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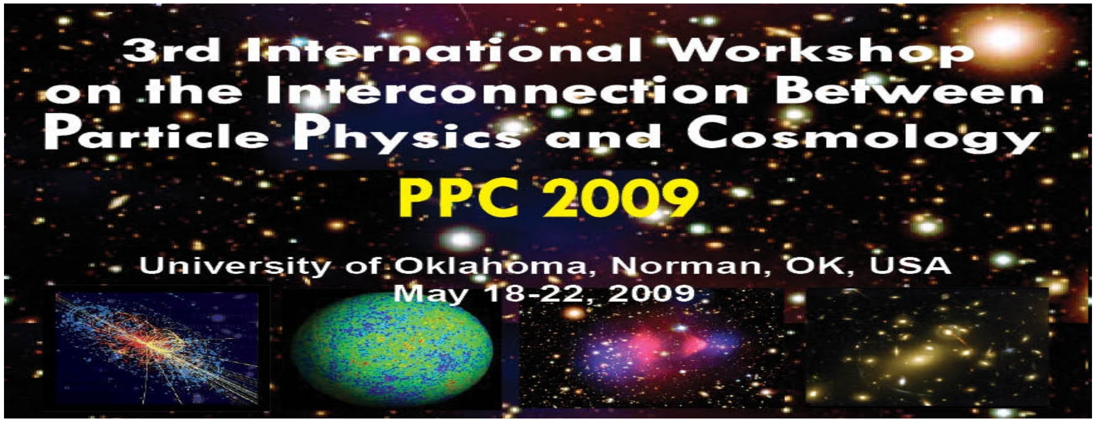
Neutrino Mass Seesaw, Baryogenesis and LHC

R. N. Mohapatra



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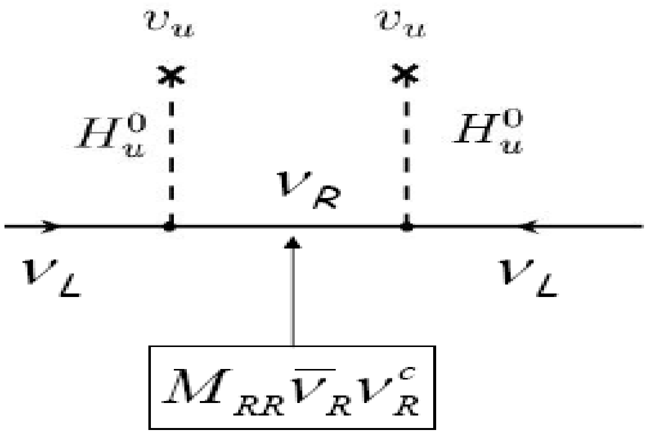
Premise of the Talk:

- Seesaw paradigm provides a simple way to understand small neutrino masses.
- Seesaw scale however is not predicted by nu- masses and could therefore be in the range accessible to LHC (~TeVs) making the idea testable.
- Physics related to seesaw mechanism is believed to explain the observed matter-anti-matter asymmetry of the Universe.
- How can we test physics related to seesaw+ baryogenesis at LHC ?

Seesaw Paradigm

- **Why** $m_\nu << m_{q,l}$ **?**
- **Type I:** **Add right handed neutrinos** N_R **to SM with Majorana mass:** $L_Y = h_\nu \overline{L} H N_R + M_R NN$
- M_R Breaks B-L : New scale and new physics beyond SM.
- After electroweak symmetry breaking

$$\boxed{m_\nu \cong -\frac{h_\nu{}^2 v_{wk}{}^2}{M_R}}$$

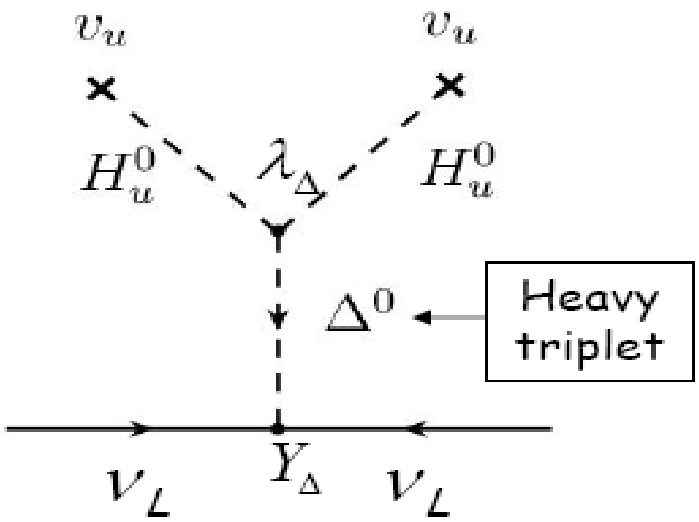


- Minkowski (77) Gell-Mann, Ramond Slansky,Yanagida, R.N.M.,Senjanovic,Glashow (79)

Type II Seesaw

- **Type II:** Break B-L symmetry by adding a triplet Higgs instead to SM $\vec{\Delta} = (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- $\vec{\Delta}$ acquires a vev via its SM Higgs coupling:

$$v_\Delta = \lambda_\Delta \mu \frac{v_{wk}^2}{M_\Delta^2}$$



$$\boxed{m_\nu = Y_\Delta v_\Delta}$$

Lazaridis, Shafi, Wetterich; R.N.M.,Senjanovic; Schecter,Valle;… (80)

Seeking the Seesaw physics

(i) Neutrino masses → seesaw scale much lower than Planck scale ; Easy to understand if the scale is associated with a symmetry.

(ii) Local B-L symmetry is the obvious symmetry.

- **What is the B-L breaking scale ?**

  (Nu mases cannot tell since we do not know Dirac mass m_D)
- **What new physics comes with it ?**
- **How to test it experimentally ?**

B-L symmetry scale

- $\boxed{m_D \approx m_t}$ Type I seesaw + Δm^2_{atm} → $M_R \approx 10^{14} GeV$ GUT SCALE - 10^{16} GeV-

Small neutrino mass could be indication for SUSYGUT;
Many interesting SO(10) GUT models.

- **No collider signals ! Possible tests in nu-osc.**
- **With SUSY, in** $\mu \rightarrow e + \gamma$ **.**

- $\boxed{m_D \approx m_e}$ so that seesaw scale is around **TeV** (corresponding Yukawa~ 10^{-6}) **;**
- **Not unnatural** since it is protected by chiral sym. $N \leftrightarrow -N$ and **M**R breaks L ; hence multiplicatively renormalized;
- **Many collider signals,** $\mu \rightarrow e + \gamma$**,** $\beta\beta_{0\nu}$

Seesaw and Origin of matter

- **Proposal:** Heavy ν_R decays:

$$\nu_R \to L + H \qquad R = (1+\varepsilon)$$

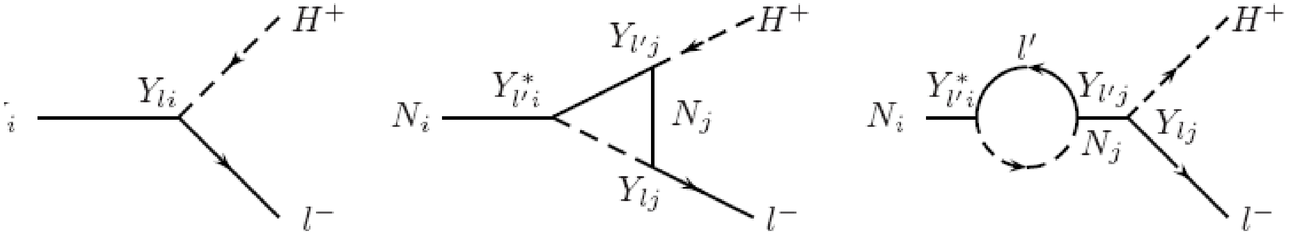
$$\nu_R \to \bar{L} + \bar{H} \qquad \bar{R} = (1-\varepsilon)$$

- **Generates lepton asymmetry:**
- **Gets converted to baryons via sphaleron interactions;**
- **No new interactions needed other than those already used for generating neutrino masses !!**
- **Seesaw provides a common understanding of both neutrino masses and origin of matter in the Universe.**

(Fukugita and Yanagida ,1986)

Two kinds of leptogenesis

- **Diagrams:**



- Two classes of models depending on RH mass pattern
- **High Scale leptogenesis**: Adequate asymmetry; lightest RH nu $M \geq 10^9 GeV$ for hierarchical RH nu's.
  (Buchmuller, Plumacher,di Bari; Davidson, Ibarra)
- **Resonant leptogenesis**: **degenerate** N's, self energy diagram dominates:~ $\frac{1}{M_i^2 - M_j^2 + M\Gamma}$; Resonance when $M_i \cong M_j$;works for all B-L scales.

  (Flanz, Paschos, Sarkar, Weiss; Pilaftsis, Underwood)

AN ISSUE WITH HIGH SCALE SUSY LEPTOGENESIS

- Recall the lower bound on the lightest RH neutrino mass $M_N \geq 3 \times 10^9$ GeV for enough baryons for non-resonant leptogenesis.
- **Problem for supersymmetric models:**

they have gravitinos with TeV mass that are produced during inflation reheat along with all SM particles-

- **Will overclose the universe if stable for T_R>10^9 GeV.**
- **If unstable, Once produced they live too long -effect the success of BBN. T_R upper limit near a 1000TeV.**
- **No such conflict for TeV scale resonant leptogenesis !! Goes well with TeV seesaw !**

Bottom up embeddings of TeV scale seesaw

- **U(1)$_{B-L}$ embedding:**

$$SU(2)_L \times U(1)_Y \rightarrow SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$$

- **Requires RH neutrino $N(1,\frac{1}{2},-1)$ for anomaly cancellation- fulfills one seesaw ingredient !**
- **(LH)^2 operator forbidden;**
- **For low B-L scale(TeV range), need B-L=2 Higgs $\delta_R(1,-1,+2)$ to break symmetry to implement seesaw, if no new physics upto Planck scale.**
- **When supersymmetrized, $\delta_R(1,-1,+2)$ breaking B-L leads to automatic R-parity →a stable dark matter.**

Testing seesaw with Z′ decay

- **LHC can detect Z′ upto 4 TeV**
- (Petriello, Quackenbush; Rizzo; Del Aguila, Aguilar-Savedra………)
- **At LHC, PP→Z′+X**

$$\downarrow$$

$$\mathbf{NN} \rightarrow \ell^{\pm} + x + \ell^{\pm} + x$$

- **Leading to like sign dilepton production**

$pp \rightarrow l^{+}l^{+} + X$ **and opposite sign etc. (X=jets)**

- **Dilepton events have a branching ratio ~20%; Inv mass of N's can be reconstructed (no missing E)**

TeV scale Resonant leptogenesis with Z′

- **Conditions:**

(i) RH neutrinos must be degenerate in mass to the level of $M_1 - M_2 << M_{1,2}$; since h~10^-5 degeneracy could be anywhere from $10^{-2} - 10^{-10}$

(ii) Since there are fast processes at that temperature, the net lepton asymmetry and primordial lepton asym are related by

$$\eta_B \simeq 10^{-2} \sum_{i,\alpha} \varepsilon_{i\alpha}\, \kappa_{i\alpha}$$

where $\kappa < 1$ and depends on the rates for Z′ mediated scatt. $e^+ e^- \rightarrow NN$ and inverse decay $lH \rightarrow N$

κ Details

- Finding κ :

$$\kappa_{i\alpha}(z, z_{\text{in}}) \simeq \int_{z_{\text{in}}}^{z} \mathrm{d}z' \frac{\mathrm{d}N_{N_i}^{\text{eq}}}{\mathrm{d}z'} \frac{D(K_i, z')}{D(K_i, z') + 4S_{Z'}(z')N_{N_i}^{\text{eq}}(z')} \times \exp\left(-\int_{z'}^{z} \sum_i W^{\text{ID}}(K_{i\alpha}, z'')\mathrm{d}z''\right), \quad (5)$$

where $N_{N_i}^{\text{eq}}(z) = \frac{1}{2}z^2\mathcal{K}_2(z)$, $D(K, z) = Kz\mathcal{K}_1(z)/\mathcal{K}_2(z)$

(Buchmuller,dibari Plumacher)

- Note: κ very small, when S >> D- i.e. lighter Z';
- **As M$_{Z'}$ increases, S ~ D, κ gets bigger and there is a large range where adequate leptogen is possible**. Implies a lower limit on M$_{Z'}$

Can LHC Directly probe the primordial lepton asym. ?

- Since $\eta_B \approx 10^{-2}\varepsilon_l \kappa$, small efficiency κ means ε_l large ; Search for where κ is tiny so ε_l if order 1.
- Detectable at LHC by searching for like sign leptons
- **(Blanchet, Chacko, Granor, RNM: arXiv:0904.2974)**
- **Basic idea:**

$$\varepsilon_l = \frac{\sum_\alpha \left[\Gamma(N_i \to \ell_\alpha^+ W^-) - \Gamma(N_i \to \ell_\alpha^- W^+)\right]}{\sum_\alpha \left[\Gamma(N_i \to \ell_\alpha^+ W^-) + \Gamma(N_i \to \ell_\alpha^- W^+)\right]}$$

- **At LHC, PP→Z'+X**

$$N \to l^{\pm} W^{\mp}, \overset{(-)}{\nu} Z$$

↓

- 25% of time **NN→$\ell^{\pm} x \ell^{\pm} x$**
- **Look for a CP violating observable !**

Direct probe of resonant leptogenesis, contd.

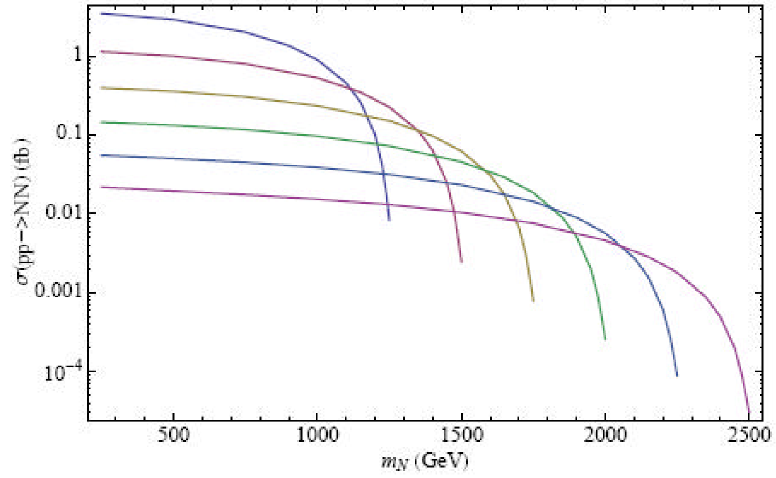
- **Relation between primordial lepton asymmetry and CP violating LHC observable:**

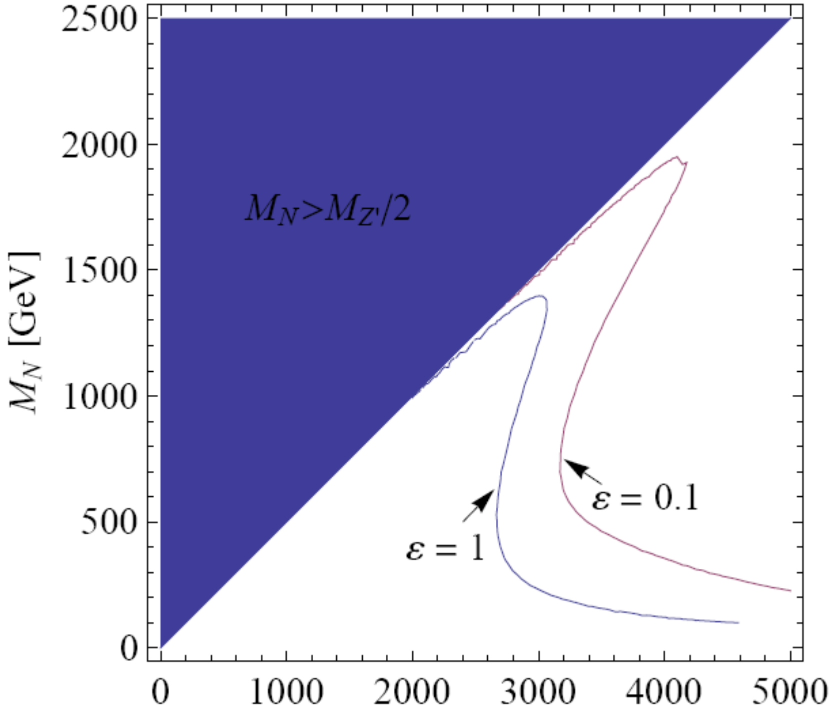
$$\frac{\Sigma_{\alpha\beta}[\Gamma(l_\alpha^+ l_\beta^+)-\Gamma(l_\alpha^- l_\beta^-)]}{\Sigma[\Gamma^{++}+\Gamma^{--}]}=\frac{2\varepsilon_l}{3}$$

- Will hold for susy case if the RH sneutrinos are not degenerate i.e. B-mu term not very small as in soft leptogenesis.
- Independent of neutrino mass pattern.

Range of Z′-N masses where leptogenesis can be probed:

- For certain ranges of Z′-N mass, κ very small so that ε_l ~0.1-1 possible; this can be visible at LHC: (graph below M$_{Z'}$ 2.5-5 TeV)





Numbers

- 300 fb^-1, expect 255 dilepton events (85% det eff.)
- 90% of events with jets or one missing E.
- With no CP violation: 31.5 ++ and - - events;
- Can detect $\varepsilon \geq 0.1$ at 2 sigma level.
- **Such an observation will be a direct probe of leptogenesis, if RH mass deg. is established from inv mass study.**
- How to know if the observed asymmetry is not due just one RH decay with CP violation or non-deg RH:

Testing for degeneracy

- **For non-degenerate neutrinos, the LHC CP asymmetry comes from the vertex correction and is necessarily small. If it is some high scale physics enhancing this asymmetry**
- **For one N, there are 5 observables, $N_{l_\alpha l_\beta}$ but only two inputs; we have three relations: $N_{e\mu} = \sqrt{N_{ee} N_{\mu\mu}}$**

and two others for other flavors;

- **For 2 N's, 4 inputs and 5 observables; only one relation. none for three !**
- **None for three RH's.**

How natural is degenerate RH spectrum ?

- Model: $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$ xO(3)$_H$ with RH nu's triplet under O(3)$_H$ – all other fermion fields singlet.
- Higgs: $\chi(1,-1,+2)_1; \sigma(1,0,0)_a$1,2 + SM like Higgs.
- **Seesaw arises from following Yukawa Lagrangian**: $L = fN_a N_a \chi + \frac{(N\sigma)^2 \chi}{M^2} + LH(N\sigma)/M + \ldots$
- Choose $\frac{<\sigma>}{M} \sim 10^{-5}$ will give desired parameters.
- Since Dirac Yukawas are ~10^-5, RH neutrino mass splitting is radiatively stable -leptogen can be probed.

Left-right embedding

- **Left-right Model:** $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- **Solves SUSY and Strong CP in addition to automatic RP**
- Unless M_{W_R} > 18 TeV, L-violating scatterings e.g.

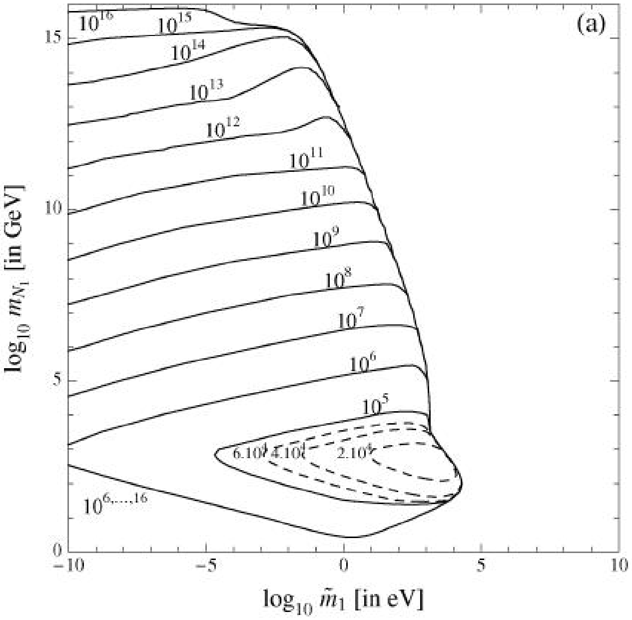
$e_R + u_R \rightarrow N + d_R$ **will** erase lepton asymmetry.

(Frere, Hambye and Vertongen)

Sym br. to $U(1)_{I_{3R}} \times U(1)_{B-L}$

then to SM at TeV-

to do resonant lepto.



Resonant leptogenesis in LR model

- Key question is whether degenerate RH neutrino spectrum is radiatively stable to have leptogeneesis possible !!
- **Yes- since largest rad correction to RH masses is** $$\frac{\delta M_N}{M_N} \sim \frac{h_\tau^2}{16\pi^2} \sim 10^{-6}$$
- Whereas CP asymmetry is: $$\varepsilon \sim \frac{\mathrm{Im}[(h^+h)^2]}{h^+h\frac{\delta M_N}{M_N}}$$
- Which gives for h~10^-5.5, $\varepsilon \sim 10^{-5}$
- Not visible from Z' decay but nonetheless a viable low scale model for leptogenesis and dark matter !!

What if RH neutrinos are TeV scale but nondegenerate ?

- Can one have seesaw scale around a TeV so LHC can see it and still understand the origin of matter related to seesaw physics ?

- Yes- baryogenesis then must arise below 100 GeV scale unless it of totally different origin e.g. EWB or Affleck-Dine or…

New Baryogenesis Mechanism with TeV Q-L unified seesaw

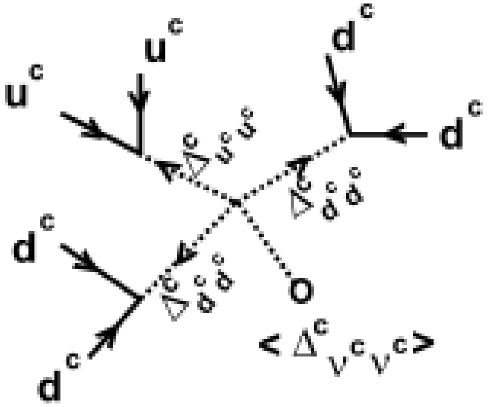
- SU(2)$_L$xU(1)$_R$xU(1)$_{B-L}$ ⊂ SU(2)$_L$xU(1)$_R$xSU(4)$_{PS.}$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} \nu \\ e \end{pmatrix}_L , \begin{matrix} u_R \, \nu_R \\ d_R \, e_R \end{matrix} \rightarrow \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R} ;$$

- **Recall** Origin of RH nu mass for seesaw is from $NN\Delta_{\nu_R\nu_R}$
- **Q-L unif. implies quark partners for** $\Delta_{\nu_R\nu_R}$ **i.e.** $\Delta_{u^c u^c}$ **- color sextet scalars coupling to up quarks** ; similar for dd- only right handed quarks couple. **Come from (1, 1, 10)**
- SU(4)$_{PS}$ **breaks to** U(1)$_{B-L}$ **above 100 TeV**

Baryon violation graph

- $\mathcal{L}_I = \frac{h_{ij}}{2}\Delta_{d^c d^c} d^c_i d^c_j + \frac{l_{ij}}{2}\Delta_{u^c u^c} u^c_i u^c_j + \lambda \Delta_{u^c u^c}\Delta_{d^c d^c}\Delta_{d^c d^c}\Delta_{\nu_R \nu_R}$
- + h. c.
- Δ B=2 but no Δ B=1; hence proton is stable but neutron can convert to anti-neutron!
- N-N-bar diagram



- (RNM, Marshak,1980)

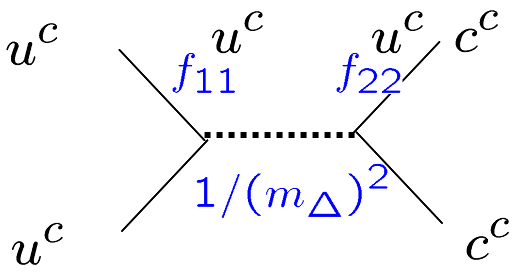
- λ coupling crucial to get baryogenesis (see later)

PHENOMENOLOGICAL ASPECTS

$$W_Y \supset f\psi^c\Delta^c\psi \to f_{ij}\Delta_{u^cu^c}\, u_i^c u_j^c + f_{ij}\Delta_{d^cd^c}\, d_i^c d_j^c + \ldots$$

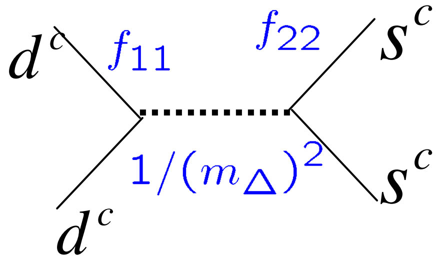
Constraints by rare processes

$D^0 - \overline{D^0}$ **mixing**



$\Delta_{u^cu^c}$ *exchange*

$K - \overline{K}$



$\Delta_{d^cd^c}$

Similarly B-B-bar etc. Can generate neutrino masses - satisfying FCNC

Details of FCNC constraints:

- **Hadroni**

$$\frac{f_{uu_{11}} f_{uu_{22}}}{[m_{\Delta^0_{uu}}(\mathrm{TeV})]^2} \lesssim 1.26 \times 10^{-6}$$

$$\frac{f_{dd_{11}} f_{dd_{22}}}{[m_{\Delta^0_{dd}}(\mathrm{TeV})]^2} \lesssim 2.2 \times 10^{-6}$$

$$\frac{f_{dd_{22}} f_{dd_{33}}}{[m_{\Delta^0_{dd}}(\mathrm{TeV})]^2} \lesssim 1.29 \times 10^{-4}$$

$$\frac{f_{11_{dd}} f_{33_{dd}}}{[m_{\Delta^0_{dd}}(\mathrm{TeV})]^2} \lesssim 5.42 \times 10^{-6}$$

$\mu \rightarrow e + \gamma$

$$\frac{f_{11} f_{12}}{[m_{\Delta^{++}}(\mathrm{TeV})]^2} = G_F \sqrt{BR_1} \leq 1.17 \times 10^{-5}$$

Examples of color sextet couplings that work.

- Down sector:

$$f_{dd} = \begin{pmatrix} 0 & 0.95 & 1 \\ 0.95 & 0 & 0.01 \\ 1 & 0.01 & -0.0627357 \end{pmatrix} 10^{-2}$$

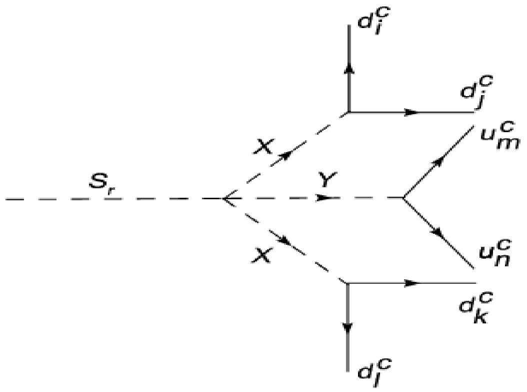
$$f_{uu} = \begin{pmatrix} .3 & * & * \\ * & 0 & * \\ * & * & .3 \end{pmatrix}$$

- Fits neutrino mass via type I seesaw.

Origin of matter

- (Babu, Nasri, RNM, 2006)
- Call Re $\Delta_{\nu_R\nu_R}$ = S$_r$; S-vev generates seesaw and

Baryon number is broken once $\langle S \rangle \neq 0$
leading to B-violating decays $S_r \to 6q, \quad S_r \to 6\overline{q}$

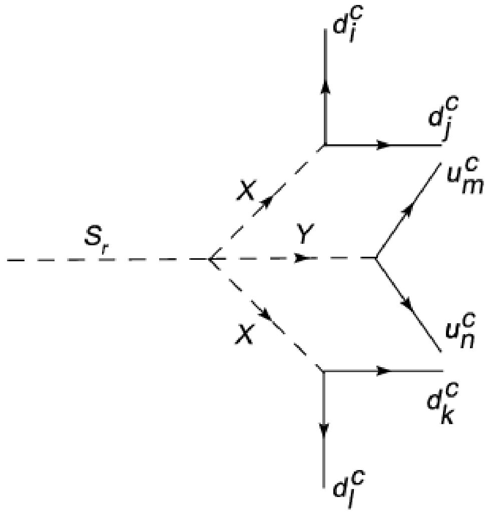


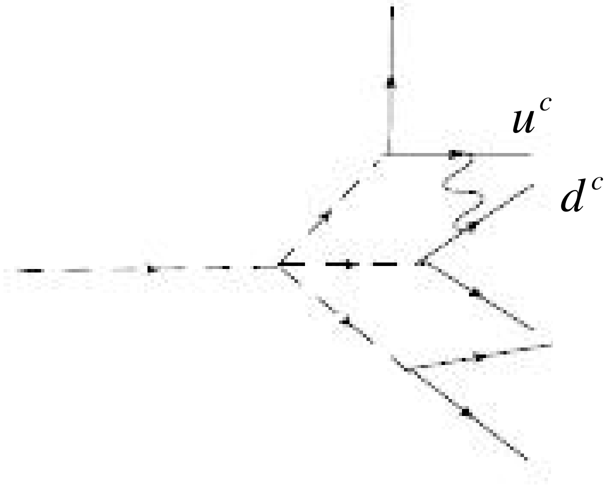
$$\Gamma(S_r \to 6q) \simeq \frac{18P\lambda_2^2 h^2 g^2 M_{S_r}^{13}}{(2\pi)^9 (6M_X)^{12}}$$

- S-mass ~TeV since B-L breaks near TeV.
- Due to strong dependence on **X** (sextet) mass, requiring it to be less than BBN time restricts **X** mass near or less than TeV.

Direct Baryogenesis

- Baryogenesis must occur after sphaleron decoupling to survive since there are both L and B-violating processes.
- Due to high dimensional operator of B-violation, these processes are very slow and go out of eq. at low T (< GeV)
-





- Only CKM CPV enough to generate B-asymmetry !!

Limit on S_r and color sextet masses:

- Two key constraints:

$$\frac{\epsilon_B^{\text{vertex}}}{\text{Br}} \simeq -\frac{\alpha_2}{4}\frac{6\ \text{Im}\ [f_{31}^2 m_t V_{tb} m_b f_{33}^* m_t V_{tb} m_b]}{(\text{Tr}[f^\dagger f])^3 M_W^2 M_S^2}$$

→ M_s < 500-700 GeV **to get right amount of baryons.**

- **Decay before BBN temp:**

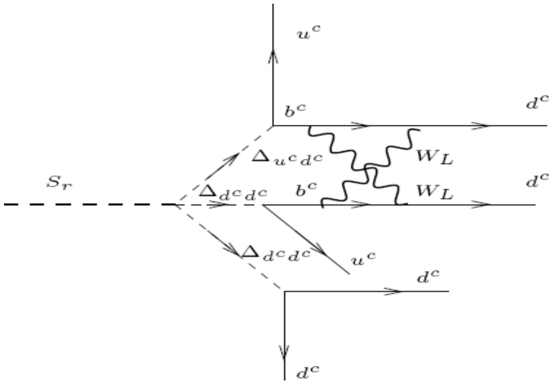
$$\Gamma(S_r \to 6q) \simeq \frac{18 P \lambda_2^2 h^2 g^2 M_{S_r}^{13}}{(2\pi)^9 (6M_X)^{12}}$$

- **Implies M_s< M_x < 2 M_s.**

Two experimental implications:

- $n-\bar{n}$ **oscillation:** successful baryogenesis implies that color sextets are light (< TeV) (Babu, RNM, Nasri,06; Babu, Dev, RNM'08);

  $n-\bar{n}$ **arises via the diagram:**

  $$\tau_{n\bar{n}} \approx 10^9 - 10^{11}\ \sec.$$

- **Present limit: ILL >10^8 sec. similar bounds from Soudan,S-K etc.**
- **10^11 sec. reachable with available facilities !!**
- **A collaboration for NNbar search with about 40 members exists-Exploration of various reactor sites under way.**

Color sextet scalars at LHC

- Low seesaw scale + baryogenesis requires that sextet scalars must be around or below a TeV:
- Two production modes at LHC:

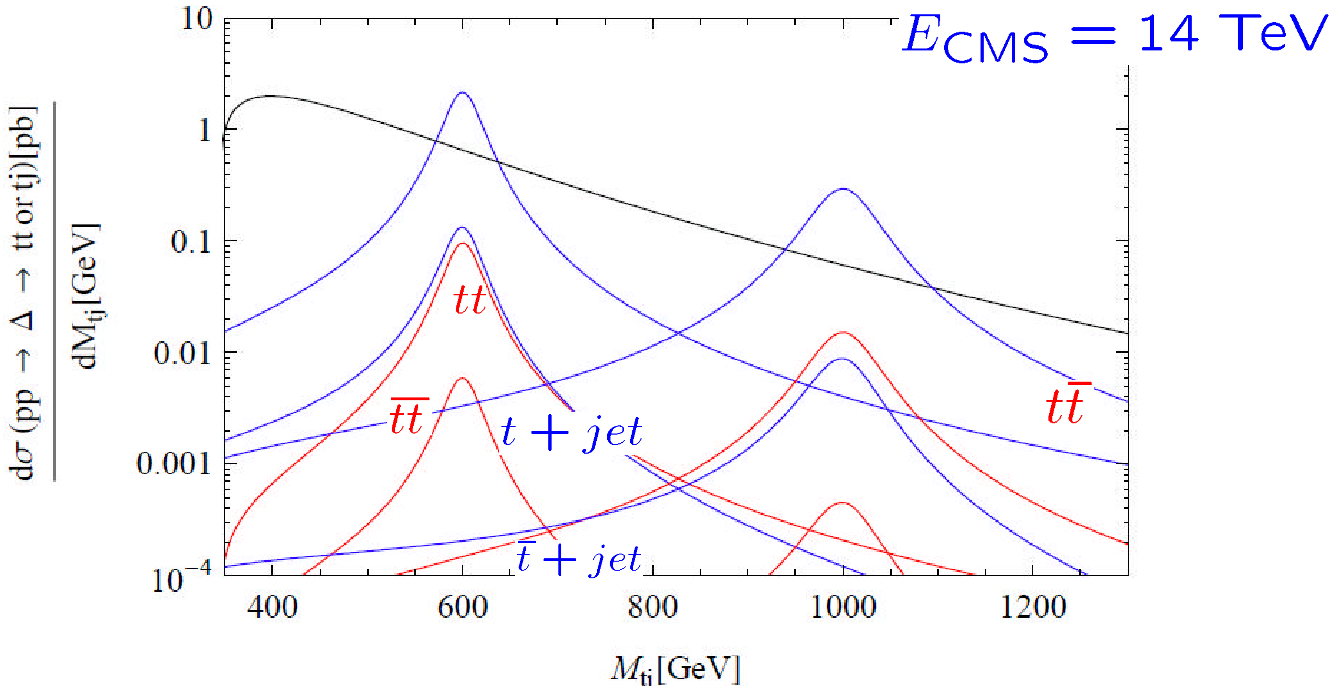
(I) Single production: $uu \to \overline{\Delta}_{u^cu^c} \to tt$ or $t + \text{jet}$

(II) Drell-Yan pair production: $q\bar{q} \to G \to \Delta_{u^cu^c}\Delta^*_{u^cu^c}$

- Distinct signatures: like sign dileptons+ missing E.

SINGLE SEXTET PRODUCTION AT LHC:

$$f_{ij} = \begin{bmatrix} 0.3 & 0 & 0.3 \\ 0 & 0 & 0 \\ 0.3 & 0 & 0.3 \end{bmatrix}$$



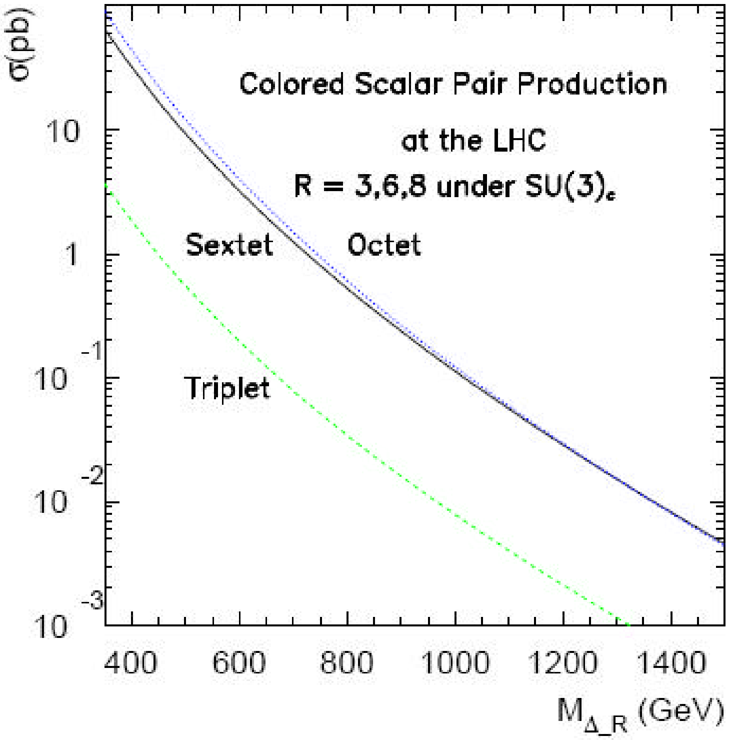
Diquark has a baryon number & LHC is ``pp'' machine

→ $\sigma(tt) \gg \sigma(\overline{tt}), \qquad \sigma(t + jet) \gg \sigma(\bar{t} + jet)$

Depends on Yukawa coupling: RNM, Okada, Yu,07

Pair Production of Deltas

- Due to color sextet nature, Drell-Yan production reasonable:
- Leads to $tt\bar{t}\bar{t}$ final states:
- Can be probed upto a TeV using like sign dilepton mode.
- Chen,Klem,Rentala,Wang'08
- Lewis, Pheno '09.



Conclusion:

- TEV scale seesaw with origin of matter leads to distinct signals at LHC.
- **For certain ranges of the Z′-N mass, LHC can probe resonant leptogenesis directly i.e. find Z′-N in the allowed range simultaneously with large CP asymmetry and two or more deg RH N → direct observation of leptogenesis.**
- **Color sextet Higgs arise in a quark-lepton unified version of seesaw; can be seen at LHC - another window to TeV scale seesaw physics as well as baryogenesis. In this case, Z′ is beyond the LHC range due to baryogenesis constraints.**