2HDM with spontaneous Higgs symmetry breaking

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Extension of Higgs sector

- a new boson was discovered on July 4, 2012.

- spin and parity : 0^+ (other hypotheses are excluded at 95% C.L. or higher)

  - the SM Higgs boson?
  - exist extra Higgs bosons?

- "Is it the Standard Model Higgs?" is far from being settled.

(Lecture by Ian Low)

- Multi-Higgs scenarios may be motivated by SUSY or GUT, etc.

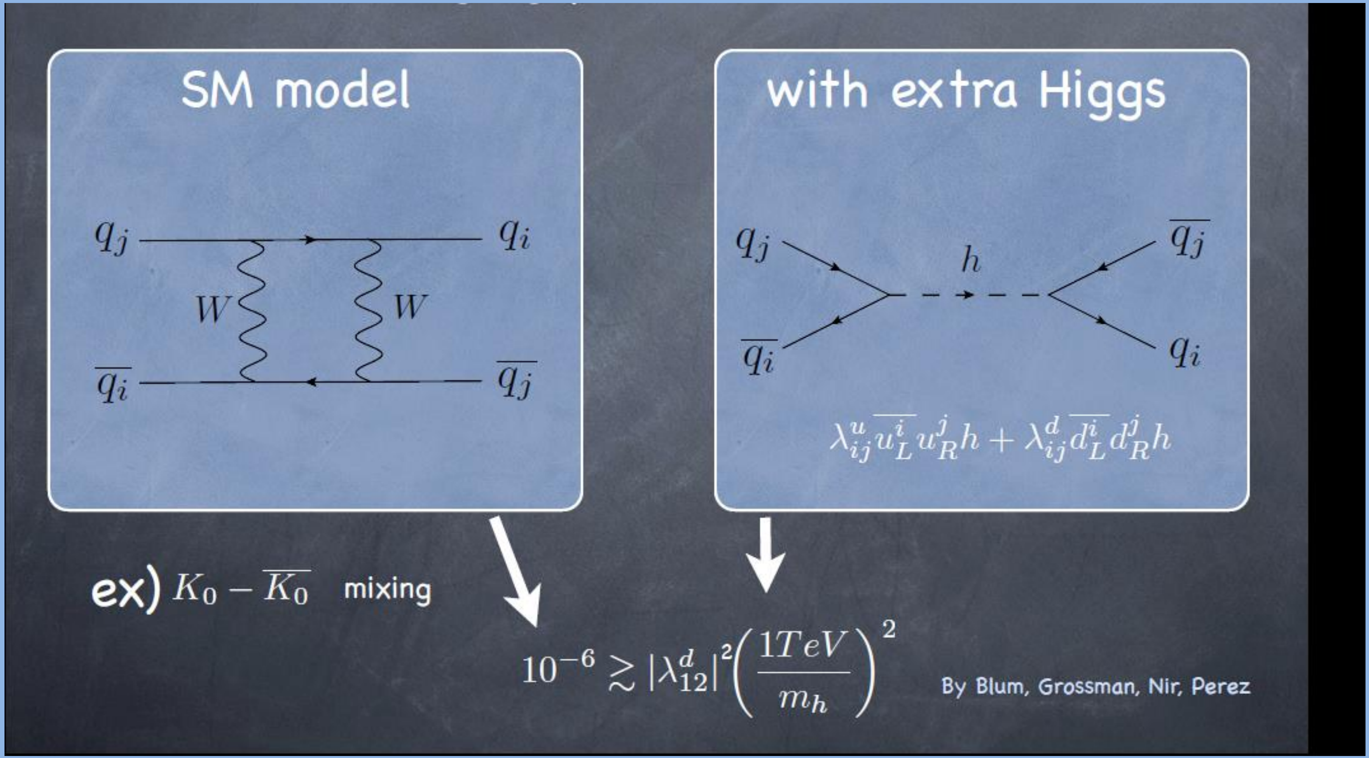
- two Higgs doublet models and chiral U(1)′ models.

Two Higgs Double Model

• One of the simplest models to extend the SM Higgs sector.

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

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



Z_2 symmetry

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

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

→ Natural Flavor Conservation (NFC).

Type	H_1	H_2	U_R	D_R	E_R	N_R	Q_L, L	
I	$+$	$-$	$+$	$+$	$+$	$+$	$+$	
II	$+$	$-$	$+$	$-$	$-$	$+$	$+$	
III'	$+$	$-$	$+$	$+$	$-$	$-$	$+$	=Type X, lepton specific
IV	$+$	$-$	$+$	$-$	$+$	$-$	$+$	=Type Y, flipped

- Type I : $V_y = y_{ij}^U \overline{Q_{Li}} \widetilde{H_1} U_{Rj} + y_{ij}^D \overline{Q_{Li}} H_1 D_{Rj} + y_{ij}^E \overline{L_i} H_1 E_{Rj} + y_{ij}^N \overline{L_i} \widetilde{H_1} N_{Rj}.$
- Type II : $V_y = y_{ij}^U \overline{Q_{Li}} \widetilde{H_1} U_{Rj} + y_{ij}^D \overline{Q_{Li}} H_2 D_{Rj} + y_{ij}^E \overline{L_i} H_2 E_{Rj} + y_{ij}^N \overline{L_i} \widetilde{H_1} N_{Rj}.$
- Type III : $V_y = y_{ij}^U \overline{Q_{Li}} \widetilde{H_1} U_{Rj} + y_{ij}^D \overline{Q_{Li}} H_1 D_{Rj} + y_{ij}^E \overline{L_i} H_2 E_{Rj} + y_{ij}^N \overline{L_i} \widetilde{H_2} N_{Rj}.$
- Type IV : $V_y = y_{ij}^U \overline{Q_{Li}} \widetilde{H_1} U_{Rj} + y_{ij}^D \overline{Q_{Li}} H_2 D_{Rj} + y_{ij}^E \overline{L_i} H_1 E_{Rj} + y_{ij}^N \overline{L_i} \widetilde{H_2} N_{Rj}.$

Each sector (mass matrices) depends on one Higgs (VEV).

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 Z_2 symmetric 2HDM potential

$$\boxed{\begin{aligned} V(\Phi_1,\Phi_2) \;&=\; m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ &+\; \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}] \end{aligned}}$$

- the origin of such a discrete symmetry?

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.

$Z_2 \to gauged\ U(1)_H$ ⟶ massless eaten ⟶ light gauge boson (Z_H)

$$BH_1^\dagger H_2 \to \langle\Phi\rangle H_1^\dagger H_2$$

□ required (?)

- 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.

$$V_y = y^U_{ij}\overline{Q_{Li}}\widetilde{H_1}U_{Rj} + y^D_{ij}\overline{Q_{Li}}H_1 D_{Rj} + y^E_{ij}\overline{L_i}H_1 E_{Rj} + y^N_{ij}\overline{L_i}\widetilde{H_1}N_{Rj}.$$

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

U_R	D_R	Q_L	L	E_R	N_R	H_1	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.

Type-II 2HDM

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

$$V_y = y^U_{ij}\overline{Q_{Li}}\widetilde{H_1}U_{Rj} + y^D_{ij}\overline{Q_{Li}}H_2 D_{Rj} + y^E_{ij}\overline{L_i}H_2 E_{Rj} + y^N_{ij}\overline{L_i}\widetilde{H_1}N_{Rj}.$$

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.

$U(1)_H^3$

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$
q_{Li}	3	1	2/3	$\hat{Q}_L = u + \hat{Q}_R$
q_{Ri}	3	1	2/3	$\hat{Q}_R$
n_{Li}	1	1	0	$\hat{n}_L = u + \hat{n}_R$
n_{Ri}	1	1	0	$\hat{n}_R$

$U(1)_Y U(1)_H^2$

Two SM vector-like pairs

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 $U(1)_H$

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

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

Theoretical constraints

- perturbativity

  - couplings should not be larger than some value which makes a perturbative treatment meaningless.

- 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

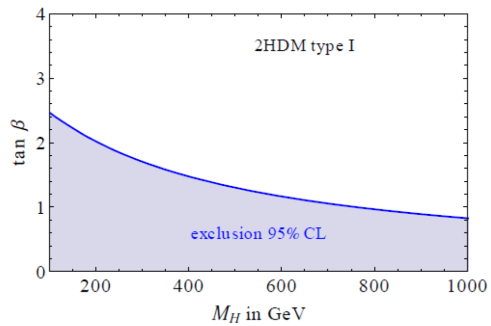
$$\lambda_\Phi > 0,\ \lambda_1 > \frac{\widetilde{\lambda}_1^2}{\lambda_\Phi},\ \lambda_2 > \frac{\widetilde{\lambda}_2^2}{\lambda_\Phi},\ \lambda_3 - \frac{\widetilde{\lambda}_1 \widetilde{\lambda}_2}{\lambda_\Phi} > -\sqrt{\left(\lambda_1 - \frac{\widetilde{\lambda}_1^2}{\lambda_\Phi}\right)\left(\lambda_2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

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

Experimental constraints

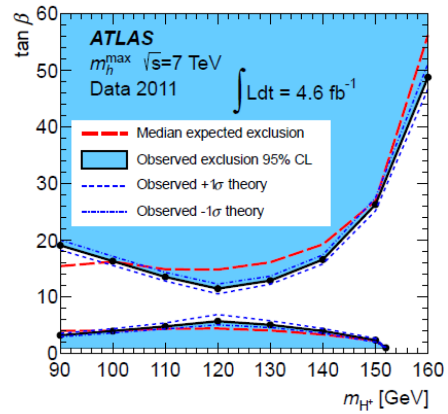
- charged Higgs

$b \to s\gamma$



$\tan\beta \geq 1$

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



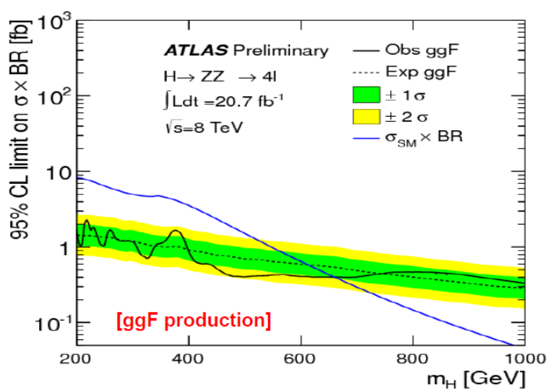
- should be corrected in the type-I 2HDM

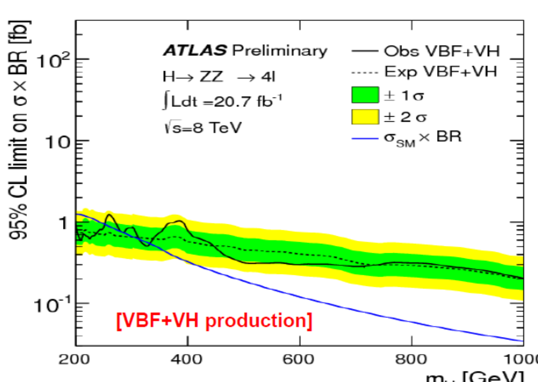
$$\mu_j^i = \frac{\sigma(pp \to h)^j \mathrm{Br}(h \to i)}{\sigma(pp \to h)^j_{\mathrm{SM}} \mathrm{Br}(h \to i)_{\mathrm{SM}}}$$

- Heavy Higgs search

➔ **Upper limits on production cross section × branching ratio**

$H \to ZZ \to 4l$





$\mu_{gg}^{ZZ} \lesssim 0.1$

$\mu_{\mathrm{VBF}}^{ZZ} \lesssim 1$

ATLAS−CONF−2013−013

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.

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

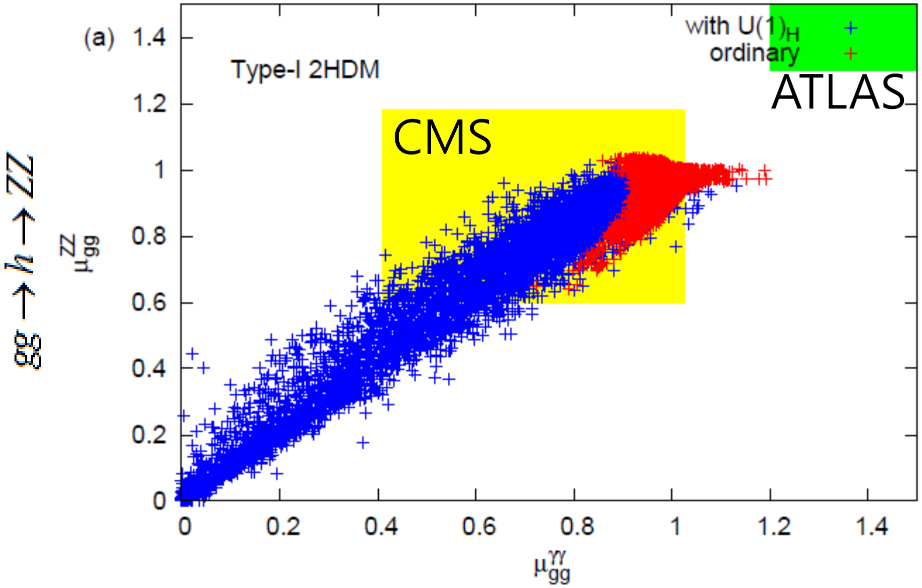
Baak et al., EPJC 72, 2205 (2012)

- If Z_H couples with the SM fermions, need to analyze full one-loop amplitudes with Z_H.
- consider two cases (in the type-I 2HDM).

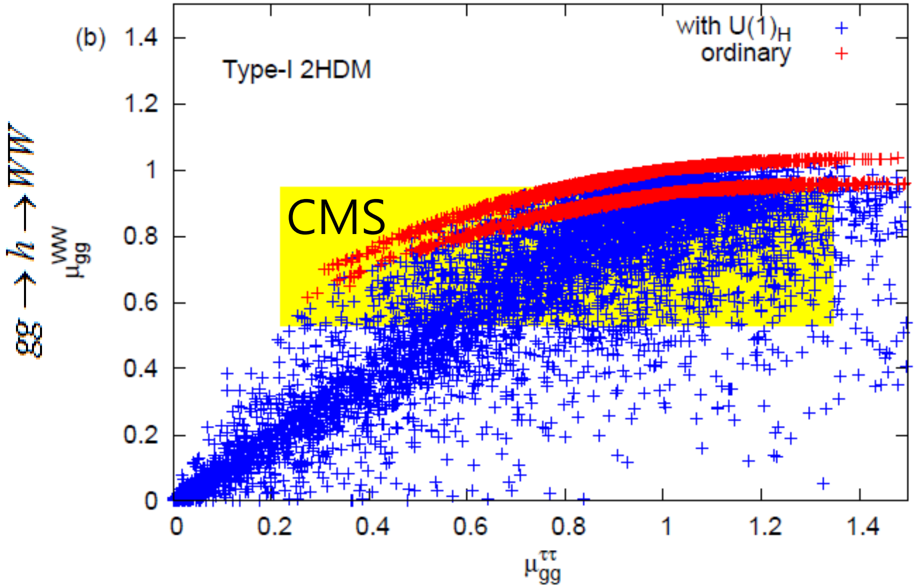
1. Z_H is decoupled in the limit of m_{Z_H}>>EW scale.
2. Z_H is fermiophobic for u=d=0.

2HDM with Φ

- the gg fusion



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



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

- consistent with CMS in the 1σ level while consistent with ATLAS in the 2σ.
- In the ordinary type-I 2HDM, $0.8 \lesssim \mu_{gg}^{\gamma\gamma} \lesssim 1.2$ and $0.6 \lesssim \mu_{gg}^{ZZ} \lesssim 1.1$.
- In the type-I 2HDM with U(1)$_H$, $0 \lesssim \mu_{gg}^{\gamma\gamma} \lesssim 1.2$ and $0 \lesssim \mu_{gg}^{ZZ} \lesssim 1.1$.
- distinguishable in the region of $\mu_{gg}^{\gamma\gamma} \lesssim 0.8$ and $\mu_{gg}^{ZZ} \lesssim 0.6$.

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.

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

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

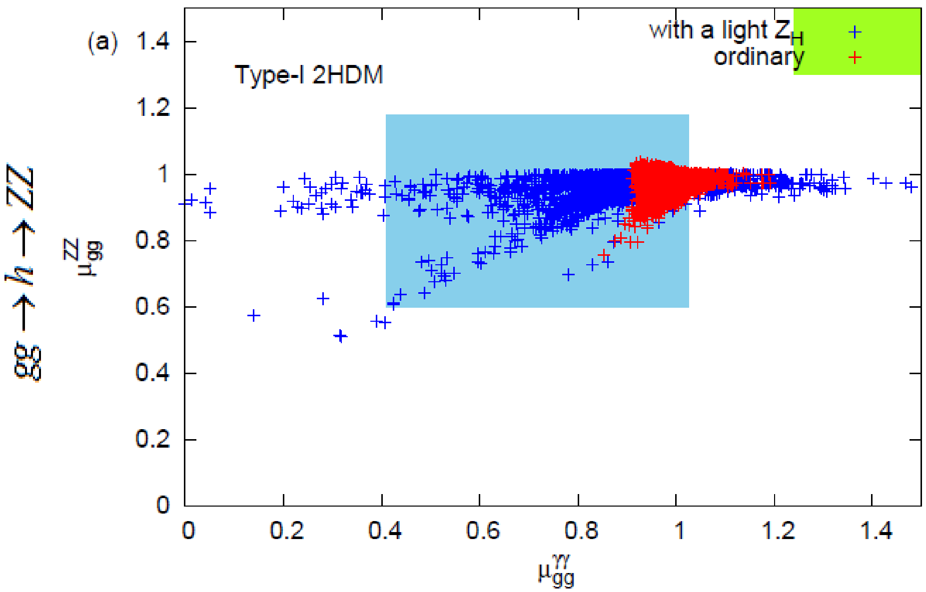
$$\sigma(e^+e^- \to \mu^+\mu^-).$$

- requires $\xi < 10^{-3}$, which is safe for the Drell-Yan process at LHC.

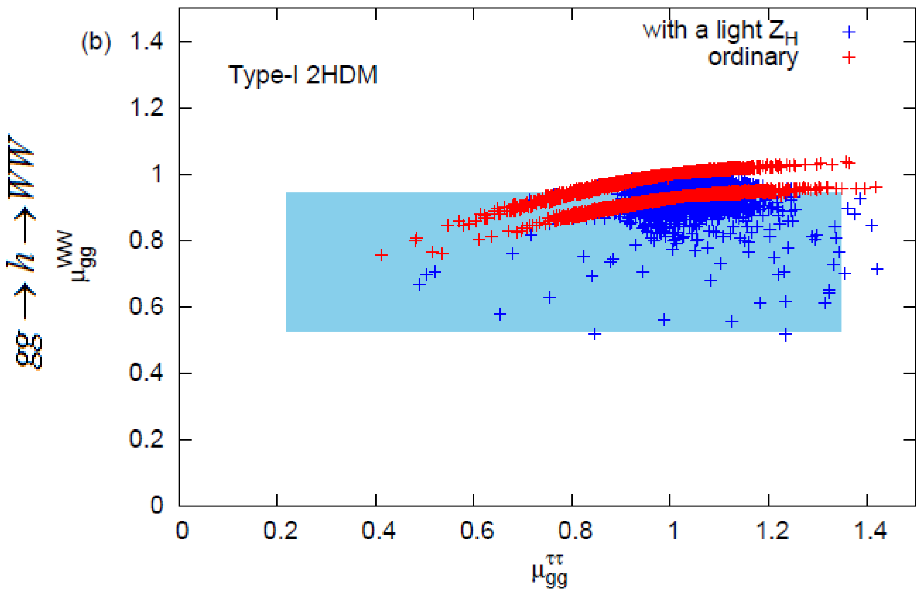
- impose the constraints on S,T,U at the one-loop level.

2HDM with fermiophobic Z_H

- gg fusion



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



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

Conclusions

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

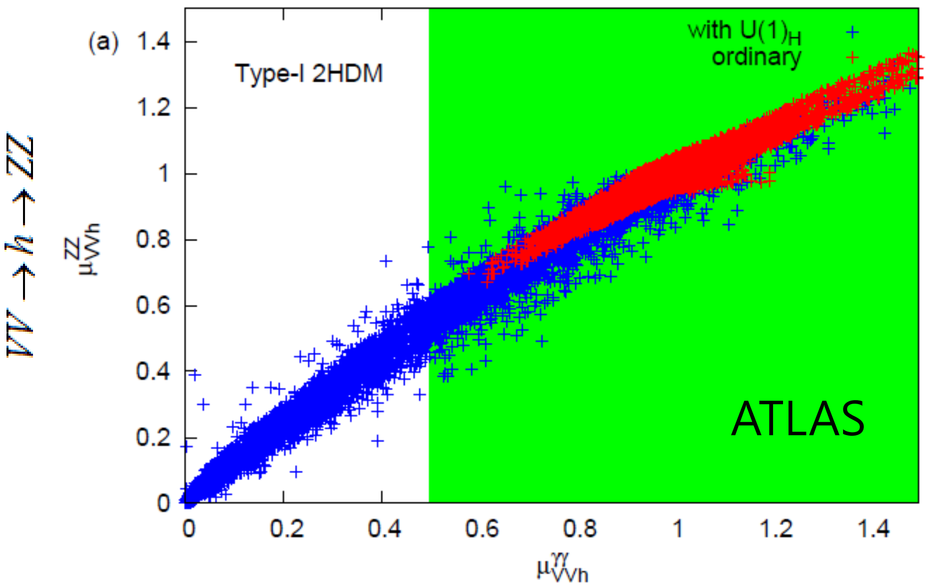
• easily realize "Natural Flavor Conservation" for proper $U(1)_H$ assignment.

• studied the Higgs production at the LHC in the type-I 2HDM with spontaneous Higgs symmetry breaking by considering theoretical and experimental constraints.

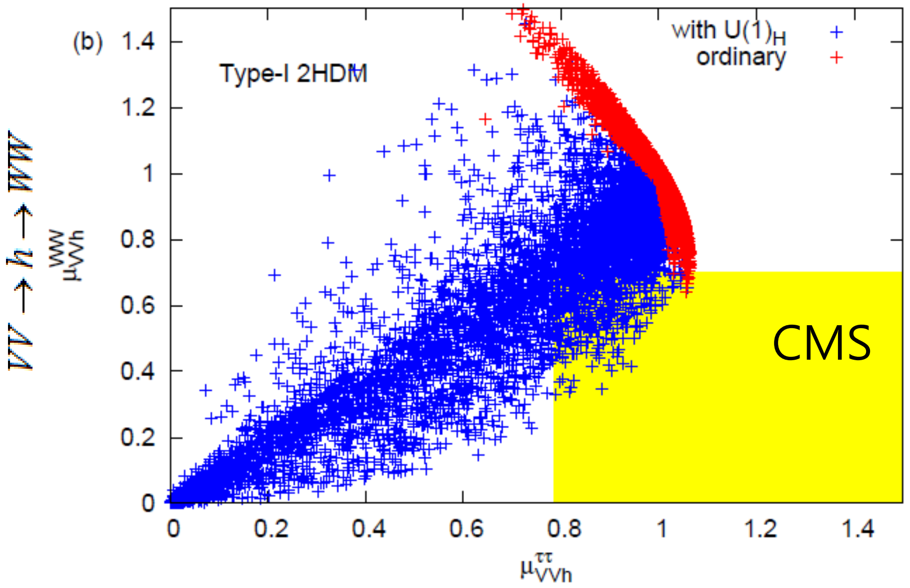
• For small $\mu_{gg}^{\gamma\gamma}$ and μ_{gg}^{ZZ}, it is possible to distinguish from the ordinary 2HDM.

2HDM with Φ

- the vector boson fusion



$VV \to h \to \gamma\gamma$



$VV \to h \to \tau\tau$

- experimental uncertainties are large.

$$\mu^{WW}_{VVh} = -0.047^{+0.747}_{-0.555} \qquad \mu^{\tau\tau}_{VVh} = 1.423^{+0.696}_{-0.637}$$

- the signal strengths could be larger than the SM prediction in the small cosα or large sinβ limit.

$$\lambda_{hVV} = \cos\alpha_1 \sin(\beta - \alpha), \quad \lambda_{hff} = \cos\alpha \cos\alpha_1 / \sin\beta.$$