Hidden Light Higgs Scenario in Two Higgs Doublet Models

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Based on the work in collaboration with S.Chang, J.P.Lee, J. Song (PRD92,075023(2015))

Introduction

- Implications on the Higgs discovery
  - completing the journey in the SM
  - EWSB mechanism is uncovered
  - m_H is determined

- Since we believe that the SM is not the ultimate theory of nature, new physics beyond the SM is inevitable.

- There is no reason for prohibiting additional Higgs doublets

→ pursuing search for additional Higgs is a good direction toward NP

Introduction

- Full data sets at 7 & 8 TeV reveal that the observed state with a mass 125 GeV is quite SM-like .

- That fact implies that extensions of the SM including extended Higgs will be significantly constrained by the data.

- Null results in search for the heavy neutral & charged Higgs
  → points to the decoupling limit of 2HDM where other scalars except for 125 GeV state are heavy enough
- The phenomenology of the decoupling limit generally mimic that of the SM

Introduction

- What we have done in this work
  - What if the 125 GeV state is the heavier CP even neutral Higgs in two Higgs doublet model (2HDM) ?
  - How severely LHC data constrain the possibility?

- Where is the lighter CP even neutral Higgs ?
  - it must have escaped LEP searches
  - any signal for lighter sector might be hidden in the LHC data

- We call this possibility Hidden light Higgs scenario
  - This scenario can be strongly constrained from various data
  - m_A , $m_{H^\pm}$ & some of Higgs couplings are narrowly constrained

Brief review on 2HDM

- Let's consider a 2HDM with CP invariance and softly broken Z_2 symmetry

  - Expression for two Higgs doublets

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(\eta_1 + i\chi_1) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(\eta_2 + i\chi_2) \end{pmatrix}$$

- Lagrangian :

$$L = D_\mu \Phi_1^\dagger D^\mu \Phi_1 + D_\mu \Phi_2^\dagger D^\mu \Phi_2 + L_Y - V(\Phi_1, \Phi_2)$$

$$D_\mu = \partial_\mu - igW_\mu^a \sigma^a/2 - ig' Y_{\Phi_i} A_\mu$$

- Yukawa terms :

$$\bar{Q}_{L,i}(Y_{u,1}^{ij}\tilde{\Phi}_1 + Y_{u,2}^{ij}\Phi_2)u_{R,j} + \bar{Q}_{L,i}(Y_{d,1}^{ij}\Phi_1 + Y_{d,2}^{ij}\tilde{\Phi}_2)d_{R,j}$$

$$+ \quad \bar{L}_{L,i}(Y_{l,1}^{ij}\Phi_1 + Y_{l,2}^{ij}\tilde{\Phi}_2)l_{R,j} + h.c.,$$

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

- When two Higgs doublets acquire different VEVs, the mass terms read,

$$m_u^{ij} = Y_{u,1}^{ij} v_1 + Y_{u,2}^{ij} v_2, \quad m_d^{ij} = Y_{d,1}^{ij} v_1 + Y_{d,2}^{ij} v_2,$$

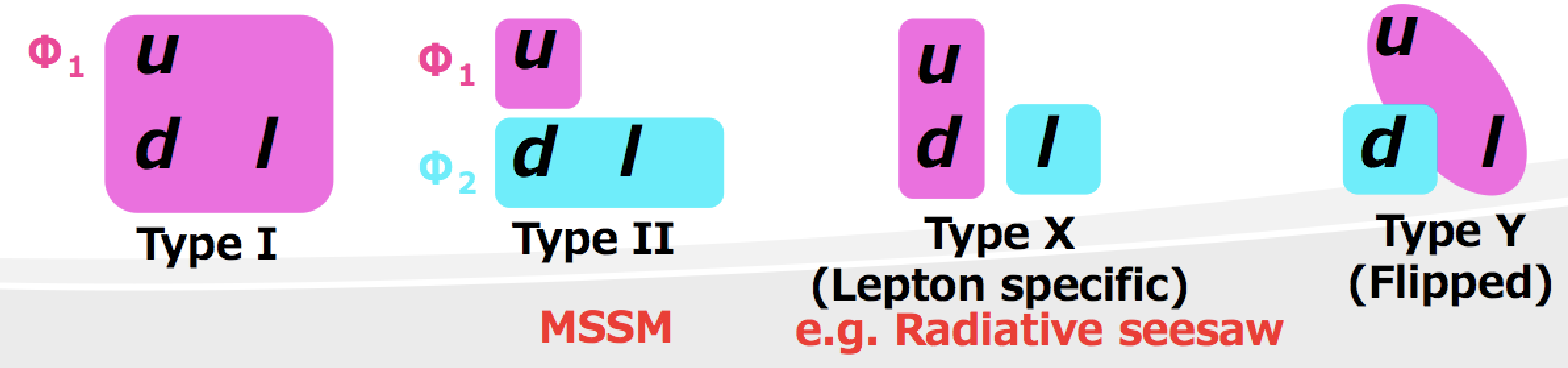
- Diagonalization of the mass matrix will not give diagonal Yukawa couplings ⇒ induce large, unacceptable tree-level FCNC in the Higgs sector.

- To avoid FCNCs, easiest way is to impose Z_2 symmetry under which

$$\Phi_1 \to \Phi_1, \qquad \Phi_2 \to -\Phi_2$$

- 4 types of Yukawa Interactions are possible :

	Φ_1	Φ_2	Q^i	L^i	u_R^i	d_R^i	e_R^i
Type-I	+	−	+	+	−	−	−
Type-II	+	−	+	+	−	+	+
Type-X	+	−	+	+	−	−	+
Type-Y	+	−	+	+	−	+	−



- Alternative way : to impose U(1) symmetry (Pecci, Quinn 1977)

$$\Phi_1 \to \Phi_1 \quad , \Phi_2 \to e^{i\omega}\Phi_2$$

- Flavor-dependent local U(1) symmetry ⇨ (Ko,Omura,Yu)

Higgs potential

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

- For CP conserving case:
  - all parameters, vacuum expectation values are real.

- Z_2 symmetry requires $m_{12}^2 = \lambda_6 = \lambda_7 = 0$

- But, we can avoid FCNC while keeping $m_{12}^2 \neq 0$

Higgs Boson Spectroscopy:

- Rotating scalar fields to mass eigenstates:

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

Of the original 8 scalar degrees of freedom, 3 Goldstone bosons ($G^\pm$ and G) are eaten by the $W^\pm$ and Z.

- The remaining 5 physical Higgs particles are:
  - 2 CP-even scalars (h^0, H^0) CP-odd scalar (A^0) and a pair of $H^\pm$

- One CP-odd neutral Higgs with squared-mass:

$$m_A^2 = \frac{m_{12}^2}{c_\beta s_\beta} - 2\lambda_5 v^2.$$

- Two charged Higgs with squared-mass:

$$m_{H^\pm}^2 = \frac{m_{12}^2}{c_\beta s_\beta} - (\lambda_4 + \lambda_5)v^2,$$

- And two CP-even Higgs that mix.

$$\mathcal{M}_0^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \qquad \mathcal{M}_{11}^2 = m_{12}^2 t_\beta^2 + \frac{\lambda_1 v^2}{1 + t_\beta^2}, \qquad \mathcal{M}_{22}^2 = \frac{m_{12}^2}{t_\beta^2} + \lambda_2 v^2 \frac{t_\beta^2}{1 + t_\beta^2}$$

$$\mathcal{M}_{12}^2 = -m_{12}^2 + \lambda_{345} v^2 \frac{t_\beta}{1 + t_\beta^2}, \qquad m_{H,h}^2 = \frac{1}{2}\left[\mathcal{M}_{11}^2 + \mathcal{M}_{22}^2 \pm \sqrt{(\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2)^2 + 4(\mathcal{M}_{12}^2)^2}\right].$$

- Yukawa interactions normalized by the corresponding SM values:

	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	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

- Then, the SM Higgs boson is a mixture of h^0 and H^0

$$H^{SM} = s_{\beta-\alpha}\, h^0 + c_{\beta-\alpha} H^0$$

- α is the mixing between h^0 and H^0, $tan\beta = v_2/v_1$

- The alignment limit : $c_{\beta-\alpha} = 1$

- In the alignment limit : interactions proportional to $\sin(\beta-\alpha)$ vanish

Higgs couplings to gauge bosons become

$$g_{hVV} = 0 \quad , \quad g_{HVV} = g_{hVV}^{SM}$$

$$g_{hAZ} = \frac{g\cos(\beta-\alpha)}{2\cos\theta_W} = \frac{g}{2\cos\theta_W} \qquad g_{HAZ} = \frac{-g\sin(\beta-\alpha)}{2\cos\theta_W} = 0$$

Couplings of h and H to gauge boson pairs or vector-scalar bosons

$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$
HW^+W^-	hW^+W^-
HZZ	hZZ
ZAh	Z[illegible]
$W^{\pm}H^{\mp}h$	[illegible]H
$ZW^{\pm}H^{\mp}h$	$ZW^{\pm}H^{\mp}H$
$\gamma W^{\pm}H^{\mp}h$	$\gamma W^{\pm}H^{\mp}H$

- Yukawa couplings of 125 GeV state H^0

	$c_{\beta-\alpha} - \frac{s_{\beta-\alpha}}{t_\beta}$	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$
Type I	$\hat{y}^H_{uu}, \hat{y}^H_{dd}, \hat{y}^H_{\ell\ell}$	
Type II	$\hat{y}^H_{uu}$	$\hat{y}^H_{dd}, \hat{y}^H_{\ell\ell}$
Type X	$\hat{y}^H_{uu}, \hat{y}^H_{dd}$	$\hat{y}^H_{\ell\ell}$
Type Y	$\hat{y}^H_{uu}, \hat{y}^H_{\ell\ell}$	$\hat{y}^H_{dd}$

- In the exact alignment limit, all Yukawas for H^0 are the same as in SM

- deviations from the alignment limit : $\propto t_\beta$ or $1/t_\beta$

- Since FCNC requires $t_\beta \geq 1$, $t_\beta s_{\beta-\alpha}$ yields much larger deviation

Constraints

- Theoretical constraints
  - stability condition : the scalar potential is positive at large value so that it is stable.

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

  - Satisfying tree-level unitarity bounds

    (Arhib, arXiv:hep-ph/0012353;

    Branco, Ferreira, Lavoura, Rebelo, Sher, Silva, Phys. Rep. 516, 1 (2012))

  - Requiring couplings to be perturbative.

  - we donot require the global minimum of the potential

Constraints

- Pre-LHC constraints

  - LEP bounds on h^0 with mass below 114 GeV:

    strongest bound comes from $e^+e^- \to Z^0 h^0 \to Z^0 jj$

    $\xi^2 = (g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}^{\mathrm{SM}})^2$ depending on mass

  - LEP bounds on $H^\pm$: from the channel for charged Higgs production

    $$m_{H^\pm} \geq 80 \text{ GeV}$$

  - $\Delta\rho$ in the EW precision data : $\Delta\rho = 0.00040 \pm 0.00024$

    new contributions are suppressed if $m_A \simeq m_{H^\pm}$ or $m_H \simeq m_{H^\pm}$

    the latter is prohibited by FCNC constraints in types II and Y.

Constraints

- Pre-LHC constraints

-B-physics constraints :

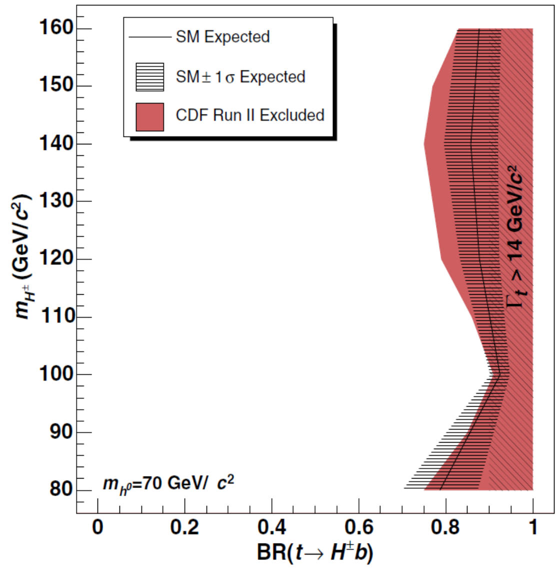
ΔM_{B_d} : excludes small t_β region for all types of 2HDM

$b \to s\,\gamma$: excludes light charged Higgs mass regions in type II & Y

- bound from $t \to b\,H^{\pm}$

- A light charged Higgs could have appeared in $t \to b\,H^{\pm}$ if kinematically allowed.

- we include Tevatron bound on BR($t \to b\,H^{\pm}$)



Constraints

- LHC constraints
  - Higgs mass bound : $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$ GeV
    we exclude the possibility : $m_H = m_A$ & $m_h = m_H$

  - LHC search for charged Higgs boson : (talk by Rui)
    - since the direct production of $H^{\pm}$ is very small, bound for charged Higgs is weak in general.
    - strongest bound comes from the channel $pp \to t\bar{t} \to b\bar{b}H^{\pm}W^{\mp}$
      followed by $H^{\pm} \to \tau^{\pm}\nu_{\tau}$

Constraints

- LHC constraints

- LHC search for A^0 : A^0 is the only heavy neutral scalar in HLHS

→ exclusion limit from no excess in heavy neutral Higgs search via the processes : $gg \to A^0 \to \gamma\gamma$, $gg \to A^0 \to \tau^+\tau^-$ & $b\bar{b} \to A^0 \to \tau^+\tau^-$

Constraints

- LHC constraints

  -Global fit to the LHC data associated with 125 GeV state :

  we consider the signal strength identified with the ratio of the observed event rate to the SM expectation in specific production channel X and specific decay mode Y

$$R^{\mathrm{prduction}}_{\mathrm{decay}} = \frac{\sigma(X) BR(Y)}{\sigma_{SM}(X) BR_{SM}(Y)}$$

Constraints

- LHC constraints
  - the LHC data at 7 & 8

TABLE II. Summary of the LHC Higgs signal strengths at 7 and 8 TeV.

Production	ATLAS	CMS
$gg\mathrm{F} + t\bar{t}h$	$\tilde{R}^{gg\mathrm{F}}_{\gamma\gamma} = 1.32 \pm 0.38$ [3], $\tilde{R}^{t\bar{t}h}_{\gamma\gamma} = 1.3^{+2.6}_{-1.7}$ [4]	$\tilde{R}^{gg\mathrm{F}+t\bar{t}h}_{\gamma\gamma} = 1.13^{+0.37}_{-0.31}$ [5]
	$\tilde{R}^{gg\mathrm{F}}_{WW} = 1.01^{+0.27}_{-0.20}$ [77]	$\tilde{R}^{gg\mathrm{F}}_{WW} = 0.74^{+0.22}_{-0.20}$ [82]
	$\tilde{R}^{gg\mathrm{F}+t\bar{t}h}_{ZZ} = 1.52^{+0.85}_{-0.65}$ [78]	$\tilde{R}^{gg\mathrm{F}+t\bar{t}h}_{ZZ} = 0.80^{+0.46}_{-0.36}$ [83]
	$\tilde{R}^{gg\mathrm{F}}_{\tau\tau} = 1.93^{+1.45}_{-1.15}$ [79]	$\tilde{R}^{gg\mathrm{F}}_{\tau\tau} = 0.93 \pm 0.42$ [84]
	$\tilde{R}^{t\bar{t}h}_{b\bar{b}} = 1.7 \pm 1.4$ [80,81]	$\tilde{R}^{t\bar{t}h}_{b\bar{b}} = 0.67^{+1.35}_{-1.33}$ [85]
$\mathrm{VBF} + Vh$	$\tilde{R}^{\mathrm{VBF}}_{\gamma\gamma} = 0.8 \pm 0.7$,	$\tilde{R}^{\mathrm{VBF}+Vh}_{\gamma\gamma} = 1.15^{+0.63}_{-0.58}$ [5]
	$\tilde{R}^{WH}_{\gamma\gamma} = 1.0 \pm 1.6$, $\tilde{R}^{ZH}_{\gamma\gamma} = 0.1^{+3.7}_{-0.1}$ [3]	$\tilde{R}^{\mathrm{VBF}}_{WW} = 0.60^{+0.57}_{-0.46}$, $\tilde{R}^{Vh}_{WW} = 0.39^{+1.97}_{-1.87}$ [82]
	$\tilde{R}^{\mathrm{VBF}}_{WW} = 1.28^{+0.53}_{-0.45}$ [77]	$\tilde{R}^{\mathrm{VBF}+Vh}_{ZZ} = 1.7^{+2.2}_{-2.1}$ [83]
	$\tilde{R}^{\mathrm{VBF}+Vh}_{ZZ} = 0.90^{+4.5}_{-2.0}$ [78]	$\tilde{R}^{\mathrm{VBF}}_{\tau\tau} = 0.94 \pm 0.41$,
	$\tilde{R}^{\mathrm{VBF}+Vh}_{\tau\tau} = 1.24^{+0.58}_{-0.54}$ [79]	$\tilde{R}^{Vh}_{\tau\tau} = -0.33 \pm 1.02$ [84]
	$\tilde{R}^{Vh}_{b\bar{b}} = 0.51^{+0.40}_{-0.37}$ [86]	$\tilde{R}^{\mathrm{VBF}}_{b\bar{b}} = 0.7 \pm 1.4$ [85],
		$\tilde{R}^{Vh}_{b\bar{b}} = 1.0 \pm 0.5$ [87]

Constraints

- LHC constraints
  - we take into account "feed down" effects :

    125 GeV state H^0 can be produced as a result of feed down from the production of heavier state

    (Dumont, Gunion, Jiang, Kraml, (2014), Arhrib, Ferreira, Santos,(2014))

    in hidden light Higgs scenario, the dominant FD effect is dominantly from the inclusive decay $A^0 \to H^0$

$$\begin{aligned}\mathcal{P}_{\rm FD}(A^0 \to H^0 + X) = &\, 2{\rm Br}(A^0 \to H^+H^-){\rm Br}(H^+ \to W^+H^0)^2 + {\rm Br}(A^0 \to Z^0H^0) \\ &+ 2{\rm Br}(A^0 \to W^-H^+){\rm Br}(H^+ \to W^+H^0) \\ &+ 2{\rm Br}(A^0 \to H^+H^-){\rm Br}(H^+ \to W^+H^0)\{1 - {\rm Br}(H^+ \to W^+H^0)\}.\end{aligned}$$

  - in HLHS, $A^0 \to Z^0H^0$ favored by pre-LHC data

Constraints

- LHC constraints

  - Defining new FD signal strength :

$$\mu_{ii}^{\mathrm{FD:ZH}} = \frac{\sigma(pp \to gg \to A^0)\mathrm{Br}(A^0 \to Z^0 H^0)}{\sigma(pp \to Z^0 h_{\mathrm{SM}})} \times \frac{\mathrm{Br}(H^0 \to ii)}{\mathrm{Br}(h_{\mathrm{SM}} \to ii)}, \qquad i = \gamma,\ W,\ Z,\ \tau,\ b.$$

  - In the χ^2 analysis, we include $\mu_{ii}^{\mathrm{FD:ZH}}$ to R_{ii}^{ZH}

Results

- We scan 7 parameters $\lambda_{1,....,5}, t_\beta$ & m_{12}^2 over the ranges:

$$\lambda_{1,2} \in [0, 4\pi], \qquad \lambda_{3,4,5} \in [-4\pi, 4\pi],$$
$$t_\beta \in [1, 50], \qquad m_{12}^2 \in [-(2\ \text{TeV})^2, (2\ \text{TeV})^2]$$

- We apply 3 steps of bounds :
  - Step1 : theoretical bounds → yellow
  - Step2 : pre-LHC bounds → **green**
  - Step3 : LHC bounds → red

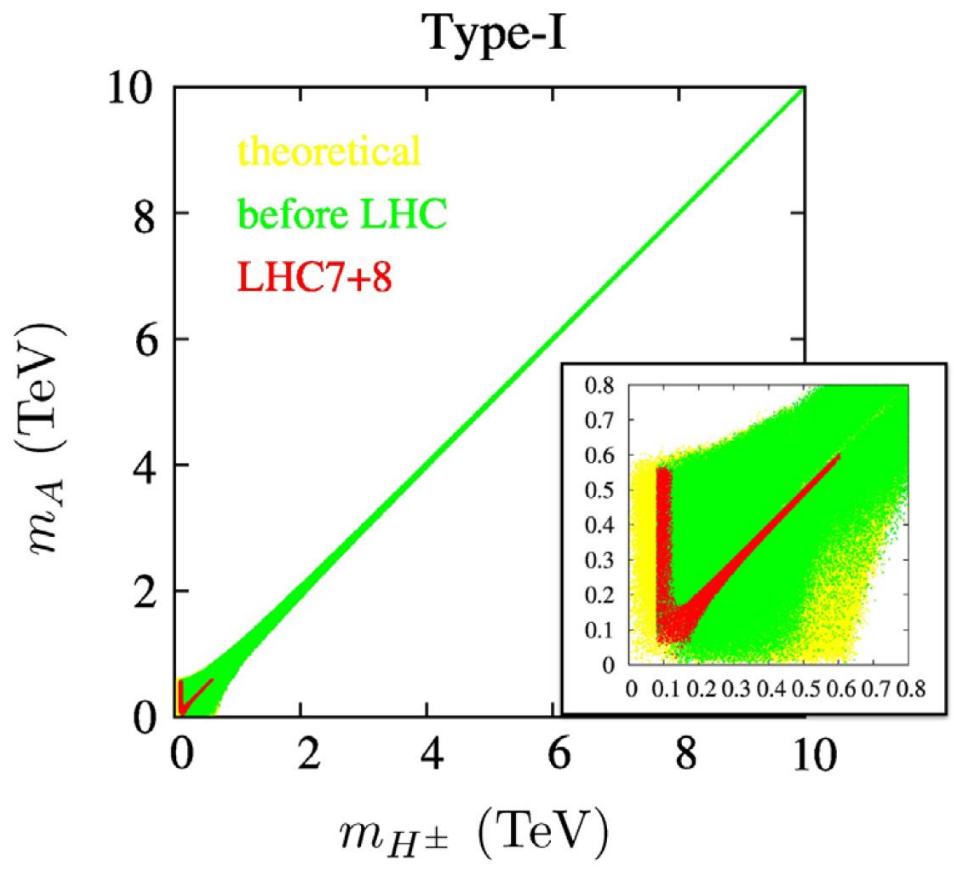
red points satisfy all the constraints

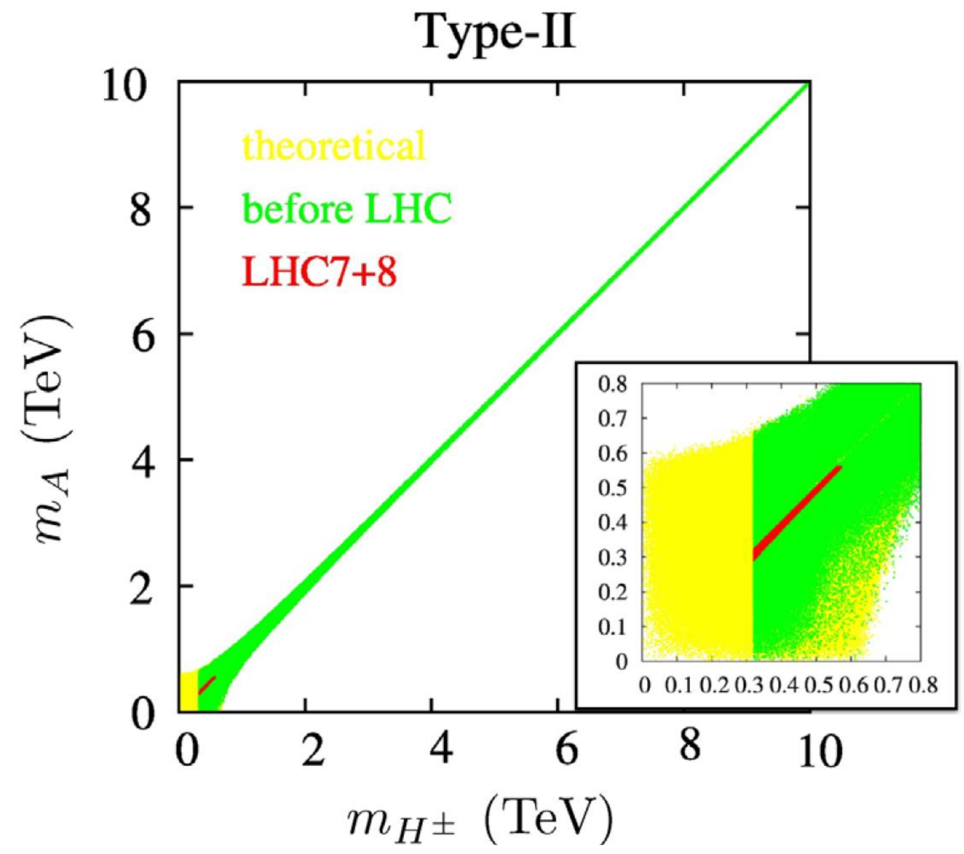
- χ^2_{min} = 0.40(I), 0.51(II), 0.51(X),0.50(Y), 0.49(SM)

The best fit points in 2HDM explain the data as good as the SM

Results

Allowed regions in the plane $(m_A\,, m_{H^\pm})$ for Type I & II

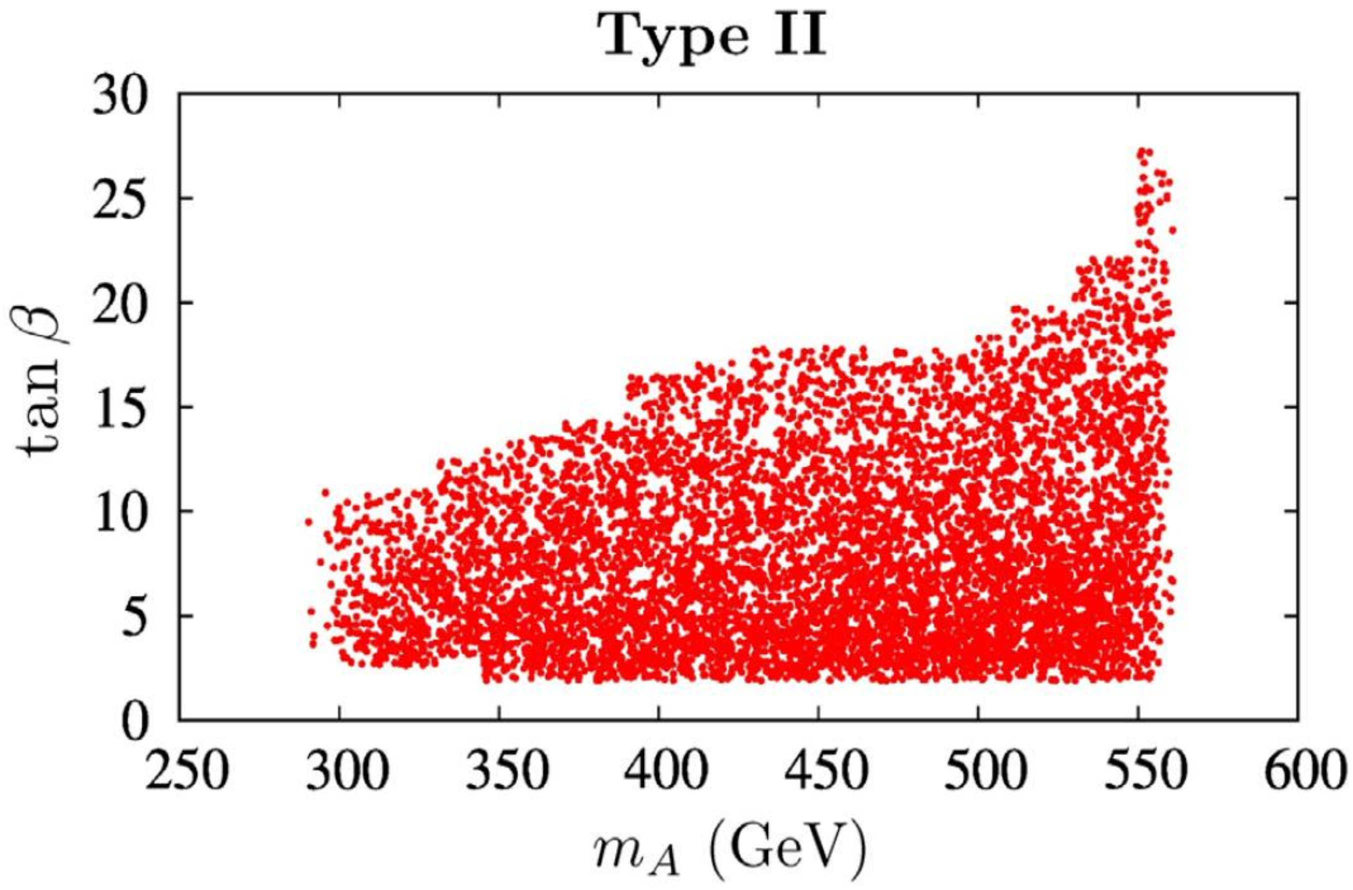




Contrary to the ordinary scenario, there exist upper bounds on $m_A, m_{H^\pm}$

Results

- Constraints on $\tan\beta$ (strongly constrained from LHC heavy Higgs data in type II)



Allowed regions in the plane $(m_A\,, tan\beta)$ for Type II

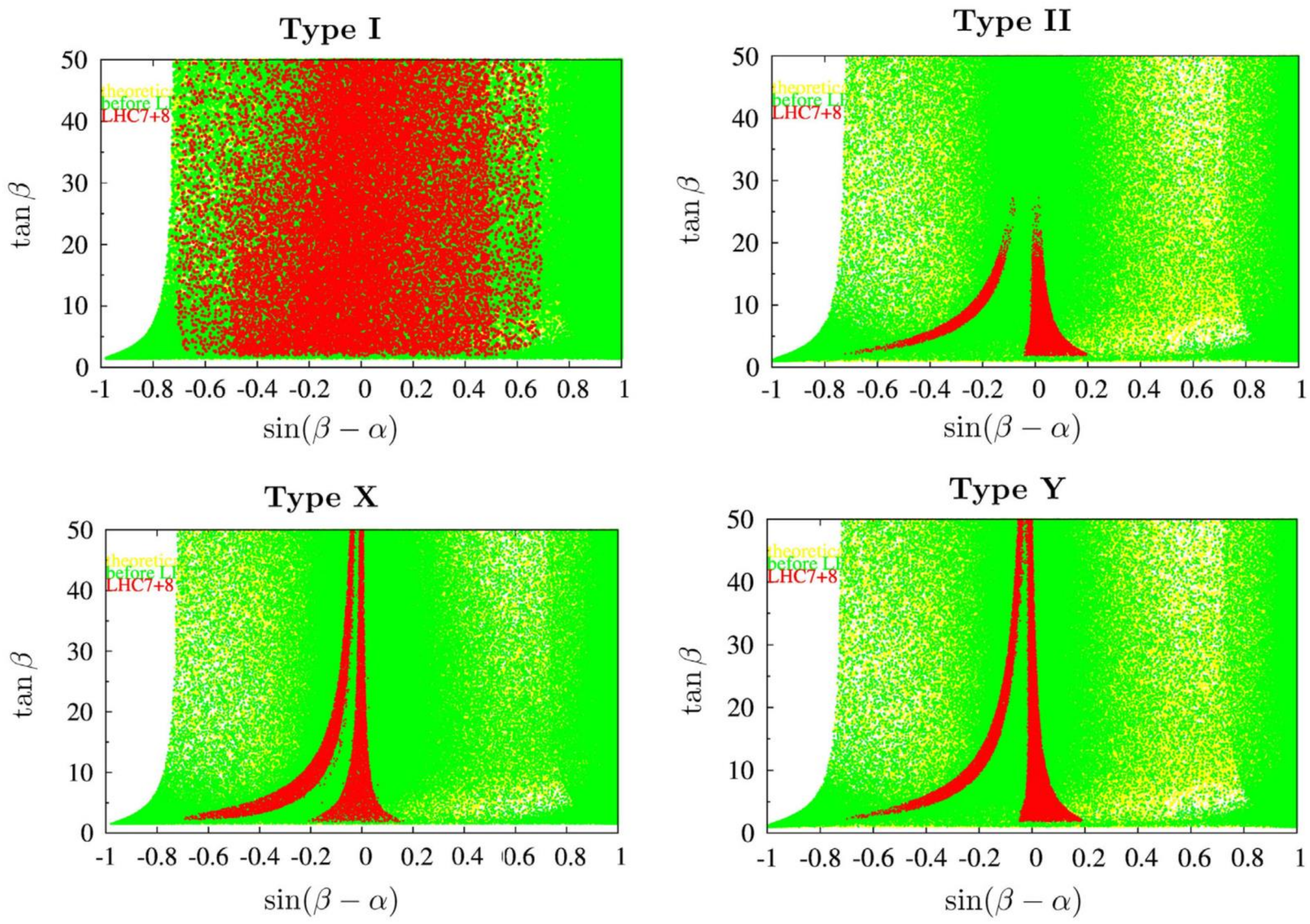
- Small t_β excluded by $\gamma\gamma$ channel through gg fusion production
- Large t_β excluded by

$$b\bar{b} \to A^0 \to \tau^+\tau^-$$

- Constraint for type X & Y is not strong yet.
- In Type I, all Yukawa couplings are proportional to t_β, which is weakly constrained.

Results

Deviation from the alignment limit is allowed ?

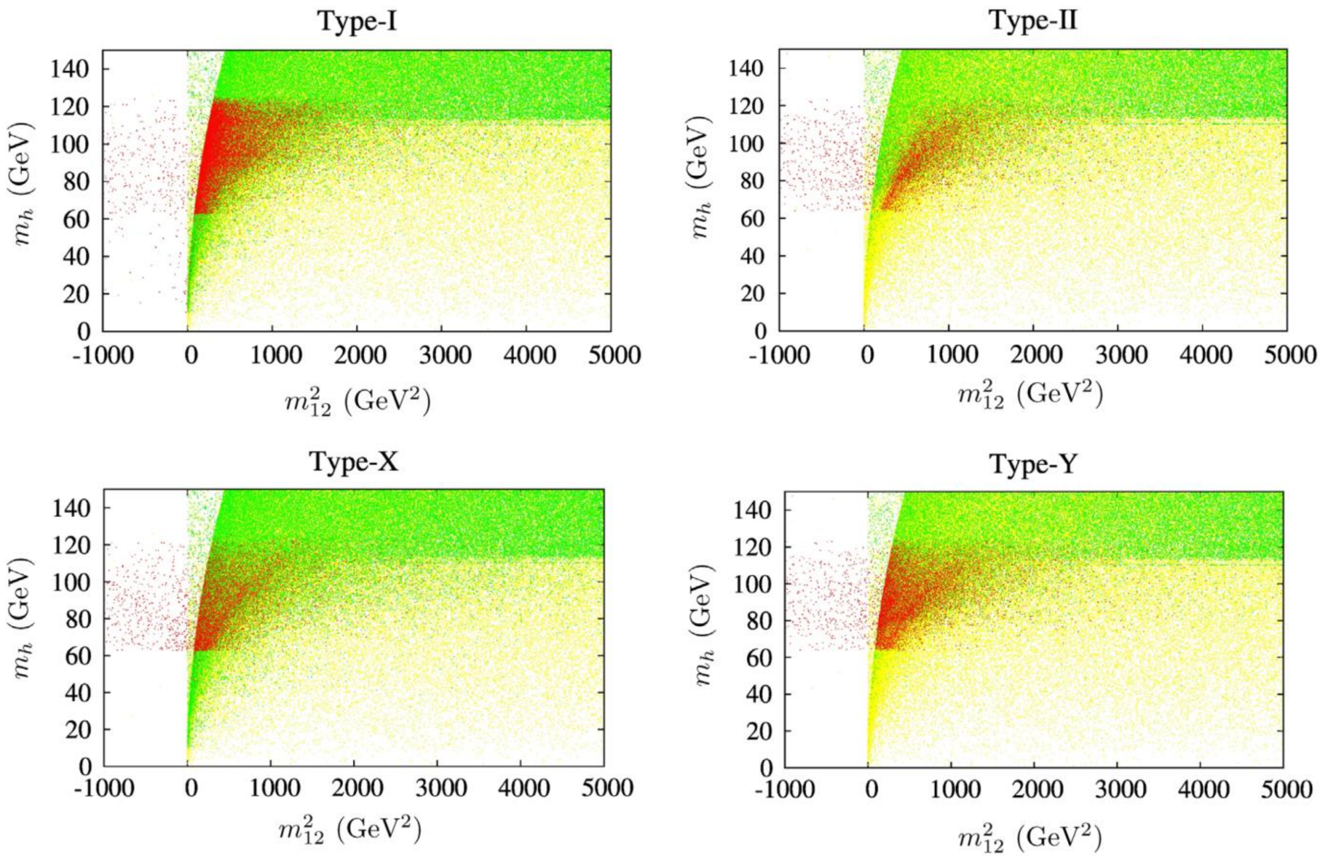


Results

How large m_{12}^2 could be ?

-the condition $m_H = 125$ GeV strongly constrains the scale m_{12}^2 .

-LEP bounds exclude the most of parameter space for $m_h < 114$ GeV.



- LHC data prefers low scale of m_{12}^2

$|m_{12}| < 45$ GeV

Results

- Effects of the possible decay $H^0 \to h^0 h^0$
  - it may affect the LHC Higgs signal strength measurement.
  - in the alignment limit, Hhh coupling is sizable in general

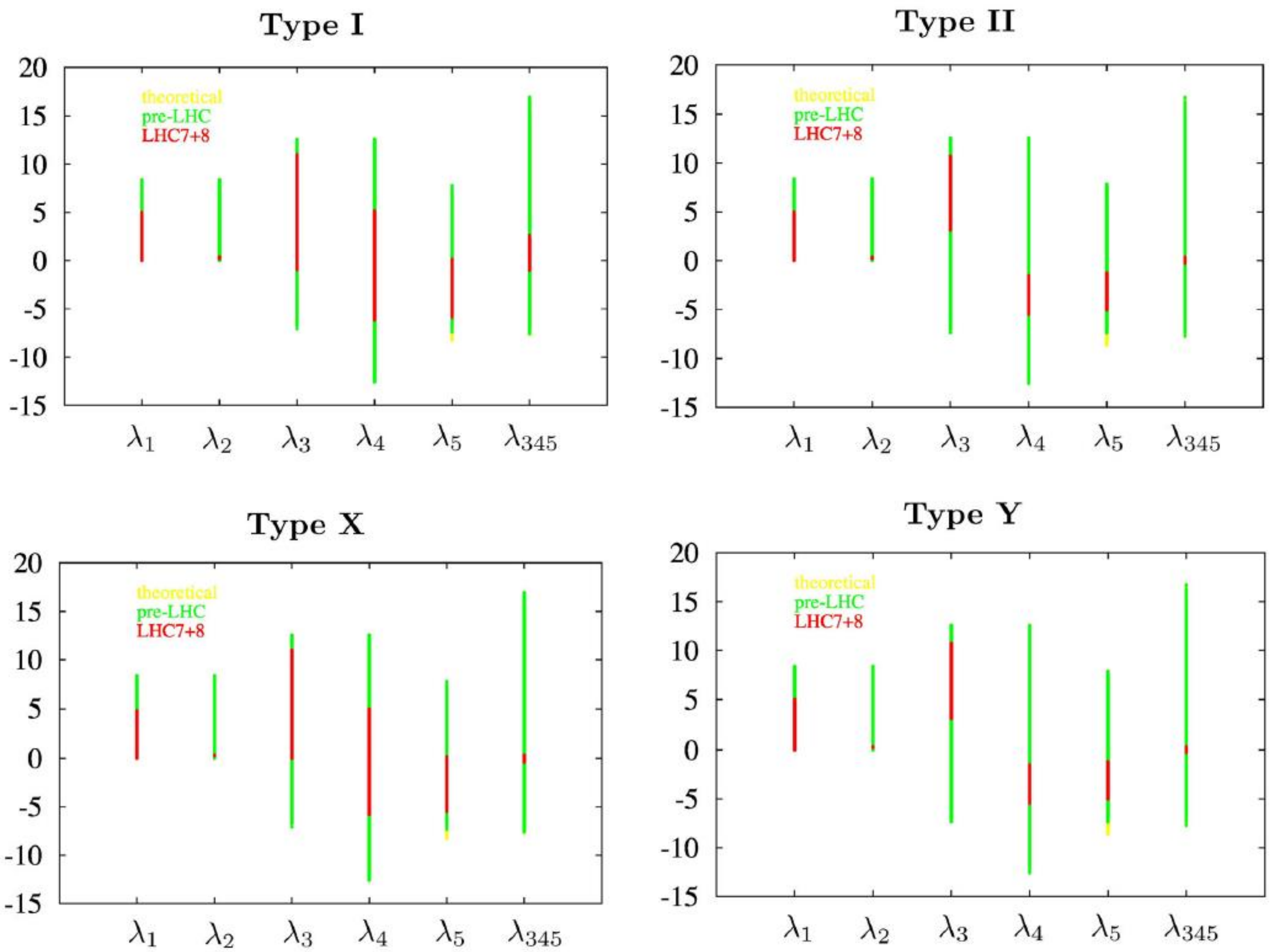
$$\hat{g}_{Hhh} = \frac{1}{3}\left[1 + 2\frac{m_h^2}{m_H^2} - 2\left(t_\beta + \frac{1}{t_\beta}\right)\frac{m_{12}^2}{m_H^2}\right] + \mathcal{O}(s_{\beta-\alpha}).$$

H-h-h coupling normalized by $g_{hhh}^{\rm SM} = 3m_{h_{\rm SM}}^2/v,$

  - Since the alignment limit is preferred in type II, X, Y, $\hat{g}_{Hhh}$ is too large to accommodate the LHC data unless m_{12}^2 & t_β are tuned to suppress it.
  - LHC data prefer $m_h > m_H/2$ in type II, X, Y
  - $m_h < m_H/2$ is allowed but less probable due to requiring small $\hat{g}_{Hhh}$

Results

How Higgs couplings can strongly be constrained?



- For all types, $\lambda_2 \sim 0.26$ mainly due to $m_H = 125$ GeV
- $\lambda_{345} (= \lambda_3 + \lambda_4 + \lambda_5)$ is also constrained in type II, X, Y
- Others are not seriously constrained

Results

Bounds on Higgs couplings

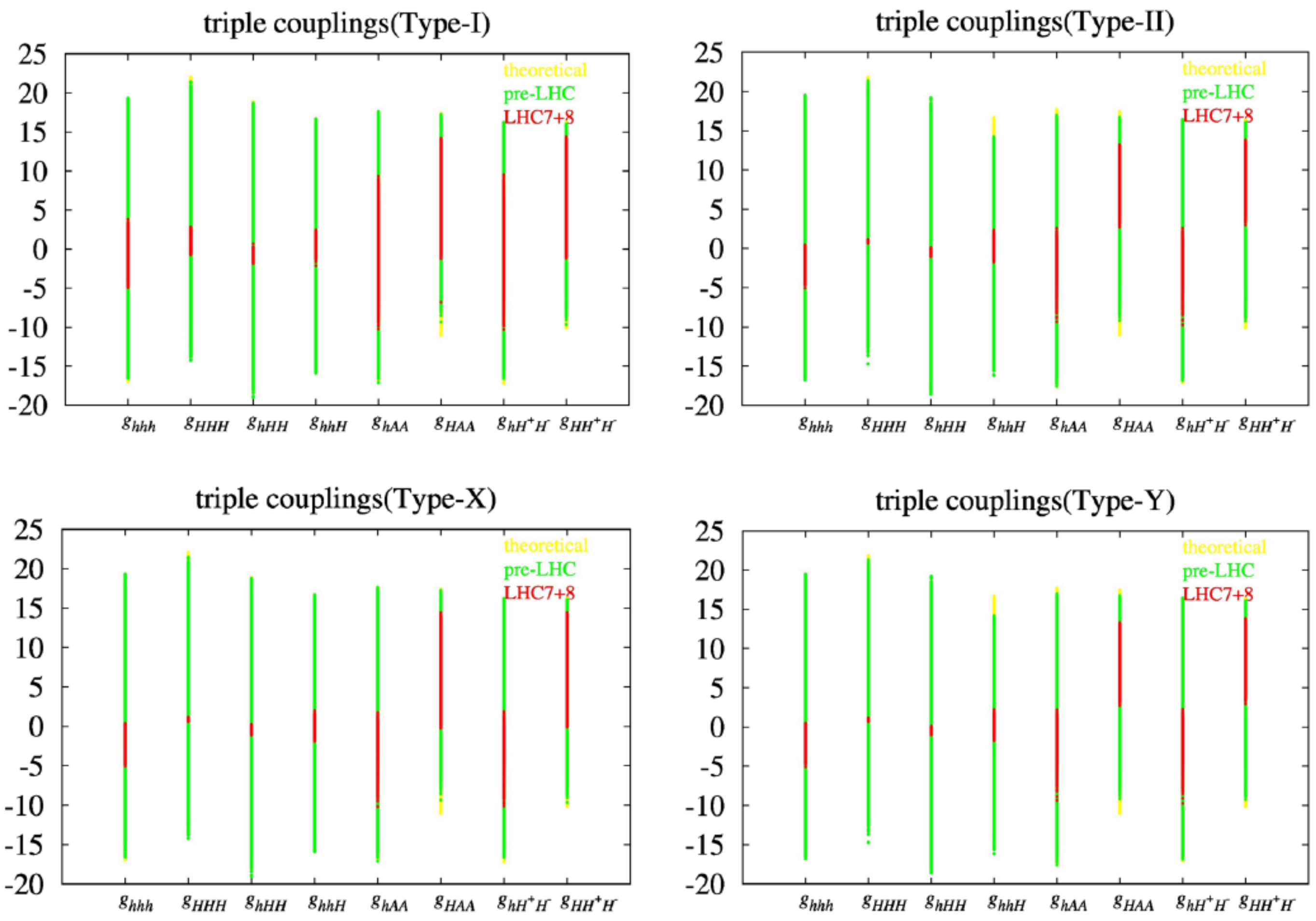


FIG. 7 (color online). Constraints on $\hat{g}_{\phi_i\phi_j\phi_k}$ for Type I, II, X, and Y. Color scheme is the same as in Fig. 1.

Results

Bounds on Higgs couplings

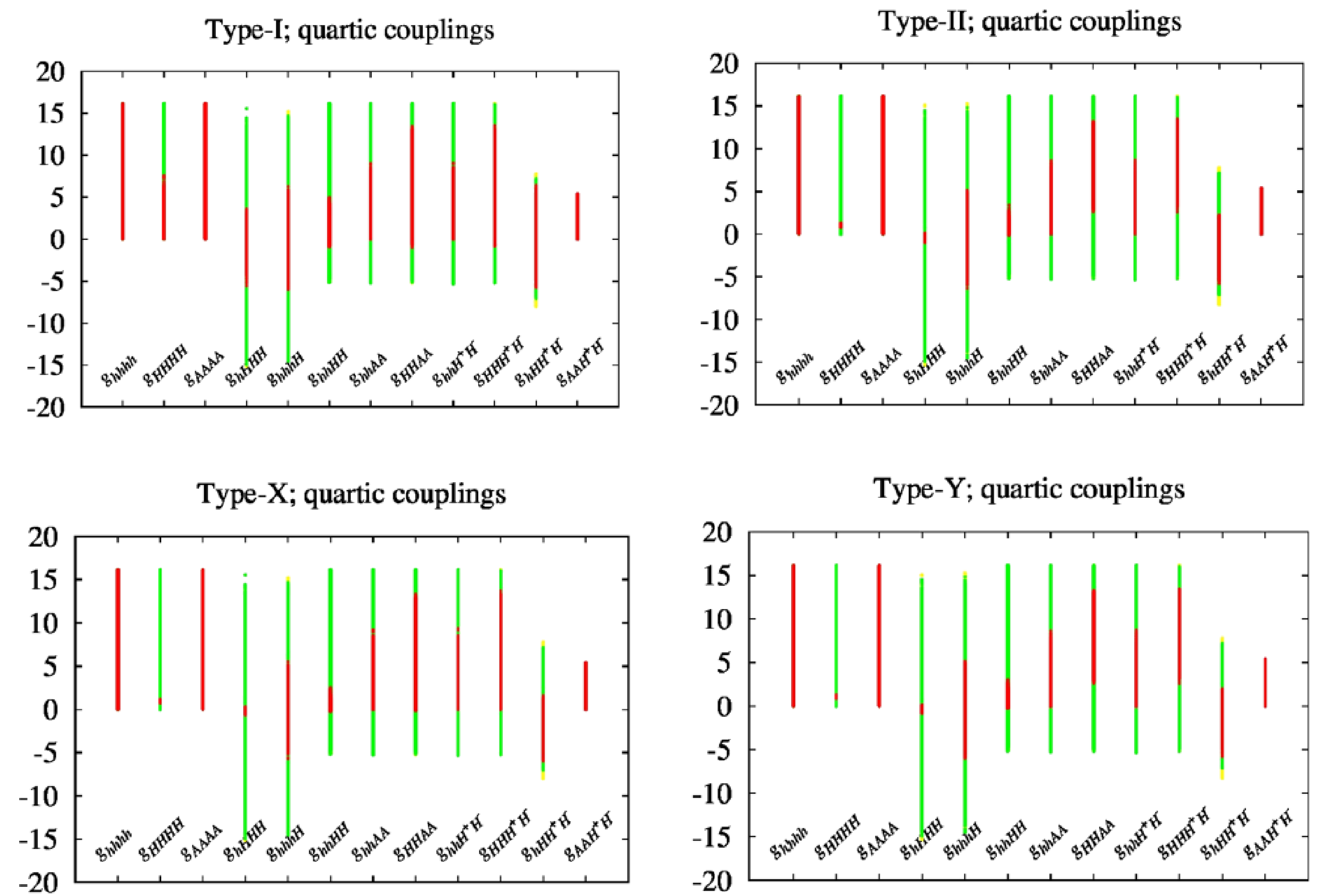
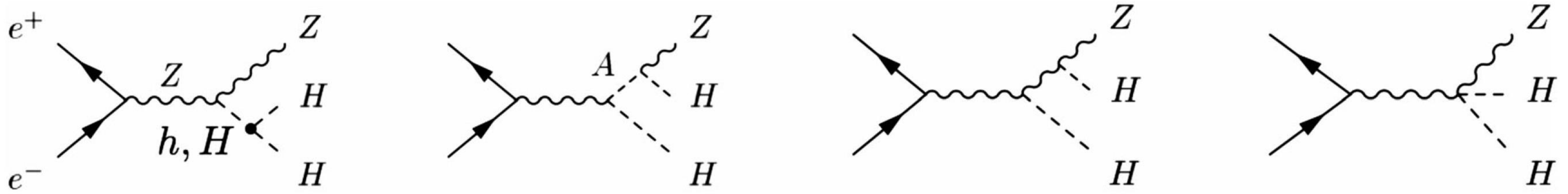
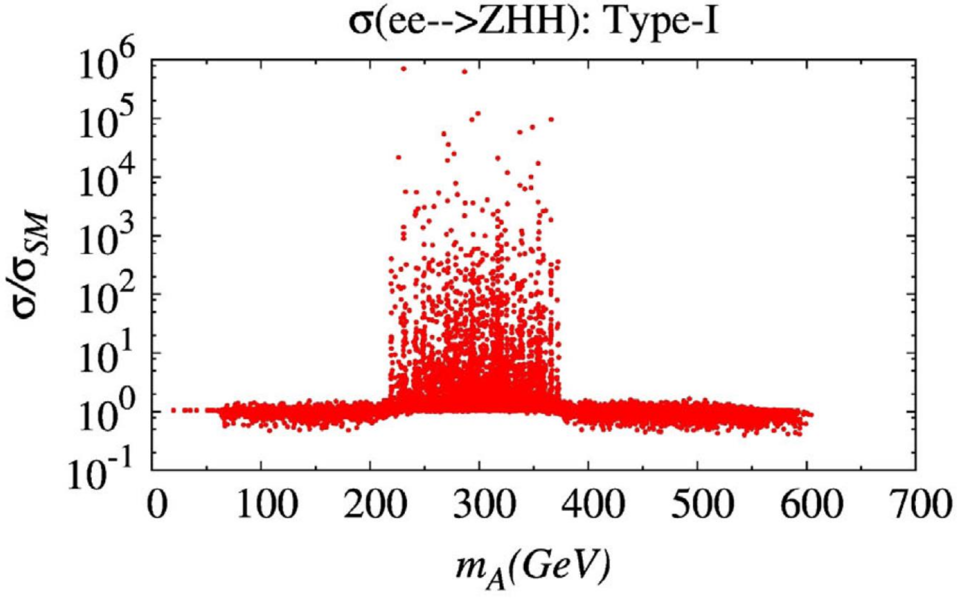


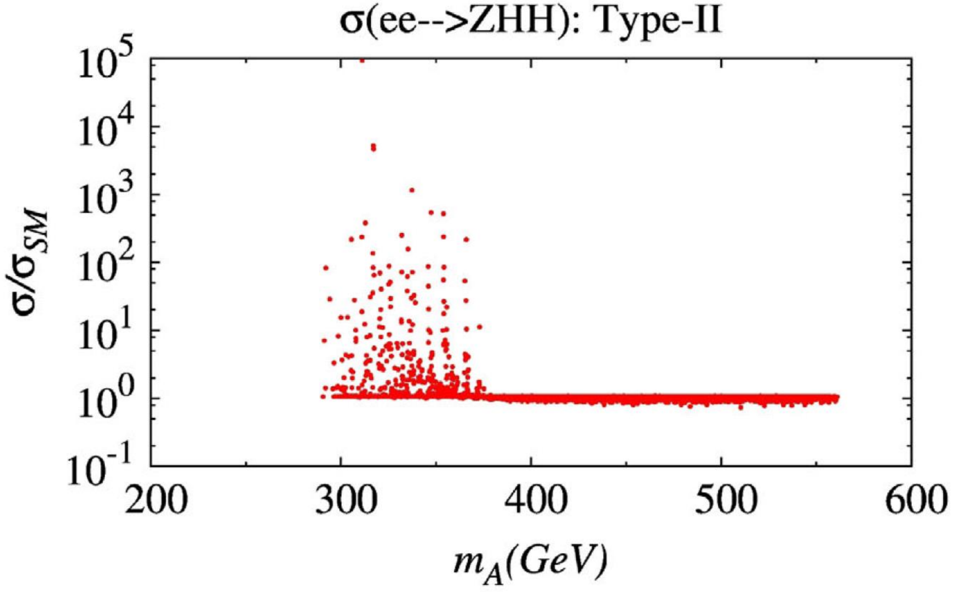
FIG. 8 (color online). Constraints on $\hat{g}_{\phi_i\phi_j\phi_k\phi_\ell}$ for Type I, II, X, and Y. Color scheme is the same as in Fig. 1.

Prediction

Future prospect of $e^+e^- \to Z^0H^0H^0$



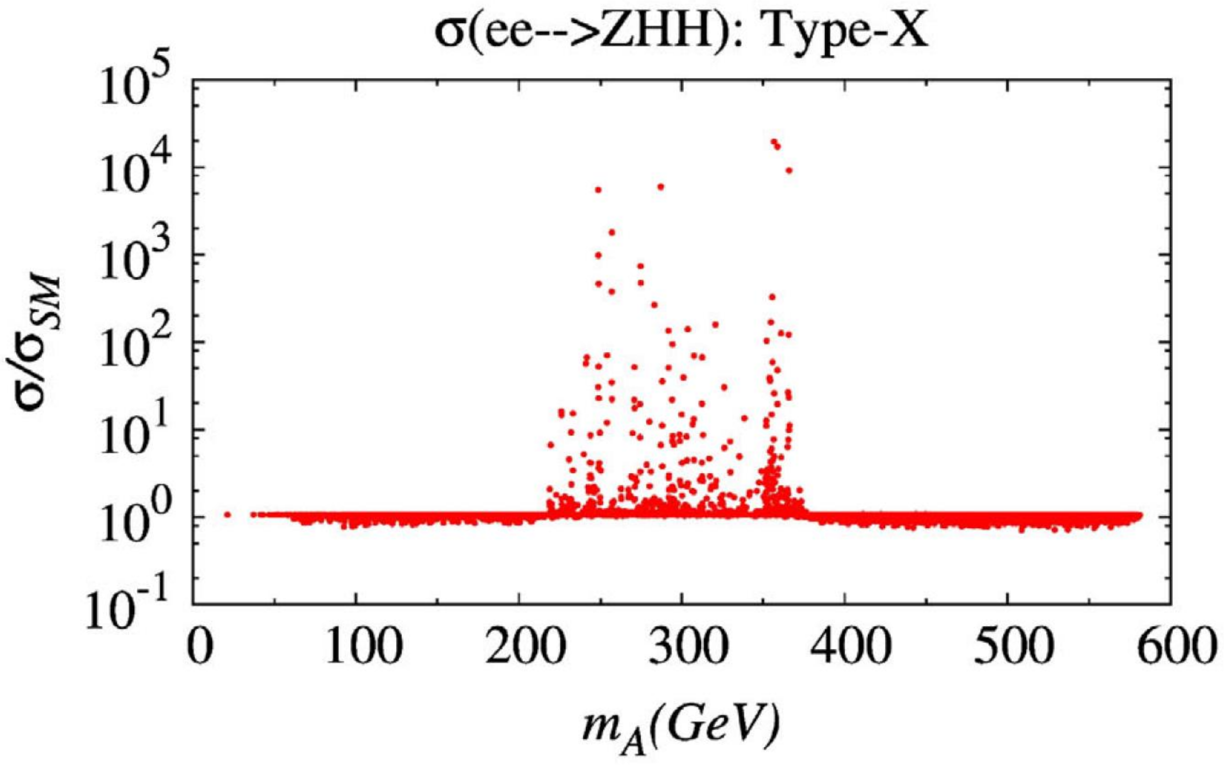


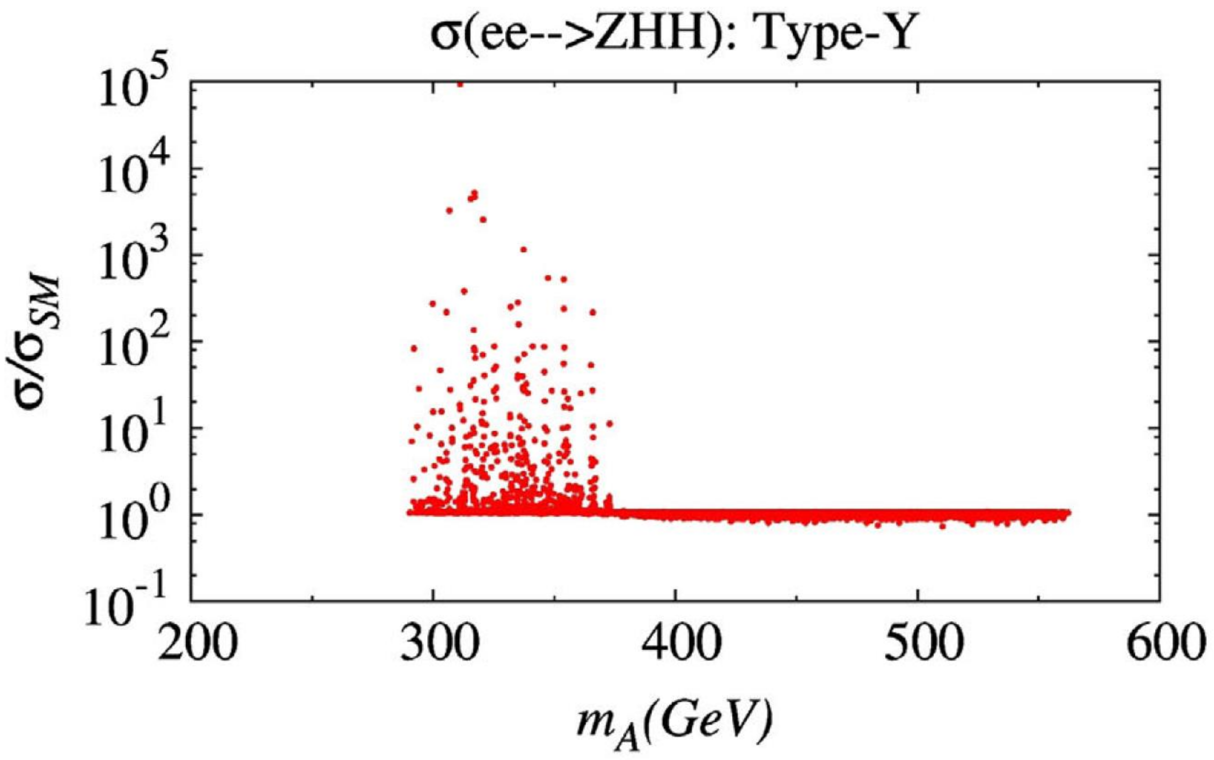


At $\sqrt{s}$ =500 GeV

Prediction

Future prospect of $e^+e^- \to Z^0H^0H^0$





Conclusion

- We have investigated what the LHC data tell us about the hidden light Higgs scenario in 2HDM with CP invariance and softly broken Z_2 sym.
- We found that the LHC data combined with other current constraints do not exclude the possibility that the observed 125 GeV Higgs is the heavier CP-even Higgs boson H^0 and the lighter one h^0 is buried in the region of < 120 GeV.
- A remarkable consequence is that m_{12}^2 can not be large thanks to the condition $m_H = 125$ GeV , which renders m_A , $m_{H^\pm}$ rather light below 600 GeV.
- Higgs couplings are also narrowly constrained.

Contributions of vector-like quarks to Higgs decay rates to gg & γγ

-In order to incorporate NNLO QCD and NLO EW corrections,
we take the well-known SM Higgs results for production & decay
and multiply them by the relative factor defined by

$$c_{jj}^{h/H} = \frac{\Gamma(h/H \to jj)}{\Gamma(H_{\rm SM} \to jj)},$$

Conclusion

-Motivated by a hint of a new resonance at 750 GeV observed in the di-photon channel of LHC Run 2 at 13 TeV, we have investigated if a top-phobic heavy neutral Higgs in the aligned 2 HDM can be responsible for the signal.

-It is hard to explain the signal in the context of pure 2HDM.

- To achieve large $\sigma(gg \to H)BR(H \to \gamma\gamma)$, we introduce VLQs.

- Relatively large signal rate observed at 13 TeV is efficiently accounted for by reducing the total decay width and thus increasing the di-photon BR.

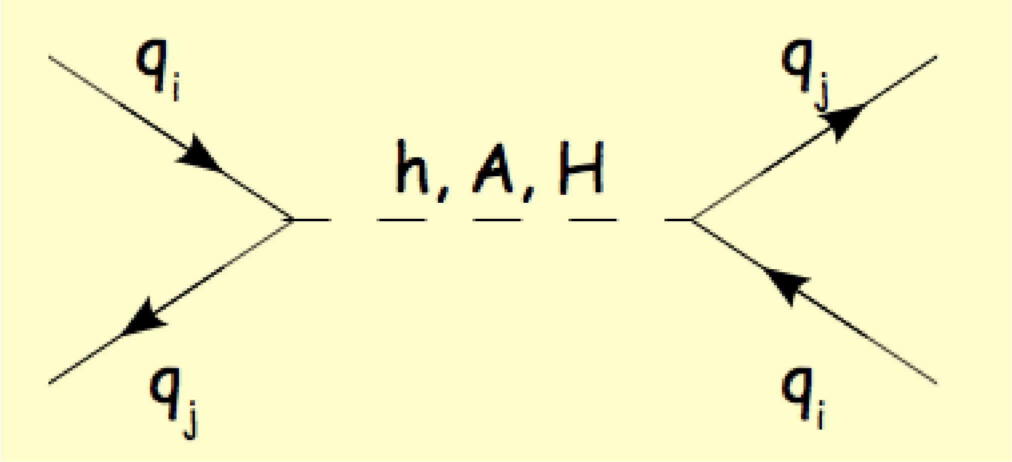
-While top-phobic H^0 cannot explain 750 GeV signal in type I, in type II, it can be responsible for 750 GeV resonance for small y_{fU} and large y_{fD}.

Introduction

- What the LHC results tells us so far
  - Higgs data on the 125 GeV state : in consistent with the SM, no significant excess from the SM
    → strongly constrain any new physics

  - Null results in search for the heavy neutral & charged Higgs
    → points to the decoupling limit where other scalars except for 125 GeV state are heavy
- The phenomenology of the decoupling limit generally mimic that of the SM

- Flavor changing neutral currents at the tree level, mediated by the Higgs bosons



No loop suppression of the four fermion operators!

- (e.g.) $\bar{d}sh$ term leads to tree-level $K-\overline{K}$ mixing !