2HDM for the LHC Higgs boson data at $\sqrt{s} = 7$ and 8 TeV

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Motivation

- The LHC has discovered a Higgs-like particle of mass 126 GeV in 2012.
- The ATLAS and CMS updated the Higgs search results with the data of 5/fb(7 TeV) + 21/fb(8 TeV) in 2013.
- The particle gets closer to the SM Higgs, with its couplings as well as spin-parity.
- But it could be "**a Higgs**" of some extended model, rather than "the Higgs" of the SM.
- The 2-Higgs doublet model (2HDM) is a good candidate for such a possibility.

2 HDM

One more scalar doublet

$$H_u = \left(\begin{array}{c} H_u^+ \\ \frac{v_u + H_u^0 + i A_u^0}{\sqrt{2}} \end{array} \right) , \qquad H_d = \left(\begin{array}{c} H_d^+ \\ \frac{v_d + H_d^0 + i A_d^0}{\sqrt{2}} \end{array} \right)$$

$$\tan\beta = \frac{v_u}{v_d}$$

$$\begin{aligned} h^0 &= -H_d^0 \sin\alpha + H_u^0 \cos\alpha, \\ H^0 &= H_d^0 \cos\alpha + H_u^0 \sin\alpha, \end{aligned}$$

Physical states

5 Higgs bosons

h^0 : CP-even light neutral
H^0 : CP-even heavy neutral
A^0 : CP-odd pseudoscalar
$H^{\pm}$: charged scalar

Model Categorization with Z_2 sym

Avoiding the tree-level FCNC

$$\mathcal{L}_{\text{yukawa}}^{\text{THDM}} = -\bar{Q}_L Y_u \tilde{\Phi}_u u_R - \bar{Q}_L Y_d \Phi_d d_R - \bar{L}_L Y_\ell \Phi_\ell \ell_R + \text{H.c.},$$

TABLE I. Variation in charge assignments of the Z_2 symmetry.

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	$+$	$-$	$-$	$-$	$-$	$+$
Type II	$+$	$-$	$-$	$+$	$+$	$+$
Type X	$+$	$-$	$-$	$-$	$+$	$+$
Type Y	$+$	$-$	$-$	$+$	$-$	$+$

Aoki et al., PRD80,015017

Two Scenarios

Scenario-1

The observed particle is the lightest CP-even Higgs h^0.

Scenario-2

The observed particle is the heavy CP-even Higgs H^0, and the lightest h^0 is buried in the lower mass region.

Effective Lagrangian

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

$h = h^0$ (in S1) *or* H^0 (in S2)

Yukawa couplings

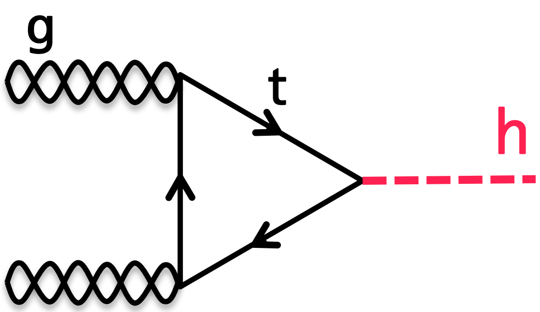
$$\mathcal{L}_{\rm Yuk} = -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(\widehat{y}_f^h \bar{f} f h^0 + \widehat{y}_f^H \bar{f} f H^0\right)$$

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

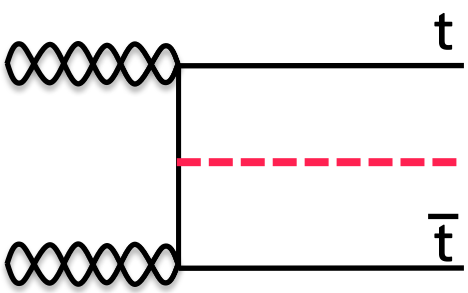
DATA & CONSTRAINTS

ggF+$t\bar{t}h$ vs VBF+Vh

gluon fusion (ggF)

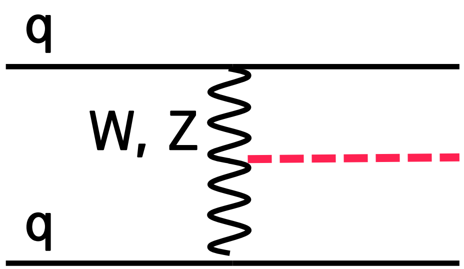


$t\bar{t}$ fusion ($t\bar{t}h$)

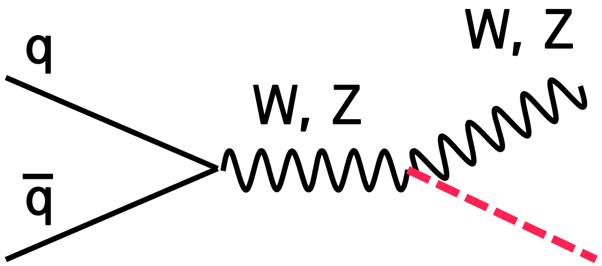


$t\bar{t}h$ vertex

vector boson fusion (VBF)



Higgs-strahlung (Vh)



Vh vertex

LHC Data after Moriond-2013

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

Production	ATLAS	CMS
$ggF + t\bar{t}h$	$\widetilde{R}^{\,ggF+t\bar{t}h}_{\gamma\gamma} = 1.47^{+0.66}_{-0.52}$ [40] $\widetilde{R}^{\,ggF}_{WW} = 0.82 \pm 0.36$ [41] $\widetilde{R}^{\,ggF+t\bar{t}h}_{ZZ} = 1.8^{+0.8}_{-0.5}$ [42] $\widetilde{R}^{\,ggF}_{\tau\tau} = 2.2^{+2.6}_{-2.3}$ [6]	$\widetilde{R}^{\,ggF+t\bar{t}h}_{\gamma\gamma} = 0.52 \pm 0.5$ [44] $\widetilde{R}^{\,ggF}_{WW} = 0.73^{+0.22}_{-0.20}$ [5] $\widetilde{R}^{\,ggF+t\bar{t}h}_{ZZ} = 0.9^{+0.5}_{-0.4}$ [34] $\widetilde{R}^{\,ggF}_{\tau\tau} = 0.77^{+0.58}_{-0.55}$ [45]
$\mathrm{VBF} + Vh$	$\widetilde{R}^{\,\mathrm{VBF}+Vh}_{\gamma\gamma} = 1.73^{+1.27}_{-1.11}$ [40] $\widetilde{R}^{\,\mathrm{VBF}}_{WW} = 1.66 \pm 0.79$ [41] $\widetilde{R}^{\,\mathrm{VBF}+Vh}_{ZZ} = 1.2^{+3.8}_{-1.4}$ [42] $\widetilde{R}^{\,\mathrm{VBF}+Vh}_{\tau\tau} = -0.32^{+1.7}_{-1.5}$ [6] $\widetilde{R}^{\,\mathrm{VBF}+Vh}_{b\bar{b}} = -0.40 \pm 1.0$ [43]	$\widetilde{R}^{\,\mathrm{VBF}+Vh}_{\gamma\gamma} = 1.48^{+1.5}_{-1.1}$ [44] $\widetilde{R}^{\,\mathrm{VBF}}_{WW} = -0.05^{+0.75}_{-0.56}$, $\widetilde{R}^{\,Vh}_{WW} = 0.51^{+1.26}_{-0.94}$ [5] $\widetilde{R}^{\,\mathrm{VBF}+Vh}_{ZZ} = 1.0^{+2.4}_{-2.3}$ [34] $\widetilde{R}^{\,\mathrm{VBF}}_{\tau\tau} = 1.42^{+0.70}_{-0.64}$, $\widetilde{R}^{\,Vh}_{\tau\tau} = 0.98^{+1.68}_{-1.50}$ [45] $\widetilde{R}^{\,\mathrm{VBF}+Vh}_{b\bar{b}} = 1.15 \pm 0.62$ [5]

signal strength

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

Signal strengths in 2HDM

$$R^{ggF}_{\gamma\gamma} = \left| \frac{c_g c_\gamma}{c_{\gamma,\mathrm{SM}} C^h_{\mathrm{tot}}} \right|^2, \qquad R^{ggF}_{ii} = \left| \frac{c_g c_i}{C^h_{\mathrm{tot}}} \right|^2$$

$$R^{\mathrm{VBF}}_{ii} = R^{Vh}_{ii} = R^{\mathrm{VBF}+Vh}_{ii} = \left| \frac{c_V c_i}{C^h_{\mathrm{tot}}} \right|^2,$$

$$R^{\mathrm{VBF}}_{\gamma\gamma} = R^{Vh}_{\gamma\gamma} = R^{\mathrm{VBF}+Vh}_{\gamma\gamma} = \left| \frac{c_\gamma c_V}{c_{\gamma,\mathrm{SM}} C^h_{\mathrm{tot}}} \right|^2,$$

$$C^h_{\mathrm{tot}} = \sqrt{\Gamma^h_{\mathrm{tot}}/\Gamma^{h_{\mathrm{SM}}}_{\mathrm{tot}}}, \text{ and } i = W, Z, \tau, b.$$

χ^2 - fitting

theory

data

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

1-σ deviation

Constraints

Flavor

$\mathrm{Br}(B \to X_s\gamma)$ excludes
small $M_{H^\pm} \lesssim 300$ GeV for Type-II and Type-Y;
small tanβ for Type-I and Type-X.

ΔM_{B_d} excludes small tanβ .

Electroweak Precision Test

$\Delta\rho$ suppression:
almost degenerate A and $H^\pm$, or

$$M_h \simeq M_A, \qquad M_H \simeq M_{H^\pm}, \qquad \sin^2(\alpha - \beta) \simeq 1$$

LEP for S-2

Non-observation of the Higgs
in lower mass region <114 GeV at e^+e^- collisions.

perturbativity

$$\frac{(y_{t,b})^2}{4\pi} \lesssim 1 \quad \to \quad 0.3 \lesssim \tan\beta \lesssim 50$$

Our Constraints

$H^{\pm}$ is assumed to be heavy:
$M_{H^{\pm}} \geq 400$ GeV

$\tan\beta > 1$ for Type-I, X
$\tan\beta > 0.5$ for Type-II, Y

$|\xi|^2 = |c_V|^2 \times \frac{\mathrm{Br}(h^0 \to jj)}{\mathrm{Br}(h_{\mathrm{SM}} \to jj)} < 0.155$ (in S-2)

RESULTS

Best-fit points & couplings in S-1

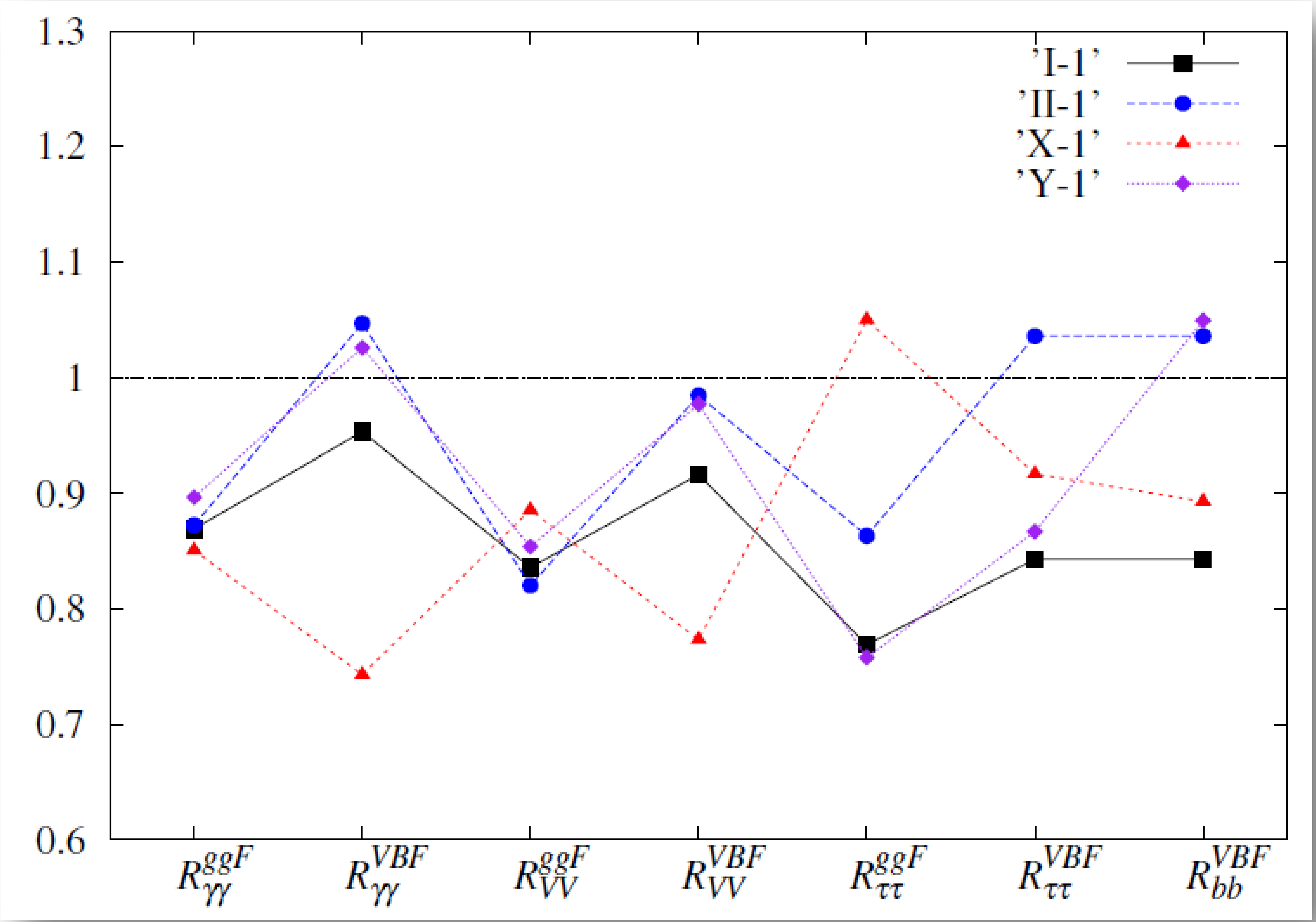
$$c_V = \sin(\beta - \alpha), \quad c_b = \widehat{y}_d^h, \quad c_\tau = \widehat{y}_\ell^h, \quad c_t = c_c = \widehat{y}_u^h.$$

	$\widehat{y}_u^h$	$\widehat{y}_d^h$	$\widehat{y}_\ell^h$
Type I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
Type II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Type X	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
Type Y	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

$$\chi^2_{\rm SM}\big|_{\rm d.o.f.=20} = 10.82.$$

Type	$\chi^2_{\rm min}$	$\tan\beta$	α	c_V	c_b	c_τ	c_t
I-1	9.42	9.89	-0.48	0.93	0.89	0.89	0.89
II-1	9.49	0.57	-1.10	1.00	1.02	1.02	0.92
X-1	9.85	5.29	0.19	0.93	1.00	-1.01	1.00
Y-1	9.77	0.79	-0.95	1.00	1.04	0.94	0.94

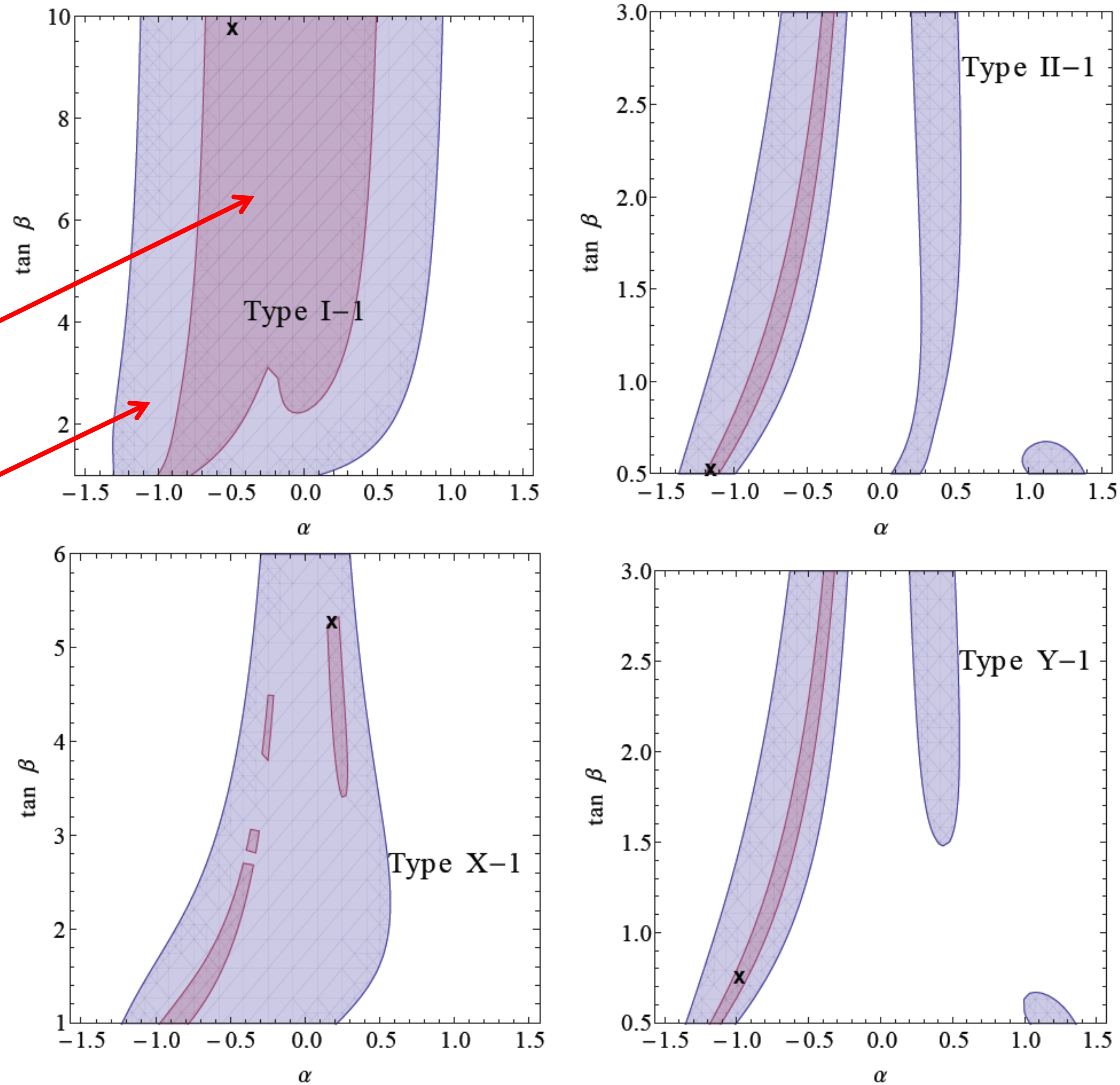
R for Scenario-1



Allowed (α, $\tan\beta$) in Scenario-1

$\chi^2 < \chi^2_{SM}$

90% C.L.



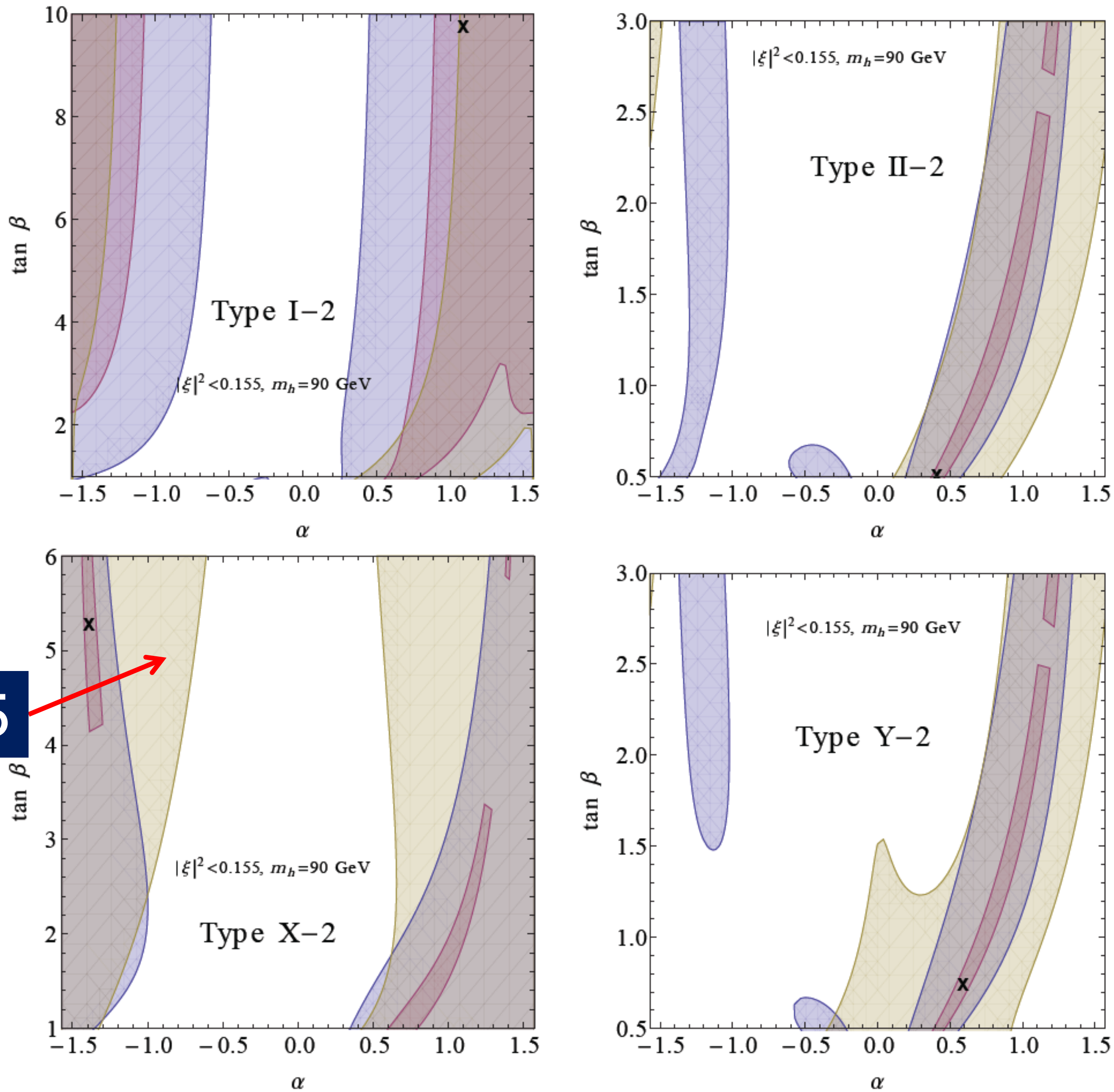
Best-fit points & couplings in S-2

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

	$\widehat{y}_u^H$	$\widehat{y}_d^H$	$\widehat{y}_\ell^H$
Type I	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$
Type II	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$
Type X	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$
Type Y	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$

Type	$\chi^2_{\rm min}$	$\tan\beta$	α	c_V^H	c_b^H	c_τ^H	c_t^H
I-2	9.42	9.79	1.09	0.93	0.89	0.89	0.89
II-2	9.48	0.55	0.46	1.00	1.02	1.02	0.92
X-2	9.85	5.21	-1.38	-0.93	-1.00	1.02	-1.00
Y-2	9.77	0.77	0.61	1.00	1.03	0.94	0.94

Allowed (α, tanβ) in Scenario-2

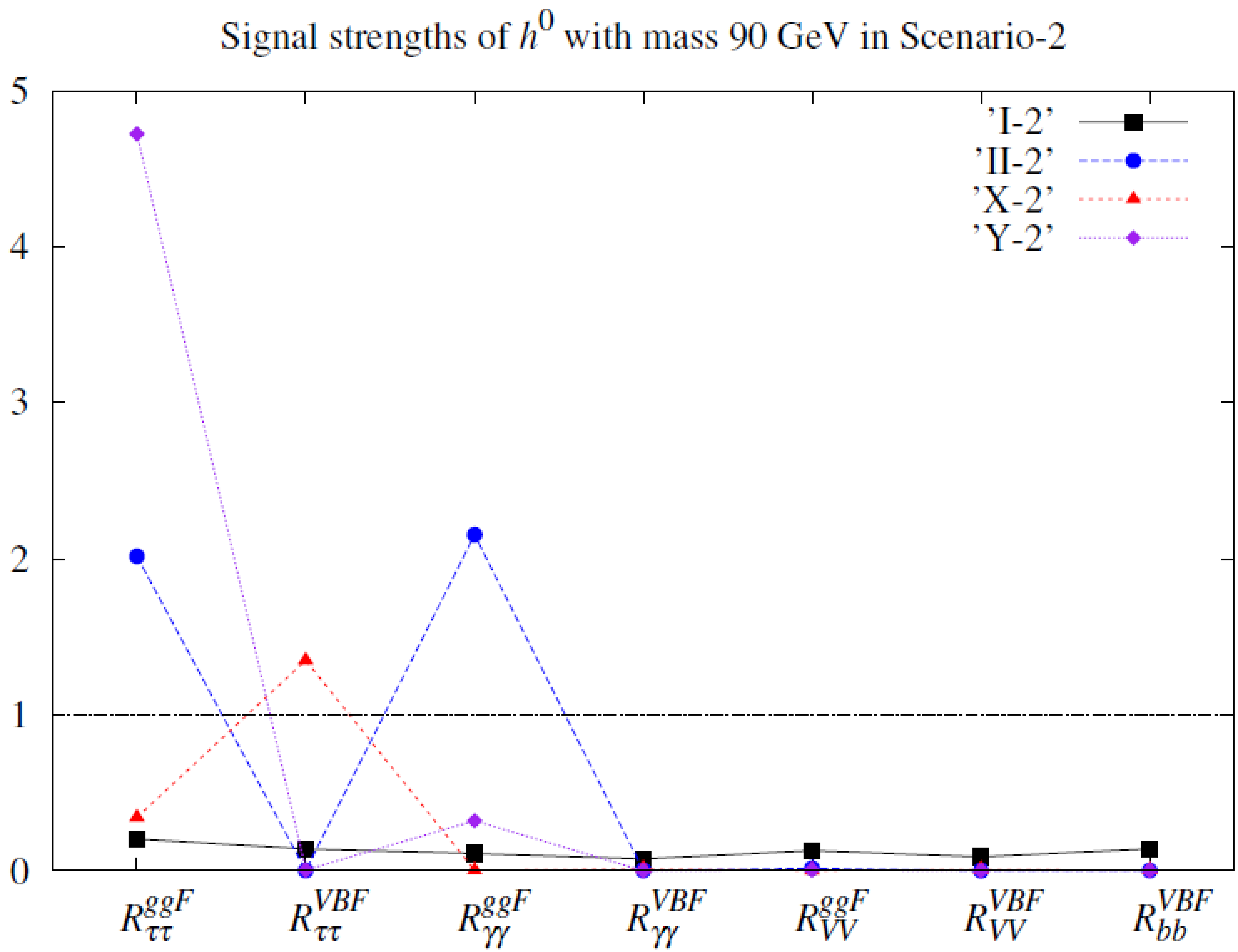


$|\xi^2| < 0.155$

Predictions for the light h of 90 GeV

Type	$R_{\gamma\gamma}^{ggF}$	$R_{\tau\tau}^{ggF}$	$R_{\tau\tau}^{\text{VBF}}$	c_V^h	c_b^h	c_τ^h	c_t^h
I-2	0.11	0.20	0.14	0.37	0.47	0.47	0.47
II-2	2.2	2.0	1.1×10^{-3}	0.04	-0.51	-0.51	1.90
X-2	2.7×10^{-3}	0.34	1.3	0.37	0.20	5.2	0.20
Y-2	0.32	4.7	5.2×10^{-3}	4.6×10^{-2}	-0.72	1.34	1.34

R values for the light h in S-2



Conclusion

- The observed boson could be the lightest CP-even h^0 or the heavy CP-even H^0 of the 2HDM.
- The 2HDM explains the LHC Higgs data very well, or better than the SM.
- It is possible that the observed particle is H^0 while h^0 is buried in the 90-100 GeV.
- The lightest h^0 could appear in the $\gamma\gamma$ or $\tau\tau$ channels in the Type-II, X, Y models.
- High precision measurements below 1% level is needed to distinguish various models.