Post-sphaleron Baryogenesis

K.S. Babu
Oklahoma State University

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K.S. Babu, R.N. Mohapatra, S. Nasri, Phys. Rev. Lett. (2007)
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Baryon number violation in the Standard Model

- B is a global symmetry of SM classically
- Nonperturbative weak interaction effects lead to B violation

't Hooft (1976)

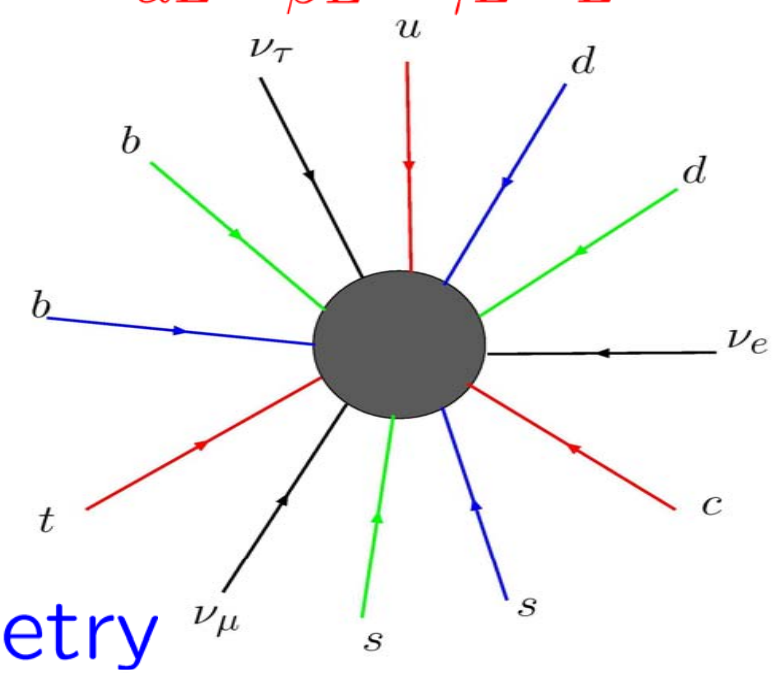
$$\mathcal{O}_{\text{eff}} = c\left(\frac{1}{m_W}\right)^{14} e^{\frac{-2\pi}{\alpha_2}} \prod_{i=1}^{3} (\epsilon^{\alpha\beta\gamma} Q^i_{\alpha L} Q^i_{\beta L} Q^i_{\gamma L} L^i_L)$$

- $\Delta B = \Delta L = 3$

  Eg: $ppn \to e^+ e^+ \overline{\nu}$

$$\text{Rate} \quad \propto \quad \left| e^{-\frac{2\pi}{\alpha_2}} \right|^2$$

$$\sim \quad 10^{-165}$$



- Relevant for baryon asymmetry

Kuzmin, Rubakov, Shaposhnikov (1985)

Sphalerons and Baryogenesis

- Sphaleron interaction rate:

$$\Gamma_{\text{sph}} \sim \alpha_W^5 T \sim 10^{-6} T$$

In equilibrium for $T \sim (10^2 - 10^{12})$ GeV

Can help generate (or erase) baryon asymmetry

$$\eta = \frac{\eta_B - \eta_{\overline{B}}}{s} \simeq 8 \times 10^{-11} \text{ (BBN, WMAP)}$$

Popular B geneation 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

- Leptogenesis
  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

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

Possible B violating couplings

$\Delta B = 1$ couplings (e.g. $QQQL$) must decouple before $T \sim 10^{15}$ GeV (proton decay)

$\Delta B = 2$ couplings can be in equilibrium until $T \sim 10^{5}$ GeV $(n - \overline{n})$ oscillations

$\Delta B = 3$ or higher will be in conflict with nucleosynthesis

Focus on $\Delta B = 2$ processes

S couplings

$$\frac{S}{\Lambda^9}(u_R d_R d_R u_R d_R d_R)$$

$$\frac{S}{\Lambda^9}(QQ d_R QQ d_R)$$

$$\frac{S}{\Lambda^9}(QQ u_R d_R d_R d_R)$$

S acquires vacuum expectation value and breaks Baryon number

S_r decays to 6 quarks as well as into 6 antiquarks

$$S_r \to 6q, \quad S_r \to 6\overline{q}$$

Leads to baryon asymmetry

Explicit Model

$$L = \frac{h_{ij}}{2} X d_i^c d_j^c + \frac{f_{ij}}{2} Y u_i^c u_j^c + \frac{g_{ij}}{2} Z (u_i^c d_j^c + u_j^c d_i^c)$$
$$+ \frac{\lambda_1}{2} S X^2 Y + \frac{\lambda_2}{2} S X Z^2 + h.c$$

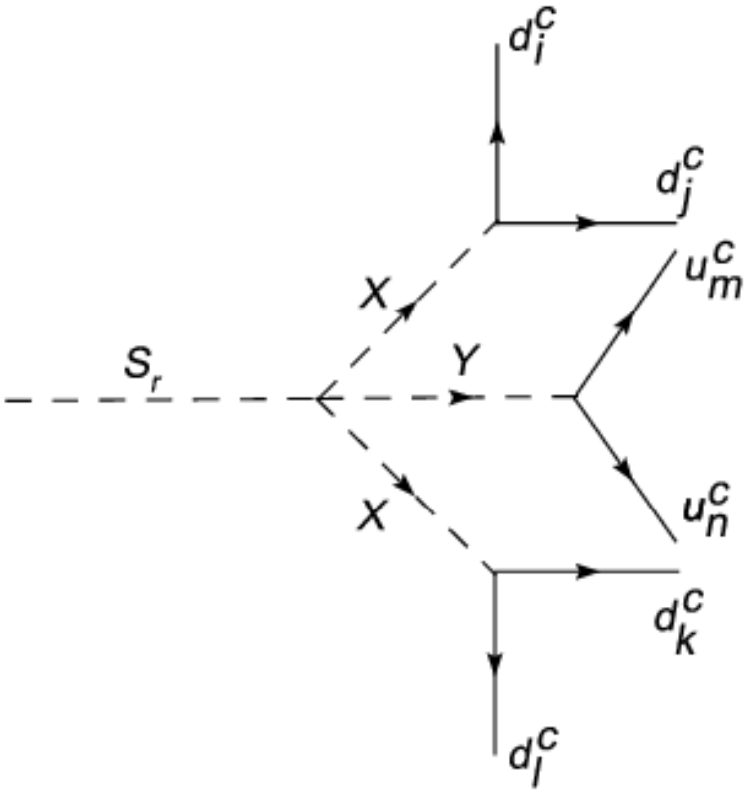
$X,\ Y,\ Z$ are colored scalars

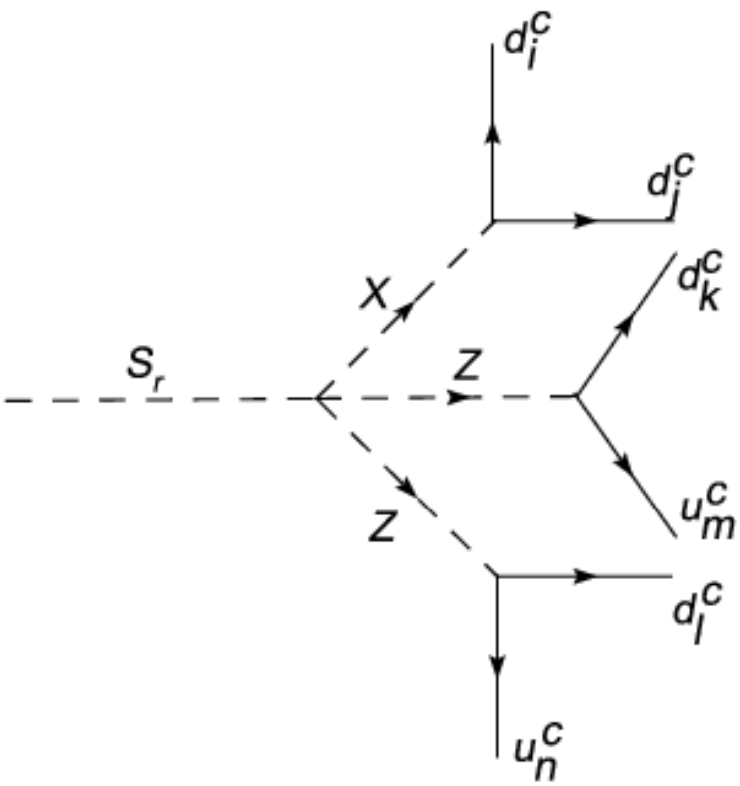
Part of Higgs sector of Pati-Salam symmetry $SU(4)_c \times SU(2)_L \times SU(2)_R$

Baryon number is broken once $\langle S \rangle \neq 0$

$$S_r \to 6q, \quad S_r \to 6\overline{q}$$

B violating decay of S



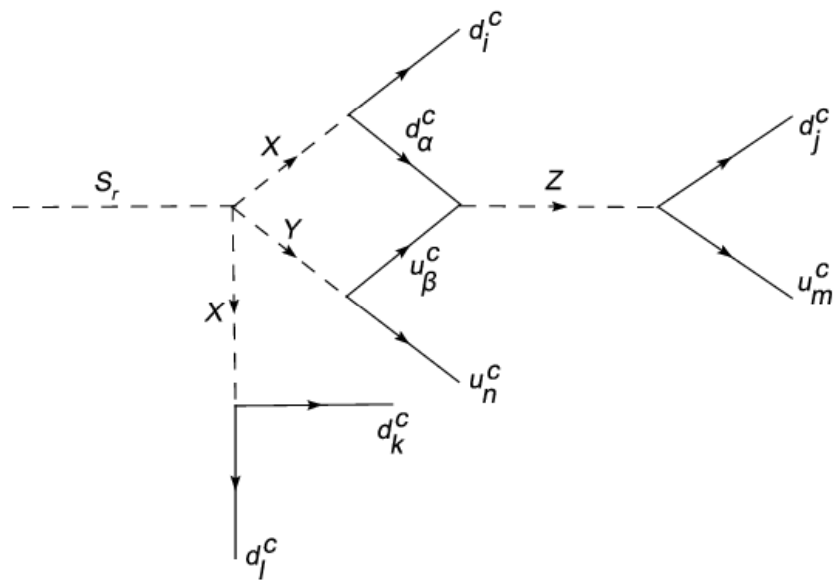


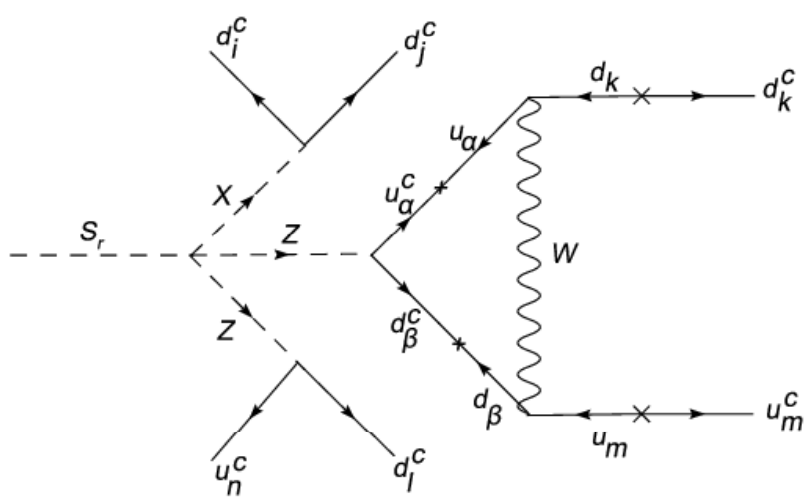
$$\Gamma(S_r \to 6q) \simeq \frac{18 P \lambda_2^2 h^2 g^2 M_{S_r}^{13}}{(2\pi)^9 (6 M_X)^{12}}$$

$P = 2.05,\ M_X = 1$ TeV, $M_{S_r} = 100$ GeV

$\to \tau(S_r) \simeq 10^{-2}$ sec

CP Asymmetry





Model Predictions

$$\epsilon_B \simeq -\frac{\alpha_2}{4}\frac{\mathrm{Im}\,\mathrm{Tr}[g^T \hat{M}_u V g^\dagger V^* \hat{M}_d]}{\mathrm{Tr}(g^\dagger g)} \simeq 10^{-8}$$

$$\eta_B \simeq \epsilon_B \frac{T_d}{M_{S_r}}$$

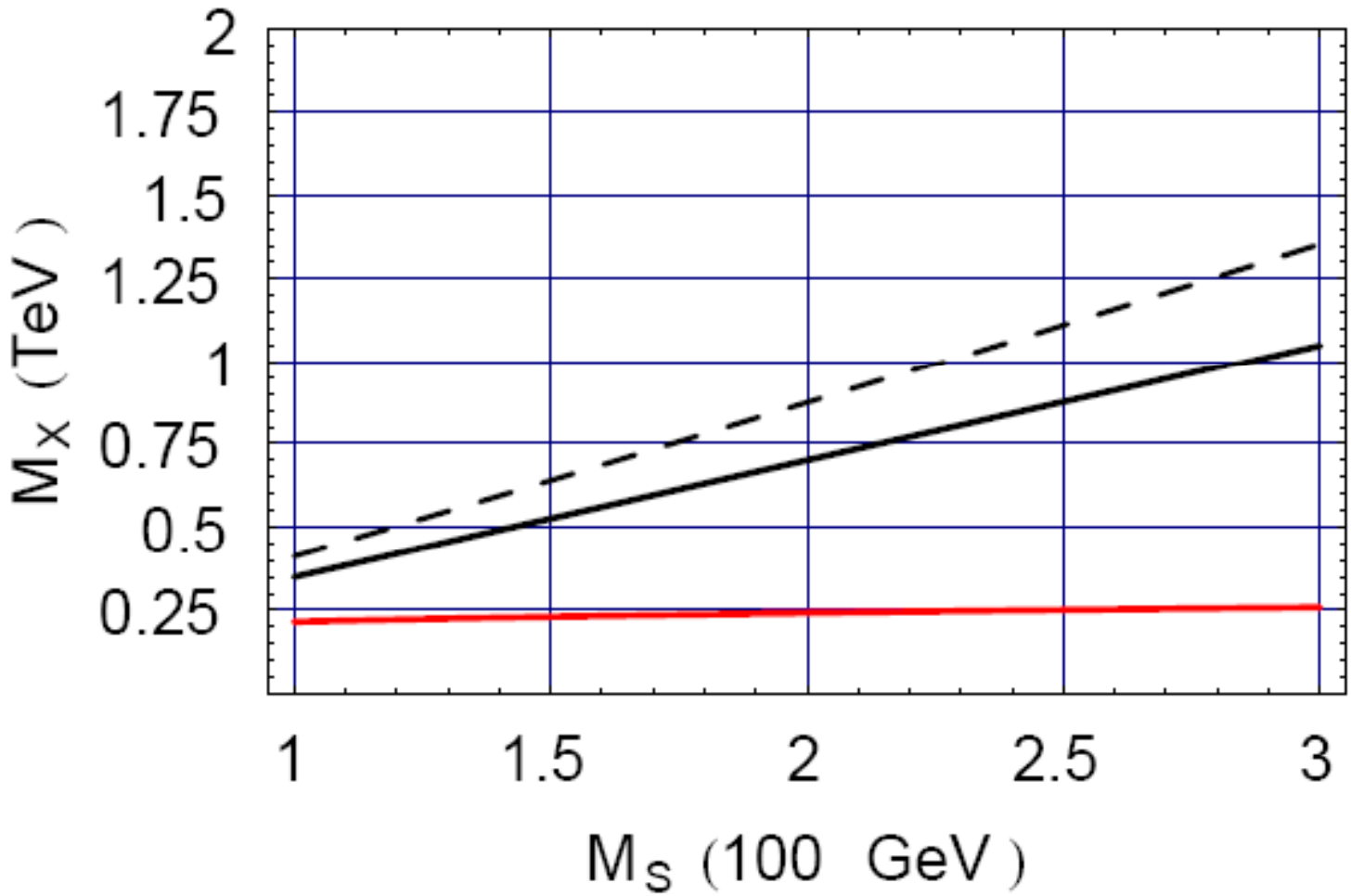
T_d: Temperature when S_r begins to decay

To have $T_d/M_{S_r} \sim 10^{-2}$, and $T_d \geq 200$ MeV, $M_{S_r} = 100 - 300$ GeV

Neutron-antineutron transition rate is predicted

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

Colored scalars with mass ~ 1 TeV accessible to LHC


2
1.75
1.5
1.25
1
0.75
0.5
0.25
M_X (TeV)
1
1.5
2
2.5
3
M_S (100 GeV)

B Violating decays of N

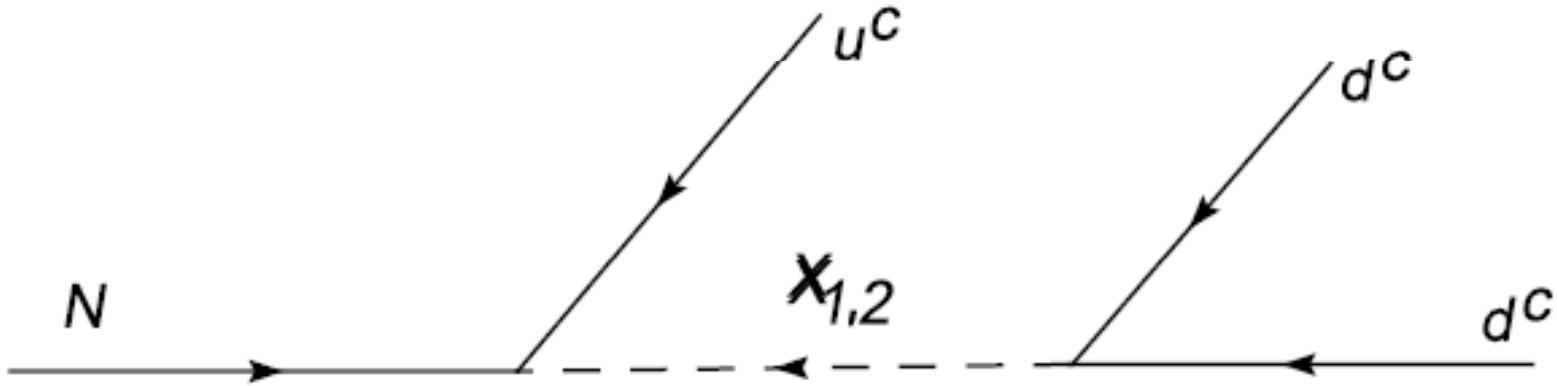
$$L = \lambda_i N u_i^c X + \lambda'_{ij} \overline{X} d_i^c d_j^c + \frac{M_N}{2} N N + M_X X \overline{X}$$

Violates baryon number via Majorana mass of N

When supersymmetry is assumed,
$\tilde{N}$ is naturally dark matter candidate

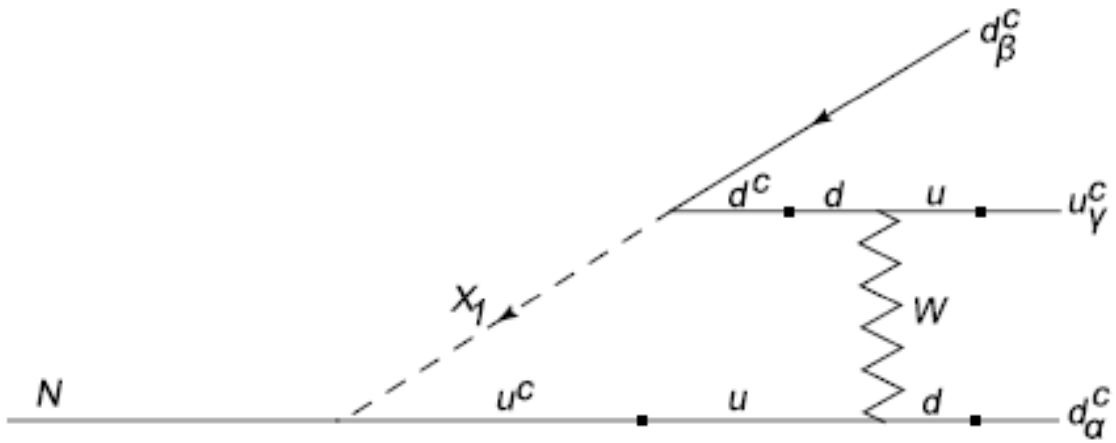
$n - \overline{n}$ oscillation occurs with a lifetime
of $(10^9 - 10^{11})$ sec

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



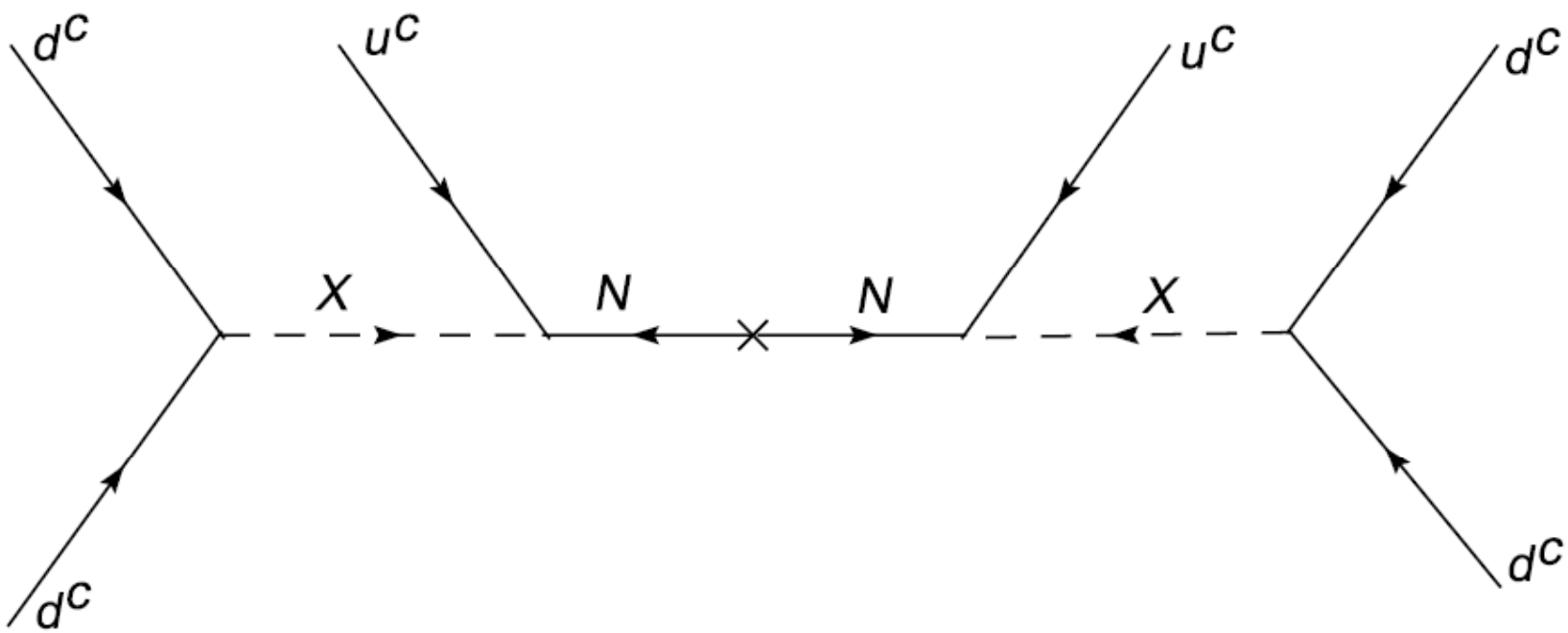
$$\Gamma_N = \frac{3}{64}\frac{(\lambda^\dagger\lambda)\mathrm{Tr}[\lambda'^\dagger\lambda')]}{192\pi^3}M_N^5\sin^2 2\theta\left(\frac{1}{M_{X_1}^2}-\frac{1}{M_{X_2}^2}\right)^2$$

CP asymmetry



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

n-nbar oscillations



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

Summary and Conclusions

New mechanism for baryon asymmetry generation has been proposed

Does not rely on sphalerons

Colored scalars at TeV scale should be accessible to LHC

In supersymmetric version, baryogenesis and dark matter may be unified

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

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