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

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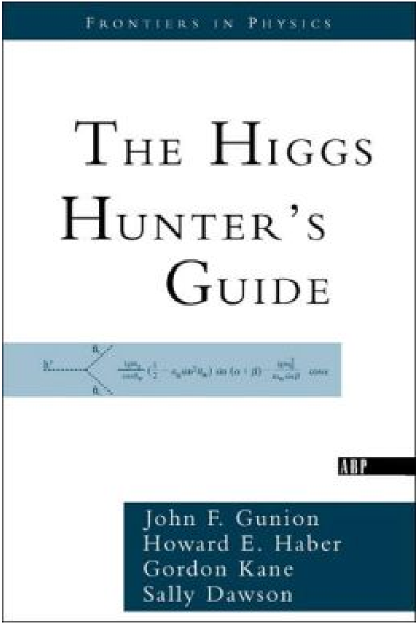
A compact version was delivered in the YSF session at the Moriond 2013 EW.

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



- 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- A little bit out of date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.


国际新闻
INTERNATIONAL NEWS
新快报
A29

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！”

物理学家们纷纷发博表期待

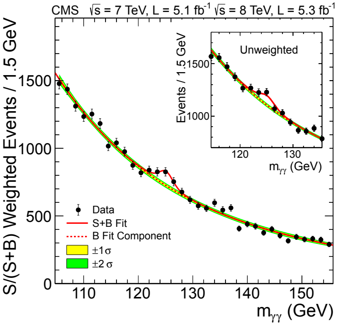
83岁希格斯：未想过有生之年等到

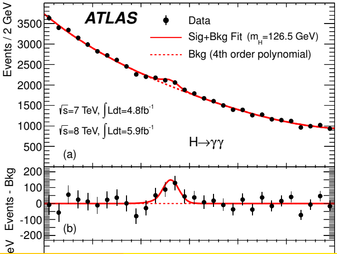
还需时间确认 意义堪比阿波罗登月

网友围观：好像很牛 但是不懂

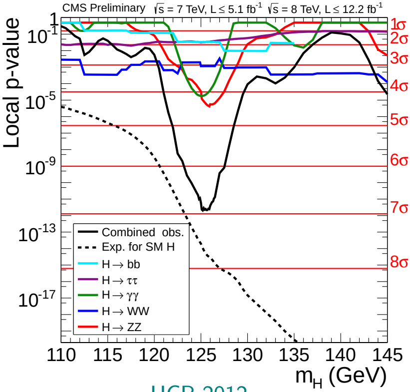
希格斯－玻色子是个啥？

“这该死的粒子！”

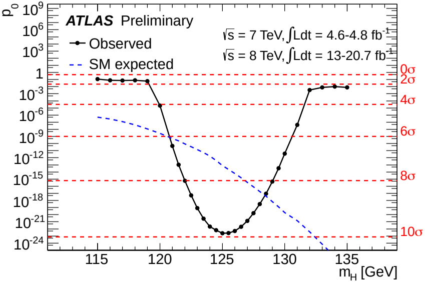




ATLAS updated the local p-values at the Moriond 2013.



HCP-2012



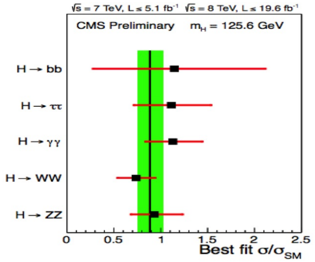
ATLAS-CONF-2013-034

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

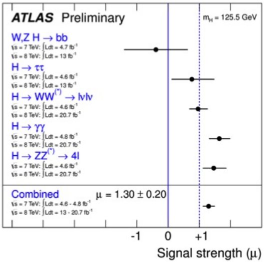
With the new data, "Seeing is believing" !

125 GeV Higgs-like signal at the Moriond 2013 QCD

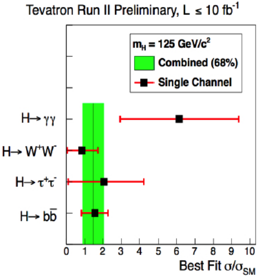
LPSC workshop



ATLAS-CONF-2013-034



Moriond 13 EW



	gg fusion			inclusive	VH
$m_h \sim 125$	$ZZ^* \to 4\ell$	$\gamma\gamma$	$\tau^+\tau^-$	$WW^* \to 2\ell 2\nu$	$Vb\bar{b}$
ATLAS	$1.8^{+0.8}_{-0.5}$	$1.6^{+0.42}_{-0.36}$	0.7 ± 0.7	1.01 ± 0.3	-0.4 ± 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 ± 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 $H \to b\bar{b}$ 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?

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.

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

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

2HDM Higgs sector

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

The models we studied

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

2HDM Higgs sector

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3. "soft" Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$) breaking: $m_{12}^2 \neq 0$; $\lambda_6 = \lambda_7 = 0$.

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

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

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

Electroweak symmetry breaking

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2 charged scalars: $H^\pm$

2HDM Yukawa sector

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

We consider the Type I and Type II models, in which tree level FCNC are completely absent due to some symmetry. [1]

Model	u^i_R	d^i_R	e^i_R	Realization
Type I	Φ_2	Φ_2	Φ_2	$\Phi_1 \to -\Phi_1$
Type II	Φ_2	Φ_1	Φ_1	$\Phi_1 \to -\Phi_1, d^i_R \to -d^i_R$

$$\begin{aligned}\mathcal{L}^{\mathbf{2HDM}}_{\mathbf{Yukawa}} &= -\sum_{f=u,d,\ell}\frac{m_f}{v}\left(\xi^h_f\bar{f}fh + \xi^H_f\bar{f}fH - i\xi^A_f\bar{f}\gamma_5 fA\right)\\ &\quad -\left\{\frac{\sqrt{2}V_{ud}}{v}\,\bar{u}\left(m_u\xi^A_u\mathrm{P}_L + m_d\xi^A_d\mathrm{P}_R\right)dH^+ + \frac{\sqrt{2}m_\ell\xi^A_\ell}{v}\,\overline{\nu_L}\ell_R H^{\mathbf{1}} + \text{h.c.}\right\}\end{aligned}$$

	ξ^h_u	ξ^h_d	ξ^h_ℓ	ξ^H_u	ξ^H_d	ξ^H_ℓ	ξ^A_u	ξ^A_d	ξ^A_ℓ
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: $g_{\mathrm{SM}}\sin(\beta-\alpha)$

[1] *Paschos-Glashow-Weinberg theorem: if all fermions with the same quantum numbers couple to the same Higgs multiplet, then FCNC will be absent.*

Basic Constraints

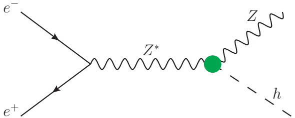
- Theoretically, (denoted jointly as SUP)
  1. **Vacuum stability**
     The potential must be bounded from below (positivity).
  2. **Unitarity**
     Requiring the largest eigenvalue for the tree-level for full multi-state scattering matrix in (h, H, A) space to be less than the upper limit 16π.
  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).

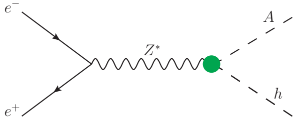
$$-0.3 < S < 0.33; -0.34 < T < 0.35; -0.25 < U < 0.41 \; (\pm 3\sigma)$$

  2. LEP constraints on Higgs mass limits.
  3. B-physics constraints.
  4. the anomalous magnetic moment of the muon $\delta a_\mu \equiv (g-2)_\mu^{\mathbf{BSM}}$ (IGNORED).

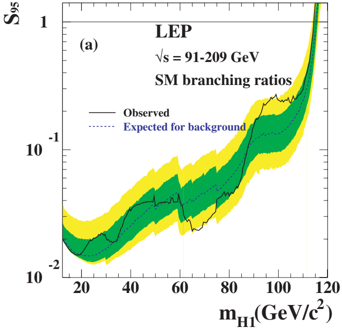
LEP constraints on Higgs mass limits

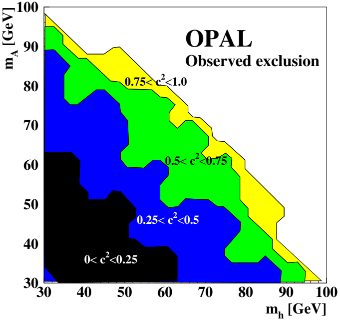


$$\frac{\sigma(e^+e^- \to Z\,h)}{\sigma(e^+e^- \to Z\,h_{\rm SM})} \sim \sin^2(\alpha - \beta)$$



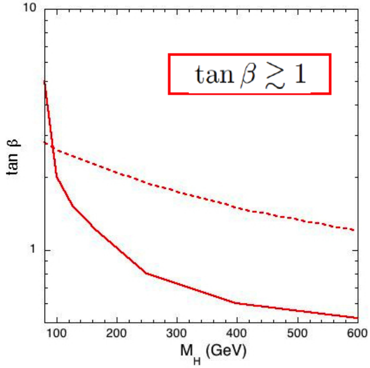
$$\frac{\sigma(e^+e^- \to A\,h)}{\sigma(e^+e^- \to Z\,h_{\rm SM})} \sim \cos^2(\alpha - \beta)$$



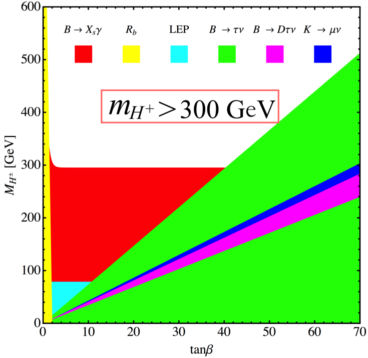


B-physics constraints ($\mathrm{BR}(B_s \to X_s\gamma)$, R_b, ΔM_{B_s}, ϵ_K, $\mathrm{BR}(B^+ \to \tau^+\nu_\tau)$ and $\mathrm{BR}(B^+ \to D\tau^+\nu_\tau)$): set up lower bound on $m_{H^\pm}$.

Type I



Type II



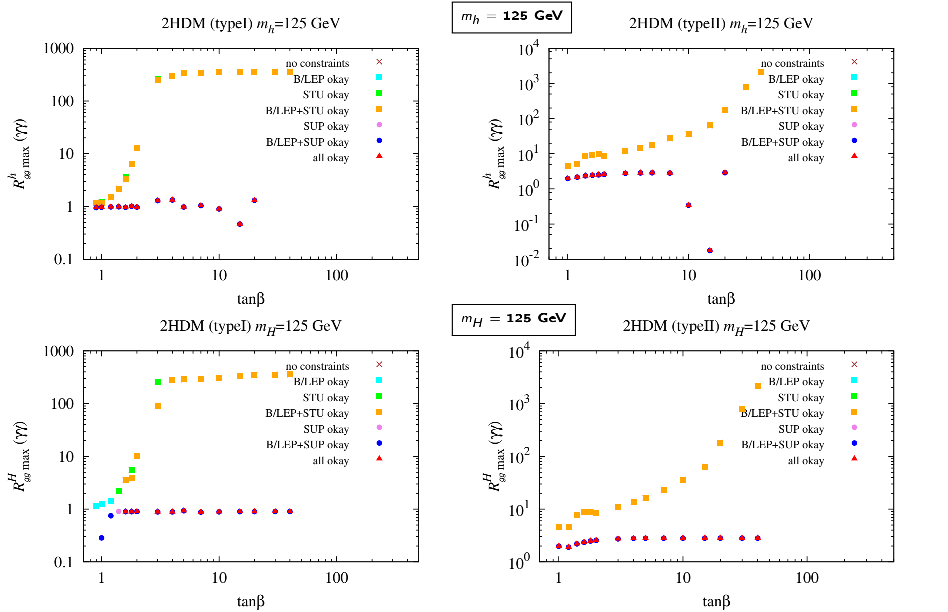
Solid: R_b for $Z \to b\bar{b}$, ϵ_K and Δm_{B_s}

Dash: $\bar{B} \to X_s\gamma$ in models with FCNC

Single Scalar Scenarios

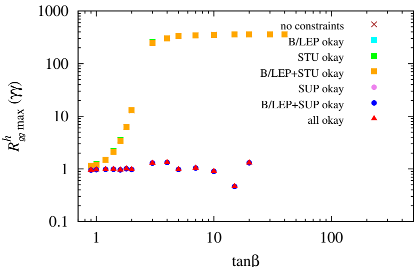
- h or H either lies at 125 GeV.

SUP **DECREASE** the $\gamma\gamma$ rate $R_Y^{h_i}(X) \equiv \frac{\sigma(Y\to h_i)\ \mathrm{BR}(h_i\to X)}{\sigma(Y\to h_{\rm SM})\ \mathrm{BR}(h_{\rm SM}\to X)}, h_i = h, H, A$



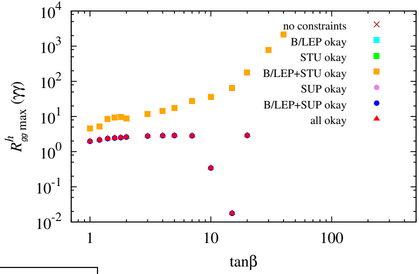
SUP **DECREASE** the $\gamma\gamma$ rate $R_Y^{h_i}(X) \equiv \frac{\sigma(Y \to h_i)\ \mathrm{BR}(h_i \to X)}{\sigma(Y \to h_{SM})\ \mathrm{BR}(h_{SM} \to X)}, h_i = h, H, A$

2HDM (typeI) m_h=125 GeV

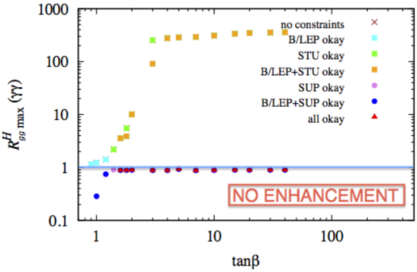


m_h = 125 GeV

2HDM (typeII) m_h=125 GeV

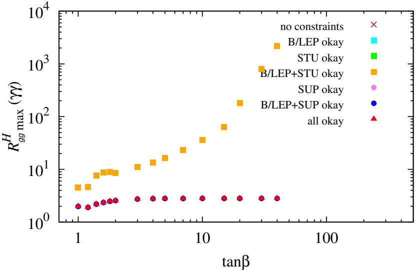


2HDM (typeI) m_H=125 GeV



m_H = 125 GeV

2HDM (typeII) m_H=125 GeV



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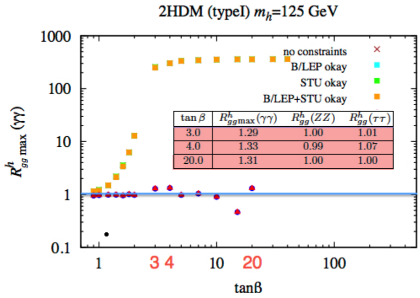
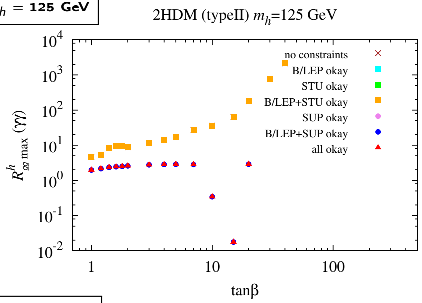
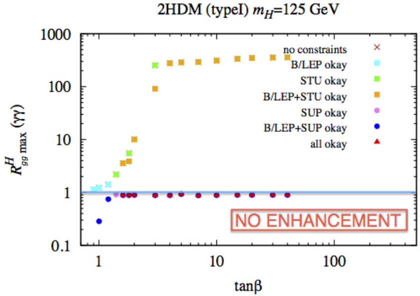


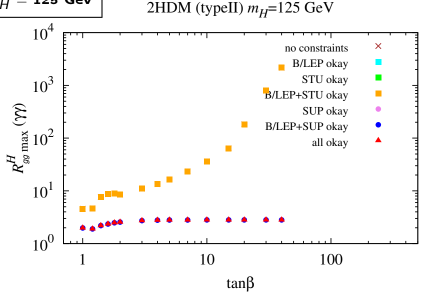
$\tan\beta$	$R^h_{gg\max}(\gamma\gamma)$	$R^h_{gg}(ZZ)$	$R^h_{gg}(\tau\tau)$
3.0	1.29	1.00	1.01
4.0	1.33	0.99	1.07
20.0	1.31	1.00	1.00

m_h = 125 GeV



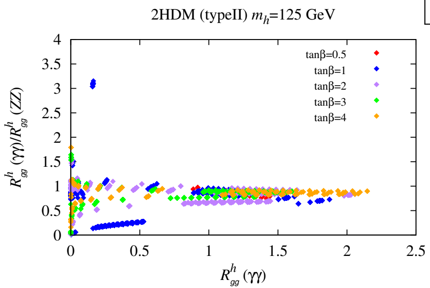


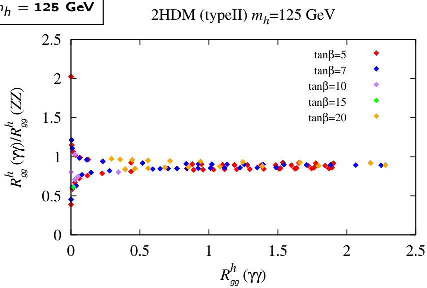
m_H = 125 GeV



$\gamma\gamma$ – ZZ rate correlation (Type II)

$m_h = 125$ GeV





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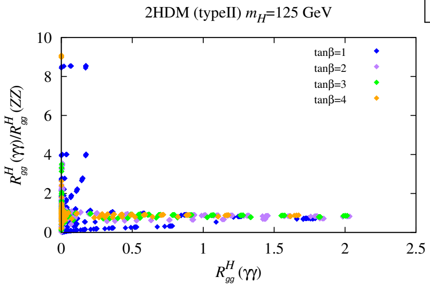
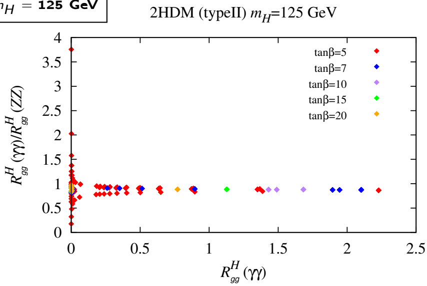




In the Type II models $R_{gg}(ZZ) > R_{gg}(\gamma\gamma)$. $R_{gg}(ZZ) < 2.6$ only plotted.

Is it possible that the excess in the Higgs $\to \gamma\gamma$ 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.

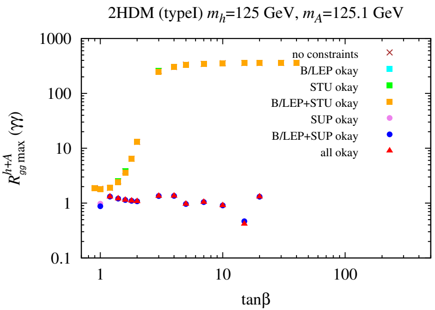
Degenerate Scalar Scenarios

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)

$m_h = 125$ GeV, $m_A \sim 125$ GeV



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

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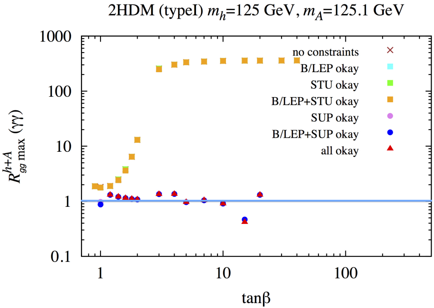
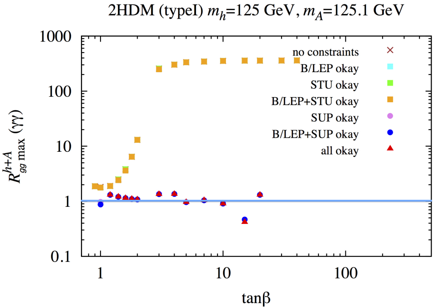


- $R^{h+A}_{gg}(\gamma\gamma)$ can be significantly enhanced.

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

$m_h = 125$ GeV, $m_A \sim 125$ GeV

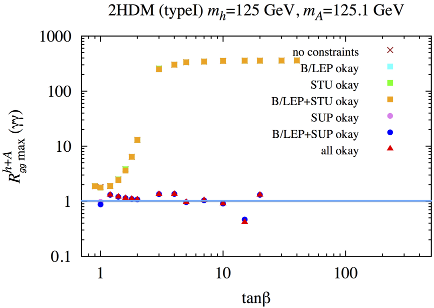


$\tan\beta$	$R^{h+A}_{gg\max}(\gamma\gamma)$	$R^{A}_{gg}(\gamma\gamma)$	$R^{h+A}_{gg}(ZZ)$	$R^{h+A}_{gg}(\tau\tau)$
1.2	1.31	0.41	1.02	3.35
1.4	1.21	0.30	0.99	2.61
1.6	1.14	0.23	1.01	2.32
1.8	1.10	0.18	1.00	1.98
2.0	1.08	0.15	0.98	1.73
3.0	1.34	0.06	1.00	1.31
4.0	1.35	0.03	0.99	1.21
7.0	1.04	0.01	0.99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

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

$m_h = 125$ GeV, $m_A \sim 125$ GeV



$\tan\beta$	$R^{h+A}_{gg\,max}(\gamma\gamma)$	$R^{A}_{gg}(\gamma\gamma)$	$R^{h+A}_{gg}(ZZ)$	$R^{h+A}_{gg}(\tau\tau)$
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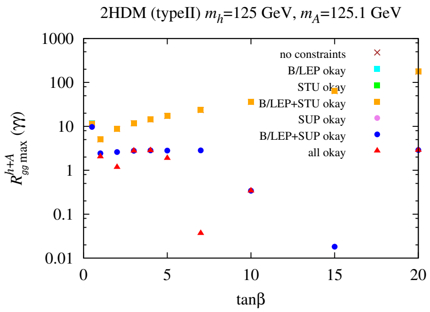
4.0	1.35	0.03	0.99	1.21
7.0	1.04	0.01	0.99	1.00
20.0	1.31	0.00	1.00	1.00

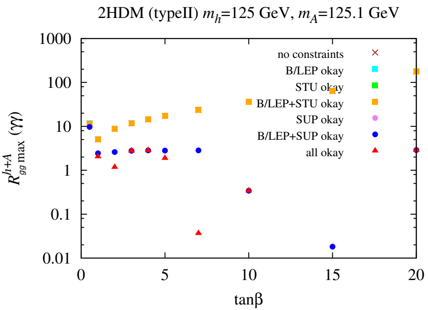
- $R^{h+A}_{gg}(\gamma\gamma)$ can be significantly enhanced.
- $R^{A}_{gg}(\gamma\gamma)$ turns out to be tiny at large $\tan\beta$.
- Large $\tau\tau$ rate at small $\tan\beta$ because of the A contribution.
- **Only** $\tan\beta = 20$, **both an enhanced** $\gamma\gamma$ **rate and SM-like** ZZ **and**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

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

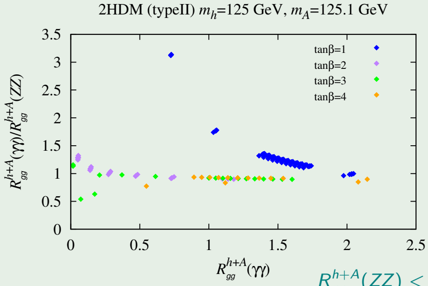


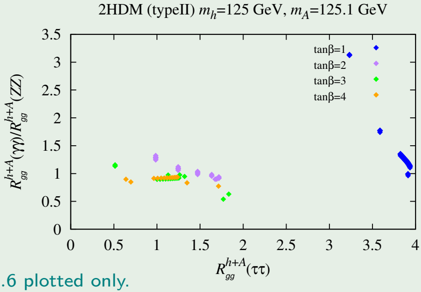
- Substantial enhancement in the $R_{gg}^{h+A}(\gamma\gamma)$ can be achieved.
- Mostly associated with $R_{gg}^{h+A}(ZZ) > R_{gg}^{h+A}(\gamma\gamma)$.
- The exception has large $\tau\tau$ rate.

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



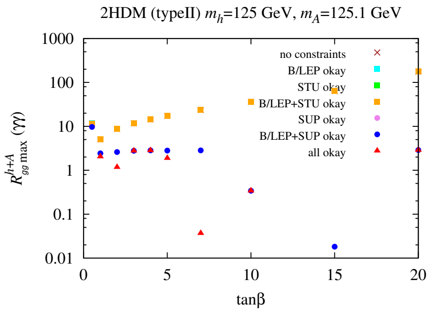
- Substantial enhancement in the $R^{h+A}_{gg}(\gamma\gamma)$ can be achieved.
- Mostly associated with $R^{h+A}_{gg}(ZZ) > R^{h+A}_{gg}(\gamma\gamma)$.
- The exception has large $\tau\tau$ rate.



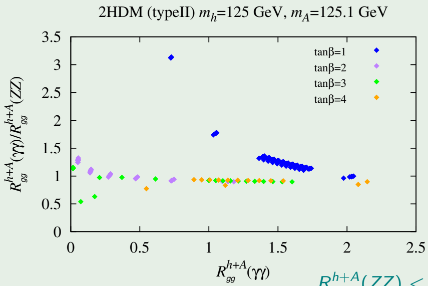


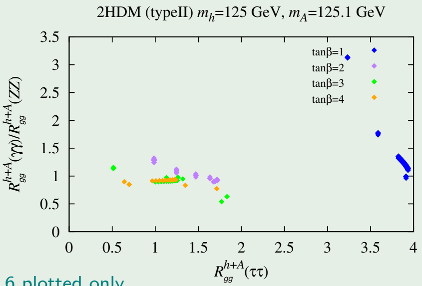
$R^{h+A}_{gg}(ZZ) < 2.6$ plotted only.

$\gamma\gamma$ 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.

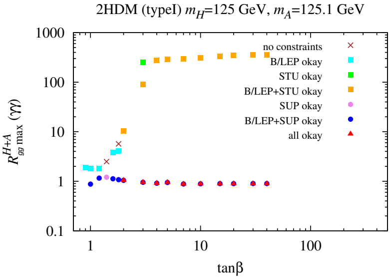


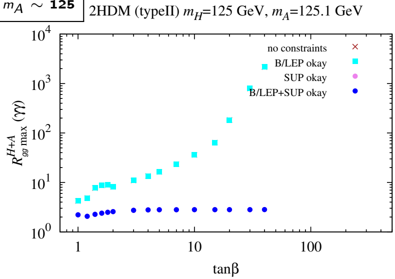


$R_{gg}^{h+A}(ZZ) < 2.6$ plotted only.

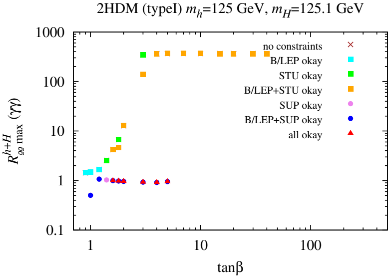
LESS ATTRACTIVE

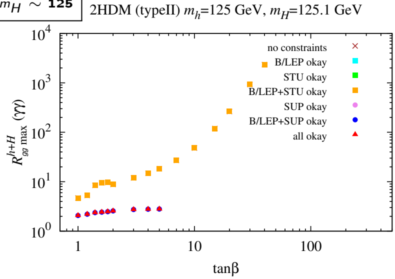
$m_H = \mathbf{125}$, $m_A \sim \mathbf{125}$





$m_h = \mathbf{125}$, $m_H \sim \mathbf{125}$





NO substantial $\gamma\gamma$ enhancement

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

Conclusions

- 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 **able** to give a significantly enhanced or SM-like $\gamma\gamma$ signal with the ZZ at the same order and a more or less SM-like $\tau\tau$ rates.

Future Work and Outlook

- But, if $R^h_{gg}(\gamma\gamma)$ 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 χ^2 technique to globally fit LHC data is working in progress.
- 2HDM+singlets with a dark matter candidate is also an natural extension that is studying in progress.

Thank you

To me, 2012 was a productive year.

It is just the start of my research career, wish your staying tuned.

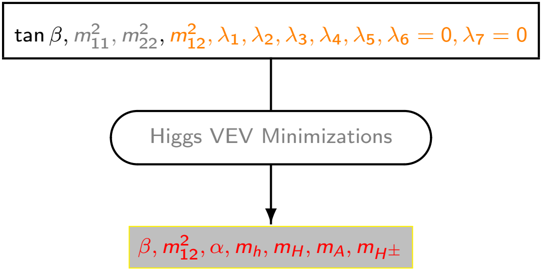
Back Up

2HDM: two complex doublets Φ_1 and Φ_2 ($Y = +1$)

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

$0 \le \beta \le \pi/2$, $-\pi/2 \le \alpha \le \pi/2$.

- 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,. . . ,1000}	125	125.1	125+{0.1,. . . ,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^2]	$\{-1000^2, \ldots, 1000^2\}$				

Type I single 125 Higgs

$m_H = 125$ GeV

$\tan\beta$	$R^H_{gg\max}(\gamma\gamma)$	$R^H_{gg}(ZZ)$	$R^H_{gg}(b\bar{b})$	$R^H_{\rm VBF}(\gamma\gamma)$	$R^H_{\rm VBF}(ZZ)$	$R^H_{\rm VBF}(b\bar{b})$	m_h	m_A	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$\mathcal{A}^H_{H^\pm}/\mathcal{A}$	δa_μ
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	10	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

NO ENHANCEMENT

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

$m_h = 125$ GeV

	$\tan\beta$	$R^h_{gg\max}(\gamma\gamma)$	$R^h_{gg}(ZZ)$	$R^h_{gg}(b\bar{b})$	$R^h_{\rm VBF}(\gamma\gamma)$	$R^h_{\rm VBF}(ZZ)$	$R^h_{\rm VBF}(b\bar{b})$	m_H	m_A	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$\mathcal{A}^h_{H^\pm}/\mathcal{A}$	δa_μ
	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
SMALL	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
LARGE	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

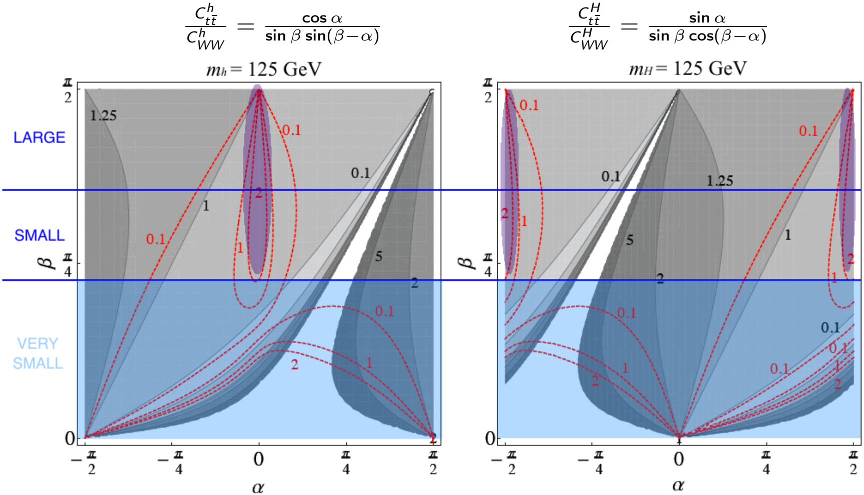
$$r_s \equiv \frac{R^s_{gg}(\gamma\gamma)}{R^s_{gg}(ZZ)} = \frac{\Gamma(s \to \gamma\gamma)/\Gamma(h_{SM} \to \gamma\gamma)}{\Gamma(s \to ZZ)/\Gamma(h_{SM} \to ZZ)}$$

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

$$\boxed{r_s < 1 \Longrightarrow 1 < \frac{C^s_{t\bar{t}}}{C^s_{WW}} < 2\frac{\mathcal{A}^{SM}_W}{\mathcal{A}^{SM}_t} - 1 \simeq 9}$$

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

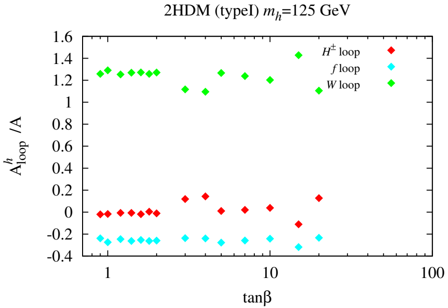
$\gamma\gamma - ZZ$ Correlation Analysis

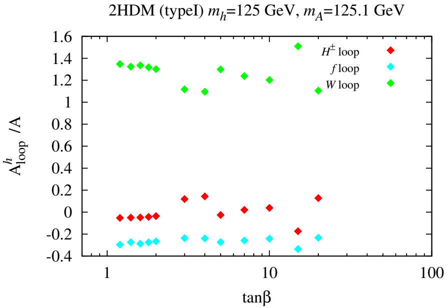


Red numbers give values of $R^s_{gg}(\gamma\gamma)$ while black ones show constant r_s values.

The white region correspond to $r_s > 10.75$.

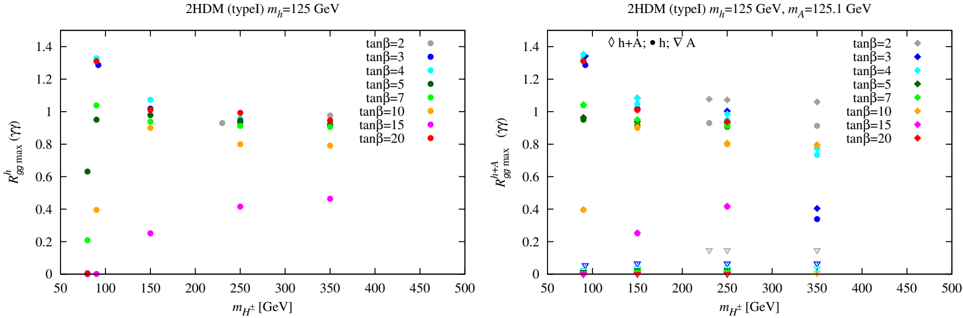
$\gamma\gamma$ enhancement mechanism in the Type I





- At the $\tan\beta = 3, 4, 20$, the relative charged Higgs contribution reaches nearly ~ 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 ...