125 GeV Scalar Bosons in 2 Doublet Models (2DMs)

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EW Interactions and Unified Theories session
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- A. Drozd, B. Grzadkowski, J. F. Gunion and YJ, *Two-Higgs-Doublet Models and Enhanced Rates for a 125 GeV Higgs*, arXiv:1211.3580[hep-ph].

What is the nature of 125 GeV state observed at the LHC?

- a substantial excess in the di-photon final state
- a more or less SM-like rate in the $ZZ \to 4\ell$ channel
- ......

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

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

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The models we studied

1. Type I and Type II models: tree level FCNC are completely absent.
2. NO explicit $\mathcal{CP}$ violation
3. NO spontaneous $\mathcal{CP}$ breaking

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$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]$$
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5. 2 CP-even neutral scalars: h, H
   1 CP-odd neutral pseudoscalar: A
   2 charged scalars: $H^\pm$

Basic Constraints

- Theoretically, (denoted jointly as SUP)
  1. **Vacuum stability**
  2. **Unitarity**
  3. **Perturbativity**

- 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).

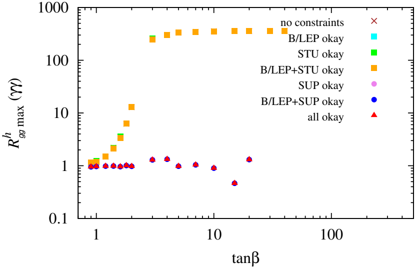
Single Scalar Scenarios

- h or H either lies at 125 GeV.

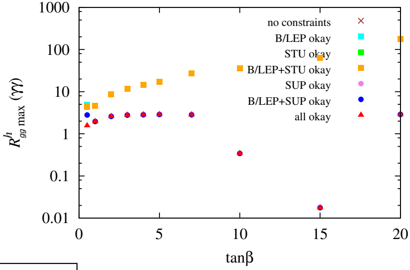
SUP **DECREASE** the $\gamma\gamma$ rate $R_Y^{h_i}(X) \equiv \frac{\sigma(Y\to h_i)\ \mathrm{BR}(h_i\to X)}{\sigma(Y\to h_{\mathrm{SM}})\ \mathrm{BR}(h_{\mathrm{SM}}\to X)}, h_i = h, H, A$

$m_h = 125$ GeV

2HDM (typeI) m_h=125 GeV



2HDM (typeII) m_h=125 GeV



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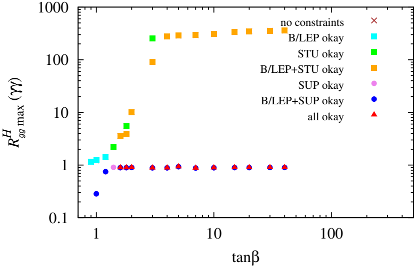
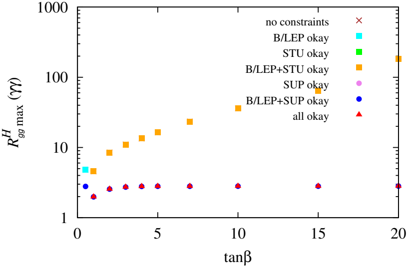


2HDM (typeII) m_H=125 GeV



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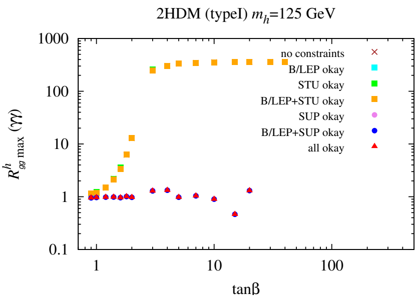

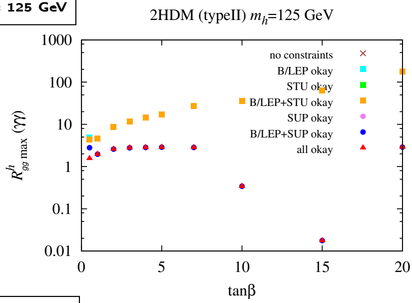

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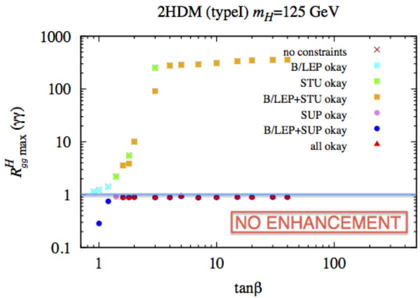

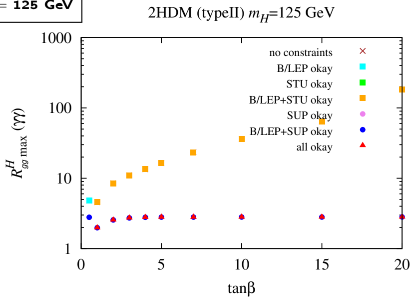

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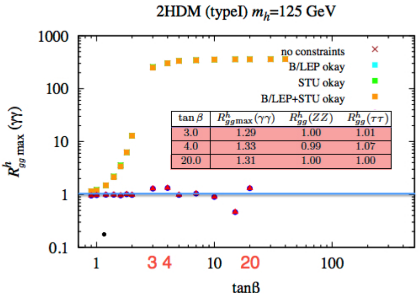
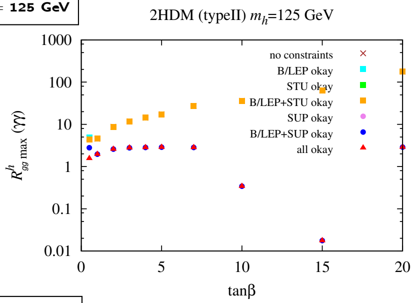
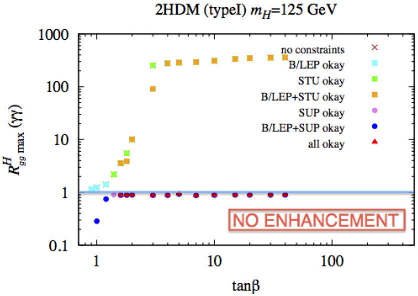


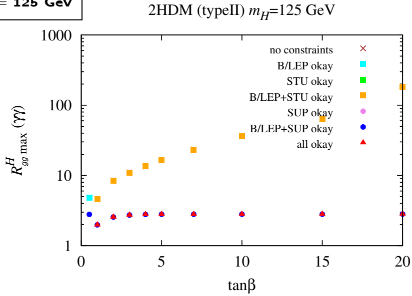
$\tan\beta$	$R^h_{gg\max}(\gamma\gamma)$	$R^h_{gg}(ZZ)$	$R^h_{gg}(\tau\tau)$
3.0	1.29	1.00	1.01
4.0	1.33	0.99	1.07
20.0	1.31	1.00	1.00

m_h = **125 GeV**





m_H = **125 GeV**

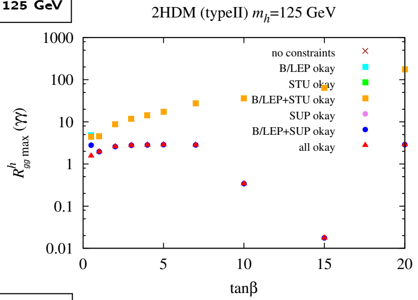


SUP **DECREASE** the maximum $\gamma\gamma$ rate (Type II)

m_h = **125 GeV**

$\tan\beta$	$R^h_{gg\max}(\gamma\gamma)$	$R^h_{gg}(ZZ)$	$R^h_{gg}(\tau\tau)$	R^h_{VBF}	
0.5	1.56	2.69	1.84	0.52	
1.0	1.97	3.36	0.39	0.65	
2.0	2.59	3.36	0.00	1.48	
3.0	2.78	3.29	0.00	2.01	
4.0	2.84	3.25	0.00	2.24	
5.0	2.87	3.23	0.00	2.37	
7.0	2.83	3.21	0.00	2.42	
10.0	0.34	0.43	1.89	0.22	
15.0	0.02	0.03	4.06	0.00	0.0
20.0	2.89	3.19	0.00	2.57	2.8

TABLE IV: Table of maximum $R^h_{gg}(\gamma\gamma)$ values for the Type I
initial and/or final states. The input parameters that give the



m_H = **125 GeV**

$\tan\beta$	$R^H_{gg\max}(\gamma\gamma)$	$R^H_{gg}(ZZ)$	$R^H_{gg}(\tau\tau)$	R^H_{V}
1.0	1.99	3.24	0.52	0.
2.0	2.56	3.36	0.00	1.4
3.0	2.73	3.29	0.00	1.97
4.0	2.78	3.25	0.00	2.20
5.0	2.81	3.23	0.00	2.32
7.0	2.80	3.21	0.00	2.40
10.0	2.81	3.20	0.00	2.46
15.0	2.82	3.19	0.00	2.49
20.0	2.82	3.19	0.00	2.50

TABLE VI: Table of maximum $R^H_{gg}(\gamma\gamma)$ values for the Ty
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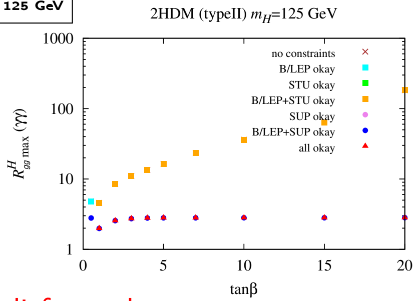

seems to be disfavored

Degenerate Scalar Scenarios

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.

- h and A both lie at the 125 GeV mass.
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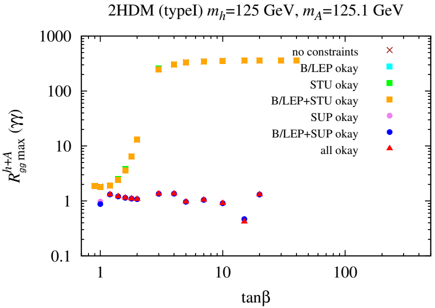
$\gamma\gamma$ Enhancement achieved (Type I)

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



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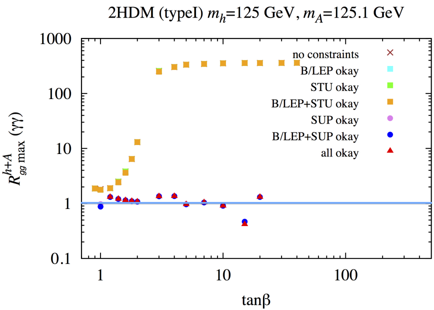

- $R^{h+A}_{gg}(\gamma\gamma)$ can be significantly enhanced.

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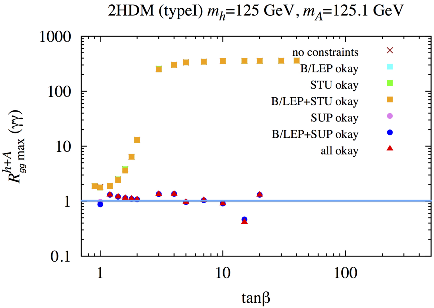

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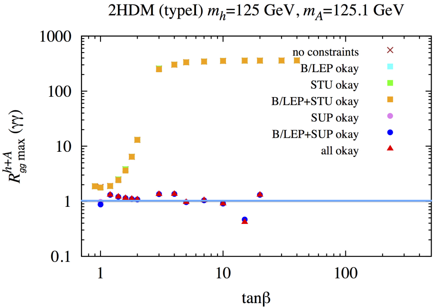
1.2	1.31	0.41	1.02	3.35
1.4	1.21	0.30	0.99	2.61
1.6	1.14	0.23	1.01	2.32
1.8	1.10	0.18	1.00	1.98
2.0	1.08	0.15	0.98	1.73
3.0	1.34	0.06	1.00	1.31
4.0	1.35	0.03	0.99	1.21
7.0	1.04	0.01	0.99	1.00
20.0	1.31	0.00	1.00	1.00

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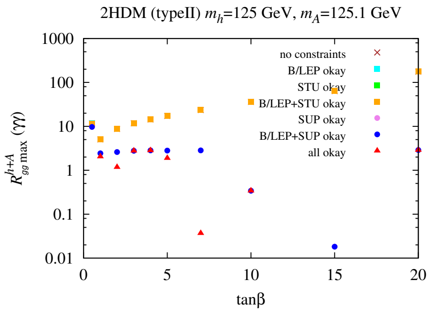
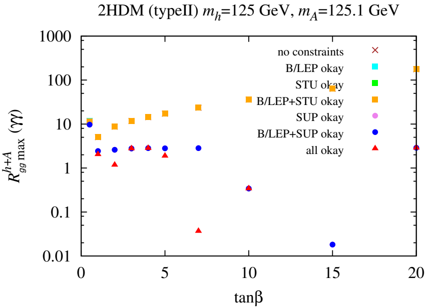
- $R^{h+A}_{gg}(\gamma\gamma)$ can be significantly enhanced.
- $R^{A}_{gg}(\gamma\gamma)$ turns out to be tiny at large $\tan\beta$.
- Large $\tau\tau$ rate at small $\tan\beta$ because of the A contribution.
- **Only** $\tan\beta = 20$, **both an enhanced** $\gamma\gamma$ **rate and SM-like** ZZ **and**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

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



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



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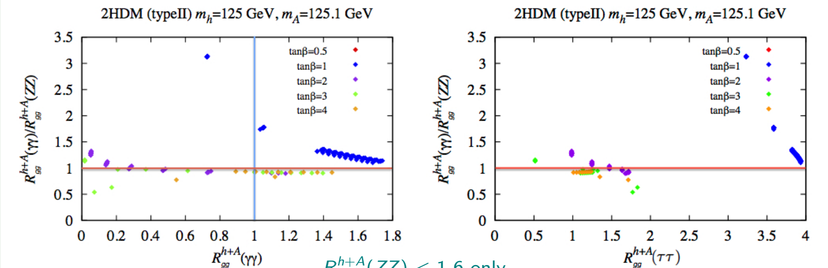
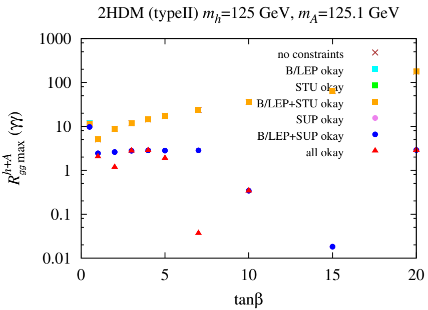


$R_{gg}^{h+A}(ZZ) < 1.6$ only

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



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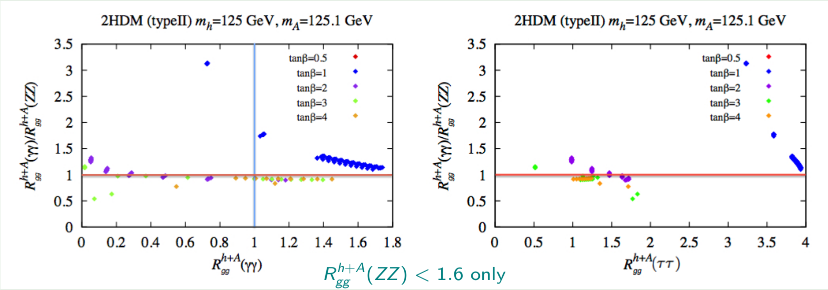

$R_{gg}^{h+A}(ZZ) < 1.6$ only

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 II model is **unable** to give a significantly enhanced $\gamma\gamma$ signal while maintaining the SM-like ZZ and $\tau\tau$ rates.
  3. The Type I model **could** provide a consistent picture if the LHC results converge to only a modest enhancement for $R^h_{gg}(\gamma\gamma) \lesssim 1.4$.

Thank you

Thanks to Prof. Gunion for his patient guidance and help,
and strong recommendations for my US NSF 2013 LHC-TI Fellowship application.

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

Back Up

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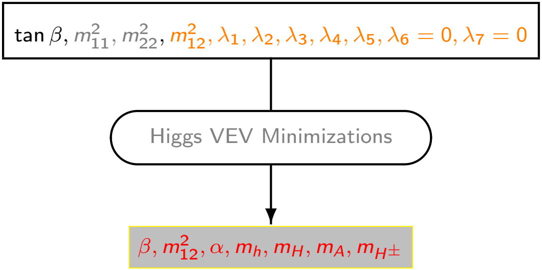
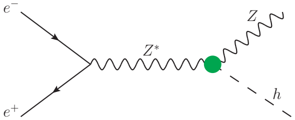
$0 \le \beta \le \pi/2$, $-\pi/2 \le \alpha \le \pi/2$.

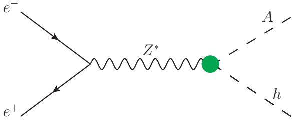
- Free independent parameter set



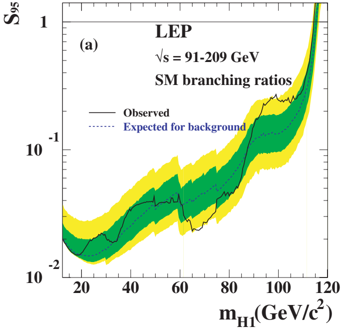
LEP constraints on Higgs mass limits

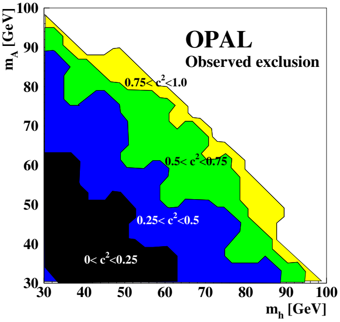


$$\frac{\sigma(e^+e^- \to Z\, h)}{\sigma(e^+e^- \to Z\, h_{\rm SM})} \sim \sin^2(\alpha - \beta)$$



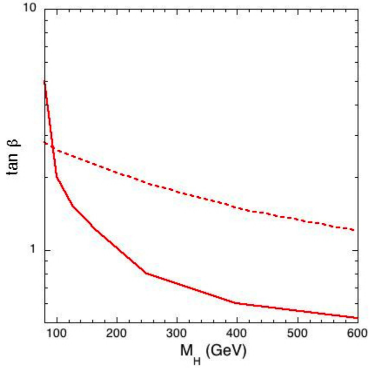
$$\frac{\sigma(e^+e^- \to A\, h)}{\sigma(e^+e^- \to Z\, h_{\rm SM})} \sim \cos^2(\alpha - \beta)$$



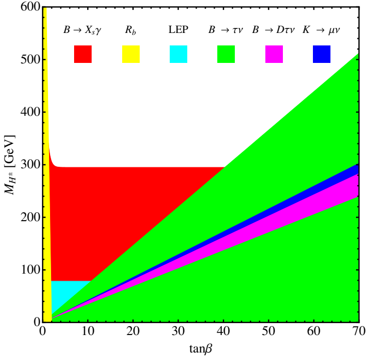


B-physics constraints ($\mathrm{BR}(B_s \to X_s\gamma)$, R_b, ΔM_{B_s}, ϵ_K, $\mathrm{BR}(B^+ \to \tau^+\nu_\tau)$ and $\mathrm{BR}(B^+ \to D\tau^+\nu_\tau)$): set up lower bound on $m_{H^\pm}$.

Type I



Type II

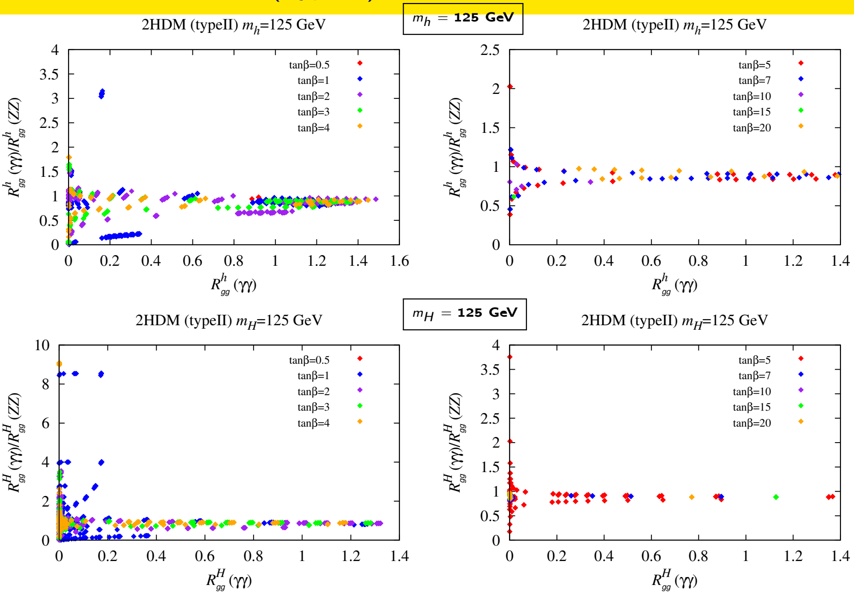


Solid: R_b for $Z \to b\bar{b}$, ϵ_K and Δm_{B_s}
Dash: $\bar{B} \to X_s\gamma$ in models with FCNC

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]	$\{-1000^2, \ldots, 1000^2\}$				

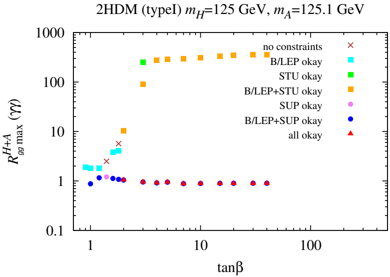
$\gamma\gamma$ – ZZ rate correlation (Type II)

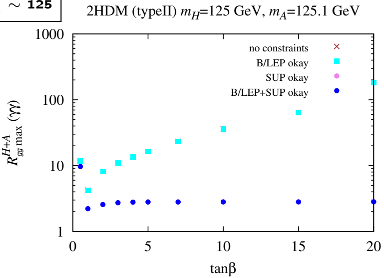


In the Type II models $R_{gg}(ZZ) > R_{gg}(\gamma\gamma)$. $\Longrightarrow$ They seems to be disfavored.

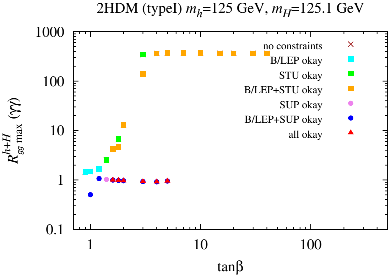
LESS ATTRACTIVE

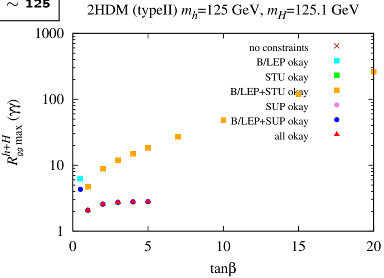
$m_H = 125$, $m_A \sim 125$





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





NO substantial $\gamma\gamma$ enhancement

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