Dirac neutrinos from a second Higgs doublet

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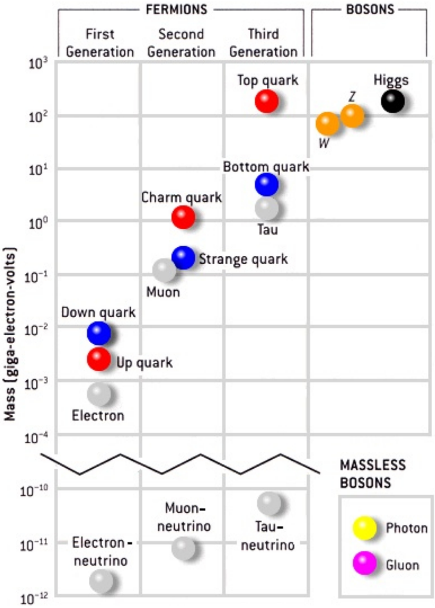
In collaboration with Heather Logan

Problem: Neutrinos are small



Model

Field Content:

$$\text{SM} \quad + \quad \Phi_\nu = \begin{pmatrix} \phi_\nu^+ \\ (v_\nu + \phi_\nu^{0,r} + i\phi_\nu^{0,i})/\sqrt{2} \end{pmatrix} \quad + \quad \nu_{R_i}$$

Symmetry:

	Φ_ν	ν_{R_i}	Everything else
U(1)	$+1$	$+1$	0

$$\mathcal{L}(\Phi_\nu, \nu_{R_i}, X) = \mathcal{L}(\Phi_\nu e^{i(+1)\theta}, \nu_{R_i} e^{i(+1)\theta}, X e^{i(0)\theta})$$

Lagrangian

$$\mathcal{L}_{Yuk} = -y_{ij}^{\ell}\bar{e}_{R_i}\Phi_{SM}^{\dagger}L_{L_j} - y_{ij}^{\nu}\bar{\nu}_{R_i}\tilde{\Phi}_{\nu}^{\dagger}L_{L_j} + \text{h.c.}$$

Lagrangian

$$\mathcal{L}_{Yuk} = -y^{\ell}_{ij}\bar{e}_{R_i}\Phi^{\dagger}_{SM}L_{L_j} - y^{\nu}_{ij}\bar{\nu}_{R_i}\tilde{\Phi}^{\dagger}_{\nu}L_{L_j} + \text{h.c.}$$

$$\begin{aligned} -y^{\nu}_{ij}\bar{\nu}_{R_i}\tilde{\Phi}^{\dagger}_{\nu}L_{L_j} &= -\frac{y^{\nu}_{ij}v_{\nu}}{\sqrt{2}}\bar{\nu}_{R_i}\nu_{L_j} - \frac{y^{\nu}_{ij}}{\sqrt{2}}\phi^{0,r}_{\nu}\bar{\nu}_{R_i}\nu_{L_j} \\ &\quad -i\frac{y^{\nu}_{ij}}{\sqrt{2}}\phi^{0,i}_{\nu}\bar{\nu}_{R_i}\nu_{L_j} + y^{\nu}_{ij}\phi^{+}_{\nu}\bar{\nu}_{R_i}\ell_{L_j} \end{aligned}$$

Lagrangian

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$$M_{\nu} = \frac{y^{\nu}_{ij}v_{\nu}}{\sqrt{2}}$$

Lagrangian

$$\mathcal{L}_{Yuk} = -y^{\ell}_{ij}\bar{e}_{R_i}\Phi^{\dagger}_{SM}L_{L_j} - y^{\nu}_{ij}\bar{\nu}_{R_i}\tilde{\Phi}^{\dagger}_{\nu}L_{L_j} + \text{h.c.}$$

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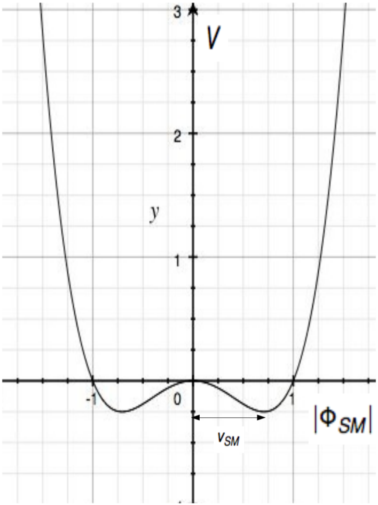
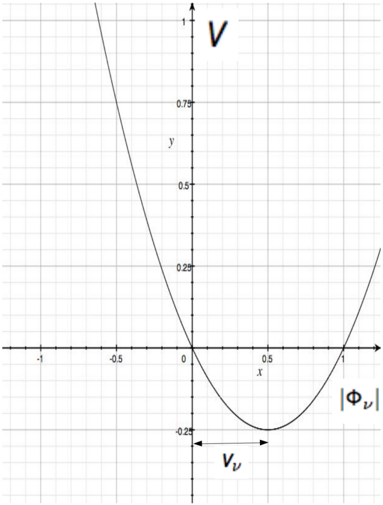
$$M_{\nu} = \frac{y^{\nu}_{ij}v_{\nu}}{\sqrt{2}}$$

$$\begin{aligned} V &= m^2_{11}\Phi^{\dagger}_{SM}\Phi_{SM} + m^2_{22}\Phi^{\dagger}_{\nu}\Phi_{\nu} - \left[m^2_{12}\Phi^{\dagger}_{SM}\Phi_{\nu} + \text{h.c.}\right] \\ &\quad + \frac{1}{2}\lambda_1\left(\Phi^{\dagger}_{SM}\Phi_{SM}\right)^2 + \frac{1}{2}\lambda_2\left(\Phi^{\dagger}_{\nu}\Phi_{\nu}\right)^2 \\ &\quad + \lambda_3\left(\Phi^{\dagger}_{SM}\Phi_{SM}\right)\left(\Phi^{\dagger}_{\nu}\Phi_{\nu}\right) + \lambda_4\left(\Phi^{\dagger}_{SM}\Phi_{\nu}\right)\left(\Phi^{\dagger}_{\nu}\Phi_{SM}\right) \end{aligned}$$

Symmetry breaking





Particles

Dirac neutrinos:

$$\nu_1 \quad \nu_2 \quad \nu_3$$

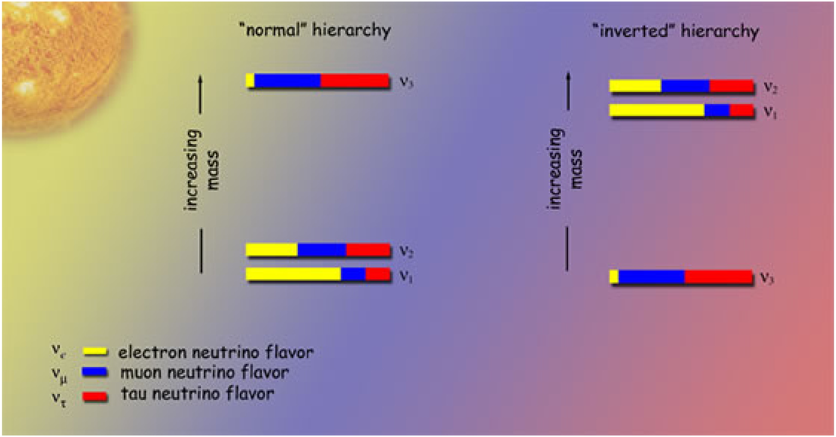
Scalar particles:

$$h \quad H^{\pm} \quad H^0 \quad A^0$$

mixing of order: $\frac{v_\nu}{v_{SM}}$

$$\mathcal{L}_{Yuk} = \frac{m_{\nu_i}}{v_\nu} H^0 \bar{\nu}_i \nu_i - \frac{i m_{\nu_i}}{v_\nu} A^0 \bar{\nu}_i \gamma_5 \nu_i - \sqrt{2} \frac{m_{\nu_i}}{v_\nu} [U^*_{\ell i} H^+ \bar{\nu}_i P_L e_\ell + \text{h.c.}]$$

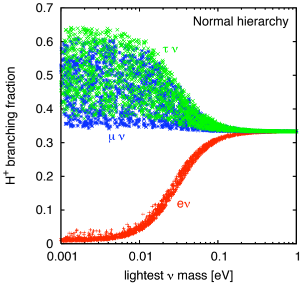
Neutrino mixing



stolen from Berkeley Lab

H^+ decay

$$BR(H^+ \to \ell^+ \nu) = \frac{\sum_i m_{\nu_i}^2 |U_{\ell i}|^2}{\sum_\ell \left[\sum_i m_{\nu_i}^2 |U_{\ell i}|^2\right]}$$



Processes

Signal:

$$pp \rightarrow H^+H^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$$

Background:

$$pp \rightarrow VV \rightarrow \ell^+\nu\ell^-\bar{\nu};\ V = W,\ Z,\ \text{or}\ \gamma$$

$$pp \rightarrow t\bar{t} \rightarrow \ell^+\nu\ell^-\bar{\nu}b\bar{b}$$

Can we find the model at LHC?

Simulate events with MadGraph/MadEvent

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$\downarrow$

Pass events through PYTHIA/PGS

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Apply cuts

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Apply cuts

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Apply k factors to approximate NLO

Can we find the model at LHC?

Simulate events with MadGraph/MadEvent

↓

Pass events through PYTHIA/PGS

↓

Apply cuts

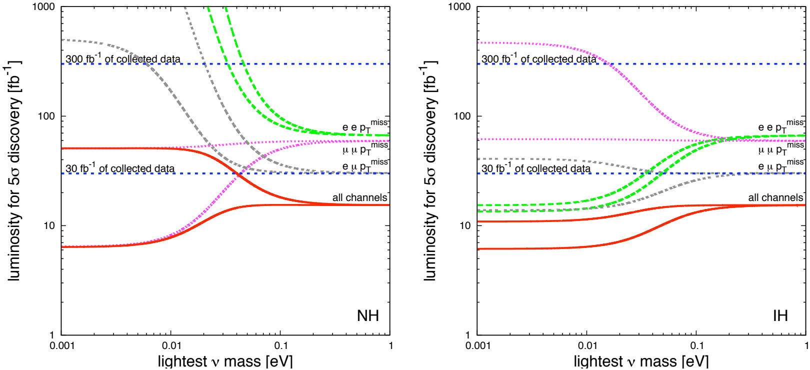
↓

Apply k factors to approximate NLO

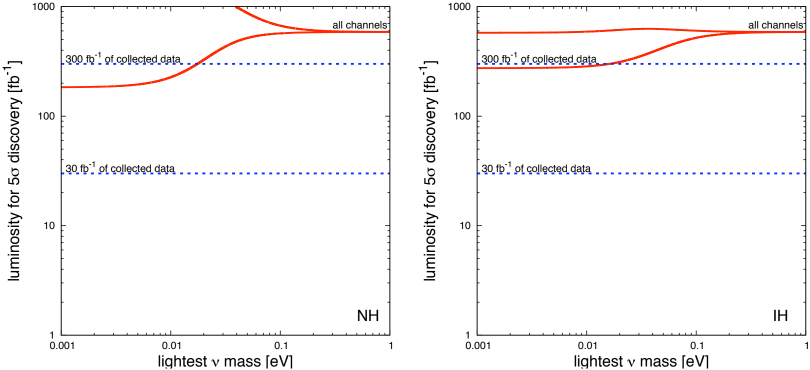
↓

Check the ratio of signal to background

Significance at LHC for $M_{H^+} = 100$ GeV



Significance at LHC for $M_{H^+} = 300$ GeV



Conclusion

- Model explains small neutrino masses
- Has the possibility of being detected at LHC

Cuts

Cut name	Explanation
Basic cuts	Present are a lepton and antilepton, both with $p_\ell > 20$ GeV. Also, $p_T^{miss} > 30$ GeV. For parton level, there is cut applied so that $\|\eta_e\| < 3.0$ and $\|\eta_\mu\| < 2.4$.
Jet veto	Designed to reduce $t\bar{t}$ background, any event with a jet of $p_T^{jet} > 30$ GeV was cut. For parton level, the veto is only applied when $\|\eta_{jet}\| < 5.0$.
Z pole veto	To eliminate events that include $Z \to \ell^+\ell^-$, we veto events with the invariant mass of the two leptons between 80 GeV and 100 GeV (applied only to $e^+e^-p_T^{miss}$ and $\mu^+\mu^-p_T^{miss}$ final state events).
H_T' cut	To eliminate the background mediated by $W/Z/\gamma$, we make use of the mass difference of these particles versus H^+, and also the spin difference of these particles (1) versus H^+ (0). It was found that the best way to accomplish this was to cut on $H_T' \equiv p_T^{\ell^+} + p_T^{\ell^-} + p_T^{miss}$. For $M_{H^+} = 100$ GeV, we require $H_T' > 200$ GeV, and for $M_{H^+} = 300$ GeV, $H_T' > 600$ GeV.

Next-to-leading order (NLO)

$$|\mathcal{M}|^2_{NLO} = |\mathcal{M}_{LO} + \mathcal{M}_{1-loop}|^2 + |\mathcal{M}|^2_{1-jet}$$

$$\sigma_{NLO} = k\sigma_{LO} + \sigma_{1-jet}$$

$$\sigma_{NLO} = m\sigma^{cut}_{LO} + n\sigma^{cut}_{1-jet}$$