Two Higgs Doublet Models for the LHC Higgs data at $\sqrt{s}$= 7 and 8 TeV.

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(S. Chang, SK, J. Lee, K. Lee, S. Park, J. Song to appear in JHEP : arXiv:1310.3374)

Updated JHEP1305 (2013) 075, arXiv: 1210.3439

Outline

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- Summary

Current status of LHC data for Higgs

- Both ATLAS and CMS have looked for Higgs

  - via the production : $ggF,\ VBF,\ Vh,\ t\bar{t}h$

  - in several decay channels : $\gamma\gamma\ , WW^*,\ ZZ^*,\ \bar{b}b,\ \ \bar{\tau}\,\tau$

- Recently, they have updated the Higgs search results using the full data recorded in 2011 and 2012 with the integrated luminosity up to $5(21)\ fb^{-1}$ at 7(8) TeV.

- The new data support the SM Higgs boson interpretation further, even though each individual channel is still fluctuating.

- The angular distribution of 4 leptons in the $Z\,Z^*$ channel is compatible with the SM prediction $J^P = 0^+$, other spin states like $J^P = 0^-, 1^-$, 1^+, 2^+ are excluded at 97.8%

Current status of LHC data for Higgs

- The excess in the diphoton channel decreased in the updated data.

$\mu_{\gamma\gamma}$=3.44±1.26 (5fb^{-1}, 7TeV), 1.34 ± 0.94 (5.3fb^{-1}, 8TeV)

$\mu_{\gamma\gamma}=1.65^{+0.34}_{-0.30}$ (ATLAS), $0.78^{+0.28}_{-0.26}$ (CMS-MVA mass-fact.)

$1.11^{+0.32}_{-0.30}$ (CMS-cut-based)

$\mu_{\gamma\gamma}$=1.17±0.27 (ATLAS), $1.12^{+0.26}_{-0.23}$ (CMS)

- Even though the data seem to indicate very SM-like Higgs boson, other scalar candidates in various new physics models are not excluded yet.

Two Higgs Doublet Models

- The aim of the work is to investigate in the framework of 2HDM with CPC
  - how much parameter space of 2HDM still survives especially outside the decoupling region ? (updated previous work : JHEP05,075,2013)
  - whether 2HDM can explain the current data better than the SM ?
  - whether there is any chance to miss the light Higgs boson h^0 with H^0 being the observed one ?

- Scalar potential in 2 HDM

$$
\begin{aligned}
V(\Phi_1,\Phi_2) \; &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) \\
&+\frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
&+\frac{1}{2}\lambda_5((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2) + \frac{1}{2}\lambda_6((\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + h.c.) + \frac{1}{2}\lambda_7((\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c)
\end{aligned}
$$

Two Higgs Doublet Models

- To suppress FCNC, we assume a softly broken Z_2 symmetry :

  $(\lambda_6 = \lambda_7 = 0,\ \ m_{12}^2 \neq 0\ )$

- For stable vacuum, $\lambda_1 > 0\,, \quad \lambda_2 > 0\,, \quad \lambda_3 > -(\lambda_1\lambda_2)^{1/2}$

  $\lambda_3 + \lambda_4 - |\lambda_5| > -(\lambda_1\lambda_2)^{1/2}$

- Physical states of neutral CP-even states :

  $h^0 = -Re\Phi_2^0 \sin\alpha + Re\Phi_1^0 \cos\alpha\ , \quad H^0 = Re\Phi_1^0 \cos\alpha + Re\Phi_2^0 \sin\alpha,$

  $(-\pi/2 \leq \alpha \leq \pi/2)$

- Charged scalar states :

  $G^\pm = \Phi_1^\pm \cos\beta + \Phi_2^\pm \sin\beta\ , \qquad H^\pm = -\Phi_1^\pm \sin\beta + \Phi_2^\pm \cos\beta$

- CP-odd scalar states :

  $G^0 = Im\Phi_1^0 \cos\beta + Im\Phi_2^0 \sin\beta\ , \quad A^0 = -Im\Phi_1^0 \sin\beta + Im\Phi_2^0 \cos\beta$

Two Higgs Doublet Models

4 Types of 2HDM depending on the assignment of charges for q_i and l_i under Z_2 symmetry : type I, type II, type X(lepton-specific), type Y(flipped)

Type I $\hat{\xi}_d \bar{Q}_L \Phi_2 d_R + \hat{\xi}_u \bar{Q}_L \widetilde{\Phi}_2 u_R + \hat{\xi}_l \bar{L}_L \Phi_2 e_R + h.c$

Type II $\hat{\xi}_d \bar{Q}_L \Phi_1 d_R + \hat{\xi}_u \bar{Q}_L \widetilde{\Phi}_2 u_R + \hat{\xi}_l \bar{L}_L \Phi_1 e_R + h.c$

Type X $\hat{\xi}_d \bar{Q}_L \Phi_2 d_R + \hat{\xi}_u \bar{Q}_L \widetilde{\Phi}_2 u_R + \hat{\xi}_l \bar{L}_L \Phi_1 e_R + h.c$

Type Y $\hat{\xi}_d \bar{Q}_L \Phi_1 d_R + \hat{\xi}_u \bar{Q}_L \widetilde{\Phi}_2 u_R + \hat{\xi}_l \bar{L}_L \Phi_1 e_R + h.c$

$$\Phi_i = \begin{pmatrix} \Phi_i^\dagger \\ \Phi_i^0 \end{pmatrix}$$

$$\tilde{\Phi}_i = i\sigma_2 \Phi_i^* = \begin{pmatrix} \Phi_i^0 \\ -\Phi_i^- \end{pmatrix}$$

- Yukawa interactions associated with neutral Higgs :

$$L_k = -\sum \frac{m_f}{v} (\xi_h^f \bar{f} f h^0 + \xi_H^f \bar{f} f H^0 - i \xi_A^f \bar{f} \gamma_5 f A^0)$$

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Two scenarios for probing 2HDM

- Since the observed boson is compatible with not $J^P = 0^-$ but $J^P = 0^+$, we take two options :
  - (scenario-1) : h^0 is the 125 GeV Higgs observed at the LHC
  - (scenario-II) : H^0 is the 125 GeV Higgs observed at the LHC while h^0 has been missed.
- Effective Lagrangian at the scale of $\mu = m_h$ *:(Carmi, Falkowski, Kuflik, Volansky, '12)*

$$L = c_V \frac{2m_W^2}{v} h W_\mu^+ W_\mu^- + c_V \frac{2m_Z^2}{v} h Z_\mu Z_\mu - c_b \frac{m_b}{v} h\bar{b}b - c_\tau \frac{m_\tau}{v} h\bar{\tau}\tau$$
$$- c_c \frac{m_c}{v} h\bar{c}c + c_g \frac{\alpha_s}{12\pi v} h G^a_{\mu\nu} G^{a\mu\nu} + c_\gamma \frac{\alpha}{\pi v} h A_{\mu\nu} A^{\mu\nu}$$

($h = h^0$ for scenario-I, $h = H^0$ for scenario-II)

- SM values for the coefficients :

$$c_{V,SM} = c_{f,SM} = 1, \quad c_{g,SM} \approx 1.03, \quad c_{\gamma,SM} \approx -0.81$$

- Useful parameterization for the observed signal in the Higgs search at the LHC : ratio of the observed event rate to SM prediction which is identified with signal strength : $\hat{\mu} = \sigma/\sigma_{SM}$

$$R_{\texttt{decay}}^{\texttt{production}} \equiv \frac{\sum_j \sigma(pp \to j \to h) \times \mathrm{B}(h \to \texttt{decay})|_{\mathrm{observed}}}{\sum_j \sigma(pp \to j \to h) \times \mathrm{B}(h \to \texttt{decay})|_{\mathrm{SM}}},$$

(production : ggF, VBF, Vh, $t\bar{t}h$, decay : $\gamma\gamma, WW^*, ZZ^*, \bar{b}b, \bar{\tau}\tau$)

- In terms of effective couplings :

$$R_{\gamma\gamma}^{ggF} = \left|\frac{c_g c_\gamma}{c_{\gamma,\mathrm{SM}} C_{\mathrm{tot}}^h}\right|^2, \qquad R_{ii}^{ggF} = \left|\frac{c_g c_i}{C_{\mathrm{tot}}^h}\right|^2,$$

$$R_{ii}^{\mathrm{VBF}} = R_{ii}^{Vh} = R_{ii}^{\mathrm{VBF}+Vh} = \left|\frac{c_V c_i}{C_{\mathrm{tot}}^h}\right|^2,$$

$$R_{\gamma\gamma}^{\mathrm{VBF}} = R_{\gamma\gamma}^{Vh} = R_{\gamma\gamma}^{\mathrm{VBF}+Vh} = \left|\frac{c_\gamma c_V}{c_{\gamma,\mathrm{SM}} C_{\mathrm{tot}}^h}\right|^2,$$

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

- Loop induced effective couplings :

$$c_g = \sum_{q=t,b,c} c_q \mathcal{A}^h_{1/2}(x_q), \qquad x_i = m_h^2/4m_i^2$$

$$c_\gamma = \frac{2}{9}\sum_{u=c,t} c_u \mathcal{A}^h_{1/2}(x_u) + \frac{1}{18} c_b \mathcal{A}^h_{1/2}(x_b) + \frac{1}{6} c_\tau \mathcal{A}^h_{1/2}(x_\tau) - c_V \mathcal{A}^h_1(x_W)$$
$$+ \frac{\lambda_{hH^+H^-}}{2c_W^2}\left(\frac{m_W}{M_{H^\pm}}\right)^2 \mathcal{A}^h_0(x_{H^\pm}),$$

$$\mathcal{A}^h_{1/2}(x) = \frac{3}{2x^2}\left[(x-1)f(x) + x\right],$$
$$\mathcal{A}^h_1(x) = \frac{1}{8x^2}\left[3(2x-1)f(x) + 3x + 2x^2\right]$$
$$\mathcal{A}^h_0(x) = -\frac{1}{8x^2}\left[x - f(x)\right]$$

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

Global Fit

- LHC data

Table 1. Summary of the LHC Higgs signals at 7 and 8 TeV.

Production	ATLAS	CMS
$ggF + t\bar{t}h$	$\widetilde{R}^{ggF+t\bar{t}h}_{\gamma\gamma} = 1.47^{+0.66}_{-0.52}$ [46] $\widetilde{R}^{ggF}_{WW} = 0.82 \pm 0.36$ [48] $\widetilde{R}^{ggF+t\bar{t}h}_{ZZ} = 1.8^{+0.8}_{-0.5}$ [49] $\widetilde{R}^{ggF}_{\tau\tau} = 1.0^{+2.1}_{-1.4}$ [50]	$\widetilde{R}^{ggF+t\bar{t}h}_{\gamma\gamma} = 0.52 \pm 0.5$ [47] $\widetilde{R}^{ggF}_{WW} = 0.73^{+0.22}_{-0.20}$ [5] $\widetilde{R}^{ggF+t\bar{t}h}_{ZZ} = 0.9^{+0.5}_{-0.4}$ [35] $\widetilde{R}^{ggF}_{\tau\tau} = 0.93 \pm 0.42$ [51]
$\mathrm{VBF} + Vh$	$\widetilde{R}^{\mathrm{VBF}+Vh}_{\gamma\gamma} = 1.73^{+1.27}_{-1.11}$ [46] $\widetilde{R}^{\mathrm{VBF}}_{WW} = 1.66 \pm 0.79$ [48] $\widetilde{R}^{\mathrm{VBF}+Vh}_{ZZ} = 1.2^{+3.8}_{-1.4}$ [49] $\widetilde{R}^{\mathrm{VBF}+Vh}_{\tau\tau} = 1.5^{+1.1}_{-1.0}$ [50] $\widetilde{R}^{\mathrm{VBF}+Vh}_{b\bar{b}} = 0.20 \pm 0.64$ [52]	$\widetilde{R}^{\mathrm{VBF}+Vh}_{\gamma\gamma} = 1.48^{+1.5}_{-1.1}$ [47] $\widetilde{R}^{\mathrm{VBF}}_{WW} = -0.05^{+0.75}_{-0.56}$, $\widetilde{R}^{Vh}_{WW} = 0.51^{+1.26}_{-0.94}$ [5] $\widetilde{R}^{\mathrm{VBF}+Vh}_{ZZ} = 1.0^{+2.4}_{-2.3}$ [35] $\widetilde{R}^{\mathrm{VBF}}_{\tau\tau} = 0.94 \pm 0.41$, $\widetilde{R}^{Vh}_{\tau\tau} = -0.33 \pm 1.02$ [51] $\widetilde{R}^{\mathrm{VBF}+Vh}_{b\bar{b}} = 0.96 \pm 0.47$ [53]

- Constraints from flavor physics :
  - flavor physics constrains 2HDM parameters, especially $(\tan\beta,\, m_{H^\pm})$
  - $b \to s\,\gamma$, ΔM_{B_d} : prohibit small $\tan\beta$, $m_{H^\pm} \geq 320$ GeV for types II, Y

    lighter $H^\pm$ allowed for types I, X

- Constraints from electroweak precision data : S , $\Delta\rho$
  - constraints from R_b is weaker than those from flavor physics

- Performing global fit to the LHC data in the parameter space allowed by various constraints,

$$\chi^2 = \sum_{i=1}^{20} \frac{(R_i - \widetilde{R}_i)^2}{\sigma_i^2}, \qquad \chi^2_{\rm SM}\big|_{\rm d.o.f.=20} = 12.40.$$

- In Scenario-I : $c_V = \sin(\beta - \alpha)$, $c_b = \xi_d^h$, $c_\tau = \xi_l^h$, $c_t = \xi_u^h$

  -2HDM with 2 fit parameters has 18 d.o.f.

Table 2. The best-fit points and the corresponding couplings in Scenario-1. Note that $\chi^2_{\rm SM}/{\rm d.o.f} = 0.62$.

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

- At the best fit points, c_τ in type X and c_b in type Y are negative because c_τ and c_b are $-\dfrac{\sin\alpha}{\cos\beta}$ and those points are located in positive α.

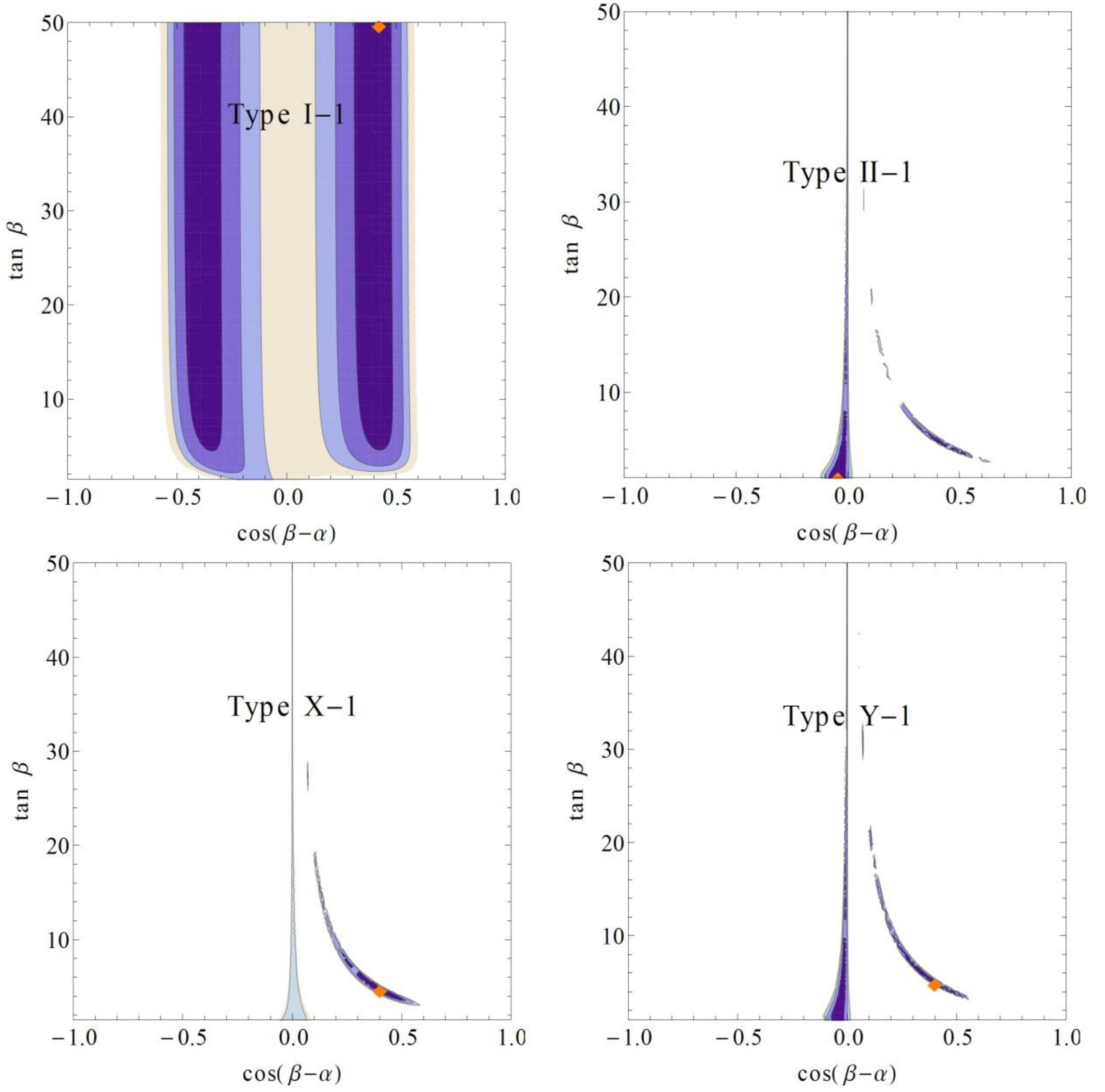


Figure 1. Allowed regions of the Scenario-1 at 1σ in the parameter space of $(\cos(\beta-\alpha), \tan\beta)$ for Type I, Type II, Type X, and Type Y models. The darker the region is, the smaller the χ^2 value is. The decoupling limit is along the central line, $\cos(\beta-\alpha) = 0$. Orange diamonds denote the best-fit points for each type.

- Type I is exceptional and the allowed region at 1 σ is much more widespread than those of other types.

- The allowed regions for Type II, X and Y, of which the shape and location look alike to each other, are very limited.

- Along the decoupling limit, only a narrow band remains.

- Away from it, most of parameter space is excluded at 1 σ except for an island group of the shape of a short ribbon.

- While types II and Y prefer the decoupling limit, the island region is preferred in type X.

- To see whether we can distinguish each type from the data, we compare signal strengths, especially, $R_{\gamma\gamma}^{VBF}$

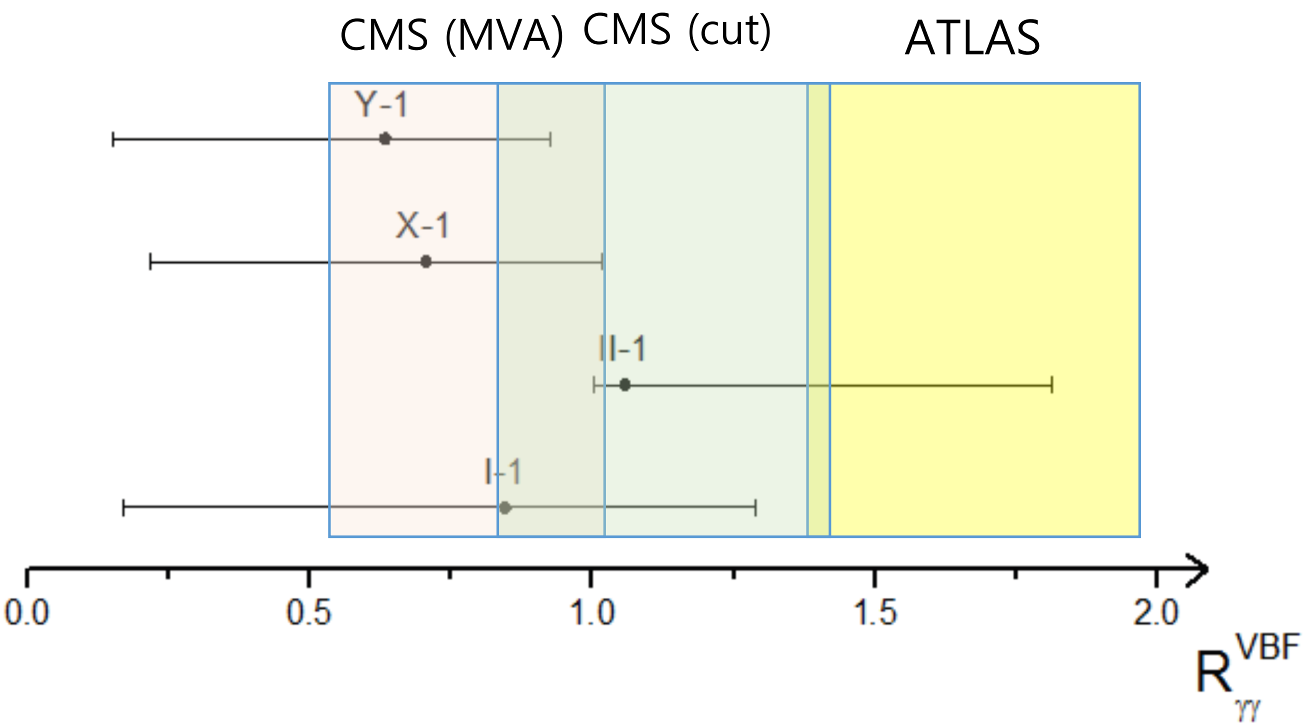


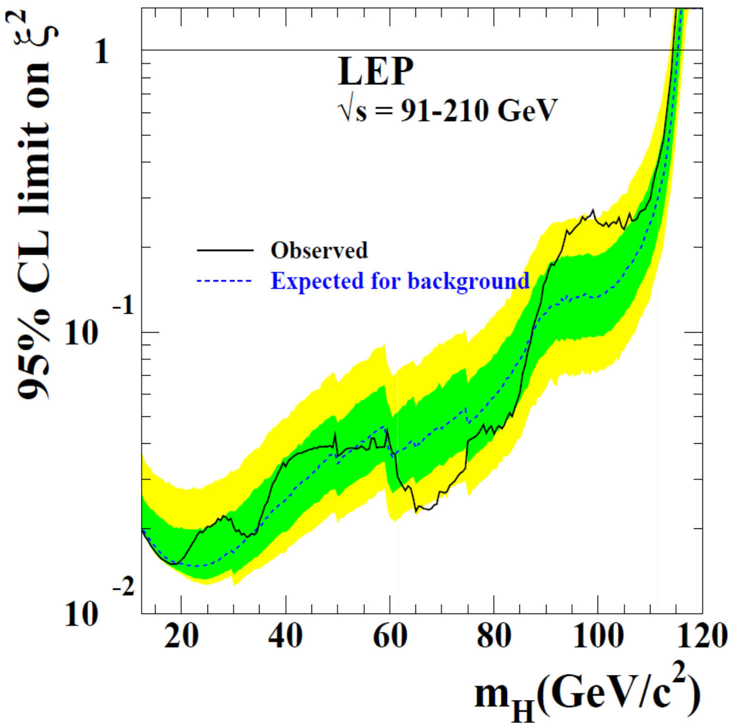
Figure 2. Signal strength $R_{\gamma\gamma}^{\rm VBF}$ for models of I-1, II-1, X-1, and Y-1 with 1σ. The black blobs are the predictions of the best-fit point.

- In Scenario-II : $c_V = \cos(\beta - \alpha)$, $c_b = \xi_d^H$, $c_\tau = \xi_l^H$, $c_t = \xi_u^H$
- We demand that the event rate of flavor-independent jet decay of light higgs boson h^0 be smaller than the exp. limit.

LEP search: $e^+e^- \to Z^* \to Zh \to \ell^+\ell^- + jj$

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

Constrained by LEP result



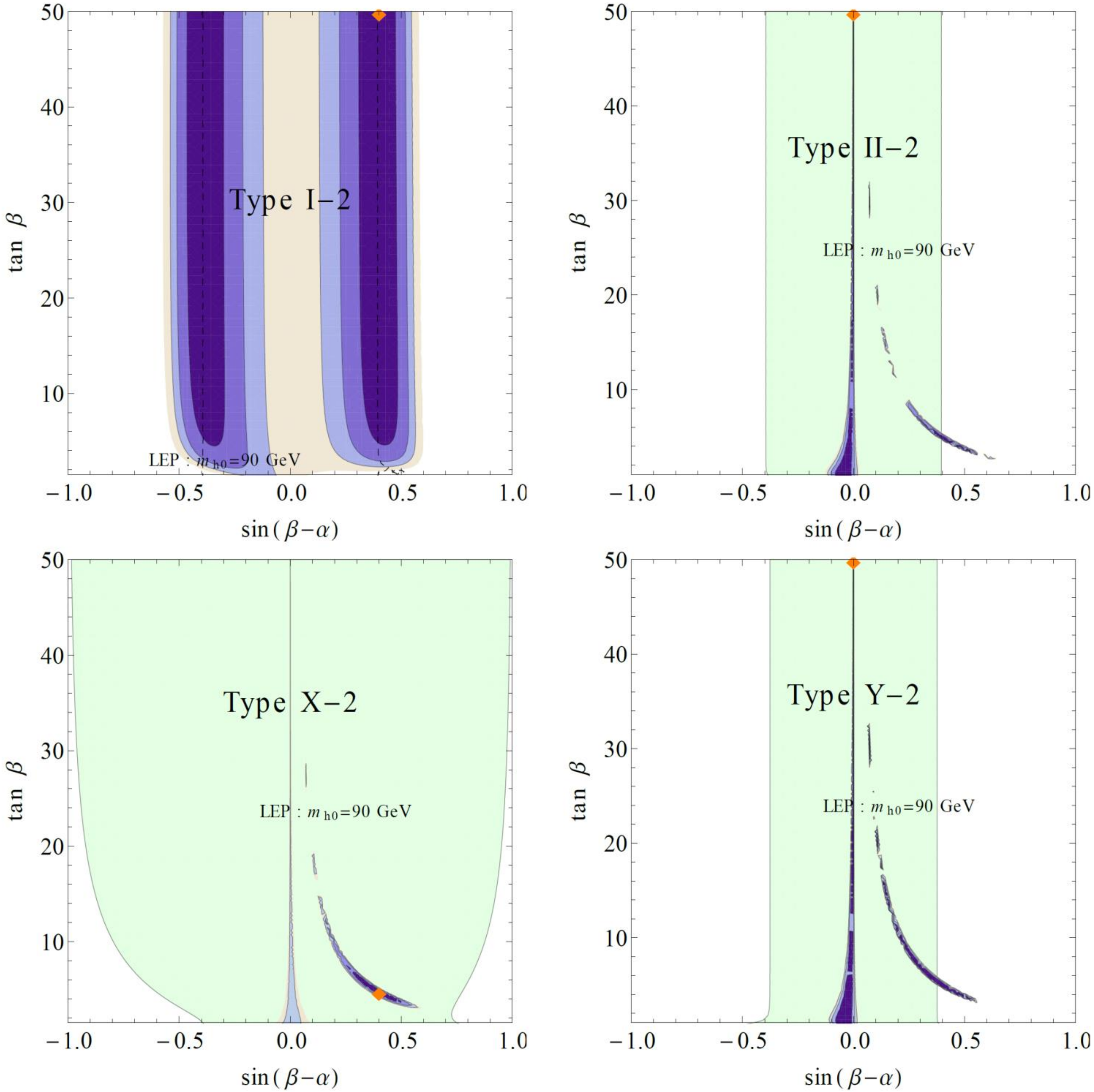
(Ex. taking $m_{h_0} = 90$ GeV, $|\xi|^2 < 0.155$)

Table 3. The best-fit points and the corresponding couplings in Scenario-2.

Type	$\chi^2_{\rm min}$/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	-0.93	-0.93	-0.93
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	1.00	1.00

- Scenario-II (type-II & Y) has slightly better χ^2 due to that the process, $H^0 \to h^0 h^{0*} \to 4b$, possibly occurs for large $\tan\beta$.

  This mode increases the total decay width Γ^h_{tot} , so the predictions of $R's$ get closer to measurements, thus χ^2 gets decreased.



- 1 σ allowed parameter space.
- Green regions: LEP allowed for $m_{h^0} = 90$ GeV

- The darker the allowed region is, the smaller the χ^2 value is.

- The pattern of the allowed region for each types in scenario-II is similar to that in scenario-I because of the relation, $\alpha_{scenario-2}+\pi/2 = \alpha_{scenario-1}$.

Summary

- We have updated global fit to the LHC Higgs data in CPC 2HDM with a softly broken Z_2 symmetry.
- 4 types of models are comprehensively investigated.
- We have considered two scenarios where the observed 126 GeV boson is the light CP-even Higgs h^0(scenario-I) or the heavy CP-even H^0 (scenario-II).
- We have found that in both scenarios the current LHC data constrain 2HDM quite strongly.
- While a large portion of the parameter space is allowed at 1σ in type I, Types II,X,Y are strongly constrained.
- Type II and Y prefer the decoupling limit.

Summary

- An interesting possibility is the scenario-II where the observed boson is the heavy CP-even Higgs of the 2HDM while the light CP-even Higgs is buried in the mass window of 90-100 GeV.
- It is very likely that all of 4 types of 2HDM may survive with large LHC data in the future.

- The preference to negative c_τ in type X is attributed to the CMS reduced rates of $\tilde{R}_{\gamma\gamma}^{ggF+t\bar{t}h}$, $\tilde{R}_{WW}^{ggF}$, $\tilde{R}_{WW}^{VBF}$.

- With negative c_τ , τ contribution to $\gamma\gamma$ channel has the same sign with W contribution, which leads to smaller c_V .

$$-\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \sim 1$$

$$\frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) \sim 1$$

$$\frac{\cos\alpha}{\cos\beta} = \cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha) \sim \tan\beta$$

$$\frac{\sin\alpha}{\sin\beta} = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha) \sim -\cot\beta$$

- To confirm the elusiveness of the light CP-even Higgs boson, we predict and compare $R_{\gamma\gamma}^{ggF}$, $R_{\gamma\gamma}^{VBF}$ for the best fit points in each types.

Table 4. The best-fit points and the corresponding couplings of the light CP-even Higgs boson with mass $m_h = 90$ GeV in Scenario-2.

Type	I-2	II-2	X-2	Y-2
$R_{\gamma\gamma}^{\mathrm{ggF}}$	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}

- For all types, the di-photon signals are negligible and c_V are all much smaller than the SM one.
- At the LHC, the observation of this resonance in di-photon channel is very unlikely.