Update on the post-sphaleron baryogenesis model prediction for neutron-antineutron oscillation time

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Theoretical Innovations for Future Experiments Regarding $B$ Violation

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Outline

- Post-Sphaleron Baryogenesis [Babu, Mohapatra, Nasri (PRL '06)]

- A UV-complete model [Babu, BD, Mohapatra (PRD '08)]

- Low-energy constraints (Neutrino masses and mixing, FCNC, BAU)

- Upper limit on $n - \bar{n}$ oscillation time [Babu, BD, Fortes, Mohapatra (PRD '13)]

- 2020 update (in light of recent lattice, neutrino and LHC results)
  [Babu, Chauhan, BD, Mohapatra, Thapa (work in progress)]

- Conclusion
Why PSB is Compelling?

- BAU requires $B$ violation. [Sakharov (JETP Lett. '67)]

- $\Delta B = 1$: Proton decay constraints require very high scale $\sim 10^{16}$ GeV. [Nath, Fileviez Perez (Phys. Rept. '07)]

- $\Delta B = 2$: Induced by dimension-9 operator

  $$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^5} qqqqqq$$

- High-dimension implies scale can be as low as $\Lambda \sim 10^6$ GeV.

- Observable signature: $n - \bar{n}$ oscillation. [Phillips, Snow, Babu et al. (Phys. Rept. '16)]
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- **Post-sphaleron baryogenesis:** Deep connection between BAU and $n - \bar{n}$ oscillation.

- BAU is generated below 100 GeV, after the EW sphalerons go out-of-equilibrium. [Babu, Mohapatra, Nasri (PRL ’06)]

- Low reheating temperature consistent with wide range of inflation models.

- **More compelling than EW baryogenesis.** [Ann Nelson (INT Workshop ’17)]
Basic Idea of PSB

- A (pseudo)scalar $S$ decays to baryons, violating $B$.
- $\Delta B = 1$ is strongly constrained by proton decay and cannot lead to successful PSB.
- $\Delta B = 2$ decay of $S$, if violates CP and occurs out-of-equilibrium, can generate BAU below $T = 100$ GeV.
- The same $\Delta B = 2$ operator leads to $n - \bar{n}$.
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The same $\Delta B = 2$ operator leads to $n - \bar{n}$.

Naturally realized in quark-lepton unified models, with $S$ identified as the Higgs boson of $B - L$ breaking.

Yukawa couplings that affect PSB and $n - \bar{n}$ are the same as the ones that generate neutrino masses via seesaw.

Requiring successful BAU and observed neutrino oscillation parameters lead to a concrete, quantitative prediction for $n - \bar{n}$ amplitude.
$SU(2)_L \times SU(2)_R \times SU(4)_c$ [Pati, Salam (PRD '74)]
Quark-Lepton Symmetric Model

\begin{align*}
SU(2)_L \times SU(2)_R \times SU(4)_c
\end{align*}

\begin{align*}
(1,1,15) & \quad M_c \gtrsim 1400 \text{ TeV} \\
SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c
\end{align*}

[Senjanović, Mohapatra (PRD '75)]

\begin{align*}
\text{(from } K_L^0 \rightarrow \mu^\pm e^{\mp}\text{)} & \\
\text{[Mohapatra, Pati (PRD '75)]}
\end{align*}

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\text{No } \Delta B = 1 \text{ processes since } B-L \text{ is broken by two units.}
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[Valencia, Willenbrock (PRD '94)]
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\[ SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c \]

(1,3,10) \[ \nu_{BL} \gtrsim 200 \text{ TeV} \]

\[ SU(2)_L \times U(1)_{Y} \times SU(3)_c \]

No \( \Delta B = 1 \) processes since \( B - L \) is broken by two units.

[Pati, Salam (PRD '74)]

(from \( K^0_L \rightarrow \mu^\pm e'^\mp \))

[Valencia, Willenbrock (PRD '94)]

[Mohapatra, Pati (PRD '75)]

[Senjanović, Mohapatra (PRD '75)]

[Mohapatra, Marshak (PRL '80)]
(\(B - L\))-breaking Scalars

- Under \(SU(2)_L \times U(1)_Y \times SU(3)_c\),
  \[
  \Delta(1, 3, \overline{10}) = \Delta_{uu}(1, -\frac{8}{3}, 6^*) \oplus \Delta_{ud}(1, -\frac{2}{3}, 6^*) \oplus \Delta_{dd}(1, +\frac{4}{3}, 6^*) \\
  \oplus \Delta_{ue}(1, \frac{2}{3}, 3^*) \oplus \Delta_{uv}(1, -\frac{4}{3}, 3^*) \\
  \oplus \Delta_{de}(1, \frac{8}{3}, 3^*) \oplus \Delta_{d\nu}(1, \frac{2}{3}, 3^*) \\
  \oplus \Delta_{ee}(1, 4, 1) \oplus \Delta_{\nu e}(1, 2, 1) \oplus \Delta_{\nu \nu}(1, 0, 1).
  \]

- \(\Delta_{uu}, \Delta_{ud}, \Delta_{dd}\) (diquarks) generate \(B\) violation.
- \(\Delta_{\nu \nu}\) (singlet) breaks the \(B - L\) symmetry and provides a real scalar field \(S\) for PSB:
  \[
  \Delta_{\nu \nu} = \nu_{BL} + \frac{1}{\sqrt{2}}(S + iG^0)
  \]
Diquark Interactions and $B$-violating Decay of $S$

- Interactions of color-sextet diquarks and $B$-violating couplings:

\[
\mathcal{L}_I = \frac{f_{ij}}{2} \Delta_{dd} d_i d_j + \frac{h_{ij}}{2} \Delta_{uu} u_i u_j + \frac{g_{ij}}{2\sqrt{2}} \Delta_{ud} (u_i d_j + u_j d_i) \\
+ \frac{\lambda}{2} \Delta_{\nu\nu} \Delta_{dd} \Delta_{ud} \Delta_{ud} + \lambda' \Delta_{\nu\nu} \Delta_{uu} \Delta_{dd} \Delta_{dd} + \text{H.c.}
\]

- Boundary conditions: $f_{ij} = g_{ij} = h_{ij}$ and $\lambda = \lambda'$ in the PS symmetry limit.

- Couplings only to RH quarks due to L-R embedding.

- In general, $\Delta_{ud}$ could couple to both LH and RH quark bilinears, leading to EDM.

[Bell, Corbett, Nee, Ramsey-Musolf (PRD '19)]
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[Bell, Corbett, Nee, Ramsey-Musolf (PRD '19)]

- The real scalar field $S$ can decay into 6$q$ and 6$q\bar{q}$, thus violating $B$ by two units.
- $S$ must be the lightest of the $(1, 3, \overline{10})$ multiplet to forbid its $B$-conserving decays involving on-shell $\Delta_{qq}$. 

[Diagram of diquark interactions and decay modes]
\[ \Gamma_S \equiv \Gamma(S \rightarrow 6q) + \Gamma(S \rightarrow 6\bar{q}) = \frac{P}{\pi^9 \cdot 2^{25} \cdot 45} \frac{12}{4} |\lambda|^2 \text{Tr}(f^\dagger f)\text{Tr}(\hat{g}^\dagger \hat{g})^2 \left( \frac{M_S^{13}}{M_{\Delta_{ud}}^8 M_{\Delta_{dd}}^4} \right) \]

where \( P = 1.13 \times 10^{-4} \) is a phase space factor (for \( M_{\Delta_{ud}}/M_S, M_{\Delta_{dd}}/M_S \gg 1 \)).
Thermal History of $S$ Decay

$$\Gamma_S \equiv \Gamma(S \to 6q) + \Gamma(S \to 6\bar{q}) = \frac{P}{\pi^9 \cdot 2^{25} \cdot 45} \frac{12}{4} |\lambda|^2 \text{Tr}(f^\dagger f) [\text{Tr}(\hat{g}^\dagger \hat{g})]^2 \left( \frac{M_S^{13}}{M_{\Delta_{ud}}^8} \frac{M_{\Delta_{dd}}^4}{M_S} \right)$$

where $P = 1.13 \times 10^{-4}$ is a phase space factor (for $M_{\Delta_{ud}}/M_S, M_{\Delta_{dd}}/M_S \gg 1$).

**Conditions for PSB:**

- $\Gamma_{S \to 6q} \leq H(T_{EW})$, and $\Lambda_{QCD} \leq T_d \leq T_{EW}$.
- $S \to 6q$ must be the dominant decay mode (over $S \to Zf\bar{f}, ZZ$) $\Rightarrow v_{BL} \gtrsim 100$ TeV.
- Vacuum stability restricts $v_{BL}$ from being arbitrarily large: $\lambda v_{BL} \lesssim 2\sqrt{\pi} M_\Delta$.
- Not too much dilution: $d \equiv \frac{s_{\text{before}}}{s_{\text{after}}} \sim \frac{g_*^{-1/4} 0.6 \sqrt{\Gamma SM_{\text{Pl}}}}{n_S M_S/s(T_d)} \sim \frac{T_d}{M_S} \Rightarrow M_S \lesssim 17$ TeV.
\[ \epsilon_{\text{wave}} \simeq - \frac{8g^2}{64\pi \text{Tr}(f^\dagger f)} \delta_{i3} \Im(\hat{g}_{i\alpha}^* \hat{g}_{j\beta} V_{j\beta}^* V_{i\alpha}^*) \frac{m_t m_j}{m_t^2 - m_j^2} \sqrt{\left(1 - \frac{m_W^2}{m_t^2} + \frac{m_\beta^2}{m_t^2}\right)^2 - 4 \frac{m_\beta^2}{m_t^2}} \]

\times \left[ 2 \left(1 - \frac{m_W^2}{m_t^2} + \frac{m_\beta^2}{m_t^2}\right) - 4 \frac{m_\beta^2}{m_W^2} + \left(1 + \frac{m_\beta^2}{m_t^2}\right) \left(\frac{m_t^2}{m_W^2} + \frac{m_\beta^2}{m_W^2} - 1\right) \right] \]

\[ \epsilon_{\text{vertex}}^{(i,j \neq 3)} \simeq - \frac{8g^2}{32\pi \text{Tr}(f^\dagger f)} \Im(\hat{g}_{i\alpha}^* \hat{g}_{j\beta} V_{j\beta}^* V_{i\alpha}^*) \frac{m_\beta m_j}{m_W^2} \left[ 1 + \frac{3m_W^2}{2\langle p_1 \cdot p_2 \rangle} \ln \left(1 + \frac{2\langle p_1 \cdot p_2 \rangle}{m_W^2}\right) \right] \]

\[ \epsilon_{\text{vertex}}^{(i=3,j \neq 3)} \simeq - \frac{8g^2 \delta_{i3}}{32\pi \text{Tr}(f^\dagger f)} \Im(\hat{g}_{i\alpha}^* \hat{g}_{j\beta} V_{j\beta}^* V_{i\alpha}^*) \frac{m_\beta m_j}{m_W^2} \left[ 1 + \frac{3m_W^2}{2\langle p_1 \cdot p_2 \rangle} \ln \left(1 + \frac{2\langle p_1 \cdot p_2 \rangle}{m_t^2}\right) \right] \]

(Updated calculation)
Diquark fields lead to flavor violation, both at tree and loop levels.

\[
\mathcal{H}_{\Delta_{dd}} = -\frac{1}{8} \frac{f_i f^*_{kj}}{M^2_{\Delta_{dd}}} (d_{kR}^{\alpha} \gamma_\mu d_{iR}^{\alpha})(d_{jR}^{\beta} \gamma_\mu d_{\ell R}^{\beta}) + \frac{1}{256\pi^2} \frac{[(ff^\dagger)_{ij}(ff^\dagger)_{\ell k} + (ff^\dagger)_{ik}(ff^\dagger)_{\ell j}]}{M^2_{\Delta_{dd}}} \\
\times \left[ (d_{jR}^{\alpha} \gamma_\mu d_{iR}^{\alpha})(d_{kR}^{\beta} \gamma_\mu d_{\ell R}^{\beta}) + 5(d_{jR}^{\alpha} \gamma_\mu d_{iR}^{\beta})(d_{kR}^{\beta} \gamma_\mu d_{\ell R}^{\alpha}) \right].
\]

\[
\mathcal{H}_{\Delta_{ud}} = -\frac{1}{32} \frac{\hat{g}_{ij} \hat{g}^*_{kl}}{M^2_{\Delta_{ud}}} \left[ (\bar{u}_{kR}^{\alpha} \gamma_\mu u_{iR}^{\alpha})(d_{\ell R}^{\beta} \gamma_\mu d_{jR}^{\beta}) + (\bar{u}_{kR}^{\alpha} \gamma_\mu d_{iR}^{\alpha})(d_{\ell R}^{\beta} \gamma_\mu u_{jR}^{\beta}) \right] \\
+ \frac{1}{256\pi^2} \frac{1}{64} \frac{1}{M^2_{\Delta_{ud}}} \left[ (\hat{g}^\dagger g)^{ij}(\hat{g}^\dagger g)_{\ell k} + (\hat{g}^\dagger g)^{ik}(\hat{g}^\dagger g)_{\ell j} \right] \\
\times \left[ (d_{jR}^{\alpha} \gamma_\mu d_{iR}^{\alpha})(d_{kR}^{\beta} \gamma_\mu d_{\ell R}^{\beta}) + 5(d_{jR}^{\alpha} \gamma_\mu d_{iR}^{\beta})(d_{kR}^{\beta} \gamma_\mu d_{\ell R}^{\alpha}) \right].
\]
<table>
<thead>
<tr>
<th>Process</th>
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<tbody>
<tr>
<td>$\Delta m_{B_s}$</td>
<td>Tree</td>
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<td></td>
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<td>$\sum_{i=1}^{3}</td>
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## FCNC Constraints

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</table>

- Take $M_{\Delta_{ud}} \lesssim M_{\Delta_{dd}} \ll M_{\Delta_{uu}}$, with $M_{\Delta_{ud}} \gtrsim 3$ TeV, $M_{\Delta_{dd}} \gtrsim 5$ TeV, $M_{\Delta_{uu}} \gtrsim 200$ TeV.
- Update: $M_{\Delta_{qq}} \gtrsim 7.5$ TeV from LHC dijet constraint. [CMS Collaboration (1911.03947)]
- Could be relaxed to some extent for specific flavor structures.
The FCNC constraints enforce the Yukawa texture: [Babu, BD, Mohapatra (PRD '08)]

\[ f = \begin{pmatrix} 0 & 0.95 & 1 \\ 0.95 & 0 & 0.01 \\ 1 & 0.01 & -0.06 \end{pmatrix} \].

In the type-II seesaw dominance, \( M_\nu \propto f \implies \text{inverted mass hierarchy.} \)

Our 2008 fit yielded a "large" \( \theta_{13} \), (serendipitously) close to the 2012 Daya Bay measurement.

Update: Normal hierarchy possible by making \( f_{22} \neq 0 \), but at the expense of \( f_{13} \) (and \( n - \bar{n} \)).

A more exhaustive parameter scan for neutrino mass fits (including nonzero \( \delta_{\text{CP}} \)) currently underway.
Connection with $n - \bar{n}$ Oscillation

[Mohapatra, Marshak (PRL '80)]

Tree-level amplitude:

$$A_{n-\bar{n}}^{\text{tree}} \simeq \frac{f_{11} g_{11}^2 \lambda v_{BL}}{M_{\Delta_{dd}}^2 M_{\Delta_{ud}}^4} + \frac{f_{11}^2 h_{11} \lambda' v_{BL}}{M_{\Delta_{dd}}^4 M_{\Delta_{uu}}^2}.$$ 

But $f_{11}$ has to be vanishingly small to satisfy FCNC constraints.

Go to one-loop level to set a lower bound on the ‘effective’ $f_{11}$. 
Loop-level $n - \bar{n}$

\[ A_{n-\bar{n}}^{1-\text{loop}} \approx \frac{g^2 g_{11} g_{13} V_{ub}^* V_{td} \lambda v_{BL}}{128\pi^2 M_{\Delta_{ud}}^2} \left( \frac{m_t m_b}{m_W^2} \right) F \langle \bar{n} | O_{RLR}^2 | n \rangle \]

where the loop factor is

\[
F = \frac{1}{M_{\Delta_{ud}}^2 - M_{\Delta_{dd}}^2} \left[ \frac{1}{M_{\Delta_{ud}}^2} \ln \left( \frac{M_{\Delta_{ud}}^2}{m_W^2} \right) - \frac{1}{M_{\Delta_{dd}}^2} \ln \left( \frac{M_{\Delta_{dd}}^2}{m_W^2} \right) \right] \\
+ \frac{1}{M_{\Delta_{ud}}^2 M_{\Delta_{dd}}^2} \frac{1 - (m_t^2 / 4m_W^2)}{1 - (m_t^2 / m_W^2)} \ln \left( \frac{m_t^2}{m_W^2} \right).
\]
Effective Operator

- Relevant effective operator:

\[ O_{RLR}^2 = (u_{iT}^T Cd_{jR})(u_{kL}^T Cd_{iL})(d_{mR}^T Cd_{nR}) \Gamma_{ijklmn}^s, \]

with the color tensor \( \Gamma_{ijklmn}^s = \epsilon_{mik} \epsilon_{njl} + \epsilon_{nik} \epsilon_{mjl} + \epsilon_{mjk} \epsilon_{nil} + \epsilon_{njk} \epsilon_{mil} \).

- Matrix element in the MIT bag model: [Rao, Shrock (PLB '82)]

\[ \langle \bar{n} | O_{RLR}^2 | n \rangle = -0.314 \times 10^{-5} \text{ GeV}^6 \]

- Update: New lattice QCD result – Mike Wagman’s talk

[Rinaldi, Syritsyn, Wagman, Buchoff, Schroeder, Wasem (PRL '19; PRD '19)]

<table>
<thead>
<tr>
<th>Operator</th>
<th>( M_I^{\text{MS}}(2 \text{ GeV}) ), GeV(^6)</th>
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<th>( M_I^{\text{MS}}(2 \text{ GeV}) ) MIT bag A</th>
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<tr>
<td>( Q_1 )</td>
<td>(-46(13) \times 10^{-5} )</td>
<td>(-26(7) \times 10^{-5} )</td>
<td>4.2</td>
<td>5.2</td>
</tr>
<tr>
<td>( Q_2 )</td>
<td>(95(17) \times 10^{-5} )</td>
<td>(144(26) \times 10^{-5} )</td>
<td>7.5</td>
<td>8.7</td>
</tr>
<tr>
<td>( Q_3 )</td>
<td>(-50(12) \times 10^{-5} )</td>
<td>(-47(11) \times 10^{-5} )</td>
<td>5.1</td>
<td>6.1</td>
</tr>
<tr>
<td>( Q_5 )</td>
<td>(-1.06(48) \times 10^{-5} )</td>
<td>(-0.23(10) \times 10^{-5} )</td>
<td>-0.84</td>
<td>1.6</td>
</tr>
</tbody>
</table>

with \( \langle \bar{n} | Q_5 | n \rangle = \langle \bar{n} | Q_6 | n \rangle \) and \( Q_6 = -4O_{RLL}^2 \).

- New matrix element is 16% smaller.
Prediction for $n - \bar{n}$ Oscillation Time

\[
\tau_{n-\bar{n}}^{-1} \equiv \delta m = c_{QCD}(\mu, 1 \text{ GeV}) |A_{n-\bar{n}}^{1-\text{loop}}|.
\]

where $c_{QCD}$ is the RG running factor: \cite{Winslow, Ng (PRD '10)}

\[
c_{QCD}(\mu, 1\text{ GeV}) = \left[ \frac{\alpha_s(\mu^2_\Delta)}{\alpha_s(m_t^2)} \right]^{8/7} \left[ \frac{\alpha_s(m_t^2)}{\alpha_s(m_b^2)} \right]^{24/23} \left[ \frac{\alpha_s(m_b^2)}{\alpha_s(m_c^2)} \right]^{24/25} \left[ \frac{\alpha_s(m_c^2)}{\alpha_s(1 \text{ GeV}^2)} \right]^{8/9}
\]

\[\simeq 0.18.\]

\[\text{Probability} \]

\[\text{Probability} \]

\[\tau_{n-\bar{n}}/(10^8 \text{ sec}) \]

\cite{Babu, BD, Fortes, Mohapatra (PRD '13)}
Updated Prediction for $n - \bar{n}$ Oscillation Time

[Graph showing probability distribution for $\tau_{n-\bar{n}}/(10^8 \text{ sec})$]

[Babu, Chauhan, BD, Mohapatra, Thapa (preliminary result)]
Updated Prediction for $n - \bar{n}$ Oscillation Time

$\tau_{n-\bar{n}}/(10^8 \text{ sec})$

Probability

[ILL, Super-K]

[Babu, Chauhan, BD, Mohapatra, Thapa (preliminary result)]
Updated Prediction for $n - \bar{n}$ Oscillation Time

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Post-sphaleron baryogenesis is a compelling low-scale alternative to popular high-scale baryogenesis/leptogenesis.

Directly links BAU with $n - \bar{n}$ oscillation.

In quark-lepton symmetric models, leads to a quantitative prediction for $n - \bar{n}$ oscillation time.

Deep connection between BAU, $n - \bar{n}$ and Majorana neutrino mass.

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(Partly) within reach of future experiments.
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Stay tuned.
Understanding the Upper Limit on $n - \bar{n}$ Oscillation Time

![Graphs showing $\tau_{n-\bar{n}}/(10^8 \text{ sec})$ vs $M_{\Delta M}$ for different mass regions.](image-url)
Other diagrams for CP Violation

We summarize the results of our calculations for the $W^\pm$ exchange diagrams. If one of the external up–type quarks is the top quark, the corresponding quark line receives a wave function correction via $W^\pm$ gauge boson exchange. The baryon asymmetry from this diagram is found to be

$$
\epsilon_{\text{wave}} B_{Br} \simeq -\frac{3}{8} \alpha^2 \left(1 + \frac{m_t^4}{m_W^4}\right) Im \left[ V^* \hat{M}_2^2 V \hat{M}_u^T \hat{M}_d g^T \right]^{33} \frac{m_t m_W^2 (gg^T)}{3} (5)
$$

where $\hat{M}_u = \text{diag}(m_u, m_c, m_t)$, $\hat{M}_d = \text{diag}(m_d, m_s, m_b)$ and $V$ is the CKM matrix. $Br$ stands for the branching ratio of $S_r$ into $6q^+6q^-$. The vertex correction via the $W$ boson exchange gives an asymmetry given by

$$
\epsilon_{\text{vertex}} B_{Br} \simeq -\frac{\alpha^2}{4} Im \text{Tr} \left[ g^T \hat{M}_u^2 V g^T V^* \hat{M}_d \right] \text{Tr} (g^T g^T) .
$$

Here we have assumed that $M_{S_r} \gg m_t$. In the limit where $m_{S_r} \ll m_W$, we have the same asymmetry as in Eq. (6), but with a factor of $(-1/4)$ multiplying it. Of course in this case, decays involving final state top quark are disallowed, which is to be implemented by removing the top quark contribution in the trace of Eq. (6).

These $W^\pm$ loops do not conflict with the theorem of Ref. [14] which states that baryon asymmetry

$$
\epsilon_{\text{diamond}} \simeq \frac{8}{16\pi \text{Tr}(f^T f)^2} \langle \hat{g}_{nm} f_j h_{n\beta} \rangle \frac{M_Z^2 m_j m_\beta}{M_X^2 M_Y^2} \left(1 - \frac{m_j^2}{m_i^2 + m_\alpha^2 + 2 \langle p_1 \cdot p_2 \rangle}\right)
$$

This generates absorptive part and CP violation in $\chi \rightarrow 6q$: 

\[\chi \rightarrow uu \, \nu \, \nu \, \nu \, \nu \, \nu \]

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Other diagrams for CP Violation

We summarize the results of our calculations for the $W^\pm$ exchange diagrams. If one of the external up–type quarks is the top quark, the corresponding quark line receives a wave function correction via $W^\pm$ gauge boson exchange. The baryon asymmetry from this diagram is found to be

$$\epsilon_{\text{wave}} \sim -8\pi \frac{M_Z^2 m_j m_\beta}{M_X M_Y^2} \left(1 - \frac{m_j^2}{m_i^2 + m_\alpha^2 + 2\langle p_1 \cdot p_2 \rangle}\right)$$

where $\hat{M}_u = \text{diag}(m_u, m_c, m_t)$ and $\hat{M}_d = \text{diag}(m_d, m_s, m_b)$ and $V$ is the CKM matrix. $B_{\text{Br}}$ stands for the branching ratio of $\sigma$ into $6q + 6q$.

The vertex correction via the $W$ boson exchange gives an asymmetry given by

$$\epsilon_{\text{vertex}} \sim -4\pi \text{Tr} \left( \hat{g}_T \hat{M}_u V g^\dagger V^* \hat{M}_d \right) \text{Tr}(g^\dagger g).$$

Here we have assumed that $M_{\sigma} \gg m_t$. In the limit where $m_{\sigma} \ll m_W$, we have the same asymmetry as in Eq. (6), but with a factor of $-1/4$ multiplying it. Of course in this case, decays involving final state top quark are disallowed, which is to be implemented by removing the top quark contribution in the trace of Eq. (6).

$\epsilon_{\text{diamond}} \sim \frac{8}{16\pi \text{Tr}(f^\dagger f)} \Im \left( \hat{g}_{nm}^* f_j^m \hat{g}_{\beta j}^* h_{n\beta} \right) \frac{M_Z^2 m_j m_\beta}{M_X M_Y^2} \left(1 - \frac{m_j^2}{m_i^2 + m_\alpha^2 + 2\langle p_1 \cdot p_2 \rangle}\right)$

This generates absorptive part and CP violation in $\sigma! 6q$: $\sigma \nu_R \nu_R \bar{d} \bar{d}\bar{d}\bar{d} \bar{u} \bar{u} \bar{u} \bar{u}$.