Neutron-Antineutron Oscillation, Low-scale Baryogenesis, Dark Matter and LHC Physics

BHUPAL DEV

Washington University in St. Louis

R. Allahverdi, BD and B. Dutta, arXiv:1711.xxxxx.

BD and R. N. Mohapatra, Phys. Rev. D **92**, 016007 (2015) [arXiv:1504.07196].

INT Workshop on Neutron-Antineutron Oscillations

University of Washington, Seattle

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Proton Decay vs $n - \bar{n}$

Selection rules for ΔB

$\boxed{\Delta B = 1}$

- Proton decay
- Induced by dimension-6 operator (also dimension-5 in SUSY).
- Amplitude $\propto \Lambda^{-2}$.
- $\tau_p \gtrsim 10^{34}$ yr implies $\Lambda \gtrsim 10^{15}$ GeV.
- Proton decay requires GUT-scale physics.

$\boxed{\Delta B = 2}$

- Di-nucleon decay and $n - \bar{n}$
- Induced by dimension-9 operator.
- Amplitude $\propto \Lambda^{-5}$.
- $\Lambda \gtrsim 100$ TeV enough to satisfy experimental constraints.
- $n - \bar{n}$ oscillation could come from a TeV-scale new physics.

$\Delta B \neq 0$ could be linked to **baryogenesis** (Sakharov).

Highlights of this Talk

A simple TeV-scale SM-extension with baryogenesis, dark matter and $n - \bar{n}$.

- Introduces $\not{B}$-interactions via TeV-scale color-triplet scalars (X_α) and a singlet Majorana fermion (ψ) that couple only to the RH quarks.
- ψ is stable, and hence, a DM candidate, if $m_\psi \simeq m_p$.
- Baryogenesis occurs via out-of-equilibrium decays of X_α.
- Common origin for both baryon and DM abundance.
- Requirements of successful baryogenesis and $\Omega_{\rm DM}/\Omega_b \approx 5$ put meaningful constraints on the model parameter space.
- Observable $n - \bar{n}$ in the allowed parameter space.
- Complementarity with monojet/monotop signals at the LHC.

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The Model

- Start with the SM gauge group and add renormalizable terms that violate baryon number.
- Gauge invariance requires introduction of new colored fields.
- A minimal setup: Iso-singlet, color-triplet scalars X_α with $Y = +4/3$.
- Allows $X_\alpha d^c d^c$ terms in the Lagrangian.
- Need at least two ($\alpha = 1, 2$) to produce baryon asymmetry from X decay.

- Total baryon asymmetry vanishes after summing over all flavors of d^c.
  [Kolb, Wolfram (NPB '80)]
- Need additional $\not{B}$ interactions.
- Introduce a SM-singlet Majorana fermion ψ (also plays the role of DM).

$$\mathcal{L} \supset \left(\lambda_{\alpha i} X^*_\alpha \psi u^c_i + \lambda'_{\alpha ij} X_\alpha d^c_i d^c_j + \frac{1}{2} m_\psi \bar{\psi}^c \psi + \text{H.c.} \right) .$$

[Allahverdi, Dutta (PRD '13); BD, Mohapatra (PRD '15); Davoudiasl, Zhang (PRD '15)]

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Dark Matter

- Integrate out X_α to obtain $\psi u_i^c d_j^c d_k^c$ interaction (assuming $m_\psi \ll m_X$).
- ψ decays to three quarks (baryons) if $m_\psi \gg$ GeV.
- Also $\psi \to p + e^- + \bar{\nu}_e$ if $m_\psi > m_p + m_e$.
- Absolutely stable for $m_\psi < m_p + m_e$ (no discrete symmetry required).
- In addition, need $m_p > m_\psi + m_e$ to avoid $p \to \psi + e^+ + \nu_e$.
- So the viable scenario for ψ to be the DM candidate is (see also A. Nelson's talk)

$$m_p - m_e \leq m_\psi \leq m_p + m_e \, .$$

- ψ cannot give mass to light neutrinos through $H\psi L$ term, because this with $X\psi u^c$ and Xd^cd^c terms will induce the dimension-7 operator $HLu^cd^cd^c$ for rapid proton decay.
- **Stability of DM is linked to the stability of proton.**

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DM Relic Density

- For $m_\psi \approx m_p$, only annihilation channel is $\psi\psi \to u^c u^c$.

$$\langle \sigma_{\rm ann} v \rangle \sim \frac{|\lambda_{\alpha 1}|^4 m_\psi^2}{8\pi m_X^4} \, .$$

- For $m_X \sim \mathcal{O}$(1 TeV), even $\lambda \sim \mathcal{O}(1)$ gives $\langle \sigma_{\rm ann} v \rangle \ll 3 \times 10^{-26}~{\rm cm^3 s^{-1}}$.
- Thermal overproduction of ψ (as expected). [Lee, Weinberg (PRL '77)]

- Need a non-thermal mechanism to obtain the correct relic density.
- Late decay of a scalar (moduli) field ϕ with a low reheating temperature $T_R \leq$ GeV. [Moroi, Randall (NPB '00); Allahverdi, Dutta, Sinha (PRD '10)]

$$\frac{n_\psi}{s} = Y_\phi {\rm Br}_{\phi \to \psi} \, ,$$

where $Y_\phi = \frac{3T_R}{4m_\phi}$ is the entropy dilution due to the ϕ decay.

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Baryogenesis

- Via direct decays of $X_\alpha \to \psi u_i^c, d_i^c d_j^c$.
- Independent of sphaleron processes.
- Example of post-sphaleron baryogenesis. [Babu, Mohapatra, Nasri (PRL ’06)]
- For complex $\lambda_{\alpha i}$ or $\lambda'_{\alpha ij}$, interference of tree and one-loop contributions produces a non-zero CP asymmetry.
- In principle, either self-energy or vertex diagrams or both could contribute.
- In the non-thermal scenario, final baryon asymmetry also depends on the moduli decay rate:

$$\eta_B \simeq 7.04\, Y_\phi \sum_\alpha \mathrm{Br}_{\phi \to X_\alpha} \epsilon_\alpha \,.$$

Moduli Decay

- Naturally long-lived due to gravitationally suppressed couplings.
- Dominates the energy density of the universe before decaying.
- Must decay well before BBN ($T_{\rm BBN} \sim$ MeV).
- Decay rate: $\Gamma_\phi = \frac{c_\phi}{2\pi}\frac{m_\phi^3}{M_{\rm Pl}^2}$, where $c_\phi \sim 0.01 - 1$ (in typical string compactification scenarios, e.g. KKLT).
- Moduli decay occurs when $\Gamma_\phi \sim H \simeq 1.66\sqrt{g_*}\frac{T^2}{M_{\rm Pl}}$.
- Reheat temperature:

$$T_R \simeq c_\phi^{1/2}\left(\frac{10.75}{g_*}\right)^{1/4}\left(\frac{m_\phi}{100\ \text{TeV}}\right)^{3/2} 3.5\ \text{MeV}\,.$$

- Requiring $\text{MeV} \lesssim T_R \lesssim \text{GeV}$ implies $200\ \text{TeV} \lesssim m_\phi \lesssim 4500\ \text{TeV}$, or $10^{-9} \lesssim Y_\phi \equiv \frac{3T_R}{4m_\phi} \lesssim 10^{-7}$.
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Resonant Baryogenesis

- Similar in spirit to **resonant leptogenesis.** [Pilaftsis (PRD '97); Pilaftsis, Underwood (NPB '03; PRD '05); BD, Pilaftsis, Millington, Teresi (NPB '14)]
- Self-energy graphs dominate the CP-asymmetry for quasi-degenerate X_α's.
- Resonantly enhanced [up to $\mathcal{O}(0.1)$] for $\Delta m_X \lesssim \Gamma_X/2$.

$$\epsilon_\alpha = \frac{1}{8\pi}\frac{\sum_{ijk}\mathrm{Im}(\lambda^*_{\alpha k}\lambda_{\beta k}\lambda'^*_{\alpha ij}\lambda'_{\beta ij})}{\sum_k |\lambda_{\alpha k}|^2 + \sum_{ij}|\lambda'_{\alpha ij}|^2}\frac{(m^2_{X_\alpha} - m^2_{X_\beta})m_{X_\alpha}m_{X_\beta}}{(m^2_{X_\alpha} - m^2_{X_\beta})^2 + m^2_{X_\alpha}\Gamma^2_{X_\beta}}$$

- In the resonance limit, regulator goes as m_X/Γ_X.
- CP-asymmetry becomes *insensitive* to the mass scale m_X, as well as the overall scaling of the coupling constants.

Free Parameters and Constraints

- Free parameters: $m_X, \lambda_{\alpha i}, \lambda'_{\alpha ij}$ (with $\alpha = 1, 2$ and $i, j, k = 1, 2, 3$).
- Color antisymmetry requires that $\lambda'_{ij} = 0$ for $i = j$.
- Similarly, color conservation does not allow tree-level contributions to quark FCNCs.
- Only major constraint comes from di-nucleon decay (like $pp \to KK$): $|\lambda_{\alpha 1}\lambda'_{\alpha 12}| \lesssim 10^{-6}(m_X/1\ \mathrm{TeV})^2$.

- We assume λ'_{12} small, while leave $\lambda_{\alpha 1}$ as a free parameter.
- For simplicity, also assume $|\lambda_{1i}| = |\lambda_{2i}| \equiv |\lambda| \quad \forall\, i = 1, 2, 3$.
- Similarly, take $|\lambda'_{1ij}| = |\lambda'_{2ij}| \equiv |\lambda'_{ij}|$.
- Left with only four parameters $m_X, \lambda, \lambda'_{13,23}$.

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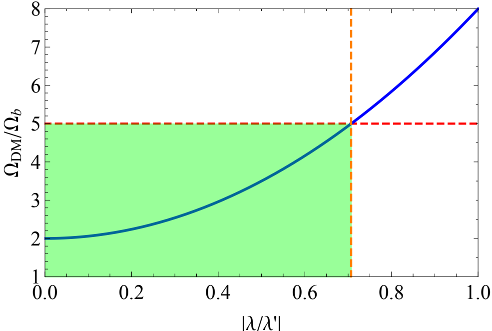
DM-to-Baryon Ratio

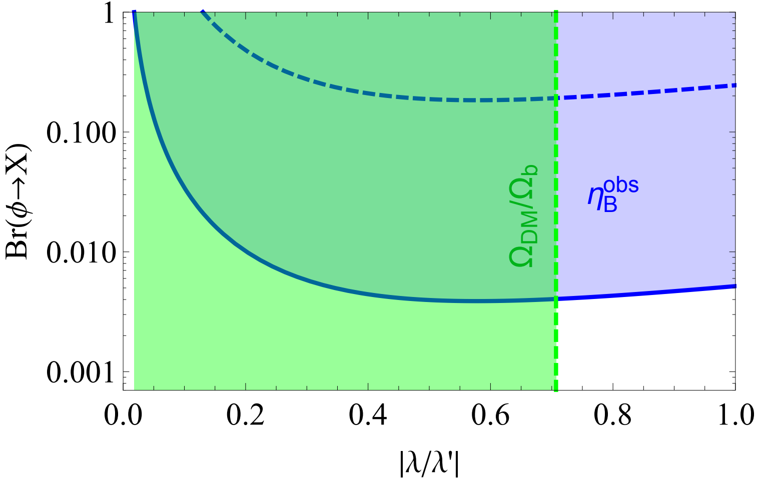
- Both DM and baryonic matter have a common origin from moduli decay.

$$\frac{\Omega_{\rm DM}}{\Omega_b} = \frac{{\rm Br}_{\phi\to\psi}}{\sum_\alpha \epsilon_\alpha {\rm Br}_{\phi\to X_\alpha}}$$

- ${\rm Br}^{\rm total}_{\phi\to\psi} = {\rm Br}^{\rm direct}_{\phi\to\psi} + \sum_\alpha {\rm Br}_{\phi\to X_\alpha}{\rm Br}_{X_\alpha\to\psi} \geq \sum_\alpha {\rm Br}_{\phi\to X_\alpha}{\rm Br}_{X_\alpha\to\psi}$.
- This implies $\frac{\Omega_{\rm DM}}{\Omega_b} \geq \frac{{\rm Br}_{X\to\psi}}{\epsilon}$.
- $\frac{\Omega_{\rm DM}}{\Omega_b} \approx 5$ imposes an **upper bound** on the ratio $|\lambda/\lambda'| \lesssim 1/\sqrt{2}$, independent of m_X, m_ϕ.



Baryon Asymmetry



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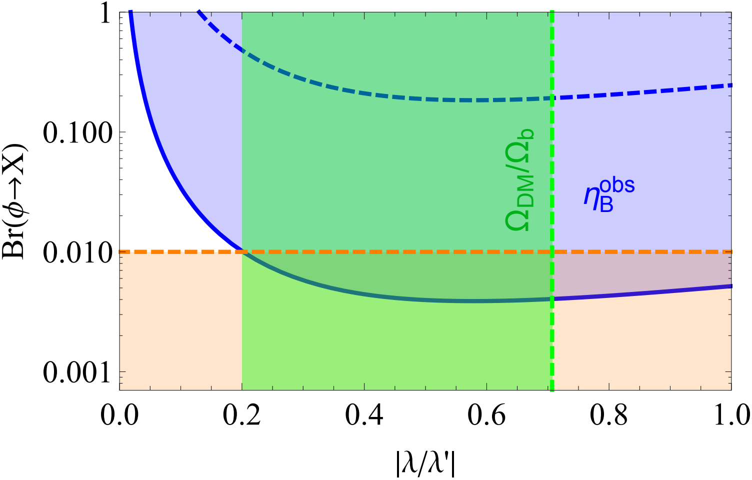

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$n-\bar{n}$ Oscillation

- Effective $\not{B}$ operator $\psi u^c d^c d^c$ (integrating out X_α). [Babu, Mohapatra, Nasri (PRL ’07)]
- Induces $n-\bar{n}$ oscillation for Majorana N.
- Tree-level amplitude vanishes due to color-antisymmetry.
- Non-zero amplitude at one-loop level: [BD, Mohapatra (PRD ’15)]

$$G_{n-\bar{n}} \simeq \frac{1}{16\pi^2}\frac{|\lambda_{\alpha 1}|^2|\lambda'_{\alpha 13}|^4 m_\psi}{m_{X_\alpha}^6}\log\left(\frac{m_{X_\alpha}^2}{m_\psi^2}\right)$$
$$\simeq (1.9\times 10^{-28}\ \mathrm{GeV}^{-5})\left(\frac{|\lambda_{\alpha 1}|}{0.03}\right)^2\left(\frac{|\lambda'_{\alpha 13}|}{0.04}\right)^4\left(\frac{1\ \mathrm{TeV}}{m_X}\right)^6 .$$

- Observable oscillation time for $m_X \sim \mathcal{O}$(TeV):

$$\tau_{n\bar{n}} \simeq (3.0\times 10^8\ \mathrm{sec})\left(\frac{0.03}{|\lambda_{\alpha 1}|}\right)^2\left(\frac{0.04}{|\lambda'_{\alpha 13}|}\right)^4\left(\frac{m_X}{1\ \mathrm{TeV}}\right)^6 .$$

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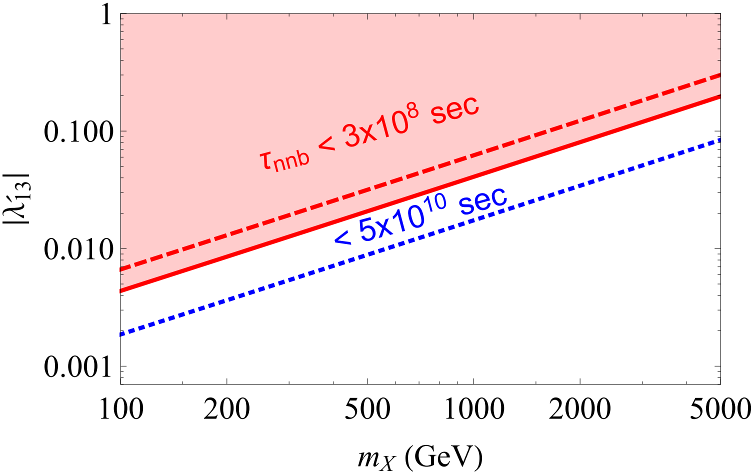
Constraint from $n - \bar{n}$



- There is a lower limit on $|\lambda'_{13}| \gtrsim 10^{-11}$ requiring that X decay temperature is above QCD scale.
- But the corresponding upper limit on $\tau_{n\bar{n}}$ is useless (10^{62} sec).

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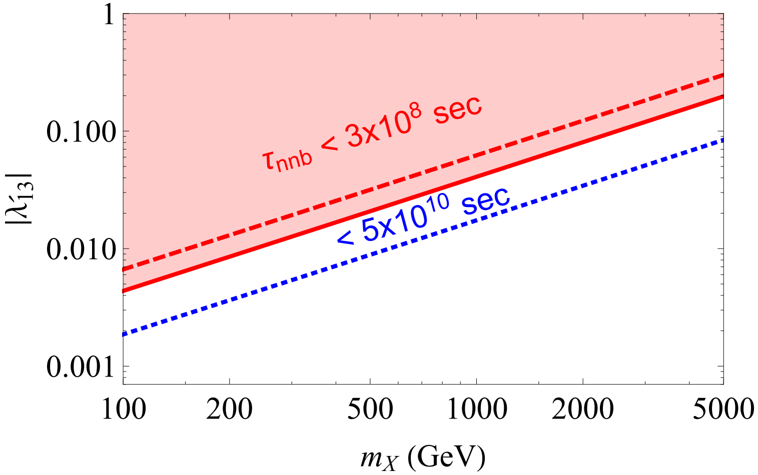

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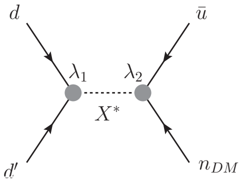
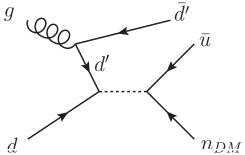
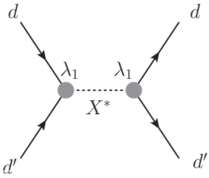
Collider Signals



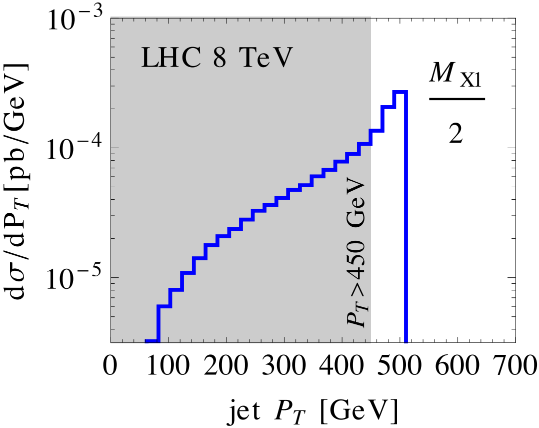


- DM production $pp \to \psi u^c$ gives a monojet (monotop for $\lambda_{\alpha 3}$) signal.
- For $\lambda'_{13,23}$, the quark annihilation must involve the b-quark PDF (small).
- Another way: gluon splitting into $b\bar{b}$.
- Extra b can be used for event tagging.
- The color-triplet scalar will also give a dijet resonance at the LHC.

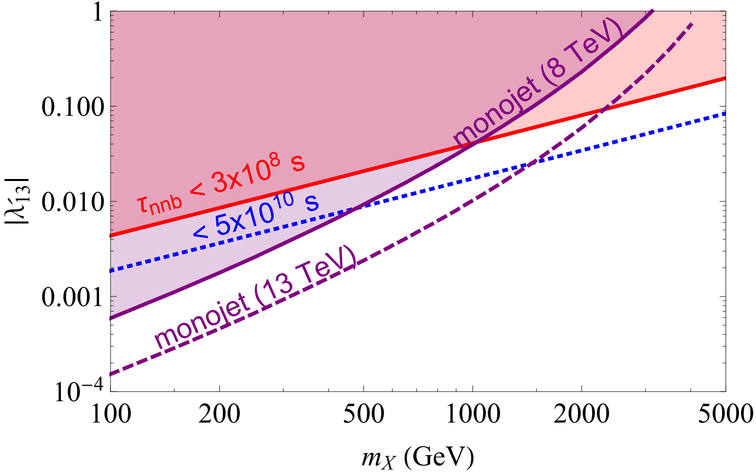


Monojet

- Different from other DM production at the LHC: $pp \to$ DM DM.
- Will give a Jacobian peak in the jet p_T distribution. [Duta, Gao, Kamon (PRD ’14)]



$n\bar{n}$ - LHC Complementarity



Conclusion

- A simple TeV-scale model of B-violation for baryogenesis and dark matter.
- Stability of dark matter linked to that of proton (no ad-hoc symmetry required).
- DM-to-baryon abundance ratio easily explained.
- Imposes an upper limit on the coupling ratio $|\lambda/\lambda'|$.
- Successful baryogenesis imposes a lower bound on $|\lambda/\lambda'|$.
- Potentially observable $n - \bar{n}$ oscillation rate.
- No EDM constraints.
- Distinct monojet and dijet signatures at the LHC.
- Complementarity between monojet and $n - \bar{n}$.