

# 125 GeV Higgs Bosons in Two-Higgs Doublet Models after Moriond 2013

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A compact version was delivered in the YSF session at the Moriond 2013 EW.

• A. Drozd, B. Grzadkowski, J. F. Gunion and YJ, arXiv:1211.3580 [hep-ph]



# THE HIGGS HUNTER'S GUIDE

$$K \frac{1}{s} \frac{1}{s} \left( \frac{1}{2} - \frac{1}{2} \frac{1}{s} \right) \sin(\alpha + \beta) - \frac{1}{s} \frac{1}{s} \cos \alpha$$

ARP

John F. Gunion  
Howard E. Haber  
Gordon Kane  
Sally Dawson

- Republished in 2000
- A little bit out of date
- Still a bible on Higgs boson physics

# July 4th, 2012—A HISTORIC moment in science. It is a privilege to witness the Higgs discovery.



## 天哪！这真是“上帝粒子”吗？

欧洲核子中心激动宣布可能发现希格斯-玻色子：“我们对宇宙的理解，将要改变！”



新华社电，在为期两天的会议中，来自欧洲核子研究中心的科学家们激动地宣布，他们可能发现了上帝粒子。

**物理学家的狂欢发疯前奏**

【新华社日内瓦4日电】欧洲核子研究中心(CERN)宣布，可能发现了上帝粒子。这一消息在日内瓦的科学家们中引起了巨大的轰动。科学家们表示，这一发现将改变我们对宇宙的理解。

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**83岁物理学大师：未想过有生之年等到**

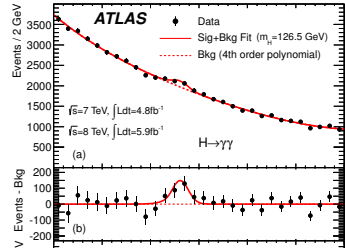
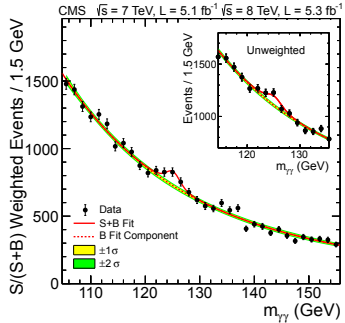
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**还期待得确认 意义堪比阿波罗登月**

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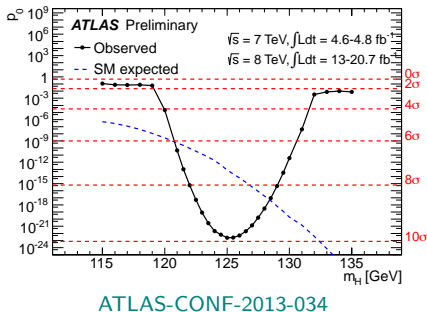
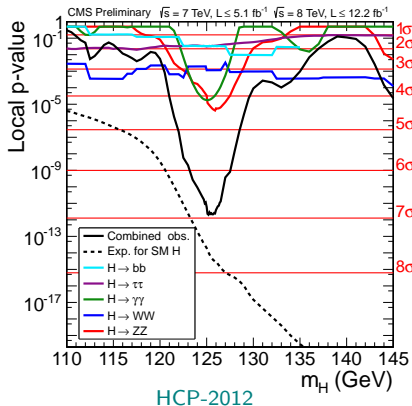
**“这该死的粒子”**

【新华社日内瓦4日电】欧洲核子研究中心(CERN)宣布，可能发现了上帝粒子。这一消息在日内瓦的科学家们中引起了巨大的轰动。科学家们表示，这一发现将改变我们对宇宙的理解。



# 125 GeV Higgs-like signal at the LHC

ATLAS updated the local p-values at the Moriond 2013.

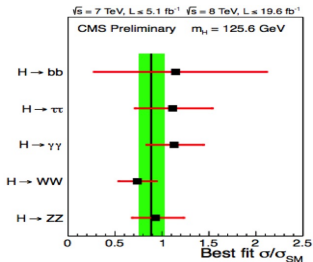


CMS and ATLAS provide an essentially  $7\sigma$  and  $10\sigma$  signal, respectively, for a Higgs-like resonance with mass of order 123–128 GeV.

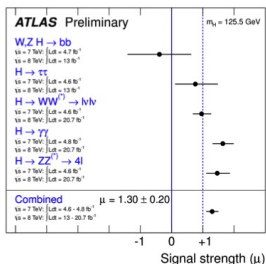
With the new data, “Seeing is believing” !

# 125 GeV Higgs-like signal at the Moriond 2013 QCD

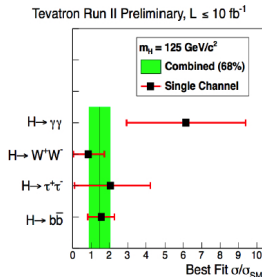
LPSC workshop



ATLAS-CONF-2013-034



Moriond 13 EW



$m_h \sim 125$	gg fusion		$\tau^+\tau^-$	inclusive	VH
	$ZZ^* \rightarrow 4l$	$\gamma\gamma$			
ATLAS	$1.8^{+0.8}_{-0.5}$	$1.6^{+0.42}_{-0.36}$	$0.7 \pm 0.7$	$1.01 \pm 0.3$	$-0.4 \pm 1.1$
CMS	$0.9^{+0.5}_{-0.4}$	$0.78^{+0.28}_{-0.26}$ (MVA) $1.11^{+0.32}_{-0.3}$ (CiC)	$0.75^{+0.5}_{-0.52}$	$0.76 \pm 0.21$	$1.3^{+0.7}_{-0.6}$
	high mass resolution		poor mass resolution		

Tevatron: the evidence for the Higgs boson is based principally on the  $W + H$  with  $H \rightarrow b\bar{b}$  decay mode, the observed enhancements relative to the SM rate by a factor of  $1.56^{+0.72}_{-0.73}$ .

# Whether or not it *is* the SM Higgs?



# Why two Higgs-Doublet Model (2HDM)?

- 1 The simplest non-trivial extension on the Higgs sector beyond the SM.
  - Duplicate a complex  $SU(2)_L$  Higgs doublet with the same hypercharge  $Y = +1$ .
  - More physical Higgs states.
- 2 Type II realized in the MSSM.

## 2HDM Higgs sector

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



## 2HDM Higgs sector

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

### The models we studied

- 1 NO explicit  $\mathcal{CP}$  violation: all  $\lambda_i$  and  $m_{12}^2$  are assumed to be real.
- 2 NO spontaneous  $\mathcal{CP}$  breaking: take  $\xi = 0$ .

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free parameters:  $\tan \beta, m_{12}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$

## 2HDM Higgs sector

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### Electroweak symmetry breaking

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v \cos \beta + \rho_1 + i\eta_1)/\sqrt{2} \end{pmatrix} \\ \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (e^{i\xi} v \sin \beta + \rho_2 + i\eta_2)/\sqrt{2} \end{pmatrix}$$

2 CP-even neutral scalars:  $h = -\rho_1 \sin \alpha + \rho_2 \cos \alpha$   
 $H = \rho_1 \cos \alpha + \rho_2 \sin \alpha$

1 CP-odd neutral pseudoscalar:  $A = -\eta_1 \sin \beta + \eta_2 \cos \beta$

2 charged scalars:  $H^\pm$

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our inputs:  $m_h, m_H, m_A, m_{H^\pm}, \tan \beta, \sin \alpha, m_{12}^2$

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2 charged scalars:  $H^\pm$

$$\mathcal{L} = y_{ij}^1 \bar{\psi}_i \psi_j \Phi_1 + y_{ij}^2 \bar{\psi}_i \psi_j \Phi_2$$

We consider the Type I and Type II models, in which tree level FCNC are completely absent due to some symmetry. <sup>1</sup>

Model	$u_R^i$	$d_R^i$	$e_R^i$	Realization
Type I	$\Phi_2$	$\Phi_2$	$\Phi_2$	$\Phi_1 \rightarrow -\Phi_1$
Type II	$\Phi_2$	$\Phi_1$	$\Phi_1$	$\Phi_1 \rightarrow -\Phi_1, d_R^i \rightarrow -d_R^i$

$$\mathcal{L}_{\text{Yukawa}}^{\text{2HDM}} = - \sum_{f=u,d,\ell} \frac{m_f}{v} \left( \xi_f^h \bar{f} f h + \xi_f^H \bar{f} f H - i \xi_f^A \bar{f} \gamma_5 f A \right) - \left\{ \frac{\sqrt{2} V_{ud}}{v} \bar{u} \left( m_u \xi_u^A P_L + m_d \xi_d^A P_R \right) d H^+ + \frac{\sqrt{2} m_\ell \xi_\ell^A}{v} \bar{\nu}_L \ell_R H^1 + \text{h.c.} \right\}$$

	$\xi_u^h$	$\xi_d^h$	$\xi_\ell^h$	$\xi_u^H$	$\xi_d^H$	$\xi_\ell^H$	$\xi_u^A$	$\xi_d^A$	$\xi_\ell^A$
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	$\frac{\cos \alpha}{\sin \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$-\frac{\sin \alpha}{\cos \beta}$	$\frac{\sin \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\frac{\cos \alpha}{\cos \beta}$	$\cot \beta$	$\tan \beta$	$\tan \beta$

Higgs-gauge boson couplings:  $g_{SM} \sin(\beta - \alpha)$

<sup>1</sup> Paschos-Glashow-Weinberg theorem: if all fermions with the same quantum numbers couple to the same Higgs multiplet, then FCNC will be absent.

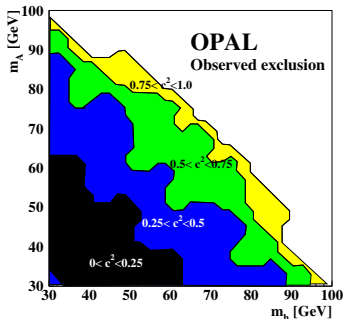
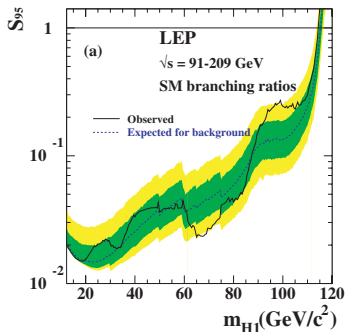
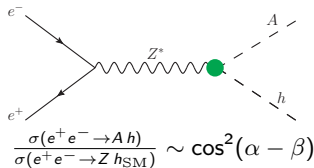
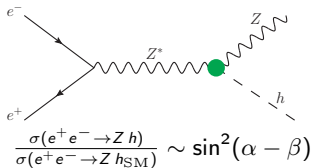
- Theoretically, (denoted jointly as **SUP**)
  - 1 **Vacuum stability**  
The potential must be bounded from below (positivity).
  - 2 **Unitarity**  
Requiring the largest eigenvalue for the tree-level for full multi-state scattering matrix in  $(h, H, A)$  space to be less than the upper limit  $16\pi$ .
  - 3 **Perturbativity**  
All self couplings among the mass eigenstates and Yukawa coupling must be finite,  $|\Lambda_i| < 4\pi$ .
- Experimentally,
  - 1 Precision electroweak constraints (denoted STU).

$$-0.3 < S < 0.33; -0.34 < T < 0.35; -0.25 < U < 0.41 (\pm 3\sigma)$$
  - 2 **LEP constraints** on Higgs mass limits.
  - 3 **B-physics constraints**.
  - 4 the anomalous magnetic moment of the muon  $\delta a_\mu \equiv (g - 2)_\mu^{\text{BSM}}$  (IGNORED).



# Basic Constraints – LEP

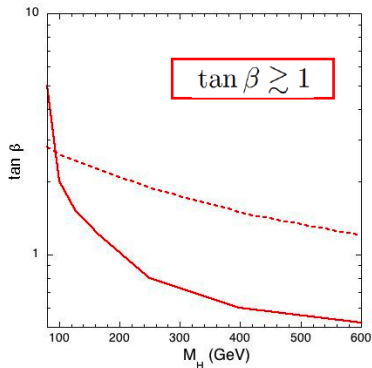
LEP constraints on Higgs mass limits



# Basic Constraints – $B$ -physics

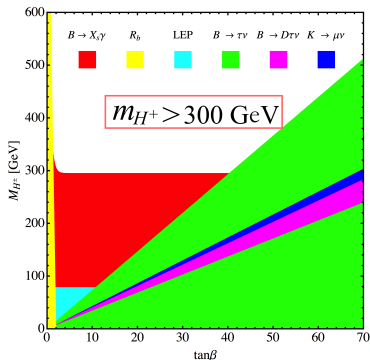
$B$ -physics constraints ( $\text{BR}(B_s \rightarrow X_s \gamma)$ ,  $R_b$ ,  $\Delta M_{B_s}$ ,  $\epsilon_K$ ,  $\text{BR}(B^+ \rightarrow \tau^+ \nu_\tau)$  and  $\text{BR}(B^+ \rightarrow D \tau^+ \nu_\tau)$ ): set up lower bound on  $m_{H^\pm}$ .

Type I



Solid:  $R_b$  for  $Z \rightarrow b\bar{b}$ ,  $\epsilon_K$  and  $\Delta m_{B_s}$   
 Dash:  $\bar{B} \rightarrow X_s \gamma$  in models with FCNC

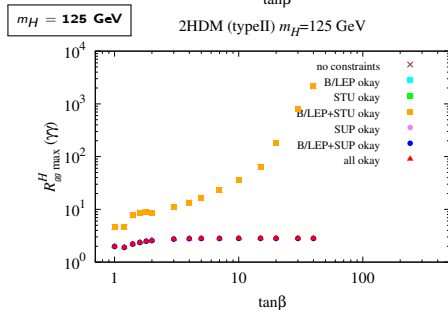
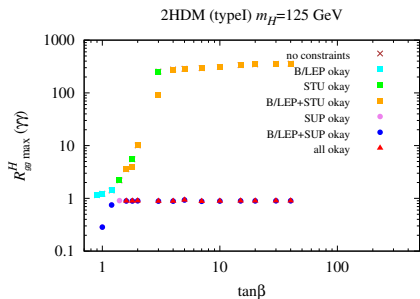
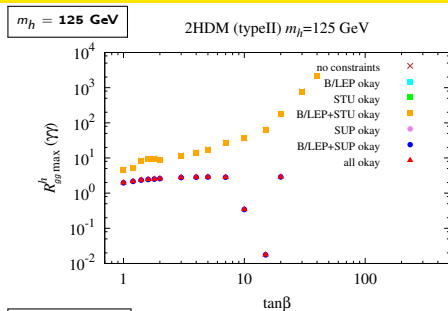
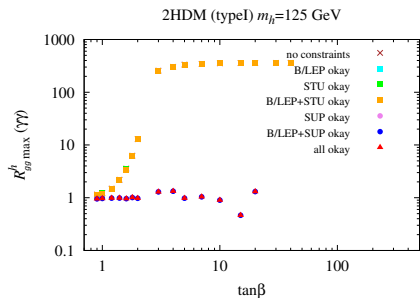
Type II



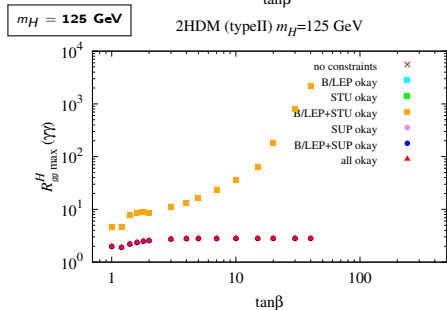
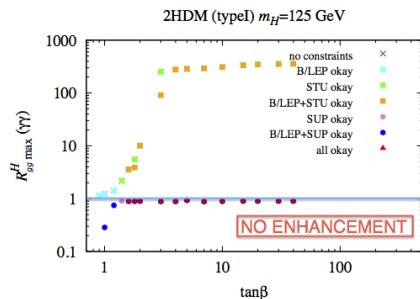
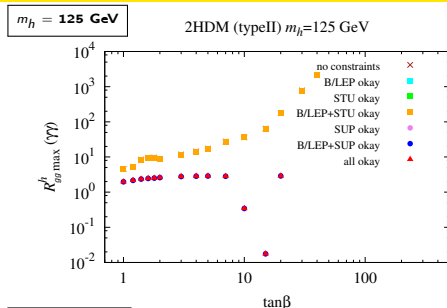
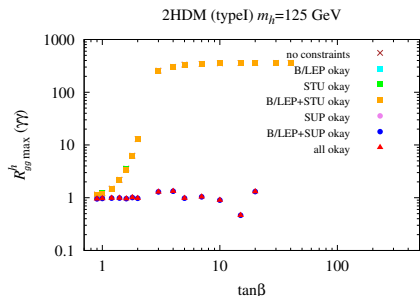
# Single Scalar Scenarios

- $h$  or  $H$  either lies at 125 GeV.

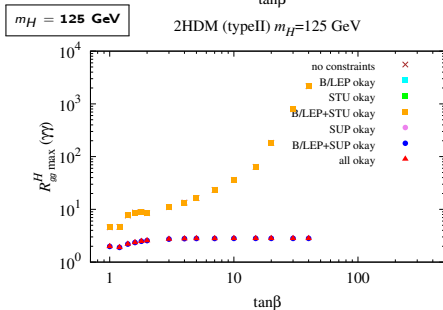
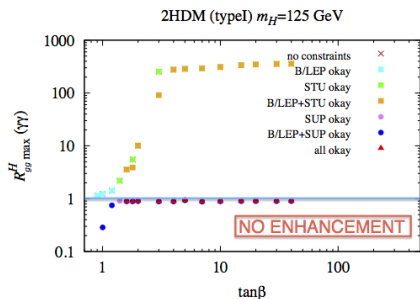
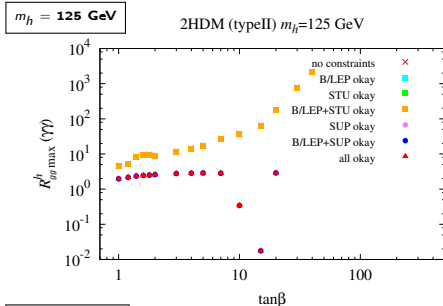
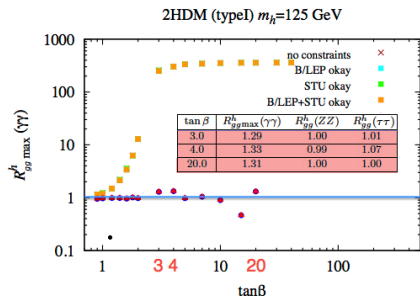
# SUP DECREASE the $\gamma\gamma$ rate $R_Y^{h_i}(X) \equiv \frac{\sigma(Y \rightarrow h_i) \text{BR}(h_i \rightarrow X)}{\sigma(Y \rightarrow h_{\text{SM}}) \text{BR}(h_{\text{SM}} \rightarrow X)}$ , $h_i = h, H, A$



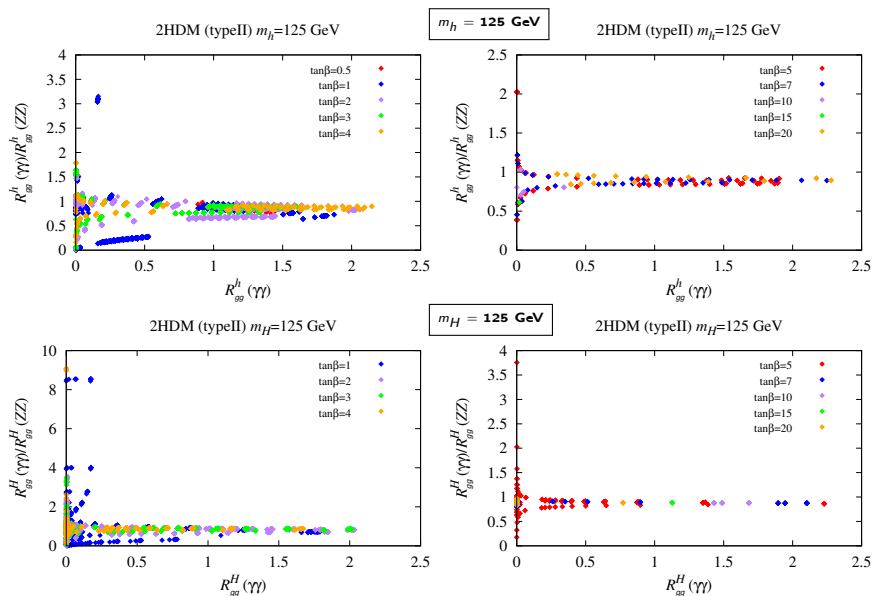
# SUP DECREASE the $\gamma\gamma$ rate $R_Y^{h_i}(X) \equiv \frac{\sigma(Y \rightarrow h_i) \text{BR}(h_i \rightarrow X)}{\sigma(Y \rightarrow h_{\text{SM}}) \text{BR}(h_{\text{SM}} \rightarrow X)}$ , $h_i = h, H, A$



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# $\gamma\gamma - ZZ$ rate correlation (Type II)



In the Type II models  $R_{gg}(ZZ) > R_{gg}(\gamma\gamma)$ .  $R_{gg}(ZZ) < 2.6$  only plotted.

Is it possible that the excess in the Higgs  $\rightarrow \gamma\gamma$  is due to two 2HDMs degenerate states?

Yes, the signal at 125 GeV cannot be pure  $A$  since at the tree level the  $A$  does not couple to  $ZZ$ , a final state that is definitely present at 125 GeV.



# Degenerate Scalar Scenarios

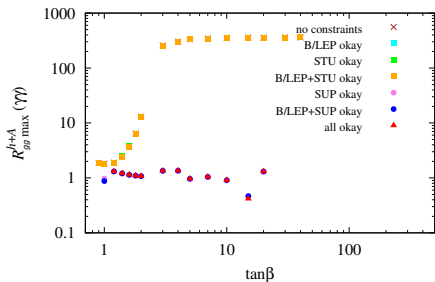
Choices for the degenerate pairs:

- $h$  and  $A$  both lie at the 125 GeV mass.
- $H$  and  $A$  both lie at the 125 GeV mass.
- $h$  and  $H$  both lie at the 125 GeV mass.

# $\gamma\gamma$ Enhancement achieved (Type I)

$$m_h = 125 \text{ GeV}, m_A \sim 125 \text{ GeV}$$

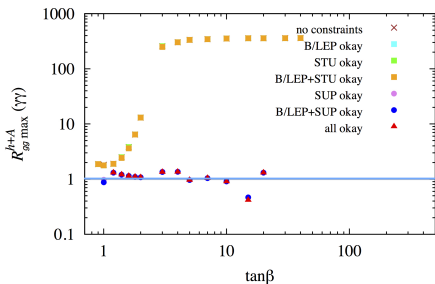
2HDM (typeI)  $m_h=125 \text{ GeV}, m_A=125.1 \text{ GeV}$



# $\gamma\gamma$ Enhancement achieved (Type I)

$$m_h = 125 \text{ GeV}, m_A \sim 125 \text{ GeV}$$

2HDM (typeI)  $m_h=125 \text{ GeV}, m_A=125.1 \text{ GeV}$

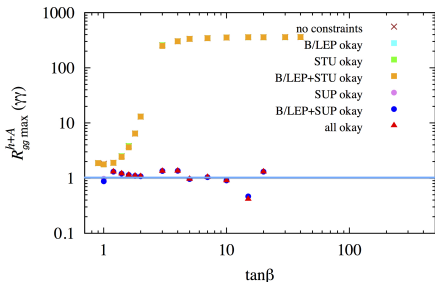


- $R_{gg}^{h+A}(\gamma\gamma)$  can be significantly enhanced.

# $\gamma\gamma$ Enhancement achieved (Type I)

$$m_h = 125 \text{ GeV}, m_A \sim 125 \text{ GeV}$$

2HDM (typeI)  $m_h=125 \text{ GeV}, m_A=125.1 \text{ GeV}$



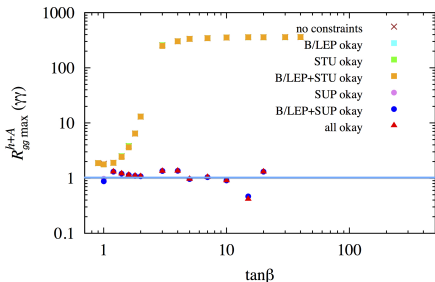
$\tan\beta$	$R_{gg}^{h+A}(\gamma\gamma)$	$R_{gg}^A(\gamma\gamma)$	$R_{gg}^{h+A}(ZZ)$	$R_{gg}^{h+A}(\tau\tau)$
1.2	1.31	0.41	1.02	3.35
1.4	1.21	0.30	0.99	2.61
1.6	1.14	0.23	1.01	2.32
1.8	1.10	0.18	1.00	1.98
2.0	1.08	0.15	0.98	1.73
3.0	1.34	0.06	1.00	1.31
4.0	1.35	0.03	0.99	1.21
7.0	1.04	0.01	0.99	1.00
20.0	1.31	0.00	1.00	1.00

- $R_{gg}^{h+A}(\gamma\gamma)$  can be significantly enhanced.
- $R_{gg}^A(\gamma\gamma)$  turns out to be tiny at large  $\tan\beta$ .
- Large  $\tau\tau$  rate at small  $\tan\beta$  because of the  $A$  contribution.

# $\gamma\gamma$ Enhancement achieved (Type I)

$$m_h = 125 \text{ GeV}, m_A \sim 125 \text{ GeV}$$

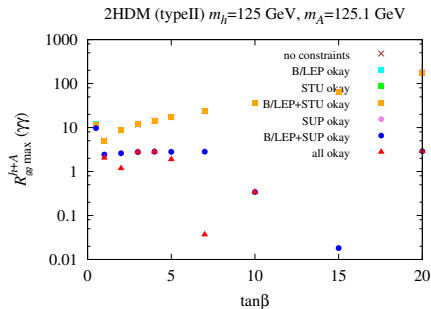
2HDM (typeI)  $m_h=125 \text{ GeV}, m_A=125.1 \text{ GeV}$



$\tan\beta$	$R_{gg}^{h+A}(\gamma\gamma)$	$R_{gg}^A(\gamma\gamma)$	$R_{gg}^{h+A}(ZZ)$	$R_{gg}^{h+A}(\tau\tau)$
1.2	1.31	0.41	1.02	3.35
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7.0	1.04	0.01	0.99	1.00
20.0	1.31	0.00	1.00	1.00

- $R_{gg}^{h+A}(\gamma\gamma)$  can be significantly enhanced.
- $R_{gg}^A(\gamma\gamma)$  turns out to be tiny at large  $\tan\beta$ .
- Large  $\tau\tau$  rate at small  $\tan\beta$  because of the  $A$  contribution.
- **Only  $\tan\beta = 20$ , both an enhanced  $\gamma\gamma$  rate and SM-like  $ZZ$  and  $\tau\tau$  rates!!!**

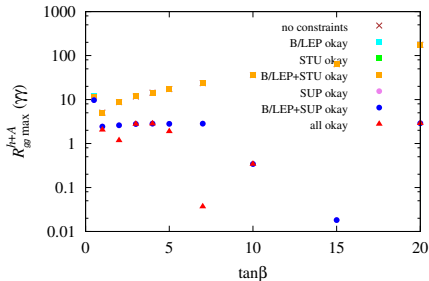
# $\gamma\gamma$ Enhancement achieved (Type II)



- Substantial enhancement in the  $R_{gg}^{h+A}(\gamma\gamma)$  can be achieved.
- Mostly associated with  $R_{gg}^{h+A}(ZZ) > R_{gg}^{h+A}(\gamma\gamma)$ .
- The exception has large  $\tau\tau$  rate.

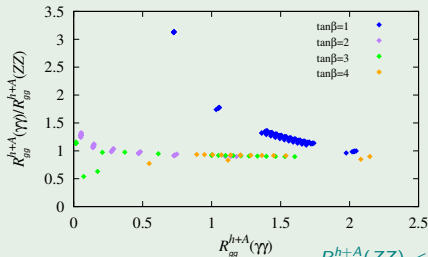
# $\gamma\gamma$ Enhancement achieved (Type II)

2HDM (typeII)  $m_h=125$  GeV,  $m_A=125.1$  GeV



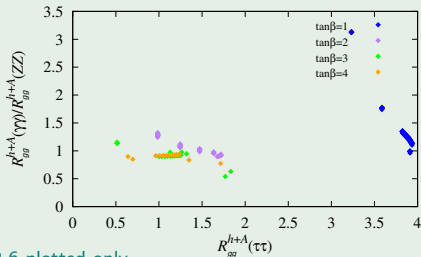
- Substantial enhancement in the  $R_{gg}^{h+A}(\gamma\gamma)$  can be achieved.
- Mostly associated with  $R_{gg}^{h+A}(ZZ) > R_{gg}^{h+A}(\gamma\gamma)$ .
- The exception has large  $\tau\tau$  rate.

2HDM (typeII)  $m_h=125$  GeV,  $m_A=125.1$  GeV



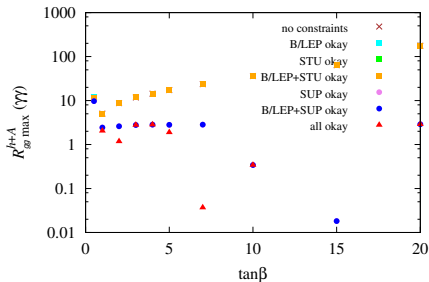
$R_{gg}^{h+A}(ZZ) < 2.6$  plotted only.

2HDM (typeII)  $m_h=125$  GeV,  $m_A=125.1$  GeV



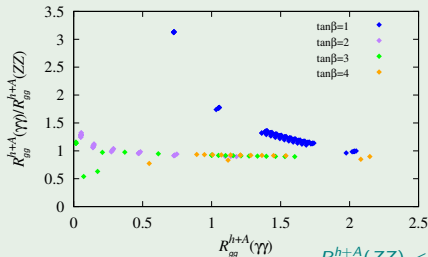
# $\gamma\gamma$ Enhancement achieved (Type II)

2HDM (typeII)  $m_h=125$  GeV,  $m_A=125.1$  GeV



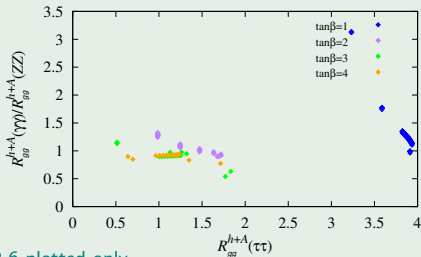
- Substantial enhancement in the  $R_{gg}^{h+A}(\gamma\gamma)$  can be achieved.
- Mostly associated with  $R_{gg}^{h+A}(ZZ) > R_{gg}^{h+A}(\gamma\gamma)$ .
- The exception has large  $\tau\tau$  rate.

2HDM (typeII)  $m_h=125$  GeV,  $m_A=125.1$  GeV



$R_{gg}^{h+A}(ZZ) < 2.6$  plotted only.

2HDM (typeII)  $m_h=125$  GeV,  $m_A=125.1$  GeV



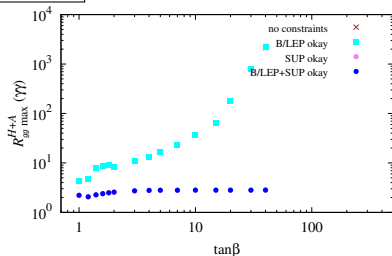
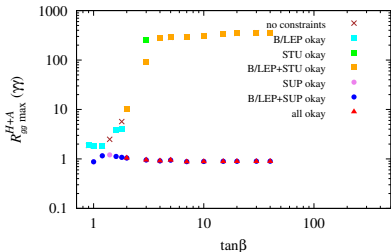


# LESS ATTRACTIVE

2HDM (typeI)  $m_H=125$  GeV,  $m_A=125.1$  GeV

$m_H = 125, m_A \sim 125$

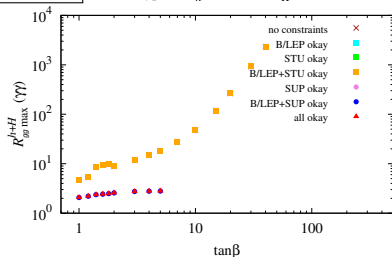
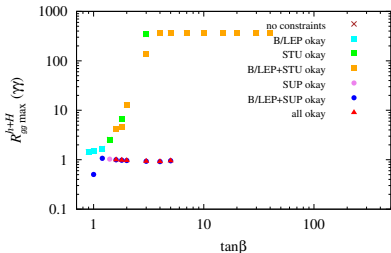
2HDM (typeII)  $m_H=125$  GeV,  $m_A=125.1$  GeV



2HDM (typeI)  $m_h=125$  GeV,  $m_H=125.1$  GeV

$m_h = 125, m_H \sim 125$

2HDM (typeII)  $m_h=125$  GeV,  $m_H=125.1$  GeV



NO substantial  $\gamma\gamma$  enhancement

Unwished  $R_{gg}(ZZ) > R_{gg}(\gamma\gamma)$

- It seems likely that the scalar boson responsible for EWSB has emerged. Perhaps, other scalar objects are emerging.
- In the 2HDM,
  - ① In both Type I and Type II models, SUP plays the key role in limiting the (possible) maximal  $\gamma\gamma$  enhancement.
  - ② The Type I model **could** provide a consistent picture if the MVA analysis by CMS is confirmed to be true.
  - ③ The Type II model is **unable** is able to give a significantly enhanced  $\gamma\gamma$  signal with the  $\overline{ZZ}$  at the same order and a more or less SM-like  $\tau\tau$  rates.

- But, if  $R_{gg}^h(\gamma\gamma)$  is definitively measured to have a value much above 1.4 while the  $ZZ$  and  $\tau\tau$  channels show little enhancement then there is no consistent 2HDM Type I description. In addition to Type II, one could go beyond the 2HDM to include new physics such as supersymmetry.
- Adopt  $\chi^2$  technique to globally fit LHC data is working in progress.
- 2HDM+singlets with a dark matter candidate is also a natural extension that is studying in progress.

*Instead of being the end of story, the recent discovery of the 125 GeV Higgs-like signal has brought particle physics research into the start of a new era. We are in the midst of an exciting debate on the nature of the 125 GeV state.*

*We are currently waiting to see if the future LHC data supports the various multi-Higgs proposals outlined earlier, or, alternatively, suggests that alternative theories are Nature's choice.*



*Thank you*

To me, 2012 was a productive year.  
It is just the start of my research career, wish your staying tuned.

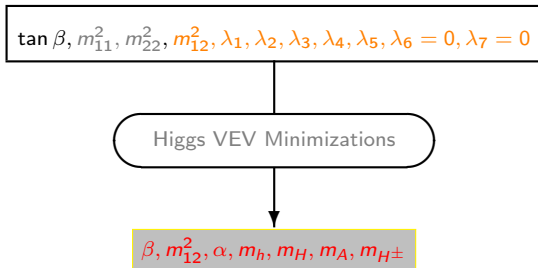
# Back Up

## 2HDM: two complex doublets $\Phi_1$ and $\Phi_2$ ( $Y = +1$ )

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

$$0 \leq \beta \leq \pi/2, \quad -\pi/2 \leq \alpha \leq \pi/2.$$

- Free independent parameter set



We have performed five scans over the parameter space with the range of variation.

	scenario I	scenario II	scenario III	scenario IV	scenario V
$m_h$ [GeV]	125	{10, ..., 124.9}	125	125	{10, ..., 124.9}
$m_H$ [GeV]	$125 + \{0.1, \dots, 1000\}$	125	125.1	$125 + \{0.1, \dots, 1000\}$	125
$m_A$ [GeV]	{10, ..., 1000}	{10, ..., 1000}	{10, ..., 1000}	125.1	125.1
$m_{H^\pm}$ [GeV]	1500 ( $\tan \beta = 0.5$ ); 800 ( $\tan \beta = 1$ ); 250, 350 ( $\tan \beta = 2$ ); 90, 150, 250, 350 ( $\tan \beta > 2$ ) for Type I 600 ( $\tan \beta = 0.5$ ); 500 ( $\tan \beta = 1$ ); 340 ( $\tan \beta = 2$ ); 320 ( $\tan \beta > 2$ ) for Type II				
$\tan \beta$	{0.5, ..., 20}				
$\sin \alpha$	{-1, ..., 1}				
$m_{12}^2$ [GeV <sup>2</sup> ]	{-1000 <sup>2</sup> , ..., 1000 <sup>2</sup> }				

# Type I single 125 Higgs

$m_H = 125 \text{ GeV}$

$\tan \beta$	$R_{gg}^{H \max}(\gamma\gamma)$	$R_{gg}^H(ZZ)$	$R_{gg}^H(bb)$	$R_{VBF}^H(\gamma\gamma)$	$R_{VBF}^H(ZZ)$	$R_{VBF}^H(bb)$	$m_h$	$m_A$	$m_{H\pm}$	$m_{12}$	$\sin \alpha$	$\mathcal{A}_{H\pm}^H/A$	$\delta a_\mu$
2.0	0.90	1.00	1.02	0.89	0.99	1.00	125	400	350	50	0.9	-0.05	-2.1
3.0	0.89	0.96	0.88	0.97	1.05	0.96	125	400	350	50	0.9	-0.05	-1.8
4.0	0.89	0.97	1.09	0.79	0.86	0.97	105	500	90	50	1.0	-0.03	-1.7
5.0	0.93	0.98	1.06	0.86	0.90	0.98	125	500	90	50	1.0	-0.01	-1.6
7.0	0.88	0.99	1.03	0.85	0.95	0.99	65	400	350	0	1.0	-0.05	1.6
10.0	0.89	1.00	1.02	0.87	0.98	1.00	45	400	350	0	1.0	-0.05	-1.6
15.0	0.90	1.00	1.01	0.89	0.99	1.00	5	400	350	0	-1.0	-0.05	-1.6
20.0	0.90	1.00	1.00	0.89	0.99	1.00	25	400	350	0	-1.0	-0.05	-1.5

TABLE V: Table of maximum  $R_{gg}^H(\gamma\gamma)$  values for the Type I 2HDM with  $m_H = 125 \text{ GeV}$  and associated  $R$  values for other initial and/or final states. The input parameters that give the maximal  $R_{gg}^H(\gamma\gamma)$  value are also tabulated.

$m_h = 125 \text{ GeV}$

$\tan \beta$	$R_{gg}^{h \max}(\gamma\gamma)$	$R_{gg}^h(ZZ)$	$R_{gg}^h(bb)$	$R_{VBF}^h(\gamma\gamma)$	$R_{VBF}^h(ZZ)$	$R_{VBF}^h(bb)$	$m_H$	$m_A$	$m_{H\pm}$	$m_{12}$	$\sin \alpha$	$\mathcal{A}_{H\pm}^h/A$	$\delta a_\mu$
0.9	0.95	0.94	0.76	1.17	1.16	0.94	875	750	900	500	-0.8	-0.02	-2.1
1.0	0.97	1.00	1.02	0.95	0.98	1.00	875	750	850	500	-0.7	-0.02	-2.3
1.2	0.98	0.96	0.83	1.13	1.10	0.96	625	750	612	400	-0.7	-0.01	-2.0
1.4	0.99	0.99	0.96	1.02	1.03	0.99	525	750	460	300	-0.6	-0.01	-2.0
1.6	0.96	0.97	0.87	1.07	1.08	0.97	625	400	360	200	-0.6	-0.02	-1.9
1.8	1.01	1.00	0.98	1.03	1.01	1.00	425	400	285	200	-0.5	0.00	-2.0
2.0	0.98	0.98	0.92	1.04	1.04	0.98	425	500	350	200	-0.5	-0.01	-1.8
3.0	1.29	1.00	1.01	1.27	0.99	1.00	225	200	92	100	-0.3	0.12	-1.8
4.0	1.33	0.99	1.07	1.24	0.93	0.99	225	200	90	100	-0.1	0.14	-1.7
5.0	0.98	0.98	1.06	0.90	0.91	0.98	225	400	150	100	-0.0	0.01	-1.6
7.0	1.04	0.99	0.98	1.06	1.01	0.99	135	500	90	50	-0.2	0.02	-1.6
10.0	0.90	0.81	0.74	0.99	0.89	0.81	175	500	150	50	-0.5	0.04	-1.5
15.0	0.46	0.59	0.66	0.41	0.53	0.59	225	400	350	50	0.6	-0.11	-1.4
20.0	1.31	1.00	1.00	1.30	0.99	1.00	225	200	90	50	-0.0	0.13	-1.5

SMALL

LARGE



$$r_s \equiv \frac{R_{gg}^s(\gamma\gamma)}{R_{gg}^s(ZZ)} = \frac{\Gamma(s \rightarrow \gamma\gamma)/\Gamma(h_{SM} \rightarrow \gamma\gamma)}{\Gamma(s \rightarrow ZZ)/\Gamma(h_{SM} \rightarrow ZZ)}$$

$$r_s \simeq \frac{(C_{WW}^s)^2}{(C_{ZZ}^s)^2} \left( \frac{\mathcal{A}_W^{SM} - \frac{C_{t\bar{t}}^s}{C_{WW}^s} \mathcal{A}_t^{SM} + \mathcal{A}_{H\pm} \text{ term}}{\mathcal{A}_W^{SM} - \mathcal{A}_t^{SM}} \right)^2 = \left( \frac{\mathcal{A}_W^{SM} - \frac{C_{t\bar{t}}^s}{C_{WW}^s} \mathcal{A}_t^{SM}}{\mathcal{A}_W^{SM} - \mathcal{A}_t^{SM}} \right)^2$$

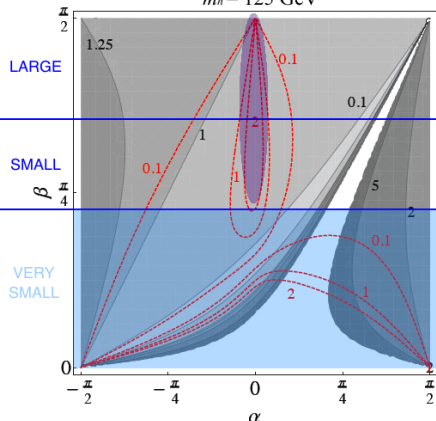
$$r_s < 1 \implies 1 < \frac{C_{t\bar{t}}^s}{C_{WW}^s} < 2 \frac{\mathcal{A}_W^{SM}}{\mathcal{A}_t^{SM}} - 1 \simeq 9$$

When  $C_{t\bar{t}}^s/C_{WW}^s$  is outside of the above interval then  $r_s > 1$ .

# $\gamma\gamma - ZZ$ Correlation Analysis

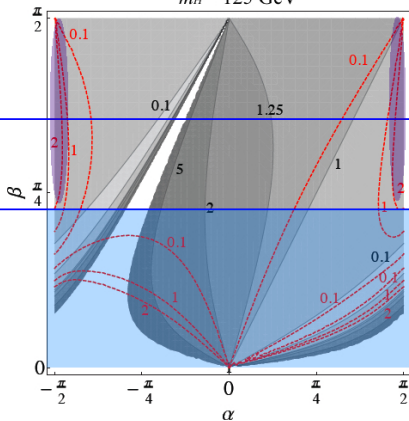
$$\frac{C_{t\bar{t}}^h}{C_{WW}^h} = \frac{\cos \alpha}{\sin \beta \sin(\beta - \alpha)}$$

$m_h = 125$  GeV



$$\frac{C_{t\bar{t}}^H}{C_{WW}^H} = \frac{\sin \alpha}{\sin \beta \cos(\beta - \alpha)}$$

$m_H = 125$  GeV

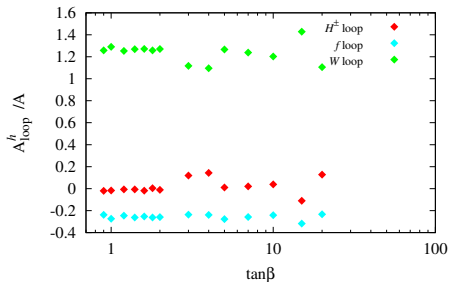


Red numbers give values of  $R_{\gamma\gamma}^s(\gamma\gamma)$  while black ones show constant  $r_s$  values.

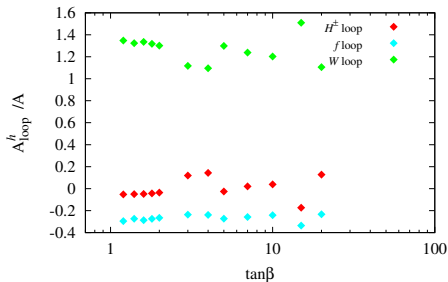
The white region correspond to  $r_s > 10.75$ .

# $\gamma\gamma$ enhancement mechanism in the Type I

2HDM (typeI)  $m_H=125$  GeV

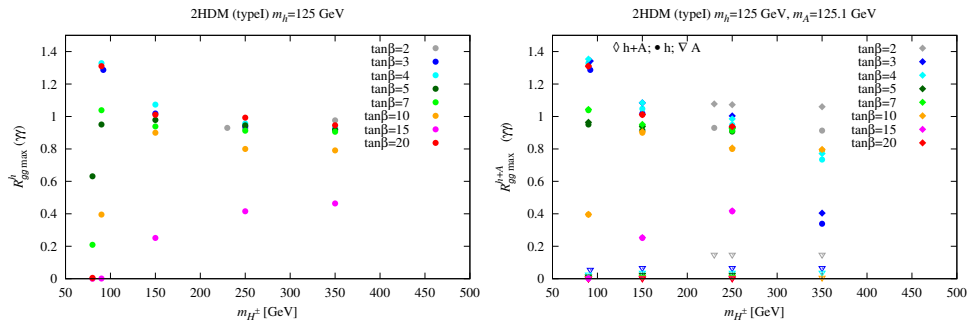


2HDM (typeI)  $m_H=125$  GeV,  $m_A=125.1$  GeV



- At the  $\tan\beta = 3, 4, 20$ , the relative **charged Higgs contribution** reaches nearly  $\sim 0.2$  and is as large as the fermionic loop contribution, but of the opposite sign.
- **The  $\gamma\gamma$  enhancement is usually associated with large  $A_{H^\pm} / A$ .**
- Moreover, although the dominant loop is the  $W$  loop, the  $H^\pm$  loop may contribute as much as the dominant (top quark) fermionic loop.

# Correlation on the $\gamma\gamma$ rate and charged Higgs mass



- Unexpectedly, the  $\gamma\gamma$  rate does **NOT ALWAYS** go up when charged Higgs mass approaches to its lowest bound constrained by the B-physics data.
- There might exist multiple local peak structure ...