New Mechanism for Neutrino Mass Generation and triply charged Higgs boson at the LHC

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Goals

- To provide a new mechanism for light neutrino mass generation with new mass scale at the TeV.
- To connect the neutrino physics with the physics that can be explored at the LHC, even possibly at the Tevatron.
- Explore new signals for Higgs bosons

Outline of Talk

- Introduction
- Model and the Formalism
- Phenomenological Implications
- Conclusions and Outlook

Introduction

- The existence of neutrino masses are now firmly established. $m_\nu \sim 10^{-2}$ eV $\Rightarrow$ 1st and only indication for physics beyond the SM
- m_ν is about a billion times smaller the quark and charged lepton masses
- What is the mechanism for such a tiny neutrino mass generation?

Introduction

- Most popular mechanism : see-saw, $m_\nu \sim \frac{m_D^2}{M}$
  $\Rightarrow$ dimension 5 operator: $L_{eff} = \frac{f}{M}\, l\, l\, H\, H$

  The observed neutrino mass, $m_\nu \sim 10^{-2}$ eV.

- If $M = M_{PL}$, then m_ν is too small

- If $M = M_{GUT}$, then m_ν is still too small

- $M \sim 10^{14}$ GeV is needed
  $\rightarrow$ A new symmetry breaking scale (N_R)

- This scale is too high $\rightarrow$ No connection can be made to the physics to be explored at the LHC or Tevatron
  $\Rightarrow$ need $M \sim$ TeV.

- It is possible the dim. 5 operator does not contribute to neutrino masses in a significant way.
  $\Rightarrow$ next operator (dim. 7) : $L_{eff.} = \frac{f}{M^3} llHH(H^\dagger H)$

- This by itself is not enough to make $M \sim$ TeV, need $f \sim 10^{-9}$.

- We propose a model in which $f \sim y_1 y_2 \lambda_4$ with each $\sim 10^{-3}$ (domain of natural values)

- This gives $M \sim$TeV scale to obtain neutrino masses in the range $10^{-2} - 10^{-1}$ eV.
  $\Rightarrow$ connect to physics at the LHC and Tevatron.

Model & Formalism

- Gauge Symmetry : $SM = SU(3)_c \times SU(2)_L \times U(1)_Y$

- Usual SM model fermions,
  $+$ a pair of vector-like $SU(2)_L$ triplet leptons transforming as $(1, 3, 2)$ and $(1, 3, -2)$, $\Sigma + \bar{\Sigma}$, $\Sigma = (\Sigma^{++}, \Sigma^{+}, \Sigma^{0})$,
  $+$ a new isospin $\frac{3}{2}$ Higgs, Φ, $\Phi = (\Phi^{+++}, \Phi^{++}, \Phi^{+}, \Phi^{0})$

- Φ has positive mass square, but acquires a tiny VEV through Higgs potential via interaction with H.

- Σ has interactions with SM lepton doublets, H as well as Φ.

- Higgs Potential

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

- Minimization of $V \Rightarrow \langle \Phi_0 \rangle \equiv v_\Phi \sim -\lambda_4 \frac{v_H^3}{M_\Phi^2}$

Light neutrino mass generation:

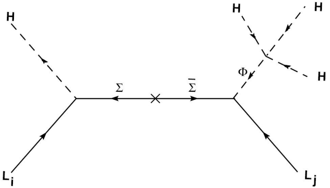
- $L = y_i l_i H^* \Sigma + \bar{y}_i l_i \Phi \bar{\Sigma} + M_\Sigma \Sigma \bar{\Sigma}$
  $y_i, \bar{y}_i \Rightarrow$ dimensionless Yukawa couplings.
- $\rightarrow L_{eff} = \frac{(y_i \bar{y}_j + y_j \bar{y}_i)}{M_\Sigma} l_i l_j H^* \Phi + h.c.$

  with $v_\Phi = -\lambda_4 \frac{v_H^3}{M_\Phi^2}$

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

  $\Rightarrow$ This is the dimension 7 neutrino mass generation mechanism with Φ replaced by HHH/M_Φ^2.

- $m_\nu \sim 10^{-2} - 10^{-1}$ eV range with M_Σ and M_Φ at the TeV scale.



- Mass Spectrum of Φ

$$M^2_{\Phi_i} = M^2_\Phi + \lambda_2 v_H^2 - \frac{1}{2}\lambda_3 I_{3i} v^2,$$

where $I_{3i} = (3/2, 1/2, -1/2, -3/2)$ for $(\Phi^{+++}, \Phi^{++}, \Phi^{+}, \Phi^{0})$ respectively.

- Two possible hierarchies for the spectrum of Φ
Positive λ_3 : $M_{\Phi^{+++}} < M_{\Phi^{++}} < M_{\Phi^{+}} < M_{\Phi^{o}}$
Negative λ_3 : $M_{\Phi^{+++}} > M_{\Phi^{++}} > M_{\Phi^{+}} > M_{\Phi^{o}}$.

- Note that the mass square difference, ΔM^2 among consecutive components are the same, and is equal to $(1/2)\lambda_3 v_H^2$.

Relevant parameters in our model and existing constraints:

- Parameters : v_Φ, ΔM, M_Φ, M_Σ (ΔM = mass splitting)
- v_Φ : Φ has isospin 3/2, contribute to ρ parameter at the the tree level. $\rho = 1 - (6v_\Phi^2/v_H^2)$. Experiment: $\rho = 1.0000^{+0.0011}_{-0.0007}$, At 3σ level $v_\Phi < 2.5$ GeV.
- The mass splittings between the components of Φ induces an additional positive contribution to ρ at one loop level, $\Delta\rho \simeq (5\alpha_2)/(6\pi)(\Delta M/m_W)^2$. $\Rightarrow \Delta M < 38$ GeV .
- There is also a theoretical lower limit on ΔM arising from the radiative correction at the one loop $\Rightarrow \Delta M \geq 1.4 GeV$ for $M_\Phi \sim 1$ TeV
  (This is actually a naturalness lower limit, since these corrections are not finite, with the infinity absorbed in the renormalization of λ_4.)

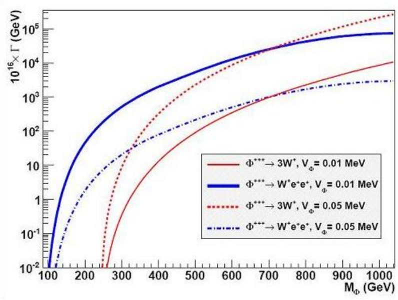
Experimental constraints

- Mass of Φ: LEP2: $>$ 100 GeV for charged Φ,
- CDF and D0 Collaborations have looked for stable CHAMPS (charged massive particle).
- Using CDF cross sections times branching ratio limits, we obltain
  $>$ 120 GeV for stable, charged Φ^{+++}

Phenomenological Implications

- Decays of Φ's in the model
- Production
- Signals
- Other implications
- Two possible scenarios: Φ^{+++} lightest or Φ^{+++} heaviest. Consider the case in which Φ^{+++} lightest
  $\Rightarrow$ phenomenological implications most distinctive with displaced vertices.

A. Decays



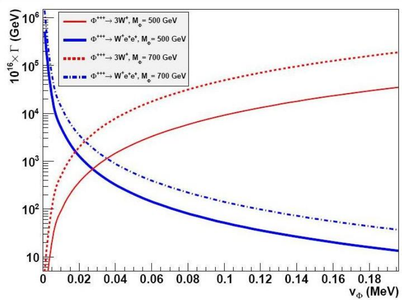
- Two possible decay modes

  $\Phi^{+++} \rightarrow W^+W^+W^+$

  $\Phi^{+++} \rightarrow W^+l^+l^+$

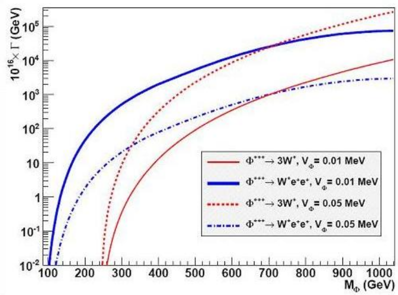
- $W^+W^+W^+$ mode dominate for higher values of v_Φ

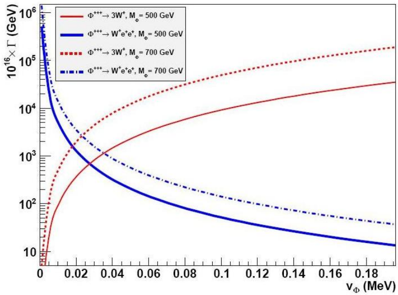
- $W^+l^+l^+$ dominate for smaller values of v_Φ



A. Decays

- Crossing point:
  $v_\Phi \sim 0.02 - 0.03$ MeV.
- For $v_\Phi \sim 0.02 - 0.03$ MeV,
  for $M_\Phi = 500$ GeV,
  $\Gamma < 10^{-12} - 6x10^{-14}$ GeV
  $\Rightarrow$ Displaced Vertices.
- For lower masses, widths are even smaller $\rightarrow \Phi^{+++}$ can escape the detector !!
- For $v_\Phi > 0.2$ MeV, Φ^{+++} will immediately decay to $W^+W^+W^+$.

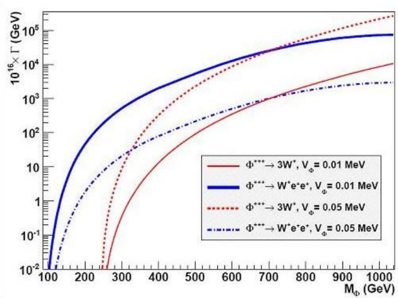


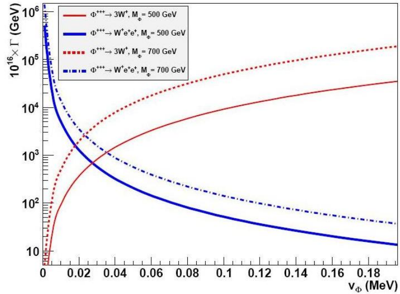


Phenomenological Implications

Test of the model

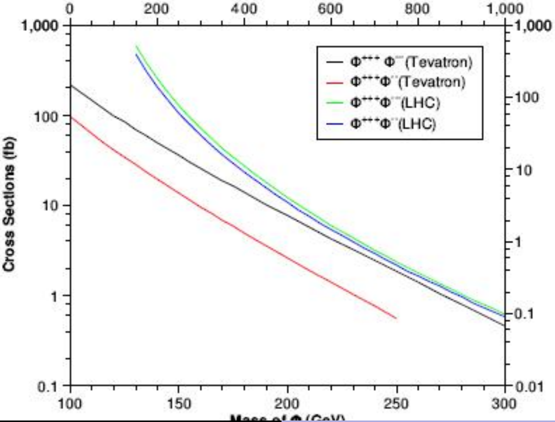
- for $v_\Phi > 0.05$ MeV, $\Phi^{+++} \to W^+W^+W^+$
- For $v_\Phi \sim 0.01 - 0.06$ MeV, $\Phi^{+++} \to W^+W^+W^+$, or $\Phi^{+++} \to W^+l^+l^+$ with displaced vertices
- For $v_\Phi < 0.01$ MeV, $\Phi^{+++} \to W^+l^+l^+$ with no displaced vertices





B. Productions

- pp or $p\bar{p} \to \Phi^{+++}\Phi^{---} \to 6W$ or $4Wl^{+}l^{+}$, $4Wl^{-}l^{-}$ or $2Wl^{+}l^{+}l^{-}l^{-}$ with or wthout displaced vertices depending on v_{Φ}.



Phenomenological Implications

- With displaced vertices, only few events are needed.
- LHC Reach (with displaced vertices)
  with 1 inverse fb, $\sim$ 400 GeV
  with 10 inverse fb, $\sim$ 650 GeV
  with 100 inverse fb, $\sim$ 1 TeV
- LHC Reach (without displaced vertices)
  with 1 inverse fb, $\sim$ 250 GeV
  with 10 inverse fb, $\sim$ 400 GeV
  with 100 inverse fb, $\sim$ 800 GeV

C. Other Implications

- Φ multiplet with tiny VEV essentially behaves like an innert Higgs
  $\Rightarrow$ SM Higgs mass can be raised to $\sim 400 - 500$ GeV if v_Φ is large $\sim$ few - 38 GeV.
  In that case, $H \to \Phi^{+++}\Phi^{---}$

- Neutrino mass hierarchy
  If mass of $\Phi^{+++} < 3W$, then $\Phi^{+++} \to W^+ l^+ l^+$ dominate
  $\Rightarrow$ ee, $e\mu$, $\mu\mu$, along with τ's.
  Dominance of $\mu\mu \to$ Normal Hierarchy
  Dominance of $e\mu$ (ee) $\Rightarrow$Inverted Hierarchy

Conclusions

- Presented a new mechanism for the generation of neutrino masses
- via dimension 7 operators: $\frac{1}{M^3} llHH(H^\dagger H)$
- Leads to new formula for the light neutrino masses : $m_\nu \sim \frac{v^4}{M^3}$
- This is distinct from the usual see-saw formulae : $m_\nu \sim \frac{v^2}{M}$
- Scale of new physics can be naturally at the TeV scale

Conclusions (continued)

- Microscopic theory that generated $d = 7$ operator has an isospin $3/2$ Higgs multiplet Φ containing triply charged Higgs boson with mass around $\sim$ TeV or less.
- Can be produced at the LHC (and possibly at the Tevatron)
- Distinctive multi-W and multi-lepton final states
- Can be long-lived with the possibility of displaced vertices, or even escaping the detector
- Leptonic decay modes carry information about the nature of neutrino mass hierarchy