GDR Terascale - Montpellier

May 15th, 2013

Flavorless baryon number violation

Christopher Smith

- Outline

I. A brief history of baryon and lepton number

II. Flavorless B and L violation

III. B violation in the MSSM

I. History

Baryon number conservation was a theoretical dogma

Theoretically obvious:

1929, Dirac & Weyl: Conserved proton charge to forbid $p^+ e^- \rightarrow \gamma\gamma$.

1938, Stueckelberg: Conserved hadron charge - to forbid $p^\pm \rightarrow e^\pm \gamma$,
- to allow $n^0 \rightarrow p^+ e^- \nu$.

1949, Wigner: Conserved baryon charge - to forbid $p^\pm \rightarrow e^\pm \gamma, e\pi, \nu\pi$,
- to allow $\pi^\pm \rightarrow e^\pm \nu$,...

Experimentally obvious:

1954, Goldhaber: Radiation from our body's p^+ decay does not kill us?

$\Rightarrow \tau(p^+) > 10^{16}$ years $\approx 10^6 \times$ Age of the Universe.

First true exp. $\Rightarrow \tau(p^+) > 10^{21}$ years $\approx 10^{11} \times$ Age of the Universe.

Later, many "big tank" experiments were designed to look for p^+ decay.

Lepton number conservation was a theoretical oddity

Theoretically dubious:

1937, Majorana: Neutrinos could be their own antiparticle.

1939, Furry: Neutrinoless double beta decay $0\nu\beta\beta = 2n^{0} \rightarrow 2p^{+} + 2e^{-}$.

Experimentally resuscitated:

- $0\nu\beta\beta$ not observed,
- $\nu \neq \bar{\nu}$ (Cowan-Reines, Davis, 1956),
- $\nu_e \neq \nu_\mu$ (Lederman et al., 1962),
- $\mu^{\pm} \rightarrow e^{\pm} + \gamma$ not observed.

Lepton family number must be conserved (1960, Lee & Yang)

Hence so is total lepton number: $\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\tau \equiv \mathcal{L}$

Held until the proton decay experiments found neutrino oscillations!

The modern puzzle

End of the sixties: Both $\mathcal{B}$ and $\mathcal{L}$ appear conserved in the SM

Leptons (e, ν,...) have $\mathcal{L} = +1$,

Quarks have $\mathcal{B} = +1/3 \Rightarrow$ nucleons have $\mathcal{B} = +1$.

End of the seventies: Theorists lose all faith in $\mathcal{B}$ and $\mathcal{L}$ conservation

1967, Sakharov: Conditions for a baryon asymmetry in the Universe

1974, Georgi–Glashow: GUT predict $\mathcal{B}$ and $\mathcal{L}$ violation.

1976, 't Hooft: $\mathcal{B} + \mathcal{L}$ is anomalous in the Standard Model.

1977, Seesaw: Right-handed neutrinos bring us back to Majorana.

But, experiments do not see that: $\tau(p^+ \to \pi^0 e^+) > 8.2 \times 10^{33}$ years

$\tau(0\nu\beta\beta) > 1.9 \times 10^{25}$ years

Are we looking in the right place?

II. Flavorless B and L violation

A. How to violate $\mathcal{B}$ and/or $\mathcal{L}$ in a flavor-diagonal way?

How to naturally pass all bounds on $\mathcal{B}$ and $\mathcal{L}$ violating processes?

$$\mathcal{L}_{eff} = \sum_i \frac{c_i}{\Lambda^{d-4}} Q_i^d$$

Its scale is very high → like in GUT

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

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

The anomaly is a bit special (non-perturbative):

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

Extremely weak: $g_{an} \sim \exp(-2\pi \sin^2\theta_W / \alpha_{em}) \sim 10^{-80}$.

A. How to violate $\mathcal{B}$ and/or $\mathcal{L}$ in a flavor-diagonal way?

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

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

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

In the SM: Scalar products = perturbative couplings.
Cross products = anomalous couplings.

Beyond the SM: Both could arise perturbatively.

A. How to violate $\mathcal{B}$ and/or $\mathcal{L}$ in a flavor-diagonal way?

CS '11

Selection rules:

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

  $N_F = 3$ 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

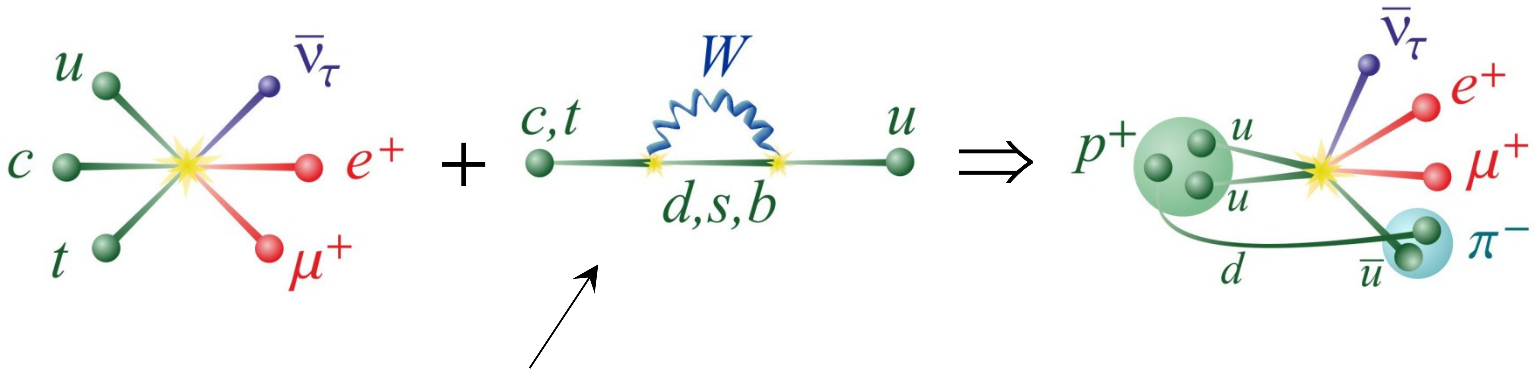
Durieux, Gérard, Maltoni, CS '12

$\Delta\mathcal{B}$	$\Delta\mathcal{L}$	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.

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

$\mathcal{B}$ and $\mathcal{L}$ 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.

D. Discovery channels at the LHC

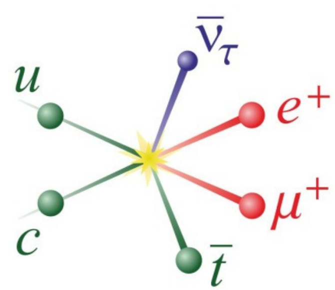
Durieux, Gérard, Maltoni, CS ‘12

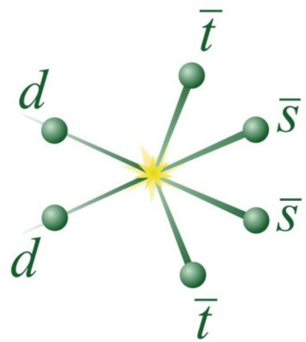
Tops are just fine: flavor transitions are not needed.

Baryon number (jets) & lepton number (ν’s) are not measurable.

Final State: Look for same-sign leptons and tops.

$\Delta\mathcal{B} = 3\Delta\mathcal{L}$





$\Delta\mathcal{B} = 2$

D. Discovery channels at the LHC

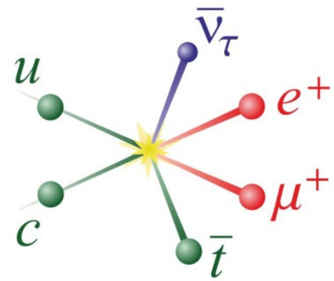
Durieux, Gérard, Maltoni, CS '12

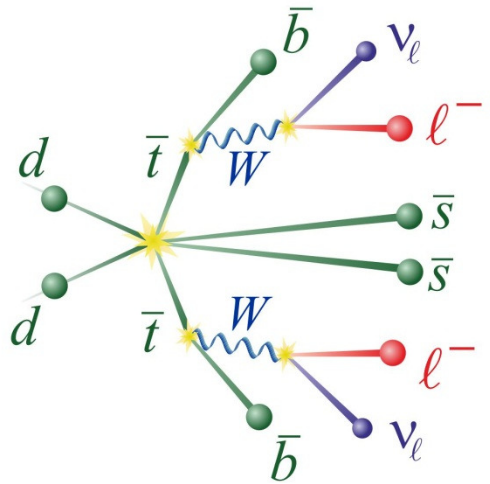
Tops are just fine: flavor transitions are not needed.

Baryon number (jets) & lepton number (ν's) are not measurable.

Final State: Look for same-sign leptons and tops.

$\Delta\mathcal{B} = 3\Delta\mathcal{L}$





$\Delta\mathcal{B} = 2$

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

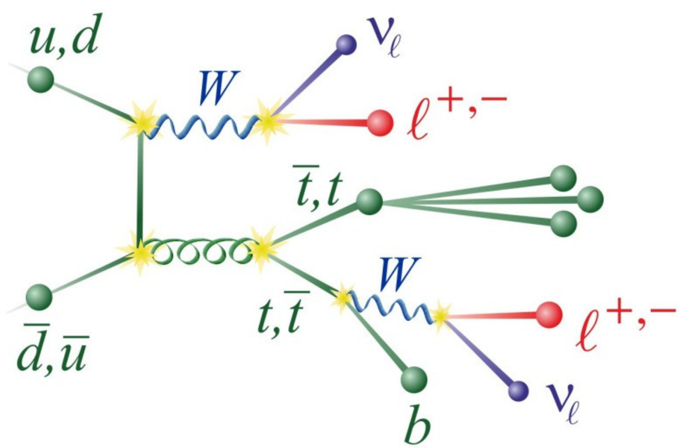
Look for $e^\pm e^\pm$, $\mu^\pm\mu^\pm$, and/or $e^\pm\mu^\pm$ charge asymmetry.

D. Discovery channels at the LHC

Campbell, Ellis ‘12

Same-sign charge asymmetry: a smoking gun for $\mathcal{B}$ violation!

In the SM, the rate is small and the asymmetry is positive:



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

$$A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) \approx +50\%$$

for all $\ell, \ell' = e, \mu$.

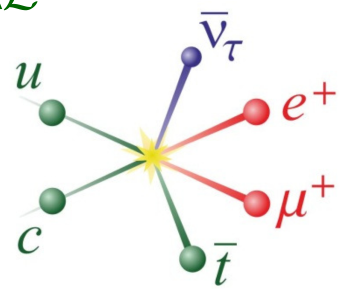
The vast majority of $\mathcal{B}$-conserving New Physics produces:

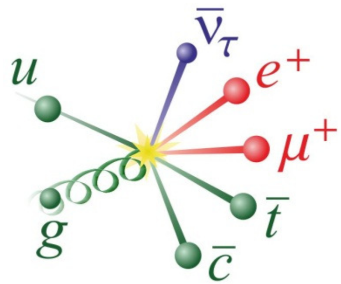
$$A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) > 0 \quad \text{for all } \ell, \ell' = e, \mu .$$

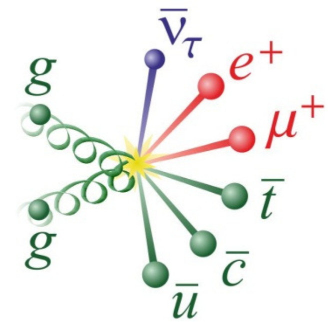
D. Discovery channels at the LHC

Same-sign charge asymmetry: a smoking gun for $\mathcal{B}$ violation!

$\Delta\mathcal{B} = 3\Delta\mathcal{L}$

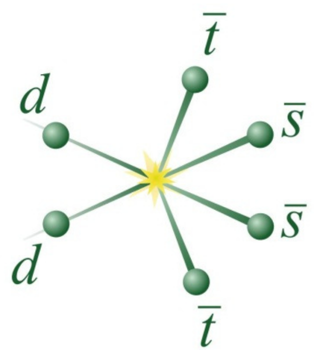


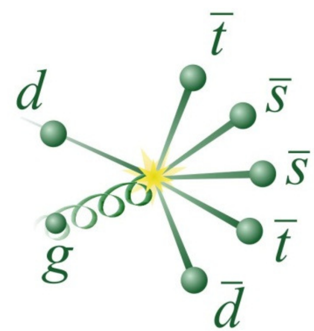


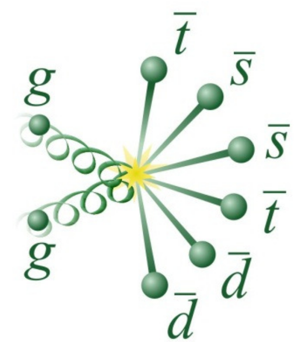


$A_{SS}(e^+\mu^+ - e^-\mu^-) > +80\%$ $\qquad$ $A_{SS}(e^+\mu^+ - e^-\mu^-) = 0$

$\Delta\mathcal{B} = 2$







$A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) < -80\%$ $\qquad$ $A_{SS}(\ell^+\ell'^+ - \ell^-\ell'^-) = 0$

for all $\ell, \ell' = e, \mu$.

III. B violation in the MSSM

A. Flavor-diagonal $\mathcal{R}$-parity violation in the MSSM

Nikolidakis, CS '07

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

Violates selection rules:

$\Delta\mathcal{L}=3$ hierarchies

$\oplus$

$\Delta\mathcal{L}=2$ neutrino mass

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

Yukawa-induced hierarchies:

Full:

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 EW-scale squark masses!

A. Flavor-diagonal $\mathcal{R}$-parity violation in the MSSM

Nikolidakis, CS '07

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

Violates selection rules:

$\Delta\mathcal{L} = 3$ hierarchies

$\oplus$

$\Delta\mathcal{L} = 2$ neutrino mass

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

Yukawa-induced hierarchies:

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

$\tan\beta = 50$

Full:

λ''	ds	sb	bd
u	4	4	4
c	3	4	4
t	0	3	3

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 EW-scale squark masses!

B. Stealth supersymmetry at the LHC?

Dominant $\not{\mathcal{B}}$ 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.

$\nearrow$

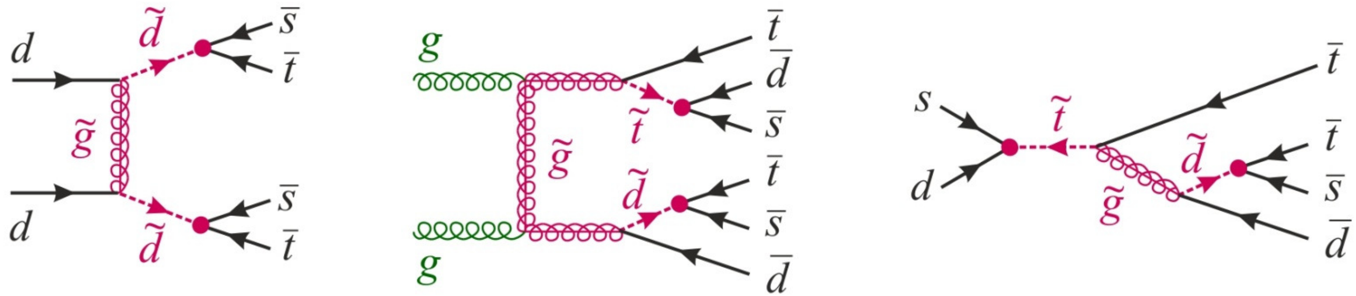
The LSP decays into quarks, so it needs not be colorless & neutral.

- No missing E_T (except from ν) ← RPC channels used up to now
- Supersymmetry is hidden in the increased hadronic activity.

C. Characteristic signatures of the $\not{B}$ violating MSSM

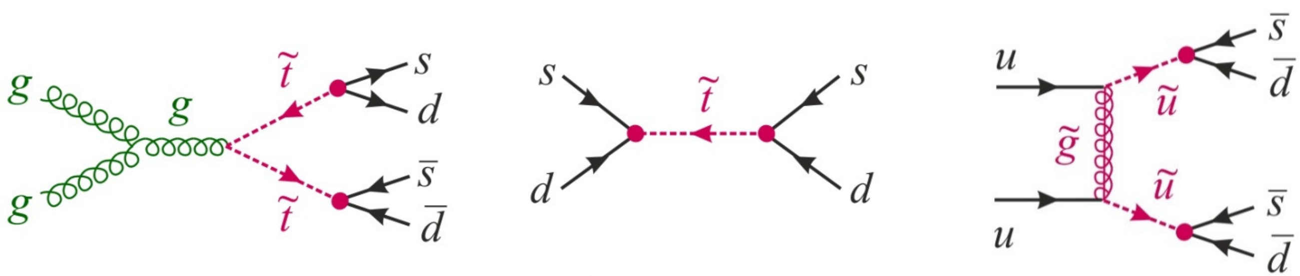
Durieux, CS, to appear

- Same sign top pairs → same sign lepton pairs.



Large rates, characteristic $\Delta B = 2$ signature, small backgrounds.

- Dijet resonances from intermediate up-type squarks.

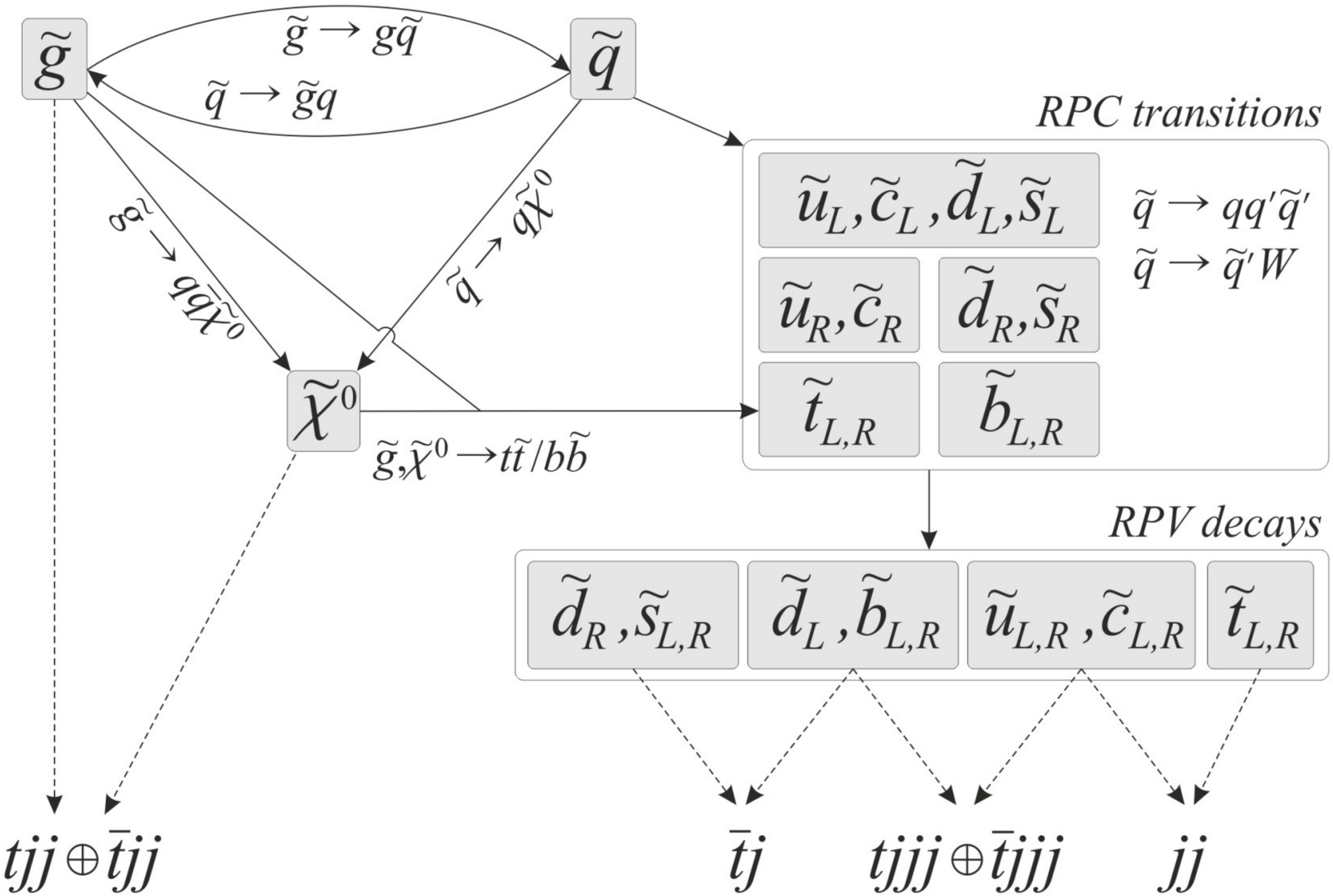


Large backgrounds from $\Delta B = 0$ QCD processes.

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

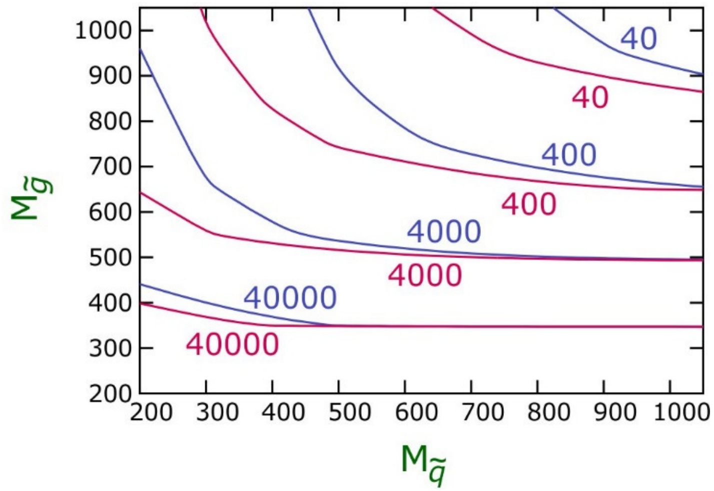
C. Characteristic signatures of the $\not{B}$ violating MSSM

Durieux, CS, to appear



C. Characteristic signatures of the $\not{B}$ violating MSSM

Durieux, CS, to appear

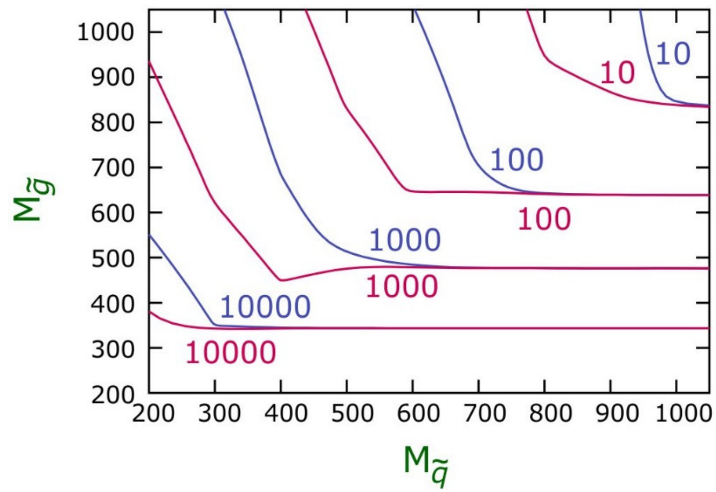


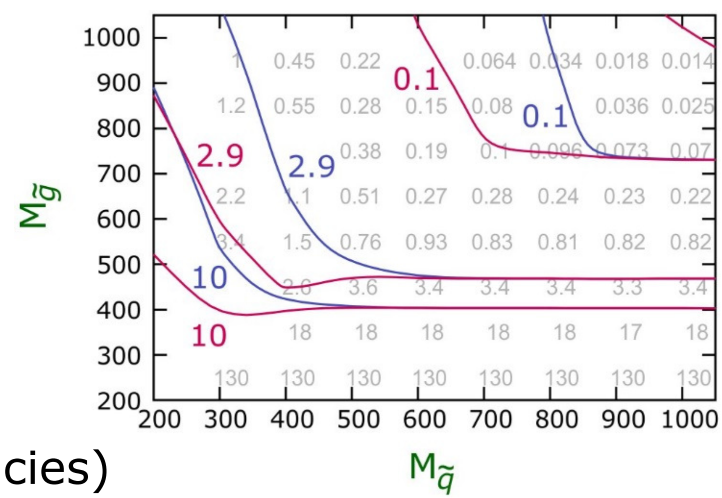
QCD processes: $gg \to \tilde{g}\tilde{g}$

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

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

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



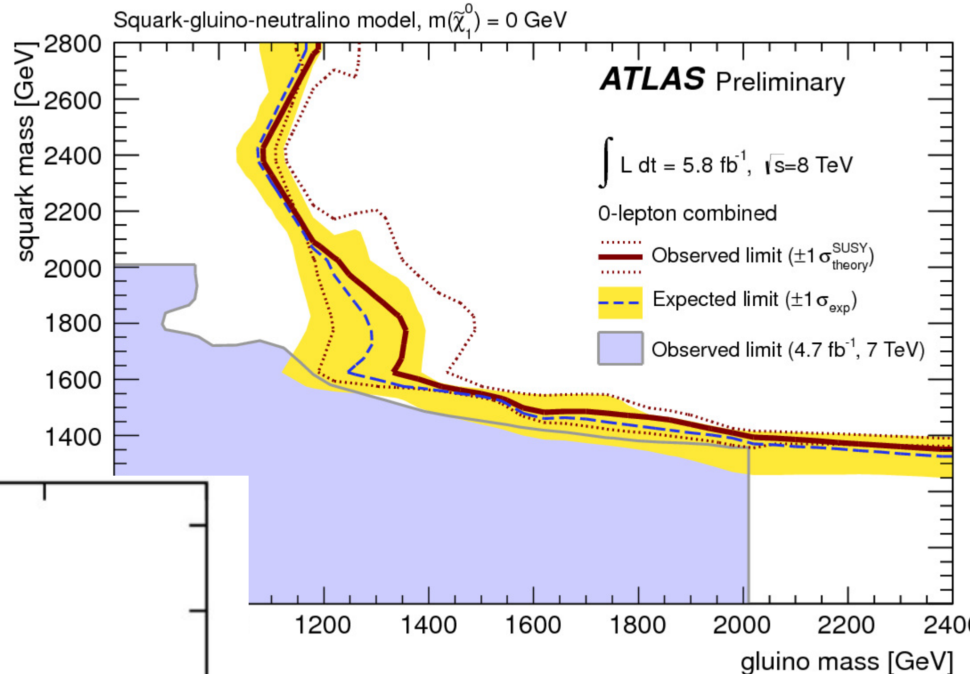


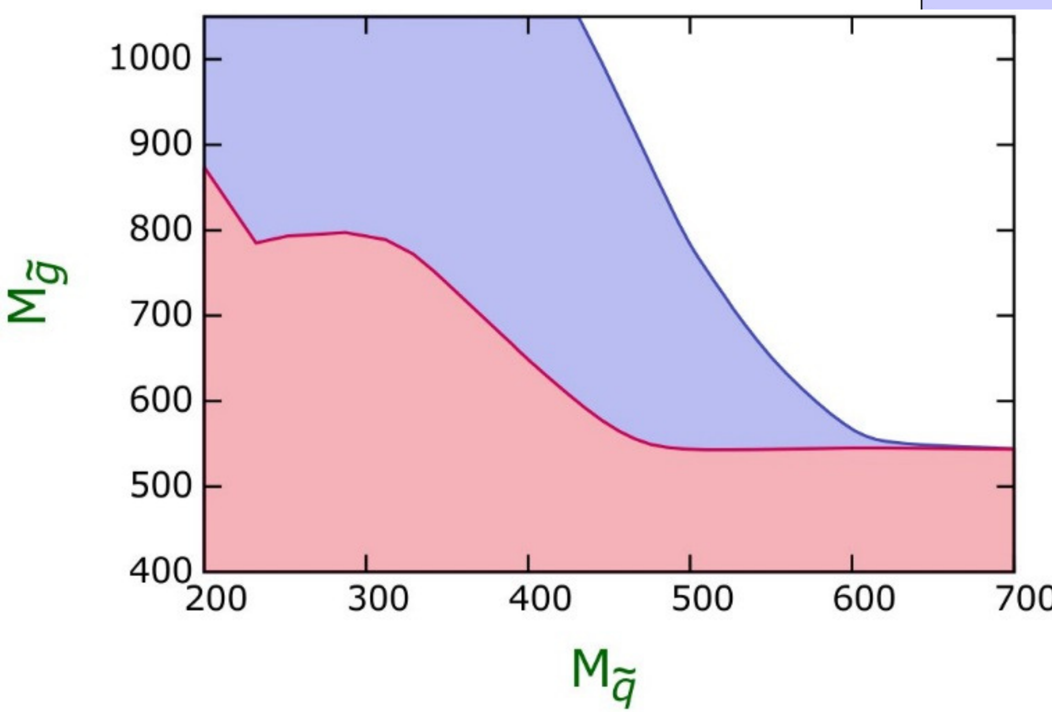
With top leptonic decays
(CMS SR0 region, including lepton & b efficiencies)

C. Characteristic signatures of the $\not{\mathcal{B}}$ violating MSSM

Durieux, CS, to appear

MSSM with $\mathcal{R}$ parity



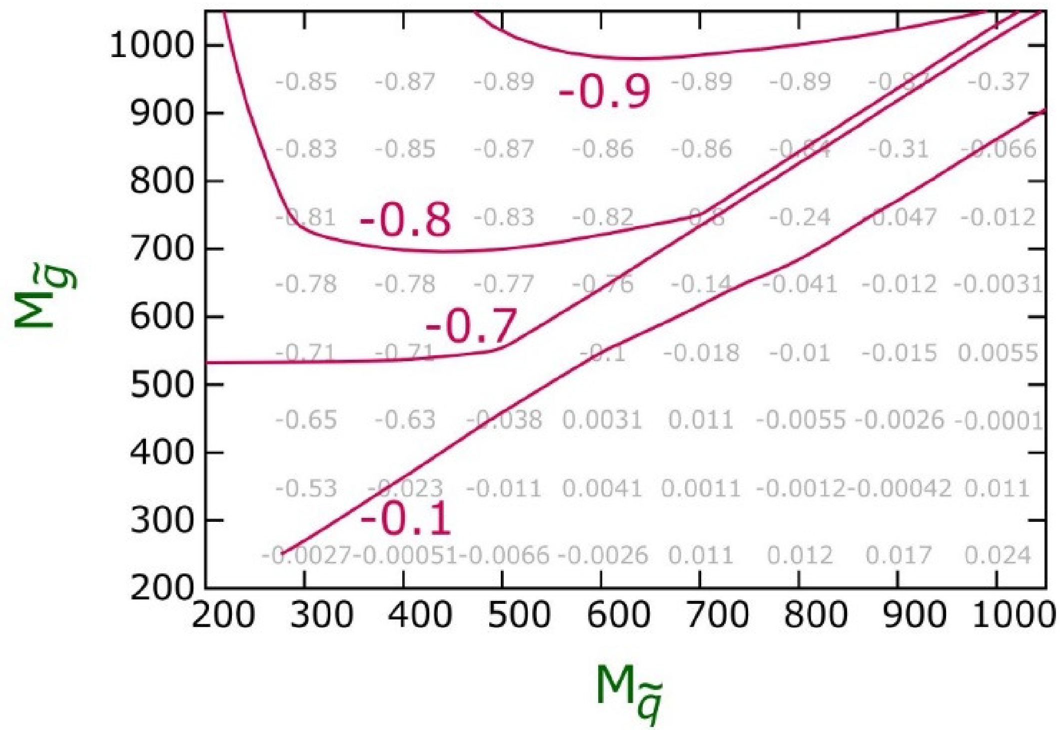


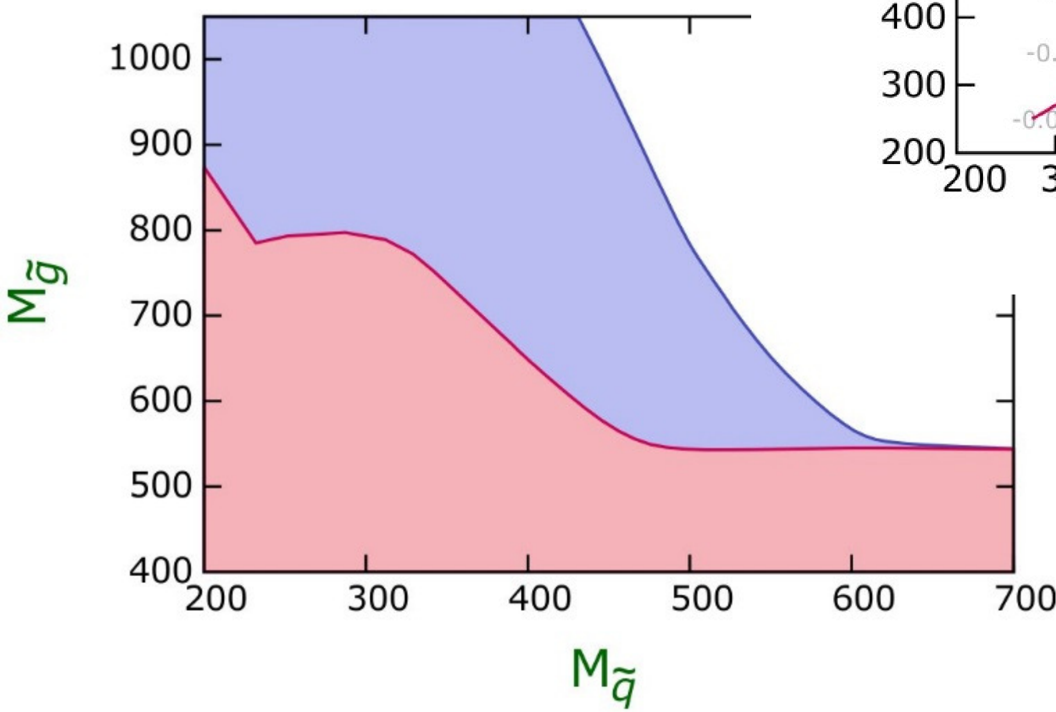
MSSM without $\mathcal{R}$ parity

C. Characteristic signatures of the $\mathcal{B}$ violating MSSM

Durieux, CS, to appear

Lepton charge asymmetry:





MSSM without $\mathcal{R}$ parity

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:

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

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

$$gg\rightarrow\bar{t}\,\bar{t}+\bar{d}\,\bar{d}\,\bar{s}\,\bar{s}+h.c.$$

- In supersymmetry, the main motivation for R-parity is removed!

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

  → Bypass current bounds on sparticle masses.

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