Baryon Number Violation via Majorana Neutrinos

Early Universe, LHC, Deep Underground

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Brookhaven Forum, 7 Oct 2015

Hooman Davoudiasl, **Y.Z.**, PRD92 (2015) 1, 016005, arXiv:1504.07244

Outline

Simple & New framework

connect neutrino masses to origin of cosmic baryon asymmetry

$\not{B}$ effective operators of right-handed neutrinos

Offers distinct LHC signatures

Prospects for nucleon decay

Neutrino mass

Our point of departure:

$$|\Delta m_A^2| \simeq 2.35 \times 10^{-3}\,\mathrm{eV}^2$$

Neutrinos being massive is a fact.

$$|\Delta m_\odot^2| \simeq 7.58 \times 10^{-5}\,\mathrm{eV}^2$$

Clear evidence of physics beyond SM.

If stick to SM particle content, neutrino mass may arise from dimension 5 operator, or higher.

$$\frac{(LH)^2}{\Lambda} \qquad \Rightarrow \Lambda \gtrsim 10^{14}\,\mathrm{GeV}$$

Consequence of Majorana mass: lepton number violation.

Seesaw Mechanism

In this talk, I assume RHNs exist, and type-I seesaw at work.

$$\mathcal{L} = \bar{N} i \partial\!\!\!/ N - M_N N^2 - Y_\nu \bar{N} L H$$

After EWSB, general mass matrix

$$\begin{pmatrix} 0 & Y_\nu v \\ Y_\nu^T v & M_N \end{pmatrix} \qquad \Rightarrow \frac{Y_\nu^2}{M_N} = \frac{1}{\Lambda}$$

An important point: M_N scale not fixed

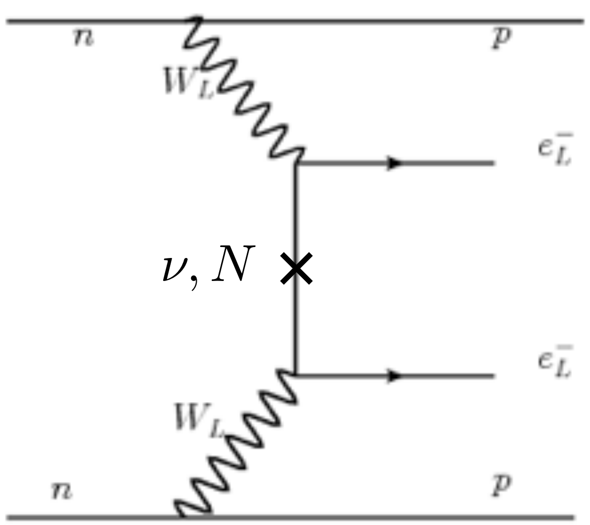
I will consider RHN near TeV scale, Yukawa~$10^{-6.}$

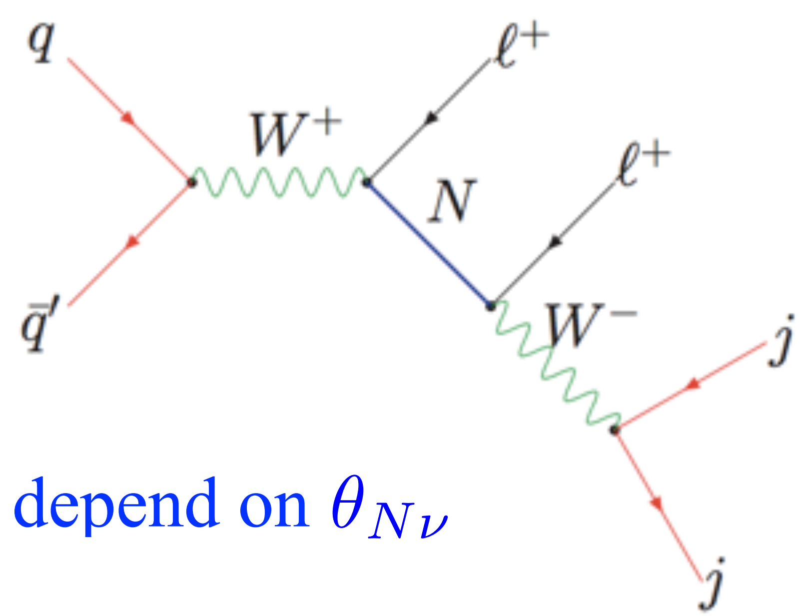
- More tests in low energy and collider experiments.

Weak-TeV scale Seesaw

Majorana neutrino mass usually means violating lepton number.

Ways to search for LNV.





depend on $\theta_{N\nu}$

neutrinoless double beta decay

Racah; Furry, 1937

LHC and future hadron colliders

Keung, Senjanovic, 1983

RH neutrino interactions

Heavy-light neutrino mixing: natural value

$$\theta_{N\nu} \sim \sqrt{\frac{M_\nu}{M_N}} \sim 10^{-6}$$

Cross section at 13 TeV

$$\sigma_{(M_N = 100\,\mathrm{GeV})} \simeq 30\,\mathrm{pb} \times \theta_{N\nu}^2$$

This also indicates:

With natural value $\theta_{N\nu} \sim 10^{-6}$, production and decay of N via W-boson is easily overtaken by further “new physics” of N.

Davoudiasl, Y.Z., arXiv:1504.07244

New physics of RHN

In this work, we consider RHNs having higher dimensional operators.

Options:

- d=5: $\bar{N}N(H^\dagger H)$
- d=6: $[\bar{N}\gamma^\mu(1+\gamma_5)e][\bar{d}\gamma_\mu(1+\gamma_5)u]$ $\cdots\cdots$

$$\frac{\lambda_a^{ijk}}{\Lambda^2}[N_a u_i d_j d_k]_R + \frac{\kappa_a^{ilm}}{\Lambda^2}[N_a d_i]_R[Q_l Q_m]_L + \text{h.c.}$$

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BNV operators

BNV operators with SM fields (no RHNs)

Weinberg, 1979

$$\mathcal{L}_{d=6} \sim [QQ]_L[QL]_L$$
$$+[QQ]_L[ue]_R + [ud]_R[ue]_R$$
$$+[QL]_L[ud]_R$$

What we added is just similar extension involving RHNs.

$$\frac{\lambda_a^{ijk}}{\Lambda^2}[N_a u_i d_j d_k]_R + \frac{\kappa_a^{ilm}}{\Lambda^2}[N_a d_i]_R[Q_l Q_m]_L + \text{h.c.}$$

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When are they important?

Compare the two partial decay rates of RHN

$$\Gamma_{N\to 3q} = \frac{|\lambda|^2 M_N^5}{1024\pi^3\Lambda^5} \qquad \Gamma_{N\to W^+\ell^-} = 10^{-14} M_N \left(\frac{\theta_{N\nu}}{10^{-6}}\right)^2$$

For $M_N \sim$ a few hundred GeV, $\Gamma_{N\to 3q}$ dominates when

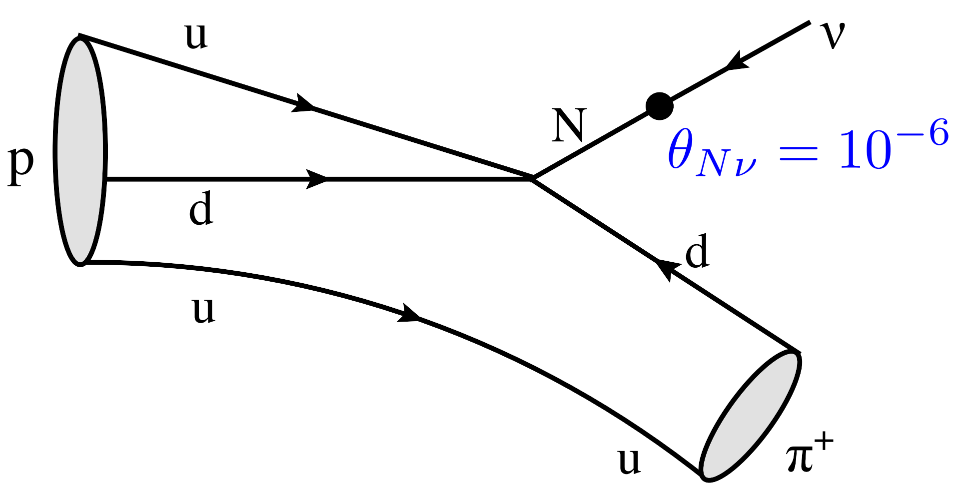
$$\Lambda/\sqrt{\lambda} \lesssim 10 - 30\,\mathrm{TeV}$$

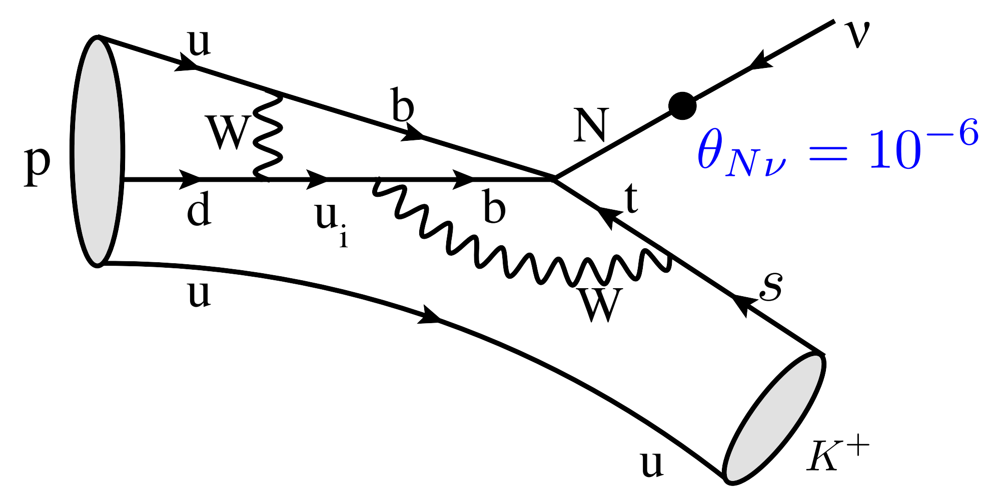
Is such low cutoff scale allowed?

What are the implications/How to test?

Nucleon constraints

Proton decay from *Nudd+LHN*





Least constrained for the operator $Ntbb$ (t, b: RH mass eigenstates)

Proton decay: W dressing $\Rightarrow \Lambda/\sqrt{\lambda} > 1.5\,\mathrm{TeV}$

(2 loop, mass insertion, CKM suppression, small $\theta_{N\nu}$)

Davoudiasl, Y.Z., arXiv:1504.07244

The Setup

Define the model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + Y_\nu \bar{N} L H + \lambda_a \frac{[\bar{N}_a^c P_R b][\bar{t}^c P_R b]}{\Lambda^2} \qquad (a = 1, 2)$$

The operator *NdQQ* is always strongly constrained.

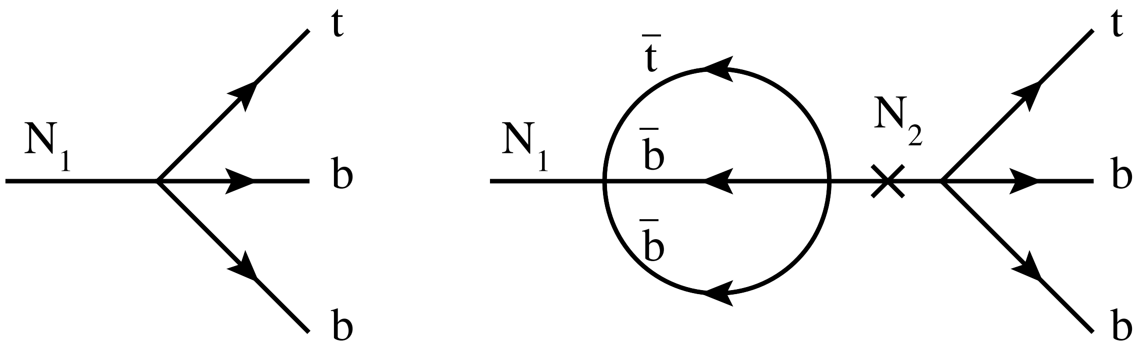
$$Q = \begin{pmatrix} u \\ V_{\rm CKM} d \end{pmatrix}$$

We assume this operator only generated at loop level.

Davoudiasl, Y.Z., arXiv:1504.07244

Baryogenesis

Tree + 2-loop diagram interference.



Final CP asymmetry

$$\varepsilon = \frac{\mathrm{Im}(\lambda_1^2 \lambda_2^{*2})}{3072\pi^3 |\lambda_1|^2} \left(\frac{M_1}{\Lambda}\right)^4 \frac{M_1 M_2}{(M_2^2 - M_1^2)}$$

If M_i is at EW scale, Λ must also be near TeV.

Take $|\lambda_i| \sim 1, \; M_1/\Lambda \sim \frac{1}{10}$ no need of degeneracy.

Davoudiasl, Y.Z., arXiv:1504.07244

Non-thermal history

If $T \sim M_N$, dangerous wash out effect, $tbb \leftrightarrow \bar{t}\bar{b}\bar{b}$

$$\frac{\Gamma_{ws}}{H} \sim \frac{T^5 M_{pl}}{\Lambda^4 M_N^2} \gg 1$$

For success baryogenesis, the universe cannot be that hot.

1) Late decay of heavy scalar (inflaton) equally into N_1 and radiation, T_{RH}~1GeV.

$$\eta \sim \varepsilon / g_* \simeq \varepsilon/100$$

2) Late decay of inflaton exclusively into N_1, then N_1 decay produces entropy.

$$\eta \sim \varepsilon \frac{T_{\rm RH}}{M_N} \simeq \varepsilon/100$$

Explicit BNV

Advantage over mechanisms using sphalerons (*e.g.* leptogenesis)

- Sphaleron process effectively stops at low temperature
- Explicit BNV interactions can still be tested today

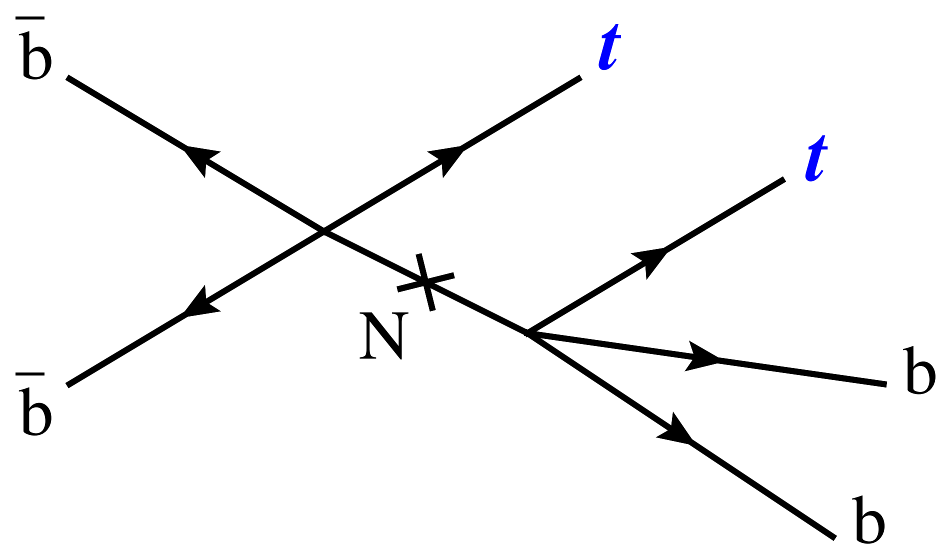
Allow direct measurement of baryon number violation today.

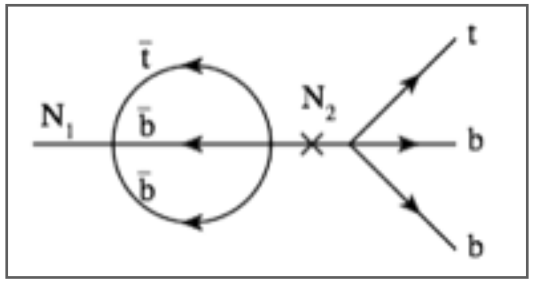
Collider signature

Special to third generation, identify B with top quark number.

Same-sign top quark events.

$$\Delta B = 2 \Leftrightarrow \Delta N_t = 2$$





Low background: top quark number is conserved by strong interactions

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Relevant cross sections

For $\Lambda/\sqrt{\lambda_1} = 1.5\,\mathrm{TeV}$, LO cross section.

$\sigma(pp \to tN \to ttbb)$				
M_a	200 GeV	500 GeV	800 GeV	1 TeV
$\sqrt{s} = 13$ TeV	0.34 fb	0.16 fb	8×10^{-2} fb	5×10^{-2} fb

Identify the sign of top quarks using their leptonic decays

Dominant background: QCD ttbar plus bbbar production, misidentify charge (rate ~10^{-4}).

CMS collaboration, arXiv: 1103.3470

At 13 TeV, NLO cross section $\sigma(pp \to t\bar{t}b\bar{b}) \sim 0.8\,\mathrm{pb}$

Bevilacquaa, M. Worek, arXiv:1403.2046

More information

For larger cutoff $\Lambda/\sqrt{\lambda} \sim 5 - 10\,\mathrm{TeV}$ and $M_N \sim 200$ GeV,

The leptonic decay of N is no longer negligible ($\theta_{N\nu} \sim 10^{-6}$).

$$\bar{b}\bar{b} \to tN, \;\; N \to W\ell$$
$$N \to tbb$$

This would help us to identify that N is the RHN for the Seesaw mechanism (same sign leptons again).

More interestingly, if this N is responsible for solar nu mass difference, N decay could result in a displaced vertex.

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Go to higher energy

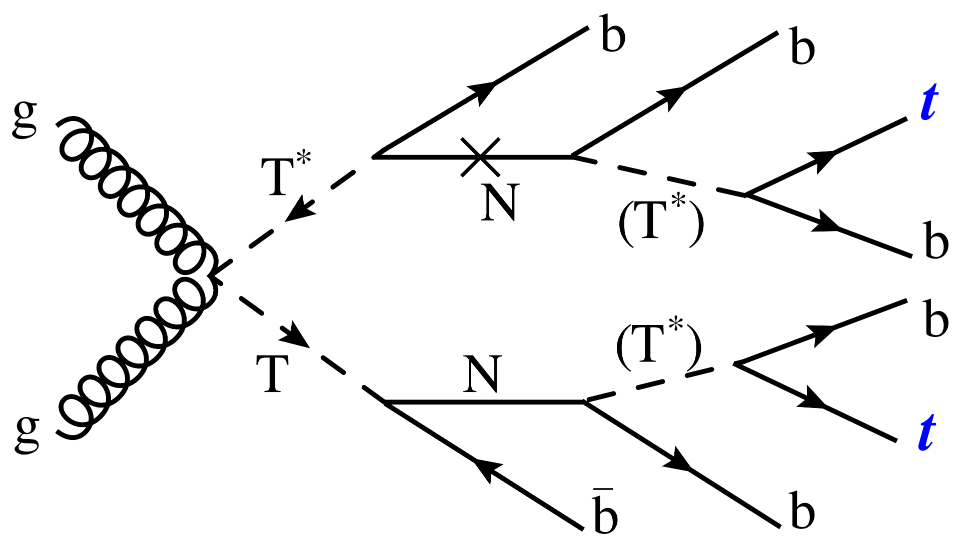
The particle responsible for TeV scale cutoff may be produced.

Simplest renormalizable model

$$\mathcal{L}_{\rm UV} = f_a\, T\, \bar{N}_a^c P_R b + f'\, T^*\, \bar{t}^c P_R b + M_T^2 |T|^2$$

T particle, color triplet, same quantum number as RH sbottom, or the triplet component of **5** of SU(5).

$\sigma(pp \to TT^*)$				
M_T	1.5 TeV	2 TeV	5 TeV	10 TeV
$\sqrt{s} = 13$ TeV	0.16 fb	0.01 fb	—	—
$\sqrt{s} = 100$ TeV	384 fb	92 fb	0.54 fb	4×10^{-3} fb



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Take home message

- The seesaw mechanism for neutrino mass is appealing. TeV seesaw models have the opportunity to be tested.

- HD operators involving RHN with TeV cutoff are allowed and generically can be relevant.

- With baryon number violating operators, we would expect new phenomenology of RHN — prepare for surprises.

- Interesting correlations between baryogenesis in early universe, collider signals, nucleon decay deep underground.

Thank you!