Enhancement of the $H^{\pm}W^{\mp}Z$ vertex in the three scalar doublet model

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Charge assignments under $Z_2 \times \tilde{Z}_2$

	$(Z_2,\ \tilde{Z}_2)$ charge							
	Φ_1	Φ_2	η	Q_L	L_L	u_R	d_R	e_R
Type-I	$(+,+)$	$(+,-)$	$(-,+)$	$(+,+)$	$(+,+)$	$(+,-)$	$(+,-)$	$(+,-)$
Type-II	$(+,+)$	$(+,-)$	$(-,+)$	$(+,+)$	$(+,+)$	$(+,-)$	$(+,+)$	$(+,+)$
Type-X	$(+,+)$	$(+,-)$	$(-,+)$	$(+,+)$	$(+,+)$	$(+,-)$	$(+,-)$	$(+,+)$
Type-Y	$(+,+)$	$(+,-)$	$(-,+)$	$(+,+)$	$(+,+)$	$(+,-)$	$(+,+)$	$(+,-)$

Φ_1, Φ_2 are the active doublets
η is the inert doublet
Symmetries:
Z_2(unbroken) guarantees stability of DM
$\tilde{Z}_2$ (soflty-broken) forbids FCNC at tree level

The potential

$$
\begin{aligned}
V = {} & \mu_\eta^2 \eta^\dagger \eta + \mu_1^2 \Phi_1^\dagger \Phi_1 + \mu_2^2 \Phi_2^\dagger \Phi_2 - (\mu_3^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) \\
& + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\
& + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{1}{2}[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}] + \frac{1}{2}\lambda_\eta (\eta^\dagger \eta)^2 \\
& + \rho_1 (\Phi_1^\dagger \Phi_1)(\eta^\dagger \eta) + \rho_2 |\Phi_1^\dagger \eta|^2 + \frac{1}{2}[\rho_3 (\Phi_1^\dagger \eta)^2 + \text{h.c.}] \\
& + \sigma_1 (\Phi_2^\dagger \Phi_2)(\eta^\dagger \eta) + \sigma_2 |\Phi_2^\dagger \eta|^2 + \frac{1}{2}[\sigma_3 (\Phi_2^\dagger \eta)^2 + \text{h.c.}]
\end{aligned}
$$

The scalar fields can be parametrised as

$$
\Phi_i = \begin{bmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + i z_i) \end{bmatrix}, \quad (i = 1, 2), \qquad \eta = \begin{bmatrix} \eta^+ \\ \frac{1}{\sqrt{2}}(\eta_H + i\eta_A) \end{bmatrix},
$$

where v_i are the VEVs of Φ_i with $v_1^2 + v_2^2 = v^2 \simeq (246\ \text{GeV})^2$. The ratio of the two VEVs is given by $\tan\beta = v_2/v_1$.

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The Yukawa Lagrangian

$$\mathcal{L}_Y = - Y_u \overline{Q}_L i\sigma_2 \Phi_u^* u_R - Y_d \overline{Q}_L \Phi_d d_R - Y_e \overline{L}_L \Phi_e e_R + \text{h.c.},$$

The interaction terms

$$-\mathcal{L}_Y^{\text{int}} = \sum_{f=u,d,e} \frac{m_f}{v} \left[\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - 2 i I_f \xi_f \overline{f} \gamma_5 f A \right]$$
$$+ \frac{\sqrt{2}}{v} \left[V_{ud} \overline{u} \left(m_d \xi_d P_R - m_u \xi_u P_L \right) d H^+ + m_e \xi_e \overline{\nu} P_R e H^+ + \text{h.c.} \right],$$

ξ_h^f and ξ_H^f are defined by

$$\xi_h^f = \sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha),$$
$$\xi_H^f = \cos(\beta - \alpha) - \xi_f \sin(\beta - \alpha),$$

SM-like limit or alignment limit defined by $\sin(\beta - \alpha) \to 1$

The Yukawa Lagrangian

	Mixing factor		
	ξ_u	ξ_d	ξ_e
Type-I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type-II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
Type-X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type-Y	$\cot\beta$	$-\tan\beta$	$\cot\beta$

The vertex

- Loop amplitude of $H^{\pm} \to W^{\pm}V$ ($V = Z,\ \gamma$)

$$i\mathcal{M}(H^{\pm} \to W^{\pm}V) = igm_W V_V^{\mu\nu} \epsilon_{W\mu}(p_W)\epsilon_{V\nu}(p_V)$$

with $V_V^{\mu\nu}$ written in terms of dimensionless form factors:

$$V_V^{\mu\nu} = g^{\mu\nu}F_V + \frac{p_V^{\mu}p_W^{\nu}}{m_W^2}G_V + i\epsilon^{\mu\nu\rho\sigma}\frac{p_{V\rho}p_{W\sigma}}{m_W^2}H_V$$

with p_W^{μ} and p_V^{μ} incoming momenta for $W^{\pm}$ and V.

- For the case of $V = \gamma$, Ward identity $V_{\gamma}^{\mu\nu}p_{\gamma\nu} = 0$. implies

$$F_{\gamma} = \frac{G_{\gamma}}{2}\left(1 - \frac{m_{H^{\pm}}^2}{m_W^2}\right)$$

where $p_W^2 = m_W^2$ and $(p_W + p_{\gamma})^2 = m_{H^{\pm}}^2$.

The vertex

- Loop amplitude of $H^{\pm} \to W^{\pm} V$ $(V = Z,\ \gamma)$

$$i\mathcal{M}(H^{\pm} \to W^{\pm} V) = i g m_W V_V^{\mu\nu} \epsilon_{W\mu}(p_W) \epsilon_{V\nu}(p_V)$$

with $V_V^{\mu\nu}$ written in terms of dimensionless form factors:

$$V_V^{\mu\nu} = g^{\mu\nu} F_V + \frac{p_V^{\mu} p_W^{\nu}}{m_W^2} G_V + i\epsilon^{\mu\nu\rho\sigma} \frac{p_{V\rho} p_{W\sigma}}{m_W^2} H_V$$

with p_W^{μ} and p_V^{μ} incoming momenta for $W^{\pm}$ and V.

- The effective Lagrangian:

$$\mathcal{L}_{\text{eff}} = f_Z H^+ W_{\mu}^- Z^{\mu} + g_V H^+ F_W^{\mu\nu} F_{V\mu\nu} + i h_V \epsilon_{\mu\nu\rho\sigma} H^+ F_W^{\mu\nu} F_V^{\rho\sigma} + \text{h.c.}$$

where $F_W^{\mu\nu}$ and $F_V^{\mu\nu}$ are the field strength tensors.
The coefficient f_Z has mass dimension one whereas g_V and h_V have mass dimension minus one.

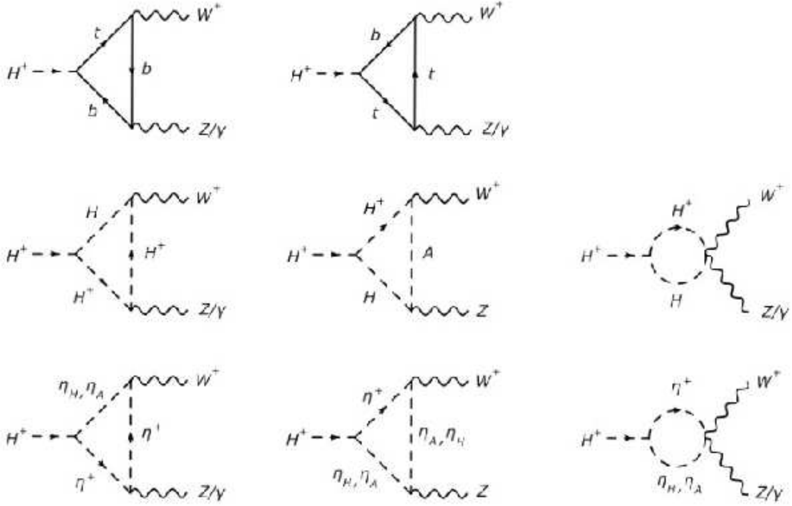
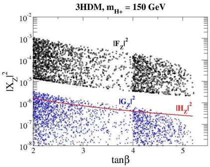
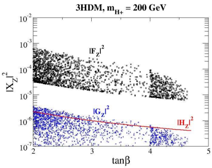
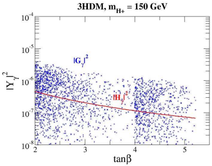


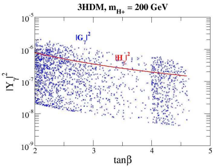
Figure : The 1PI diagrams for the HWZ and $HW\gamma$ vertices. The diagrams which vanish in the limit $\sin(\beta-\alpha)=1$ are not displayed.

Form Factors





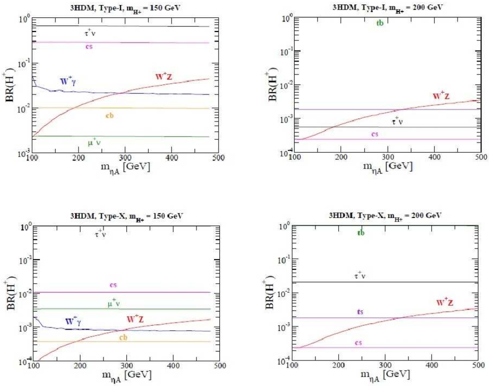




Calculations are made in Type I and X (light $m_{H\pm}$ is more interesting)

$m_H = m_{H\pm}$, -400^2 GeV^2 $< M^2 <$ 400^2 GeV^2, 100 GeV$<$ $m_A <$ 260 (350) GeV, $\tan\beta = 2.5$ in the last plot

Branching Ratios



- If $m_{H^\pm} < m_t$: $t \to H^\pm b$ dominant
- If $m_{H^\pm} > m_t$: $H^\pm$-strahlung dominant

Cross sections

For the signature

$$pp \to b\bar{b}H^{\pm}W^{\mp} \to b\bar{b}W^{\pm}W^{\mp}V$$

$$\sigma^{\rm top}_{S,V} = 2 \times \sigma_{t\bar{t}} \times [1 - {\rm BR}(t \to H^{\pm}b)] \times {\rm BR}(t \to H^{\pm}b) \times {\rm BR}(H^{\pm} \to W^{\pm}V), \quad (1)$$

Also EW productions e.g.

$$pp \to H^{\pm}A/H^{\pm}H \to W^{\pm}V + X^0$$

$$pp \to H^{+}H^{-} \to W^{\pm}V + X^{\pm}$$

$$\sigma^{\rm EW}_{S,V} = (\sigma_{H^{\pm}A} + \sigma_{H^{\pm}H} + 2\sigma_{H^{+}H^{-}}) \times {\rm BR}(H^{\pm} \to W^{\pm}V), \quad (2)$$

	Type-I	Type-X
$\sigma^{\rm top}_{S,Z}$ [fb]	(390, 700, 29)	(15, 28, 1.6)
$\sigma^{\rm top}_{S,\gamma}$ [fb]	(940, 420, 1.4)	(35, 16, 0.075)
$\sigma^{\rm EW}_{S,Z}$ [fb]	(2.3, 7.5, 46)	(0.087, 0.30, 2.5)
$\sigma^{\rm EW}_{S,\gamma}$ [fb]	(5.5, 4.5, 2.2)	(0.20, 0.17, 0.12)

here we are considering the three cases $m_{H^{\pm}} = 130$, 150 and 170 GeV

Summary

- The scalar bosons from the inert doublet give an additional contribution
- $|F_Z|^2$ can be one order of magnitude greater than the one predicted in the 2HDM
- In Type I and X Yukawa interactions, branching ratios are enhanced (10% level)
- The detection with early data at Run 2 of $H^\pm \to W^\pm Z$ signals could represent circumstantial evidence of a 3HDM structure of the Higgs sector