Two-Higgs-Doublet Models and Enhanced Rates for a 125 GeV Higgs.

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Outline:

- what is 2HDM?
- 2HDM - setup of the analysis
  - constraints on the model (theoretical and experimental)
  - different mass hierarchy scenarios
- results and conclusions

- A. Drozd, B. Grządkowski, J. Gunion, Y. Jiang, arXiv:1211.3580 Two-Higgs-Doublet Models and Enhanced Rates for a 125 GeV Higgs
- Ferreira, Santos, Sher, Silva, Haber and others

The general Higgs sector potential:

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

$$\Phi_a = \begin{pmatrix} \varphi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix} \qquad a = 1, 2$$

where $v_1 = v\cos\beta$, $v_2 = v\sin\beta$, $v \approx 246$ GeV, $0 \leqslant \beta \leqslant \pi/2$

Neutral physical states: $(-\pi/2 \leqslant \alpha \leqslant \pi/2)$

$$h = -\rho_1\sin\alpha + \rho_2\cos\alpha, \qquad H = \rho_1\cos\alpha + \rho_2\sin\alpha$$

$$A = -\eta_1\sin\beta + \eta_2\cos\beta$$

Lagrangian Yukawa:

$$\mathcal{L}_{\mathrm{Y}}^{(\mathrm{q})} = \bar{\mathrm{Q}}_{\mathrm{L}} \tilde{\Gamma}_1 \mathrm{u}_{\mathrm{R}} \tilde{\Phi}_1 + \bar{\mathrm{Q}}_{\mathrm{L}} \Gamma_1 \mathrm{d}_{\mathrm{R}} \Phi_1 + \bar{\mathrm{Q}}_{\mathrm{L}} \tilde{\Gamma}_2 \mathrm{u}_{\mathrm{R}} \tilde{\Phi}_2 + \bar{\mathrm{Q}}_{\mathrm{L}} \Gamma_2 \mathrm{d}_{\mathrm{R}} \Phi_2 + \mathrm{h.c.}$$

and

$$\mathrm{M}_{\mathrm{u}} = -\tilde{\Gamma}_1 < \tilde{\Phi}_1 > -\tilde{\Gamma}_2 < \tilde{\Phi}_2 >, \quad \mathrm{M}_{\mathrm{d}} = -\Gamma_1 < \Phi_1 > -\Gamma_2 < \Phi_2 >$$

- Type I: $\Phi_1 \to -\Phi_1$, $\lambda_6 = \lambda_7 = 0$
  (Z_2 softly broken by $m_{12}^2 \neq 0$)
- Type II: $\Phi_1 \to -\Phi_1$ and $d_R \to -d_R$, $\lambda_6 = \lambda_7 = 0$
  (Z_2 softly broken by $m_{12}^2 \neq 0$)

Parameters

- 7 parameters in scalar potential, multiple possible basis

General basis:

- $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$
- m_{12}^2, $\mathrm{tg}\,\beta$

Physical basis:

- $m_h, m_H, m_A, m_{H^\pm}, \sin(\beta - \alpha)$
- m_{12}^2, $\mathrm{tg}\,\beta$

- 2 types of Yukawa interaction

Constraints

Theoretical Constraints (SUP):

- tree level vacuum Stability

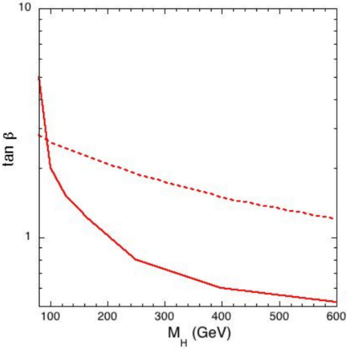
  $$\lambda_1, \lambda_2 > 0 \qquad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}$$

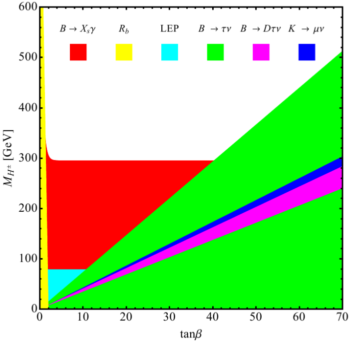
  $$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2} \text{ (when } \lambda_6 = \lambda_7 = 0)$$

- perturbative Unitarity $|\mathrm{L_i}| < 8\pi$
- Perturbativity $|\mathrm{C_{h_j h_j h_k h_l}}| < 4\pi$

Experimental Constraints:

- precision electroweak data: S,T,U constraints
- bounds in the $(m_{H^\pm}, \mathrm{tg}\,\beta)$ plane from various B-physics constraints for the type I/II (0805.2141, 1006.0470, 0912.0267)



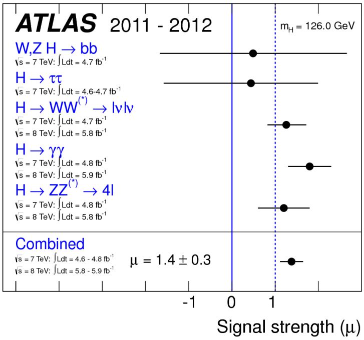


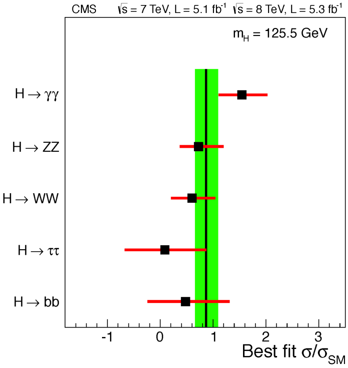
LEFT: solid line: bounds from $Z \to b\bar{b}$, ϵ_K, Δ_{B_s}; dashed: bounds from $B \to \gamma X_s$
RIGHT: bounds from various B-physics constraints for the typeII model

LHC signal normalized to SM predictions

$$R^{h_i}_{gg}(X) \equiv (C^{h_i}_{gg})^2 \, \frac{BR(h_i \to X)}{BR(h_{SM} \to X)}, \quad R^{h_i}_{VBF}(X) \equiv (C^{h_i}_{WW})^2 \, \frac{BR(h_i \to X)}{BR(h_{SM} \to X)}$$

$C^{h_i}_{gg}, C^{h_i}_{WW}$ are ratios of $gg \to h_i$, $WW \to h_i$ couplings to the SM





Input parameters:

- model type (I or II)
- physical masses $(m_h, m_H, m_A, m_{H^\pm})$
- $\text{tg}\,\beta$
- m_{12}^2

2HDMC code:

D. Eriksson, J. Rathsman and O. Stal,
Comput. Phys. Commun. 181, 189 (2010), arXiv:0902.0851

Different Possible Scenarios:

I. $m_h \simeq 125\text{GeV}$

II. $m_H \simeq 125\text{GeV}$

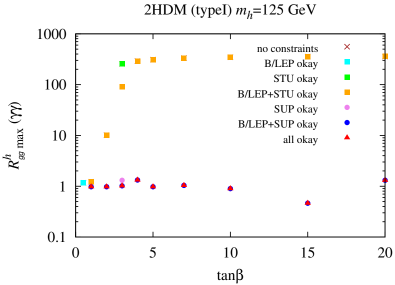
III. $m_h \simeq m_H \simeq 125\text{GeV}$

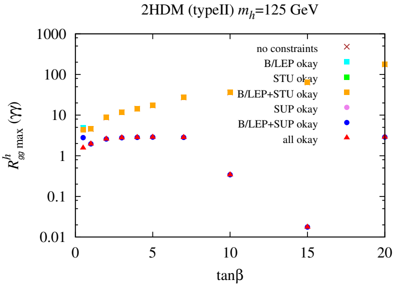
IV. $m_h \simeq m_A \simeq 125\text{GeV}$

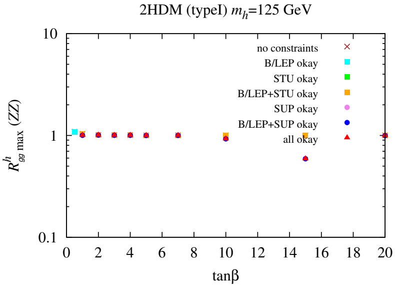
V. $m_H \simeq m_A \simeq 125\text{GeV}$

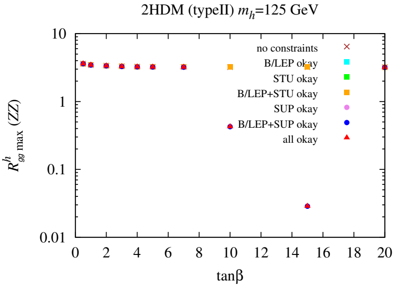
	scenario I	scenario II	scenario III	scenario IV	scenario V
m_h [GeV]	125	$\{10,\ldots,124.9\}$	125	125	$\{10,\ldots,124.9\}$
m_H [GeV]	$125+\{0.1,\ldots,1000\}$	125	125.1	$125+\{0.1,\ldots,1000\}$	125
m_A [GeV]	$\{10,\ldots,1000\}$	$\{10,\ldots,1000\}$	$\{10,\ldots,1000\}$	125.1	125.1
$m_{H^\pm}$ [GeV]	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]	$\{-1000^2,\ldots,1000^2\}$				

TABLE II: Range of parameters adopted in the scans. The values of $m_{H^\pm}$ are bounded from below by the constraints from B physics, see Fig. 15 and Fig. 18 of [12] for the Type II and Type I models, respectively.


2HDM (typeI) m_h=125 GeV
R^h_{gg} max ($\gamma\gamma$)
tanβ
1000
100
10
1
0.1
0
5
10
15
20
no constraints
B/LEP okay
STU okay
B/LEP+STU okay
SUP okay
B/LEP+SUP okay
all okay


2HDM (typeII) m_h=125 GeV
R^h_{gg} max ($\gamma\gamma$)
tanβ
1000
100
10
1
0.1
0.01
0
5
10
15
20
no constraints
B/LEP okay
STU okay
B/LEP+STU okay
SUP okay
B/LEP+SUP okay
all okay


2HDM (typeI) m_h=125 GeV
R^h_{gg} max (ZZ)
tanβ
10
1
0.1
0
2
4
6
8
10
12
14
16
18
20
no constraints
B/LEP okay
STU okay
B/LEP+STU okay
SUP okay
B/LEP+SUP okay
all okay


2HDM (typeII) m_h=125 GeV
R^h_{gg} max (ZZ)
tanβ
10
1
0.1
0.01
0
2
4
6
8
10
12
14
16
18
20
no constraints
B/LEP okay
STU okay
B/LEP+STU okay
SUP okay
B/LEP+SUP okay
all okay

$\mathrm{m_h} = 125\mathrm{GeV}$

$\tan\beta$	$R^h_{gg\max}(\gamma\gamma)$	$R^h_{gg}(ZZ)$	$R^h_{gg}(b\bar{b})$	$R^h_{\mathrm{VBF}}(\gamma\gamma)$	$R^h_{\mathrm{VBF}}(ZZ)$	$R^h_{\mathrm{VBF}}(b\bar{b})$	m_H	m_A	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$\mathcal{A}^h_{H^\pm}/\mathcal{A}$	δa_μ
1.0	0.98	1.00	1.02	0.96	0.98	1.00	875	750	800	500	-0.7	-0.01	-2.3
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	1.02	0.98	0.92	1.08	1.04	0.98	225	400	150	100	-0.4	0.01	-1.7
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

TABLE III: 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.

$\tan\beta$	$R^h_{gg\max}(\gamma\gamma)$	$R^h_{gg}(ZZ)$	$R^h_{gg}(b\bar{b})$	$R^h_{\mathrm{VBF}}(\gamma\gamma)$	$R^h_{\mathrm{VBF}}(ZZ)$	$R^h_{\mathrm{VBF}}(b\bar{b})$	m_H	m_A	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$\mathcal{A}^h_{H^\pm}/\mathcal{A}$	δa_μ
0.5	1.56	2.69	1.84	0.52	0.89	0.61	425	500	600	100	-0.7	-0.06	-0.5
1.0	1.97	3.36	0.39	0.65	1.11	0.13	125	500	500	100	-0.2	-0.06	0.7
2.0	2.59	3.36	0.00	1.48	1.92	0.00	225	200	340	100	-0.0	-0.05	1.6
3.0	2.78	3.29	0.00	2.01	2.37	0.00	225	200	320	100	-0.0	-0.05	1.6
4.0	2.84	3.25	0.00	2.24	2.57	0.00	225	200	320	100	-0.0	-0.04	1.6
5.0	2.87	3.23	0.00	2.37	2.66	0.00	225	200	320	100	-0.0	-0.04	1.6
7.0	2.83	3.21	0.00	2.42	2.75	0.00	135	300	320	50	-0.0	-0.05	0.8
10.0	0.34	0.43	1.89	0.22	0.28	1.23	325	200	320	100	0.2	-0.08	3.5
15.0	0.02	0.03	4.06	0.00	0.01	0.87	225	200	320	50	0.6	-0.14	5.3
20.0	2.89	3.19	0.00	2.57	2.83	0.00	225	200	320	50	-0.0	-0.04	2.4

TABLE IV: Table of maximum $R^h_{gg}(\gamma\gamma)$ values for the Type II 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.

$\mathrm{m_H} = 125\mathrm{GeV}$

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

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.

$\tan\beta$	$R^H_{gg\max}(\gamma\gamma)$	$R^H_{gg}(ZZ)$	$R^H_{gg}(b\bar{b})$	$R^H_{\rm VBF}(\gamma\gamma)$	$R^H_{\rm VBF}(ZZ)$	$R^H_{\rm VBF}(b\bar{b})$	m_h	m_A	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$\mathcal{A}^H_{H^\pm}/\mathcal{A}$	δa_μ
1.0	1.99	3.24	0.52	0.71	1.16	0.19	125	500	500	100	1.0	-0.06	0.7
2.0	2.56	3.36	0.00	1.46	1.92	0.00	125	300	340	50	1.0	-0.06	1.1
3.0	2.73	3.29	0.00	1.97	2.37	0.00	125	300	320	50	1.0	-0.05	1.0
4.0	2.78	3.25	0.00	2.20	2.57	0.00	125	300	320	50	-1.0	-0.05	1.0
5.0	2.81	3.23	0.00	2.32	2.66	0.00	125	300	320	50	-1.0	-0.05	0.9
7.0	2.80	3.21	0.00	2.40	2.75	0.00	65	300	320	10	-1.0	-0.06	-0.0
10.0	2.81	3.20	0.00	2.46	2.79	0.00	45	300	320	0	-1.0	-0.06	-2.8
15.0	2.82	3.19	0.00	2.49	2.82	0.00	25	300	320	0	-1.0	-0.05	-16.9
20.0	2.82	3.19	0.00	2.50	2.83	0.00	25	300	320	0	-1.0	-0.05	-30.8

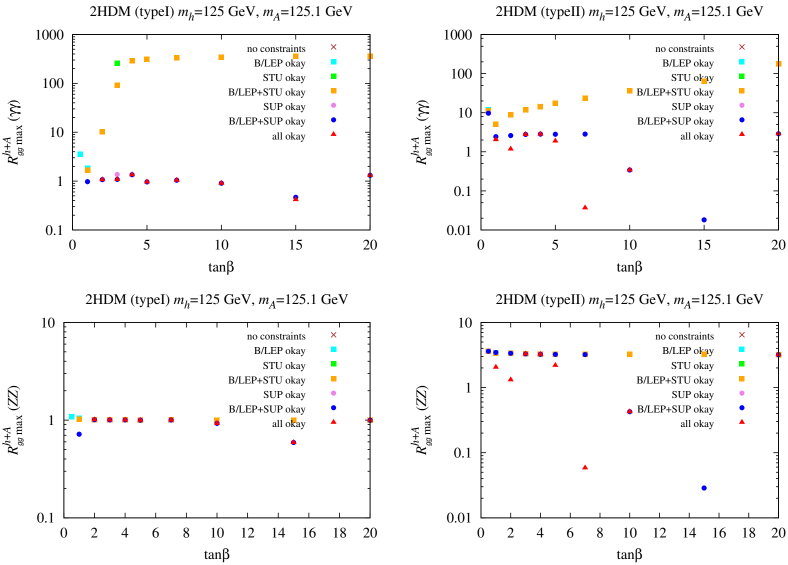
TABLE VI: Table of maximum $R^H_{gg}(\gamma\gamma)$ values for the Type II 2HDM with $m_H = 125$ GeV and associated R values for other initial and/or final states. The input parameters that give the maximal $R^H_{gg}(\gamma\gamma)$ value are also tabulated.

Degenerate Scenarios:

III. $m_h \simeq m_H \simeq 125\text{GeV}$

IV. $m_h \simeq m_A \simeq 125\text{GeV}$

V. $m_H \simeq m_A \simeq 125\text{GeV}$



2HDM (typeI) m_h=125 GeV, m_A=125.1 GeV
2HDM (typeII) m_h=125 GeV, m_A=125.1 GeV
no constraints
B/LEP okay
STU okay
B/LEP+STU okay
SUP okay
B/LEP+SUP okay
all okay
R^{h+A}_{gg} max ($\gamma\gamma$)
R^{h+A}_{gg} max (ZZ)
tanβ

$m_h = m_A = 125$GeV

$\tan\beta$	$R^{h+A}_{gg\max}(\gamma\gamma)$	$R^h_{gg}(\gamma\gamma)$	$R^A_{gg}(\gamma\gamma)$	$R^{h+A}_{gg}(ZZ)$	$R^{h+A}_{gg}(b\bar{b})$	$R^h_{\rm VBF}(\gamma\gamma)$	$R^h_{\rm VBF}(ZZ)$	$R^h_{\rm VBF}(b\bar{b})$	m_H	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$\mathcal{A}^h_{H^\pm}/\mathcal{A}$	δa_μ
2.0	1.07	0.92	0.15	0.98	1.73	0.98	1.04	0.98	325	250	100	-0.5	-0.04	-2.2
3.0	1.08	1.02	0.07	0.98	1.28	1.08	1.04	0.98	225	150	100	-0.4	0.01	-1.9
4.0	1.35	1.33	0.03	0.99	1.21	1.24	0.93	0.99	225	90	100	-0.1	0.14	-1.8
5.0	0.96	0.95	0.01	1.00	1.07	0.95	1.00	1.00	135	90	50	-0.2	-0.03	-1.7
7.0	1.04	1.04	0.01	0.99	1.00	1.06	1.01	0.99	135	90	50	-0.2	0.02	-1.6
10.0	0.91	0.90	0.01	0.81	0.77	0.99	0.89	0.81	175	150	50	-0.5	0.04	-1.5
15.0	0.42	0.42	0.00	0.59	0.67	0.37	0.53	0.59	225	250	50	0.6	-0.17	-1.4
20.0	1.31	1.31	0.00	1.00	1.00	1.30	0.99	1.00	225	90	50	-0.0	0.13	-1.6

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

$\tan\beta$	$R^{h+A}_{gg\max}(\gamma\gamma)$	$R^h_{gg}(\gamma\gamma)$	$R^A_{gg}(\gamma\gamma)$	$R^{h+A}_{gg}(ZZ)$	$R^{h+A}_{gg}(b\bar{b})$	$R^h_{\rm VBF}(\gamma\gamma)$	$R^h_{\rm VBF}(ZZ)$	$R^h_{\rm VBF}(b\bar{b})$	m_H	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$\mathcal{A}^h_{H^\pm}/\mathcal{A}$	δa_μ
1.0	2.05	1.58	0.47	2.05	3.91	0.93	1.22	0.65	525	500	100	-0.5	-0.06	1.3
2.0	1.18	1.17	0.01	1.31	1.68	1.07	1.20	0.87	325	340	100	-0.4	-0.05	1.5
3.0	2.78	2.78	0.00	3.29	0.27	2.01	2.37	0.00	225	320	100	-0.0	-0.05	2.3
4.0	2.84	2.84	0.00	3.25	0.23	2.24	2.57	0.00	225	320	100	-0.0	-0.04	2.3
5.0	1.89	1.89	0.00	2.19	0.95	1.41	1.64	0.47	225	320	100	0.1	-0.05	2.7
7.0	0.04	0.04	0.00	0.06	2.85	0.01	0.02	0.75	325	320	100	0.6	-0.15	5.2
10.0	0.34	0.34	0.00	0.43	3.66	0.22	0.28	1.23	325	320	100	0.2	-0.08	4.7
20.0	2.89	2.89	0.00	3.19	8.03	2.57	2.83	0.00	225	320	50	-0.0	-0.04	5.6

TABLE VIII: Table of maximum $R^{h+A}_{gg}(\gamma\gamma)$ values for the Type II 2HDM with $m_h = m_A = 125$ GeV and associated R values for other initial and/or final states. The input parameters that give the maximal $R^{h+A}_{gg}(\gamma\gamma)$ value are also tabulated.

Conclusions:

- theoretical constraints (SUP) very important
- easier to enhance R_{gg} for the type II model:
  - $R^{h^i \, type \, II}_{gg \, max}(\gamma\gamma) \leqslant 3$,
  - $R^{h^i \, type \, I}_{gg \, max}(\gamma\gamma) \leqslant 1.3$,
- type II model implies too strong ZZ signal:
  - $R^{h(H)}_{gg}(\gamma\gamma) < R^{h(H)}_{gg}(ZZ)$

  or too strong $b\bar{b}$ signal:
  - $R^{h+A}_{gg}(b\bar{b}) > 3.75$ for $R^{h+A}_{gg}(\gamma\gamma) > 1.3 > R^{h+A}_{gg}(ZZ)$
- $H^{\pm}$ effects up to $\sim 20\%$

Optimal signal for the type I model for $\mathrm{tg}\,\beta = 4, 20$ within the scenarios: I (mh = 125 GeV) and IV (mh = mA = 125 GeV).

- light charged Higgs $\sim$ 90GeV

Thank you for your attention

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