Two–Loop Neutrino Mass Generation through Leptoquarks

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Outline

- Motivation
- Two–loop neutrino mass model via leptoquarks
- Lepton flavor violation (LFV) constraints
- Collider signal
- Conclusions

Motivation

- Some puzzles in neutrino sector: the smallness of neutrino mass, the mass hierarchy, and θ_{13}.

- The origin of neutrino mass and its magnitude need to be explained.

- Several mechanisms that can explain the smallness of neutrino mass are:
  - ⋆ Seesaw mechanism (Minkowski, 1977; Gell-Mann *et al.*, 1980; Yanagida, 1979; Mohapatra & Senjanović, 1980).
    → new physics near GUT scale.
  - ⋆ Radiative mass generation mechanism (Zee, 1980; Babu, 1988).
    → loop suppression, so the new physics scale could be at TeV.

- Radiative mass generation mechanism could be tested at the LHC.

Review of $\Delta L = 2$ Operators

Some of operators (Babu & Leung, 2002):

1. $\mathcal{O}_1 \sim L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl}$: Standard seesaw.
2. $\mathcal{O}_2 \sim L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl}$: Zee's model.
3. $\mathcal{O}_3 \sim L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}$: MSSM with $\not{R}$.
4. $\mathcal{O}_4 \sim L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij}$: to be discussed.

Model

- We introduce new interactions under $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge group:

$$\mathcal{L} = Y_{ij} L_i^\alpha d_j^c \Omega^\beta \epsilon_{\alpha\beta} + F_{ij} e_i^c u_i^c \chi^{-1/3} + \mu \Omega^\dagger H \chi^{-1/3} + \text{h.c.}$$

with

$$\Omega \equiv \left(\begin{array}{c} \omega^{2/3} \\ \omega^{-1/3} \end{array} \right) \text{ and } \chi^{-1/3}$$

- The simultaneous presence of these three terms will break lepton number and together with SM interactions can be used to generate neutrino mass at two–loop level.
- The μ parameter will cause mixing between $\chi^{-1/3}$ and $\omega^{-1/3}$,

$$\left(\begin{array}{cc} m_\omega^2 & \mu v \\ \mu v & m_\chi^2 \end{array} \right) \Rightarrow \sin 2\theta = \frac{2\mu v}{M_2^2 - M_1^2}$$

$$M_{1,2}^2 = \tfrac{1}{2} \left[m_\omega^2 + m_\chi^2 \mp \sqrt{(m_\omega^2 - m_\chi^2)^2 + 4\mu^2 v^2} \right]$$

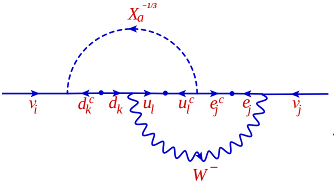
Limit on μ

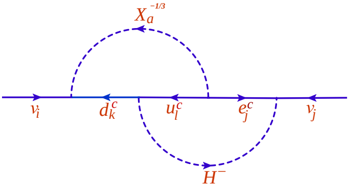
- Before symmetry breaking, $\omega^{2/3}$ and $\omega^{-1/3}$ have common mass m_ω^2.
- There exists also quartic interaction: $\lambda|H^\dagger\Omega|^2$.
- Electroweak symmetry breaking causes splitting, and this splitting is constrained by ρ parameter (C. Amsler *et al.*, 2008),

$$|\Delta m| < 57 \text{ GeV} \quad \text{at } 95\% \text{ c.l.}$$

- This puts limit on μ parameter: $\mu < 0.65\ M_1$.

Neutrino Mass Model





$$
\begin{aligned}
(M_\nu)_{ij} &= \hat{m}_0 Y_{ik} (D_d)_k (V^T)_{kl} (D_u)_l (F^\dagger)_{lj} (D_\ell)_j I_{jkl} + \text{transpose}, \\
\hat{m}_0 &= \left(\frac{C g^2 \sin 2\theta}{(16\pi^2)^2} \right) \left(\frac{m_t m_b m_\tau}{M_1^2} \right); \; C = 3, \\
I_{jkl}(M_1^2, M_2^2, m_W^2) &= \frac{M_1^2}{m_W^2 - m_{\ell_j}^2} \sum_{a=1,2} (-1)^a \int_0^1 dx \int_0^\infty t dt \left(\frac{1}{t + M_a^2} - \frac{1}{t + m_{d_k}^2} \right) \\
&\quad \times \ln \left[\frac{m_W^2 (1-x) + m_{u_l}^2 x + t x (1-x)}{m_{\ell_j}^2 (1-x) + m_{u_l}^2 x + t x (1-x)} \right] .
\end{aligned}
$$

Neutrino Mass Model

The neutrino mass matrix:

$$M_\nu \simeq m_0 \begin{pmatrix} 0 & \frac{1}{2}\frac{m_\mu}{m_\tau}xy & \frac{1}{2}y \\ \frac{1}{2}\frac{m_\mu}{m_\tau}xy & \frac{m_\mu}{m_\tau}xz & \frac{1}{2}z + \frac{1}{2}\frac{m_\mu}{m_\tau}x \\ \frac{1}{2}y & \frac{1}{2}z + \frac{1}{2}\frac{m_\mu}{m_\tau}x & 1 \end{pmatrix} + \delta M_\nu$$

$$x \equiv \frac{F^*_{23}}{F^*_{33}}, \quad y \equiv \frac{Y_{13}}{Y_{33}}, \quad z \equiv \frac{Y_{23}}{Y_{33}}, \quad m_0 = 2\ \hat{m}_0 F^*_{33} Y_{33} I_{jk3}.$$

δM_ν is suppressed.

Comments:

1. This mass matrix has normal hierarchy pattern:
   $|x| \sim m_\tau / m_\mu,\ |y| \sim |z| \sim 1.$
2. The determinant is highly suppressed:

$$\begin{aligned} \mathrm{Det}\ M_\nu \simeq & \frac{m_0^3}{4}\left(\frac{m_c}{m_t}\right)\left(\frac{m_s}{m_b}\right)\left(\frac{m_\mu}{m_\tau}\right)\left(x\frac{F^*_{32}}{F^*_{33}} - \frac{F^*_{22}}{F^*_{33}}\right) \\ & \times\left[y\left(y\frac{Y_{22}}{Y_{33}} - z\frac{Y_{12}}{Y_{33}}\right) + \left(\frac{m_\mu}{m_\tau}\right)xy\left(\frac{Y_{12}}{Y_{33}} - y\frac{Y_{32}}{Y_{33}}\right)\right] \end{aligned}$$

3. The (1,1) entry, $(M_\nu)_{11} \simeq m_0 y \frac{F^*_{13}}{F_{33}} \frac{m_e}{m_\tau}$ is highly suppressed too.

Neutrino Mass Model

- The predictions:

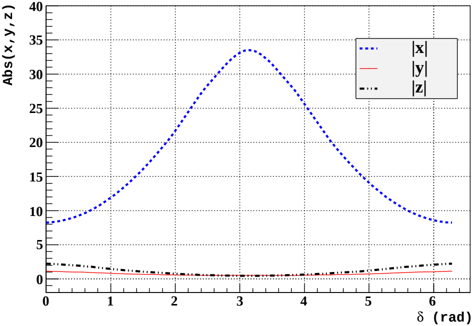
$$\begin{aligned} m_1 &\simeq 0, \\ \alpha &\simeq 0,\ \beta \simeq 2\delta - \pi \\ \tan^2\theta_{13} &\simeq \frac{m_2}{m_3}\sin^2\theta_{12}. \end{aligned}$$

- Use (Schwetz *et al.*, 2008): $\Delta m^2_{21} = 7.65 \times 10^{-5}\ \mathrm{eV}^2,\ \Delta m^2_{31} = 2.40 \times 10^{-3}\ \mathrm{eV}^2,\ \sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}$;

$\sin^2\theta_{12}$	$\sin^2\theta_{13}$ (pred.)
0.304	0.051
0.288	0.049
0.272	0.046
0.256	0.044

Current upper limit: $\sin^2\theta_{13} \leq 0.041\ (2\sigma),\ 0.056\ (3\sigma)$.

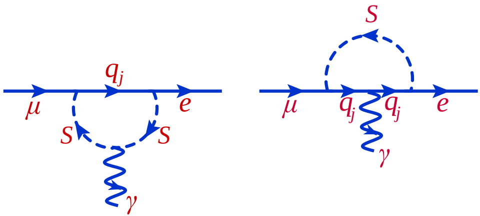
Neutrino Mass Model



$$\begin{aligned} x &= \frac{12.21 - 4.17e^{i\delta}}{0.726 + 0.248e^{i\delta}}, \quad y = \frac{-0.112e^{i\delta}(2.927 + e^{i\delta})}{-0.473 + 0.018e^{i\delta} + 0.062e^{2i\delta}}, \\ z &= \frac{0.473 + 0.342e^{i\delta} + 0.062e^{2i\delta}}{0.473 - 0.018e^{i\delta} - 0.062e^{2i\delta}}. \end{aligned}$$

Experimental Constraints

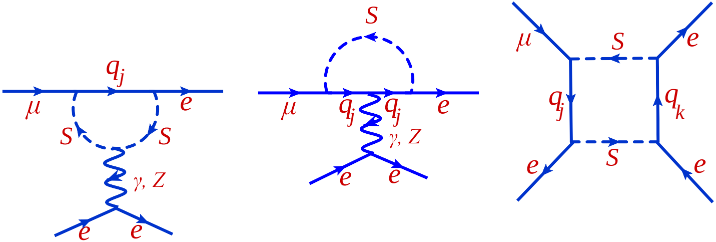
- $\mu^- \to e^-\gamma$



In the limit d_j masses equal to zero, these two diagrams cancel because the left one is twice smaller in magnitude than the right one, whereas the charge of $\omega^{2/3}$ is twice larger than d_j and is opposite.
$\to Y_{ij}$ are not constrained.

Experimental Constraints

- $\mu^- \to e^+ e^- e^-$



Since photon is off-shell, there is another contribution for $\omega^{2/3}$ mediated process.
$\to Y_{ij}$ are constrained.

Experimental Constraints

Just considering the couplings contributing to neutrino masses, Y_{i3} and F_{i3}: $|F_{23}| \sim 16|F_{33}|$ and $|Y_{13}| \sim |Y_{23}| \sim |Y_{33}|$

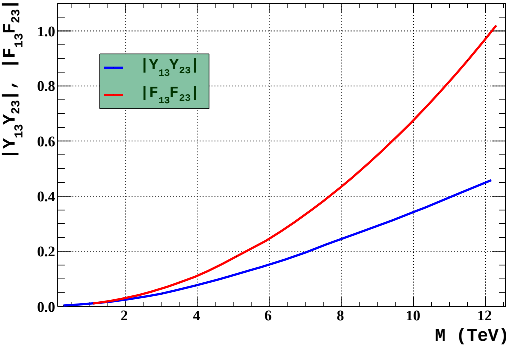
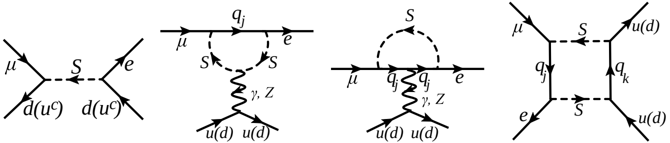


Figure: The upper limit of $Y_{13}Y_{23}$ and $F_{13}F_{23}$ as function of leptoquark masses with $\theta = \pi/4$.

The lightest leptoquark cannot be heavier than 12 TeV otherwise neutrino mass will be too small.

Experimental Constraints

- $\mu - e$ Conversion in the Nuclei



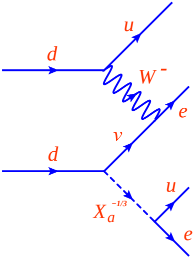
For Ti at 1 TeV,

$$\begin{aligned} |Y_{13}^* Y_{23}| &< 10^{-3} \text{ and } |F_{13} F_{23}^*| < 10^{-4} \\ |Y_{11}^* Y_{21}| &< 10^{-6} \text{ and } |F_{11} F_{21}^*| < 10^{-6} \rightarrow \text{ tree level} \end{aligned}$$

This can be improved in future experiment as sensitivity reaches 10^{-16} (COMET Collaboration, Cui *et al.*, 2009).

Experimental Constraints

- Neutrinoless Double Beta Decay ($0\nu\beta\beta$)
  Since (1,1) entry is zero, $0\nu\beta\beta$ cannot happen through changing the internal neutrino helicity but rather



$$|Y_{11}^* F_{11}| < 1.7 \times 10^{-6} \left(\frac{M_1}{1\ \mathrm{TeV}}\right)^2 \left(\frac{0.5\ \mathrm{TeV}}{\mu}\right).$$

Collider Signal

- The $\omega^{2/3}$ and $X_a^{-1/3}$ may be produced at colliders, through pair production or single production.
- The signature of $\omega^{2/3}$: 2 leptons + jets
- The signatures of $X_a^{-1/3}$: 2 leptons + jets, lepton + jets + ME.
- The $\omega^{2/3}$ decay modes:

$$\Gamma(\omega^{2/3} \to e^+ b) \ : \ \Gamma(\omega^{2/3} \to \mu^+ b) \ : \ \Gamma(\omega^{2/3} \to \tau^+ b) \ = \ |y|^2 \ : \ |z|^2 \ : \ 1.$$

- The $X_a^{-1/3}$ decay modes:

$$\Gamma(X_a^{-1/3} \to \mu^- t) \ : \ \Gamma(X_a^{-1/3} \to \tau^- t) \ = \ |x|^2 \ : \ 1.$$

$\to \mu^-$ will be observed more than τ^-.

- These will provide another way of measuring δ.

Conclusions

- This model could generate neutrino mass at TeV scale.
- The neutrino mass spectrum is predicted to be normal hierarchy.
- θ_{13} is predicted to be near the upper limit.
- Knowing the leptoquark decay widths will lead to determination of δ.
- Neutrinoless double beta decay may be observed although this model suggests normal hierarchy.

Thank You