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

- Neutrino oscillation data gives

$$\Delta m^2_{21} = 0.759 \pm 0.020 \times 10^{-4} eV^2,$$
$$|\Delta m^2_{32}| = 0.243 \pm 0.013 \times 10^{-2} eV^2,$$

$$\sin^2 2\theta_{12} = 0.87 \pm 0.03$$

$$\sin^2 2\theta_{23} > 0.92$$

$$\sin^2 2\theta_{13} < 0.19, CL = 90\%$$

Introduction

Most popular mechanism for light neutrino mass generatio:Type I see-saw

- Add a right handed neutrino, N_R to the SM
  Then we have

  $$L = y_\nu l N_R \tilde{H} + M N_R^T C^{-1} N_R.$$

  For the light ν mass matrix, we obtain

  $$M_\nu = \begin{pmatrix} 0 & y_\nu v \\ y_\nu v & M \end{pmatrix}$$

  $\Rightarrow m_\nu = y_\nu^2 \frac{v^2}{M}$, or $m_\nu M = y_\nu^2 v^2$

Introduction

Type I see-saw

- $m_\nu \;\sim \frac{m_D^2}{M}$
  The corresponding effective interaction in SM $\Rightarrow$ 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.

Introduction

Type II see-saw

- Introduce a Higgs triplet, $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$,
  Then we can write
  $L = y_\nu l \ l \ \Delta$
  $\Rightarrow m_\nu = y_\nu < \Delta >$
- The potential
  $V(H, \Delta) = -\mu HH\Delta + M_\Delta^2 \Delta^\dagger \Delta \Rightarrow < \Delta > = \frac{\mu v^2}{M_\Delta^2}$
- Effective operator : $L = \frac{1}{M} llHH$, with $M = \frac{M_\Delta^2}{\mu}$.
- If $\mu \sim M_\Delta$, then, $M_\Delta \sim 10^{14}$ GeV.
- If$\mu \sim v$, then, $M_\Delta \sim 10^3$ GeV requires $y_\nu \sim 10^{-10}$ $\Rightarrow$highly unnatural

Introduction

Type III see-saw

- Introduce a triplet lepton, $\Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$,
  Σ has zero hypercharge.
- This gives an effective dimension 5 operator,

$$L = \frac{1}{M} llHH,$$
$$\Rightarrow m_\nu = y_\nu^2 \frac{v^2}{M_\Sigma}$$

- $\Sigma \sim 10^{14}$ GeV.

Introduction

- 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 $(1, 3, -2)$, $\quad \Sigma + \bar{\Sigma},\ \Sigma = (\Sigma^{++}, \Sigma^{+}, \Sigma^{0})$,
  $+$ 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

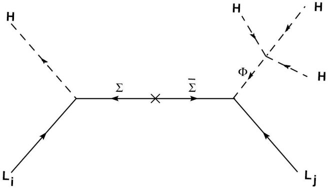
Light neutrino mass generation:

- $L = y_i l_i H^* \Sigma + \bar{y}_i l_i \Phi \bar{\Sigma} + M_\Sigma \Sigma \bar{\Sigma}$
  $y_i, \bar{y}_i \Rightarrow$ 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.

Model & Formalism

Light neutrino mass generation: Comments

- $L_{eff} = \frac{y_i \bar{y}_j}{M_\Sigma} l_i l_j H^* \Phi; \qquad m_\nu = \frac{\lambda_4}{2}(y_i \bar{y}_j + \bar{y}_i y_j)\frac{v_H^4}{M_\Sigma M_\Phi^2})$
- Neutrino mass relation is
  $m_\nu M^3 \sim v^4$.
  This is distinct from the traditional see-saw relation
  $m_\nu M \sim v^2$.
- We can realize both the normal hiearchy and the inverted mass hierarchy.

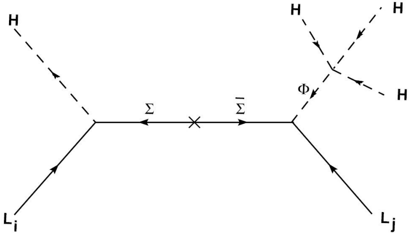
- This is the highest isospin multiplet we can use with renormalizable interaction (dimension 4).

- With just one Σ, one of light neutrino is massless. This is consistent with current data. However, adding more than one Σ, all neutrinos can acquire masses.

Model & Formalism

One lop correction in our model

- 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. We find $\Delta m_\nu / m_\nu \sim \frac{3}{64\pi^2} \frac{M^2}{v^2}$, which is $<< 1$ for $M <$ TeV.



- In the SUSY version of our model, the loop diagrams will be further suppressed.

Model & Formalism

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

Model& and the Formalism

Relevant parameters in our model and existing constraints:

- Parameters : v_Φ, ΔM, M_Φ, M_Σ ($\Delta M =$ 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.)

Model& and the Formalism

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.

Phenomenological Implications

A. Decays

- Two possible decay modes

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

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

- 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.
- Couplings $(\Phi^{+++}\Phi^{--}W^-)$: $\sqrt{\frac{3}{2}}g(p_1 - p_2)_\mu$

$(\Phi^{++}W^-W^-)$: $\sqrt{3}g^2 v_\Phi$

$(\Phi^{++}l_i^-l_j^-)$: $m^\nu_{ij}/(2\sqrt{3}v_\Phi)$

Phenomenological Implications

A. Decays

- Decay widths

decay rates are found to be

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

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

where I, J are dimensionless integrals ($\simeq 1$ for $M_\Phi \gg m_W$).

Phenomenological Implications

A. Decays

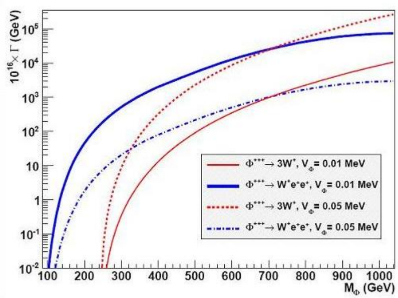
- Two possible decay modes

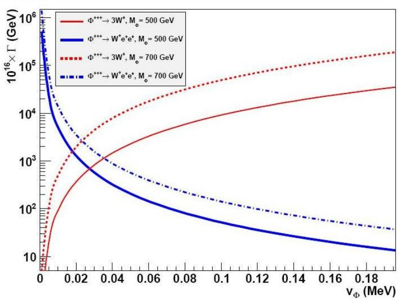
  $\Phi^{+++} \to W^+W^+W^+$

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

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

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

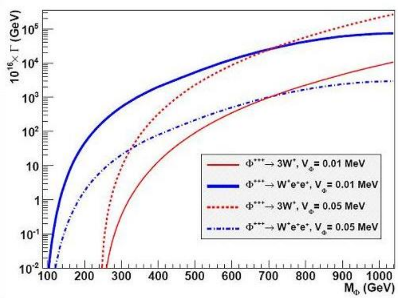


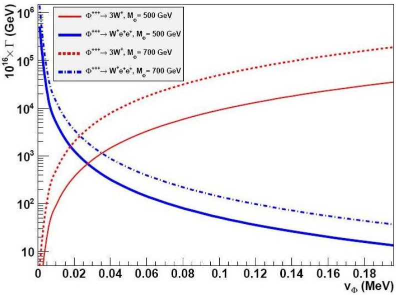


Phenomenological Implications

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

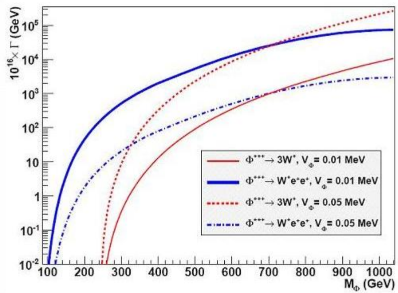


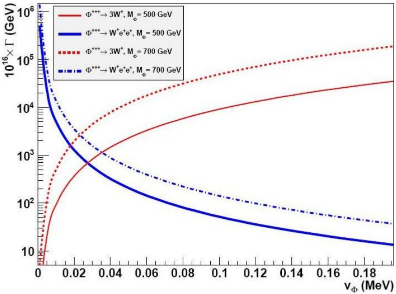


Phenomenological Implications

Test of the model

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

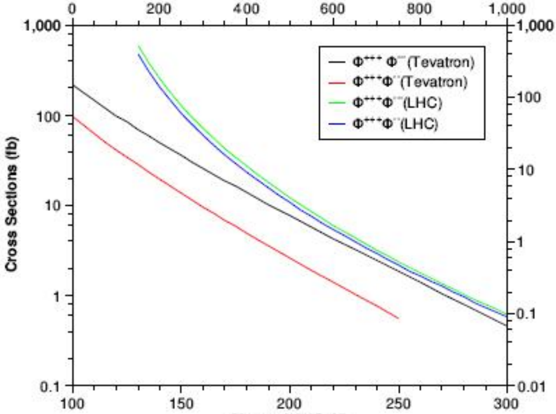




Phenomenological Implications

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

Phenomenological Implications

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
- Each case also gives lesser number of jets plus charged leptons at high p_T

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

- 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