Right Handed Neutrinos and Higgs Boson Decay

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(work in progress)

Motivation

Davis Homestake mine
SuperK
SNO
Kamland

neutrino masses

beyond the Standard Model

implications for
electroweak physics,
LHC physics ?

Dirac or Majorana?

Majorana: What is the mass scale?

Only mass scales we know of are

Λ_{QCD} , m_{EW} , M_{Pl}

Explore the possibility that a common dynamics generates both the electroweak and right-handed neutrino mass scales

Λ new physics

m_h

m_R

Assume physics for generating M_R and m_H at the weak scale, in the form of new states. Integrate out those states to get:

$$\mathcal{L}_{eff} = \mathcal{L}_{\mathcal{R}} + \underbrace{\frac{1}{\Lambda}\mathcal{O}_{d=5}}_{\text{contain } \nu_R} + \frac{1}{\Lambda^2}\mathcal{O}_{d=6} + \cdots$$

Will focus on $d = 5$ and $d = 6$ operators, with a focus on higgs phenomenology.

* Will see that the higher dimension operators may have important implications for the higgs boson searches (Strassler, Zurek)

(Manohar, Wise)

Outline

* consequences of higher dimension operators
  - modify decay width of higgs
  - long-lived right-handed neutrino

* Minimal Flavour Violation hypothesis
  - sharper predictions
    - expected size, flavour violation

* Detection

Consider

Standard Model (1 higgs doublet)

+ 3 right-handed neutrinos with $M_R \sim M_{EW}$

$$\mathcal{L}_{\mathcal{R}} = \frac{1}{2} M_R \nu_R \nu_R + \lambda_\nu H^* L \nu_R + \lambda_l H L e^c$$

See-saw leads to :

$$m_{\nu_L} \simeq \lambda_\nu \frac{1}{M_R} \lambda_\nu^T v^2$$

Typically need

$$\lambda_\nu \simeq 4 * 10^{-7} \left(\frac{m_{\nu_L}}{1/10\mathrm{eV}}\right)^{1/2} \left(\frac{M_R}{100\mathrm{GeV}}\right)^{1/2}$$

Why focus on the nonrenormalizable operators? Renormalizable couplings

$$\lambda_\nu \simeq 10^{-7} - 10^{-6}$$

much too tiny for

$$h \to \nu_L \nu_R$$

to be detected

Begin with dimension 5 :

$$O_1 = \frac{\lambda'}{\Lambda} L^* H L^* H$$

After electroweak symmetry breaking

$$h \to \nu_L \nu_L$$

but rate too tiny since we need

$$\frac{\lambda' v^2}{\Lambda} < m_{\nu_L}$$

- will later see that this can occur naturally

Other operators can be eliminated by the equations of motion.

$$\mathcal{O} = \frac{1}{\Lambda} \partial^\mu \bar{\nu}_R \gamma^\mu L H^*$$

$$\downarrow$$

$$\frac{1}{\Lambda} M_R \nu_R L H^*$$

$$+ \frac{1}{\Lambda} \lambda_\nu L H^* L H^*$$

Last d=5 operator:

$$\mathcal{O} = \frac{1}{\Lambda} H^* H \nu_R \nu_R$$

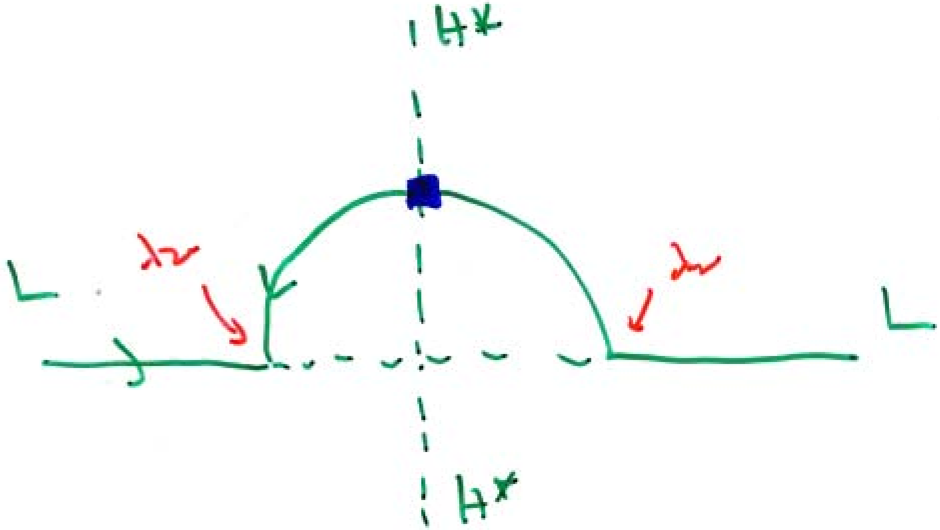
Very interesting operator! Electroweak symmetry breaking leads to

$$\delta M_R = \frac{v^2}{\Lambda}$$

Operator only modifies RH neutrino mass.

$\frac{\lambda'}{\Lambda} L H^* L H^*$ generated

at two loops:



$$\delta\lambda \sim \left(\frac{1}{16\pi^2}\right)^2 \lambda_\nu \lambda_\nu$$

$$\delta m_{\nu_L} \simeq \left(\frac{1}{16\pi^2}\right)^2 \underbrace{\left(\frac{\lambda_\nu^2 v^2}{M_R}\right)}_{m_{\nu_L}|_{\text{t.o.}}} \left(\frac{M_R}{\Lambda}\right)$$

To recap $d=5$ operators

$$O_1 = \frac{\lambda'}{\Lambda} L H^* L H^*$$

require $\lambda' \lesssim \lambda_\nu \lambda_\nu$

$$O_2 = \frac{\lambda}{\Lambda} \partial^\mu \bar{\nu}_R \gamma_\mu L H^*$$

redundant

$$O_3 = \frac{H^* H}{\Lambda} \nu_R \nu_R$$

relatively unconstrained

$$\mathcal{O}_3 = \frac{1}{\Lambda} H^* H \nu_R \nu_R$$

Will focus on

$$2M_R < m_h$$

Higgs can decay into the right-handed neutrinos!

$$h \to \nu_R \nu_R$$

For a single flavour,

$$\Gamma[h \to \nu_R \nu_R] = \frac{v^2}{4\pi\Lambda^2} m_h \left(1 - \frac{4M_R^2}{m_h^2}\right)^{3/2}$$

Width relative to other decay modes can be large. Compare to $h \to b\bar{b}$

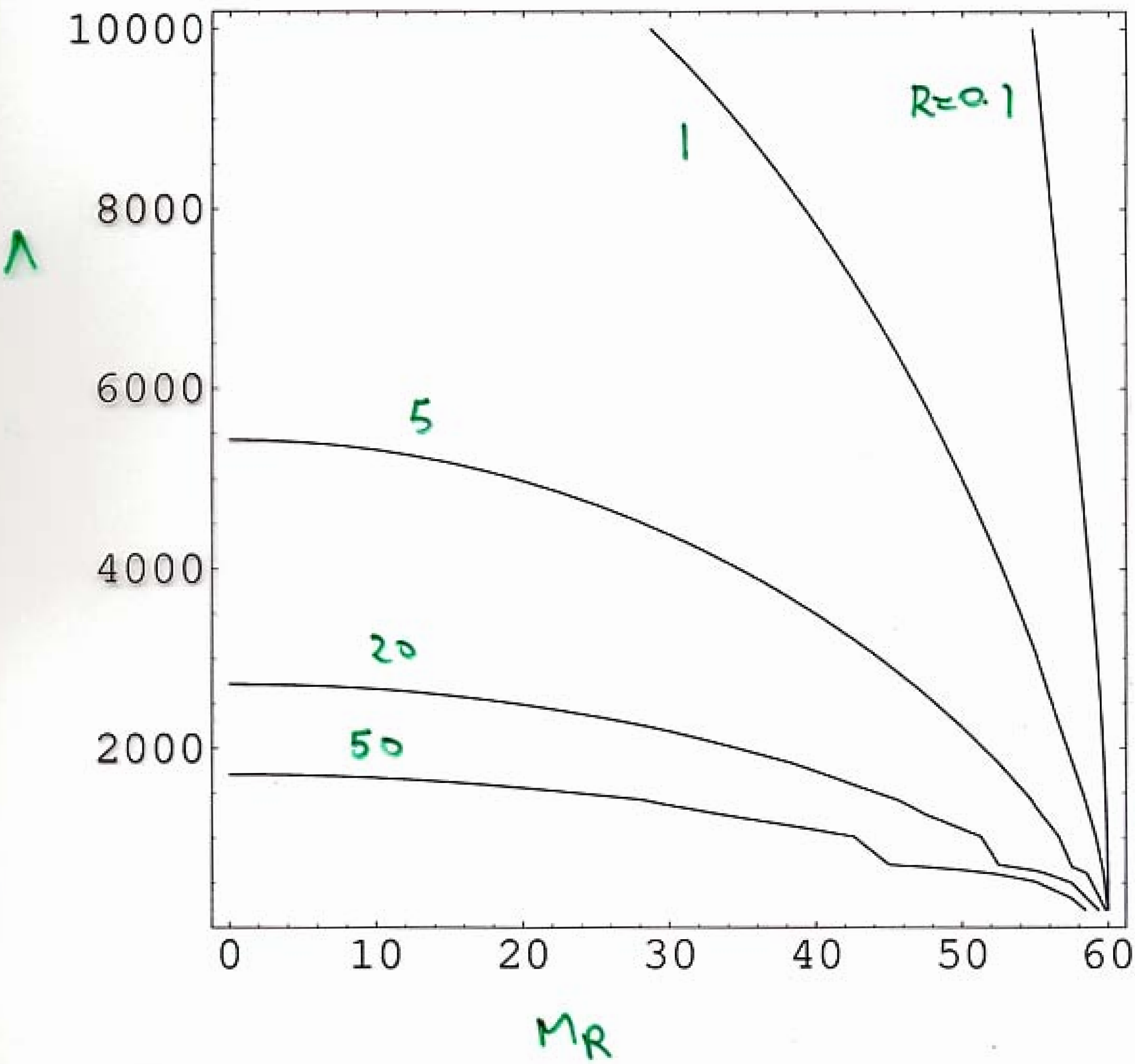
$$R_b = \frac{\Gamma[h \to \nu_R \nu_R]}{\Gamma[h \to b\bar{b}]} = \frac{2}{3} \frac{v^4}{m_b^2 \Lambda^2} \left(1 - \frac{4M_R^2}{m_h^2}\right)^{3/2}$$

$$R_b \gg 1$$

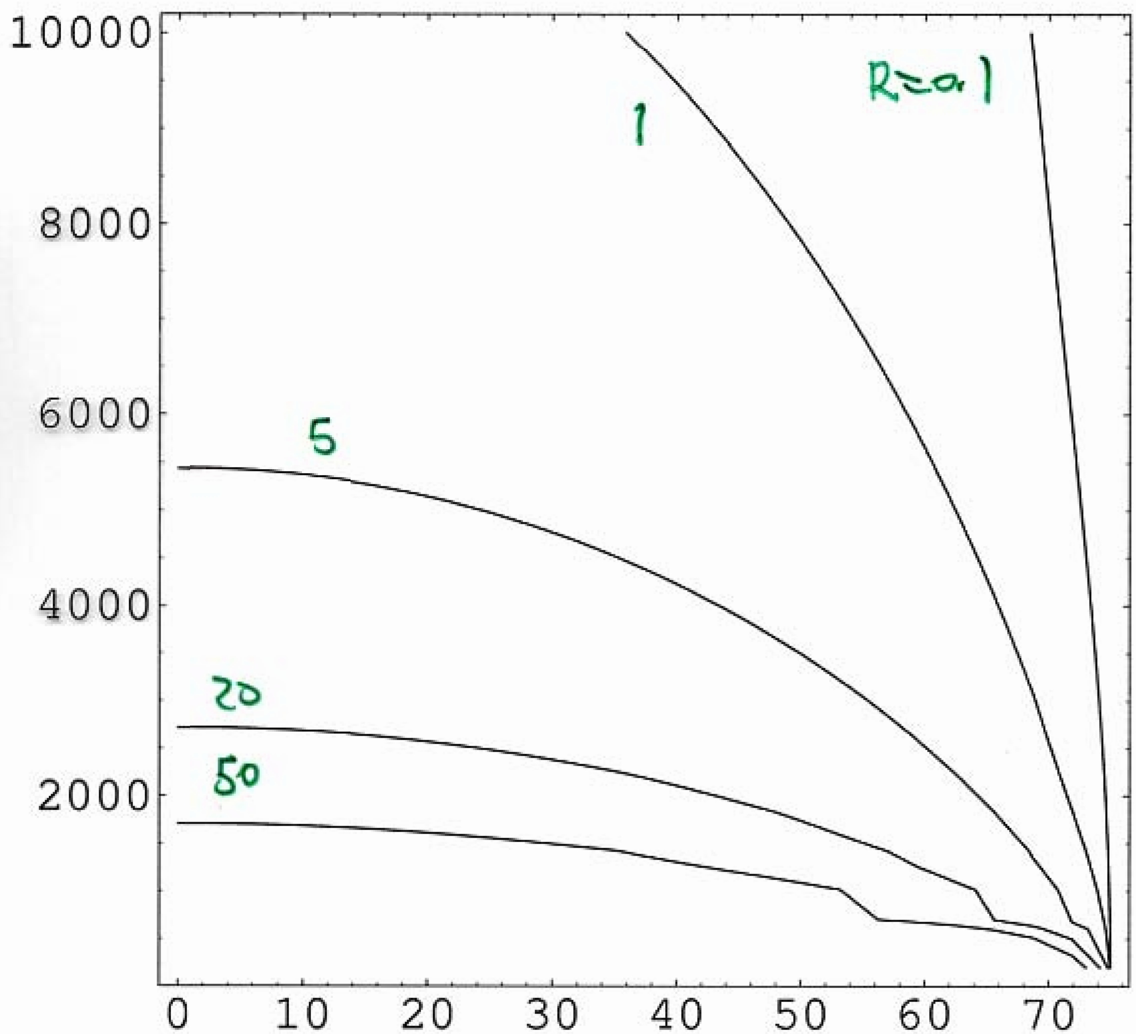
for $\Lambda \ll v^2/m_b \sim$ 10TeV. Won't observe $\gamma\gamma$ mode unless Λ is $\approx$ 10 TeV.

For three flavours, higgs decay width to all three right-handed neutrinos is greater than the $b\bar{b}$ mode up to $\Lambda \simeq$ 17 TeV.

$$R = \Gamma[h \to \nu_R \nu_R]/\Gamma[h \to b\bar{b}] \quad , \quad m_h = 120 \text{ GeV}$$



$$R = \Gamma[h \to \nu_R \nu_R]/\Gamma[h \to b\bar{b}] \quad , \quad m_h = 150 \text{ GeV}$$



Other interesting kinematic region is

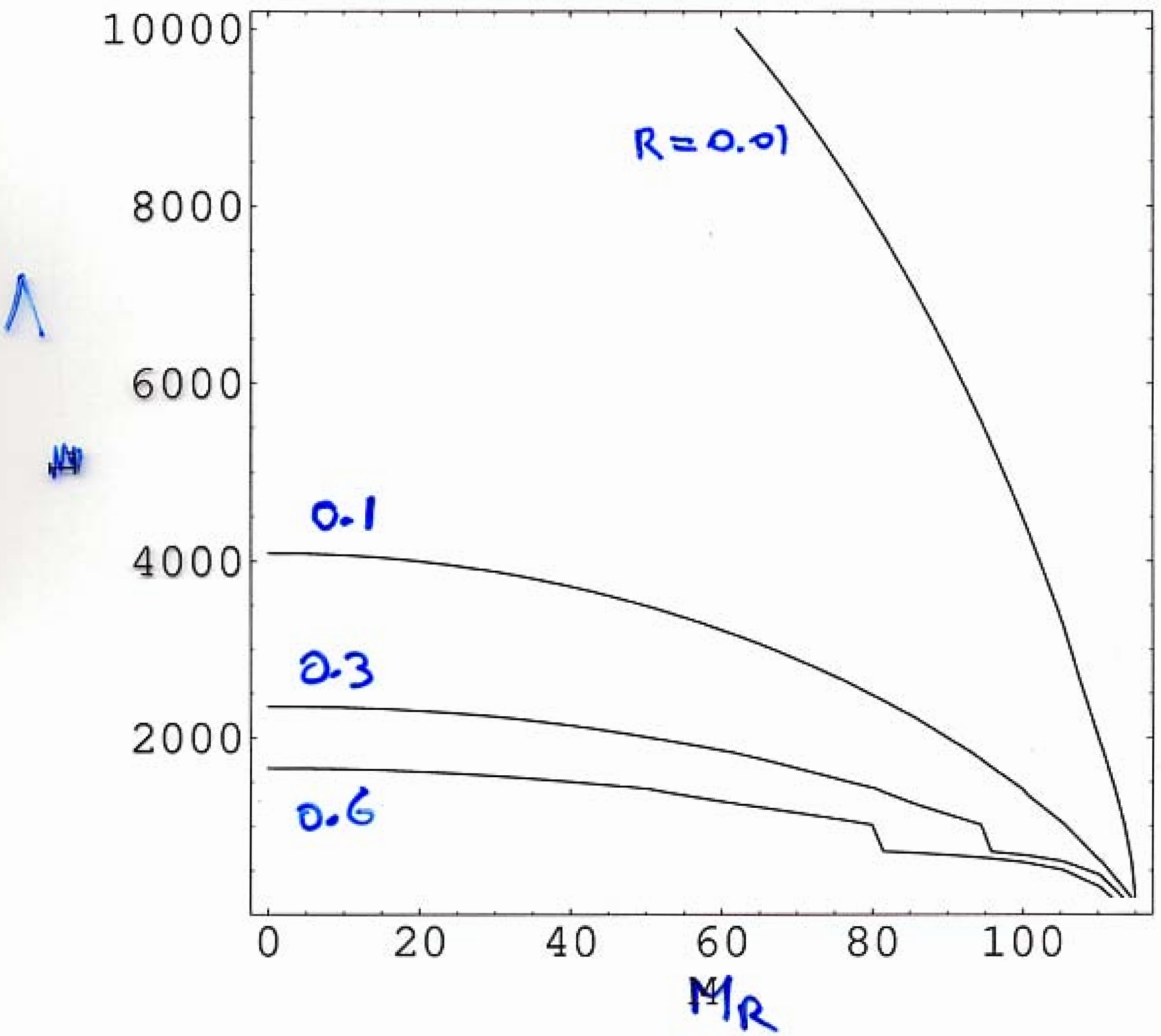
$$\begin{aligned} m_h &> 2m_W \\ m_h &> 2M_R \end{aligned}$$

Partial decay widths to $v_R v_R$ and WW comparable. For Higgs decay into all three right-handed neutrinos

$$R_W = 12\frac{v^4}{m_h^2\Lambda^2} \times \text{phase space factors}$$

$$= \frac{\sum_i \Gamma(h \to v_R v_R)}{\Gamma(h \to WW)}$$

$$R = \sum_{i=1}^{3} \Gamma[h \to \nu_R \nu_R]/\Gamma[h \to WW] \ , \ m_h = 230 \text{ GeV}$$



Have seen that, if kinematically allowed, the higgs boson can have significant branching fractions into right-handed neutrinos. Can be the dominant decay channel.

What occurs next depends on the lifetime and decay mode of the right-handed neutrinos

- Right-handed neutrino long-lived (detector stable)
  - Invisible decay

- Right-handed neutrino decays within the detector
  - $\Rightarrow$ Focus of the rest of the talk. Again, will do an operator analysis.

– Will see that this is the more natural scenario

Decay of Right-handed neutrinos

dimension 5

$$O_5 = \frac{1}{\Lambda} \nu_R \sigma^{\mu\nu} \nu_R B_{\mu\nu}$$

Cascade decay $\quad \nu_{Ri} \to \nu_{Rj \neq i} + \gamma$

down to lightest RH neutrino

- prompt decay (if coefficient $O(1)$)
- operator may naturally be tiny

dimension 6

Here there are a number of operators.

Focus on magnetic moment operators

$$O_B = \frac{\lambda_B}{\Lambda^2} \nu_R \sigma^{\mu\nu} L H^* B_{\mu\nu}$$

$$O_W = \frac{\lambda_W}{\Lambda^2} \nu_R \sigma^{\mu\nu} L \tau^a H^* W^a_{\mu\nu}$$

Magnetic Moment Operators

Electroweak symmetry breaking generates Dirac magnetic moments

$$\mathcal{O}_{4,5} \rightarrow \frac{\lambda_{ij}^{(6)} v}{\Lambda^2}(\overline{\nu}_{R,i}\sigma^{\mu\nu}\nu_{L,j})\,(F_{\mu\nu} + bZ_{\mu\nu}) + \frac{\lambda_{ij}^{(5)} v}{\Lambda^2}(\overline{\nu}_{R,i}\sigma^{\mu\nu}e_{L,j})W_{\mu\nu}^{+}$$

Possible decays of the right-handed neutrino are then:

$$\nu_R \rightarrow \nu_L + \gamma$$

And if kinematically allowed,

$$\nu_R \rightarrow W + e \quad , Z + \nu_L$$

Higgs production has the following cascade decays:

$$\begin{aligned} h &\to \nu_R \nu_R \\ &\to \gamma\gamma + \nu_L \nu_L \end{aligned}$$

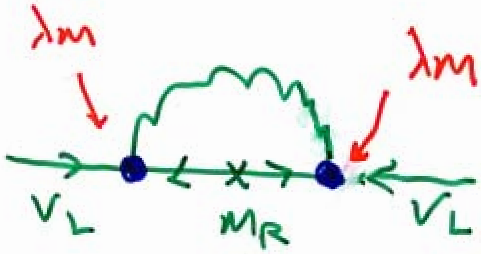
If $M_R > m_W$:

$$\begin{aligned} h &\to \nu_R \nu_R \\ &\to WWee \end{aligned}$$

or

$$\begin{aligned} h &\to \nu_R \nu_R \\ &\to We\gamma\nu_L \end{aligned}$$

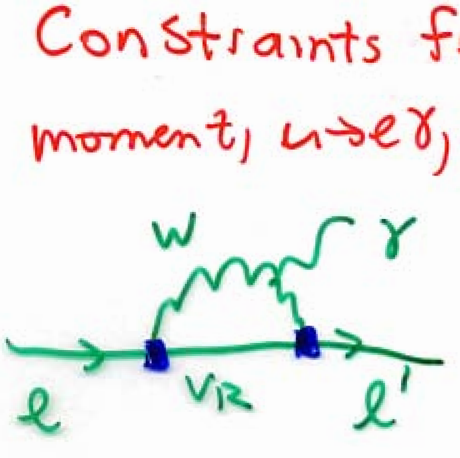
Strongest constraint from neutrino masses:



$$\delta m_{\nu_L} \simeq \frac{\lambda_M \lambda_M^T}{16\pi^2} \frac{v^2}{\Lambda^2} M_R \lesssim O\left(\frac{1}{10}\right) eV$$

$$\Rightarrow \lambda_M \lesssim 4 \cdot 10^{-5} \left(\frac{TeV}{\Lambda}\right)\left(\frac{100 GeV}{M_R}\right)^{1/2}$$

Constraints from the neutrino magnetic moment, $\mu \to e\gamma$, electron EDM are weaker.



Compute

$$\Gamma[\nu_R \to \gamma + \nu_L] + \Gamma[\nu_R \to \gamma + \bar{\nu}_L] \simeq \frac{1}{4\pi}|\lambda m|^2 \frac{v^2}{\Lambda^4} M_R^3$$

$$\Gamma = 10^{-8}\left(\frac{|\lambda m|^2}{10^{-9}}\right) \text{MeV} \left(\frac{M_R}{100\,\text{GeV}}\right)^3 \left(\frac{\text{TeV}}{\Lambda}\right)^4$$

Compare to

$$\Gamma_{\tau a\nu} \simeq 10^{-9}\,\text{MeV}$$

With $c\tau_\tau \simeq 100\,\mu m$ Right-handed neutrinos have $c\tau \gtrsim 10\,\mu m$

Large range of parameters where the right handed neutrino decays in the detector, and couplings are consistent with bounds from the neutrino mass.

Minimal Flavour Violation

Hypothesis

Chivukula, Georgi
Buras et al.
D'Ambrosio, Giudice,
Isidori, Strumia

Yukawa couplings and mass parameters only source of irreducible flavour violation

$(M_R)_{3\times3}$

$(\lambda_\nu)_{3\times3}$

$(\lambda_e)_{3\times3}$

Flavour violation appearing in higher-dimension operators reducible

Rule

promote mass & Yukawa couplings to fields transforming under

$$SU(3)_{\nu_R} \times SU(3)_L \times SU(3)_{e^c} \times U(1)_{LN}$$

flavour symmetry

$$\lambda_\nu \longrightarrow U^*_{\nu_R} \, \lambda_\nu \, U^\dagger_L \times e^{i\alpha_{LN}}$$

$$M_R \rightarrow U^*_{\nu_R} \, M_R \, U^\dagger_{\nu_R}$$

$$\lambda_e \longrightarrow U^*_L \, \lambda_e \, U^\dagger_{e^c}$$

Apply to higher dimension operators involving RH neutrinos

Simplifying assumption:

$$(M_R)_{ij} = M\,\delta_{ij}$$

only source of flavor violation are the Yukawa couplings

$$SU(3)_{\nu_R} \to O(3)_{\nu_R}$$

$$\nu_R \to O\,\nu_R$$

$$\lambda_\nu \to O_{\nu_R}\,\lambda_\nu\,U_L^\dagger\,e^{i\alpha_{2N}}$$

operator analysis on $\tau \to \mu\gamma$, $\mu \to e\gamma$, $\mu \to e$ (Cirigliano, Grinstein, Isidori, Wise)

Examples

1) $\nu_R \left(M \mathbb{1} + \frac{H^+ H}{\Lambda} \left(\mathbb{1} + \lambda_\nu \lambda_\nu^+ \right) \right) \nu_R$ ✓

↳ large width

$h \to \nu_R \nu_R$

↳ $(\Delta M_R)_{ij} \underset{CP}{\approx} m_{\nu\, ij}$

2) $\frac{1}{\Lambda} L H L H$ $\qquad$ $\lambda_\nu^T \lambda_\nu$

a priori dangerous, $\qquad$ OK

but violates $U(1)_{LN}$

3) $\frac{1}{\Lambda} \partial_\mu \nu_R \gamma^\mu L H^*$ $\qquad$ λ_ν $\qquad$ OK

However, none of these operators are relevant for ν_R decay

Long List of Operators

d=5

2ν_R

$\frac{1}{\Lambda} \nu_{R_i} \sigma^{\mu\nu} \nu_{R_j} \; B_{\mu\nu}$ $\quad [\lambda_\nu \lambda_\nu^\dagger]_{AS} \stackrel{CP}{=} 0$

$\frac{1}{\Lambda} \nu_{R_i} \partial^\mu \nu_{R_j} \; H^\dagger D_\mu H$ $\quad [\lambda_\nu \lambda_\nu^\dagger]_{AS} \stackrel{CP}{=} 0$

d=6

2 fermi

$\frac{1}{\Lambda^2} \bar{\nu}_R \gamma^\mu e^c \; H D_\mu H$ $\quad \lambda_\nu^* \lambda_e$ suppressed

$\frac{1}{\Lambda^2} \partial^\mu \nu_R L \quad D^\mu H^*$ $\quad \lambda_\nu$

$\frac{1}{\Lambda^2} \nu_R D_\mu L \quad D^\mu H^*$ $\quad \lambda_\nu$

$\frac{1}{\Lambda^2} \nu_R L H^* \quad H H^*$ $\quad \lambda_\nu$

4-fermi

$\frac{1}{\Lambda^2} (\nu_R L)(e^c L)$ $\quad \lambda_\nu | \lambda_e$ suppressed

magnetic moment

$\frac{1}{\Lambda^2} \nu_R \sigma^{\mu\nu} L \; H^* B_{\mu\nu}$ $\quad \lambda_\nu$ ✓

$\frac{1}{\Lambda^2} \nu_R \sigma^{\mu\nu} L \tau^a H^* \; W^a_{\mu\nu}$ $\quad \lambda_\nu$ ✓

and recall $\lambda_\nu \sim 10^{-7}$

Focus on magnetic moment operators

$$\lambda_M = \lambda v$$

Assume CP conservation $\lambda_\nu^* = \lambda_\nu$

Then the LH neutrino masses $(m_{\nu_L} \sim \lambda_\nu \lambda_\nu^+)$ and λ_ν can be simultaneously diagonalized

$$\nu_R \to O_R \nu_R$$

$$\nu_L \to U_{\nu_L} \nu_L$$

Consequences:

$$\nu_{R\,i} \to \nu_{L\,i} + \gamma$$

$$\Gamma \propto m_{\nu_{L\,i}}$$

$$\boxed{c\tau_i = 10\,\mathrm{cm}\left(\frac{1/10\,\mathrm{eV}}{m_{\nu_L i}}\right)\left(\frac{100\,\mathrm{GeV}}{m_R}\right)^4\left(\frac{\Lambda}{\mathrm{TeV}}\right)^4}$$

Size of displaced vertex depends on pattern of neutrino masses

- degenerate $m_{\nu_L i} \sim \frac{1}{20}\,\mathrm{eV}$ — 20cm
- hierarchy
  - $(m_{\nu_L})_{\text{heaviest}} \sim \frac{1}{20}\,\mathrm{eV}$ — 20cm
  - $(m_{\nu_L})_{\text{2nd heaviest}} \sim 10^{-2}\,\mathrm{eV}$ — 1m
- degenerate $m_{\nu_L i} \sim \mathrm{eV}$ — 1cm
- $(m_{\nu_L})_{\text{lightest}} < 10^{-3}\,\mathrm{eV}$ — 10m and probably invisible

W- magnetic moment operator

If $M_{\nu_R} > m_W$

charged-lepton neutrino mixing matrix

$\nu_{R_i} \to W \ell_j$ $\qquad \Gamma \propto m_{\nu_{2i}} |U_{ij}|^2$

$\sin^2 2\theta_{12} = 0.86$ $\quad 1 \leftrightarrow 2$

$\sin^2 2\theta_{23} > 0.92$ $\quad 2 \leftrightarrow 3$

$\sin^2 2\theta_{13} < 0.19$ $\quad 3 \cdots 1$

Pattern of charged leptons at displaced vertices depends on LH neutrino mass hierarchy

normal scenario $\quad$ 3, 2, 1 $\uparrow$ mass

mostly τ, μ	equal τ, μ, e	mostly e, μ
γ	γ	γ
20 cm	1 m	?
ν_3 decay	ν_2 decay	ν_1 decay

Inverted scenario

2
1
3

$\sin^2\theta_{12} = 0.86$
$\sin^2 2\theta_{23} > 0.92$
$\sin^2\theta_{13} < 0.19$

equal
τ, μ, e

γ

20cm

ν_2 decay

mostly
e, μ

γ

1m

ν_1 decay

mostly
τ, μ

γ

?

ν_3 decay

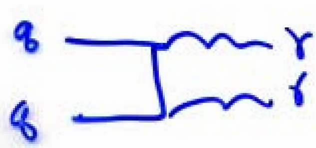
Detection

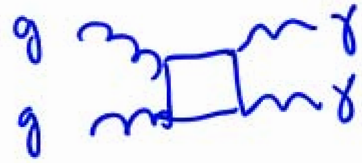
$$h \to \gamma\gamma + \not{E}_T \qquad \sigma(h) \sim 30\,pb$$

backgrounds

1) $pp \to \gamma\gamma$ continuum

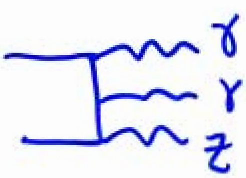
$$\sigma \sim 1\,pb/GeV \qquad m_{\gamma\gamma} \approx 100\,GeV \pm 50\,GeV$$

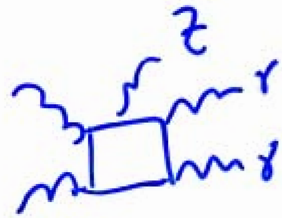


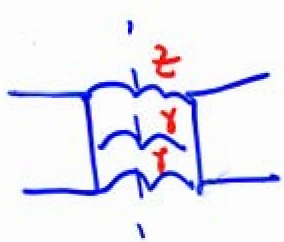


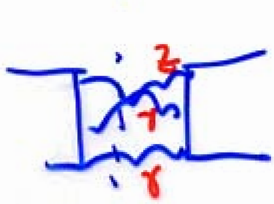
• cut on missing E_T

2) $pp \to \gamma\gamma Z$
$\quad\;\; \hookrightarrow \nu\bar{\nu}$









$$\sigma_{prod}(\gamma\gamma Z) \approx 6^2 \frac{g^2}{16\pi^2}\, \sigma_{prod}(\gamma\gamma)$$

$$\approx \frac{1}{10}\, \sigma_{prod}(\gamma\gamma)$$

$$\approx 0.1\ pb/GeV$$

Background

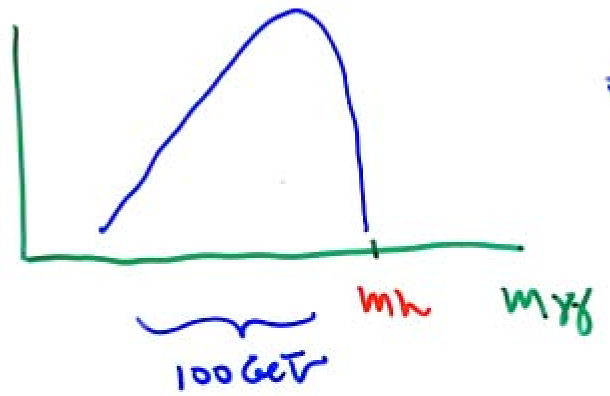
$$\sigma_{prod}(\gamma\gamma Z) \approx 0.1 \text{ pb/GeV}$$

$$\downarrow \nu$$

$$\sigma_{prod}(\gamma\gamma + \not{E}_T) \approx 0.02 \text{ pb/GeV}$$

Signal

$$\frac{d\sigma_{prod}(h\to\gamma\gamma+\not{E}_T)}{dm}$$



$$\Rightarrow \sigma_{Signal} \approx \frac{30 \text{ pb}}{100 \text{ GeV}} \approx 0.3 \text{ pb/GeV}$$

Main background may be fake missing energy signal from continuum $\gamma\gamma$ production

Conclusions

* Explored the consequences of higher-dimension operators linking electroweak scale right-handed neutrinos with the Higgs boson, gauge bosons and leptons

  * drastically modify Higgs boson width
    - dominant decay mode $m_h < 2m_W$
    - comparable to $h \to WW$

  * long-lived right neutrinos

    $c\tau \approx 20\ \mu m - 1m$

* general operator analysis in the 'Minimal Flavour Violation hypothesis'

- proposed scenario naturally accomodated
- striking predictions for right-handed neutrino decays