Constraining the 2HDM and identifying benchmarks

2HDM Type II Yukawa

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Preamble

- Higgs particle found! SM?
- 2HDM excluded?
- not quite
- but parameter space severely constrained
- Look for charged Higgs!

2HDM notation 1

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

No FCNC:

$$\lambda_6 = 0; \quad \lambda_7 = 0$$

Allow CPV: $\lambda_5, \quad m_{12}^2$ complex

2HDM notation 2

$$\Phi_i = \begin{pmatrix} \varphi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \eta_i + i\chi_i) \end{pmatrix}$$

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix}$$

$$\eta_3 = -\sin\beta\chi_1 + \cos\beta\chi_2$$

$$R\mathcal{M}^2 R^{\mathrm{T}} = \mathcal{M}^2_{\mathrm{diag}} = \mathrm{diag}(M_1^2, M_2^2, M_3^2)$$

2HDM notation 3

2 vs 3   1 vs 3   1 vs 2

$$R = R_3\, R_2\, R_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_3 & \sin\alpha_3 \\ 0 & -\sin\alpha_3 & \cos\alpha_3 \end{pmatrix} \begin{pmatrix} \cos\alpha_2 & 0 & \sin\alpha_2 \\ 0 & 1 & 0 \\ -\sin\alpha_2 & 0 & \cos\alpha_2 \end{pmatrix} \begin{pmatrix} \cos\alpha_1 & \sin\alpha_1 & 0 \\ -\sin\alpha_1 & \cos\alpha_1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_1\, c_2 & s_1\, c_2 & s_2 \\ -(c_1\, s_2\, s_3 + s_1\, c_3) & c_1\, c_3 - s_1\, s_2\, s_3 & c_2\, s_3 \\ -c_1\, s_2\, c_3 + s_1\, s_3 & -(c_1\, s_3 + s_1\, s_2\, c_3) & c_2\, c_3 \end{pmatrix}$$

PDG convention

$$c_i = \cos\alpha_i,\ s_i = \sin\alpha_i$$

CP-conserving limits:

$$\begin{aligned} &H_1 \text{ odd:} \quad \alpha_2 \simeq \pm\pi/2,\ \alpha_1, \alpha_3 \text{ arbitrary}, \\ &H_2 \text{ odd:} \quad \alpha_2 = 0,\ \alpha_3 = \pi/2,\ \alpha_1 \text{ arbitrary}, \\ &H_3 \text{ odd:} \quad \alpha_2 = \alpha_3 = 0,\ \alpha_1 \text{ arbitrary}. \end{aligned}$$

Yukawa couplings

$$H_j b\bar{b}: \qquad \frac{-ig\, m_b}{2\, m_W} \frac{1}{\cos\beta} \left[R_{j1} - i\gamma_5 \sin\beta R_{j3}\right],$$

$$H_j t\bar{t}: \qquad \frac{-ig\, m_t}{2\, m_W} \frac{1}{\sin\beta} \left[R_{j2} - i\gamma_5 \cos\beta R_{j3}\right].$$

$$H^+ b\bar{t}: \qquad \frac{ig}{2\sqrt{2}\, m_W} V_{tb}[m_b(1+\gamma_5)\tan\beta + m_t(1-\gamma_5)\cot\beta],$$

$$H^- t\bar{b}: \qquad \frac{ig}{2\sqrt{2}\, m_W} V_{tb}^*[m_b(1-\gamma_5)\tan\beta + m_t(1+\gamma_5)\cot\beta].$$

Gauge couplings

$$H_j ZZ : \qquad [\cos\beta R_{j1} + \sin\beta R_{j2}], \quad \text{for } j = 1,$$

Off-shell: $H_1 \to ZZ,\, WW$

On-shell: $H_{2,3} \to ZZ,\, WW$

$$H_j H^\pm W^\mp : \qquad \frac{g}{2}[\mp i(\sin\beta R_{j1} - \cos\beta R_{j2}) + R_{j3}](p^j_\mu - p^\pm_\mu).$$

Entering total widths: $H_{2,3} \to H_1 Z$

Parameters

Input: $\tan\beta,\ (M_1,\ M_2),\ (M_{H^\pm},\ \mu^2),\ (\alpha_1,\ \alpha_2,\ \alpha_3)$

Reconstruct:

$$M_3^2 = \frac{M_1^2 R_{13}(R_{12}\tan\beta - R_{11}) + M_2^2 R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}$$

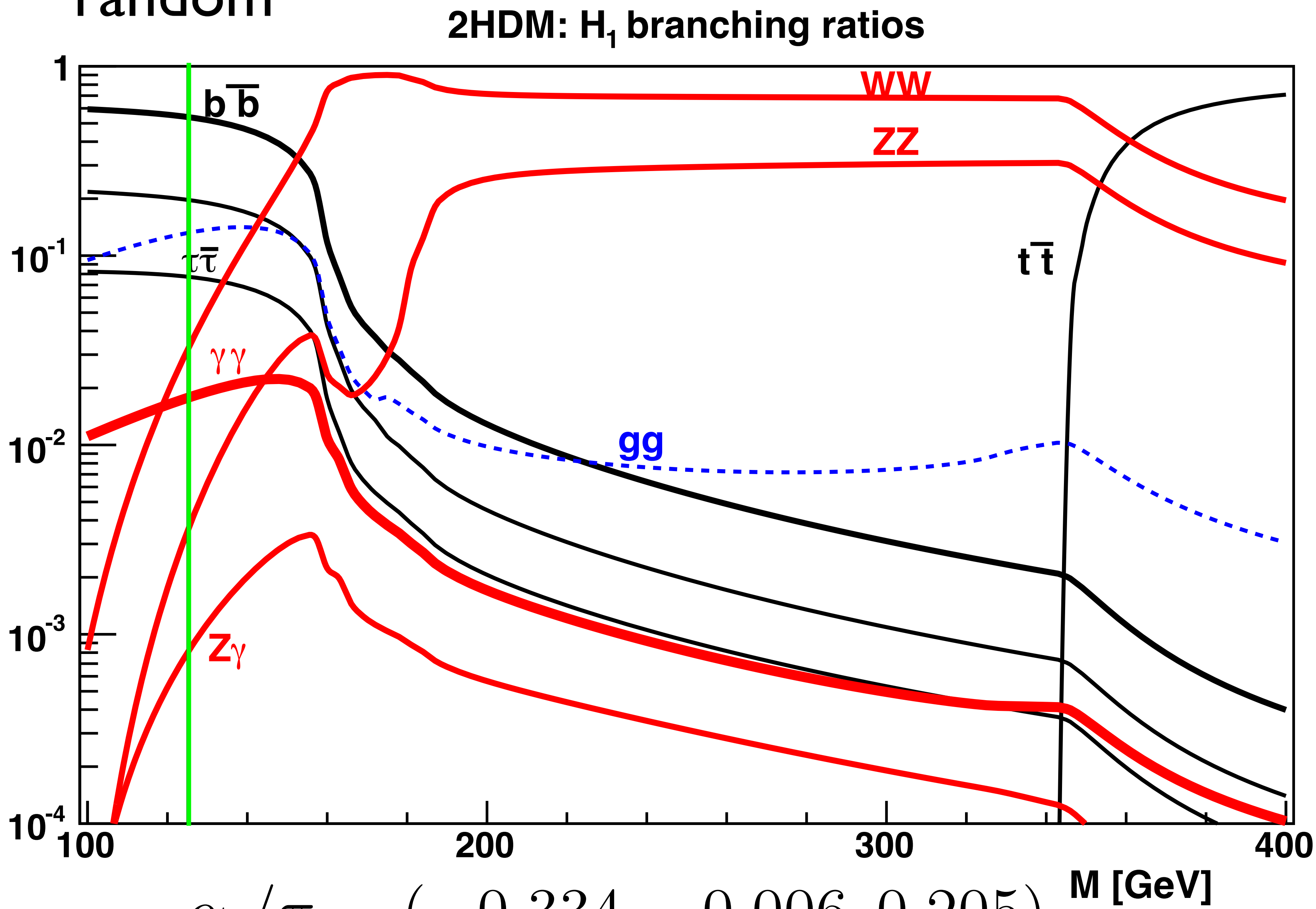
Explicit expressions for

$$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \mathrm{Re}\,\lambda_5, \mathrm{Im}\,\lambda_5$$

in terms of input

Branching ratios

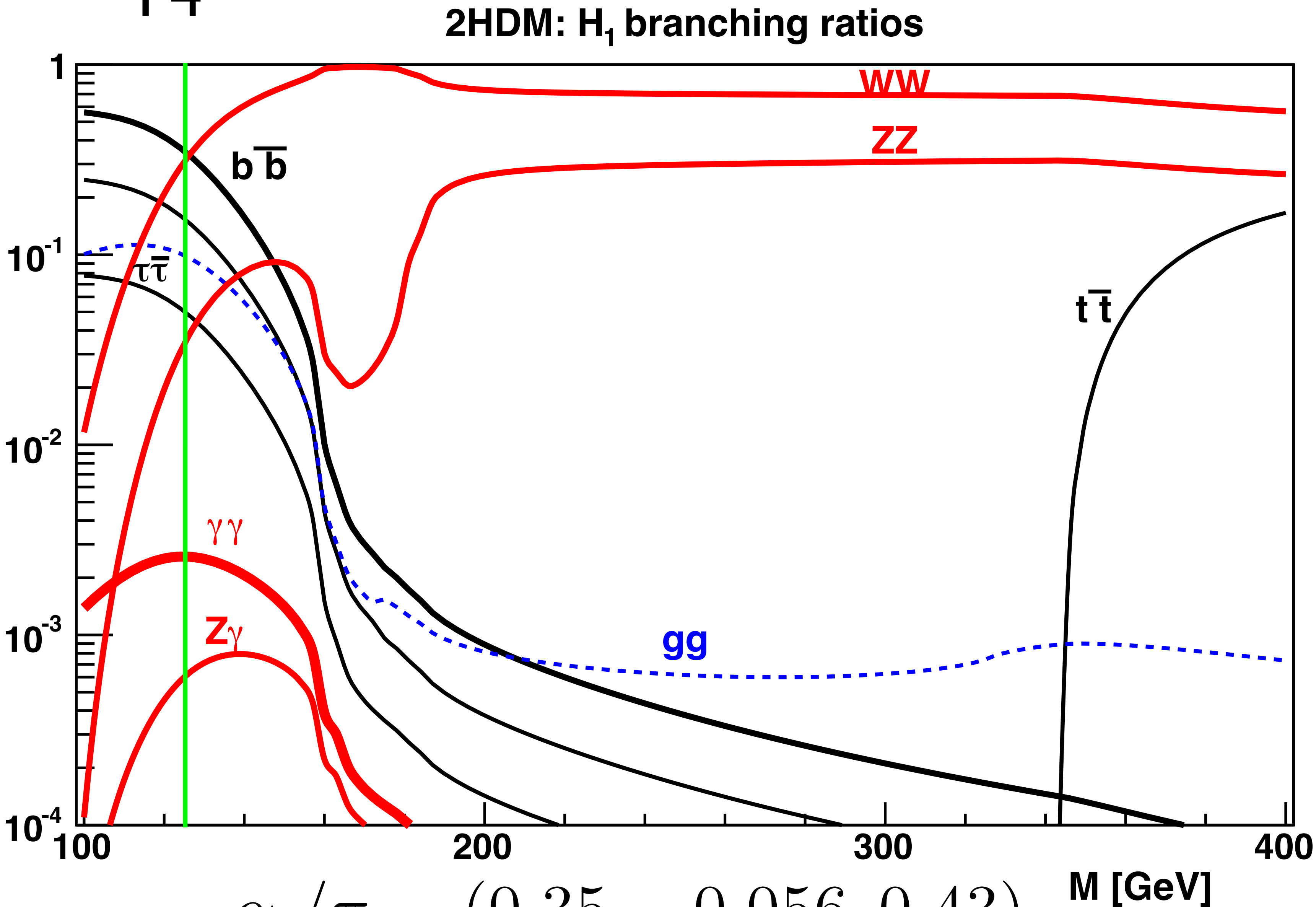
random



$$\alpha_i/\pi = (-0.334, -0.006, 0.205)$$

Branching ratios

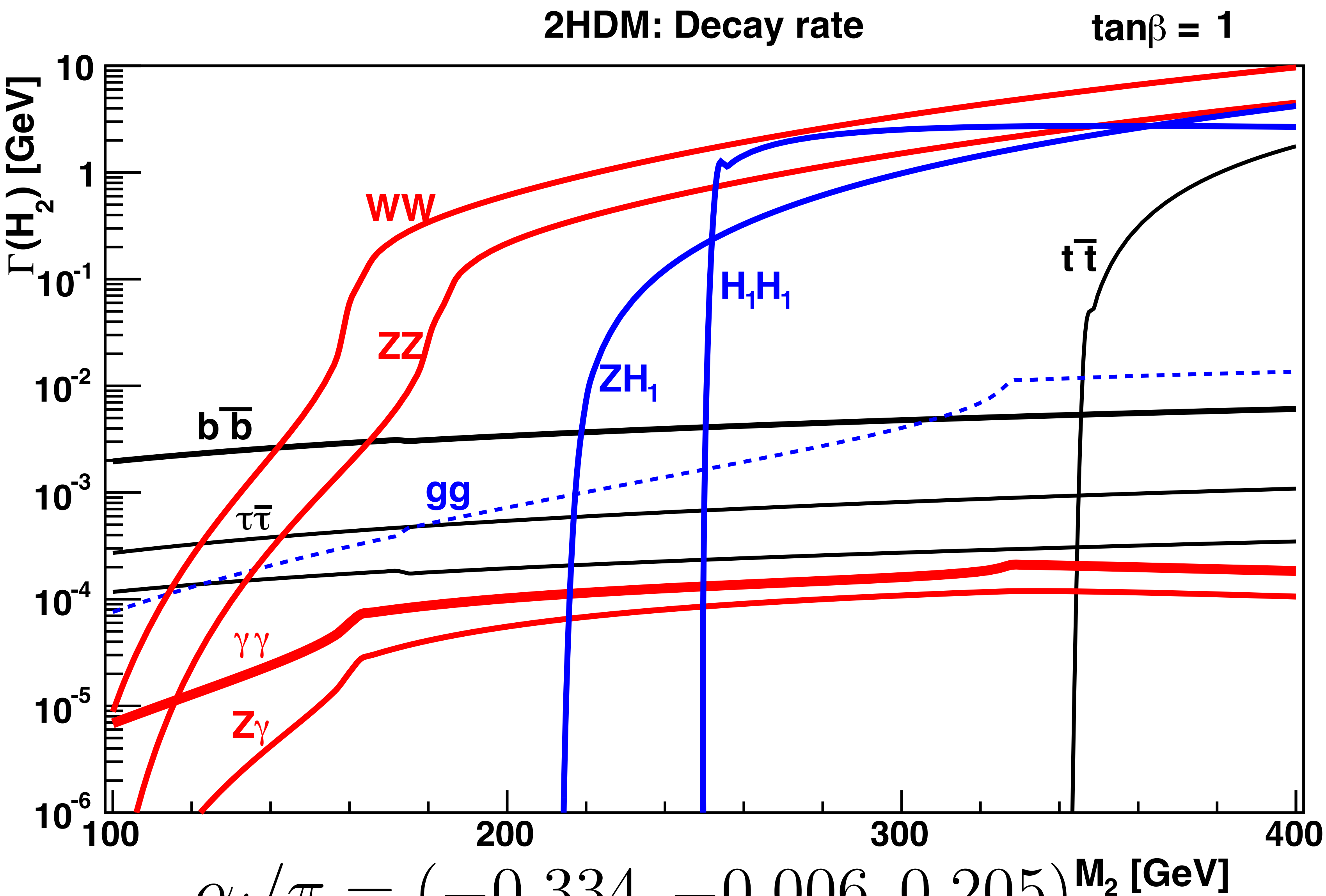
P4



$$\alpha_i/\pi = (0.35, -0.056, 0.43)$$

Decay rates

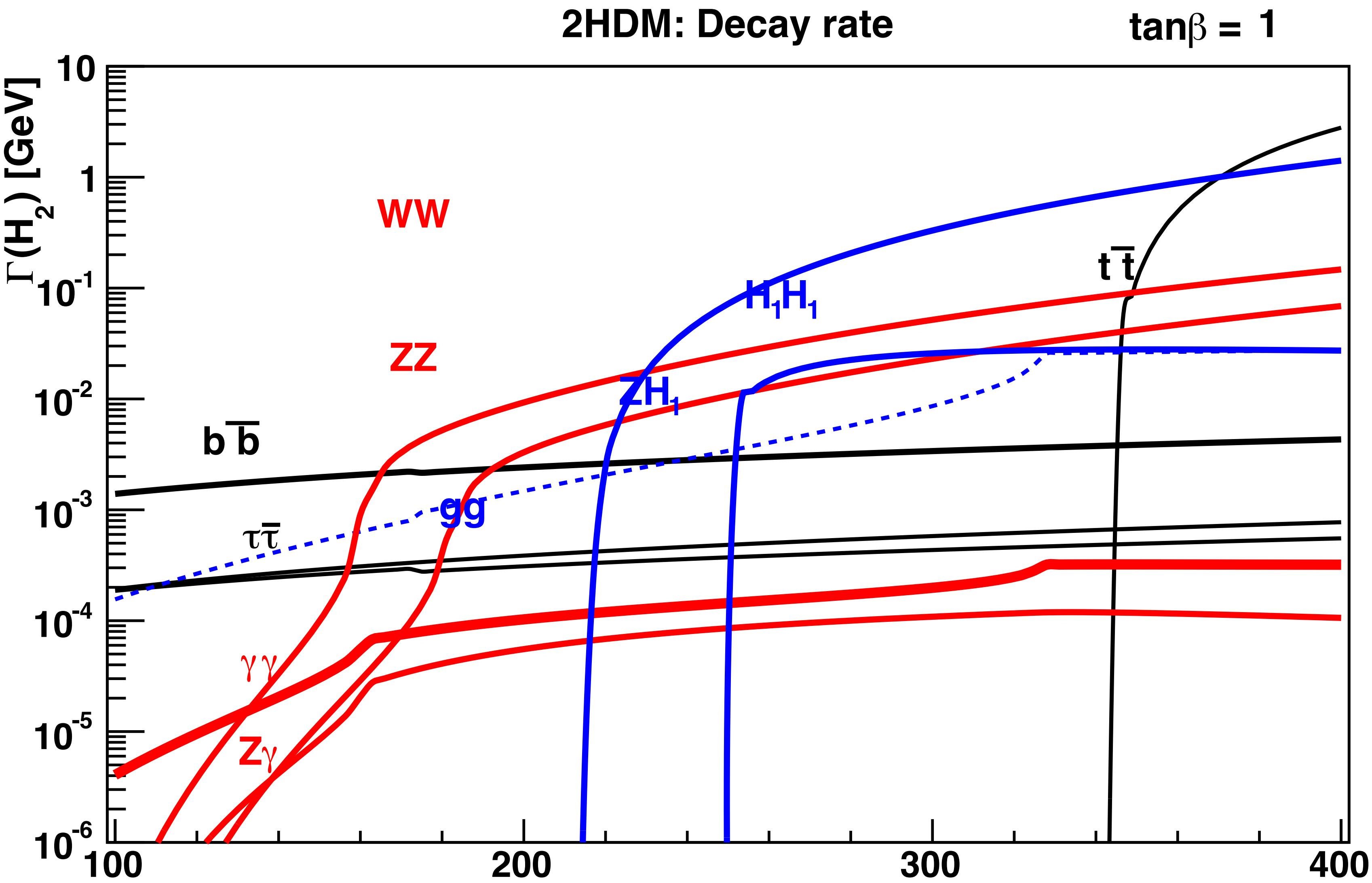
random



$$\alpha_i/\pi = (-0.334, -0.006, 0.205)$$

Decay rates

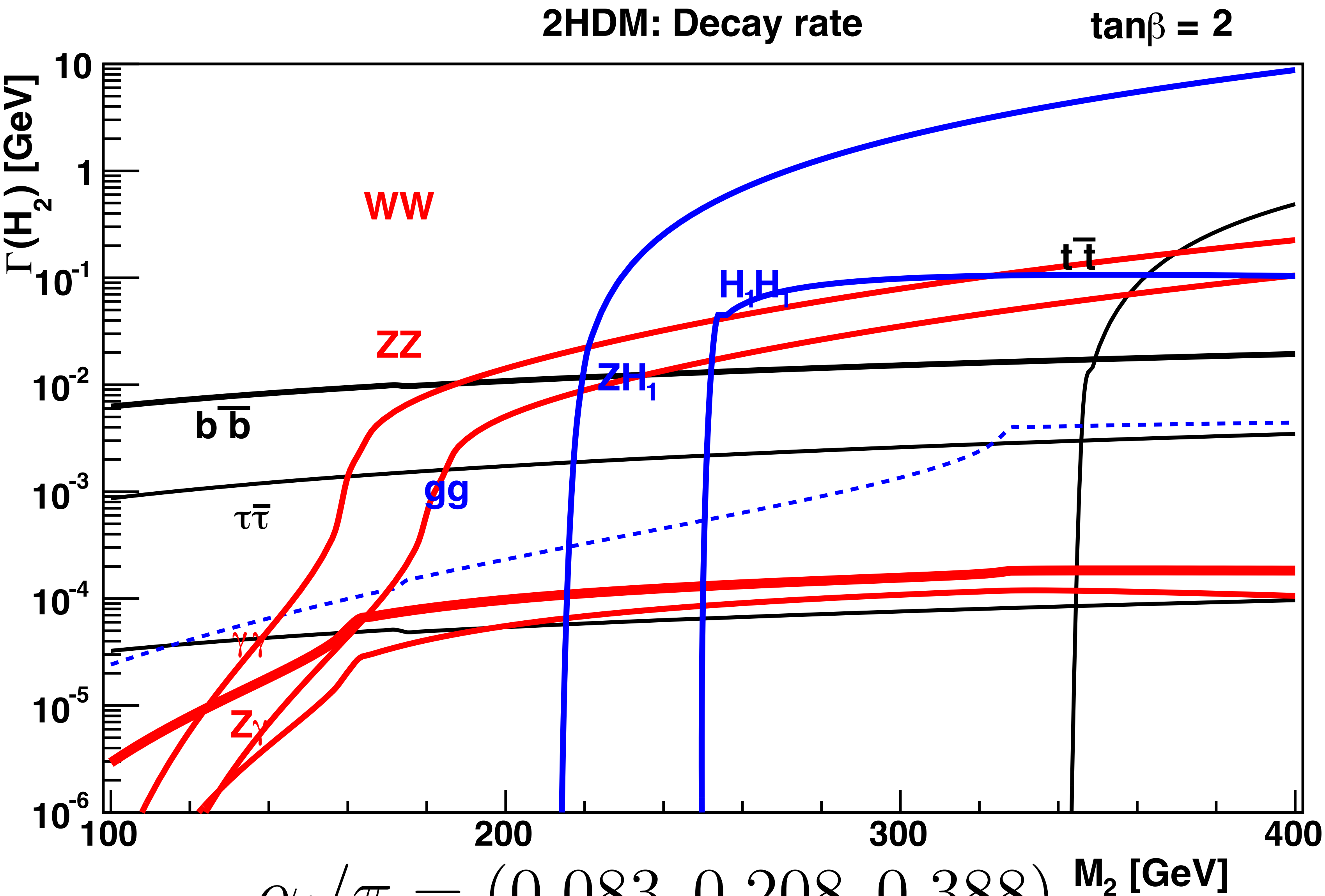
P4



$$\alpha_i/\pi = (0.35, -0.056, 0.43)$$

Decay rates

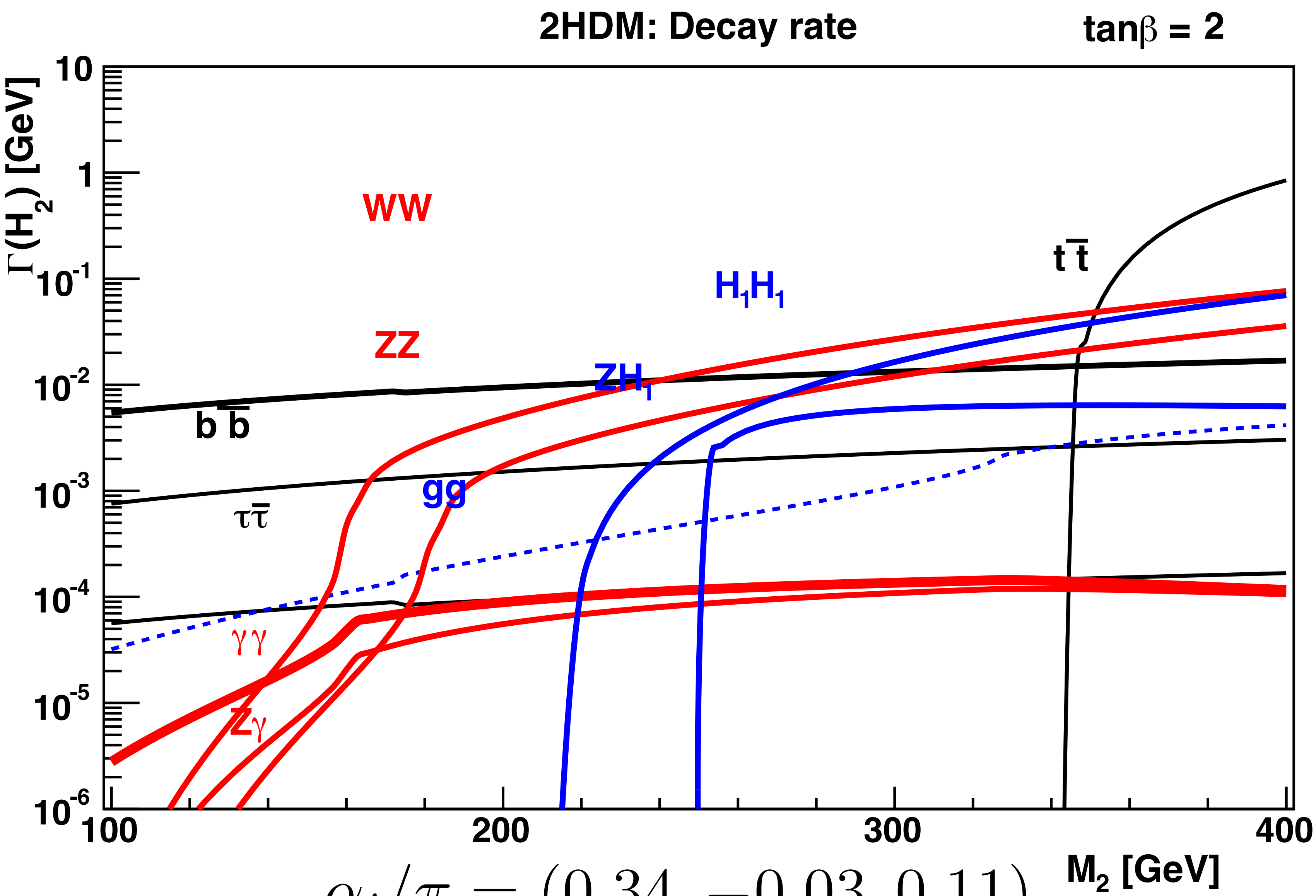
random



$$\alpha_i/\pi = (0.083, 0.208, 0.388)$$

Decay rates

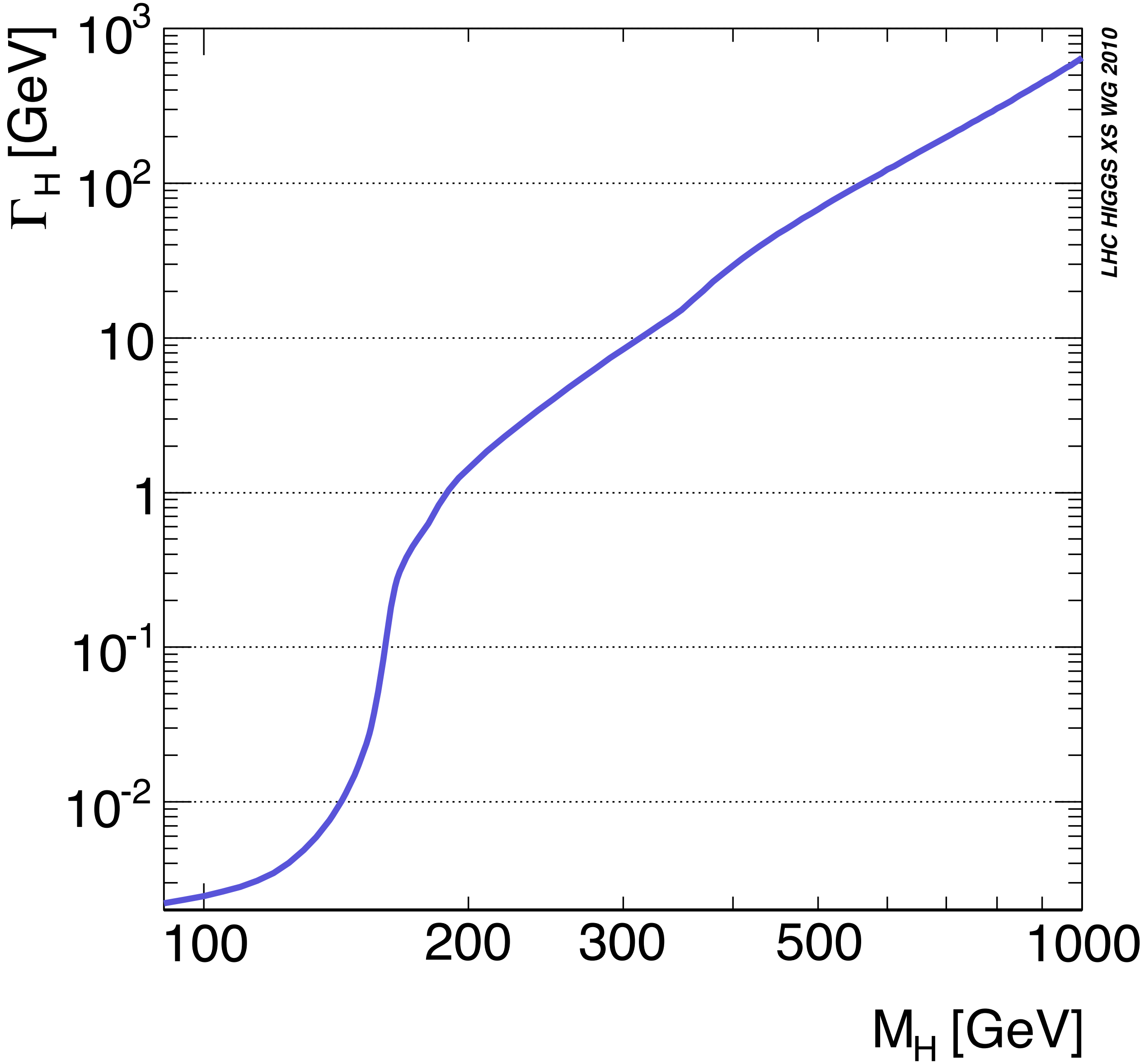
P8



$$\alpha_i/\pi = (0.34, -0.03, 0.11)$$

SM decay rate

stronger coupling to WW



H_2 (for example at 300 GeV) and H_3
must decay more slowly than SM Higgs (at same mass),
in order for model not to be excluded by LHC data

Constraints-theory

- Positivity
  - Explicit conditions
- Unitarity
  - Explicit conditions
- Perturbativity
- Global minimum
  - Three coupled cubic equations

Constraints-experiment

- $b \to s\gamma$
- $\Gamma(Z \to b\bar{b})$
- $B \to \tau\nu(X)$, $B \to D\tau\nu$, $D \to \tau\nu$
- $B_0 \leftrightarrow \bar{B}_0$
- $B_{d,s} \to \mu^+\mu^-$
- EW constraints: S, T
- Electron EDM
- LHC: $H_1 \to \gamma\gamma$
- LHC: $H_{2,3} \to W^+W^-$

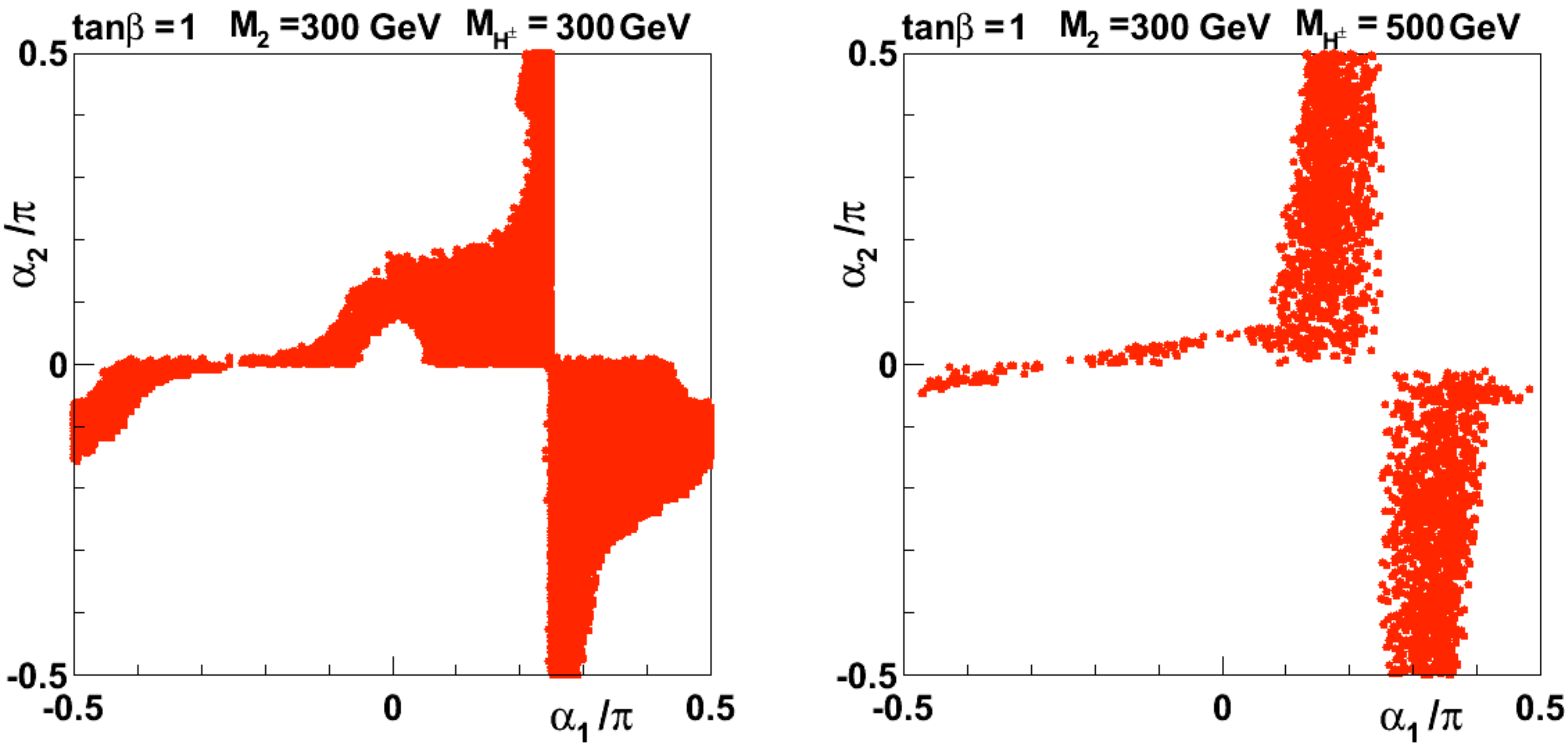
Parameters

Input: $\tan\beta,\ (M_1,\ M_2),\ (M_{H^\pm},\ \mu^2),\ (\alpha_1,\ \alpha_2,\ \alpha_3)$

	$\tan\beta$	$(M_1,\ M_2)$	$(M_{H^\pm},\ \mu^2)$	$(\alpha_1,\ \alpha_2,\ \alpha_3)$
Typically:	step	fix	step	scan

Allowed regions (red)

Ignore LHC (apologies)



LHC constraints

1 $gg \to H_1 \to \gamma\gamma$

$$R_{\gamma\gamma} = \frac{\Gamma(H_1 \to gg)\mathrm{BR}(H_1 \to \gamma\gamma)}{\Gamma(H_{\mathrm{SM}} \to gg)\mathrm{BR}(H_{\mathrm{SM}} \to \gamma\gamma)}$$

Triangle diagrams modified by couplings, also axial term

$$0.5 \leq R_{\gamma\gamma} \leq 2.0$$

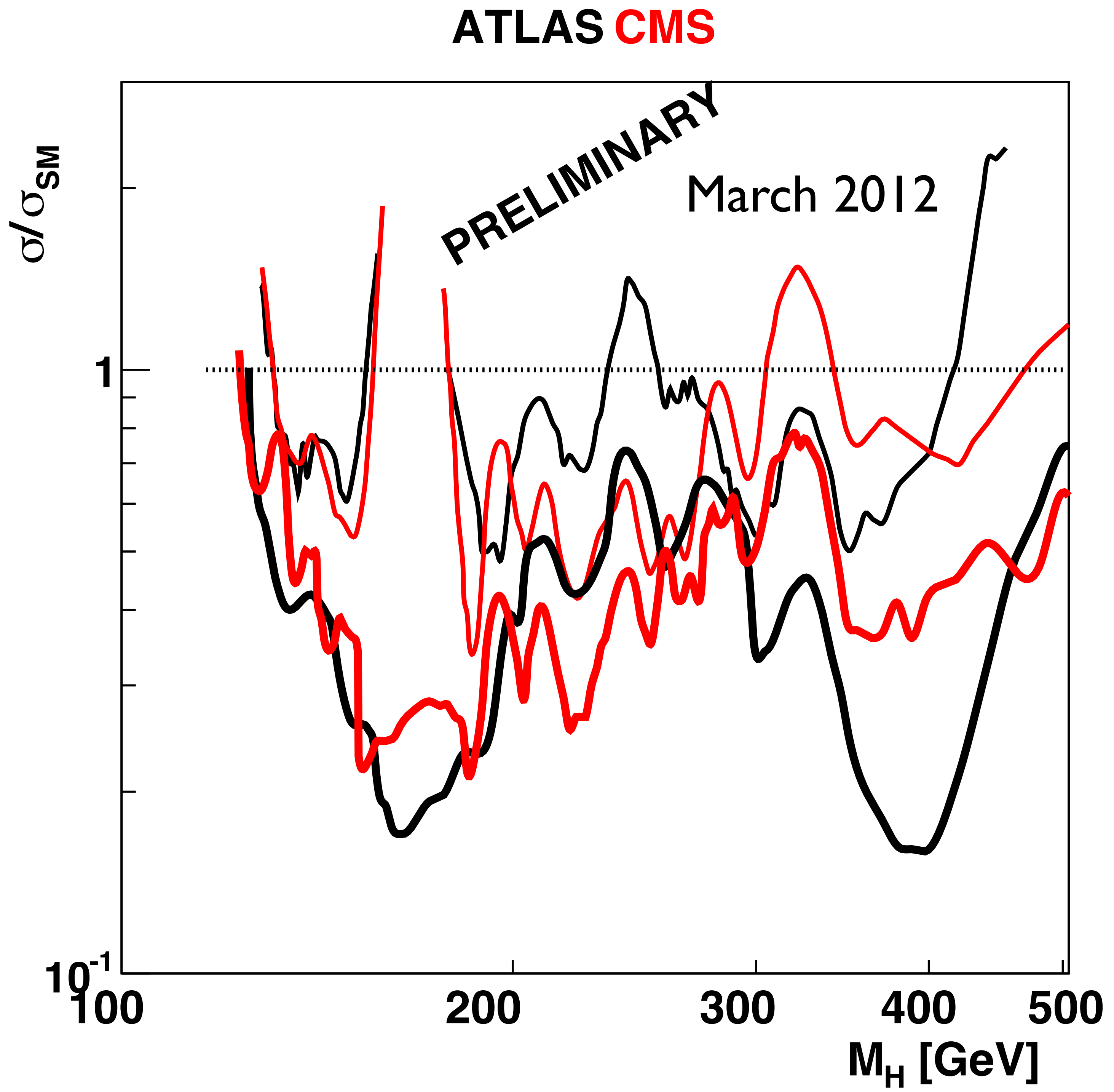
---

2 $gg \to H_{2,3} \to W^+W^-$

$$R_{ZZ} = \frac{\Gamma(H_j \to gg)\mathrm{BR}(H_j \to ZZ)}{\Gamma(H_{\mathrm{SM}} \to gg)\mathrm{BR}(H_{\mathrm{SM}} \to ZZ)}$$

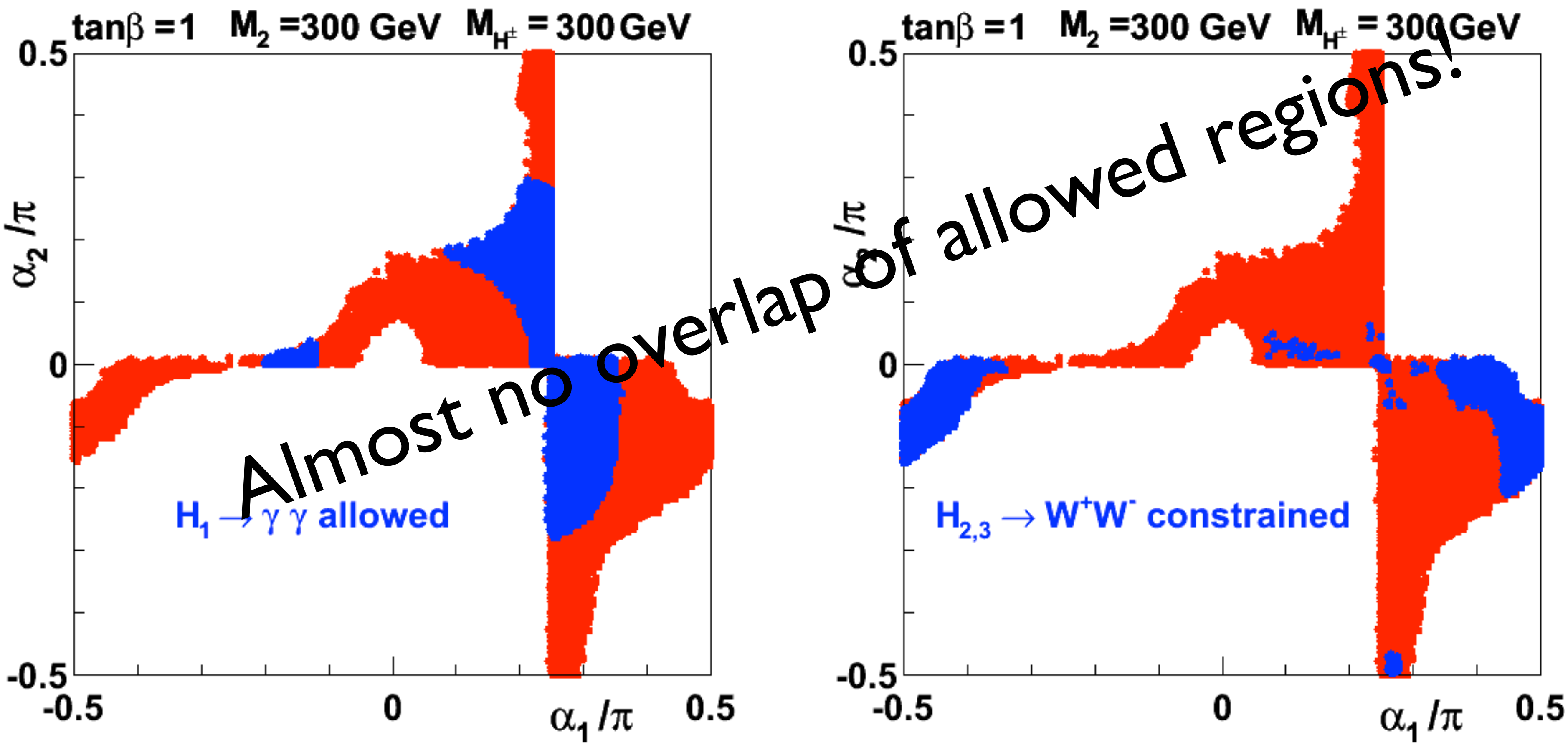
bounded

Adopt LHC (ATLAS & CMS) 95% CL


ATLAS CMS
PRELIMINARY
March 2012
σ/σSM
1
10-1
100
200
300
400
500
MH [GeV]

Allowed regions

LHC constraints

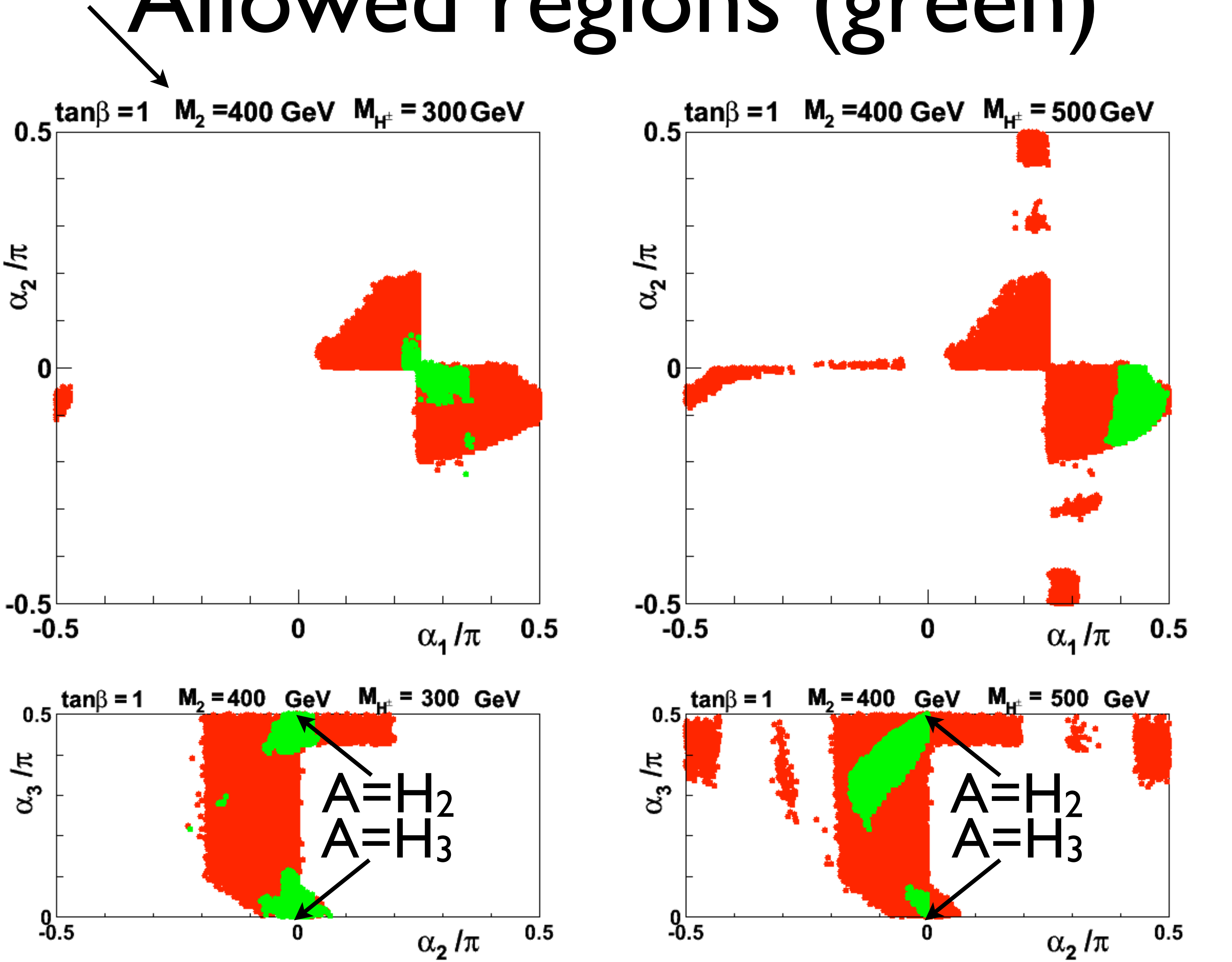


Almost no overlap of allowed regions!

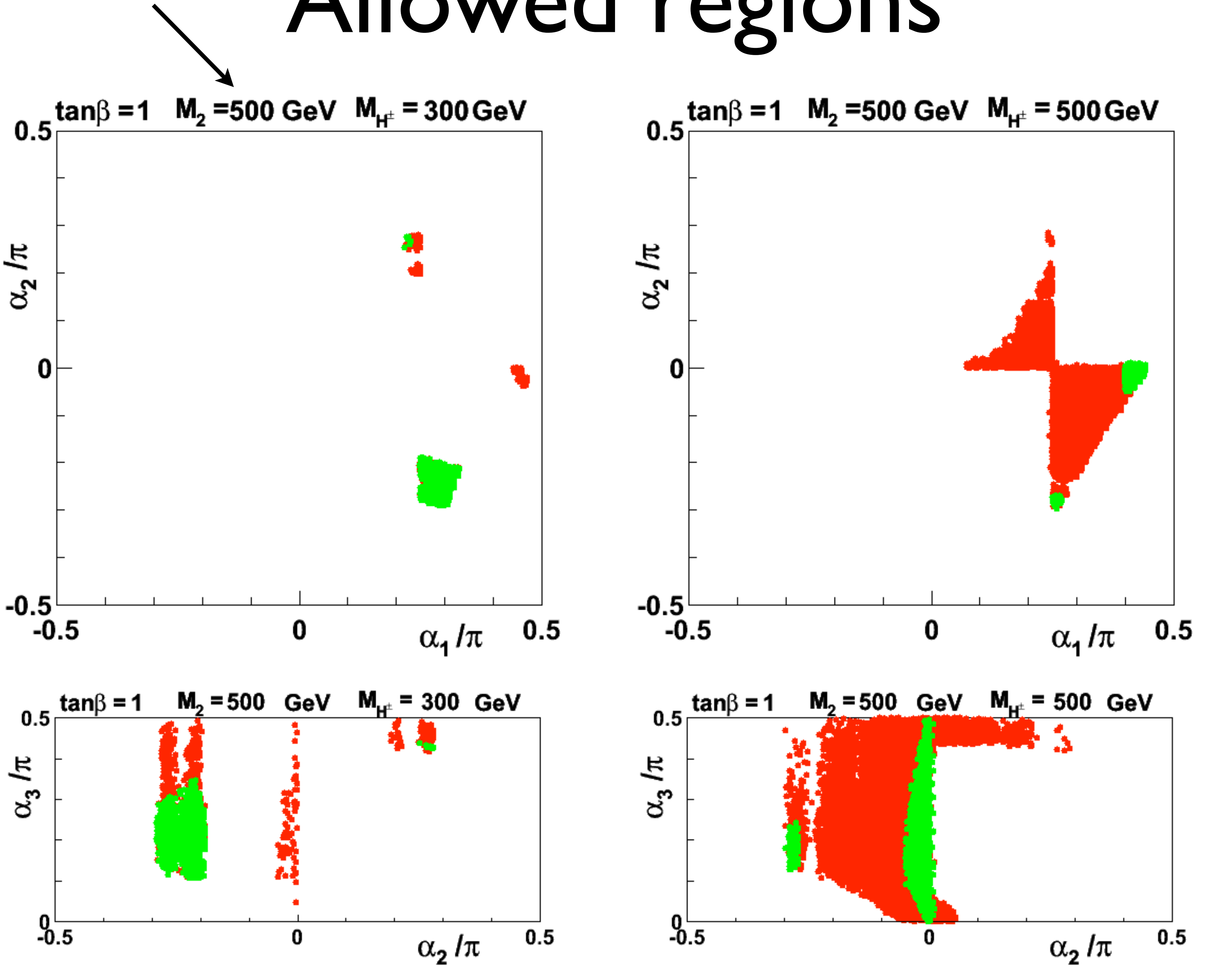
Next:

- Combine all constraints:

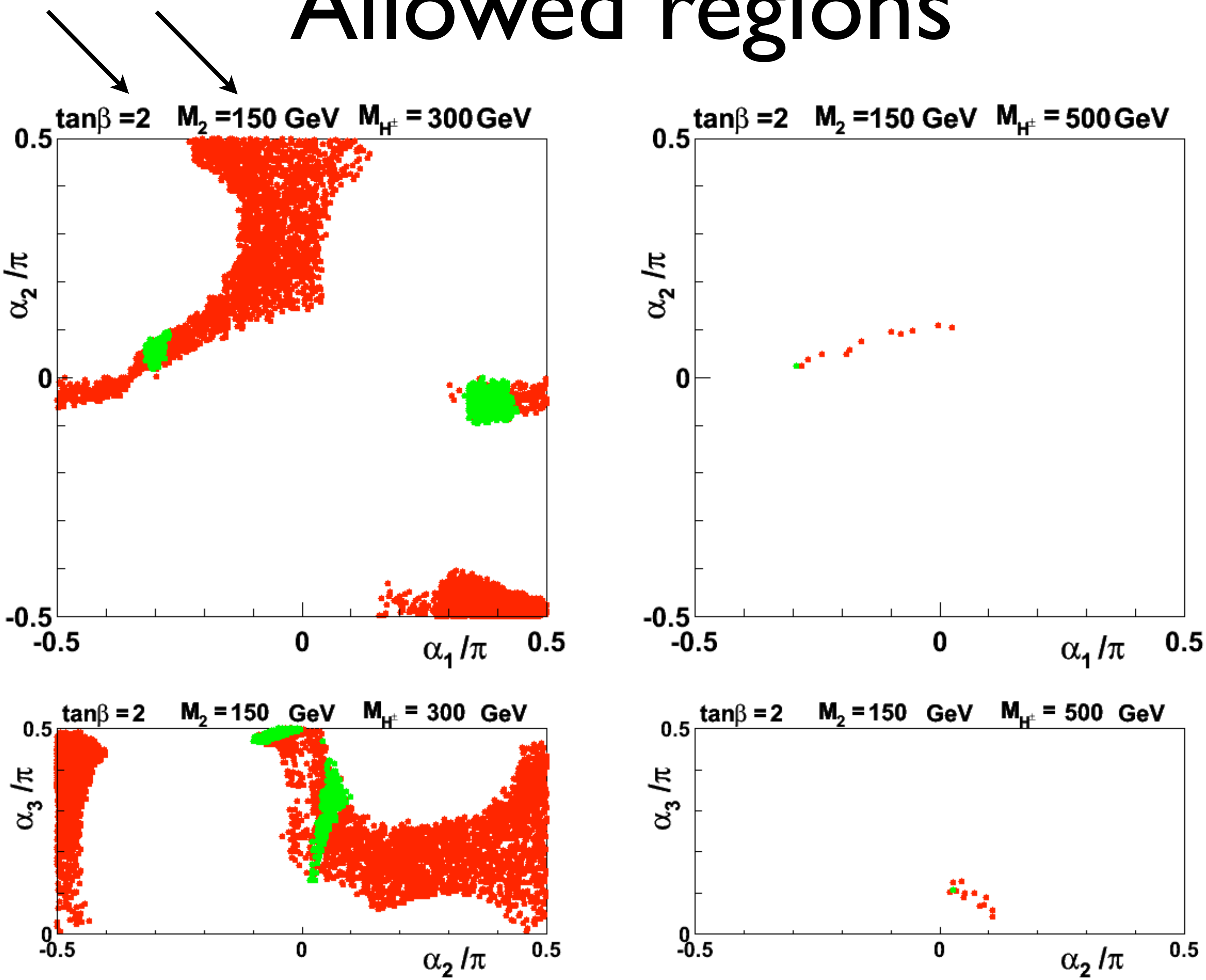
Allowed regions (green)



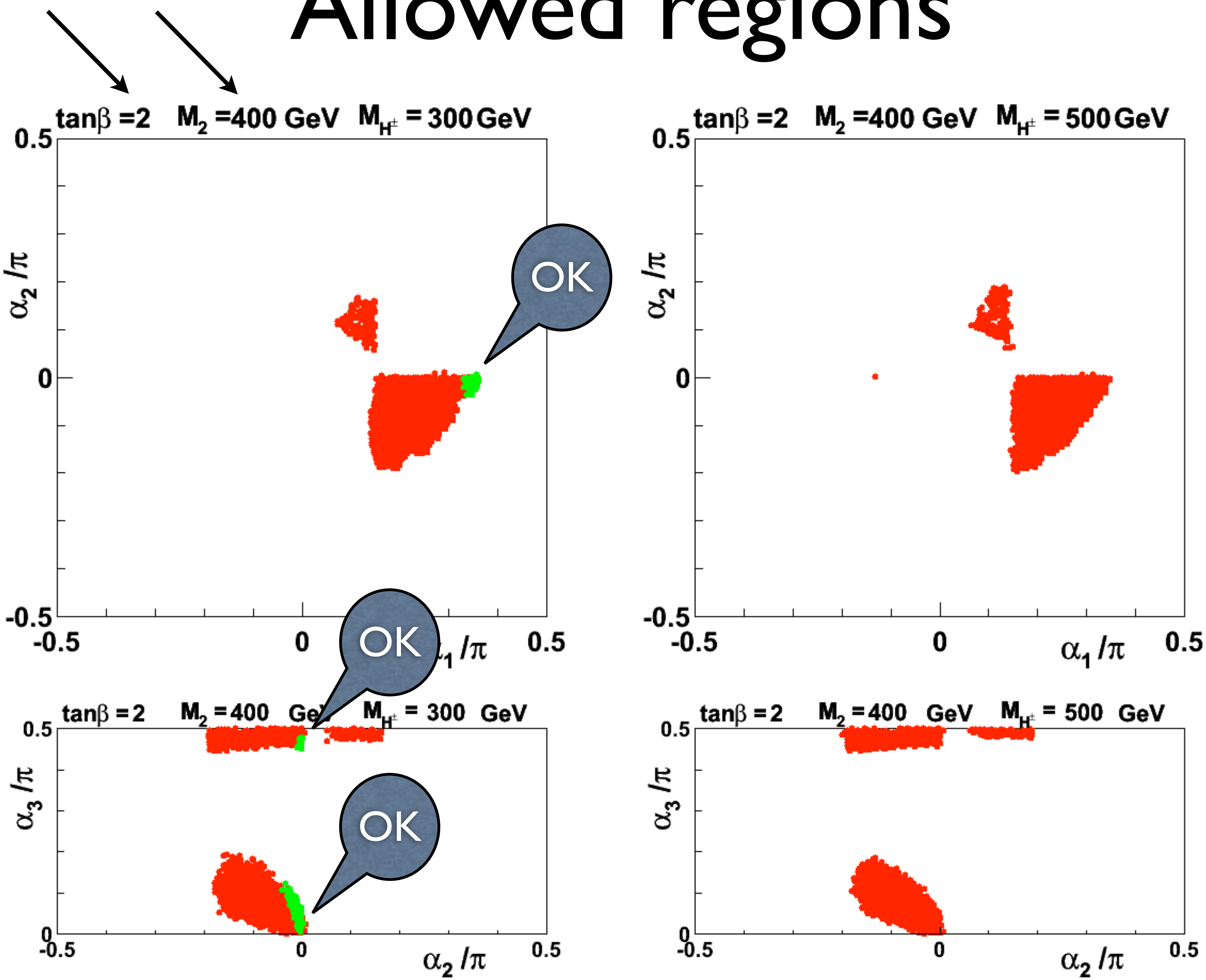
Allowed regions



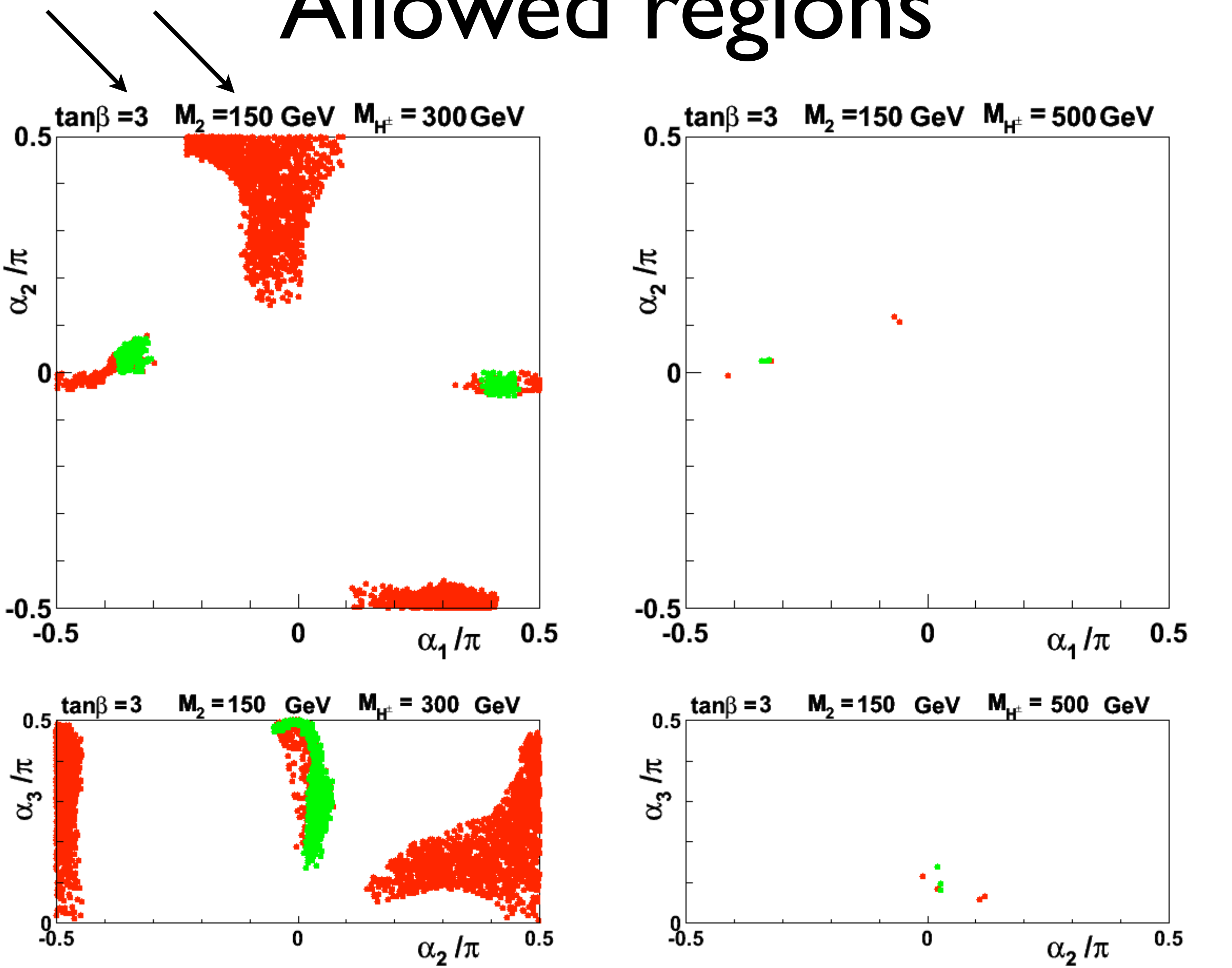
Allowed regions



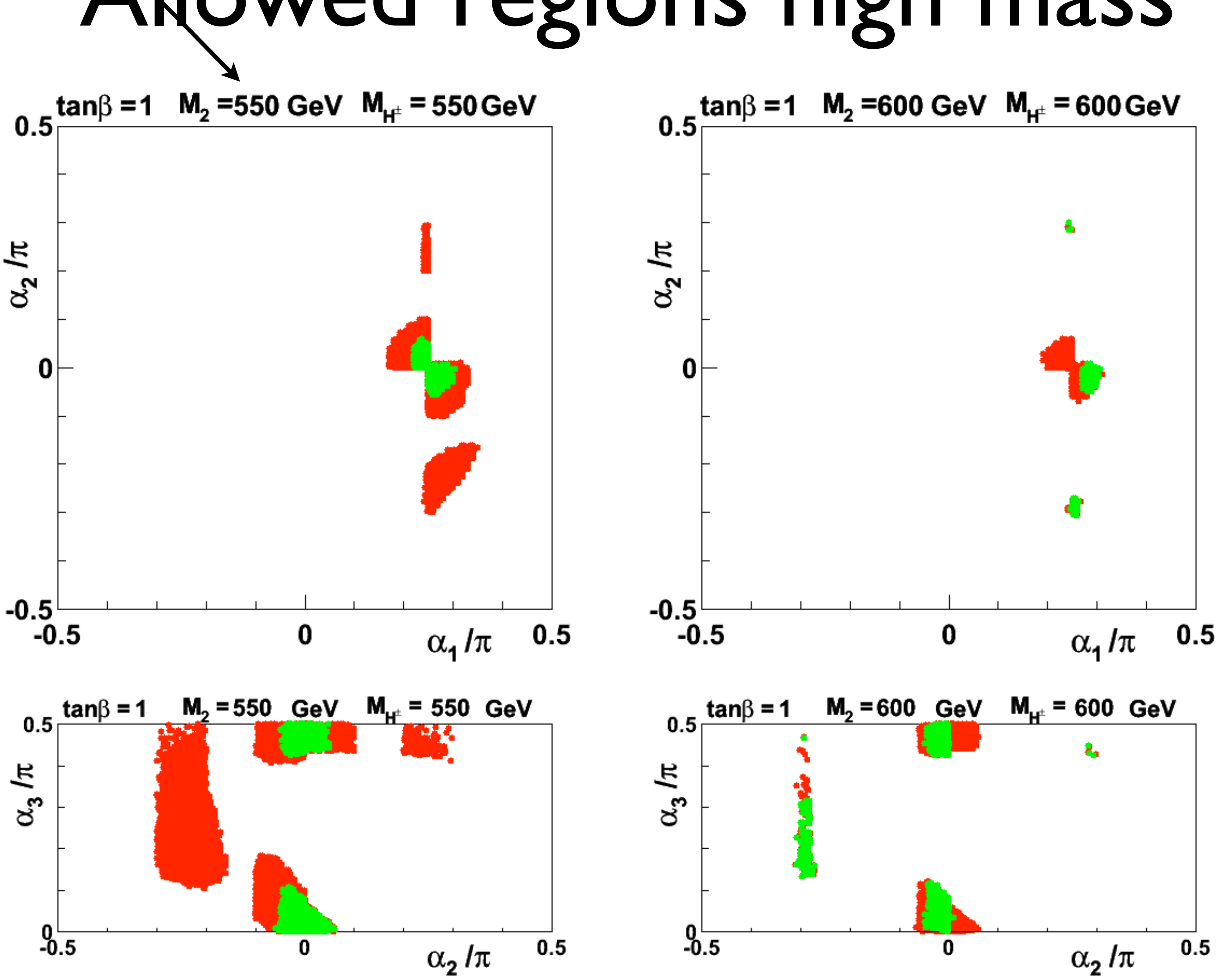
Allowed regions



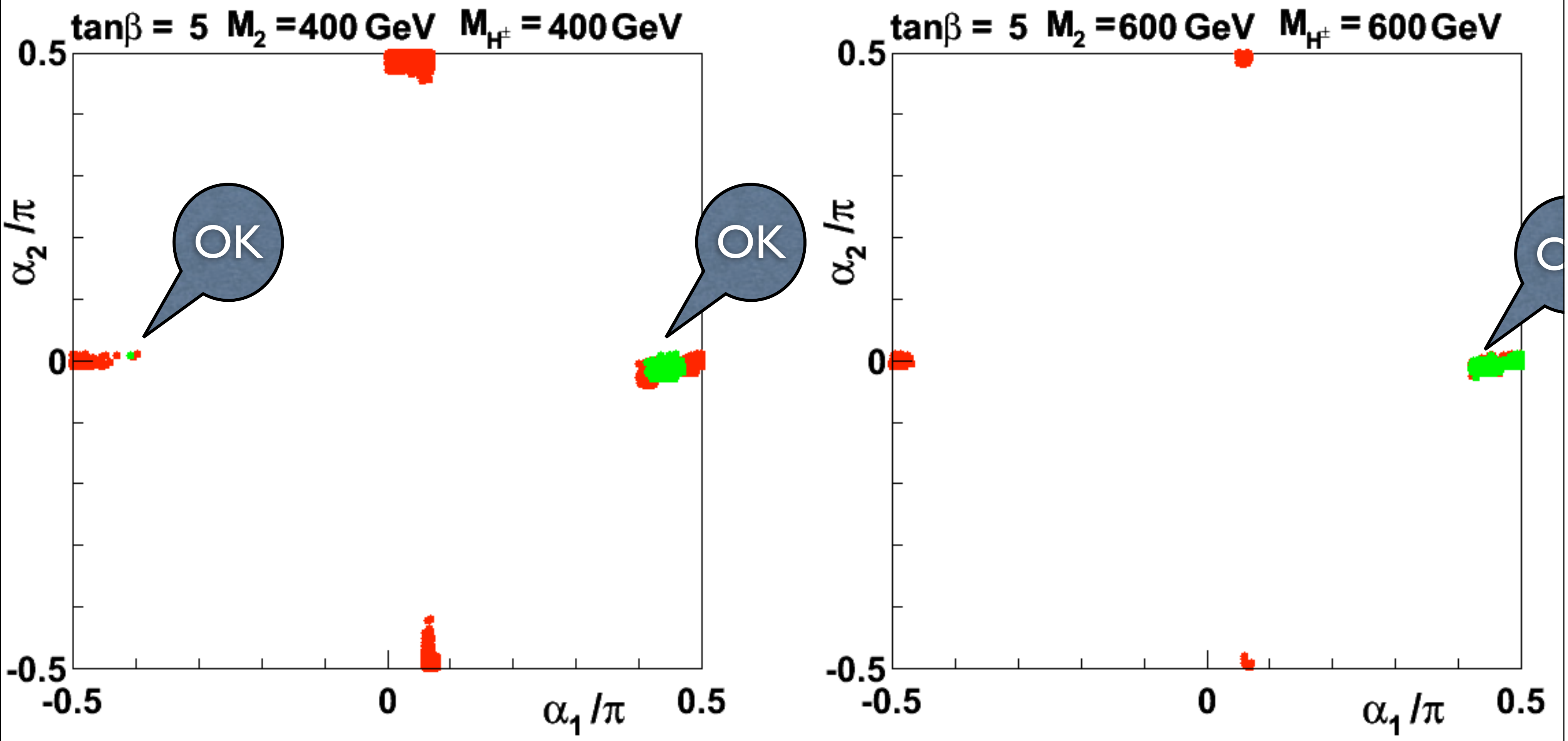
Allowed regions



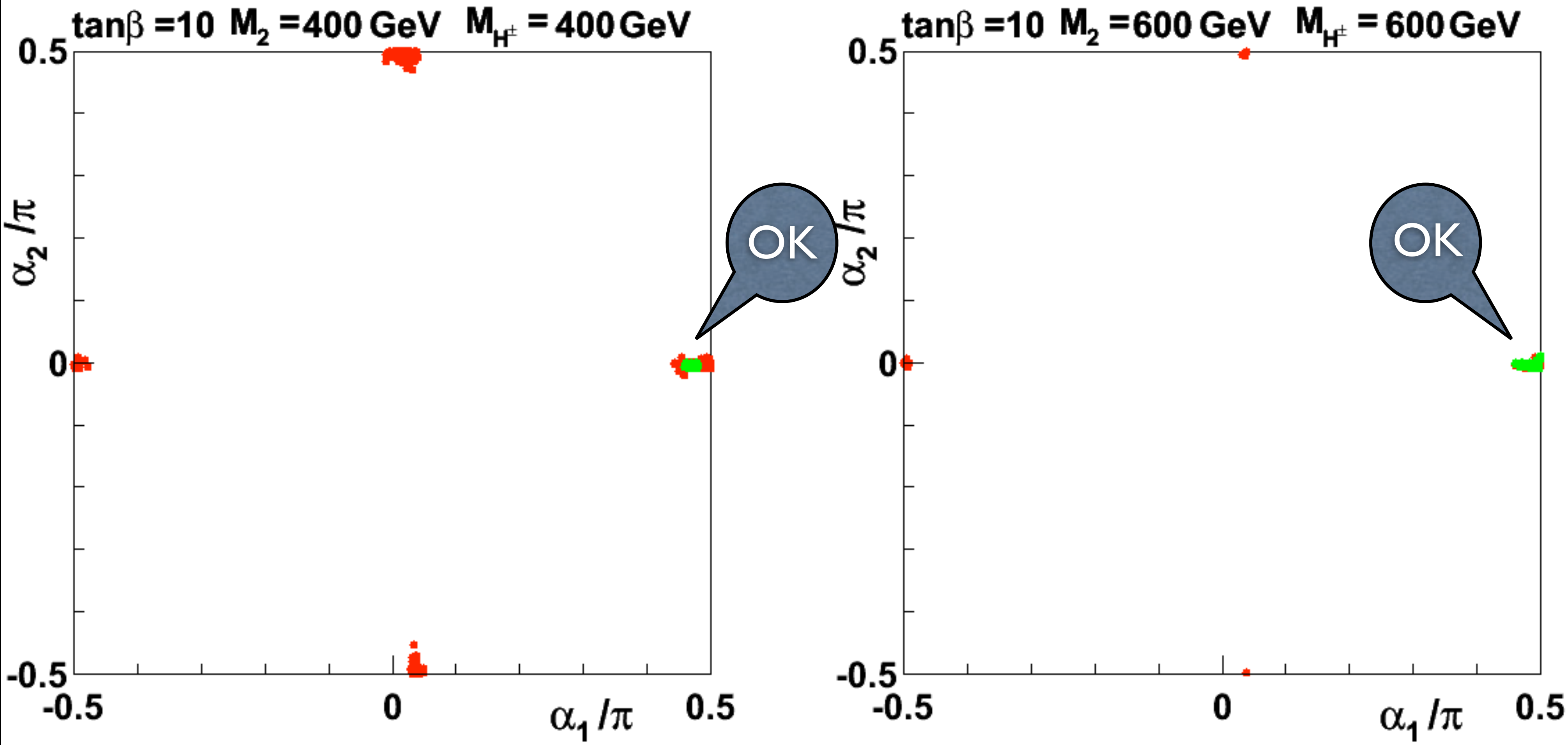
Allowed regions high mass



Allowed regions high tanbeta



Allowed regions high tanbeta



Decoupling

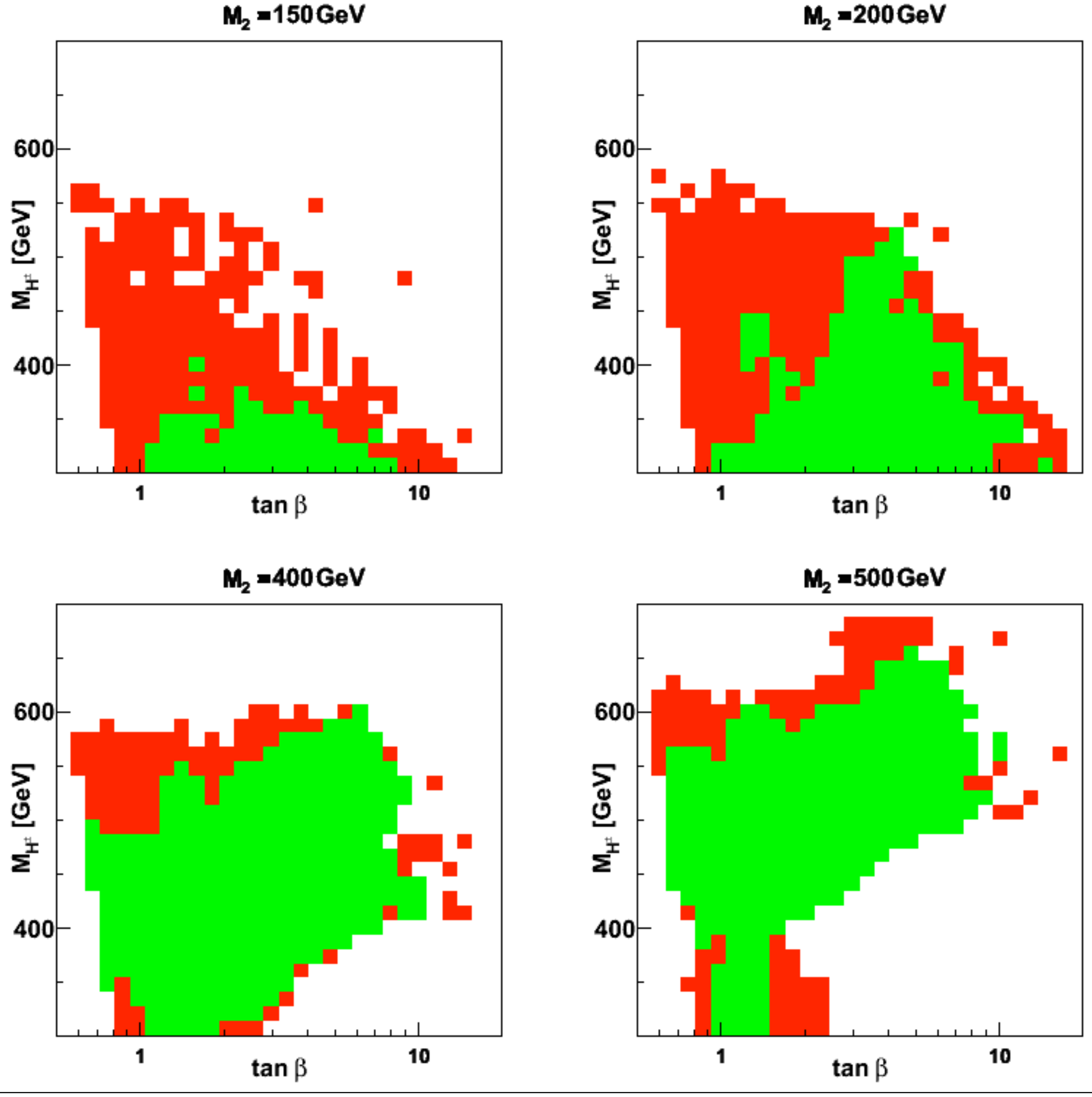
$A=H_2, A=H_3$

$$\text{Decoupling 1:} \quad (\alpha_1, \alpha_2) \sim (\pm\pi/2, 0)$$

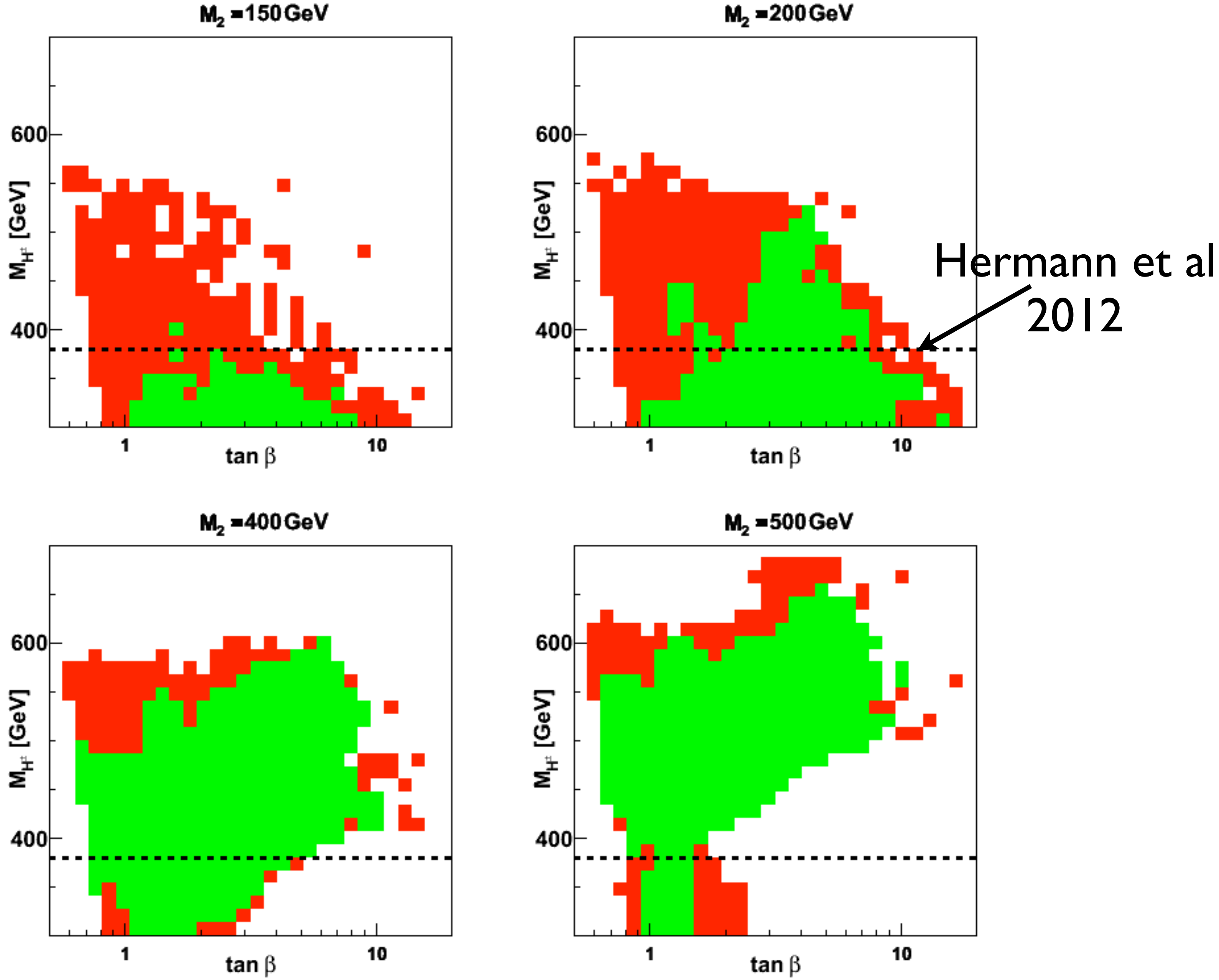
$$\text{Decoupling 2:} \quad (\alpha_1, \alpha_2) \sim (0, \pm\pi/2)$$

$A=H_1$ Excluded by LHC

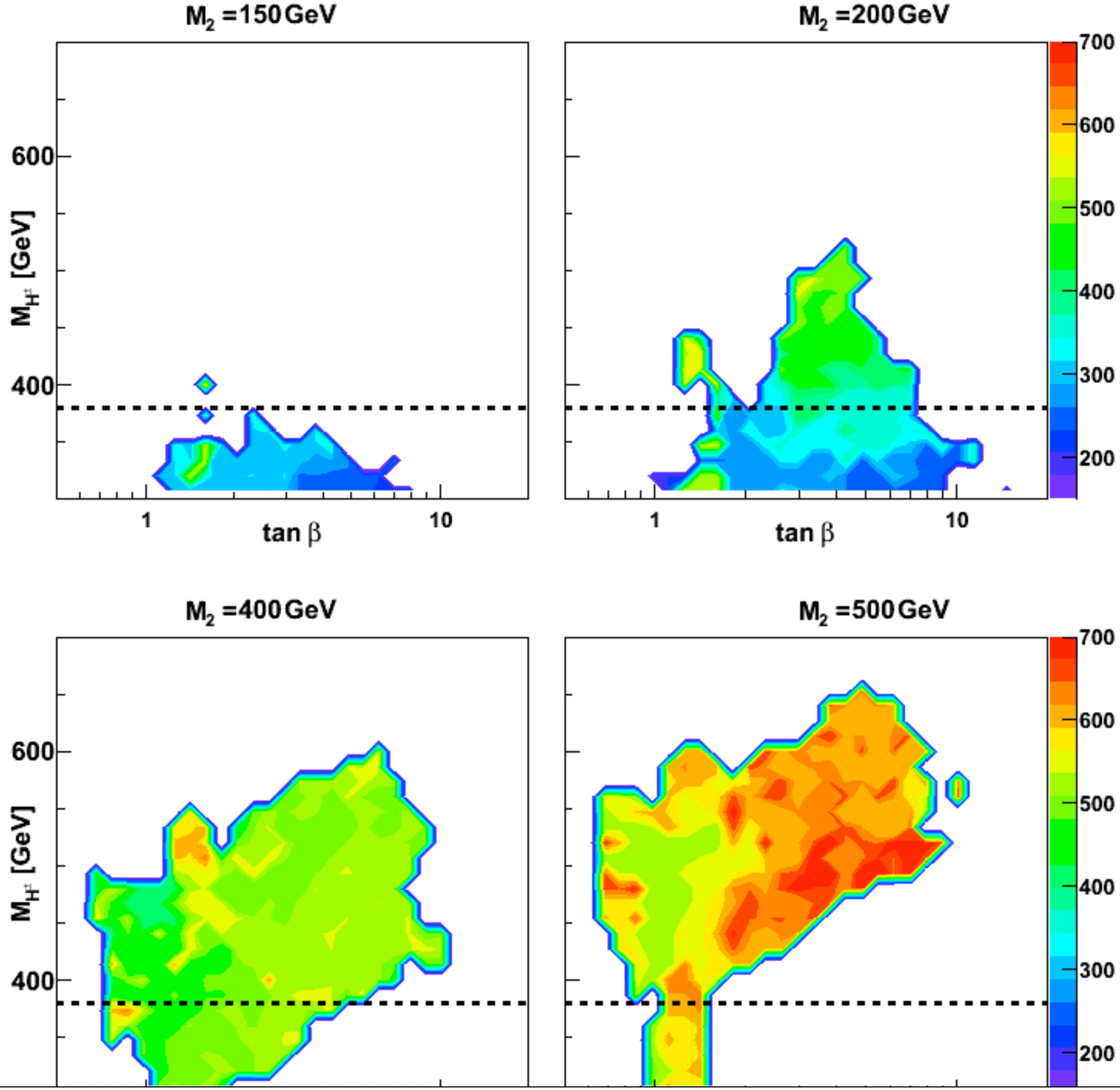
Overview $0.5 \leq R_{\gamma\gamma} \leq 2.0$



Overview $0.5 \leq R_{\gamma\gamma} \leq 2.0$



H_3 mass, M_3

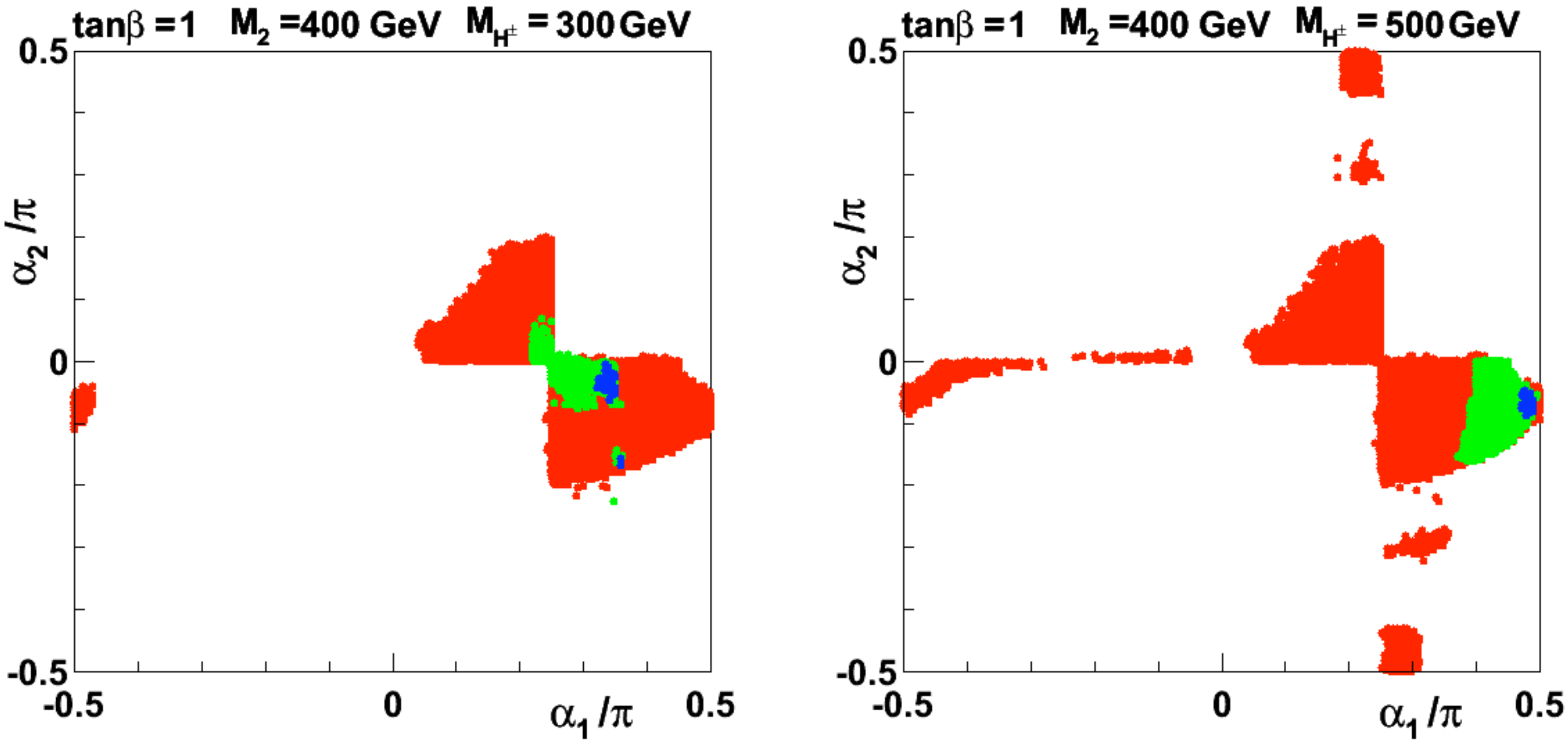


M2 =150GeV
M2 =200GeV
M2 =400GeV
M2 =500GeV
MH± [GeV]
tan β
600
400
1
10
700
600
500
400
300
200

$H_1 \to \gamma\gamma$

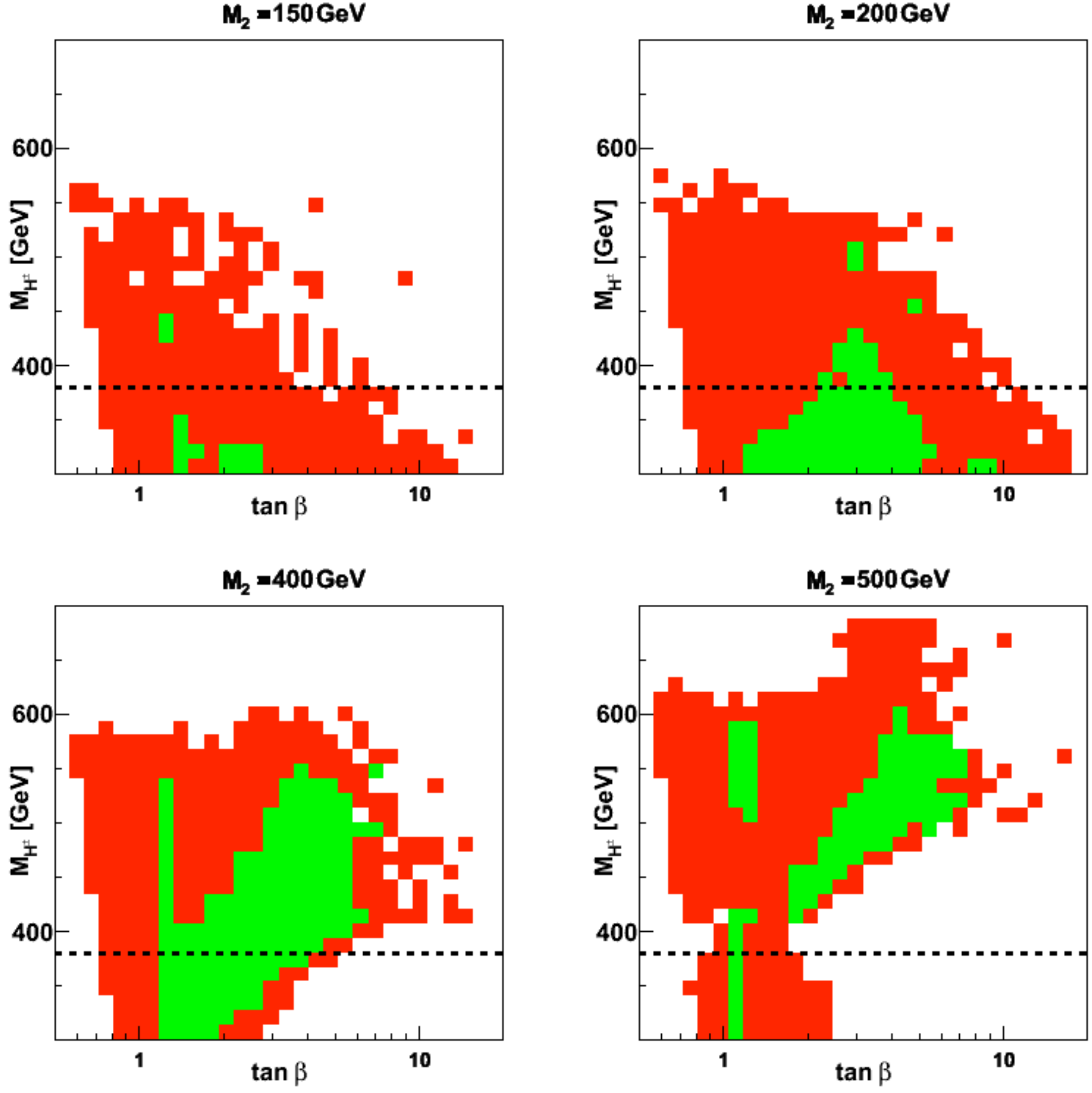
- $R_{\gamma\gamma} > 1?$
- In SM W and t loop interfere destructively
- $H_j t\bar{t}:$ $\qquad \dfrac{-ig\, m_t}{2\, m_W}\dfrac{1}{\sin\beta}\,[R_{j2} - i\gamma_5 \cos\beta R_{j3}].$
- Flip sign of t-loop?
- $R_{12} = s_1 c_2, \quad s_1 < 0? \quad c_2 < 0?$
- Also γ_5 term (additive)

Tight: $1.5 \leq R_{\gamma\gamma} \leq 2.0$



Blue region satisfies tight constraint

Tight: $1.5 \leq R_{\gamma\gamma} \leq 2.0$



Charged Higgs Benchmarks

	α_1/π	α_2/π	α_3/π	$\tan\beta$	M_2	$M_{H^\pm}^{\min}, M_{H^\pm}^{\max}$
P_1	0.23	0.06	0.005	1	300	300,325
P_2	0.35	-0.014	0.48	1	300	300,415
P_3	0.35	-0.015	0.496	1	350	300,450
P_4	0.35	-0.056	0.43	1	400	300,455
P_5	0.33	-0.21	0.23	1	450	300,470
P_6	0.27	-0.26	0.25	1	500	300,340
P_7	0.39	-0.07	0.33	2	300	300,405
P_8	0.34	-0.03	0.11	2	400	300,315
P_9	0.47	-0.006	0.05	10	400	400,440
P_{10}	0.49	-0.002	0.06	10	600	600,700

Requirements:

- Not excluded by theoretical arguments
- Not excluded by experimental data
- Good production cross section
- Good BR for decay to $W + H_1$
- Moderate background

Proposed channel:

$$pp \to W^{\pm} H^{\mp} (+X)$$
$$\to W^{+} W^{-} H_1$$
$$\to \underbrace{jj}_{W} \underbrace{\ell^{\pm}\nu}_{W} \underbrace{b\bar{b}}_{H_1}$$

Proposed channel:

$$pp \to W^\pm H^\mp (+X)$$

$$\to W^+ W^- H_1$$

$$\to \underbrace{jj}_{W} \underbrace{\ell^\pm \nu}_{W} \underbrace{b\bar{b}}_{H_1}$$

$H_j H^\pm W^\mp$ **coupling squared:**

$$\sim (\sin\beta R_{j1} - \cos\beta R_{j2})^2 + R_{j3}^2$$

$$H_1 H^\pm W^\mp : = \sin^2(\beta - \alpha_1)\cos^2\alpha_2 + \sin^2\alpha_2$$

Proposed channel:

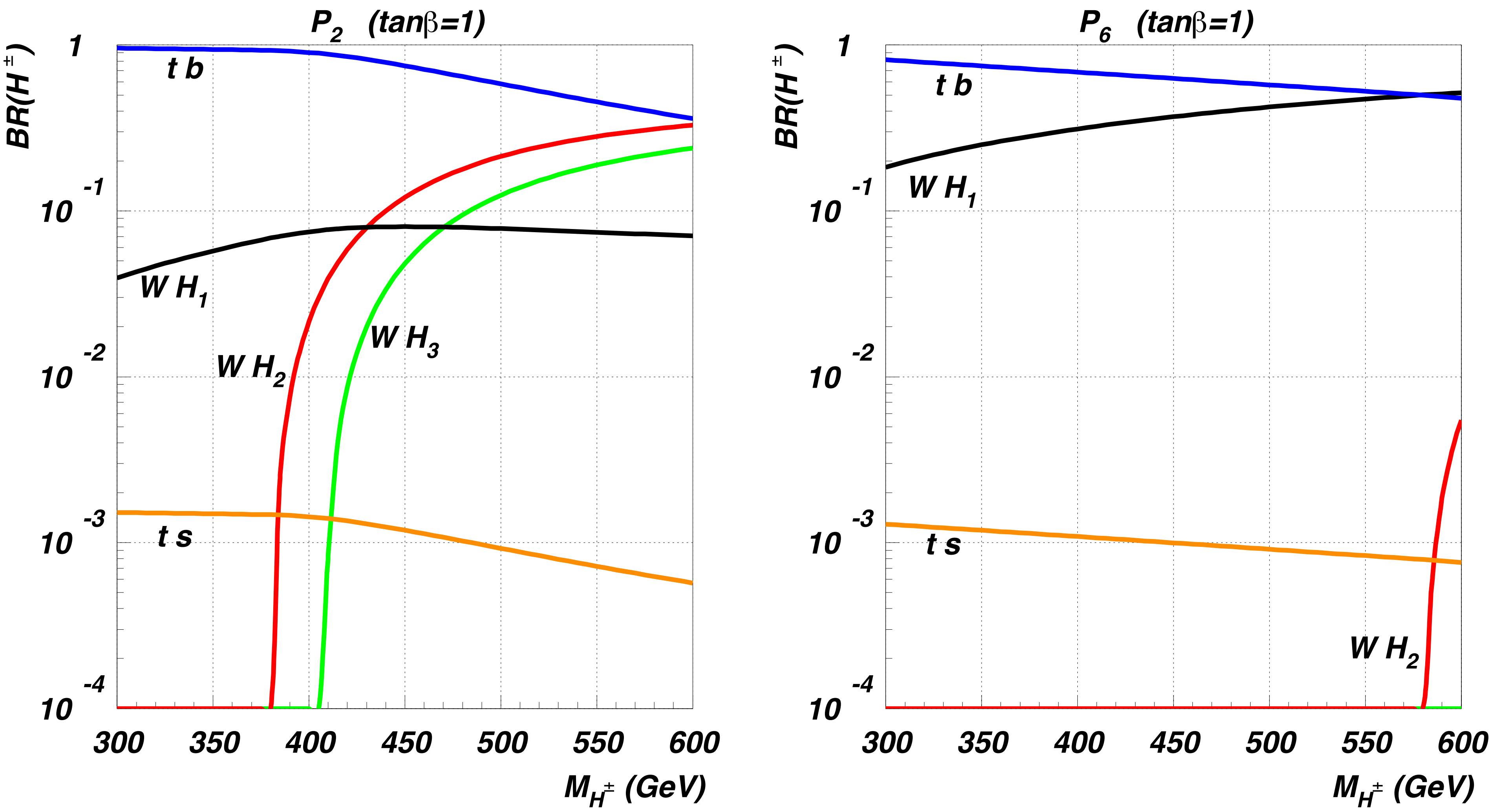
$$pp \to W^\pm H^\mp (+X)$$
$$\to W^+ W^- H_1$$
$$\to \underbrace{jj}_{W} \underbrace{\ell^\pm \nu}_{W} \underbrace{b\bar{b}}_{H_1}$$

$H_j H^\pm W^\mp$ **coupling squared:**

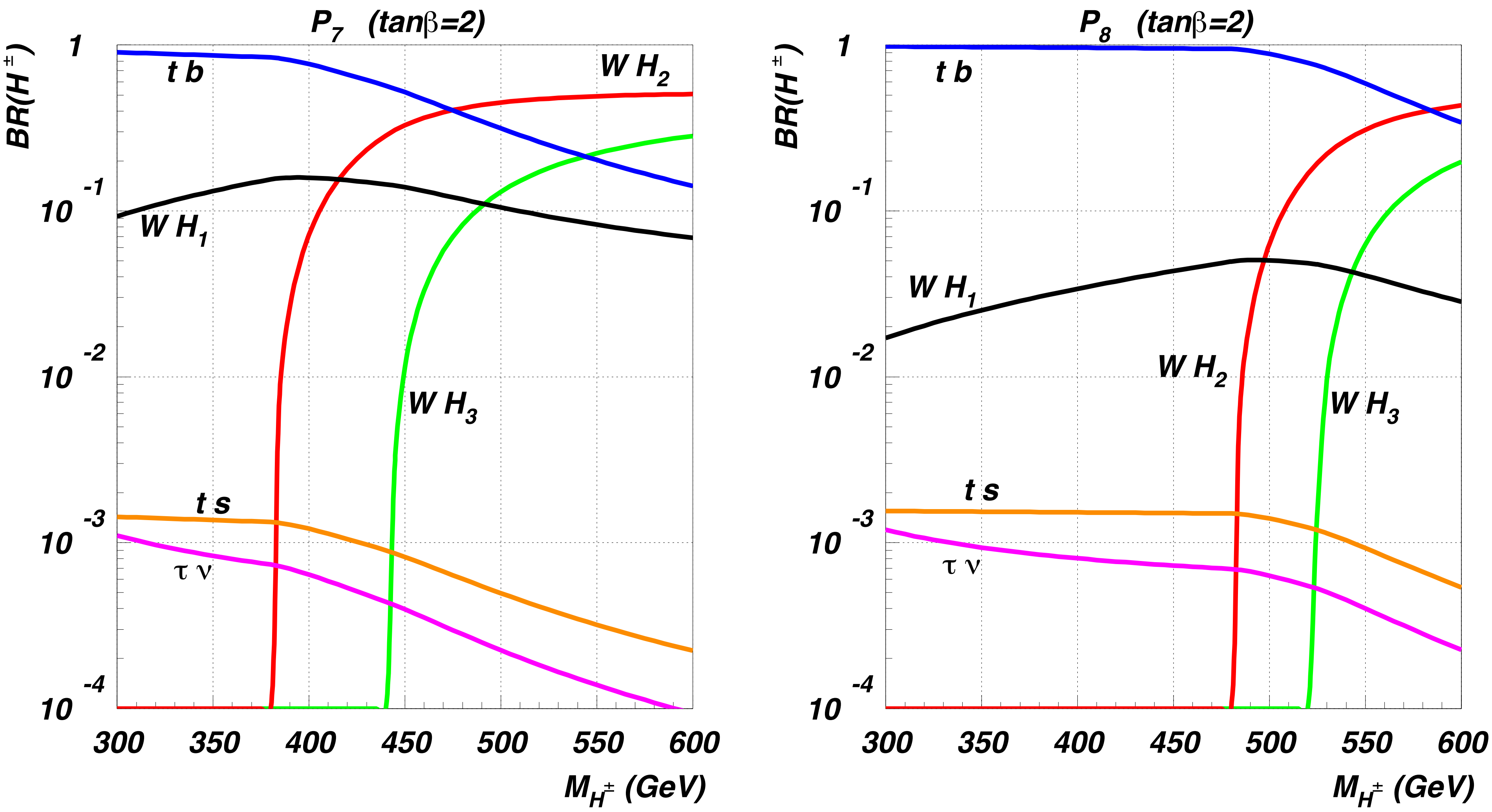
$$\sim (\sin\beta R_{j1} - \cos\beta R_{j2})^2 + R_{j3}^2$$

$$H_1 H^\pm W^\mp : \quad = \sin^2(\beta - \alpha_1) + \sin^2\alpha_2 \cos^2(\beta - \alpha_1)$$

Branching ratios:

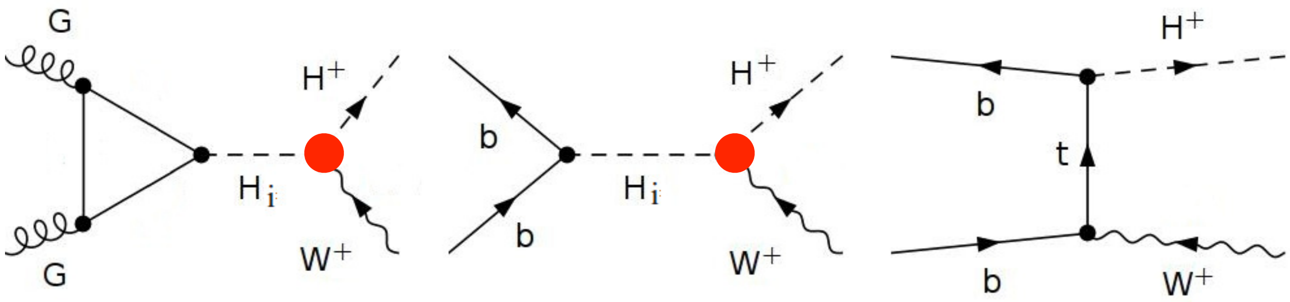


Branching ratios:



Dominant production mechanisms

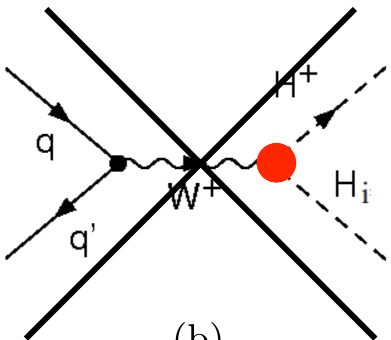
Coupling may depend on details



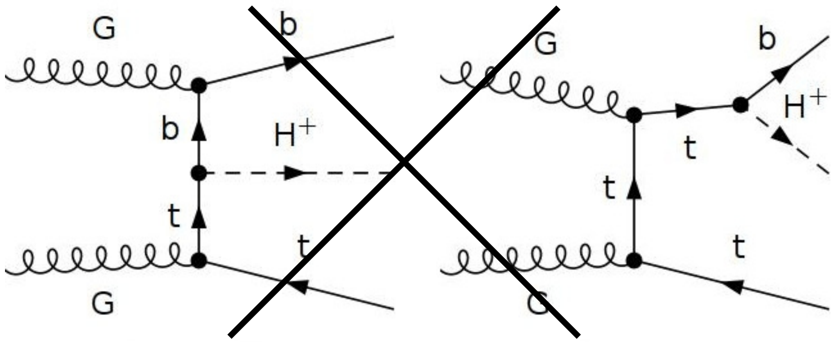
(a)

irreducible background

small



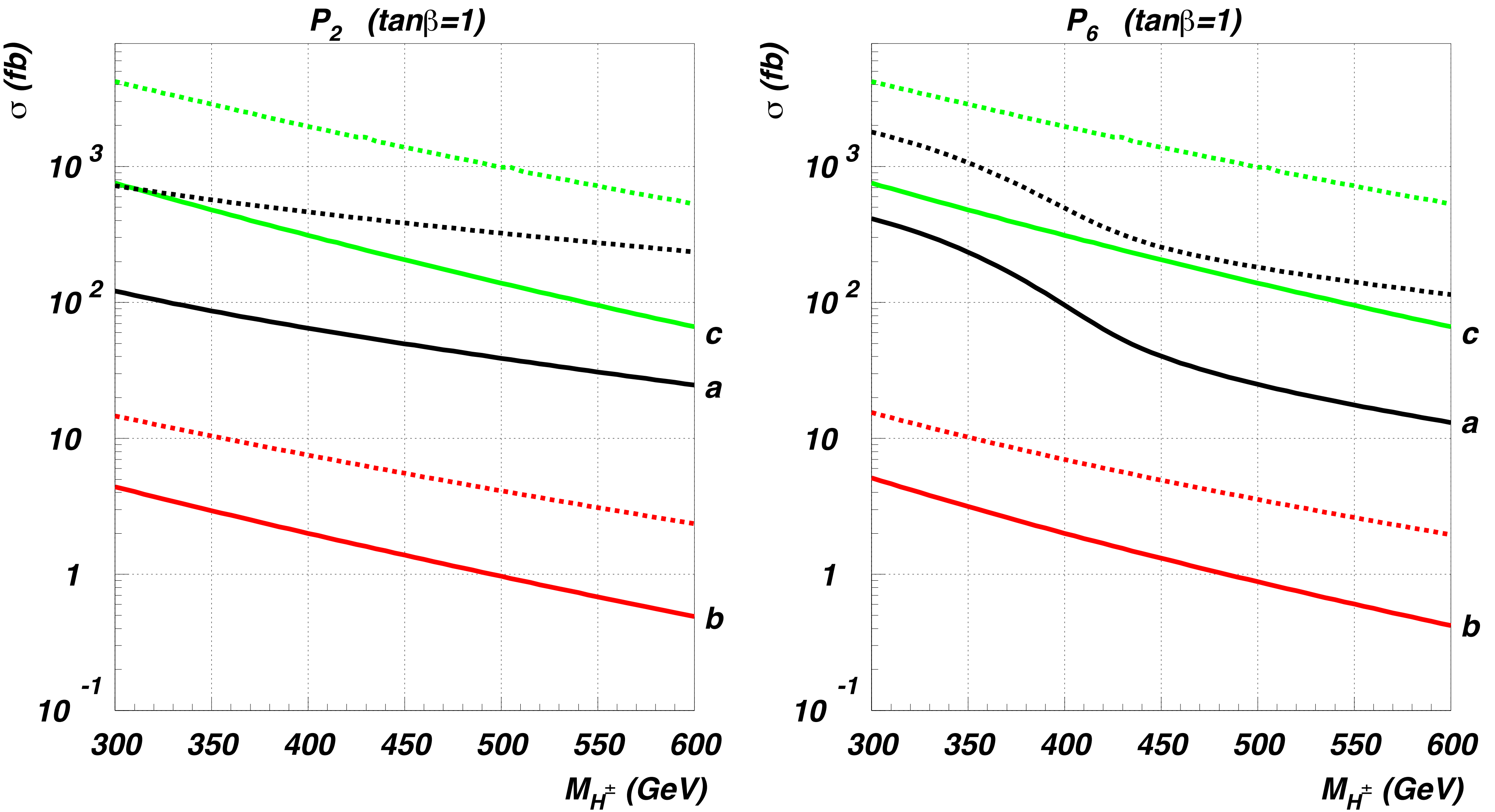
(b)



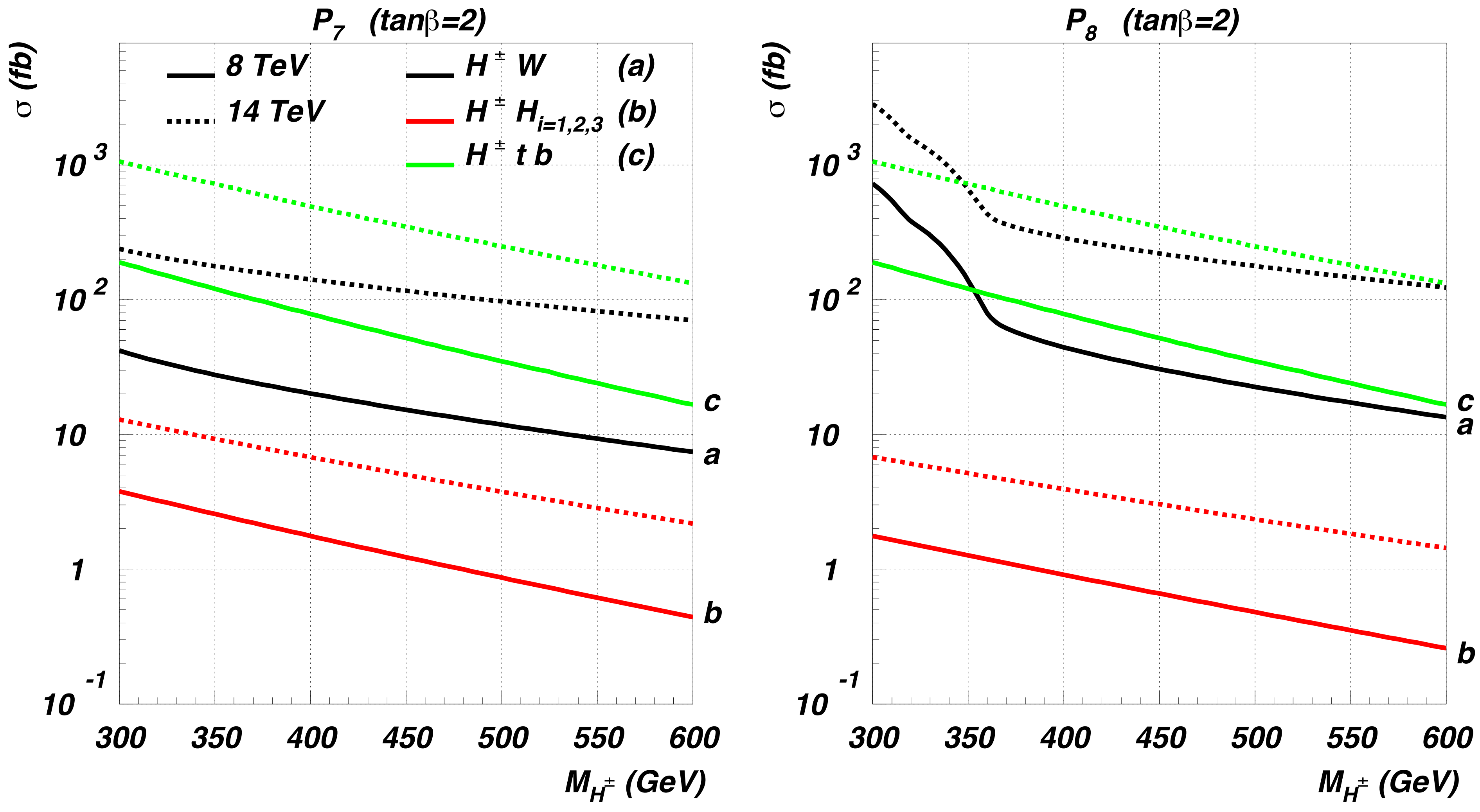
(c)

$t \to bW$

Cross sections: legend next page



Cross sections:



Background

- $t\bar{t} \to b\bar{b}W^+W^-$
- cross section larger by factor 10^3
- impose generic cuts, BG reduction by factor 40, signal reduction by 2-3

Generic cuts

1) **Kinematics:** standard detector cuts

$$p_\ell^T > 15 \text{ GeV}, \qquad |\eta_\ell| < 2.5,$$
$$p_j^T > 20 \text{ GeV}, \qquad |\eta_j| < 3,$$
$$|\Delta R_{jj}| > 0.5, \qquad |\Delta R_{\ell j}| > 0.5;$$

2) **light Higgs reconstruction:**

$$\left| M(b\bar{b}) - 125 \text{ GeV} \right| < 20 \text{ GeV}\,;$$

3) **hadronic W reconstruction ($W_h \to jj$):**

$$|M(jj) - 80 \text{ GeV}| < 20 \text{ GeV}\,;$$

Generic cuts

4) **top veto**: if $\Delta R(b_1, W_h) < \Delta R(b_2, W_h)$, then

$$M(b_1 jj) > 200 \text{ GeV}\,, \qquad M_T(b_2 \ell \nu) > 200 \text{ GeV}\,,$$

disfavor top, for each b-quark separately

otherwise $1 \leftrightarrow 2$;

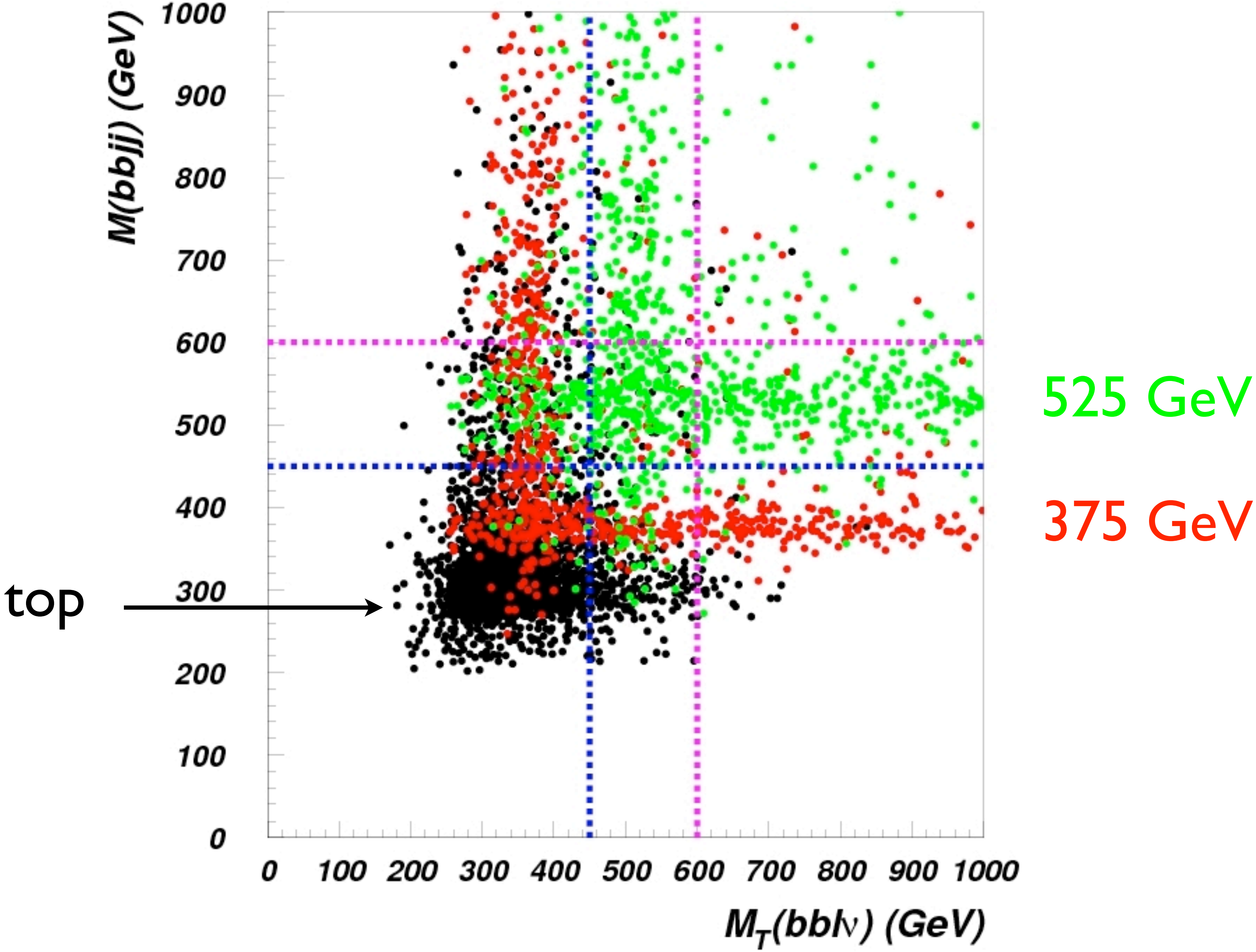
5) **same-hemisphere b quarks:**

$$\frac{\mathbf{p}_{b_1}}{|\mathbf{p}_{b_1}|} \cdot \frac{\mathbf{p}_{b_2}}{|\mathbf{p}_{b_2}|} > 0\,.$$

Additional anti-top cut

Idea: Since $M_{H^{\pm}} > m_t$

One of the W's should form high invariant mass with $b\bar{b}$ pair


M(bbjj) (GeV)
1000
900
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
$M_T(bbl\nu)$ (GeV)
525 GeV
375 GeV
top

Possible cuts

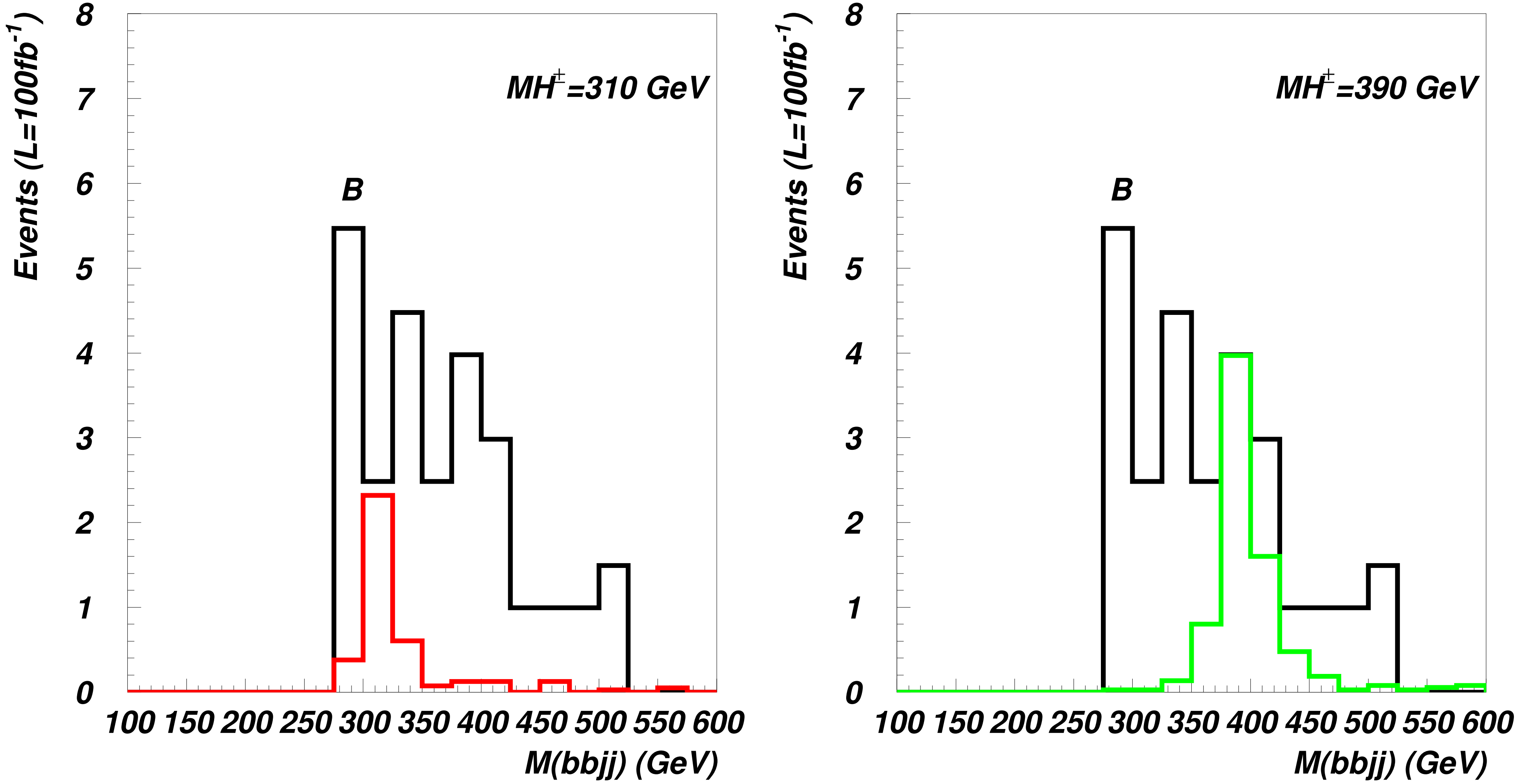
"squared cut": $\mathrm{C}_{\mathrm{squ}} = \max\left(M(b\bar{b}jj), M_T(b\bar{b}\ell\nu)\right) > M_{\mathrm{lim}}$

"single cut": $\mathrm{C}_{\mathrm{sng}} = M_T(b\bar{b}\ell\nu) > M_{\mathrm{lim}}\,.$

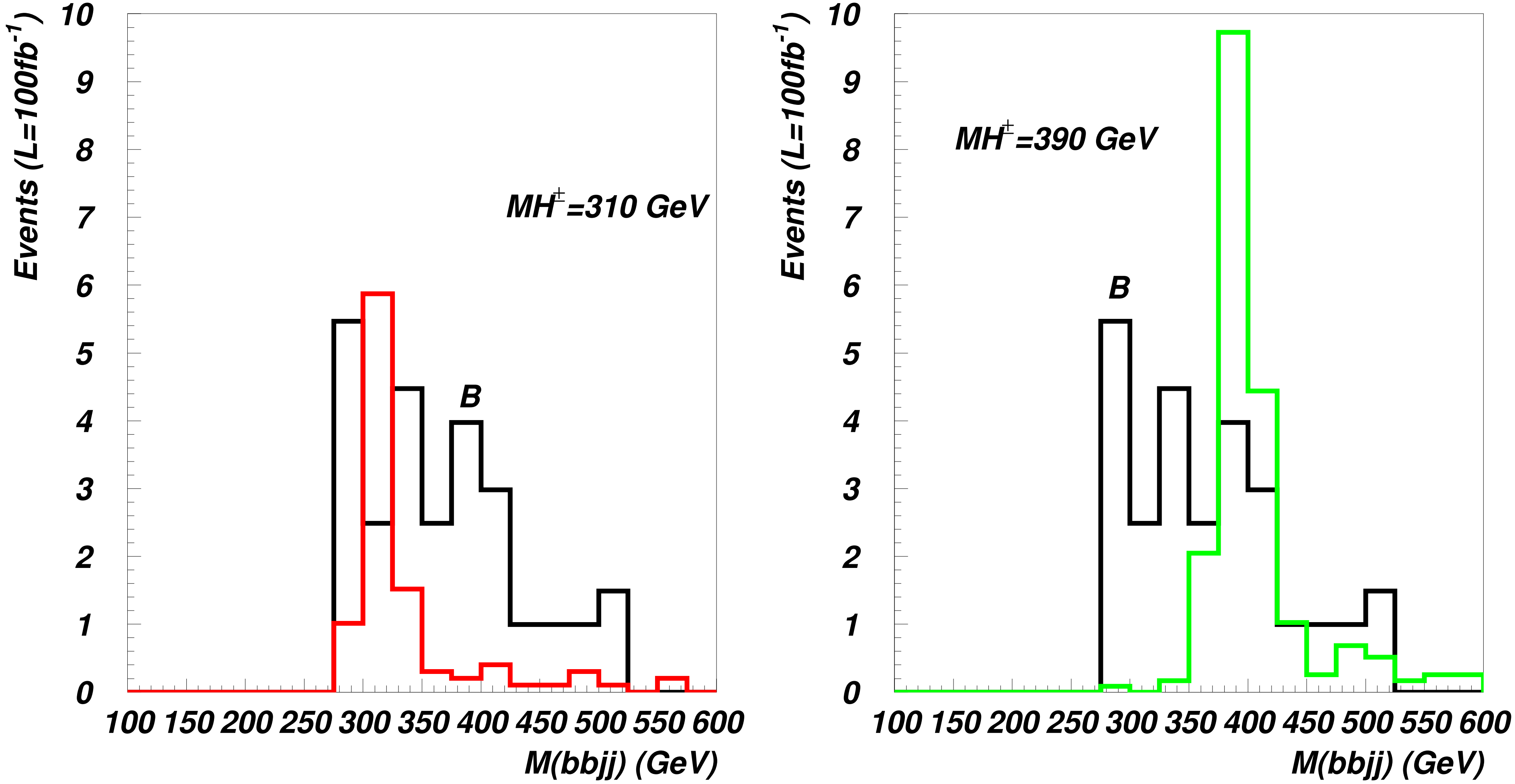
Choose: $\mathrm{C}_{\mathrm{sng}}$

$$M_{\mathrm{lim}} = 600\ \mathrm{GeV}$$

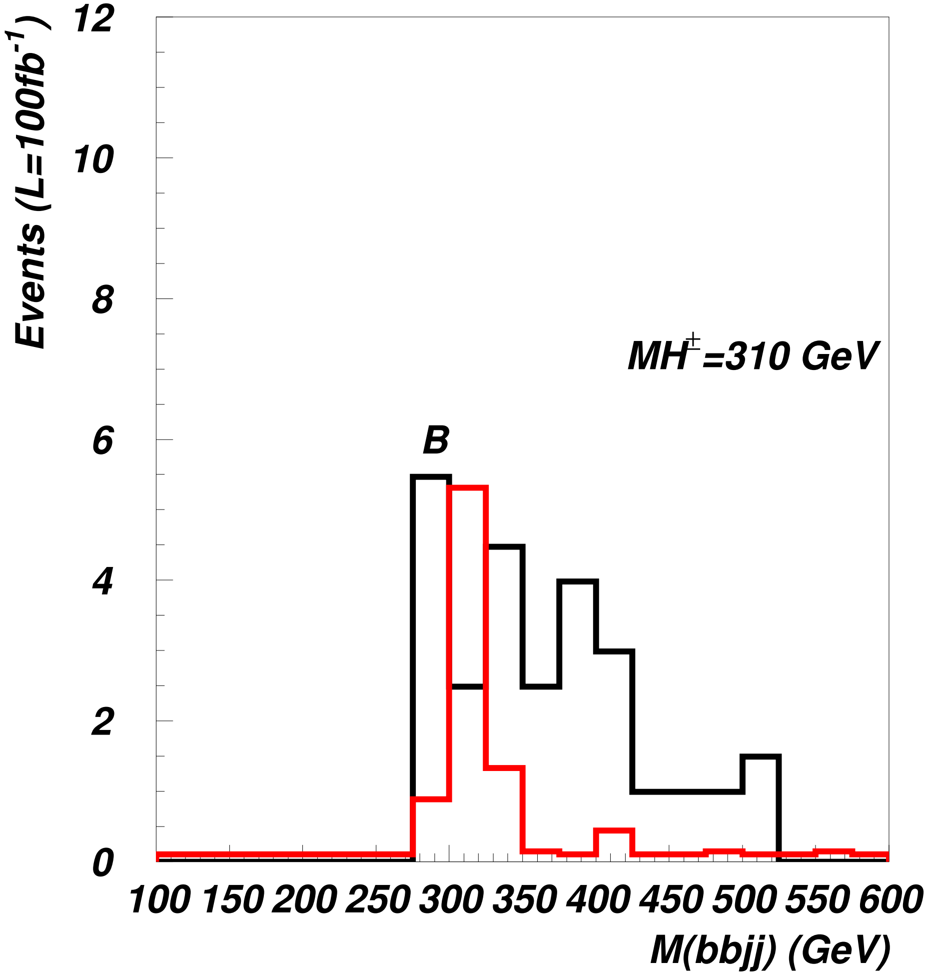
$$P_2 : \tan\beta = 1, \quad M_2 = 300 \text{ GeV}, \quad \alpha_i = \{0.35, -0.014, 0.48\}$$

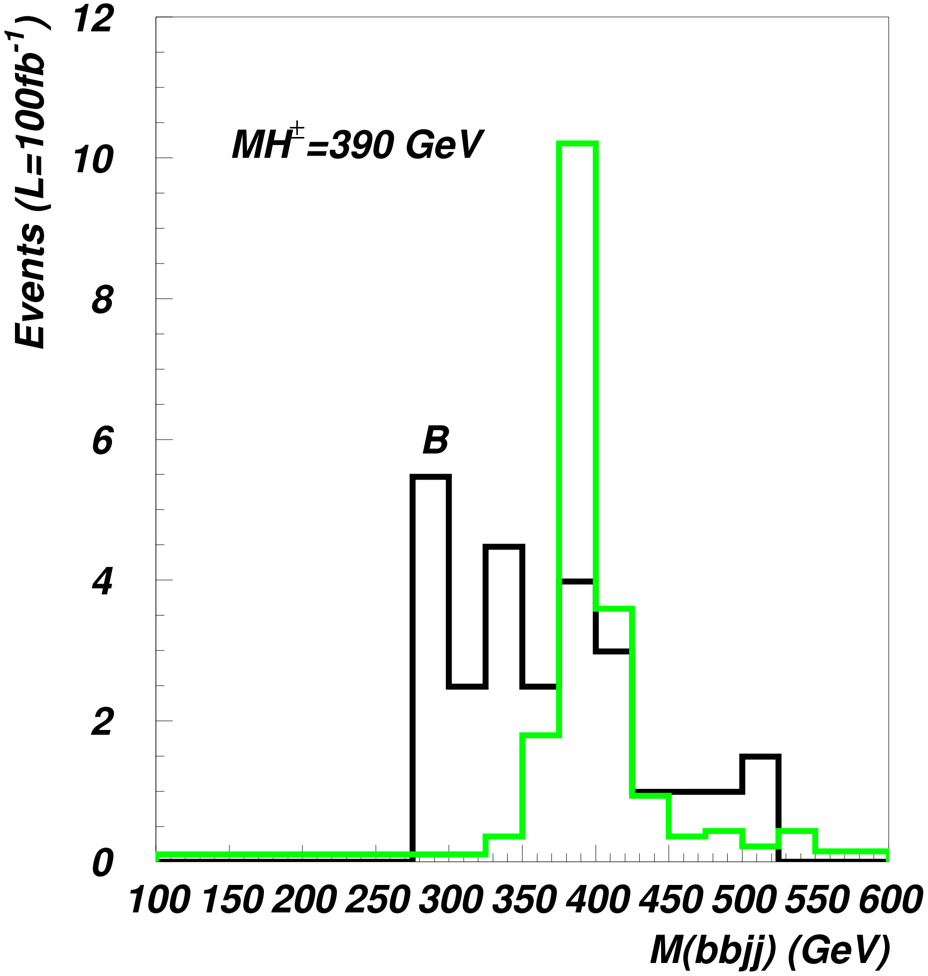


$$P_3 : \tan\beta = 1, \quad M_2 = 350 \text{ GeV}, \quad \alpha_i = \{0.35, -0.015, 0.496\}$$

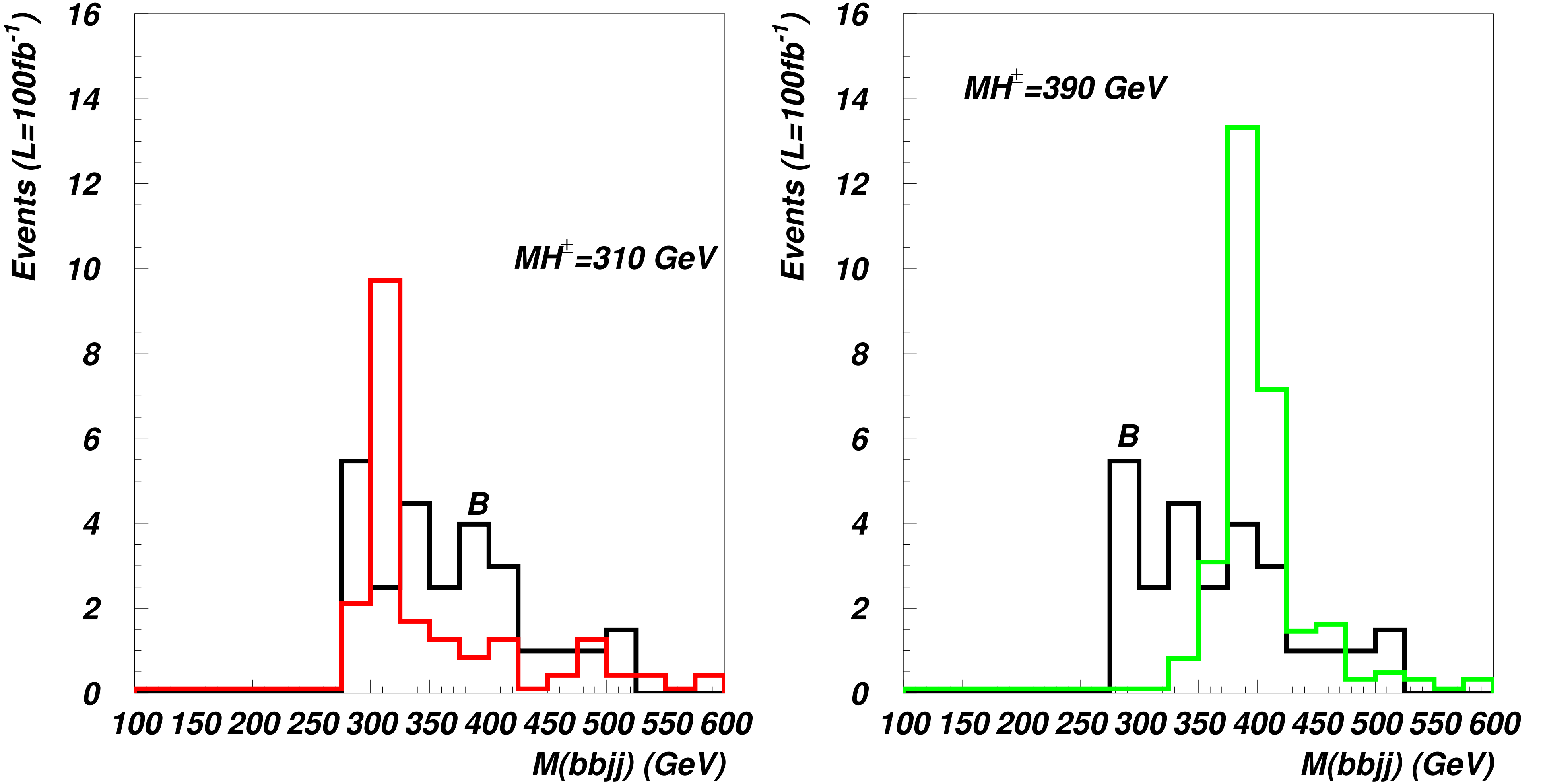


$$P_4 : \tan\beta = 1, \quad M_2 = 400 \text{ GeV}, \quad \alpha_i = \{0.35, -0.056, 0.43\}$$

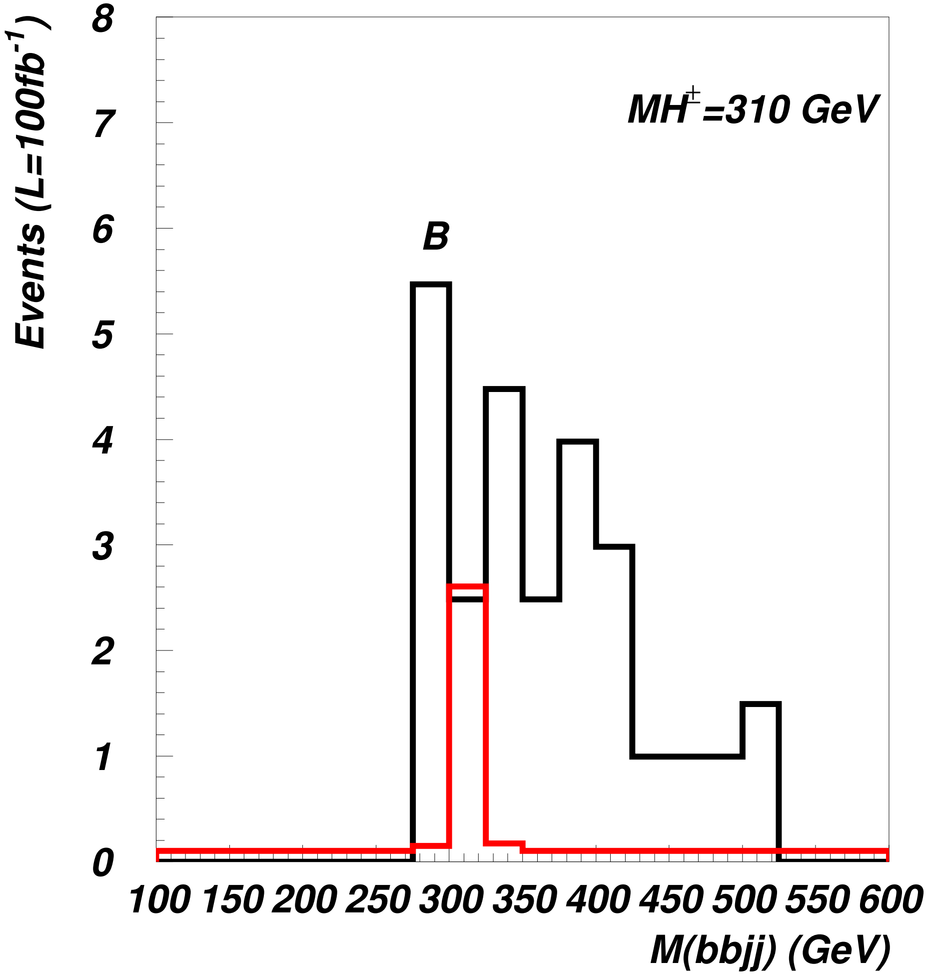


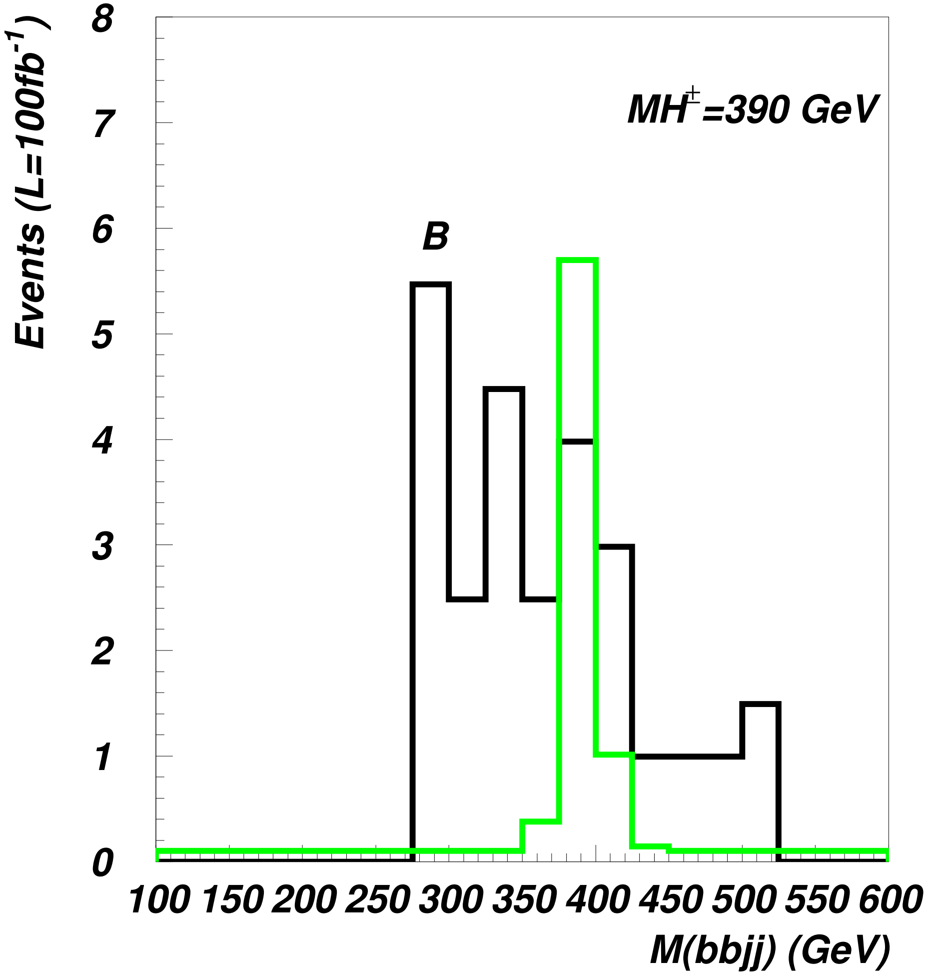


$$P_5 : \tan\beta = 1, \quad M_2 = 450 \text{ GeV}, \quad \alpha_i = \{0.33, -0.21, 0.23\}$$



$$P_7 : \tan\beta = 2, \quad M_2 = 300 \text{ GeV}, \quad \alpha_i = \{0.39, -0.07, 0.33\}$$





Possible cuts

“squared cut”: $\mathrm{C}_{\mathrm{squ}} = \max\big(M(b\bar{b}jj), M_T(b\bar{b}\ell\nu)\big) > M_{\mathrm{lim}}$

“single cut”: $\mathrm{C}_{\mathrm{sng}} = M_T(b\bar{b}\ell\nu) > M_{\mathrm{lim}}\,.$

Choose: $\mathrm{C}_{\mathrm{sng}}$

$$M_{\mathrm{lim}} = 600\ \mathrm{GeV}$$

Also:

peak cut: $|M - M_{H^\pm}| < 50\ \mathrm{GeV}$

	$M_{H^\pm} = 310$ GeV		$M_{H^\pm} = 390$ GeV	
	Events	$S/\sqrt{B}$	Events	$S/\sqrt{B}$
$t\bar{t}$	24.9			
peak	11.9	–	9.9	–
P_1	3.8	0.8	–	–
peak	2.6	0.8	–	–
P_2	4.7	1.0	8.8	1.8
peak	3.3	1.0	7.3	2.3
P_3	11.3	2.3	22.0	4.4
peak	7.7	2.3	17.2	5.4
P_4	10.0	2.0	20.3	4.1
peak	7.8	2.3	16.0	5.1
P_5	21.1	4.2	30.2	6.1
peak	13.9	4.1	25.0	7.9
P_6	14.0	2.8	–	–
peak	9.4	2.8	–	–
P_7	3.1	0.6	7.4	1.5
peak	2.8	0.8	7.3	2.3
P_8	1.2	0.2	–	–
peak	1.2	0.4	–	–

Conclusions

- 2HDM II parameter space is severely constrained by LHC data
- Parts of 2HDM II parameter space are still open
- SM would be excluded by charged Higgs discovery
- $pp \to \underbrace{jj}_{W}\underbrace{\ell^{\pm}\nu}_{W}\underbrace{b\bar{b}}_{H_1}$ channel allows detection in part of parameter space