Double Higgs boson production in see-saw type II and the Georgi-Machacek model

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based on
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Motivation

Higgs boson h ($M_h = 125$ GeV) was discovered at LHC in 2012.

The next steps to check the scalar sector of the Standard Model (SM) are

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Large integrated luminosity is required so $2h$ production will not be found in the nearest future at LHC, if there is no New Physics.

$$\Phi \equiv \begin{bmatrix} \Phi^+ \\ \Phi^0 \end{bmatrix} \equiv \begin{bmatrix} \Phi^+ \\ \frac{1}{\sqrt{2}} (v + \varphi + i\chi) \end{bmatrix}, \qquad \Delta \equiv \frac{\vec{\Delta}\vec{\sigma}}{\sqrt{2}} \equiv \begin{bmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \delta^0 & -\frac{\delta^+}{\sqrt{2}} \end{bmatrix}, \delta^0 = \frac{v_\Delta + \delta + i\eta}{\sqrt{2}}.$$

$$\begin{aligned} \mathcal{L} &= |D_\mu \Phi|^2 + \frac{1}{2} m_\Phi^2 \left(\Phi^\dagger \Phi\right) - \frac{\lambda}{2} \left(\Phi^\dagger \Phi\right)^2 + \\ &+ \mathrm{Tr}\left[(D_\mu \Delta)^\dagger (D_\mu \Delta)\right] - M_\Delta^2 \mathrm{Tr}\left[\Delta^\dagger \Delta\right] - \\ &- \frac{\mu}{\sqrt{2}} \left(\Phi^T i\sigma^2 \Delta^\dagger \Phi + h.c.\right) - \\ &- \frac{1}{\sqrt{2}} \left(Y_{\Delta ij} \bar{L}_i i\sigma^2 \Delta C \bar{L}_j + h.c.\right), \end{aligned}$$

Neutrino mass matrix $M_{ij} = v_\Delta Y_{\Delta ij}$.

Y_Δ is large, v_Δ is small
(neutrino masses are small due to smallness of v_Δ)

Coupling of Δ to Z, W, h: $\propto v_\Delta$
Coupling of Δ to fermions: $\propto \frac{m_\nu}{v_\Delta}$

Mode $\Delta^0 \to \nu\nu$ dominates in Δ^0 decays

Mode $\Delta^{++} \to l^+ l^+$ dominates in Δ^{++} decays

Search for Δ^{++}:

$$Z^0/\gamma \to \Delta^{++}\Delta^{--} \to l^+ l^+ l^- l^-$$

$$\Downarrow$$

$M_\Delta > 400$ GeV according to LHC data

2nd scenario

$Y_\triangle$ is small, $v_\triangle$ is large
(neutrino masses are small due to smallness of $Y_\triangle$)

Diboson decays dominate in Δ^0, Δ^{++} decays

Search for Δ^{++}: $M_\triangle \gtrsim 100$GeV

Vector bosons masses and limit on v_Δ

$$\mathcal{L}_{V^2} = g^2 \left|\delta^0\right|^2 W^+W^- + \frac{1}{2}g^2 \left|\Phi^0\right|^2 W^+W^- + \bar{g}^2 \left|\delta^0\right|^2 Z^2 + \frac{1}{4}\bar{g}^2 \left|\Phi^0\right|^2 Z^2.$$

$$\begin{cases} M_W^2 & = & \frac{g^2}{4}\left(v^2 + 2v_\Delta^2\right), \\ M_Z^2 & = & \frac{\bar{g}^2}{4}\left(v^2 + 4v_\Delta^2\right). \end{cases}$$

$$v^2 + 2v_\Delta^2 = (246\ \text{GeV})^2,$$

$$\frac{M_W}{M_Z} \approx \left(\frac{M_W}{M_Z}\right)_{\text{SM}} \left(1 - \frac{v_\Delta^2}{v^2}\right).$$

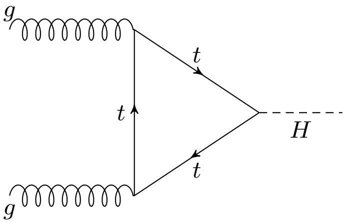
$$v_\Delta < 5\ \text{GeV}$$

Mixing

$$V(\varphi,\delta) = \frac{1}{2}\lambda v^2\varphi^2 + \frac{1}{2}M_\Delta^2\delta^2 - \mu v\varphi\delta = \frac{1}{2}\begin{bmatrix}\varphi & \delta\end{bmatrix}\begin{bmatrix}\lambda v^2 & -\mu v \\ -\mu v & M_\Delta^2\end{bmatrix}\begin{bmatrix}\varphi \\ \delta\end{bmatrix}$$

$$\begin{bmatrix}h \\ H\end{bmatrix} = \begin{bmatrix}\cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha\end{bmatrix}\begin{bmatrix}\varphi \\ \delta\end{bmatrix}$$

$$\tan 2\alpha = \frac{4v_\Delta}{v}\frac{M_\Delta^2}{M_\Delta^2 - \lambda v^2}$$



H production

$$\underline{v_\Delta = 5 \text{ GeV}, \qquad M_H = 300 \text{ GeV}}$$

$$\sin^2 \alpha \approx \left[(2v_\Delta/v) \, / \, \left(1 - M_h^2/M_H^2\right)\right]^2 \approx 2.4 \cdot 10^{-3}$$

gluon fusion

M_h (GeV)	125	300
$\sigma_{gg\to h}$ (pb)	$49.97 \pm 10\%$	$11.07 \pm 10\%$
M_H (GeV)	X	300
$\sigma_{gg\to H}$ (fb)	X	$25 \pm 10\%$

vector boson fusion

$$\sigma_{ZZ\to H} = \left(\frac{2v_\Delta}{v}\frac{1 - 2M_h^2/M_H^2}{1 - M_h^2/M_H^2}\right)^2 \times \left(\sigma_{ZZ\to h}\right)^{\text{SM}} \approx 10^{-3} \times \left(\sigma_{ZZ\to h}\right)^{\text{SM}}$$

$$\sigma_{ZZ\to H} = 0.365(1) \text{ fb}$$

H decays

$$\Gamma_{H\to hh} = \frac{v_\Delta^2}{v^4}\frac{M_H^3}{8\pi}\left[\frac{1+2\left(\frac{M_h}{M_H}\right)^2}{1-\left(\frac{M_h}{M_H}\right)^2}\right]^2\sqrt{1-4\frac{M_h^2}{M_H^2}}, \qquad 77\%$$

$$\Gamma_{H\to ZZ} = \frac{v_\Delta^2}{v^4}\frac{M_H^3}{8\pi}\left[\frac{1-2\left(\frac{M_h}{M_H}\right)^2}{1-\left(\frac{M_h}{M_H}\right)^2}\right]^2\left(1-4\frac{M_Z^2}{M_H^2}+12\frac{M_Z^4}{M_H^4}\right)\sqrt{1-4\frac{M_Z^2}{M_H^2}}, \qquad 19\%$$

$$\Gamma_{H\to WW} = \frac{v_\Delta^2}{v^4}\frac{M_H^3}{4\pi}\left[\frac{M_h^2/M_H^2}{1-\left(\frac{M_h}{M_H}\right)^2}\right]^2\left(1-4\frac{M_W^2}{M_H^2}+12\frac{M_W^4}{M_H^4}\right)\sqrt{1-4\frac{M_W^2}{M_H^2}}, \qquad 3\%$$

$$\Gamma_{H\to gg} = \frac{v_\Delta^2}{v^4}\frac{M_H^3}{2\pi}\left(\frac{\alpha_s}{3\pi}\right)^2\left(1-\frac{M_h^2}{M_H^2}\right)^{-2}, \qquad 0.05\%$$

$$\Gamma_{H\to t\bar{t}} = \frac{v_\Delta^2}{v^4}\frac{N_c m_t^2 M_H}{2\pi}\frac{1}{(1-M_h^2/M_H^2)^2}\left(1-4\frac{m_t^2}{M_H^2}\right)^{3/2}, \qquad 0\%$$

$$\underline{\sigma(pp\to H+X)\times \mathrm{Br}(H\to hh)\approx 20\ \text{fb}}$$

Georgi-Machacek model

$$\Phi = \begin{bmatrix} \Phi^{0*} & \Phi^{+} \\ \Phi^{-} & \Phi^{0} \end{bmatrix}, \qquad \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} v & 0 \\ 0 & v \end{bmatrix}$$

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$$X = \begin{bmatrix} \delta^{0*} & \xi^{+} & \delta^{++} \\ \delta^{-} & \xi^{0} & \delta^{+} \\ \delta^{--} & \xi^{-} & \delta^{0} \end{bmatrix}, \qquad \langle X \rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} v_\Delta & 0 & 0 \\ 0 & v_\Delta & 0 \\ 0 & 0 & v_\Delta \end{bmatrix}$$

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$$\left\{ \begin{array}{rcl} M_W^2 & = & \frac{g^2}{4} \left(v^2 + 4 v_\Delta^2 \right), \\ M_Z^2 & = & \frac{\bar{g}^2}{4} \left(v^2 + 4 v_\Delta^2 \right), \end{array} \right. \Rightarrow \frac{M_W}{M_Z} = \left(\frac{M_W}{M_Z} \right)_{SM}$$

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Two singlets which mix to form mass eigenstates h and H are:

$$\begin{cases} H_1^0 = \varphi, \\ H_2^0 = \sqrt{\frac{2}{3}}\delta + \sqrt{\frac{1}{3}}\xi^0, \end{cases}$$

Georgi-Machacek model

h coupling constants:

$$\begin{aligned} \kappa_V &\approx 1 + 3\left(\tfrac{v_\Delta}{v}\right)^2 \\ \kappa_f &\approx 1 - \left(\tfrac{v_\Delta}{v}\right)^2 \end{aligned}$$

$$\mu \equiv \frac{\sigma}{\sigma_{SM}} \cdot \frac{\mathrm{Br}}{\mathrm{Br}_{\mathrm{SM}}} = 1 + \mathcal{O}\left(\frac{v_\Delta^2}{v^2}\right)$$

$$\mu_{\tau\bar{\tau}} \approx 1 - \left(2\frac{v_\Delta}{v}\right)^2, \qquad \mu_{VV} \approx 1 + \left(2\frac{v_\Delta}{v}\right)^2, \qquad \mu_{b\bar{b}} \approx 1 + \left(\frac{2v_\Delta}{v}\right)^2.$$

The value $v_\Delta = 50$ GeV is not excluded!

$\sigma\,(pp \to H + X) \sim 2.5$ pb

Branching ratios

$$\Gamma_{H\to hh} \approx \frac{v_\Delta^2}{v_\phi^4}\frac{3M_H^3}{16\pi}\left[\frac{1+2\left(\frac{M_h}{M_H}\right)^2}{1-\left(\frac{M_h}{M_H}\right)^2}\right]^2\sqrt{1-4\frac{M_h^2}{M_H^2}}, \qquad 98\%$$

$$\Gamma_{H\to ZZ} \approx \frac{v_\Delta^2}{v_\phi^4}\frac{M_H^3}{48\pi}\left[\frac{1-4\left(\frac{M_h}{M_H}\right)^2}{1-\left(\frac{M_h}{M_H}\right)^2}\right]^2\left(1-4\frac{M_Z^2}{M_H^2}+12\frac{M_Z^4}{M_H^4}\right)\sqrt{1-4\frac{M_Z^2}{M_H^2}}, \qquad 0.6\%$$

$$\Gamma_{H\to WW} \approx \frac{v_\Delta^2}{v_\phi^4}\frac{M_H^3}{24\pi}\left[\frac{1-4\left(\frac{M_h}{M_H}\right)^2}{1-\left(\frac{M_h}{M_H}\right)^2}\right]^2\left(1-4\frac{M_W^2}{M_H^2}+12\frac{M_W^4}{M_H^4}\right)\sqrt{1-4\frac{M_W^2}{M_H^2}}. \qquad 1.4\%$$

$\mathrm{Br}\,(H\to hh)\approx 98\%$ for $M_H = 300$ GeV,
so direct searches in $H\to ZZ$ mode do not lead to additional limits.

Conclusions

- Introduction of the isotriplet with hypercharge $Y_\Delta = 2$ increases the $2h$ cross section by the value which is comparable with that in SM.

- In the Georgi–Machacek model custodial symmetry is preserved so the limits on model parameters are much weaker and it is possible to significantly enhance the production of new scalar H.

- In the Georgi–Machacek model ZZ and WW decay modes can be very suppressed so $H \to hh$ decays dominate.

Thank you!