Associated pair production of charged Higgs bosons at linear collider in the Seesaw Type II model

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work in progress ....

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Table of contents

Review : HTM 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 Φ,

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

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

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

* After EWSB, ϕ^0 and δ^0 acquire vevs denoted as v_d and v_t with $v^2 = v_d^2 + 2\, v_t^2 = (246\,\mathrm{GeV})^2$.
  in the Seesaw Type-II

$$m_\nu \approx Y_\Delta \mu v_d^2 / M_\Delta^2$$

Potential & Higgs masses

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

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

* After EWSB, 7 physical Higgs states :

$$\begin{aligned} &H^{\pm\pm} \,\mathrm{and}\, H^\pm, \quad (\Delta m = m_{H^{\pm\pm}}^2 - m_{H^{\pm\pm}}^2 = \lambda_4/4) \\ &A, \\ &H, \\ &h \end{aligned}$$

* In what follows, we assume h to be the observed 125 GeV

Theo. Constraints

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

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

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

$$(\lambda \geq 0)\ \wedge\ (\lambda_{23}^{+} \geq 0)\ \wedge\ (\lambda_2 + \lambda_3/2 \geq 0)\ \wedge\ (\lambda_1 + \sqrt{\lambda\,\lambda_{23}^{+}} \geq 0)$$
$$\wedge\ (\lambda_{14}^{+} + \sqrt{\lambda\,\lambda_{23}^{+}} \geq 0)\ \wedge$$
$$\left(\lambda_3\sqrt{\lambda} \leq |\lambda_4|\sqrt{\lambda_{23}^{+}}\ \vee\ 2\lambda_1 + \lambda_4 + \sqrt{(2\lambda\lambda_3 - \lambda_4^2)(2\lambda_2/\lambda_3 + 1)} \geq 0\right)$$

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

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

Exp. Constraints

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.

Looking for NP

Search for simply charged Higgs boson

- $gg \to b\bar{b}H^+H^-$ [S. Moretti et all, Eur.Phys.J. C33 (2004) 41-52 (2004)].
- $e^+e^-, \mu^+\mu^- \to H^+H^-$ [M. Hashemi, Commun.Theor.Phys. 61 (2014)].
- $q\bar{q} \to H^+H^-$ [J. Baglio, PoS CHARGED(2016) 027].

Search for doubly charged Higgs boson

- $q\bar{q} \to H^{++}H^{--} \to 2w^+2w^-$ [A. G. Akeroyd et al, PhysRevD.72.035011 (2005)].
- $p\bar{p} \to H^{++}H^{--}X \to 2\mu^+2\mu^-$ [V.M. Abazov et al, D0 Collaboration, PhysRevLett.101.071803 (2008)].
- $e^+e^- \to H^{++}H^{--} \to 2w^+2w^-$ [P. Agrawal et al, PhysRevD.98.015024 (2018)].

ZH^+H^- and $ZH^{++}H^{--}$ within Type-II Seesaw Model !!!

$e^+e^- \to ZH^\pm H^\mp$ process

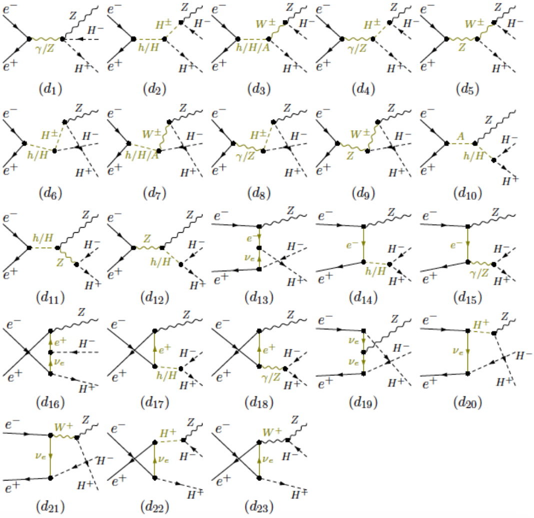


Figure: Generic Feynman diagrams for $e^+e^- \to ZH^\pm H^\mp$ process.

$e^+e^- \to ZH^{\pm\pm}H^{\mp\mp}$ process

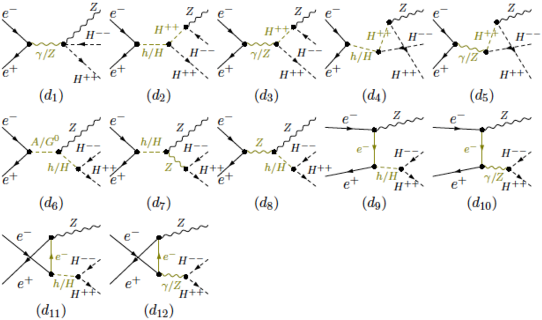
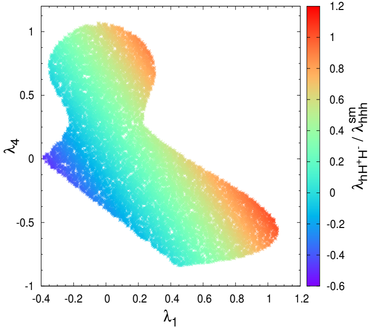


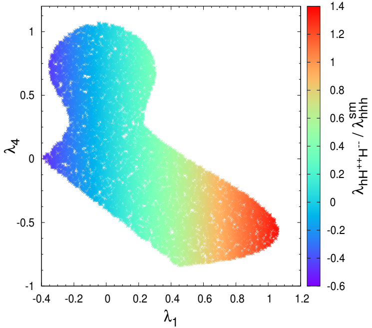
Figure: Generic Feynman diagrams for $e^+e^- \to ZH^{\pm\pm}H^{\mp\mp}$ process.

Involved Couplings

$c_{H^+H^-\gamma Z}$	$\frac{ie^2}{c_w s_w}(c_w^2 s_{\beta'}^2 - (1+c_{\beta'}^2)s_w^2)$	$\approx -2i\, e^2\, s_w/c_w$
$c_{H^+H^-ZZ}$	$\frac{ie^2}{2c_w^2 s_w^2}(c_w^4 s_{\beta'}^2 - 2s_w^2 c_w^2 s_{\beta'}^2 + (1+3c_{\beta'}^2)s_w^4)$	$\approx +2i\, e^2\, s_w^2/c_w^2$
$c_{H^{++}H^{--}\gamma Z}$	$\frac{4ie^2}{c_w s_w}(c_w^2 - s_w^2)$	
$c_{H^{++}H^{--}ZZ}$	$\frac{2ie^2}{c_w^2 s_w^2}(c_w^2 - s_w^2)^2$	
$c_{ZZ[h,H]}$	$\frac{iem_W}{c_w^2 s_w}\left[c_\alpha c_{\beta'} + 2\sqrt{2}s_\alpha s_{\beta'}, 2\sqrt{2}c_\alpha s_{\beta'} - s_\alpha c_{\beta'}\right]$	$\approx \frac{iem_W}{c_w^2 s_w}[1,0]$
$c_{H^+H^-\gamma}$	ie	
$c_{H^{++}H^{--}\gamma}$	$2ie$	
$c_{H^+H^-Z}$	$\frac{ie}{2c_w s_w}((1+c_{\beta'}^2)s_w^2 - s_{\beta'}^2 c_w^2)$	ies_w/c_w
$c_{H^{++}H^{--}Z}$	$\frac{ie}{c_w s_w}(s_w^2 - c_w^2)$	
$c_{H^+H^-h}$	$-\frac{1}{2}((2\tilde{\lambda}_{14}^+ c_\alpha v_d + 4\lambda_{23}^+ s_\alpha v_t)c_{\beta'}^2 + c_{\beta'} s_{\beta'}(4\mu c_\alpha -$ $\sqrt{2}(v_d s_\alpha + v_t c_\alpha)\lambda_4) + s_{\beta'}^2(\lambda v_d c_\alpha + 2\lambda_1 s_\alpha v_t))$	$\approx (\lambda_1 + \frac{\lambda_4}{2})v_d$
$c_{H^{++}H^{--}h}$	$-(\lambda_1 v_d c_\alpha + 2\lambda_2 v_t s_\alpha)$	$\approx \lambda_1 v_d$
$c_{H^+H^-H}$	$+\frac{1}{2}((2\tilde{\lambda}_{14}^+ s_\alpha v_d - 4\lambda_{23}^+ c_\alpha v_t)c_{\beta'}^2 + c_{\beta'} s_{\beta'}(4\mu s_\alpha +$ $\sqrt{2}(v_d c_\alpha - v_t s_\alpha)\lambda_4) + s_{\beta'}^2(\lambda v_d s_\alpha - 2\lambda_1 c_\alpha v_t))$	$\approx -2\lambda_{23}^+ v_t$
$c_{H^{++}H^{--}H}$	$+(\lambda_1 v_d s_\alpha - 2\lambda_2 v_t c_\alpha)$	$\approx -2\lambda_2 v_t$
$c_{e\bar{e}[h,H]}$	$\frac{iem_e}{2m_w s_w}\left[\frac{c_\alpha}{c_{\beta'}}, -\frac{s_\alpha}{c_{\beta'}}\right]$	$\frac{iem_e}{2m_w s_w}[1,0]$
$c_{H^+\nu_i^T \bar{e}_j}$	$C(c_{\beta'}/v_t)(m_\nu^{diag} V_{PMNS}^\dagger)^{ij} P_L$	

Space parameters

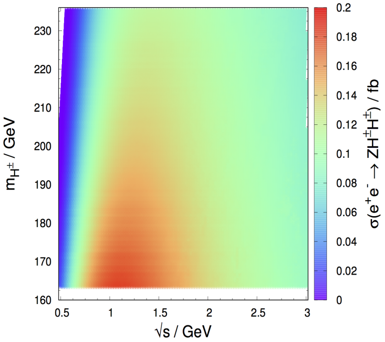


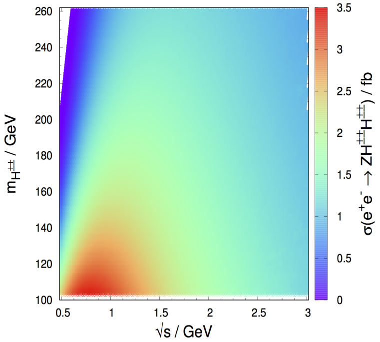


- ∗ High sensitivity to λ_1 and $\lambda_1 + \lambda_4$.
- ∗ Linear dependence on $\lambda_1 + \frac{1}{2}\lambda_4$ for the hH^+H^-
- ∗ $hH^{++}H^{--}$ mainly depends on λ_1
- ∗ NP is to contribute either constructively or destructively.

$\sigma_{ZH^\pm H^\mp}$, $\sigma_{ZH^{\pm\pm}H^{\mp\mp}}$ vs $\sqrt{s}$

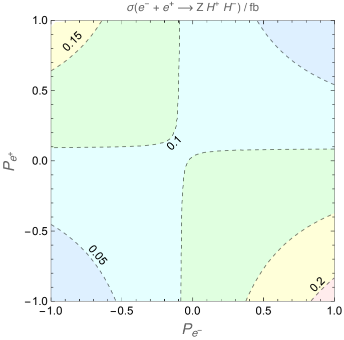
Using FeynArts/FormCalc Mathematica packages

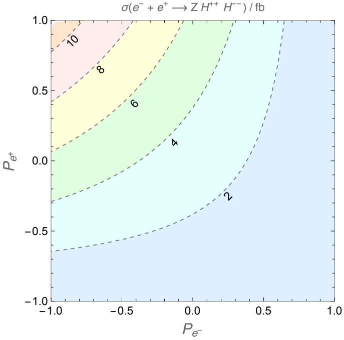




* Improvement can reach 0.2 *fb* at $\sqrt{s} = 1$ TeV for $\sigma_{ZH^\pm H^\mp}$.
* Trilinear coupling $\lambda_{hH^+H^-}/\lambda^{SM}_{hH^+H^-} - 1 \in [-60\%, +20\%]$.
* $\sigma_{ZH^{\pm\pm}H^{\mp\mp}}$ is highly enhanced and drops about 3.4 *fb*

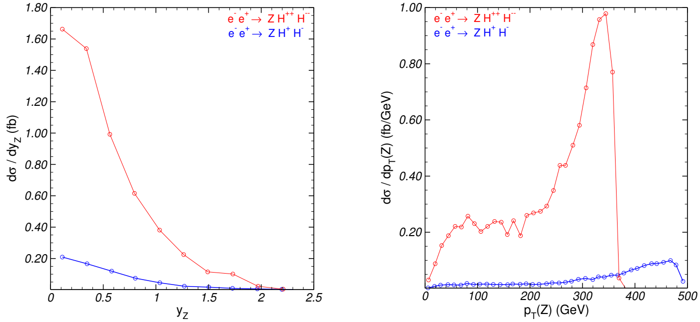
P_{e^-} and P_{e^+} effects





- Two configurations $(P_{e^+}, P_{e^-}) = (\geq +70\%, \leq -60\%)$ and $(\leq -90\%, \geq +90\%)$ that can enhance $\sigma_{ZH^\pm H^\mp}$ the cross section up to 0.15 and 0.2 *fb*.
- $\sigma_{ZH^{\pm\pm}H^{\mp\mp}}$ is dropped significantly at the left top corner where it is over 10*fb*.
- For $(P_{e^-}, P_{e^+}) = (> 0, < 0)$, $\sigma_{ZH^{\pm\pm}H^{\mp\mp}} \searrow$ diagonally.

Diff. cross section



- ∗ $y_Z \leq 1\,(1.5)$ remains largely enough to reap more than $\approx 90\%$ of the events for $\sigma_{ZH^\pm H^\mp}$ $(\sigma_{ZH^{\pm\pm}H^{\mp\mp}})$.
- ∗ most of events for $\sigma_{ZH^\pm H^\mp}$ concentrates at a wide range of p_T^Z.
- ∗ $300 \leq p_T^Z/GeV \leq 400$ is amply sufficient to recover almost all the data for the $ZH^\pm H^\mp$ production.

Conclusion

* ILC is expected to play a crucial role in understanding the nature of the Higgs boson H125 and also the NP BSM due to the clean beams in the initial state.
* For the HTM, VEV had to be very small, i.e. $v_\Delta \ll v$.
* Observation of a simply and/or doubly charged Higgs boson would thus be undoubted evidence of an underlying HTM structure.
* Tree-level processes $e^+e^- \to ZH^+H^-$, $ZH^{++}H^{--}$ could provide a direct handle on the trilinear Higgs self couplings.