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

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## 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

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

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

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

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

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# Potential & Higgs masses

The scalar potential of the Higgs fields $\Phi$ and $\Delta$ is [A. Arhrib et al, Phys. Rev. D 84, 095005 (2011), P. Fileviez Perez et al, Phys. Rev. D 78, 015018 (2008)] .

$$
\begin{aligned}
V(\Phi, \Delta) &= m_\Phi^2 \Phi^\dagger \Phi + M_\Delta^2 \mathrm{Tr}(\Delta^\dagger \Delta) + \left(\mu \Phi^T i\tau_2 \Delta^\dagger \Phi + \mathrm{h.c.}\right) \\
&+ \frac{\lambda}{4}(\Phi^\dagger \Phi)^2 + \lambda_1 (\Phi^\dagger \Phi)\mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_2 \left[\mathrm{Tr}(\Delta^\dagger \Delta)\right]^2 \\
&+ \lambda_3 \mathrm{Tr}[(\Delta^\dagger \Delta)^2] + \lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi,
\end{aligned}
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&+ \lambda_3 \mathrm{Tr}[(\Delta^\dagger\Delta)^2] + \lambda_4 \Phi^\dagger\Delta\Delta^\dagger\Phi,
\end{aligned}
$$

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

Then 7 physical Higgs states :

$$
\begin{gathered}
H^{\pm\pm}, H^{\pm}, \\
A^0, \\
H^0, \\
\& \; h^0 = SM - like.
\end{gathered}
$$

# Theo. Exp. Constraints

## Theoretical requirements

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

$$|\lambda| \leq 16\pi,\ |\lambda_1 + \lambda_4| \leq 8\pi,\ |\lambda_1| \leq 8\pi,\ |2\lambda_1 + 3\lambda_4| \leq 16\pi,$$

$$|2\lambda_1 - \lambda_4| \leq 16\pi,\ |\lambda_2| \leq 4\pi,\ |\lambda_2 + \lambda_3| \leq 4\pi,\ |2\lambda_2 - \lambda_3| \leq 8\pi,$$

$$|\lambda + 4\lambda_2 + 8\lambda_3 \pm \sqrt{(\lambda - 4\lambda_2 - 8\lambda_3)^2 + 16\lambda_4^2}\ | \leq 32\pi,$$

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

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**BFB** [C. Bonilla, et al, Phys. Rev. D. 92, 075028 (2015)]

$$(\lambda \ge 0)\ \wedge\ (\lambda_{23}^+ \ge 0)\ \wedge\ (\lambda_2 + \lambda_3/2 \ge 0)\ \wedge\ (\lambda_1 + \sqrt{\lambda\,\lambda_{23}^+} \ge 0)$$

$$\wedge\ (\lambda_{14}^+ + \sqrt{\lambda\,\lambda_{23}^+} \ge 0)\ \wedge$$

$$\left(\lambda_3\sqrt{\lambda} \le |\lambda_4|\sqrt{\lambda_{23}^+}\ \vee\ 2\lambda_1 + \lambda_4 + \sqrt{(\lambda - \lambda_4^2)(2\lambda_2/\lambda_3 + 1)} \ge 0\right)$$




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# Theo. Exp. Constraints

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$$|\lambda| \leq 16\pi,\ |\lambda_1+\lambda_4| \leq 8\pi,\ |\lambda_1| \leq 8\pi,\ |2\lambda_1+3\lambda_4| \leq 16\pi,$$
$$|2\lambda_1-\lambda_4| \leq 16\pi,\ |\lambda_2| \leq 4\pi,\ |\lambda_2+\lambda_3| \leq 4\pi,\ |2\lambda_2-\lambda_3| \leq 8\pi,$$
$$|\lambda+4\lambda_2+8\lambda_3 \pm \sqrt{(\lambda-4\lambda_2-8\lambda_3)^2+16\lambda_4^2}\,| \leq 32\pi,$$
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$$(\lambda \geq 0)\ \wedge\ (\lambda_{23}^{+} \geq 0)\ \wedge\ (\lambda_2+\lambda_3/2 \geq 0)\ \wedge\ (\lambda_1+\sqrt{\lambda\,\lambda_{23}^{+}} \geq 0)$$
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$$\left(\lambda_3\sqrt{\lambda} \leq |\lambda_4|\sqrt{\lambda_{23}^{+}}\ \vee\ 2\lambda_1+\lambda_4+\sqrt{(\lambda-\lambda_4^2)(2\lambda_2/\lambda_3+1)} \geq 0\right)$$

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

$$T_d = -2Tr(I_n)\sum_f m_f^2/v_d^2 + 3(\lambda+2\lambda_1+\lambda_4) + 2(m_W^2/v^2)(2+1/c_w^2),$$
$$T_t = (2\lambda_1+8\lambda_2+6\lambda_3+\lambda_4) + 4(m_W^2/v^2)(1+1/c_w^2)$$

# Theo. Exp. Constraints

## 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 : $m_{H^{\pm\pm}} \geq 97.3$ GeV.
- ∗ From LHC
  - ○ For $v_t \lesssim 10^{-4}$ GeV, $m_{H^{\pm\pm}} > 820$ GeV.
  - ○ For $v_t \gtrsim 10^{-4}$ GeV, $m_{H^{\pm\pm}} > 90 - 100$ GeV.

# Processes

## $e^+ e^- \to \gamma\, h^0$

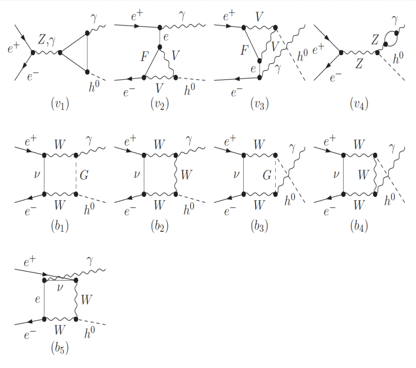


Figure: Generic Feynman diagrams involving the various contributions to $e^- e^+ \to \gamma\, h^0$ process in the HTM. In all diagrams $V$ stands for $W\,\mathrm{and/or\,Z}$.

# Processes

## $e^{-}\gamma \rightarrow e^{-}\, h^{0}$

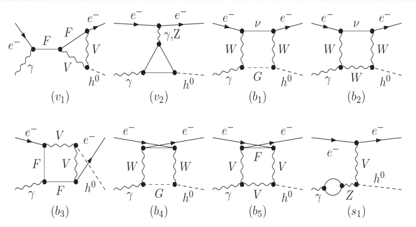


Figure: Generic Feynman diagrams involving the various contributions to $e^{-}\, e^{+} \rightarrow \gamma\, h^{0}$ process in the HTM. In all diagrams $V$ stands for $W$ and/or Z .




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# Observables

for illustrative purpose we introduce the ratio,

$$R_{\gamma h^0} \equiv \frac{\sigma(e^+e^- \to \gamma h^0)}{\sigma_{\rm SM}(e^+e^- \to \gamma H)}, \; R_{e^- h^0} \equiv \frac{\sigma(e^-\gamma \to e^- h^0)}{\sigma_{\rm SM}(e^-\gamma \to e^- H)}$$

$$R_{\gamma V} \equiv \frac{\sigma(gg \to h^0) \times Br(h^0 \to \gamma V)}{\sigma(gg \to h^0)^{\rm SM} \times Br(h^0 \to \gamma V)^{\rm SM}} \; (V = \gamma, Z)$$

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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

## Allowed space parameters

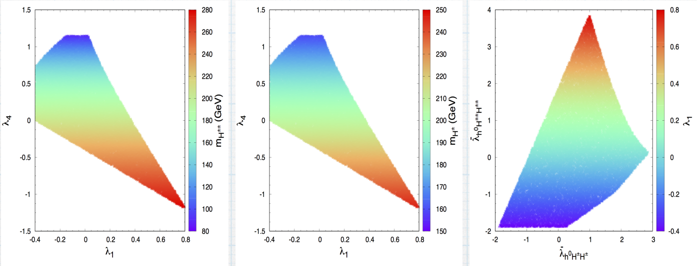


Figure: The allowed space parameter of the HTM given by the variation of $m_{H^{\pm\pm}}$ (left) and $m_{H^{\pm}}$ (middle) in $(\lambda_1, \lambda_4)$ plane, and the correlation between $\bar{\lambda}_{h^0 H^+ H^-}$ and $\bar{\lambda}_{h^0 H^{++} H^{--}}$ following the sign of $\lambda_1$. Input parameters are $\lambda = 0.522$ ($m_{h^0} = 125.09$ GeV), $\lambda_3 = 2\lambda_2 = 0.2$, $v_t = \mu = 1$ GeV.




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# Numerical

## $\sigma(e^+e^- \to \gamma h^0)$, $\sigma(e^-\gamma \to e^- h^0)$ vs $\sqrt{s}$ in the HTM

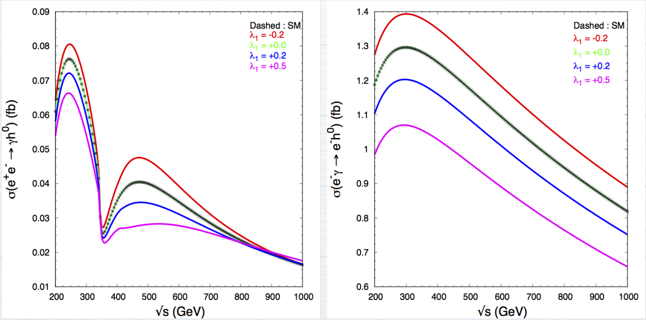


Figure: Cross sections for the $e^+e^-$ ($e^-\gamma$) $\to \gamma h^0$ ($e^- h^0$) processes in HTM as a function of center-of-mass energy for various values of $\lambda_1$. We take : $\lambda = 0.522$ ($m_{h^0} = 125.09$ GeV), $\lambda_3 = 2\lambda_2 = 0.2$, $v_t = \mu = 1$ GeV and $\lambda_4 = 0$. The SM limit is achieved for $\lambda_1 = 0$.




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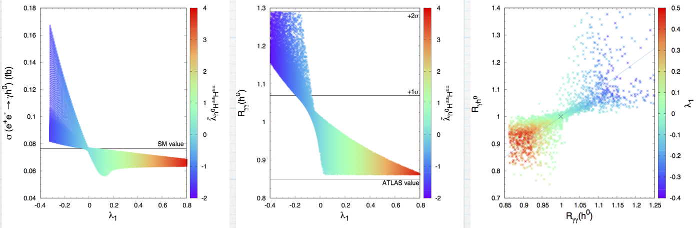
# Numerical

## $\sigma(e^+e^- \to \gamma h^0)$ vs $R_{\gamma V}(h^0)$



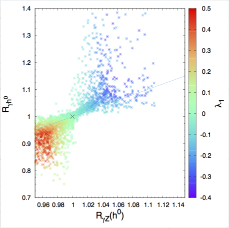




Figure: $\sigma(e^+e^- \to \gamma h^0)$ (fb) and $R_{\gamma\gamma}(h^0)$ as a function of $\lambda_1$ in the HTM for $\sqrt{s} = 250$ GeV. $R_{\gamma h^0}$ and $R_{\gamma V}$ correlations following the $\lambda_1$ sign.

# Numerical

## $\sigma(e^-\gamma \to e^- h^0)$ vs $R_{\gamma V}(h^0)$

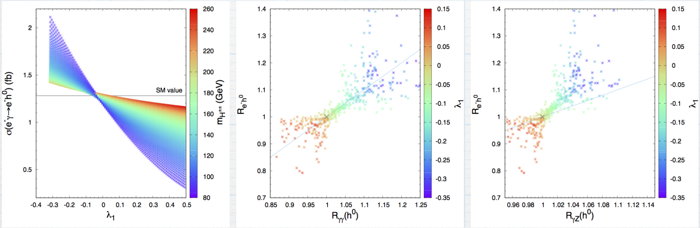



Figure: Variation of $\sigma(e^-\gamma \to e^- h^0)$ (fb), $R_{e^- h^0}$, $R_{\gamma\gamma}(h^0)$ and $R_{\gamma Z}(h^0)$ as a function of $\lambda_1$ in the HTM for $\sqrt{s} = 250$ GeV.

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## Correlation

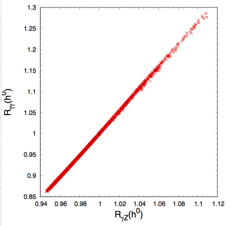


Figure: $R_{\gamma\gamma}(h^0)$ and $R_{\gamma Z}(h^0)$ correlation in the HTM.

# 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.



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∗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 $e^+e^- \to \gamma h^0$ and $e^-\gamma \to e^- h^0$ can be the key in the framework of HTM.



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# Conclusion

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- the one-loop processes $e^+e^- \to \gamma h^0$ and $e^-\gamma \to e^- h^0$ 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.

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- ∗the one-loop processes $e^+e^- \to \gamma h^0$ and $e^-\gamma \to e^- h^0$ 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

# Perspective

Thank you for your attention



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