Baryon number violation in the top sector

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Based on 2409.00218, in collaboration with
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Introduction

Baryon Number Violation (BNV) never directly observed

However essential to understand our Universe talk by Susic

Numerous recent BNV works beyond proton decay searches, eg talk by Heeck

Many recent works on BSM mainly coupled to top, eg see talk by Marzocca

What if BNV occurs due to new physics mainly coupled to the top quark?

Baryon Number Violation in tops: direct searches

- BNV in the SMEFT starts with dimension-6 operators
- Direct searches can test potential BNV in the top-quark sector

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Search for Baryon Number Violation in Top Quark Production and Decay Using Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.*[*]
(CMS Collaboration)

(Received 28 February 2024; accepted 8 May 2024; published 13 June 2024)

TABLE II. Expected and observed 95% CL upper limits on the BNV effective couplings and top quark BNV branching fractions.

Vertex	C_x	C_x/Λ^2 [TeV^{-2}] Exp.	C_x/Λ^2 [TeV^{-2}] Obs.	$\mathcal{B}_x$ [10^{-6}] Exp.	$\mathcal{B}_x$ [10^{-6}] Obs.
$teud$	s	0.055	0.048	0.015	0.011
	t	0.031	0.027	0.005	0.003
$t\mu ud$	s	0.046	0.036	0.010	0.006
	t	0.025	0.020	0.003	0.002

- Impressive precision, significantly improving previous results

- Could we expect a nonzero result in a general BSM scenario?

Baryon Number Violation in the LEFT

- Very stringent bounds on BNV from nucleon decay searches (SK)

Channel	Limit [10^{30} years]
$p \to \pi^0 e^+$	2.4×10^4
$p \to \pi^0 \mu^+$	1.6×10^4
$p \to \pi^+ \bar{\nu}$	3.9×10^2
$p \to K^0 e^+$	1.0×10^3
$p \to K^0 \mu^+$	4.5×10^3
$p \to K^+ \bar{\nu}$	5.9×10^3
$n \to \pi^- e^+$	5.3×10^3
$n \to \pi^- \mu^+$	3.5×10^3
$n \to \pi^0 \bar{\nu}$	1.1×10^3
$n \to K^0 \bar{\nu}$	1.3×10^2

- Energy scale of the process $\Lambda \lesssim 1\,\mathrm{GeV}$
- Described by the LEFT, where there are no top-quark operators
- However the presence of top-quark operators at the LHC scale, as any other high-energy effect, do leave a measurable imprint at low energies

Top operators in the SMEFT

- Gauge invariance connects processes with and without tops.
  For example, SMEFT operator is not $\varepsilon_{\alpha\beta\gamma}\, d_R^\alpha C u_R^\beta\, t_L^\gamma C e_L$ but

$$\varepsilon_{\alpha\beta\gamma}\, d_R^\alpha C u_R^\beta \left(t_L^\gamma C e_L - b_L^\gamma C \nu_L \right)$$

- Operator basis Alonso et al. '14

$$\begin{aligned}
\mathcal{Q}^{duq\ell}_{prst} &= \varepsilon_{\alpha\beta\gamma}\, \varepsilon_{ij}\, (d_p^\alpha\ C\, u_r^\beta)\, (q_s^{i\gamma}\ C\, \ell_t^j)\ , \\
\mathcal{Q}^{qque}_{prst} &= \varepsilon_{\alpha\beta\gamma}\, \varepsilon_{ij}\, (q_p^{i\alpha}\ C\, q_r^{j\beta})\, (u_s^\gamma\ C\, e_t)\ , \\
\mathcal{Q}^{qqq\ell}_{prst} &= \varepsilon_{\alpha\beta\gamma}\, \varepsilon_{il}\, \varepsilon_{jk}\, (q_p^{i\alpha}\ C\, q_r^{j\beta})\, (q_s^{k\gamma}\ C\, \ell_t^l)\ , \\
\mathcal{Q}^{duue}_{prst} &= \varepsilon_{\alpha\beta\gamma}\, (d_p^\alpha\ C\, u_r^\beta)\, (u_s^\gamma\ C\, e_t)\ .
\end{aligned}$$

- Nucleon decays mediated by light-quark operators in mass basis,
  misaligned with respect to flavor basis, $u_L = U_L^u u_L'$, $d_L = U_L^d d_L'$.

$$\mathcal{Q}^{duq\ell}_{113\ell} \supset \varepsilon_{\alpha\beta\gamma}\ U^u_{R,11} U^d_{R,11} \left({d'}_R^{1\alpha}\, C\, {u'}_R^{1\beta} \right) \cdot \left(U^u_{L,31}\, {u'}_L^{1\gamma} C e_{L,\ell} - U^d_{L,31}\, {d'}_L^{1\gamma} C \nu_{L,\ell} \right)$$

- Cannot simultaneously take $u_L = u_L'$ and $d_L = d_L'$

Top operators in the SMEFT: IR logs

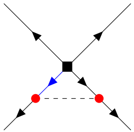
- Try to only generate operators with $t_R = t'_R$
- No light-quark operators generated at tree-level
- Yet pure SM interactions systematically convert top quarks into light quarks
- Issue already seen at the level of Yukawa matrix

$$Y_u^{\rm diag}(\Lambda_{\rm UV}) \to Y_u^{\rm not\ diag}(\Lambda_{\rm EW}) \Rightarrow t_R \to -\frac{3}{2}\frac{\epsilon_\pi\, y_t\, y_u}{y_t^2 - y_u^2} \ln\frac{\Lambda_{\rm UV}^2}{\Lambda_{\rm EW}^2} \sum_{k=d,s,b} V_{tk}\, y_k^2\, V_{uk}^*\, u'_R$$

$\epsilon_\pi \equiv 1/(4\pi)^2$. Let us take $Y_u^{\rm diag}(\Lambda_{\rm EW})$ basis

Top operators in the SMEFT: IR logs

- Yet pure SM interactions systematically convert tops into light quarks
- If a top-quark operator is generated at a UV scale, light-quark operators are generated at the EW one via SMEFT β functions.



Alonso et al '14

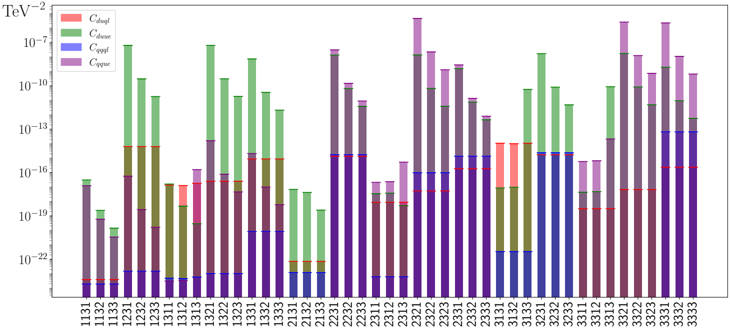
- For example

$$C^{qqq\ell}_{131\ell}(\Lambda_{\rm EW}) \propto C^{duq\ell}_{131\ell}(\Lambda_{\rm UV})\,\epsilon_\pi \ln \frac{\Lambda^2_{\rm UV}}{\Lambda^2_{\rm EW}} + \cdots$$

- Suppressed by loop and Yukawa factors
- Let us quantify this

Indirect bounds on top operators

- Use SMEFT-LEFT state-of-art, implemented in `DsixTools`
- Assume one operator is induced at a time at LHC scale, $\Lambda = 1\,\mathrm{TeV}$
- Bounds on corresponding Wilson from nucleon decays



- Typically $10-20$ orders of magnitude more stringent than direct bounds
- Can we qualitatively understand hierarchy of bars?

Parametric suppression of dominant effect

Keep only up to leading logarithm, L

$C^{duq\ell}$		
$1\,1\,3\,\ell$	V_{32}	$p \to K^+\bar{\nu}$
$2\,1\,3\,\ell$	V_{31}	$p \to K^+\bar{\nu}$
$i\,a\,3\,\ell$	$(Y_d)_{1i}\,(Y_u)_{aa}\,V_{a1}\,V_{32}\,L$	$p \to K^+\bar{\nu}$
$i\,3\,2\,\ell$	$(Y_d)_{1i}\,(Y_u)_{33}\,V_{31}\,V_{22}\,L$	$p \to K^+\bar{\nu}$
$1\,3\,1\,\ell$	$(Y_d)_{11}\,(Y_u)_{33}\,V_{11}\,V_{32}\,L$	$p \to K^+\bar{\nu}$
$a\,3\,1\,\ell$	$(Y_d)_{2a}\,(Y_u)_{33}\,V_{22}\,V_{31}\,L$	$p \to K^+\bar{\nu}$
$3\,1\,3\,\ell\,^*$	$(Y_d)_{23}\,(Y_d)_{32}\,V_{21}\,L$	$p \to K^+\bar{\nu}$

C^{qque}		
$1\,3\,1\,1$	V_{31}	$p \to \pi^0 e^+$
$1\,3\,1\,2$	V_{31}	$p \to \pi^0 \mu^+$
$i\,3\,1\,3$	$(Y_e)_{33}\,(Y_d)_{32}\,V_{i1}\,L$	$p \to K^+\bar{\nu}$
$a\,3\,1\,1$	$(Y_d)_{13}\,(Y_d)_{33}\,V_{a1}\,L$	$p \to \pi^0 e^+$
$a\,3\,1\,2$	$(Y_d)_{13}\,(Y_d)_{33}\,V_{a1}\,L$	$p \to \pi^0 \mu^+$
$1\,3\,2\,\ell$	$(Y_e)_{\ell\ell}\,(Y_u)_{22}\,V_{22}\,V_{31}\,L$	$p \to K^+\bar{\nu}$
$1\,i\,3\,\ell$	$(Y_e)_{\ell\ell}\,(Y_u)_{33}\,V_{i1}\,V_{32}\,L$	$p \to K^+\bar{\nu}$

$C^{qqq\ell}$		
$i\,1\,3\,\ell$	$V_{i1}\,V_{32}$	$p \to K^+\bar{\nu}$
$1\,3\,1\,\ell$	$V_{11}\,V_{32}$	$p \to K^+\bar{\nu}$
$2\,3\,1\,\ell$	$V_{22}\,V_{31}$	$p \to K^+\bar{\nu}$
$1\,2\,3\,\ell$	$V_{21}\,V_{32}$	$p \to K^+\bar{\nu}$
$1\,3\,2\,\ell$	$V_{31}\,V_{22}$	$p \to K^+\bar{\nu}$
$1\,3\,3\,\ell$	$g^2\,V_{31}\,V_{32}\,L$	$p \to K^+\bar{\nu}$
$a\,3\,3\,\ell$	$(Y_d)_{13}\,(Y_d)_{33}\,V_{a2}\,V_{31}\,L$	$p \to K^+\bar{\nu}$
$2\,2\,3\,\ell$	$(Y_d)_{23}\,(Y_d)_{13}\,V_{21}\,V_{32}\,L$	$p \to K^+\bar{\nu}$
$3\,2\,3\,\ell$	$(Y_d)_{33}\,(Y_d)_{13}\,V_{21}\,V_{32}\,L$	$p \to K^+\bar{\nu}$
$2\,3\,2\,\ell$	$(Y_d)_{33}\,(Y_d)_{13}\,V_{21}\,V_{22}\,L$	$p \to K^+\bar{\nu}$

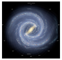
C^{duue}		
$1\,1\,3\,1$	$(Y_d)_{11}\,(Y_u)_{33}\,V_{31}\,L$	$p \to \pi^0 e^+$
$1\,1\,3\,a$	$(Y_e)_{aa}\,(Y_u)_{33}\,V_{32}\,L$	$p \to K^+\bar{\nu}$
$1\,3\,1\,1$	$(Y_d)_{11}\,(Y_u)_{33}\,V_{31}\,L$	$p \to \pi^0 e^+$
$1\,3\,1\,a$	$(Y_e)_{aa}\,(Y_u)_{33}\,V_{32}\,L$	$p \to K^+\bar{\nu}$
$2\,1\,3\,1$	$(Y_d)_{12}\,(Y_u)_{33}\,V_{31}\,L$	$p \to \pi^0 e^+$
$2\,1\,3\,a$	$(Y_e)_{aa}\,(Y_u)_{33}\,V_{31}\,L$	$p \to K^+\bar{\nu}$
$2\,3\,1\,c$	$(Y_d)_{12}\,(Y_u)_{33}\,V_{31}\,L$	$p \to \pi^0 \ell^+$
$2\,3\,1\,3$	$(Y_e)_{33}\,(Y_u)_{33}\,V_{31}\,L$	$p \to K^+\bar{\nu}$
$3\,1\,3\,c$	$(Y_d)_{13}\,(Y_u)_{33}\,V_{31}\,L$	$p \to \pi^0 \ell^+$
$3\,3\,1\,c$	$(Y_d)_{13}\,(Y_u)_{33}\,V_{31}\,L$	$p \to \pi^0 \ell^+$

Hierarchy of bars easily understood from this table

Conclusions and outlook

- EFT analysis of indirect bounds on dimension-6 BNV top-quark operators
- Typically 10 – 20 orders of magnitude more stringent than collider
- Not a theorem, but level of fine-tuning hard to realize

$$\underbrace{\mathrm{d}\Gamma_{p\to\cdots}} \sim \left|a C_{\mathrm{light}}(\Lambda_{\mathrm{UV}}) + b \ln \frac{\Lambda_{\mathrm{UV}}}{\Lambda_{\mathrm{eff}}} \underbrace{C_{\mathrm{top}}(\Lambda_{\mathrm{UV}})}\right|^2$$



- More exotic set-ups (light BSM, Phys.Rev.Lett. 120 (2018) 19, 191801, or beyond $\Delta B = \Delta L = 1$, Phys.Lett.B 721 (2013) 82-85) may be easier for colliders
- Currently exploring possible avenues involving relatively light BSM

Thank you