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Prediction of light diquarks observable at LHC from baryogenesis models

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Outline

- Post-Sphaleron Baryogenesis (PSB) – a TeV scale mechanism
- A working model for PSB within quark-lepton unified scheme
- Prediction of neutrino mass hierarchy and mixing parameters
- Prediction of light color sextets
- Other predictions and conclusion

Post-Sphaleron Baryogenesis (PSB)

- Beyond Standard Model scenarios required to explain the observed baryon asymmetry in our Universe.
- **Post-sphaleron baryogenesis** – a possible low-energy alternative to other popular models. [Babu, Mohapatra, and Nasri (2006, 2007)]
- A TeV scale mechanism – occurs after the electroweak sphalerons have gone out of thermal equilibrium.
- A B-number carrying complex scalar field S acquires a TeV scale vev.
- Baryon asymmetry generated by W-loop corrections to the direct decay of S_r (real part of S) having weak scale mass (~ 100 GeV).
- Can be embedded into a quark-lepton unification scheme.
- Predicts TeV scale colored scalar sextets (observable at the LHC).
- Also predicts observable $n - \bar{n}$ oscillation.

G_{224} Embedding

- Based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes SU(4)_c$ (Pati-Salam).

  Fermion sector: $\psi(2,1,4) \oplus \psi^c(1,2,\overline{4})$.

  Higgs sector: $\phi_1(2,2,1)$ and $\phi_2(2,2,15)$ to give mass to the fermions.

  $\Delta^c(1,3,10) \oplus \bar{\Delta}^c(1,3,\overline{10})$ to break the $B-L$ symmetry.

  [Mohapatra and Marshak (1980)]

$$\mathcal{L}_{\text{Yukawa}} = i f_{ij} \Psi_i^{c^T} \tau_2 \Delta^c \Psi_j^{c^T} + h_{ij}^a \Psi_i \Phi_a \Psi_j^c + \text{h.c.}$$

- The Δ^c field can be decomposed under $SU(2)_L \otimes U(1)_Y \otimes SU(3)_c$:

$$\bar{\Delta}^c(1,3,\overline{10}) \equiv \boldsymbol{\Delta}_{u^c u^c}(1,\frac{8}{3},6^*) \oplus \boldsymbol{\Delta}_{u^c d^c}(1,\frac{2}{3},6^*) \oplus \boldsymbol{\Delta}_{d^c d^c}(1,-\frac{4}{3},6^*)$$
$$\oplus \Delta_{u^c \nu^c}(1,\frac{4}{3},3^*) \oplus \Delta_{d^c \nu^c}(1,-\frac{2}{3},3^*) \oplus \Delta_{u^c e^c}(1,-\frac{2}{3},3^*) \oplus \Delta_{d^c e^c}(1,-\frac{8}{3},3^*)$$
$$\oplus \boldsymbol{\Delta}_{\boldsymbol{\nu^c \nu^c}}(\mathbf{1},\mathbf{0},\mathbf{1}) \oplus \Delta_{e^c \nu^c}(1,-2,1) \oplus \Delta_{e^c e^c}(1,-4,1)$$

- $\Delta_{\nu^c \nu^c}$ is identified as S and $\langle S \rangle \equiv v_{BL}$ breaks $SU(4)_c$ to $SU(3)_c \otimes U(1)_{B-L}$.

- New $SU(3)_c$ sextet scalar fields $\Delta_{u^c u^c,\ u^c d^c,\ d^c d^c}$.

The PSB Lagrangian

- The starting PSB Lagrangian (non-SUSY case) is

$$\begin{aligned}\mathcal{L}_{\text{PSB}} &= \frac{h_{ij}}{2}\Delta_{d^c d^c} d_i^c d_j^c + \frac{l_{ij}}{2}\Delta_{u^c u^c} u_i^c u_j^c + \frac{g_{ij}}{2}\Delta_{u^c d^c}(u_i^c d_j^c + u_j^c d_i^c) \\ &+ \frac{\lambda_1}{2} S\Delta_{u^c u^c}\Delta_{d^c d^c}\Delta_{d^c d^c} + \frac{\lambda_2}{2} S\Delta_{d^c d^c}\Delta_{u^c d^c}\Delta_{u^c d^c} + \text{h.c.}\end{aligned}$$

- Due to $SU(4)_c$ symmetry, we have

$$h_{ij} = l_{ij} = g_{ij} \equiv f_{ij}, \text{ and } \lambda_1 = \lambda_2 \equiv \lambda$$

- Low-energy constraints on m_Δ and f_{ij} from tree-level FCNC effects and $n - \bar{n}$ oscillation period.
- Other constraints come from the neutrino sector and baryogenesis.
- In the non-SUSY case, all the m_Δ's are expected to be light, with typical masses in TeV range.
- Must find a suitable f-matrix satisfying all the constraints.

Low Energy Constraints on f_{ij} and m_Δ

- Tree level flavor changing neutral current constraints from $K-\overline{K},\ D-\overline{D},\ B_{d,s}-\overline{B}_{d,s}$ mixings. [Particle Data Group (2008)]

$$K^0(d\bar{s})-\overline{K}^0(\bar{d}s) \quad : \quad \frac{f_{dd,11}f_{dd,22}}{[m_{\Delta_{d^c d^c}}/\mathrm{TeV}]^2} \leq 3.3\times 10^{-6}$$

$$B_s^0(s\bar{b})-\overline{B}_s^0(\bar{s}b) \quad : \quad \frac{f_{dd,22}f_{dd,33}}{[m_{\Delta_{d^c d^c}}/\mathrm{TeV}]^2} \leq 2.0\times 10^{-4}$$

$$B_d^0(d\bar{b})-\overline{B}_d^0(\bar{d}b) \quad : \quad \frac{f_{dd,11}f_{dd,33}}{[m_{\Delta_{d^c d^c}}/\mathrm{TeV}]^2} \leq 7.6\times 10^{-6}$$

$$D^0(u\bar{c})-\overline{D}^0(\bar{u}c) \quad : \quad \frac{f_{uu,11}f_{uu,22}}{[m_{\Delta_{u^c u^c}}/\mathrm{TeV}]^2} \leq 2.0\times 10^{-6}$$

- In addition, lepton family violating modes such as $\mu^- \to e^-e^+e^-$ imply

$$\frac{f_{ee,11}f_{ee,12}}{[m_{\Delta^{++}}/\mathrm{TeV}]^2} \leq 3.3\times 10^{-5}$$

- Cannot suppress the FCNC effects by simply raising m_Δ as they have to satisfy the baryogenesis constraints as well.

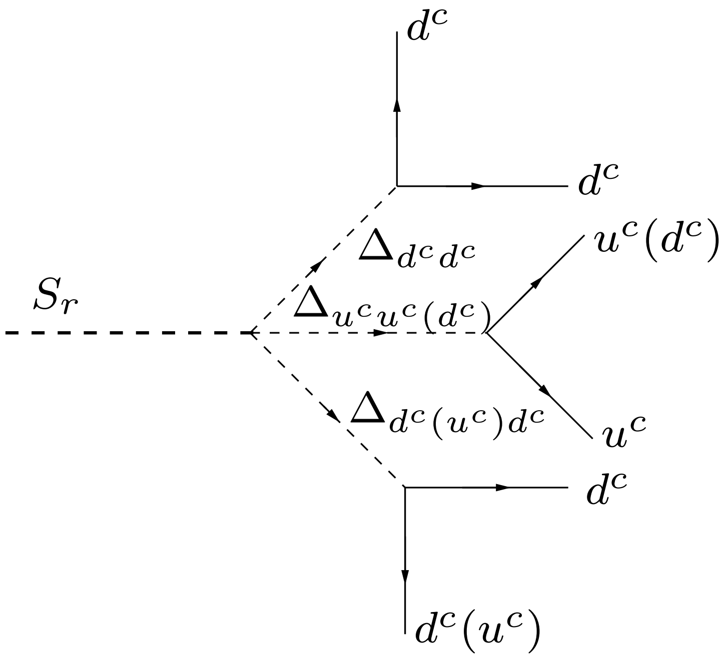
Another Low Energy Constraint

- Another constraint comes from the present limits on $n - \bar{n}$ oscillation period: [Baldo-Ceolin *et al.* (1994); Chung *et al.* (2002); Ganezer (2007)]

$$\tau_{n-\bar{n}} \geq 10^8 \text{ sec.}$$

- In a generic model of our type, the tree-level contribution to the $n - \bar{n}$ operator implies

$$G_{n-\bar{n}} \simeq \frac{\lambda_1 \langle S \rangle f^2_{dd,11} f_{uu,11}}{M^4_{\Delta_{d^c d^c}} M^2_{\Delta_{u^c u^c}}} + \frac{\lambda_2 \langle S \rangle f_{dd,11} f^2_{ud,11}}{M^2_{\Delta_{d^c d^c}} M^4_{\Delta_{u^c d^c}}} \leq 10^{-28} \text{ GeV}^{-5}$$



A Working Model

[Babu, B.D., and Mohapatra (2009)]

- We choose f_{dd} in the down-quark mass eigenstate basis. Then

$$\begin{aligned} f_{ud} &= V_{\mathrm{CKM}} f_{dd} \\ f_{uu} &= V_{\mathrm{CKM}} f_{dd} V_{\mathrm{CKM}}^T \\ f_{\nu\nu} &= U_l f_{dd} U_l^T = f_{ee} \end{aligned}$$

- FCNC constraints are satisfied for a TeV mass $\Delta_{d^c d^c}$ and $\Delta_{u^c d^c}$, and 100 TeV mass $\Delta_{u^c u^c}$, if we choose

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

- Could have allowed a small non-zero (1,1) entry; but $n - \bar{n}$ constraint limits it to $< 10^{-12}$. Other entries chosen to satisfy the neutrino constraints.
- For $f_{\nu\nu}$, we apply a unitary rotation

$$U_l = \begin{pmatrix} \cos\Theta & \sin\Theta & 0 \\ -\sin\Theta & \cos\Theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{with } \Theta = 0.23$$

Neutrino Mass Spectrum

- In general, a combination of Type-I and Type-II see-saw:

$$M_\nu = \gamma \frac{v_{wk}^2}{v_{BL}} f_{\nu\nu} - M_\nu^{\rm Dirac} (v_{BL} f_{\nu\nu})^{-1} \left(M_\nu^{\rm Dirac}\right)^T$$

- Can set $M_\nu^{\rm Dirac} = 0$ by an appropriate choice of the Yukawa couplings and Higgs multiplets.
- Direct link between neutrino mass matrix and coupling matrix f which yields testable consequences in the neutrino sector.
- The neutrino masses and mixing constraints are satisfied only for an inverted mass hierarchy ($m_2^2 > m_1^2 \gg m_3^2$):

$$m_1 \simeq 0.0478\,{\rm eV},\ m_2 \simeq -0.0487\,{\rm eV},\ m_3 \simeq -0.0014\,{\rm eV}$$

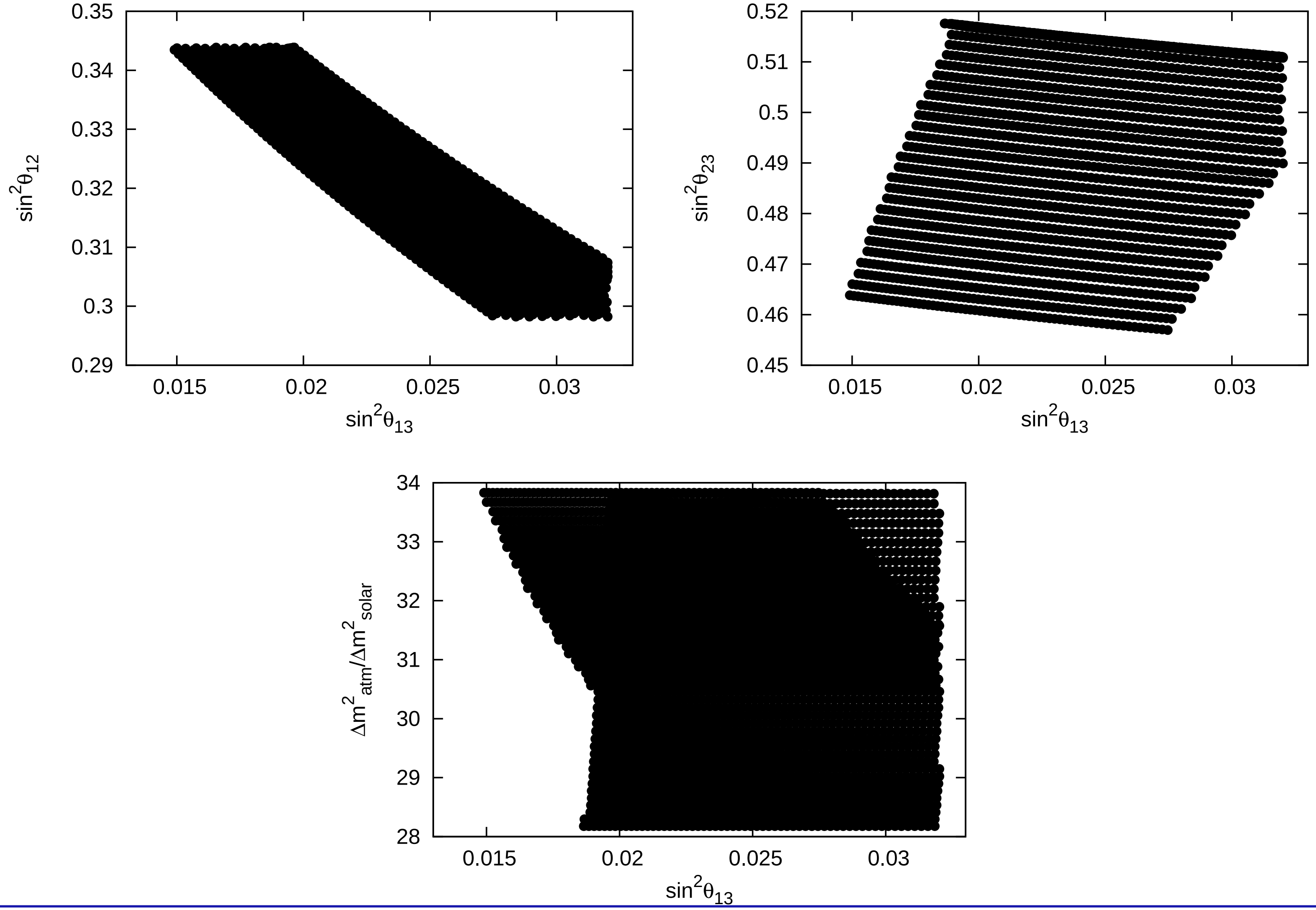
- In agreement with observed neutrino mixing parameters:

$$\frac{\Delta m_{\rm atm}^2}{\Delta m_\odot^2} \simeq 30,\ \theta_\odot \simeq 35^0,\ \theta_{\rm atm} \simeq 46^0$$

- Predicts a non-zero, large $\theta_{13} \simeq 8^0$.
- Observable in the ongoing (Double CHOOZ) and planned (Daya Bay) neutrino experiments. [Ardellier *et al.* (2006); Chu (2008)]

Lower Bound on θ_{13}

- Varying the known neutrino parameters within the experimentally allowed range yields a lower bound on θ_{13}.
- Can be used to falsify the model by future experiments.



The PSB Mechanism

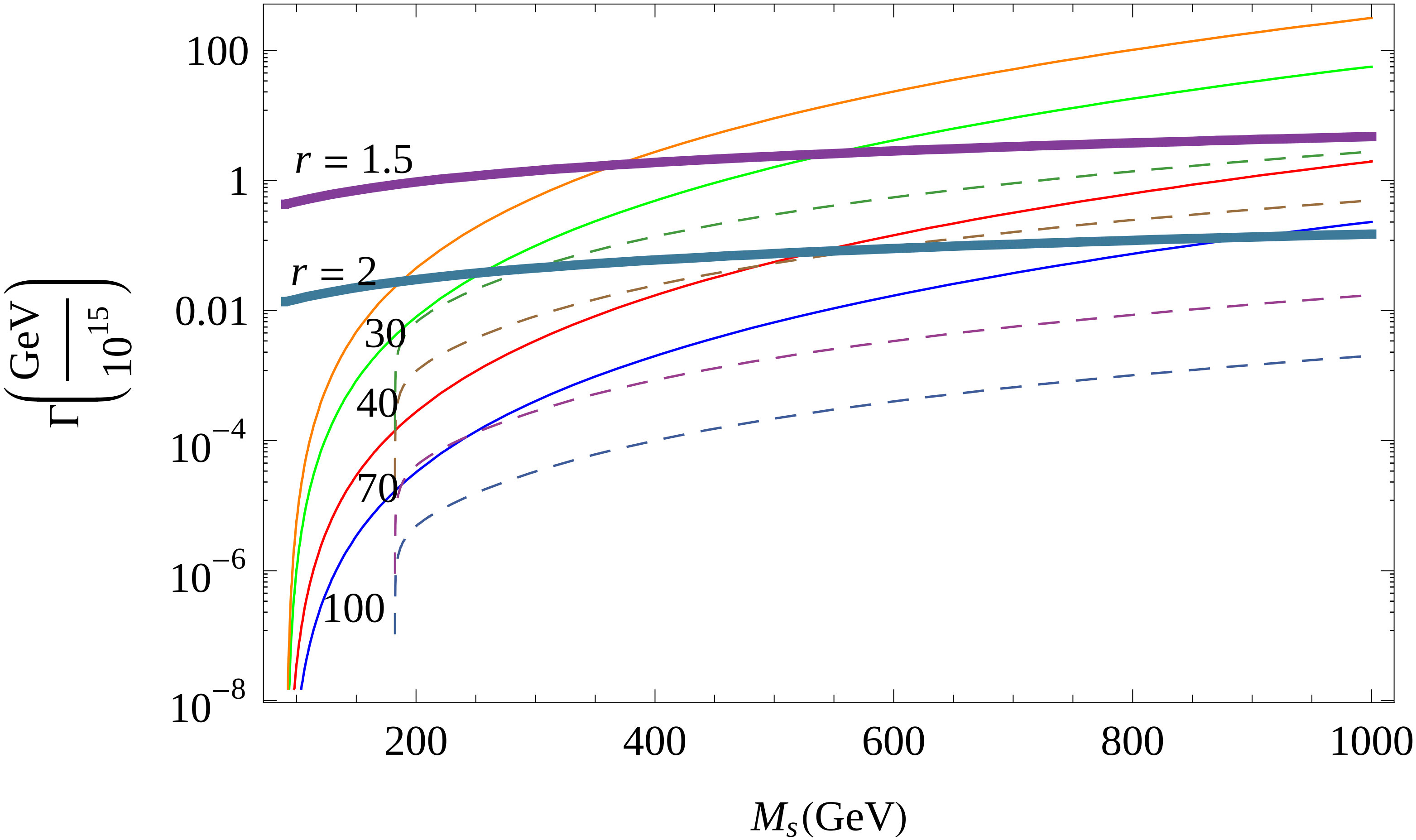
- No $B-L$ violation for temperatures above the $SU(4)_c$ scale ($\sim$ 100 TeV).
- Below $SU(4)_c$ scale, sphalerons in thermal equilibrium erase any pre- existing B-asymmetry down to $m_\Delta \sim 1$ TeV scale.
- B-asymmetry must be generated fresh below the sphaleron decoupling temperature (somewhere below 1 TeV).
- Need the following mass hierarchy:

$$m_t < M_S(\sim 500\ \mathrm{GeV}) < M_{\Delta_{d^c d^c}} \sim M_{\Delta_{u^c d^c}}(\sim 1\ \ \mathrm{TeV}) \ll M_{\Delta_{u^c u^c}}(\sim 100\ \mathrm{TeV})$$

- For $T \leq M_S$, B-asymmetry is produced by $S_r \rightarrow 6q^c$ decay (with $\Delta B = 2$).
- Other decay modes of S_r should be suppressed $\Longrightarrow$ constraints on v_{BL} and the ratio M_S/M_Δ.

Dominant Decay Modes for S_r

$S_r \to Z f^c \bar{f}^c$ (thin solid lines), $S_r \to ZZ$ (thin dashed lines) for various values of v_{BL} (in TeV) and $S_r \to 6q^c$ (thick solid lines) for two typical values of $r = M_{\Delta_{u^c d^c, d^c d^c}}/M_S$.



Need $v_{BL} \geq 50$ TeV for $S_r \to 6q^c$ to be the primary decay mode.

The Decoupling Temperature

- For temperatures $T \leq M_S$, the $S_r \to 6q^c$ decay rate remains constant with temperature:

$$\Gamma_{6q^c} \simeq \frac{36}{(2\pi)^9} \frac{(\mathrm{Tr}[f^\dagger f])^3 \lambda^2 M_S^{13}}{(6M_\Delta)^{12}}$$

- The Hubble expansion rate, however, decreases as the universe cools down:

$$\Gamma_H \simeq 1.66 g_*^{1/2} \frac{T^2}{M_{\mathrm{Pl}}}$$

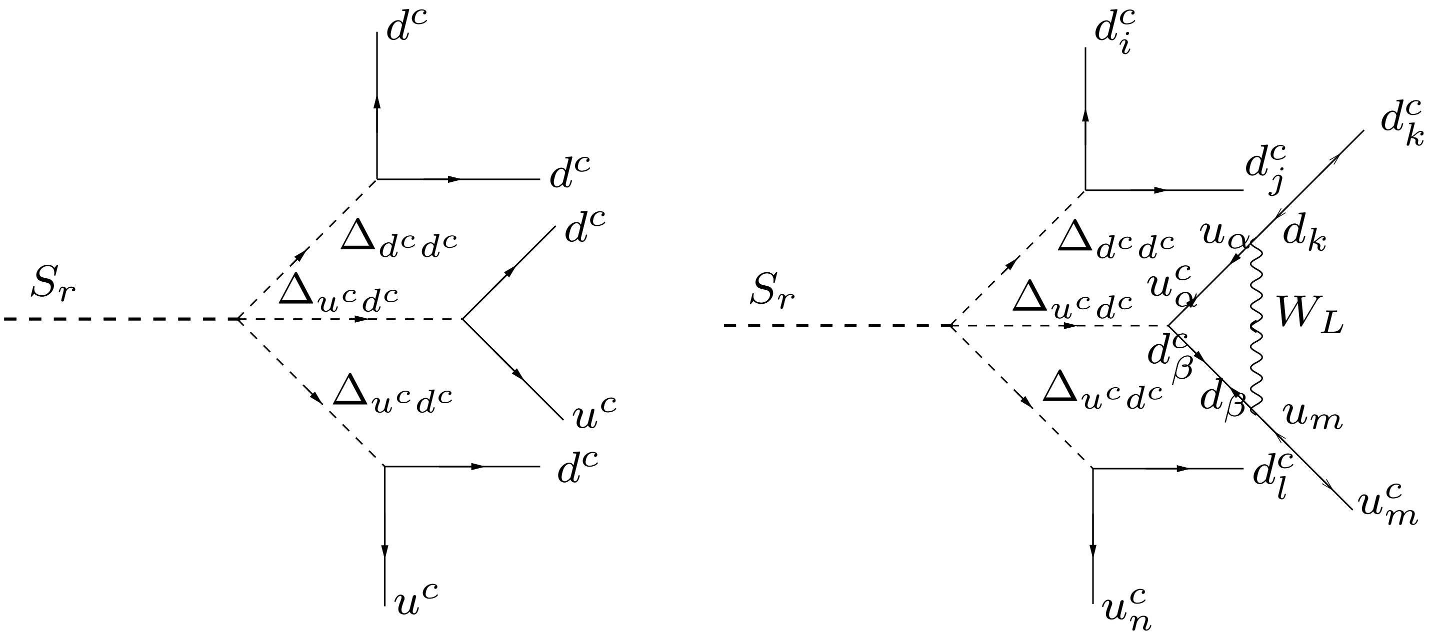
- The S-field decouples from the cosmic soup when $\Gamma_H = \Gamma_{6q^c}$, i.e. at a temperature

$$T_d \simeq 6.1 \ \mathrm{GeV}^{1/2} \left(\frac{M_S^{13}}{M_\Delta^{12}} \right)^{1/2}$$

- T_d must be below ~ 100 GeV (electroweak phase transition scale) and above 200 MeV (QCD scale) to produce adequate baryogenesis.
- Increasing M_Δ arbitrarily to satisfy FCNC constraints would lower the T_d value below QCD scale!
- For $M_S \sim 500$ GeV and $M_\Delta \sim 1$ TeV, we get $T_d \simeq 2$ GeV.

Baryon Asymmetry

- Arises from the interference of tree- and one-loop level diagrams:



$$\frac{\epsilon_B^{\rm vertex}}{\rm Br} \simeq -\frac{\alpha_2}{4}\,\frac{6\,{\rm Im}\,[x^2 f_{31}^2 m_t V_{tb} m_b f_{33}^* m_t V_{tb} m_b]}{({\rm Tr}[f^\dagger f])^3 M_W^2 M_S^2} \sim (2-3)\times 10^{-8}$$

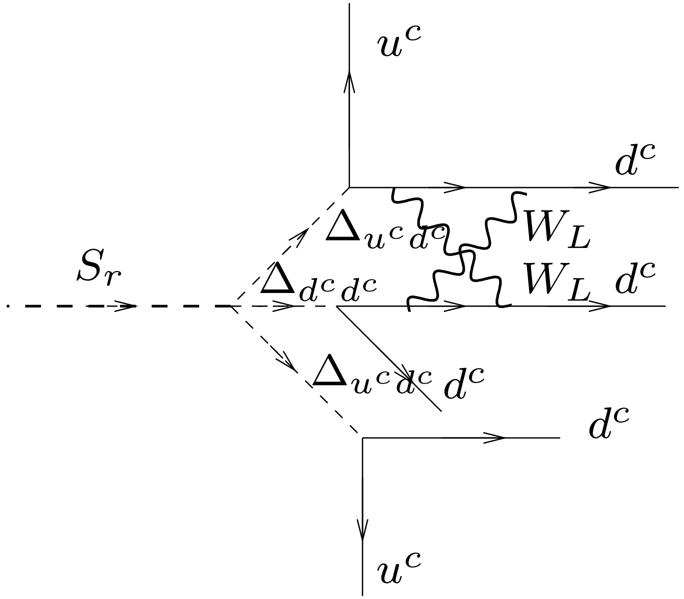
- To obtain the observable quantity η_B, multiply ϵ_B with dilution factors:

$$d_1 = \frac{g_*(T_{\rm rec}\sim 1\ {\rm eV})}{g_*(T_d \sim 1\ {\rm GeV})} \sim \frac{5.5}{62.75} = 0.088,\quad d_2 = \frac{T_d^3}{T_>^3} \simeq \frac{0.32 g_* T_>}{0.12 M_S + 0.32 g_* T_d} \simeq 0.25$$

- Predicted value agrees with the observed $\eta_B^{\rm CMB} \sim 6\times 10^{-10}$. [Nolta *et al.* (2008)]

Neutron-anti neutron Oscillation

- Generated by an effective $\Delta B = 2$ operator of the form $u^c d^c d^c\ u^c d^c d^c$.



$$G_{n-\bar{n}} \simeq \frac{f_{ud,11} f_{ud,13} f_{dd,13} \lambda v_{BL}}{M^4_{\Delta_{u^c d^c}} M^2_{\Delta_{d^c d^c}}} \frac{g^4 V_{td}^2 m_b^2 m_t^2}{(16\pi^2)^2 m_W^4} \log\left(\frac{m_b^2}{m_W^2}\right) \sim 10^{-30}\ \mathrm{GeV}^{-5}$$

- The $n - \bar{n}$ transition time is given by

$$\tau_{n-\bar{n}} = \frac{\hbar}{G_{n-\bar{n}} \Lambda^6_{\mathrm{QCD}}} \sim 10^{9-10}\ \mathrm{sec.}$$

- Predicted value accessible to current and future experiments (e.g. Super-K, DUSEL). [Kamyshkov (2002)]

Colored Scalars observable at LHC

- Color sextet diquark scalar fields with TeV scale mass.
- Can be observed in the pp collisions at the LHC.
- The valence quarks in the two protons can produce $\Delta_{u^c d^c}$ fields which can decay to $t+$ jets.
- Could be either an s-channel single production [Mohapatra, Okada, and Yu (2008)] or Drell-Yan pair production [Chen *et al.* (2008)].
- The s-channel process will have a resonant enhancement and will appear as a signal above the SM background.
- The Drell-Yan pair production can give signals of type $bbl^{\pm}l^{\pm}jj+$ missing energy.

  [*Talk by Kai Wang*]

Conclusion

- The PSB mechanism is an attractive possibility for baryogenesis, with no conflict with observations so far.
- The theory can be naturally embedded into a TeV scale quark-lepton unified model, leading to observable predictions.
- The couplings responsible for baryogenesis get intimately linked to the neutrino masses by see-saw mechanism.
- Adequate baryogenesis predicts an inverted mass hierarchy for neutrinos and a large θ_{13} mixing angle, both of which are observable in the ongoing and proposed neutrino experiments.
- Predicts color sextet fields with TeV scale masses testable in collider experiments such as the LHC.
- Also predicts an observable neutron-antineutron oscillation time.

Thank you !