Testing Radiative Mechanism for Neutrino Mass Generation

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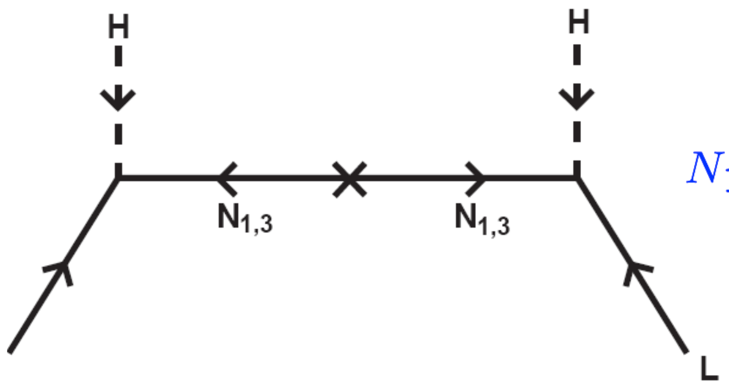
Outline

- Some general remarks
- Specific models
- Experimental tests

Majorana Neutrinos and Seesaw Mechanism

Type (I,III) seesaw

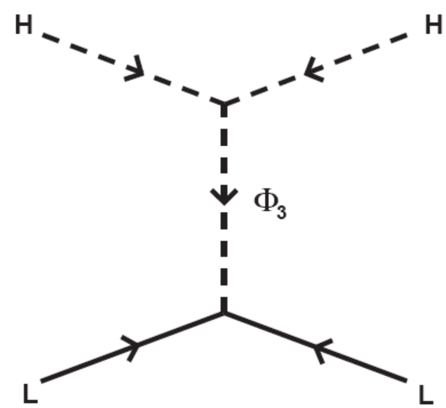


$N_1 : (1, 1, 0)$, $N_3 : (1, 3, 0)$

Minkowski (1977)
Yanagida (1979)
Gell-Mann, Ramond, & Slansky (1980)
Mohapatra & Senjanovic (1980)

Foot, Lew, He, & Joshi (1989)

Type II seesaw



$\Phi_3 : (1, 3, +1)$

Mohapatra & Senjanovic (1980)
Schechter & Valle (1980)
Lazarides, Shafi, & Wetterich (1981)

$$\mathcal{L}_{\text{eff}} = \frac{LLHH}{M} \Rightarrow m_\nu \sim \frac{v^2}{M}$$

Effective Delta(L) =2 operators for neutrino masses

Standard seesaw operator

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

Operators with four fermions:

C.N. Leung, KSB (2003)

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

Choi, Jeong, Song (2002)
De Gouvea, Jenkins (2008)
Angel, Volkas (2012)

Operators with six fermions:

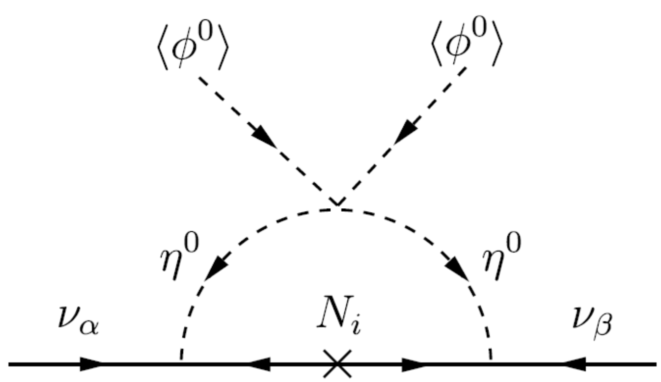
$$
\begin{aligned}
\mathcal{O}_9 &= L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_{10} &= L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_{11} &= \{L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl}, \quad L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}\} \\
\mathcal{O}_{12} &= \{L^iL^j\bar{Q}_i\bar{u^c}\bar{Q}_j\bar{u^c}, \quad L^iL^j\bar{Q}_k\bar{u^c}\bar{Q}_l\bar{u^c}\epsilon_{ij}\epsilon^{kl}\} \\
\mathcal{O}_{13} &= L^iL^j\bar{Q}_i\bar{u^c}L^le^c\epsilon_{jl} \\
\mathcal{O}_{14} &= \{L^iL^j\bar{Q}_k\bar{u^c}Q^kd^c\epsilon_{ij}, \quad L^iL^j\bar{Q}_i\bar{u^c}Q^ld^c\epsilon_{jl}\} \\
\mathcal{O}_{15} &= L^iL^jL^kd^c\bar{L}_i\bar{u^c}\epsilon_{jk} \\
\mathcal{O}_{16} &= L^iL^je^cd^c\bar{e^c}\bar{u^c}\epsilon_{ij} \\
\mathcal{O}_{17} &= L^iL^jd^cd^c\bar{d^c}\bar{u^c}\epsilon_{ij} \\
\mathcal{O}_{18} &= L^iL^jd^cu^c\bar{u^c}\bar{u^c}\epsilon_{ij} \\
\mathcal{O}_{19} &= L^iQ^jd^cd^c\bar{e^c}\bar{u^c}\epsilon_{ij} \\
\mathcal{O}_{20} &= L^id^c\bar{Q}_i\bar{u^c}\bar{e^c}\bar{u^c}
\end{aligned}
$$

Dimension 5 operator through loops

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

without light fermion mass factor

Example: Inert Doublet Model **E. Ma (2006)**



$$m_\nu \approx \frac{Y_\nu^2 \lambda_5 v^2}{16\pi^2} \frac{M_R}{M_\eta^2 + M_R^2}$$

From m_ν alone, $M_R, M_\eta \sim 10^{12}$ GeV will work

Dark matter would require $M_R \sim M_\eta \sim$ TeV

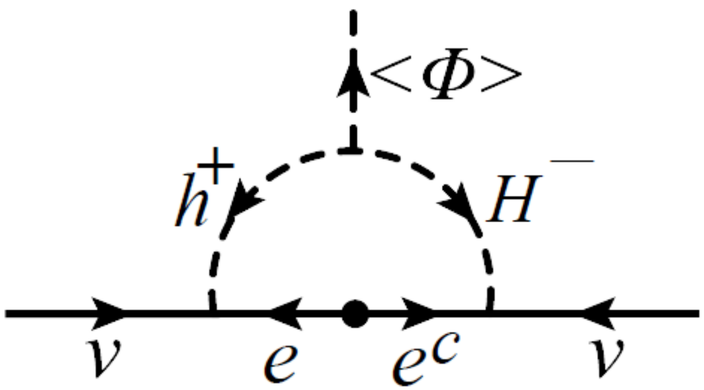
Dimension 5 operator with one light fermion mass

$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl}$ can arise at loops with one light fermion mass factor

Example: General Zee model

A. Zee (1980)

Effective operator: $\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl}$



$$m_\nu \approx \frac{f Y'_\ell}{16\pi^2}(m_\ell v)\frac{\mu}{M_h^2 + M_H^2}$$

For $Y'_\ell, f \sim 1$, $M_h, M_H \sim 10^{10}$ GeV will work

If $Y'_\ell = Y_\ell \Rightarrow m_\nu \sim m_\ell^2$

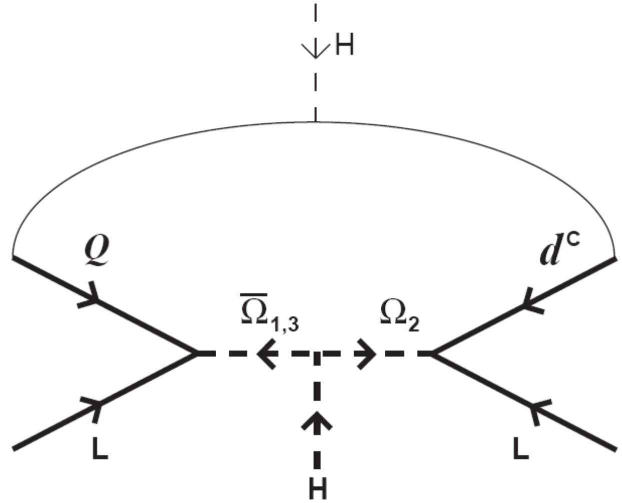
L. Wolfenstein (1981)

This version excluded by solar + KamLand 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 supersymmetric models



$\overline{\Omega}_1 : (3^*, 1, \frac{1}{3}),\ \Omega_2 : (3, 2, \frac{1}{6})$

$$m_\nu \approx \frac{(\lambda')^2}{16\pi^2}\frac{m_b^2 A}{\tilde{M}^2}$$

Widely studied in literature

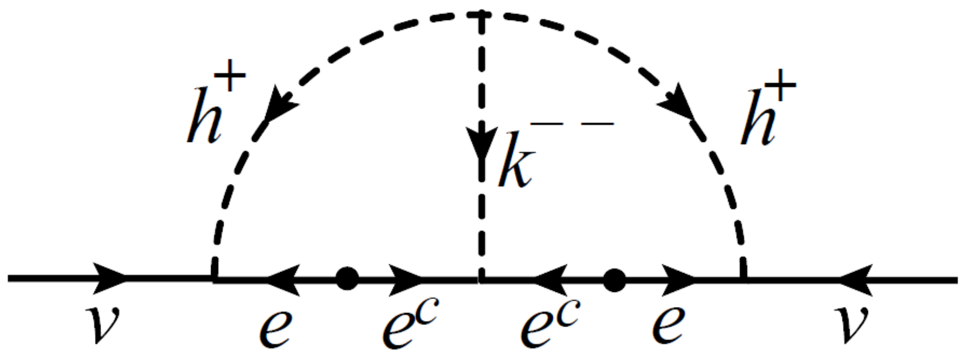
L. Hall. M. Suzuki (1984)
J. Ellis, G. Gelmini, G. Ross, J. Valle (1985)
S. Dawson (1985)
V. Barger, G. Giudice, T. Han (1989)
T. Banks et. al. (1995)
F. Borzumati et. al. (1996)
G. Bhattacharyya (1996)
H.K. Dreiner (1997)
R. Barbier et. al., Phys. Rept. (2005)

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

$$\mathcal{L} = f_{ij} L_i^a L_j^b h^+ \epsilon_{ab} + g_{ij} e_i^c e_j^c k^{--} + \mu h^+ h^+ k^{--} + \text{h.c.}$$

$$\Downarrow$$

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij} \epsilon_{kl}$$



A. Zee, (1985)
Babu (1988)

Consistent with all neutrino oscillation data

Predicts doubly charged Higgs boson with TeV mass

One neutrino is nearly massless

Two–loop neutrino mass model

$$(\mathcal{M}_\nu)_{ab} = 16\mu f_{ac} m_c g^*_{cd} I_{cd} m_d f_{bd}$$

$$I_{cd} = \int \frac{d^4k}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} \frac{1}{(k^2 - m_c^2)} \frac{1}{(k^2 - m_h^2)} \frac{1}{(q^2 - m_d^2)} \frac{1}{(q^2 - m_h^2)} \frac{1}{(k-q)^2 - m_k^2}.$$

$$I_{cd} \simeq I = \frac{1}{(16\pi^2)^2} \frac{1}{m_h^2} \tilde{I}\left(\frac{m_k^2}{m_h^2}\right)$$

$$\tilde{I}(r) = -\int_0^1 dx \int_0^{1-x} dy \frac{1-y}{x + (r-1)y + y^2} \log \frac{y(1-y)}{x + ry}$$

$$\tilde{I}(r) = \begin{cases} 1 + \frac{3}{\pi^2}(\log^2 r - 1) & \text{for } r \gg 1 \\ 1 & \text{for } r \to 0 \end{cases}$$

$$M_\nu = \xi f \omega f^T$$

$$f_{ab} = -f_{ba}, \quad \omega_{ab} = g_{ab} m_a m_b$$

Two–loop neutrino mass model

f has an eigenvector with zero eigenvalue:

$$v_0^T = (1, -\epsilon, \epsilon'); \quad f v_0 = 0 \ .$$

$$\epsilon = f_{e\tau}/f_{\mu\tau}, \quad \epsilon' = f = e\mu/f_{\mu\tau}$$

v_0 is an eigenvector of M_ν with zero eigenvalue: $M_\nu v_0 = 0$

$$\epsilon = \frac{m_{12}m_{33} - m_{13}m_{23}}{m_{22}m_{33} - m_{23}^2} \qquad \epsilon' = \frac{m_{12}m_{23} - m_{13}m_{22}}{m_{22}m_{33} - m_{23}^2}$$

$$\epsilon \ = \ \tan\theta_{12} \, \frac{\cos\theta_{23}}{\cos\theta_{13}} \ + \ \tan\theta_{13} \, \sin\theta_{23} \, e^{-i\delta}$$

Normal hierarchy

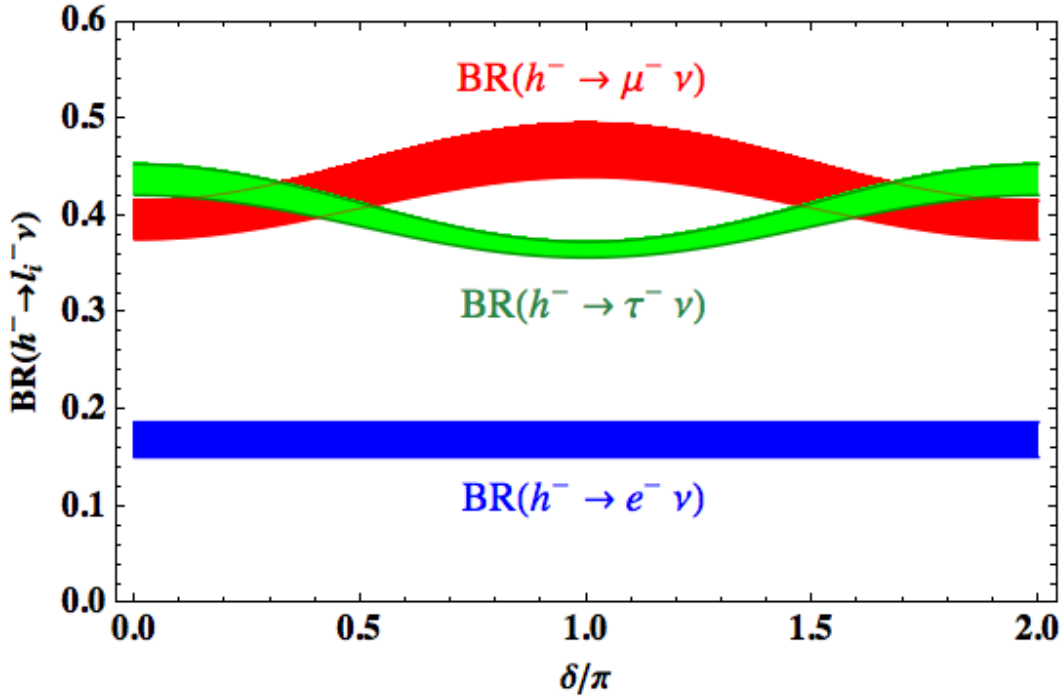
$$\epsilon' \ = \ \tan\theta_{12} \, \frac{\sin\theta_{23}}{\cos\theta_{13}} \ - \ \tan\theta_{13} \, \cos\theta_{23} \, e^{-i\delta}$$

Two–loop neutrino mass model (cont.)

Inverted hierrarchy:

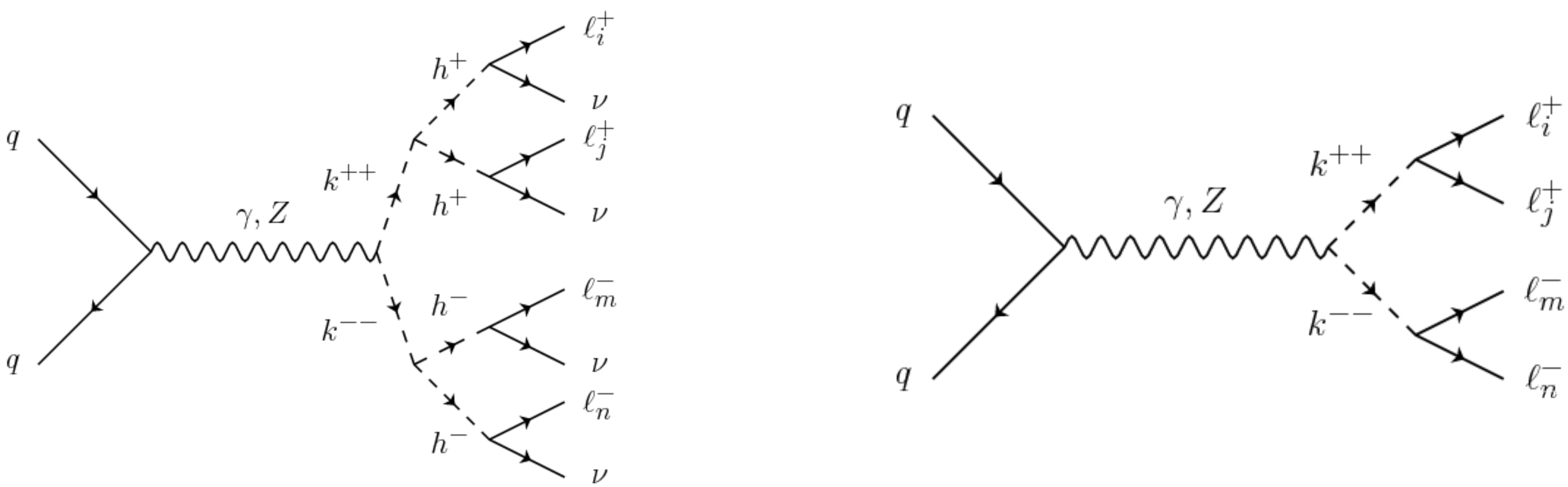
$$\epsilon = -\sin\theta_{23}\ \cot\theta_{13}\ e^{-i\delta} \quad , \quad \epsilon' = \cos\theta_{23}\ \cot\theta_{13}\ e^{-i\delta}$$

$h^- \to \ell^- \nu$ branching ratios fixed:



Producion of $h^+h^+h^-h^-$

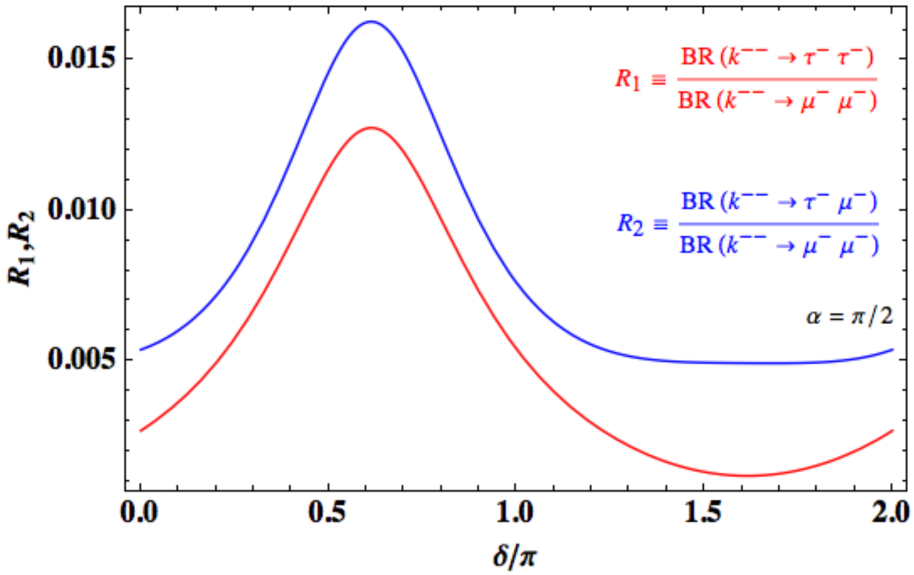
$pp \to k^{++}k^{--}$ with $k^{++} \to h^+h^+$

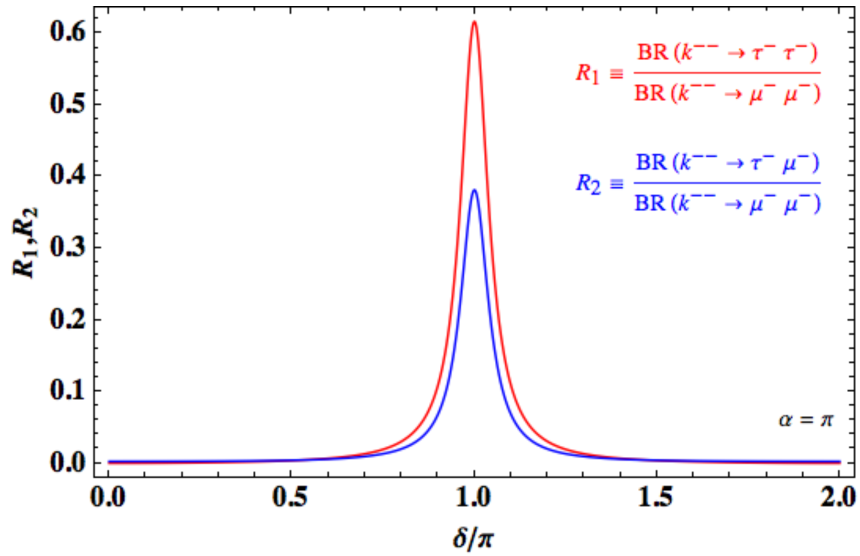


CMS limit of $m_{k^{++}} > 355$ GeV not applicable for $k^{++} \to h^+h^+$ decay

Branching ratios of $k^{++} \to \ell^+\ell^+$ predicted from neutrino data

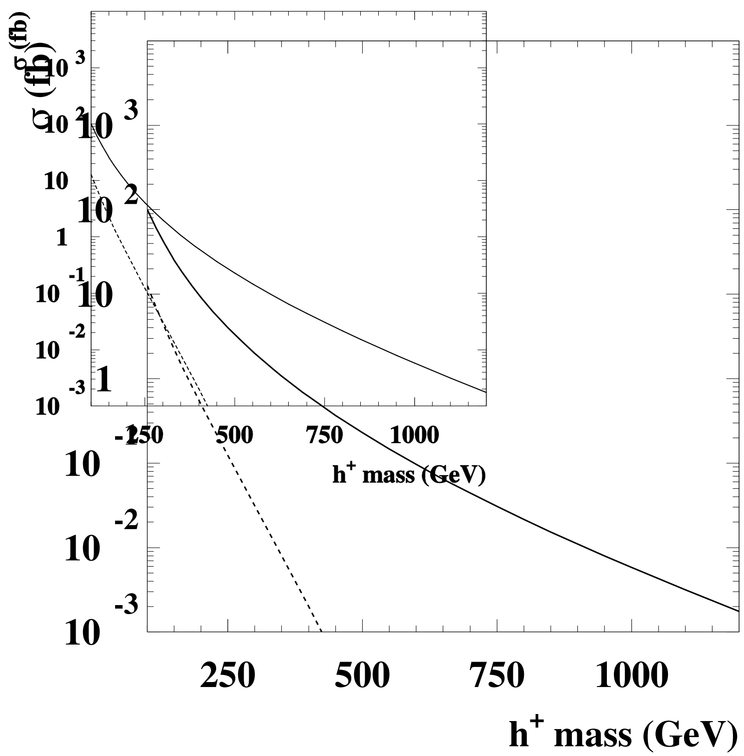
Branching ratio for $k^{++} \to \ell^+\ell^+$

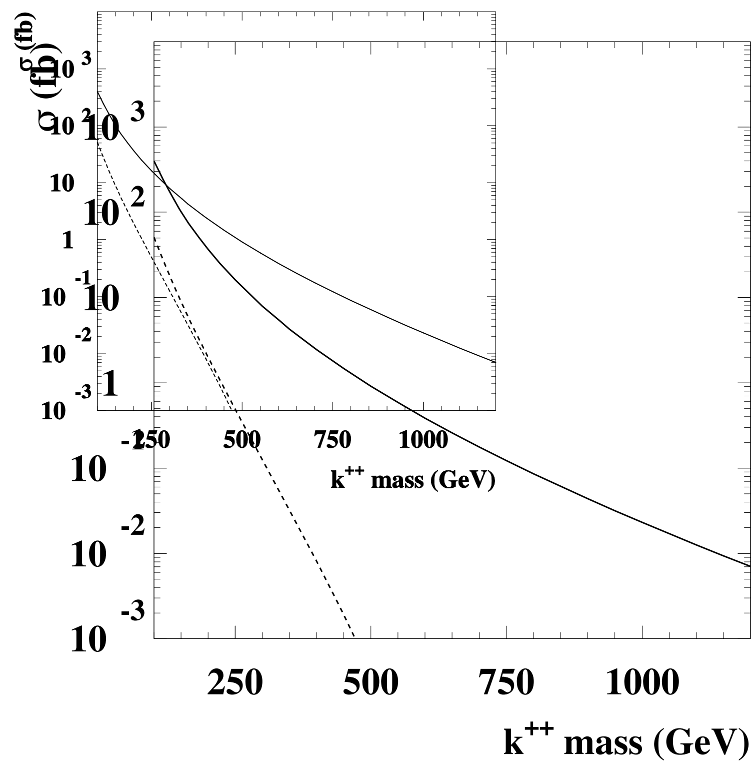




Relative branching ratio gives insight into Majorana phases

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



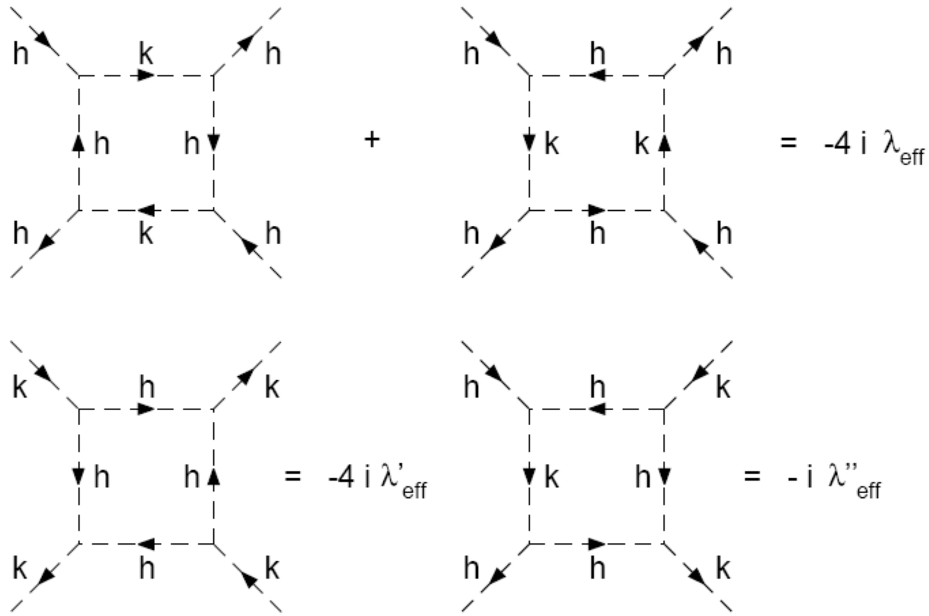


LHC: Solid line, Tevatron: dashed

Detailed study:

K.S. Babu, C. Macesanu (2005)
D. Sierra, M. Hirsch (2006)
M. Nebot, J. Oliver, D. Paolo, A. Santamaria (2008)

Perturbativity constraints on μ



$$-\mathcal{L}_{eff} = \lambda_{eff}(h^+)^2(h^-)^2 \; + \; \lambda'_{eff}(k^{++})^2(k^{--})^2 \; + \; \lambda''_{eff}(h^+h^-)(k^{--}k^{++})$$

$$\mu \; < \; \begin{cases} m_h \times (6\pi^2)^{1/4} & \text{if } m_k \approx m_h \\ m_h \times (2\pi^2)^{1/4} & \text{if } m_k \ll m_h \\ m_h \times (24\pi^2)^{1/4} & \text{if } m_k \gg m_h \; . \end{cases}$$

Lepton flavor violation constraints

Process	Experiment (90% CL)	Bound (90% CL)
$\mu^- \to e^+ e^- e^-$	BR$< 1.0 \times 10^{-12}$	$\lvert g_{e\mu} g^*_{ee} \rvert < 2.3 \times 10^{-5} \, (m_k/\text{TeV})^2$
$\tau^- \to e^+ e^- e^-$	BR$< 3.6 \times 10^{-8}$	$\lvert g_{e\tau} g^*_{ee} \rvert < 0.010 \, (m_k/\text{TeV})^2$
$\tau^- \to e^+ e^- \mu^-$	BR$< 2.7 \times 10^{-8}$	$\lvert g_{e\tau} g^*_{e\mu} \rvert < 0.006 \, (m_k/\text{TeV})^2$
$\tau^- \to e^+ \mu^- \mu^-$	BR$< 2.3 \times 10^{-8}$	$\lvert g_{e\tau} g^*_{\mu\mu} \rvert < 0.008 \, (m_k/\text{TeV})^2$
$\tau^- \to \mu^+ e^- e^-$	BR$< 2.0 \times 10^{-8}$	$\lvert g_{\mu\tau} g^*_{ee} \rvert < 0.008 \, (m_k/\text{TeV})^2$
$\tau^- \to \mu^+ e^- \mu^-$	BR$< 3.7 \times 10^{-8}$	$\lvert g_{\mu\tau} g^*_{e\mu} \rvert < 0.008 \, (m_k/\text{TeV})^2$
$\tau^- \to \mu^+ \mu^- \mu^-$	BR$< 3.2 \times 10^{-8}$	$\lvert g_{\mu\tau} g^*_{\mu\mu} \rvert < 0.010 \, (m_k/\text{TeV})^2$
$\mu^+ e^- \to \mu^- e^+$	$G_{M\bar{M}} < 0.003 G_F$	$\lvert g_{ee} g^*_{\mu\mu} \rvert < 0.2 \, (m_k/\text{TeV})^2$

Universality and LFV constraints

SM Test	Experiment	Bound (90%CL)
lept./hadr. univ.	$\sum_{q=d,s,b} \|V_{uq}^{exp}\|^2 = 0.9992 \pm 0.0011$	$\|f_{e\mu}\|^2 < 0.015\,(m_h/\mathrm{TeV})^2$
μ/e universality	$g_\mu^{exp}/g_e^{exp} = 1.0001 \pm 0.0020$	$\big\|\|f_{\mu\tau}\|^2 - \|f_{e\tau}\|^2\big\| < 0.05\,(m_h/\mathrm{TeV})^2$
τ/μ universality	$g_\tau^{exp}/g_\mu^{exp} = 1.0004 \pm 0.0022$	$\big\|\|f_{e\tau}\|^2 - \|f_{e\mu}\|^2\big\| < 0.06\,(m_h/\mathrm{TeV})^2$
τ/e universality	$g_\tau^{exp}/g_e^{exp} = 1.0004 \pm 0.0023$	$\big\|\|f_{\mu\tau}\|^2 - \|f_{e\mu}\|^2\big\| < 0.06\,(m_h/\mathrm{TeV})^2$

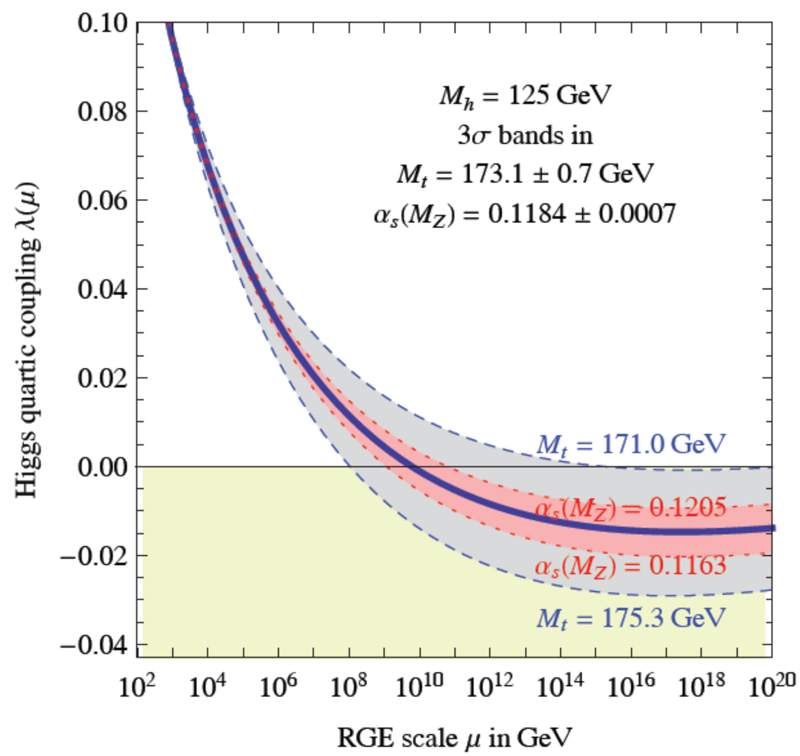
Table II: Constraints from universality of charged currents.

Experiment	Bound (90%CL)
$\delta a_e = (12 \pm 10) \times 10^{-12}$	$r\left(\|f_{e\mu}\|^2 + \|f_{e\tau}\|^2\right) + 4\left(\|g_{ee}\|^2 + \|g_{e\mu}\|^2 + \|g_{e\tau}\|^2\right) < 5.5 \times 10^3\,(m_k/\mathrm{TeV})^2$
$\delta a_\mu = (21 \pm 10) \times 10^{-10}$	$r\left(\|f_{e\mu}\|^2 + \|f_{\mu\tau}\|^2\right) + 4\left(\|g_{e\mu}\|^2 + \|g_{\mu\mu}\|^2 + \|g_{\mu\tau}\|^2\right) < 7.9\,(m_k/\mathrm{TeV})^2$
$BR(\mu \to e\gamma) < 1.2 \times 10^{-11}$	$r^2\|f_{e\tau}^* f_{\mu\tau}\|^2 + 16\|g_{ee}^* g_{e\mu} + g_{e\mu}^* g_{\mu\mu} + g_{e\tau}^* g_{\mu\tau}\|^2 < 3.4 \times 10^{-5}\,(m_k/\mathrm{TeV})^4$
$BR(\tau \to e\gamma) < 1.1 \times 10^{-7}$	$r^2\|f_{e\mu}^* f_{\mu\tau}\|^2 + 16\|g_{ee}^* g_{e\tau} + g_{e\mu}^* g_{\mu\tau} + g_{e\tau}^* g_{\tau\tau}\|^2 < 1.7\,(m_k/\mathrm{TeV})^4$
$BR(\tau \to \mu\gamma) < 4.5 \times 10^{-8}$	$r^2\|f_{e\mu}^* f_{e\tau}\|^2 + 16\|g_{e\mu}^* g_{e\tau} + g_{\mu\mu}^* g_{\mu\tau} + g_{\mu\tau}^* g_{\tau\tau}\|^2 < 0.7\,(m_k/\mathrm{TeV})^4$

Table III: Constraints from lepton number violating photon interactions.

Boundedness of Higgs potential

In the Standard Model with $m_H = 125$ GeV Higgs potential becomes unbounded at $\mu \sim 10^{10}$ GeV



deGrassi et. al. (2012)

Boundedness in Two–loop model

$$
\begin{aligned}
V \;&=\; -\mu_1^2\Phi^\dagger\Phi + \mu_2^2 h^+h^- + \mu_3^2 k^{++}k^{--} + \{\mu h^+h^+k^{--} + h.c.\} \\
&+\; \frac{\lambda_1}{2}(\Phi^\dagger\Phi)^2 + \frac{\lambda_2}{2}(h^+h^-)^2 + \frac{\lambda_3}{2}(k^{++}k^{--})^2 \\
&+\; \lambda_4(\Phi^\dagger\Phi)(h^+h^-) + \lambda_5(\Phi^\dagger\Phi)(k^{++}k^{--}) + \lambda_6(h^+h^-)(k^{++}k^{--})
\end{aligned}
$$

Boundedness $\Rightarrow$

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > 0$$

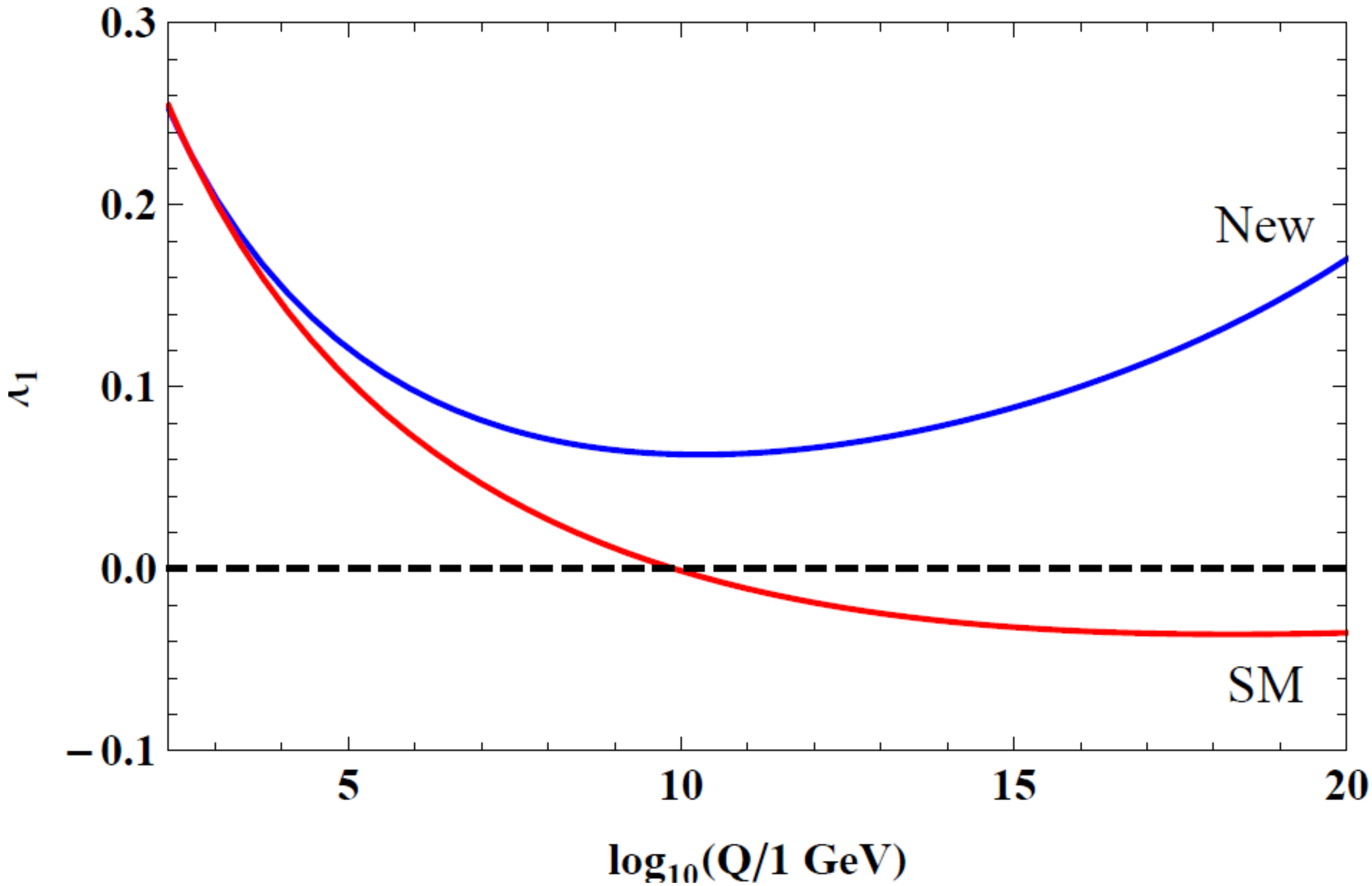
$$\lambda_4 + \sqrt{\lambda_1\lambda_2} \geq 0, \quad \lambda_3 + \sqrt{\lambda_1\lambda_3} \geq 0, \quad \lambda_6 + \sqrt{\lambda_2\lambda_3} \geq 0$$

$$\lambda_4\sqrt{\lambda_3} + \lambda_6\sqrt{\lambda_1} + \lambda_5\sqrt{\lambda_2} + \sqrt{\lambda_1\lambda_2\lambda_3} \geq 0 \quad \text{or} \quad \mathrm{Det}(\widehat{\lambda}) \geq 0$$

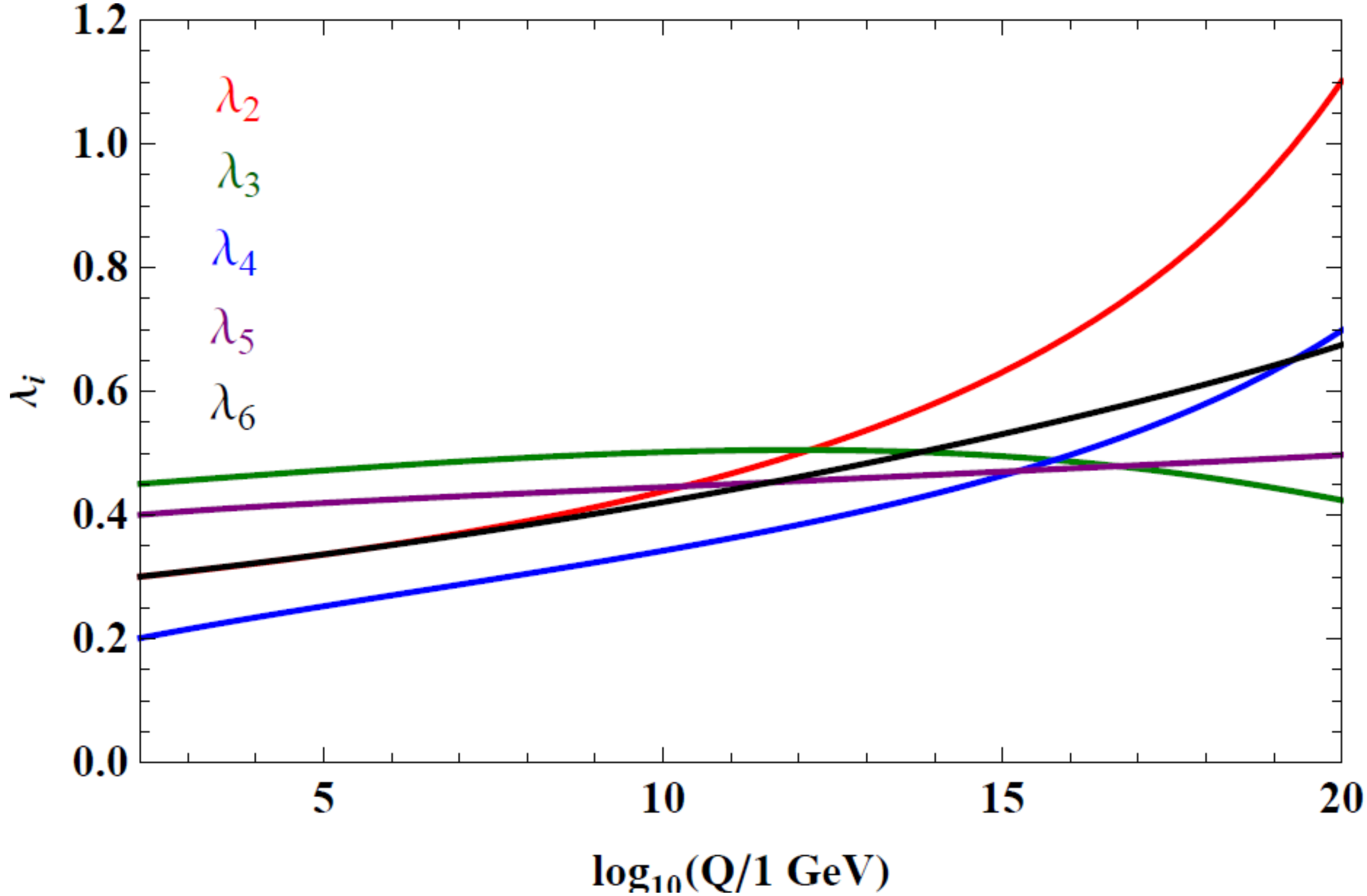
Related to Co-positivity of matrices

Hadeler (1983)

Evolution of λ_1



J. Julio, KB (2012)



$$\lambda_1 = 0.258, \quad \lambda_2 = 0.3, \quad \lambda_3 = 0.45,$$
$$\lambda_4 = 0.2, \quad \lambda_5 = 0.4, \quad \lambda_6 = 0.3, h_{\mu\tau} = 0.25.$$

Neutrino mass model with Leptoquarks

K.S. Babu, J. Julio (2010)

$\mathcal{O}_8$ 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

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

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

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

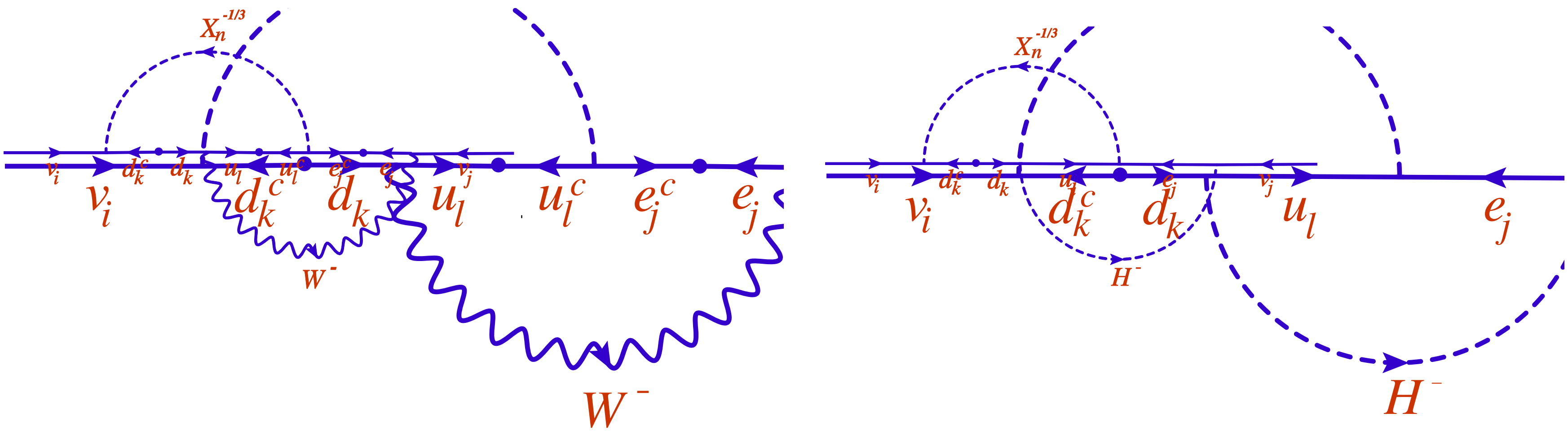
B is unbroken, but L is softly broken

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

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

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

Neutrino phenomenology

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

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

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

Note that (1,1) entry is zero

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

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

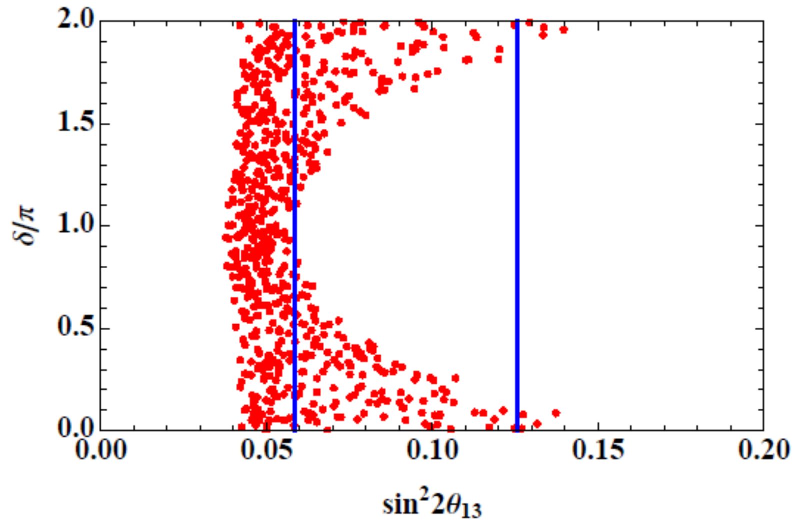
$\beta = 2\delta + \pi, \quad \alpha = 0$ (Majorana phases)

Predictions for $w \gg 1$

- For $w \gg 1$,

$$w \equiv \frac{F_{32}^*}{F_{33}^*}\frac{Y_{32}}{Y_{33}}\left(\frac{m_c}{m_t}\right)\left(\frac{m_s}{m_b}\right)\frac{I_{jk2}}{I_{jk3}} \gg 1 \quad \rightarrow \quad |F_{33}Y_{33}| \ll |F_{32}Y_{32}|$$

- This could generate $(M_\nu)_{13} \simeq (M_\nu)_{11} \simeq 0$.
  Glashow, Frampton, & Marfatia (2002)
  Xing (2002)



- The value of θ_{13} is consistent with current measurements (the blue lines correspond to 2σ allowed value from Daya Bay).

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

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

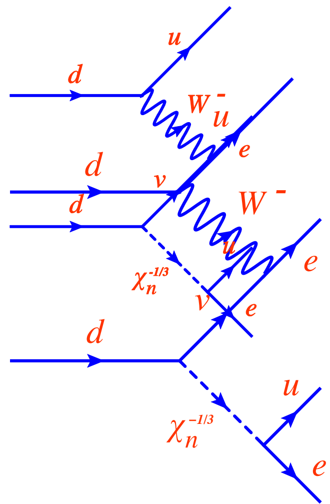
Further checks provided

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

Neutrinoless double beta decay

$(M_\nu)_{11} \simeq 0 \Rightarrow$ No neutrino mass contribution to $\beta\beta_{0\nu}$

Vector-scalar exchange:



K.S. Babu, R.N. Mohapatra (1995)

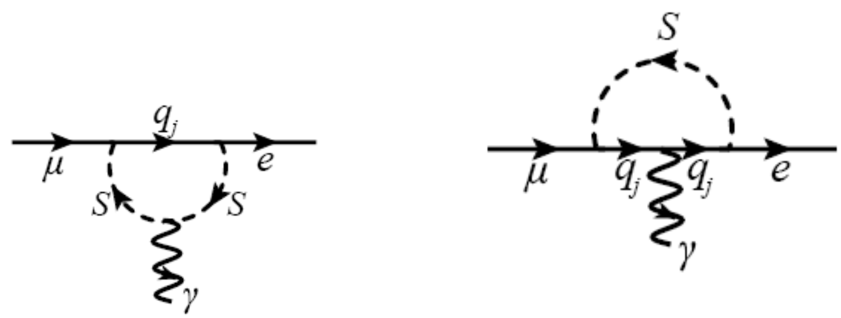
$$\mathcal{L}_{\rm eff} = \frac{G_F^2}{2}\,\epsilon\,\overline{u}\gamma^\mu(1-\gamma_5)d\left[\overline{u}(1+\gamma_5)d\overline{e}\gamma_\mu(1-\gamma_5)\frac{1}{\not{q}}e^c + \frac{1}{4}\overline{u}\sigma^{\alpha\beta}(1+\gamma_5)d\overline{e}\gamma_\mu(1-\gamma_5)\frac{1}{\not{q}}\sigma_{\alpha\beta}e^c\right]$$

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

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

Normal mass hierarchy and observable $\beta\beta_{0\nu}$ possible

$\mu \to e\gamma$ Predictions



Process	BR	Constraint
$\mu \to e\gamma$	$< 1.2 \times 10^{-11}$	$\frac{\left\|F_3(x_b)Y^*_{13}Y_{23}\right\|^2}{m_\Omega^4} + \frac{\left\|\frac{1}{12}F_{11}F^*_{21}+\frac{1}{12}F_{12}F^*_{22}+F_4(x_t)F_{13}F^*_{23}\right\|^2}{m_\chi^4} < \frac{3.1\times10^{-19}}{\mathrm{GeV}^4}$
$\tau \to e\gamma$	$< 1.1 \times 10^{-7}$	$\frac{\left\|F_3(x_b)Y^*_{13}Y_{33}\right\|^2}{m_\Omega^4} + \frac{\left\|\frac{1}{12}F_{11}F^*_{31}+\frac{1}{12}F_{12}F^*_{32}+F_4(x_t)F_{13}F^*_{33}\right\|^2}{m_\chi^4} < \frac{1.6\times10^{-14}}{\mathrm{GeV}^4}$
$\tau \to \mu\gamma$	$< 4.5 \times 10^{-8}$	$\frac{\left\|F_3(x_b)Y^*_{23}Y_{33}\right\|^2}{m_\Omega^4} + \frac{\left\|\frac{1}{12}F_{21}F^*_{31}+\frac{1}{12}F_{22}F^*_{32}+F_4(x_t)F_{23}F^*_{33}\right\|^2}{m_\chi^4} < \frac{6.7\times10^{-15}}{\mathrm{GeV}^4}$

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

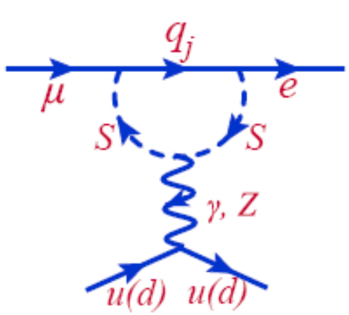
GIM suppression!

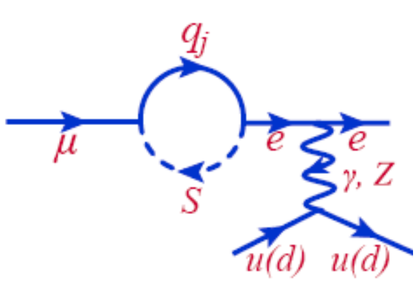
$$A \propto \left(\frac{m_b^2}{M_{\mathrm{LQ}}^2}\right)$$

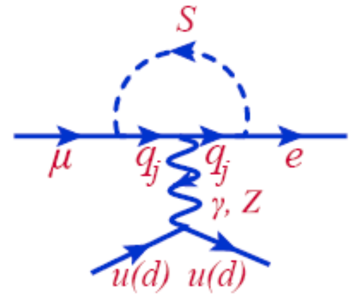
$\mu - e$ Conversion in Nuclei

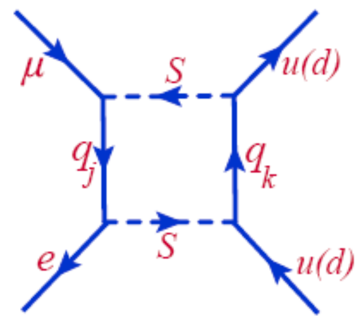
$$\mathrm{BR}(\mu N \to e N) = \frac{|\vec{p}_e| E_e m_\mu^3 G_F^2 \alpha^3 Z_{\rm eff}^4 F_p^2}{8\pi^2 Z\, \Gamma_N} \left| g_L^u (A+Z) + g_L^d (2A - Z) + 2Z\Delta g_L \right|^2 + L \leftrightarrow R$$

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

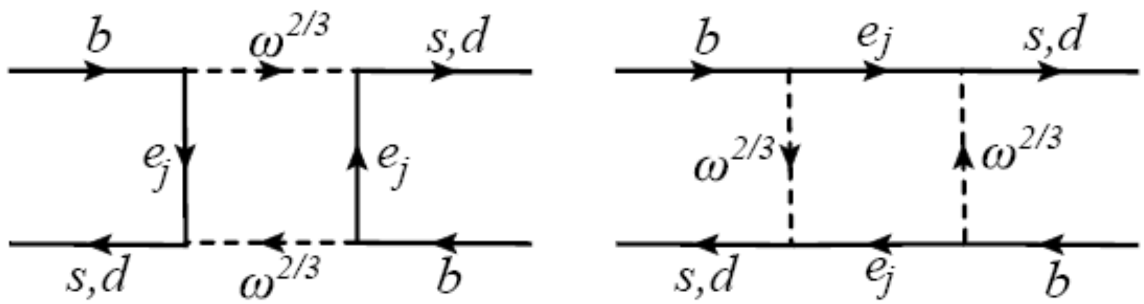








$B_s - \overline{B}_s$ mixing



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

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

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

Predicts $B_s \to \tau^+\tau^-$ decay at the percent level:

$$\text{BR}(B_s \to \tau^+\tau^-) = 0.28\% \left(\frac{|Y_{32}Y_{33}|}{0.07}\right)^2 \left(\frac{300\ \text{GeV}}{m_\omega}\right)^4 \left(\frac{f_{B_s}}{0.24\ \text{GeV}}\right)^2$$

Radiative Dirac Neutrino Masses

K.S. Babu, X.G. He (1988)

Left-right symmetric model with minimal Higgs content:

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Higgs: $(1,2,1,1/2) + (1,1,2,1/2)$

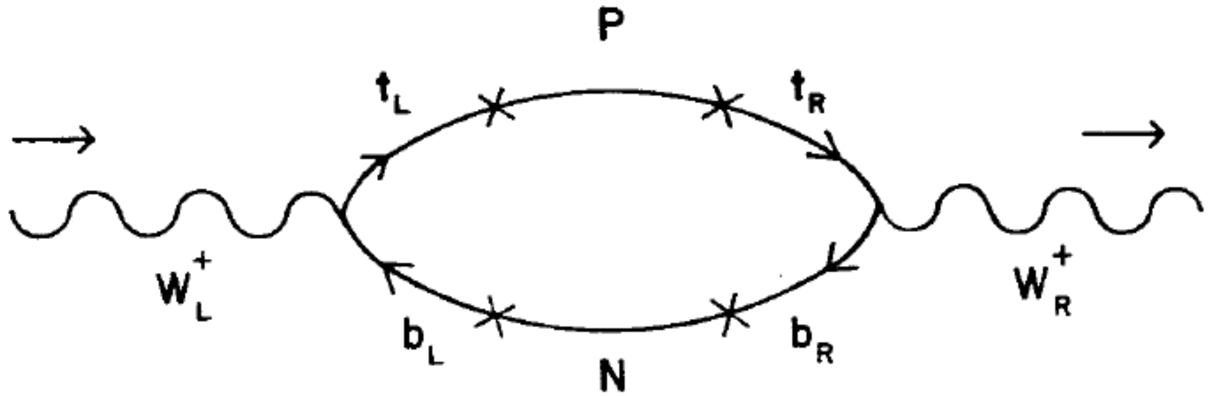
Ferrmion mass generation via singlet fermions:

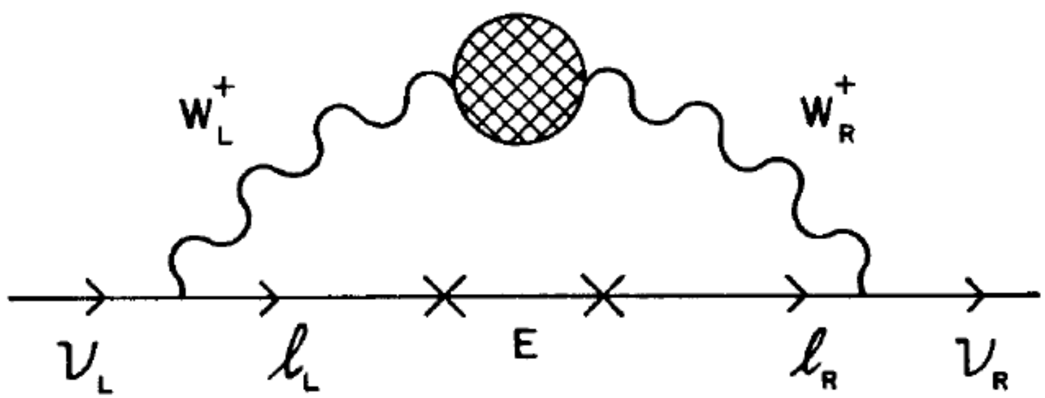
$$P(3,1,1,2/3) + N(3,1,1,-1/3) + E(1,1,1,1)$$

All charged ferrmions get mass via seesaw

Neutrinos are Dirac particles here, no seesaw for neutrinos!

Chang, Mohapatra (1987)
Davidson, Wali (1988)
Babu Mohapatra (1988)





$$m_\nu \simeq \frac{g^4}{512\pi^4}\left(\frac{m_t m_b}{M_{W_L}^2}\right)\frac{M^2}{M_{W_R}^2}m_\ell$$

Summary and Conclusions

- Radiative neutrino mass generation a natural alternative to seesaw
- New particles must exist at the TeV scale in many cases
- Scalar decays probe neutrino mass generation and CP violation