Comprehensive study of two Higgs doublet model in light of new boson with 125 GeV mass

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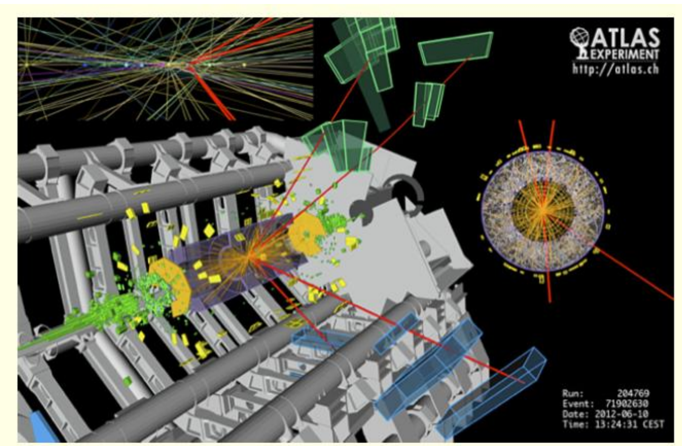
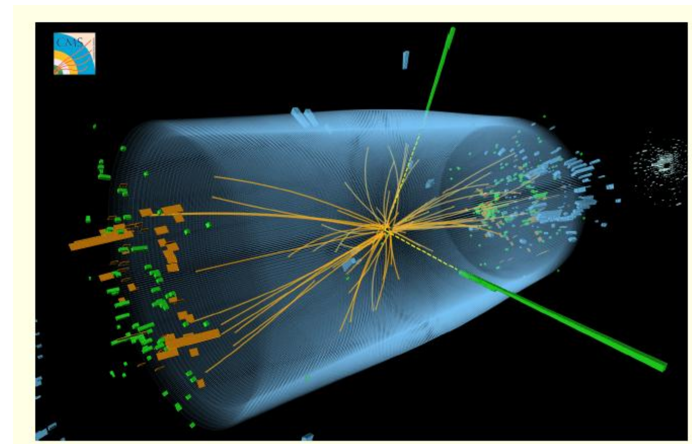
Sin Kyu Kang
(Seoul-Tech)

Based on arXiv:1210.3439
in collaboration with S. Chang, J. P. Lee, K. Y. Lee , S. Park and J. Song

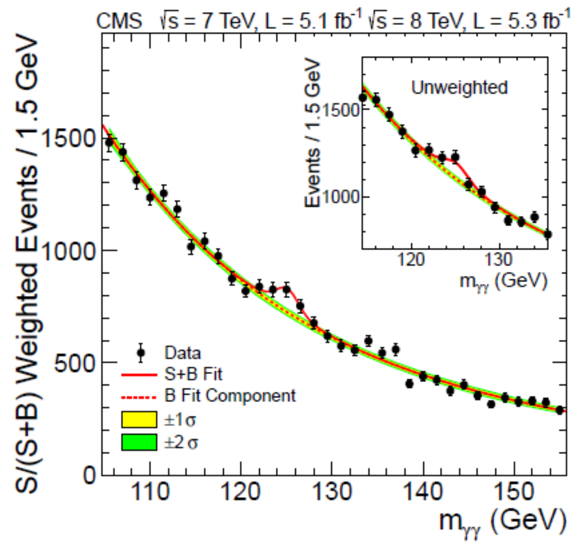
Discovery of new boson

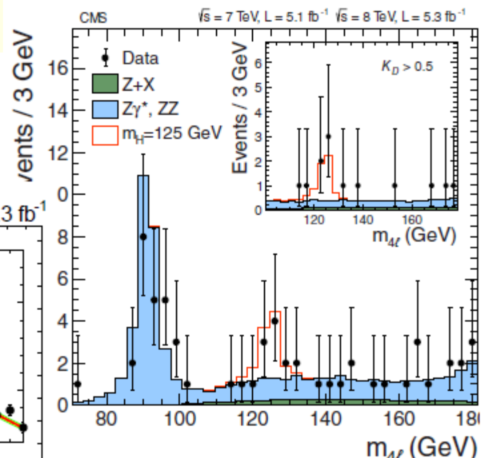


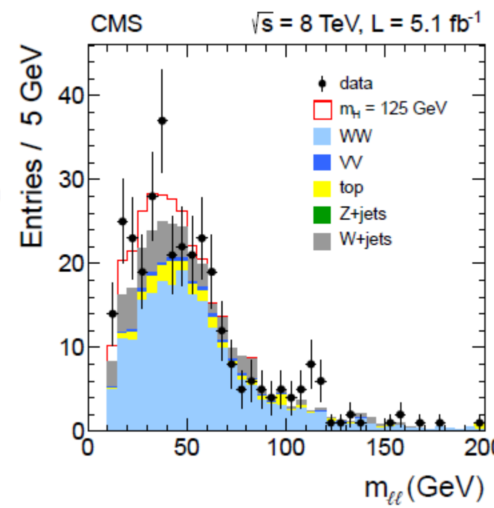


[arXiv:1207.7214 [hep-ex]].

[arXiv:1207.7235 [hep-ex]]







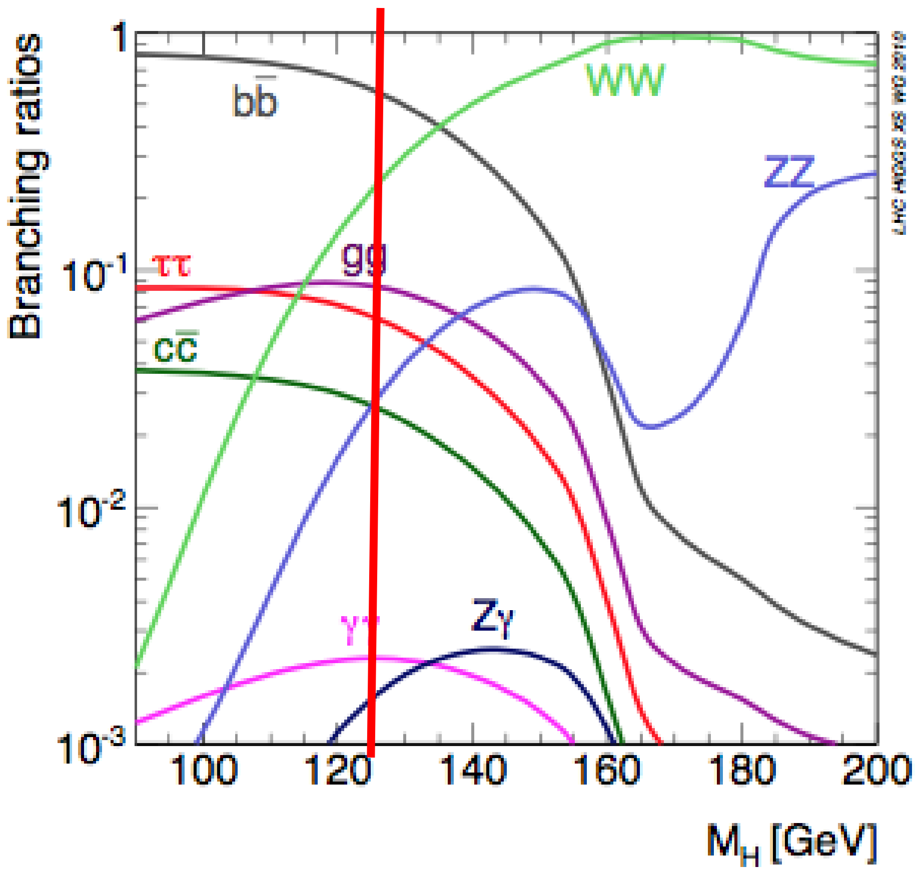
Discovery of new boson

- The analysis by CMS and ATLAS using the combined 7 & 8 TeV data indicates observation of a signal for a boson with mass around 125 GeV

- It can be a spin zero particle that is a remnant of spontaneous symmetry breaking which gives mass to gauge bosons , quarks and leptons.

(Brout, Englert, Higgs, Guralnik, Hagen, Kibble, '64)

Discovery of new boson

- Masic number : 125 GeV ➡ maximized $Br(h \to \gamma\gamma)$
- 

Enables us to probe various decay modes

Discovery of new boson

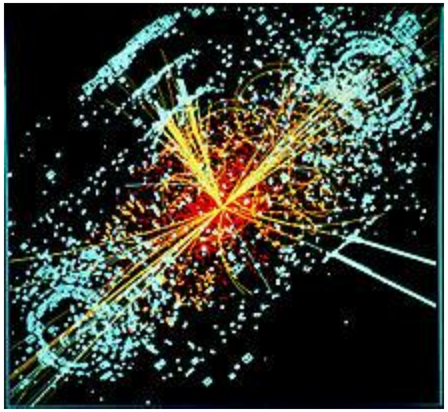
- What is the underlying physics for the new boson ?
  - Standard Model
  - Supersymmetric standard model
  - Two Higgs Doublet models
  - Composite Higgs… etc.

- To definitely answer to this question, we need more data

- The verification that the new boson is an SM Higgs will come by testing all the couplings, i.e., couplings to femion-anti-fermion pairs and to di-bosons : (Zeppenfeld, SUSY12)

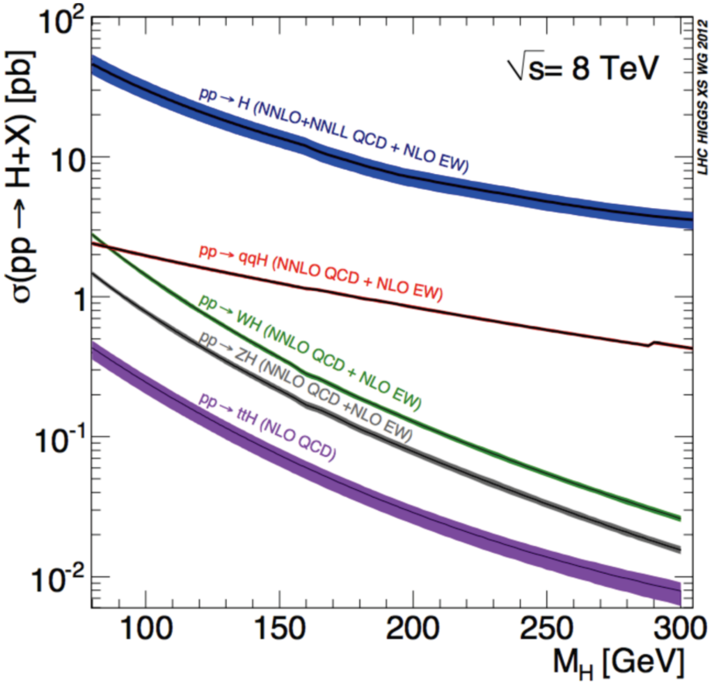
$$h\bar{f}\,f\,,\ hWW\,,\ hZZ\,,\ h\gamma\gamma,\ hZ\gamma$$

- Important clues to new physics can emerge by looking at deviations of the Higgs boson couplings from the standard model predictions.



What we observed at the LCH

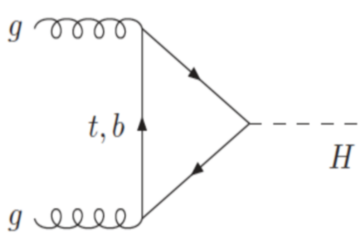
Main channels for SM Higgs observation



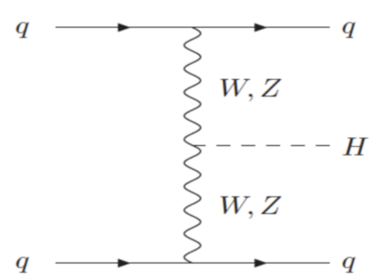
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ \rightarrow 4l$
- $H \rightarrow WW \rightarrow 2l2\nu$
- $H \rightarrow \tau\tau$
- $H \rightarrow bb$

M$_H$ [GeV]

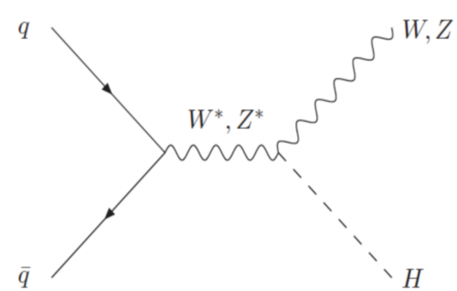
ggH



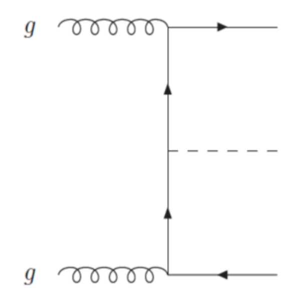
VBF



VH

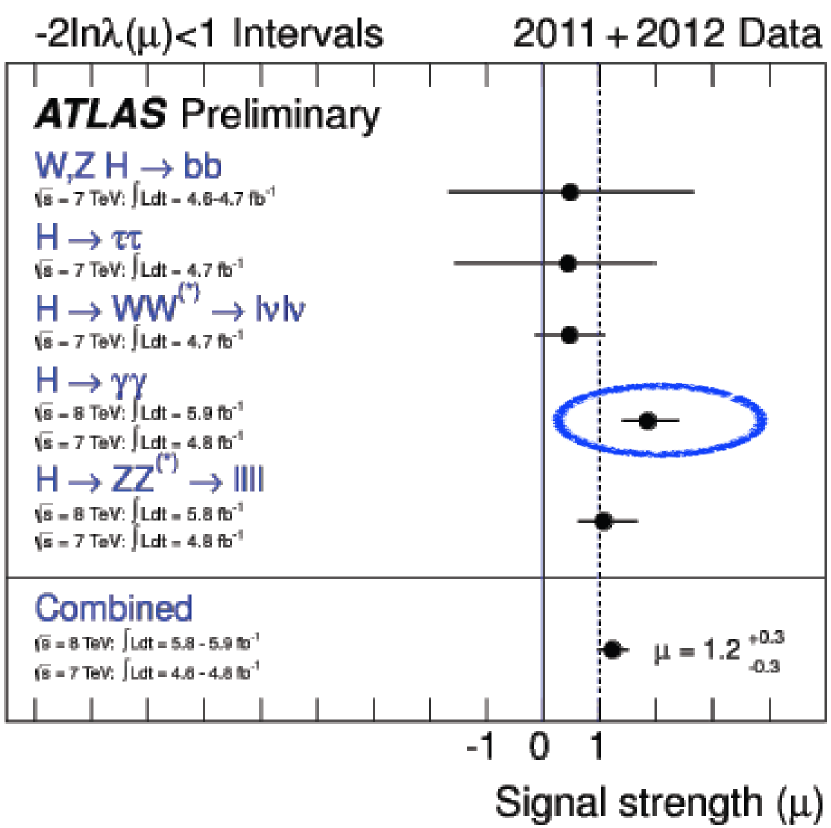


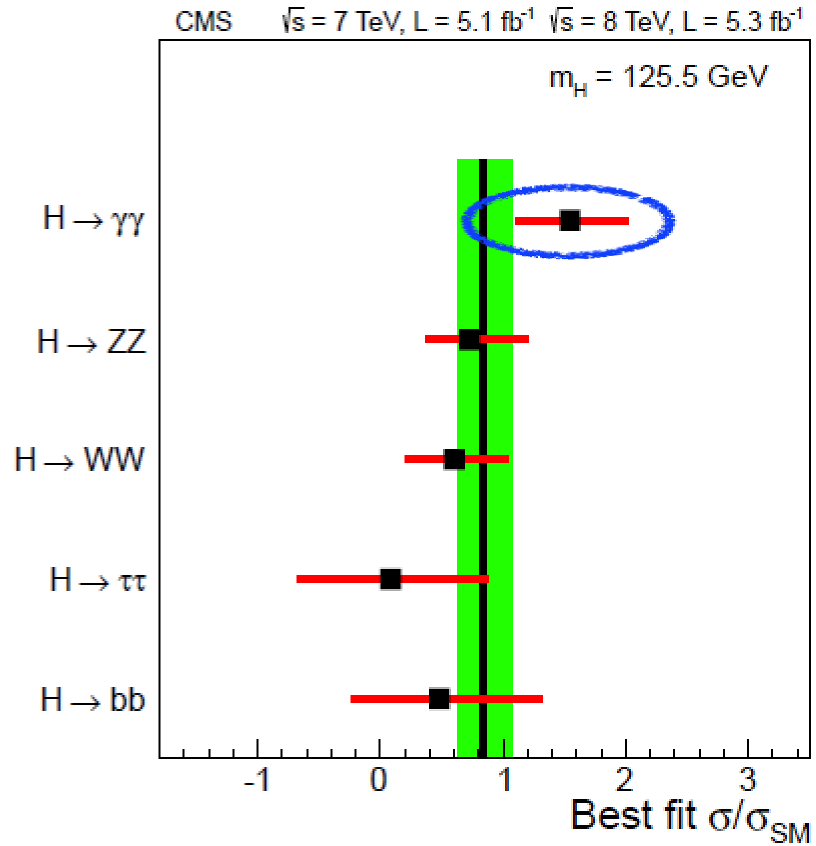
ttH



Exploit all four production modes

- Interestingly, CMS and ATLAS have observed an excess in the signal strength for di-photon channel





- As extensively studied, to enhance R$\gamma\gamma$ one may add extra particles in the loops :

$$R_{\gamma\gamma} \equiv \frac{\sigma(pp \to h)_{obs}}{\sigma(pp \to h)_{SM}} \left[-1.28(1+\delta_V) + 0.28(1+\delta_f) + \delta_s\right]^2$$

(Carena, Low, Wagner, arXiv:1206.1082)

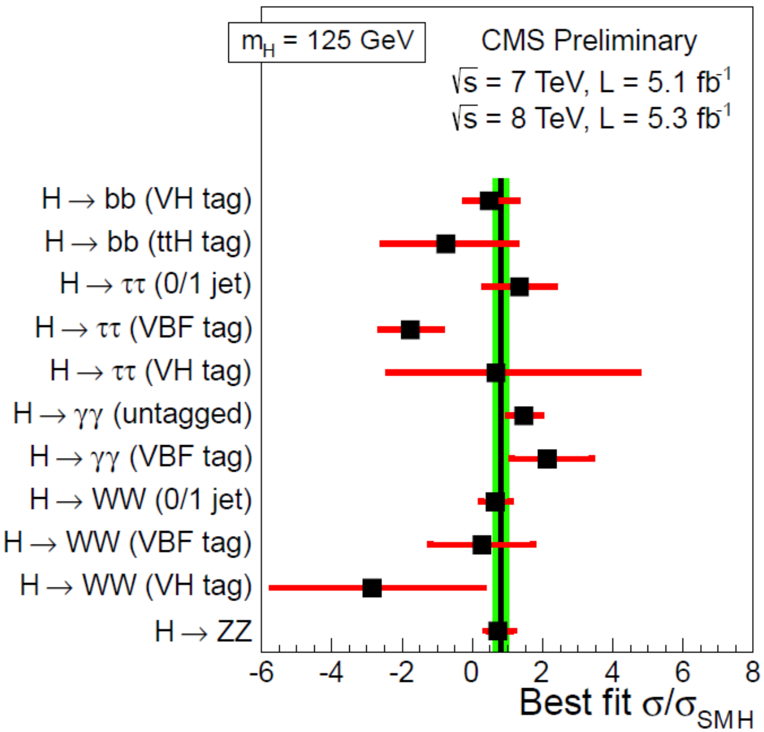
- But, we need more understanding QCD contributions to $R_{\gamma\gamma}$

(Baglio, Djouadi, Godbole arXiv:1207.1451)

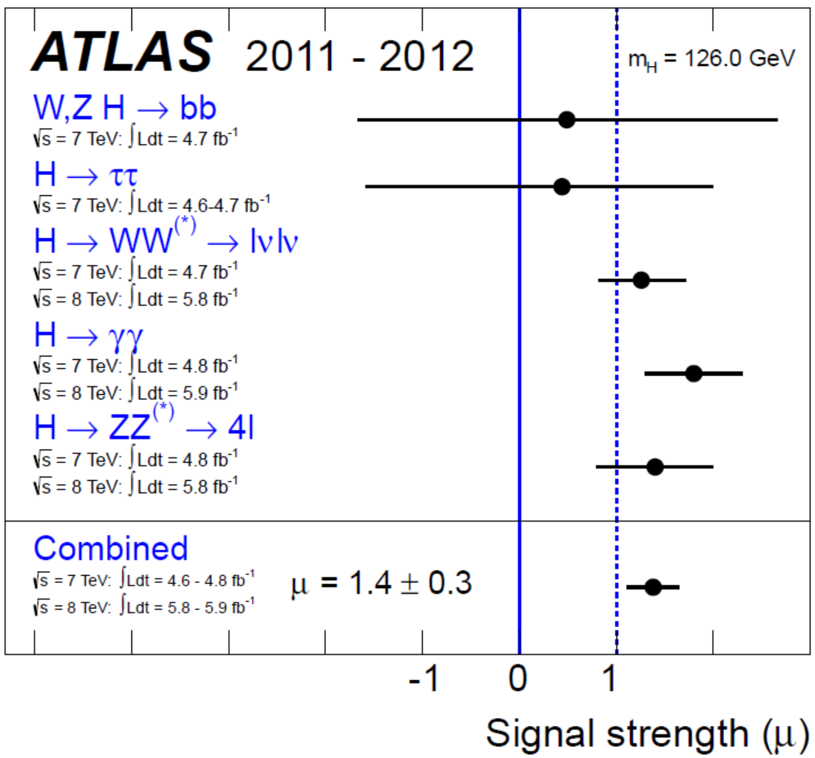
- What others ?

Summary of measured channels

CMS data



ATLAS data



Motivation on this work

- Motivated by the discovery of new boson and hint for new physics beyond the SM, we investigate if 2HDM can be compatible with the data obtained by CMS & ATLAS

- We perform the global fit to the data and show if there exists parameter space of 2HDM leading to better fit than the SM.

Why 2HDM ?

- Various models such as MSSM, DSB, Little Higgs etc. have specific (extended) Higgs sector, so extended Higgs sector is window to new physics.

- It is natural to examine experimental results appeared to be deviated from the SM within the context of 2HDM.

Two Higgs Doublet Models

- There are two complex doublets for the Higgs

$$\Phi_1 = \begin{pmatrix} \phi_1^{\ +} \\ \dfrac{v_1 + \phi_1^{\ 0} + iA_1^{\ 0}}{\sqrt{2}} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^{\ +} \\ \dfrac{v_2 + \phi_2^{\ 0} + iA_2^{\ 0}}{\sqrt{2}} \end{pmatrix}$$

- There are five physical scalars :

$$h^0 ,\ H^0 ,\ A^0 , H^{\pm}$$

$$h^0 = \sqrt{2}(\phi_1^0 \sin\alpha - \phi_2^0 \cos\alpha)$$

$$H^0 = -\sqrt{2}(\phi_1^0 \cos\alpha + \phi_2^0 \sin\alpha)$$

$$A^0 = \sqrt{2}(A_1^0 \sin\beta - A_2^0 \cos\beta)$$

- Since the SM Higgs is

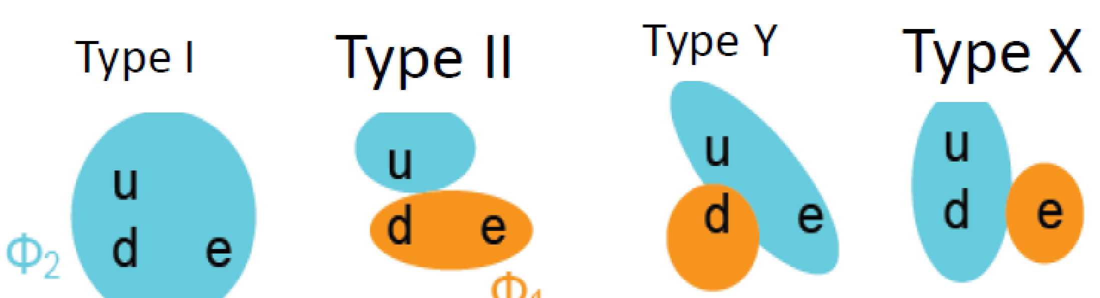
$$h_{SM} = h^0 \sin(\alpha-\beta) - H^0 \cos(\alpha-\beta)$$

$\boldsymbol{h^0}$ becomes identical with h_{SM} *if* $\sin(\alpha-\beta)=1$

⇨ decoupling limit

- To suppress FCNC at the leading order, one can impose a discrete symmetry such that one fermion couples with only one Higgs doublet.

⇨ four types of 2 HDM (I, II, X, Y)



- We parameterize the Yukawa interactions

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

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

	$\widehat{y}_u^h$	$\widehat{y}_d^h$	$\widehat{y}_\ell^h$	$\widehat{y}_u^H$	$\widehat{y}_d^H$	$\widehat{y}_\ell^H$	$\widehat{y}_u^A$	$\widehat{y}_d^A$	$\widehat{y}_\ell^A$
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	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$	$\tan\beta$	$-\cot\beta$

- In 4 types of 2HDM, we consider 3 possible scenarios

  - Scenario-1 : The observed signal is from the lighter CP even neutral Higgs h^0
  - Scenario-2 : The observed signal is from the heavier CP even neutral Higgs H^0
  - Scenario-3 : The observed signal is from two almost degenerate h^0, A^0

Experimental Constraints

$$\Delta\rho \equiv \rho^{obs} - \rho^{SM} = 0.0002 \pm 0.0007$$

New contributions to 👎❒ in 2HDM

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

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

An interesting condition for small 👎❒ :

$$M_{h^0} \approx M_{A^0}\,,\ M_{H^\pm} \approx M_{H^0} \text{ and } \sin^2(\alpha-\beta) \approx 1$$

Experimental Constraints

- Constraints on tanβ and $M_{H^\pm}$ are from various physics such as leptonic decays of B/D mesons, ΔM_B, b→sγ, and $Z \to \bar{b}b$
- Data on b→sγ exclude :

  - small mass region of $M_{H^\pm}(< 295\, GeV)$for II & Y

  - small tanβ (<1) region for I & X

  (Misiak et al.'07, Kanemura et al. '09)
- B→ $\tau\, \nu$ $/D_s \to \tau\nu$: constraints for type II

  (Rozanska, '10, Deschamps et al. '10, Mahmoudi, Stal, '10)

Parameterizing observed Higgs Signal

- Observed signal in the Higgs search at the LHC is given by the ratio of the observed event rate of a specific channel to the SM expectation,

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

- production = ggF, VBF, Vh
- decay = $\gamma\gamma$, WW, ZZ, bb, $\tau\tau$

- Non-negligible # of Higgs events from ggF pass the diject tag.
- The dijet-tagged gluon fusion is about 38% of the tagged VBF in the SM (S.Chatrchyan et al.PLB710,403)

$$
\begin{aligned}
R_{ii}^{\mathrm{VBF}} &= \frac{\sigma(pp \to hjj)\mathrm{Br}(h \to ii)}{\sigma(pp \to h_{\mathrm{SM}}jj)\mathrm{Br}(h_{\mathrm{SM}} \to ii)} \\
&= \frac{\epsilon_{gg\mathrm{F}} \cdot \sigma(gg \to h) + \epsilon_{\mathrm{VBF}} \cdot \sigma(VV \to h)}{\epsilon_{gg\mathrm{F}} \cdot \sigma(gg \to h_{\mathrm{SM}}) + \epsilon_{\mathrm{VBF}} \cdot \sigma(VV \to h_{\mathrm{SM}})} \cdot \left| \frac{\mathrm{Br}(h \to ii)}{\mathrm{Br}(h_{\mathrm{SM}} \to ii)} \right|^2
\end{aligned}
$$

- Here ♏$_{\mathbf{ggF}}$ and ♏$_{\mathbf{VBF}}$ are the efficiencies of the gluon fusion and the VBF, respectively, to pass the VBF selection cuts.

- Based on $R^{\texttt{production}}_{\texttt{decay}}$, we perform global ♍🗎 fit of model parameters to the observed Higgs signal strength,

$$x^2 = \sum_{i=1}^{N} \frac{(R_i - \widetilde{R_i})^2}{{\sigma_i}^2}$$

Summary of the LHC Higgs Signals

	ATLAS and CMS	CMS
7 TeV	$\widetilde{R}^{ggF}_{\gamma\gamma} = 1.66 \pm 0.50$, $\widetilde{R}^{ggF}_{WW} = 0.58 \pm 0.41$ $\widetilde{R}^{ggF}_{WW} = 0.58 \pm 0.41$, $\widetilde{R}^{ggF}_{ZZ} = 0.79 \pm 0.41$ $\widetilde{R}^{ggF}_{\tau\tau} = 0.75 \pm 1.02$, $\widetilde{R}^{Vh}_{bb} = 0.62 \pm 1.09$	$\widetilde{R}^{ggF}_{\gamma\gamma} = 1.66 \pm 0.50$, $\widetilde{R}^{Vh}_{WW} = 2.75 \pm 2.96$ $\widetilde{R}^{VBF}_{\tau\tau} = -1.61 \pm 1.25$, $\widetilde{R}^{Vh}_{\tau\tau} = 0.659 \pm 3.07$
8 TeV	$\widetilde{R}^{ggF}_{\gamma\gamma} = 1.69 \pm 0.44$, $\widetilde{R}^{VBF}_{\gamma\gamma} = 1.34 \pm 0.94$ $\widetilde{R}^{ggF}_{WW} = 1.38 \pm 0.49$, $\widetilde{R}^{ggF}_{ZZ} = 0.85 \pm 0.40$	$\widetilde{R}^{VBF}_{WW} = 1.34 \pm 1.82$, $\widetilde{R}^{ggF}_{\tau\tau} = 2.14 \pm 1.48$ $\widetilde{R}^{VBF}_{\tau\tau} = -1.73 \pm 1.25$, $\widetilde{R}^{Vh}_{b\bar{b}} = 0.43 \pm 0.80$

Single particle scenarios (Scenario-1 & 2)

- Effetcive Lagrangian

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

- For m_h=125 GeV, the SM values :

$$
\boldsymbol{C_{V,SM} = C_{f,SM}|_{f=t,b,c,\tau} = 1,}
$$

$$
\boldsymbol{C_{g,SM} \cong 1, \qquad\qquad C_{\gamma,SM} \cong -0.81}
$$

- Approximately,

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

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

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

$$\widehat{R}^h_{\mathrm{VBF}} = \frac{\epsilon_{ggF} \cdot |c_g|^2 \sigma^{SM}_{gg\to h} + \epsilon_{\mathrm{VBF}} \cdot |c_V|^2 \sigma^{SM}_{\mathrm{VBF}}}{\epsilon_{ggF} \cdot \sigma^{SM}_{gg\to h} + \epsilon_{\mathrm{VBF}} \cdot \sigma^{SM}_{\mathrm{VBF}}}$$

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

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

$$\Gamma_{tot} = |C_{tot}|^2 \Gamma_{tot}^{\mathrm{SM}}$$

for $m_h = 125$ GeV, $\Gamma_{tot}^{\mathrm{SM}} \simeq 4.0\,\mathrm{MeV}$

$$|C_{tot}|^2 \simeq$$

$$0.58|c_b|^2 + 0.24|c_V|^2 + 0.09\frac{|\hat{c}_g|^2}{\left|\hat{c}_g^{\mathrm{SM}}\right|^2} + 0.06|c_\tau|^2 + 0.03|c_c|^2$$

Degenerate scenario

- Effective Lagrangian

$$\mathcal{L}_{\rm eff}^{A} = \mathcal{L}_{\rm eff} - a_b \frac{m_b}{v} A\, \bar{b}\gamma_5 b - a_\tau \frac{m_\tau}{v} A\, \bar{\tau}\gamma_5 \tau - a_t \frac{m_t}{v} A\, \bar{t}\gamma_5 t$$

$$+ a_g \frac{\alpha_s}{12\pi v} A\, G^a_{\mu\nu} G^{a\mu\nu} + a_\gamma \frac{\alpha}{\pi v} A\, A_{\mu\nu} A^{\mu\nu}$$

$$a_g = a_t \mathcal{A}^A_{1/2}(x_t) + a_b \mathcal{A}^A_{1/2}(x_b),$$

$$a_\gamma = \frac{2}{9} a_t \mathcal{A}^A_{1/2}(x_t) + \frac{1}{18} a_b \mathcal{A}^A_{1/2}(x_b) + \frac{1}{6} a_\tau \mathcal{A}^A_{1/2}(x_\tau),$$

- Relevant Higgs event rates :

$$R_{\gamma\gamma}^{gg\mathrm{F}} = \left|\frac{c_g c_\gamma}{c_{\gamma,\mathrm{SM}} C_{\mathrm{tot}}^h}\right|^2 + \left|\frac{a_g a_\gamma}{c_{\gamma,\mathrm{SM}} C_{\mathrm{tot}}^A}\right|^2,$$

$$R_{\tau\tau}^{gg\mathrm{F}} = \left|\frac{c_g c_\tau}{C_{\mathrm{tot}}^h}\right|^2 + \left|\frac{a_g a_\tau}{C_{\mathrm{tot}}^A}\right|^2,$$

$$R_{\gamma\gamma}^{\mathrm{VBF}} = \widehat{R}_{\mathrm{VBF}}^h \left|\frac{c_\gamma}{c_{\gamma,SM} C_{\mathrm{tot}}^h}\right|^2 + \widehat{R}_{\mathrm{VBF}}^A \left|\frac{a_\gamma}{c_{\gamma,SM} C_{\mathrm{tot}}^A}\right|^2,$$

$$R_{\tau\tau}^{\mathrm{VBF}} = \widehat{R}_{\mathrm{VBF}}^h \left|\frac{c_\tau}{C_{\mathrm{tot}}^h}\right|^2 + \widehat{R}_{\mathrm{VBF}}^A \left|\frac{a_\tau}{C_{\mathrm{tot}}^A}\right|^2,$$

$$\widehat{R}_{\mathrm{VBF}}^A = \frac{\epsilon_{gg\mathrm{F}} \cdot |a_g|^2 \sigma_{gg\to h}^{SM}}{\epsilon_{gg\mathrm{F}} \cdot \sigma_{gg\to h}^{SM} + \epsilon_{\mathrm{VBF}} \cdot \sigma_{\mathrm{VBF}}^{SM}}$$

Numerical Results

- Considering bounds from flavor physics, most studies of 2HDM in the literature assume tanβ>1 and large $M_{H^{\pm}}$.
- But, if 2HDM is not the final theory but an effective way to describe the Higgs sector, we may relax the constraint on tanβ
- The parameters we scan : α, β
- We consider two cases : unconstrained & flavor-constrained
- For unconstrained : scan all the parameter space $-\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2}$, 0.1<tanβ<50

- For flavor-constrained:
  - we assume rather heavy charged scalar like $M_{H^{\pm}} \sim 1\ \mathrm{TeV}$, which limits tan$\beta$ as

    type-I & -X : tan$\beta \geq 1$

    type-II & -Y : tan$\beta \geq 0.5$

Scenario-1

- Effective couplings :

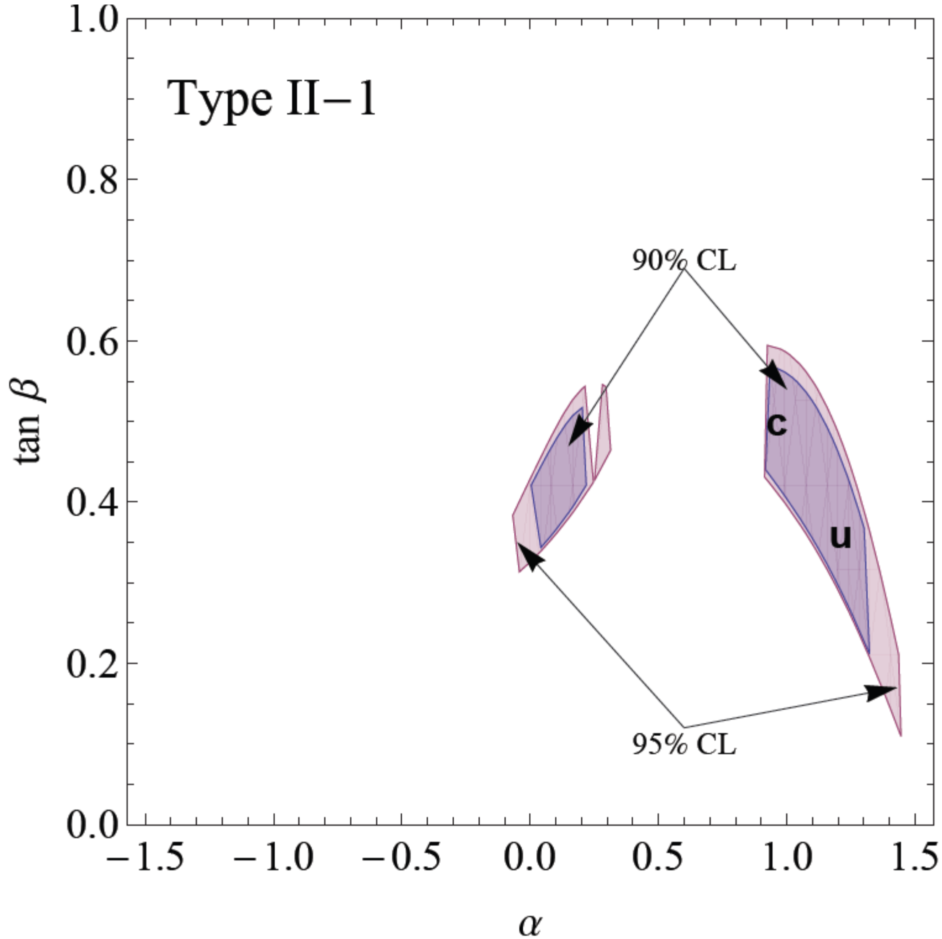
$$c_V = \sin(\beta - \alpha), \quad c_b = \widehat{y}_d^h, \quad c_\tau = \widehat{y}_\ell^h, \quad c_t = c_c = \widehat{y}_u^h$$

- Best-fit points for scenario-1 in 4 types of 2HDM

	`Unconstrained`	`Flavor-constrained`
2HDM Type	$(\chi^2_{\rm min},\ \alpha,\ \tan\beta)$	$(\chi^2_{\rm min},\ \alpha,\ \tan\beta)$
Type I-1	$(16.15,\ 1.38,\ 0.21)$	$(30.12,\ -0.97,\ 1.02)$
Type II-1 ✓	$(16.16,\ 1.21,\ 0.36)$	$(20.31,\ 0.96,\ 0.50)$
Type X-1	$(15.24,\ 1.19,\ 0.27)$	$(28.55,\ -0.001,\ 49.76)$
Type Y-1	$(15.80,\ 1.38,\ 0.21)$	$(23.89,\ 1.06,\ 0.51)$

$\chi^2|_{99\%\ \rm C.L.} = 34.8,\ \chi^2|_{95\%\ \rm C.L.} = 28.9$ $\qquad$ $\chi^2_{\rm SM}|_{\rm d.o.f.=18} = 23.04.$

Contours for 90 (95)% in Type II-1 model



- Excludes large tanβ region above 0.6 at 95% which sets lower bound on charged scalar mass > 800 GeV

- Effective couplings and the Higgs signal rates R's at the best-fit points in type II-1

Type II-1: `Unconstrained`	Type II-1: `Flavor-constrained`
$(\chi^2_{\rm min},\ \alpha,\ \tan\beta) = (16.16,\ 1.21,\ 0.36)$	$(\chi^2_{\rm min},\ \alpha,\ \tan\beta) = (20.31,\ 0.96,\ 0.50)$
$c_V = -0.76, \quad c_g = 1.12, \quad c_\gamma = 0.88$ $c_b = c_\tau = -0.99, \quad c_t = c_c = 1.05$	$c_V = -0.47, \quad c_g = 1.35, \quad c_\gamma = 0.69$ $c_b = c_\tau = -0.91, \quad c_t = c_c = 1.28$
$R^{gg\rm F}_{\gamma\gamma} = 1.61, \quad R^{\rm VBF}_{\gamma\gamma} = 0.99$ $R^{gg\rm F}_{WW} = 0.79, \quad R^{\rm VBF}_{WW} = 0.49, \quad R^{gg\rm F}_{ZZ} = 0.79$ $R^{Vh}_{b\bar b} = 0.63, \quad R^{gg\rm F}_{\tau\tau} = 1.34, \quad R^{\rm VBF}_{\tau\tau} = 0.82$	$R^{gg\rm F}_{\gamma\gamma} = 1.67, \quad R^{\rm VBF}_{\gamma\gamma} = 0.61$ $R^{gg\rm F}_{WW} = 0.51, \quad R^{\rm VBF}_{WW} = 0.18, \quad R^{gg\rm F}_{ZZ} = 0.51$ $R^{Vh}_{b\bar b} = 0.23, \quad R^{gg\rm F}_{\tau\tau} = 1.90, \quad R^{\rm VBF}_{\tau\tau} = 0.70$

Scenario-2

- Effective couplings :

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

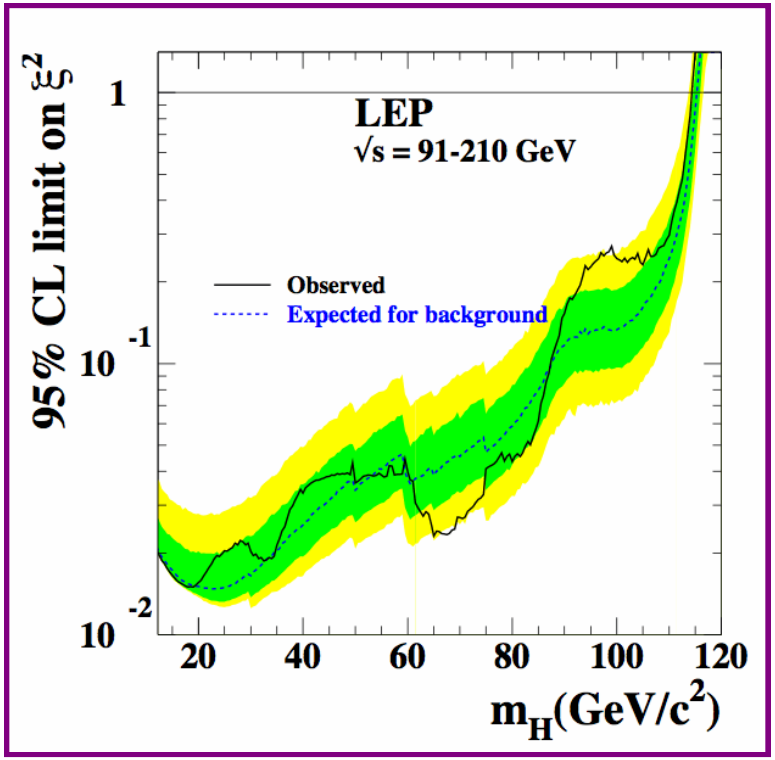
- Best-fit points for scenario-2 in 4 types of 2HDM

	Unconstrained	Flavor-LEP-constrained
2HDM Type	$(\chi^2_{\rm min},\ \alpha,\ \tan\beta)$	$(\chi^2_{\rm min},\ \alpha,\ \tan\beta)$
Type I-2	$(16.11,\ -0.15,\ 0.17)$	$(30.08,\ 0.59,\ 1.01)$
Type II-2	$(15.92,\ -0.29,\ 0.30)$	$(30.87,\ 1.55,\ 48.5)$
Type X-2	$(15.16,\ -0.35,\ 0.27)$	$(28.55,\ 1.57,\ 49.82)$
Type Y-2	$(15.77,\ -0.15,\ 0.17)$	$(31.91,\ -1.55,\ 48.12)$

$$\chi^2_{\rm SM}\Big|_{\rm d.o.f.=18} = 23.04.$$

LEP constraints

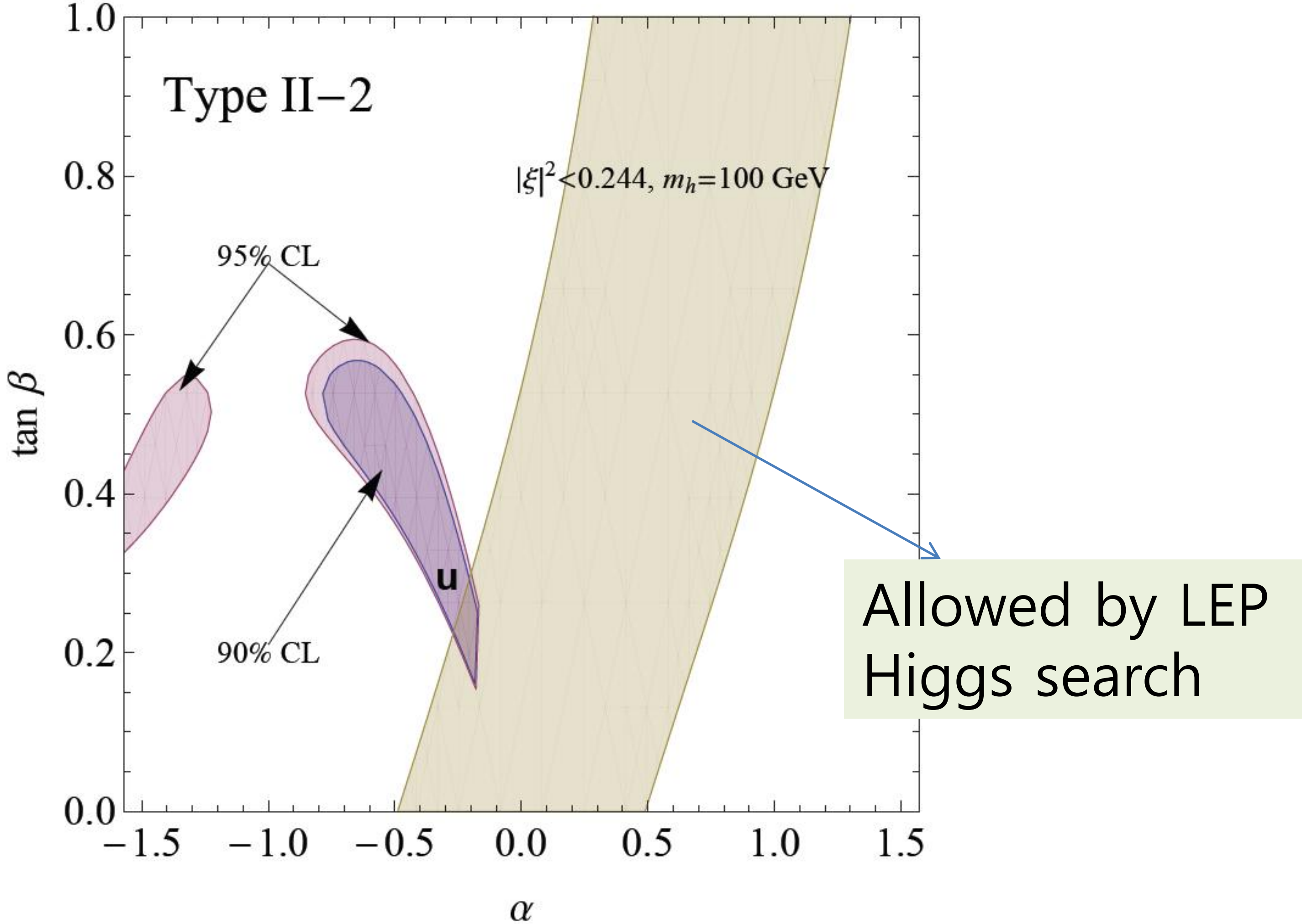
- From the LEP search for light Higgs via $e^+e^- \to Z^* \to Zh \to l^+l^- + jj$



constraint on

$$|\xi|^2 = |C_V|^2 \frac{Br(h \to jj)}{Br(h_{SM} \to jj)}$$

(Barate et al.[LEP working group]'03, Schael et al., '06)



Contours for 90 (95)% in Type II-2 model where $h = H^0$.

Scenario-3

- Best-fit points for scenario-3 in 4 types of 2HDM

	Unconstrained	Flavor-EW-constrained
2HDM Type	$(\chi^2_{\rm min},\, \alpha,\, \tan\beta)$	$(\chi^2_{\rm min},\, \alpha,\, \tan\beta)$
Type I-3	$(27.52,\ -0.98,\ 1.37)$	$(29.38,\ -0.68,\ 1.62)$
Type II-3	$(28.62,\ 0.23,\ 0.74)$	$(31, 03,\ -0.14,\ 5.93)$
Type X-3	$(15.92,\ -0.34,\ 0.58)$	$(27.94,\ -0.007,\ 8.32)$
Type Y-3	$(30.63,\ -0.75,\ 1.19)$	

- Only type X-3 has better ${x_{\mathbf{min}}}^2$ than the SM
- For F-E constrained case, type X-3 marginally allowed at 95% C.L.

Summary

- We investigated the possibility that the observed new boson may not be the SM Higgs but another boson in 2HDM.
- We comprehensively studied 4 types of 2HDM with 3 scenarios.
- Considering phenomenological constraints such as flavor physics, EW data and LEP search for the Higgs, we find that scenario-1 (new boson is h^0) in type-II & Y provide better or similarly good fit to the data than the SM. Most other scenarios are disfavored at 95% C.L.