Unified Description of Baryogenesis and Dark Matter

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K.S. Babu, R.N. Mohapatra, S. Nasri, Phys. Rev. Lett. 98:161301 (2007)

Motivation

Three areas where particle physics models crucial in cosmology

- Provides a natural dark matter candidate
- Expalins the baryon asymmetry as a dynamical phenomenon
- Expalains inflation in a natural way

A unified description desirable

“Standard” Picture

Lightest SUSY particle is cold dark matter

Baryon asymmetry generated in the out of equilibrium decay of N_1, the lightest right handed neutrino from seesaw mechanism

Both ideas well motived

SUSY $\Rightarrow$ gauge hierarchy, coupling unification
B asymmetry $\Rightarrow$ Neutrino masses

But unrelated

In detail, realization raises some questions

Dark Matter in Minimal SUSY

Reproducing right dark matter abundance strains SUSY breaking parameters

Allowed regions excluded by data (LEP)

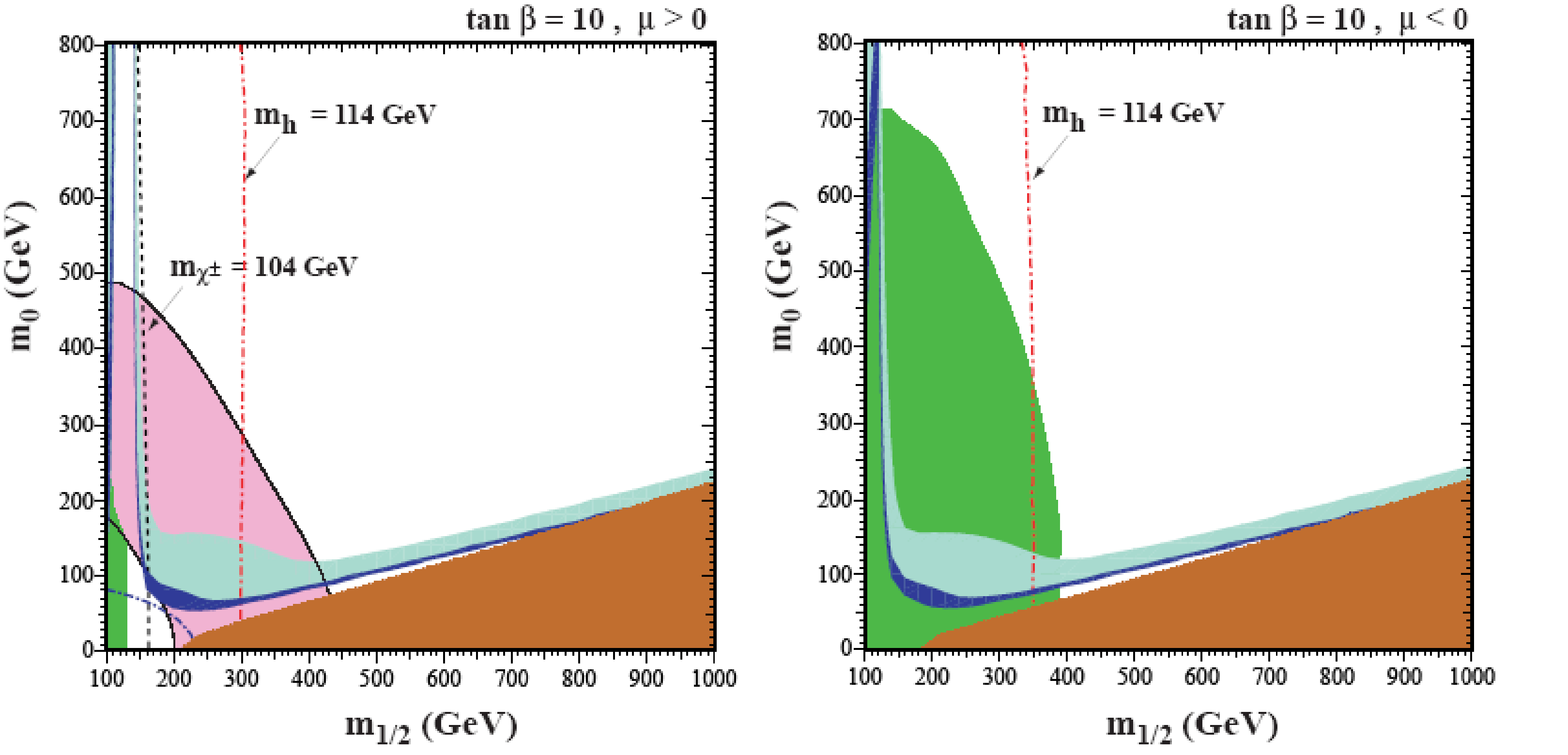
Or

Must obey critical relations among a priori unrelated parameters

Eg:

$$\begin{aligned} M_{1/2} &= 4.4\ m_0 \\ M_1 &= M_2 \end{aligned}$$

Bino LSP



Thin blue strip – dark matter allowed

Ellis, Olive, Santoso (2003)

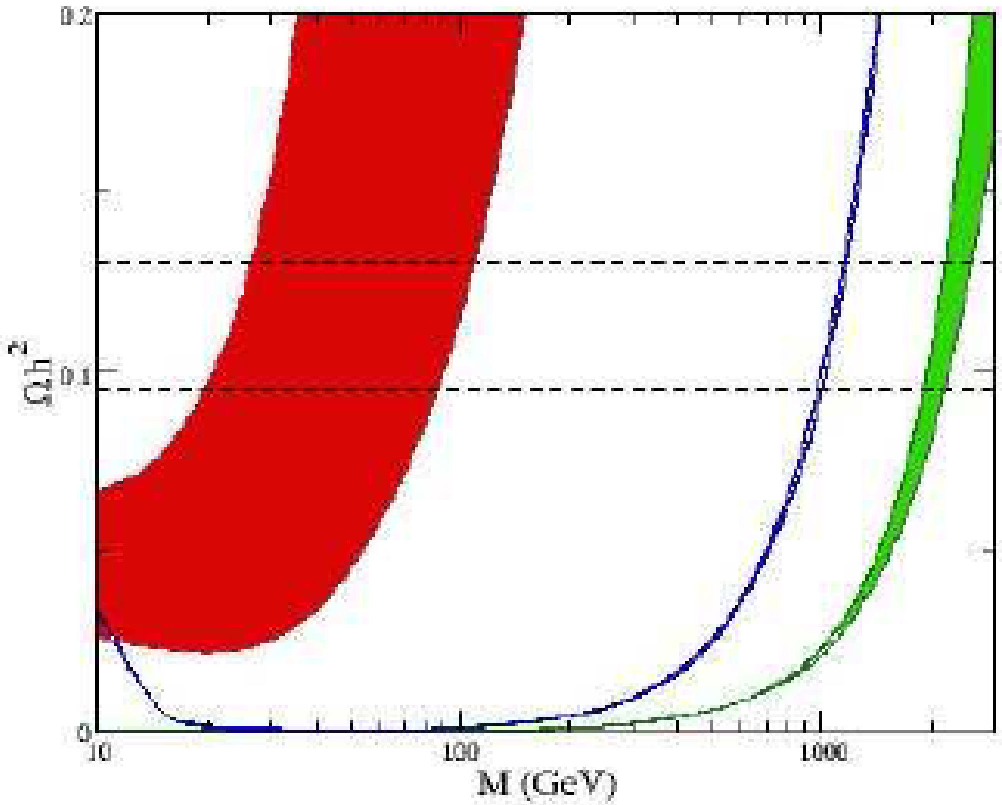


Figure 1: The three bands show the contribution to Ωh^2 from pure Bino LSP with $0.3 < M_1/m_{\tilde{e}_R} < 0.9$ (red band), Higgsino LSP with $1.5 < m_{\tilde{\iota}}/\mu < \infty$ (blue band) and Wino LSP with $1.5 < m_{\tilde{\ell}_L}/M_2 < \infty$ (green band).

Arkani-Hamed, Delgado, Guidice (2006)

Popular B generation mechanisms

- GUT scale baryogenesis
  $X \to ql, qq$
  X: colored GUT scale Higgs or gauge boson
  Asymmetry washed out by sphalerons

- Electroweak baryogenesis
  Phase transition is too weak (or Higgs mass too low)
  Plausible in MSSM (Carena, Wagner,..)

- Leptogenesis with hierarchical ν_R's
  Heavy ν_R decays: $\nu_R \to L + H$, $\nu_R \to \overline{L} + \overline{H}$
  Requires $M_R \geq 3 \times 10^9$ GeV (Davidson-Ibarra)
  In supersymmetry, gravitino production requires
  $T_{RH} \leq 3 \times 10^7$ GeV
  Conflict

Proposal for B generation and Dark Matter

Introduce a chiral singlet superfield N into MSSM at TeV scale

Decay of N–fermion generates B asymmetry

$\tilde{N}$ scalar is the LSP

Decay of N and annihilation of $\tilde{N}$ mediated by same interaction

N may be left-over ν_R from seesaw
(Two ν_R enough to explain neutrino data)

$\tilde{N}$ naturally LSP in SUGRA like SUSY breaking

Post-sphaleron baryogenesis

Baryogeneis occurs after sphalerons decouple

$$T \leq 200 \text{ GeV}$$

New particle with mass ~ 100 GeV decays violating B

New particle may be boson (S) or fermion (N)

S or N must couple to B violating current

Unified Model

Extend MSSM with one singlet superfiled N

Add color triplets $(X, \overline{X})$ for B violation

$$W = \lambda_i N u_i^c X + \lambda'_{ij} \overline{X} d_i^c d_j^c + \frac{M_N}{2} N N + M_X X \overline{X}$$

Violates baryon number via Majorana mass of N

There is no rapid proton decay $(\Delta B = 2)$

Can be embedded in a GUT
$(X, \overline{X}) \subset (10 + \overline{10})$ of $SU(5)$

Gauge coupling unification preserved

Unified Model (cont.)

Hierarchy of masses:

$$M_N \sim 100 \text{ GeV}$$
$$M_{\tilde{N}_1} \sim 100 \text{ GeV}$$
$$M_X \sim 1 \text{ TeV}$$

$\tilde{N}_1$ stable $\Rightarrow$ DM
N unstable $\Rightarrow$ BAU

N decays into 3 quarks, as well as into 3 antiquarks

$$N \longrightarrow u^c d^c d^c, \qquad N \longrightarrow \overline{u^c}\ \overline{d^c}\ \overline{d^c}$$

- The Lagrangian including soft SUSY breaking terms:

$$
\begin{aligned}
\bullet - \mathcal{L}_{\rm scalar} &= |M_X|^2(|X|^2 + |\overline{X}|^2) + m_X^2|X|^2 + m_{\overline{X}}^2|\overline{X}|^2 \\
&+ (B_X M_X X\overline{X} + h.c) + |M_N|^2|\tilde{N}|^2 + m_{\tilde{N}}^2|\tilde{N}|^2 \\
&+ (\frac{1}{2}B_N M_N \tilde{N}\tilde{N} + h.c.)
\end{aligned}
$$

- Two mass eigenstates X_1 and X_2 :

$$
\begin{aligned}
X &= \cos\theta X_1 - \sin\theta e^{-i\phi}X_2; \\
\overline{X}^* &= \sin\theta e^{i\phi}X_1 + \cos\theta X_2
\end{aligned}
$$

- $\tan 2\theta = \dfrac{|2B_X M_X|}{|m_X^2 - m_{\overline{X}}^2|}$; $\phi = \mathrm{Arg}(B_X M_X)\mathrm{sgn}(m_X^2 - m_{\overline{X}}^2)$.

- The two mass eigenvalues are

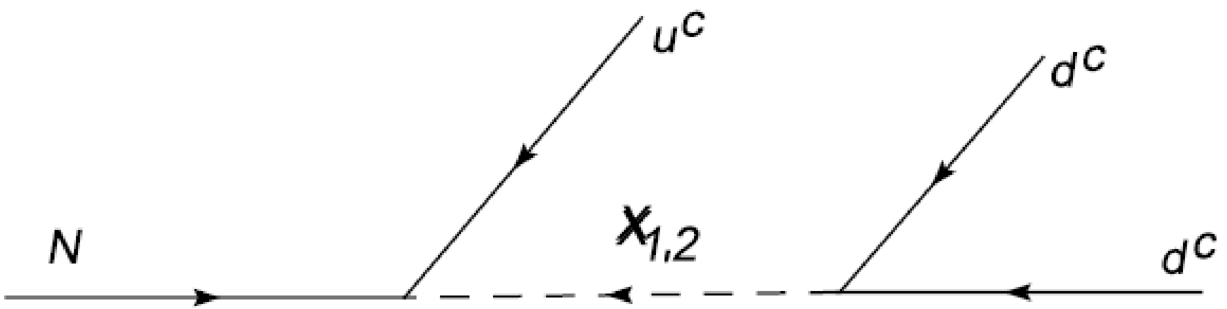
$$M_{X_{1,2}}^2 = |M_X|^2 + \frac{m_X^2 + m_{\overline{X}}^2}{2} \pm \sqrt{\left(\frac{m_X^2 - m_{\overline{X}}^2}{2}\right)^2 + |B_X M_X|^2}$$

- The two *real* mass eigenstates from the $\tilde{N}$ field :

$$M_{\tilde{N}_{1,2}}^2 = m_{\tilde{N}}^2 + |M_N|^2 \pm |B_N M_N|$$

N decay

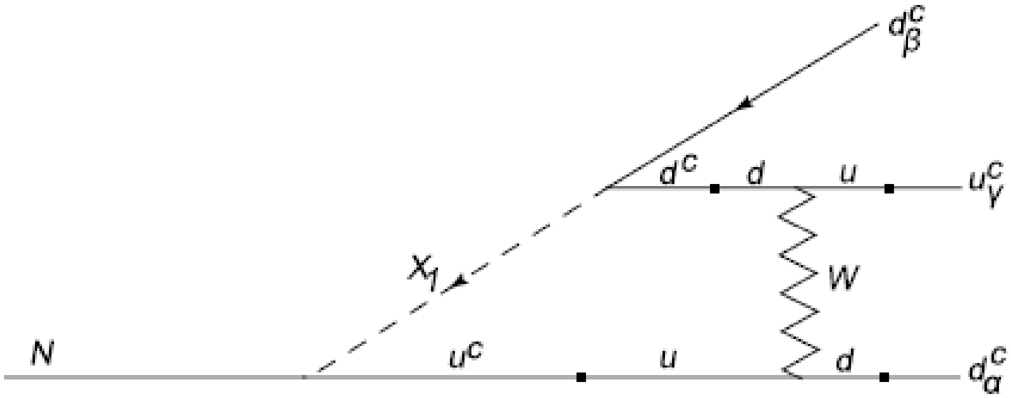
$$\Gamma(N \to d^c d^c d^c + h.c) \leq \sqrt{g_*}\frac{T^2}{M_{Pl}}$$



$$\Gamma_N = \frac{3}{64}\frac{(\lambda^\dagger\lambda)\mathrm{Tr}[\lambda'^\dagger\lambda')]}{192\pi^3} M_N^5 \sin^2 2\theta \left(\frac{1}{M_{X_1}^2} - \frac{1}{M_{X_2}^2}\right)^2$$

For $[(\lambda^\dagger\lambda)\mathrm{Tr}(\lambda'^\dagger\lambda')]^{1/2} \sim 10^{-3}$, N decay goes out of equilibrium below its mass

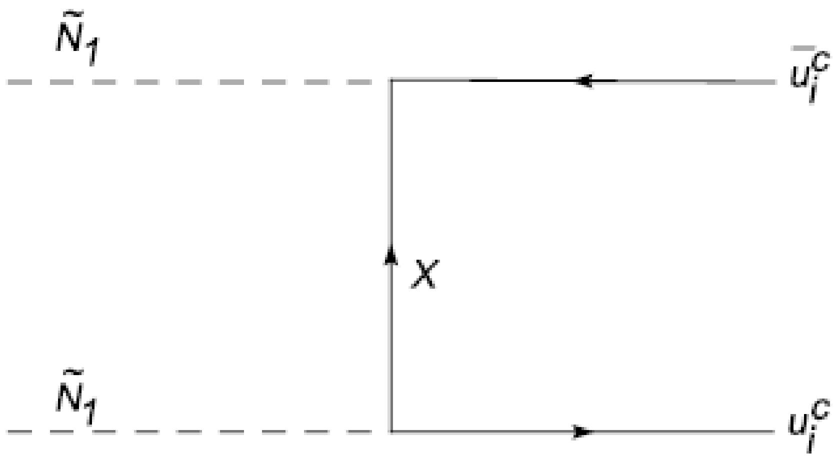
CP asymmetry



$$\epsilon \equiv \frac{\Gamma(N \to 3q^c) - \Gamma(N \to 3\overline{q^c})}{\Gamma_T} \simeq (-\alpha_2/4)\frac{(m_c m_t m_s m_b)}{(m_W^2 m_N^2)}$$

$\frac{n_B}{s} \simeq 6 \times 10^{-10}$ reproduced

Dark Matter

- Relic density:
  - 

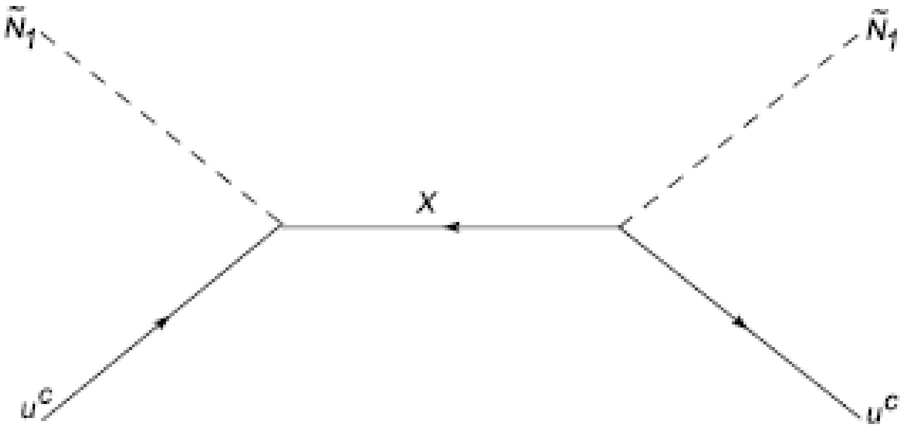
  - $\sigma(\tilde{N}_1 \tilde{N}_1 \to q\bar{q}) v_{\rm rel} = \frac{3(\lambda^\dagger \lambda)^2}{8\pi s} \left(\frac{a}{b} \tanh^{-1}(\frac{b}{a}) - 1 \right)$

where

$$a = 2E^2 - M^2_{\tilde{N}_1} + M^2_X; \quad b = 2E|\overrightarrow{p}| \ .$$

  - For $\lambda_3 \sim 1/3$, $M_{\widetilde{N_1}} \sim 300\ GeV$, $M_X \sim 500\ GeV$
    $\Rightarrow \Omega_{\widetilde{N_1}} h^2 \simeq 0.1$

- Direct detection:

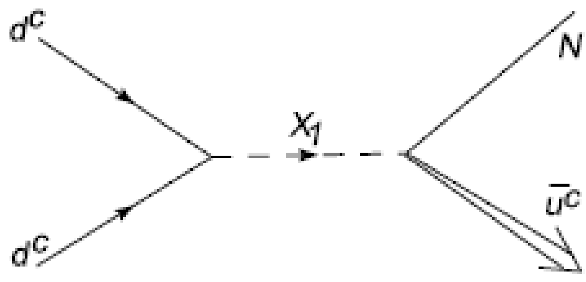
  - 

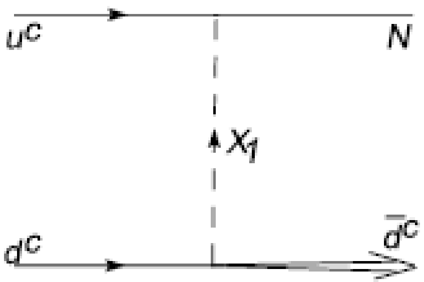
  - $\sigma_{\tilde{N}_1+p} \simeq \frac{|\lambda_1|^4 m_p^2}{4\pi M_X^4}\left(\frac{A+Z}{A}\right)^2$

  - For $\lambda_1 \sim 0.1$, $M_X \sim 500\ GeV$
    $\sigma_{\tilde{N}_1+p} \simeq 10^{-8}\ pb \Rightarrow$ within the reach of SuperCDMS

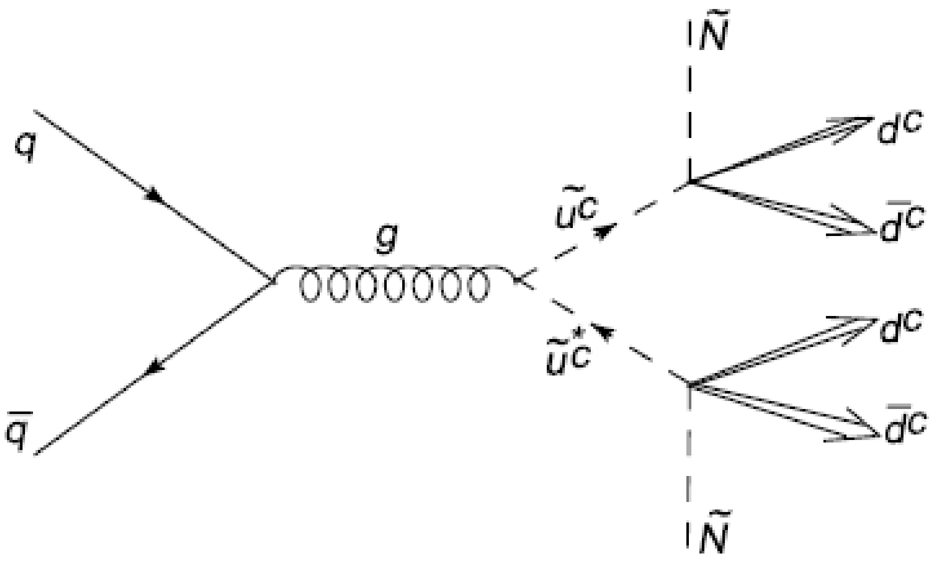
Signature at LHC

- Monojet + missing energy signals from X production in pp collision:

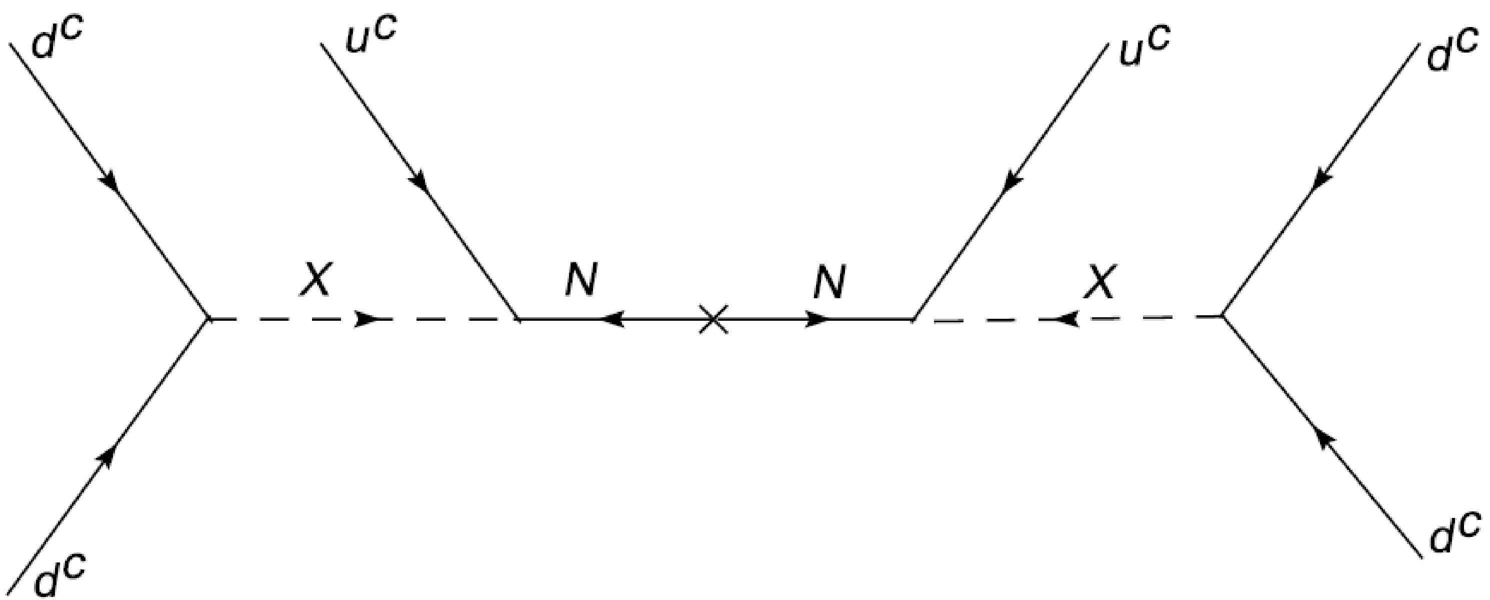




- 4 jets + missing energy from :



n-nbar oscillations



$$\tau(n - \overline{n}) \sim (10^9 - 10^{11}) \text{ sec}$$

Summary and Conclusions

New mechanism that unifies baryon asymmetry generation and dark matter has been proposed

B generation does not rely on sphalerons

$\tilde{N}_1$ dark matter natural, and releases tight constraints on SUSY parameters

Colored scalars at TeV scale should be accessible to LHC

Predicts observable $n - \overline{n}$ oscillations with

$$\tau(n - \overline{n}) \sim (10^9 - 10^{11}) \text{ sec}$$