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

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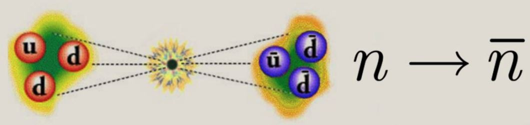

Theoretical Innovations for Future Experiments Regarding B Violation

University of Massachusetts, Amherst

August 4, 2020

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

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

- 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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- Observable signature: $n - \bar{n}$ oscillation. [Phillips, Snow, Babu *et al.* (Phys. Rept. '16)]
- 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.
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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.

Quark-Lepton Symmetric Model

$$\boxed{SU(2)_L \times SU(2)_R \times SU(4)_c}$$

[Pati, Salam (PRD '74)]

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$$(\mathbf{1},\mathbf{1},\mathbf{15}) \; \Big\Downarrow \; M_c \gtrsim 1400 \ \mathrm{TeV}$$

(from $K_L^0 \to \mu^\pm e^\mp$)

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$$(\mathbf{1},\mathbf{3},\overline{\mathbf{10}}) \;\Big\Downarrow\; v_{BL}\ (\gtrsim 200\ \text{TeV})$$

[Mohapatra, Marshak (PRL '80)]

$$\boxed{SU(2)_L \times U(1)_Y \times SU(3)_c}$$

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

- Under $SU(2)_L \times U(1)_Y \times SU(3)_c$,

$$
\begin{aligned}
\Delta(\mathbf{1},\mathbf{3},\overline{\mathbf{10}}) \quad = \quad & \Delta_{uu}(\mathbf{1},-\frac{8}{3},\mathbf{6}^*) \oplus \Delta_{ud}(\mathbf{1},-\frac{2}{3},\mathbf{6}^*) \oplus \Delta_{dd}(\mathbf{1},+\frac{4}{3},\mathbf{6}^*) \\
& \oplus \Delta_{ue}(\mathbf{1},\frac{2}{3},\mathbf{3}^*) \oplus \Delta_{u\nu}(\mathbf{1},-\frac{4}{3},\mathbf{3}^*) \\
& \oplus \Delta_{de}(\mathbf{1},\frac{8}{3},\mathbf{3}^*) \oplus \Delta_{d\nu}(\mathbf{1},\frac{2}{3},\mathbf{3}^*) \\
& \oplus \Delta_{ee}(\mathbf{1},4,\mathbf{1}) \oplus \Delta_{\nu e}(\mathbf{1},2,\mathbf{1}) \oplus \Delta_{\nu\nu}(\mathbf{1},0,\mathbf{1}) \ .
\end{aligned}
$$

- Δ_{uu}, Δ_{ud}, Δ_{dd} (diquarks) generate B violation.
- $\Delta_{\nu\nu}$ (singlet) breaks the $B-L$ symmetry and provides a real scalar field S for PSB:

$$
\Delta_{\nu\nu} = v_{BL} + \frac{1}{\sqrt{2}}(S + iG^0)
$$

Diquark Interactions and B-violating Decay of S

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

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

- 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, Δ_{ud} could couple to both LH and RH quark bilinears, leading to EDM.
  [Bell, Corbett, Nee, Ramsey-Musolf (PRD '19)]

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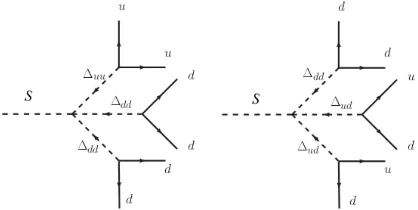
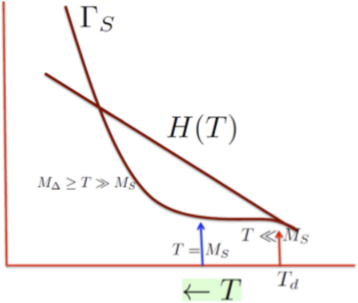
- Couplings only to RH quarks due to L-R embedding.
- In general, Δ_{ud} could couple to both LH and RH quark bilinears, leading to EDM. [Bell, Corbett, Nee, Ramsey-Musolf (PRD '19)]
- The real scalar field S can decay into $6q$ and $6\bar{q}$, thus violating B by two units.
- S must be the lightest of the $(\mathbf{1}, \mathbf{3}, \overline{\mathbf{10}})$ multiplet to forbid its B-conserving decays involving on-shell Δ_{qq}.



Thermal History of S Decay

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

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



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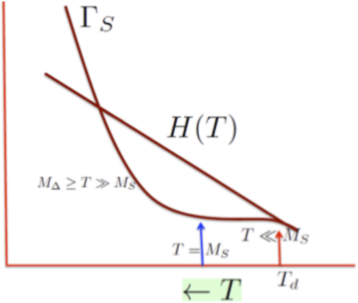
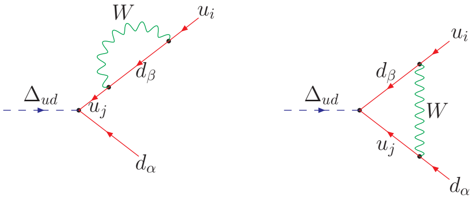


Conditions for PSB:

- $\Gamma_{S\to 6q} \leq H(T_{\rm EW})$, and $\Lambda_{\rm QCD} \leq T_d \leq T_{\rm EW}$.
- $S \to 6q$ must be the dominant decay mode (over $S \to Zf\bar{f}, ZZ$) $\Longrightarrow$ $v_{BL} \gtrsim 100$ TeV.
- Vacuum stability restricts v_{BL} from being arbitrarily large: $\lambda v_{BL} \lesssim 2\sqrt{\pi} M_\Delta$.
- Not too much dilution: $d \equiv \frac{s_{\rm before}}{s_{\rm after}} \simeq \frac{g_*^{-1/4} 0.6\sqrt{\Gamma_S M_{\rm Pl}}}{n_S M_S / s(T_d)} \sim \frac{T_d}{M_S} \Longrightarrow M_S \lesssim 17$ TeV.

CP Asymmetry



$$\epsilon_{\text{wave}} \simeq -\frac{8g^2}{64\pi\,\text{Tr}(f^\dagger f)}\delta_{i3}\Im(\hat{g}^*_{i\alpha}\hat{g}_{j\alpha}V_{j\beta}V^*_{i\beta})\frac{m_t m_j}{m_t^2 - m_j^2}\sqrt{\left(1-\frac{m_W^2}{m_t^2}+\frac{m_\beta^2}{m_t^2}\right)^2 - 4\frac{m_\beta^2}{m_t^2}}$$
$$\times\left[2\left(1-\frac{m_W^2}{m_t^2}+\frac{m_\beta^2}{m_t^2}\right)-4\frac{m_\beta^2}{m_W^2}+\left(1+\frac{m_\beta^2}{m_t^2}\right)\left(\frac{m_t^2}{m_W^2}+\frac{m_\beta^2}{m_W^2}-1\right)\right]$$

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

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

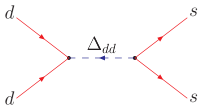
(Updated calculation)

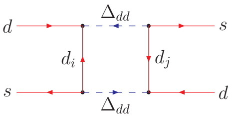
Flavor Violation

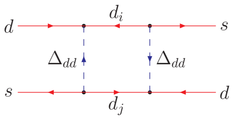
Diquark fields lead to flavor violation, both at tree and loop levels.

$$\mathcal{H}_{\Delta_{dd}} = -\frac{1}{8}\frac{f_{i\ell}f^*_{kj}}{M^2_{\Delta_{dd}}}(\overline{d}^\alpha_{kR}\gamma_\mu d^\alpha_{iR})(\overline{d}^\beta_{jR}\gamma^\mu d^\beta_{\ell R}) + \frac{1}{256\pi^2}\frac{[(ff^\dagger)_{ij}(ff^\dagger)_{\ell k} + (ff^\dagger)_{ik}(ff^\dagger)_{\ell j}]}{M^2_{\Delta_{dd}}} \times \left[(\overline{d}^\alpha_{jR}\gamma_\mu d^\alpha_{iR})(\overline{d}^\beta_{kR}\gamma^\mu d^\beta_{\ell R}) + 5(\overline{d}^\alpha_{jR}\gamma_\mu d^\beta_{iR})(\overline{d}^\beta_{kR}\gamma^\mu d^\alpha_{\ell R})\right] .$$

$$\mathcal{H}_{\Delta_{ud}} = -\frac{1}{32}\frac{\widehat{g}_{ij}\widehat{g}^*_{kl}}{M^2_{\Delta_{ud}}}\left[(\overline{u}^\alpha_{kR}\gamma_\mu u^\alpha_{iR})(\overline{d}^\beta_{\ell R}\gamma^\mu d^\beta_{jR}) + (\overline{u}^\alpha_{kR}\gamma_\mu d^\alpha_{iR})(\overline{d}^\beta_{\ell R}\gamma^\mu u^\beta_{jR})\right] + \frac{1}{256\pi^2}\frac{1}{64}\frac{1}{M^2_{\Delta_{ud}}}\left[(\widehat{g}\widehat{g}^\dagger)_{ij}(\widehat{g}\widehat{g}^\dagger)_{\ell k} + (\widehat{g}\widehat{g}^\dagger)_{ik}(\widehat{g}\widehat{g}^\dagger)_{\ell j}\right] \times \left[(\overline{d}^\alpha_{jR}\gamma_\mu d^\alpha_{iR})(\overline{d}^\beta_{kR}\gamma^\mu d^\beta_{\ell R}) + 5(\overline{d}^\alpha_{jR}\gamma_\mu d^\beta_{iR})(\overline{d}^\beta_{kR}\gamma^\mu d^\alpha_{\ell R})\right]$$







FCNC Constraints

Process	Diagram	Constraint on Couplings
Δm_{B_s}	Tree	$\lvert f_{22} f_{33}^*\rvert \le 7.04 \times 10^{-4} \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)^2$
	Box	$\sum_{i=1}^{3} \lvert f_{i3} f_{i2}^*\rvert \le 0.14 \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)$
	Box	$\sum_{i=1}^{3} \lvert \hat{g}_{i3} \hat{g}_{i2}^*\rvert \le 1.09 \left(\frac{M_{\Delta_{ud}}}{1\ \mathrm{TeV}}\right)$
Δm_{B_d}	Tree	$\lvert f_{11} f_{33}^*\rvert \le 2.75 \times 10^{-5} \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)^2$
	Box	$\sum_{i=1}^{3} \lvert f_{i3} f_{i1}^*\rvert \le 0.03 \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)$
	Box	$\sum_{i=1}^{3} \lvert \hat{g}_{i3} \hat{g}_{i1}^*\rvert \le 0.21 \left(\frac{M_{\Delta_{ud}}}{1\ \mathrm{TeV}}\right)$
Δm_K	Tree	$\lvert f_{11} f_{22}^*\rvert \le 6.56 \times 10^{-6} \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)^2$
	Box	$\sum_{i=1}^{3} \lvert f_{i2} f_{i1}^*\rvert \le 0.01 \left(\frac{M_{\Delta_{dd}}}{1\ \mathrm{TeV}}\right)$
	Box	$\sum_{i=1}^{3} \lvert \hat{g}_{i1} \hat{g}_{i2}^*\rvert \le 0.10 \left(\frac{M_{\Delta_{ud}}}{1\ \mathrm{TeV}}\right)$
Δm_D	Tree	$\lvert h_{11} h_{22}^*\rvert \le 3.72 \times 10^{-6} \left(\frac{M_{\Delta_{uu}}}{1\ \mathrm{TeV}}\right)^2$
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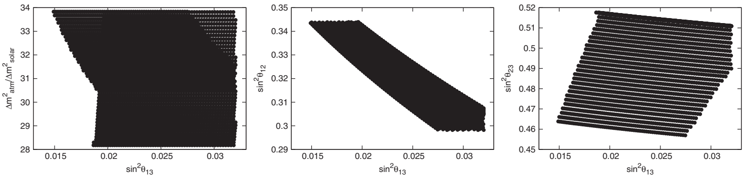
- Take $M_{\Delta_{ud}} \lesssim M_{\Delta_{dd}} \ll M_{\Delta_{uu}}$, with $M_{\Delta_{ud}} \gtrsim 3$ TeV, $M_{\Delta_{dd}} \gtrsim 5$ TeV, $M_{\Delta_{uu}} \gtrsim 200$ TeV.
- Update: $M_{\Delta_{qq}} \gtrsim 7.5$ TeV from LHC dijet constraint. [CMS Collaboration (1911.03947)]
- Could be relaxed to some extent for specific flavor structures.

Neutrino Masses and Mixing

- The FCNC constraints enforce the Yukawa texture: [Babu, BD, Mohapatra (PRD '08)]

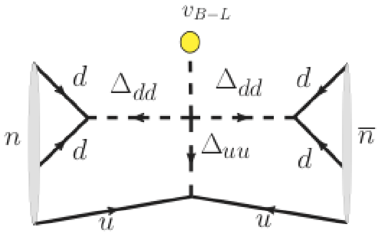
$$f = \begin{pmatrix} 0 & 0.95 & 1 \\ 0.95 & 0 & 0.01 \\ 1 & 0.01 & -0.06 \end{pmatrix} .$$

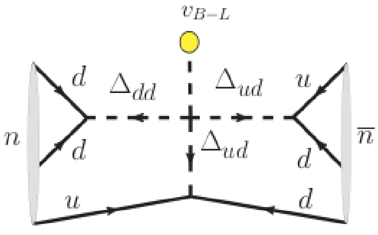
- In the type-II seesaw dominance, $M_\nu \propto f \Longrightarrow$ inverted mass hierarchy.
- Our 2008 fit yielded a "large" θ_{13}, (serendipitously) close to the 2012 Daya Bay measurement.



- 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 $\delta_{\rm CP}$) currently underway.

[Mohapatra, Marshak (PRL '80)]

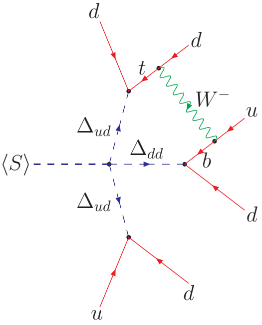




- Tree-level amplitude:

$$A^{\rm tree}_{n-\bar{n}} \simeq \frac{f_{11} g_{11}^2 \lambda v_{BL}}{M^2_{\Delta_{dd}} M^4_{\Delta_{ud}}} + \frac{f_{11}^2 h_{11} \lambda' v_{BL}}{M^4_{\Delta_{dd}} M^2_{\Delta_{uu}}} \, .$$

- 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}.



$$A^{1-\mathrm{loop}}_{n-\bar{n}} \simeq \frac{g^2 g_{11} g_{13} f_{13} V^*_{ub} V_{td} \lambda v_{BL}}{128\pi^2 M^2_{\Delta_{ud}}} \left(\frac{m_t m_b}{m_W^2} \right) F \langle \bar{n} | \mathcal{O}^2_{RLR} | n \rangle$$

where the loop factor is

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

Effective Operator

- Relevant effective operator:

$$\mathcal{O}^2_{RLR} = (u^T_{iR} C d_{jR})(u^T_{kL} C d_{lL})(d^T_{mR} C d_{nR})\Gamma^s_{ijklmn},$$

with the color tensor $\Gamma^s_{ijklmn} = \epsilon_{mik}\epsilon_{njl} + \epsilon_{nik}\epsilon_{mjl} + \epsilon_{mjk}\epsilon_{nil} + \epsilon_{njk}\epsilon_{mil}$.

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

$$\langle \bar{n}|\mathcal{O}^2_{RLR}|n\rangle = -0.314 \times 10^{-5}\ \mathrm{GeV}^6$$

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

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

Operator	$\mathcal{M}_I^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV})$,	$\mathcal{M}_I^{\overline{\mathrm{MS}}}(700\ \mathrm{TeV})$,	$\frac{\mathcal{M}_I^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV})}{\mathrm{MIT\ bag\ A}}$	$\frac{\mathcal{M}_I^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV})}{\mathrm{MIT\ bag\ B}}$
Q_1	$-46(13) \times 10^{-5}\ \mathrm{GeV}^6$	$-26(7) \times 10^{-5}\ \mathrm{GeV}^6$	4.2	5.2
Q_2	$95(17) \times 10^{-5}\ \mathrm{GeV}^6$	$144(26) \times 10^{-5}\ \mathrm{GeV}^6$	7.5	8.7
Q_3	$-50(12) \times 10^{-5}\ \mathrm{GeV}^6$	$-47(11) \times 10^{-5}\ \mathrm{GeV}^6$	5.1	6.1
Q_5	$-1.06(48) \times 10^{-5}\ \mathrm{GeV}^6$	$-0.23(10) \times 10^{-5}\ \mathrm{GeV}^6$	-0.84	1.6

with $\langle \bar{n}|Q_5|n\rangle = \langle \bar{n}|Q_6|n\rangle$ and $Q_6 = -4\mathcal{O}^2_{RLL}$.

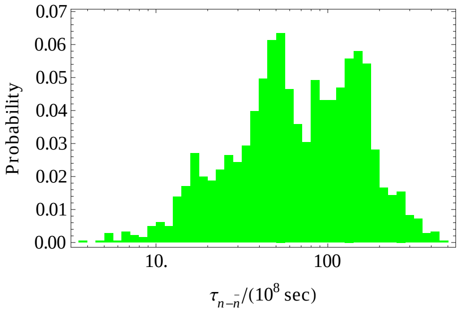
- New matrix element is 16% smaller.

Prediction for $n-\bar{n}$ Oscillation Time

$$\tau^{-1}_{n-\bar{n}} \equiv \delta m = c_{\rm QCD}(\mu_\Delta, 1~{\rm GeV}) \left| A^{1-{\rm loop}}_{n-\bar{n}} \right| .$$

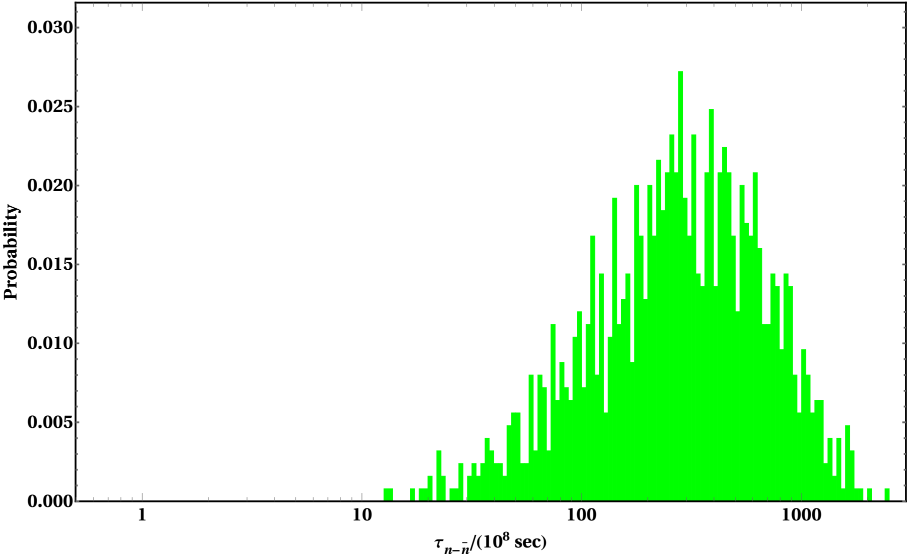
where $c_{\rm QCD}$ is the RG running factor: [Winslow, Ng (PRD '10)]

$$\begin{aligned} c_{\rm QCD}(\mu_\Delta, 1{\rm GeV}) &= \left[\frac{\alpha_s(\mu_\Delta^2)}{\alpha_s(m_t^2)}\right]^{8/7} \left[\frac{\alpha_s(m_t^2)}{\alpha_s(m_b^2)}\right]^{24/23} \left[\frac{\alpha_s(m_b^2)}{\alpha_s(m_c^2)}\right]^{24/25} \left[\frac{\alpha_s(m_c^2)}{\alpha_s(1~{\rm GeV}^2)}\right]^{8/9} \\ &\simeq 0.18. \end{aligned}$$



[Babu, BD, Fortes, Mohapatra (PRD '13)]

Updated Prediction for $n - \bar{n}$ Oscillation Time



[Babu, Chauhan, BD, Mohapatra, Thapa (preliminary result)]

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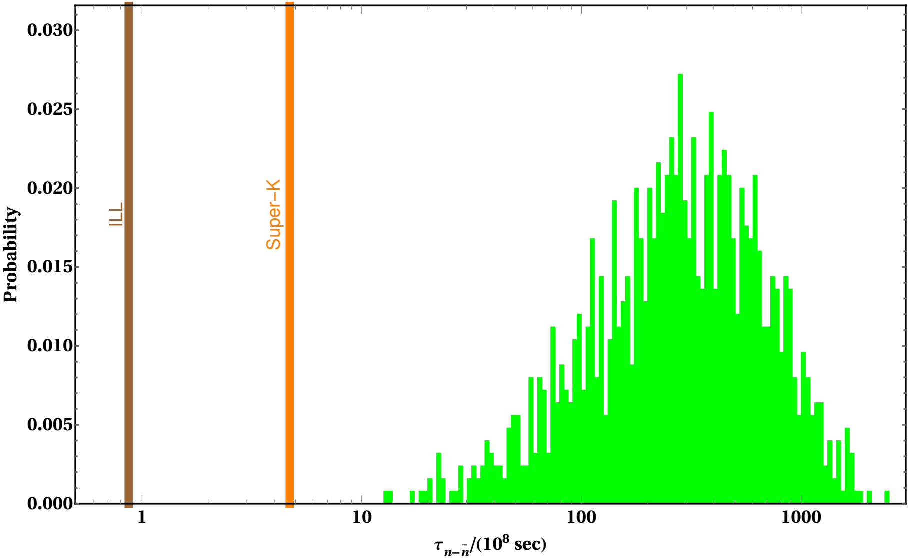

[Babu, Chauhan, BD, Mohapatra, Thapa (preliminary result)]

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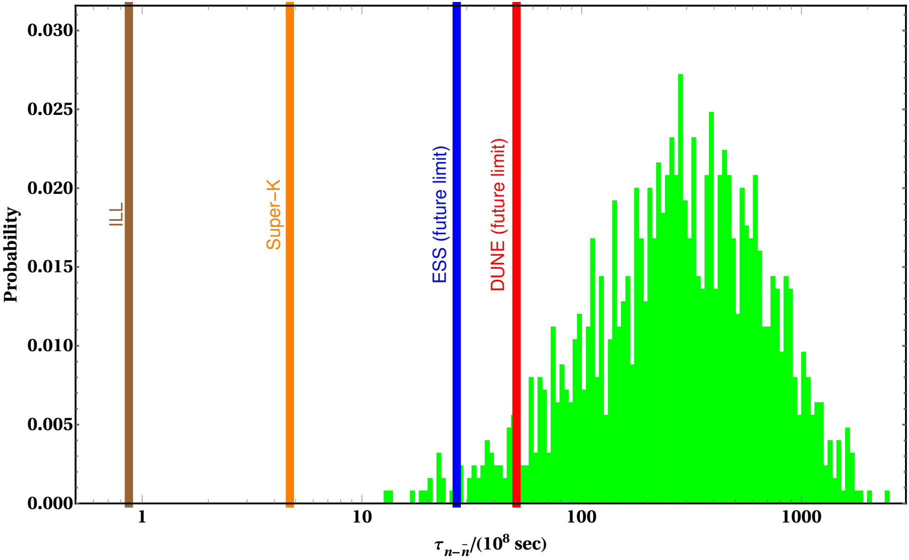

[Babu, Chauhan, BD, Mohapatra, Thapa (preliminary result)]

Conclusion

- 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.
- $\tau_{n-\bar{n}} \approx (10^9 - 10^{11})$ sec is the preferred range from PSB.
- (Partly) within reach of future experiments.

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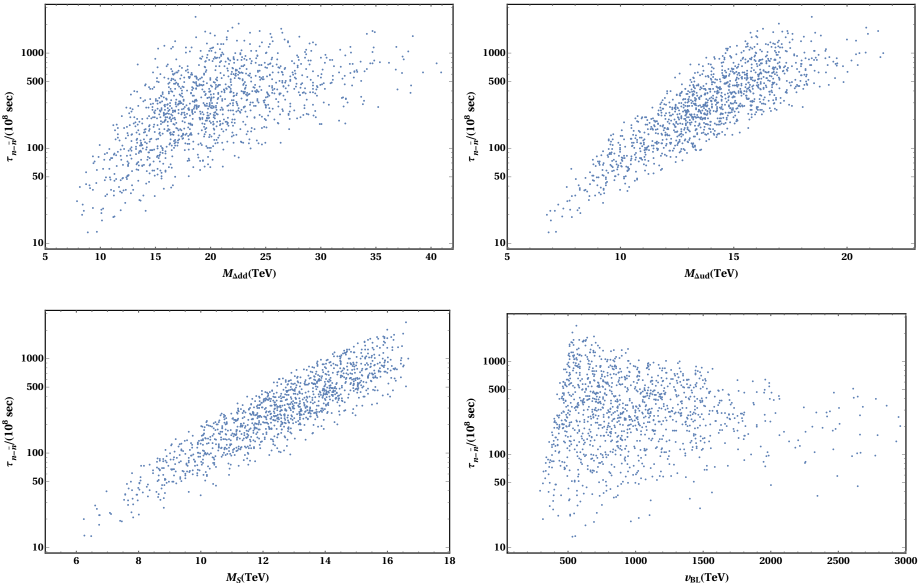
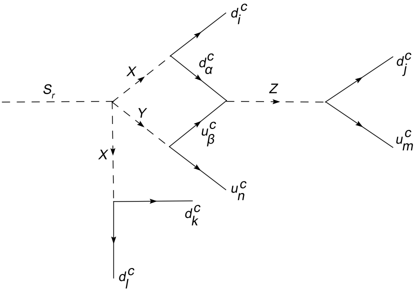
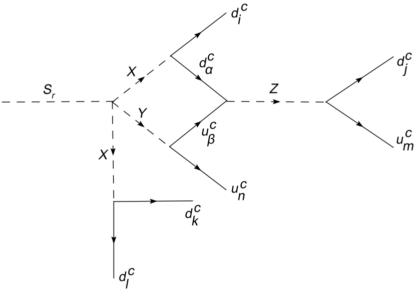
Stay tuned.

Understanding the Upper Limit on $n - \bar{n}$ Oscillation Time





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



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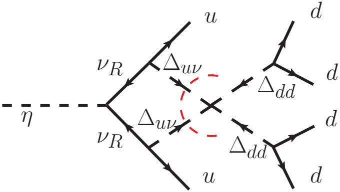

$$\epsilon \simeq \frac{|f|^2 \Im(\lambda\lambda'^*)}{8\pi(|\lambda|^2 + \Gamma_4/\Gamma_6)} \left(\frac{M^2_{\Delta_{dd}}}{M^2_{\nu_R}}\right)$$