TRIESTE - IFAE 2017

Extended Higgs sector @ LHC

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IFAE 2017

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Based on

arXiv:1607.01933 [hep-ph] - P. Bandyopadhyay, C. Corianò, A. C. and L. Delle Rose

arXiv:1512.08651 [hep-ph] - P. Bandyopadhyay, C. Corianò and A. C.

arXiv:1510.06309 [hep-ph] - P. Bandyopadhyay, C. Corianò and A. C.

arXiv:1506.03634 [hep-ph] - P. Bandyopadhyay, C. Corianò and A. C.

Contents

The Superpotential

$$W_{TNMSSM} = W_{Yuk} + W_{Scal}$$

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$$W_{Yuk} = y_t \hat{U} \hat{H}_u \cdot \hat{Q} - y_b \hat{D} \hat{H}_d \cdot \hat{Q} - y_\tau \hat{E} \hat{H}_d \cdot \hat{L}$$

The Superpotential

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$$W_{Yuk} = y_t \hat{U} \hat{H}_u \cdot \hat{Q} - y_b \hat{D} \hat{H}_d \cdot \hat{Q} - y_\tau \hat{E} \hat{H}_d \cdot \hat{L}$$

$$W_{Scal} = \lambda_T \hat{H}_d \cdot \hat{T} \hat{H}_u + \lambda_S \hat{S} \hat{H}_d \cdot \hat{H}_u + \frac{\kappa}{3} \hat{S}^3 + \lambda_{TS} \hat{S} \, \mathrm{Tr}[\hat{T}^2]$$

$$\hat{T} = \begin{pmatrix} \sqrt{\frac{1}{2}} \hat{T}^0 & \hat{T}_2^+ \\ \hat{T}_1^- & -\sqrt{\frac{1}{2}} \hat{T}^0 \end{pmatrix}, \qquad \hat{H}_u = \begin{pmatrix} \hat{H}_u^+ \\ \hat{H}_u^0 \end{pmatrix}, \qquad \hat{H}_d = \begin{pmatrix} \hat{H}_d^0 \\ \hat{H}_d^- \end{pmatrix}$$

A Global U(1) Symmetry

$$
\begin{aligned}
V_{soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + m_T^2 |T|^2 \\
+ m_Q^2 |Q|^2 + m_U^2 |U|^2 + m_D^2 |D|^2 \\
+ (A_S S H_d . H_u + A_\kappa S^3 + A_T H_d . T . H_u + A_{TS} S Tr(T^2) \\
+ A_U U H_U . Q + A_D D H_D . Q + h.c)
\end{aligned}
$$

A Global U(1) Symmetry

$$V_{soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + m_T^2 |T|^2$$
$$+ m_Q^2 |Q|^2 + m_U^2 |U|^2 + m_D^2 |D|^2$$
$$+ (A_S S H_d . H_u + A_\kappa S^3 + A_T H_d . T . H_u + A_{TS} S Tr(T^2)$$
$$+ A_U U H_U . Q + A_D D H_D . Q + h.c)$$

If the $A_i \to 0$ there is a global U(1) symmetry

$$(\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S}) \to e^{i\phi} (\hat{H}_u, \hat{H}_d, \hat{T}, \hat{S})$$

Breaking softly this extra symmetry with $A_i \sim 1$ GeV we have a light pseudoscalar, $m_{a_1} \sim 10$ GeV

The Structure of the Physical Higgses

$$h_i = \mathcal{R}^S_{ij} H_j, \quad h_i = (h_1, h_2, h_3, h_4) \quad H_i = (H^0_{u,r}, H^0_{d,r}, S_r, T^0_r)$$
$$a_i = \mathcal{R}^P_{ij} A_j, \quad a_i = (a_0, a_1, a_2, a_3) \quad A_i = (H^0_{u,i}, H^0_{d,i}, S_i, T^0_i)$$
$$h^\pm_i = \mathcal{R}^C_{ij} H^\pm_j, \quad h^\pm_i = (h^\pm_0, h^\pm_1, h^\pm_2, h^\pm_3) \quad H^+_i = (H^+_u, T^+_2, H^{-*}_d, T^{-*}_1)$$

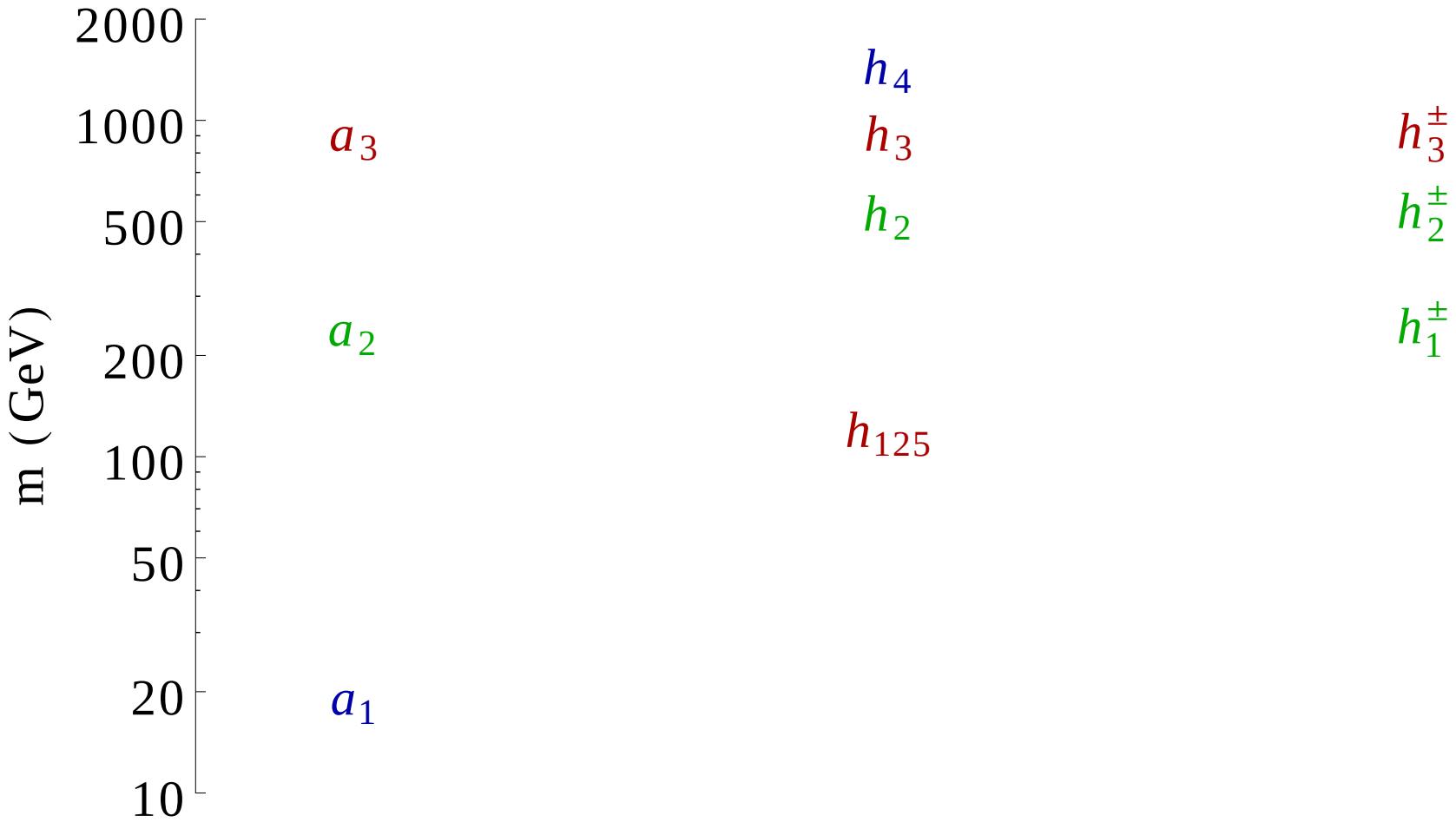
$$h_i|_D = (\mathcal{R}^S_{i,1})^2 + (\mathcal{R}^S_{i,2})^2, \; a_i|_D = (\mathcal{R}^P_{i,1})^2 + (\mathcal{R}^P_{i,2})^2$$

$$h_i|_S = (\mathcal{R}^S_{i3})^2, \; a_i|_S = (\mathcal{R}^P_{i3})^2$$

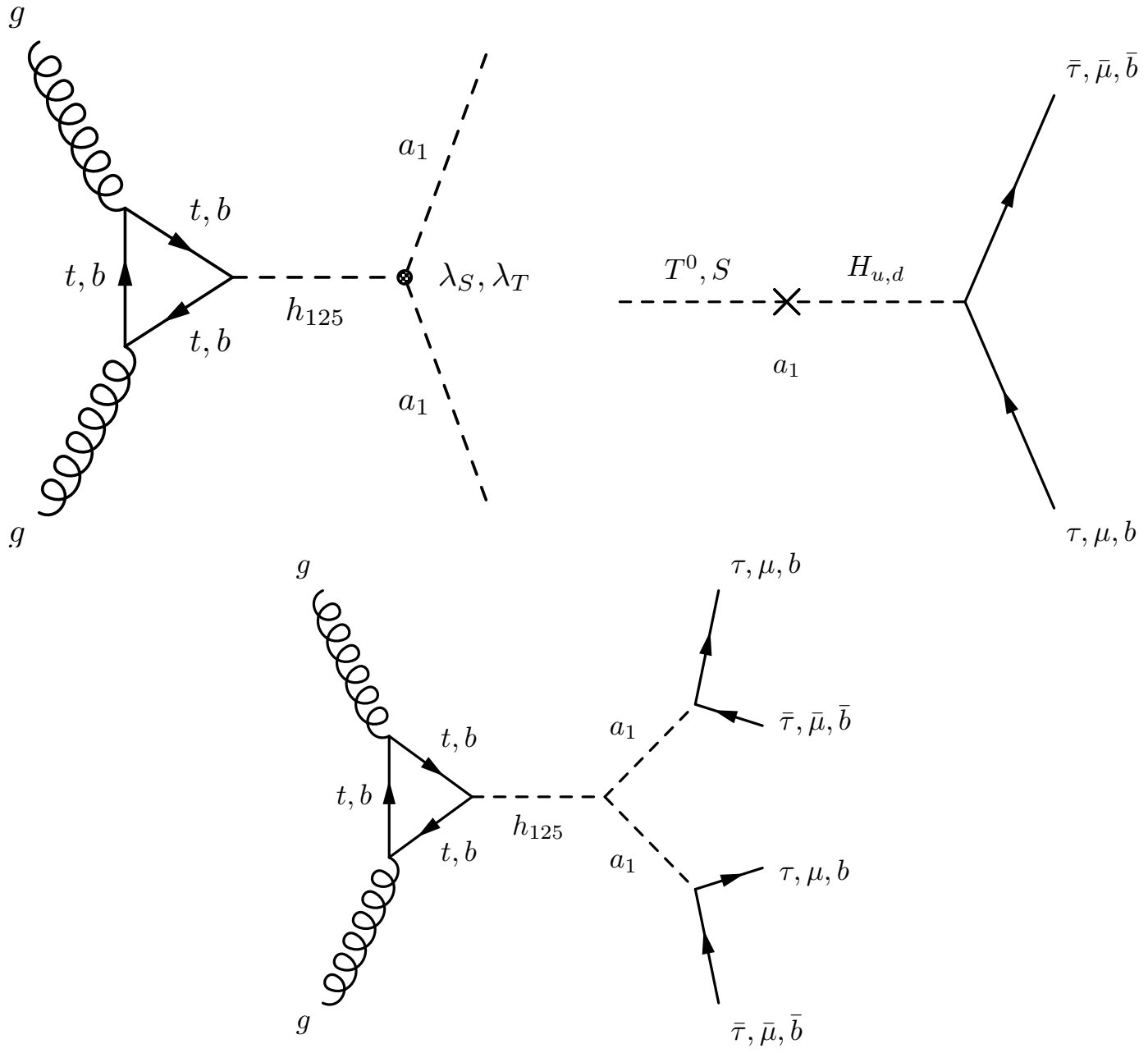
$$h_i|_T = (\mathcal{R}^S_{i4})^2, \; a_i|_T = (\mathcal{R}^P_{i4})^2$$

$$h^\pm_i|_D = (\mathcal{R}^C_{i1})^2 + (\mathcal{R}^C_{i3})^2, \; h^\pm_i|_T = (\mathcal{R}^C_{i2})^2 + (\mathcal{R}^C_{i4})^2$$

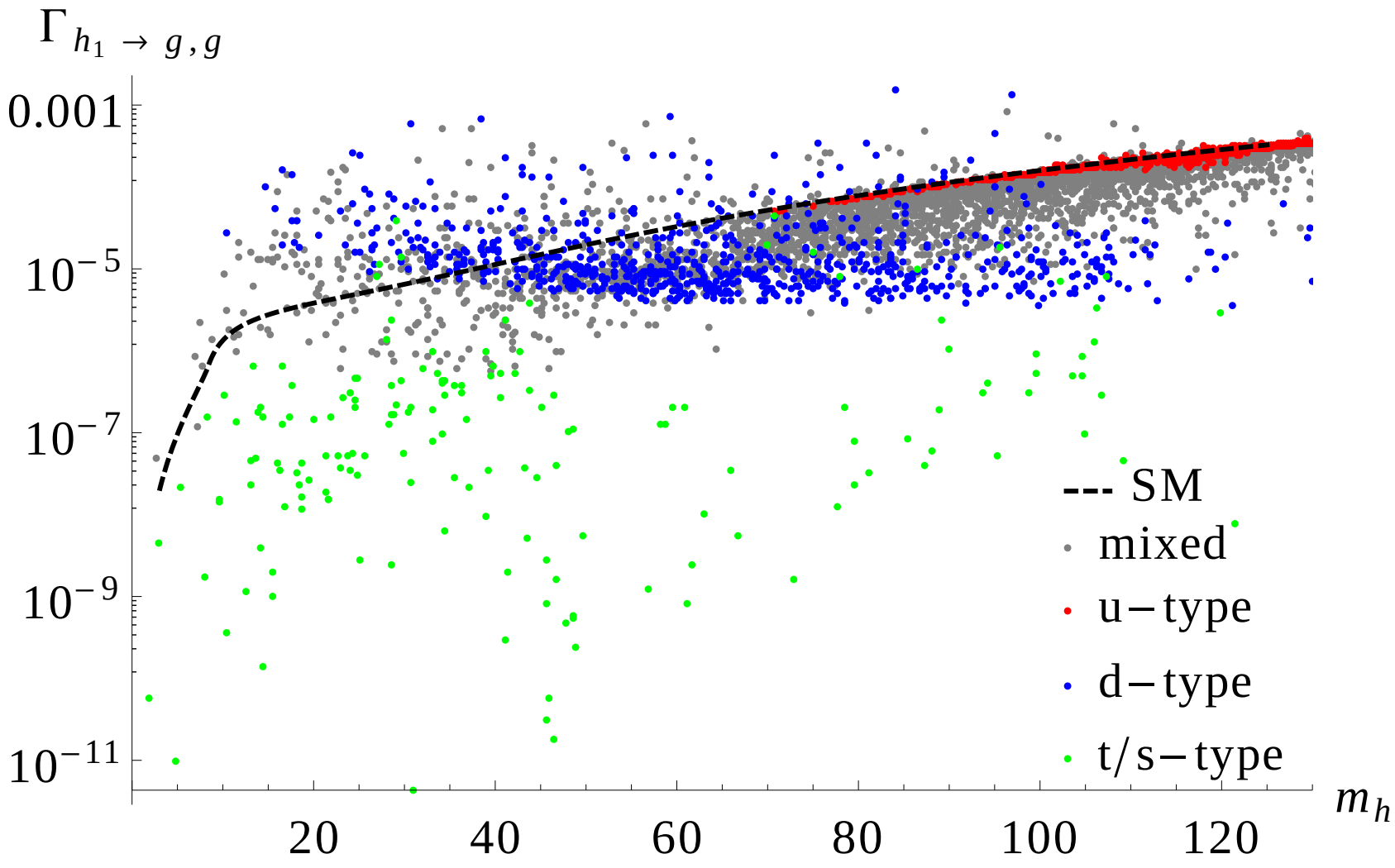
A Tipical Mass Spectrum



Pseudoscalar Pair



Gluon Fusion Production



Benchmark Points

Benchmark Points	BP1	BP2	BP3
m_{h_1}	~ 125	~ 125	117.73
m_{h_2}	183.58	162.59	~ 125
m_{a_1}	20.50	57.02	36.79

$\mathcal{B}r(a_1 \to \bar{b}b) \sim 94\%$ $\quad$ $\mathcal{B}r(a_1 \to \bar{\tau}\tau) \sim 6\%$

Results

Number of events at 100 fb^{-1} for c.m.e. of 14 TeV.

Final states	Benchmark			Backgrounds				
	BP1	BP2	BP3	$t\bar{t}$	ZZ	Zh	$b\bar{b}h$	$b\bar{b}Z$
$n_j \leq 5\,[2b_{\text{jet}} + 2\tau_{\text{jet}}]$ & $\not{p}_T \leq 30$ GeV	220.10	591.46	310.19	1824.08	199.50	39.56	11.87	4903.05
& $p_T^{bj_{1,2}} \leq 50$GeV & $\lvert m_{bb} - m_Z \rvert > 10$ GeV	211.30	568.14	289.02	410.83	73.04	7.87	3.96	2941.83
& $\lvert m_{bb} - m_{h_{125}} \rvert > 10$ GeV	211.30	565.32	289.02	386.18	73.04	7.52	3.96	2614.96
& $\lvert m_{\tau\tau} - m_Z \rvert > 10$ GeV	211.30	560.37	289.02	312.23	62.13	6.29	3.46	2397.04
& $\lvert m_{\tau\tau} - m_{h_{125}} \rvert > 10$ GeV	211.30	560.37	289.02	287.58	62.13	6.18	2.97	2397.04
& $m_{\tau\tau} < 125$GeV	211.30	560.37	289.02	254.71	62.13	6.18	2.97	2397.04
& $m_{bb} < 125$GeV	211.30	559.66	289.02	230.06	62.13	6.07	2.97	2288.09
Significance	4.00	9.98	5.39					
& $p_1 : \lvert m_{bb} - m_{a_1} \rvert \leq 10$GeV	198.82	281.95	216.04	24.65 65.73 65.73	0.00 26.16 8.72	0.22 1.46 1.34	0.49 0.49 1.00	326.87 1307.48 435.83
Significance	8.47	6.87	8.01					
& $p_2 : \lvert m_{\tau\tau} - m_{a_1} \rvert \leq 10$GeV	205.29	229.66	203.63	65.73 73.95 41.08	3.27 28.34 13.08	0.33 1.46 1.57	0.00 0.49 1.48	0.00 762.70 0.00
Significance	**12.40**	6.94	**12.65**					

Contents

$h^{\pm} \to W^{\pm} Z$

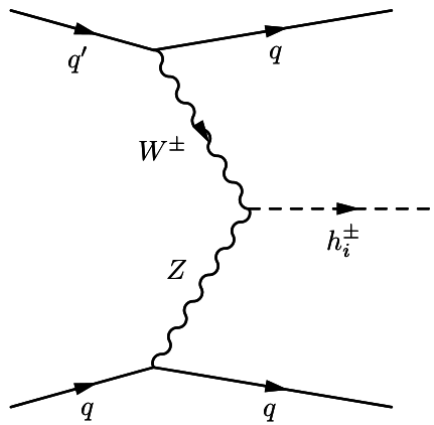
Theories with triplets have a tree-level vertex $h_i^{\pm} - W^{\mp} - Z$ which breaks the custodial symmetry. In our case it's

$$g_{h_i^{\pm} W^{\mp} Z} = -\frac{i}{2}\left(g_L\, g_Y \left(v_u \sin\beta\, \mathcal{R}^C_{i1} - v_d \cos\beta\, \mathcal{R}^C_{i3}\right) + \sqrt{2}\, g_L^2 v_T \left(\mathcal{R}^C_{i2} + \mathcal{R}^C_{i4}\right)\right)$$

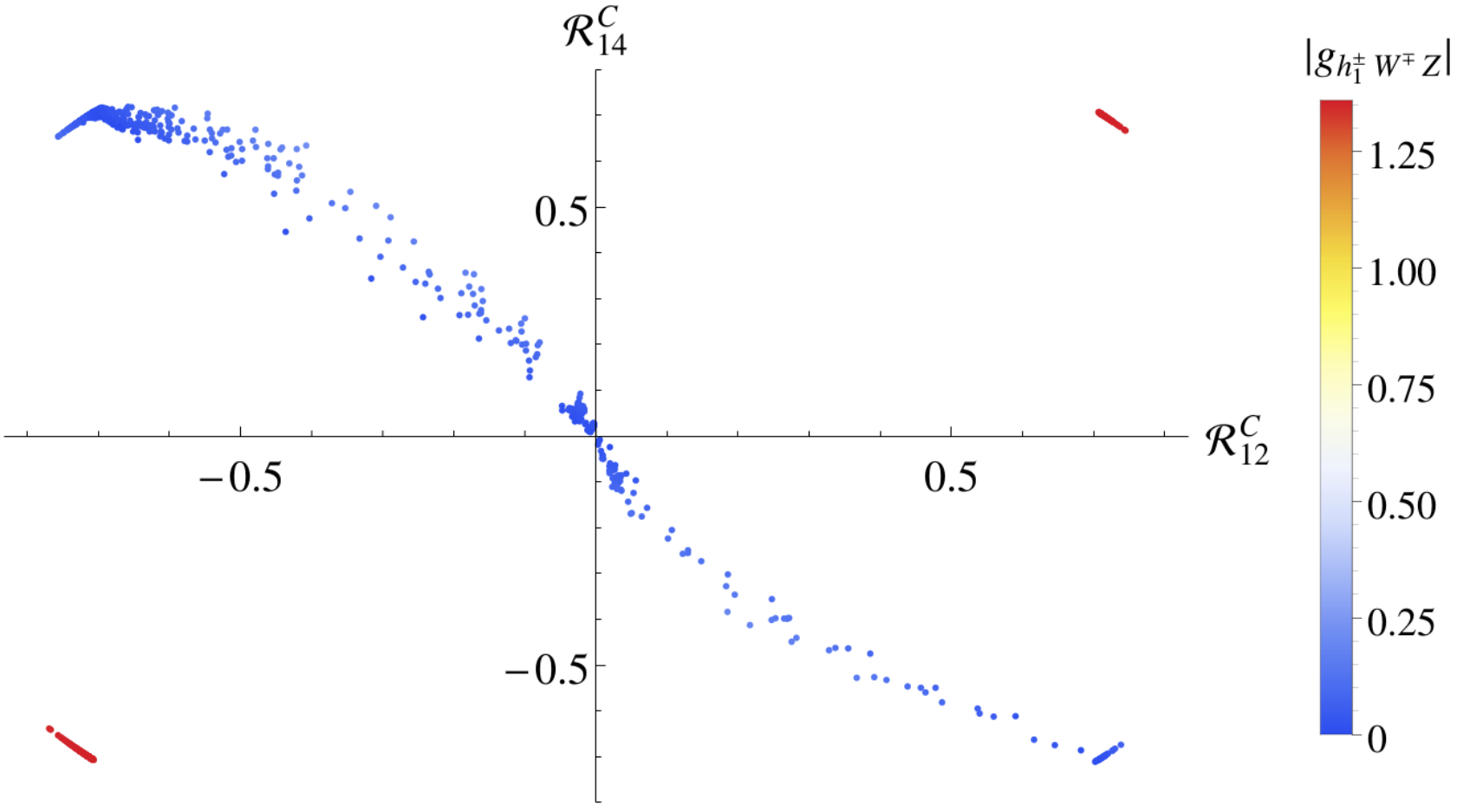
The on-shell decay width is

$$\Gamma_{h_i^{\pm} \to W^{\pm} Z} = \frac{G_F\, \cos^2\theta_W}{8\sqrt{2}\pi} m^3_{h_i^{\pm}} |g_{h_i^{\pm} W^{\mp} Z}|^2 \sqrt{\lambda(1, x_W, x_Z)} \left(8\, x_W\, x_Z + (1 - x_W - x_Z)^2\right)$$

where $\lambda(x, y, z) = (x - y - z)^2 - 4\, y\, z$ and $x_{Z,W} = \dfrac{m^2_{Z,W}}{m^2_{h_i^{\pm}}}$.

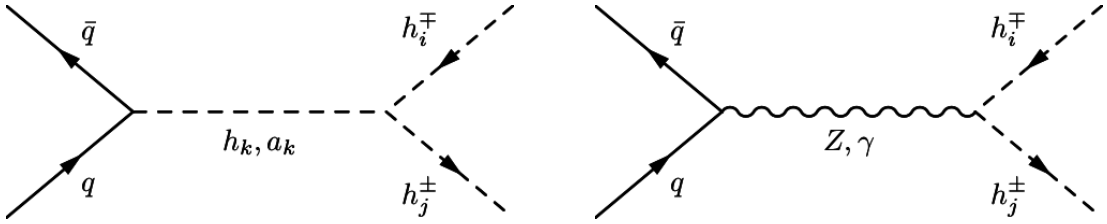


$g_{h_i^\pm W^\mp Z}$


$\mathcal{R}^C_{14}$
0.5
−0.5
−0.5
0.5
$\mathcal{R}^C_{12}$
$|g_{h_1^\pm W^\mp Z}|$
1.25
1.00
0.75
0.50
0.25
0

Charged Higgs Pair Production

The production processes for the charged Higgs pair are



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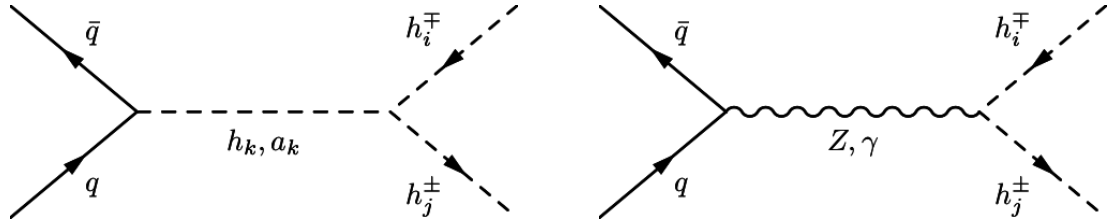
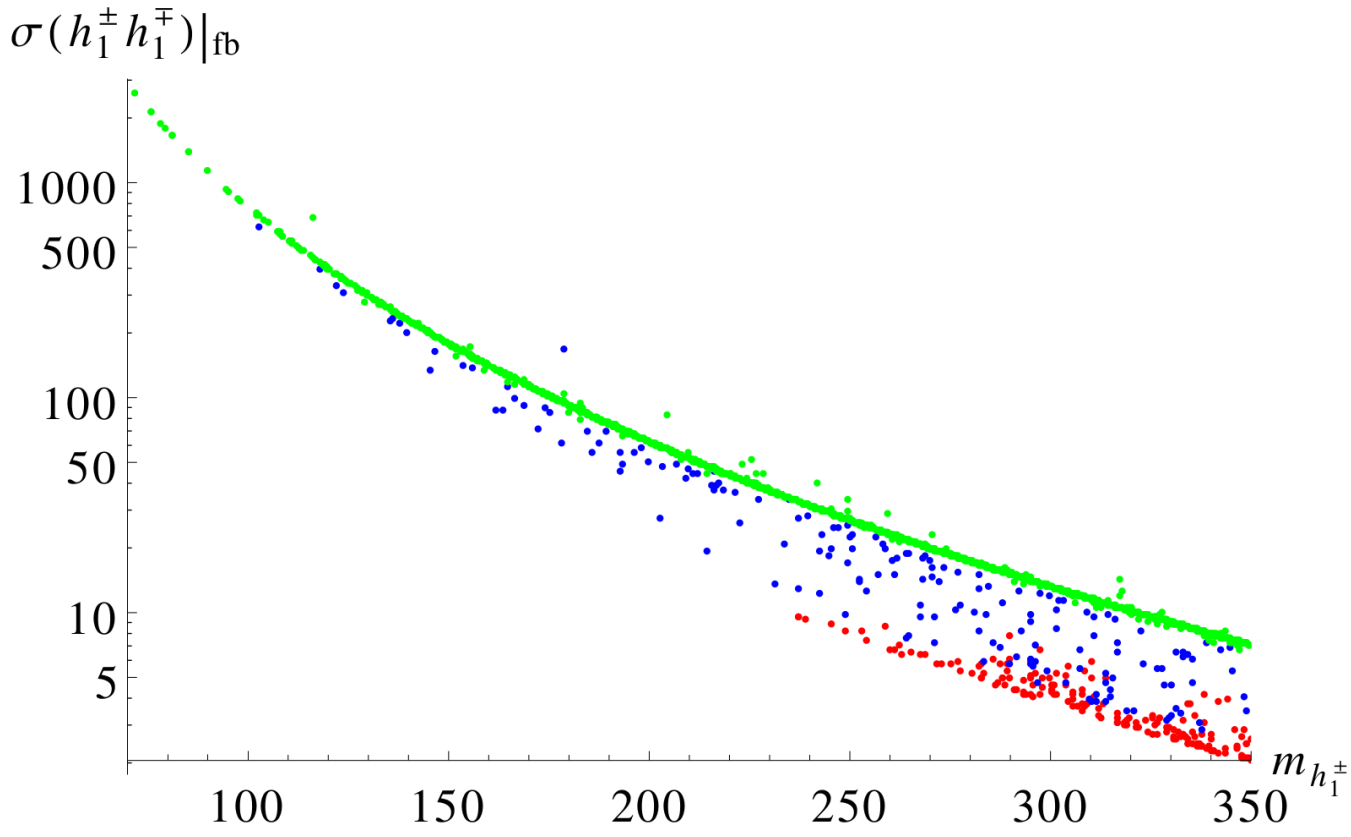
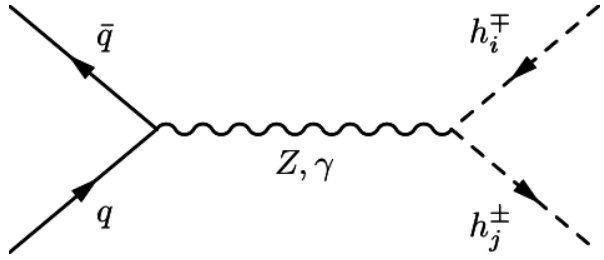
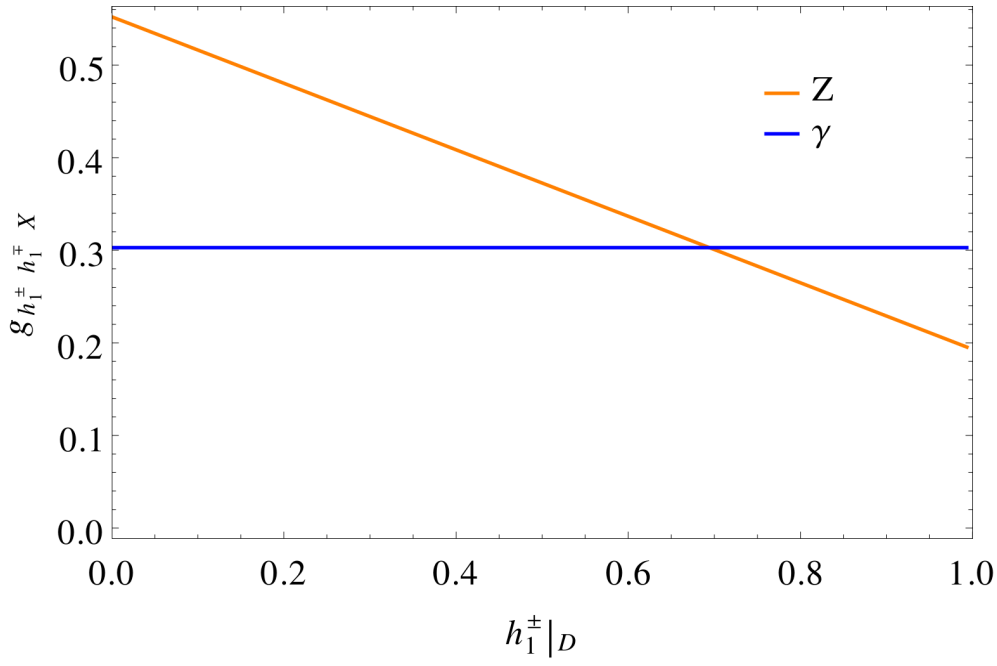




Z, γ contibution to $\sigma(h_1^{\pm} h_1^{\mp})$





$g_L \cos\theta_w$

$W^{\pm} - W^{\mp} - Z$

$\frac{g_L}{2} \frac{\cos 2\theta_w}{\cos\theta_w}$

$\mathrm{MSSM-like}$

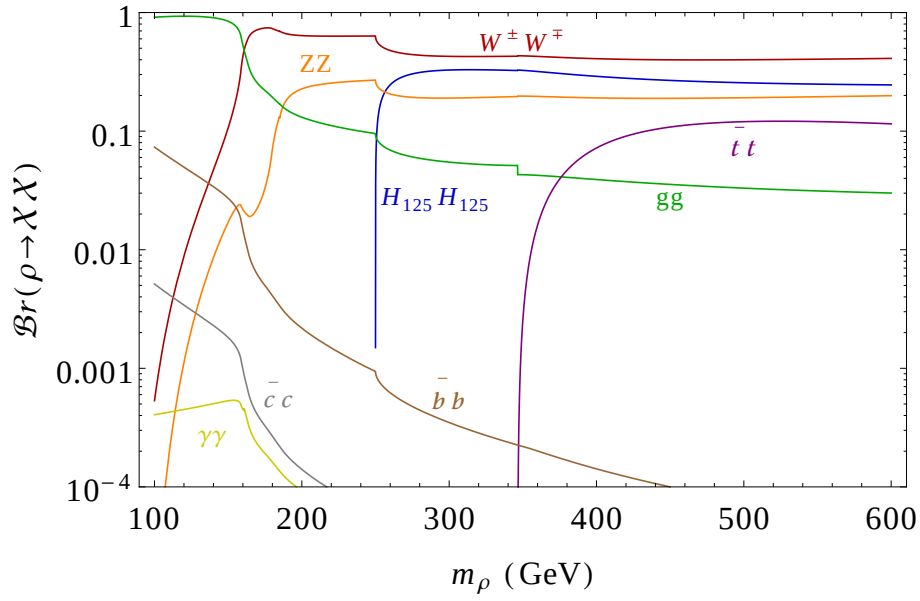
(Preliminary) Results

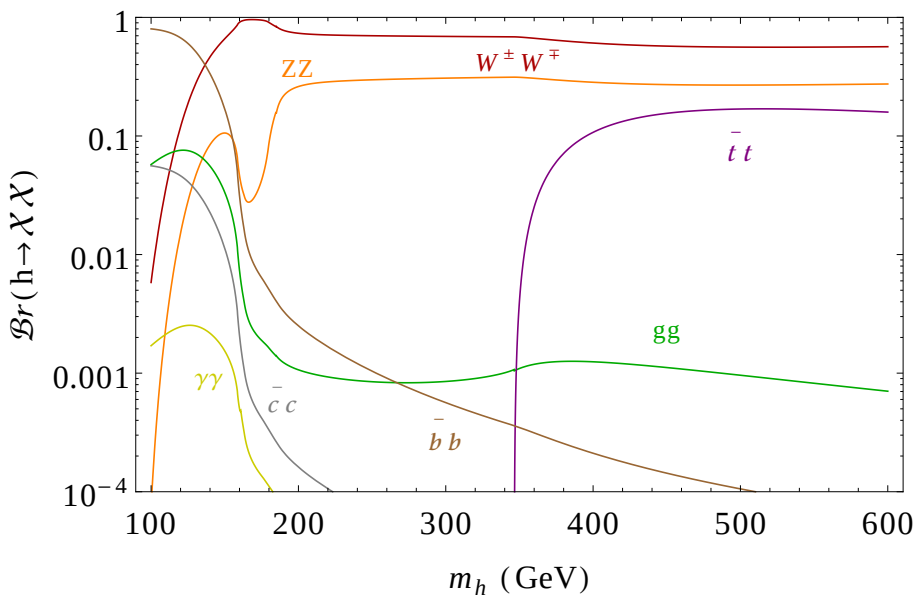
Decay Channels			# of Events	
			Signal	Backgrounds
BP1	$a_1 W^{\pm} Z W^{\mp}$	$\geq 3\ell + 2\tau + \not{E}_T$	1	6
		$\geq 3\ell + 2b + \not{E}_T$	21	39
BP2	$a_1 W^{\pm} \tau\nu_\tau$	$3\tau + 1\ell + \not{E}_T$	13	< 1
	$a_1 W^{\pm} a_1 W^{\mp}$	$2b + 2\tau + 2\ell + \not{E}_T$	164	38
BP3	$Z W^{\pm} \tau\nu_\tau$	$1\tau + 3\ell + \not{E}_T$	9	19
	$Z\, W^{\pm}\, Z\, W^{\mp}$	$\geq 5\ell + \not{E}_T$	228	23
		$\geq 1\ell + 2b + 2\tau + \not{E}_T$	29	246

Contents

Classical Scale Invariant Extension of the SM

$$\mathcal{L}_{int} = -\frac{1}{\Lambda}\rho T^{\mu}_{\mu\, SM}$$

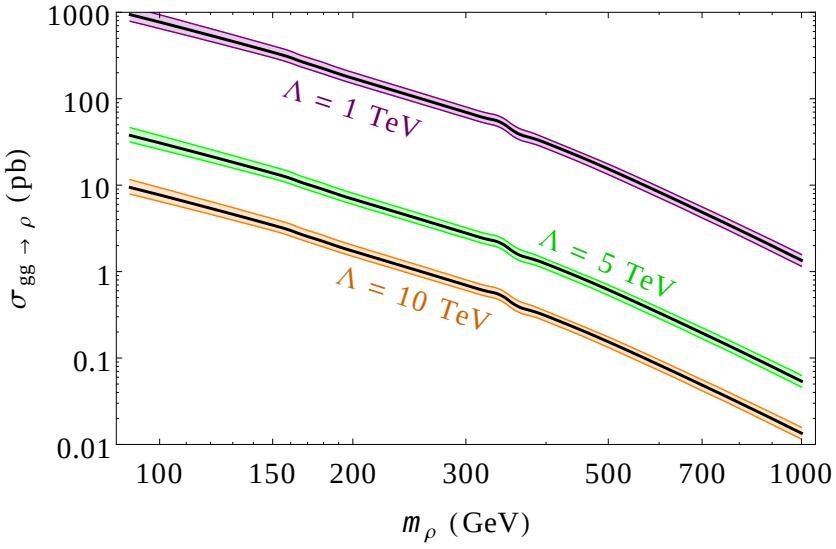


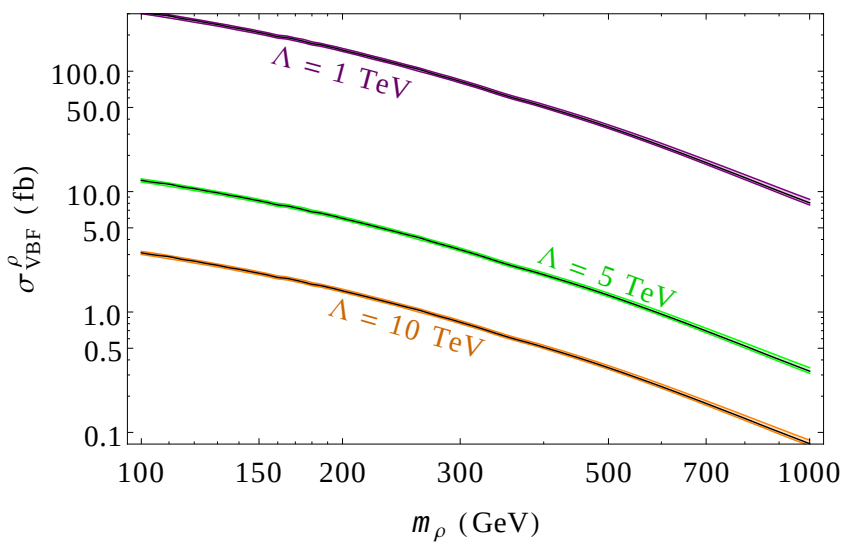


Constrainign the Breaking Scale Λ...

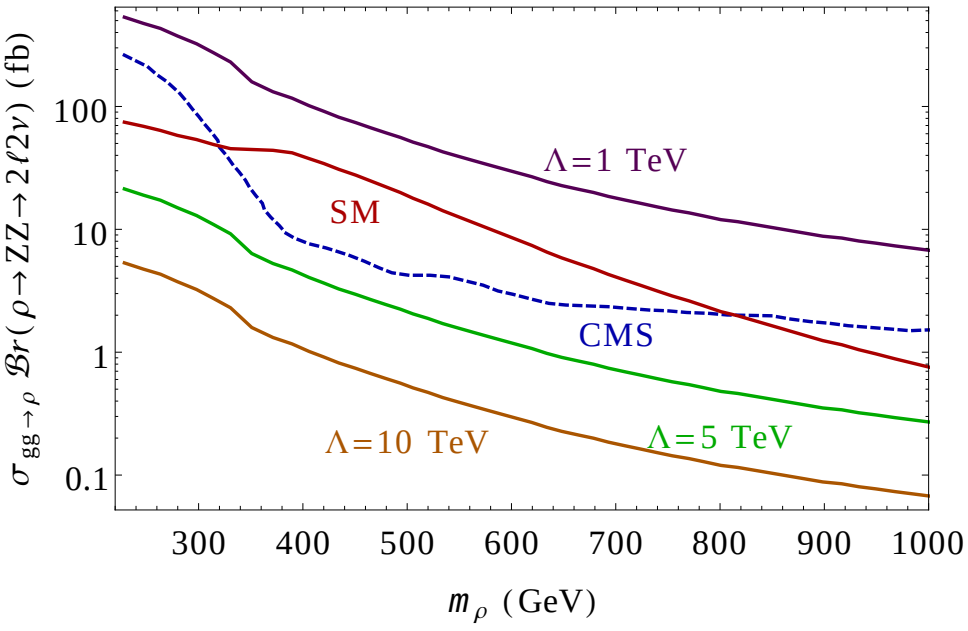
$$\sigma_{gg\to\rho} = \sigma_{gg\to H}\,\frac{\Gamma_{\rho\to gg}}{\Gamma_{H\to gg}}$$

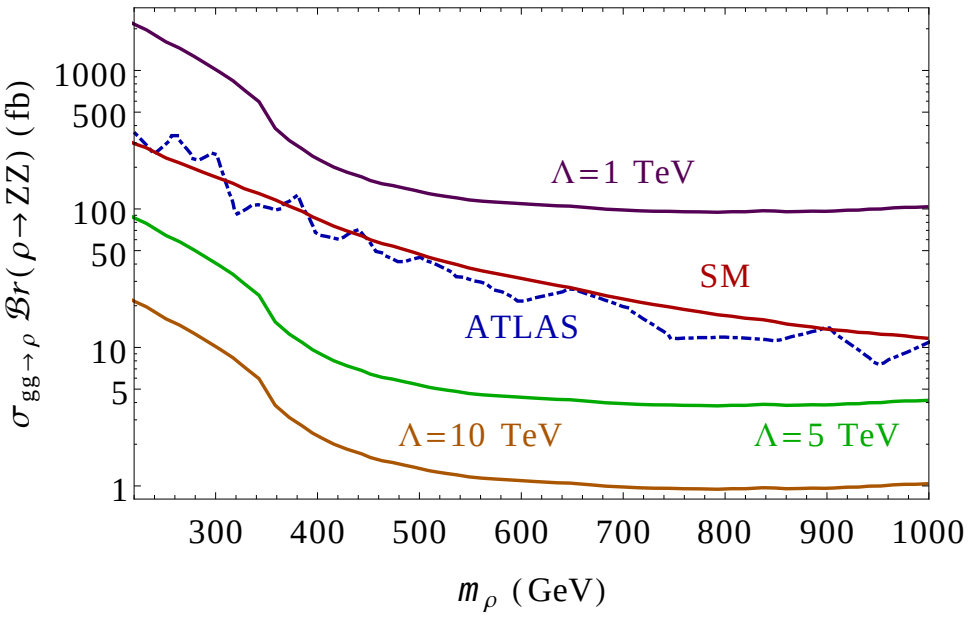
$$\frac{\Gamma_{\rho\to gg}}{\Gamma_{H\to gg}} = \frac{v^2}{\Lambda^2}\frac{m_\rho^3}{m_H^3}\frac{\left|\beta_{QCD} + x_t\left[1+(1-x_t)\,f(x_t)\right]\right|^2}{\left|x_t\left[1+(1-x_t)\,f(x_t)\right]\right|^2}$$





...from Heavy Higgs Searches @ LHC

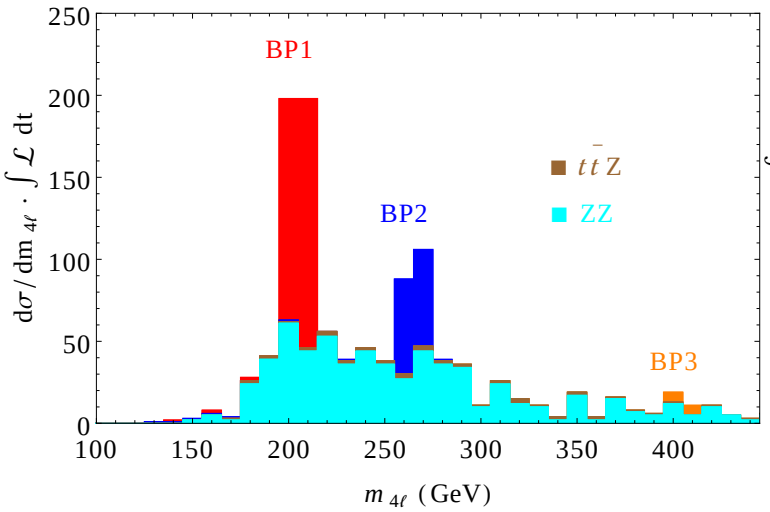


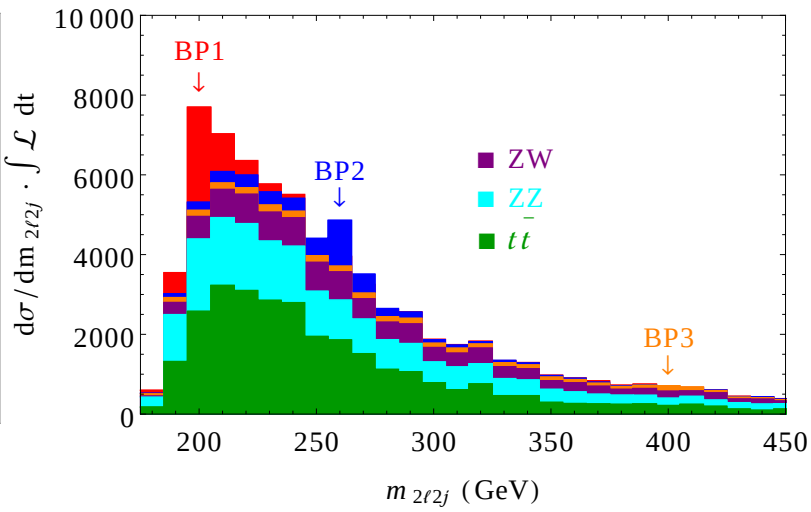


$$\Lambda \gtrsim 5\,\mathrm{TeV}$$

Results

Final states	Benchmark	Backgrounds				
	BP1	$t\bar{t}$	$t\bar{t}Z$	tZW	VV	VVV
$\geq 3\ell + \not{p}_T \leq 30\,\mathrm{GeV}$	494.97	275.52	65.17	22.29	6879.42	765.11
$+ \lvert m_{ll} - m_Z \rvert < 5\,\mathrm{GeV}$	384.47	68.88	62.68	20.93	2514.92	16.16
$+ n_{\mathrm{b_{jet}}} = 0$	377.56	9.84	17.64	10.08	2479.66	15.13
Significance	7.00					
$\mathcal{L}_5$	51 fb^{-1}					
$\geq 4\ell + \not{p}_T \leq 30\,\mathrm{GeV}$	273.96	0.00	3.32	1.36	1655.99	34.18
$+ \lvert m_{ll} - m_Z \rvert < 5\,\mathrm{GeV}$	218.71	0.00	3.11	1.16	627.38	4.44
Significance	7.48					
$\mathcal{L}_5$	45 fb^{-1}					





Thanks