Baryon number violation at the LHC: The top option

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`Phys.Rev.D 85 (2012) 016006`
`(arXiv:1107.3805 [hep-ph])`

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23 March 2012
Alliance Top Quark Workshop 2012

Outline

- The baryon number
  - Non-conserving models
  - Experimental evidence and constraints
- The minimal effective BNV model
  - Effective operators
  - Experimental constraints
  - Top phenomenology at the LHC

Motivation

for baryon number violation (BNV)

- strong theoretical support

  in nearly all possible models, SM included

- no direct experimental observation

  very strong bounds from nucleon decay
  but hint from the B–$\overline{B}$ asymmetry

for an effective approach

- model independent

  valuable given the wealth of BSM extensions

- simple description of the relevant physics

for searches at the LHC, with top quarks

- in a new energy range
- in second and third generations
- almost at the quark level
- with unique experimental signatures

Outline

The baryon number

A Noether charge associated with a global, accidental and classical $U(1)_B$ symmetry of the SM Lagrangian

$$B = \frac{1}{N_c} \sum_{a=1}^{N_f} \int \mathrm{d}^3\mathbf{x} \left[\bar{q}_a \gamma^0 q^a + \bar{u}_a \gamma^0 u^a + \bar{d}_a \gamma^0 d^a \right]$$

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Non-conserving theories

The SM: thanks to the $(B+L)$-anomaly [Adler (1969), Bell–Jackiw (1969)]

- by *instanton* tunnelling transitions (at a negligible rate) [t'Hooft (1976)]
- by thermal *sphaleron* transitions (for temperatures $\gtrsim$ 100 GeV) [Klinkhamer–Manton (1984)]

GUT models: thanks to extra gauge/scalar bosons

e.g. in a minimal SU(5), new $(\mathbf{3}, \overline{\mathbf{2}}, -5/6)$ vector and $(\mathbf{3}, \mathbf{1}, -1/3)$ scalar [Georgi–Glashow (1974)]

SUSY models [Weinberg (1982)]

R-parity violating interactions $(\overline{\mathcal{U}}\,\overline{\mathcal{D}}\,\overline{\mathcal{D}})$

dimension-five operators ($\mathcal{QQQL}$ and $\overline{\mathcal{U}}\,\overline{\mathcal{U}}\,\overline{\mathcal{D}}\,\overline{\mathcal{E}}$)

Black-holes physics [Bekenstein (1972)]

...

Baryon number violation

Experimentally

Evidence from the baryon–anti-baryon asymmetry

Universe around us made of matter (rather than anti-matter):

- $\bar{p}$ fluxes in cosmic rays compatible with secondary production
- no strong and characteristic γ emissions observed

Standard baryogenesis requires B-violation [Sakharov (1967)]

to create a net excess of Bs (or segregate Bs and $\overline{B}$s)

from a B–$\overline{B}$ symmetric initial condition

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Constraints from matter stability

$|\Delta B| = 1$

- Nucleon decays:
  - disappearance searches (process independent bounds)
  - decay products searches

    $\tau_p/\mathrm{Br}(p \to \pi^0 e^+) > 0.82 \times 10^{34}\mathrm{yr}$ (90% CL) [SuperK (2009)]
- τ lepton, D and B mesons decays [Argus, Belle, BaBar, Cleo (1992-2011)]
- $Z \to pe^-$ or $p\mu^-$ decays [Opal (1999)]

$|\Delta B| = 2$

- $n - \bar{n}$ oscillation (free or bounded) [ILL (1994), Soudan-2 (2002)]
- nn, np, pp dinucleon decays (bounded) [Frejus (1991)]

Outline

The minimal effective BNV model

minimal mass-dimension
SM fields (interaction eigenstates: q, l, u, d, e)
Lorentz and $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariance

$\rightarrow$ a basis of five scalar operators

[Weinberg, Wilczek–Zee, Abbott–Wise (1979-1980)]

· QQQL form: dimension-six
$B - L$ conserving

$$O^{(1)}_{abcd} \equiv (\overline{d^c})^{\alpha}_a (u)^{\beta}_b \;\; (\overline{q^c})^{i\gamma}_c (l)^j_d \quad \epsilon_{\alpha\beta\gamma} \;\; \epsilon_{ij}$$

$$O^{(2)}_{abcd} \equiv (\overline{q^c})^{i\alpha}_a (q)^{j\beta}_b \; (\overline{u^c})^{\gamma}_c (e)_d \quad \epsilon_{\alpha\beta\gamma} \;\; \epsilon_{ij}$$

$$O^{(3)}_{abcd} \equiv (\overline{q^c})^{i\alpha}_a (q)^{j\beta}_b \; (\overline{q^c})^{k\gamma}_c (l)^l_d \quad \epsilon_{\alpha\beta\gamma} \;\; \epsilon_{ij}\epsilon_{kl}$$

$$O^{(4)}_{abcd} \equiv (\overline{q^c})^{i\alpha}_a (q)^{j\beta}_b \; (\overline{q^c})^{k\gamma}_c (l)^l_d \quad \epsilon_{\alpha\beta\gamma} \;\; [\epsilon\boldsymbol{\tau}]_{ij} \cdot [\epsilon\boldsymbol{\tau}]_{kl}$$

$$O^{(5)}_{abcd} \equiv (\overline{d^c})^{\alpha}_a (u)^{\beta}_b \;\; (\overline{u^c})^{\gamma}_c (e)_d \quad \epsilon_{\alpha\beta\gamma}$$

$\psi^c \equiv C\overline{\psi}^T$
a, b, c, d: flavour
i, j, k, l: $\mathrm{SU}(2)_L$
α, β, γ: colour

The minimal effective BNV model

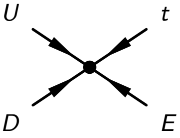
- in the physical basis (flavour generic U, D and E)
- with a top quark
- with a charged lepton but no neutrino
  - Angular momentum conservation gives $\Delta(L+3B) \in 2\mathbb{Z}$
  - So, one single charged lepton implies $\Delta B \neq 0$
  - But $|\Delta L| = 1$ cannot be ensured in presence of $\not{E}_T$

$\rightarrow$ a basis of two scalar operators: [Dong et al. (2012)]

$$O^{(s)} \equiv \left[\overline{t^c_\alpha}(a\,P_L + b\,P_R)D_\beta\right]\left[\overline{U^c_\gamma}(c\,P_L + d\,P_R)E\right]\epsilon^{\alpha\beta\gamma}$$
$$O^{(t)} \equiv \left[\overline{t^c_\alpha}(a'\,P_L + b'\,P_R)E\right]\left[\overline{U^c_\beta}(c'\,P_L + d'\,P_R)D_\gamma\right]\epsilon^{\alpha\beta\gamma}$$

where a, ..., d' are flavour dependent, dimensionless parameters

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\left(O^{(s)} + O^{(t)} + h.c.\right)$$



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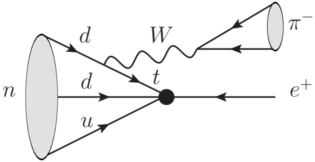

$\rightarrow$ formidable strong constraints

less stringent for effective coupling with higher generation fermions

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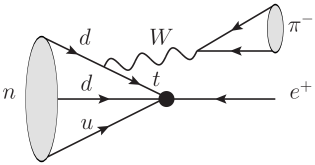

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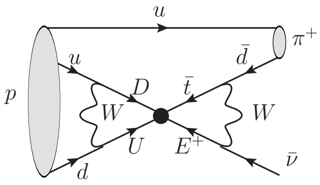
- at loop level



→ fixing flavours to $tcb\mu$ gives:

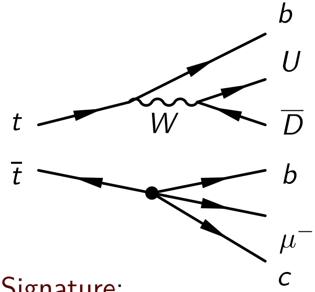
$$\frac{c_6^{tcb\mu}}{\Lambda^2} \lesssim \frac{10^{-11} - 10^{-16}}{(1\ \text{TeV})^2}$$

but *GIM-like* cancellations could occur when summing on all possible *UDUE* flavours

Top BNV decay

Signal

$t\bar{t}$: SM hadronic + BNV



Signature:

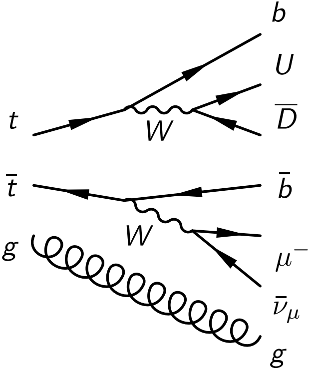
- 5 jets, 1 single charged lepton
- 2 same-sign b's
- no $\not{E}_t$

Branching ratio:

$$\mathrm{Br}(\bar{t} \to b\mu^- c) = 1.2 \times 10^{-6}\ [A + B + C] \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^4$$

Background

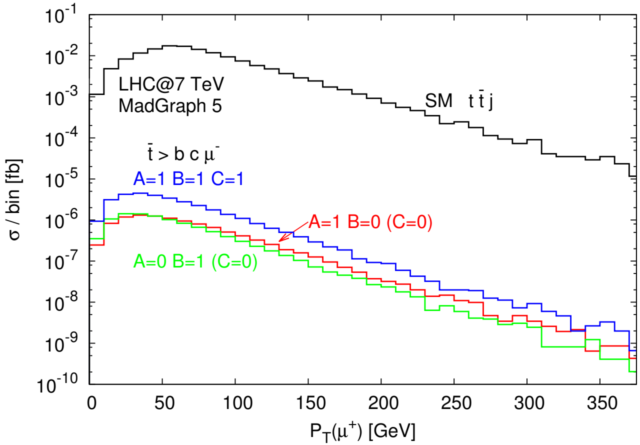
$t\bar{t}j$: SM hadronic + SM leptonic



neglecting all masses w.r.t. m_t

$$A \equiv \left(|a|^2 + |b|^2\right)\left(|c|^2 + |d|^2\right)$$
$$B \equiv \left(|a'|^2 + |b'|^2\right)\left(|c'|^2 + |d'|^2\right)$$
$$C \equiv \Re\mathfrak{e}\left\{a^* c^* a' c' + b^* d^* b' d'\right\}$$

Top BNV decay

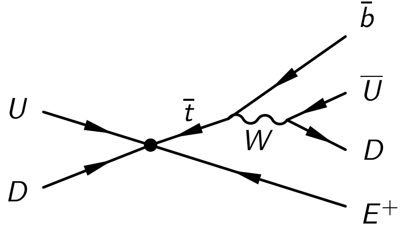


Jets: $p_T > 40$ GeV, $|\eta| < 2.5$, $\Delta R_{jj} > 0.5$
Muon: $|\eta| < 2.5$, $\Delta R_{j\mu} > 0.5$
Background: $\not{E}_T < 30$ GeV

BNV top production

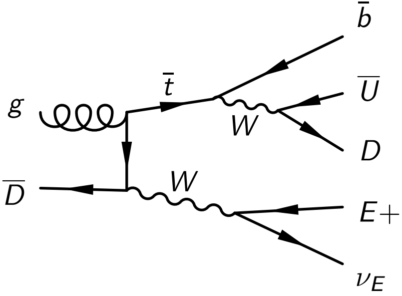
Signal

BNV top production



Background

SM tW production



Signature:

– 3 jets, 1 single charged lepton

– no $\not{E}_t$

BNV top production

$$\hat{\sigma}_t^{\mathrm{BNV}} = \frac{1}{96\pi\Lambda^4} \int_{m_t^2-\hat{s}}^{0} \mathrm{d}\hat{t} \left[A\frac{\hat{t}\left(\hat{t}-m_t^2\right)}{\hat{s}^2} + B\frac{\left(\hat{s}-m_t^2\right)}{\hat{s}} + 2C\frac{\hat{t}}{\hat{s}} \right]$$

neglecting all masses w.r.t. m_t

$$= \frac{\hat{s}}{96\pi\Lambda^4}\left(1-\frac{m_t^2}{\hat{s}}\right)^2 \left[\left(\frac{A}{3}+B+C\right)+\frac{m_t^2}{\hat{s}}\frac{A}{6}\right]$$

$\hat{s}$ growth: The effective theory assumes $\sqrt{\hat{s}} \ll \Lambda$.
We impose $\sqrt{\hat{s}} < \Lambda$ for consistency.

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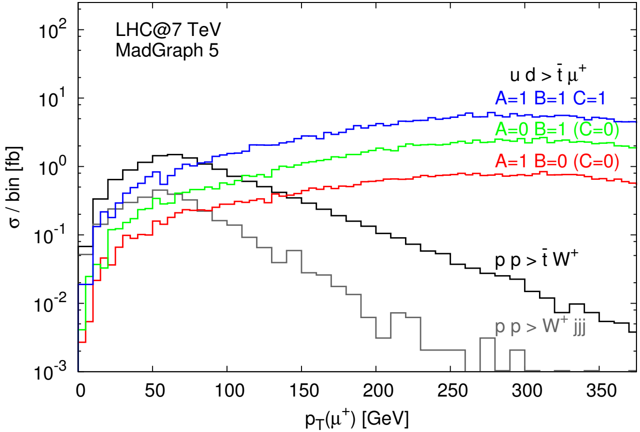
For representative flavour assignations:

σ[fb] A B C	most PDF favoured $ud \to \bar{t}E^+$ $\bar{u}\bar{d} \to tE^-$	two flavour pairs $ub \to \bar{t}e^+$ $\bar{u}\bar{b} \to te^-$	most PDF suppressed two flavour pairs $cb \to \bar{t}\mu^+$ $\bar{c}\bar{b} \to t\mu^-$
1 0 0	250 14	30 3.1	1.2 1.2
0 1 0	910 45	110 9.1	3.7 3.7
1 1 1	2 100 110	240 22	9.1 9.1

MadGraph 5, LHC@7 TeV, $\sqrt{\hat{s}} < \Lambda = 1$ TeV

BNV top production



$\sqrt{\hat{s}} < \Lambda = 1$ TeV

Decays: $W^+ \to \mu^+ \nu_\mu$, $\quad \bar{t} \to \bar{b}\, j\, j$

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Backgrounds: $\not{E}_T < 30$ GeV

W^+ jjj: $|m_{jjj} - m_t| < 40$ GeV, $\quad b$ tag

Summary and conclusions

Baryon number violation:

- well motivated from a theoretical point of view
- a privileged probe for new physics
- evidence from baryogenesis, strong low energy bounds

... but no measurement at TeV scales

The minimal effective BNV model:

- with lowest dimensional operators
- for exploring top BNV phenomenology
- a powerful, simplified, and model independent framework