Effective theory approach to portly neutrinos. Theory and application

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The main issue

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

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

If M does not allow a conserved fermion #

$\Rightarrow$ N $\sim$ Majorana $\Rightarrow$ LNV signals

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

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

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

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

Masses & 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
$(\bar{N} N^c) \left\langle \phi^\dagger \phi \right\rangle / \Lambda$

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

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

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

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

$$m_{\text{heavy}} = M + \cdots$$

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

Newer physics

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

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

- $\mathcal{O}$: 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

- Largest effects from tree-level generated operators

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

Dimension 5 terms

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

ν_L Majorana mass $\sim v^2/\Lambda$
+ H interactions

ν_R Majorana mass $\sim v^2/\Lambda$
+ H interactions

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

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

$$\mathcal{O}_{duNe} = (\bar{d}\gamma^\mu u)(\bar{N}\gamma^\mu e) \qquad \mathcal{O}_{fNN} = (\bar{f}\gamma_\mu f)(\bar{N}\gamma^\mu N)$$
$$\mathcal{O}_{LNLe} = (\bar{L}N)\varepsilon(\bar{L}e) \qquad \mathcal{O}_{LNQd} = (\bar{L}N)\varepsilon(\bar{Q}d)$$
$$\mathcal{O}_{QuNL} = (\bar{Q}u)(\bar{N}L) \qquad \mathcal{O}_{QNLd} = (\bar{Q}N)\varepsilon(\bar{L}d)$$
$$\mathcal{O}_{LN} = |\bar{L}N|^2 \qquad \mathcal{O}_{QN} = |\bar{Q}N|^2$$
$$\mathcal{O}_{NN} = (\bar{N}N^c)^2 \qquad \mathcal{O}'_{NN} = |\bar{N}N^c|^2$$

+ B-violating operators + loop generated operators

Generated by

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

$$
\begin{aligned}
\mathcal{O}_{NN\phi} &= i(\phi^\dagger D_\mu \phi)(\bar{N}\gamma^\mu N), \\
\mathcal{O}_{Ne\phi} &= i(\phi^T \varepsilon D_\mu \phi)(\bar{N}\gamma^\mu e) \\
\mathcal{O}_{duNe} &= (\bar{d}\gamma^\mu u)(\bar{N}\gamma^\mu e) \\
\mathcal{O}_{fNN} &= (\bar{f}\gamma_\mu f)(\bar{N}\gamma^\mu N), \\
\mathcal{O}_{LNLe} &= (\bar{L}N)\varepsilon(\bar{L}e) \\
\mathcal{O}_{LNQd} &= (\bar{L}N)\varepsilon(\bar{Q}d) \\
\mathcal{O}_{QuNL} &= (\bar{Q}u)(\bar{N}L) \\
\mathcal{O}_{QNLd} &= (\bar{Q}N)\varepsilon(\bar{L}d), \\
\mathcal{O}_{LN} &= |\bar{L}N|^2 \\
\mathcal{O}_{QN} &= |\bar{Q}N|^2 \\
\mathcal{O}_{NN} &= (\bar{N}N^c)^2 \\
\mathcal{O}'_{NN} &= |\bar{N}N^c|^2
\end{aligned}
$$

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

Lagrangian

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

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

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

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

$$\hookrightarrow \ell^+\ j\ j$$

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

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

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

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

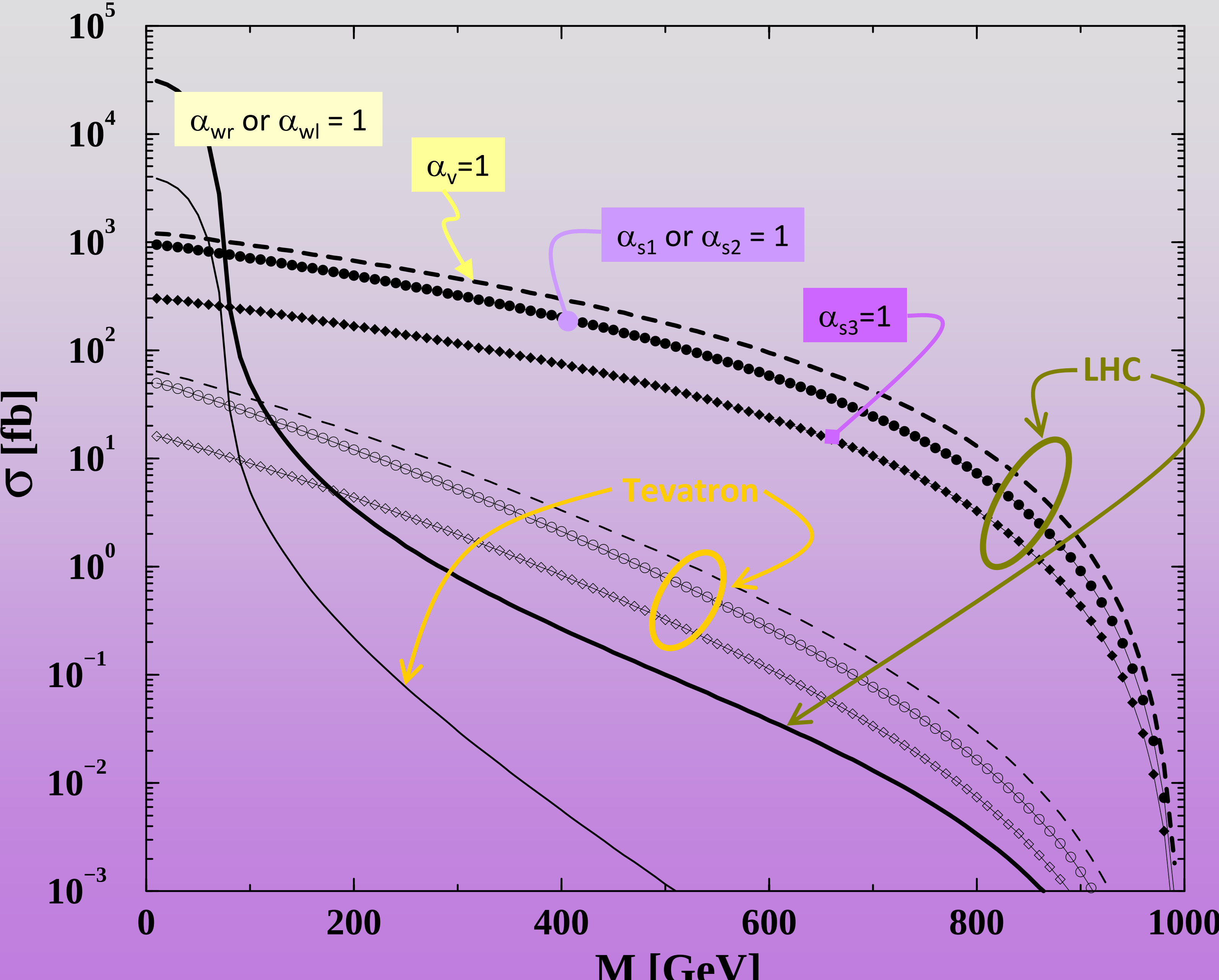
$\theta:\ \ell-u$ (CM) scattering angle

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

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

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

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



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

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

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

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

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

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

Conclusions

- **Standard approach: $N\,l\,W$ coupling suppressed**

- **Merely seeing a few 100 GeV $N \to$ physics beyond N+SM**

- **New physics effects described by**

  Specific models $\to$ valid at all energies

  Effective theories $\to$ valid below Λ

- **Model-independent $\mathcal{L}_{\text{eff}}$ cannot fully distinguish between models …**

$$W' \; or \; \text{leptoquarks} \to (\bar{d}\gamma^\mu u)(\bar{N}\gamma^\mu e)$$

  … but it does estimate the scale.

- **New physics effects can be dramatic, but not as dramatic resonance peaks**