Radiative Neutrino Mass Generation and its Experimental Signals

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"LHC: From Here to Where?"

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New results based on:

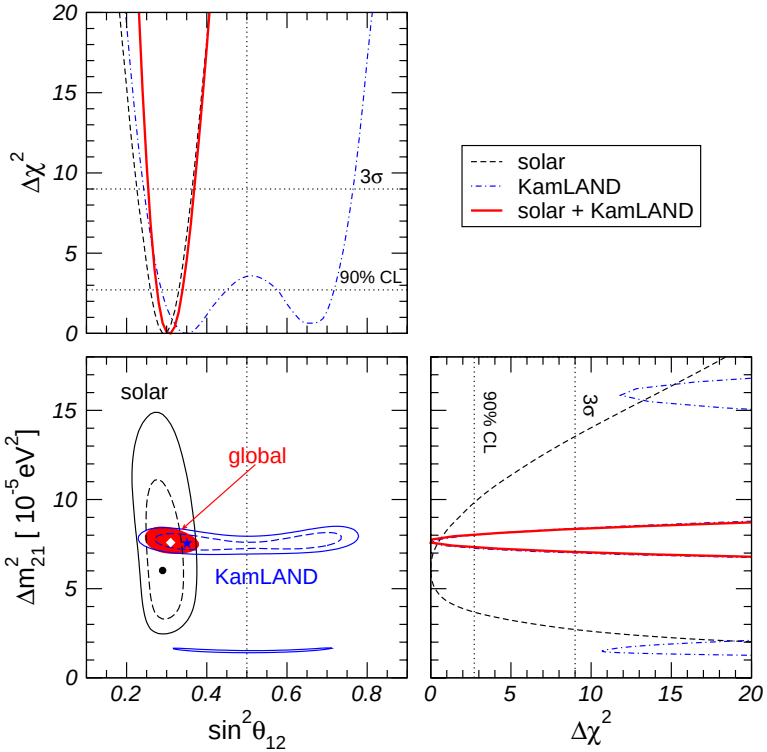
"Two loop neutrino mass generation through leptoquarks",

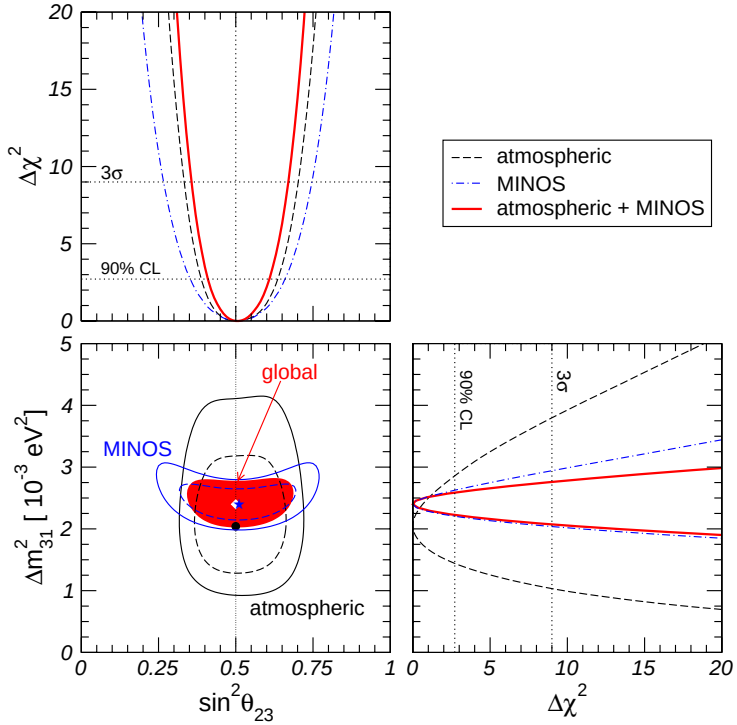
K.S. Babu and J. Julio, arXiv: 1006.1092 [hep-ph].

Outline

- Brief review of seesaw and its possible collider tests
- Effective operator approach for neutrino masses and radiative mass generation
- New two loop neutrino mass model with leptoquarks
- Testing neutrino mass generation in leptoquark decays and in lepton flavor violation
- Predictions for rare decays
- New CP violation in $B_s - \bar{B}_s$ mixing
- Conclusions

Current status of neutrino oscillation data





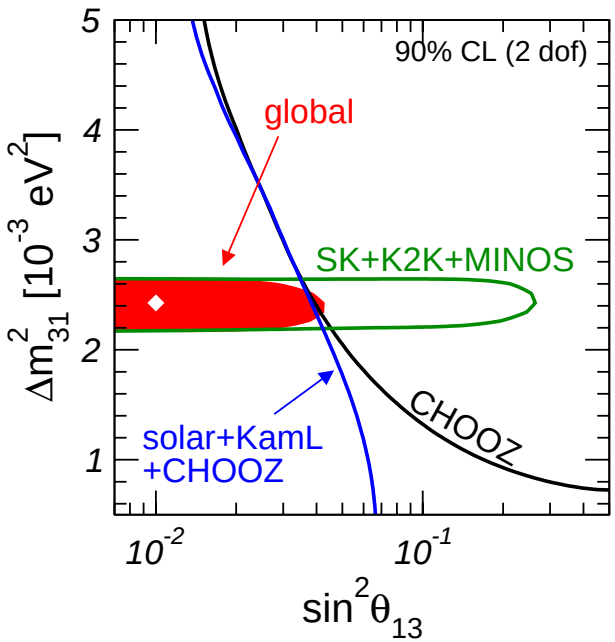
$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}$$

$$\Delta m^2_{21} = 7.65^{+0.23}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}$$

$$|\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2$$

T. Schwetz, M.A. Tortola, J.W.F.Valle, New J.Phys.10, 113011 (2008)



Constraints on θ_{13}

parameter	best fit	2σ	3σ
Δm^2_{21} [10^{-5}eV^2]	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2]	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

Summary of data

Seesaw Mechanism for Neutrino Mass

$(\nu,\ \nu^c)$ Mass Matrix:

Gell-Mann, Ramond, Slansky (1979)
Yanagida (1979)
Mohapatra, Senjanovic (1979)
Minkowski (1977)

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

m_D breaks $SU(2)_L \times U(1)_Y$ symmetry $\Rightarrow m_D \leq$ 200 GeV

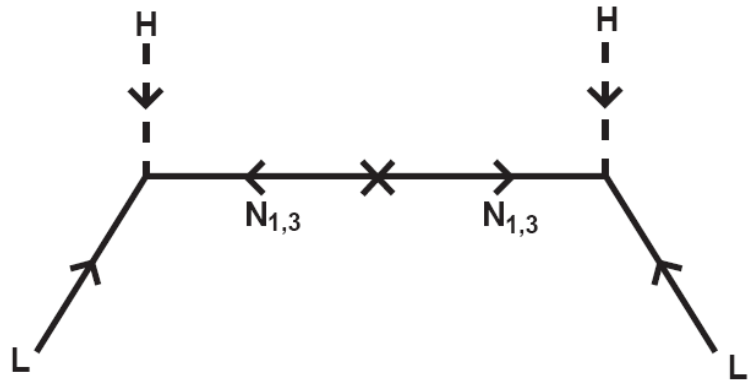
M_R not protected by any symmetry and can be large, $M_R \sim 10^{14}$ GeV

$$m_\nu(\text{light}) \approx \frac{m_D^2}{M_R} \sim 10^{-2}\ \text{eV}$$

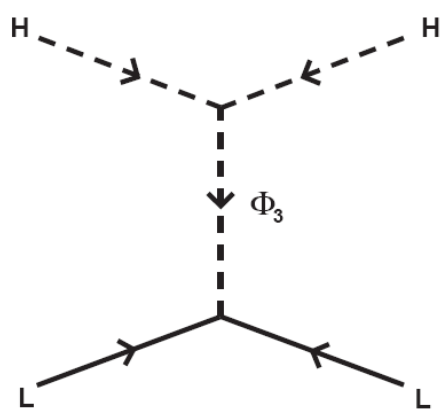
$$m_\nu(\text{heavy}) \approx M_R \sim 10^{14}\ \text{GeV}$$

Origin of seesaw mechanism

Type (I,III) seesaw



Type II seesaw



$$m_\nu \sim \frac{v^2}{M}$$

Is seesaw testable at the LHC?

ν^c mass of order few hundred GeV needed

Large $\nu^c - \nu$ mixing possible:

$$m_D = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} v, \quad M_R = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} m_R$$

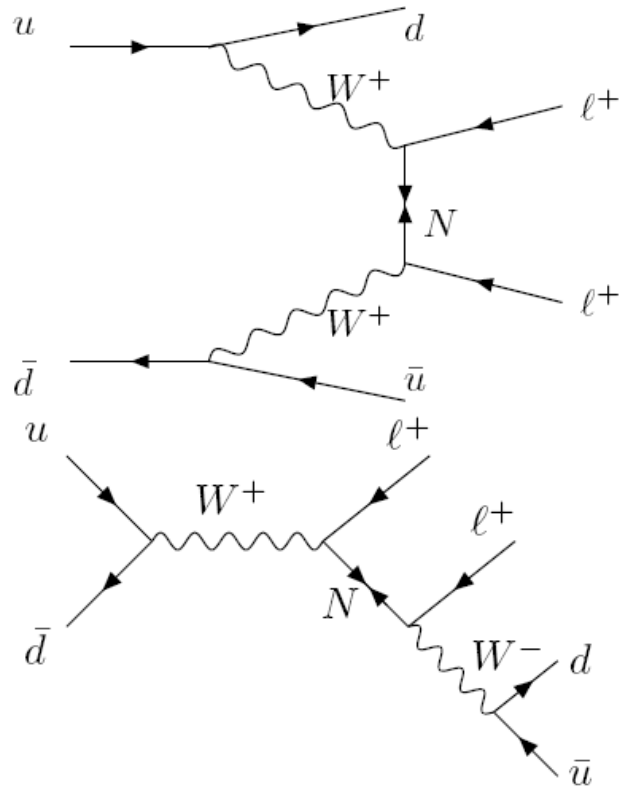
$$\Rightarrow \qquad M_\nu = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

Three family analysis gives no new solution

Kersten, Smirnov (2007)

$\nu^c - \nu$ mixing at 10% level is ok

Lepton number violation at the LHC?



T. Han, B. Zhang (2006)

$$\sum_N \frac{V_{eN}^2}{M_N} < 5 \times 10^{-8}\ \text{GeV}^{-1} \text{ from } \beta\beta_{0\nu}$$

Same sign dimuons with no missing E_T signal of $\Delta L = 2$

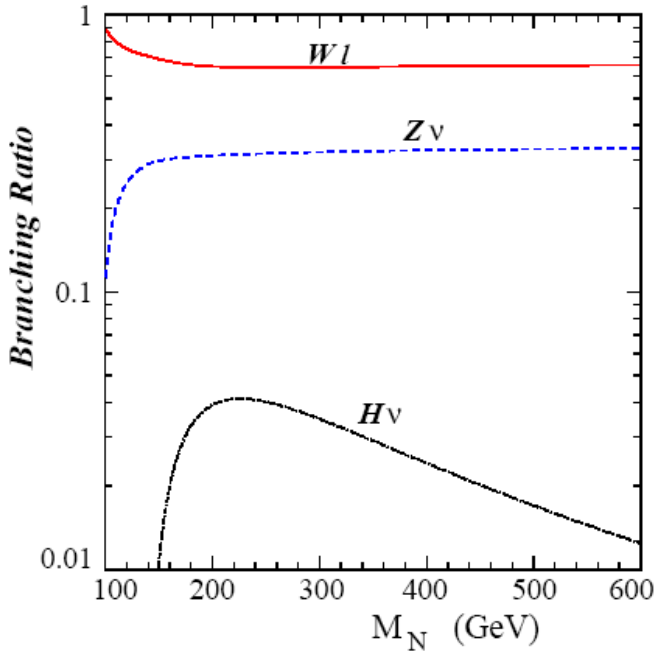
LHC reach upto 400 GeV on N mass

If B-L is gauged:

N can be pair produced via Z' exchange

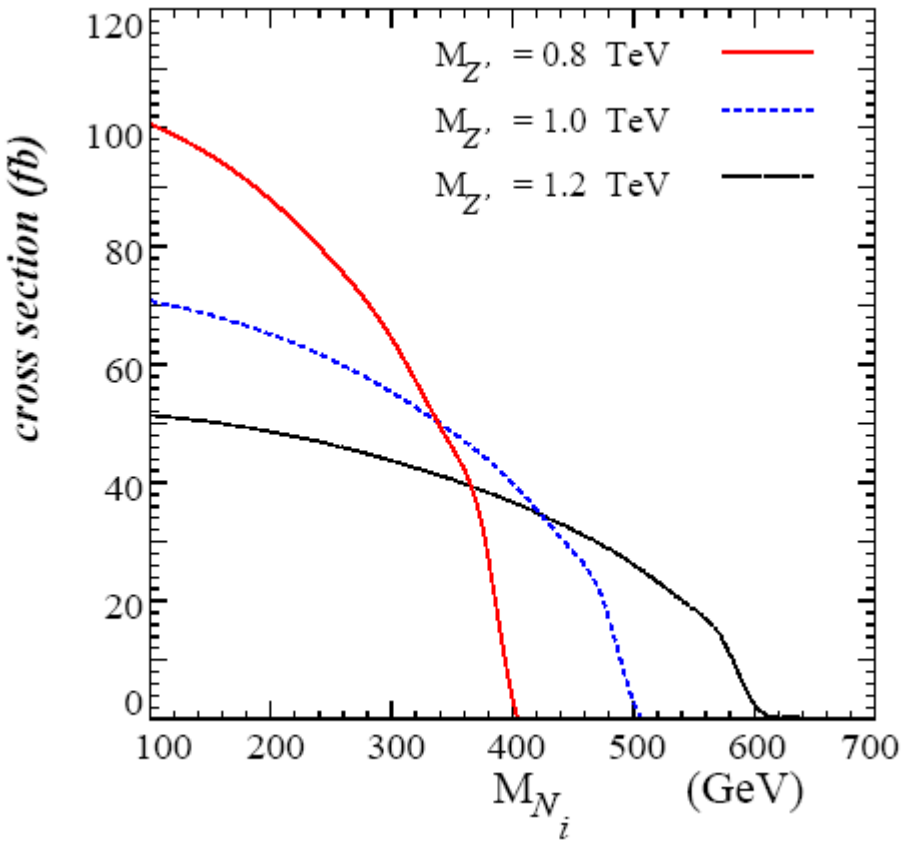
N decays into $\ell^{\pm}W^{\mp}$

Huitu, Khalil, Okada, Rai (2008)



Signals: $pp \to \ell^+\ell^-\ell^+\ell^- + E_T$

SM background: $4W$ ($\sim$ 6 fb) and WWZ ($\sim$ 200 fb)



N pair production cross section at LHC

LHC reach on N mass: upto 400 GeV (Z' must be of ordet TeV)

Possible probe of baryon asymmetry **Blanchet, Chacko, Mohapatra**

Effective operator for neutrino masses

Standard seesaw operator

KB, C.N. Leung (2003)

$$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik} \epsilon_{jl}$$

Operators with four fermions:

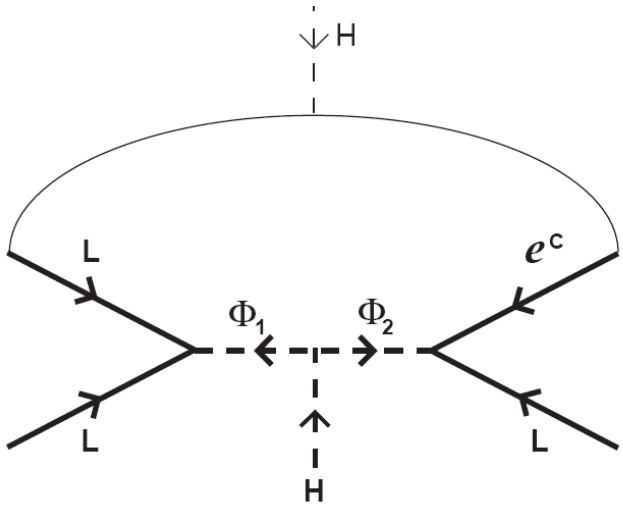
$$\begin{aligned}
\mathcal{O}_2 &= L^i L^j L^k e^c H^l \epsilon_{ij} \epsilon_{kl} \\
\mathcal{O}_3 &= \{ L^i L^j Q^k d^c H^l \epsilon_{ij} \epsilon_{kl}, \quad L^i L^j Q^k d^c H^l \epsilon_{ik} \epsilon_{jl} \} \\
\mathcal{O}_4 &= \{ L^i L^j \bar{Q}_i \bar{u}^c H^k \epsilon_{jk}, \quad L^i L^j \bar{Q}_k \bar{u}^c H^k \epsilon_{ij} \} \\
\mathcal{O}_5 &= L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl} \epsilon_{km} \\
\mathcal{O}_6 &= L^i L^j \bar{Q}_k \bar{u}^c H^l H^k \bar{H}_i \epsilon_{jl} \\
\mathcal{O}_7 &= L^i Q^j \bar{e}^c \bar{Q}_k H^k H^l H^m \epsilon_{il} \epsilon_{jm} \\
\mathcal{O}_8 &= L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij}
\end{aligned}$$

Operators with six fermions:

$$
\begin{aligned}
\mathcal{O}_9 &= L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_{10} &= L^i L^j L^k e^c Q^l d^c \epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_{11} &= \{L^i L^j Q^k d^c Q^l d^c \epsilon_{ij}\epsilon_{kl}, \quad L^i L^j Q^k d^c Q^l d^c \epsilon_{ik}\epsilon_{jl}\} \\
\mathcal{O}_{12} &= \{L^i L^j \bar{Q}_i \bar{u}^c \bar{Q}_j \bar{u}^c, \quad L^i L^j \bar{Q}_k \bar{u}^c \bar{Q}_l \bar{u}^c \epsilon_{ij}\epsilon^{kl}\} \\
\mathcal{O}_{13} &= L^i L^j \bar{Q}_i \bar{u}^c L^l e^c \epsilon_{jl} \\
\mathcal{O}_{14} &= \{L^i L^j \bar{Q}_k \bar{u}^c Q^k d^c \epsilon_{ij}, \quad L^i L^j \bar{Q}_i \bar{u}^c Q^l d^c \epsilon_{jl}\} \\
\mathcal{O}_{15} &= L^i L^j L^k d^c \bar{L}_i \bar{u}^c \epsilon_{jk} \\
\mathcal{O}_{16} &= L^i L^j e^c d^c \bar{e}^c \bar{u}^c \epsilon_{ij} \\
\mathcal{O}_{17} &= L^i L^j d^c d^c \bar{d}^c \bar{u}^c \epsilon_{ij} \\
\mathcal{O}_{18} &= L^i L^j d^c u^c \bar{u}^c \bar{u}^c \epsilon_{ij} \\
\mathcal{O}_{19} &= L^i Q^j d^c d^c \bar{e}^c \bar{u}^c \epsilon_{ij} \\
\mathcal{O}_{20} &= L^i d^c \bar{Q}_i \bar{u}^c \bar{e}^c \bar{u}^c
\end{aligned}
$$

$\mathcal{O}_2$ model of neutrino mass

$$\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij} \epsilon_{kl} \qquad \Rightarrow \qquad \text{Zee model}$$



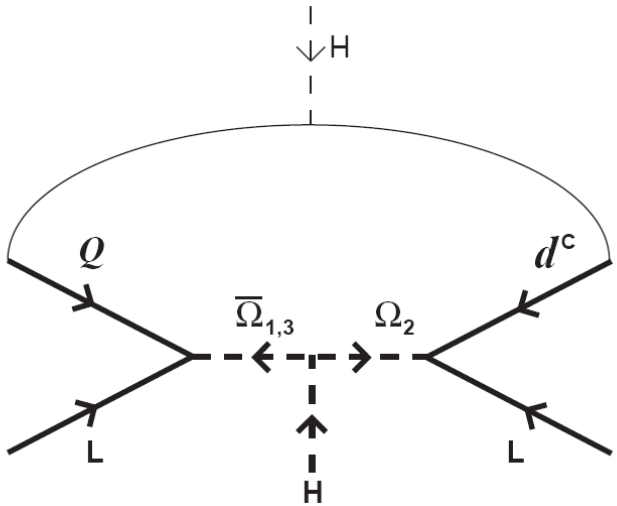
$$M_\nu = \begin{pmatrix} 0 & m_1 & m_2 \\ m_1 & 0 & m_3 \\ m_2 & m_3 & 0 \end{pmatrix}$$

Excluded by neutrino data

$\mathcal{O}_3$ model of neutrino mass

$$\mathcal{O}_3 = \{L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}, \quad L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}\}$$

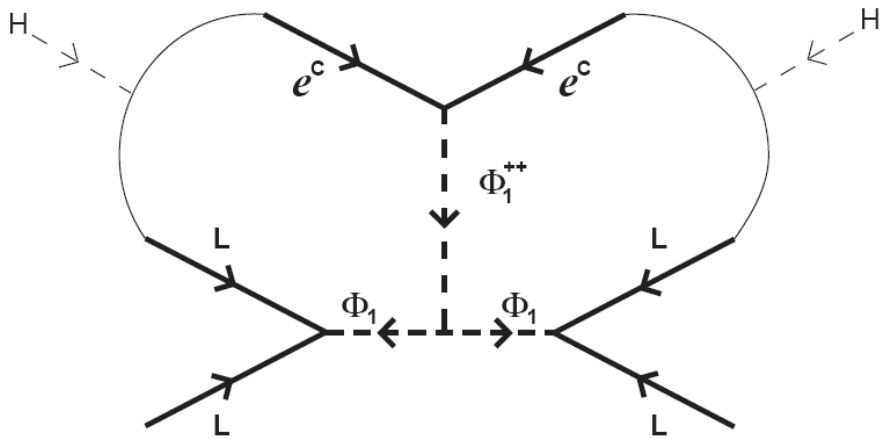
R–parity violating models



Widely studied

Two–loop neutrino mass generation via $\mathcal{O}_9$

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl} \qquad \Rightarrow \quad \text{Zee, Babu}$$

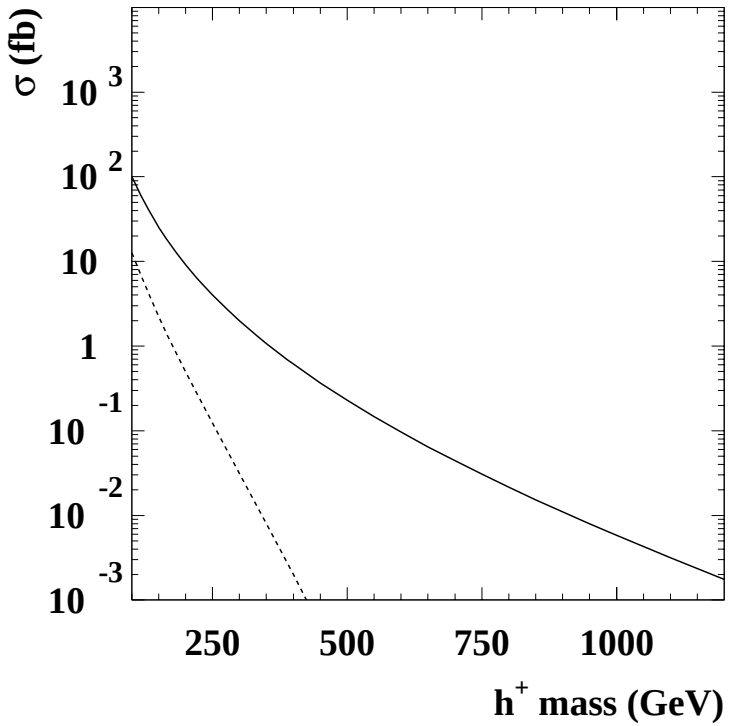


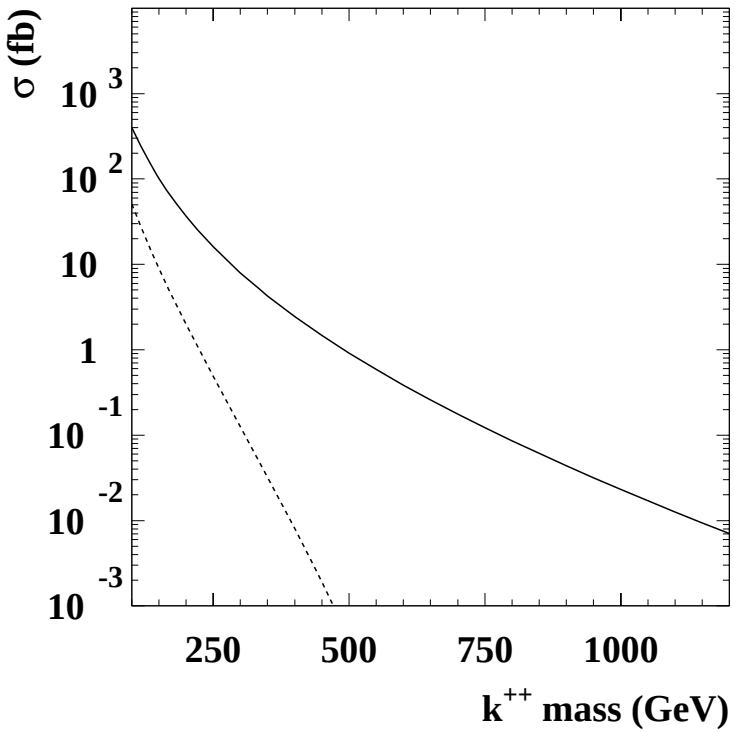
Consistent with neutrino data

Predicts doubly charged Higgs boson

One neutrino is nearly massless

Cross section for h^+ and k^{++} at LHC and Tevatron





LHC: Solid line, Tevatron: dashed

KB, C. Macesanu (2005)
Nebot, Oliver, Paolo, Santamaria (2008)

New two loop neutrino mass model with Leptoquarks

$\mathcal{O}_8$ can be induced via scalar leptoquarks

$$\mathcal{O}_8 = L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij}$$

M_ν arises as $d = 7$ operators at two loop

$$m_\nu \sim \frac{m_t\, m_b\, m_\tau\, \mu v}{(16\pi^2)^2 M^4}$$

Leptoquark within reach of LHC

Leptoquark branching ratios probe m_ν

Leptoquark Model for neutrino mass

Add two leptoquark fields to standard model

$$\Omega(3,2,1/6) = \begin{bmatrix} \omega^{2/3} \\ \omega^{-1/3} \end{bmatrix}, \quad \chi^{-1/3}(3,1,-1/3)$$

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

$$V = \mu\ \Omega^\dagger H \chi^{-1/3} + h.c.$$

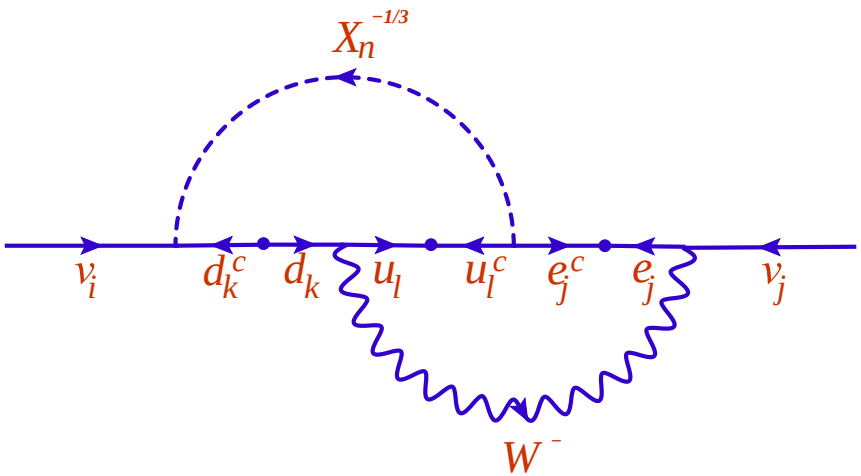
B is unbroken, but L is softly broken

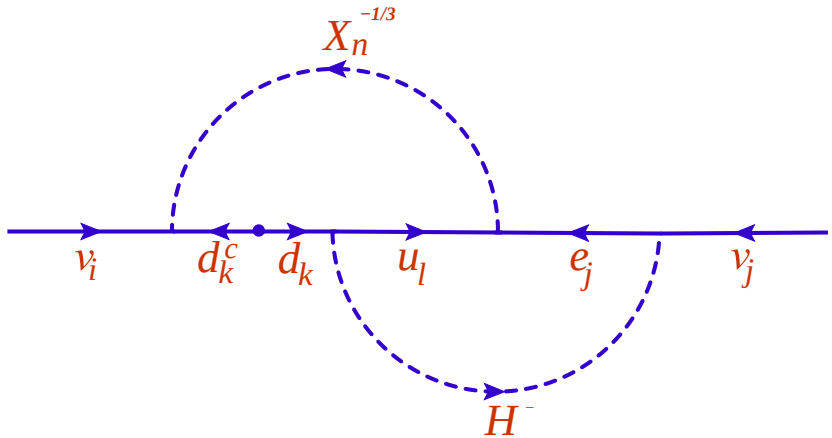
$$\begin{aligned} \mathcal{L}_\nu &= Y_{ij}(\nu_i d_j^c \omega^{-1/3} - e_i d_j^c \omega^{2/3}) + F_{ij} e_i^c u_j^c \chi^{-1/3} + h.c. \\ V &= \mu(\omega^{-2/3} H^+ + \omega^{1/3} H^0)\chi^{-1/3} + h.c. \end{aligned}$$

$$M^2_{\text{LQ}} = \begin{pmatrix} m_\omega^2 & \mu v \\ \mu^* v & m_\chi^2 \end{pmatrix}$$

Mass eigenvalues $M^2_{1,2}$, mixing θ

Neutrino mass generation



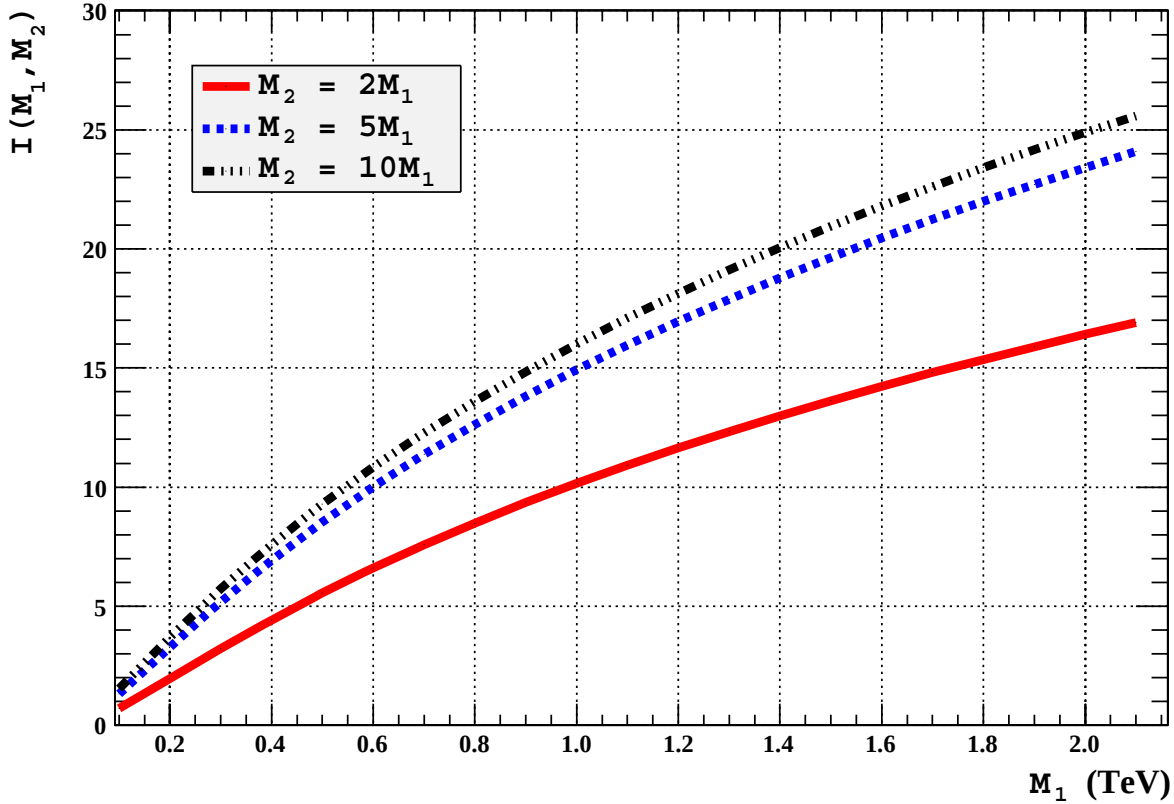


$$M_\nu = \hat{m}_0 \hat{I} \left[Y D_d V^T D_u F^\dagger D_\ell + D_\ell F^* D_u V D_d Y^T \right]$$

$$\hat{m}_0 = \left(\frac{C g^2 \sin 2\theta}{(16\pi^2)^2} \right) \left(\frac{m_t m_b m_\tau}{M_1^2} \right)$$

$$D_u = \text{diag.} \left[\frac{m_u}{m_t}, \ \frac{m_c}{m_t}, \ 1 \right], \quad D_d = \text{diag.} \left[\frac{m_d}{m_b}, \ \frac{m_s}{m_b}, \ 1 \right], \quad D_\ell = \text{diag.} \left[\frac{m_e}{m_\tau}, \ \frac{m_\mu}{m_\tau}, \ 1 \right]$$

$\hat{I}$: Loop integral function



$$I_{jkl}(M_1^2, M_2^2, m_W^2) = \frac{M_1^2}{m_W^2 - m_j^2} \sum_{a=1,2} (-1)^a \int_0^1 dx \int_0^\infty t dt \left(\frac{1}{t + M_a^2} \; \frac{1}{t + m_k^2} \right)$$

$$\times \quad \ln \left[\frac{m_W^2(1-x) + m_l^2 x + tx(1-x)}{m_j^2(1-x) + m_l^2 x + tx(1-x)} \right] .$$

$$\simeq \left(1 - \frac{M_1^2}{M_2^2}\right) \left[1 + \frac{\pi^2}{3} + \frac{\left(M_1^2 \ln\frac{M_2^2}{M_W^2} - M_2^2 \ln\frac{M_1^2}{m_W^2}\right)}{M_1^2 - M_2^2} + \frac{1}{2} \frac{\left(M_1^2 \ln^2\frac{M_2^2}{m_W^2} - M_2^2 \ln^2\frac{M_1^2}{m_W^2}\right)}{M_1^2 - M_2^2} \right] .$$

Neutrino phenomenology

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

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

$$w \equiv \frac{F^*_{32}}{F^*_{33}} \frac{Y_{32}}{Y_{33}} \left(\frac{m_c}{m_t}\right) \left(\frac{m_s}{m_b}\right) \frac{I_{jk2}}{I_{jk3}}$$

Note that (1,1) entry is zero

This matrix has zero determinant (if $w \ll 1$) $\Rightarrow$

$$m_1 = 0, \quad \tan^2\theta_{13} = \frac{m_2}{m_3}\sin^2\theta_{12}$$

$$\beta = 2\delta + \pi, \quad \alpha = 0 \quad \text{(Majorana phases)}$$

Neutrino phenomenology (cont.)

Fit to oscillation data ($w \ll 1$):

$$\Delta m^2_{\text{solar}} = 7.65 \times 10^{-5}\ \text{eV}^2,\ \Delta m^2_{\text{atm}} = 2.40 \times 10^{-3}\ \text{eV}^2$$

$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016} \qquad \sin^2\theta_{23} = 0.50 \Rightarrow$$

$$\sin^2\theta_{13} = \{0.051 - 0.044\}$$

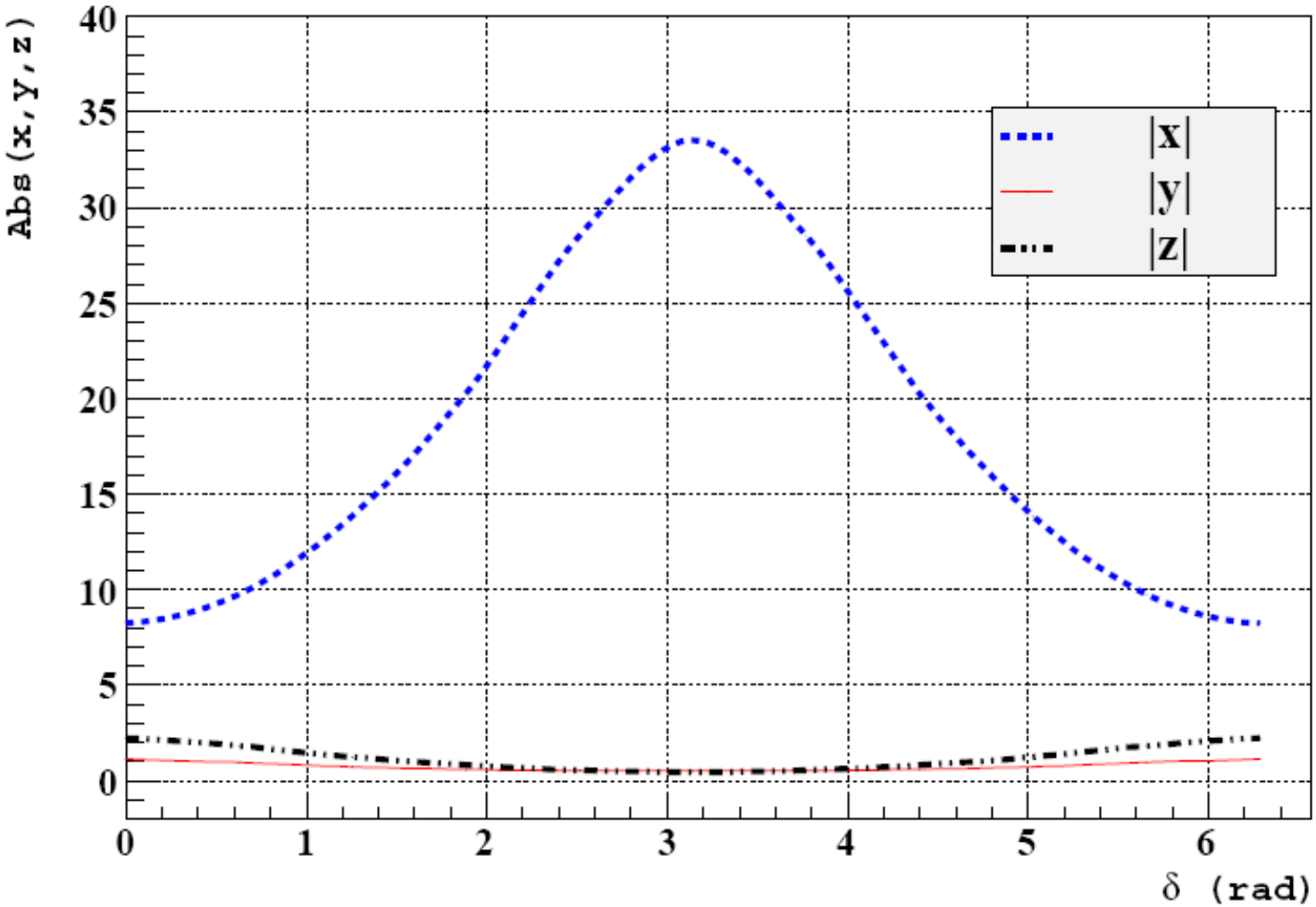
For central values of parameters

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

For $\delta = 0$, $(x, y, z) = (8.25, 1.12, 2.23)$

For $\delta = \pi$, $(x, y, z) = (34.28, -0.50, 0.45)$

x,y,z versus delta



Leptoquark branching ratios

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

Measuring any of the branching ratios will fix δ

Measuring two ratios overconstrains and gives checks

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

Further checks provided

Since $|x| \gg 1$, μ will dominate final states

Special case: w >> 1

$$(M_\nu)_{11} = (M_\nu)_{13} \simeq 0$$

$$\sin^2\theta_{13} \simeq \frac{|\Delta m^2_{\rm solar}|/|\Delta m^2_{\rm atm}|}{\left|\cot^2\theta_{12} - e^{i2(\alpha-\beta)}\tan^2\theta_{12}\right|},$$

$$\tan 2(\beta+\delta) \simeq \frac{\tan^2\theta_{12}\sin 2(\alpha-\beta)}{\cot^2\theta_{12} - \tan^2\theta_{12}\cos 2(\alpha-\beta)}$$

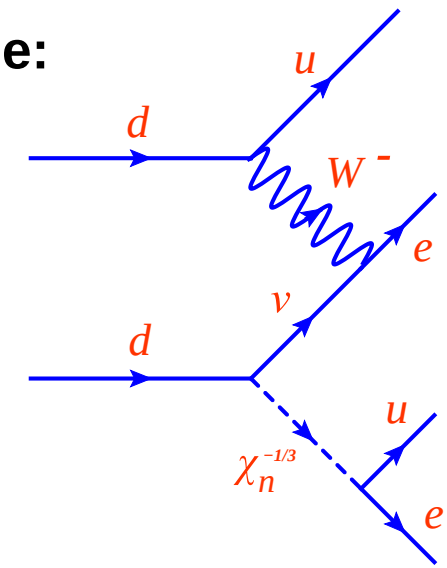
$$\Rightarrow \quad \sin^2\theta_{13} = (0.012 - 0.017)$$

Frampton. Glashow, Marfatia (2002)
Xing (2002)

Leptoquark mass = (300 – 500) GeV

Neutrinoless double beta decay

Vector-scalar exchange:



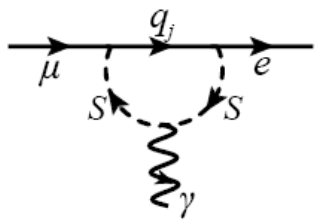
Babu, Mohapatra (1995)

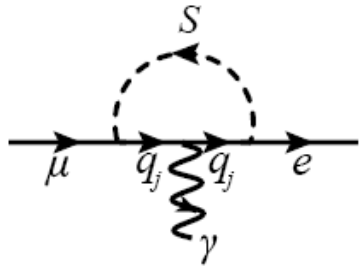
$$\mathcal{L}_{\text{eff}} = \frac{G_F^2}{2}\,\epsilon\,\overline{u}\gamma^\mu(1-\gamma_5)d\left[\overline{u}(1+\gamma_5)d\overline{e}\gamma_\mu(1-\gamma_5)\frac{1}{\not{q}}e^c + \frac{1}{4}\overline{u}\sigma^{\alpha\beta}(1+\gamma_5)d\overline{e}\gamma_\mu(1-\gamma_5)\frac{1}{\not{q}}\sigma_{\alpha\beta}e^c\right]$$

$$\epsilon = \frac{Y_{11}^* F_{11}}{2\sqrt{2}M_1^2 G_F}\sin 2\theta\left(1-\frac{M_1^2}{M_2^2}\right)$$

$$|Y_{11}^* F_{11}| < 8.4\times 10^{-7}\left(\frac{M_1}{1\ \text{TeV}}\right)^2\left(\frac{M_2}{1\ \text{TeV}}\right)^2\left(\frac{1\ \text{TeV}}{\mu}\right)$$

Mu → e gamma predictions





Process	BR	Constraint
$\mu \to e\gamma$	$< 1.2 \times 10^{-11}$	$\frac{\left\lvert F_3(x_b) Y_{13}^* Y_{23}\right\rvert^2}{m_\Omega^4} + \frac{\left\lvert \frac{1}{12} F_{11} F_{21}^* + \frac{1}{12} F_{12} F_{22}^* + F_4(x_t) F_{13} F_{23}^*\right\rvert^2}{m_\chi^4} < \frac{3.1\times 10^{-19}}{\mathrm{GeV}^4}$
$\tau \to e\gamma$	$< 1.1 \times 10^{-7}$	$\frac{\left\lvert F_3(x_b) Y_{13}^* Y_{33}\right\rvert^2}{m_\Omega^4} + \frac{\left\lvert \frac{1}{12} F_{11} F_{31}^* + \frac{1}{12} F_{12} F_{32}^* + F_4(x_t) F_{13} F_{33}^*\right\rvert^2}{m_\chi^4} < \frac{1.6\times 10^{-14}}{\mathrm{GeV}^4}$
$\tau \to \mu\gamma$	$< 4.5 \times 10^{-8}$	$\frac{\left\lvert F_3(x_b) Y_{23}^* Y_{33}\right\rvert^2}{m_\Omega^4} + \frac{\left\lvert \frac{1}{12} F_{21} F_{31}^* + \frac{1}{12} F_{22} F_{32}^* + F_4(x_t) F_{23} F_{33}^*\right\rvert^2}{m_\chi^4} < \frac{6.7\times 10^{-15}}{\mathrm{GeV}^4}$

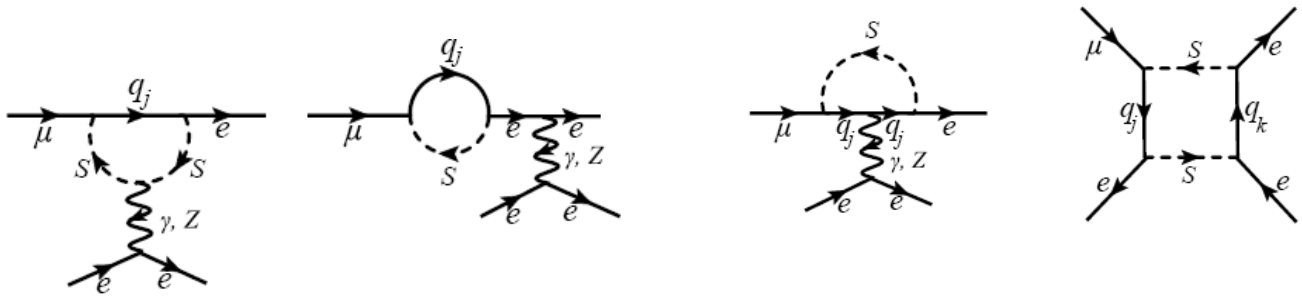
Table 1: The constraints from $\ell_i \to \ell_j \gamma$.

GIM suppression!

Mu-e conversion in nuclei

$$\mathrm{BR}(\mu N \to eN) = \frac{|\vec{p}_e| E_e m_\mu^3 G_F^2 \alpha^3 Z_{\mathrm{eff}}^4 F_p^2}{8\pi^2 Z\ \Gamma_N} \left| g_L^u (A+Z) + g_L^d (2A-Z) + 2Z\Delta g_L \right|^2$$
$$+ L \leftrightarrow R$$

Element	BR	Z_{eff}	F_p	Constraint
^{48}Ti	$< 4.3 \times 10^{-12}$	17.61	0.53	$\left\lvert \frac{a_j^L Y_{ij}^* Y_{2j}}{m_\Omega^2} + \frac{a_j^R F_{1j} F_{2j}^*}{m_\chi^2} \right\rvert^2 + \left\lvert \frac{b_j^L Y_{ij}^* Y_{2j}}{m_\Omega^2} + \frac{b_j^R F_{1j} F_{2j}^*}{m_\chi^2} \right\rvert^2 < \frac{5.2\times10^{-16}}{\mathrm{GeV}^4}$
^{208}Pb	$< 4.6 \times 10^{-11}$	33.81	0.15	$\left\lvert \frac{a_j^L Y_{ij}^* Y_{2j}}{m_\Omega^2} + \frac{a_j^R F_{1j} F_{2j}^*}{m_\chi^2} \right\rvert^2 + \left\lvert \frac{b_j^L Y_{ij}^* Y_{2j}}{m_\Omega^2} + \frac{b_j^R F_{1j} F_{2j}^*}{m_\chi^2} \right\rvert^2 < \frac{9.7\times10^{-14}}{\mathrm{GeV}^4}$



Muon anomalous magnetic moment

$$\delta(g-2)_\mu = 3.9 \times 10^{-10} \left(\frac{300\ \text{GeV}}{m_\chi}\right)^2 \left(|F_{21}|^2 + |F_{22}|^2 - F_4(x_t)\,|F_{23}|^2\right)$$

$$\delta(g-2)_\mu^{\text{exp}} = (24.6 \pm 8.0) \times 10^{-10}$$

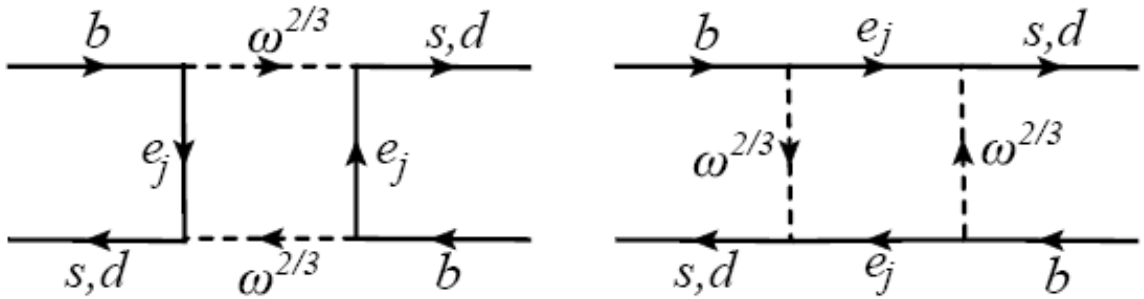
Leptonic D_s decay:

$$\text{BR}(D_s \to \ell\nu) = \frac{m_{D_s}}{8\pi}\tau_{D_s} f_{D_s}^2 G_F^2 |V_{cs}|^2 \left[1 + \frac{|Y_{i2}^* F_{22}|^2}{128 M_1^4 G_F^2 |V_{cs}|^2}\sin^2 2\theta \left(1 - \frac{M_1^2}{M_2^2}\right)^2\right]\left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2 m_\ell^2$$

$$f_{D_s}^{\text{lattice}} = (241 \pm 3)\ \text{MeV}$$

$$f_{D_s}^{\text{expt}} = (257.5 \pm 6.1)\ \text{MeV}$$

$B_s - \overline{B}_s$ mixing



$$\mathcal{L}_{\text{eff}}^{\text{new}} = -\frac{\left(Y_{i2}Y_{i3}^*\right)^2}{128\pi^2 m_\omega^2}\left(\overline{s_R}\gamma^\mu b_R\right)\left(\overline{s_R}\gamma_\mu b_R\right)$$

$$\left\langle B_s \left| -\mathcal{L}_{\text{eff}}^{\text{new}} \right| \overline{B}_s \right\rangle = \frac{\left(Y_{i2}Y_{i3}^*\right)^2}{192\pi^2 m_\omega^2}\, m_{B_s} f_{B_s}^2 B_1^{B_s}(\mu)\eta_1^{B_s}(\mu)$$

New CP violation can be as large as 40%

LQ mass $<$ 500 GeV needed

DØ Dimuon data:

$$A_{sl}^b = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$$

$$A_{sl}^b(SM) = -2.3^{+0.5}_{-0.6} \times 10^{-4}$$

3.2 σ discrepancy

New contributions:

$$\Delta M_s = \Delta M_s^{\text{SM}} \left| 1 + h_s e^{2i\sigma} \right|$$

Best fit parameters: (Ligeti, Papucci, Perez, Zupan 2010)

$\{h_s = 0.5,\ \sigma = 120^o\}$ or $\{h_s = 1.8,\ \sigma = 100^o\}$

$h_s = 0.42,\ \sigma = 120^o$ realized with leptoquarks

Summary and Conclusions

- Radiative neutrino mass generation a natural alternative to seesaw
- New particles must exist at the TeV scale
- Leptoquark decays probe neutrino mass generation and CP violation
- Large θ_{13} predicted