New Mechanism for Neutrino Mass Generation and Triply Charged Higgs Boson at the LHC

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In this talk, I present a new mechanism for the generation of neutrino masses via dimension 7 operators: $\ell \ell H H \bar{H}H / M^3$. This leads to new formula for the light neutrino masses, $m_\nu \sim v^4 / M^3$. This is distinct from the usual seesaw formulae: $m_\nu \sim v^2 / M$. The scale of new physics can naturally be at the TeV scale. Microscopic theory that generated $d = 7$ operator has an isospin $3/2$ Higgs multiplet $\Phi$ containing a triply charged Higgs boson with mass around $\sim$ TeV or less. These particles can be produced at the LHC (and possibly at the Tevatron) with distinctive multi-$W$ and multi-lepton final states. For some choice of the parameter space, these particles can also be long-lived with the possibility of displaced vertices, or even escaping the detector. Their leptonic decay modes carry information about the nature of the neutrino mass hierarchy.

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1. Introduction

The existence of neutrino masses is now firmly established. This is the first indication for physics beyond the SM; other indications being the existence of dark matter and baryon asymmetry of the universe. The neutrino mass $m_\nu \sim 10^{-2}$ eV is about a billion times smaller than the quark and charged lepton masses. What is the mechanism for such a tiny neutrino mass generation? The most popular mechanism for generating neutrino masses is the see-saw mechanism $[\mathbb{1}, m_\nu \sim m_3^2/M]$. The corresponding effective interaction in the SM is the dimension 5 operator: $\mathcal{L}_{\text{eff}} = (f/M^3) H H H H$. This implies a new symmetry breaking scale $M$. This scale is too high and no connection can be made to the physics to be explored at the LHC or Tevatron. It is important to explore alternate mechanisms $[\mathbb{2}, \mathbb{3}, \mathbb{4}]$ which can be more directly tested.

It is possible that the dimension 5 operator does not contribute to neutrino masses in a significant way. The next operator (dimension 7) is $\mathcal{L}_{\text{eff}} = (f/M^3) H H H (H^6 H)$. This by itself is not enough to make $M \sim \text{TeV}$ because it requires $f \sim 10^{-9}$. We propose a model in which $f \sim y_1 y_2 \lambda_4$ with each factor $\sim 10^{-3}$ (domain of natural values). This gives $M \sim \text{TeV}$ for neutrino masses in the range $10^{-2} - 10^{-1}$ eV. This will connect the neutrino physics to the physics being explored at the LHC and Tevatron.

2. Model and the formalism

The gauge symmetry in our model is the $SM = SU(3)_c \times SU(2)_L \times U(1)_Y$. In addition to the usual SM fields, there is a pair of vector-like $SU(2)_L$ triplet leptons $\Sigma = \Sigma$ transforming as $(1,3,2)$ and $(1,3,-2)$ where $\Sigma = (\Sigma^{++}, \Sigma^+, \Sigma^0)$, and a new isospin $3/2$ Higgs $\Phi$ with components $(\Phi^{++}, \Phi^+, \Phi^0)$. The $\Phi$ has positive mass squared term, but acquires a tiny VEV through interactions with $H$. The $\Sigma$ has interactions with the SM lepton doublets, $H$, and $\Phi$.

The Higgs potential in our model is given by

$$V = -\mu_H^2 H^\dagger H + M^2_\Phi \Phi^\dagger \Phi + \lambda (H^\dagger H)^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 (H^\dagger H) (\Phi^\dagger \Phi) + \lambda_3 (H^\dagger H) (\Phi^\dagger T_A \Phi) + \lambda_4 (HHH \Phi + \Phi^\dagger H^\dagger H^\dagger H^\dagger).$$

Minimization of $V$ gives $\langle \Phi_0 \rangle \equiv v_\Phi \sim -\lambda_4 v_H^3/M^2_\Phi$.

**Light neutrino mass generation:** The light neutrino masses are generated by combining the following interactions: $\mathcal{L} = y_i l_i H^\dagger \Sigma + \bar{y}_i l_i H^\dagger \Sigma + M_2 \Sigma \Sigma$ where $y_i, \bar{y}_i$ are dimensionless Yukawa couplings. This gives rise to an effective dimension 7 interaction (see Fig. 1),

$$\mathcal{L}_{\text{eff}} = \frac{(y_i \bar{y}_j + y_j \bar{y}_i)}{M_\Sigma} l_i l_j H^* \Phi + h.c., \quad \text{with } v_\Phi = -\lambda_4 v_H^3/M^2_\Phi,$$

with $(y_1, y_2, \lambda_4) \sim 10^{-3}$.

**Mass spectrum of $\Phi$:** The mass spectrum of $\Phi$ is given by $M^2_{\Phi} = M^2_\Phi + \lambda_2 v_H^2 - \frac{1}{2} \lambda_3 I_3 v^2$, where $I_3 = (3/2, 1/2, -1/2, -3/2)$ for $(\Phi^{++}, \Phi^+, \Phi^0)$ respectively. The two possible hierarchies for the spectrum of $\Phi$ are

Positive $\lambda_3 : M_{\Phi^{++}} < M_{\Phi^+} < M_{\Phi^0}$ \hspace{1cm} Negative $\lambda_3 : M_{\Phi^{++}} > M_{\Phi^+} > M_{\Phi^0}$.

**Parameters and existing constraints:** The model parameters are $v_\Phi, M_\Phi, M_\Sigma, \text{and } \Delta M$.

The $\Phi$ has isospin $3/2$ and contributes to the $\rho$ parameter at tree level, $\rho = 1 - (6v_\Phi^2/v_H^2)$. The experimental value is $\rho = 1.00000_{+0.00111}^{-0.0001}$. At the $3\sigma$ level we get $v_\Phi < 2.5$ GeV. The mass
splittings between the components of $\Phi$ induces an additional positive contribution to $\rho$ at one loop level, $\Delta \rho \simeq \frac{5g^2}{6\pi}(\Delta M/m_W)^2$, thus $\Delta M < 38$ GeV.

**Experimental constraints:** A charged $\Phi$ has a mass bound from LEP2 to be $> 100$ GeV [6]. The CDF and D0 Collaborations have looked for stable CHAMPS (charged massive particle). Using CDF cross sections times branching ratio limits, we obtain mass $> 120$ GeV for stable, charged $\Phi^{+++}$ [7].

**Productions:** In hadronic collisions, the triply charged Higgs bosons can be pair produced via the Drell-Yan process. Their cross sections at the Tevatron and the LHC (at 14 TeV) are shown in Fig. 2, where $pp$ or $p\bar{p} \to \Phi^{+++}\Phi^{−−−} \to 6W, 4Wl^+l^+, 4Wl^−l^−$, or $2Wl^+l^−l^−l^−$ with or without displaced vertices, depending on $v_\Phi$.

### 3. Phenomenological Implications

The two possible mass hierarchies of $\Phi$ have $\Phi^{+++}$ as the lightest or heaviest. We consider the case in which $\Phi^{+++}$ is the lightest. The phenomenological implications are most distinctive with displaced vertices for this case.

**Decays:** There are two possible decay modes. The $\Phi^{+++} \to W^+W^+W^+$ mode dominates for higher values of $v_\Phi$. The $\Phi^{+++} \to W^+l^+l^+$ mode dominates for smaller values of $v_\Phi$.

The decay widths into the two modes are shown in Figs. 3 and 4. Note the crossing point is $v_\Phi \sim 0.02$–0.03 MeV. For $M_\Phi = 500$ GeV, $\Gamma < 10^{-12}$ – $6 \times 10^{-14}$ GeV, and we get displaced vertices. For lower masses, widths are even smaller; $\Phi^{+++}$ can escape the detector! For $v_\Phi > 0.2$ MeV, $\Phi^{+++}$ will immediately decay to $W^+W^+W^+$.

**The SM Higgs mass:** The $\Phi$ multiplet with tiny VEV essentially behaves like an inert Higgs [8]. The SM Higgs mass can be raised to $\sim 400$–500 GeV, if $v_\Phi$ is large (few $\sim$ 38 GeV). In that case, $H \to \Phi^{+++}\Phi^{−−−}$.

**Neutrino mass hierarchy:** If the mass of $\Phi^{+++}$ is less than $3m_W$, then $\Phi^{+++} \to W^+l^+l^+$ dominates. This will give rise to $ee, e\mu, \mu\mu$, along with $\tau$’s. Dominance of $e\mu$ will indicate the normal hierarchy for the light neutrino masses, while the dominance of $e\mu$ and $ee$ will indicate the inverted hierarchy.
4. Conclusions

We have presented a new mechanism for neutrino mass generation with a new scale at the TeV. The model links neutrino physics with the physics of the TeV scale to be explored, and can be tested at the LHC.

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References


