Double Higgs boson production with isotripet scalars

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based on
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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

- Measurement of the coupling constants of the h-boson with other SM particles ($t\bar{t}, WW, ZZ, b\bar{b}, \tau\bar{\tau}, \ldots$) with better accuracy

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(see talk by M. Flechl)

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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.

See-saw type II

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

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

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

1st scenario

$\underline{Y_\Delta \text{ is large, } v_\Delta \text{ is small}}$

(neutrino masses are small due to smallness of v_Δ - "natural" case)

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_Δ is small, v_Δ is large
(neutrino masses are small due to smallness of Y_Δ - lack of "naturalness")

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

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

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

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

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

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

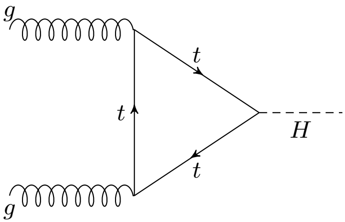
$$v_\Delta < 5\ \text{GeV}$$

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

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

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!