Neutrino-LHC Connection and Triply Charged Higgs Boson

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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 physcis 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 $m_\nu \sim 10^{-2}$ eV $\sim \frac{m_D^2}{M}$
  $\longrightarrow$ dimension 5 operator: $L_{eff} = \frac{f}{M}\, l\, l\, H\, H$
- 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
  $\longrightarrow$ 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
  $\longrightarrow$ need $M \sim$ TeV.

Introduction

- It is possible the dim. 5 operator does not contribute to neutrino masses in a significant way.
  $\longrightarrow$ 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 $\sim 10^{-3} \longrightarrow M \sim$ TeV.
- This gives $M \sim$TeV scale $\longrightarrow$ 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,
  $+$ vector-like $SU(2)_L$ triplet lepton ,
  $\Sigma + \bar{\Sigma}, \ \Sigma = (\Sigma^{++}, \Sigma^{+}, \Sigma^{0})$.
  $+$ 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.

Model & Formalism

- Higgs Potential

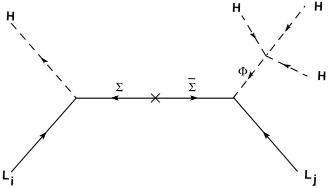
$$\begin{aligned} V = & -\mu_H^2\, H^\dagger H + M_\Phi^2\, \Phi^\dagger \Phi \\ & + \lambda (H^\dagger H)^2 + \lambda_1 (\Phi^\dagger \Phi)^2 \\ & + \lambda_2 (H^\dagger H)(\Phi^\dagger \Phi) \\ & + \lambda_3 (H^\dagger \frac{t_a}{2} H)(\Phi^\dagger \frac{T_A}{2} \Phi) \\ & + \lambda_4 (HHH\Phi + \Phi^\dagger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

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

Model & Formalism

Light neutrino mass generation:

- $L = \bar{y}_i l_i \Phi \bar{\Sigma} + y_i l_i H^* \Sigma + M_\Sigma \Sigma \bar{\Sigma}$
  $y_i, \bar{y}_i \longrightarrow$ dimensionless Yukawa couplings.
- $\longrightarrow L_{eff} = \frac{y_i \bar{y}_j}{M_\Sigma} l_i l_j \Phi H^* +$ h.c.
  with $v_\Phi = -\lambda_4 \frac{v_H^3}{M_\Phi^2}$
  $\Rightarrow m_\nu = \frac{\lambda_4}{2}(y_i \bar{y}_j + \bar{y}_i y_j) \frac{v_H^4}{M_\Sigma M_\Phi^2}$
  with $(y_1, y_2, \lambda_4) \sim 10^{-3}$,
- $m_\nu \sim 10^{-2}$ eV with M_Σ and M_Φ at the TeV scale.



Model & Formalism

- Mass Spectrum of Φ

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

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

- 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 $(1/2)\lambda_3 v_H^2$.

Model& and the Formalism

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. $\rho = 1 - (6 v_\Phi^2 / v_H^2)$. Experiment: $\rho = 1.0000^{+0.0011}_{-0.0007}$, At 3σ level $v_\Phi < 2.5$ GeV.
- The lower limit on ΔM arises from the radiative correction at the one loop. $\rightarrow \Delta M \geq 1.4 GeV$ for $M_\Phi \sim 1$ TeV
- Also $\Delta M < 38$ Gev from the contribution of Φ to the ρ parameter at the one loop level.
- Mass of Φ: LEP2: > 100 GeV for charged Φ,
  CDF: > 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.

Phenomenological Implications

A. Decays

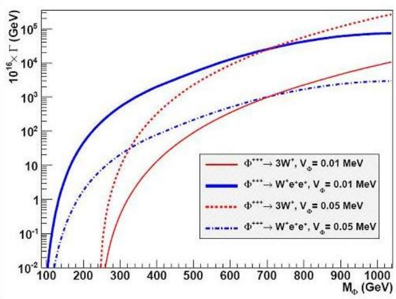
- Two possible decay modes

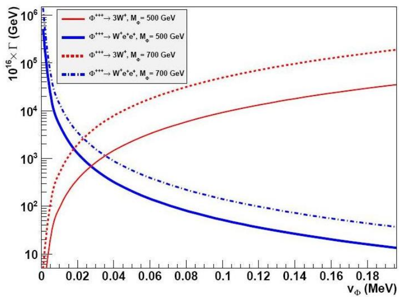
  $\Phi^{+++} \rightarrow W^+W^+W^+$

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

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

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

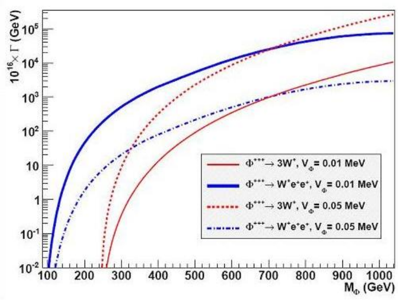


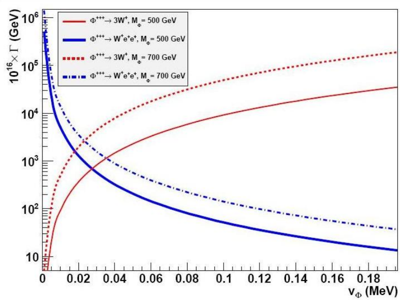


Phenomenological Implications

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 $W^+W^+W^+$.

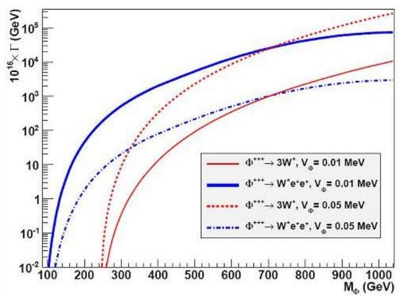


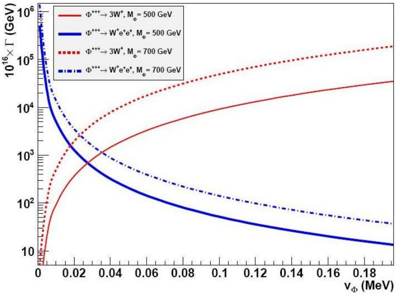


Phenomenological Implications

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

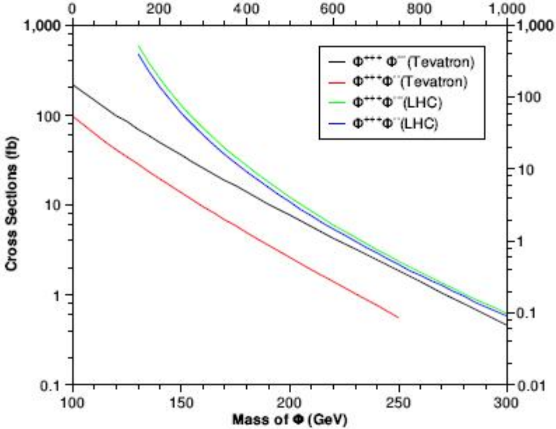




Phenomenological Implications

B. Productions

- pp or $p\bar{p} \longrightarrow \Phi^{+++}\Phi^{---} \longrightarrow 6W$ or $4Wl^+l^+$ or $Wl^+l^+l^+l^+$ 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

Phenomenological Implications

B. Productions of heavier states

- $\Phi^{+++}\Phi^{---} \to 6W \to 12$ jets with high p_T
- $\Phi^{++}\Phi^{--} \to 8W \to 16$ jets with high p_T
- $\Phi^{+}\Phi^{-} \to 10W \to 20$ jets with high p_T
- $\Phi^{0}\Phi^{0} \to 12W \to 24$ jets with high p_T or lesser number of jets with high p_T and Charged leptons.

Other Phenomenological Implications

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, $H \rightarrow \Phi^{+++}\Phi^{---}$

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