# Effective approaches to baryon number violation at the LHC

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# Outline

# 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

− simplified description

  e.g. doesn't naturally provide informations on mediators

for searches at the LHC, with top quarks

+ in a new energy range
+ with second and third quark generations
+ almost at the quark level
? with high enough sensitivities

# Outline

# The baryon number

A Noether charge associated with a global, accidental and classical symmetry of the SM Lagrangian

## Non-conserving theories

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

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

GUT models: thanks to extra gauge/scalar bosons

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

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)]

...

# The baryon number

## 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 $\gamma$ emissions observed

Standard baryogenesis requires $B$-violation to create a net excess of $B$s, or segregate $B$s and $\overline{B}$s from a $B$–$\overline{B}$ symmetric initial condition [Sakharov (1967)]

### Constraints from matter stability

$|\Delta B| = 1$

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

    $\tau_p/\mathrm{Br}(p \to \pi^0 e^+) > 0.82 \times 10^{34}$yr (90% CL) [SuperK (2009)]
- $\tau$ 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
- $nn$, $np$, $pp$ dinucleon decays

# Outline

# The minimal effective BNV model

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

$\rightarrow$ five scalar operators [Weinberg, Wilczek–Zee, Abbott–Wise (1979-1980)]

- QQQL form (dimension-six)
- $B - L$ conserving

$$
\begin{aligned}
O^{(1)}_{abcd} &\equiv (\overline{d^c})^{\alpha}_{a}(u)^{\beta}_{b}\ \ (\overline{q^c})^{i\gamma}_{c}(l)^{j}_{d} \quad \epsilon_{\alpha\beta\gamma} \ \ \epsilon_{ij} \\
O^{(2)}_{abcd} &\equiv (\overline{q^c})^{i\alpha}_{a}(q)^{j\beta}_{b}\ (\overline{u^c})^{\gamma}_{c}(e)_{d} \quad \epsilon_{\alpha\beta\gamma} \ \ \epsilon_{ij} \\
O^{(3)}_{abcd} &\equiv (\overline{q^c})^{i\alpha}_{a}(q)^{j\beta}_{b}\ (\overline{q^c})^{k\gamma}_{c}(l)^{l}_{d} \quad \epsilon_{\alpha\beta\gamma} \ \ \epsilon_{ij}\epsilon_{kl} \\
O^{(4)}_{abcd} &\equiv (\overline{q^c})^{i\alpha}_{a}(q)^{j\beta}_{b}\ (\overline{q^c})^{k\gamma}_{c}(l)^{l}_{d} \quad \epsilon_{\alpha\beta\gamma} \ \ [\epsilon\boldsymbol{\tau}]_{ij}\cdot[\epsilon\boldsymbol{\tau}]_{kl} \\
O^{(5)}_{abcd} &\equiv (\overline{d^c})^{\alpha}_{a}(u)^{\beta}_{b}\ \ (\overline{u^c})^{\gamma}_{c}(e)_{d} \quad \epsilon_{\alpha\beta\gamma}
\end{aligned}
$$

$$
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_{i=1}^{5}\left(c_6^{(i)} O_6^{(i)} + h.c.\right)
$$

# The minimal effective BNV model

## Top phenomenology at the LHC

[Dong et al. (2011)]

in the physical basis (flavour generic $U$, $D$ and $E$)
without missing energy (neutrinos excluded)
with a top quark

$\rightarrow$ two operators:

$$
\begin{aligned}
O^{(s)} &\equiv \left[\overline{t^c_\alpha}(aP_L + bP_R)D_\beta\right] \left[\overline{U^c_\gamma}(cP_L + dP_R)E\right] \quad \epsilon^{\alpha\beta\gamma} \\
O^{(t)} &\equiv \left[\overline{t^c_\alpha}(a'P_L + b'P_R)E\right] \left[\overline{U^c_\beta}(c'P_L + d'P_R)D_\gamma\right] \epsilon^{\alpha\beta\gamma}
\end{aligned}
$$

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

Processes considered

| Decay: $t \to \overline{U}\,\overline{D}\,E^+$ (e.g. $t \to \bar{c}\bar{b}\mu^+$) | Production: $U\,D \to \bar{t}\,E^+$ (e.g. $cb \to \bar{t}\mu^+$) |
| --- | --- |
| $\rightarrow \mathcal{O}(0.1)\big/\mathcal{O}(1)$ decay per $\mathrm{fb}^{-1}$ | $\rightarrow \sigma_{\text{prod}} \gtrsim 1$ fb$\big/$10 fb (PDF dependent) |

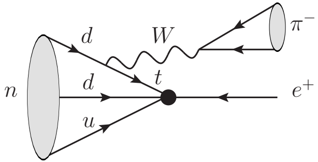
with flavours fixed, $\Lambda = 1$ TeV, unit coefficients, $\sqrt{s} = 7$ TeV$\big/$14 TeV
and $\sqrt{\hat{s}} < \Lambda$ consistency cut in production

# The minimal effective BNV model

## Indirect constraints from nucleons decays

since $O^{(s,t)}$ also contribute indirectly to nucleon decays [Hou *et al.* (2005)]

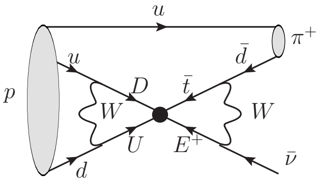
- at tree level, with $W$ emission(s):




$\rightarrow$ formidable strong constraints

less stringent for effective coupling with higher generation fermions

- at loop level:




$\rightarrow$ 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

# Outline

# Minimal Flavour Violation for BNV

The Minimal Flavour Violation (MFV) hypothesis
$\equiv$ imposing $\mathcal{L}_{\text{kin}}$ global symmetries to $\mathcal{L}_{\text{Yuk}}$ [D'Ambrosio et al. (2002)]

$\mathcal{L}_{\text{kin}} = \overline{\psi}_a \not{D} \psi^a$ is $U(N_f)$ symmetric for $\psi = q,\, l,\, u,\, d,\, e$,
so we take $G_f = \left[SU(N_f)\right]^5$ (putting aside the $U(1)_{B,L,Y,e,PC}$ factors)

and, in $\mathcal{L}_{\text{Yuk}} = [\bar{u} Y_{(u)} q]\phi + [\bar{d} Y_{(d)} q]\phi^* + [\bar{e} Y_{(e)} l]\phi^*$

$$\left( + \frac{1}{\Lambda_{(\nu)}} [\overline{l^c} Y^M_{(\nu)} l]\phi\phi \quad \text{and/or} \quad [\bar{\nu} Y^D_{(\nu)} l]\phi \right),$$

we promote the $Y_{(.)}$s to "spurion" auxiliary fields with appropriate $G_f$ transformation properties:

$$[Y_{(u)}]^u{}_q \quad [Y_{(d)}]^d{}_q \quad [Y_{(e)}]^e{}_l \quad \left( [Y^M_{(\nu)}]_{ll} \quad \text{and/or} \quad [Y^D_{(\nu)}]^\nu{}_l \right).$$

# Minimal Flavour Violation for BNV

## MFV invariant operators (without neutrino masses) [Smith (2011)]

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

Basically: 3 quarks needed for BNV and colour conservation
+ an odd number of fermions for Lorentz invariance
3 are needed for $G_f$ invariance

$\rightarrow$ minimum content of six fermions (dimension-nine):

| QQQ LLL | QQQ QQQ |
|---|---|
| $uuu\ \ ell$ | $uu\,dddd$ |
| $uuq\ \ lll$ | $u\,ddd\,qq$ |
| | $dd\,qqqq$ |

with:
- appropriate spurions and $SU(N_f)$'s $\epsilon$ tensors
- complicated explicit $SU(3)_C$, $SU(2)_L$ and Lorentz structures but all Lorentz structures reduce to scalar ones

# Minimal Flavour Violation for BNV

Adding neutrino Majorana masses [Smith (2011)]

allows (again) for dimension-six operators

since $[Y_{(e)}^\dagger Y_{(e)} Y_{(\nu)}^\dagger]^{I_1 I_2}\ [l]^{I_3}\ \epsilon_{I_1 I_2 I_3}$

$[Y_{(e)}^\dagger Y_{(e)} Y_{(\nu)}^\dagger]^{I_1 I_2}\ [Y_{(e)}^\dagger e]^{I_3}\ \epsilon_{I_1 I_2 I_3}$

are $G_f$ invariant

... but with a $m_\nu$ suppression!

indeed, considering physical eigenstates

(i.e. diagonalizing as many $Y_{(.)}$ as possible):

$$Y_{(d)} \to \lambda_d \qquad Y_{(e)} \to \lambda_e$$
$$Y_{(u)} \to \lambda_u V_{\text{CKM}} \qquad Y_{(\nu)} \to P^* \lambda_\nu P^\dagger$$

where

- $\lambda_\psi$ are real and diagonal, $= \sqrt{2} m_\psi / v$ after EWSSB
- $\lambda_\nu$ is real and diagonal, $= m_\nu \Lambda_{(\nu)} / v^2$ after EWSSB
- $P$ is the PMNS matrix

# Minimal Flavour Violation for BNV

## In the physical basis

### Six-fermion operators

- high suppression expected for first generation processes

  e.g. (di)nucleon decays, $n - \bar{n}$ oscillation

- flavour unsuppressed processes involving all three generations

  e.g. $d^{d_1} d^{d_2} d^{d_3} \epsilon_{d_1 d_2 d_3} \; [Y^\dagger_{(u)} u]^{q_1} q^{q_2} q^{q_3} \epsilon_{q_1 q_2 q_3}$

  $\rightarrow \underbrace{V_{tb}\lambda_t}_{\simeq 1} \; d_R s_R b_R \; t_R u_L s_L$

  but – $1/\Lambda^{10}$ suppression,
  – phase space suppression,
  – $\sqrt{\hat{s}} < \Lambda$ consistency cut

$$\rightarrow \quad \begin{array}{l} \mathrm{Br}(t \rightarrow 5jets) \simeq 10^{-16} \left(\dfrac{500\mathrm{GeV}}{\Lambda}\right)^{10} \\ \sigma(ud \rightarrow \bar{t} + 3jets) \simeq 10^{-6}\mathrm{fb}, \qquad \text{for } \Lambda = 500\mathrm{GeV} \end{array}$$

# Minimal Flavour Violation for BNV

## In the physical basis

### Four-fermion operators

- high suppression of first generation processes

  from $O^{(4)}$, in the *worst* case:

  $$[Y^\dagger_{(u)} Y_{(u)} q]^{q_1} [q]^{q_2} [q]^{q_3} \epsilon_{q_1 q_2 q_3} \quad [Y^\dagger_{(e)} Y_{(e)} Y^\dagger_{(\nu)}]^{l_1 l_2} [l]^{l_3} \epsilon_{l_1 l_2 l_3}$$

  $$\rightarrow \underbrace{V^\dagger_{tb} |\lambda_t|^2}_{\simeq 1} \underbrace{V_{td}}_{10^{-2}} \underbrace{|\lambda_\tau|^2}_{10^{-4}} \underbrace{[P \lambda_\nu P^T]^{\tau\mu}}_{10^{-14} \frac{\Lambda_{(\nu)}}{1\ \text{TeV}}} \quad u_L d_L s_L \nu_L$$

  leads to $p \rightarrow K^+ \nu$ of partial lifetime $> 2.3 \times 10^{33}$ yr

  $$\Longrightarrow \frac{c_6^{(4)}}{\Lambda^2} \lesssim \frac{10^{-6}}{(1\ \text{TeV})^2} \left( \frac{1\ \text{TeV}}{\Lambda_{(\nu)}} \right) \qquad \text{(naive dimensional analysis)}$$

- high suppression of processes involving all three generations, also

# Summary and conclusions

Baryon number violation:

- well motivated from a theoretical point of view
- strong experimental limits at low energies, evidence from baryogenesis

... but no measurement at TeV scales

The minimal effective BNV model:

- an effective approach, with lowest dimensional operators
- for exploring top BNV phenomenology
- without flavour theory for deriving indirect constraints

Minimal Flavour Violation for BNV:

- naturally involving second and third generations in BNV
- providing a neat correspondence between first generation BNV processes and top BNV phenomenology
- surprisingly relating small (or absent) neutrino Majorana masses and small BNV signals

... observational consequences at the LHC to be carefully examined

# Operators construction: useful relations

- $SU(2)_L$ structure:

$$\epsilon_{ij}\epsilon_{kl} - \epsilon_{ik}\epsilon_{jl} + \epsilon_{il}\epsilon_{jk} = 0$$

$$[\epsilon\boldsymbol{\tau}]_{ij} \cdot [\epsilon\boldsymbol{\tau}]_{kl} = -2\epsilon_{il}\epsilon_{jk} - \epsilon_{ij}\epsilon_{kl}$$

- Lorentz bilinears $\phi^p[C\Gamma_M^\mu]_{pq}\chi^q$
  with $\{\Gamma_M^\mu\} = \left\{\mathbb{I},\, \gamma^\mu,\, \Sigma^{\mu\mu'},\, \gamma^\mu\gamma^5,\, \gamma^5\right\} \quad (M = S, V, T, A, P)$
  satisfying $[C\Gamma_M^\mu]^T = \begin{cases} -[C\Gamma_M^\mu] & \text{for } M \in \{S, A, P\}, \\ +[C\Gamma_M^\mu] & \text{for } M \in \{V, T\}. \end{cases}$
- (Chiral) Fierz transformations [Pauli, Fierz (1937)]
  - eliminating tensors with

$$[C\Sigma^{\mu\nu}P_R]_{pq}[C\Sigma_{\mu\nu}P_L]_{rs} = 0,$$
$$[C\Sigma^{\mu\nu}P_R]_{pq}[C\Sigma_{\mu\nu}P_R]_{rs} = -4[CP_R]_{pq}[CP_R]_{rs} - 8[CP_R]_{ps}[CP_R]_{qr},$$

  - eliminating vectors with

$$[C\gamma^\mu P_R]_{pq}[C\gamma_\mu P_L]_{rs} = -2[CP_L]_{ps}[CP_R]_{qr},$$

  - keeping at most two scalars thanks to the Schouten identity

$$[CP_R]_{pq}[CP_R]_{rs} - [CP_R]_{pr}[CP_R]_{qs} + [CP_R]_{ps}[CP_R]_{qr} = 0$$

# Analytical results

Neglecting all masses but the top one

$$\sum_{\substack{\text{spins,}\\\text{colours}}} |\mathcal{M}|^2 = \frac{24}{\Lambda^4}\Big[(p_t\cdot p_D)\,(p_U\cdot p_E)\,(A+C) \\ -(p_t\cdot p_U)\,(p_D\cdot p_E)\,C \\ +(p_t\cdot p_E)\,(p_D\cdot p_U)\,(B+C)\Big]\,.$$

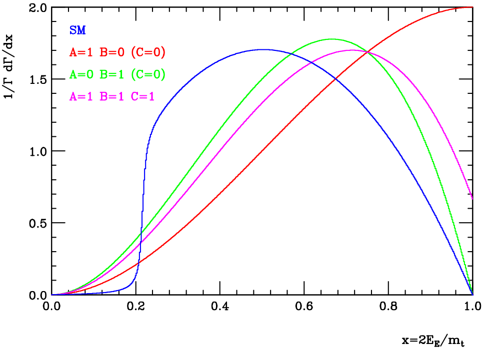
$$\text{with}\begin{cases} A\equiv\left(|a|^2+|b|^2\right)\left(|c|^2+|d|^2\right), \\ B\equiv\left(|a'|^2+|b'|^2\right)\left(|c'|^2+|d'|^2\right), \\ C\equiv\mathfrak{Re}\left\{a^*c^*a'c'+b^*d^*b'd'\right\}, \end{cases}$$

$$\Gamma_t^{\rm BNV}=\int_0^{m_t/2}\mathrm{d}E_E\,\frac{m_t^2E_E^2}{32\pi^3\Lambda^4}\left[\left(\frac{A}{3}+B+C\right)\left(1-\frac{2E_E}{m_t}\right)+\frac{A}{6}\right]=\frac{m_t^5}{192\pi^3}\frac{1}{16\Lambda^4}\left[A+B+C\right],$$

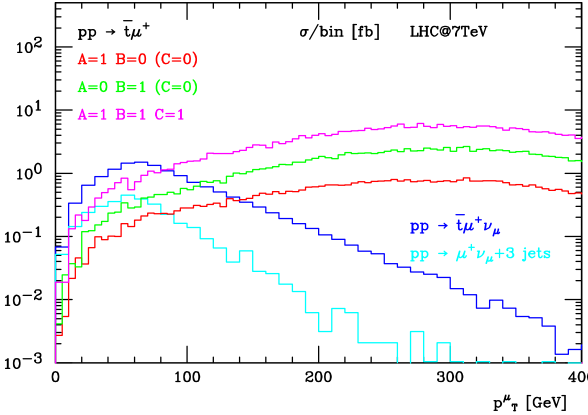
$$\hat\sigma_t^{\rm BNV}=\frac{1}{96\pi\Lambda^4}\int_{m_t^2-\hat s}^{0}\mathrm{d}\hat t\,\left[A\frac{\hat t\left(\hat t-m_t^2\right)}{\hat s^2}+B\frac{\left(\hat s-m_t^2\right)}{\hat s}+2C\frac{\hat t}{\hat s}\right]$$

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

# $t \to \overline{U}\,\overline{D}\,E^+$ vs. $t \to b\,E^+\,\nu_E$



# Charged lepton $p_T$ for $u\,d \to \mu^+\bar{t}$, $W^+$+3-jet and $\bar{t}\,W^+$




Decays: $W^+ \to \mu^+\nu_\mu$, $\quad \bar{t} \to \bar{b}\,j\,j$
Jets: $p_T > 40$ GeV, $|\eta| < 2.5$, $\Delta R_{jj} > 0.5$
Muon: $|\eta| < 2.5, \Delta R_{j\mu} > 0.5$
Backgrounds: $\not{E}_T < 30$ GeV
$W^+$+3-jet: $|m_{jjj} - m_t| < 40$ GeV, $b$ tag
$\sqrt{\hat{s}} < \Lambda = 1$ TeV