Top – LHC France
IPN - Lyon

May 19th, 2015

Same-sign top pairs

Christopher Smith

- Outline

I. Introduction

II. Flavorless B and L violation

III. B violation in the MSSM

I. Introduction

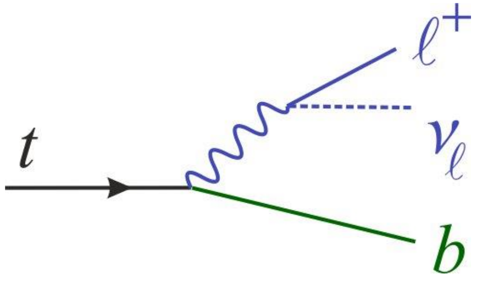
Why same-sign top quarks?

- Theoretically: Top quark is the most heavy.

  Interplay with the EW symmetry breaking,

  Crucial to induce flavor-changing neutral current (FCNC).

- Experimentally: Top flavor & electric charge can be measured.



  Same-sign top are not easily produced: B(tt) = 2/3, Q(tt) = 4/3.

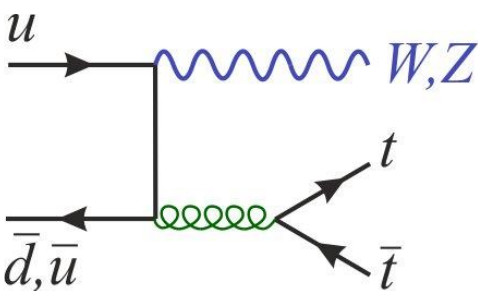
  But, the LHC collides protons: B(pp) = 2, Q(pp) = 2.

Four types of same-sign top signals

- Same-sign leptons as fake top pairs:

Same-sign lepton production occurs in most models from multiple W, Z, tops, or new exotic states.

Not really what we are interested in now, except...



It occurs in the SM also! Main background for true SST pairs:

$$\sigma_{NLO}(\ell^+\ell'^+) \approx 160\, fb\ @\ 8\,\mathrm{TeV}$$

$$A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) \approx +50\%$$ for all $\ell, \ell' = e, \mu$.

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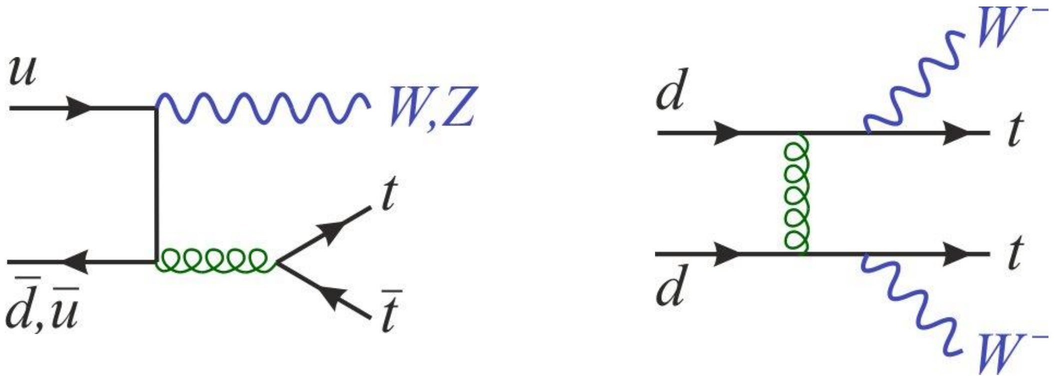

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Four types of same-sign top signals

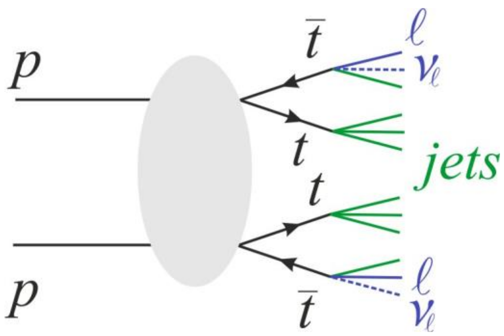
- Multi top-antitop pairs:

Same-sign tops paired with same-sign antitops.

For example, consider $t\bar{t} + t\bar{t}$:

- Both tops decay hadronically,
- Both antitops produce leptons.

(or vice-versa)



Example: sgluons, extra-dim, etc.

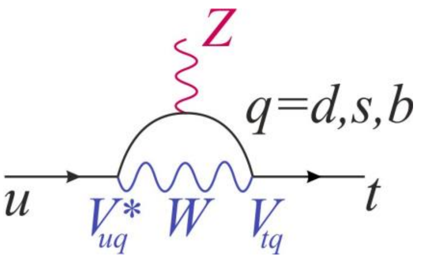
Such signals appears rather unspecific and QCD-like.

Should have $A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) \approx 0\%$.

Four types of same-sign top signals

- New FCNC current in the up-sector:

Very suppressed in the SM because of GIM:



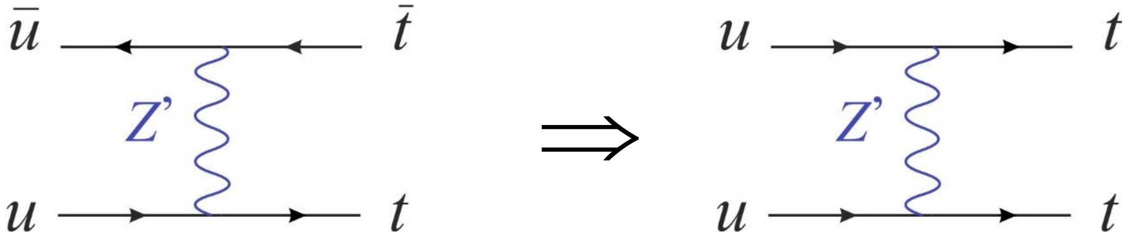
$$\sum_{q=d,s,b} V_{uq}^* V_{tq} = 0$$

Predicted in many extensions:

Color-octet, sextet, scalar or vector,

Z′, extra-dimension, top partners, 4th generation,...

Well-studied because of the Fermilab top FB asymmetry:

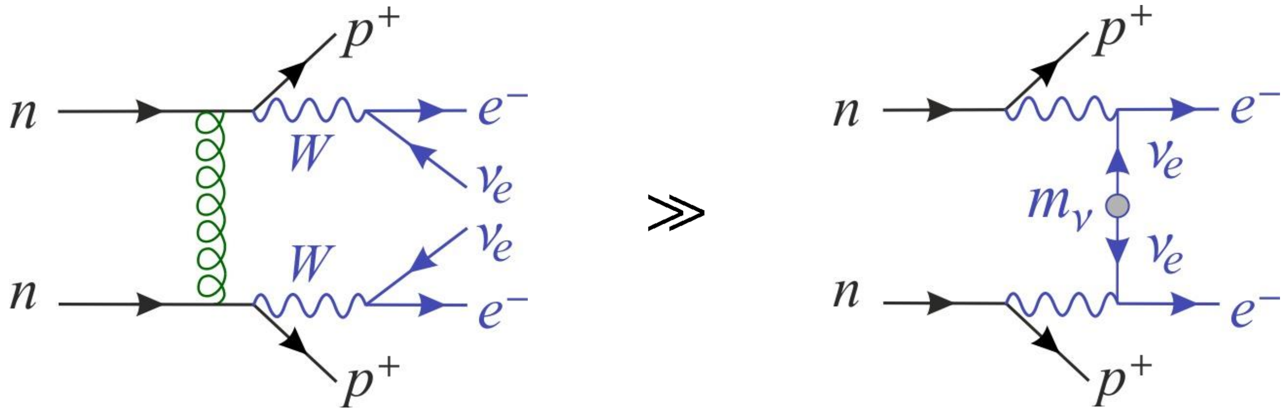


Should have $A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) \approx +100\%$.

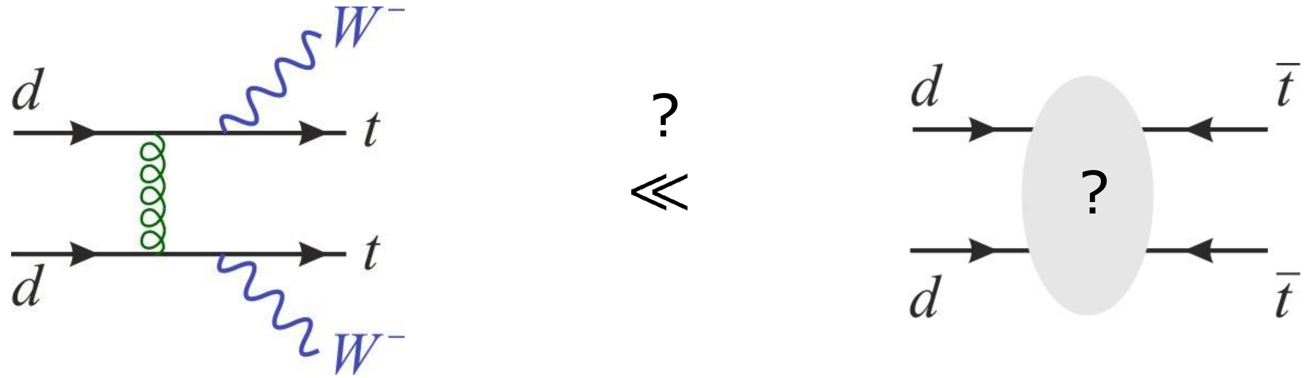
Four types of same-sign top signals

- «True» same-sign top pairs (not FCNC)

Those are peculiar processes with a broken fermion line:



Analogy: Double beta vs. Neutrinoless double beta decay.



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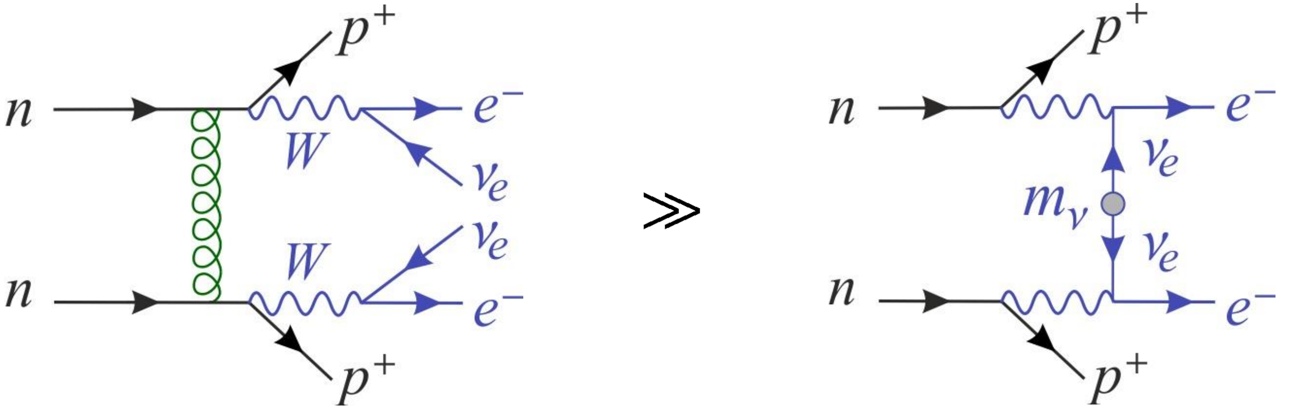
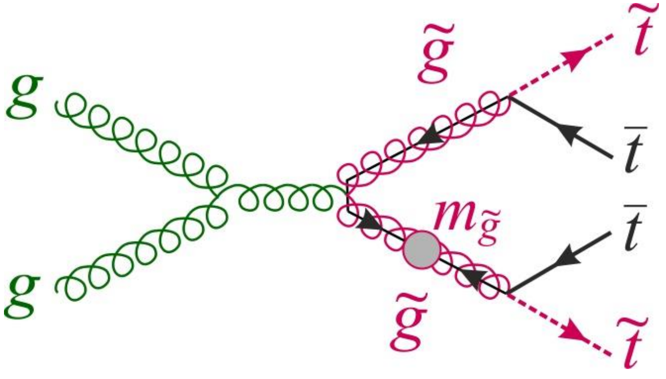


Example 1: In SUSY, thanks to the Majorana gluinos/neutralinos.



$$A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) \approx 0\%$$

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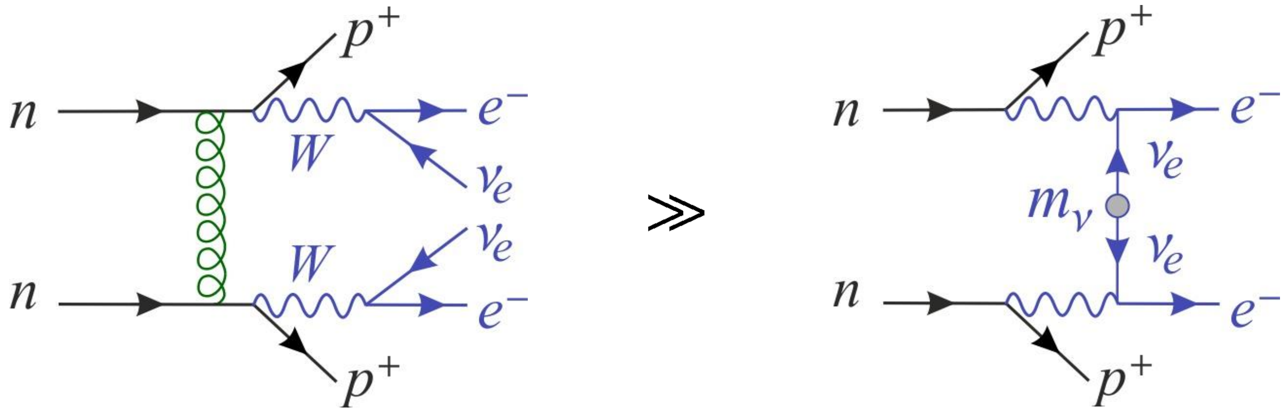
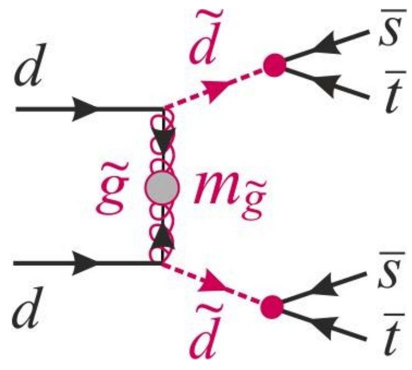


Example 2: Supersymmetric baryon number violation.



$$A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) < -80\%$$

II. Baryon number violation

A. The B and L violation puzzle

Theoretically, B and L are accidentally conserved in the SM.

Cosmologically, some B and L violation would be most welcome.

Experimentally, the bounds on B-violating processes are very tight:

For example, $\tau(p^+ \to \pi^0 e^+) > 8.2 \times 10^{33}\ yrs$.

How to naturally pass these bounds? $\mathcal{L}_{eff} = \sum_i \frac{c_i}{\Lambda^{d-4}} Q_i^d$

Its scale Λ is very high → like in GUT

Its coupling c is very small → like for the SM anomaly.

Its mass-dimension d is large → like for the SM anomaly.

Strong hint for the 2nd solution: B violation is in general flavored!

Flavor structures (= masses, mixings) are certainly non-generic.

A. How to violate B or L in a flavor-diagonal way?

SM gauge interactions are flavor blind (= SU(3)[5] symmetry).

$$(u,c,t)\begin{cases}\text{Scalar: } \delta^{IJ} q^I \bar{q}^J = u\bar{u} + c\bar{c} + t\bar{t} & (\Delta B = 0)\\ \text{Cross: } \varepsilon^{IJK} q^I q^J q^K = uct - cut + ctu - \ldots & (\Delta B = 1)\end{cases}$$

$$(e,\mu,\nu_\tau)\begin{cases}\text{Scalar: } \delta^{IJ} \ell^I \bar{\ell}^J = e^- e^+ + \mu^- \mu^+ + \nu_\tau \bar{\nu}_\tau & (\Delta L = 0)\\ \text{Cross: } \varepsilon^{IJK} \ell^I \ell^J \ell^K = e\mu\nu_\tau - \tau\mu\nu_e + \tau e\nu_\mu - \ldots & (\Delta L = 3)\end{cases}$$

In the SM: Scalar products = perturbative couplings.

Cross products = anomalous couplings:

$$\mathcal{H}_{eff} = g_{an} \times \underbrace{d_L s_L b_L \otimes u_L c_L t_L \otimes u_L c_L t_L}_{\Delta B = 3} \otimes \underbrace{e_L^- \mu_L^- \tau_L^-}_{\Delta L = 3} + \ldots$$

$$g_{an} \sim 10^{-80}$$

A. How to violate B or L in a flavor-diagonal way?

CS '11

Selection rules:

- Steps of three: $\Delta L = \mathbb{Z} N_F$ and $\Delta B = \mathbb{Z} N_F / N_C$.

  $N_F = 3$ families, $N_C = 3$ colors.

- All three generations always participate:

  $\varepsilon^{IJK} \neq 0$ iff $I \neq J \neq K$.

- At least six fermions to form a Lorentz invariant.

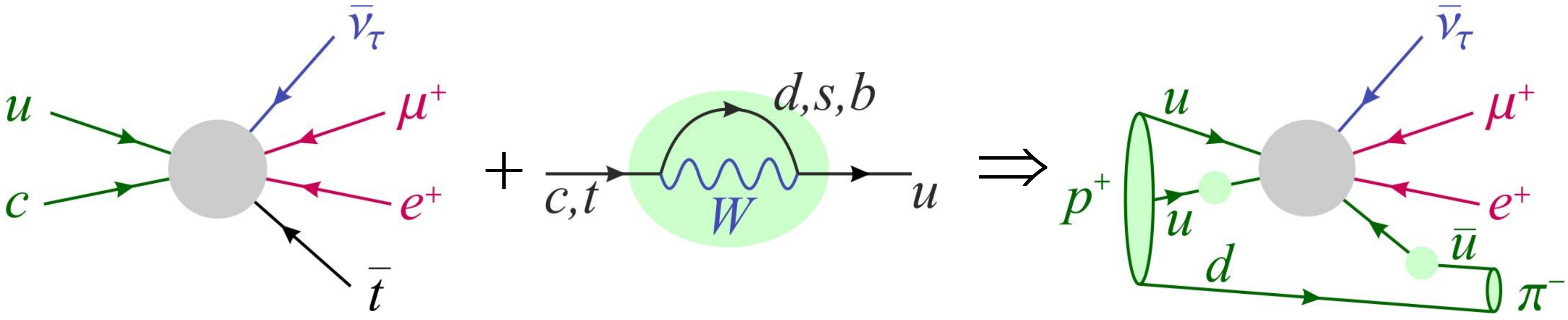
B. Most accessible flavor-diagonal channels

Durieux, Gérard, Maltoni, CS '12

ΔB	ΔL	Core	Example
0	±6	$\varepsilon^{IJK}\nu^I\nu^J\nu^K \otimes \varepsilon^{IJK}\nu^I\nu^J\nu^K$	$\nu_e\nu_\mu\nu_\tau \otimes \nu_e\nu_\mu\nu_\tau$
±1	±3	$\varepsilon^{IJK}u^Iu^Ju^K \otimes \varepsilon^{IJK}\ell^I\ell^J\nu^K$	$tcu \otimes e^-\mu^-\nu_\tau$
		$\varepsilon^{IJK}u^Iu^Jd^K \otimes \varepsilon^{IJK}\ell^I\nu^J\nu^K$	$tcd \otimes e^-\nu_\mu\nu_\tau$
		$\varepsilon^{IJK}u^Id^Jd^K \otimes \varepsilon^{IJK}\nu^I\nu^J\nu^K$	$bsd \otimes \nu_e\nu_\mu\nu_\tau$
±1	∓3	$\varepsilon^{IJK}u^Id^Jd^K \otimes \varepsilon^{IJK}\bar{\nu}^I\bar{\nu}^J\bar{\nu}^K$	$tsd \otimes \bar{\nu}_e\bar{\nu}_\mu\bar{\nu}_\tau$
		$\varepsilon^{IJK}d^Id^Jd^K \otimes \varepsilon^{IJK}\bar{\ell}^I\bar{\nu}^J\bar{\nu}^K$	$bsd \otimes e^+\bar{\nu}_\mu\bar{\nu}_\tau$
±2	0	$\varepsilon^{IJK}u^Id^Jd^K \otimes \varepsilon^{IJK}u^Id^Jd^K$	$tsd \otimes tsd$

Proton decay & neutron oscillations are kinematically forbidden?

C. Induced flavor non-diagonal effects – The MFV hypothesis



Quark flavor transitions needed for proton decay

Those occur in the SM, but are suppressed.

Even with new physics, experiments tell us they are small.

B and L violating couplings end up highly hierarchical

Their size is highly dependent on the flavors involved.

The proton is stable enough for TeV-scale new particles.

Long proton lifetime $\longleftrightarrow$ No NP effects at flavor factories.

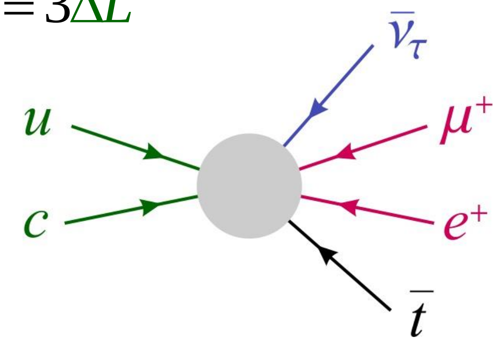
D. Discovery channels at the LHC

Durieux, Gérard, Maltoni, CS ‘12

Tops are just fine: flavor transitions are not needed.

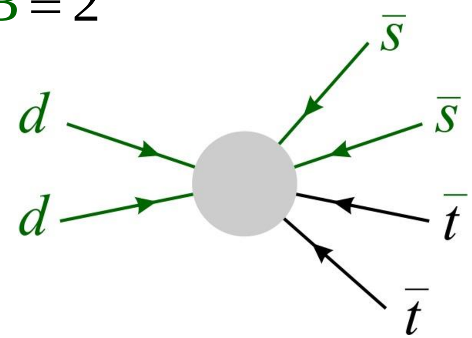
Final State: Look for same-sign leptons.

$\Delta B = 3\Delta L$



$A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) \approx +100\%$

$\Delta B = 2$



$A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) \approx -100\%$

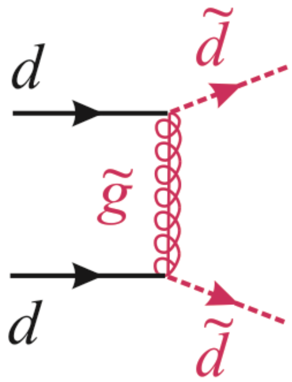
Initial State: The LHC collides $p^+ p^+$ which has $\mathcal{B} = 2$.

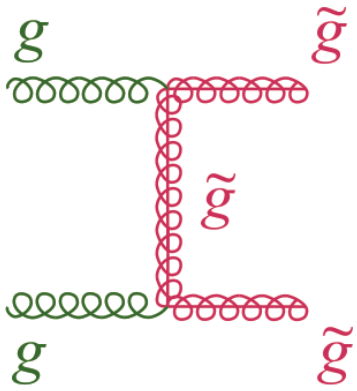
Look for $e^\pm e^\pm$, $\mu^\pm \mu^\pm$, and/or $e^\pm \mu^\pm$ charge asymmetry.

III. B violation in the MSSM

A. Baryon number violation in supersymmetry

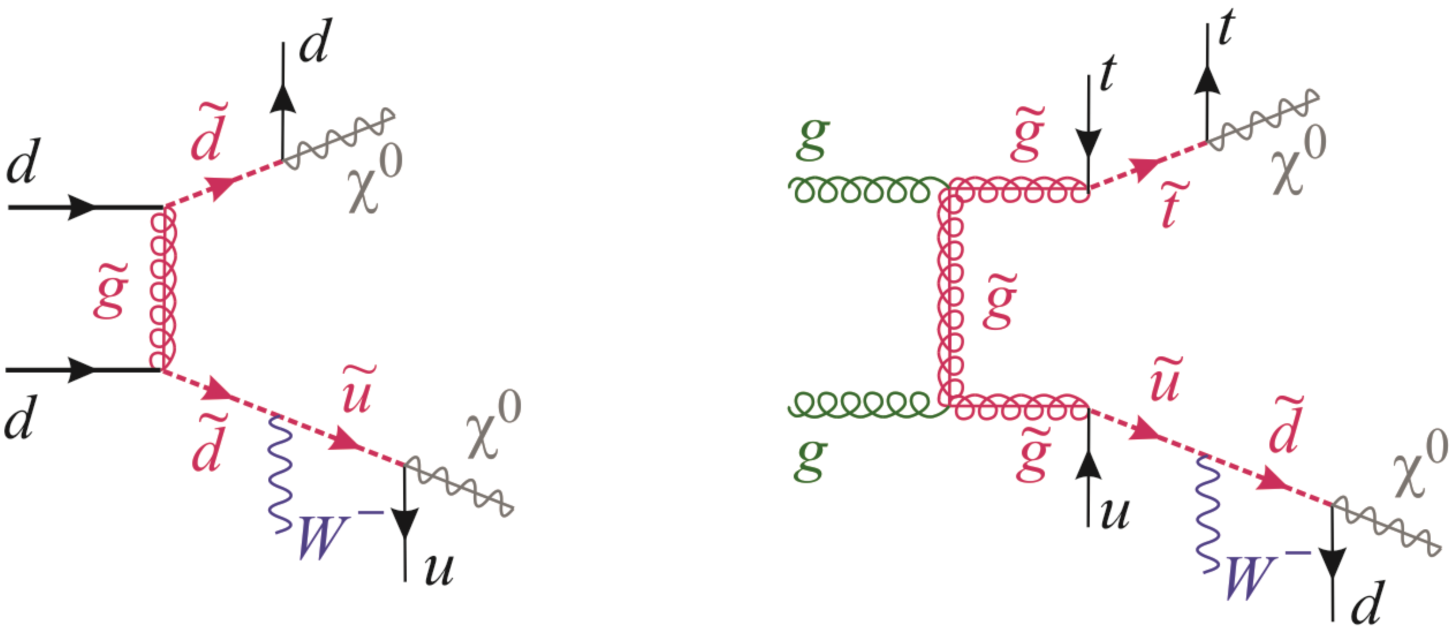
Current squark & gluino mass bounds are tight





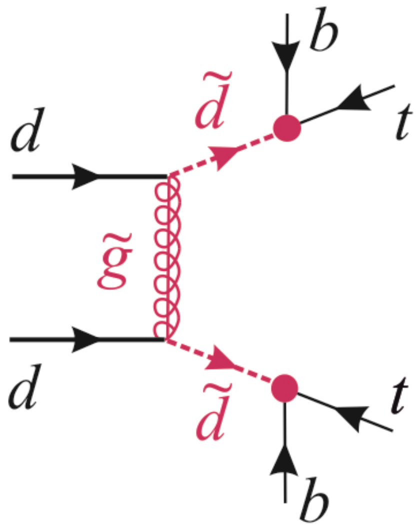
A. Baryon number violation in supersymmetry

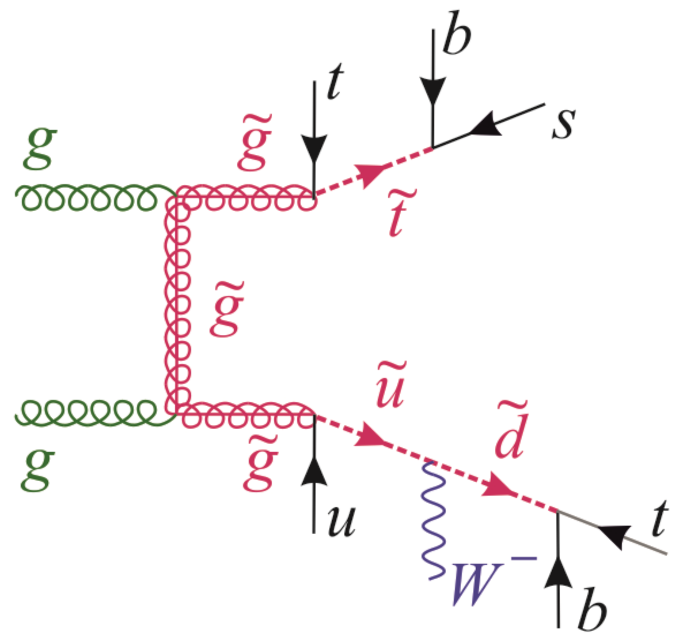
But, they are derived from missing energy channels, e.g.,



A. Baryon number violation in supersymmetry

And thus can be evaded if R-parity is violated (baryonically):





B. Flavored R-parity violation in the MSSM

Nikolidakis, CS '07

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

Violates selection rules:

$\Delta L = 3$ hierarchies

$\oplus$

$\Delta L = 2$ neutrino mass

$$\lambda'^{IJK} \sim \varepsilon^{ILM} (\underbrace{v \mathrm{Y}_\nu^T \mathrm{M}_R^{-1} \mathrm{Y}_\nu}_{m_\nu / v} \mathrm{Y}_e^\dagger \mathrm{Y}_e)^{LM} \mathrm{Y}_d^{KJ}$$

Yukawa-induced hierarchies:

$$\lambda''^{IJK} \sim \varepsilon^{LJK} (\mathrm{Y}_u \mathrm{Y}_d^\dagger)^{IL}$$

Dominant

$$\lambda''^{IJK} \sim \varepsilon^{LMN} \mathrm{Y}_u^{IL} \mathrm{Y}_d^{JM} \mathrm{Y}_d^{KN}$$

Holomorphic

B. Flavored R-parity violation in the MSSM

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Violates selection rules:

$\Delta L = 3$ hierarchies

$\oplus$

$\Delta L = 2$ neutrino mass

$$\Rightarrow \begin{cases} \lambda^{IJK} < 10^{-13} \\ \lambda'^{IJK} < 10^{-17} \end{cases}$$

Yukawa-induced hierarchies:

Dominant :

λ''	ds	sb	bd
u	5	5	5
c	4	6	5
t	1	5	4

$x \equiv \mathcal{O}(10^{-x})$

$\tan\beta = 5$

Holomorphic:

Csaki, Grossman, Heidenreich '11

λ''	ds	sb	bd
u	13	8	10
c	10	6	7
t	6	5	6

Proton decay is slow enough even for TeV-scale squark masses!

B. Flavored R-parity violation in the MSSM

Nikolidakis, CS '07

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Violates selection rules:

$\Delta L = 3$ hierarchies

$\oplus$

$\Delta L = 2$ neutrino mass

$$\Rightarrow \begin{cases} \lambda^{IJK} < 10^{-12} \\ \lambda'^{IJK} < 10^{-14} \end{cases}$$

Yukawa-induced hierarchies:

Dominant :

λ''	ds	sb	bd
u	4	4	4
c	3	4	4
t	0	3	3

$x \equiv \mathcal{O}(10^{-x})$

$\tan\beta = 50$

Holomorphic:

Csaki, Grossman, Heidenreich '11

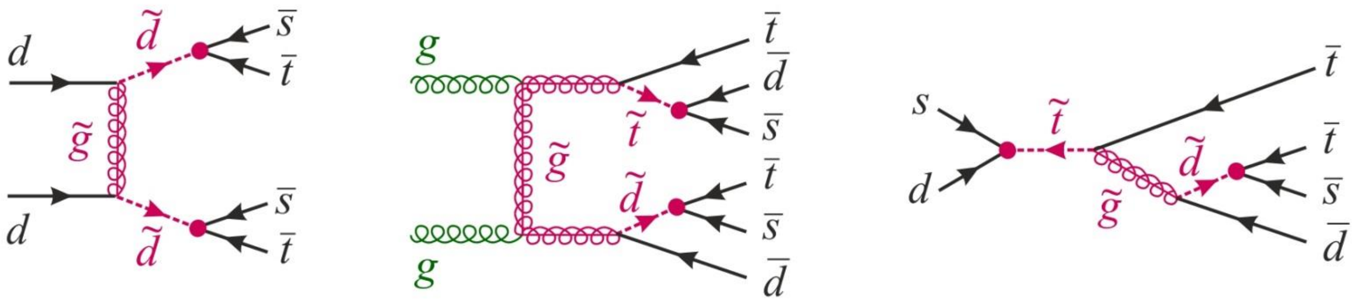
λ''	ds	sb	bd
u	11	6	8
c	8	4	5
t	4	3	4

Proton decay is slow enough even for TeV-scale squark masses!

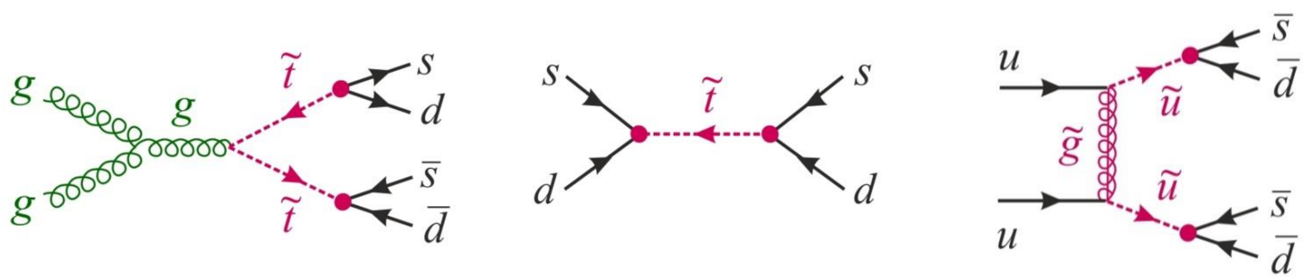
C. Characteristic signatures of the B violating MSSM

Dominant B-violation through $\lambda''_{312} \leq \mathcal{O}(1)$: $\tilde{t}_R d_R s_R,\ t_R \tilde{d}_R s_R,\ t_R d_R \tilde{s}_R$.

- Same sign top pairs → same sign lepton pairs.



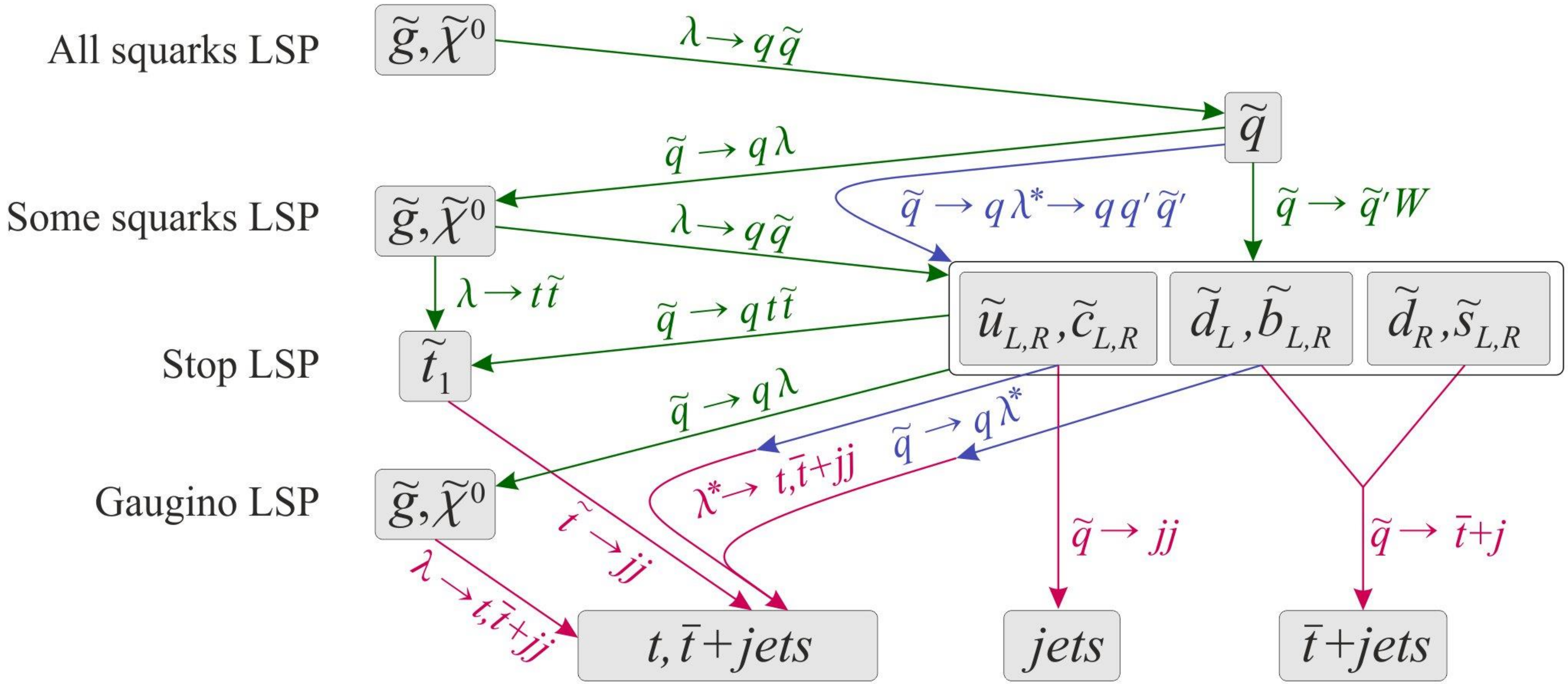
- Dijet resonances from intermediate up-type squarks.



- R-hadrons? Without large mass splitting, sparticles decay too quickly.

C. Characteristic signatures of the B violating MSSM

Durieux, CS, '13



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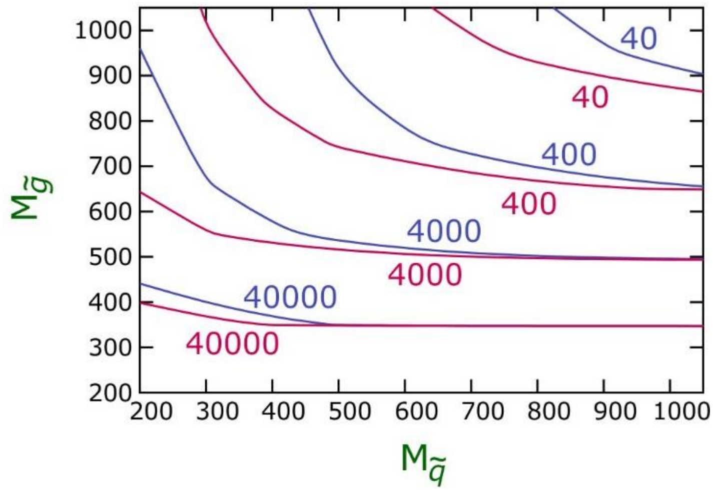
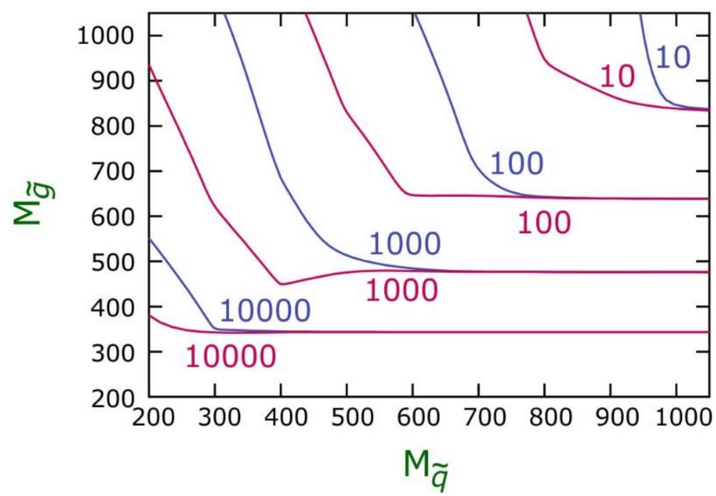


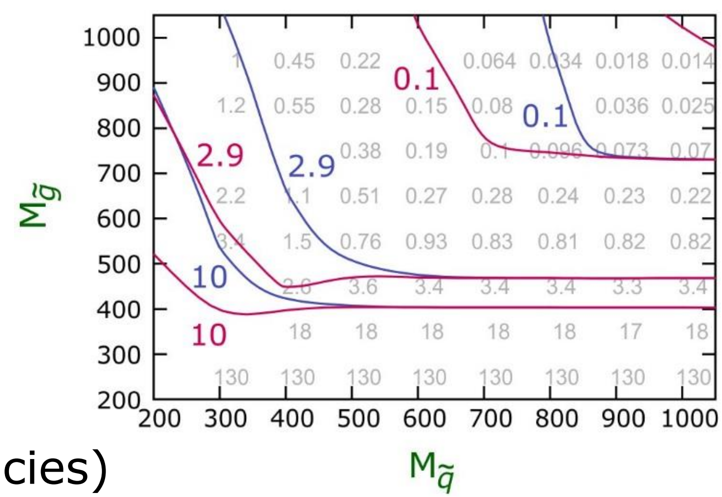
QCD processes: $gg \to \tilde{g}\tilde{g}$

$$gd \to \tilde{g}\tilde{d}_R + \tilde{g}\tilde{d}_L$$

$$dd \to \tilde{d}_R\tilde{d}_R + 2\tilde{d}_R\tilde{d}_L + \tilde{d}_L\tilde{d}_L$$

$\bar{t} + \bar{t}$ production via the RPV decays $\tilde{g} \to \bar{t}\,\bar{d}\,\bar{s}$, $\tilde{d}_R \to \bar{t}\,\bar{s}$, $\tilde{d}_L \to \bar{t}\,\bar{s}$



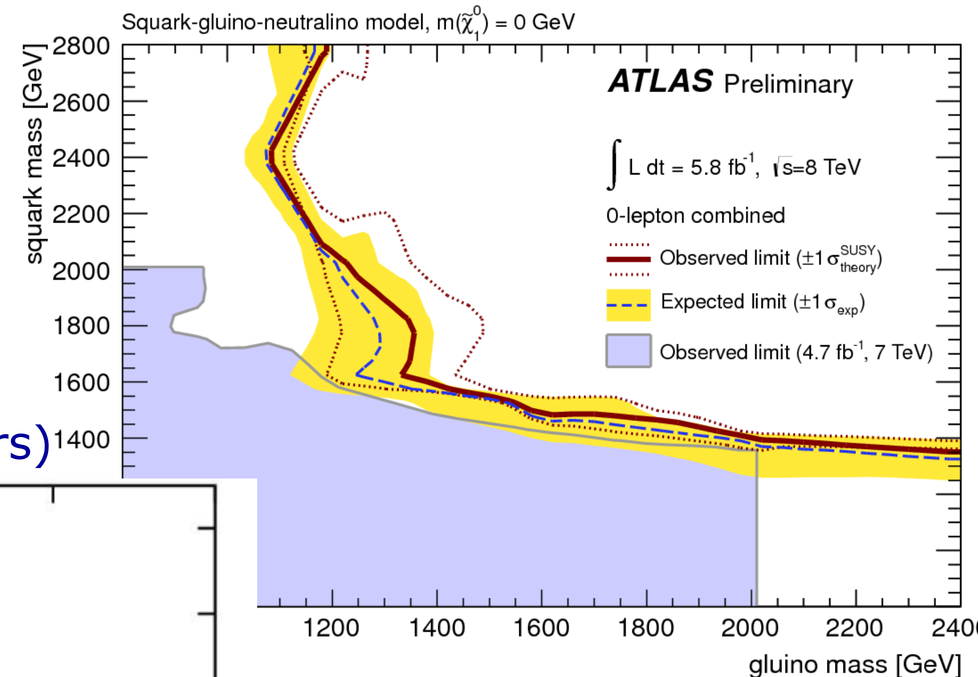


With top leptonic decays
(CMS SR0 region, including lepton & b efficiencies)

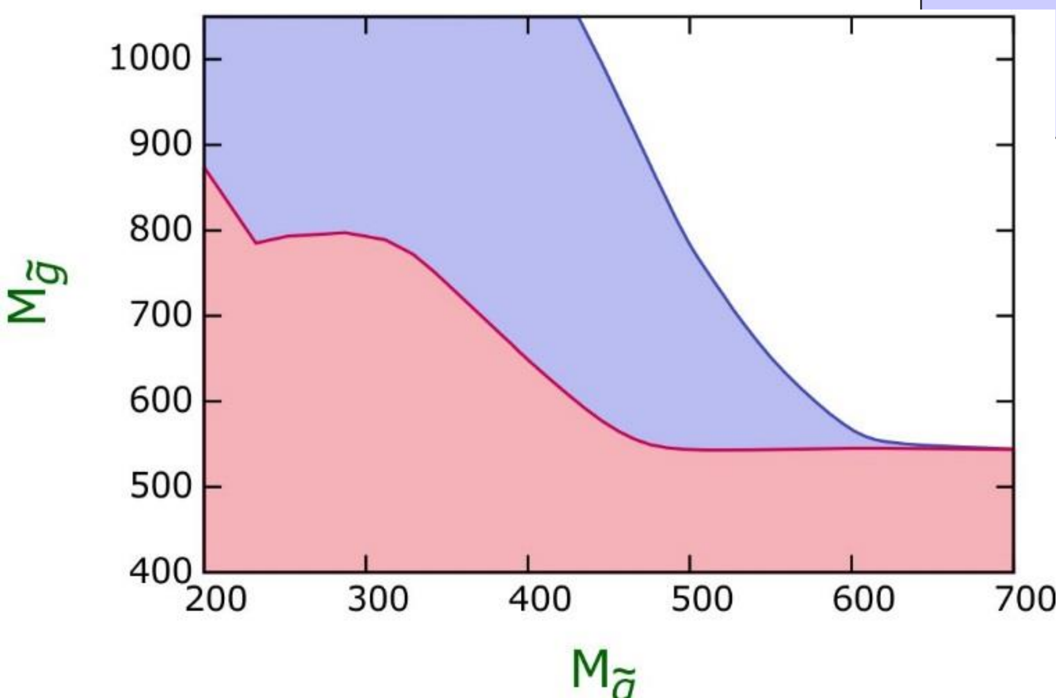
C. Characteristic signatures of the B violating MSSM

Durieux, CS, ‘13

MSSM with R-parity



(from CMS same sign lepton pairs)

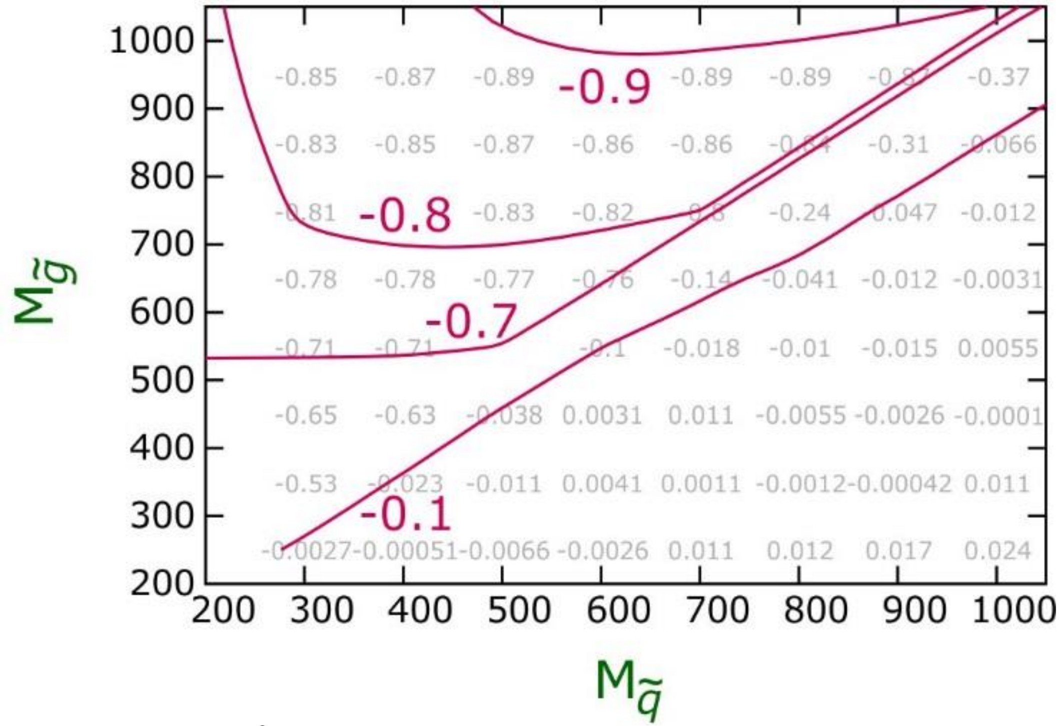


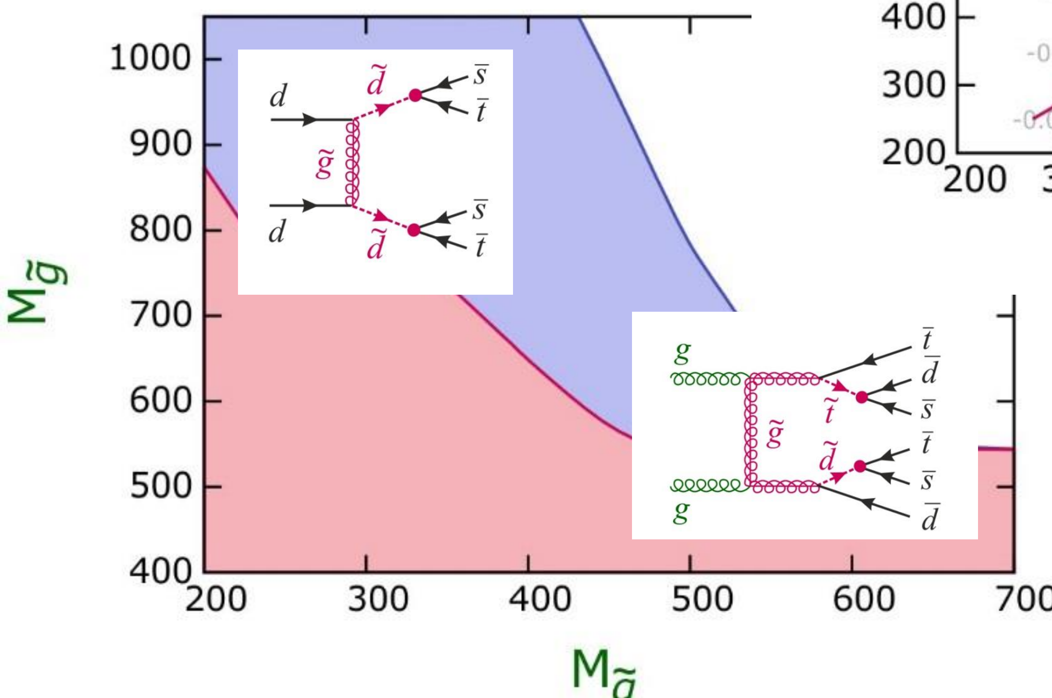
MSSM without R-parity

C. Characteristic signatures of the B violating MSSM

Durieux, CS, ‘13

Lepton charge asymmetry:





MSSM without R-parity

Conclusion

- Same-sign top quarks offer a unique window for NP searches:

  Small SM background, but occurs in many NP extensions.

  Exploit the LHC as an asymmetric baryon factory!

- Low-energy B and 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 same-sign top quarks!

- In supersymmetry, the main motivation for R-parity is questionable…

  No sizable L violation, but large B violating couplings.

  → Bypass current bounds on sparticle masses.

  → Look for same sign top pairs, and lepton charge asymmetry.