Multi-Higgs doublet models with spontaneous Higgs symmetry breaking

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Based on PLB 717, 202 (2013);
JHEP03 (2013) 151;
arXiv:1309.7156
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PASCOS 2013, Taipei, Taiwan, Nov 21, 2013

A Higgs boson

- A Higgs boson was discovered at LHC.
- spin and parity : 0^+ (other hypotheses are excluded at 95% C.L. or higher)
- "Is it the Standard Model Higgs?" is far from being settled.
  - the SM Higgs boson?
  - one of Higgs bosons in an extended model?
- Multi-Higgs scenarios may be motivated by SUSY or GUT, etc.
- two Higgs doublet models and chiral U(1)′ models (MHDM)
  - Higgs physics (heavy, pseudoscalar, charged Higgs physics)
  - dark matter physics (Inert doublet model)
  - experimental anomalies (top A_{FB} at Tevatron, $B \to D(*)\tau\nu$ at BaBAR)

Two Higgs Double Model

• One of the simplest models to extend the SM Higgs sector, but have rich phenomenology.

• In general, the models with many Higgs fields suffer from Flavor changing process.

• strong constraints on the Flavor changing neutral current (FCNC).

$$M(B_d - \bar{B}_d) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + c_{NP} \frac{1}{\Lambda^2}$$

c_{NP}:

$$\sim 1 \xrightarrow{\text{tree/strong + generic flavor}} \Lambda \gtrsim 2\times 10^4 \text{ TeV [K]}$$

$$\sim 1/(16\pi^2) \xrightarrow{\text{loop + generic flavor}} \Lambda \gtrsim 2\times 10^3 \text{ TeV [K]}$$

$$\sim (y_t V_{ti}^* V_{tj})^2 \xrightarrow{\text{tree/strong + “alignment”}} \Lambda \gtrsim 5 \text{ TeV [K \& B]}$$

$$\sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2) \xrightarrow{\text{loop + “alignment”}} \Lambda \gtrsim 0.5 \text{ TeV [K \& B]}$$

From Gino Isidori's talk at KEKPH 2013 FALL

Z_2 symmetry

- A simple way to avoid FCNC problem is to assign ad hoc Z_2 symmetry.

→ Natural Flavor Conservation (NFC). Glashow, Weinberg, PRD15, 1958 (1977)

Fermions of same electric charges get their masses from one Higgs VEV.

~ achieved by assigning new distinct charges to the two Higgs doublets as well as SM fermions.

$$Z_2 : (H_1, H_2) \rightarrow (+H_1, -H_2)$$

- Type I : $V_y = y_{ij}^U \bar{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \bar{Q}_{Li} H_1 D_{Rj} + y_{ij}^E \bar{L}_i H_1 E_{Rj} + y_{ij}^N \bar{L}_i \tilde{H}_1 N_{Rj}$

Type	H_1	H_2	U_R	D_R	E_R	N_R	Q_L, L
I	+	−	+	+	+	+	+
II	+	−	+	−	−	+	+
X	+	−	+	+	−	−	+
Y	+	−	+	−	+	−	+

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$$Z_2 : (H_1, H_2) \to (+H_1, -H_2)$$

- Type II : $V_y = y_{ij}^U \overline{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \overline{Q}_{Li} H_2 D_{Rj} + y_{ij}^E \overline{L}_i H_2 E_{Rj} + y_{ij}^N \overline{L}_i \tilde{H}_1 N_{Rj}$

Type	H_1	H_2	U_R	D_R	E_R	N_R	Q_L, L
I	+	−	+	+	+	+	+
II	+	−	+	−	−	+	+
X	+	−	+	+	−	−	+
Y	+	−	+	−	+	−	+

Generic problems of 2HDM

- It is well known that discrete symmetry could generate a domain wall problem when it is spontaneously broken.

- Usually the Z_2 symmetry is assumed to be broken softly by a dim-2 operator, $H_1^\dagger H_2$ term.

The softly broken Z2 symmetric 2HDM potential

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - (m_{12}^2 H_1^\dagger H_2 + h.c.) + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2$$

$$+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{1}{2}\lambda_5 [(H_1^\dagger H_2)^2 + h.c.]$$

- the origin of such a discrete symmetry and softly breaking term?

2HDM with spontaneous Higgs Symmetry breaking

propose to replace the Z_2 symmetry in 2HDM by new $U(1)_H$ symmetry associated with Higgs flavors.

$$Z_2 \rightarrow \text{gauged } U(1)_H \rightarrow \text{massless mode is eaten} \rightarrow \underline{\text{light gauge boson } (Z_H)}$$

disfavored by the ρ parameter

- To make Z_H heavy, one may introduce a singlet scalar Φ.

$$\Phi H_1^\dagger H_2 \rightarrow \langle \Phi \rangle H_1^\dagger H_2$$

- H_1 and H_2 have different $U(1)_H$ charges.
- Higgs signal will be changed by Φ and Z_H.
- no domain wall problem.

Type-I 2HDM

- Only one Higgs couples with fermions.

$$V_y = y_{ij}^U \overline{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \overline{Q}_{Li} H_1 D_{Rj} + y_{ij}^E \overline{L}_i H_1 E_{Rj} + y_{ij}^N \overline{L}_i \tilde{H}_1 N_{Rj}$$

- anomaly free $U(1)_H$ with RH neutrino.

U_R	D_R	Q_L	L	E_R	N_R	H_1
u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$

There appear an infinite number of new models.

Type-I 2HDM

- Only one Higgs couples with fermions.

$$V_y = y_{ij}^U \overline{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \overline{Q}_{Li} H_1 D_{Rj} + y_{ij}^E \overline{L}_i H_1 E_{Rj} + y_{ij}^N \overline{L}_i \tilde{H}_1 N_{Rj}$$

- anomaly free $U(1)_H$ with RH neutrino.

U_R	D_R	Q_R	L	E_R	N_R	H_1	Type
u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$	
0	0	0	0	0	0	0	$h_2 \neq 0$
$1/3$	$1/3$	$1/3$	-1	-1	-1	0	$U(1)_{B-L}$
1	-1	0	0	-1	1	1	$U(1)_R$
$2/3$	$-1/3$	$1/6$	$-1/2$	-1	0	$1/2$	$U(1)_Y$

- SM fermions are $U(1)_H$ singlets.
- Z_H is fermiophobic and Higgphilic.
- $H^{\pm}W^{\mp}Z_H$ is the main source of production and discovery of Z_H.

Ko,Omura,Yu, PLB717,202(2013)

Type-II 2HDM

- H_1 couples to the up-type fermions, while H_2 couples to the down-type fermions.

$$V_y = y_{ij}^U \bar{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \bar{Q}_{Li} H_2 D_{Rj} + y_{ij}^E \bar{L}_i H_2 E_{Rj} + y_{ij}^N \bar{L}_i \tilde{H}_1 N_{Rj}$$

U_R	D_R	Q_L	L	E_R	N_R	H_1	H_2
u	0	0	0	0	u	u	0

- Requires extra chiral fermions for cancellation of gauge anomaly.

for example, $E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$.

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
Q^i	3	2	1/6	$-1/3$	1	-1	-2
U_R^i	3	1	2/3	2/3	-1	1	2
D_R^i	3	1	$-1/3$	$-1/3$	-1	-3	-1
L_i	1	2	$-1/2$	0	1	3	1
E_R^i	1	1	-1	0	-1	1	2
N_R^i	1	1	0	1	-1	5	5
H_1	1	2	1/2	0	2	2	-1
H_2	1	2	1/2	1	-2	2	4

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
q_L^i	3	1	$-1/3$	2/3	-2	2	4
q_R^i	3	1	$-1/3$	$-1/3$	2	2	-1
l_L^i	1	2	$-1/2$	0	-2	-2	1
l_R^i	1	2	$-1/2$	-1	2	-2	-4
n_L^i	1	1	0	-1	4	0	-5

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
Φ	1	1	0	1	-4	0	5

Higgs Potential

- in the ordinary 2HDM with Z_2 symmetry

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + (m_{12}^2 H_1^\dagger H_2 + h.c.) + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2$$
$$+\lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{1}{2}\lambda_5 [(H_1^\dagger H_2)^2 + h.c.].$$

not invariant under $U(1)_H$

- in the case with Φ, $H_1^\dagger H_2 \Phi$ is gauge-invariant if $h_\phi = h_1 - h_2$.

$$\Delta V = m_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_\Phi}{2}(\Phi^\dagger \Phi)^2 + (\mu H_1^\dagger H_2 \Phi + h.c.)$$
$$+ \mu_1 H_1^\dagger H_1 \Phi^\dagger \Phi + \mu_2 H_2^\dagger H_2 \Phi^\dagger \Phi,$$

Source of pseudo-scalar mass

- in the 2HDM with $U(1)_H$

$$V = \hat{m}_1^2(|\Phi|^2) H_1^\dagger H_1 + \hat{m}_2^2(|\Phi|^2) H_2^\dagger H_2 - \left(m_3^2(\Phi) H_1^\dagger H_2 + h.c.\right)$$
$$+\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$
$$+m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4.$$

$$\hat{m}_i^2(|\Phi|^2) = m_i^2 + \widetilde{\lambda}_i |\Phi|^2 \qquad m_3^2(\Phi) = \mu \Phi^n, \text{ where } n = (q_{H_1} - q_{H_2})/q_\Phi$$

Higgs Potential

- VEVs and Higgs fields in the interaction eigenstates

$$H_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i}{\sqrt{2}} + \frac{1}{\sqrt{2}}(h_i + i\chi_i) \end{pmatrix}, \Phi = \frac{1}{\sqrt{2}}(v_\Phi + h_\Phi + i\chi_\Phi).$$

- charged Higgs

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

- pseudoscalar Higgs

$$\begin{pmatrix} \chi_\Phi \\ \chi_1 \\ \chi_2 \end{pmatrix} = \begin{pmatrix} 0 \\ \cos\beta \\ \sin\beta \end{pmatrix} G_1 + \frac{v_\Phi}{\sqrt{v_\Phi^2 + (nv\cos\beta\sin\beta)^2}} \begin{pmatrix} 1 \\ \frac{nv}{v_\Phi}\cos\beta\sin^2\beta \\ -\frac{nv}{v_\Phi}\cos^2\beta\sin\beta \end{pmatrix} G_2$$
$$+ \frac{v_\Phi}{\sqrt{v_\Phi^2 + (nv\cos\beta\sin\beta)^2}} \begin{pmatrix} \frac{nv}{v_\Phi}\cos\beta\sin\beta \\ -\sin\beta \\ \cos\beta \end{pmatrix} A.$$

- neutral Higgs

$$\begin{pmatrix} h_\Phi \\ h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \cos\alpha_1 & 0 & -\sin\alpha_1 \\ 0 & 1 & 0 \\ \sin\alpha_1 & 0 & \cos\alpha_1 \end{pmatrix} \begin{pmatrix} \cos\alpha_2 & -\sin\alpha_2 & 0 \\ \sin\alpha_2 & \cos\alpha_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \tilde{h} \\ H \\ h \end{pmatrix}$$

- 2 charged Higgs + 1 pseudoscalar Higgs + 3 neutral Higgs bosons

Theoretical constraints

- perturbativity

  - couplings should not be larger than some values to make a perturbative treatment meaningful.

- unitarity

  - the scattering matrix elements satisfy unitary limits.

- vacuum stability

  - Higgs potential is bounded from below.

$\langle \Phi \rangle = 0$ direction

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

$\langle \Phi \rangle \neq 0$ direction

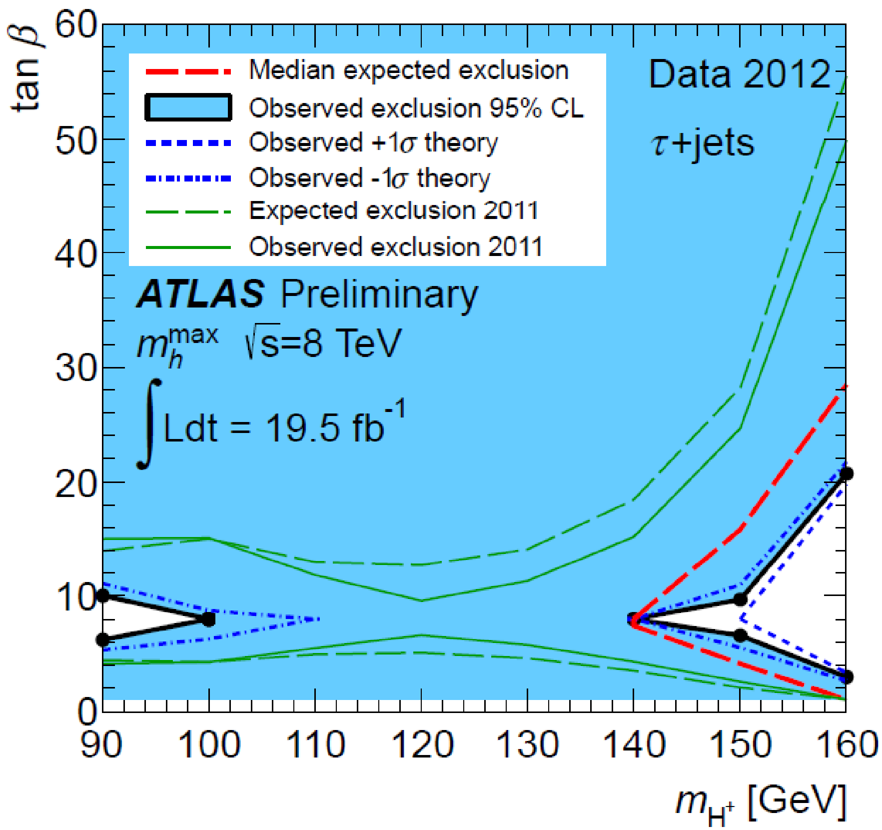
$$\lambda_\Phi > 0, \ \lambda_1 > \frac{\widetilde{\lambda}_1^2}{\lambda_\Phi}, \ \lambda_2 > \frac{\widetilde{\lambda}_2^2}{\lambda_\Phi}, \ \lambda_3 - \frac{\widetilde{\lambda}_1 \widetilde{\lambda}_2}{\lambda_\Phi} > -\sqrt{\left(\lambda_1 - \frac{\widetilde{\lambda}_1^2}{\lambda_\Phi}\right)\left(\lambda_2 - \frac{\widetilde{\lambda}_2^2}{\lambda_\Phi}\right)},$$

$$\lambda_3 + \lambda_4 - \frac{\widetilde{\lambda}_1 \widetilde{\lambda}_2}{\lambda_\Phi} > -\sqrt{\left(\lambda_1 - \frac{\widetilde{\lambda}_1^2}{\lambda_\Phi}\right)\left(\lambda_2 - \frac{\widetilde{\lambda}_2^2}{\lambda_\Phi}\right)}.$$

Charged Higgs boson at LHC

$$pp \to t\bar{t} \to b\bar{b}W^+H^-$$

- type-II 2HDM



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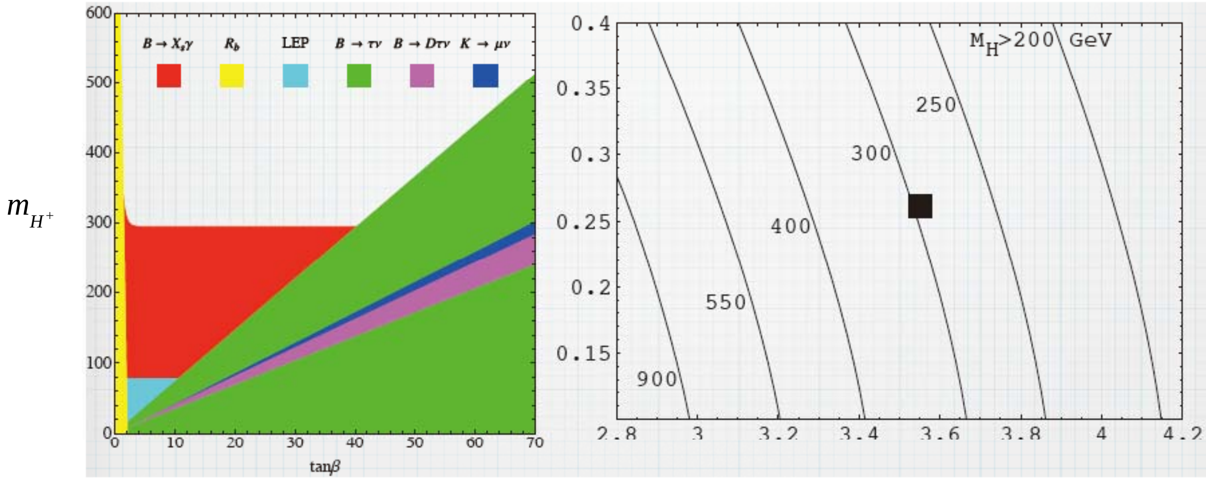
$b \to s\gamma$

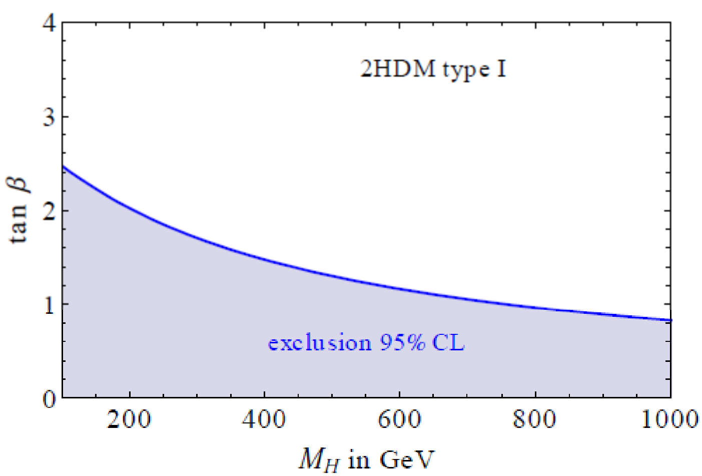
- type-II 2HDM

Kwon, KIAS Phenomenology Workshop 2011



$$m_{H+} > 300 \text{ GeV @ 95\% CL for all } \tan\beta$$

- type-I 2HDM



Hermann,Misiak,Steinhauser, JHEP1211 (2012) 036

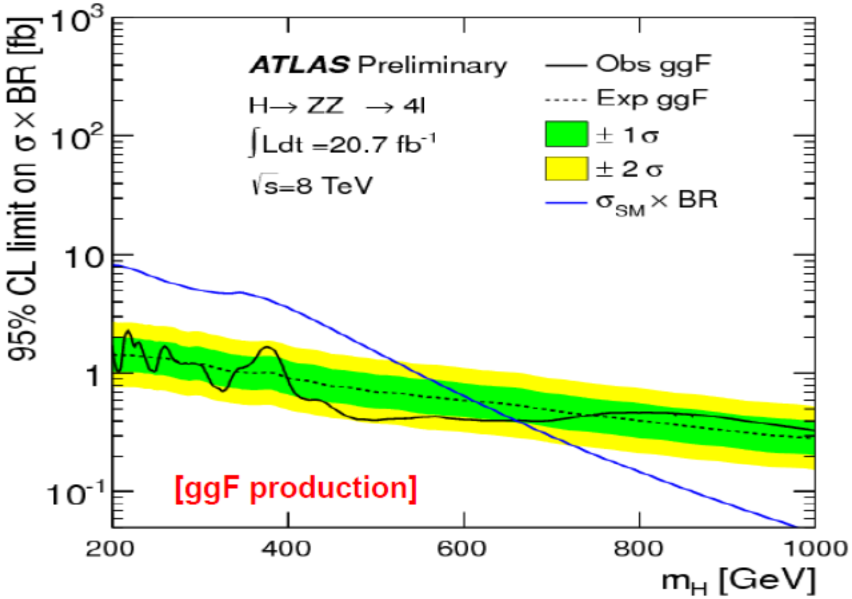
$\tan\beta \geq 1$

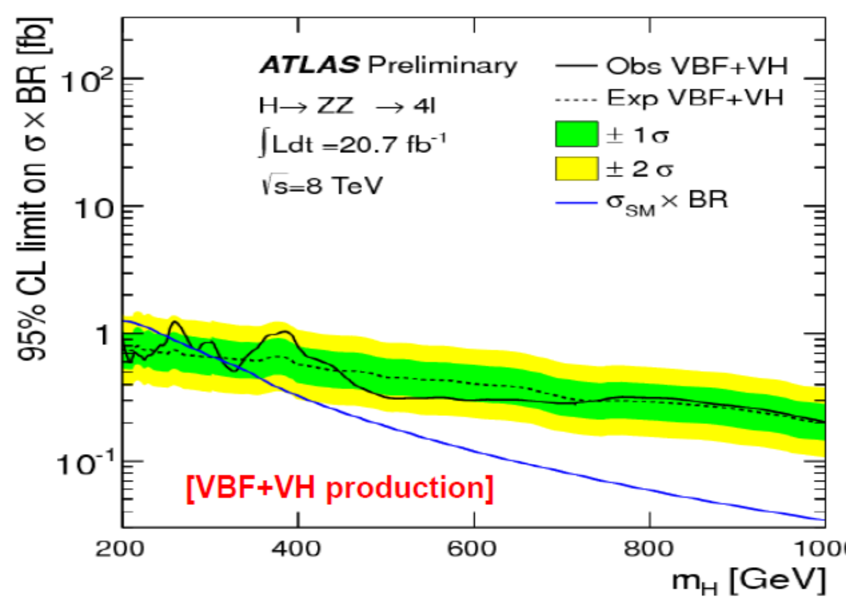
Heavy Higgs search at LHC

$H \to ZZ \to 4l$

$$\mu_j^i = \frac{\sigma(pp \to h)^j \mathrm{Br}(h \to i)}{\sigma(pp \to h)^j_{\mathrm{SM}} \mathrm{Br}(h \to i)_{\mathrm{SM}}}$$

➔ Upper limits on production cross section × branching ratio





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$$\mu_{gg}^{ZZ} \lesssim 0.1 \qquad \mu_{\mathrm{VBF}}^{ZZ} \lesssim 1$$

EWPOs in 2HDM with $U(1)_H$

• SM + extended Higgs sector + Z_H (+ extra fermions).

• oblique parameters : S,T,U

- the dominant effects of new physics appear in self energies of gauge bosons.

$$S = 0.03 \pm 0.10,\ T = 0.05 \pm 0.12,\ U = 0.03 \pm 0.10,$$

Baak et al., EPJC 72, 2205 (2012)

• If Z_H couples with the SM fermions, need to analyze full one-loop amplitudes with Z_H.

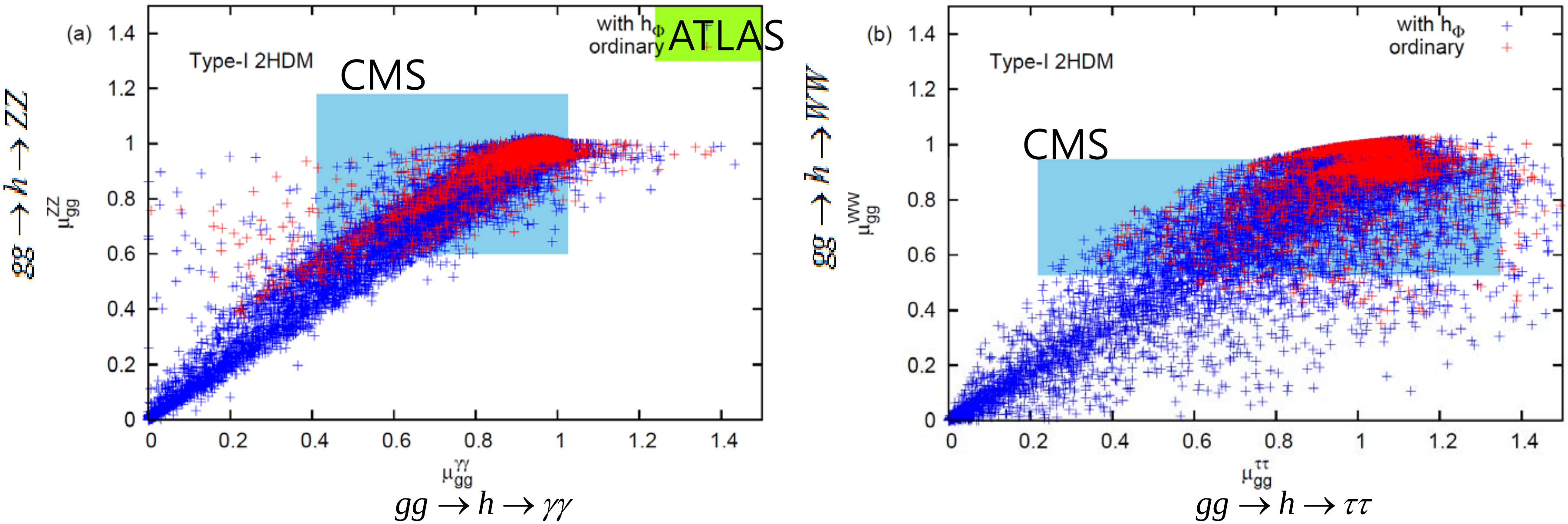
• consider two cases.

1. Z_H is decoupled in the limit of m_{Z_H}>>EW scale.

2. Z_H is fermiophobic for u=d=0.

Type-I 2HDM with h_Φ

- the gg fusion

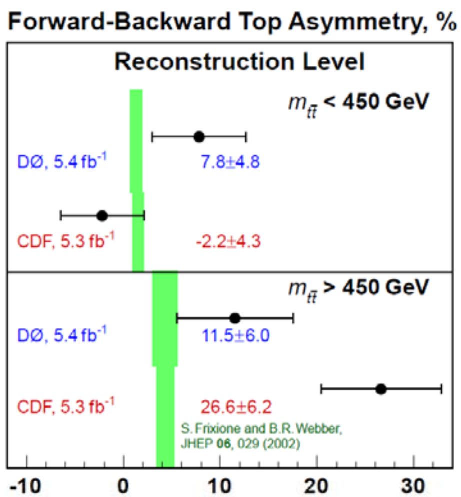


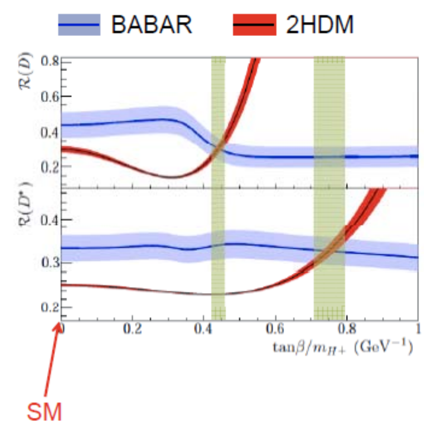
- consistent with CMS in the 1σ level while consistent with ATLAS in the 2σ.
- difficult to distinguish because the current experimental values are consistent with the SM prediction.
- essential to discover the extra scalar bosons and the new gauge boson.

Ko,Omura,Yu, arxiv:1309.7156

Chiral U(1)′ model

• 2HDM with spontaneous Higgs symmetry breaking respects the MFV hypothesis, but experimental anomalies imply large FCNCs.





$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

• we slightly breaks the NFC crietrion.

• assign flavor-dependent $U(1)_H$ charges to generate FCNCs.

• difficult to assign flavor-dependent charges to down-type quarks due to the strong constraints from FCNC experiments → assign U(1)′ charges only to right-handed up-type quarks (flavor-dependent).

Chiral U(1)′ model

- Charge assignment : SM fermions

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
Q_1	3	2	1/6	q_L
Q_2	3	2	1/6	q_L
Q_3	3	2	1/6	q_L
$\overline{D_1}$	$\overline{3}$	1	1/3	$-q_L$
$\overline{D_2}$	$\overline{3}$	1	1/3	$-q_L$
$\overline{D_3}$	$\overline{3}$	1	1/3	$-q_L$
$\overline{U_1}$	$\overline{3}$	1	$-2/3$	u_1
$\overline{U_2}$	$\overline{3}$	1	$-2/3$	u_2
$\overline{U_3}$	$\overline{3}$	1	$-2/3$	u_3
H	1	2	1/2	0

Left-handed quarks and right-handed down-type quarks have universal couplings.

Flavor-dependent

Higgs

Ko,Omura,Yu, JHEP01 (2012) 147

Chiral U(1)′ model

- Charge assignment : Higgs fields

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H_1	1	2	1/2	$-q_L - u_1$
H_2	1	2	1/2	$-q_L - u_2$
H_3	1	2	1/2	$-q_L - u_3$
Φ	1	1	1	$-q_\Phi$

- introduce three Higgs doublets charged under U(1)′ in addition to H uncharged under U(1)′.

$$\begin{aligned} V_y = & \; y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ & + y^d_{ij} \overline{D_j} Q_i i\tau_2 H^\dagger \\ & + y^e_{ij} \overline{E_j} L_i i\tau_2 H^\dagger + y^n_{ij} H \overline{N_j} L_i . \end{aligned}$$

- The U(1)′ is spontaneously broken by U(1)′ charged complex scalar Φ.

Ko,Omura,Yu, JHEP01 (2012) 147

Chiral U(1)′ model

- Anomaly cancelation requires extra fermions I: SU(2) doublets

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q'	3	2	1/6	$-(q_1+q_2+q_3)$
D'_R	3	1	−1/3	$-(d_1+d_2+d_3)$
U'_R	3	1	2/3	$-(u_1+u_2+u_3)$
L'	1	2	−1/2	0
E'	1	1	−1	0
l_{L1}	1	2	−1/2	Q_L
l_{R1}	1	2	−1/2	Q_R
l_{L2}	1	2	−1/2	$-Q_L$
l_{R2}	1	2	−1/2	$-Q_R$

one extra generation

$SU(2)_L{}^2\cdot U(1)'$

vector-like pairs

$U(1)'^2\cdot U(1)$

a candidate for CDM

Ko,Omura,Yu, JHEP01 (2012) 147

Effective Hamiltonian

- Effective Hamiltonian for B→D(*)τν

$$H_{\rm eff} = C^{qb}_{\rm SM}(\overline{q_L}\gamma_\mu b_L)(\overline{\tau_L}\gamma^\mu \nu_L) + C^{qb}_R(\overline{q_L} b_R)(\overline{\tau_R}\nu_L) + C^{qb}_L(\overline{q_R} b_L)(\overline{\tau_R}\nu_L)$$

Charged Higgs

$$\frac{C^{qb}_L}{C^{qb}_{\rm SM}} = \frac{m_q m_\tau}{m^2_{h+}}\tan^2\beta - \sum_l \frac{V_{lb}}{V_{qb}}\frac{m^u_l m_\tau (g^u_R)_{lq}}{m^2_{h+}\cos^2\beta},$$

$$\frac{C^{qb}_R}{C^{qb}_{\rm SM}} = -\frac{m_b m_\tau}{m^2_{h+}}\tan^2\beta.$$

New terms in chiral U(1)´ model

Flavor-independent

- diagonalization matrix g_R

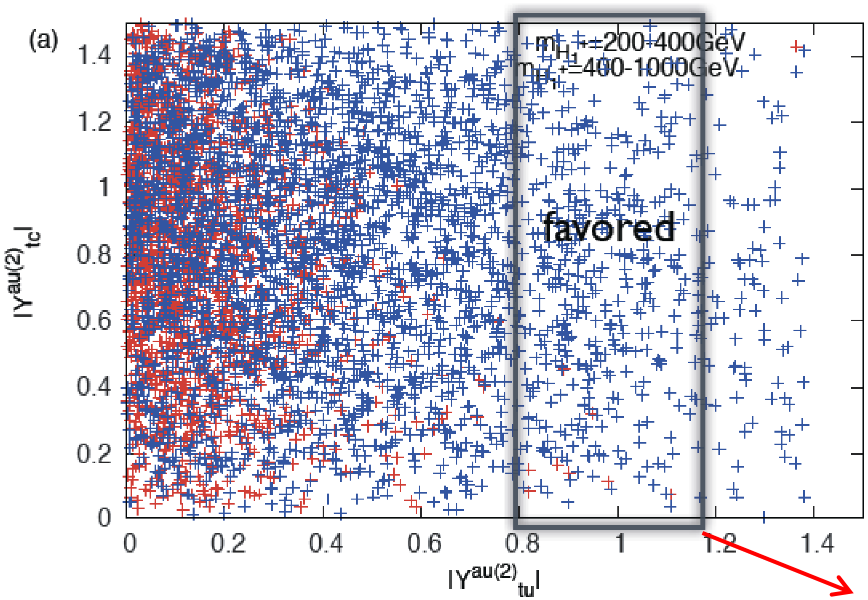
$(g^u_R)_{ij} = \delta_{ij}$: the same as the type-II 2HDM.

$(g^u_R)_{ij} \neq \delta_{ij}$: generate non-MFV interactions.

3HDM

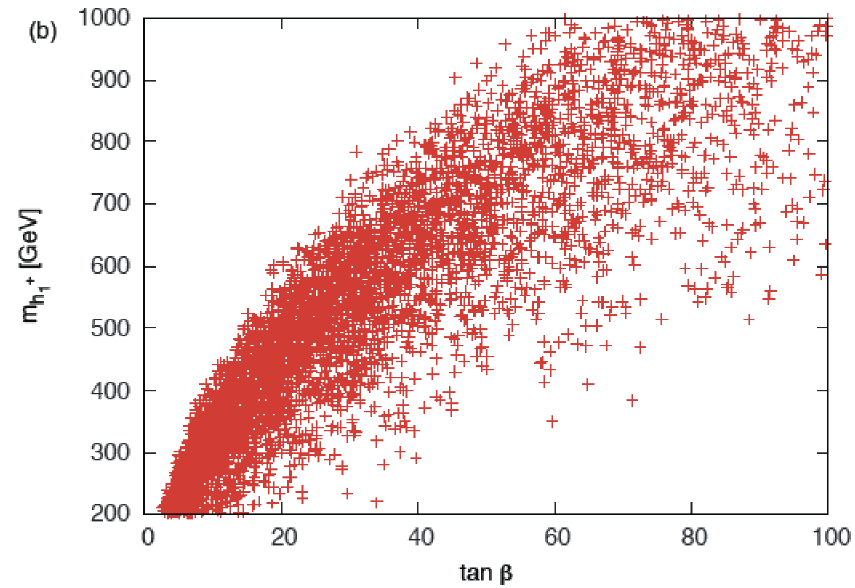
$(u_k) = (1, 0, -1)$

- 2 pairs of charged Higgs + 2 CP-odd pseudoscalars.
- parameter spaces are large → not difficult to find the allowed region without fine-tuning.
- ex) degenerate case $m_{h_1^+} = m_{h_2^+}$



$+ \ \ldots\ 200\text{GeV} \leq m_{h_1^+} \leq 400\text{GeV}$

$+ \ \ldots\ 400\text{GeV} \leq m_{h_1^+} \leq 1000\text{GeV}$



favored by the top A_{FB} anomaly at Tevatron.

Ko,Omura,Yu, JHEP03 (2013) 151

Conclusions

• We proposed a new resoluton of the Higgs mediated FCNC problem in 2HDM with gauged $U(1)_H$.

• rich phenomenology : extra scalars, Z_H, dark matter, and extra fermions.

• might be possible to distinguish our model from the ordinary 2HDM in a certain parameter regions, but essential to discover the new scalars and gauge boson.

• We also constructed MHDMs, where gauged U(1) controls FCNC.

• In 3HDM, it might be possible to achieve top A_{FB}, BABAR discrepancies, and $B \rightarrow \tau \nu$, but necessary more detailed study.

Thank you for your attention.

Back up

2HDM with fermiophobic Z_H

- realized with u=d=0 and assume $\alpha_1 = \alpha_2 = 0$.
- Z_H can mix with the Z boson.

$$M^2 = \begin{pmatrix} g_Z^2 v^2 & -g_Z g_H (h_1 v_1^2 + h_2 v_2^2) \\ -g_Z g_H (h_1 v_1^2 + h_2 v_2^2) & g_H^2 (h_1^2 v_1^2 + h_2^2 v_2^2) \end{pmatrix}$$

- affects EWPOs and Drell-Yan process.
- requires that corrections to the most sensitive variables are within the errors of the SM prediction.

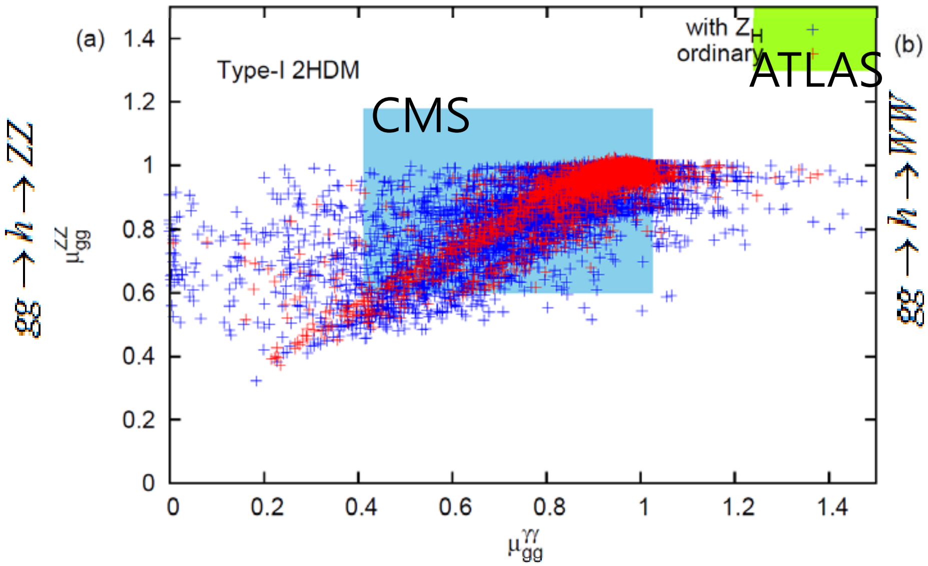
$$\rho_{\mathrm{2HDM}}^{\mathrm{tree}} = 1 + \frac{\Delta M_{ZZ_H}^2}{M_{Z0}^2}\xi, \text{ where } \rho_{\mathrm{SM}} = 1.01051 \pm 0.00011.$$

$$\Gamma_Z = 2.4961 \pm 0.0010 \text{ GeV}.$$

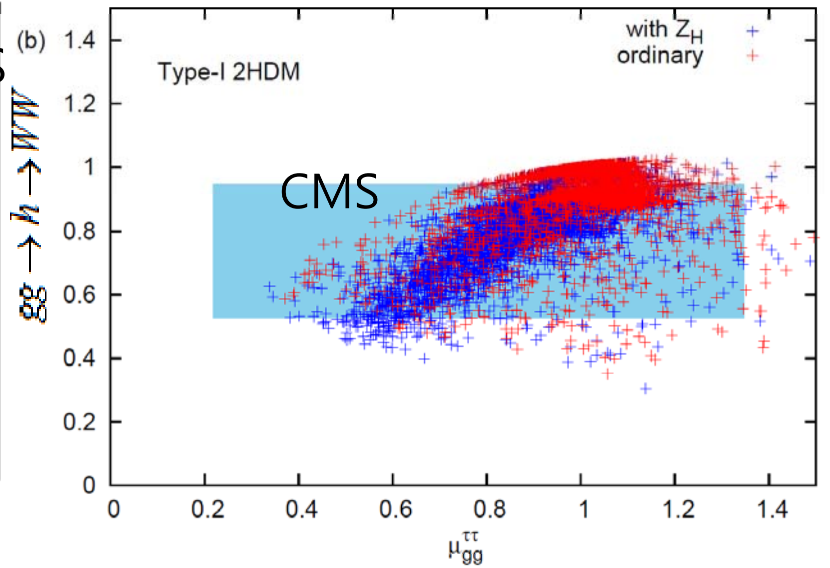
- requires $\xi < 10^{-3}$, which is safe for the Drell-Yan process at LHC.
- impose the constraints on S,T,U at the one-loop level.

Type-I 2HDM with fermiophobic Z_H

- gg fusion



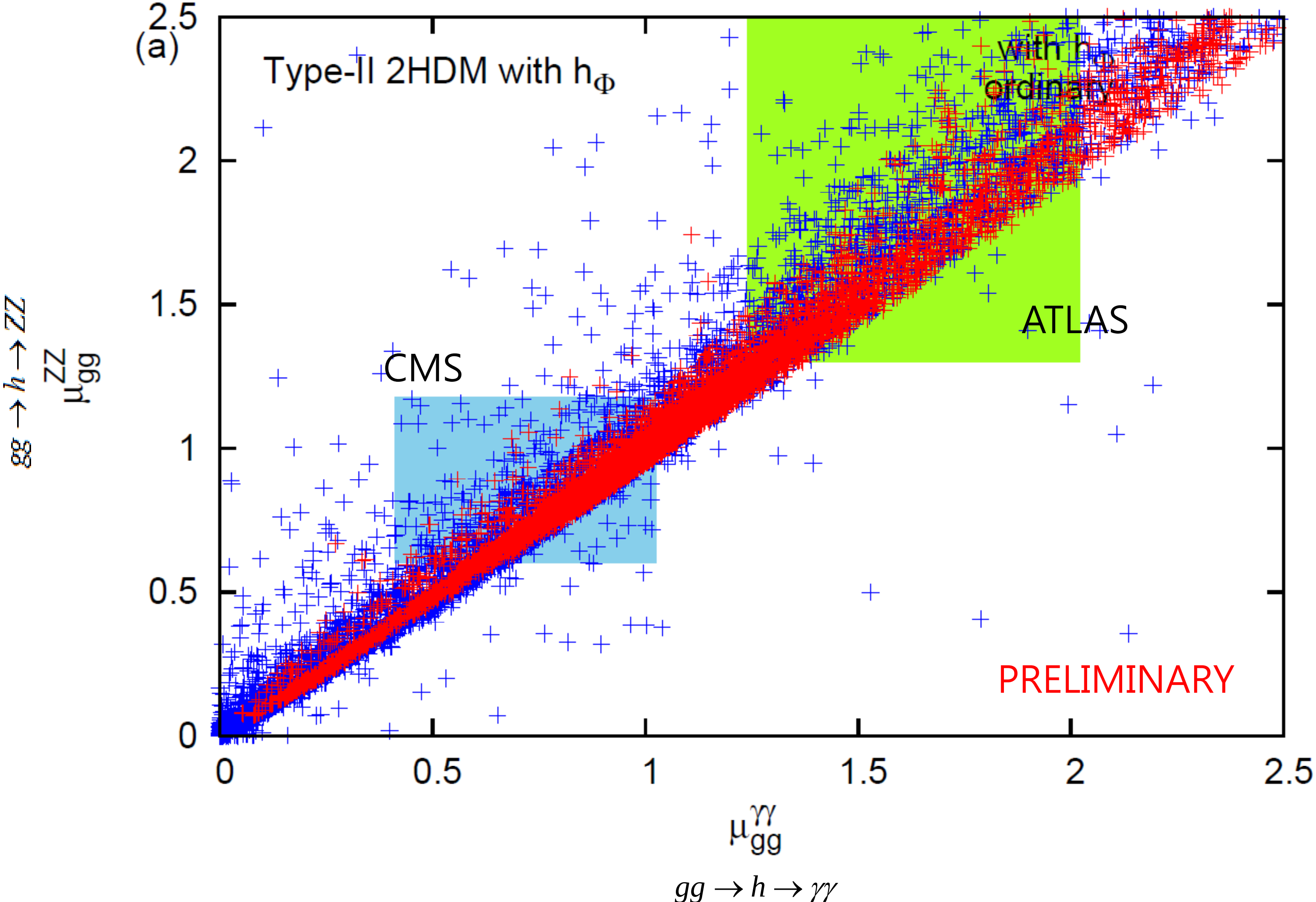
$gg \to h \to \gamma\gamma$



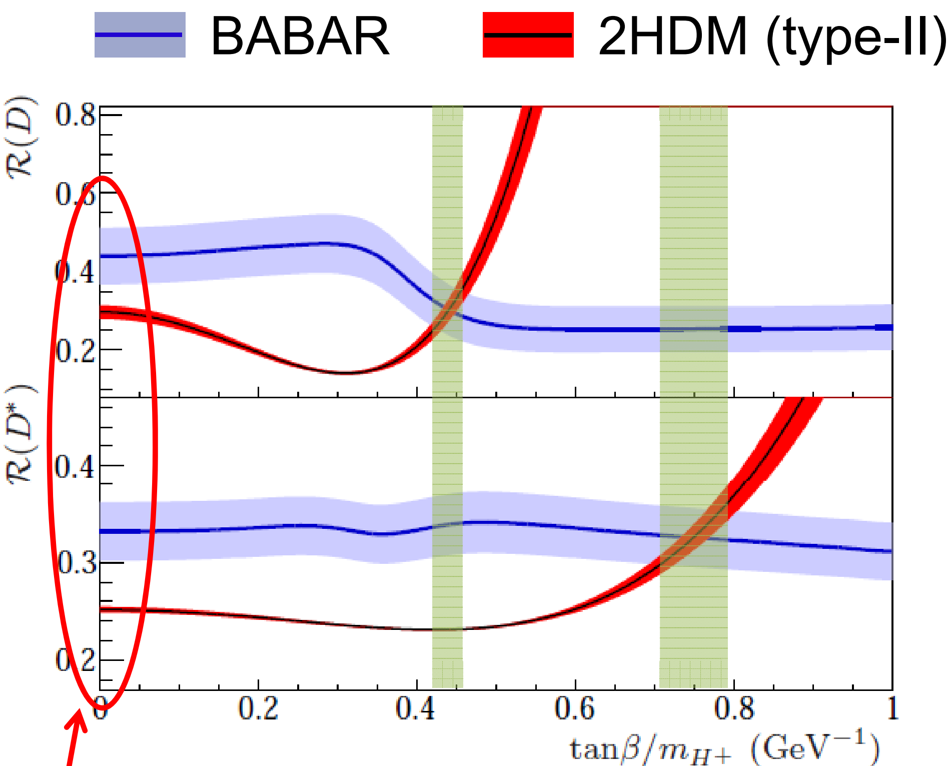
$gg \to h \to \tau\tau$

Type-II 2HDM with h_Φ

- gg fusion



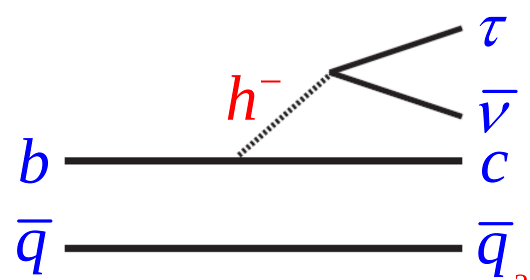
$B \to D^{(*)}\tau\nu$



BABAR, PRL109, 101802 (2012)

SM (3.4σ deviation)

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$



Type II $\propto m_\tau m_b \dfrac{\tan^2\beta}{m_{H^\pm}^2}$

Type I $\propto m_\tau m_b \dfrac{1}{\tan^2\beta\, m_{H^\pm}^2}$

Type X,Y $\propto m_\tau m_b \dfrac{1}{m_{H^\pm}^2}$

- Combination of $R(D)$ and $R(D^*)$ excludes 2HDMs with 99.8% probability.

- could be explained in the chiral U(1) model.

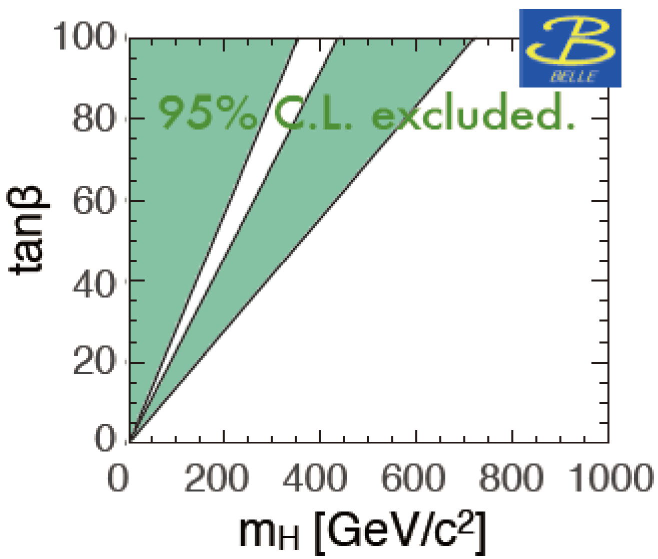
Ko,Omura,Yu, JHEP03 (2013) 151

BR($B \to \tau\nu$)

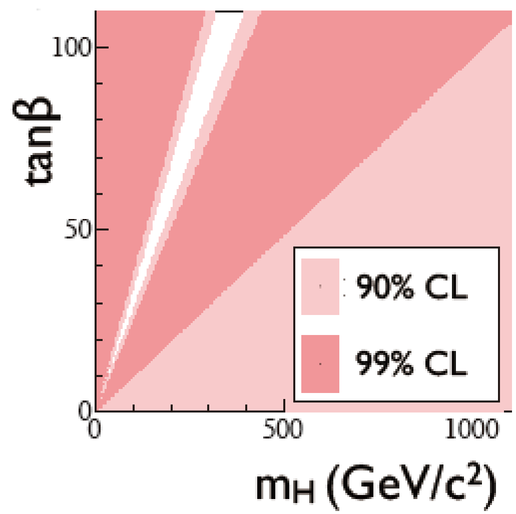
- type-II 2HDM

Kwon, NRF2013

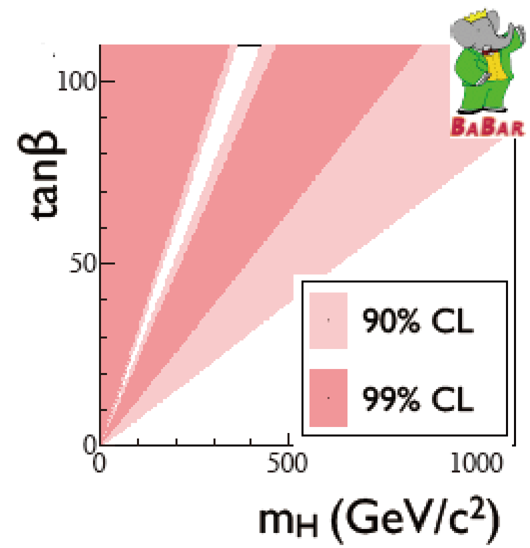
$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = \mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu_\tau) \times \left[1 - (m_B^2/m_H^2)\tan^2\beta\right]^2$$



V_{ub} from excl.+incl. b→ulν



V_{ub} from exclusive b→ulν



V_{ub} from inclusive b→ulν