Color Sextet Scalars

in Colliders, Cosmology and low energy physics

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Plan:

- **TeV mass color sextet scalars** *(über-Higgses)*
- **Neutrino mass + quark-lepton unification→ a motivation for Color sextet scalars**
- **Can have TeV to sub-TeV mass;**
- **Lead to new phenomena:**

  (i) neutron-anti-neutron oscillation- no proton decay

  (ii) new way to understand the origin of matter;

  (iii) FCNC effects

  (iv) New signals at LHC

NEW TEV SCALE SCALARS

- **Bottom-up view: What are possible TeV mass <u>scalars</u> that could couple to SM fermions** (quarks) **without making trouble ?**

SM

- **Color quantum no.** $\{1\}$ $\{3,3^*\}$ $\{6,6^*\}$

couples to $\bar{Q}u,..$ QQ, QL $(QQ)_6$

SM Higgs

$\otimes$ **Leads to p-decay**

Allowed; are they there ?

Their interaction and new class of baryon violation

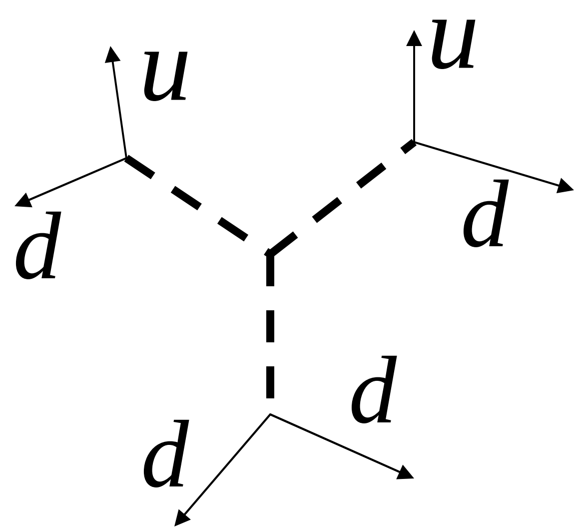
- **Three types of sextet scalars**: $\Delta_{uu}, \Delta_{ud}, \Delta_{dd}$

- **Their interactions:** $\mu \Delta_{ud} \Delta_{ud} \Delta_{dd}$ **+**

$$L = f_{uu} u^c u^c \Delta_{uu} + f_{ud} u^c d^c \Delta_{ud} + f_{dd} d^c d^c \Delta_{dd} + h.c.$$

- **Leads to B=2 baryon violation:** $n \leftrightarrow \overline{n}$

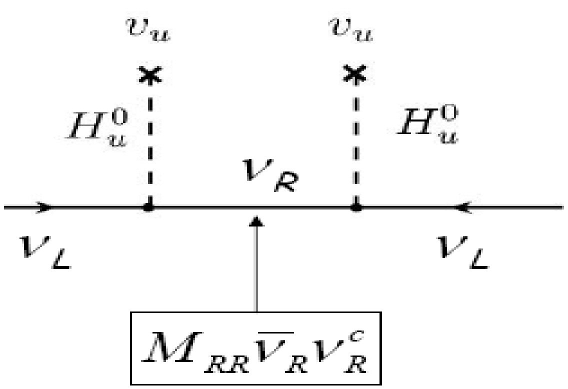
$$G_{B=2} \sim \frac{f^3 \mu}{M_{\Delta}^6}$$



Sextet scalars from Seesaw Paradigm for neutrinos

- **Seesaw mechanism:** **SM+ Majorana** N

$$L_Y = h_\nu \bar{L} H N_R + M_R NN$$



- M_R New scale

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

-Neutrino majorana

→small nu mass natural since $M_R >> hv_{wk}$

- Minkowski,Gell-Mann, Ramond Slansky,Yanagida, Mohapatra,Senjanovic,Glashow

Origin of scale M_R

- **Standard model: gauge sym.** $SU(2)_L \times U(1)_Y$
- **Fermions:**

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R \quad d_R$$

$$m_\nu = 0 \quad \leftarrow \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R$$

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- $N_R \rightarrow$ **Gauge group**:

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

- New scale - breaking

New Scalars for symmetry breaking and fermion masses

$$\phi = \begin{pmatrix} \phi_1^{\ 0} & \phi_2^{\ +} \\ \phi_1^{\ -} & \phi_2^{\ 0} \end{pmatrix}$$

$$\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^{+} & \Delta^{++} \\ \Delta^{0} & -\frac{1}{\sqrt{2}}\Delta^{+} \end{pmatrix}$$

$$\phi = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$$

$$< \Delta >= \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

Break symmetry

$$L = h\overline{Q}_L \phi Q_R + f(LL\Delta_L + RR\Delta_R) + h.c.$$

Seesaw from LR

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

Nu-masses

$$\begin{pmatrix} 0 & 0 \\ 0 & M \end{pmatrix}$$

$$\downarrow \quad <\Delta_R> \neq 0$$

$$M_{W_R}, M_{Z'} \neq 0$$

$$SU(2)_L \otimes U(1)_Y$$

$$\downarrow \quad <\phi> = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$$

$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

$$U(1)_{em} \quad M_{W_L}, M_Z \neq 0; m_{q,l} \neq 0$$

Seesaw matrix: seesaw scale is LR scale

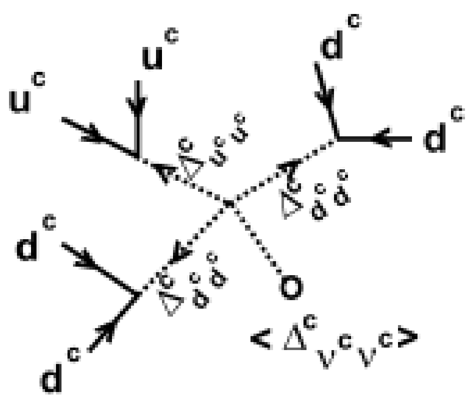
Quark-lepton Unification and color sextets

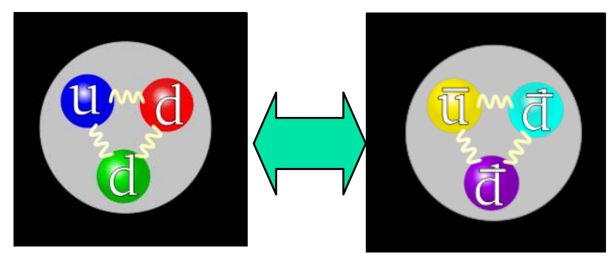
- LR+QL → $\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$
- Gauge group: $SU(2)_L \times SU(2)_R \times SU(4)_c$ **(Pati, Salam'74)**
- **New Higgses for seesaw:** **(Mohapatra,Marshak'80)**
- $\Delta_{ll} LL$ → $\Delta_{qq} QQ$ **Color sextets**
- **(1,3,2) → (1,3,10)**

+ lepto-quarks

New phenomena associated with sextets

- <u>n-n-bar oscillation</u> **but no proton decay**
- Majorana neutrino→ L=2;
- n-n-bar oscillation → B=2 **(Mohapatra, Marshak'80)**
- **n-n-bar diagram:**



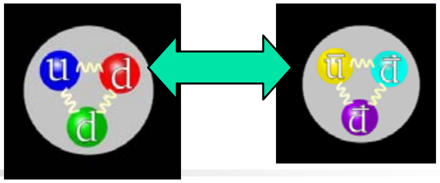


$$A_{n\bar{n}} \sim \frac{\lambda f_{qq}^{3}}{M_{\Delta}^{5}}$$

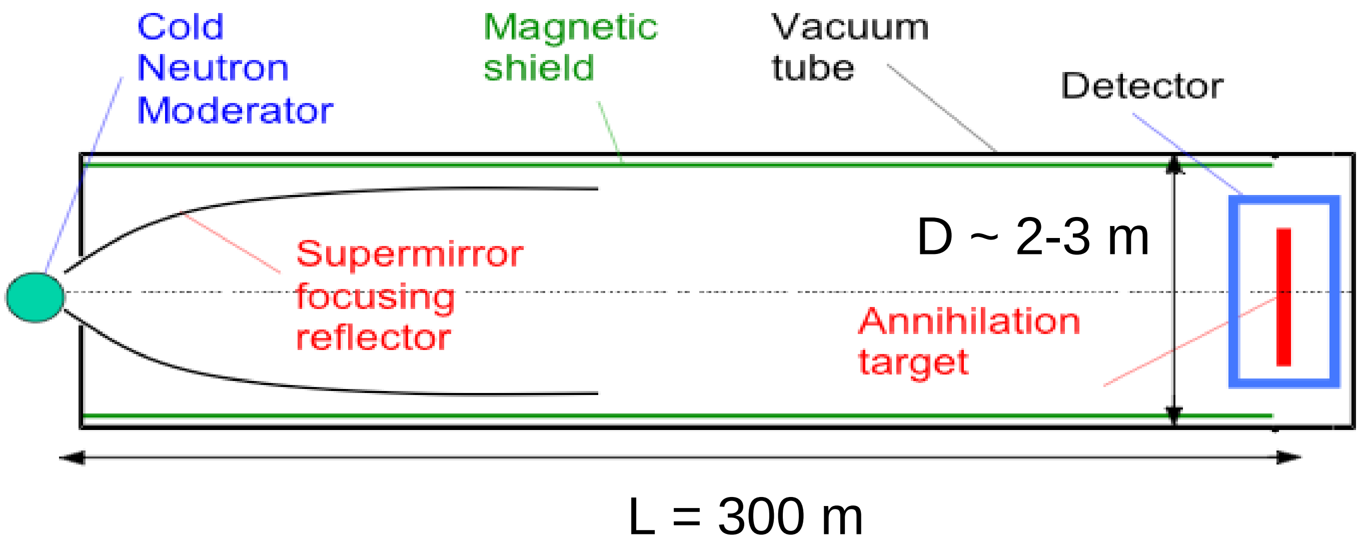
$$\delta_{n\bar{n}} = A_{n\bar{n}} \Lambda_{QCD}^{6} \Rightarrow \tau_{n\bar{n}} = \frac{\hbar}{\delta_{n\bar{n}}}$$

- **Oscillation time:**
- $M_{\Delta} \sim TeV$ $\quad \tau_{n\bar{n}}$ ≃ yr to few years **; Observable!**

Search for n-n-bar Osc. current status



- **Free neutron oscillation in reactors: generic setup**



- **Current bound (ILL'94)**

$$\text{with L} \sim 90\text{ m and } \langle t \rangle = 0.11\text{ sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6 \times 10^{-18}$$

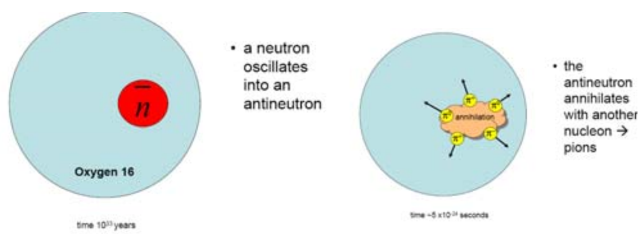
$$\tau > 8.6 \times 10^{7}\text{ sec}$$

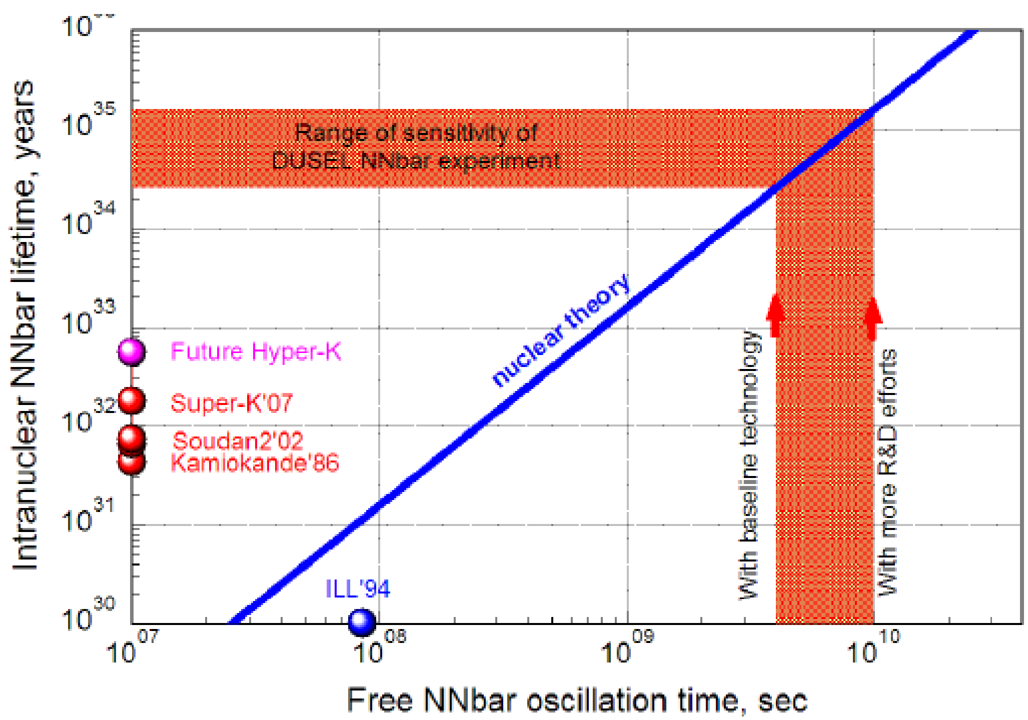
- **Searching for new site: NANO workshop'Feb.'11**

Bound neutron:

- **Searches in nucleon decay expts: S-K, Soudan, IMB…**

τ_{nucl} à $2\cdot 10^{32}\, yr$ (SK-2009)





$$\tau_{Nuc} = R\tau^2_{free}$$

$$R = 0.3\times 10^{23}\ \sec^{-1}$$

- **Future**

n-n-bar as complementary to proton decay search

- Proton decay will search B-L (Seesaw) scale in the range of GUT scale (~ 10^14 GeV or higher);
- Neutron-anti-neutron oscillation will search B-L from few TeV (without susy) to 10^11 GeV (with susy).
- Urge new direct search for NNbar.
- There is a proto-collaboration **(NANO)**

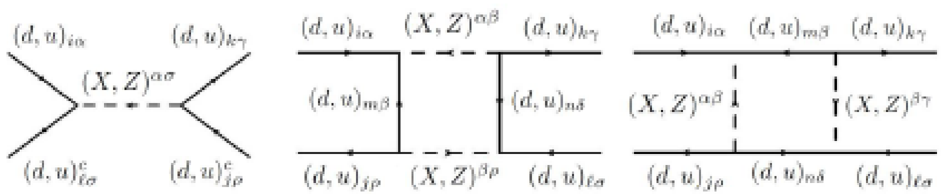
Can diquarks be naturally light in high B-L scale models

- So far we have assumed that seesaw scale is also in the TeV range.
- In susy seesaw models, even for seesaw scale in the 10^10 range, due to accidental global symmetry of the superpotential, $\Delta_{u^c u^c}$ can be naturally in TeV range

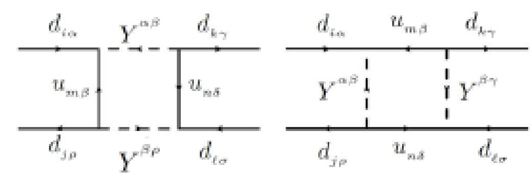
(Chacko, Mohapatra'98)

Light diquarks and FCNC

- Tree and box diagrams lead to FCNC effects



(dd and uu sextets)



ud sextets:

- **Tree graph constraints**: (Babu, Fortes, RNM'2011(to appear))

  --TeV mass dd-sextets: $f_{11}^{dd} \neq 0;\ f_{22,33}^{dd} \approx 0$ (at least 2 diags tiny)

  (from B-B-bar and K-K-bar)

  --TeV mass uu-sextets: $f_{22}^{uu} \approx 0;\ f_{11,33}^{uu} \neq 0$

  (D-D-bar)

Light diquarks-off-diagonal couplings

- Only box diagrams lead to FCNC effects:
- Allowed domain:

--TeV mass dd-sextets: $|f_{i3} f_{i1}^*| < 0.0302$

(from B-B-bar and K-K-bar) $|f_{i2} f_{i1}^*| < 0.0147$

--TeV mass uu-sextets: $|f_{i2} f_{i1}^*| < 0.0111$

(D-D-bar)

- Many allowed textures for uu coupling: e.g.

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

Color sextets and some anomalies:

- Sextet induced Bs-Bs-bar mixing with CP violation in its coupling can explain Tevatron dimuon anomaly:

- There is also an anomaly in understanding ε_K
  in SM (Buras-Guadagnoli) : ε_K and $B \to J/\psi + K_S$
  involve sin 2 β =0.79+/-.039 0.672+/-0.023

  Color sextet contribution can resolve this.
- Anomaly in B-decay-(sextets can resolve)

  $A_{CP}(B^0 \to K^+\pi^-) = -9.7 \pm 1.2\%; A_{CP}(B^+ \to K^+\pi^0) = 5.0 \pm 2.5\%$
- Explaining decay anomalies require ud mass < TeV

Color sextet scalars at LHC

- Two production modes at LHC:

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

xsection calculated in **(RNM, Okada, Yu'07;)** resonance peaks above SM background- decay to tt or tj **depending on color sextet coupling texture**;

- CDF limit with 6.1 fb^-1 $\sigma(tt + \bar{t}\bar{t}) \times \text{Br}(W \to \ell\nu)^2 < 54\,\text{fb}\,,$

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

model indep. **(Chen, Klem, Rentala, Wang, 08)**

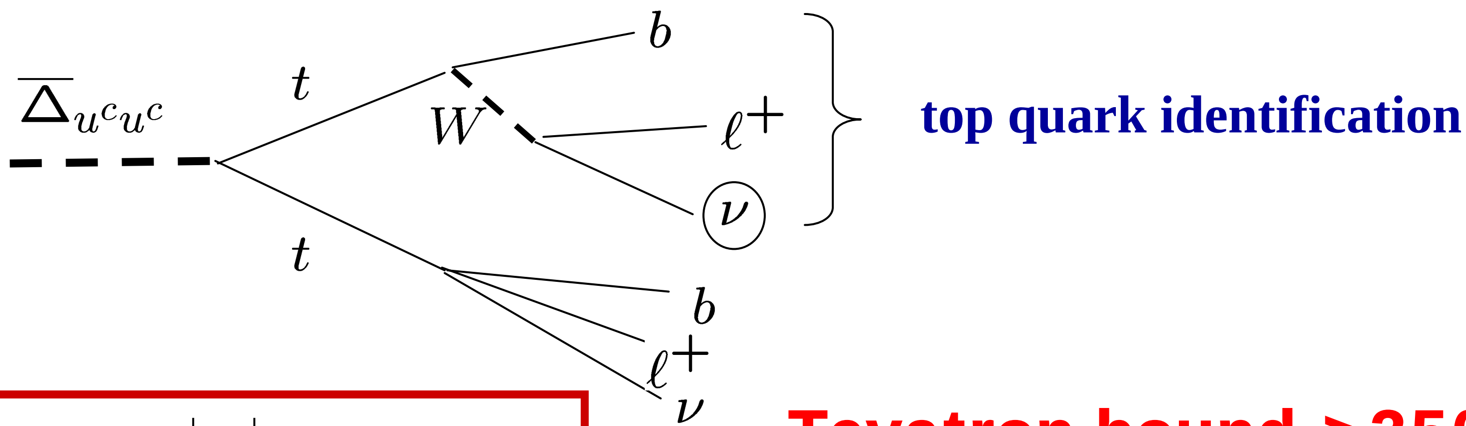
- Leads to $tt\bar{t}\bar{t}$ final states: **LHC reach < TeV**

(Berger, Cao, Chen, Shaughnessy, Zhang'10; Han, Lewis'09)

Signal for single production

So, our target is
$$\begin{cases} uu \to \overline{\Delta}_{u^c u^c} \to tt \text{ or } t + \text{jet} \\ \bar{u}\bar{u} \to \overline{\Delta}^*_{u^c u^c} \to \bar{t}\bar{t} \text{ or } \bar{t} + \text{jet} \end{cases}$$

<u>**To measure diquark mass (final state invariant mass)**</u>



$$pp \to \ell^{\pm}\ell^{\pm}bb + Nj + ..$$

-Tevatron bound >350 GeV.
-LHC can probe till TeV.

Single Sextet production at LHC: (model dep.)

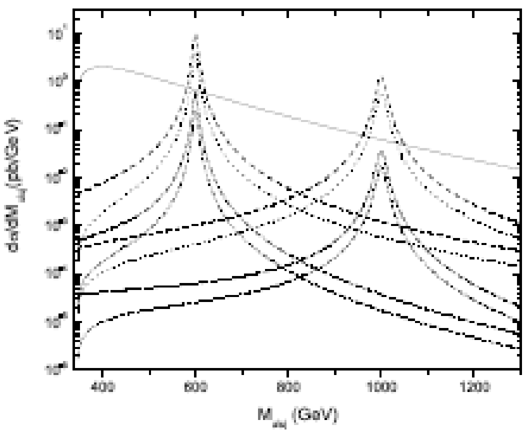
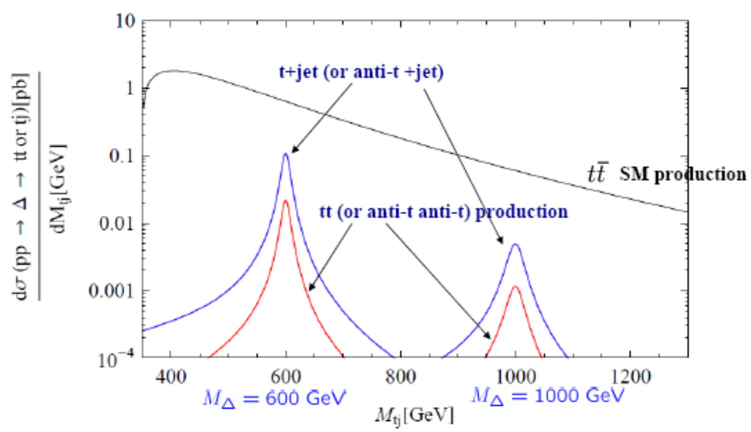


FIG. 2: The differential cross sections for tj (dashed line), tt (dotted line), $\bar{t}j$ (dashed-dotted line) and $\bar{t}\bar{t}$ (dashed-dotted-dotted line) as a function of the invariant mass of final state $M_{u_i u_j}$. The left peak corresponds to $m_\Delta = 600(\text{GeV})$ and the right one to $m_\Delta = 1$ TeV. The solid line is the standard model $t\bar{t}$ background.

$E_{\text{CMS}} = 14$ TeV



Production from sea quarks

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

$\rightarrow$ $\sigma(tt) \gg \sigma(\overline{tt}), \quad \sigma(t + jet) \gg \sigma(\bar{t} + jet)$

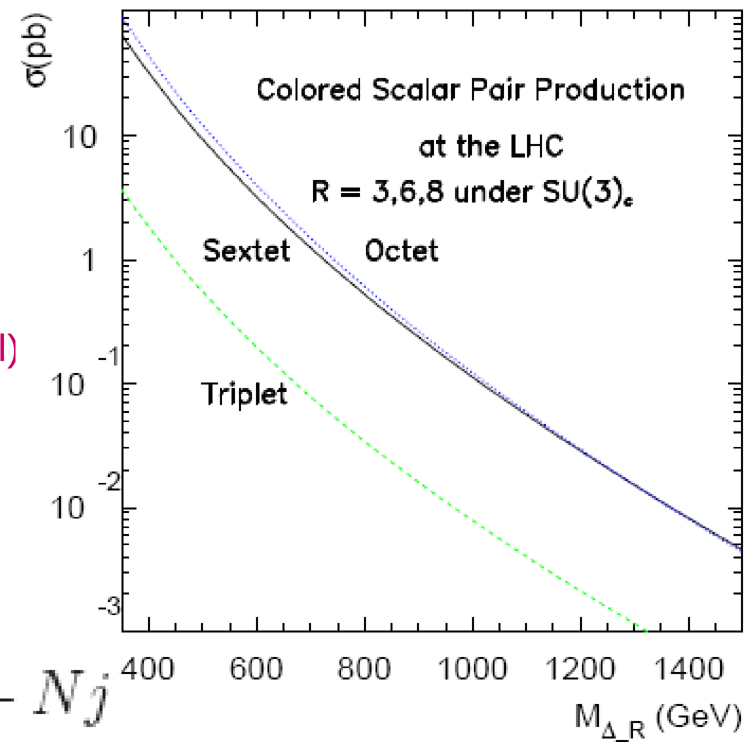
Depends on Yukawa coupling

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

Pair Production of Deltas

- Due to color sextet nature, Drell-Yan production enhanced- independent of Yukawa coupling

  (model indep)



- Leads to $tt\bar{t}\bar{t}$ final states (Chen et al)

- Signal

$$pp \to \bar{\Phi}_6\Phi_6 \to tt\bar{t}\bar{t} \to 4b + \ell^\pm\ell^\pm + \not{E}_T + Nj$$

Observable nn-bar and baryogenesis

- If nn-bar is observable, it erases any preexisting baryon asymmetry above 100 GeV.

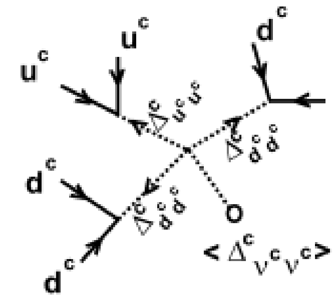
- New way to understand must involve NN-bar necessarily.
- Note NNbar being a high dim operator goes out of eq. below EW scale- must involve baryogenesis without help from sphalerons.

Post sphaleron baryogenesis

New way to understand Origin of matter

- 224 model realization of color sextets: there is a neutral field accompanying color sextets, S with effective int.

$$\frac{S}{\Lambda^6} u_R d_R d_R u_R d_R d_R$$



S

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

Babu, Nasri, RNM'06; Babu, Dev, RNM'09

Post sphaleron baryogenesis

- Due to high dimension, S-decay occurs below EW scale; → **after sphaleron decoupling**.
- Requires light sextets (~TeV mass)

- For a certain parameter domain of the model, adequate baryon asymmetry implies nn-bar transition time < 10^10 sec. (observable using current reactor fluxes)

Conclusion:

- **Color sextets** in the TeV range are motivated by seesaw paradigm for neutrino masses and quark-lepton unification (hint from $m_b \cong m_\tau$; $m_\mu = 3m_s$ at M)

- **Lead to observable NNbar oscillation and new mechanism for baryogenesis.**
- **LHC-an ideal machine to search for sub-TeV mass.**

- **nn-bar** complementary to proton decay for understanding the seesaw physics and new direct search important for true understanding of seesaw and B-L symmetry.