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

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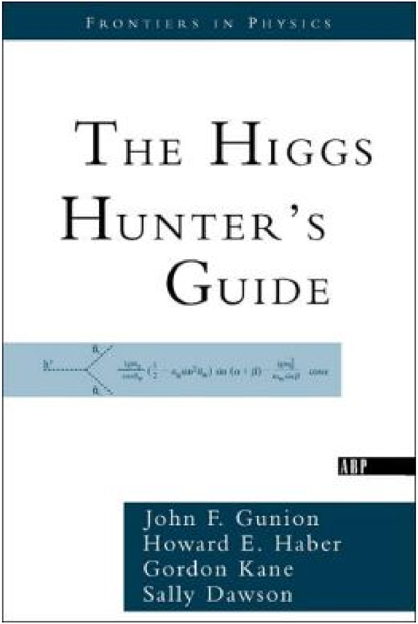
03/27/2013

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- A little bit out of date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

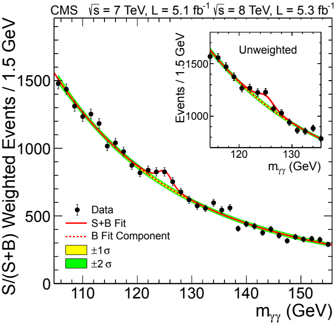
天哪！这真是“上帝粒子”吗？

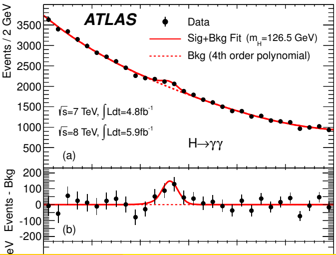
欧洲核子中心激动宣布可能发现希格斯－玻色子：“我们对宇宙的理解，将要改变！”

网友围观：好像很牛 但是不懂

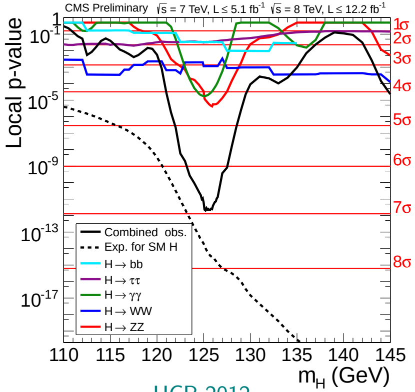
83岁希格斯：未想过有生之年等到

“这该死的粒子！”

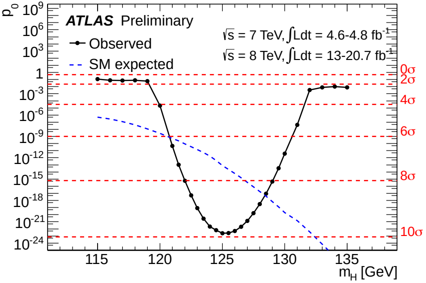




ATLAS updated the local p-values at the Moriond 2013.



HCP-2012



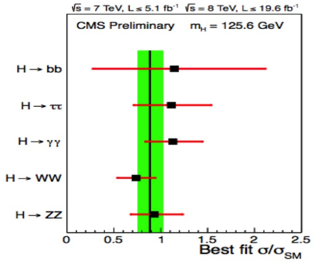
ATLAS-CONF-2013-034

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

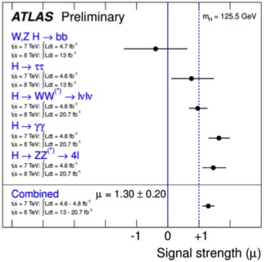
With the new data, “Seeing is believing” !

125 GeV Higgs-like signal at the Moriond 2013 QCD

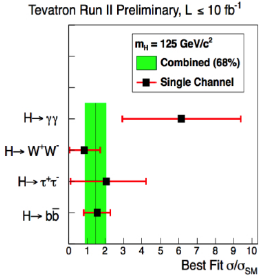
LPSC workshop



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?

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

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

2HDM Higgs sector

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]$$
$$+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$
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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 $\xi = 0$.

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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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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	$\Phi_1 \to -\Phi_1, d^i_R \to -d^i_R$

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

	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, $|\Lambda_i| < 4\pi$.

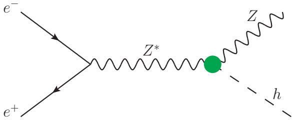
- Experimentally,
  1. Precision electroweak constraints (denoted STU).

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

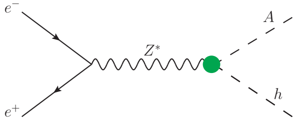
  2. LEP constraints on Higgs mass limits.
  3. B-physics constraints.
  4. the anomalous magnetic moment of the muon $\delta a_\mu \equiv (g-2)_\mu^{\mathbf{BSM}}$ (IGNORED).

Basic Constraints – LEP

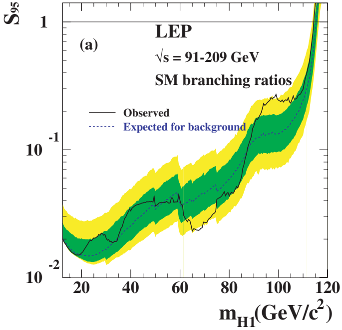
LEP constraints on Higgs mass limits

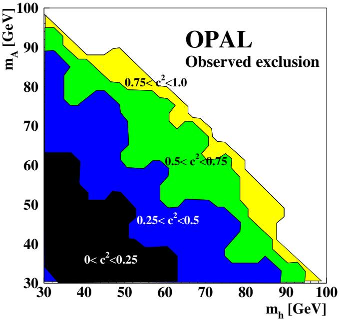


$$\frac{\sigma(e^+e^- \to Z\, h)}{\sigma(e^+e^- \to Z\, h_{\rm SM})} \sim \sin^2(\alpha - \beta)$$



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

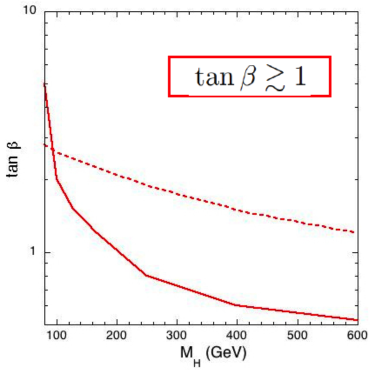




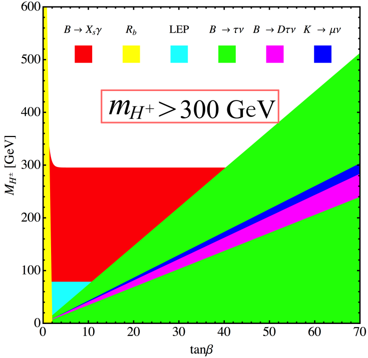
Basic Constraints – B-physics

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



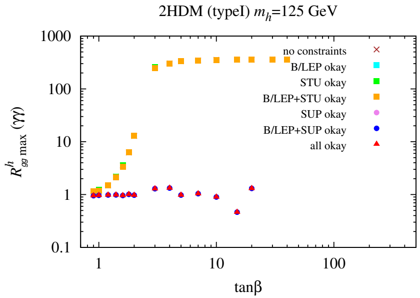
Solid: R_b for $Z \to b\bar{b}$, ϵ_K and Δm_{B_s}
Dash: $\bar{B} \to X_s\gamma$ in models with FCNC

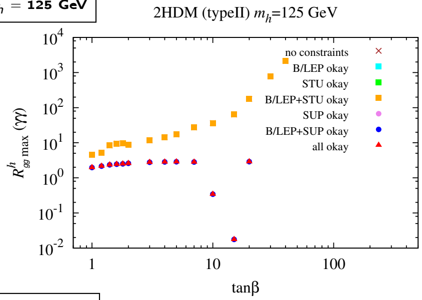
Single Scalar Scenarios

- h or H either lies at 125 GeV.

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

$m_h = \mathbf{125\ GeV}$





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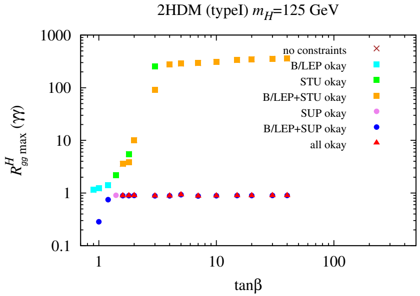

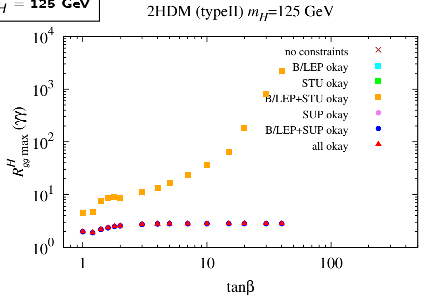

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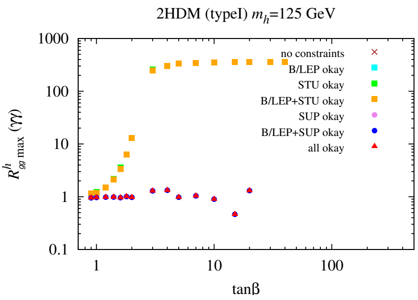
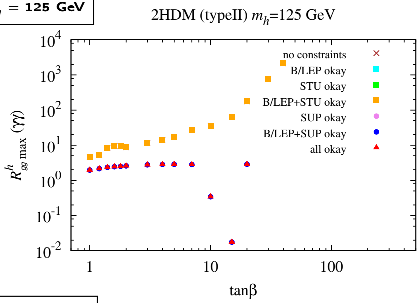
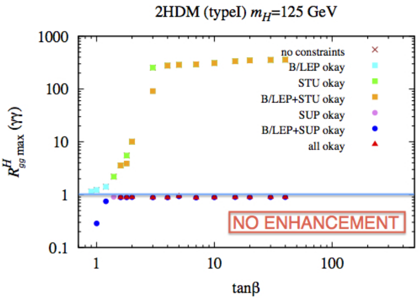
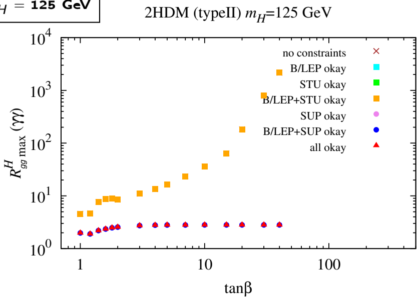
m_h = **125 GeV**





m_H = **125 GeV**





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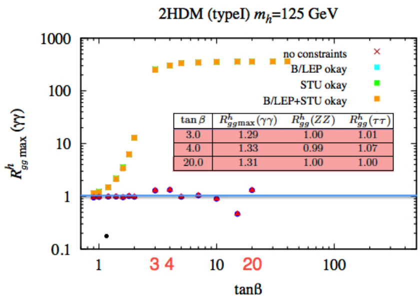
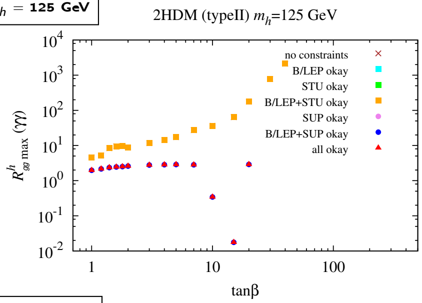
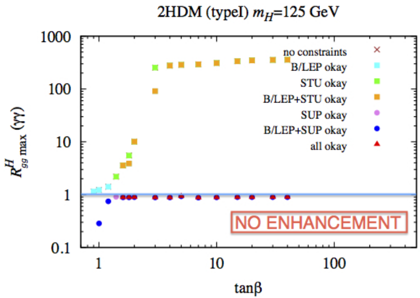
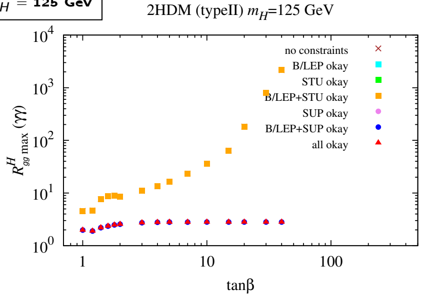


m_h = 125 GeV

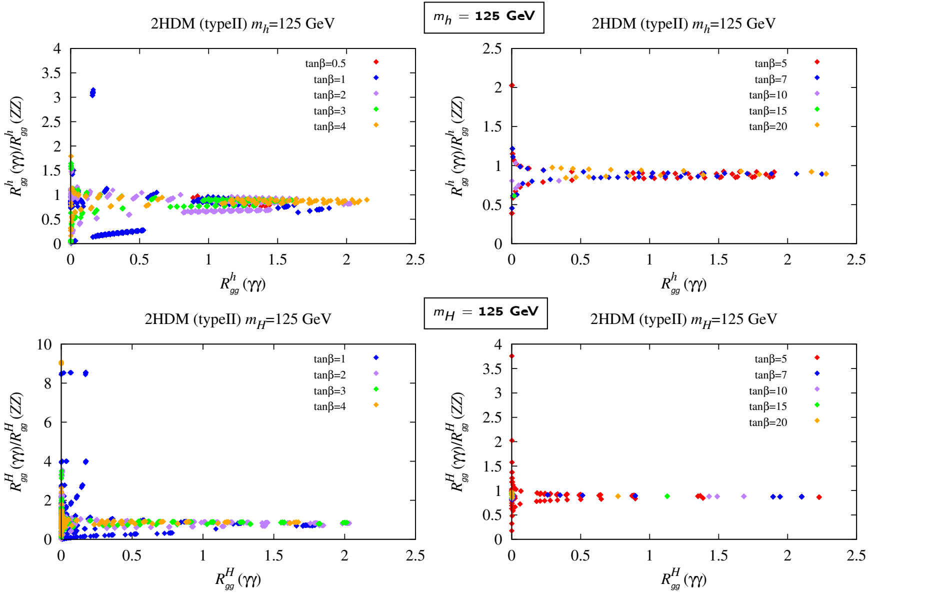




m_H = 125 GeV



$\gamma\gamma$ – 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 $\to \gamma\gamma$ 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.

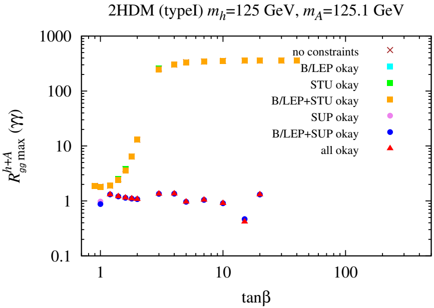
Degenerate Scalar Scenarios

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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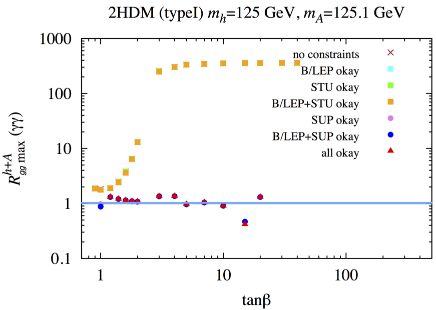
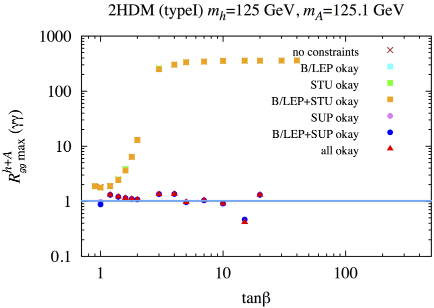


- $R^{h+A}_{gg}(\gamma\gamma)$ can be significantly enhanced.

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

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

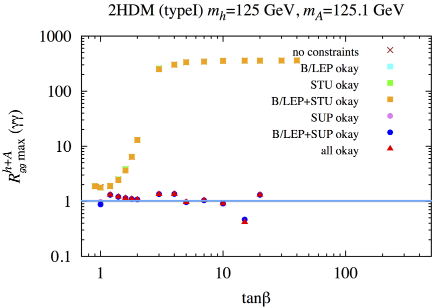


$\tan\beta$	$R^{h+A}_{gg\max}(\gamma\gamma)$	$R^{A}_{gg}(\gamma\gamma)$	$R^{h+A}_{gg}(ZZ)$	$R^{h+A}_{gg}(\tau\tau)$
1.2	1.31	0.41	1.02	3.35
1.4	1.21	0.30	0.99	2.61
1.6	1.14	0.23	1.01	2.32
1.8	1.10	0.18	1.00	1.98
2.0	1.08	0.15	0.98	1.73
3.0	1.34	0.06	1.00	1.31
4.0	1.35	0.03	0.99	1.21
7.0	1.04	0.01	0.99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



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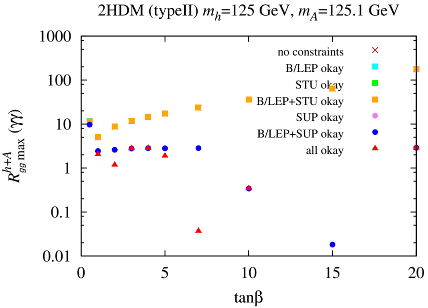
20.0	1.31	0.00	1.00	1.00

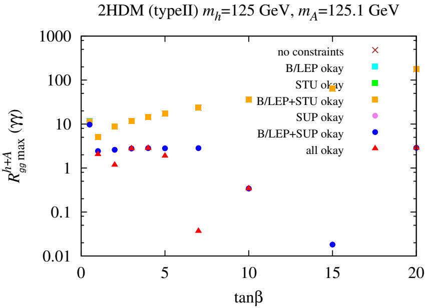
- $R^{h+A}_{gg}(\gamma\gamma)$ can be significantly enhanced.
- $R^{A}_{gg}(\gamma\gamma)$ turns out to be tiny at large $\tan\beta$.
- Large $\tau\tau$ rate at small $\tan\beta$ because of the A contribution.
- **Only** $\tan\beta = 20$, **both an enhanced** $\gamma\gamma$ **rate and SM-like** ZZ **and**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



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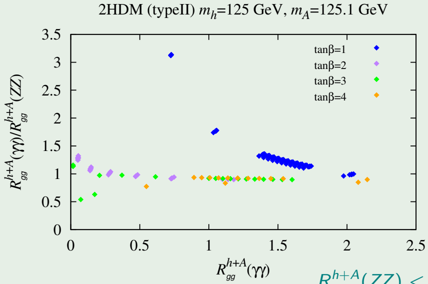
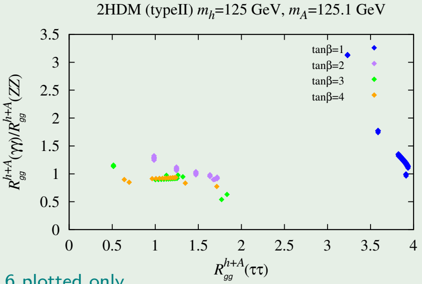
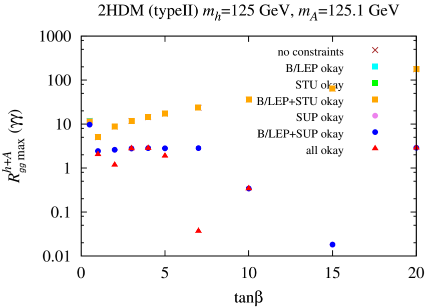




$R_{gg}^{h+A}(ZZ) < 2.6$ plotted only.



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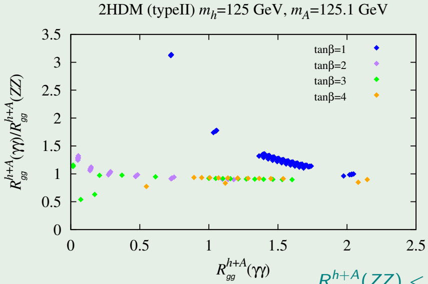
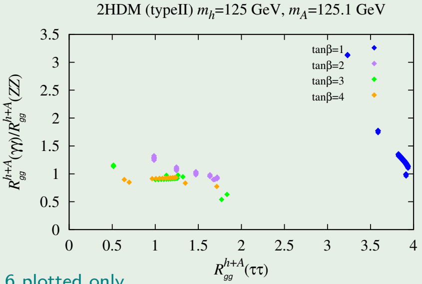


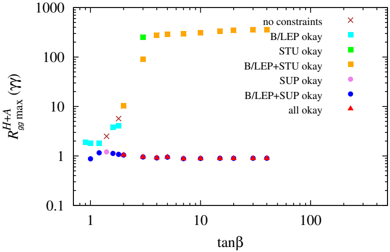


$R_{gg}^{h+A}(ZZ) < 2.6$ plotted only.

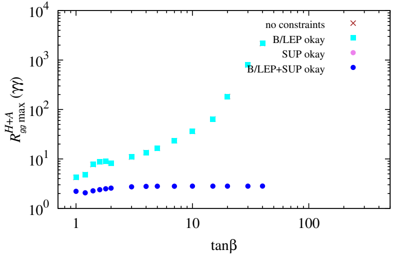
LESS ATTRACTIVE

$m_H = 125$, $m_A \sim 125$

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

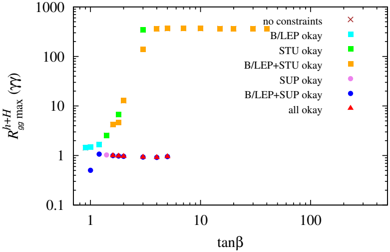


2HDM (typeII) m_H=125 GeV, m_A=125.1 GeV

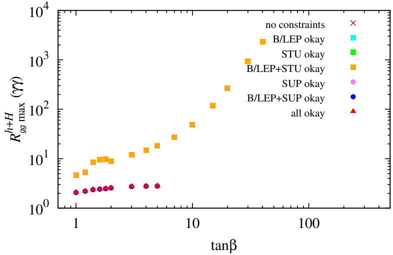


$m_h = 125$, $m_H \sim 125$

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



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



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 **unable** is able to give a significantly enhanced $\gamma\gamma$ 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.

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 Φ_1 and Φ_2 $(Y = +1)$

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

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

- Free independent parameter set

$\tan\beta, m_{11}^2, m_{22}^2, m_{12}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6 = 0, \lambda_7 = 0$

↓

Higgs VEV Minimizations

↓

$\beta, m_{12}^2, \alpha, m_h, m_H, m_A, m_{H^\pm}$

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	$\{10, \ldots, 124.9\}$	125	125	$\{10, \ldots, 124.9\}$
m_H [GeV]	$125+\{0.1, \ldots, 1000\}$	125	125.1	$125+\{0.1, \ldots, 1000\}$	125
m_A [GeV]	$\{10, \ldots, 1000\}$	$\{10, \ldots, 1000\}$	$\{10, \ldots, 1000\}$	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				
$\tan\beta$	$\{0.5, \ldots, 20\}$				
$\sin\alpha$	$\{-1, \ldots, 1\}$				
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

SMALL: $\tan\beta$ = 0.9 to 2.0; LARGE: $\tan\beta$ = 3.0 to 20.0

$\tan\beta$	$R^h_{gg\max}(\gamma\gamma)$	$R^h_{gg}(ZZ)$	$R^h_{gg}(b\bar{b})$	$R^h_{\rm VBF}(\gamma\gamma)$	$R^h_{\rm VBF}(ZZ)$	$R^h_{\rm VBF}(b\bar{b})$	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
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

$\gamma\gamma - ZZ$ Correlation Analysis

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

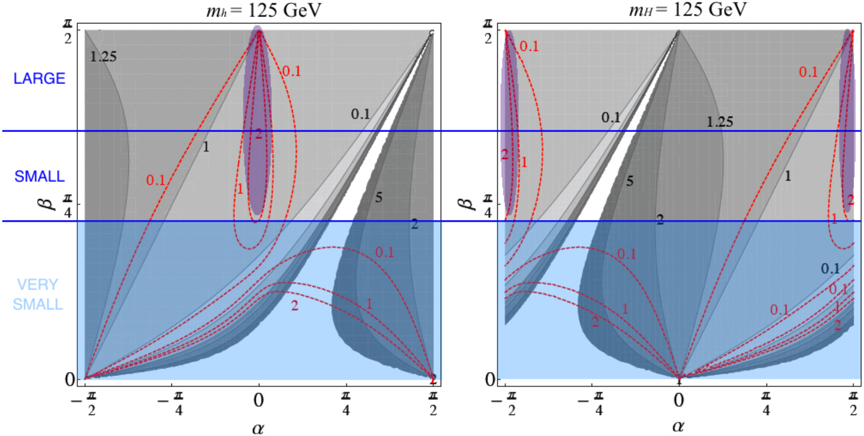
$$r_s \simeq \frac{(C^s_{WW})^2}{(C^s_{ZZ})^2} \left(\frac{\mathcal{A}^{SM}_W - \frac{C^s_{t\bar{t}}}{C^s_{WW}} \mathcal{A}^{SM}_t + \mathcal{A}_{H^\pm}\,\text{term}}{\mathcal{A}^{SM}_W - \mathcal{A}^{SM}_t} \right)^2 = \left(\frac{\mathcal{A}^{SM}_W - \frac{C^s_{t\bar{t}}}{C^s_{WW}} \mathcal{A}^{SM}_t}{\mathcal{A}^{SM}_W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

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

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

$\gamma\gamma - ZZ$ Correlation Analysis

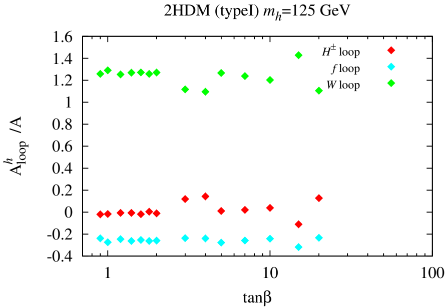
$$\frac{C^h_{t\bar{t}}}{C^h_{WW}} = \frac{\cos\alpha}{\sin\beta\,\sin(\beta-\alpha)} \qquad \frac{C^H_{t\bar{t}}}{C^H_{WW}} = \frac{\sin\alpha}{\sin\beta\,\cos(\beta-\alpha)}$$

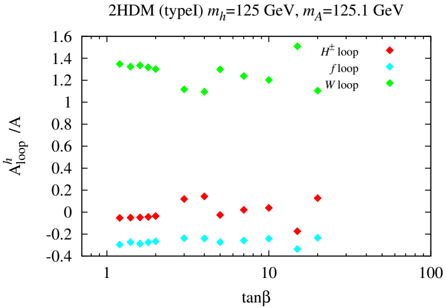


Red numbers give values of $R^s_{gg}(\gamma\gamma)$ while black ones show constant r_s values.

The white region correspond to $r_s > 10.75$.

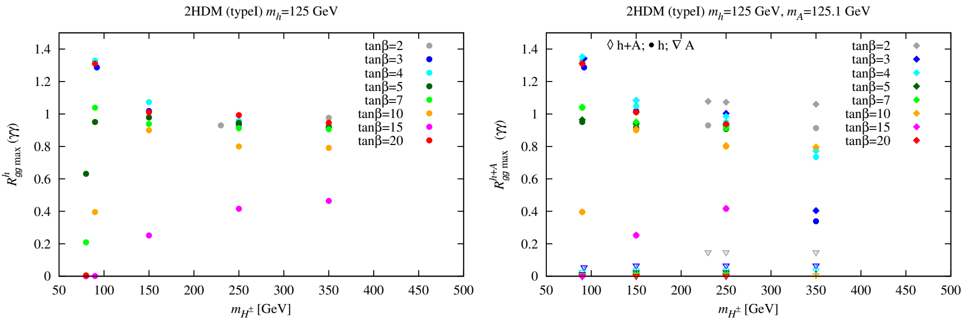
$\gamma\gamma$ enhancement mechanism in the Type I





- 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 ...