Looking Beyond the Standard Model through the Neutron Portal

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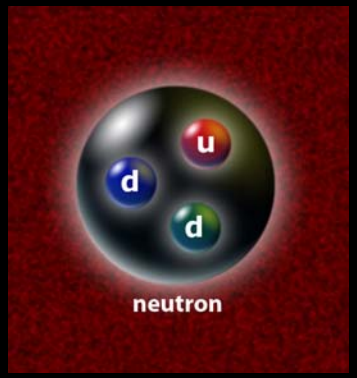


Based on:

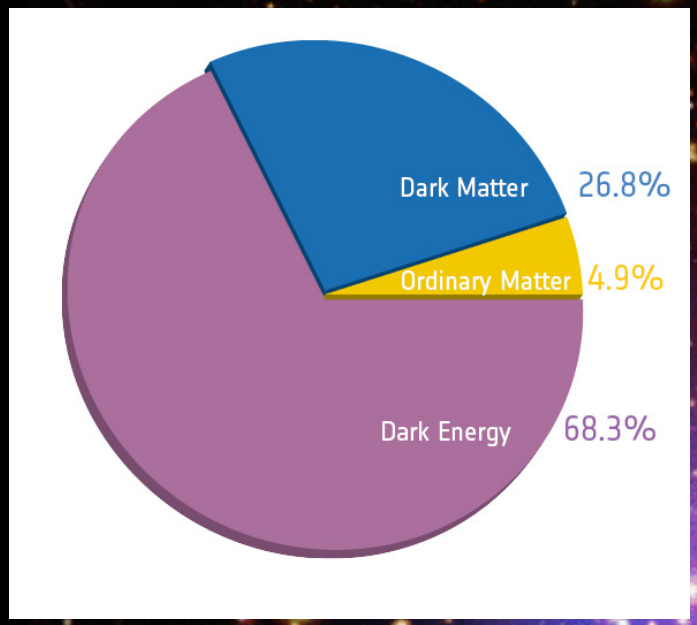
H.D. and Y. Zhang, Phys. Rev. D **92**, no. 1, 016005 (2015) [arXiv:1504.07244 [hep-ph]]

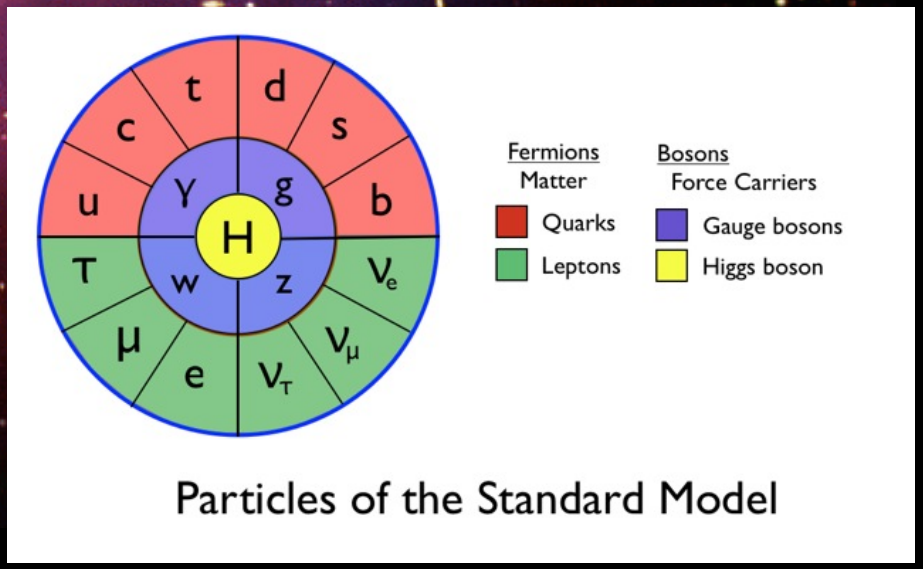
H.D., Phys. Rev. Lett. **114**, no. 5, 051802 (2015), [1409.4823]

H.D., D.E. Morrissey, K. Sigurdson and S. Tulin, Phys. Rev. Lett. **105**, 211304 (2010) [arXiv:1008.2399 [hep-ph]]; Phys. Rev. D **84**, 096008 (2011) [arXiv:1106.4320 [hep-ph]]

TRIUMF Theory Workshop, October 28-30, 2015

We need more than the Standard Model to explain natural phenomena





- Open Questions:

Neutrino masses, dark matter, baryon asymmetry, dark energy,. . .

- What are the missing ingredients?

(i) Expand the SM (*e.g.* MSSM): direct contact with new physics

- SM gauge interactions act on new states

(ii) New (dark) sectors: indirect contact through "portals"

- New states do not have SM charges; *we focus on this possibility*

- Portal: dominant "entrance" into a new sector

- Dim-4: $H^\dagger H \phi^2$ (Higgs), $F^Y_{\mu\nu} F_d^{\mu\nu}$ (Kinetic mixing), ...
- Scalar singlet ϕ; dark $U(1)_d$ force; ...

- Dim-5: $(H^\dagger H \bar{\psi}\psi)/M$ (Higgs-fermion),...
- Fermion singlet ψ; ...

- Dim-6: $\boxed{\mathbf{u^i d^j d^k X/M^2}}$ (Neutron)
- Baryon number violation via a dark state X HD, Morrissey, Sigurdson, Tulin, 2010
- X could be dark matter or a right-handed neutrino

- We will consider B violating interactions via **neutron portal**

- *(I)* $m_X \lesssim 1$ GeV (light quarks)
- *(II)* $m_X \gtrsim 100$ GeV

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

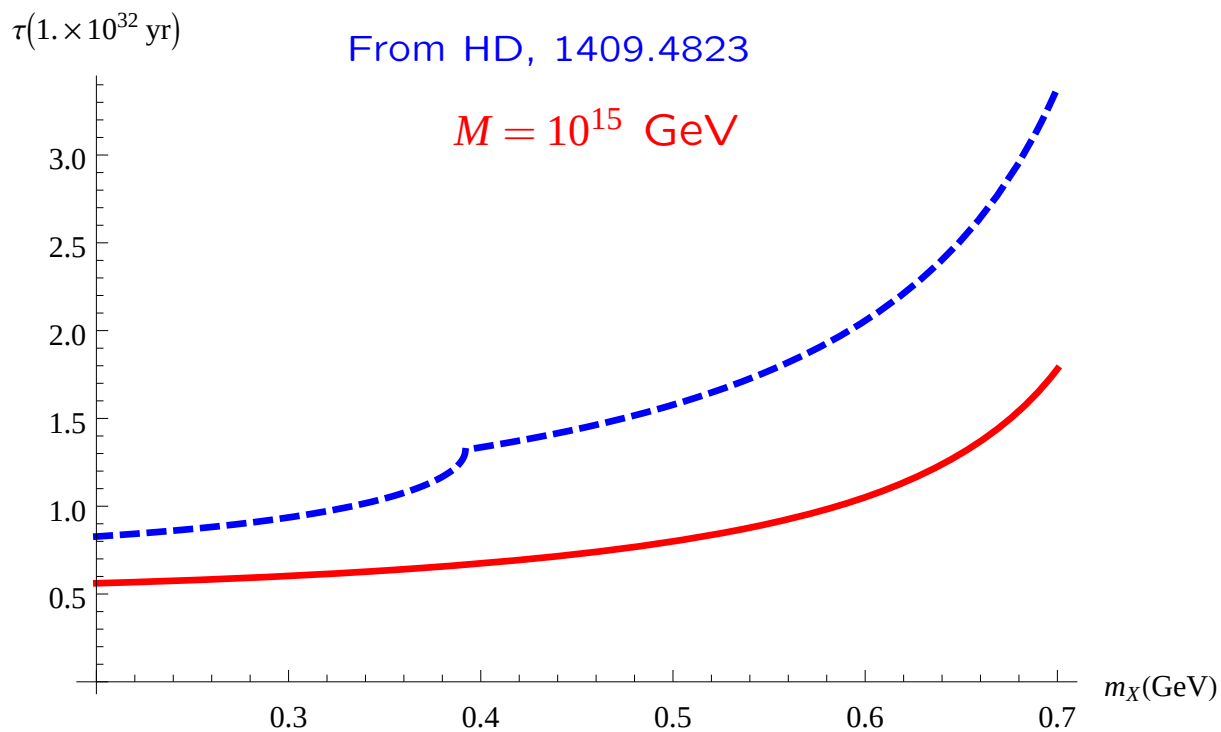
(I) $uddX/M^2$: $m_X \lesssim 1$ GeV

- Nucleon "dark" decay modes; $M \gtrsim 10^{15}$ GeV

- For $p_{\rm meson}$ of $\mathscr{O}(100\ \text{MeV})$ can use chiral perturbation theory

Claudson, Wise, Hall, 1982

- $p \to X\pi^+$ (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

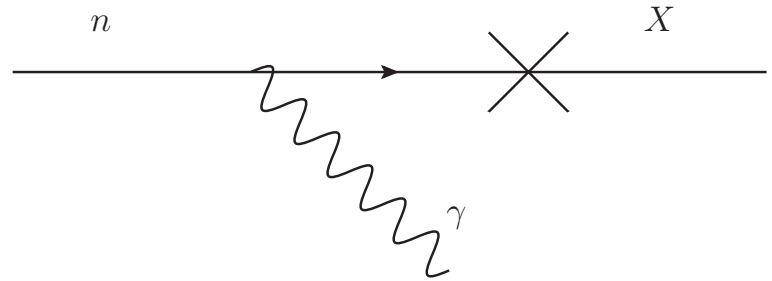
Soudan 2 Collaboration, 2000

- $\tau[n \to \pi^0(\eta)\bar{\nu}] > 1.12(1.58) \times 10^{32}$ yr McGrew et al., 1999

- 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)



★ For $m_X \gtrsim$ few $\times 100$ MeV, final states have non-standard kinematics

- Experimental handle on new modes
- Existing bounds not directly applicable

Example:

- $p \to \pi^+ \bar{\nu}$, with $p_{\pi^+} \simeq 459$ MeV
- Simulations: π^+ exiting Fe nucleus on average lose $\sim p_{\pi^+}/2$
- 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
- π^+ from Fe nucleus may not pass the cut and lead to missed events

- X maybe charged under $U(1)_d$, mediated by light Z_d

- Possible to have $n \to X Z_d$

- $U(1)_d$ coupling g_d; kinetic mixing with photon or mass mixing with Z

- May be motivated by DM models or $g_\mu - 2$ data

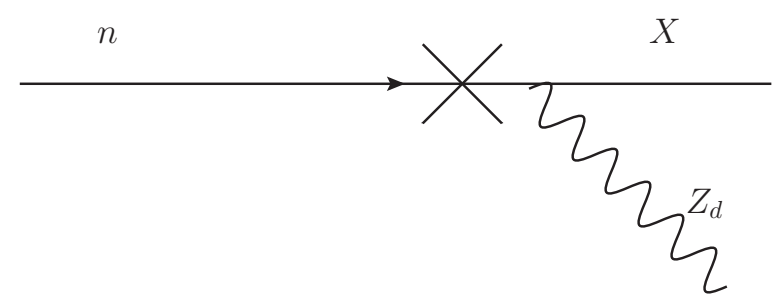
Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2009; Pospelov 2009

- $Q_d = 1$, $\alpha_d = \alpha$, $M = 10^{15}$ 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



(II) $uddX/M^2$: $m_X \gtrsim 100$ GeV

- Possibility of direct baryogenesis; $M \gtrsim 1$ TeV

(A) Dexiogenesis HD, Zhang, 2015 (dexios: Greek for right hand)

- X: Majorana neutrinos of weak scale mass

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

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

- Left-handed fields $\to$ light quarks after mass diagonalization

- Focus on $(t,b)_R$ to avoid severe nucleon decay bounds

$$\frac{\lambda_a}{\Lambda^2}[\overline{N}_a^c P_R b][\overline{t^c} P_R b]$$

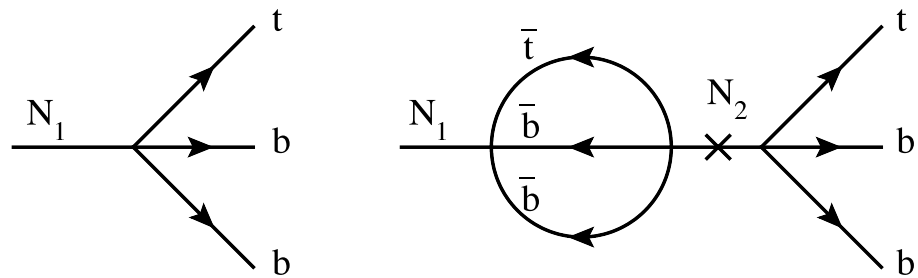
Minimal choice $a = 1,2$ for realistic seesaw; $\lambda_a \in \mathbb{C}$

- Baryogenesis at 2-loop

- Non-thermal production of N_1
- N_1 decaying out-of-equilibrium

$$\Gamma_{N_1} = \frac{|\lambda_1|^2 M_1^5}{1024\pi^3\Lambda^4} F\left(m_t^2/M_1^2\right),$$

$$F(x) = 1 - 8x - 12x^2 \log x + 8x^3 - x^4$$



- $\Gamma_{N_1 \to W\ell} \lesssim 10^{-12}\,\text{GeV}[y_N^a/10^{-6}]^2[M_1/(200\,\text{GeV})]$

$y_N^a \lesssim 10^{-6}\sqrt{M_1/(200\,\text{GeV})}$

For $M_1 \gtrsim$ few $\times$ 100 GeV and $\Lambda/\sqrt{\lambda_1} \lesssim 25$ TeV, $\Gamma_{N_1 \to W\ell}$ sub-dominant

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

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

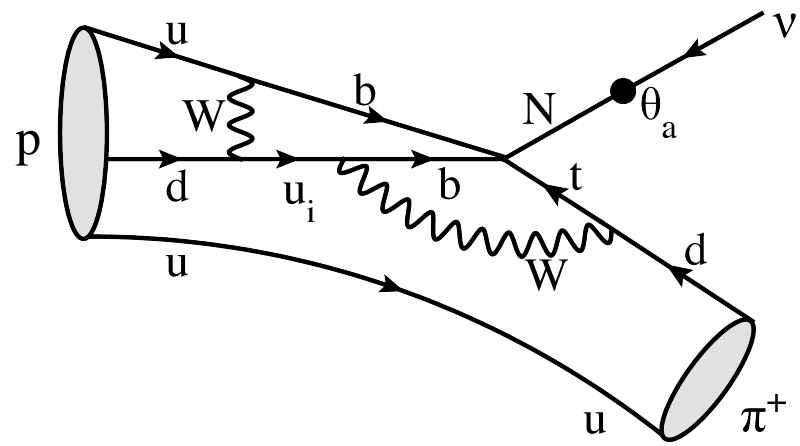
- Important constraints from nucleon decay

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

- $g_A = 1.27$, $f_\pi = 131\,\text{MeV}$, $\alpha_h \approx -0.01125\,\text{GeV}^3$ (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



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

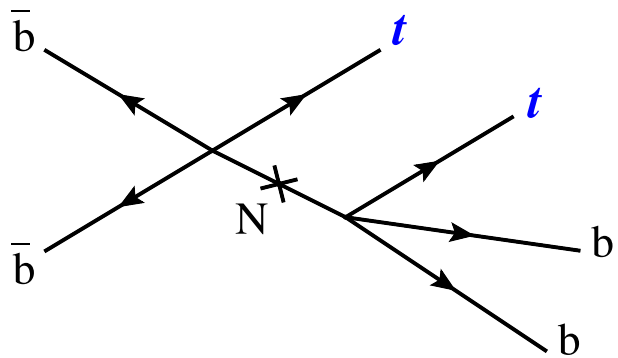
- Within reach of proposed nucleon decay experiments

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

- LHC signature: same sign tops

$\sigma(pp \to tN \to ttbb)$ for $\Lambda/\sqrt{\lambda_a} = 1.5\,\text{TeV}$				
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

Not excluded by the existing 8 TeV LHC data



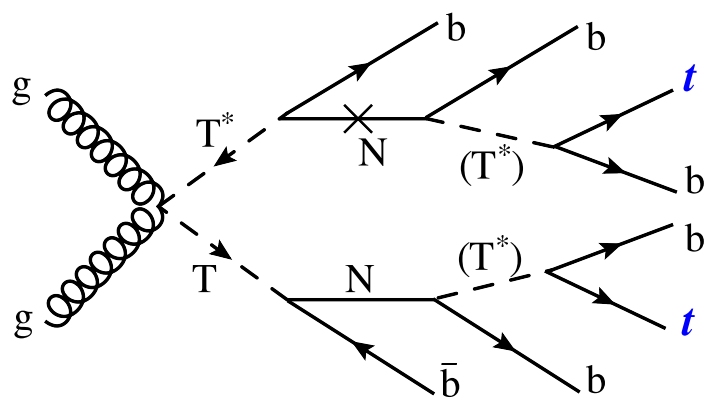
- LHC signal and baryogenesis mediated by the same operator

- Simple UV completion: color triplet scalar T

$$\mathscr{L}_{\rm UV} = f_a T \bar{N}_a^c P_R b + f' T^* \bar{t}^c P_R b + M_T^2 |T|^2 \qquad (\lambda_a/\Lambda^2 \equiv f_a f'/M_T^2)$$

- 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



- $M_1 = 200$ GeV, $\Lambda/\sqrt{\lambda_1} \gtrsim 7$ TeV: displaced vertex $c\tau_{N_1} \gtrsim 100$ μm

- UV model: $M_T \sim 1-2$ TeV and $f_a \sim f' \sim 0.2$.

- For $y_N^1 \lesssim 10^{-7}$ (solar neutrino mass difference): $\Gamma(N_1 \to W\ell) \sim \Gamma(N_1 \to tbb)$

- Leptonic decays can identify N_1 as a RH neutrino.

(B) Hylogenesis H.D., Morrissey, Sigurdson, Tulin, 2010 (hyle: Greek for matter)

- Unified scenario for visible and dark matter asymmetries
- X: Dirac fermion with baryon number; $m_X \gtrsim 1$ TeV
- Generalized global B for both visible and hidden sectors
- X_1, $\bar{X}_1$ produced non-thermally; *e.g.* reheating after inflation
- Out-of-equilibrium, CP-violating decays of X_1, $\bar{X}_1$:

(1) SM (quarks); (2) dark matter: scalar Φ and fermion Y.

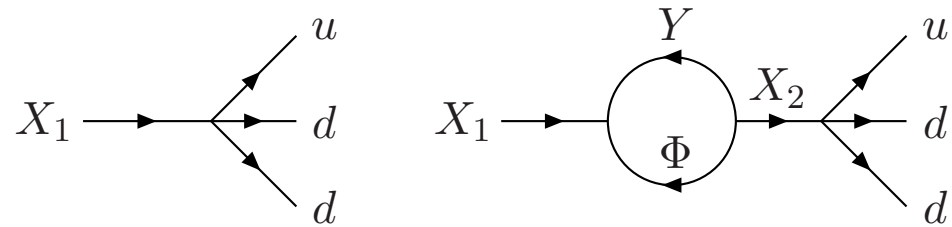
- **CPT**: $\Delta B(\mathrm{SM}) = -\Delta B(\mathrm{DM})$ with $B_X = -(B_Y + B_\Phi) = 1$.
- Matter stability: symmetries and

$$|m_Y - m_\Phi| < m_p + m_e \quad ; \quad m_p < m_Y + m_\Phi + m_e \quad ; \quad 1.7 \text{ GeV} \lesssim m_\Phi, m_Y \lesssim 2.9 \text{ GeV}$$

- SM coupled to hidden sector via the "neutron portal"

$$-\mathscr{L} \supset (\lambda_a/M^2)\,\bar{X}_a P_R d\; \bar{u}^c P_R d + \zeta_a \bar{X}_a Y^c \Phi^* + \text{h.c.}$$

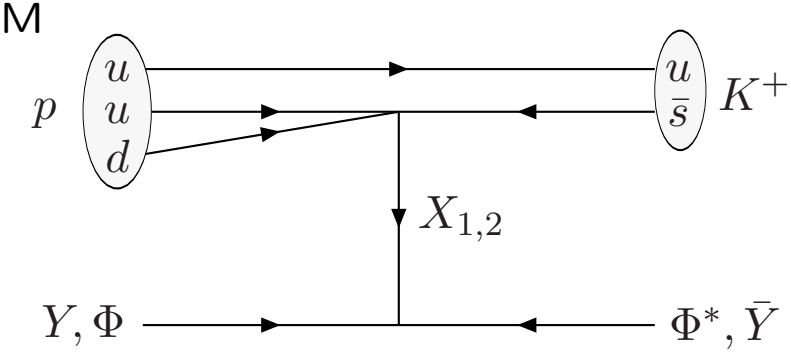
- SM baryon asymmetry from:



$$\varepsilon \simeq \frac{m_{X_1}^5 \,\mathrm{Im}[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]}{256\pi^3 |\zeta_1|^2 M^4 m_{X_2}}$$

$[\Gamma_{X_1} \simeq \Gamma(X_1 \to \bar{Y}\Phi^*);\; m_{X_2} \gg m_{X_1}]$

- A potential consequence: **Induced Nucleon Decay (IND)**
- Annihilation of nucleons in scattering from DM
- A new approach to direct detection of DM
- $YN \to \Phi^* M$ and $\Phi N \to \bar{Y} M$ (M a meson).



- Mimics standard $N \to M\nu$, but with *different kinematics*.

Decay mode	p_M^{SND} (MeV)	p_M^{IND} (MeV)
$N \to \pi$	460	800 - 1400
$N \to K$	340	680 - 1360
$N \to \eta$	310	650 - 1340

- χPT estimate, summed over $p\Phi \to K^+\overline{Y}$ and $pY \to K^+\Phi^*$:

$$(\sigma v)_{IND} = \mathscr{C}\,(10^{-39}\mathrm{cm}^3/s)\ \left|\sum_a \frac{\mathrm{TeV}^3}{m_{X_a} M^2/\lambda_a^* \zeta_a}\right|^2 \quad ; \quad 0.5 < \mathscr{C} < 1.6.$$

- Effective lifetime:

$$\tau_p = (0.3\,\mathrm{GeV cm}^{-3}/\mathrm{n_{DM}}) \times [10^{-39}\mathrm{cm}^3\mathrm{s}^{-1}/(\sigma\mathrm{v})_{\mathrm{IND}}] \simeq 10^{32}\ \mathrm{yr}.$$

- Current bound on $p \to K^+\overline{\nu}$: $\tau_p = 5.9 \times 10^{33}$ yr

Super-Kamiokande Collaboration, 2014

- The bounds are not directly applicable due to different kinematics.

- For example, because of collimated decay products of boosted final states

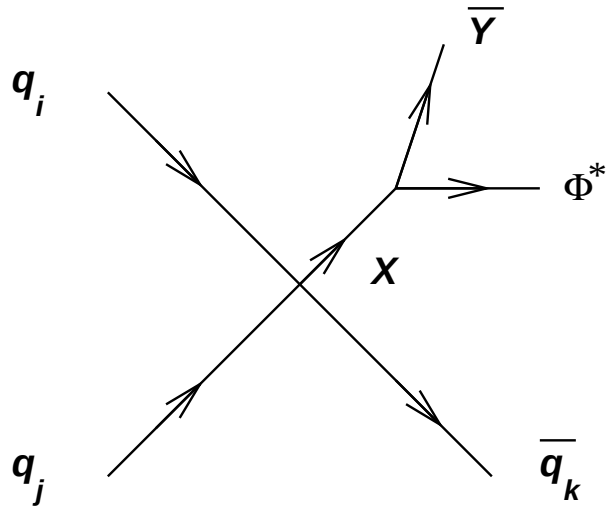
- Lattice results needed for more reliable estimates

See, *e.g.*, E. Shintani's talk at Brookhaven Forum 2015

LHC Signals of Hylogenesis

- Monojet (mono t/b) from the neutron portal: $q_i q_j \to \bar{q}_k X_{1,2}$
- Focus on the lighter $X_1 \equiv X$ and

$$-\mathscr{L} \supset \frac{\lambda}{M^2}(X_L^\dagger s_R)(u_R d_R) + \zeta X Y \Phi + H.C.,$$



- Enhancement near X pole, but $m_X \lesssim M$ (hylogenesis): loss of effective theory.
- Mimic UV physics by boson exchange with mass M and width $\Gamma = \mathscr{C} M$, $\mathscr{C} = 1/5, 1/50$.

$$\frac{\lambda}{M^2} \to \frac{\lambda}{\hat{s} - M^2 + i\sqrt{\hat{s}}\Gamma} \quad ; \quad \frac{\lambda}{M^2} \to \frac{\lambda}{\hat{t} - M^2},$$

- LHC, $\sqrt{s} = 14$ TeV; $\lambda = 1$ and $\zeta = 0.7$
- Cuts: $p_T > 500$ GeV, $|\eta| < 3.2$; efficiency factor: 85%

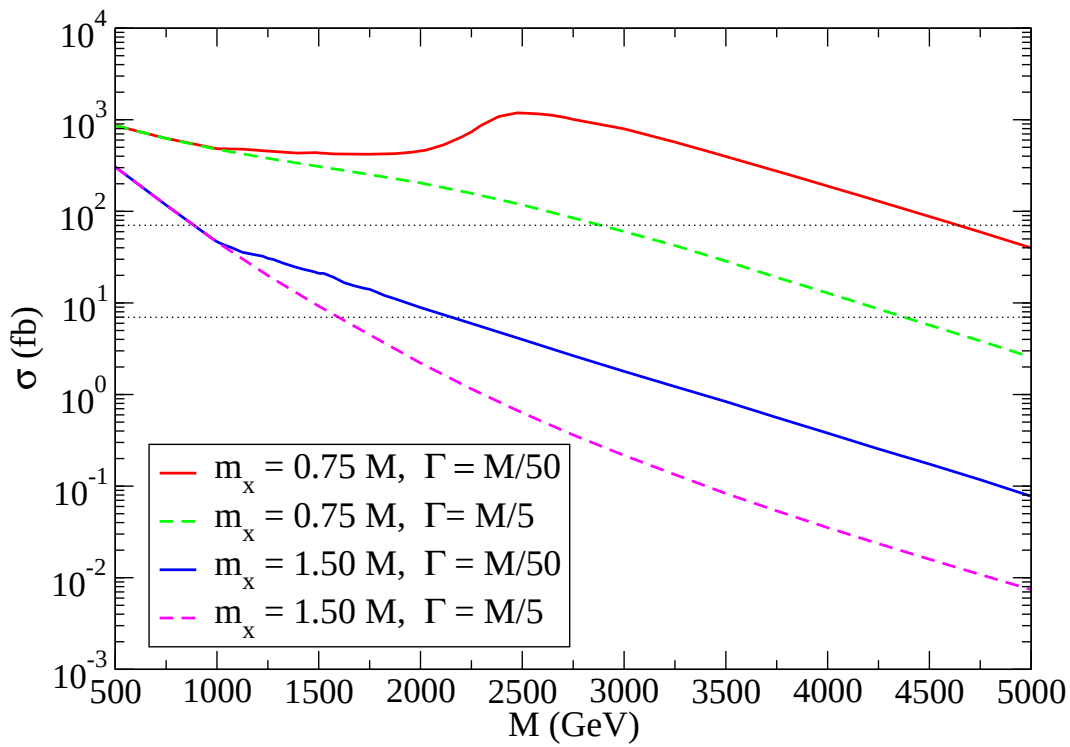
Background estimate: L. Vacavant, I. Hinchliffe, 2001
J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. Tait, H.-B. Yu, 2010

- $S/\sqrt{B} > 5$ for $\int L\,dt = 1,100$ fb^{-1} (dotted lines)

- IND, mono-jet signals correlated:
- $M \sim$ TeV

- Mono-top or -bottom signals:
- $sd \to X\bar{t}$, ...

See also:
J. Andrea, B. Fuks, F. Maltoni, 2011
J. Kamenik, J. Zupan, 2011



HD, Morrissey, Sigurdson, Tulin, 1106.4320

Concluding Remarks

- Dark state X (DM, Majorana N): B-violation via neutron portal

- Nucleon decay into sub-GeV X could probe the dark sector

- Independent of local abundance
- Does not require any appreciable X coupling to SM

- For weak scale X: direct baryogenesis

Dexiogenesis with $X = N$

- Distinct LHC signature: same sign tops
- Concomitant nucleon decay signals, potentially accessible to experiments

Hylogenesis

- Asymmetric DM
- For TeV scale cutoff, correlated signals :

(i) Potentially observable nucleon annihilation in DM scattering (IND)

(ii) LHC mono jet (t/b) signals