New physics in Majorana neutrinos at the LHC

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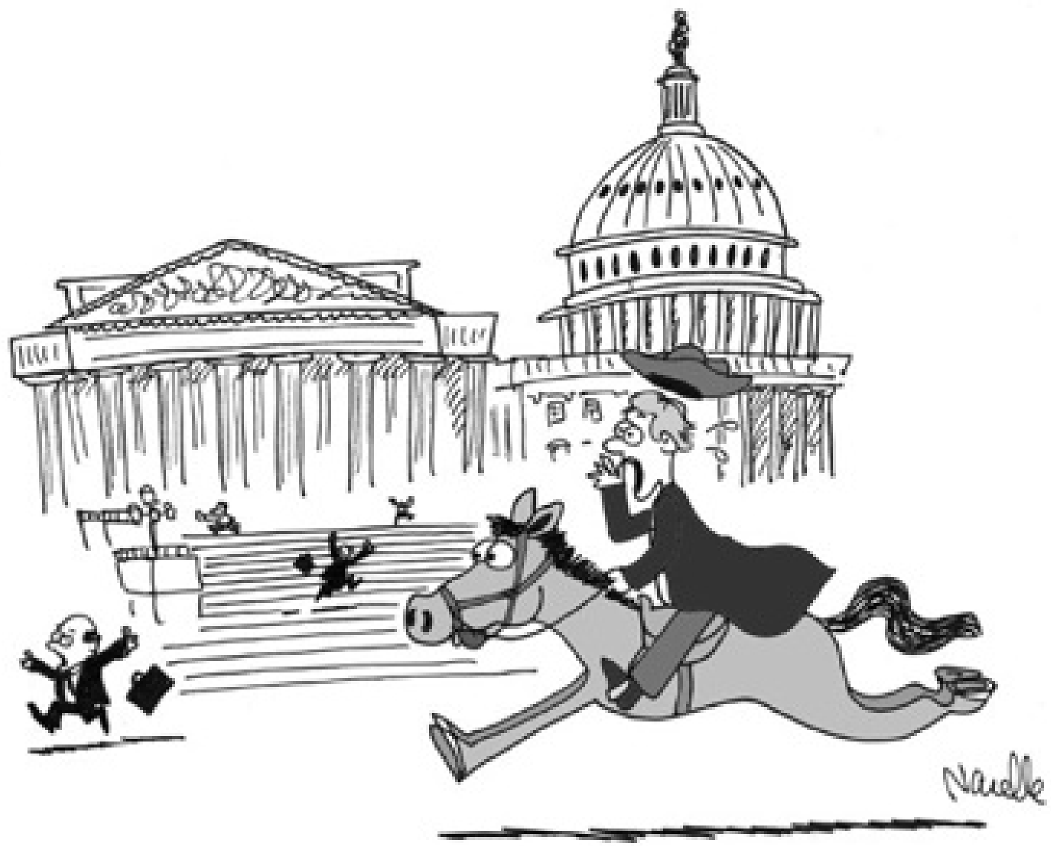


The facts are coming! The facts are coming!

Introduction

Some information about neutrinos:

- ν_L – SM couplings
- Masses
- Mixing angles (some)

Many possibilities for non-standard interactions

Best described using an effective Lagrangian

Some limits can be derived now …

… others at the LHC

Example

ν oscillations *suggest* the presence of ν_R = N:

$$\mathcal{L}_{\nu SM} \equiv \mathcal{L}_{SM} + \left(\bar{N}_a M_{ab} N_b^c / 2 - \bar{L}_i \tilde{\phi} Y_{ia} N_a + \text{H.c.} \right)$$

$$m_\nu = -m_D M^{-1} m_D^T, \quad m_D = \langle \phi \rangle Y = vY/\sqrt{2}$$

Two examples giving $m_\nu \sim 0.01$ eV:

- M $\sim 10^{15}$ GeV, $m_D \sim m_W$ (Y $\sim$ 1)
- M $\sim$ 100 GeV, $m_D \sim m_{electron}/10$ (Y $\sim 10^{-7}$)

But the N **decouple** in both cases:

When M $\sim 10^{15}$ GeV because they are very heavy

When M $\sim$ 100 GeV because they couple weakly:

$$\mathcal{L}^{W}_{V-A} = -(g/\sqrt{8}) U_{\ell N} \overline{N^c} \gamma^\mu (1-\gamma_5) \ell W^+_\mu + \text{H.c.}$$

$$U_{\ell N} \sim \sqrt{m_\nu/M} \sim Y \sim 10^{-7}$$

At least as far as $\mathcal{L}_{\nu\,SM}$ is concerned

Effective interactions

Observable N effects likely imply more new physics

I will assume the newer physics has scale Λ …

$$\Lambda > M$$

$$1\ \text{TeV} > M > 100\ \text{GeV}$$

… and that the scale Λ is not directly probed

$\Rightarrow$ use an effective $\mathcal{L}$ to describe the N – SM interactions

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\nu SM} + \sum_{n=5}^{\infty} \Lambda^{4-n} \sum_i \alpha_i \mathcal{O}_i^{(n)}$$

- $\mathcal{O}$: gauge-invariant built of N and SM fields
- The α_i cannot be calculated (unless the underlying physics is known) …

… but they can be bound by naturality

- Weakly coupled: Largest effects from tree-level generated operators
- Strongly coupled: coefficient estimates using NDA

Dimension 5 terms

L: left-handed lepton isodoublets
Q: left-handed quark isodoublets
e: right-handed charged lepton isosinglets
u, d: right-handed charged quark isosinglets
ϕ: scalar isodoublet
B: $U(1)$ gauge field
W^I: $SU(2)$ gauge fields

Tree-level generated

$(\bar{L}\tilde{\phi})(\phi^\dagger L^c)$ — ν_L Majorana mass $\sim v^2/\Lambda$ + H interactions

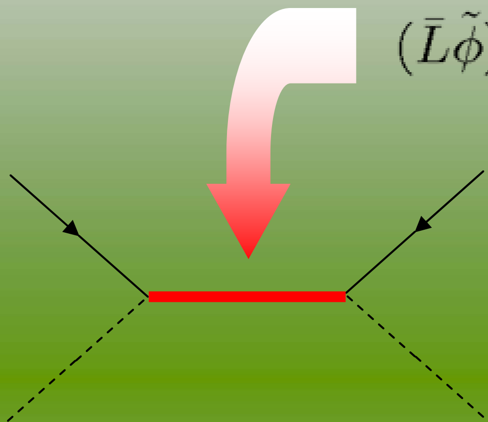
$(\bar{N}N^c)(\phi^\dagger\phi)$ — ν_R Majorana mass $\sim v^2/\Lambda$ + H interactions

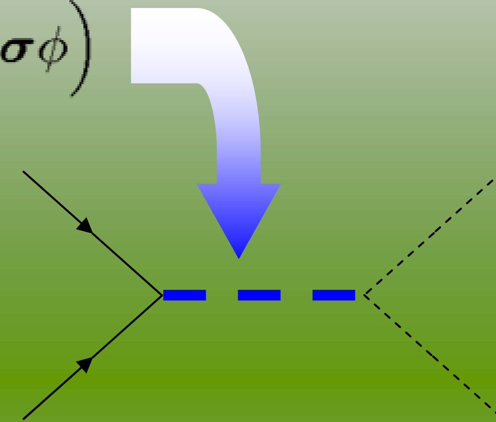
Loop generated

$(\bar{N}\sigma_{\mu\nu}N^c)B^{\mu\nu}$ — ν_R Majorana magnetic moment; Z coupling (Arcadi's talk)

Heavy mediators (example):

$$(\bar{L}\tilde{\phi})(\phi^\dagger L^c) = \frac{1}{2}\left(\bar{L}\boldsymbol{\sigma}L\right)\cdot\left(\tilde{\phi}^\dagger\boldsymbol{\sigma}\phi\right)$$





Type 1 see-saw:
Fermion isosinglet,
hypercharge = 0

or

Type III see-saw:
Fermion isotriplet,
hypercharge = 0

Type 2 see-saw:
Scalar isotriplet,
hypercharge = 1

Dimension 6 terms

L: left-handed lepton isodoublets
Q: left-handed quark isodoublets
e: right-handed charged lepton isosinglets
u, d: right-handed charged quark isosinglets
ϕ: scalar isodoublet
B: $U(1)$ gauge field
W^I: $SU(2)$ gauge fields

Two basic types of tree-level generated operators:

- 4-fermion interactions
- Fermion –vector boson interactions

+ B-violating operators

+ loop-generated operators

4-fermion operators

All SM fermions

$$\mathcal{O}_{fN} = (\bar{f}\gamma_\mu f)(\bar{N}\gamma^\mu N)$$
$$\mathcal{O}_{duNe} = (\bar{d}\gamma^\mu u)(\bar{N}\gamma^\mu e)$$
$$\mathcal{O}_{QuNL} = (\bar{Q}\gamma^\mu L)(\bar{N}\gamma^\mu u)$$

$$\mathcal{O}_{Lf} = (\bar{f}\gamma_\mu f)(\bar{L}\gamma^\mu L)$$
$$\mathcal{O}_{LQ}^{(3)} = (\bar{L}\gamma_\mu \tau^I L)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$\mathcal{O}_{NN} = (\bar{N}N^c)^2$$
$$\mathcal{O}_{LNQd} = (\bar{L}N)\varepsilon(\bar{Q}d)$$
$$\mathcal{O}_{QNLd} = (\bar{Q}N)\varepsilon(\bar{L}d)$$
$$\mathcal{O}_{LNLe} = (\bar{L}N)\varepsilon(\bar{L}e)$$

Fermion-vector boson operators

$$\mathcal{O}_{LN\phi} = (\phi^\dagger \phi)(\bar{L} N \tilde{\phi})$$
$$\mathcal{O}_{NN\phi} = i(\phi^\dagger D_\mu \phi)(\bar{N} \gamma^\mu N)$$
$$\mathcal{O}_{Ne\phi} = i(\phi^T \varepsilon D_\mu \phi)(\bar{N} \gamma^\mu e)$$

$$\mathcal{O}_{\phi L}^{(1)} = \left(\phi^\dagger D_\mu \phi\right)\left(\bar{L} \gamma^\mu L\right)$$
$$\mathcal{O}_{\phi L}^{(1)} = \left(\phi^\dagger \tau^I D_\mu \phi\right)\left(\bar{L} \tau^I \gamma^\mu L\right)$$

Mediators

Generated by

- W_R
- Leptoquarks
- Extended scalar sector
- Z', W'
- Heavy fermions

$(\bar{f}\gamma_\mu f)(\bar{N}\gamma^\mu N)$

$(\bar{d}\gamma_\mu u)(\bar{N}\gamma^\mu e)$

$(\bar{Q}\gamma_\mu L)(\bar{N}\gamma^\mu u)$

$(\bar{f}\gamma_\mu f)(\bar{L}\gamma^\mu L)$

$(\bar{Q}\tau^I\gamma_\mu Q)(\bar{L}\tau^I\gamma^\mu L)$

$(\bar{N}N^c)^2$

$(\bar{L}N)\varepsilon(\bar{Q}d)$

$(\bar{Q}N)\varepsilon(\bar{L}d)$

$(\bar{L}N)\varepsilon(\bar{L}e)$

$|\phi|^2(\bar{L}N\tilde{\phi})$

$(\phi^\dagger D_\mu\phi)\,(\bar{N}\gamma^\mu N)$

$i\,(\phi^T\varepsilon D_\mu\phi)\,(\bar{N}\gamma^\mu e)$

$(\phi^\dagger D_\mu\phi)\,(\bar{L}\gamma^\mu L)$

$(\phi^\dagger\tau^I D_\mu\phi)\,(\bar{L}\tau^I\gamma^\mu L)$

Masses and mixings

Dirac mass:
$m = \langle \phi \rangle \, Y = v \, Y$

$$\mathcal{L}_{\nu \text{ mass}} = \frac{1}{2}\bar{N} M N^c - \bar{\nu}_L m N + \bar{\nu}_L \mu \nu_L^c + \text{H.c.}$$

Absorbed the effects of
$(\bar{N} N^c) \langle \phi^\dagger \phi \rangle / \Lambda$

From $(\bar{L}\tilde{\phi})(\phi^\dagger L^c)$

Naturally small: $\mu \sim v^2/\Lambda$

$$\text{Simplest hierarchy}: M \gg m = vY \gg \mu = \frac{v^2}{\Lambda}$$

$$\text{masses}: \quad \begin{array}{l} m_{\text{light}} = \mu + (\mathbf{Im} m) M^{-1} (\mathbf{Im} m)^T - (\mathbf{Re} m) M^{-1} (\mathbf{Re} m)^T + \cdots \\ m_{\text{heavy}} = M + \cdots \end{array}$$

$$\nu_L - N \text{ mixing}: \sim \frac{m}{M} \lesssim \sqrt{\frac{m_{\text{light}}}{M}}$$

Applications

$$pp,\ p\bar{p} \longrightarrow \ell^+ \ell^+ j\ j$$

Lagrangian

$$\begin{aligned}\mathcal{L}^N_{eff} = \Lambda^{-2}\Big[& -\sqrt{2} v m_{\rm w} \alpha_{{\rm w}l} \overline{N^c} \gamma^\mu e_L W^+_\mu \\ & -\sqrt{2} v m_{\rm w} \alpha_{\rm wr} \bar{N} \gamma^\mu e_R W^+_\mu \\ & +\alpha_{\rm v} \left(\bar{d}_R \gamma^\mu u_R\right)\left(\bar{N}\gamma_\mu e_R\right) \\ & +\alpha_{\rm s1} \left(\bar{u}_R d_L\right)\left(\bar{e}_L N\right) \\ & -\alpha_{\rm s2} \left(\bar{u}_L d_R\right)\left(\bar{e}_L N\right) \\ & +\alpha_{\rm s3} \left(\bar{u}_L N\right)\left(\bar{e}_L d_R\right) + \text{H.c.}\Big]\end{aligned}$$

From $\mathcal{L}_{\nu\,\rm SM}$
Small coupling $\sim 10^{-7}$

From $i(\phi^T \varepsilon D_\mu \phi)(\bar{N}\gamma^\mu e)$

$$u\,\bar{d} \to N \quad \ell^+$$
$$\hookrightarrow \ell^+\, j\, j$$

$$\begin{aligned}\mathcal{L}_{eff}^N \;=\; \Lambda^{-2}\Big[& -\sqrt{2}v m_{\rm w}\alpha_{{\rm w}l}\overline{N^c}\gamma^\mu e_L W_\mu^+ \\ & -\sqrt{2}v m_{\rm w}\alpha_{{\rm w}r}\bar{N}\gamma^\mu e_R W_\mu^+ \\ & +\alpha_{\rm v}\left(\bar{d}_R\gamma^\mu u_R\right)\left(\bar{N}\gamma_\mu e_R\right) \\ & +\alpha_{\rm s1}\left(\bar{u}_R d_L\right)\left(\bar{e}_L N\right) \\ & -\alpha_{\rm s2}\left(\bar{u}_L d_R\right)\left(\bar{e}_L N\right) \\ & +\alpha_{\rm s3}\left(\bar{u}_L N\right)\left(\bar{e}_L d_R\right) + {\rm H.c.}\Big]\end{aligned}$$

$$\begin{aligned}\frac{d\hat{\sigma}}{dc_\theta} = \frac{(\hat{s}-M^2)^2}{128\pi\,\hat{s}\Lambda^4} & \left\{\alpha_{\rm s1}^2 + \alpha_{\rm s2}^2 - \alpha_{\rm s2}\alpha_{\rm s3}(1+c_\theta) + \alpha_{\rm s3}^2\Upsilon_+ \right. \\ & \left. +4\alpha_{\rm v}^2\Upsilon_- + 16\left(\alpha_{{\rm w}l}^2\Upsilon_- + \alpha_{{\rm w}r}^2\Upsilon_+\right)\Pi_{\rm w}(\hat{s})\right\} ,\end{aligned}$$

$$\begin{aligned}\frac{d\Gamma}{dx} = \frac{M}{128\pi^3}\left(\frac{M}{\Lambda}\right)^4 & \left\{\left(\alpha_{\rm s1}^2 + \alpha_{\rm s2}^2 - \alpha_{\rm s2}\alpha_{\rm s3}\right) f_{\rm s} \right. \\ & \left. + \left[\alpha_{\rm s3}^2 + 4\alpha_{\rm v}^2 + 16\left(\alpha_{{\rm w}l}^2 + \alpha_{{\rm w}r}^2\right)\Pi_{\rm w}((M-2E_\ell)M)\right] f_{\rm v}\right\}\end{aligned}$$

$\Pi_{\rm w}(\hat{s}) \equiv m_{\rm w}^4\left[(\hat{s}-m_{\rm w}^2)^2 + (m_{\rm w}\Gamma_{\rm w})^2\right]^{-1}$

$\Upsilon_\pm = \frac{1}{4}[(1 \pm c_\theta)^2 + M^2 s_\theta^2/\hat{s}]$

$\theta :\ \ell - u$ (CM) scattering angle

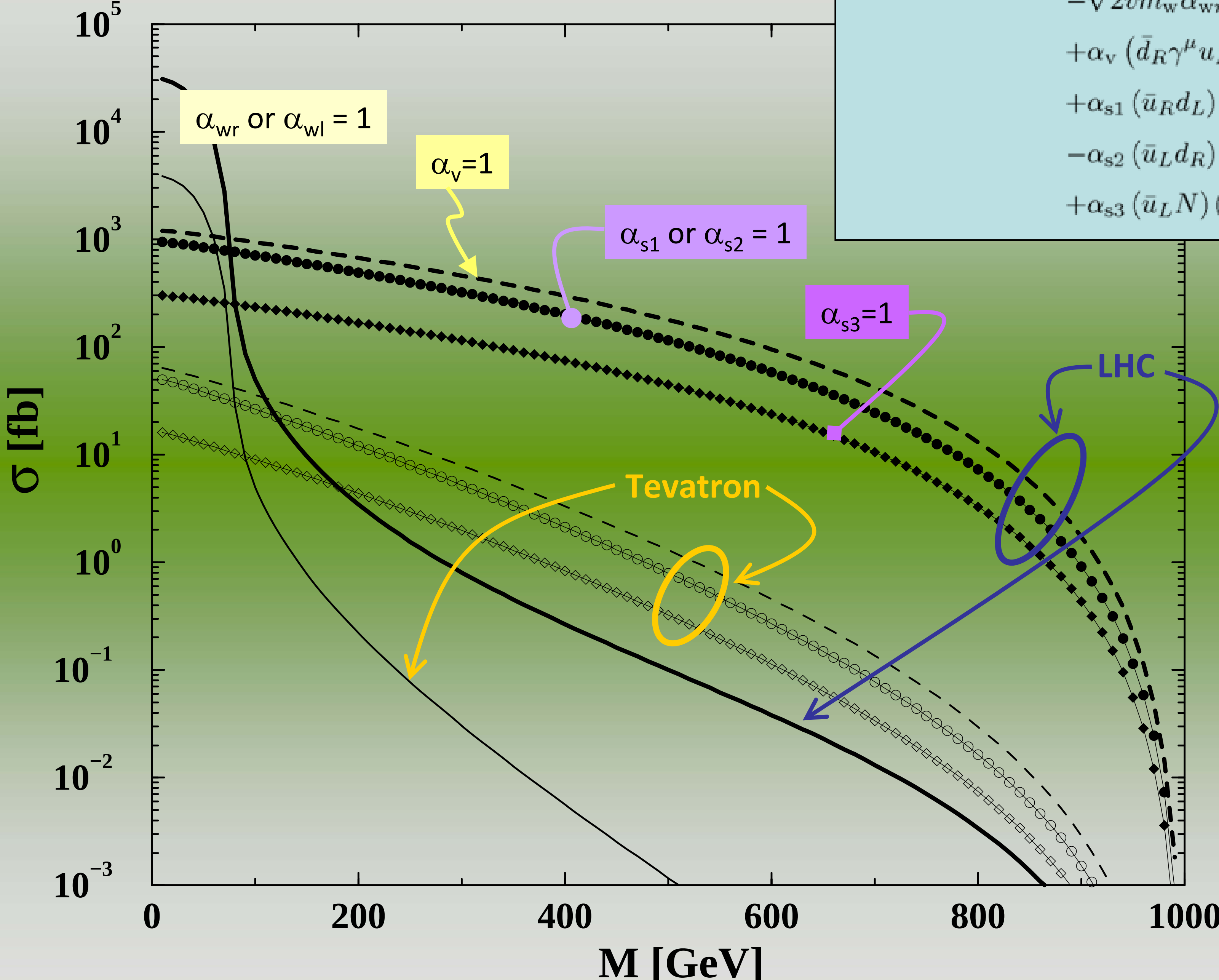
$f_{\rm s} = 6x^2(1-2x)$

$f_{\rm v} = x^2(3-4x);$

$x = E_\ell/M$ in the N rest frame

$|\cos\theta| < 0.9, \quad \sqrt{\hat{s}} < \Lambda = 1\,\mathrm{TeV}$

$$\begin{aligned}\mathcal{L}^{N}_{eff} \;=\; \Lambda^{-2}\Big[& -\sqrt{2} v m_{\rm w} \alpha_{{\rm w}l} \overline{N^c} \gamma^\mu e_L W^+_\mu \\ & -\sqrt{2} v m_{\rm w} \alpha_{{\rm w}r} \bar{N} \gamma^\mu e_R W^+_\mu \\ & +\alpha_{\rm v} \left(\bar{d}_R \gamma^\mu u_R\right)\left(\bar{N}\gamma_\mu e_R\right) \\ & +\alpha_{\rm s1} \left(\bar{u}_R d_L\right)\left(\bar{e}_L N\right) \\ & -\alpha_{\rm s2} \left(\bar{u}_L d_R\right)\left(\bar{e}_L N\right) \\ & +\alpha_{\rm s3} \left(\bar{u}_L N\right)\left(\bar{e}_L d_R\right) + \mathrm{H.c.}\Big]\end{aligned}$$



$$\left.\begin{array}{l} M \lesssim 200 \text{ GeV}, \\ \Lambda \sim \mathcal{O}(1) \text{ TeV}, \\ \alpha_{wr} \sim \mathcal{O}(1) \ (\alpha_i = 0 \text{ otherwise}) \end{array}\right\} 5\sigma \text{ effect @ LHC}$$

$$\left.\begin{array}{l} M \lesssim 600 \text{ GeV}, \\ \Lambda \sim \mathcal{O}(1) \text{ TeV}, \\ \alpha_{\rm v} \sim \mathcal{O}(1) \ (\alpha_i = 0 \text{ otherwise}) \end{array}\right\} \sigma \gtrsim 100\text{fb} \quad (\text{LHC})$$

W_R or vector leptoquark

Other observables

A_{FB} = θ asymmetry
A^y_{FB} = double asymmetry in θ and the rapidity *y*

$M = 200\text{GeV}$	non-zero coefficient				
	α_{wl}	α_{wr}	α_{v}	$\alpha_{s1,s2}$	α_{s3}
A_{FB} (Tevatron)	0.55	−0.55	0.62	0	−0.62
A^y_{FB} (Tevatron)	0.11	−0.11	0.12	0	−0.12
A^y_{FB} (LHC)	0.35	−0.35	0.40	0	−0.40

$$\frac{d\sigma}{dM_{jj}}, \quad \frac{d\sigma}{dM_{\ell\ell}} : \quad \text{discriminate between } \alpha_{\mathrm{w}r} \text{ and } \alpha_{\mathrm{v}}$$

$$\int \frac{d\Gamma}{dx} g(x) dx \ \text{ separates } \begin{cases} \alpha_{\mathrm{s}1}^2 + \alpha_{\mathrm{s}2}^2 - \alpha_{\mathrm{s}2}\alpha_{\mathrm{s}3} \\ \alpha_{\mathrm{s}3}^2 + 4\alpha_{\mathrm{v}}^2 \\ \alpha_{\mathrm{w}l}^2 + \alpha_{\mathrm{w}r}^2 \end{cases}$$

$$\frac{d\Gamma}{dx} = \frac{M}{128\pi^3}\left(\frac{M}{\Lambda}\right)^4 \left\{ \left(\alpha_{\mathrm{s}1}^2 + \alpha_{\mathrm{s}2}^2 - \alpha_{\mathrm{s}2}\alpha_{\mathrm{s}3}\right) f_{\mathrm{s}} + \left[\alpha_{\mathrm{s}3}^2 + 4\alpha_{\mathrm{v}}^2 + 16\left(\alpha_{\mathrm{w}l}^2 + \alpha_{\mathrm{w}r}^2\right)\Pi_{\mathrm{w}}((M - 2E_\ell)M)\right] f_{\mathrm{v}} \right\}$$

ν oscillations

Mass terms

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\bar{\nu} P_L M \nu^c - \bar{\nu}\frac{v^2 f}{2\Lambda} P_R \nu^c - \bar{\nu} m P_R \nu + \text{H.c}$$

N Majorana mass

Dirac mass + density effects

ν_L Majorana mass (naturally small)

$$m = \frac{v\lambda}{\sqrt{2}} + \frac{1}{\Lambda^2}\left[g_u\ (\bar{u}P_L u) + g_d\ (\bar{d}P_R d) + g_{e\,L}\ (\bar{e}P_L e) + g_{e\,R}\ (\bar{e}P_R e)\right]$$

Yukawa coupling

Density-dependent mass terms

Current terms

Spin-spin coupling

$$\propto (\bar\nu \boldsymbol{\Sigma} P_R \nu) \cdot \left[g'_d (\bar d_L \boldsymbol{\Sigma} d_R) + g'_e (\bar e_L \boldsymbol{\Sigma} e_R)/12 \right]$$

(gauge invariance precludes ν-u terms to this order)

$$\mathcal{L}_{\rm int} = \bar\nu \gamma_\mu \left(P_R \mathcal{J}_R^\mu + P_L \mathcal{J}_L^\mu \right) \nu + \bar\nu \sigma^{\mu\nu} T_{\mu\nu} P_R \nu + {\rm H.c}$$

$\propto 1/v^2$: dominant
ν–flavor diagonal

$\propto 1/\Lambda^2$: subdominant
not ν–flavor diagonal

$$\mathcal{J}_L^\mu = J_{SM}^\mu + \frac{1}{\Lambda^2} \sum_f g_{Lf}\, \bar f \gamma^\mu f$$

$$\mathcal{J}_R^\mu = \frac{1}{\Lambda^2} \sum_f g_{Rf}\, \bar f \gamma^\mu f$$

No SM background

$$T^{\mu\nu} = \frac{1}{2\Lambda^2} \left[\frac{1}{12} g'_e\, \bar e \sigma^{\mu\nu} e + g'_d\, \bar d \sigma^{\mu\nu} d \right]$$

$M \gg E$
type 1 see-saw

Generic form of the various terms

$$\mathbb{H}_{\rm osc} = \begin{pmatrix} -\frac{\Delta m^2}{2E}\cos 2\theta + \sqrt{2}\,G_F n + \delta_1 & \frac{\Delta m^2}{2E}\sin^2\theta + \delta_2 \\ \frac{\Delta m^2}{2E}\sin^2\theta + \delta_2^* & \frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}\,G_F n - \delta_1 \end{pmatrix}$$

$\mathcal{J}_L$ $\quad m \quad$ $\mathcal{J}_R$

$$\delta_{1,2} \sim \frac{n}{\Lambda^2}\left(1 + \varepsilon + \varepsilon^2\right)$$

$$\varepsilon \sim \frac{m_D}{M} \quad \Rightarrow \quad m_{\rm light} \sim \varepsilon m_D$$

m_{light} = 0.1 eV, M=100 GeV
$\Rightarrow$ $\varepsilon \sim 10^{-6}$

Conclusions

- $\mathcal{L}_{eff}$ useful parameterization … but valid only below Λ

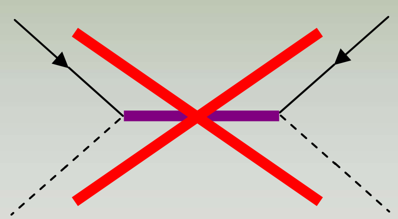
- Constraints on operator coefficients → restrictions on ***all*** models
  But a non-zero coefficient does not single out a specific model

- Possible interesting collider effects.
  For example, merely seeing a few 100 GeV N → physics beyond N+SM

- New physics oscillation effects suppressed by m_D/M (for large M)

- New physics oscillation effects for small M might be more interesting

- **Important caveat**:
  - o strongest effects from tree-level generated operators
  - o there are many models where these are absent
    For example those with a symmetry such that
    new particles → non singlets
    SM → singlets



- Understanding how $\mathcal{L}_{eff}$ is generated can lead to useful connections. E.g.
  - o Observing ν_R magmom → y=1 fermion isosinglet *E*,
  - o ⇒ look for Z-coupling universality violation
  - o ⇒ learn about $E \, \psi_{SM} \, \phi$ couplings