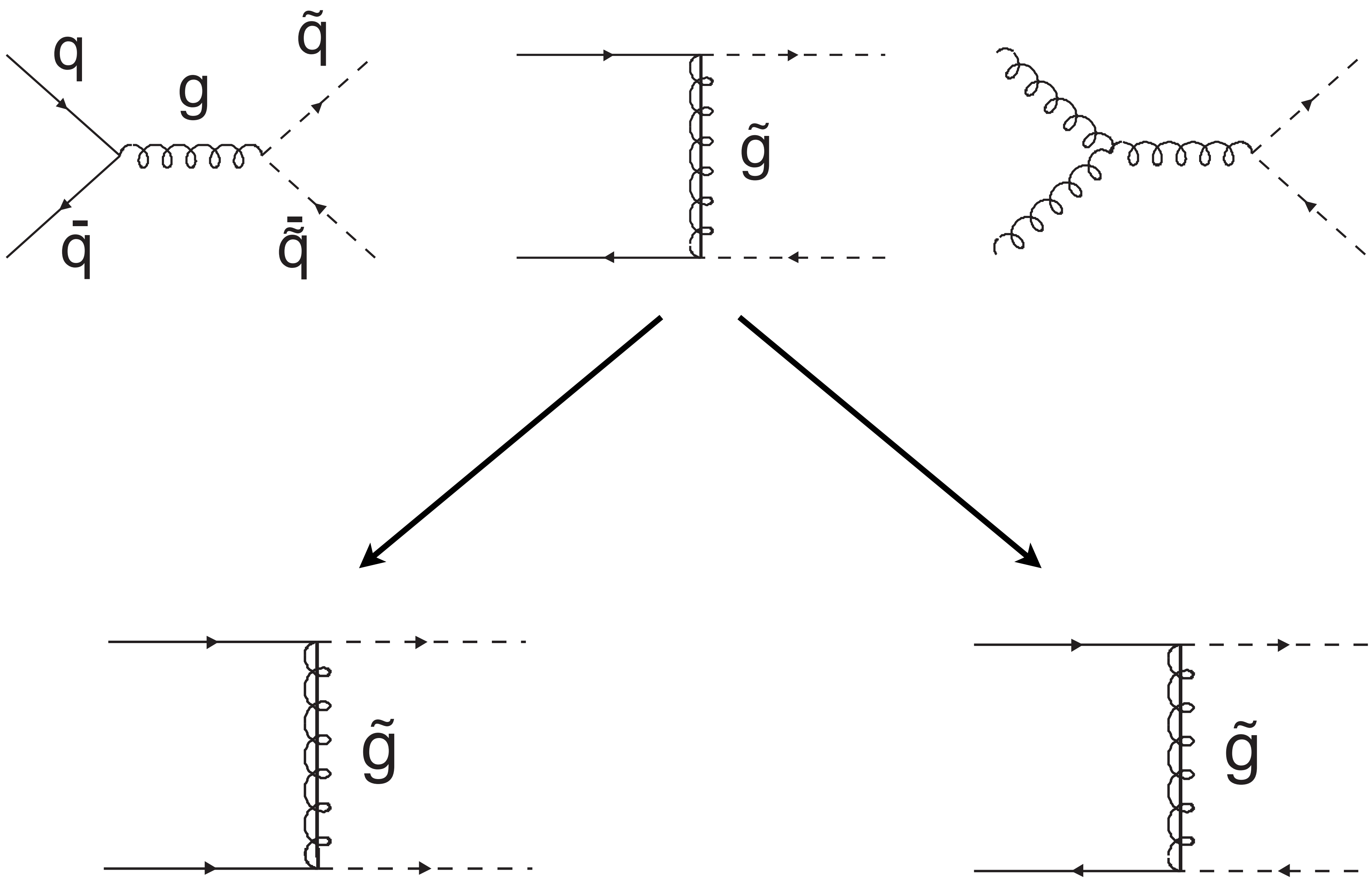


Squark and/or gluino production (LO)

with heavy gluino



Squark production (LO)



LL, RR absent

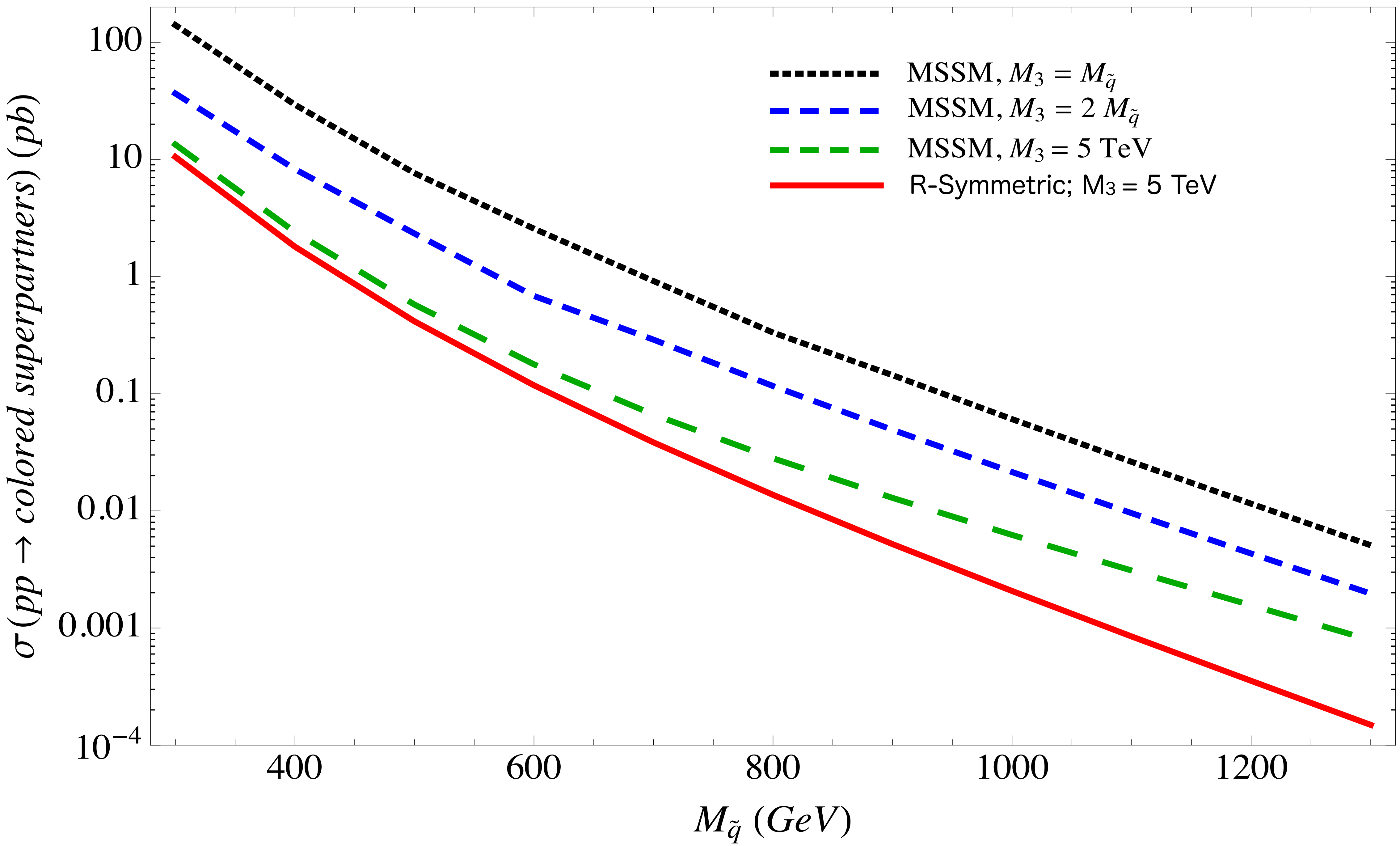
LR suppressed $1/M^2$

suppressed $1/M^2$ & PDFs

Bottom Line:

Colored Sparticle Production in
R-Symmetric Supersymmetric Models
Substantially Suppressed at LHC

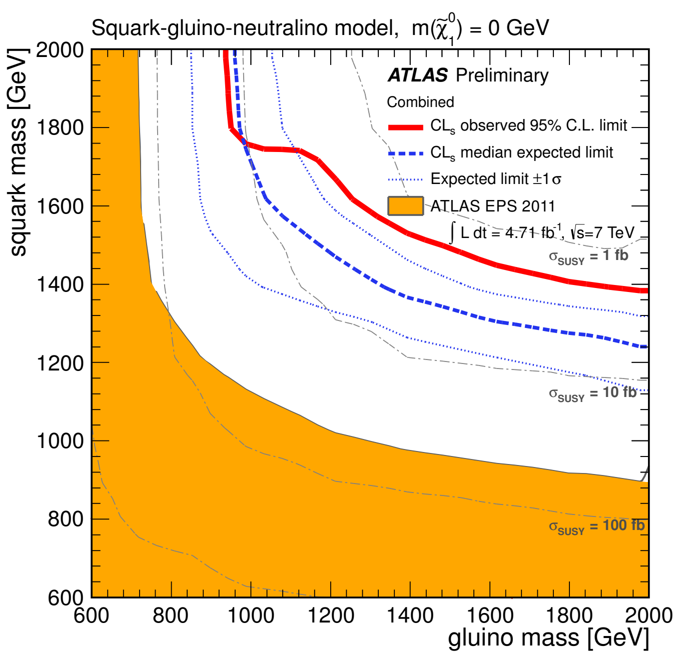
Colored Sparticle Cross Sections [LHC @ 8 TeV]

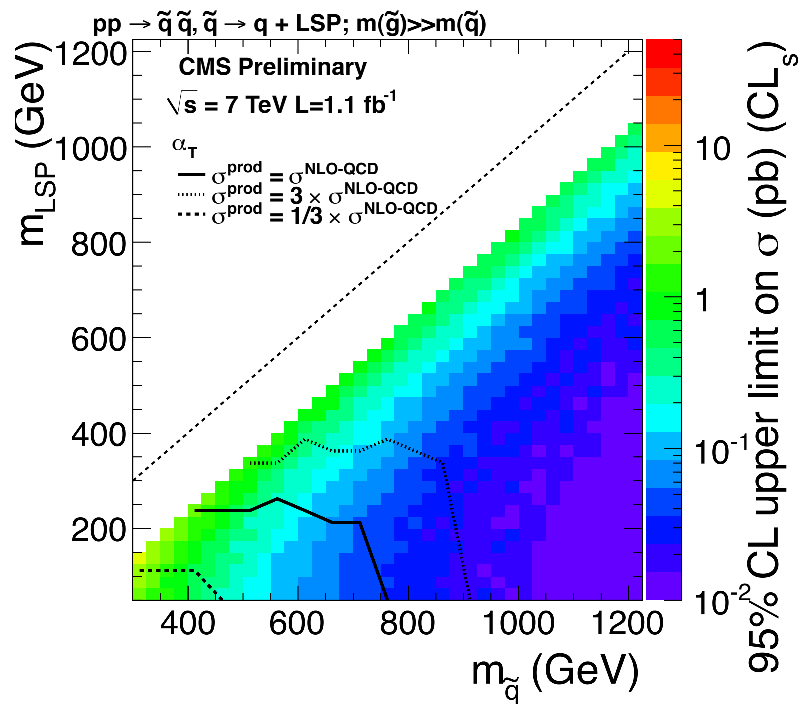


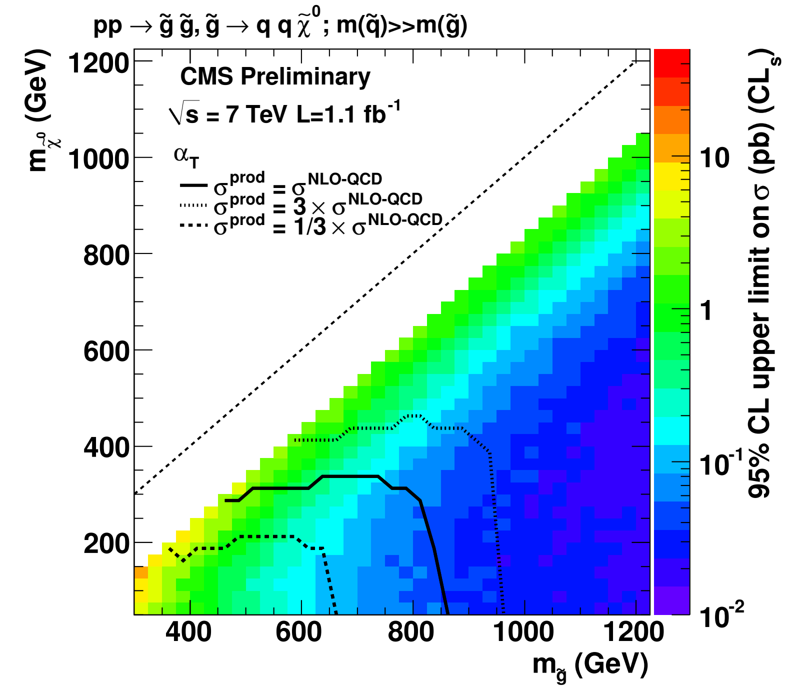
GK & Martin

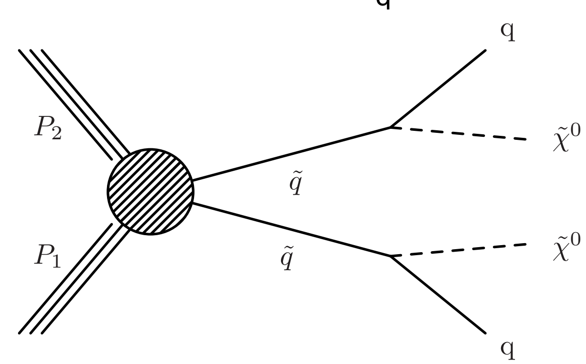
Impact on “Simplified Models”

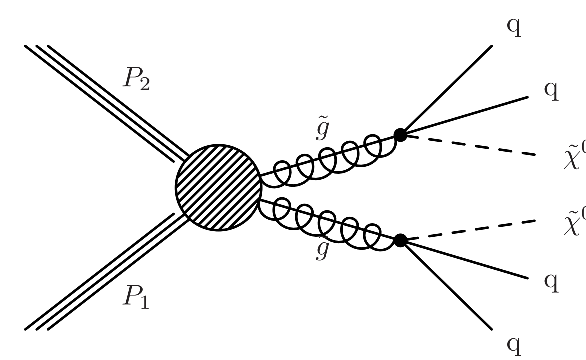
Examples of Simplified Models Bounded @ LHC











- massless LSP

- bounds in (M3, Msq) plane

- gluino >> sq

- bounds in (Msq, LSP) plane

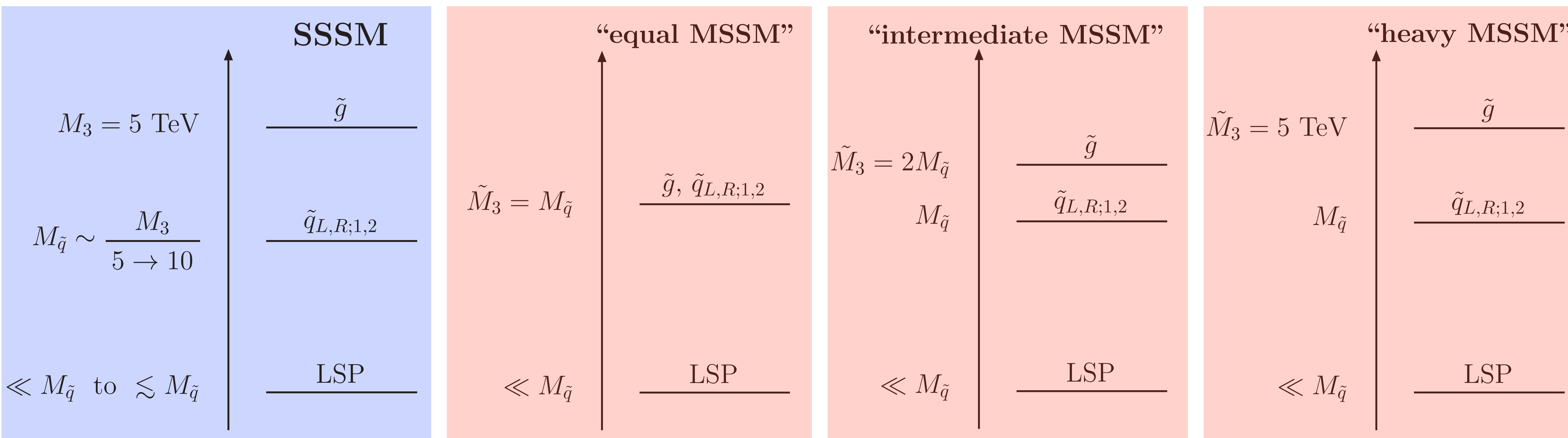
- sq >> gluino

- bounds in (M3, LSP) plane

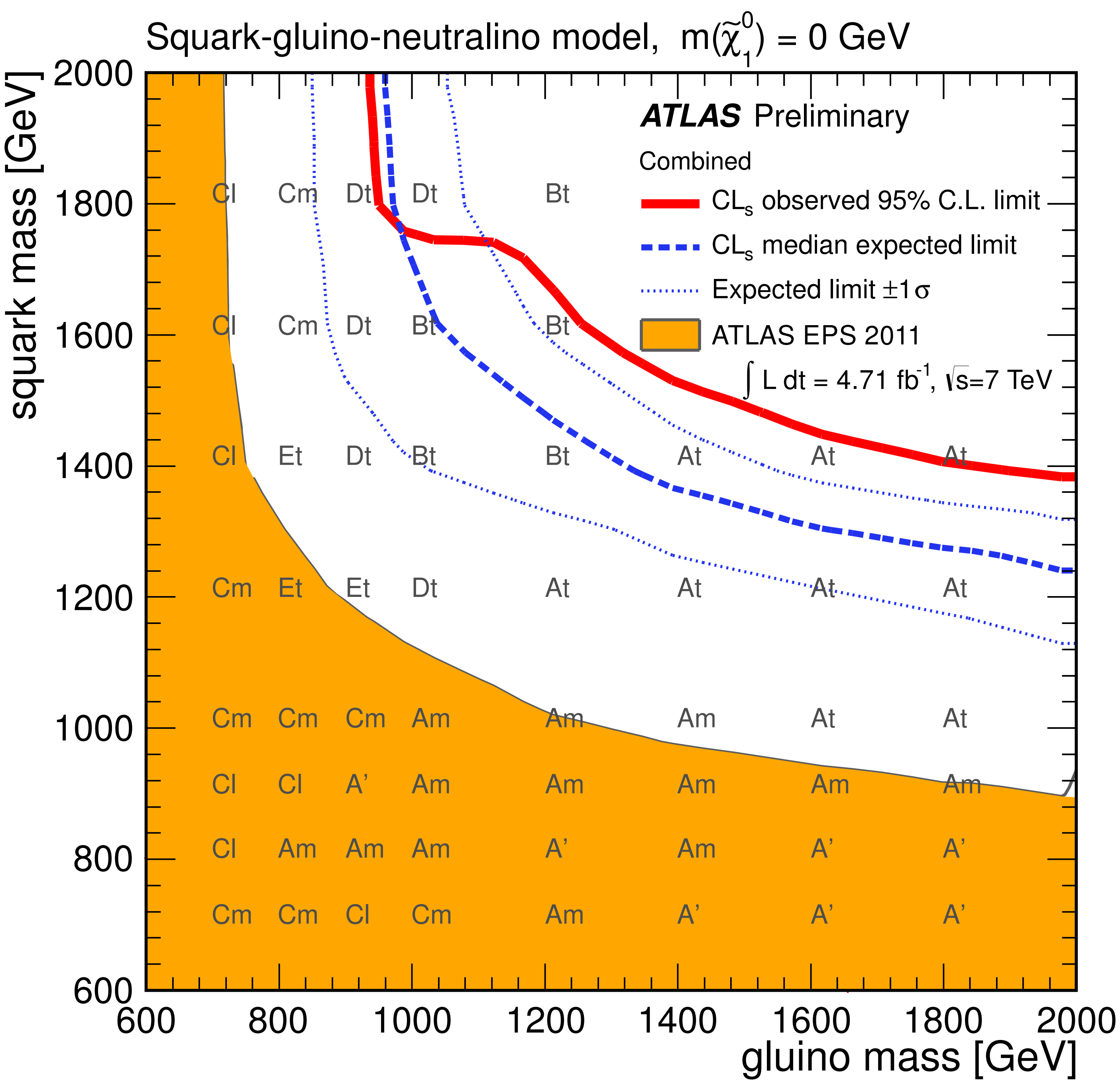
Dirac versus Majorana Gluino Simplified Models

Dirac gluino

Majorana gluino



ATLAS jets + missing search strategy



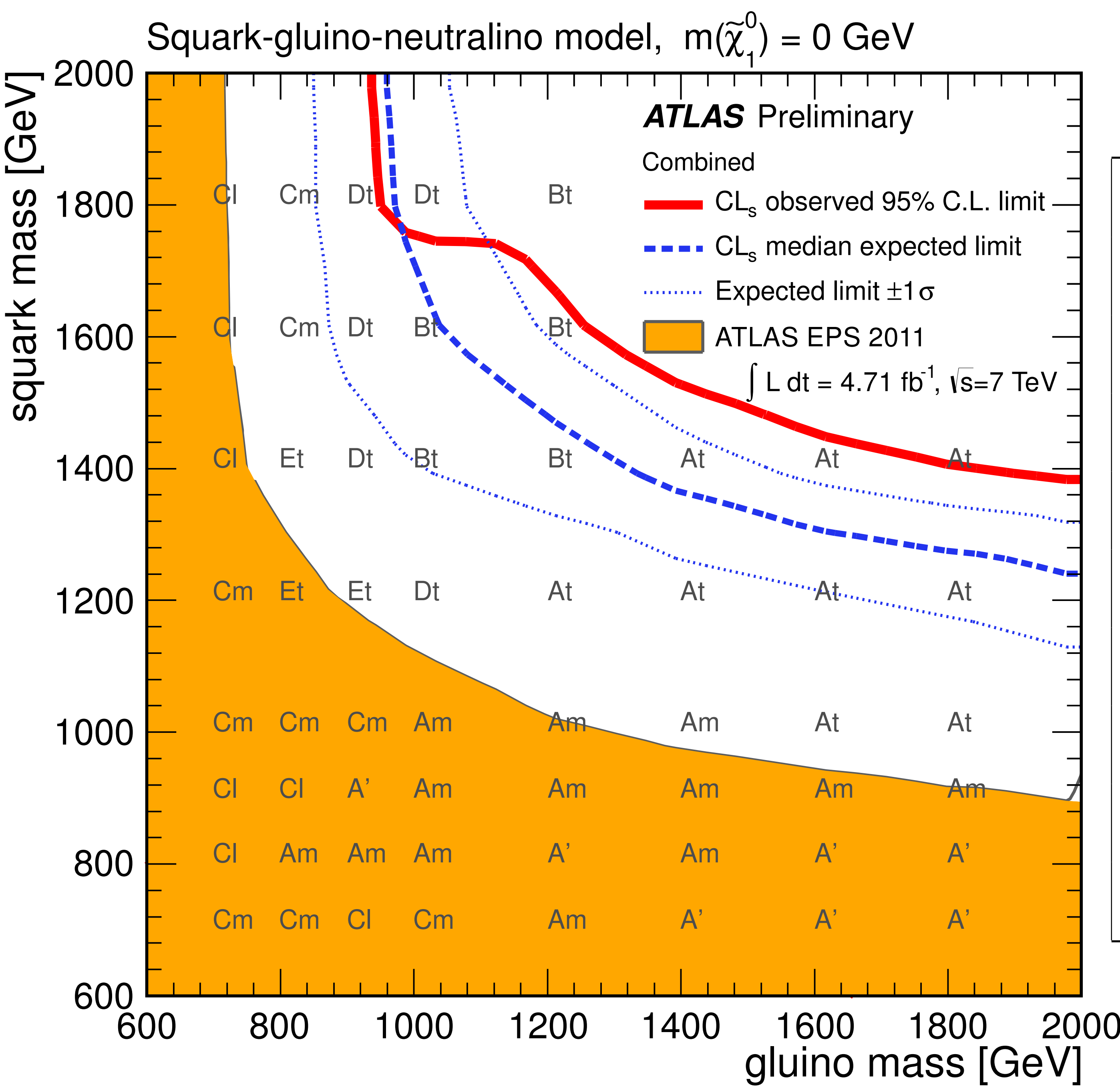
0 leptons; all jets pT > 40 GeV

Requirement	Channel					
	A	A’	B	C	D	E
E_T^{miss}[GeV] >	160					
$p_T(j_1)$ [GeV] >	130					
$p_T(j_2)$ [GeV] >	60					
$p_T(j_3)$ [GeV] >	–	–	60	60	60	60
$p_T(j_4)$ [GeV] >	–	–	–	60	60	60
$p_T(j_5)$ [GeV] >	–	–	–	–	40	40
$p_T(j_6)$ [GeV] >	–	–	–	–	–	40
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$ >	0.4 ($i = \{1, 2, (3)\}$)			0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_T > 40$ GeV jets)		
$E_T^{miss}/m_{eff}(Nj)$ >	0.3 (2j)	0.4 (2j)	0.25 (3j)	0.25 (4j)	0.2 (5j)	0.15 (6j)
m_{eff}(incl.) [GeV] >	1900/1400/–	–/1200/–	1900/–/–	1500/1200/900	1500/–/–	1400/1200/900

tight mid | mid | tight | tight mid loose | tight | tight mid loose

ATLAS-CONF-2012-033

ATLAS jets + missing search strategy



	At	Am	Am’	Bt
$t\bar{t}$+ Single Top	0.22 ± 0.35 (0.046)	7 ± 5 (5.1)	11 ± 3.4 (10)	0.21 ± 0.33 (0.066)
Z/γ+jets	2.9 ± 1.5 (3.1)	31 ± 9.9 (34)	64 ± 20 (69)	2.5 ± 1.4 (1.6)
W+jets	2.1 ± 0.99 (1.9)	19 ± 4.5 (21)	26 ± 4.6 (30)	0.97 ± 0.6 (0.84)
Multi-jets	0 ± 0.0024 (0.002)	0.14 ± 0.24 (0.13)	0 ± 0.13 (0.38)	0 ± 0.0034 (0.0032)
Di-Bosons	1.7 ± 0.95 (2)	7.3 ± 3.7 (7.5)	15 ± 7.4 (16)	1.7 ± 0.95 (1.9)
Total	$7 \pm 0.999 \pm 2.26$	$64.8 \pm 10.2 \pm 6.92$	$115 \pm 19 \pm 9.69$	$5.39 \pm 0.951 \pm 2.01$
Data	1	59	85	1
local p-value (Gaus. σ)	0.98(-2.1)	0.65(-0.4)	0.9(-1.3)	0.95(-1.7)
UL on N_{BSM}	$2.9(6.1^{4.2}_{9})$	$25(28^{20}_{39})$	$29(43^{32}_{60})$	$3.1(5.5^{3.8}_{8.3})$
UL on σ_{BSM} /(fb)	$0.62(1.3^{0.89}_{1.9})$	$5.3(6^{4.3}_{8.2})$	$6.2(9.2^{6.7}_{13})$	$0.65(1.2^{0.8}_{1.8})$

ATLAS-CONF-2012-033

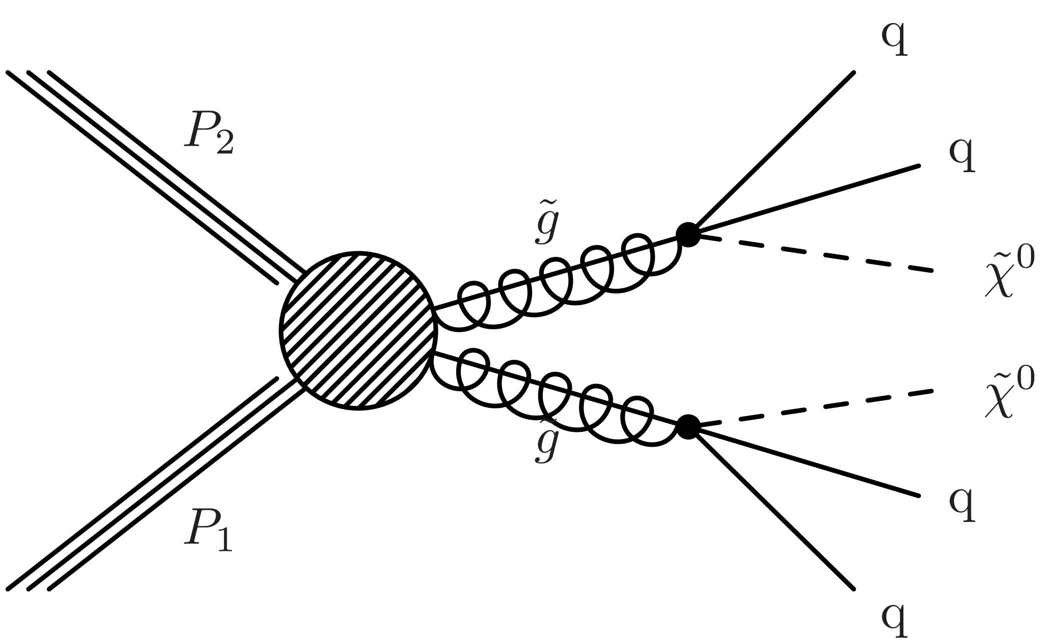
ATLAS Search Bounds

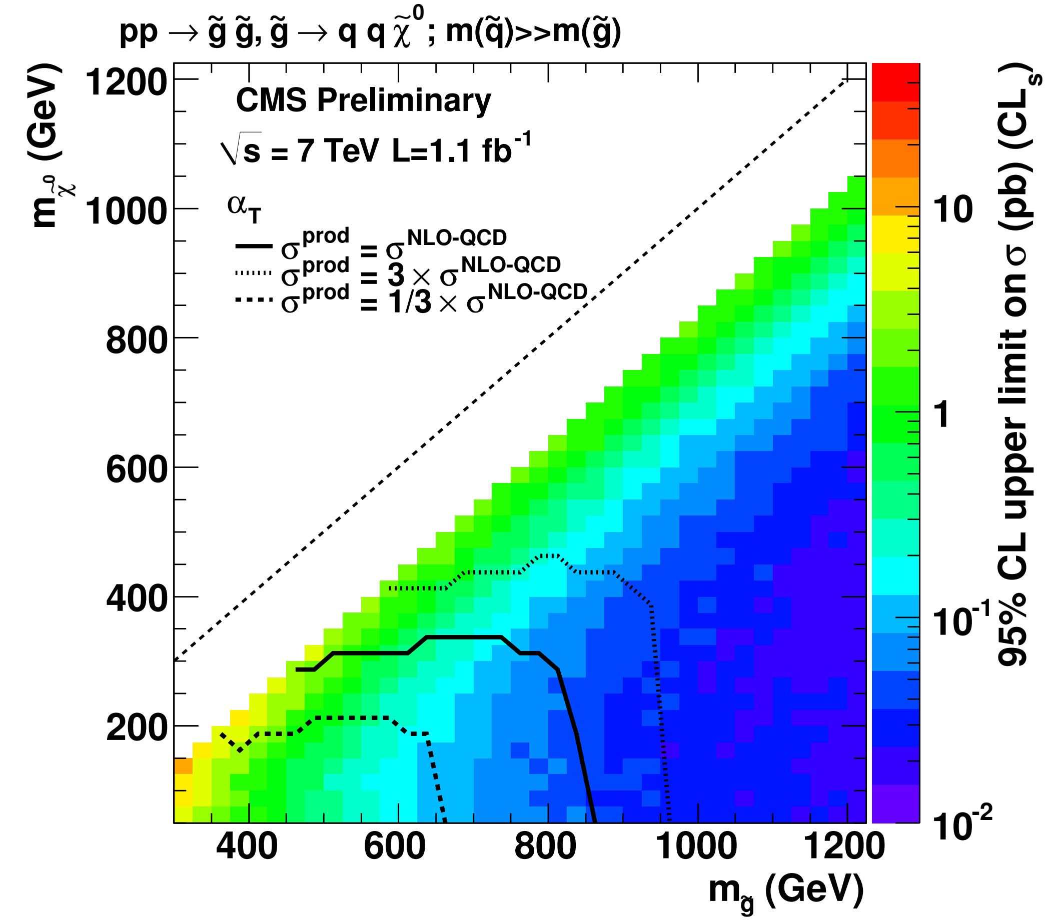
SSSM	MSSM	MSSM	MSSM
M3 = 5 TeV	M3 = Msq	M3 = 2 Msq	M3 = 5 TeV

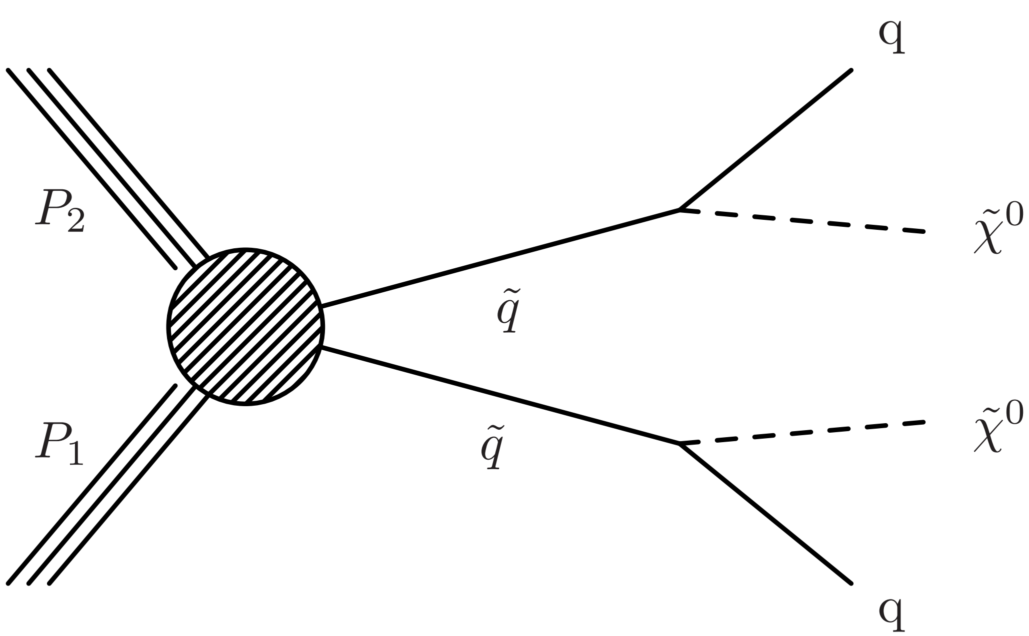
1st,2nd generation squark mass

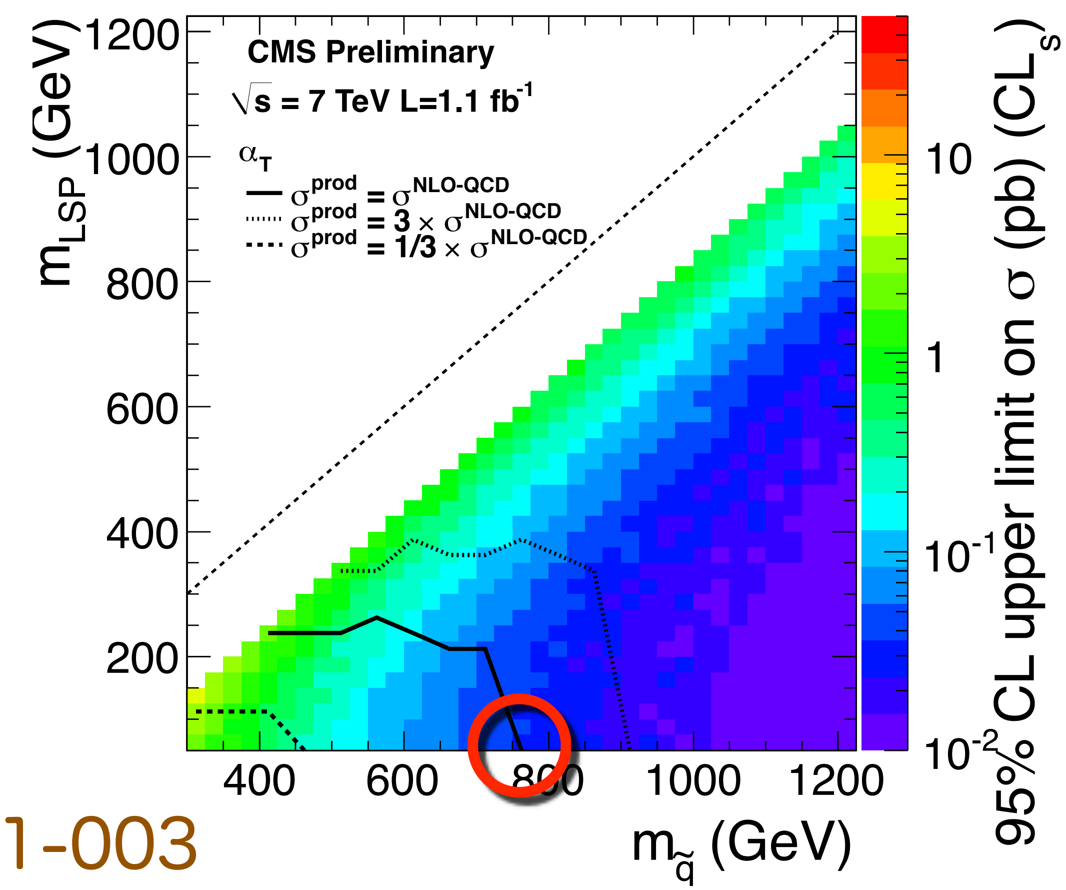
Kribs & Martin

CMS Bounds on Simplified Models [α_T]









CMS-SUS-11-003

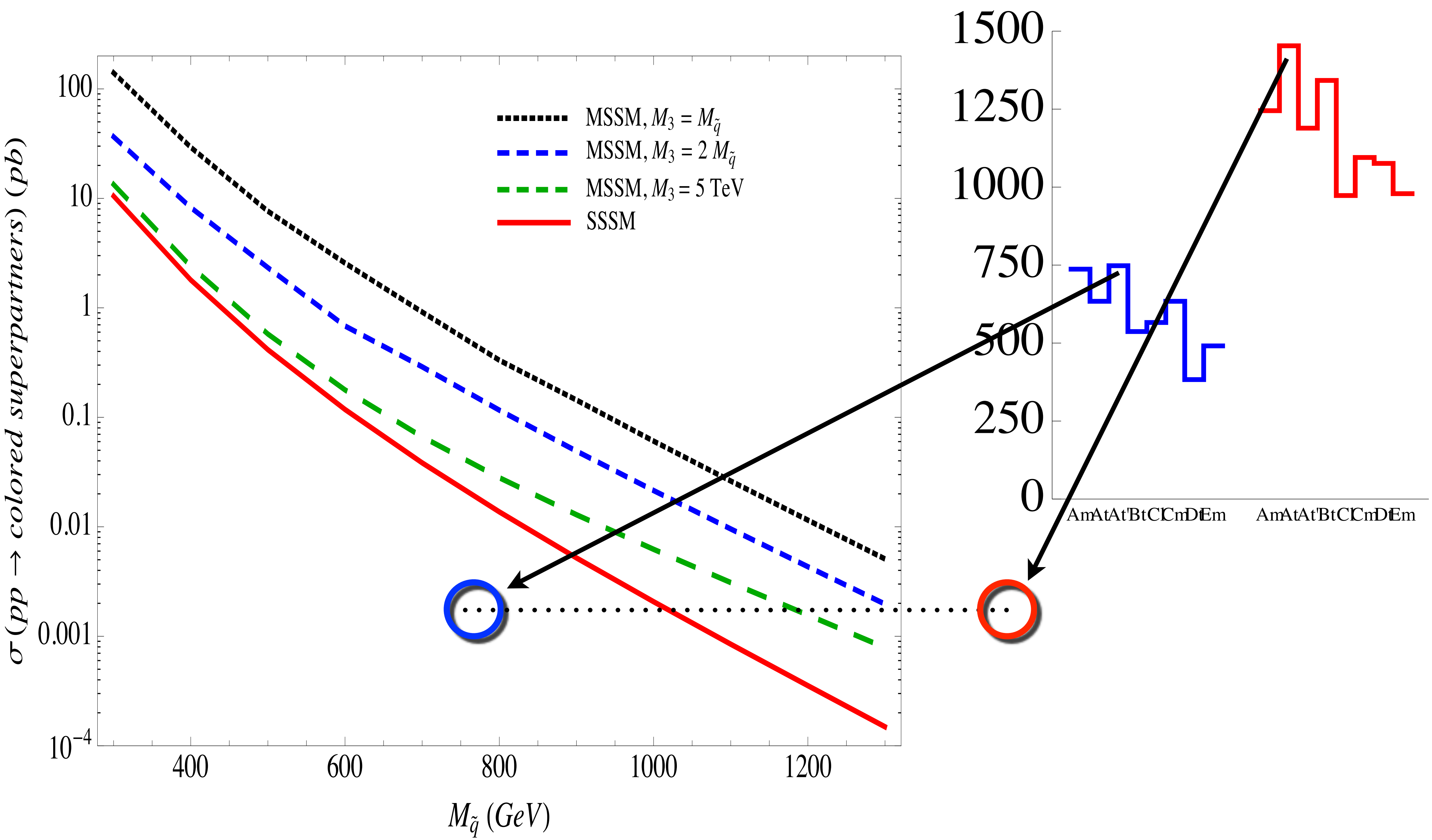
CMS α_T Search Bounds

SSSM	MSSM	MSSM	MSSM
M3 = 5 TeV	M3 = Msq	M3 = 2 Msq	M3 = 5 TeV

1st,2nd generation squark mass

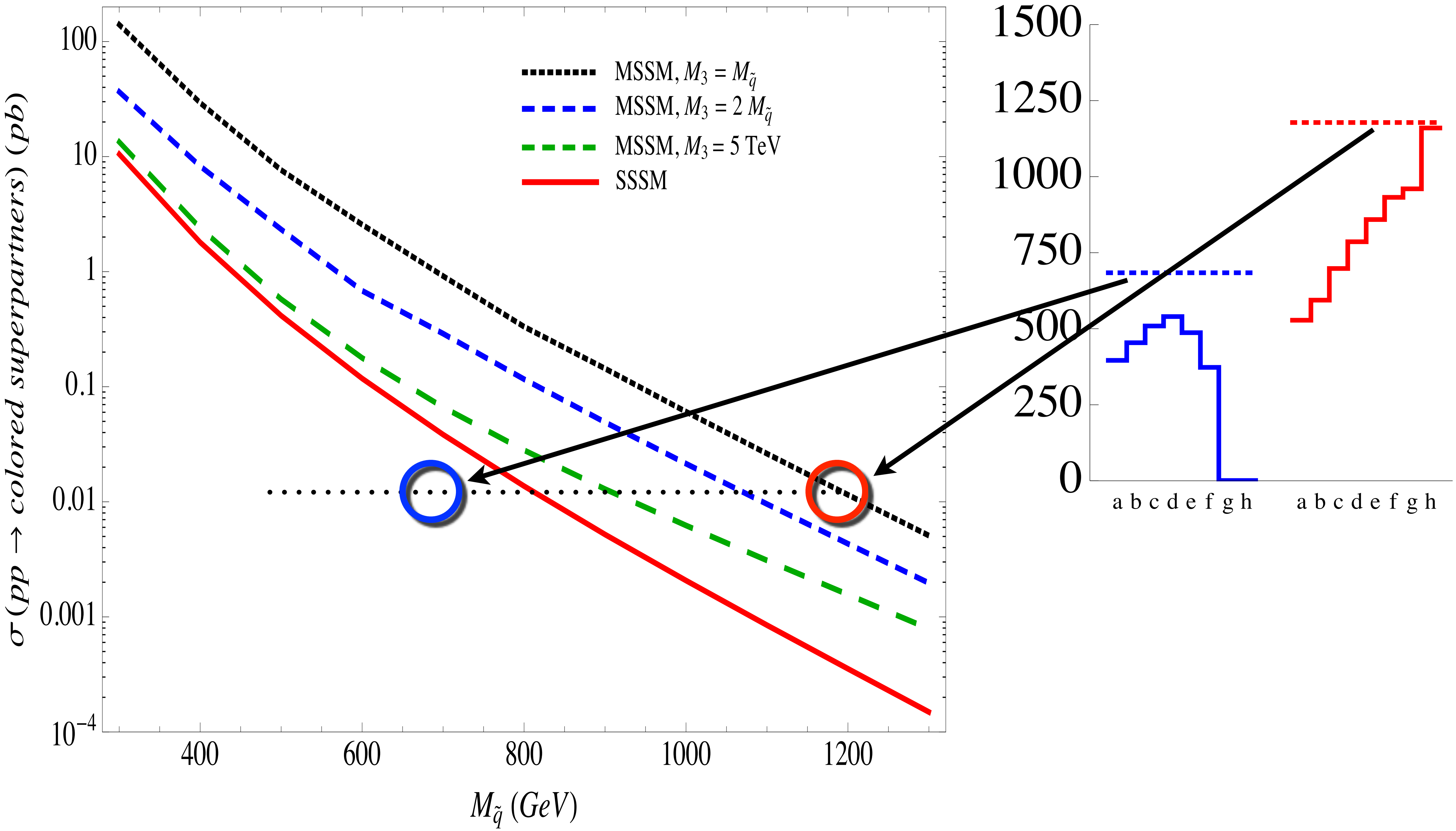
Kribs & Martin

Effectiveness of ATLAS strategy



GK & Martin

Effectiveness of CMS α_T strategy



GK & Martin