ASSOCIATED PRODUCTION OF HIGGS BOSON AT LINEAR COLLIDER WITHIN SEESEAW TYPE II MODEL

November 29, 2018

Larbi Rahili
rahililarbi@gmail.com

in collaboration with: A. Arhrib and R. Benbrik

based on work to be appear in: Frontiers in Physics

EPTHE, Department of Physics, Faculty of Sciences
Ibn Zohr University, Agadir
Morocco
Higgs Triplet Model as extension BSM

* As motivation, the HTM relating directly the smallness of the neutrino masses. [R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980)].

* In addition to the SM Higgs field $\Phi$,

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} \sim (1, 2, 1),$$

* the HTM contains an additional $SU(2)_L$ triplet Higgs field

$$\Delta = \begin{pmatrix} \Delta^+ \\ \Delta^0 \\ -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix} \sim (1, 3, 2).$$

* We denote the neutral components of the SM doublet and triplet Higgs fields as:

$$\Phi^0 = \frac{1}{\sqrt{2}}(\phi^0 + i\chi^0)$$
$$\Delta^0 = \frac{1}{\sqrt{2}}(\delta^0 + i\eta^0).$$
Review

Higgs Triplet Model as extension BSM

* As motivation, the HTM relating directly the smallness of the neutrino masses. [R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980)].

* In addition to the SM Higgs field $\Phi$,

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi_0 \end{pmatrix} \sim (1, 2, 1),$$

* the HTM contains an additional $SU(2)_L$ triplet Higgs field

$$\Delta = \begin{pmatrix} \Delta^+ \\ \frac{\Delta^+ + \Delta^0}{\sqrt{2}} \\ -\frac{\Delta^+ + \Delta^0}{\sqrt{2}} \end{pmatrix} \sim (1, 3, 2).$$

* We denote the neutral components of the SM doublet and triplet Higgs fields as:

$$\Phi_0 = \frac{1}{\sqrt{2}}(\phi^0 + i\chi^0) \quad \text{and} \quad \Delta^0 = \frac{1}{\sqrt{2}}(\delta^0 + i\eta^0)$$

in the HTM: $m_{\nu} \approx Y_{\Delta\mu}v_d^2/M_{\Delta}^2$. 

HTM model
Review
Scalar Potential
Theo. Exp. Constraints
Associated production
$e^+\bar{e} \rightarrow \gamma h^0$
$e^-\gamma \rightarrow e^- h^0$
$R_{\gamma} \gamma \nu vs R_{\gamma} \nu^2$ and $R_{\nu} h^0$
Numerical results
$\sigma(e^+\bar{e} \rightarrow \gamma h^0)$
$\sigma(e^-\gamma \rightarrow e^- h^0)$
$R_{\gamma} \gamma_h^0 vs R_{\gamma} \gamma_z(h^0)$
Conclusion/Perspective

EPTHE, Dept. of Physics
FSA, Ibn Zohr University
Agadir, Morocco
Potential & Higgs masses


$$V(\Phi, \Delta) = m_\Phi^2 \Phi^\dagger \Phi + M_\Delta^2 \text{Tr}(\Delta^\dagger \Delta) + \left( \mu \Phi^T i \tau_2 \Delta^\dagger \Phi + \text{h.c.} \right)$$

$$+ \frac{\lambda}{4} (\Phi^\dagger \Phi)^2 + \lambda_1 (\Phi^\dagger \Phi) \text{Tr}(\Delta^\dagger \Delta) + \lambda_2 \left[ \text{Tr}(\Delta^\dagger \Delta) \right]^2$$

$$+ \lambda_3 \text{Tr}\left[(\Delta^\dagger \Delta)^2\right] + \lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi,$$

$$V(\Phi, \Delta) = m_\Phi^2 \Phi^\dagger \Phi + M_\Delta^2 \text{Tr}(\Delta^\dagger \Delta) + \left(\mu \Phi^T i\tau_2 \Delta^\dagger \Phi + \text{h.c.}\right)$$

$$+ \frac{\lambda}{4} (\Phi^\dagger \Phi)^2 + \lambda_1 (\Phi^\dagger \Phi) \text{Tr}(\Delta^\dagger \Delta) + \lambda_2 \left[\text{Tr}(\Delta^\dagger \Delta)\right]^2$$

$$+ \lambda_3 \text{Tr}[(\Delta^\dagger \Delta)^2] + \lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi,$$

After EWSB, $\phi^0$ and $\delta^0$ acquire vevs denoted as $v_d$ and $v_t$ with $v^2 = v_d^2 + 2 v_t^2 = (246 \text{ GeV})^2$.

Then 7 physical Higgs states:

$H^{\pm\pm}, H^{\pm},$

$A^0,$

$H^0,$

& $h^0 = \text{SM - like}$. 

$R_\gamma Y\gamma$ vs $R_\gamma Y$ and $R_\gamma h^0$

$\sigma(e^+ e^- \rightarrow \gamma h^0)$

$\sigma(e^- \gamma \rightarrow e^- h^0)$

$R_\gamma Y(h^0)$ vs $R_\gamma Z(h^0)$

Conclusion/Perspective
Theo. Exp. Constraints

Theoretical requirements

Unitarity [A. Arhrib et al, Phys. Rev. D. 84, 095005 (2011)]

\[
|\lambda| \leq 16\pi, \quad |\lambda_1 + \lambda_4| \leq 8\pi, \quad |\lambda_1| \leq 8\pi, \quad |2\lambda_1 + 3\lambda_4| \leq 16\pi, \\
|2\lambda_1 - \lambda_4| \leq 16\pi, \quad |\lambda_2| \leq 4\pi, \quad |\lambda_2 + \lambda_3| \leq 4\pi, \quad |2\lambda_2 - \lambda_3| \leq 8\pi, \\
|\lambda + 4\lambda_2 + 8\lambda_3| \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2} \leq 32\pi, \\
|3\lambda + 16\lambda_2 + 12\lambda_3| \pm \sqrt{(3\lambda - 16\lambda_2 - 12\lambda_3)^2 + 24(2\lambda_1 + \lambda_4)^2} \leq 32\pi
\]
Theo. Exp. Constraints

Theoretical requirements

Unitarity [A. Arhrib et al, Phys. Rev. D. 84, 095005 (2011)]

\[
|\lambda| \leq 16\pi, \ |\lambda_1 + \lambda_4| \leq 8\pi, \ |\lambda_1| \leq 8\pi, \ |2\lambda_1 + 3\lambda_4| \leq 16\pi, \\
|2\lambda_1 - \lambda_4| \leq 16\pi, \ |\lambda_2| \leq 4\pi, \ |\lambda_2 + \lambda_3| \leq 4\pi, \ |2\lambda_2 - \lambda_3| \leq 8\pi, \\
|\lambda + 4\lambda_2 + 8\lambda_3 \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2}| \leq 32\pi, \\
|3\lambda + 16\lambda_2 + 12\lambda_3 \pm \sqrt{(3\lambda - 16\lambda_2 - 12\lambda_3)^2 + 24(2\lambda_1 + \lambda_4)^2}| \leq 32\pi
\]


\[
(\lambda \geq 0) \land (\lambda_{23}^+ \geq 0) \land (\lambda_2 + \lambda_3/2 \geq 0) \land (\lambda_1 + \sqrt{\lambda \lambda_{23}^+} \geq 0) \\
\land (\lambda_{14}^+ + \sqrt{\lambda \lambda_{23}^+} \geq 0) \land \\
(\lambda_3 \sqrt{\lambda} \leq |\lambda_4| \sqrt{\lambda_{23}^+} \lor 2\lambda_1 + \lambda_4 + \sqrt{(\lambda - \lambda_4^2)(2\lambda_2/\lambda_3 + 1)} \geq 0)
\]
Theo. Exp. Constraints

Theoretical requirements

**Unitarity** [A. Arhrib et al, Phys. Rev. D. 84, 095005 (2011)]

\[
|\lambda| \leq 16\pi, \quad |\lambda_1 + \lambda_4| \leq 8\pi, \quad |\lambda_1| \leq 8\pi, \quad |2\lambda_1 + 3\lambda_4| \leq 16\pi, \\
|2\lambda_1 - \lambda_4| \leq 16\pi, \quad |\lambda_2| \leq 4\pi, \quad |\lambda_2 + \lambda_3| \leq 4\pi, \quad |2\lambda_2 - \lambda_3| \leq 8\pi, \\
|\lambda + 4\lambda_2 + 8\lambda_3 \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2}| \leq 32\pi, \\
|3\lambda + 16\lambda_2 + 12\lambda_3 \pm \sqrt{(3\lambda - 16\lambda_2 - 12\lambda_3)^2 + 24(2\lambda_1 + \lambda_4)^2}| \leq 32\pi
\]


\[
(\lambda \geq 0) \land (\lambda_{23}^+ \geq 0) \land (\lambda_2 + \lambda_3/2 \geq 0) \land (\lambda_1 + \sqrt{\lambda\lambda_{23}^+} \geq 0) \\
\land (\lambda_{14}^+ + \sqrt{\lambda\lambda_{23}^+} \geq 0) \land \\
\left(\lambda_3\sqrt{\lambda} \leq |\lambda_4|\sqrt{\lambda_{23}^+} \lor 2\lambda_1 + \lambda_4 + \sqrt{(\lambda - \lambda_4^2)(2\lambda_2/\lambda_3 + 1)} \geq 0\right)
\]

**Veltman Condition** [M. Chabab et al, Phys. Rev. D. 93, 035026 (2016)]

\[
T_d = -2Tr(I_n) \sum_{f} m_f^2/v_Q^2 + 3(\lambda + 2\lambda_1 + \lambda_4) + 2(m_W^2/v^2)(2 + 1/c_W^2), \\
T_t = (2\lambda_1 + 8\lambda_2 + 6\lambda_3 + \lambda_4) + 4(m_W^2/v^2)(1 + 1/c_W^2)
\]
Experimental requirements

For the neutral Higgs bosons:
* From LEP direct search results: $m_H, m_A \geq 80 - 90$ GeV.

As for the singly charged Higgs boson:
* From LEP direct search results: $m_{H^\pm} \geq 78$ GeV.
* LHC limits may not applicable.

In the case of the doubly charged Higgs boson:
* From LEP direct search results: $m_{H^{\mp\mp}} \geq 97.3$ GeV.
* From LHC
  o For $v_t \lesssim 10^{-4}$ GeV, $m_{H^{\pm\mp}} > 820$ GeV.
  o For $v_t \gtrsim 10^{-4}$ GeV, $m_{H^{\pm\mp}} > 90 - 100$ GeV.
Processes

e^+e^- \rightarrow \gamma h^0

Figure: Generic Feynman diagrams involving the various contributions to \( e^- e^+ \rightarrow \gamma h^0 \) process in the HTM. In all diagrams \( V \) stands for \( W \) and/or \( Z \).
\[ e^- \gamma \rightarrow e^- h^0 \]

**Figure:** Generic Feynman diagrams involving the various contributions to \( e^- e^+ \rightarrow \gamma h^0 \) process in the HTM. In all diagrams \( V \) stands for \( W \) and/or \( Z \).
for illustrative purpose we introduce the ratio,

\[ R_{\gamma h^0} \equiv \frac{\sigma(e^+e^- \to \gamma h^0)}{\sigma_{\text{SM}}(e^+e^- \to \gamma H)}, \quad R_{e^- h^0} \equiv \frac{\sigma(e^-\gamma \to e^- h^0)}{\sigma_{\text{SM}}(e^-\gamma \to e^- H)} \]

\[ R_{\gamma V} \equiv \frac{\sigma(gg \to h^0) \times Br(h^0 \to \gamma V)}{\sigma_{\text{SM}}(gg \to h^0) \times Br(h^0 \to \gamma V)} \quad (V = \gamma, Z) \]
for illustrative purpose we introduce the ratio,

\[ R_{\gamma h^0} \equiv \frac{\sigma(e^+ e^- \to \gamma h^0)}{\sigma_{SM}(e^+ e^- \to \gamma H)}, \quad R_{e^- h^0} \equiv \frac{\sigma(e^- \gamma \to e^- h^0)}{\sigma_{SM}(e^- \gamma \to e^- H)} \]

\[ R_{\gamma V} \equiv \frac{\sigma(gg \to h^0) \times Br(h^0 \to \gamma V)}{\sigma(gg \to h^0)_{SM} \times Br(h^0 \to \gamma V)_{SM}} \quad (V = \gamma, Z) \]

Note that the one-loop amplitudes for \( h^0 \to \gamma \gamma, \gamma Z \), as well as for the two processes \( e^+ e^- \to \gamma h^0 \) and \( e^- \gamma \to e^- h^0 \) receive an additional contribution from \( H^\pm \) and \( H^{\pm \pm} \) Higgs bosons.

\[ \bar{\lambda}_{h^0 H^+ H^-} \approx \frac{s_W}{e m_W} \lambda_1 v_d c_\alpha \]

\[ \bar{\lambda}_{h^0 H^+ H^-} \approx \frac{s_W}{e m_W} (\lambda_1 + 0.5 \lambda_4) v_d \]
Numerical

Associated production of Higgs boson at Linear Collider within Seesaw Type II Model

Larbi Rahili

HTM model
Review
Scalar Potential
Theo. Exp. Constraints
Associated production
\( e^+ e^- \rightarrow \gamma h^0 \)
\( e^- \gamma \rightarrow e^- h^0 \)
\( R_{\gamma \nu} \nu vs R_{\gamma Z} \nu^2 \) and \( R_{\gamma h^0} \)
Numerical results
\( \sigma (e^+ e^- \rightarrow \gamma h^0) \)
\( \sigma (e^- \gamma \rightarrow e^- h^0) \)
\( R_{\gamma \gamma} (h^0) vs R_{\gamma Z} (h^0) \)
Conclusion/Perspective

EPTHE, Dept. of Physics
FSA, Ibn Zohr University
Agadir, Morocco

allowed space parameters

Figure: The allowed space parameter of the HTM given by the variation of \( m_{H^\pm \pm} \) (left) and \( m_{H^\pm} \) (middle) in \((\lambda_1, \lambda_4)\) plane, and the correlation between \( \ln_{H^0 H^+ H^-} \) and \( \ln_{H^0 H^+ H^-} \) following the sign of \( \lambda_1 \). Input parameters are \( \lambda = 0.522 \) \((m_{h^0} = 125.09 \text{ GeV})\), \( \lambda_3 = 2\lambda_2 = 0.2\), \( \nu_t = \mu = 1 \text{ GeV} \).
Associated production of Higgs boson at Linear Collider within Seesaw Type II Model

Larbi Rahili

HTM model
Review
Scalar Potential
Theo. Exp. Constraints
Associated production
\( e^+ e^- \rightarrow \gamma h^0 \)
\( e^- \gamma \rightarrow e^- h^0 \)
\( R_{\gamma \gamma} \gamma \) vs \( R_{\gamma Z} \gamma \) and \( R_{e h^0} \)
Numerical results
\( \sigma (e^+ e^- \rightarrow \gamma h^0) \)
\( \sigma (e^- \gamma \rightarrow e^- h^0) \)
\( R_{\gamma \gamma} \gamma (h^0) \) vs \( R_{\gamma Z} (h^0) \)

Figure: Cross sections for the \( e^+ e^- (e^- \gamma) \rightarrow \gamma h^0 (e^- h^0) \) processes in HTM as a function of center-of-mass energy for various values of \( \lambda_1 \).

We take : \( \lambda = 0.522 \) \( (m_{h^0} = 125.09 \text{ GeV}) \), \( \lambda_3 = 2 \lambda_2 = 0.2 \), \( v_t = \mu = 1 \) GeV and \( \lambda_4 = 0 \). The SM limit is achieved for \( \lambda_1 = 0 \).
Associated production of Higgs boson at Linear Collider within Seesaw Type II Model

Larbi Rahili

HTM model
Review
Scalar Potential
Theo. Exp. Constraints

Associated production
\( e^+ e^- \rightarrow \gamma h^0 \)
\( e^- \gamma \rightarrow e^- h^0 \)
\( R_{\gamma \gamma} \) vs \( R_{\gamma \nu} \) and \( R_{\gamma h^0} \)

Numerical results
\( \sigma(e^+ e^- \rightarrow \gamma h^0) \ (fb) \) and \( R_{\gamma \gamma}(h^0) \)
as a function of \( \lambda_1 \) in the HTM for \( \sqrt{s} = 250 \) GeV. \( R_{\gamma h^0} \) and \( R_{\gamma \nu} \) correlations following the \( \lambda_1 \) sign.

Figure: \( \sigma(e^+ e^- \rightarrow \gamma h^0) \ (fb) \) and \( R_{\gamma \gamma}(h^0) \) as a function of \( \lambda_1 \) in the HTM for \( \sqrt{s} = 250 \) GeV. \( R_{\gamma h^0} \) and \( R_{\gamma \nu} \) correlations following the \( \lambda_1 \) sign.
Numerical

$$\sigma(e^- \gamma \rightarrow e^- h^0) \text{ vs } R_{\gamma \nu}(h^0)$$

Figure: Variation of $\sigma (e^- \gamma \rightarrow e^- h^0)$ (fb), $R_{e^- h^0}$, $R_{\gamma \gamma}(h^0)$ and $R_{\gamma Z}(h^0)$ as a function of $\lambda_1$ in the HTM for $\sqrt{s} = 250$ GeV.
Numerical

Correlation

Figure: $R_{\gamma\gamma}(h^0)$ and $R_{\gamma Z}(h^0)$ correlation in the HTM.
*ILC is expected to play a crucial role in understanding the nature of the Higgs boson due to the clean beams in the initial state.
Conclusion

* ILC is expected to play a crucial role in understanding the nature of the Higgs boson due to the clean beams in the initial state.

* The one-loop processes \(e^+ e^- \rightarrow \gamma h^0\) and \(e^- \gamma \rightarrow e^- h^0\) can be the key in the framework of HTM.
Conclusion

* ILC is expected to play a crucial role in understanding the nature of the Higgs boson due to the clean beams in the initial state.
* The one-loop processes $e^+e^- \rightarrow \gamma h^0$ and $e^-\gamma \rightarrow e^- h^0$ can be the key in the framework of HTM.
* Singly (-doubly) charged Higgs loops in HTM can modify significantly the cross section compared to the SM predictions.
**Conclusion**

* ILC is expected to play a crucial role in understanding the nature of the Higgs boson due to the clean beams in the initial state.
* The one-loop processes $e^+ e^- \rightarrow \gamma h^0$ and $e^- \gamma \rightarrow e^- h^0$ can be the key in the framework of HTM.
* Singly (-doubly) charged Higgs loops in HTM can modify significantly the cross section compared to the SM predictions.
* Correlation between $R_{\gamma h^0}$, $R_{e^- h^0}$ and $R_{\gamma\gamma}(h^0)$ can be mainly positive for $\sqrt{s} = 250$ GeV depending on the HTM parameter space.
Thank you for your attention