Multi-Higgs Impacts on the ρ parameters, a Neutral Higgs to WW, ZZ and a Charged Higgs to WZ

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arXiv: 1803.05254 (J.-Y. Cen, R-H. Chen, X-G He, J.-Y. Su)
arXiv: 1805.01698 (C-W. Chiang, X-G He, G. Li)

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Standard Model and Higgs Physics

Standard Model is based on $SU(3)_C xSU(2)_L xU(1)_Y$ gauge interaction.

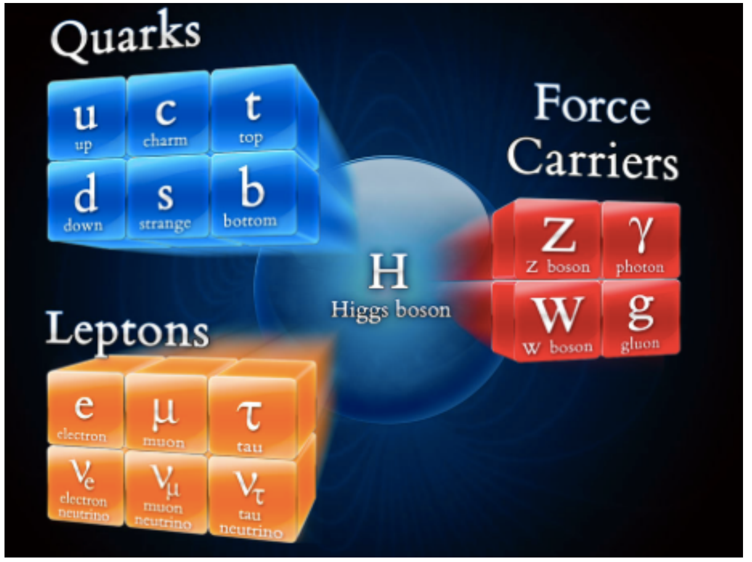
Only one Higgs doublet Φ (H) doing all jobs

Symmetry breaking

Generate masses for all SM particles

One physical neutral scalar Higgs boson ϕ^0 (η)

The "God" particle



When going beyond SM, more possibilities!

Multi-dobulet Higgs, Singlet Higgs and higher dimensional Higgs multi-plets…

SM Higgs couplings properties

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)\,,$$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ \phi^0 + i a^0 \end{pmatrix},$$

$$V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$D_\mu \Phi = (\partial_\mu + i g \sigma^a W^a_\mu / 2 + i g' Y B_\mu / 2)\Phi$$

$$\mathcal{L}_{\text{Yukawa}} = -\hat{h}_{d_{ij}} \bar{q}_{L_i} \Phi\, d_{R_j} - \hat{h}_{u_{ij}} \bar{q}_{L_i} \tilde{\Phi} u_{R_j} - \hat{h}_{l_{ij}} \bar{l}_{L_i} \Phi\, e_{R_j} + h.c.,$$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

$$m_W^2 = \frac{g^2 v^2}{4}\,, \quad m_Z^2 = \frac{(g'^2 + g^2) v^2}{4}.$$

$$\frac{g^2}{g'^2 + g^2} = \cos^2\theta_W$$

$$\mathcal{L} = -g_{Hff}\bar{f}fH + \frac{g_{HHH}}{6}H^3 + \frac{g_{HHHH}}{24}H^4$$

$$+\delta_V V_\mu V^\mu \left(g_{HVV}H + \frac{g_{HHVV}}{2}H^2\right)$$

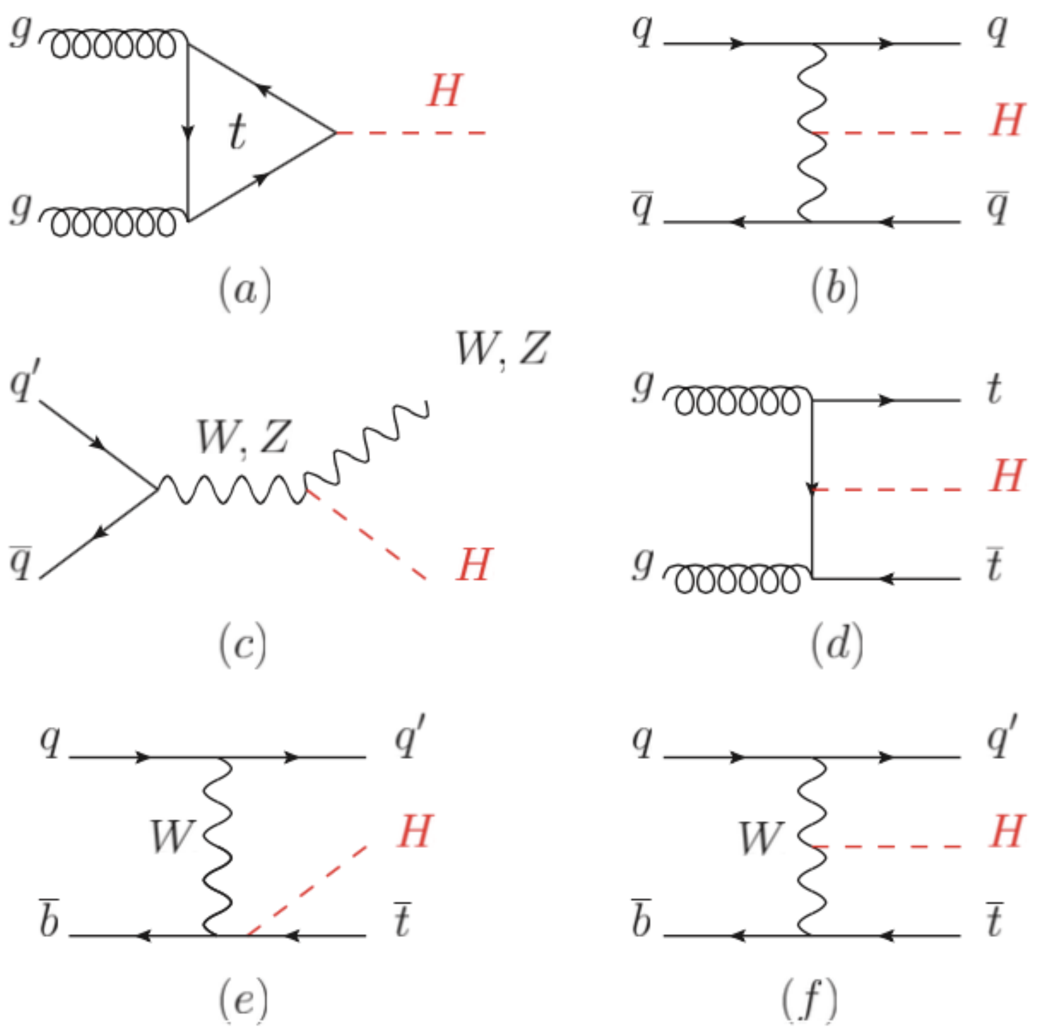
($H=\phi^0$ (h))

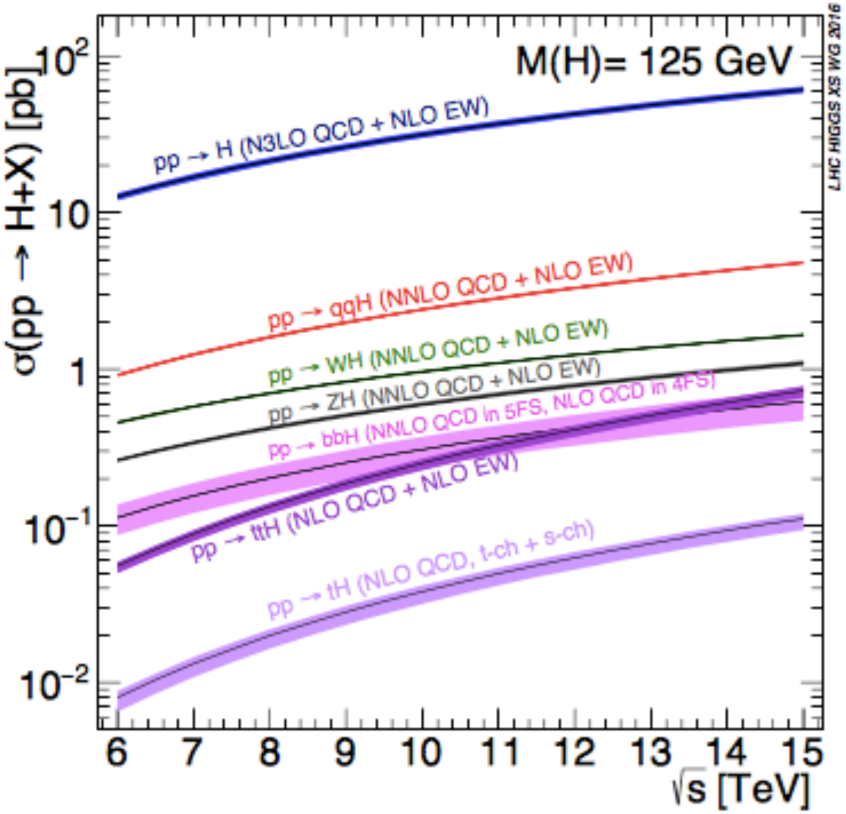
$$g_{Hf\bar{f}} = \frac{m_f}{v},\ g_{HVV} = \frac{2m_V^2}{v},\ g_{HHVV} = \frac{2m_V^2}{v^2},$$

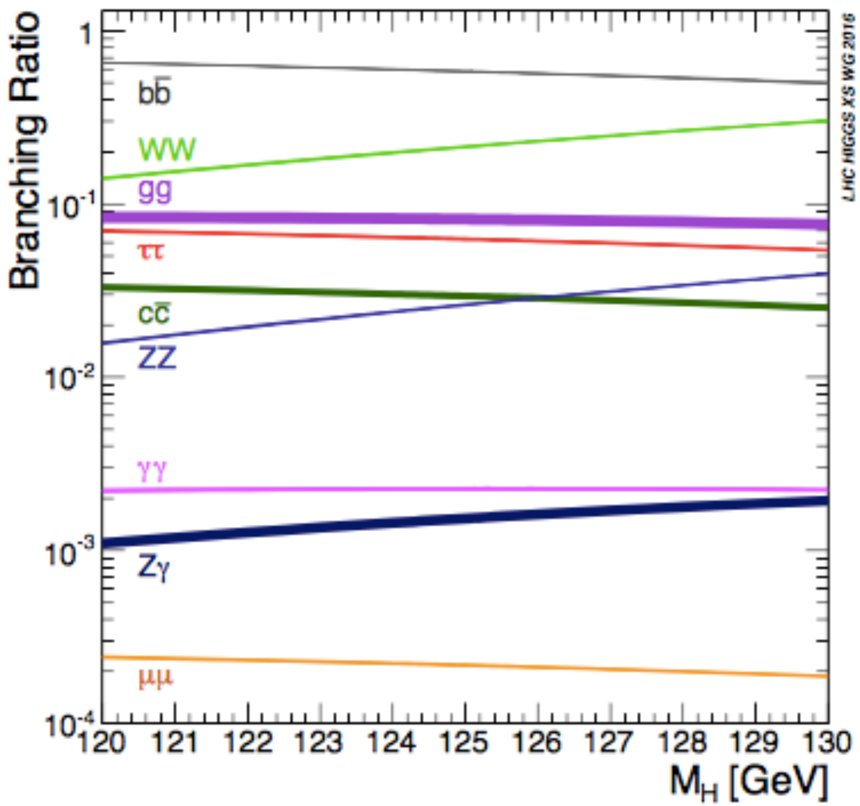
$$g_{HHH} = \frac{3m_H^2}{v},\ g_{HHHH} = \frac{3m_H^2}{v^2},$$

$V = \mathrm{W}^{\pm}$ or Z and $\delta_W = 1, \delta_Z = 1/2.$ $\lambda_{WZ}=\delta_W/2\delta_Z=1$

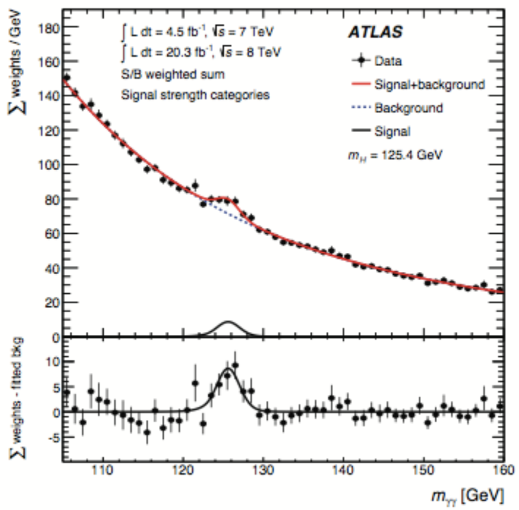
Main contributions for pp to H X

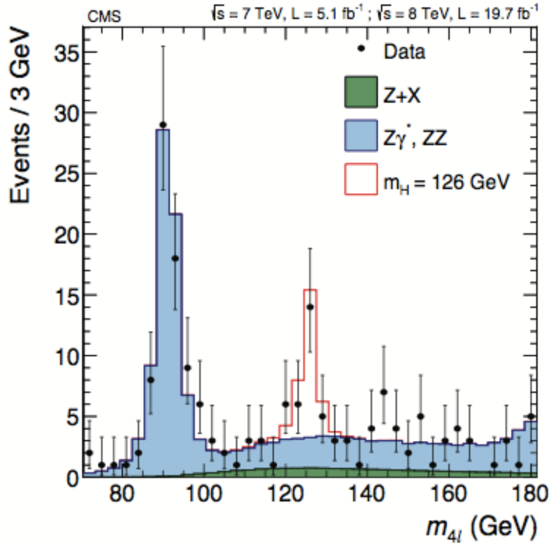


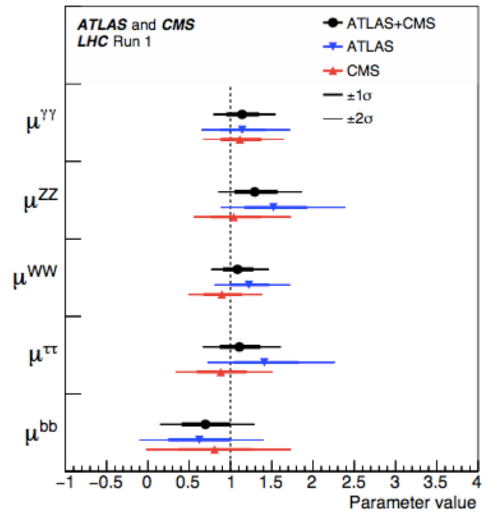

M(H)= 125 GeV
pp → H (N3LO QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD + NLO EW)
pp → bbH (NNLO QCD in 5FS, NLO QCD in 4FS)
pp → ttH (NLO QCD + NLO EW)
pp → tH (NLO QCD, t-ch + s-ch)
σ(pp → H+X) [pb]
√s [TeV]
LHC HIGGS XS WG 2016

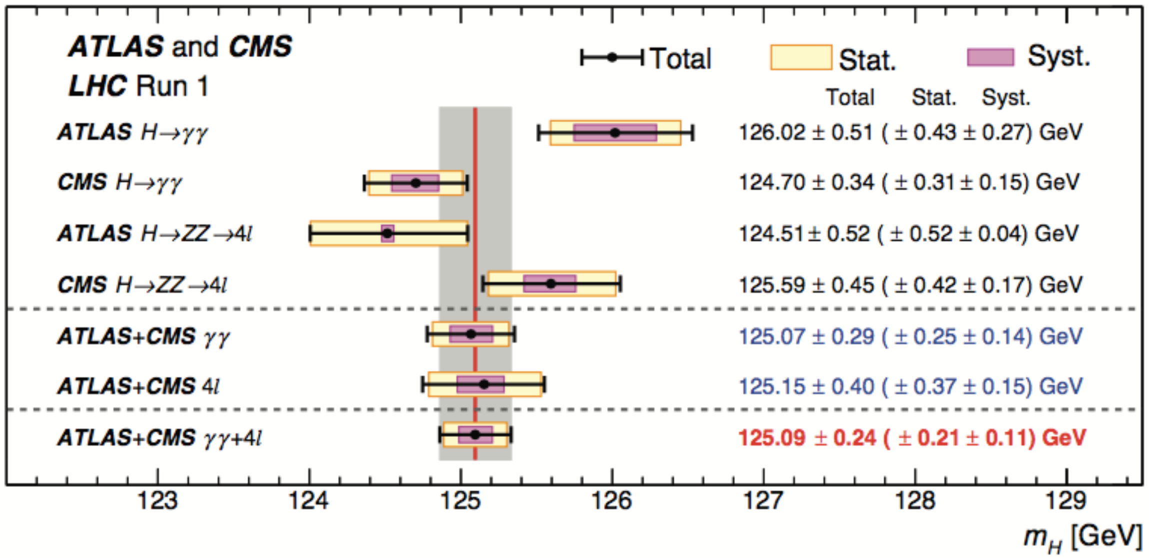

Branching Ratio
bb̄
WW
gg
ττ
cc̄
ZZ
γγ
Zγ
μμ
M_H [GeV]
LHC HIGGS XS WG 2016

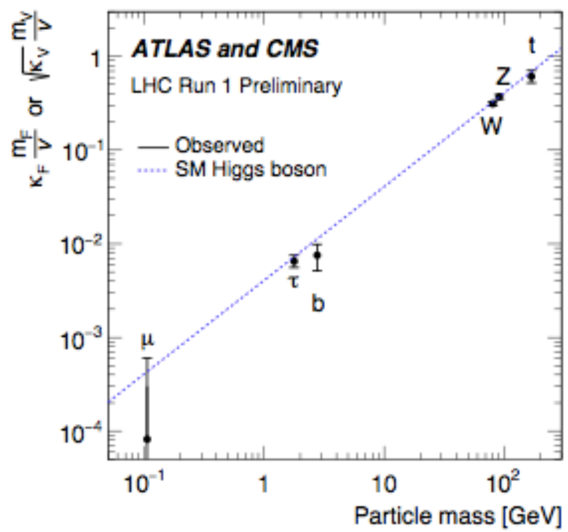
The 125 GeV Higgs is consistent with SM one!











Beyond SM Higgs properties ?

H: (J, Y)

Concentrate on ρ and λ_W

In general there will be charged Higgs bosons

$$\rho = \frac{\sum_i (J_i(J_i+1) - Y_i^2) v_i^2}{\sum_i 2Y_i^2 v_i^2}\,, \qquad \rho = 1.00037 \pm 0.00023$$

$$L = g_Z^{h_i}(g^2/\cos^2\theta_W) h_i Z_\mu Z^\mu + 2 g_W^{h_i}(g^2) h_i W_\mu^+ W^{-\mu}\,,$$

$$g_Z^{h_i} = Y_i^2 v_i \text{ and } g_W^{h_i} = (1/2)(J_i(J_i+1) - Y_i^2) v_i$$

$$\lambda_{WZ}^{h_i} = g_W^{h_i} / g_Z^{h_i}$$

Theoretical models with different Higgs Couplings

J-Y Cen, R-H Chen, X-G He and J-Y Su, aXiv: 1803.05245

A general model H (2,-1/2), χ (3,1), ξ (3,0)

$$H = \begin{pmatrix} h^0 \\ h^- \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^+/\sqrt{2} & \chi^{++} \\ \chi^0 & -\chi^+/\sqrt{2} \end{pmatrix}, \quad \xi = \begin{pmatrix} \xi^0/\sqrt{2} & \xi^+ \\ \xi^- & -\xi^0/\sqrt{2} \end{pmatrix}$$

$$h^0 = \frac{v_H + h_H + iI_H}{\sqrt{2}}, \quad \chi^0 = \frac{v_\chi + h_\chi + iI_\chi}{\sqrt{2}}, \quad \xi^0 = v_\xi + h_\xi$$

$$L = (D_\mu H)^\dagger D^\mu H + \frac{1}{2}(D_\mu \xi)^\dagger D^\mu \xi + (D_\mu \chi)^\dagger D^\mu \chi - V(H, \chi, \xi) ,$$

$$\begin{aligned} V(H,\chi,\xi) \; = \; & \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_\chi^2 Tr(\chi^\dagger \chi) + \frac{1}{2}\mu_\xi^2 Tr(\xi\xi) \\ + \; & \lambda_\chi (Tr(\chi^\dagger \chi))^2 + \lambda'_\chi Tr(\chi^\dagger \chi \chi^\dagger \chi) + \frac{1}{4}\lambda_\xi (Tr(\xi\xi))^2 \\ + \; & \frac{\kappa_1}{2}(H^\dagger H) Tr(\xi\xi) + \kappa_2 (H^\dagger H) Tr(\chi^\dagger \chi) + \kappa_3 (H^\dagger \chi \chi^\dagger H) \\ + \; & \frac{\kappa_4}{4} Tr(\xi\xi) Tr(\chi^\dagger \chi) + \kappa_5 Tr[\xi \chi^\dagger] Tr[\xi \chi] \\ + \; & \mu_{\xi HH} H^\dagger \xi H + \{\mu_{\chi HH} H^T \chi H + \lambda H^T \chi \xi H + H.C.\} + \mu_{\xi \chi\chi} Tr[\chi^\dagger \xi \chi] \end{aligned}$$

$$\rho \equiv \frac{m_W^2}{\cos^2\theta_W m_Z^2} = \frac{v_H^2 + 2v_\chi^2 + 4v_\xi^2}{v_H^2 + 4v_\chi^2}$$

If h_H, h_χ and h_ξ are mass eigenstates,

$$\lambda_{WZ}^{h_H} = 1\,, \qquad \lambda_{WZ}^{h_\chi} = \frac{1}{2}\,,$$

and $\lambda_{WZ}^{h_\xi}$ would be infinite since h_ξ does not couple to Z boson.

But h_H, h_χ and h_ξ are in general not mass eigen-states.
Need to be more careful.

Physical Higgs boson

$$\begin{pmatrix} h_H \\ h_\xi \\ h_\chi \end{pmatrix} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} \begin{pmatrix} h_1^m \\ h_2^m \\ h_3^m \end{pmatrix}$$

$$A^0 = (2v_\chi I_H + v I_\chi)/\sqrt{v^2 + 4v_\chi^2}$$

$$\chi^{++}$$

$$H_3^+ = \frac{1}{N_2}(-(4v_\xi^2 + 2v_\chi^2)h^+ + 2v_H v_\xi \xi^+ - \sqrt{2} v_H v_\chi \chi^+) ,$$

$$H_5^+ = \frac{1}{N_3}(\sqrt{2} v_\chi \xi^+ + 2v_\xi \chi^+) ,$$

$$N_2^2 = (4v_\xi^2 + 2v_\chi^2)^2 + 4v_H^2 v_\xi^2 + 2v_H^2 v_\chi^2 ,$$

$$N_3^2 = 4v_\xi^2 + 2v_\chi^2 .$$

$$\begin{pmatrix} H_3 \\ H_5 \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} H_3^m \\ H_5^m \end{pmatrix}$$

$$\lambda_{WZ}^{h_i^m} = \frac{v_H \alpha_{1i} + 4v_\xi \alpha_{2i} + 2v_\chi \alpha_{3i}}{v_H \alpha_{1i} + 4v_\chi \alpha_{3i}} = 1 + \frac{2(2v_\xi \alpha_{2i} - v_\chi \alpha_{3i})}{v_H \alpha_{1i} + 4v_\chi \alpha_{3i}}$$

Imposing ρ =1

$$\rho \equiv \frac{m_W^2}{\cos^2\theta_W m_Z^2} = \frac{v_H^2 + 2v_\chi^2 + 4v_\xi^2}{v_H^2 + 4v_\chi^2} = 1 \,,$$

$$v_\xi = \frac{v_\chi}{\sqrt{2}} \,. \qquad \lambda_{WZ}^{h_i^m} = 1 + \frac{2v_\chi(\sqrt{2}\alpha_{2i} - \alpha_{3i})}{v_H\alpha_{1i} + 4v_\chi\alpha_{3i}}$$

Example α_{13} =0

$$\begin{pmatrix} h_H \\ h_\xi \\ h_\chi \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\cos\gamma\sin\alpha & \cos\gamma\cos\alpha & \sin\gamma \\ \sin\gamma\sin\alpha & -\sin\gamma\cos\alpha & \cos\gamma \end{pmatrix} \begin{pmatrix} h_1^m \\ h_2^m \\ h_3^m \end{pmatrix}$$

$$\lambda_{WZ}^{h_1^m} = 1 - \frac{2v_\chi(\sqrt{2}\cos\gamma + \sin\gamma)}{v_H\cot\alpha + 4v_\chi\sin\gamma} \,,$$

$$\lambda_{WZ}^{h_2^m} = 1 + \frac{2v_\chi(\sqrt{2}\cos\gamma + \sin\gamma)}{v_H\tan\alpha - 4v_\chi\sin\gamma} \,,$$

$$\lambda_{WZ}^{h_3^m} = \frac{1}{2} + \frac{1}{\sqrt{2}}\tan\gamma \,.$$

λ_{WZ} can vary a wide range

The Georgi-Machacek model,
ρ=1 protected by Custodial symmetryeorg

$$\Phi = \begin{pmatrix} h^{0*} & h^+ \\ -h^{+*} & h^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix} \quad P = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 & i & 0 \\ 0 & 0 & \sqrt{2} \\ 1 & i & 0 \end{pmatrix}$$

$$\begin{aligned} V_{GM} &= \frac{1}{2}m_1^2 Tr(\Phi^\dagger\Phi) + \frac{1}{2}m_2^2 Tr(\Delta^\dagger\Delta) + \lambda_1(Tr(\Phi^\dagger\Phi))^2 + \lambda_2(Tr(\Delta^\dagger\Delta))^2 \\ &+ \lambda_3 Tr(\Delta^\dagger\Delta\Delta^\dagger\Delta) + \lambda_4 Tr(\Phi^\dagger\Phi)Tr(\Delta^\dagger\Delta) + \lambda_5 Tr(\Phi^\dagger\frac{\sigma^a}{2}\Phi\frac{\sigma^b}{2})Tr(\Delta^\dagger T^a \Delta T^b) \\ &+ \mu_1 Tr(\Phi^\dagger\frac{\sigma^a}{2}\Phi\frac{\sigma^b}{2})Tr(P^\dagger\Delta P) + \mu_2 Tr(\Delta T^a \Delta T^b)Tr(P^\dagger\Delta P) , \end{aligned}$$

Conditions for the general model => Georgi-Machacek model,

$$\begin{aligned} &\mu_H^2 = m_1^2 , \quad \mu_\xi^2 = m_2^2 , \quad \mu_\chi^2 = m_2^2 , \\ &\lambda_H = 4\lambda_1 , \quad \lambda_\xi = 4\lambda_2 + 4\lambda_3 , \quad \lambda_\chi = 4\lambda_2 + 6\lambda_3 , \lambda'_\chi = -4\lambda_3 \\ &\kappa_1 = 4\lambda_4 , \quad \kappa_2 = 4\lambda_4 + \lambda_5 , \quad \kappa_3 = -2\lambda_5 , \quad \kappa_4 = 16\lambda_2 , \quad \kappa_5 = 4\lambda_3 \\ &\mu_{\xi HH} = \frac{\mu_1}{\sqrt{2}} , \quad \mu_{\chi HH} = \frac{\mu_1}{2} , \quad \mu_{\xi\chi\chi} = -6\sqrt{2}\mu_2 , \lambda = \sqrt{2}\lambda_5 , \end{aligned}$$

In the GM model

$$\begin{pmatrix} h_H \\ h_\xi \\ h_\chi \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sqrt{\frac{1}{3}}\sin\alpha & \sqrt{\frac{1}{3}}\cos\alpha & -\sqrt{\frac{2}{3}} \\ -\sqrt{\frac{2}{3}}\sin\alpha & \sqrt{\frac{2}{3}}\cos\alpha & \sqrt{\frac{1}{3}} \end{pmatrix} \begin{pmatrix} h_1^m \\ h_2^m \\ h_3^m \end{pmatrix}$$

$$\lambda_{WZ}^{h_1^m} = 1\,, \quad \lambda_{WZ}^{h_2^m} = 1\,, \quad \lambda_{WZ}^{h_3^m} = -\frac{1}{2}$$

Charged Higgs bosons

$$h_2^{m+} = H_3^+ = \frac{2\sqrt{2}v_\chi h^+ - v_H\xi^+ - v_H\chi^+}{\sqrt{2v_H^2 + 8v_\chi^2}}, \qquad h_3^{m+} = H_5^+ = \frac{1}{\sqrt{2}}(\xi^+ - \chi^+)$$

$$L = \frac{v_H g^2}{2c_W}(1 - c_W^2)h^+ W_\mu^- Z^\mu - \frac{\sqrt{2}v_\chi g^2}{2c_W}(2 - c_W^2)h_\chi^+ W_\mu^- Z^\mu - c_W v_\xi g^2 h_\xi^+ W_\mu^- Z^\mu$$

$$L = \frac{g^2}{2c_W}\frac{v_H(2v_\chi^2 - 4v_\xi^2)}{N_2} H_3^+ W_\mu^- Z^\mu - \frac{g^2}{2c_W}\frac{4\sqrt{2}v_\chi v_\xi}{N_3} H_5^+ W_\mu^- Z^\mu \qquad v_\xi = v_\chi/\sqrt{2},$$

In general model

No charged Higgs in SM. No HWZ tree couplings in multi-doublet Higgs models

$$L = \left(\frac{g^2}{2c_W}\frac{v_H(2v_\chi^2 - 4v_\xi^2)}{N_2}\cos\delta + \frac{g^2}{2c_W}\frac{4\sqrt{2}v_\chi v_\xi}{N_3}\sin\delta\right) H_3^{m+} W_\mu^- Z^\mu$$
$$+ \left(\frac{g^2}{2c_W}\frac{v_H(2v_\chi^2 - 4v_\xi^2)}{N_2}\sin\delta - \frac{g^2}{2c_W}\frac{4\sqrt{2}v_\chi v_\xi}{N_3}\cos\delta\right) H_5^{m+} W_\mu^- Z^\mu$$

Measuring the ratio of HWW and HZZ couplings

C.-W. Chiang, X.-G. Heand Gang Li, arXiv: 1805.01698

$$g_{HWW} = \kappa_W g_{hWW}^{\rm SM}, \quad g_{HZZ} = \kappa_Z g_{hZZ}^{\rm SM}, \qquad \lambda_{WZ} \equiv \kappa_W/\kappa_Z \ .$$

LHC run I 2σ range

$$-1.10 \lesssim \lambda_{WZ} \lesssim -0.73 \quad \text{or} \quad 0.72 \lesssim \lambda_{WZ} \lesssim 1.10,$$

LHC run II 2σ range

$$-1.39 \lesssim \lambda_{WZ} \lesssim -0.97 \quad \text{or} \quad 0.92 \lesssim \lambda_{WZ} \lesssim 1.37$$

At the HL-LHC with an integrated luminosity of 3 ab^{-1},

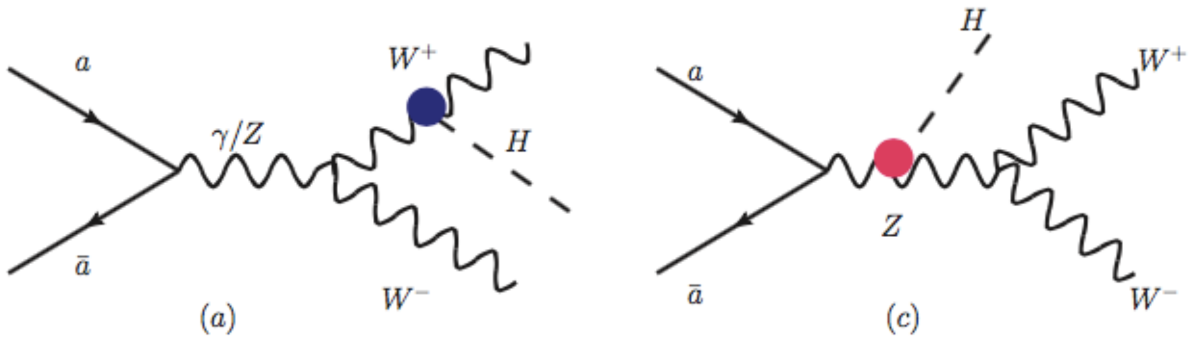
$$\delta\kappa_W/|\kappa_W| \le 5\%, \quad \delta\kappa_Z/|\kappa_Z| \le 4\%,$$

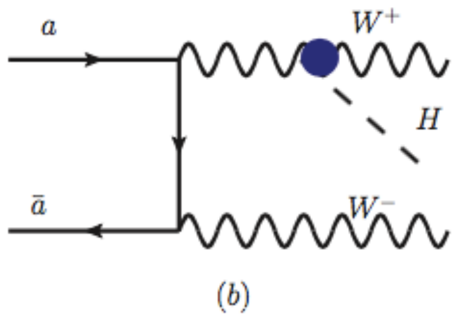
Can reach

$$\delta\kappa_W/|\kappa_W| \le 5\%, \quad \delta\kappa_Z/|\kappa_Z| \le 4\%,$$

Measuring λ_{WZ} using W^+W^-H production

W^+W^-H **PRODUCTION AT HADRON COLLIDERS**



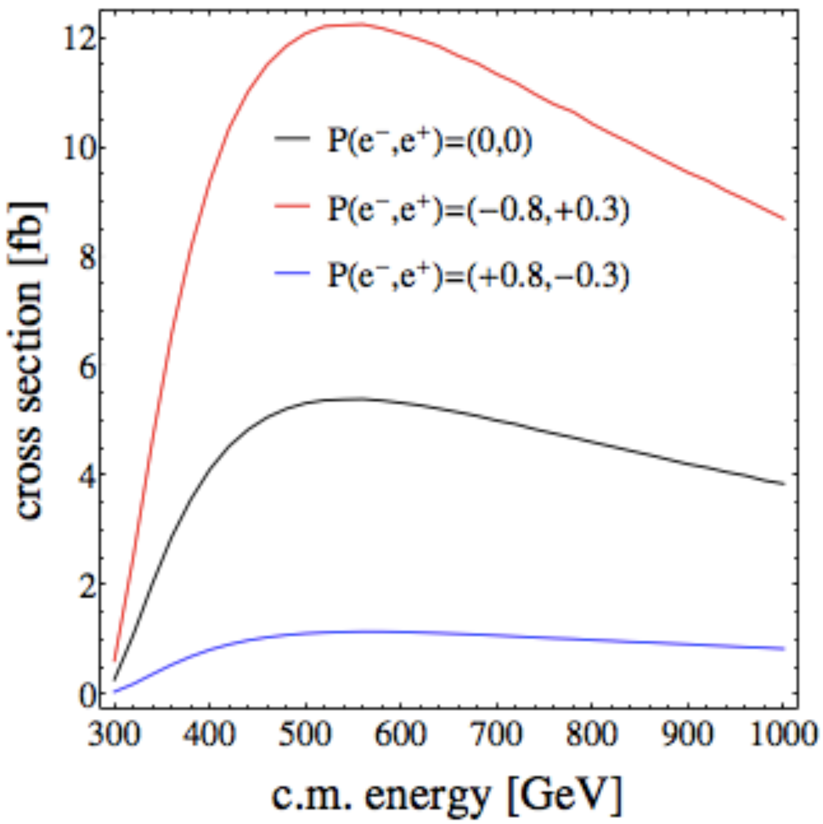


$$\sigma_{\text{prod}} = \kappa_W^2 \left[\sigma_W + \lambda_{WZ}^{-1}\sigma_{WZ} + \lambda_{WZ}^{-2}\sigma_Z\right]$$

At LHC, too much back ground not practical

e^+e^- machine may be a better place for such a study.

$e^+e^- \to W^+W^-H$



Benchmark scenarios

$$\text{BP1:}\quad \kappa_W = 1,\ \kappa_Z = 1,$$

$$\text{BP2:}\quad \kappa_W = 1,\ \kappa_Z = -1,$$

$$\text{BP3:}\quad \kappa_W = 1,\ \kappa_Z = 0.$$

Total cross section

$$\sigma_{\rm BP1} = 12\ \text{fb},\quad \sigma_{\rm BP2} = 17.11\ \text{fb},\quad \sigma_{\rm BP3} = 13.54\ \text{fb}.$$

$$\sigma_W = 13.54\ \text{fb},\quad \sigma_Z = 1.015\ \text{fb},\quad \sigma_{WZ} = -2.555\ \text{fb}.$$

$$\sigma_S = \kappa_W^2 \left(\sigma_W \epsilon_W + \lambda_{WZ}^{-1} \sigma_{WZ} \epsilon_{WZ} + \lambda_{WZ}^{-2} \sigma_Z \epsilon_Z\right) \mathcal{B},$$

B = (κ_W,κ_Z) combined branching ratio of H and W

$$\epsilon_W = \frac{\sigma_{\rm BP3}\epsilon_{\rm BP3}}{\sigma_W},$$
$$\epsilon_{WZ} = \frac{\sigma_{\rm BP1}\epsilon_{\rm BP1} - \sigma_{\rm BP2}\epsilon_{\rm BP2}}{2\sigma_{WZ}},$$
$$\epsilon_Z = \frac{\sigma_{\rm BP1}\epsilon_{\rm BP1} - \sigma_{\rm BP3}\epsilon_{\rm BP3}}{\sigma_Z} - \frac{\sigma_{\rm BP1}\epsilon_{\rm BP1} - \sigma_{\rm BP2}\epsilon_{\rm BP2}}{2\sigma_Z}.$$

These are cut coefficients for various parts.

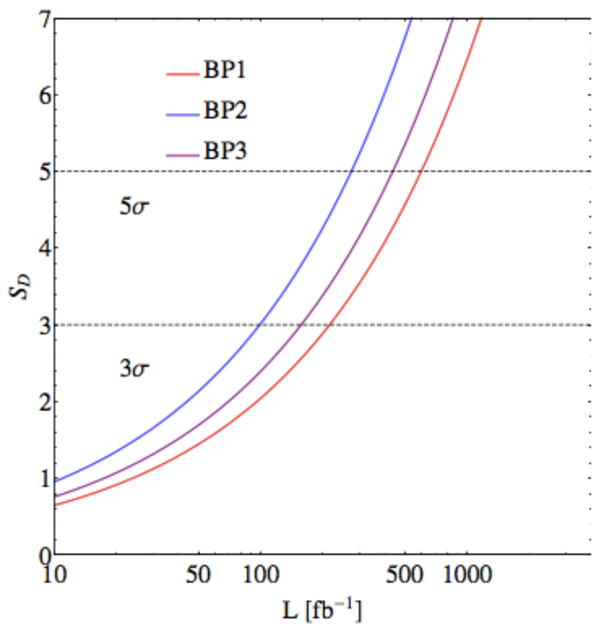
ILC 500 GeV as an example

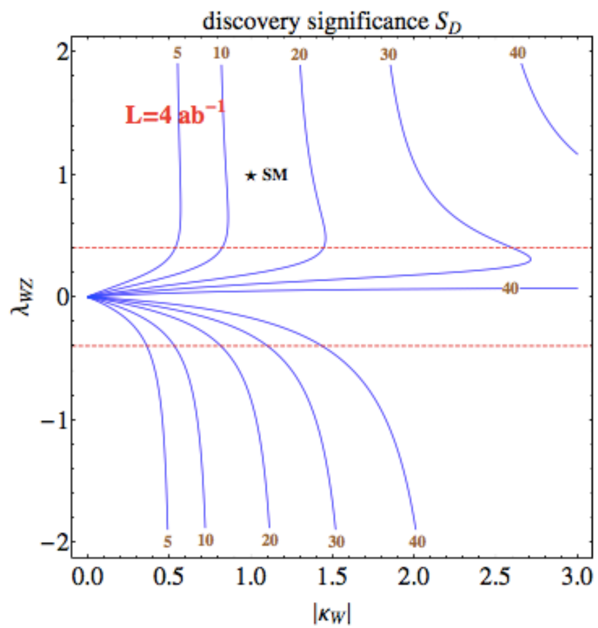
A. The $H \to b\bar{b}$ case

$e^+e^- \to W^+W^-H$ in the $jj\ell^\pm bb$ channel,

$$p_T^j > 20 \text{ GeV}, \quad p_T^\ell > 10 \text{ GeV}, \quad |\eta_{\ell,j}| < 2.5, \quad \Delta R_{mn} > 0.4, \quad m, n = j, \ell,$$

$$\Delta R_{ij} \equiv \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2},$$

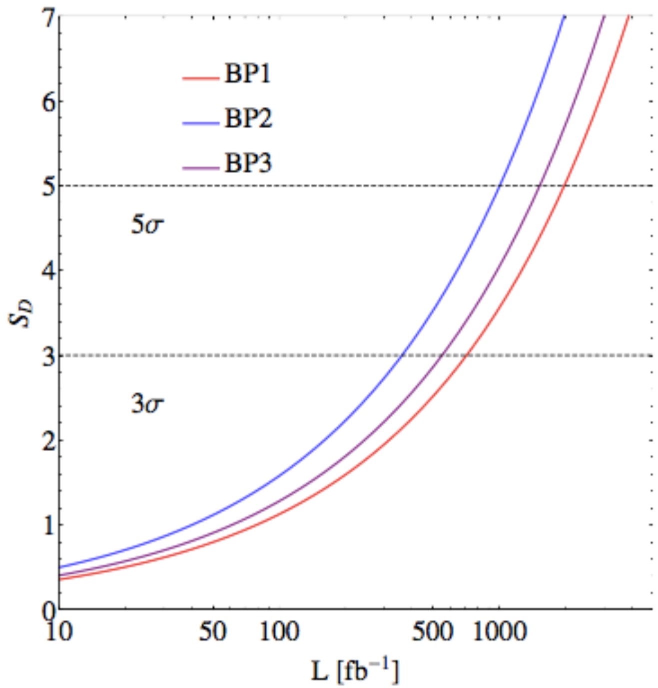


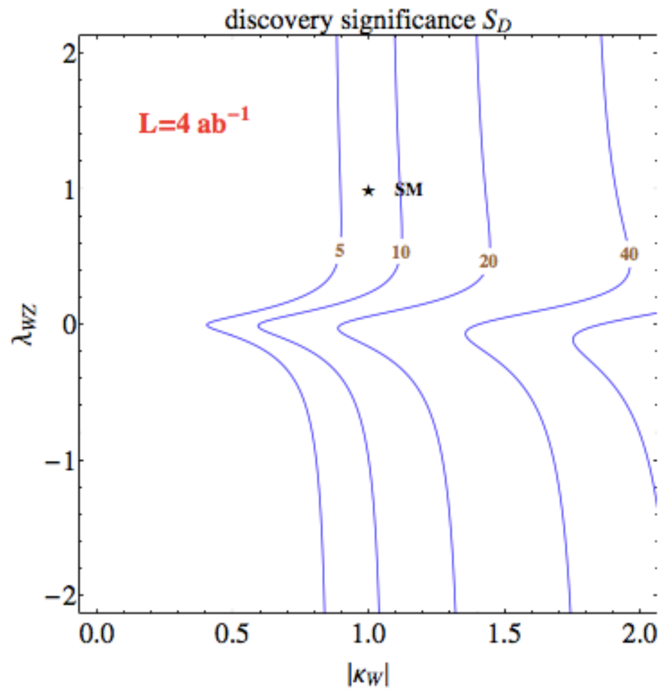


B. The $H \to W^+W^-$ case

$e^+e^- \to W^+W^-H$ in the $\ell^\pm\ell^\pm\ell^\mp jj$

$$|m_{jj} - m_W| < 15 \text{ GeV}, \quad |m^{\text{SFOS}}_{\ell^+\ell^-} - m_Z| > 25 \text{ GeV}.$$





Conclusions

Beyond SM Higgs sector can have very different couplings of Higgs to gauge bosons compared with SM.

Even with $\rho = 1$ constraint, the ratio λ_{WZ} can still take a wide ranges. Need experimental data to reveal Higgs sector structure.

Deviations from SM predictions is possible to be studied at ILC.