Three-generation baryon and lepton number violation at the LHC

Gauthier Durieux
FNRS Research Fellow at CP3 − UCLouvain

`Phys.Lett.B 721 (2013) 82`
`arXiv:1210.6598 [hep-ph]`
C.Smith (LPSC, Grenoble), G.D., J.-M.Gérard, F.Maltoni (CP3 − UCLouvain)

Portoroz
15 April 2013

Three-generation B and L violation at the LHC

*The **flavour symmetries** of the SM gauge sector,*

broken like in the SM Yukawa Lagrangian,

*naturally make **B** and **L** violation **suppressed at low energy***

*and **accessible at the LHC**,*

*in **resonant processes***

*involving all **three generations**.*

Our starting points

At low energies, B and L violation are severely constrained in

* proton/neutron decays
* dinucleon decays and neutron oscillations
* heavy meson, τ and Z decays

$U(1)_B$ and $U(1)_L$ are doubtful global symmetries

* already violated non-perturbatively in the SM ($B - L$ anomaly-free)
* not naturally conserved BSM (*accidental*)
* violated for baryogenesis and if neutrinos are Majorana, respectively

At the LHC,

* a new energy range is probed directly
* higher generations are directly accessible

BSM flavour structures cannot be generic

Model independence is aimed

Flavour

The SM flavour structure

[Chivukula–Georgi (1987)]

- **SM gauge sector**: a $SU(3_{\text{gen.}})$ flavour symmetry for each fermion

$$\delta^a_b \left(\bar{q}_a \not{D} q^b + \bar{u}_a \not{D} u^b + \bar{d}_a \not{D} d^b + \bar{l}_a \not{D} l^b + \bar{e}_a \not{D} e^b \right) \qquad \text{with } a, b \in \{1, 2, 3_{\text{gen.}}\}$$

- $SU(3_{\text{gen.}})^{5_{\text{ferm.}}}$ broken by the **SM Yukawa sector**,
  in a highly specific way

Our flavour assumption

Impose 1. the **strict conservation of $SU(3_{\text{gen.}})^{5_{\text{ferm.}}}$**
2. a **SM-like breaking**, well supported experimentally

Three-generation B and L violation

1. B and L violation, and $SU(3_{\text{gen.}})^{5_{\text{ferm.}}}$ conservation: $\epsilon_{abc}\,\psi^a\psi^b\psi^c$

   $+$ Lorentz invariance (even number of fermions)

   $\rightarrow$ at least **six fermions** and all **three generations** involved

2. Hierarchical SM-like breaking, with small FCNC:

   $\rightarrow$ still at least six fermions and **costly changes of generations**

- with six fermions $\Rightarrow$ four selection rules
- with overall electric charge conservation $\Rightarrow$ seven fermionic cores

ΔB	ΔL	Fermionic cores	Examples
0	± 6	NNN NNN	$\nu_e\,\nu_\mu\,\nu_\tau\;\;\nu_e\,\nu_\mu\,\nu_\tau$
± 1	± 3	UUU EEN	$\boldsymbol{t\,c\,u\;\;e^-\,\mu^-\,\nu_\tau}$
		UUD ENN	$t\,c\,d\;\;e^-\,\nu_\mu\,\nu_\tau$
		UDD NNN	$t\,s\,d\;\;\nu_e\,\nu_\mu\,\nu_\tau$
± 1	∓ 3	UDD $\bar{\text{N}}\bar{\text{N}}\bar{\text{N}}$	$t\,s\,d\;\;\bar{\nu}_e\,\bar{\nu}_\mu\,\bar{\nu}_\tau$
		DDD $\bar{\text{E}}\bar{\text{N}}\bar{\text{N}}$	$b\,s\,d\;\;e^+\,\bar{\nu}_\mu\,\bar{\nu}_\tau$
± 2	0	UDD UDD	$\boldsymbol{t\,s\,d\;\;t\,s\,d}$
			$t\,c\,d\;\;b\,s\,d$

Low-energy and LHC

At low energy: natural suppressions of operators

- Four-fermion operators not allowed
- Six-fermion operators with first generations only, flavour suppressed

$\rightarrow$ B and L violation allowed in the TeV range [Smith (2012)]

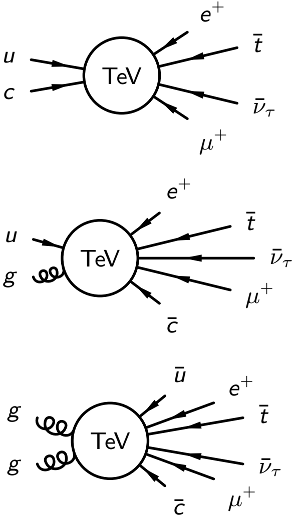
At the LHC: unsuppressed resonant processes

- Involving all three generations
- With same-sign fermions

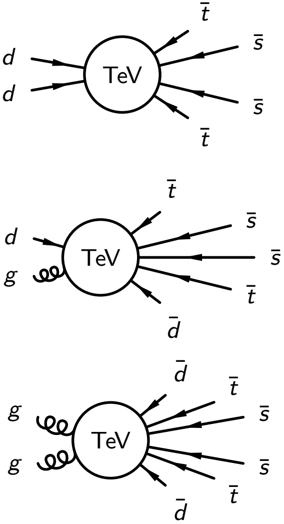
$\rightarrow$ Characteristc same-sign leptons/tops signatures

Resonant (non-local) fermionic channels

$(\Delta B; \Delta L) = (\pm 1; \pm 3)$



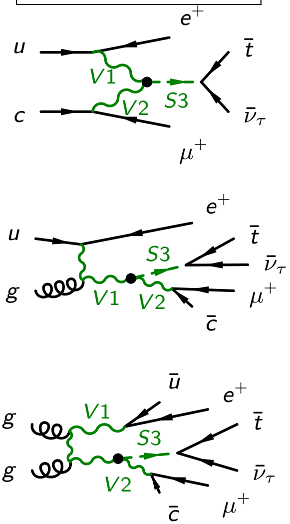
$(\Delta B; \Delta L) = (\pm 2; 0)$



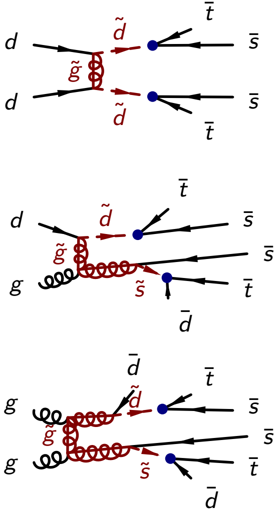
- Initial valence quark(s) $\Rightarrow$ charge asymmetry
- Initial gluon(s) $\Rightarrow$ possibly favoured by the resonances structure

Illustrative simplified models

$(\Delta B; \Delta L) = (\pm 1; \pm 3)$



$(\Delta B; \Delta L) = (\pm 2; 0)$



Leptoquarks: two vectors (eu, μc or τt), one scalar ($\nu_e u$, $\nu_\mu c$ or $\nu_\tau t$ chiral couplings)

RPV: superQCD ($\tilde{q}$ and $\tilde{g}$ only), λ''_{tds} only (from $\lambda''_{abc}\,\overline{\mathcal{U}}_a\,\overline{\mathcal{D}}_b\,\overline{\mathcal{D}}_c$)

Charge asymmetries and rates

LQ LHC@8 TeV	$c_i = 0.6$, $m_{V_i} = 1$ TeV, $m_{S_i} = 500$ GeV	**RPV** LHC@8 TeV	$\lambda''_{tds} = 0.1$, $m_{\tilde q} = 600$, $m_{\tilde g} = 750$,	0.1, 800 GeV, 650 GeV
$u\,c \to \bar t\, e^+ \mu^+ \bar\nu_\tau$:	0.0029 fb	$d\,d \to \bar t\,\bar t\,\bar s\,\bar s$:	30 fb	0.012 fb
$A_{ll}^{\rm LQ} =$	$+0.93$	$A_{ll}^{\rm RPV} =$	-0.95	-0.98
$u\,g \to \bar t\,\bar c\, e^+ \mu^+ \bar\nu_\tau$:	0.018 fb	$g\,d \to \bar t\,\bar t\,\bar s\,\bar s\,d$:	16 fb	1.2 fb
$A_{ll}^{\rm LQ} =$	$+0.96$	$A_{ll}^{\rm RPV} =$	-0.80	-0.81
$g\,g \to \bar t\,\bar c\,\bar u\, e^+ \mu^+ \bar\nu_\tau$:	0.0019 fb	$g\,g \to \bar t\,\bar t\,\bar s\,\bar s\,\bar d\,\bar d$:	1.7 fb	38 fb
$A_{ll}^{\rm LQ} =$	0	$A_{ll}^{\rm RPV} =$	0	0
$p\,p \to \bar t\, e^+ \mu^+ + X$:	0.023 fb	$p\,p \to \bar t\,\bar t + X$:	48 fb	39 fb
$A_{ll}^{\rm LQ\ TOT} =$	$+0.88$	$A_{ll}^{\rm RPV\ TOT} =$	-0.87	-0.025

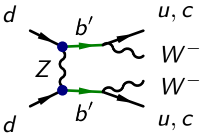
[FeynRules-MadGraph 5, no cuts]

Strategy:

– inclusive search for same-sign (flavour-different) dileptons

– compute the charge asymmetry in NP rates: $A_{ll}^{\rm NP} \equiv \dfrac{\langle ++\rangle - \langle --\rangle}{\langle ++\rangle + \langle --\rangle}$

Note $A_{ll}^{\rm NP} < 0$ **points at** B **and** L **violation**
or at very special and constrained scenarios like:



Three-generation B and L violation at the LHC

A SM-like flavour structure,
suppressing naturally low-energy B and L violation

A model independent classification of allowed channels

Resonant processes with striking signatures at the LHC

- $\bar{t}\, e^+ \mu^+$ and $\bar{t}\, \bar{t}$ + jets
- Charge asymmetries discriminate between scenarios.
- $A_{ll}^{\text{NP}} < 0$ would be a smoking gun.

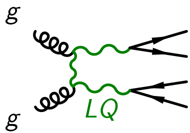
Master table

ΔB	ΔL	Fermionic cores	Examples	Promising LHC processes	$A_{e\mu}$
0	± 6	NNN NNN	$\nu_e\,\nu_\mu\,\nu_\tau \otimes \nu_e\,\nu_\mu\,\nu_\tau$	$u\,\bar{u} \to e^-\,\mu^-\,\nu_\tau \nu_e \nu_\mu \nu_\tau \quad W^+ W^+$	0
± 1	± 3	UUU EEN	$\boldsymbol{t\,c\,u \otimes e^-\,\mu^-\,\nu_\tau}$	$\boldsymbol{u\,c \to \bar{t} \quad e^+\,\mu^+\,\bar{\nu}_\tau}$	**+**
				$\boldsymbol{u\,g \to \bar{t}\,\bar{c} \quad e^+\,\mu^+\,\bar{\nu}_\tau}$	**+**
				$\boldsymbol{g\,g \to \bar{t}\,\bar{c}\,\bar{u} \quad e^+\,\mu^+\,\bar{\nu}_\tau}$	**0**
				$u\,c \to \bar{t} \quad e^+\,\mu^+\,\tau^+ \quad W^-$	+
		UUD ENN	$t\,c\,d \otimes e^-\,\nu_\mu\,\nu_\tau$	$d\,c \to \bar{t} \quad e^+\,\mu^+\,\bar{\nu}_\tau \quad W^-$	+
		UDD NNN	$t\,s\,d \otimes \nu_e\,\nu_\mu\,\nu_\tau$	$d\,s \to \bar{t} \quad e^+\,\mu^+\,\bar{\nu}_\tau \quad W^- W^-$	+
± 1	∓ 3	UDD N̄N̄N̄	$t\,s\,d \otimes \bar{\nu}_e\,\bar{\nu}_\mu\,\bar{\nu}_\tau$	$d\,s \to \bar{t} \quad e^-\,\mu^-\,\nu_\tau \quad W^+ W^+$	−
		DDD ĒN̄N̄	$b\,s\,d \otimes e^+\,\bar{\nu}_\mu\,\bar{\nu}_\tau$	$d\,s \to \bar{t} \quad e^-\,\mu^-\,\nu_\tau \quad W^+ W^+$	−
± 2	0	UDD UDD	$\boldsymbol{t\,s\,d \otimes t\,s\,d}$	$\boldsymbol{d\,d \to \bar{t}\,\bar{t} \quad \bar{s}\,\bar{s}}$	**−**
				$\boldsymbol{d\,g \to \bar{t}\,\bar{t} \quad \bar{s}\,\bar{s} \quad \bar{d}}$	**−**
				$\boldsymbol{g\,g \to \bar{t}\,\bar{t} \quad \bar{s}\,\bar{s} \quad \bar{d}\,\bar{d}}$	**0**
			$t\,c\,d \otimes b\,s\,d$	$d\,u \to \bar{t}\,\bar{t} \quad \bar{s}\,\bar{s} \quad W^+$	−
				$d\,d \to \bar{t}\,\bar{t} \quad \bar{c}\,\bar{s} \quad W^+$	−

Simplified models vs LHC searches

LQ

- QCD pair production

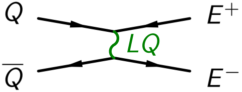


vectors: eu, μc
scalar: $\nu_\tau t$

scalar	ej	> 830 GeV	CMS, 7 TeV, 5/fb
scalar	μj	> 840 GeV	CMS, 7 TeV, 5/fb
scalar	$b\nu$	> 350 GeV	CMS, 7 TeV, 1.8/fb
scalar	$b\tau$	> 535 GeV	ATLAS, 7 TeV, 4.7/fb
vector	$b\tau$	> 760 GeV	CMS, 7 TeV, 4.8/fb

$\rightarrow$ Constrains the mass alone

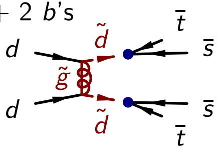
- m_{ee} and $m_{\mu\mu}$
  LHC@8 TeV: ATLAS and CMS, 20/fb



$\rightarrow$ Constrains the coupling (mass fixed)

RPV

- SSDL + 2 b's



Latest CMS, 8 TeV, 10.5/fb

SR8: 2 same-sign leptons $p_T > 20$ GeV, $|\eta| < 2.4$
2 jets + 2 b's $p_T > 40$ GeV, $|\eta| < 2.4$
$\not{E}_T > 0$ GeV
$H_T > 320$ GeV
< 10.5 BSM events at 95% CL

Acceptance $\simeq$ a few $\times 10^{-3}$:
- $1/4$ of signal passes cuts
- $(60\%)^2$ efficiency for two b-tags
- $(60\%)^2$ for two ℓ's
- $(2/9)^2$ for two semi-ℓ top decays

$\rightarrow \sigma^{\rm RPV}(pp \rightarrow \bar{t}\bar{t} + X) \lesssim \mathcal{O}(100 \text{ fb})$

Simplified models at 14 TeV

LQ LHC@8 (14) TeV	$c_i = 0.6$, $m_{V_i} = 1$ TeV, $m_{S_i} = 500$ GeV	**RPV** LHC@8 (14) TeV	$\lambda''_{tds} = 0.1$, $m_{\tilde{q}} = 600$, $m_{\tilde{g}} = 750$,	0.1, 800 GeV, 650 GeV
$u\,c \to \bar{t}\,e^+\,\mu^+\,\bar{\nu}_\tau$:	0.0029 (0.025) fb	$d\,d \to \bar{t}\,\bar{t}\,\bar{s}\,\bar{s}$:	30 (110) fb	0.012 (0.065) fb
$A_{ll}^{\rm LQ} =$	+0.93 (+0.90)	$A_{ll}^{\rm RPV} =$	−0.95 (−0.88)	−0.98 (−0.92)
$u\,g \to \bar{t}\,\bar{c}\,e^+\,\mu^+\,\bar{\nu}_\tau$:	0.018 (0.40) fb	$g\,d \to \bar{t}\,\bar{t}\,\bar{s}\,\bar{s}\,d$:	16 (140) fb	1.2 (12) fb
$A_{ll}^{\rm LQ} =$	+0.96 (+0.94)	$A_{ll}^{\rm RPV} =$	−0.80 (−0.69)	−0.81 (−0.69)
$g\,g \to \bar{t}\,\bar{c}\,\bar{u}\,e^+\,\mu^+\bar{\nu}_\tau$:	0.0019 (0.25) fb	$g\,g \to \bar{t}\,\bar{t}\,\bar{s}\,\bar{s}\,\bar{d}\,\bar{d}$:	1.7 (33) fb	38 (590) fb
$A_{ll}^{\rm LQ} =$	0 (0)	$A_{ll}^{\rm RPV} =$	0 (0)	0 (0)
$p\,p \to \bar{t}\,e^+\,\mu^+ + X$:	0.023 (0.65) fb	$p\,p \to \bar{t}\,\bar{t} + X$:	48 (280) fb	39 (602) fb
$A_{ll}^{\rm LQ\ TOT} =$	+0.88 (+0.58)	$A_{ll}^{\rm RPV\ TOT} =$	−0.87 (−0.68)	−0.025 (−0.014)

[FeynRules-MadGraph 5, no cuts]