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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: $l\,l\,H\,H(H^\dagger H)/M^3$. This leads to new formula for the light neutrino masses, $m_\nu \sim v^4/M^3$. This is distinct from the usual see-saw 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 Φ 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 [1], $m_\nu \sim m_D^2/M$. The corresponding effective interaction in the SM is the dimension 5 operator: $\mathscr{L}_{\text{eff}} = (f/M)\, l\, l\, H\, H$. 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 [2, 3, 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 $\mathscr{L}_{\text{eff}} = (f/M^3)\, l\, l\, H\, H (H^\dagger H)$. This by itself is not enough to make $M \sim$ 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 $M \sim$ 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 $\Sigma + \overline{\Sigma}$ transforming as $(1,3,2)$ and $(1,3,-2)$ where $\Sigma = (\Sigma^{++}, \Sigma^{+}, \Sigma^{0})$, and a new isospin 3/2 Higgs Φ with components $(\Phi^{+++}, \Phi^{++}, \Phi^{+}, \Phi^{0})$. The Φ has positive mass squared term, but acquires a tiny VEV through interactions with H. The Σ has interactions with the SM lepton doublets, H, and Φ.

The Higgs potential in our model is given by

$$\begin{aligned} V = &- \mu_H^2\, H^\dagger H + M_\Phi^2\, \Phi^\dagger \Phi + \lambda (H^\dagger H)^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 (H^\dagger H)(\Phi^\dagger \Phi) \\ &+ \lambda_3 (H^\dagger \frac{t_a}{2} H)(\Phi^\dagger \frac{T_A}{2} \Phi) + \lambda_4 (HHH\Phi + \Phi^\dagger H^\dagger H^\dagger H^\dagger). \end{aligned}$$

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

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

$$\mathscr{L}_{eff} = \frac{(y_i \overline{y}_j + y_j \overline{y}_i)}{M_\Sigma} l_i l_j H^* \Phi + h.c., \quad \text{with } v_\Phi = -\lambda_4 \frac{v_H^3}{M_\Phi^2}, \quad \text{and with } (y_1, y_2, \lambda_4) \sim 10^{-3}.$$

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

Positive $\lambda_3 : M_{\Phi^{+++}} < M_{\Phi^{++}} < M_{\Phi^{+}} < M_{\Phi^{o}}$ Negative $\lambda_3 : M_{\Phi^{+++}} > M_{\Phi^{++}} > M_{\Phi^{+}} > M_{\Phi^{o}}$.

Parameters and existing constraints: The model parameters are v_Φ, M_Φ, M_Σ, and ΔM.

The Φ has isospin 3/2 and contributes to the ρ parameter at tree level, $\rho = 1 - (6 v_\Phi^2 / v_H^2)$. The experimental value is $\rho = 1.0000^{+0.0011}_{-0.0007}$ [5]. At the 3σ level we get $v_\Phi < 2.5$ GeV. The mass

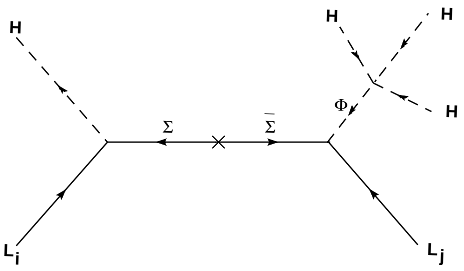

Figure 1: Effective 7 dimensional interaction.

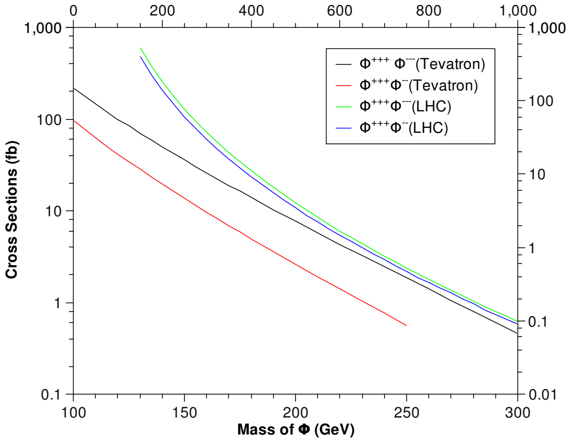

Figure 2: Production cross sections. Use top and right axes for LHC. Use bottom and left axes for Tevatron.

splittings between the components of Φ induces an additional positive contribution to ρ at one loop level, $\Delta\rho \simeq (5\alpha_2/6\pi)(\Delta M/m_W)^2$, thus $\Delta M < 38$ GeV.

Experimental constraints: A charged Φ 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 Φ^{+++} [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 $p\bar{p} \rightarrow \Phi^{+++}\Phi^{---} \rightarrow 6W$, $4Wl^+l^+$, $4Wl^-l^-$, or $2Wl^+l^+l^-l^-$ with or without displaced vertices, depending on v_Φ.

3. Phenomenological Implications

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

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

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, $\Gamma < 10^{-12} - 6\times10^{-14}$ GeV, and we get displaced vertices. For lower masses, widths are even smaller; Φ^{+++} can escape the detector! For $v_\Phi > 0.2$ MeV, Φ^{+++} will immediately decay to $W^+W^+W^+$.

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

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

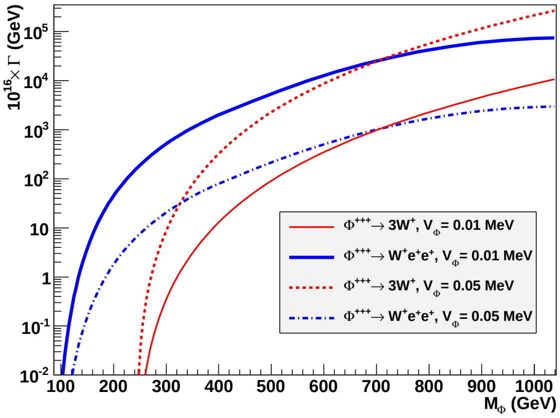

Figure 3: Decay widths as functions of M_Φ.

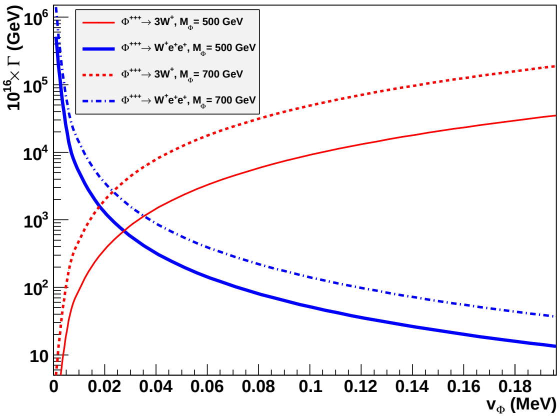

Figure 4: Decay widths as functions of v_Φ.

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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