Radiative Neutrino Mass Generation with Vector-like Quarks

Julio

in collaboration with K. S. Babu

Oklahoma State University

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Based on:

Radiative Neutrino Mass Generation with Vector-like Quarks
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Outline

- Motivation
- Two–loop neutrino mass model via vector-like quarks
- $\ell_i \to \ell_j \gamma$
- New CP violation in $B_{s,d}$ system
- Neutrinoless Double Beta Decay
- Conclusions

Motivation

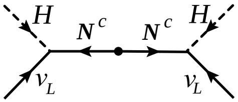
To explain the origin and magnitude of neutrino mass.

- Seesaw mechanism

$\mathcal{L} = Y_\nu N^c L H + \frac{1}{2} M_R N^c N^c$

$m_\nu \simeq \frac{m_D^2}{M_R},\ m_D = Y_\nu \langle H \rangle$

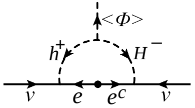
$M_R \lesssim 10^{14}$ GeV



Minkowski, 1977; Gell-Mann *et al.*, 1980; Yanagida, 1979; Mohapatra & Senjanović, 1980

- Radiative mass generation mechanism

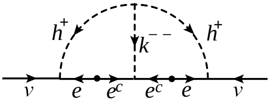
Zee Model



$$(m_\nu)_{ab} \simeq \frac{f_{ab}}{16\pi^2} \frac{(m_a^2 - m_b^2)}{\Lambda}$$

Zee, 1980

Zee-Babu Model



$$(m_\nu)_{\rm largest} \simeq \frac{f^2 g}{(16\pi^2)^2} \frac{m_\tau^2}{\Lambda}$$

Zee, 1985; Babu, 1988

$\Delta L = 2$ Operators

List of operators:

$$
\begin{aligned}
\mathcal{O}_1 &= L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \\
\mathcal{O}_2 &= L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_3 &= \{L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}, \;\; L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}\} \\
\mathcal{O}_4 &= \{L^i L^j \bar{Q}_i \bar{u^c} H^k \epsilon_{jk}, \;\; L^i L^j \bar{Q}_k \bar{u^c} H^k \epsilon_{ij}\} \\
\mathcal{O}_5 &= L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl}\epsilon_{km}
\end{aligned}
$$

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\mathcal{O}_6 &= L^i L^j \bar{Q}_k \bar{u^c} H^l H^k \bar{H}_i \epsilon_{jl} \\
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Babu & Leung, 2002

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Babu & Leung, 2002

Operator $\mathcal{O}_3 = L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}$ is the main subject in this talk.

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In constructing the Lagrangian for this operator,

1. Should not lead to the Zee-like neutrino mass model because it is disfavored by solar + KamLAND data
   Koide,2001; Frampton *et al.*, 2002
2. Should not give another type of contraction

Model

- Introducing one LQ doublet and vector-like singlet up-quarks:

$$\Omega \equiv \begin{pmatrix} \omega^{2/3} \\ \omega^{-1/3} \end{pmatrix} \sim (3,2,1/6), \quad U^c \sim (3^*,1,-2/3), \quad U \sim (3,1,2/3)$$

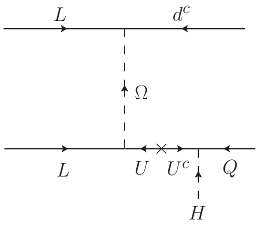
- The new interactions:

$$\mathcal{L} = g_{ij} L_i d_j^c \Omega + h_i L_i U \tilde{\Omega} - f_i Q_i U^c H - M U U^c$$

$\mathcal{L}_{\rm quart} = \lambda \, |\Omega \cdot H|^2 \rightarrow$ LQ mass splitting

$$M_u = U \begin{pmatrix} Y_u v & 0 \\ f v & M \end{pmatrix} V$$

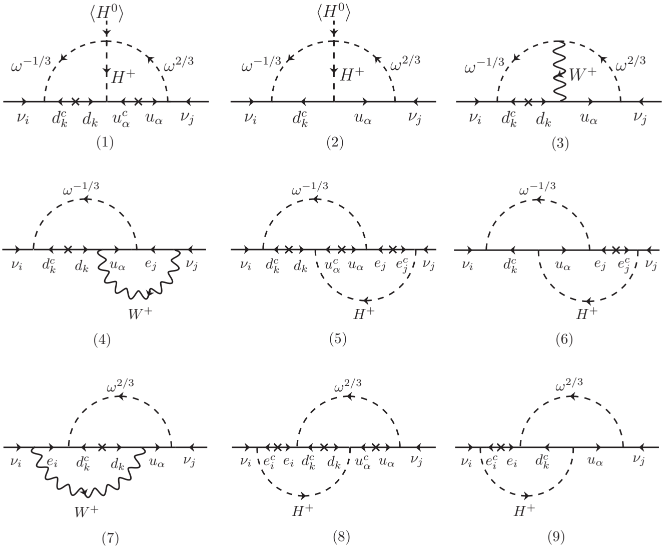
$V_{4\times 3} \equiv$ CKM matrix



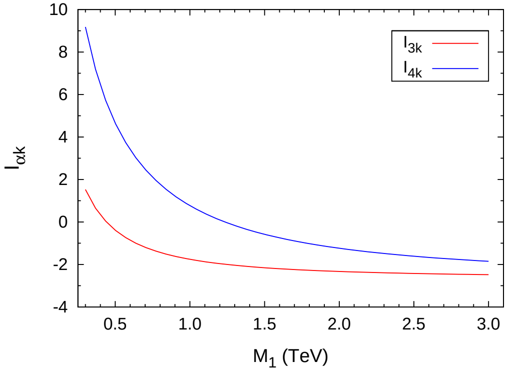
- This scenario can be embedded into MSSM with $10 + \overline{10}$ vector-like multiplet.
  Moroi & Okada, 1992;

Model

The two-loop diagrams (in R_ξ gauge):



Neutrino Mass Matrix



$M_1 \equiv$ The lightest LQ mass

$$M_{ii} = h_i \sum_{k=1}^{3} g_{ik} F_k; \qquad M_{ij} = \tfrac{1}{2}\tfrac{h_i}{h_j} M_{jj} + \tfrac{1}{2}\tfrac{h_j}{h_i} M_{ii}, \; i < j$$

$$D_d \equiv \mathrm{diag}\left(\frac{m_d}{m_b}, \frac{m_s}{m_b}, 1\right); \qquad m_0 = \frac{3}{2}\frac{g^2 m_b}{(16\pi^2)^2}$$

$$F_k = m_0 \sum_{\alpha=1}^{4} V_{\alpha 4}^{*} V_{\alpha k} (D_d)_k I_{\alpha k}$$

Neutrino Mass Matrix

$$M_\nu = \begin{pmatrix} M_{11} & \frac{1}{2}\frac{h_1}{h_2}M_{22} + \frac{1}{2}\frac{h_2}{h_1}M_{11} & \frac{1}{2}\frac{h_1}{h_3}M_{33} + \frac{1}{2}\frac{h_3}{h_1}M_{11} \\ \frac{1}{2}\frac{h_1}{h_2}M_{22} + \frac{1}{2}\frac{h_2}{h_1}M_{11} & M_{22} & \frac{1}{2}\frac{h_2}{h_3}M_{33} + \frac{1}{2}\frac{h_3}{h_2}M_{22} \\ \frac{1}{2}\frac{h_1}{h_3}M_{33} + \frac{1}{2}\frac{h_3}{h_1}M_{11} & \frac{1}{2}\frac{h_2}{h_3}M_{33} + \frac{1}{2}\frac{h_3}{h_2}M_{22} & M_{33} \end{pmatrix}$$

- det $M_\nu = 0$, so one of the neutrinos is massless.
- Both normal and inverted hierarchy can be accommodated here

Fitting

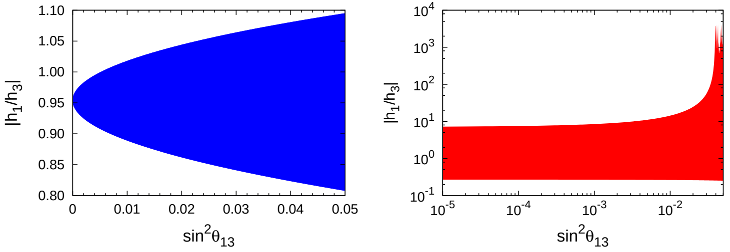
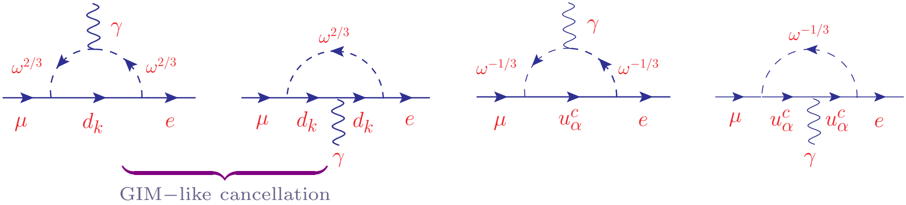


Figure: The allowed value of $\frac{h_1}{h_3}$ in NH (left panel) and IH (right panel).

- NH predicts BR $(\tau \to \mu\gamma) \simeq (5 - 10) \times$ BR $(\mu \to e\gamma)$.
- The current upper limit, BR $(\mu \to e\gamma)_{\text{exp}} \leq 1.2 \times 10^{-11}$.
- If BR $(\tau \to \mu\gamma)$ is found to be near its current upper limit (10^{-8}), the NH scenario is ruled out.

$\mu \to e\gamma$



$$\mathrm{BR}(\mu \to e\gamma) = \frac{27\alpha}{16\pi G_F^2} \left| F(x_{d_i}) \frac{g_{1i}^* g_{2i}}{M^2_{\omega^{2/3}}} + H(x_{u_\alpha}) V_{\alpha 4}^* V_{\alpha 4} \frac{h_1^* h_2}{M^2_{\omega^{1/3}}} \right|^2$$

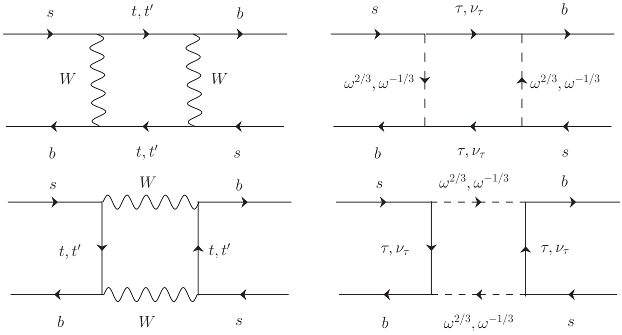
$$F(x) = -\frac{x}{12} \frac{(1-x)(5+x) + 2(2\,x+1)\,\ln x}{(1-x)^4}$$

$$H(x) = -\frac{1}{12} \frac{(1-x)(5\,x+1) + 2\,x(2+x)\,\ln x}{(1-x)^4}$$

$$x_{d_i} \equiv \frac{m^2_{d_i}}{M^2_{\omega^{2/3}}} \qquad x_{u_\alpha} \equiv \frac{m^2_{u_\alpha}}{M^2_{\omega^{1/3}}}$$

New CP Violation in B_s Meson

- This model can induce the new contributions to the $B_s - \overline{B}_s$ mixing



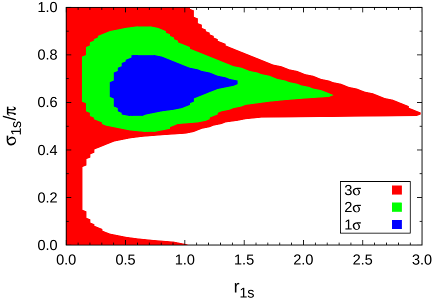
$$
\begin{aligned}
M_{12s} &= \left\{ \frac{\left(g_{32} g_{33}^*\right)^2}{192\pi^2 M_{LQ}^2} + \frac{G_F^2 m_W^2}{12\pi^2} \left[\lambda_3^2 S_0(x_3) + 2\lambda_3\lambda_4 S_0(x_3, x_4) + \lambda_4^2 S_0(x_4)\right] \right\} \\
&\quad \times m_{B_s} f_{B_s}^2 \hat{B}_{B_s}(\mu) \eta_{B_s}(\mu), \\
\lambda_\alpha &= V_{\alpha 3} V_{\alpha 2}^* \\
S_0(x, y) &\equiv \text{Inami} - \text{Lim function}
\end{aligned}
$$

New CP Violation in B_s Meson

- There is a hint of new CP violation in B_s meson from D0 (Abazov *et al.*, 2010)

$$(A^b_{sl})^{\text{obs}} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$$
$$(A^b_{sl})^{\text{SM}} = -2.3^{+0.5}_{-0.6} \times 10^{-4}$$

- In conjecture with other measurements (Δm_{B_s}, $\Delta\Gamma_s$, $S_{J/\psi\phi}$),



$$\frac{M_{12s} - M_{12s}^{\text{SM}}}{M_{12s}^{\text{SM}}} \equiv \underbrace{r_{1s} e^{i2\sigma_{1s}}}_{\text{LQ}} + \underbrace{r_{2s} e^{i2\sigma_{2s}}}_{\text{SM-like mixing}}$$

$$\frac{\Gamma_{12s} - \Gamma_{12s}^{\text{SM}}}{\Gamma_{12s}^{\text{SM}}} \equiv 0.14 \left(\frac{300\text{ GeV}}{M_2}\right)^2 r_{1s} e^{i2\sigma_{1s}}$$

$$M_{LQ} = 300\text{ GeV}$$

- The value of $r_{1s} \sim 0.8$ can be satisfied if $|g_{33}g_{32}| \sim 0.06$.

- The product of these couplings is not constrained by neutrino mass nor the LFV.

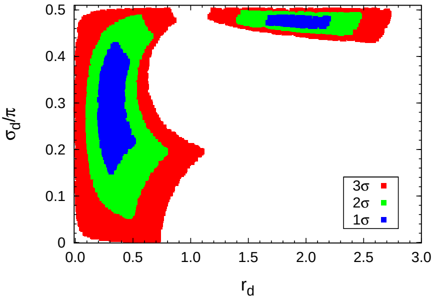
New CP Violation in B_d Meson

- The 3.2σ discrepancy in $\sin 2\beta$ determination

$$\begin{aligned} \sin 2\beta^{\text{fit}} &= 0.867 \pm 0.050 \\ \sin 2\beta^{\text{exp}} &\equiv S_{J/\psi K_s} = 0.671 \pm 0.023 \end{aligned}$$

Soni & Lunghi, 2008;
Soni & Lunghi, 2011

- If LQ is the only contribution of the new $B_d - \overline{B}_d$ mixing,



$$\begin{aligned} \Delta m_{B_d} &= \Delta m_{B_d}^{\text{SM}} \left|1 + r_d e^{i2\sigma_d}\right| \\ S_{J/\psi K_s} &= \sin\left[2\beta - \phi^{B_d}\right] \\ \phi^{B_d} &= \text{Arg}\left[1 + r_d e^{i2\sigma_d}\right] \end{aligned}$$

Neutrinoless Double Beta Decay

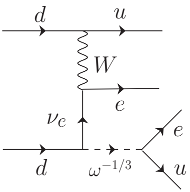
- Neutrinoless double beta decay might occur through vector-scalar exchange
  Babu & Mohapatra, 1995

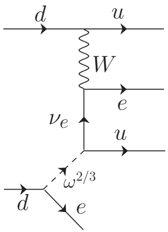
$$\mathcal{L}_{\rm eff}^{\rm new} = \frac{G_F}{4\sqrt{2}}\,\epsilon\,\left[\overline{u}\,(1+\gamma_5)\,d\,\overline{\nu}_e\,(1+\gamma_5)\,e^c \;+\; \frac{1}{2}\overline{u}\sigma^{\mu\nu}\,(1+\gamma_5)\,d\,\overline{\nu}_e\sigma_{\mu\nu}\,(1+\gamma_5)\,e^c\right]$$

$$\epsilon = \frac{g_{11}^* h_1 V_{14}^*}{2\sqrt{2}M_1^2 G_F}\left(1-\frac{M_1^2}{M_2^2}\right)$$

If $M_1 = 300$ GeV and $M_2 = 350$ GeV,

$$|g_{11}^* h_1 V_{14}| < 4.3\times 10^{-7}$$





- A sizable rate of $\beta\beta_{0\nu}$ might occur even in NH case

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Thank You