Baryon Number Violation and the Dark Sector

Hooman Davoudiasl

HET Group, Brookhaven National Laboratory

Based on:

H. D., Phys. Rev. Lett. 114, no. 5, 051802 (2015), [1409.4823]

H.D. and Y. Zhang, arXiv:1504.07244 [hep-ph]

Pheno 2015, University of Pittsburgh, May 4-6, 2015

- SM an impressive description of natural phenomena, yet incomplete

- Neutrino masses and dark matter (DM)

- Both can be addressed with "dark" states X uncharged under SM

- X: Heavy Majorana neutrino N for seesaw or DM state

- X may couple to "dark" forces

- X also could mediate violations of SM accidental symmetries

- We will consider B violating interactions

- *(I)* $m_X \lesssim 1$ GeV: $\dfrac{(Xudd)_R}{M^2}$ (light quarks)

- *(II)* $m_X \gtrsim 100$ GeV ($X = N$): $\dfrac{(Ntbb)_R}{\Lambda^2}$ (top and bottom)

Sample of recent works on related subjects: Cheung, Ishiwata 1304.0468; Baldes, Bell, Millar, Petraki, Volkas, 1410.0108; Monteux, Shin, 1412.5586; Dev, Mohapatra, 1504.07196

Case (I): $m_X \lesssim 1$ GeV

- "Neutron portal" $\dfrac{(Xudd)_R}{M^2}$ HD, Morrissey, Sigurdson, Tulin, 2010

- Potentially contributing to nucleon decay, *e.g.* $p \to X\pi^+$

- For $m_X \ll m_N - m_{\text{meson}}$ hard to distinguish from $p \to \pi^+ \nu$

- Focus on $(\text{few} \times 100\ \text{MeV}) \lesssim m_X \lesssim m_N$

- For $\mathcal{O}(100\ \text{MeV})$ meson momenta can use chiral perturbation theory

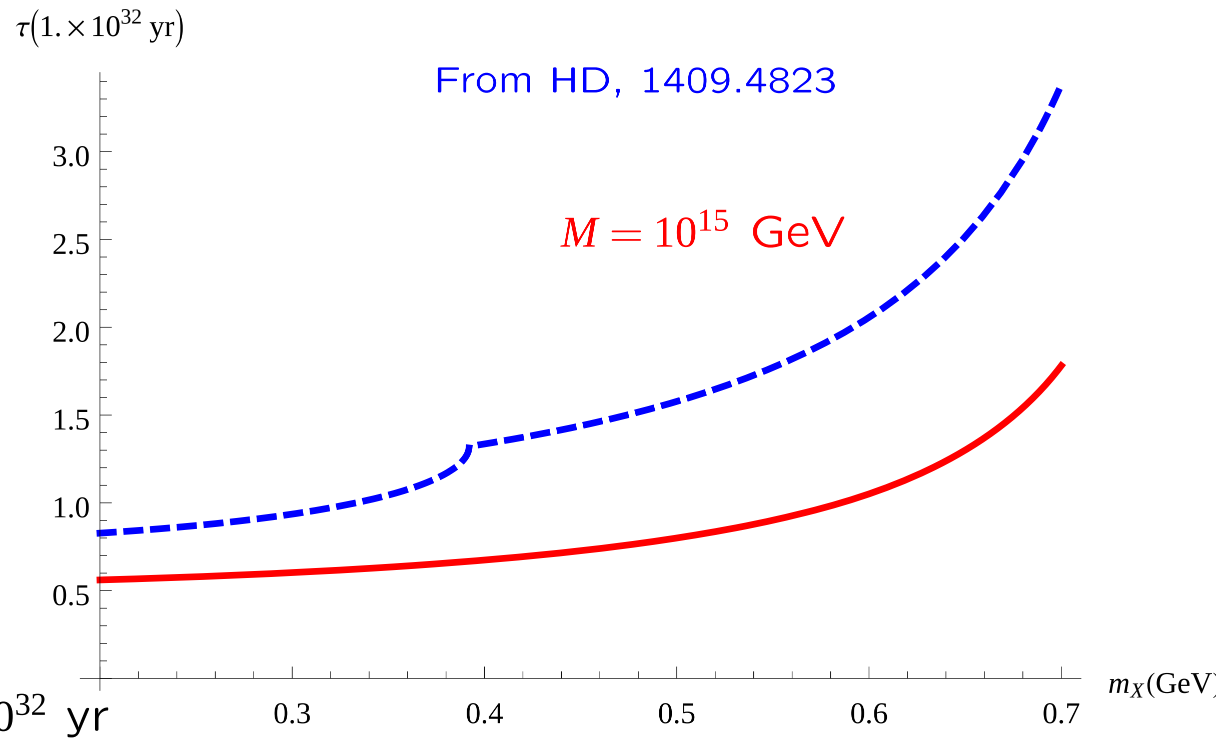
Claudson, Wise, Hall, 1982

$$\mathcal{L}_{\Delta B=0} = \frac{D+F}{2f_\pi}\left[\left(\frac{3F-D}{D+F}\right)\frac{\partial_\mu \eta}{\sqrt{3}} - \partial_\mu \pi^0\right]\bar{n}\gamma^\mu\gamma_5 n + \left(\frac{D+F}{\sqrt{2}f_\pi}\right)\partial_\mu \pi^- \bar{n}\gamma^\mu\gamma_5 p + \ldots$$

$$\mathcal{L}_{\Delta B=1} = \beta\, c_1 \overline{X^c}\left\{n_R - \frac{i}{f_\pi}\left[\frac{p_R}{\sqrt{2}}\pi^- + \frac{n_R}{2}\left(\sqrt{3}\eta - \pi^0\right)\right]\right\} \quad ; \quad (c_1 \equiv 1/M^2)$$

$D = 0.80$, $F = 0.47$, $\beta = 0.012 \pm 0.0026$ GeV^3 (lattice, *e.g.*, Aoki et al., 2008), $f_\pi \simeq 92.2$ MeV

- $p \to X\pi^+$ (solid)
- $n \to X\pi^0, \eta$ (dashed)
- Discontinuity: η threshold
- Current bounds:
- $\tau(p \to \pi^+ \bar{\nu}) > 1.6 \times 10^{31}$ yr
Soudan 2 Collaboration, 2000
- $\tau[n \to \pi^0(\eta)\bar{\nu}] > 1.12(1.58) \times 10^{32}$ yr
McGrew et al., 1999



- X final states: different kinematics, bounds not directly applicable

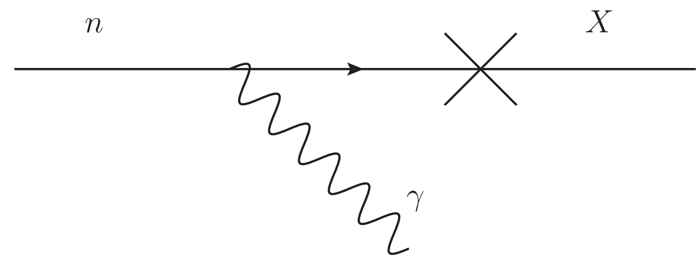
Example: $p \to \pi^+\bar{\nu}$, with $p_{\pi^+} \simeq 459$ MeV

- Simulations: π^+ exiting Fe nucleus on average lose $\sim 1/2$ their momentum
- Soudan 2 cut on π^+ momentum $p_{\pi^+} \in [140, 420]$ MeV
- $p \to X\pi^+$ with $m_X = 600$ MeV $\Rightarrow$ $p_{\pi^+} \simeq 251 < 2 \times 140$ MeV

- Neutron decay $n \to X\gamma$ possible through n magnetic moment

- For $m_N - m_X < m_\pi$, $n \to X\gamma$ dominates
- PDG: $\tau(n \to \nu\gamma) > 2.8 \times 10^{31}$ yr

$\Rightarrow M \gtrsim 10^{14}$ GeV (softer γ can affect efficiency)



- X charged under $U(1)_d$, mediated by light Z_d may yield $n \to X Z_d$

- $U(1)_d$ coupling g_d; kinetic mixing with photon or mass mixing with Z
- Possibly motivated by DM models or $g_\mu - 2$ data

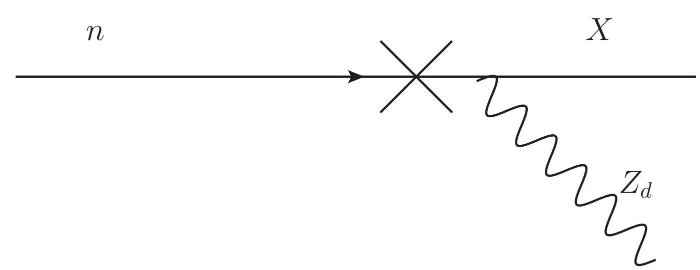
Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2009; Pospelov 2009

- $Q_d = 1$, $\alpha_d = \alpha$, $M = 10^{15}$ GeV, $m_X = 700$ MeV, and $m_{Z_d} = 50$ MeV

$\Rightarrow \tau(n \to X\pi^0) \simeq 3.4 \times 10^{32}$ yr ; $\tau(n \to X Z_d) \simeq 1.7 \times 10^{33}$ yr

- Br$(Z_d \to e^+e^-) \sim 1 \Rightarrow$ dilepton resonance

$\tau(n \to e^+e^-\nu) > 2.6 \times 10^{32}$ yr



Case (II): $m_X \gtrsim 100$ GeV

- Direct baryogenesis via Majorana neutrinos: *Dexiogenesis*

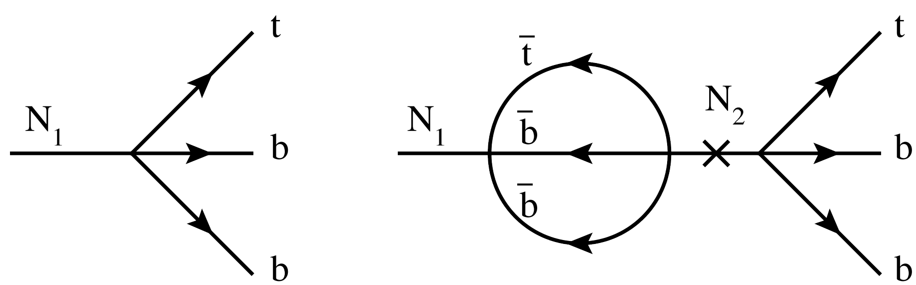
HD, Zhang, 1504.07244 (dexios: Greek for right hand)

- Seesaw mechanism with Yukawa couplings $y_N \lesssim 10^{-6}$

- Baryon number violating effective operator $\lambda_a \frac{[\overline{N_a^c} P_R b][\overline{t^c} P_R b]}{\Lambda^2}$

Minimal choice $a = 1, 2$ for realistic seesaw; $\lambda_a \in \mathbb{C}$

- Baryogenesis at 2-loop
  - Non-thermal production of N_1
  - N_1 decaying out-of-equilibrium



- Baryon asymmetry: $$\varepsilon = \frac{\mathrm{Im}(\lambda_1^2 \lambda_2^{*2})}{3072\pi^3 |\lambda_1|^2} \left(\frac{M_1}{\Lambda}\right)^4 \frac{M_1 M_2}{(M_2^2 - M_1^2)}$$ $n_B/s \sim 10^{-10}$

- $\varepsilon \gtrsim 10^{-8} \Rightarrow M_1/\Lambda \gtrsim 0.1$ ($T_{\text{reheat}} \sim 1$ GeV)

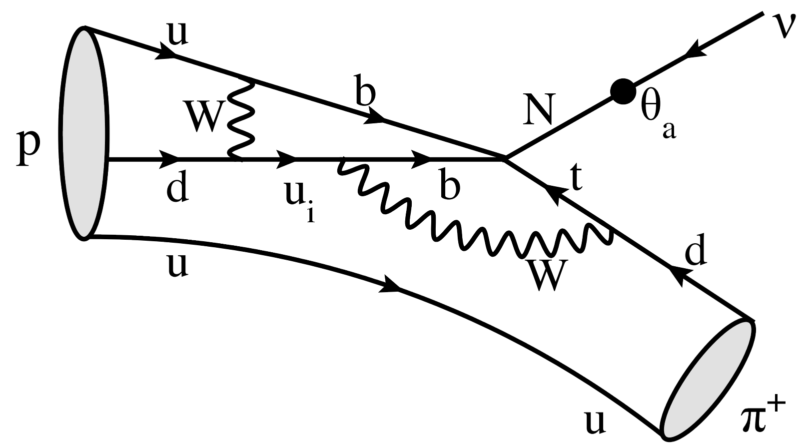
- Important constraints from nucleon decay

- $\Gamma(p \to \pi^+ \nu) = \frac{(1+g_A)^2 \alpha_h^2 m_p}{32\pi f_\pi^2} |\xi|^2$

- $g_A = 1.27$, $f_\pi = 131\,\text{MeV}$, $\alpha_h \approx -0.01125\,\text{GeV}^3$ (lattice, Aoki et al., 2006)

- $\xi \approx \frac{\Lambda_{qcd} G_F^2 m_t m_b^2 V_{td}^2 V_{ub}^* V_{tb}^*}{(16\pi^2)^2 \Lambda^2} \lambda_a \theta_a$

- θ_a: N_a-ν_L mixing



$$\tau(p \to \pi^+ \nu) \approx 2.5 \times 10^{32}\,\text{yr} \left(\frac{\Lambda/\sqrt{\lambda_a}}{1.5\,\text{TeV}}\right)^4 \left(\frac{\theta_a}{10^{-6}}\right)^{-2}$$

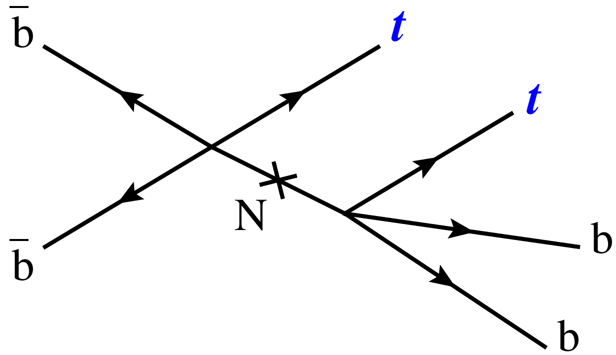
- Within reach of proposed nucleon decay experiments

- Experimental bound: $\tau(p \to \pi^+ \nu) > 1.6 \times 10^{31}\,\text{yr}$ PDG

- LHC signature: same sign tops

$\sigma(pp \to tN \to ttbb)$				
m_N	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

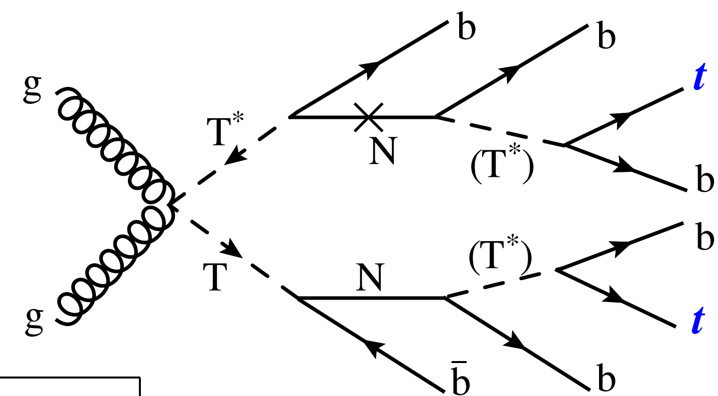
$\Lambda/\sqrt{\lambda_a} = 1.5\,\text{TeV}$



- Simple UV completion: color triplet scalar T

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

- $\lambda_a/\Lambda^2 \equiv f_a f'/M_T^2$
- Possibility: $T \in \mathbf{5}'_H$ 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

Concluding Remarks

- Dark state X (DM or Majorana N) may have B-violating interactions

- Nucleons decay into sub-GeV X could probe the dark sector
- Kinematically distinct from ν final state
- Independent of local abundance
- Does not require any appreciable X coupling to SM

- For weak scale Majorana N, direct baryogenesis: *dexiogenesis*
- Mediated by $(Ntbb)_R/\Lambda^2$ with $\Lambda \gtrsim 1$ TeV
- Distinct LHC signature: same sign tops
- Concomitant nucleon decay signals, potentially accessible to experiments
- Simple UV completion: a color triplet scalar (possible GUT connection)