Bottom-up perspective on baryon number violation

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8 January 2024 — BSM in particle physics and cosmology

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based on work in collaboration with
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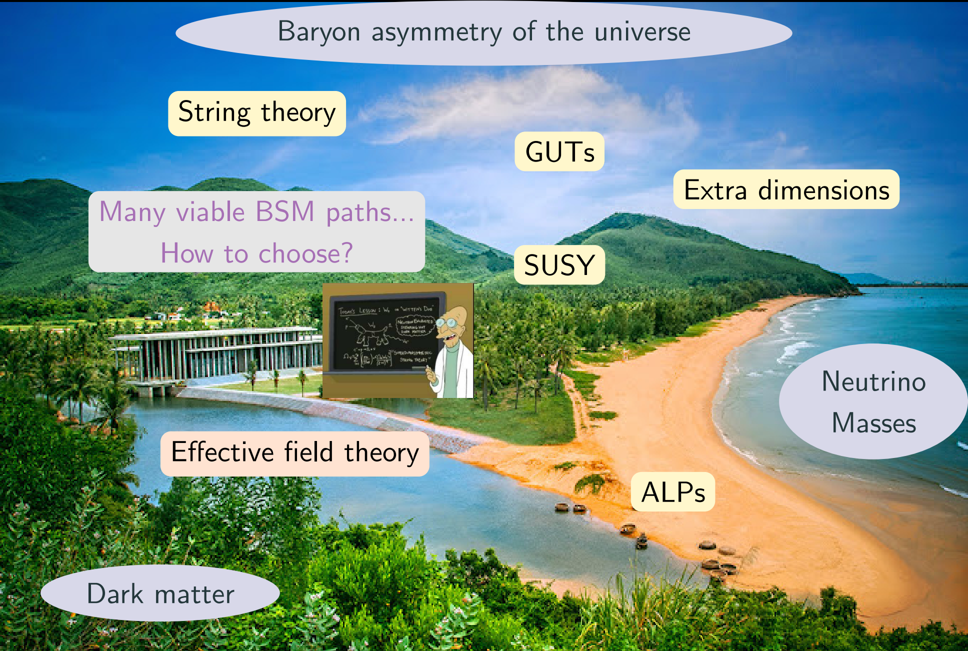
+Arnau Bas i Beneito, Arcadi Santamaria [2312.13361]

Experimental evidence for BSM physics

Experimental evidence for BSM physics and many theories



Baryon asymmetry of the universe

String theory

GUTs

Extra dimensions

Many viable BSM paths...

How to choose?

SUSY

Neutrino Masses

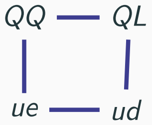
Effective field theory

ALPs

Dark matter

Standard Model as an EFT: accidental symmetries

- Lepton (L) and baryon number (B) are accidental symmetries of the renormalizable SM Lagrangian
  ($B + L$ is broken non-perturbatively)
- At dimension 5 L is violated in 2 units by the Weinberg operator
  $\Rightarrow$ Majorana neutrinos, $m_\nu \simeq \frac{v^2}{\Lambda}$, and neutrinoless double beta decay
- At dimension 6 B is violated by 1 unit by $\Delta(B - L) = 0$ operators



$\Rightarrow$ BNV nucleon decays probe highest energy scales $\Lambda \gtrsim 10^{15}$ GeV
$\Rightarrow$ B expected to be violated from top-down perspective, e.g. GUTs

Focus on
BNV nucleon decays

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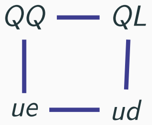

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Focus on
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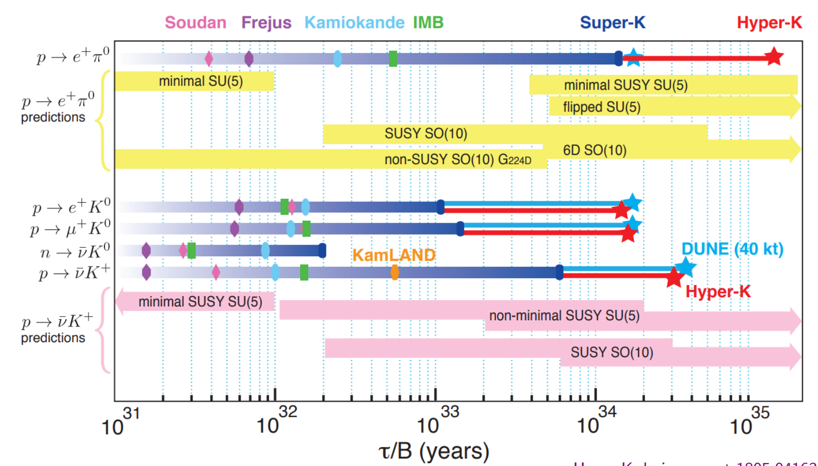
Experimental sensitivities

$$\Gamma_{p \to X} \sim \Lambda^{-4}$$

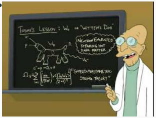


Hyper-K design report 1805.04163

BNV nucleon decay could be the next big discovery

BNV nucleon decays at tree level

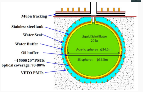
Effective field theory framework

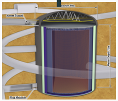


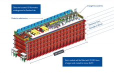
Λ — BNV

100 GeV — SM

1 GeV — hadrons







SMEFT: SU(3)$\times$SU(2)$\times$U(1)

$D6$, $\Delta(B-L)=0$: $4\psi^4$ op

$D7$, $|\Delta(B-L)|=2$: $4\psi^4 H$ and $2\psi^4 D$ op

LEFT: SU(3)$\times$U(1)$_{\rm em}$

$D6$, $\Delta(B-L)=0$: 7+2 op

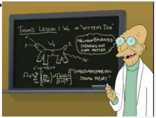
$D6$, $|\Delta(B-L)|=2$: 7 op

BχPT: U(1)$_{\rm em}$

baryons $p, n, \ldots$

mesons $\pi^\pm, \pi^0, K^\pm, \ldots$

Effective field theory framework



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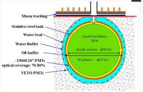
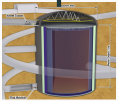
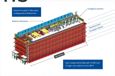
Separation of scales







Effective operators

$$\mathcal{L} = \sum_i \frac{c_i}{\Lambda^{d_i-4}} \mathcal{O}_i + \ldots$$

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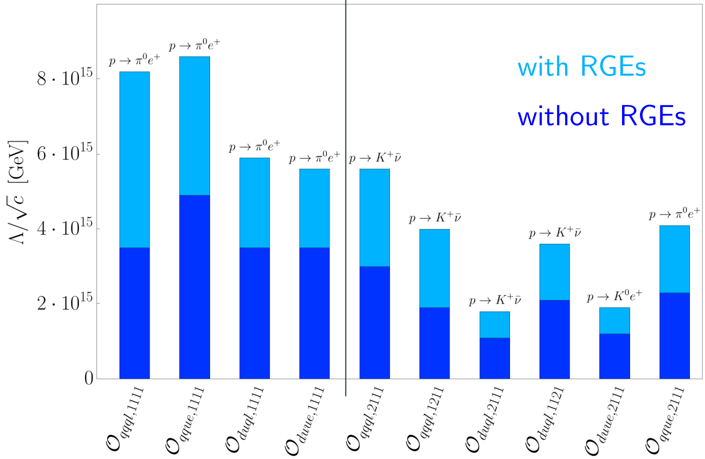
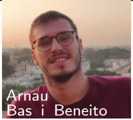
Single-operator dominance at $D = 6$: Lower limits — RGE

$\Delta(B - L) = 0$ BNV operators at $D = 6$

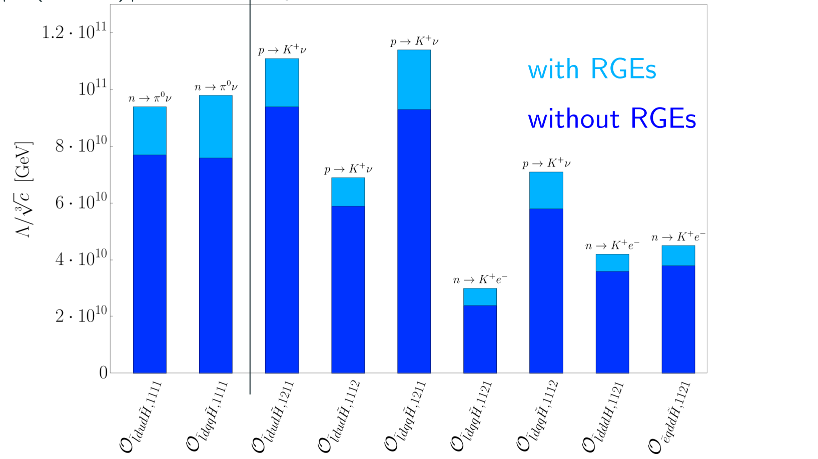




- RGE dominated by gauge interactions see Abbott, Wise PRD22 (1980) 2208
- $16\pi^2 \mu \frac{dc}{d\mu} = -4 g_3^2 c + \cdots \Rightarrow 1.3 - 2.3$ enhancement
- strongest lower limit on scale $\Lambda/\sqrt{c} \gtrsim 2 \cdot 10^{15}$ GeV

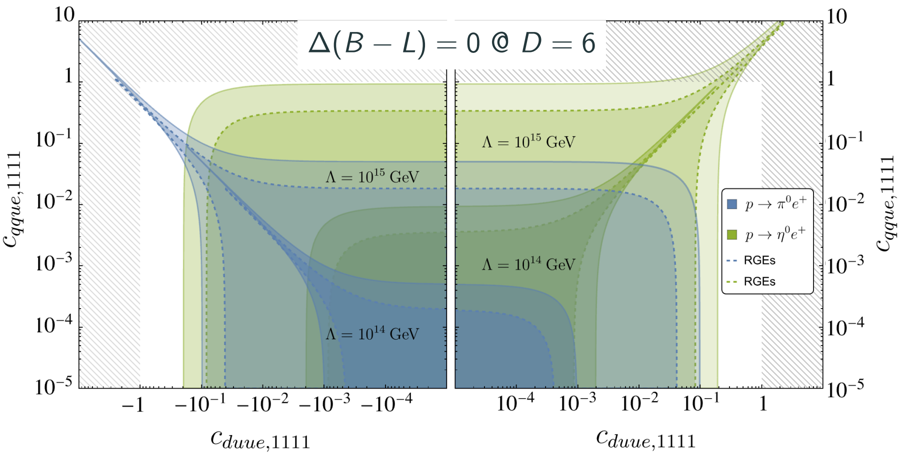
Single-operator dominance at $D = 7$: Lower limits — RGE

$|\Delta(B-L)| = 2$ BNV operators at $D = 7$



- Top quark Yukawa relevant for Higgs wave function renormalization
- $16\pi^2 \mu \frac{dc}{d\mu} = (-4g_3^2 + y_t^2)c + \cdots \Rightarrow 1.2 - 1.3$ enhancement
- strongest lower limit on scale $\Lambda/c^{3/2} \gtrsim 2 \cdot 10^{10}$ GeV

Two non-zero Wilson coefficients — complementarity



- different search channels provide complementary constraints
- there are no flat directions, even only including 2-body decays
- similar for other Wilson coefficients

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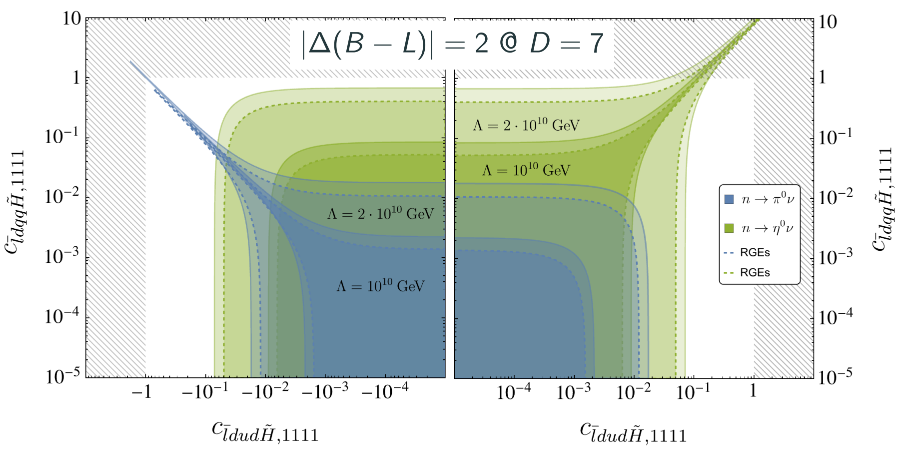

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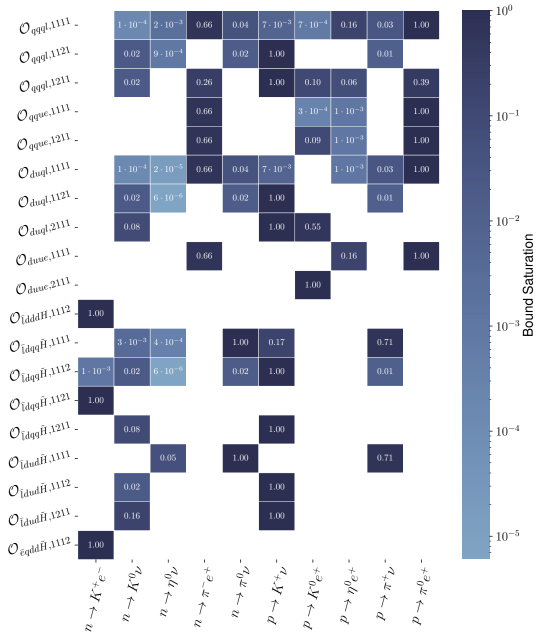
Pinning down origin of baryon number violation



Bound Saturation

$$= \frac{\Gamma_{i,\mathrm{th}}/\Gamma_{i,\mathrm{exp}}}{\Gamma_{\max,\mathrm{th}}/\Gamma_{\max,\mathrm{exp}}}$$

- $p\to\pi^0e^+$, $p\to K^+\nu$, $n\to K^+e^-$ most constraining
  $\tau_{p\to\pi^0e^+} > 24\cdot10^{33}$y,
  $\tau_{p\to K^+\nu} > 6.61\cdot10^{33}$y,
  $\tau_{n\to K^+e^-} > 0.032\cdot10^{33}$y
- some operators dominated by one decay
- several positive signals may allow to exclude/determine if single-operator dominates

Example UV model

leptoquark $\omega_2 \sim (3,1,\frac{2}{3})$ vector-like fermion $Q_1 + \bar{Q}_1^\dagger \sim (3,2,\frac{1}{6})$

D=7 operators

$$\frac{c^{ijkl}_{\bar{l}dddH}}{\Lambda^3} = \frac{y^{kl}_{dd} y^{j*}_{dQ} y^{i*}_{lQ}}{m_\omega^2 m_Q}$$

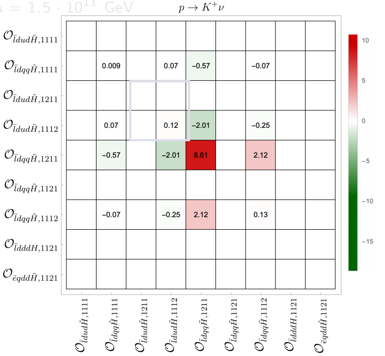
$$\frac{c^{ijkl}_{\bar{l}dud\tilde{H}}}{\Lambda^3} = 2\frac{y^{jl}_{dd} y^{k*}_{dQ} y^{i*}_{lQ}}{m_\omega^2 m_Q}$$

- y_{dd} antisymmetric

$\Rightarrow$ only kaon modes directly

- $\mathcal{O}^{1211}_{\bar{l}dddH}$: $n \to K^+ e^-$
  $\to \Lambda > 4.2 \cdot 10^{10}$ GeV
- $\mathcal{O}^{1211,1112}_{\bar{l}dud\tilde{H}}$: $p \to K^+\nu$, $n \to K^0\nu$
  $\to \Gamma(p \to K^+\nu) = 0.12 \frac{m_p^7}{\Lambda^6}(c^{1112}_{\bar{l}dud\tilde{H}})^2$
  $\to \Lambda > 5.4 \cdot 10^{10}$ GeV

$\Lambda = 1.5 \cdot 10^{11}$ GeV



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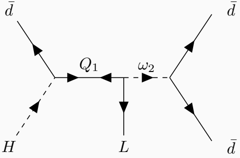

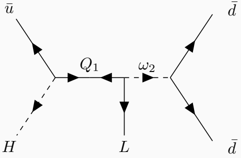

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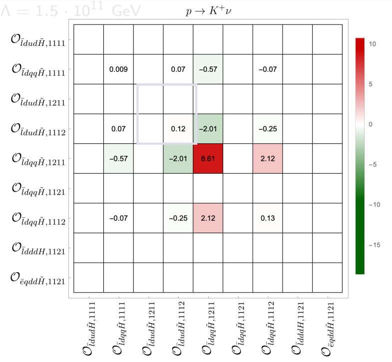

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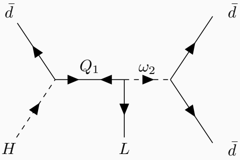

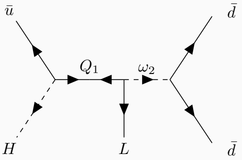

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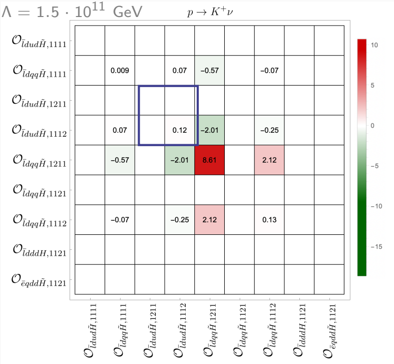

Summary of first part

- Depending on symmetries, dominant contribution from $D = 6$ operators $\Delta(B - L) = 0$ or $D = 7$ operators for $|\Delta(B - L)| = 2$

- RG corrections are important: limits on scale enhanced by $1.3 - 2.3$ $[D = 6]$ and $1.2 - 1.3$ $[D = 7]$

- It is important to search for many different decay modes.
  - Complementary constraints exclude flat directions in parameter space (explicitly demonstrated for 2-body decay modes like $p \to \pi^0 e^+, \eta e^+$).
  - Several positive signals may allow to determine origin of baryon number violation.

- Caveat: Nuclear matrix element uncertainty.

Beyond nucleon decays at tree-level

Beyond tree-level nucleon decay

What if your favourite model does not lead to BNV nucleon decay at tree level via the D=6 or D=7 operators?

Example: Pati-Salam model with $U(1)_{\rm PQ}$ 1712.04880

- no proton decay mediated by gauge bosons
- several colored scalars $(\bar{6}, 1, \frac{2}{3})$, $(8, 2, \frac{1}{2})$, $(\bar{3}, 2, -\frac{7}{6})$

$\rightarrow$ $D = 9$ operator $\mathcal{O}_{29} \equiv (\bar{e}Q)(\bar{u}Q)(\bar{d}^\dagger \bar{d}^\dagger)$ at tree level

$\rightarrow$ naively BNV nucleon decay is suppressed
$\Gamma(n \to \ell M) \sim \frac{m_p}{8\pi} \left| \frac{c_{29}}{\Lambda^5} \Lambda_{QCD}^5 \right|^2 \to \Lambda \gtrsim 10^7$ GeV

- generates $D = 7$ operator $c^{pqrs}_{\bar{e}qdd\tilde{H}} \simeq \frac{y_u^{u'}}{16\pi^2} c_{29}^{pqu'u'rs}$ at 1-loop level

$\rightarrow$ $n \to K^+ e^-$ imposes $\Lambda \gtrsim 10^{10}$ GeV

- Loop-induced nucleon decays often dominate because $\frac{\Lambda_{\rm QCD}}{\Lambda} \ll \frac{1}{16\pi^2}$

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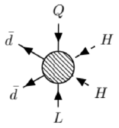
$\Rightarrow$ need predictions for loop-induced nucleon decay.

Model-independent estimates for loop-induced nucleon decay

goal: stay as model-independent as possible

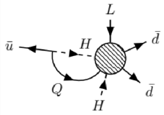
[2401.abcde]

- order of magnitude estimate is often enough
- consider tree-induced $D = 8$ and $D = 9$ BNV *types of operators* Fonseca [1907.12584] or *field strings*
- idea: estimate loop-induced $D = 6$ ($D = 7$) BNV SMEFT Wilson coefficients which are also induced in underlying UV model by closing off the tree-induced $D = 8$ ($D = 9$) operator in every possible way
- calculate BNV nucleon decay induced by the $D = 6$ and $D = 7$ operators following the standard procedure
- nuclear matrix elements using direct lattice method
  no RGE included



C_{16}^{rstu}

$L_r Q_s \bar{d}_t^\dagger \bar{d}_u^\dagger H H$



$Q_s H \to \partial \bar{u}_x^\dagger$

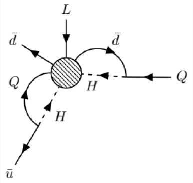
$\frac{1}{16\pi^2}[\mathbf{y}_u]^*_{xs}$

$L_r \partial \bar{u}_x^\dagger \bar{d}_t^\dagger \bar{d}_u^\dagger H$

$\bar{d}_t^\dagger H \to \partial Q_x$

$\frac{1}{16\pi^2}[\mathbf{y}_d]_{tx}$

$L_r Q_s \partial Q_x \bar{d}_u^\dagger H$



$\partial \bar{d}_u^\dagger H \to Q_y$

$\frac{1}{16\pi^2}[\mathbf{y}_d]_{uy}$

$L_r Q_y \bar{u}_x^\dagger \bar{d}_u^\dagger$

$\partial Q_s H \to \bar{u}_y^\dagger$

$\frac{1}{16\pi^2}[\mathbf{y}_u]^*_{ys}$

$L_r Q_x \bar{u}_y^\dagger \bar{d}_u^\dagger$

$\partial Q_x H \to \bar{u}_z^\dagger$

$\frac{1}{16\pi^2}[\mathbf{y}_u]^*_{zx}$

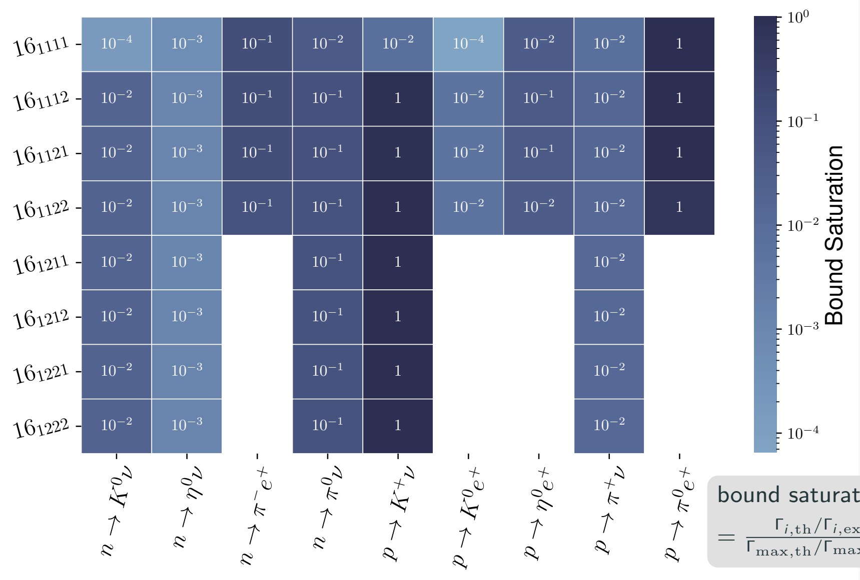
$L_r Q_s \bar{u}_z^\dagger \bar{d}_u^\dagger$

$\partial \bar{d}_u^\dagger H \to Q_w$

$\frac{1}{16\pi^2}[\mathbf{y}_d]_{uw}$

$L_r Q_s Q_x Q_w$

Example $\mathcal{O}_{16} = LQ\bar{d}^\dagger\bar{d}^\dagger HH$ — correlations



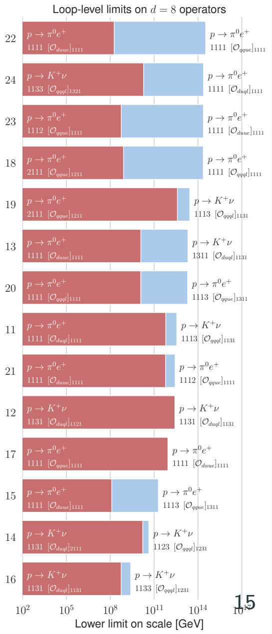
bound saturation

$$= \frac{\Gamma_{i,\mathrm{th}}/\Gamma_{i,\mathrm{exp}}}{\Gamma_{\mathrm{max,th}}/\Gamma_{\mathrm{max,exp}}}$$

Results for UV models with tree-induced $D = 8$ BNV operators

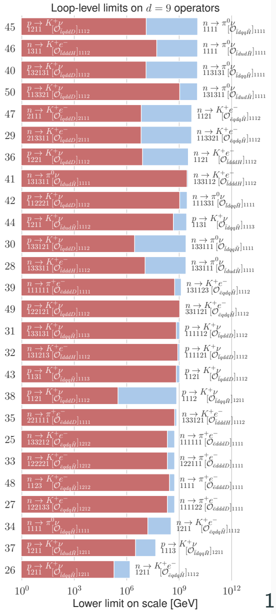
#	Operator	Matching estimate	$pqrs$	Λ [GeV]	Process
Dimension 8					
11	$DLQQ\bar{d}^\dagger H$	$C_{qqql}^{pqrs} = \frac{1}{16\pi^2} V_{ru'}^* (y_d)^{u'} C_{11}^{spqu'}$	1131	$4 \cdot 10^{12}$	$p \to K^+\nu$
12	$DL\bar{u}^\dagger \bar{d}^\dagger \bar{d}^\dagger H$	$C_{duql}^{pqrs} = \frac{1}{16\pi^2} V_{rt'}^* (y_d)^{t'} C_{12}^{sqt'p}$	1131	$3 \cdot 10^{12}$	$p \to K^+\nu$
13	$DL\bar{u}^\dagger \bar{u}^\dagger \bar{d}^\dagger H^\dagger$	$C_{duql}^{pqrs} = \frac{1}{16\pi^2} (y_u)^r C_{13}^{srqp}$	1131	$2 \cdot 10^{13}$	$p \to K^+\nu$
14	$LQ\bar{u}^\dagger \bar{u}^\dagger H^\dagger H^\dagger$	$C_{qqql}^{pqrs} = (\frac{1}{16\pi^2})^2 (y_u)^q (y_u)^r C_{14}^{spqr}$	1231	$4 \cdot 10^{10}$	$p \to K^+\nu$
15	$\bar{e}^\dagger QQ\bar{d}^\dagger HH$	$C_{qque}^{pqrs} = (\frac{1}{16\pi^2})^2 V_{pu'}^* (y_d)^{u'} (y_u)^p C_{15}^{qrsu'}$	1311	$2 \cdot 10^{11}$	$p \to \pi^0 e^+$
16	$LQ\bar{d}^\dagger \bar{d}^\dagger HH$	$C_{qqql}^{pqrs} = (\frac{1}{16\pi^2})^2 V_{qt'}^* V_{ru'}^* (y_d)^{t'} (y_d)^{u'} C_{16}^{spt'u'}$	1231	$2 \cdot 10^{9}$	$p \to K^+\nu$
17	$D\bar{e}^\dagger Q\bar{u}^\dagger \bar{u}^\dagger H^\dagger$	$C_{duue}^{pqrs} = \frac{1}{16\pi^2} V_{s'p}^* (y_d)^p C_{17}^{ss'qr}$	1111	$9 \cdot 10^{11}$	$p \to \pi^0 e^+$
18	$LQQQHH^\dagger$	$C_{qqql}^{pqrs} = \left(\frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2}\right) C_{18}^{spqr}$	1111	$2 \cdot 10^{14}$	$p \to \pi^0 e^+$
19	$DLQQ\bar{u}^\dagger H^\dagger$	$C_{qqql}^{pqrs} = \frac{1}{16\pi^2} (y_u)^r C_{19}^{spqr}$	1131	$3 \cdot 10^{13}$	$p \to K^+\nu$
20	$D\bar{e}^\dagger QQQH$	$C_{qque}^{pqrs} = \frac{1}{16\pi^2} (y_u)^p C_{20}^{qrsp}$	1311	$2 \cdot 10^{13}$	$p \to \pi^0 e^+$
21	$D\bar{e}^\dagger Q\bar{u}^\dagger \bar{d}^\dagger H$	$C_{qque}^{pqrs} = \frac{1}{16\pi^2} V_{su'}^* (y_d)^{u'} C_{21}^{qrpu'}$	1111	$3 \cdot 10^{12}$	$p \to \pi^0 e^+$
22	$\bar{e}^\dagger QQ\bar{u}^\dagger HH^\dagger$	$C_{qque}^{pqrs} = \left(\frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2}\right) C_{22}^{qrsp}$	1111	$3 \cdot 10^{14}$	$p \to \pi^0 e^+$
23	$\bar{e}^\dagger \bar{u}^\dagger \bar{u}^\dagger \bar{d}^\dagger HH^\dagger$	$C_{duue}^{pqrs} = \left(\frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2}\right) C_{23}^{sqrp}$	1111	$2 \cdot 10^{14}$	$p \to \pi^0 e^+$
24	$LQ\bar{u}^\dagger \bar{d}^\dagger HH^\dagger$	$C_{duql}^{pqrs} = \left(\frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2}\right) C_{24}^{srqp}$	1111	$2 \cdot 10^{14}$	$p \to \pi^0 e^+$

- blue most stringent limit
- red least constraining $D = 6$ operator
- results will be publicly available as pandas DataFrames, including intermediate steps in matching



Results for UV models with tree-induced $D = 9$ BNV operators

#	Operator	Matching estimate	$pqrs$	Λ [GeV]	Process
Dimension 9					
25	$\bar e^\dagger \bar e^\dagger \bar e \bar d \bar d \bar d$	$C^{pqrs}_{\bar e dddD} = \frac{1}{16\pi^2} \bar C_{25}^{r'pr'qrs}$	1111	$5 \cdot 10^8$	$n \to \pi^+ e^-$
26	$\bar e^\dagger Q^\dagger Q^\dagger Q^\dagger HHH$	$C^{pqrs}_{\bar e qdd\tilde H} = (\frac{1}{16\pi^2})^2 V_{s'r} V_{t's} (y_d)^r (y_d)^s \bar C_{26}^{ps't'q}$	1112	$2 \cdot 10^6$	$n \to K^+ e^-$
27	$\bar e^\dagger \bar d \bar d \bar d \bar d \bar d^\dagger$	$C^{pqrs}_{\bar e dddD} = \frac{1}{16\pi^2} \bar C_{27}^{pqrsw'w'}$	1111	$5 \cdot 10^8$	$n \to \pi^+ e^-$
28	$LL\bar e \bar u \bar d \bar d$	$C^{pqrs}_{\bar l dud\tilde H} = \frac{1}{16\pi^2} (y_e)^{t'} \bar C_{28}^{pt't'rqs}$	1111	$2 \cdot 10^9$	$n \to \pi^0 \nu$
29	$\bar e^\dagger Q^\dagger Q^\dagger \bar u^\dagger \bar d \bar d$	$C^{pqrs}_{\bar e qdd\tilde H} = \frac{1}{16\pi^2} (y_u)^{u'} \bar C_{29}^{pqu'u'rs}$	1112	$5 \cdot 10^9$	$n \to K^+ e^-$
30	$LL\bar e Q^\dagger Q^\dagger \bar d$	$C^{pqrs}_{\bar l dqq\tilde H} = \frac{1}{16\pi^2} (y_e)^{t'} \bar C_{30}^{t'pt'rsq}$	1111	$2 \cdot 10^9$	$n \to \pi^0 \nu$
31	$LLL^\dagger Q^\dagger \bar d \bar d$	$C^{pqrs}_{\bar l qdDd} = \frac{1}{16\pi^2} \bar C_{31}^{t'pt'qrs}$	1112	$1 \cdot 10^9$	$p \to K^+ \nu$
32	$LQ^\dagger \bar d \bar d \bar d \bar d^\dagger$	$C^{pqrs}_{\bar l qdDd} = \frac{1}{16\pi^2} \bar C_{32}^{pqw'rsw'}$	1112	$1 \cdot 10^9$	$p \to K^+ \nu$
33	$\bar e^\dagger \bar u \bar u^\dagger \bar d \bar d \bar d$	$C^{pqrs}_{\bar e dddD} = \frac{1}{16\pi^2} \bar C_{33}^{pt't'qrs}$	1111	$5 \cdot 10^8$	$n \to \pi^+ e^-$
34	$D\bar e^\dagger Q^\dagger Q^\dagger \bar d HH$	$C^{pqrs}_{\bar e qdd\tilde H} = \frac{1}{16\pi^2} V_{s's} (y_d)^s \bar C_{34}^{ps'qr}$	1112	$3 \cdot 10^8$	$n \to K^+ e^-$
35	$LL^\dagger \bar e^\dagger \bar d \bar d \bar d$	$C^{pqrs}_{\bar l dddH} = \frac{1}{16\pi^2} (y_e)^{t'} \bar C_{35}^{pt't'qrs}$	1112	$7 \cdot 10^8$	$n \to K^+ e^-$
36	$L\bar d \bar d \bar d H^\dagger H^\dagger H$	$C^{pqrs}_{\bar l dddH} = \left(\frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2}\right) \bar C_{36}^{pqrs}$	1112	$3 \cdot 10^9$	$n \to K^+ e^-$
37	$LQ^\dagger Q^\dagger \bar u HHH$	$C^{pqrs}_{\bar l dqq\tilde H} = (\frac{1}{16\pi^2})^2 V_{u'q} (y_d)^q (y_u)^{u'} \bar C_{37}^{prsu'}$	1211	$5 \cdot 10^7$	$p \to K^+ \nu$
38	$DLQ^\dagger Q^\dagger Q^\dagger HH$	$C^{pqrs}_{\bar l dqq\tilde H} = \frac{1}{16\pi^2} V_{s'q} (y_d)^q \bar C_{38}^{ps'rs}$	1211	$7 \cdot 10^8$	$p \to K^+ \nu$
39	$\bar e^\dagger Q Q^\dagger \bar d \bar d \bar d$	$C^{pqrs}_{\bar e qdd\tilde H} = \frac{1}{16\pi^2} V_{s'u'} (y_d)^{u'} \bar C_{39}^{ps'qu'rs}$	1112	$1 \cdot 10^9$	$n \to K^+ e^-$
40	$LQ^\dagger Q^\dagger Q^\dagger \bar u^\dagger \bar d$	$C^{pqrs}_{\bar l dqq\tilde H} = \frac{1}{16\pi^2} (y_u)^{v'} \bar C_{40}^{pv'rsv'q}$	1111	$1 \cdot 10^{10}$	$n \to \pi^0 \nu$
41	$LQ\bar u \bar d \bar d \bar d$	$C^{pqrs}_{\bar l dddH} = \frac{1}{16\pi^2} (y_u)^{t'} \bar C_{41}^{pt't'qrs}$	1112	$3 \cdot 10^9$	$n \to K^+ e^-$
42	$LQ^\dagger Q^\dagger Q \bar d \bar d$	$C^{pqrs}_{\bar l dqq\tilde H} = \frac{1}{16\pi^2} V_{u'v'} (y_d)^{v'} \bar C_{42}^{prsu'v'q}$	1111	$3 \cdot 10^9$	$n \to \pi^0 \nu$
43	$DLQ^\dagger \bar d \bar d HH^\dagger$	$C^{pqrs}_{\bar l qdDd} = \left(\frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2}\right) \bar C_{43}^{pqrs}$	1112	$1 \cdot 10^9$	$p \to K^+ \nu$
44	$DLQ^\dagger \bar u \bar d HH$	$C^{pqrs}_{\bar l dqq\tilde H} = \frac{1}{16\pi^2} (y_u)^s \bar C_{44}^{prsq}$	1113	$3 \cdot 10^9$	$p \to K^+ \nu$
45	$LQ^\dagger Q^\dagger \bar d HHH^\dagger$	$C^{pqrs}_{\bar l dqq\tilde H} = \left(\frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2}\right) \bar C_{45}^{prsq}$	1111	$1 \cdot 10^{10}$	$n \to \pi^0 \nu$
46	$L\bar u \bar d \bar d HHH^\dagger$	$C^{pqrs}_{\bar l dud\tilde H} = \left(\frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2}\right) \bar C_{46}^{prqs}$	1111	$1 \cdot 10^{10}$	$n \to \pi^0 \nu$
47	$\bar e^\dagger Q^\dagger \bar d \bar d HHH^\dagger$	$C^{pqrs}_{\bar e qdd\tilde H} = \left(\frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2}\right) \bar C_{47}^{pqrs}$	1112	$5 \cdot 10^9$	$n \to K^+ e^-$
48	$D\bar e^\dagger \bar d \bar d \bar d HH^\dagger$	$C^{pqrs}_{\bar e dddD} = \left(\frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2}\right) \bar C_{48}^{pqrs}$	1111	$5 \cdot 10^8$	$n \to \pi^+ e^-$
49	$L\bar e \bar e^\dagger Q^\dagger \bar d \bar d$	$C^{pqrs}_{\bar e qdd\tilde H} = \frac{1}{16\pi^2} (y_e)^{s'} \bar C_{49}^{s's'pqrs}$	1112	$1 \cdot 10^9$	$n \to K^+ e^-$
50	$LQ^\dagger \bar u \bar u^\dagger \bar d \bar d$	$C^{pqrs}_{\bar l dud\tilde H} = \frac{1}{16\pi^2} (y_u)^{u'} \bar C_{50}^{pu'ru'qs}$	1111	$1 \cdot 10^{10}$	$n \to \pi^0 \nu$



Conclusions

Take-away messages

- accidental sym's B (and L) expected to be broken
  BNV well motivated from SMEFT, broken at $D \geq 6$

- RG corrections important: limits on scale enhanced by $1.3 - 2.3$ $[D = 6]$ and $1.2 - 1.3$ $[D = 7]$

- information from BNV decay modes is complementary: flat directions excluded, may allow to determine origin

- results for BNV nucleon decays available up to $D \leq 9$

We look forward to
improved experimental sensitivities
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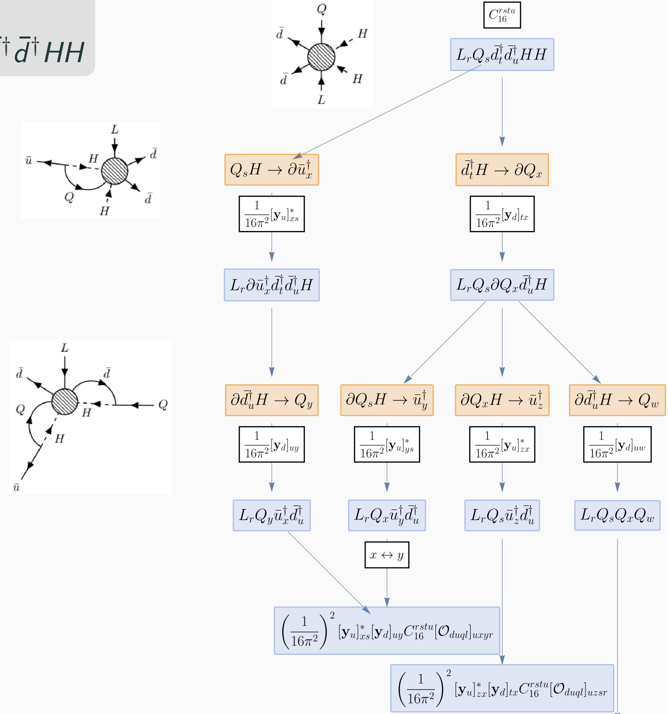
Backup slides

Example

$\mathcal{O}_{16} = LQ\bar{d}^\dagger \bar{d}^\dagger HH$



BχPT vs lattice