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New mechanism for neutrino mass generation and triply charged Higgs bosons at the LHC

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We propose a new mechanism for generating small neutrino masses which predicts the relation $m_\nu \sim v^4/M^3$, where v is the electroweak scale, rather than the conventional seesaw formula $m_\nu \sim v^2/M$. Such a mass relation is obtained via effective dimension seven operators $LLHH(H^\dagger H)/M^3$, which arise when an isospin 3/2 Higgs multiplet Φ is introduced along with isotriplet leptons. The masses of these particles are naturally in the TeV scale. The triply charged Higgs boson contained in Φ can be pair produced at the LHC and the Tevatron, with Φ^{+++} decaying into $W^+\ell^+\ell^+$ or $W^+W^+W^+$, possibly with displaced vertices. The leptonic decays of Φ^{+++} will help discriminate between normal and inverted hierarchies of neutrino masses. This scenario also allows for raising the standard Higgs boson mass to values in excess of 500 GeV.

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The existence of small neutrino masses in the range (10^{-2}–10^{-1}) eV has now been firmly established from a variety of neutrino oscillation experiments and serves as the only direct evidence for physics beyond the standard model (SM). A question of fundamental importance is how such tiny masses, many orders of magnitude below their charged fermion counterparts, are generated. The most compelling and popular explanation is the seesaw mechanism [1] which generates neutrino masses via effective dimension five operators $LLHH/M$, where $L = (\nu, e)$ is the lepton doublet, $H = (H^+, H^0)$ is the SM Higgs doublet, and M is the scale of new physics. This leads to the mass relation for light neutrinos $m_\nu \sim v^2/M$, where $\langle H^0\rangle = v$. These operators can arise at tree level by integrating out heavy right-handed neutrinos transforming as (1, 1, 0) under $SU(3)_c \times SU(2)_L \times U(1)_Y$ (type I seesaw), or (1, 3, 2) Higgs bosons (type II seesaw) [2], or (1, 3, 0) fermions (type III seesaw) [3], all with mass of order M. Neutrino oscillation data suggest $M \sim 10^{14}$ GeV, indicating that the associated new physics is likely to be not within reach of colliders. While there are several indirect benefits for the seesaw, especially the one mediated by heavy right-handed neutrinos [unification of all members of a family in $SO(10)$ grand unified theory, leptogenesis], it is difficult to fathom a direct verification of the mechanism. We feel that it is important to explore alternative mechanisms [4–6] which may be more directly tested [7,8].

In this paper we propose a new mechanism for generating tiny neutrino masses at tree level via effective dimension seven operators $LLHH(H^\dagger H)/M^3$. Such operators lead to a new formula for neutrino masses, $m_\nu \sim v^4/M^3$, which is distinct from the standard seesaw formula. Owing to the higher dimensionality of these operators, neutrino mass generation will be more readily accessible to collider experiments in this case. Suppose that the (1, 1, 0) and (1, 3, 0) fermions as well as the (1, 3, 2) Higgs bosons are not present in the fundamental theory. In this case $d = 5$ neutrino mass operators will not be induced. (Such operators may still be induced by Planck scale physics, leading to $m_\nu \sim 10^{-5}$ eV, which are not relevant.) In such a setup, the $d = 7$ operators can be the source of neutrino masses. The simplest realization of this mechanism assumes the existence of an isospin 3/2 Higgs boson $\Phi = (\Phi^{+++}, \Phi^{++}, \Phi^{+}, \Phi^0)$ and a pair of vectorlike fermions transforming as $(1, 3, 2) + (1, 3, -2)$ under the SM gauge symmetry. Φ^0 acquires an induced vacuum expectation value (VEV) via its interactions with the SM Higgs doublet H, inducing small neutrino masses. This new mass generation mechanism has interesting implications for the physics that will be explored at the LHC and the Tevatron, especially in the production and decay of triply charged Higgs boson Φ^{+++}, which can lead to displaced vertices.

Model.—Our model is based on the SM symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$. In addition to the usual fermions, we introduce a pair of vectorlike leptons $\Sigma = (\Sigma^{++}, \Sigma^{+}, \Sigma^0)$ and $\bar\Sigma = (\bar\Sigma^0, \Sigma^-, \Sigma^{--})$ transforming as (1, 3, 2) and (1, 3, −2), respectively, under the gauge group. The Higgs sector consists of an isospin 3/2 multiplet $\Phi = (\Phi^{+++}, \Phi^{++}, \Phi^{+}, \Phi^0)$ (with $Y = 3$), in addition to the SM doublet $H = (H^+, H^0)$. These new states are essential for building renormalizable models for neutrino mass generation via $d = 7$ operators.

Neutrino masses arise in the model from the renormalizable Lagrangian

$$\mathcal{L}_{\nu\text{-mass}} = Y_i L_i H^* \Sigma + \bar Y_i L_i \Phi \bar\Sigma + M_\Sigma \Sigma\bar\Sigma + \text{H.c.}, \quad (1)$$

where Y_i and $\bar Y_i$ are Yukawa couplings and i is the family index. Integrating out the Σ, $\bar\Sigma$ fermions, and using $\langle\Phi^0\rangle \equiv v_\Phi = -\lambda_5 v^3/M_\Phi^2$ (see later), $\langle H^0\rangle \equiv v$, we obtain the neutrino masses to be

$$m^\nu_{ij} = \lambda_5 (Y_i \bar Y_j + Y_j \bar Y_i) v^4/(M_\Sigma M_\Phi^2). \quad (2)$$

The tree-level diagram generating this neutrino mass is shown in Fig. 1. With $(Y_i, \bar Y_i, \lambda_5) \sim 10^{-3}$, which are all

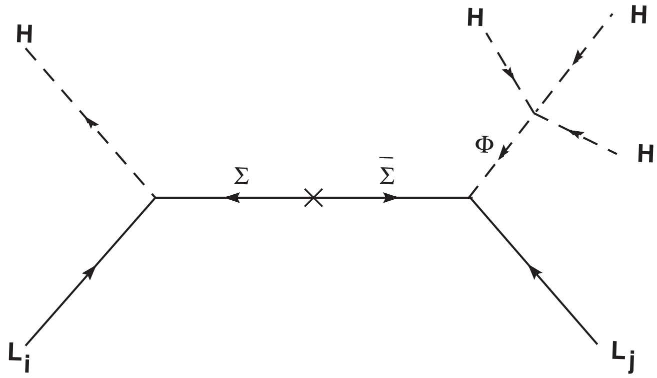

FIG. 1. Tree-level diagram generating dimension 7 seesaw operator for neutrino masses.

in the domain of natural values, we obtain neutrino masses in the $(10^{-2}$–$10^{-1})$ eV range, consistent with neutrino oscillation data, with M_Σ and M_Φ in the TeV scale. While we do not explain the mild hierarchies in these couplings, we note that setting Y_i, $\bar{Y}_i$ or λ_5 to zero will lead to an enhanced symmetry (lepton number), and so choosing these couplings to be small is technically natural. Equation (2) implies that one of the light neutrinos is massless, which is consistent with current data. This feature arises because we integrated a single pair of $\Sigma - \bar{\Sigma}$ fermions. (One can readily add more than one pair of $\Sigma - \bar{\Sigma}$ states, in which case all neutrinos will acquire masses.) Both normal hierarchy and inverted hierarchy of neutrino masses can be realized with Eq. (2). Note that our neutrino mass relation $m_\nu M^3 \sim v^4$ is distinct from the traditional seesaw relation $m_\nu M \sim v^2$. While $d = 5$ neutrino masses are not induced at tree level, they do arise at 1 loop in our model via diagrams which connect two of the H legs in Fig. 1 [9]. We find these finite corrections to be $\Delta m_\nu / m_\nu \sim \frac{3}{64\pi^2} \frac{M^2}{v^2}$, which is $\lesssim 1$ for $M \lesssim 2$ TeV. In the supersymmetry version of our model, the loop diagrams will be further suppressed.

The Higgs potential is given by

$$V = \mu_H^2 H^\dagger H + \mu_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\Phi^\dagger \Phi)^2 + \lambda_3 (H^\dagger H)(\Phi^\dagger \Phi) + \lambda_4 (H^\dagger \tau_a H)(\Phi^\dagger T_a \Phi) + \{\lambda_5 H^3 \Phi^* + \text{H.c.}\}, \quad (3)$$

where τ_a (T_a) are the generators of $SU(2)$ in the doublet (four-plet) representation. We choose, as usual in the SM, μ_H^2 to be negative, so that the vacuum breaks electroweak symmetry. μ_Φ^2 will be chosen positive, yet due to the last term in Eq. (3), the neutral member of Φ will acquire an induced VEV proportional to v^3. Specifically, we have $v = (-\mu_H^2/\lambda_1)^{1/2}$, $v_\Phi = -\lambda_5 v^3 / M_\Phi^2$, where $M_\Phi^2 = \mu_\Phi^2 + \lambda_3 v^2 + \frac{3}{4}\lambda_4 v^2$ is the mass of the neutral member Φ^0. (These expressions ignore small corrections proportional to v_Φ^2.) The mass splittings between the members of Φ are given by

$$M_i^2 = M_\Phi^2 - q_i \frac{\lambda_4}{4} v^2, \quad (4)$$

where q_i is the (non-negative) electric charge of the respective Φ_i field. We see that the mass splittings are equally spaced and that there are two possible mass orderings. For λ_4 positive, we have the ordering $M_{\Phi^{+++}} < M_{\Phi^{++}} < M_{\Phi^{++}} < M_{\Phi^0}$, while for λ_4 negative, this ordering is reversed. We define a (small) splitting parameter $\Delta M^2 \equiv (\lambda_4/4)v^2$.

The important phenomenological parameters of the model are v_Φ, ΔM, M_Φ and M_Σ. In this paper, for simplicity, we shall assume that the triplet fermions $\Sigma + \bar{\Sigma}$ have masses beyond the reach of the LHC, and focus on the signatures of the Higgs bosons from Φ. We shall explore the entire range of 100 GeV to 1 TeV for M_Φ. As discussed, the VEV v_Φ can naturally be in the sub-MeV range for M_Φ, M_Σ in the TeV range. $v_\Phi \neq 0$ modifies the tree-level relation for the electroweak ρ parameter, which is now $\rho \simeq 1 - (6v_\Phi^2/v^2)$. Comparing with the experimental constraint of $1.0000 + 0.0011(-0.0007)$ on ρ [10], we obtain, at 3σ level, $v_\Phi < 2.5$ GeV. The mass splittings between the components of Φ will induce an additional positive contribution to ρ, given by $\Delta\rho \simeq (5\alpha_2)/(6\pi)(\Delta M/m_W)^2$ [11]. This sets an upper limit of $\Delta M < 38$ GeV for the splitting parameter. There is also a theoretical lower limit of $\Delta M > 1.4$ GeV, arising from (the finite parts) of electroweak corrections [12] which we shall comply with. (This is actually a naturalness lower limit, since these corrections are not finite, with the infinity absorbed in the renormalization of λ_4.) There are experimental lower limits on the masses of Φ, $M_\Phi > 100$ GeV [13] for a charged Φ from LEP2, and $M_\phi > 120$ GeV for a stable charged Φ from the Tevatron [14].

Gauge interactions of Φ, relevant for its production and decay, are contained in $\mathcal{L}_{\text{kinetic}} = (D^\mu \Phi)^\dagger (D_\mu \Phi)$, where $D_\mu \Phi = (\partial_\mu - i g T_a W_\mu^a - i g' \frac{Y}{2} B_\mu)\Phi$.

Decay of Φ.—Focusing on the case where Φ^{+++} is the lightest among the Φ's, Φ^{+++} has two principal decay modes: $\Phi^{+++} \to W^+ W^+ W^+$ and $\Phi^{+++} \to W^+ \ell^+ \ell^+$. These decays arise through the diagrams where Φ^{+++} emits a real W^+ and an off-shell Φ^{++} which subsequently decays to either two real W^+, or two same-sign charged leptons. The relevant couplings are $\Phi^{+++}\Phi^{--}W^-$:$\sqrt{3/2} g (p_1 - p_2)_\mu$; $\Phi^{++}W^-W^-$:$\sqrt{3} g^2 v_\Phi$; $\Phi^{++}\ell_i^- \ell_j^-$:$m_{ij}^\nu/(2\sqrt{3} v_\Phi)$. The decay rates are found to be

$$\Gamma(\Phi^{+++} \to 3W) = \frac{3g^6}{2048\pi^3} \frac{v_\Phi^2 M_\Phi^5}{m_W^6} I,$$
$$\Gamma(\Phi^{+++} \to W^+ \ell^+ \ell^+) = \frac{g^2}{6144\pi^3} \frac{M_\Phi \sum_i m_i^2}{v_\Phi^2} J, \quad (5)$$

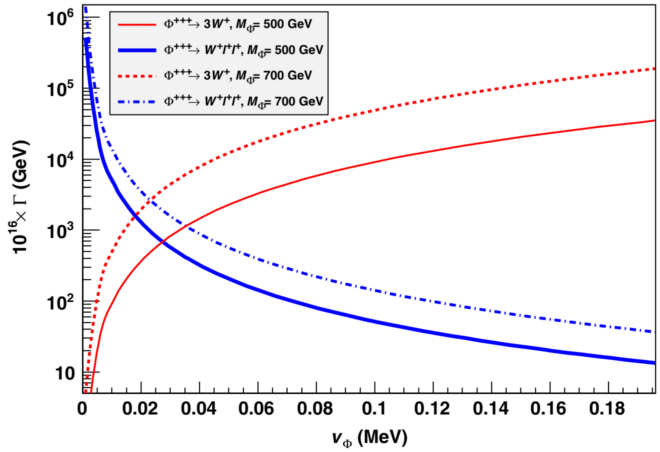

FIG. 2 (color online). Decay widths $\Gamma(\Phi^{+++} \to 3W^+)$ (red) and $\Gamma(\Phi^{+++} \to W^+\ell^+\ell^+)$ (blue) versus v_Φ. Solid lines correspond to $M_{\Phi^{+++}} = 500$ GeV, and dashed curves to $M_{\Phi^{+++}} = 700$ GeV.

where I and J are dimensionless integrals ($\simeq 1$ for $M_\Phi \gg m_W$). In Eq. (5), m_i stand for the light neutrino masses, and all flavors of leptons have been summed. For our numerical evaluation we have adopted the normal hierarchy of neutrino masses with $m_3 = 0.05$ eV. For the inverted hierarchy spectrum the leptonic widths must be multiplied by a factor of 2.

The exact results for the partial decay widths in the $W^+W^+W^+$ mode and $W^+\ell^+\ell^+$ mode are shown in Fig. 2 as a function of v_Φ for $M_\Phi = 500$ and 700 GeV. The same is shown in Fig. 3 as a function of M_Φ for $v_\Phi = 0.01$ and 0.05 MeV. The two widths are equal at $v_\Phi \sim 0.03$ MeV for $M_\Phi = 500$ GeV. For widths 10^{-12} GeV or smaller, Φ^{+++} will travel at least 0.2 mm, and thus will produce a displaced vertex in the detector. For $M_\Phi = 500$ GeV, the width for the WWW mode equals 10^{-12} GeV for $v_\Phi = 0.1$ MeV, whereas for the $W^+\ell^+\ell^+$ mode, this happens for $v_\Phi = 0.005$ MeV. Thus a 500 GeV Φ^{+++} will produce displaced vertex in the detector for a v_Φ range of 0.005–0.1 MeV. For heavier (lighter) Φ^{+++}, this range in v_Φ is smaller (larger). A few hundred GeV Φ^{+++} can travel as much as a meter in the detector before it decays.

Φ^{++} has three principal decay modes: $\Phi^{++} \to W^+W^+$, $\ell^+\ell^+$, $\Phi^{+++}W^{-*}$, and $\Phi^{+++}\pi^-$. The first two decay rates depend on the value of v_Φ, while the remaining two depend crucially on the value of ΔM. The final states are WW, two same-sign charged leptons, $WWWW^*$ or $WWW\pi$. For the singly charged Higgs Φ^+ (which mixes weakly with the SM Higgs), decay modes are $\Phi^+ \to \Phi^{++}W^{-*}$ and $\Phi^{++}\pi^-$, with the subsequent decays of Φ^{++} as above. Thus the final states will be WWW^*, $WWWW^*W^*$, $\ell^+\ell^+W^*$, and so on. Finally for the neutral component, Φ^0 (which also mixes weakly with the SM Higgs), the final state decay products can have as many as six W's ($WWWW^*W^*W^*$), or a combination of W's and charged multileptons.

Production of Φ.—At the Tevatron and the LHC, $\Phi^{+++}\Phi^{--}$ and $\Phi^{++}\Phi^{---}$ will be pair produced via s-channel W^+ and W^- exchanges, while $\Phi^{+++}\Phi^{---}$ will be pair produced via the s-channel γ and Z exchanges. The $\Phi^{+++}\Phi^{---}Z$ coupling is $-(3e\cos 2\theta_W/\sin 2\theta_W) \times (p_1 - p_2)_\mu$, while the $\phi^{+++}\phi^{--}W^-_\mu$ vertex is $\sqrt{3/2}g(p_1 - p_2)_\mu$. The cross sections for $\Phi^{+++}\Phi^{--}$ production at the LHC (pp, $\sqrt{s} = 14$ TeV) and Tevatron ($p\bar{p}$, $\sqrt{s} = 2$ TeV) are shown in Fig. 4 as a function of the mass. We have taken the masses of Φ^{+++} and Φ^{--} to be the same. (The cross section for $\Phi^{++}\Phi^{---}$ production is approximately a factor of 5 smaller at the LHC.) At the

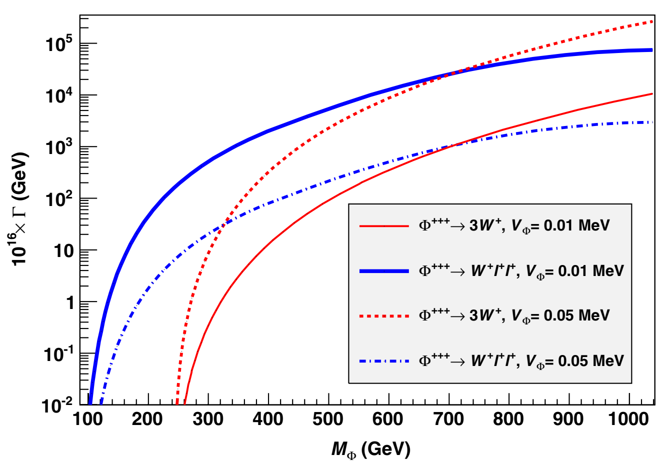

FIG. 3 (color online). Decay widths $\Gamma(\Phi^{+++} \to 3W^+)$ (red) and $\Gamma(\Phi^{+++} \to W^+\ell^+\ell^+)$ (blue) versus M_Φ. Solid lines correspond to $v_\Phi = 0.01$ MeV, and dashed curves to $v_\Phi = 0.05$ MeV.

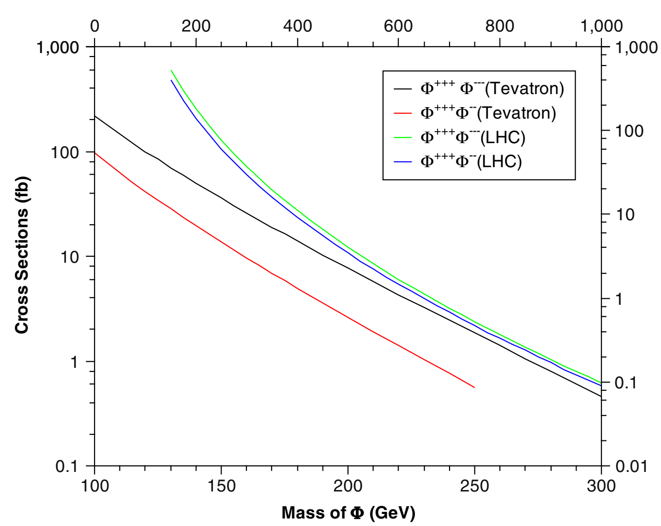

FIG. 4 (color online). Cross sections for Φ production. The top horizontal and the right vertical axes are for the LHC (pp, $\sqrt{s} = 14$ TeV), whereas the bottom horizontal and the left vertical axes are for the Tevatron ($p\bar{p}$, $\sqrt{s} = 2$ TeV).

LHC, for a mass of 500 GeV, the $\Phi^{+++}\Phi^{--}$ production cross section is about 5 fb, while it increase to about 60 fb for a mass of 250 GeV. For v_Φ in the range of 0.005–0.1 MeV, this will produce very distinctive events with displaced vertices and five W's in the final state. For very small values of v_Φ, the decay mode $\Phi^{+++} \to W^+\ell^+\ell^+$ will dominate, with the final state being $W^+\ell^+\ell^+\ell^-\ell^-$, possibly with a displaced vertex. Such events are not expected in the SM, and will be a clear signal for new physics. For the Tevatron, the cross sections are much smaller; however, there may still be such observable events. For example, for a Φ mass of 200 GeV, the cross section is about 2.6 fb corresponding to such displaced vertex events.

The cross sections for the $\Phi^{+++}\Phi^{---}$ production are also shown in Fig. 4. At the LHC, for a mass of 500 GeV, the $\Phi^{+++}\Phi^{---}$ production cross section is about 4 fb, while it increases to about 77 fb for a mass of 250 GeV. The final states from these processes will produce $6W$ or $2W$ plus four charged leptons. If v_Φ is ≤ 0.005 MeV, the final state with $2W$ plus four charged leptons will dominate. The SM background for such events will be negligible. For v_Φ in the range of $\sim$0.005–0.1 MeV, both $6W$, and $2W$ plus 4 charged lepton final states will compete. However, both final states will have displaced vertices very distinctive of new physics. For $v_\Phi > 0.1$ MeV, a $6W$ ($W^+W^+W^+W^-W^-W^-$) final state will dominate. Leptonic decays of any two same-sign W's will produce same-sign charged dileptons with high p_T, with the final state having 8 high p_T jets in addition (from the decays of the other four W's). This will serve to reduce the SM background severely, making the signal observable above the background. Thus our model can be tested in the entire v_Φ range. It is also possible that the lifetimes are so long that Φ^{+++} and Φ^{---} escape the detectors. This will produce two tracks in the detectors characteristic of heavy triply charged particles. If v_Φ is much larger, there will be no displaced vertex, but the final states with multi-W and multileptons will be very distinctive. The cross sections for the $\Phi^{+++}\Phi^{---}$ production for the Tevatron are also shown in Fig. 4. These are somewhat larger than the $\Phi^{+++}\Phi^{--}$ production cross section. Both the D0 and the CDF experiments have looked for long-lived charged massive particles which escape their detectors. Using the CDF upper limit on the cross sections we get a lower limit on such a long-lived Φ^{+++} mass of $\sim$120 GeV [14].

The cross section for $\Phi^{++}\Phi^{-}$, for the same mass, is larger by a factor (4/3) compared to that of $\Phi^{+++}\Phi^{--}$ because of slightly larger coupling, whereas the $\Phi^{++}\Phi^{--}$ pair production cross section is significantly smaller than that for $\Phi^{+++}\Phi^{---}$. However, if the masses are small enough so that they are significantly produced, the final states are very distinctive from their chain decays. For example, pair production and subsequent decays lead to $\Phi^{+++}\Phi^{---} \to 6W$, $\Phi^{++}\Phi^{--} \to 8W$, $\Phi^{+}\Phi^{-} \to 10W$, and $\Phi^0 A^0 \to 12W$ (A^0 being the neutral pseudoscalar), where some of the W's are off-shell. These are events with high charged lepton, or lepton plus jet multiplicity, all with high p_T, and are not expected in the SM.

We conclude by making a few observations. (i) The isospin $3/2$ Higgs multiplet Φ with a tiny VEV essentially behaves like the inert Higgs [15]. SM Higgs boson (H) mass can easily be raised to the range 400–600 GeV in our model. The positive correction to the ρ parameter proportional to ΔM, along with small corrections to the S parameter, weakens the usual bound of 185 GeV on the H mass. (ii) Our model makes very interesting connections between the neutrino mass hierarchy and collider physics. If the mass of the $\Phi^{+++} < 3M_W$, then the decay mode $\Phi^{+++} \to W^+\ell^+\ell^+$ will dominate, leading to final states with ee, $e\mu$ or $\mu\mu$ (along with τ's). The dominance of $\mu\mu$ events will indicate normal hierarchy, while that of $e\mu$ (ee) will indicate inverted hierarchy corresponding to relative CP parity of the two heavier states being odd (even). Since CP symmetry is broken by the Majorana phases, these decay modes can be used to measure these phases (see the first paper of Ref. [7]). (iii) The isospin $3/2$ Higgs representation can be readily embedded into the 35-dimensional representation of $SU(5)$ grand unified theory. (iv) It may be possible to lower the scale of neutrino mass generation further by using effective operators with dimensions larger than 7. However, forbidding the $d = 5$ and other lower dimensional operators will be nontrivial in this case (needing possibly additional *ad hoc* symmetries), and would make the model somewhat more complicated. In a forthcoming paper [16] we plan to present a detailed analysis of the various observations made here.

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