Phenomenology of the Higgs Triplet Model with the mass difference at the LHC

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Contents

• Introduction
• Generation mechanisms for neutrino masses
• The Higgs Triplet Model
  - Decay
  - Production
  - LHC phenomenology
• Summary
Introduction

- **Higgs sector is unknown**
  - Minimal? or Non minimal?
  - Higgs boson search is starting at LHC

- **Some new physics models predict extended Higgs models**

New physics at TeV scale

- Hierarchy problem
- Neutrino mass
- Dark matter
- Baryon asymmetry of Universe

Predict

Determine the direction of NP

Extended Higgs models as a low energy effective theory

- Two Higgs doublets
- Higgs triplet
- etc.
Generation mechanisms for neutrino masses

Majorana masses of neutrinos are given by the dimension 5 operator, where 2 units of lepton number are broken.

\[ \mathcal{L}_{\text{eff}} = \frac{c}{M} \overline{\nu}_L \nu_L \phi^0 \phi^0 \]

The Higgs boson acquires the VEV

\[ \langle \phi^0 \rangle \sim 246 \text{ GeV} \]

\[ m_\nu \sim 0.1 \text{ eV} \]

\[ c/M \sim 10^{-14} \text{ GeV}^{-1} \]

There are scenarios, where neutrino masses generate through dynamics of extended Higgs models.

Ex. 1 The type II seesaw model (at the tree level)

Ex. 2 Radiative seesaw models (at the loop level)


Generation mechanisms for neutrino masses

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Dynamics of extended Higgs model

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Ex. 2 Radiative seesaw models (at the loop level)


Type II seesaw model (Higgs Triplet Model)

The Higgs triplet field $\Delta$ ($Y = 1$) is added to the SM.

$$\mathcal{L}_{\text{typeII}} = h_{ij} \overline{L^c_i} \cdot \Delta L^j_L + \mu \Phi \cdot \Delta^\dagger \Phi + \cdots$$

$\Phi$: 1, 2, $+\frac{1}{2}$, 0
$\Delta$: 1, 3, 1, 2

When we consider the TeV scale $M_\Delta$, the L# violating coupling $\mu$ has to be of $O(10^{-10})$ GeV.

$M_\Delta$: Mass of the Triplet scalar boson.
$v_\Delta$: VEV of the triplet Higgs

$(m_\nu)_{ij} = h_{ij} \frac{\mu \langle \phi^0 \rangle^2}{M^2_\Delta} = h_{ij} v_\Delta$

$10^{-14}$ GeV$^{-1}$

$O(1)$

$O(10^{-10})$ GeV

$O(100-1000)$ GeV
The Higgs Triplet Model (HTM)

The Higgs potential

\[ V = m^2 \Phi^\dagger \Phi + M^2 \text{Tr}(\Delta^\dagger \Delta) + \left[ \mu \Phi^T i \tau_2 \Delta^\dagger \Phi + \text{h.c.} \right] + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 \left[ \text{Tr}(\Delta^\dagger \Delta) \right]^2 + \lambda_3 \text{Tr}[(\Delta^\dagger \Delta)^2] + \lambda_4 (\Phi^\dagger \Phi) \text{Tr}(\Delta^\dagger \Delta) + \lambda_5 \Phi^\dagger \Delta \Delta^\dagger \Phi. \]

\[ \Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}} (\varphi + v + i \chi) \end{pmatrix} \]

\[ \Delta = \begin{pmatrix} \Delta^+ \\ \frac{\Delta^0}{\sqrt{2}} \\ -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix} \]

\[ \Delta^0 = \frac{1}{\sqrt{2}} (\delta + v_\Delta + i \eta) \]

Mass eigenstates: (SM-like) \( h \), (Triplet-like) \( H^{++}, H^+, H, A \)

Mass spectrum:

\[ m_h^2 \sim 2 \lambda_1 v^2 \]

\[ M_\Delta^2 \equiv \frac{v^2 \mu}{\sqrt{2} v_\Delta} \]

If \( \lambda_5 < 0 \)

\[ m_{H^{++}}^2 \simeq M_\Delta^2 - \frac{v^2}{2} \lambda_5 \]

\[ m_{H^+}^2 \simeq M_\Delta^2 - \frac{v^2}{4} \lambda_5 \]

\[ m_A^2 \simeq m_H^2 = M_\Delta^2 \]

The characteristic mass spectrum: \( m_{H^{++}}^2 - m_{H^+}^2 \simeq m_{H^+}^2 - m_{\phi^0}^2 \) is predicted. Measuring this spectrum, the model can be tested!
The Higgs Triplet Model (HTM)

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\[ V = m^2 \Phi^\dagger \Phi + M^2 \text{Tr}(\Delta^\dagger \Delta) + \left[ \mu \Phi^T i \tau_2 \Delta^\dagger \Phi + \text{h.c.} \right] + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 \left[ \text{Tr}(\Delta^\dagger \Delta) \right]^2 + \lambda_3 \text{Tr}[(\Delta^\dagger \Delta)^2] + \lambda_4 (\Phi^\dagger \Phi) \text{Tr}(\Delta^\dagger \Delta) + \lambda_5 \Phi^\dagger \Delta \Delta^\dagger \Phi. \]

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\[ \Phi = \left[ \frac{1}{\sqrt{2}} (\varphi + v + i \chi) \right] \]
\[ \Delta = \left( \begin{array}{cc} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{array} \right) \]
\[ \Delta^0 = \frac{1}{\sqrt{2}} (\delta + v_\Delta + i \eta) \]

In this talk, we discuss how we can test the HTM in the case with the mass difference at the LHC.
When $H^{++} \rightarrow l^+l^+$, $m_{H^{++}} > 250 - 300$ GeV.

This bound cannot be applied when $H^{++}$ does not decay into the same sign dilepton.
Decay

The decay of Δ-like scalar bosons can be classified into 3 modes.

1. Decay via $h_{ij}$
2. Decay via $v_\Delta$
3. Decay via $g_W$

Decay of Δ++ strongly depend on $v_\Delta$ and $\Delta m$ ($\equiv m_{H^{++}} - m_{H^+}$).

Decay modes of 1 and 2 are related to each other by the relation: $(m_\nu)_{ij} = h_{ij} v_\Delta$

Decay of the triplet like scalar bosons strongly depend on $v_\Delta$ and $\Delta m$. 

Below is an example of how to classify the decay modes numerically:

- Decay via $h_{ij}$
- Decay via $v_\Delta$
- Decay via $g_W$

These decay modes are related by the relation $(m_\nu)_{ij} = h_{ij} v_\Delta$.

Decay of the triplet like scalar bosons strongly depend on $v_\Delta$ and $\Delta m$ ($\equiv m_{H^{++}} - m_{H^+}$).
Branching ratio of $H^{++}$

$\Delta m = 0$

$\Delta m = 10$ GeV

$v_\Delta = 0.1$ MeV, $m_{H^{++}} = 200$ GeV

Phenomenology of $\Delta m \neq 0$ is drastically different from that of $\Delta m = 0$.

The $H^+ \rightarrow \phi^0 W^+$ mode can be dominant in the case of $\Delta m \neq 0$.

The $\phi^0 \rightarrow bb$ mode can be dominant when $v_\Delta > \text{MeV}$.
Light $\Delta [O(100)\text{ GeV}]$ Scenario

Decay of $H^{++}$

Decay of $H^+$

Decay of $H$ or $A$

Challenging to detect

Excluded @ LHC

In large $\Delta m$ case, this region shrinks.
Production mechanisms at LHC

\( W \) associate
- depends on \( v_\Delta \rightarrow \text{Suppressed} \)

Main production process

Drell-Yan
- depends on \( g_W \)

Vector Boson Fusion
- depends on \( v_\Delta \rightarrow \text{Suppressed} \)
- depends on \( g_W \), but unitary cancellation works
  \( \rightarrow \text{Suppressed} \)
The magnitude of these production cross sections is around 1-100 fb.
By using transverse mass distribution, the masses of Δ-like scalar bosons can be reconstructed.

Missing transverse energy:

$$E_T = -\sum_{i} p_T(i)$$

Transverse mass:  
$$p_T = p_T(a) + p_T(b) + \cdots$$

$$M_T^2 = (E_T + p_T)^2$$

$$\sim 2 |E_T| |p_T| (1 - \cos \varphi)$$

Smith, Neerven, Vermaseren, PRL50, 1983

Ex. The W boson mass reconstruction
All the masses of the $\Delta$-like scalar bosons may be reconstructed.
Summary

• The type II seesaw model can be explained neutrino masses, which deduces the extended Higgs model (The Higgs triplet model).

• In the Higgs triplet model, a characteristic mass spectrum appears:

\[ m_{H^{++}}^2 - m_{H^+}^2 \simeq m_{H^+}^2 - m_{\phi^0}^2 \]

• Phenomenology of the HTM in the case with \( \Delta m \neq 0 \) is drastically different from that in the case with \( \Delta m = 0 \) (\( H^{++} \rightarrow H^+W^+ \rightarrow HW^+W^+ \)).

• In our work, we focus on the characteristic mass spectrum, and we outline how the HTM can be tested in the case with \( \Delta m \neq 0 \) at the LHC.

• By measuring the transverse mass distribution and the invariant mass distribution, the masses of the \( \Delta \)-like scalar bosons may be reconstructed.

• Background simulation is the future work to clarify the feasibility.
Back up slides
**Backgrounds**

**Signal:**  \( pp \rightarrow H^{++}H^- \rightarrow (\phi^0 W^+ W^+)(\phi^0 W^-) \rightarrow (\ell^+ \ell^+ b\bar{b} E_T)(b\bar{b}jj) \)  
8 fb

**Backgrounds:**

(A):  \( pp \rightarrow t\bar{t}W^+ W^- \rightarrow (bW^+)(\bar{b}W^-)W^+ W^- \rightarrow (b\ell^+ \nu)(\bar{b}jj)(\ell^+ \nu)(jj) \)  O(10) fb

(B):  \( pp \rightarrow t\bar{t}W^+ W^- \rightarrow (bW^+)(\bar{b}W^-)W^+ W^- \rightarrow (b\ell^+ \nu)(\bar{b}^- \nu)(jj)(jj) \)  O(10) fb

For (A), top reconstruction by the \( M_T \) and \( M_{inv} \) distributions may be used.
For (B), charge identification for leptons may be used.

**Signal:**  \( pp \rightarrow H^+ \phi^0 \rightarrow (\phi^0 W^+)(b\bar{b}) \rightarrow (\ell^+ b\bar{b} E_T)(b\bar{b}) \)  
33 fb

**Backgrounds:**

(C):  \( pp \rightarrow t\bar{t} \rightarrow (bW^+)(\bar{b}W^-) \rightarrow (b\ell^+ \nu)(\bar{b}jj) \)  O(1 pb

(D):  \( pp \rightarrow t\bar{t}\gamma^*/g^* \rightarrow (bW^+)(\bar{b}W^-)(jj) \rightarrow (b\ell^+ \nu)(\bar{b}/\nu)(jj) \)  O(10) fb

For (C), top reconstruction by the \( M_T \) and \( M_{inv} \) distributions may be used.
For (D), b-tagging and cut for the low E jet would be useful to reduce the BG.
Large $\Delta m$ case

$\Delta m = 10$ GeV

- $m_{H^-} = 140$ GeV
- $m_{H^+} = 130$ GeV
- $m_{\psi} = 119$ GeV

$\Delta m = 30$ GeV

- $m_{H^-} = 190$ GeV
- $m_{H^+} = 160$ GeV
- $m_{\psi} = 123$ GeV
Decay widths for $\Delta$-like scalar bosons

In the wide parameter regions, the decay width of the $\Delta$-like scalar bosons is much smaller than that of top quark and massive gauge bosons.
Constraint from the rho parameter

Experimental value of rho parameter is quite close to unity: \( \rho_{\text{exp}} \sim 1 \)

Theoretical prediction of rho parameter strongly depends on structure of Higgs sectors.

\[
\rho_{\text{tree}} = \frac{\sum_i v_i^2 [T_i(T_i + 1) - Y_i^2]}{\sum_i 2Y_i^2 v_i^2}
\]

- **Multi-doublet models**
  - Custodial SU(2) symmetry exists in the kinetic term of Higgs fields.
  - \( \rho_{\text{tree}} = 1 \) is predicted.
  - ★ Rho parameter deviates from unity at the 1-loop level.

- **Models with Higgs triplets**
  - Custodial SU(2) symmetry is broken in the kinetic term of Higgs fields
  - \( \rho_{\text{tree}} \neq 1 \) is predicted.

1. Triplet VEV is small compared with doublet VEV.
2. Imposing alignment among triplet VEVs, custodial SU(2) symmetry is restored.

**Triplet VEV is constrained from rho parameter**
\[
\begin{pmatrix}
\varphi^\pm \\
\Delta^\pm
\end{pmatrix} = R(\beta^\pm)
\begin{pmatrix}
w^\pm \\
H^\pm
\end{pmatrix},
\begin{pmatrix}
\chi \\
\eta
\end{pmatrix} = R(\beta_0)
\begin{pmatrix}
z \\
A
\end{pmatrix},
\begin{pmatrix}
\varphi \\
\delta
\end{pmatrix} = R(\alpha)
\begin{pmatrix}
h \\
H
\end{pmatrix},
R(\theta) = \begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\]

\[\cos \beta^\pm = \frac{v}{\sqrt{v^2 + 2v^2_\Delta}}, \quad \cos \beta_0 = \frac{v}{\sqrt{v^2 + 4v^2_\Delta}}\], \quad \tan 2\alpha \simeq \frac{v_\Delta}{v} \frac{4M^2_\Delta - 2v^2(\lambda_4 + \lambda_5)}{M^2_\Delta - 2v^2\lambda_1}.

\[
q \quad \xrightarrow{W^+} \quad q' \quad H^{++}
\]

\[
q \quad \xrightarrow{W^+} \quad H \quad q'
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>SM with ( \eta ) (( Y = 0 ))</th>
<th>SM with ( \Delta ) (( Y = 1 ))</th>
<th>SM with ( \eta ) and ( \Delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>F</td>
<td>^2 = )</td>
<td>[\frac{4v^2v^2_\eta}{\cos^2 \theta_W (v^2 + 4v^2_\eta)^2}]</td>
</tr>
<tr>
<td>( \rho_{\text{tree}} = )</td>
<td>(1 + \frac{4v^2_\eta}{v^2})</td>
<td>(1 - \frac{2v^2_\Delta}{v^2 + 4v^2_\Delta})</td>
<td>1</td>
</tr>
</tbody>
</table>

\[v_\eta = v_\Delta / \sqrt{2}\]