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Baryon and lepton number violation at the LHC

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Introduction

Definition: Leptons have $\mathcal{L}=1$,
Quarks have $\mathcal{B}=1/3 \leftarrow p^+ \sim \varepsilon^{\alpha\beta\gamma} u_\alpha u_\beta d_\gamma$.

Theoretically: Renormalizability $\Rightarrow$ no $\Delta\mathcal{B},\Delta\mathcal{L} \neq 0$ couplings in $\mathcal{L}_{SM}$.
But, $\Delta\mathcal{B},\Delta\mathcal{L} \neq 0$ effects expected beyond the SM.
(BAU, GUT, Majorana ν,...)

Experimentally, $\Delta\mathcal{B}=0$ is extremely well supported:

Proton decay: Lightest spin ½ baryon → must violate $\mathcal{B}$ and $\mathcal{L}$:

$$p^+ \to \pi^0 e^+ : 8.2\times 10^{33}\, yrs \Leftrightarrow \Gamma \sim 10^{-60}\, GeV$$

$$p^+ \to any : 2.1\times 10^{29}\, yrs \Leftrightarrow \Gamma \sim 10^{-55}\, GeV$$

Many others: $n^0 - \overline{n}^0,\ Z \to p^+ e^-,\ \tau^- \to e^+\pi^-\pi^-,\ K^+ \to \pi^- e^+ e^+,\ldots$

Could the LHC help resolve this puzzle?

- Outline

  I. Strategy

  II. Effective interactions

  III. Supersymmetry

I.　Strategy

A. The central question

Nikolidakis, CS ‘07, CS ‘11

If non-zero, why are $\mathcal{B}$ and $\mathcal{L}$ violations so small?

$\mathcal{B}$ and $\mathcal{L}$ are intrinsically flavored since they refer to quarks & leptons.

Small $\mathcal{B}$ and $\mathcal{L}$ violation $\overset{?}{\leftrightarrow}$ No NP effects at flavor factories

To answer this, use the techniques of Minimal Flavor Violation.

How large can $\mathcal{B}$ and $\mathcal{L}$ violation be in the absence of new flavor couplings?

B. Minimal Flavor Violation

How large can $\mathcal{B}$ and $\mathcal{L}$ violation be in the absence of new flavor couplings?

- Gauge interactions are flavor-blind $\Leftrightarrow$ Invariance under:

$$U(3)^5 = U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$$

Where $Q = (u_L \;\; d_L)^T,\; U = u_R^\dagger,\; D = d_R^\dagger,\; L = (\nu_L \;\; e_L)^T,\; E = e_R^\dagger$.

Chivukula, Georgi '87

- Flavor couplings = explicit breaking terms for this symmetry

In the SM, $\mathrm{Y}_u \sim m_u V_{CKM}\,,\; \mathrm{Y}_d \sim m_d\,,\; \mathrm{Y}_e \sim m_e$.

B. Minimal Flavor Violation

How large can $\mathcal{B}$ and $\mathcal{L}$ violation be in the absence of new flavor couplings?

- $\mathcal{B}$ and $\mathcal{L}$ are combinations of the flavor $U(1)$'s:

$$U(3)^5 = SU(3)^5 \times U(1)_Q \times U(1)_U \times U(1)_D \times U(1)_L \times U(1)_E$$
$$= SU(3)^5 \times U(1)_{\mathcal{B}} \times U(1)_{\mathcal{L}} \times U(1)_Y \times U(1)_{PQ} \times U(1)_E$$

- $\Delta\mathcal{B}$ and $\Delta\mathcal{L}$ couplings break $U(1)_{\mathcal{B}} \times U(1)_{\mathcal{L}}$ and maybe also $SU(3)^5$.

- MFV = Any $SU(3)^5$ breaking required to be aligned with the Yukawas.

That's what works for FCNC.

Hall, Randall '90; D'Ambrosio, Giudice, Isidori, Strumia '02,...

B. Minimal Flavor Violation

Nikolidakis, CS '07
Colangelo, Nikolidakis, CS '08
CS '11

Flavor breakings

Imagine there is a single spurion (= breaking term) $\mathbf{X}$ at the high scale

SM

NP

$$\mathbf{Y} = x_0 \mathbf{1} + x_1 \mathbf{X} + x_2 \mathbf{X}^2$$

$$x_i \sim \mathcal{O}(1)$$

$$\mathbf{A} = x_0' \mathbf{1} + x_1' \mathbf{X} + x_2' \mathbf{X}^2$$

$$x_i' \sim \mathcal{O}(1)$$

Quark/lepton masses

New flavor couplings

B. Minimal Flavor Violation

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$$x_i' \sim \mathcal{O}(1)$$

Quark/lepton masses

New flavor couplings

MFV

Redundancy $\Rightarrow$ MFV relation among flavor couplings:

$$\mathrm{A} = a_0 \mathbf{1} + a_1 \mathrm{Y} + a_2 \mathrm{Y}^2 \quad \text{with} \quad a_i \sim \mathcal{O}(1)$$

B. Minimal Flavor Violation

Nikolidakis, CS '07
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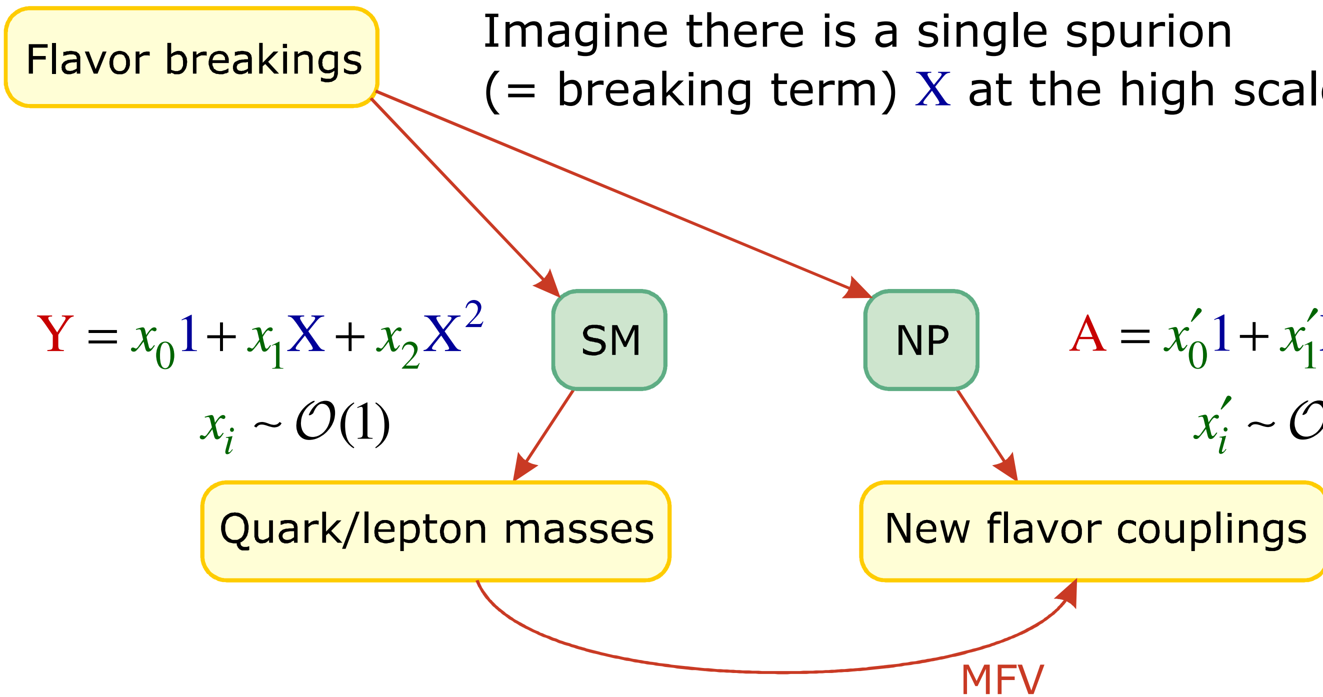
Imagine there is a single spurion (= breaking term) X at the high scale



$$\mathrm{Y} = x_0 1 + x_1 \mathrm{X} + x_2 \mathrm{X}^2 \qquad x_i \sim \mathcal{O}(1)$$

$$\mathrm{A} = x'_0 1 + x'_1 \mathrm{X} + x'_2 \mathrm{X}^2 \qquad x'_i \sim \mathcal{O}(1)$$

In this way, NP couplings inherit the hierarchies of the Yukawas:

$$\mathrm{A} = a_0 1 + a_1 \mathrm{Y}_u^\dagger \mathrm{Y}_u + a_2 \mathrm{Y}_d^\dagger \mathrm{Y}_d + \ldots \approx \begin{pmatrix} 1 & 10^{-4} & 10^{-3} \\ 10^{-4} & 1 & 10^{-2} \\ 10^{-3} & 10^{-2} & 1 \end{pmatrix} + i \begin{pmatrix} 0 & 10^{-4} & 10^{-3} \\ 10^{-4} & 0 & 10^{-4} \\ 10^{-3} & 10^{-4} & 0 \end{pmatrix}$$

II. Effective interactions

Step 1 - Only SM gauge interactions

Simplest operators breaking $U(1)_{\mathcal{B},\mathcal{L}}$ but not $SU(3)^5$...
...without any spurions (only gauge interactions).

- Epsilon contractions must involve the same three SM fields, e.g.:

$$\varepsilon^{IJK} Q^I Q^J Q^K \to \varepsilon^{IJK} (g_Q Q)^I (g_Q Q)^J (g_Q Q)^K = \det(g_Q) \varepsilon^{IJK} Q^I Q^J Q^K$$

- SM gauge invariance $\Rightarrow$ at least four epsilon contractions:

$$\mathcal{H}_{eff} = \frac{1}{\Lambda^{14}} \left[\boxed{c_1 (LQ^3)^3} + c_2 (EU^2 D)^3 + c_3 (EUQ^{\dagger 2})^3 + c_4 (LQD^\dagger U^\dagger)^3 \right]$$

This is the SM $\mathcal{B}+\mathcal{L}$ anomaly. t'Hooft '76

- Lower-dimensional $\Delta\mathcal{B}$ and $\Delta\mathcal{L}$ interactions must break $SU(3)^5$.

Step 2 - Introducing Yukawa couplings

Simplest operators breaking $U(1)_{\mathcal{B},\mathcal{L}}$ but not $SU(3)^5$...
...with Yukawa spurions (massless/Dirac neutrinos).

- The Yukawas link the $SU(3)$ spaces $\Rightarrow$ New epsilon contractions:

$$\begin{tikzcd} & SU(3)_U \\ SU(3)_Q \arrow[ur, leftrightarrow, "\mathbf{Y}_u"] \arrow[dr, leftrightarrow, "\mathbf{Y}_d"'] & \\ & SU(3)_D \end{tikzcd} \qquad \begin{tikzcd} SU(3)_L \arrow[r, leftrightarrow, "\mathbf{Y}_e"] & SU(3)_E \end{tikzcd}$$

E.g.: $\varepsilon^{IJK} Q^{\dagger I} (U\mathbf{Y}_u)^J (D\mathbf{Y}_d)^K$ $\qquad$ $\varepsilon^{IJK} L^{\dagger I} L^{\dagger J} (E\mathbf{Y}_e)^K$

- There are three notable features:

    - Steps of three: $\Delta\mathcal{L} = \mathbb{Z}N_F$ but $\Delta\mathcal{B} = \mathbb{Z}N_F / N_C$ since $\mathcal{B}(p^+) \equiv 1$.
    - Three generations participate: $\varepsilon^{IJK} \neq 0$ iff $I \neq J \neq K$.
    - High-dimensional operators: At least six fermion fields.

Step 2 - Introducing Yukawa couplings

Simplest operators breaking $U(1)_{\mathcal{B},\mathcal{L}}$ but not $SU(3)^5$...
...with Yukawa spurions (massless/Dirac neutrinos).

- Simplest operators:

$$\mathcal{H}_{eff}=\frac{1}{\Lambda^5}\Big[\underbrace{c_1 E L^{\dagger 2}U^3+c_2 L^{\dagger 3}Q^{\dagger}U^2}_{\Delta\mathcal{B},\Delta\mathcal{L}=1,3}+\underbrace{c_3 D^4 U^2+c_4 D^3 U Q^{\dagger 2}+c_5 D^2 Q^{\dagger 4}}_{\Delta\mathcal{B},\Delta\mathcal{L}=2,0}\Big]$$

can induce proton decay. can induce neutron oscillations.

- Bounds satisfied even for $\Lambda\approx 1\text{ TeV}$:

$$L^{\dagger 3}\otimes Q^{\dagger}(U\mathbf{Y}_u)^2+\ldots\rightarrow\{\bar{\nu}_\mu e_L^c\}\{\bar{\nu}_\tau s_L^c\}\{\bar{u}_R u_R^c\}\frac{m_u^2}{v^2}V_{ub}+\ldots$$

$$\Rightarrow\ \Gamma\sim\frac{m_{p^+}^{11}}{\Lambda^{10}}(10^{-13})^2\approx(10^{-60}\text{ GeV})\times\left(\frac{1\text{TeV}}{\Lambda}\right)^{10}$$

Step 3 - Introducing neutrino masses

Simplest operators breaking $U(1)_{\mathcal{B},\mathcal{L}}$ but not $SU(3)^5$...
...with Yukawa & Majorana neutrino spurions.

- A $\Delta\mathcal{L} = \pm 2$ Majorana spurion breaks the $\Delta\mathcal{L} = \mathbb{Z}N_F$ selection rule:

$$\begin{tikzcd} & SU(3)_U \\ SU(3)_Q \arrow[ur, leftrightarrow, "\mathrm{Y}_u"] \arrow[dr, leftrightarrow, "\mathrm{Y}_d"'] & \\ & SU(3)_D \end{tikzcd} \qquad \begin{tikzcd} & SU(3)_E \\ SU(3)_L \arrow[ur, leftrightarrow, "\mathrm{Y}_e"] \arrow[dr, leftrightarrow, "\mathrm{Y}_\nu"'] & \\ & SU(3)_N \arrow[loop right, "\mathrm{M}_R"] \end{tikzcd}$$

E.g.: $\varepsilon^{IJK} Q^{\dagger I} (U\mathrm{Y}_u)^J (D\mathrm{Y}_d)^K$ $\qquad$ $\varepsilon^{IJK} L^{\dagger I} (\underbrace{\nu \mathrm{Y}_\nu^T \mathrm{M}_R^{-1} \mathrm{Y}_\nu}_{m_\nu/v} \mathrm{Y}_e^\dagger \mathrm{Y}_e)^{JK}$

- Simplest operators: $\mathcal{H}_{eff} = \dfrac{1}{\Lambda^2}\left[c_1 LQ^3 + c_2 EU^2 D + c_3 EUQ^{\dagger 2} + c_4 LQD^\dagger U^\dagger\right]$

Weinberg '79

Bounds satisfied for $\Lambda \gtrsim 5\ \mathrm{TeV}$ (instead of $\Lambda \gtrsim 10^{16}$ GeV when $c_i \sim 1$).

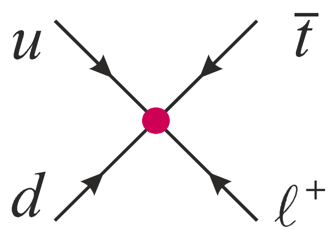
Consequences for the LHC

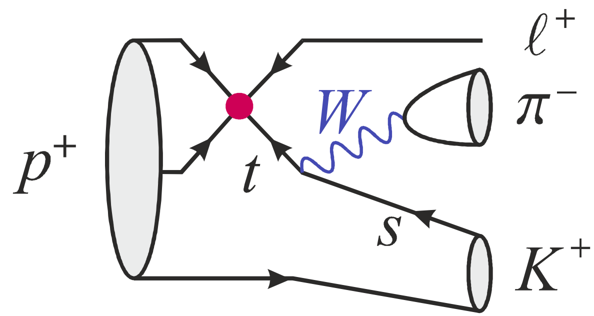
MFV → Epsilon contractions → Dominant channels involve the top!

$$\text{E.g., } \varepsilon^{LMN} u^L u^M u^N \to u + c + t \,.$$

Dimension-six: Wilson coefficients suppressed by m_ν → Negligible.

Trying to remove MFV for $\Delta\mathcal{L}$ brings back proton stability problems!





Hou, Nagashima, Soddu '05; Dong, Durieux, Gérard, Han, Maltoni '11

Dimension-nine: Some $\mathcal{O}(1)$ Wilson coefficients for top quark(s).

Proton stable enough for $\Lambda \approx 1\ \mathrm{TeV}$ ...

Effective formalism inadequate for the LHC?

Consequences for the LHC

Durieux, Gérard, Maltoni, CS '12 [soon]

Effective operators cannot be used to compute cross-sections, but can be used to estimate ratios of cross-section.

Identify the flavor channels where $\Delta\mathcal{B}$ and $\Delta\mathcal{L}$ effects can be large. (this requires considering far more than the five dim-9 operators)

$\Delta\mathcal{B},\Delta\mathcal{L}=1,3$: Dilepton & top(s)	$\Delta\mathcal{B},\Delta\mathcal{L}=2,0$: Di-top & b's
$1 \,:\, gu\to\bar{t}+\bar{c}+e^{+}\mu^{+}\bar{\nu}_{\tau}$	$1 \,:\, dd\to\bar{t}\,\bar{t}+\bar{s}\,\bar{s}$
$\lambda^{8} \,:\, gu\to\bar{t}\,\bar{t}+e^{+}\mu^{+}\bar{\nu}_{\tau}$	$\lambda^{2} \,:\, dd\to\bar{t}\,\bar{t}+\bar{b}+\bar{s}$
$\lambda^{9} \,:\, gg\to\bar{t}\,\bar{t}+\bar{c}+e^{+}\mu^{+}\bar{\nu}_{\tau}+h.c.$	$\lambda^{4} \,:\, dd\to\bar{t}\,\bar{t}+\bar{b}\,\bar{b}$
$\lambda^{11} \,:\, uu\to\bar{t}+e^{+}\mu^{+}\bar{\nu}_{\tau}$	$\lambda^{15} \,:\, gd\to\bar{t}\,\bar{t}+\bar{b}\,\bar{b}\,\bar{b}$
$\lambda^{25} \,:\, gg\to\bar{t}\,\bar{t}\,\bar{t}+e^{+}\mu^{+}\bar{\nu}_{\tau}+h.c.$	$\lambda^{26} \,:\, gg\to\bar{t}\,\bar{t}+\bar{b}\,\bar{b}\,\bar{b}\,\bar{b}+h.c.$

$\lambda^{3}\approx 1\%$

These ratios are approximate: Dynamical effects can be important!

III. Supersymmetry

A. What happens in supersymmetry?

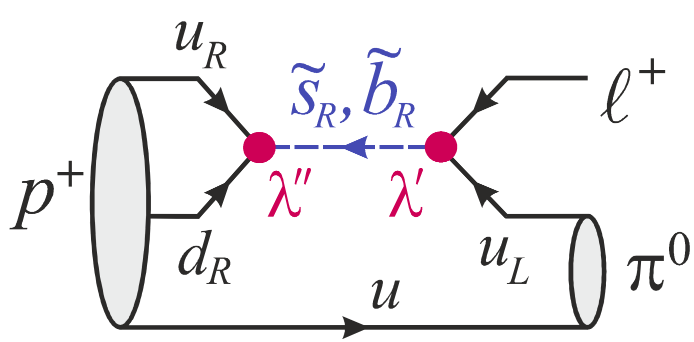
Fayet '76

Simplest operators breaking $U(1)_{\mathcal{B},\mathcal{L}}$ but not $SU(3)^5$...
...within the MSSM.

- Squarks/slepton carry $\mathcal{B}$ and $\mathcal{L}$ → Renormalizable $\Delta\mathcal{B}, \Delta\mathcal{L}$ couplings exist:

$$\mathcal{W}_{RPV} = \underbrace{\mu'^{I} L^I H_u + \lambda^{IJK} L^I L^J E^K + \lambda'^{IJK} L^I Q^J D^K}_{\Delta\mathcal{L}=1} + \underbrace{\lambda''^{IJK} U^I D^J D^K}_{\Delta\mathcal{B}=1}$$

which induce proton decay at tree-level, e.g. via:



But, $\tau_{p^+}^{\exp} \Rightarrow |\lambda'\lambda''| \leq 10^{-27}$?

- Escape route 1: Invent R-parity to get rid of all these couplings.

A. What happens in supersymmetry?

Nikolidakis, CS '07

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- Escape route 2: Minimal Flavor Violation

The $\Delta\mathcal{B}=1$ couplings are allowed, but not the $\Delta\mathcal{L}=1$ when $m_\nu = 0$.

$$\varepsilon^{IJK}(U\mathbf{Y}_u\mathbf{Y}_d^\dagger)^I D^J D^K,\ \varepsilon^{IJK}(U\mathbf{Y}_u)^I (D\mathbf{Y}_d)^J (D\mathbf{Y}_d)^K, \ldots$$

Proton decay is slow enough even for EW-scale squark masses.

A. What happens in supersymmetry?

Csaki, Grossman, Heidenreich '11

Simplest operators breaking $U(1)_{\mathcal{B},\mathcal{L}}$ but not $SU(3)^5$...
...within the MSSM.

- Holomorphy: If Yukawas = VEVs of some chiral superfields:

No $\mathbf{Y}_i^\dagger$ allowed in $\mathcal{W}_{RPV}$, only $\varepsilon^{IJK}(U\mathbf{Y}_u)^I(D\mathbf{Y}_d)^J(D\mathbf{Y}_d)^K$ permitted.

Less free parameters, and smaller couplings:

Full:

λ''	ds	sb	bd
u	4	4	4
c	3	4	4
t	$\boxed{0}$	3	3

Holomorphic:

λ''	ds	sb	bd
u	11	6	8
c	8	4	5
t	4	$\boxed{3}$	4

$$x \equiv \mathcal{O}(10^{-x}) \ , \ \tan\beta = 50$$

B. Stealth supersymmetry at the LHC?

MFV instead of R parity: No sizeable $\mathcal{L}$ violation ($\sim m_\nu$),

Dominant $\mathcal{B}$ violation through $\lambda''_{312} \leq \mathcal{O}(1)$.

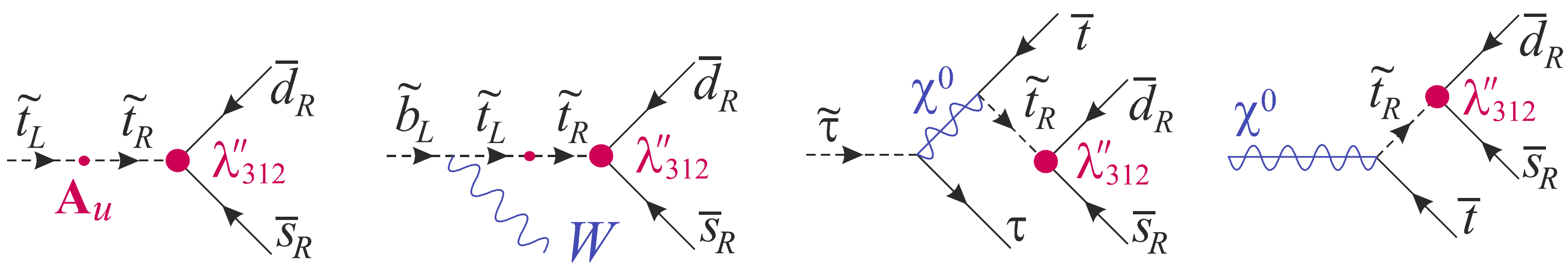
$$\downarrow$$

$$\tilde{t}_R d_R s_R,\ t_R \tilde{d}_R s_R,\ t_R d_R \tilde{s}_R$$

Theoretically, this single coupling does not change much.

Experimentally, the whole phenomenology is modified.

The LSP quickly decays, so it needs not be colorless & neutral:



Stop	Sbottom	Stau	Neutralino
$2\mu m$	$41\mu m$	$30000\mu m$	$192\mu m$

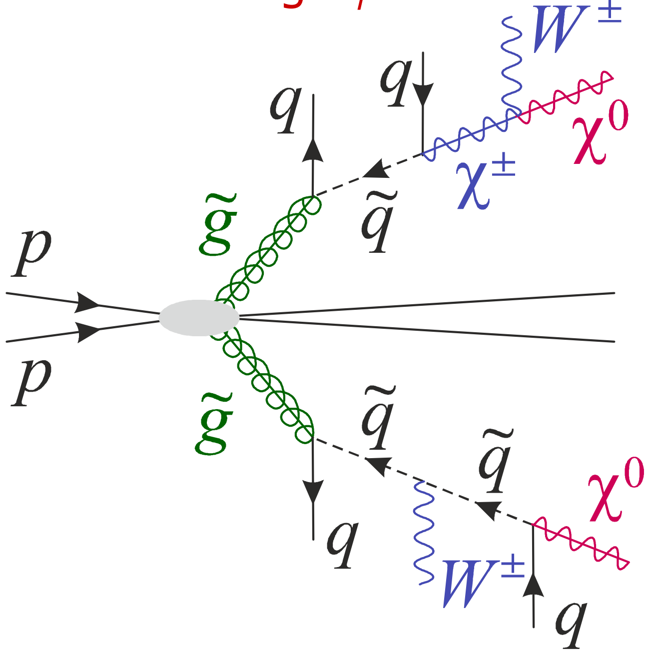
Displaced vertices with $\tan\beta = 10$, $\mathrm{M} = 300\ \mathrm{GeV}$, from Csaki, Grossman, Heidenreich '11

B. Stealth supersymmetry at the LHC?

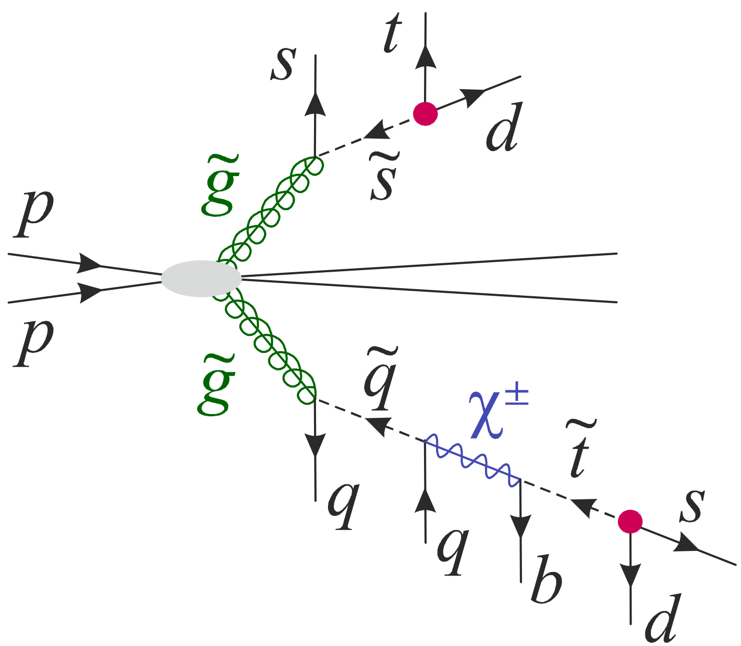
Characteristic signals: - Most decay chains end in top(s) + jet final states.

- No missing E_T (except from neutrinos).

RPC : Missing E_T



RPV : top(s) + jets



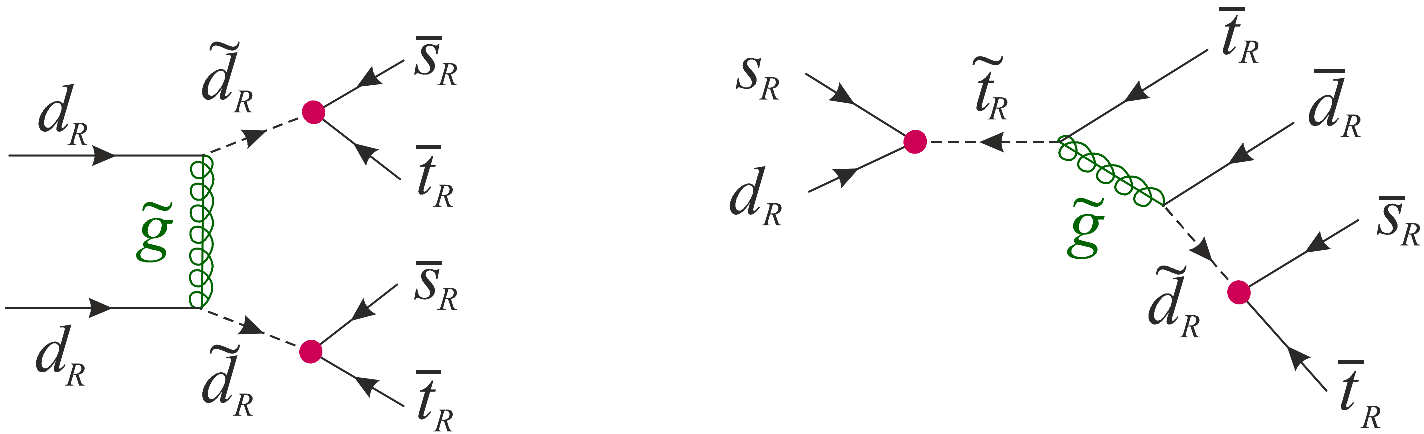
SUSY disappears from missing E_T channels (those used up to now),
Instead, sparticles shows up as multi-jet resonances (displaced vertices?).

B. Stealth supersymmetry at the LHC?

Characteristic signals: - Most decay chains end in top(s) + jet final states.

- No missing E_T (except from neutrinos).

Simplest channels → Look for two anti-tops



Large rate: $\sigma(dd \to \bar{t}\,\bar{t} + \bar{s}\,\bar{s}) \approx \sigma(dd \to \tilde{d}\tilde{d})[\mathcal{B}(\tilde{d} \to \bar{t}\,\bar{s})]^2 \approx \sigma(dd \to \tilde{d}\tilde{d})$

SUSY disappears from missing E_T channels (those used up to now),
Instead, sparticles shows up as multi-jet resonances (displaced vertices?).

B. Stealth supersymmetry at the LHC?

Many theoretical studies dedicated to $\not{B}$-violation at colliders:

Tevatron: Dimopoulos, Hall '88; Dreiner, Ross '91, Berger *et al*. '99, Chiappetta *et al*. '99; Chaichan *et al*. '00, Allanach *et al*. '01; ...

LHC: Choudhury, Datta, Maity '11, Csaki, Grossman, Heidenreich '11; ...

Experimentally, light SUSY with $\not{B}$-violation could not have been seen yet.

Resonant gluino with RPV three-jet decay @ CMS: $m_{\tilde{g}} > 280\,\mathrm{GeV}$

with a 1.9σ bump around 390 GeV...

(to be compared to $m_{\tilde{g}} \gtrsim 1\ \mathrm{TeV}$ in the CMSSM)

Resonant LSP stop: production rates relatively small for the LHC.

300 fb^{-1} at 14 TeV would be needed to exclude $m_{\tilde{t}} > 650\ \mathrm{GeV}$.

(searching for resonances in four jets)

Conclusion

Baryon and lepton number violation at the LHC?

- Low-energy $\mathcal{B}$ and $\mathcal{L}$ violating interactions are possible

    Proton stability ensured by their non-trivial flavor structure.

    No fine-tuning! Just Yukawa hierarchies + small neutrino masses.

    These hierarchies favor processes with top quarks:

$$\Delta\mathcal{B},\Delta\mathcal{L}=1,3\ :\ gu\rightarrow\bar{t}+\bar{c}+e^{+}\mu^{+}\bar{\nu}_{\tau}$$

$$\Delta\mathcal{B},\Delta\mathcal{L}=2,0\ :\ dd\rightarrow\bar{t}\,\bar{t}+\bar{s}\,\bar{s}\,,\ \bar{t}\,\bar{t}+\bar{b}+\bar{s}\,,\ \bar{t}\,\bar{t}+\bar{b}\,\bar{b}$$

- In supersymmetry, the main motivation for R-parity disappears!

    No sizable $\mathcal{L}$ violation, but large $\mathcal{B}$ violating couplings.

    → Bypass current bounds on sparticle masses.

    → Look for resonances in top(s) + jets final states, especially in:

$$\Delta\mathcal{B},\Delta\mathcal{L}=2,0\ :\ dd\rightarrow\bar{t}\,\bar{t}+\bar{s}\,\bar{s}\,,\ \bar{t}\,\bar{t}+\bar{b}+\bar{s}\,,\ \bar{t}\,\bar{t}+\bar{b}\,\bar{b}$$