Two Higgs Doublet Models after LHC run I

Talk at CTPU

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This presentation is based on

SC, S.K. Kang, J.P. Lee, K.Y. Lee, S.C. Park, J. Song, JHEP 1305, 075

and JHEP 1409, 101.

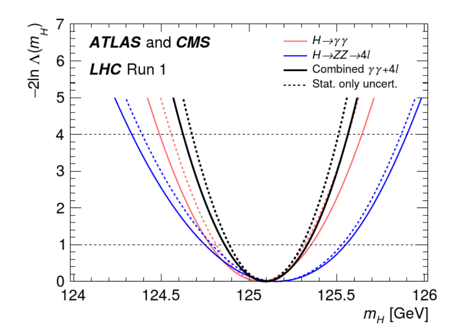
Also upcoming work by SC, S.K. Kang, J.P. Lee and J. Song.

Introduction

On 2012 CERN announced the discovery of Higgs like boson with mass ~ 125 GeV.

$$m_H = 125.09 \pm 0.24 \text{ GeV}.$$

(ATLAS and CMS 2015)



The last particle of the standard model(SM) is discoverd, but SM cannot explain,

Dark matter, Gauge hierarchy problem, Strong CP problems, Baryon asymmetry, small neutrino mass, etc..

There should be new physics beyond the standard model.

To solve the problems, many beyond the standard models(BSM) are suggested:

Minimal supersymmetric standard model(MSSM), Peccei-Quinn model, Spontaneous CP breaking model, Seesaw model, etc..

Many of them contains more than one Higgs doublets.

Two Higgs Doublet Models(2HDM)

Motivation:

- 2HDM is the simplest extension of the Standard Model.
- Many BSM contains 2HDM.
- Probe for new physics.

We assume CP is conserved in the Higgs sector, then the most general 2HDM potential is

$$
\begin{aligned}
V = \; & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \mathrm{H.c.}) \\
& + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\
& + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + \mathrm{H.c.} \right]
\end{aligned}
\tag{1}
$$

where all of the parameters are real.

We demand perturbativity as

$$
|\lambda_i| < 4\pi. \tag{2}
$$

2HDM has two complex doublets of the Higgs fields:

$$\Phi_1 = \begin{pmatrix} H_u^+ \\ \dfrac{v_u + H_u^0 + iA_u^0}{\sqrt{2}} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} H_d^+ \\ \dfrac{v_d + H_d^0 + iA_d^0}{\sqrt{2}} \end{pmatrix}. \tag{3}$$

where the SM VEV is $v = \sqrt{v_u^2 + v_d^2}$.

$$\tan\beta = v_u/v_d$$

Five physical scalars:

the light CP-even neutral scalar h^0,

the heavy CP-even neutral scalar H^0,

the CP-odd neutral scalar A^0,

and two charged Higgs bosons $H^{\pm}$.

$$h^0 = -H_d^0 \sin\alpha + H_u^0 \cos\alpha, \quad H^0 = H_d^0 \cos\alpha + H_u^0 \sin\alpha, \tag{4}$$

where α is a mixing angle in the range of $[-\pi/2, \pi/2]$.

Flavour changing neutral current(FCNC) problem

Yukawa interactions of h^0 and H^0 :

$$\mathcal{L}_{\rm Yuk} = -\sum_{f=u,d,\ell} \frac{m_f}{v} \left(\widehat{y}_f^h \bar{f} f h^0 + \widehat{y}_f^H \bar{f} f H^0 \right) . \tag{5}$$

3×3 matrices $\widehat{y}_f^h$ and $\widehat{y}_f^H$ cannot be diagonalized simultaneously.

$\rightarrow$ FCNC.

Paschos–Glashow–Weinberg theorem:

All fermions with the same quantum numbers couple to the same Higgs multiplet, FCNC will be absent.

Impose a new symmetry: Z_2, $U(1)_{\rm PQ}$, ...

We impose a discrete Z_2 symmetry in the Yukawa sector

e.g. $\Phi_2 \to -\Phi_2$ and $d^i_R \to -d^i_R$.

There are four types of 2HDM with this discrete symmetry,

Type I, Type II, Type X(Lepton-specific), and Type Y(Flipped)

A softly-broken Z_2-symmetric term, $-m^2_{12}(\Phi^\dagger_1\Phi_2 + H.c.)$ is introduced to enhance the charged Higgs boson mass.

Four types of 2HDM with natural FCNC.

Model	u_R	d_R	e_R
Type I	Φ_1	Φ_1	Φ_1
Type II	Φ_1	Φ_2	Φ_2
Type X	Φ_1	Φ_1	Φ_2
Type Y	Φ_1	Φ_2	Φ_1

The Yukawa potential for Higgs bosons are

$$\mathcal{L}_{\rm Yuk} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\widehat{y}_f^h \bar{f} f h^0 + \widehat{y}_f^H \bar{f} f H^0 - i \widehat{y}_f^A \bar{f}\gamma_5 f A^0\right) - \left\{ \frac{\sqrt{2}V_{ud}}{v}\bar{u}(m_u \widehat{y}_u^A P_L + m_d \widehat{y}_d^A P_R) d H^+ + \frac{\sqrt{2} m_\ell \widehat{y}_\ell^A}{v}\bar{\nu}_L \ell_R H^+ + \text{H.c.}\right\} \tag{6}$$

Table: The normalized Yukawa couplings of the up-type quark u, the down-type quark d, and the charged lepton ℓ, with neutral Higgs bosons.

	$\hat{y}_u^h$	$\hat{y}_d^h$	$\hat{y}_\ell^h$	$\hat{y}_u^H$	$\hat{y}_d^H$	$\hat{y}_\ell^H$	$\hat{y}_u^A$	$\hat{y}_d^A$	$\hat{y}_\ell^A$
Type I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type X	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type Y	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$	$\tan\beta$	$-\cot\beta$

Constraints on 2HDM

- Theoretical constraints:

  Unitarity, perturbativity, positivity of the potential

- pre-LHC bounds:

  Electroweak precision data, FCNC, LEP bound, etc

- LHC run-1:

  $H^{\pm}$, A^0 search, Higgs to $\gamma\gamma$, ZZ, WW, $\tau\tau$, etc

Positivity of the potential

$$\lambda_1 > 0, \lambda_2 > 0, \lambda_3 > -\sqrt{\lambda_1\lambda_2}, \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}.$$

Unitarity:

Following quantities are $\leq 8\pi$:

$$\begin{aligned}
a_\pm &= \frac{3}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{9(\lambda_1-\lambda_2)^2+(2\lambda_3+\lambda_4)^2} \\
b_\pm &= \frac{1}{2}\left(\lambda_1+\lambda_2 \pm \sqrt{(\lambda_1-\lambda_2)^2+4\lambda_4^2}\right) \\
c_\pm &= \frac{1}{2}\left(\lambda_1+\lambda_2 \pm \sqrt{(\lambda_1-\lambda_2)^2+4\lambda_5^2}\right) \\
f_+ &= \lambda_3+2\lambda_4+3\lambda_5, \quad f_- = \lambda_3+\lambda_5, \quad f_1 = f_2 = \lambda_3+\lambda_4, \\
e_1 &= \lambda_3+2\lambda_4-3\lambda_5, \quad e_2 = 2\lambda_3-\lambda_5, \quad p_1 = \lambda_3-\lambda_4,
\end{aligned} \tag{7}$$

EWPD: $\Delta\rho$ parameter

At tree level,

$$\rho_{\rm SM} = \frac{M_W}{M_Z \cos\theta_W} = 1. \tag{8}$$

$\Delta\rho$ constraints,

$$\rho_0 = \frac{\rho}{\rho_{\rm SM}} = 1 + \Delta\rho^{\rm new} \tag{9}$$

$$\Delta\rho = 0.00040 \pm 0.00024.$$

In 2HDM

$$\begin{aligned}\Delta\rho &= \frac{\sqrt{2}G_F}{(4\pi)^2}\left\{F_{\Delta\rho}(M_A^2, M_{H^\pm}^2)\right.\\ &\quad - \sin^2(\alpha-\beta)\left[F_{\Delta\rho}(M_A^2, M_H^2) - F_{\Delta\rho}(M_H^2, M_{H^\pm}^2)\right]\\ &\quad \left. - \cos^2(\alpha-\beta)\left[F_{\Delta\rho}(M_h^2, M_A^2) - F_{\Delta\rho}(M_h^2, M_{H^\pm}^2)\right]\right\}, \end{aligned} \tag{10}$$

where

$$F_{\Delta\rho}(M_1^2, M_2^2) \equiv \frac{1}{2}(M_1^2 + M_2^2) - \frac{M_1^2 M_2^2}{M_1^2 - M_2^2}\ln\frac{M_1^2}{M_2^2}. \tag{11}$$

$\Delta\rho \ll 1$ if $M_{A^0} \simeq M_{H^0}$ or $M_{h^0} \simeq M_{A^0}$, $M_{H^0} \simeq M_{H^\pm}$, and $\sin^2(\alpha-\beta) \simeq 1$.

FCNC bound ($b \to s\gamma$, $b \to \tau\nu_\tau$ etc)

(Mahmoudi and Stal 2010)

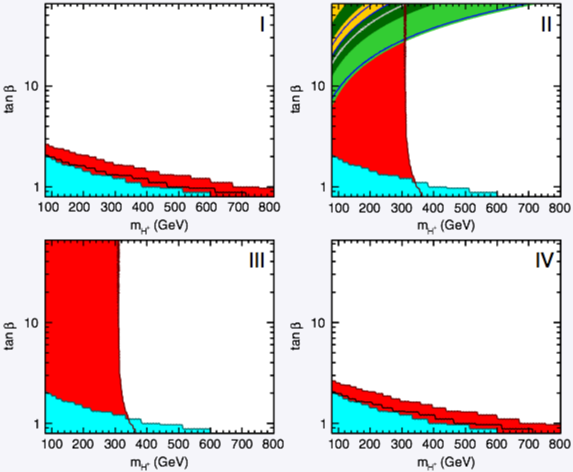


FIG. 10 (color online). Excluded regions of the (m_{H^+}, $\tan\beta$) parameter space for Z_2-symmetric 2HDM types. The color coding is as follows: BR($B \to X_s\gamma$) (red), Δ_{0-} (black contour), ΔM_{B_d} (cyan), $B_u \to \tau\nu_\tau$ (blue), $B \to D\tau\nu_\tau$ (yellow), $K \to \mu\nu_\mu$ (gray contour), $D_s \to \tau\nu_\tau$ (light green), and $D_s \to \mu\nu_\mu$ (dark green). The white region is not excluded by any of these constraints.

Two scenarios for 2HDM

Scenario-1: The new boson h is h^0.

Scenario-2: It is H^0 while h^0 has been missed.

Note: degenerate pairs of h^0-H^0, h^0-A^0, or H^0-A^0 is also possible.

Eight parameters in the general 2HDM potential with CP and a softly broken Z_2 symmetry:

v, m_{h^0}, M_{H^0}, M_{A^0}, $M_{H^\pm}$, m_{12}, α, and $\tan\beta$.

We assume heavy m_{12}, $M_{A^0} \simeq M_{H^\pm}$ with masses above 400 GeV.

In the Scenario-1, $m_{h^0} = 126\ \mathrm{GeV}$ while $M_{H^0} \geq 400\ \mathrm{GeV}$.

In the Scenario-2, $m_{h^0} < M_{H^0} = 126\ \mathrm{GeV}$.

From the flavor physics constraints, we additionally constrain $\tan\beta > 1.5$ ($\tan\beta > 1$) for Type I and Type X (Type II and Type Y).

The effective Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{eff}} &= c_V \frac{2m_W^2}{v} h\, W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h\, Z_\mu Z_\mu \\ &\quad - c_b \frac{m_b}{v} h\, \bar{b} b - c_\tau \frac{m_\tau}{v} h\, \bar{\tau}\tau - c_c \frac{m_c}{v} h\, \bar{c} c - c_t \frac{m_t}{v} h\, \bar{t} t \\ &\quad + c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^{a\mu\nu} + c_\gamma \frac{\alpha}{\pi v} h\, A_{\mu\nu} A^{\mu\nu} \,, \end{aligned} \tag{12}$$

where $h = h^0$ in Scenario-1 and $h = H^0$ in Scenario-2.

The SM values are $c_{V,\mathrm{SM}} = c_{f,\mathrm{SM}} = 1$, $c_{g,\mathrm{SM}} \simeq 1$ and $c_{\gamma,\mathrm{SM}} \simeq -0.81$.

c_g and c_γ are determined by $c_{t,b,c,\tau,V}$.

$$c_g = \sum_{q=t,b,c} c_q \mathcal{A}^h_{1/2}(x_q), \quad (13)$$

$$c_\gamma = \frac{2}{9}\sum_{u=c,t} c_u \mathcal{A}^h_{1/2}(x_u) + \frac{1}{18} c_b \mathcal{A}^h_{1/2}(x_b) + \frac{1}{6} c_\tau \mathcal{A}^h_{1/2}(x_\tau) - c_V \mathcal{A}^h_1(x_W),$$

where $x_i = m_h^2/4m_i^2$. The loop functions $A^h_{1/2,1}$ are

$$\mathcal{A}^h_{1/2}(x) = \frac{3}{2x^2}\left[(x-1)f(x)+x\right], \quad (14)$$

$$\mathcal{A}^h_1(x) = \frac{1}{8x^2}\left[3(2x-1)f(x)+2x+2x^2\right],$$

$$f(x) = \begin{cases} \arcsin^2\sqrt{x} & x \le 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-x^{-1}}}{1-\sqrt{1-x^{-1}}} - i\pi\right]^2 & x > 1 \end{cases} . \quad (15)$$

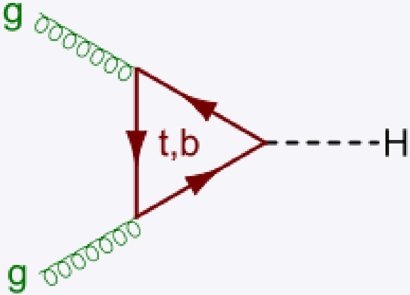
Data on the LHC Higgs search

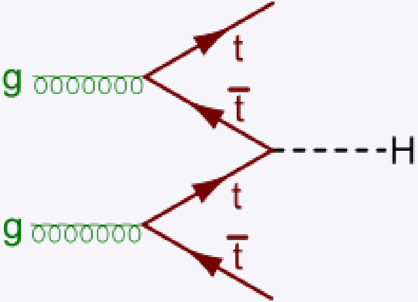
Two categories of production for ATLAS and CMS:

1. $gg\mathrm{F} + t\bar{t}h$: the combined results of the gluon fusion and the $t\bar{t}h$ production,

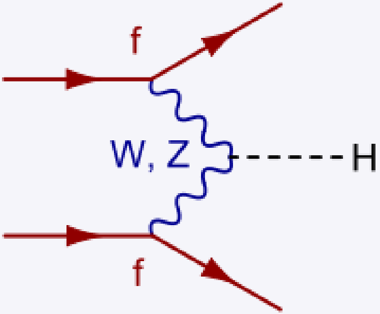
2. $\mathrm{VBF} + Vh$: the vector boson fusion (VBF) and the associated production with W or Z gauge boson.

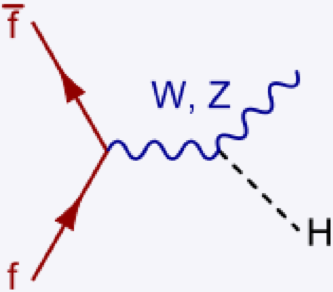
Gluon fusion (ggF) and $t\bar{t}h$ Higgs production:





Vector boson fusion(VBF) and *Vh* Higgs production.





The ratio of the observed event rate of a specific channel to the SM expectation, $R_{\texttt{decay}}^{\texttt{production}}$ (same as $\hat{\mu} = \sigma/\sigma_{\rm SM}$).

$$\begin{aligned} R_{\gamma\gamma}^{\rm ggF} &= \left|\frac{c_g\, c_\gamma}{c_{\gamma,\rm SM}\, C_{\rm tot}^h}\right|^2, \qquad R_{ii}^{\rm ggF} = \left|\frac{c_g\, c_i}{C_{\rm tot}^h}\right|^2, \\ R_{ii}^{\rm VBF} &= R_{ii}^{Vh} = R_{ii}^{{\rm VBF}+Vh} = \left|\frac{c_V\, c_i}{C_{\rm tot}^h}\right|^2, \\ R_{\gamma\gamma}^{\rm VBF} &= R_{\gamma\gamma}^{Vh} = R_{\gamma\gamma}^{{\rm VBF}+Vh} = \left|\frac{c_\gamma\, c_V}{c_{\gamma,\rm SM}\, C_{\rm tot}^h}\right|^2, \end{aligned} \tag{16}$$

where $C_{\rm tot}^h = \sqrt{\Gamma_{\rm tot}^h/\Gamma_{\rm tot}^{h_{\rm SM}}}$, and $i = W, Z, \tau, b$.

Table: Summary of the LHC Higgs signals at 7 and 8 TeV. (2013)

Production	ATLAS	CMS
$gg\mathrm{F} + t\bar{t}h$	$\widetilde{R}^{gg\mathrm{F}+t\bar{t}h}_{\gamma\gamma} = 1.47^{+0.66}_{-0.52}$ $\widetilde{R}^{gg\mathrm{F}}_{WW} = 0.82 \pm 0.36$ $\widetilde{R}^{gg\mathrm{F}+t\bar{t}h}_{ZZ} = 1.8^{+0.8}_{-0.5}$ $\widetilde{R}^{gg\mathrm{F}}_{\tau\tau} = 1.0^{+2.1}_{-1.4}$	$\widetilde{R}^{gg\mathrm{F}+t\bar{t}h}_{\gamma\gamma} = 0.52 \pm 0.5$ $\widetilde{R}^{gg\mathrm{F}}_{WW} = 0.73^{+0.22}_{-0.20}$ $\widetilde{R}^{gg\mathrm{F}+t\bar{t}h}_{ZZ} = 0.9^{+0.5}_{-0.4}$ $\widetilde{R}^{gg\mathrm{F}}_{\tau\tau} = 0.93 \pm 0.42$
$\mathrm{VBF} + Vh$	$\widetilde{R}^{\mathrm{VBF}+Vh}_{\gamma\gamma} = 1.73^{+1.27}_{-1.11}$ $\widetilde{R}^{\mathrm{VBF}}_{WW} = 1.66 \pm 0.79$ $\widetilde{R}^{\mathrm{VBF}+Vh}_{ZZ} = 1.2^{+3.8}_{-1.4}$ $\widetilde{R}^{\mathrm{VBF}+Vh}_{\tau\tau} = 1.5^{+1.1}_{-1.0}$ $\widetilde{R}^{\mathrm{VBF}+Vh}_{b\bar{b}} = 0.20 \pm 0.64$	$\widetilde{R}^{\mathrm{VBF}+Vh}_{\gamma\gamma} = 1.48^{+1.5}_{-1.1}$ $\widetilde{R}^{\mathrm{VBF}}_{WW} = -0.05^{+0.75}_{-0.56}$, $\widetilde{R}^{Vh}_{WW} = 0.51^{+1.26}_{-0.94}$ $\widetilde{R}^{\mathrm{VBF}+Vh}_{ZZ} = 1.0^{+2.4}_{-2.3}$ $\widetilde{R}^{\mathrm{VBF}}_{\tau\tau} = 0.94 \pm 0.41$, $\widetilde{R}^{Vh}_{\tau\tau} = -0.33 \pm 1.02$ $\widetilde{R}^{\mathrm{VBF}+Vh}_{b\bar{b}} = 0.96 \pm 0.47$

Results of global fits to 2013 Higgs data

Global χ^2 fits of parameters to the observed Higgs signal strength $\widetilde{R}_i$.

$$\chi^2 = \sum_{i=1}^{20} \frac{(R_i - \widetilde{R}_i)^2}{\sigma_i^2}, \tag{17}$$

i: all of the Higgs search channels, σ_i is the uncertainty of each channel

(1σ systematic errors).

$$\chi^2_{\rm SM}\big|_{\rm d.o.f.=20} = 12.40. \quad \text{or } \chi^2_{\rm SM}/{\rm d.o.f.} = 0.62. \tag{18}$$

Scenario-1

The effective couplings are

$$c_V \;=\; \sin(\beta-\alpha), \quad c_b = \widehat{y}^h_d, \quad c_\tau = \widehat{y}^h_\ell, \quad c_t = c_c = \widehat{y}^h_u. \tag{19}$$

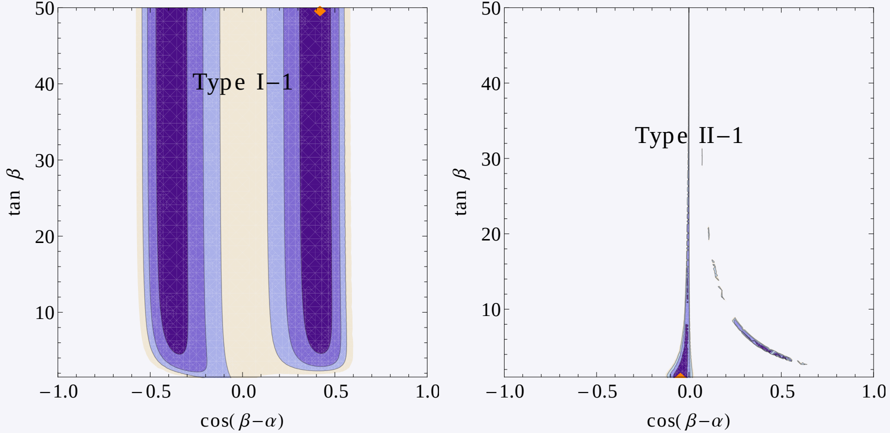
The light Higgs boson h^0 behaves exactly like the SM Higgs boson for

$$\text{Decoupling limit in Scenario-1: } \sin(\beta-\alpha) = 1. \tag{20}$$

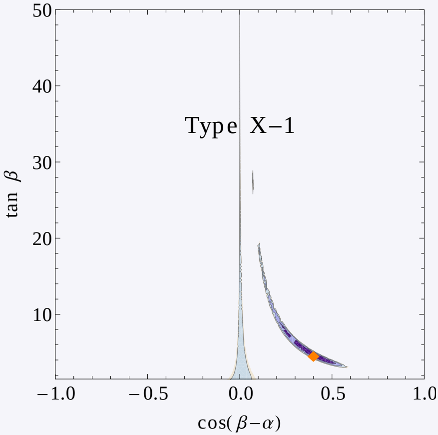
In this limit, $c_V = c_f = 1$.

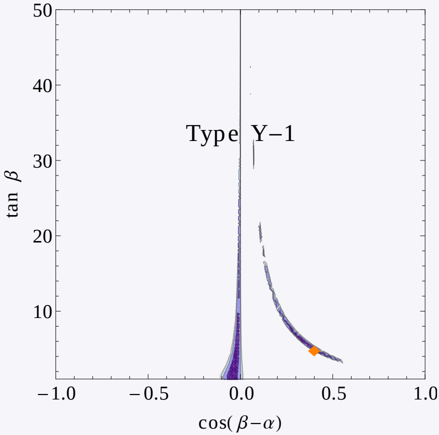
Table: The best-fit points and the corresponding couplings in Scenario-1.

Type	$\chi^2_{\rm min}/{\rm d.o.f}$	$\tan\beta$	$\cos(\beta-\alpha)$	c_V	c_b	c_τ	c_t
I-1	0.58	49.83	0.42	0.92	0.92	0.92	0.92
II-1	0.64	1.00	-0.047	1.00	1.05	1.05	0.95
X-1	0.60	4.71	0.40	0.92	1.00	-0.97	1.00
Y-1	0.62	4.94	0.40	0.92	-1.06	1.00	1.00



Allowed region of the Scenario-1 at 1σ for Type-I and II.



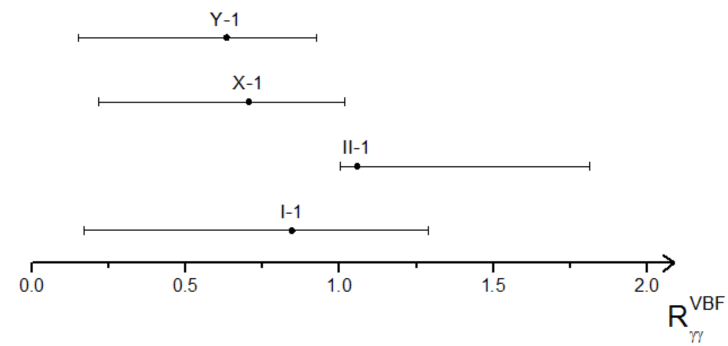


Allowed region of the Scenario-1 at 1σ for Type-X and IY.

- All of the best-fit points are as good as the SM.
- Type I best-fit point has the smallest $\chi^2_{\rm min}/{\rm d.o.f}$, although not significantly improved from the SM.
- The best-fit points in Type I, X, and Y are located away from the decoupling limit, as indicated by $\cos(\beta - \alpha) \simeq 0.4$.
- Type II best-fit point is practically the same as the SM.

$R_{\gamma\gamma}^{\mathrm{VBF}}$ for models of I-1, II-1, X-1, and Y-1 with 1σ.

The black blobs are the predictions of the best-fit point.



It is hard to distinguish a type of model from each other.

Scenario-2

The effective couplings are

$$c_V = \cos(\beta - \alpha), \quad c_b = \widehat{y}_d^H, \quad c_\tau = \widehat{y}_\ell^H, \quad c_t = c_c = \widehat{y}_u^H. \tag{21}$$

H^0 behaves exactly like the SM Higgs boson for

$$\text{Decoupling limit in Scenario-2: } \cos(\beta - \alpha) = 1. \tag{22}$$

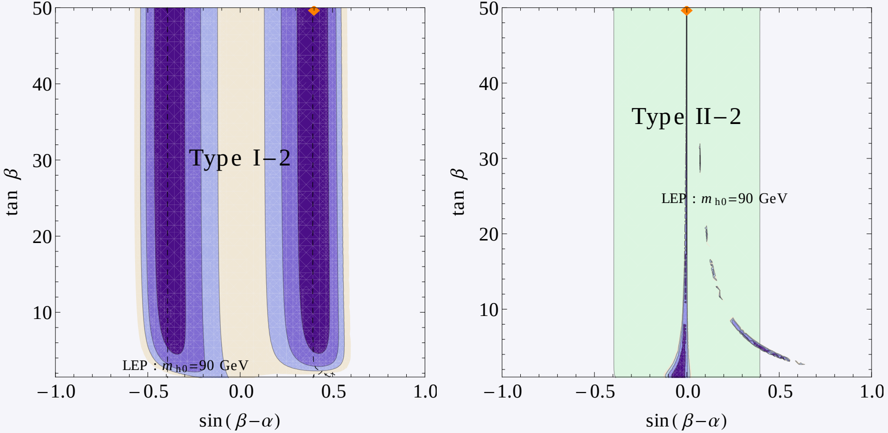
To evade the LEP Higgs search, the event rate $|\xi|^2$ of flavor-independent jet decay of h^0 should be smaller than the observed limit.

$$|\xi|^2 = |c_V|^2 \cdot \frac{\mathcal{B}(h^0 \to jj)}{\mathcal{B}(h_{\rm SM} \to jj)}. \tag{23}$$

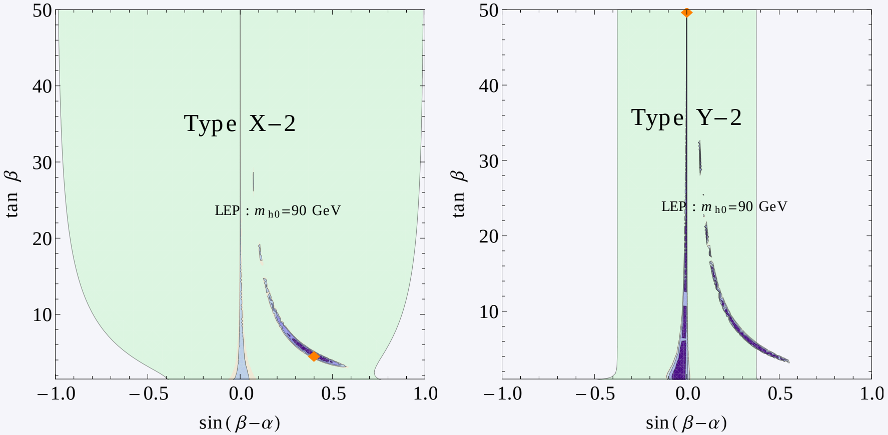
If $m_{h^0} = 90\ \mathrm{GeV}$, $|\xi|^2 < 0.155$.

Table: The best-fit points and the corresponding couplings in Scenario-2.

Type	$\chi^2_{\rm min}/{\rm d.o.f}$	$\tan\beta$	$\sin(\beta-\alpha)$	c_V^H	c_b^H	c_τ^H	c_t^H
I-2	0.58	50.0	0.40	-0.92	-0.92	-0.92	-0.92
II-2	0.59	50.0	3×10^{-4}	1.00	1.01	1.01	1.00
X-2	0.60	4.72	0.40	-0.92	-1.00	0.97	-1.00
Y-2	0.59	50.0	3×10^{-4}	1.00	1.01	1.01	1.00



Allowed region of the Scenario-2 at 1σ for Type-I and II.



Allowed region of the Scenario-2 at 1σ for Type-X and Y.

- LEP bound is rather weak.
- The results are similar to that of Scenario-1 since $\alpha_{\mathrm{s2}} + \pi/2 = \alpha_{\mathrm{s1}}$.
- $\sin(\beta - \alpha) = 0.4$ of Type-Y is excluded by LEP bound.

Diphoton signals from light Higgs boson is negligible for all 4 type of models.

Table: The best-fit points and the corresponding couplings of the light CP-even Higgs boson with mass $m_h = 90\ \mathrm{GeV}$ in Scenario-2.

Type	I-2	II-2	X-2	Y-2
$R_{\gamma\gamma}^{gg\mathrm{F}}$	0.15	4.5×10^{-3}	4.0×10^{-3}	9.0×10^{-4}
$R_{\gamma\gamma}^{\mathrm{VBF}}$	0.18	1.9×10^{-11}	1.6×10^{-2}	3.7×10^{-12}

LHC 2014 data

In previous work, we assumed very heavy $A^0, H^\pm$ mass and reduced the number of the free parameters.

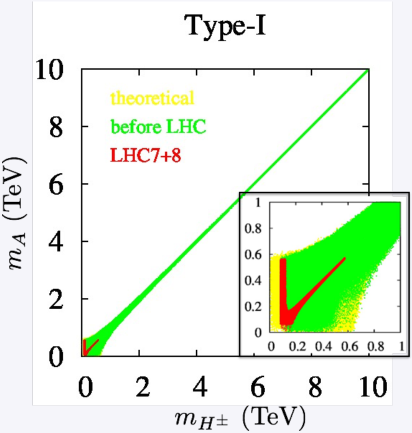
With updated 2014 LHC 7+8 TeV data, we perform the general scan for all 7 2HDM parameters for scenario-2.

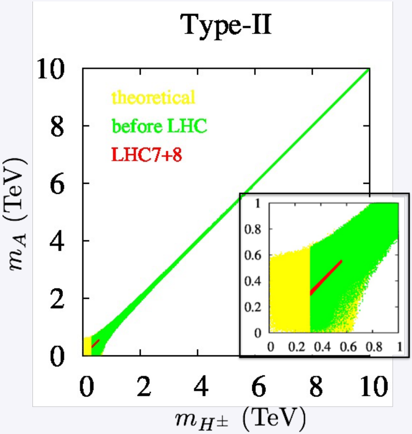
There are three stages of cut for simulations:

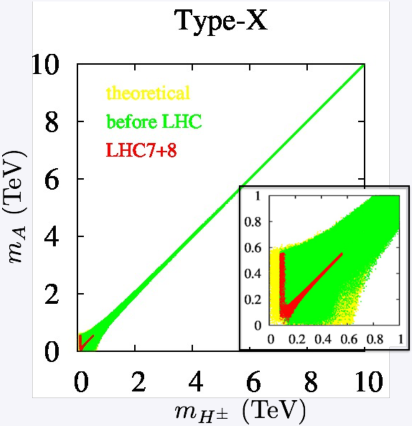
1. Theoretical bounds, 2. pre-LHC bound, 3. LHC run-1 bound.

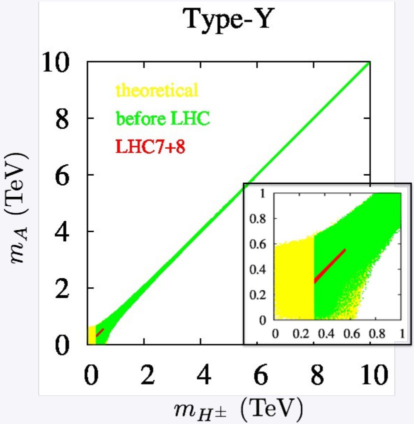
Table: Summary of the LHC Higgs signals at 7 and 8 TeV (2014).

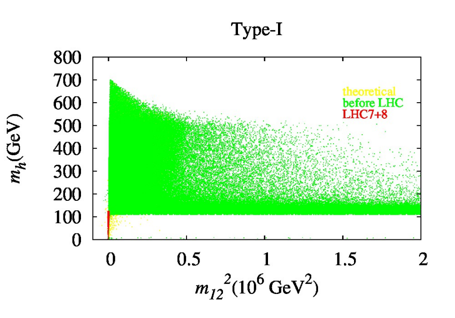
	ATLAS	CMS
$gg\mathrm{F}$ $+t\bar{t}h$	$\widetilde{R}^{gg\mathrm{F}}_{\gamma\gamma} = 1.32 \pm 0.38$ $\widetilde{R}^{t\bar{t}h}_{\gamma\gamma} = 1.3^{+2.6}_{-1.7}$	$\widetilde{R}^{gg\mathrm{F}+t\bar{t}h}_{\gamma\gamma} = 1.13^{+0.37}_{-0.31}$
	$\widetilde{R}^{gg\mathrm{F}}_{WW} = 1.01^{+0.27}_{-0.20}$	$\widetilde{R}^{gg\mathrm{F}}_{WW} = 0.74^{+0.22}_{-0.20}$
	$\widetilde{R}^{gg\mathrm{F}+t\bar{t}h}_{ZZ} = 1.52^{+0.85}_{-0.65}$	$\widetilde{R}^{gg\mathrm{F}+t\bar{t}h}_{ZZ} = 0.80^{+0.46}_{-0.36}$
	$\widetilde{R}^{gg\mathrm{F}}_{\tau\tau} = 1.93^{+1.45}_{-1.15}$	$\widetilde{R}^{gg\mathrm{F}}_{\tau\tau} = 0.93 \pm 0.42$
	$\widetilde{R}^{t\bar{t}h}_{b\bar{b}} = 1.7 \pm 1.4$	$\widetilde{R}^{t\bar{t}h}_{b\bar{b}} = 0.67^{+1.35}_{-1.33}$
VBF $+Vh$	$\widetilde{R}^{\mathrm{VBF}}_{\gamma\gamma} = 0.8 \pm 0.7$,	
	$\widetilde{R}^{WH}_{\gamma\gamma} = 1.0 \pm 1.6$, $\widetilde{R}^{ZH}_{\gamma\gamma} = 0.1^{+3.7}_{-0.1}$	$\widetilde{R}^{\mathrm{VBF}+Vh}_{\gamma\gamma} = 1.15^{+0.63}_{-0.58}$
	$\widetilde{R}^{\mathrm{VBF}}_{WW} = 1.28^{+0.53}_{-0.45}$	$\widetilde{R}^{\mathrm{VBF}}_{WW} = 0.60^{+0.57}_{-0.46}$, $\widetilde{R}^{Vh}_{WW} = 0.39^{+1.97}_{-1.87}$
	$\widetilde{R}^{\mathrm{VBF}+Vh}_{ZZ} = 0.90^{+4.5}_{-2.0}$	$\widetilde{R}^{\mathrm{VBF}+Vh}_{ZZ} = 1.7^{+2.2}_{-2.1}$
	$\widetilde{R}^{\mathrm{VBF}+Vh}_{\tau\tau} = 1.24^{+0.58}_{-0.54}$	$\widetilde{R}^{\mathrm{VBF}}_{\tau\tau} = 0.94 \pm 0.41$,
	$\widetilde{R}^{Vh}_{b\bar{b}} = 0.51^{+0.40}_{-0.37}$	$\widetilde{R}^{\mathrm{VBF}}_{b\bar{b}} = 0.7 \pm 1.4$, $\widetilde{R}^{Vh}_{b\bar{b}} = 1.0 \pm 0.5$

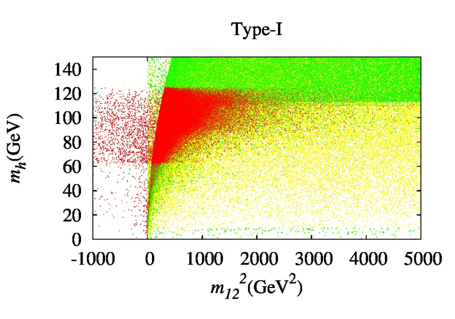

Type-I
theoretical
before LHC
LHC7+8
m_A (TeV)
$m_{H^\pm}$ (TeV)

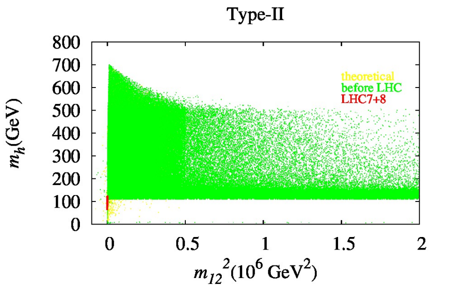

Type-II
theoretical
before LHC
LHC7+8
m_A (TeV)
$m_{H^\pm}$ (TeV)

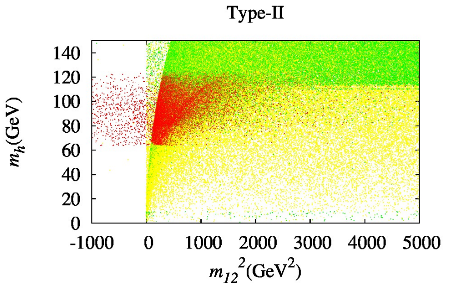

Type-X
theoretical
before LHC
LHC7+8
m_A (TeV)
$m_{H^\pm}$ (TeV)


Type-Y
theoretical
before LHC
LHC7+8
m_A (TeV)
$m_{H^\pm}$ (TeV)


Type-I
800
700
600
500
400
300
200
100
0
m_h(GeV)
0
0.5
1
1.5
2
$m_{12}{}^2(10^6\ \mathrm{GeV}^2)$
theoretical
before LHC
LHC7+8


Type-I
140
120
100
80
60
40
20
0
m_h(GeV)
-1000
0
1000
2000
3000
4000
5000
$m_{12}{}^2(\mathrm{GeV}^2)$


Type-II
800
700
600
500
400
300
200
100
0
m_h(GeV)
theoretical
before LHC
LHC7+8
0
0.5
1
1.5
2
$m_{12}{}^2(10^6\ \mathrm{GeV}^2)$


Type-II
140
120
100
80
60
40
20
0
m_h(GeV)
-1000
0
1000
2000
3000
4000
5000
$m_{12}{}^2(\mathrm{GeV}^2)$

Summary

- We study 2HDM with LHC 7+8 TeV results.
- 4 types of 2HDM with CP+Z_2 can explain LHC data as good as SM.
- But only small regions of parameters are allowed.
- Improved scan for 2HDM can give some hints of BSM.