

A New Model for the Neutrino Mass: Triply Charged Higgs Boson at the LHC

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arXiv: 0905.xxxx[hep-ph]

Talk at PHENO 09, Madison, Wisconsin, May 10 - 13, 2009

- 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 $m_\nu \sim 10^{-2} \text{ eV} \sim \frac{m_D^2}{M}$
→ dimension 5 operator: $L_{\text{eff}} = \frac{f}{M} l l H H$
- If $M = M_{PL}$, then m_ν is too small
- If $M = M_{GUT}$, then m_ν is still too small
- $M \sim 10^{14} \text{ GeV}$ is needed
→ A new symmetry breaking scale (N_R)
- This scale is too high → No connection can be made to the physics to be explored at the LHC or Tevatron
→ need $M \sim \text{TeV}$.

Introduction

- It is possible the dim. 5 operator does not contribute to neutrino masses in a significant way.
→ next operator (dim. 7) : $L_{eff.} = \frac{f}{M^3} \bar{l} l H H (H^\dagger H)$
- This by itself is not enough to make $M \sim \text{TeV}$, need $f \sim 10^{-9}$.
- We propose a model in which $f \sim y_1 y_2 \lambda_4$ with each $\sim 10^{-3} \rightarrow M \sim \text{TeV}$.
- This gives $M \sim \text{TeV}$ scale → connect to physics at the LHC and Tevatron.

- 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 ,
 $\Sigma + \bar{\Sigma}, \Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$.
+ a new isospin $\frac{3}{2}$ Higgs, $\Phi, \Phi = (\Phi^{+++}, \Phi^{++}, \Phi^+, \Phi^0)$
- 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 .

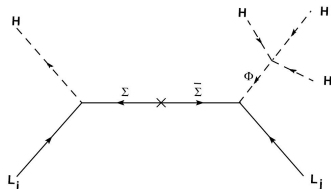
- Higgs Potential

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

- 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:

- $L = y_i l_i \Phi \Sigma + \bar{y}_i l_i H \bar{\Sigma} + M_\Sigma \Sigma \bar{\Sigma}$
 $y_i, \bar{y}_i \rightarrow$ dimensionless Yukawa couplings.
- $\rightarrow L_{\text{eff}} = \frac{y_i \bar{y}_j}{M_\Sigma} l_i l_j \Phi H$
 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.



- 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 $\lambda_4 : M_{\Phi^{+++}} < M_{\Phi^{++}} < M_{\Phi^+} < M_{\Phi^0}$
Negative $\lambda_4 : M_{\Phi^{+++}} > M_{\Phi^{++}} > M_{\Phi^+} > M_{\Phi^0}$.
- 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 tree level. $\rho = 1 - (6v_\Phi^2/v_H^2)$. Experiment: $\rho = 1.0000_{-0.0007}^{+0.0011}$, At 3σ level $v_\Phi < 2.5$ GeV.
- The lower limit on ΔM arises from the radiative correction at the one loop. $\rightarrow \Delta M \geq 1.4 \text{ GeV}$ 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

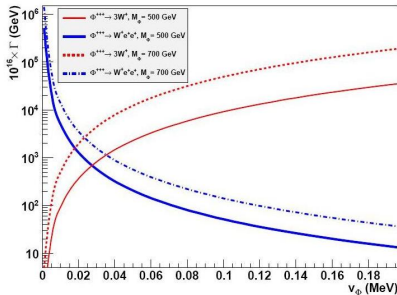
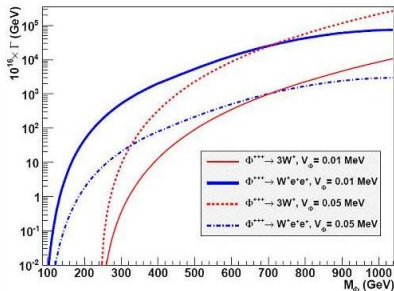
A. Decays

- Two possible decay modes

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

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

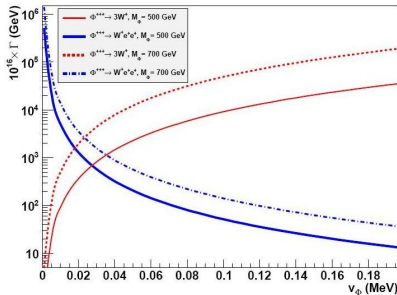
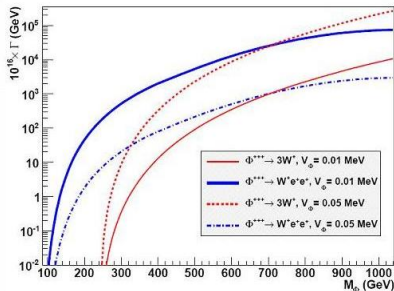
- $W^+ W^+ W^+$ mode dominate for higher values of ν_ϕ
- $W^+ I^+ I^+$ dominate for smaller values of ν_ϕ



Phenomenological Implications

A. Decays

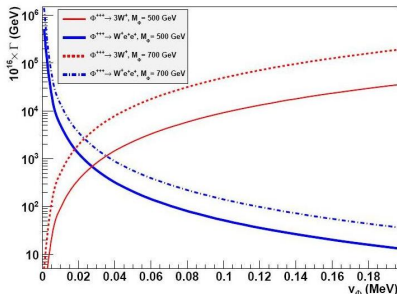
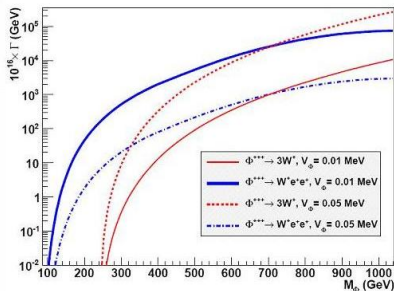
- Crossing point:
 $v_\phi \sim 0.02 - 0.03$ MeV.
- For $v_\phi \sim 0.02 - 0.03$ MeV, for $M_\phi = 500$ GeV,
 $\Gamma < 10^{-12} - 6 \times 10^{-14}$ GeV
→ Displaced Vertices.
- For lower masses, widths are even smaller → Φ^{+++} can escape the detector !!
- For $v_\phi > 0.2$ MeV, Φ^{+++} will immediately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



Phenomenological Implications

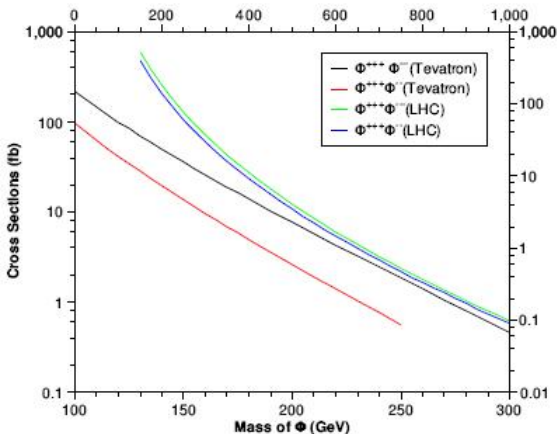
Test of the model

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



B. Productions

- pp or $p\bar{p} \rightarrow \Phi^{+++}\Phi^{---} \rightarrow 6W$ or $4Wl^+l^+$ or $Wl^+l^+l^+l^+$ with or without displaced vertices depending on ν_Φ .



Phenomenological Implications

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

B. Productions of heavier states

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

C. Other Implications

- Φ multiplet with tiny VEV essentially behaves like an inert Higgs
 - SM Higgs mass can be raised to $\sim 400 - 500$ GeV if v_Φ is large $\sim \text{few} - 38$ 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
 - $e\mu \rightarrow$ Inverted Hierarchy