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
The existence of neutrino masses are now firmly established.
\[ m_\nu \sim 10^{-2} \text{ eV} \Rightarrow \text{1st and only indication for physics beyond the SM} \]

\[ m_\nu \] 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, $m_\nu \sim \frac{m_D^2}{M}$
  ⇒ dimension 5 operator: $L_{\text{eff}} = \frac{f}{M} \bar{l} l H H$

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

- If $M = M_{PL}$, then $m_\nu$ is too small

- If $M = M_{GUT}$, then $m_\nu$ is still too small

- $M \sim 10^{14}$ 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 $M \sim$ TeV.
It is possible the dim. 5 operator does not contribute to neutrino masses in a significant way.
⇒ next operator (dim. 7) : \( L_{\text{eff.}} = \frac{f}{M^3} \| HH \rangle (H^\dagger H) \)

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 \( \sim 10^{-3} \) (domain of natural values)

This gives \( M \sim \text{TeV} \) scale to obtain neutrino masses in the range \( 10^{-2} \) – \( 10^{-1} \) eV.
⇒ 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,
  + 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, \( \Phi, \Phi = (\Phi^{+++}, \Phi^{++}, \Phi^+, \Phi^0) \)

- \( \Phi \) has positive mass square, but acquires a tiny VEV through Higgs potential via interaction with \( H \).

- \( \Sigma \) has interactions with SM lepton doublets, \( H \) as well as \( \Phi \).
Model & Formalism

- **Higgs Potential**

\[
V = -\mu_H H^\dagger H + M_\Phi^2 \Phi^\dagger \Phi \\
+ \lambda (H^\dagger H)^2 + \lambda_1 (\Phi^\dagger \Phi)^2 \\
+ \lambda_2 (H^\dagger H)(\Phi^\dagger \Phi) \\
+ \lambda_3 (H^\dagger \frac{t_a}{2} H)(\Phi^\dagger \frac{T_A}{2} \Phi) \\
+ \lambda_4 (HHH\Phi + \Phi^\dagger H^\dagger H^\dagger H^\dagger)
\]

- **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.
- \( \rightarrow L_{\text{eff}} = \frac{(y_i \bar{y}_j + y_j \bar{y}_i)}{M_{\Sigma}} l_i l_j H^* \Phi + h.c. \)

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 \( \Phi \) replaced by \( HHH / M_{\Phi}^2 \).

- \( m_\nu \sim 10^{-2} - 10^{-1} \text{ eV range with } M_{\Sigma} \text{ and } M_{\Phi} \text{ at the TeV scale.} \)
Mass Spectrum of $\Phi$

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

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

Two possible hierarchies for the spectrum of $\Phi$

Positive $\lambda_3 : M_{\Phi^{+++}} < M_{\Phi^{++}} < M_{\Phi^+} < M_{\Phi^0}$

Negative $\lambda_3 : M_{\Phi^{+++}} > M_{\Phi^{++}} > M_{\Phi^+} > M_{\Phi^0}$.

Note that the mass square difference, $\Delta M^2$ 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: $v_\Phi$, $\Delta M$, $M_\Phi$, $M_\Sigma$  
  ($\Delta M =$ mass splitting)

- $v_\Phi$: $\Phi$ has isospin $3/2$, contribute to $\rho$ parameter at the tree level. $\rho = 1 - (6v_\Phi^2/v_H^2)$. Experiment: $\rho = 1.0000^{+0.0011}_{-0.0007}$, At $3\sigma$ level $v_\Phi < 2.5$ GeV.

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

- There is also a theoretical lower limit on $\Delta M$ arising from the radiative correction at the one loop \implies $\Delta M \geq 1.4$ 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 $\lambda_4$.)
Experimental constraints

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

- Decays of $\Phi$’s in the model
- Production
- Signals
- Other implications

Two possible scenarios: $\Phi^{+++}$ lightest or $\Phi^{+++}$ heaviest.
Consider the case in which $\Phi^{+++}$ lightest
$\Rightarrow$ phenomenological implications most distinctive with displaced vertices.
Phenomenological Implications

A. Decays

- Two possible decay modes
  \( \Phi^{+++} \rightarrow W^+ W^+ W^+ \)
  \( \Phi^{+++} \rightarrow W^+ l^+ l^+ l^+ \)

- \( W^+ W^+ W^+ \) mode dominate for higher values of \( v_\Phi \)

- \( W^+ l^+ l^+ \) dominate for smaller values of \( v_\Phi \)
A. Decays

- Crossing point:
  \( \nu_{\Phi} \sim 0.02 - 0.03 \) MeV.

- For \( \nu_{\Phi} \sim 0.02 - 0.03 \) MeV, for \( M_{\Phi} = 500 \) GeV,
  \( \Gamma < 10^{-12} - 6 \times 10^{-14} \) GeV
  \( \Rightarrow \) Displaced Vertices.

- For lower masses, widths are even smaller \( \rightarrow \Phi^{+++} \) can escape the detector !!

- For \( \nu_{\Phi} > 0.2 \) MeV, \( \Phi^{+++} \) will immediately decay to \( W^+ W^+ W^+ \).
Phenomenological Implications

Test of the model

- for $\nu_\Phi > 0.05$ MeV,
  $\Phi^{+++} \rightarrow W^+ W^+ W^+$

- For $\nu_\Phi \sim 0.01 - 0.06$ MeV,
  $\Phi^{+++} \rightarrow W^+ W^+ W^+$, or
  $\Phi^{+++} \rightarrow W^+ l^+ l^+ l^+$ with displaced vertices

- For $\nu_\Phi < 0.01$ MeV,
  $\Phi^{+++} \rightarrow W^+ l^+ l^+$ with no displaced vertices
B. Productions

- $pp \text{ or } p\bar{p} \rightarrow \Phi^{+++}\Phi^{---} \rightarrow 6W \text{ or } 4Wl^+l^+, 4Wl^-l^- \text{ or } 2Wl^+l^+l^-l^- \text{ with or without displaced vertices depending on } \nu_\Phi$. 

![Graph showing cross sections vs. mass of $\Phi$](image)
With displaced vertices, only few events are needed.

LHC Reach (with displaced vertices)
with 1 inverse fb, $\sim 400 \text{ GeV}$
with 10 inverse fb, $\sim 650 \text{ GeV}$
with 100 inverse fb, $\sim 1 \text{ TeV}$

LHC Reach (without displaced vertices)
with 1 inverse fb, $\sim 250 \text{ GeV}$
with 10 inverse fb, $\sim 400 \text{ GeV}$
with 100 inverse fb, $\sim 800 \text{ GeV}$
C. Other Implications

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

- Neutrino mass hierarchy
  If mass of \( \Phi^{+++} < 3W \), then \( \Phi^{+++} \rightarrow W^+ l^+ l^+ \) dominate
  \[ \Rightarrow ee, e\mu, \mu\mu, \text{ along with } \tau' \text{ s.} \]
  Dominance of \( \mu\mu \rightarrow \text{Normal Hierarchy} \)
  Dominance of \( e\mu \) (ee) \( \Rightarrow \text{Inverted Hierarchy} \)
Conclusions

- Presented a new mechanism for the generation of neutrino masses
- via dimension 7 operators: \( \frac{1}{M^3} \ll HH(H^\dagger H) \)
- 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
Microscopic theory that generated $d = 7$ operator has an isospin $3/2$ Higgs multiplet $\Phi$ containing triply charged Higgs boson with mass around $\sim \text{TeV}$ 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