Higgs searches in the 2HDM
Phenomenology and benchmarks

Oscar Stål
Stockholm University

Hamburg Higgs Workshop
2014-10-23

Work done in collaboration with Howard Haber

Why benchmarks?

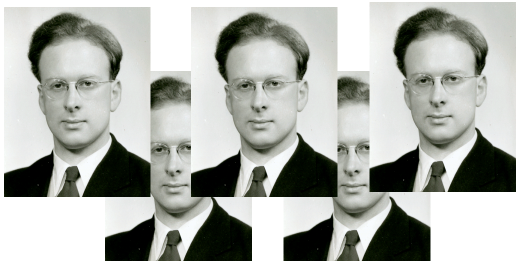
- Like most theorists (I think) I am all in favor of keeping experimental searches as model-independent as possible.

- That said, there are many situations where it also makes sense to consider specific models.

- The role of benchmarks is to
  - Motivate experimental searches to exploit all channels
  - Improve search strategies using model-specific information
  - Define unambiguous and complete sets of parameters
  - Be able to consider relevant model constraints
  - Provide language to compare exp <-> exp and exp <-> th

The general two-Higgs-doublet Model (2HDM)

- Two complex SU(2) doublets (Y=1): Φ_1, Φ_2 (five physical states)



- General 2HDM potential:

$$V_{\text{2HDM}} = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]$$
$$+ \frac{1}{2}\lambda_1 |\Phi_1|^4 + \frac{1}{2}\lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$
$$+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\right] \left(\Phi_1^\dagger \Phi_2\right) + \text{h.c.} \right\}$$

- Complex phases on $\lambda_5, \lambda_6, \lambda_7$ and m_{12} can give rise to CP-violation
  Here: CP-conserving case only (real parameters)

- Reparametrization invariance: $\Phi_a = U_{ab}\Phi_b \quad (a = 1, 2)$

S. Davidsson, H.E. Haber [hep-ph/0504050]
Review: [arXiv:1106.0034]

The Higgs basis

- Among the basis choices, there is one special case: the *Higgs basis* where only one of the doublets acquires a vev

$$H_1 = \cos\beta\Phi_1 + \sin\beta\Phi_2 \qquad \langle H_1^0 \rangle = \frac{v}{\sqrt{2}} \qquad \langle H_2^0 \rangle = 0$$

$$H_2 = -\sin\beta\Phi_1 + \cos\beta\Phi_2$$

$$\begin{aligned}\mathcal{V} \;=\; & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] \\ & + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \tfrac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \left\{ \tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + \left[Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2) \right] H_1^\dagger H_2 + \text{h.c.} \right\} ,\end{aligned}$$

Couplings

- Couplings to vector bosons determined by mixing angle

$$\frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \sin(\beta-\alpha) \qquad \frac{g_{HVV}}{g_{HVV}^{\rm SM}} = \cos(\beta-\alpha)$$

Alignment: $\sin(\beta-\alpha) \to 1$ possible with or without decoupling

- Yukawa couplings in arbitrary basis

$$\begin{aligned}
-\mathcal{L}_{\rm Y} = {} & \frac{1}{\sqrt{2}}\overline{D}\Big[\kappa^D s_{\beta-\alpha} + \rho^D c_{\beta-\alpha}\Big]Dh + \frac{1}{\sqrt{2}}\overline{D}\Big[\kappa^D c_{\beta-\alpha} - \rho^D s_{\beta-\alpha}\Big]DH + \frac{\rm i}{\sqrt{2}}\overline{D}\gamma_5\rho^D DA \\
& + \frac{1}{\sqrt{2}}\overline{U}\Big[\kappa^U s_{\beta-\alpha} + \rho^U c_{\beta-\alpha}\Big]Uh + \frac{1}{\sqrt{2}}\overline{U}\Big[\kappa^U c_{\beta-\alpha} - \rho^U s_{\beta-\alpha}\Big]UH - \frac{\rm i}{\sqrt{2}}\overline{U}\gamma_5\rho^U UA \\
& + \frac{1}{\sqrt{2}}\overline{L}\Big[\kappa^L s_{\beta-\alpha} + \rho^L c_{\beta-\alpha}\Big]Lh + \frac{1}{\sqrt{2}}\overline{L}\Big[\kappa^L c_{\beta-\alpha} - \rho^L s_{\beta-\alpha}\Big]LH + \frac{\rm i}{\sqrt{2}}\overline{L}\gamma_5\rho^L LA \\
& + \Big[\overline{U}\big(V_{\rm CKM}\rho^D P_R - \rho^U V_{\rm CKM} P_L\big)DH^+ + \overline{\nu}\rho^L P_R L H^+ + {\rm h.c.}\Big].
\end{aligned}$$

H.E. Haber, D. O'Neil [hep-ph/0602242]

- If ρ^F and κ^F are not simultaneously diagonal the Higgs sector mediates tree-level FCNC (-> strongly restricted from data)

Absence of tree-level FCNC –> 2HDM Types

- To get rid of these FCNC naturally, implement a (softly broken) Z_2 symmetry -> 2HDM *Types* depending on fermion Z_2 charges

$$\rho_F \propto \kappa_F = \frac{\sqrt{2}}{v} M_F$$

Barger, Hewitt, Philips, PRD41 (1990)

Type	U_R	D_R	L_R	ρ^U	ρ^D	ρ^L
I	$+$	$+$	$+$	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$\kappa^L \cot\beta$
II	$+$	$-$	$-$	$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$-\kappa^L \tan\beta$
III	$+$	$-$	$+$	$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$\kappa^L \cot\beta$
IV	$+$	$+$	$-$	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$-\kappa^L \tan\beta$

Type III = Type Y = “Flipped” Type IV = Type X = “Lepton-spec.”

- Promotes tan β to a physical parameter (basis with $\lambda_6 = \lambda_7 = 0$)
- MSSM: Type-II couplings at tree level, broken by Δ_b corrections

Choice of model parametrization

- Even with restrictions to CP conservation, soft Z_2 there remains seven free parameters:

$$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{12}^2, \tan\beta$$

or

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

- Hybrid basis: $m_h, m_H, \cos(\beta-\alpha), \tan\beta, Z_4, Z_5, Z_7$

$$m_H > m_h \qquad 0 < \beta < \pi/2$$
$$0 \leq s_{\beta-\alpha} \leq 1$$

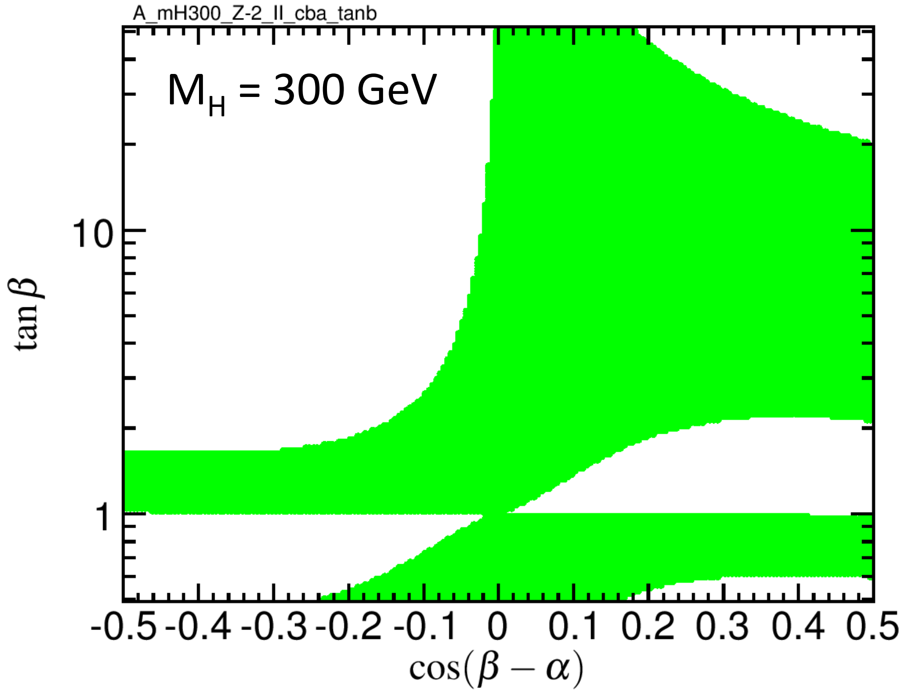
- The remaining Higgs masses are related to m_H:

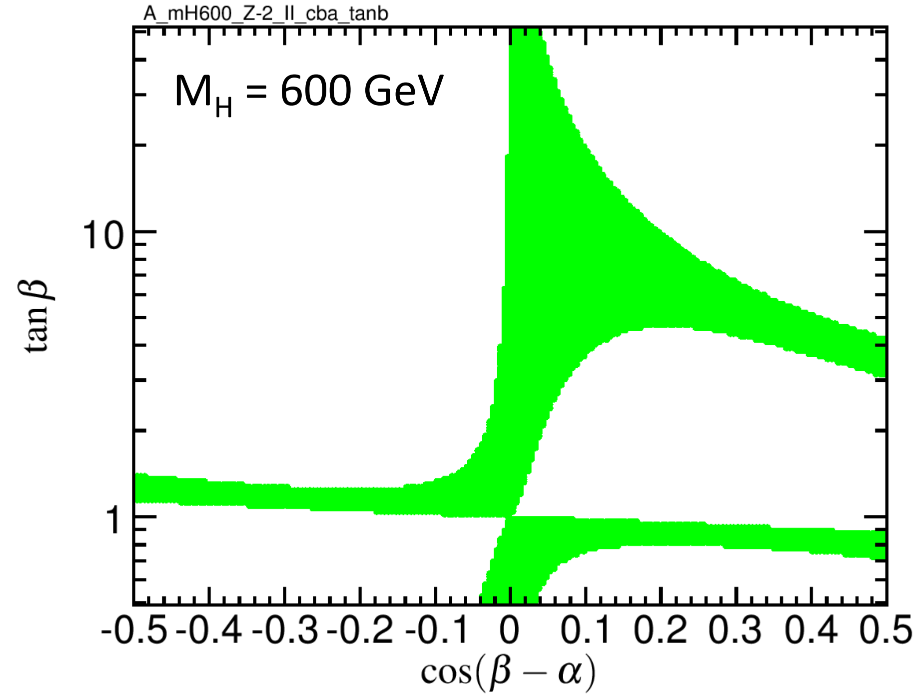
$$m_A^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 - Z_5 v^2$$
$$m_{H^\pm}^2 = m_A^2 - \frac{1}{2}(Z_4 - Z_5)v^2$$

Theoretical constraints restricts coupling space

- S-matrix unitarity and positivity of Higgs potential: $Z_i \sim \mathcal{O}(1)$

Ex: $M_h = 125$ GeV < M_H < $M_A = M_{H+}$ ($Z_4 = Z_5 < -2$, $Z_7 = 0$)





- Allowed parameter region tends towards alignment ($c_{\beta-\alpha} \to 0$) at high tan β, positive values of $c_{\beta-\alpha}$ preferred

2HDMC (2-Higgs Doublet Model Calculator)

- Object-oriented C++ code implementing the general (CP-conserving) 2HDM in different parametrizations (including new “hybrid” basis)

D. Eriksson (Ericsson), OS (Stockholm), J. Rathsman (Lund)

[0902.0851]

http://2hdmc.hepforge.org

- First released in 2009, current public version is 1.6.4

- Includes links to SusHi (cross sections), HiggsBounds (Higgs search limits), SuperIso (flavor physics), MadGraph-4 (event generation)

- Can be used either as a library, or for simple applications through one of the provided example programs for different input bases

LHC predictions

- Two bundles of codes have been compiled to provide complete 2HDM predictions of cross sections + branching ratios

SusHi + 2HDMC

Harlander, Mantler, Liebler, [1212.3249]

HIGLU+HDECAY

Spira et al, [hep-ph/9510347], [hep-ph/9704448]

LHC Higgs Cross Section Working Group

Interim recommendations for the evaluation of Higgs production cross sections and branching ratios at the LHC in the Two-Higgs-Doublet Model

R. Harlander[1], M. Mühlleitner[2], J. Rathsman[3], M. Spira[4], O. Stål[5]

[LHCHXSWG-2013-001], [1312.5571]

2HDM Benchmark scenarios

H. Haber, OS, [to appear]
(see also Baglio, Eberhardt, Nierste, Wiebusch, [1403.1264])

- Scenario A
  "Standard" scenario with lightest Higgs at 125 GeV
  $M_h = 125\ \text{GeV} < M_H < M_A = M_{H+}$

- Scenario B
  "Inverted" scenario with heavy CP-even Higgs at 125 GeV
  $M_h < M_H = 125\ \text{GeV} < M_A = M_{H+}$

- Scenario C
  Overlapping CP-even and CP-odd Higgses @ 125 GeV
  $M_h = M_A = 125\ \text{GeV} < M_H = M_{H+}$

2HDM Benchmark scenarios

- Scenario D
  Heavy CP-even Higgs with non-SM decays, e.g. $H \to A\,Z$, $H \to H^+W^-$
  $M_h = 125$ GeV $< M_A/M_{H+} < M_H$
- Scenario E
  Scenario for heavy CP-odd / charged Higgs with
  $A \to H^+ W^-$ or $H^+ \to A\, W^+$
- Scenario F
  h with SM-like couplings to up-type fermions and vector bosons, but flipped sign of coupling to down-type fermions
- Scenario G
  "MSSM"-like (mass-degenerate) scenario for heavy Higgs bosons
  $M_h = 125$ GeV $< M_H = M_A = M_{H+}$ (type II Yukawa couplings)

Scenario A

"Standard" scenario with lightest Higgs at 125 GeV

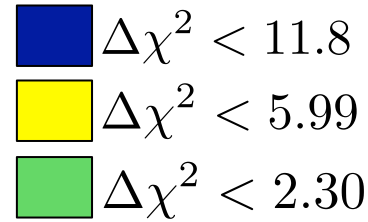
$M_h = 125$ GeV $< M_H < M_A = M_{H+}$

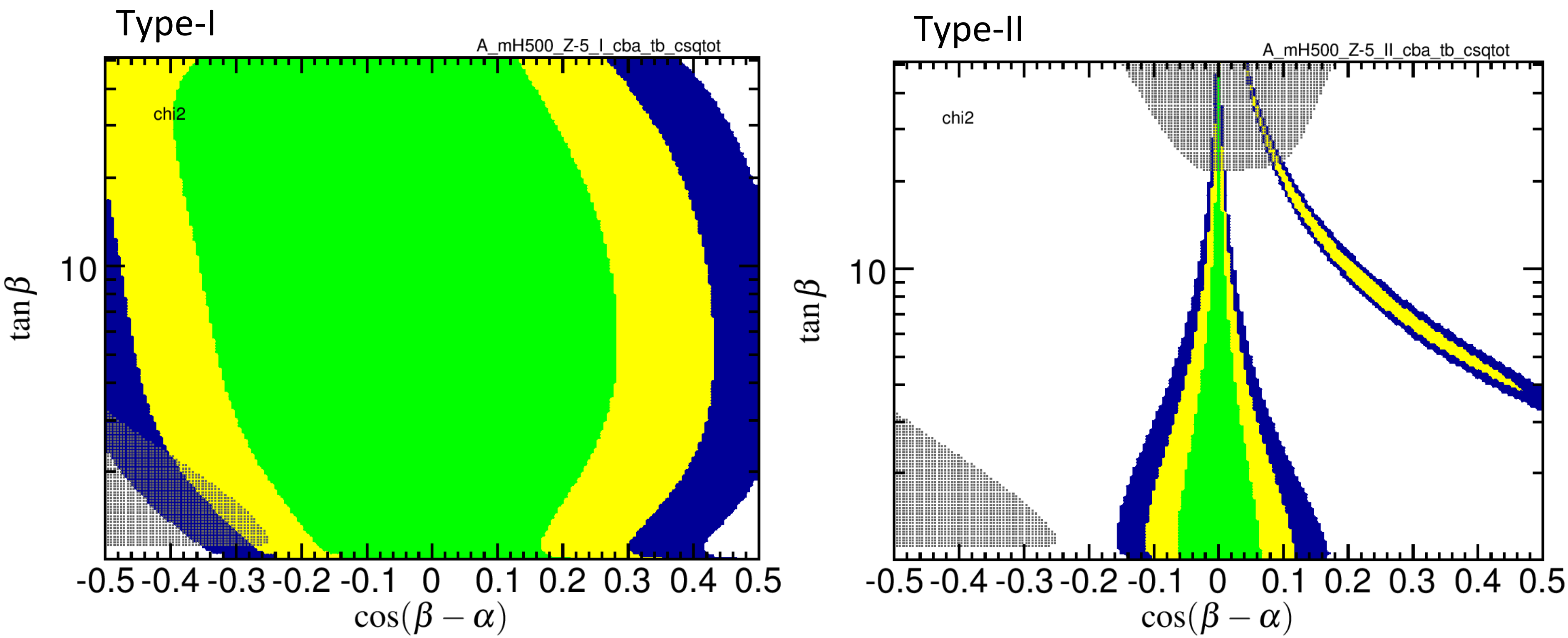
$Z_4 = Z_5 = -2$, $Z_7 = 0$

Scenario A: Light Higgs@125 GeV

- χ^2 fit of light Higgs signal rates with HiggsSignals

-> Talk by P. Bechtle



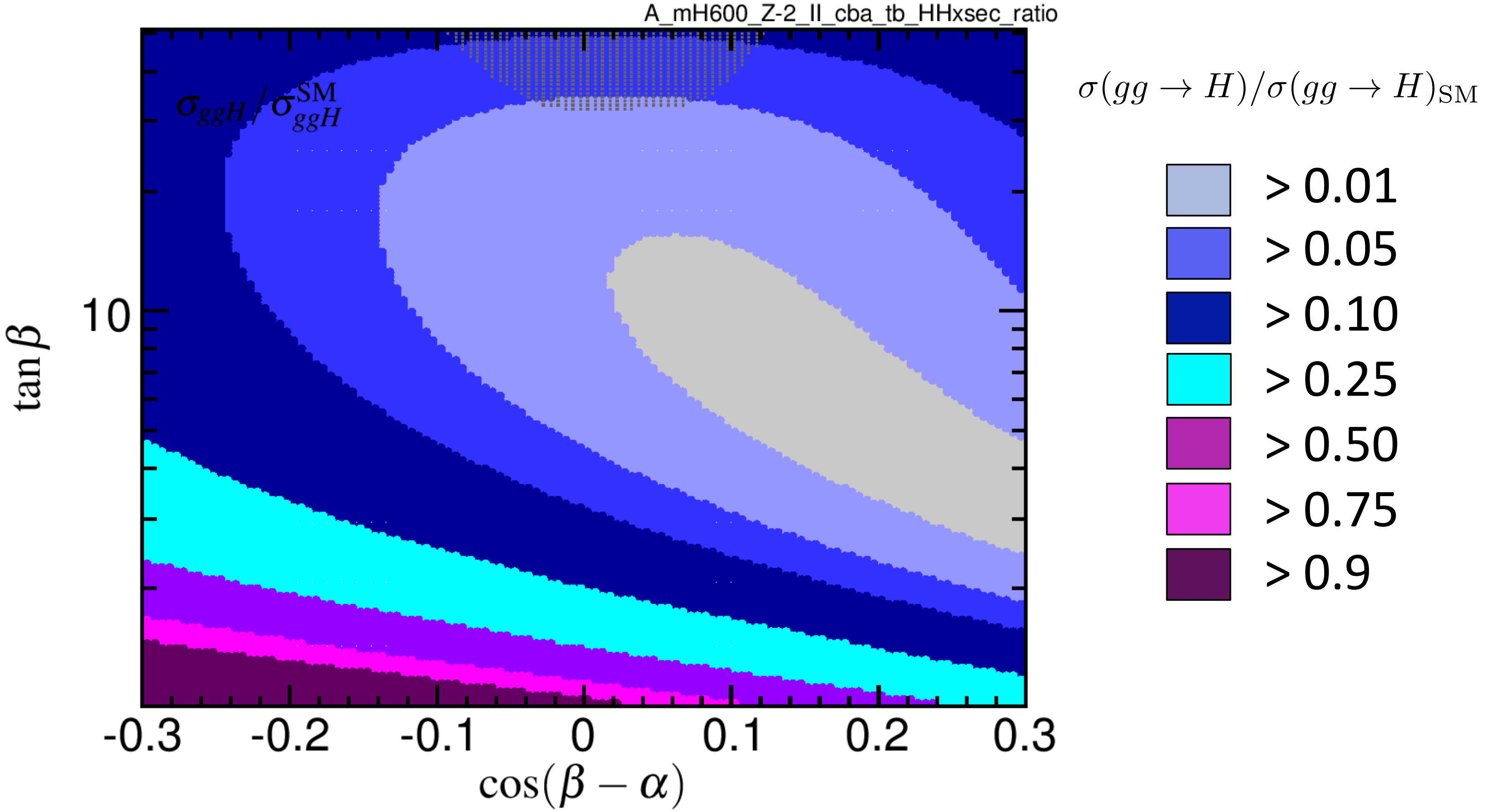


- Type-II couplings much more restricted around alignment, in particular for high tan β. Exception: flipped-sign scenario (F)

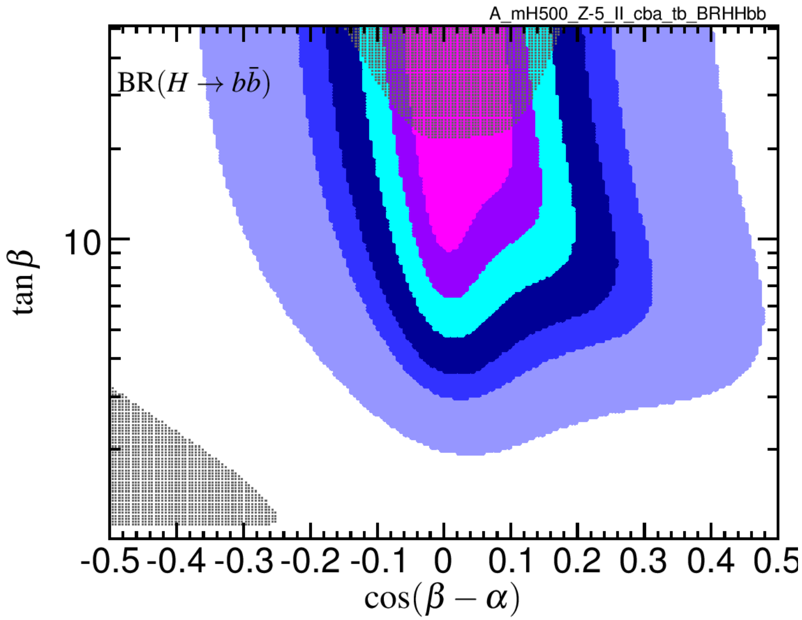
Ferreira, Haber, Gunion, Santos, [1403.4736]

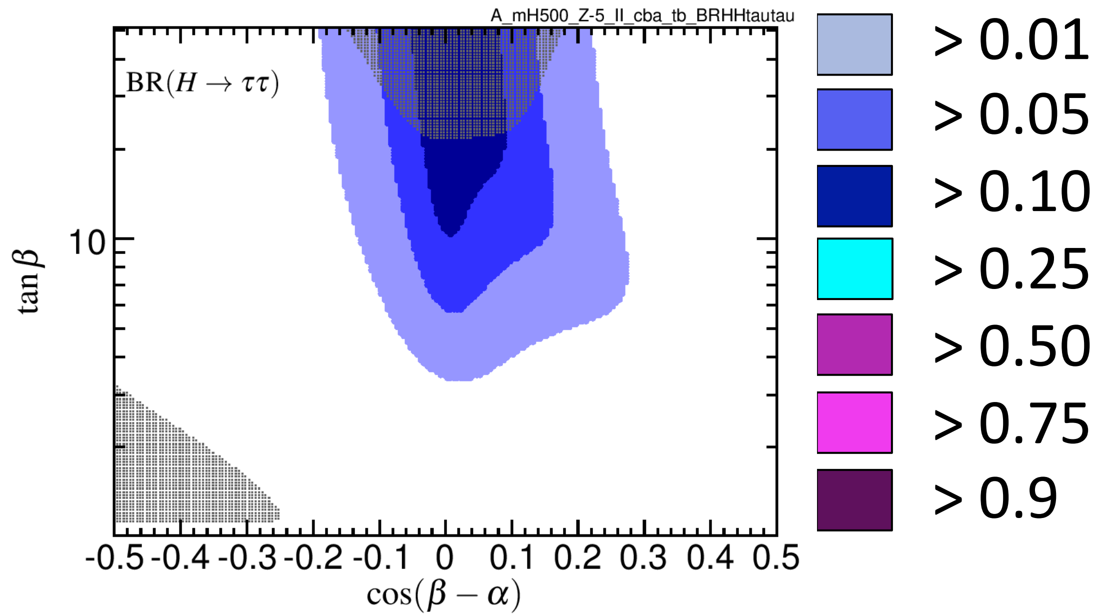
Type-II: Heavy Higgs production

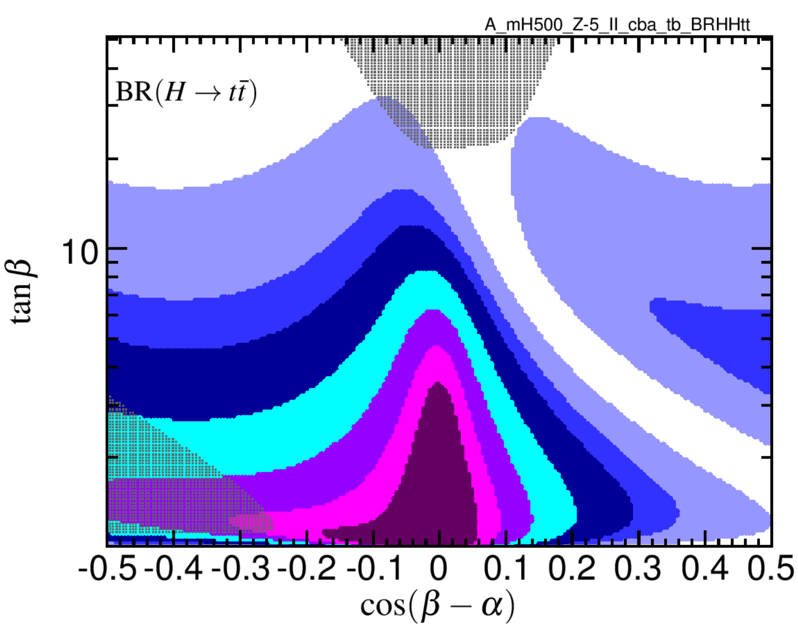
- Since the H has suppressed couplings to gauge bosons (in particular for Type-II) only gluon fusion, and at high tan β also bb -> H, are accessible



H decays to fermions

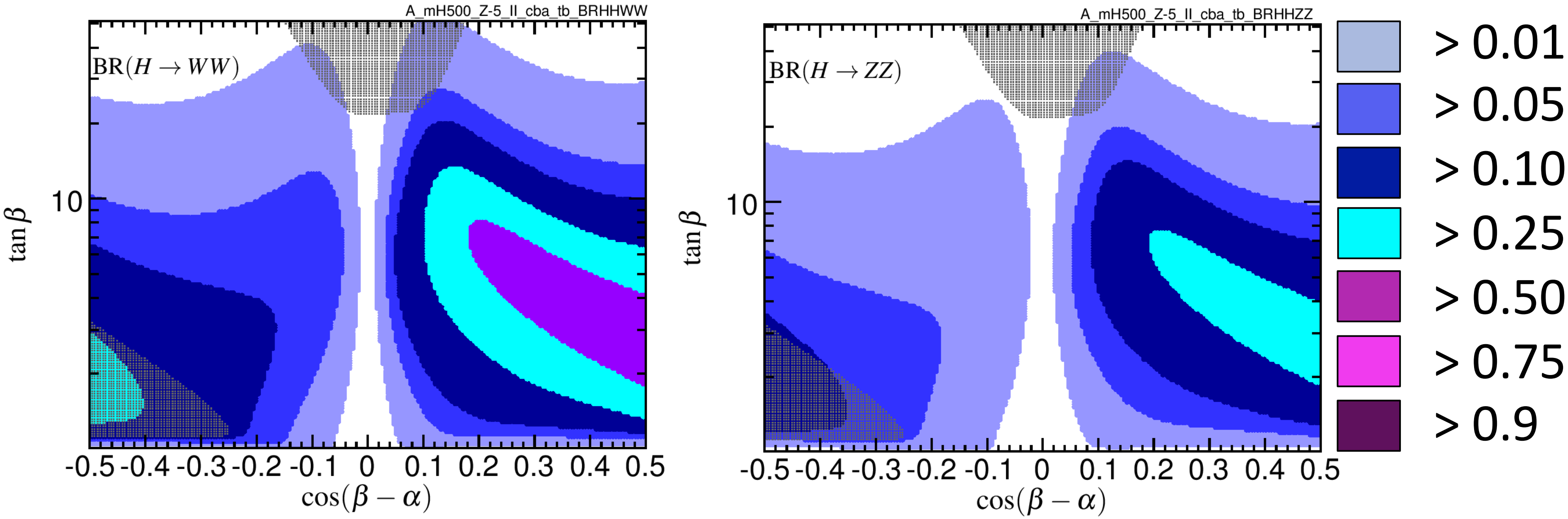


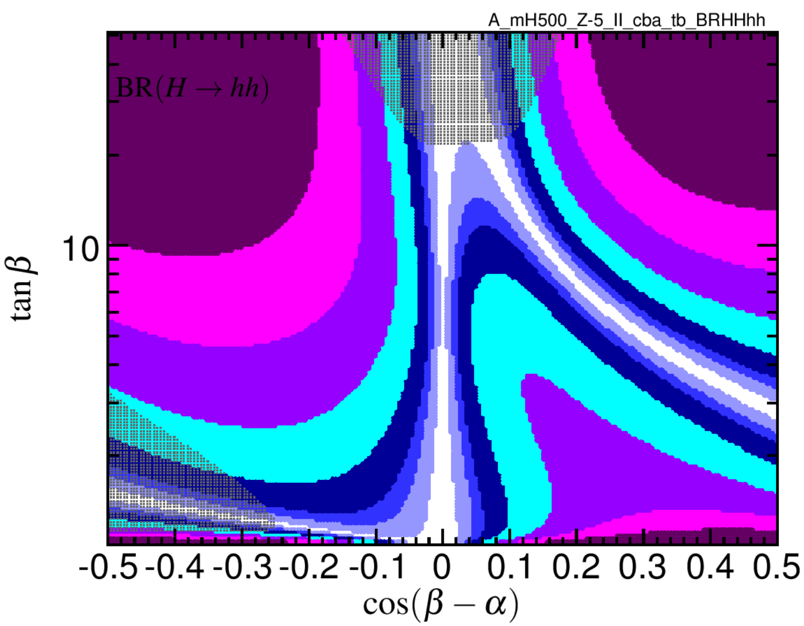




- Fermionic decays dominate close to alignment limit
- Complementarity between up- and down-type modes typical for Type-II

H decays to bosons

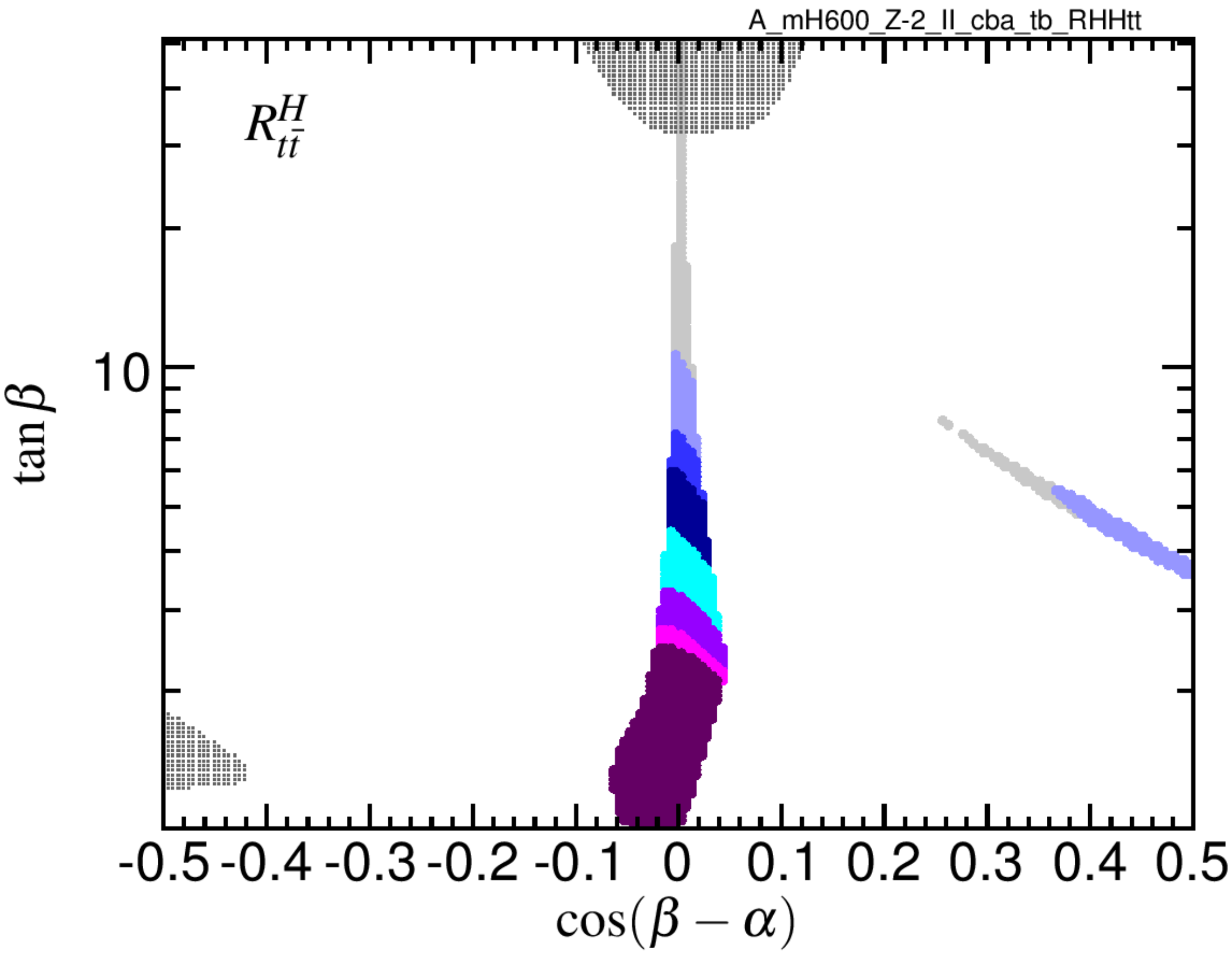




- Bosonic modes become important away from the alignment limit, difficult to access in favored region of parameter space

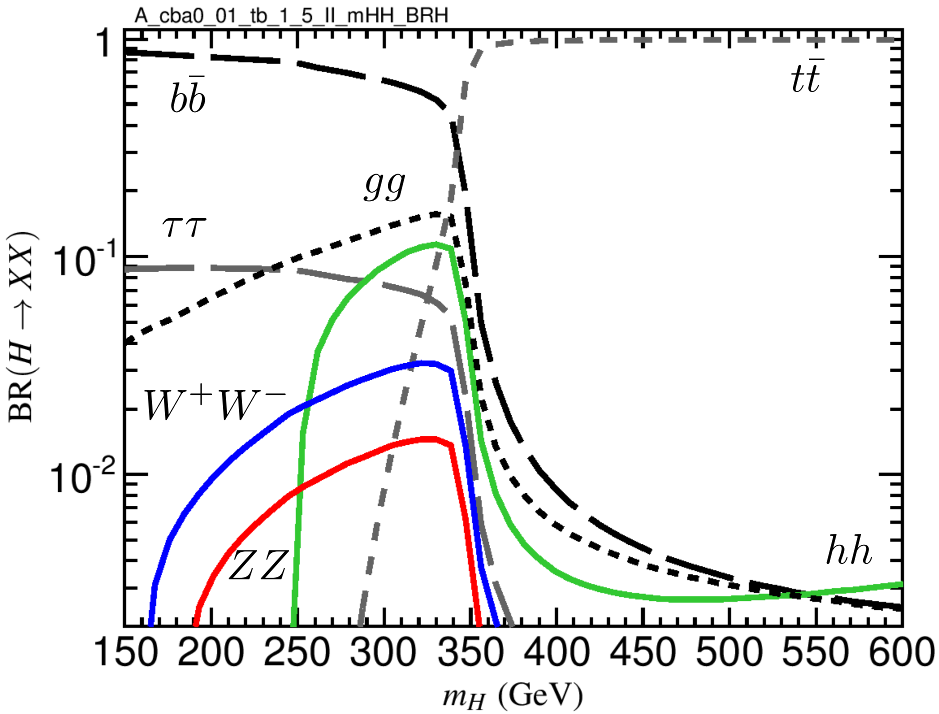
Applying the constraints

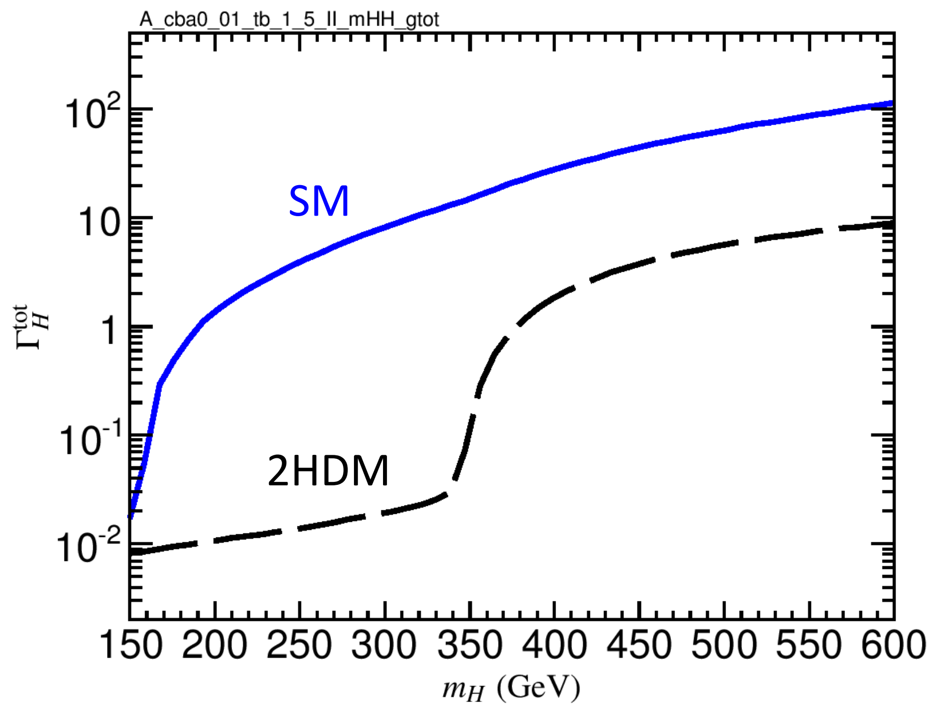
- Requiring positivity+unitarity and VV/γγ rates of lightest Higgs, h, within 20% of SM restricts the parameter space



Scenario A: Type-II Benchmark

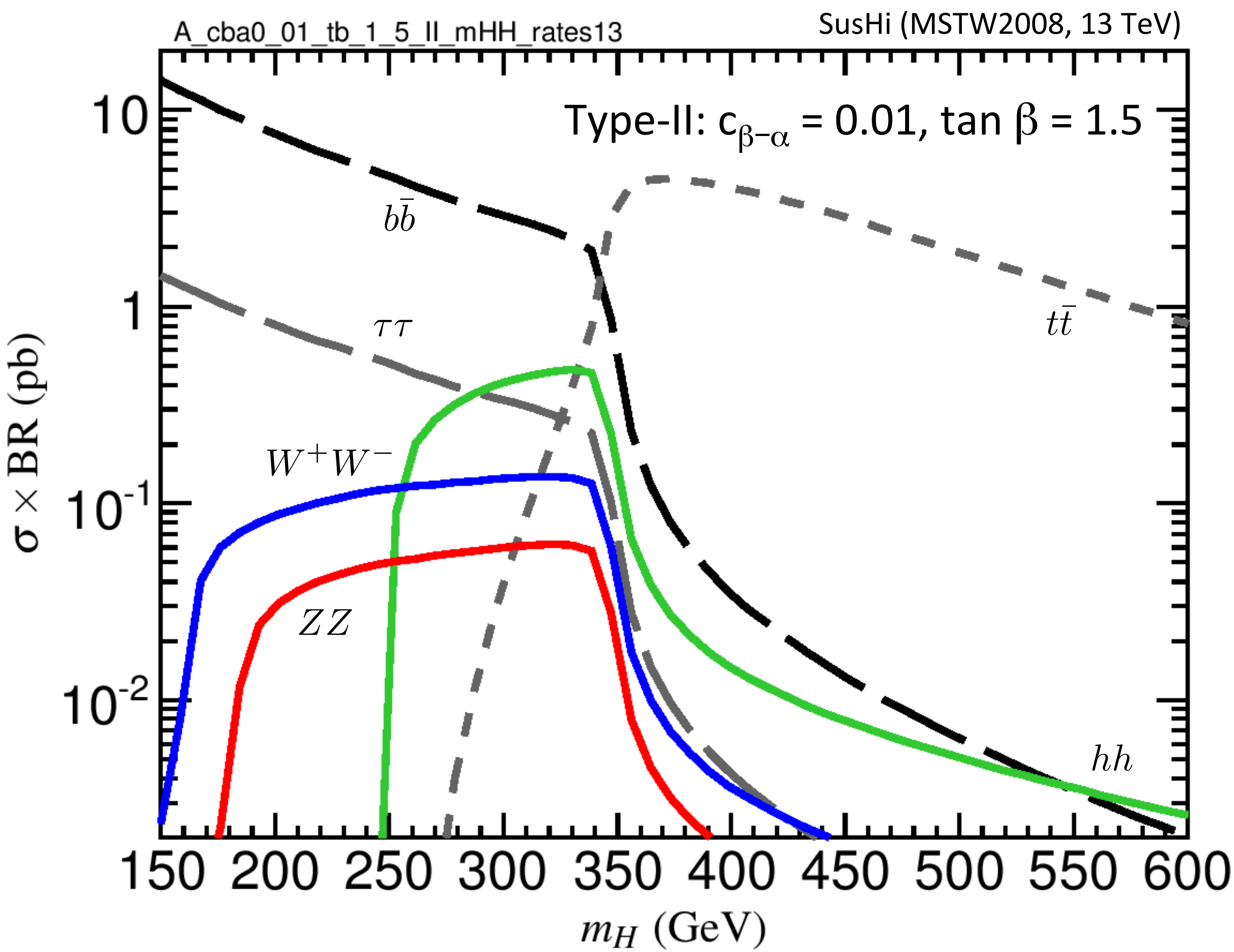
- Define benchmark scenarios by choosing fixed values for $c_{\beta\text{-}\alpha}$ and tan β inside allowed region. Ex: cos(β−α) = 0.01, tan β = 1.5





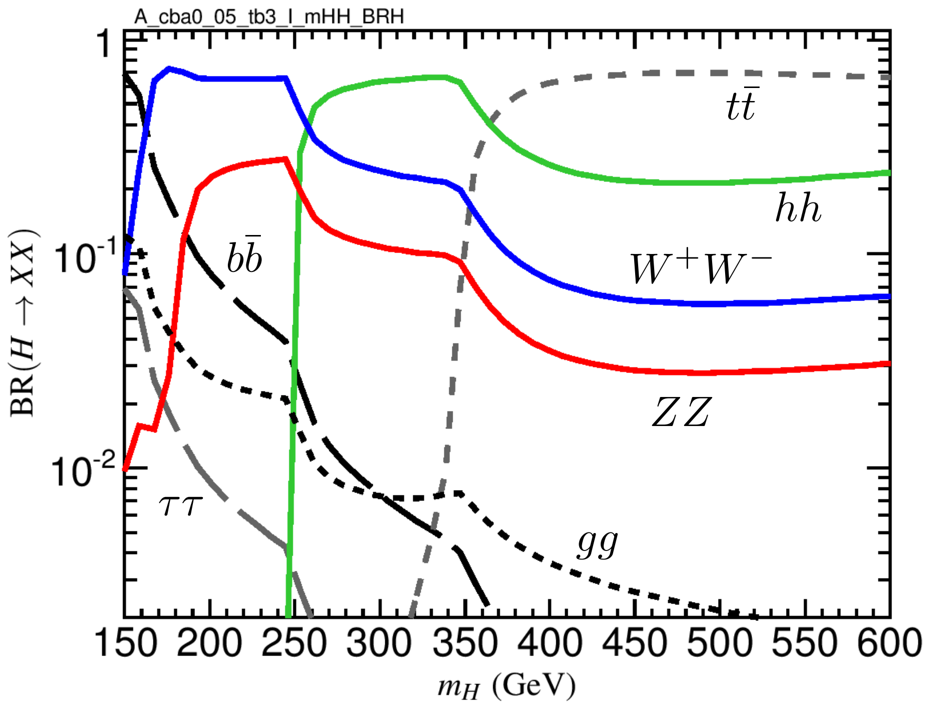
- Total H width remains relatively small, $\Gamma_H / \Gamma_{\mathrm{SM}} < 0.1$

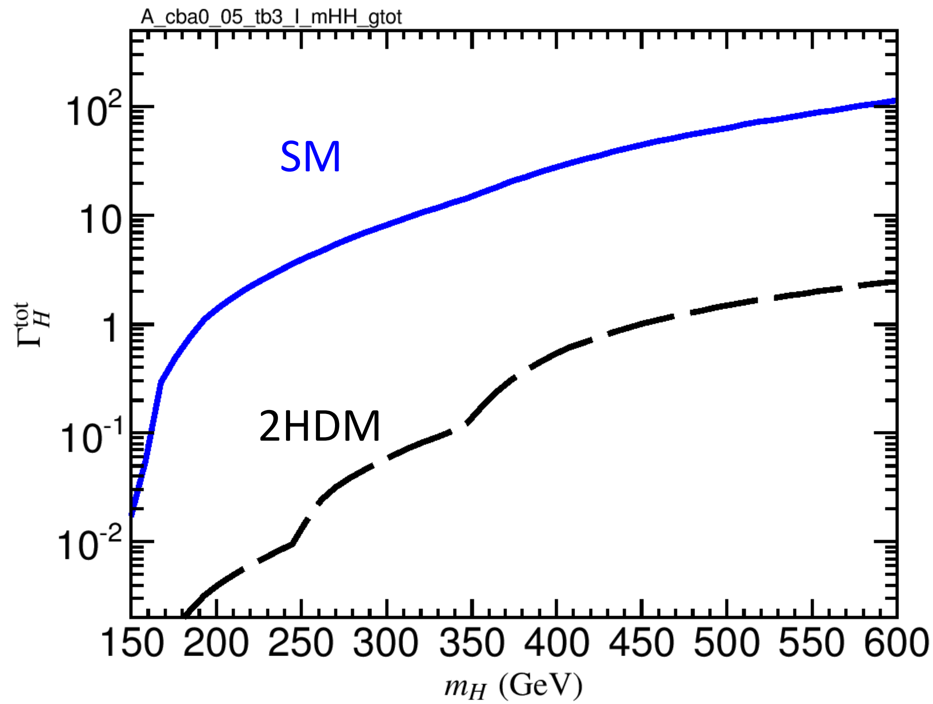
Total rates for LHC-13



Scenario A: Type-I Benchmark

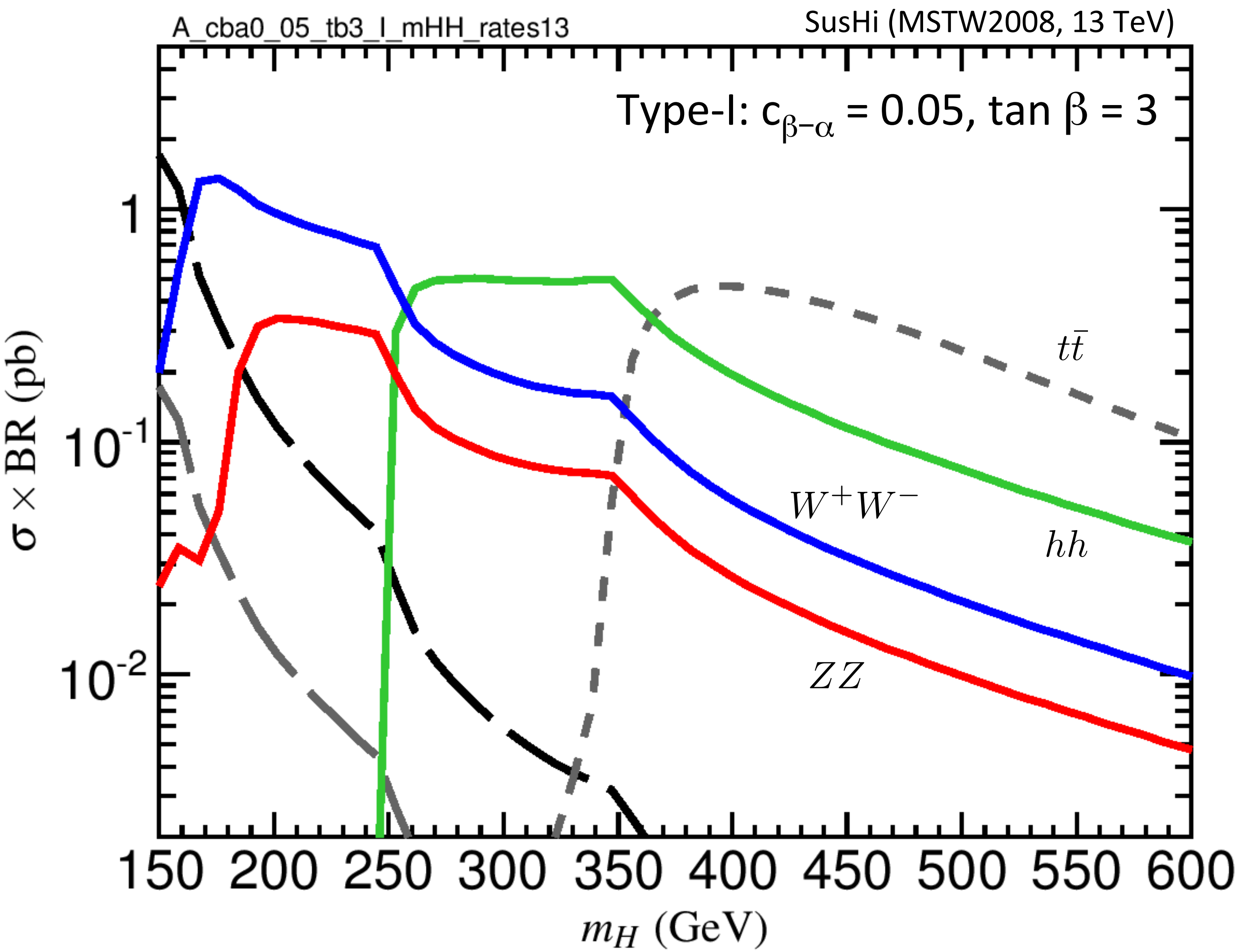
- For Type-I, larger deviations from SM in the coupling to vector bosons is allowed. Ex: cos(β−α) = 0.05, tan β = 3





- Sizeable branching ratios to bosonic final states can be accommodated, total width remains very small

Total rates at LHC-13



Scenario C

Overlapping CP-even and CP-odd Higgses @ 125 GeV

$M_h = M_A = 125$ GeV $< M_H = M_{H+}$

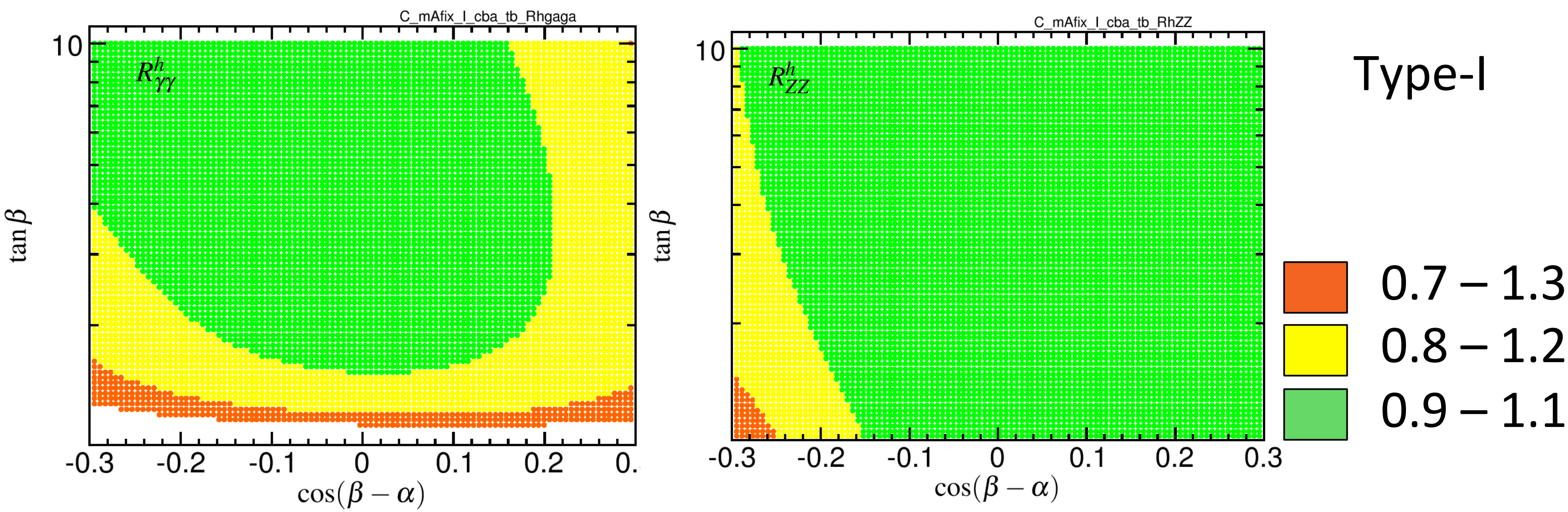
$$Z_5 = \frac{m_H^2 - m_h^2}{v^2} s_{\beta-\alpha}^2 \qquad Z_4 = -Z_5 - 2\frac{m_H^2 - m_h^2}{v^2} c_{\beta-\alpha}^2$$

$$Z_7 = -Z_5$$

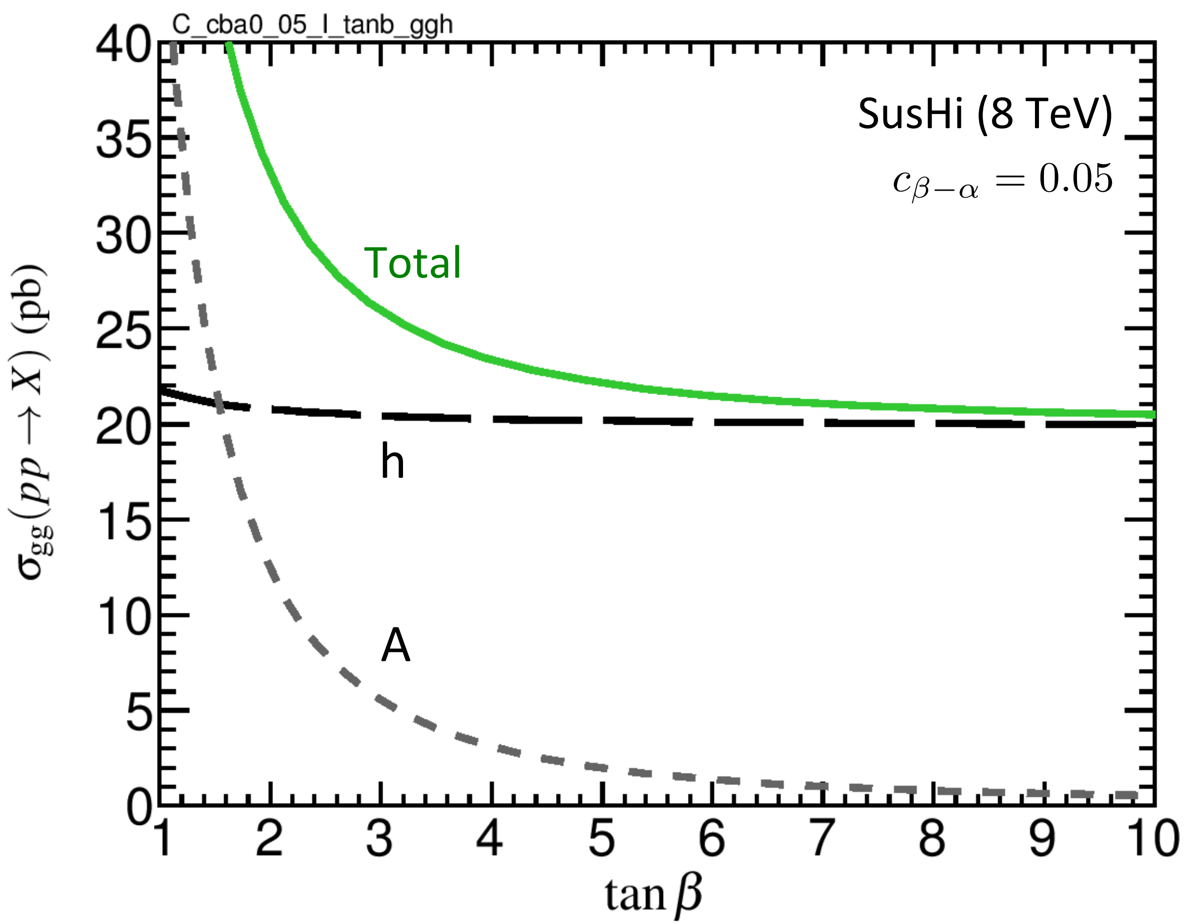
Scenario C: Degenerate states

- Our framework is CP-conserving, but Scenario C can "emulate" a CP-admixture for the signal in some channels:

  h/A -> γγ (inclusive) – *A* contribution exists, O(%) – interesting?
  h/A -> WW/ZZ (inclusive) – no tree-level A coupling
  h/A -> bb (VH) – no tree-level A coupling (inclusive/ttH - yes)
  h/A -> ττ (inclusive) – similar h/A contributions possible



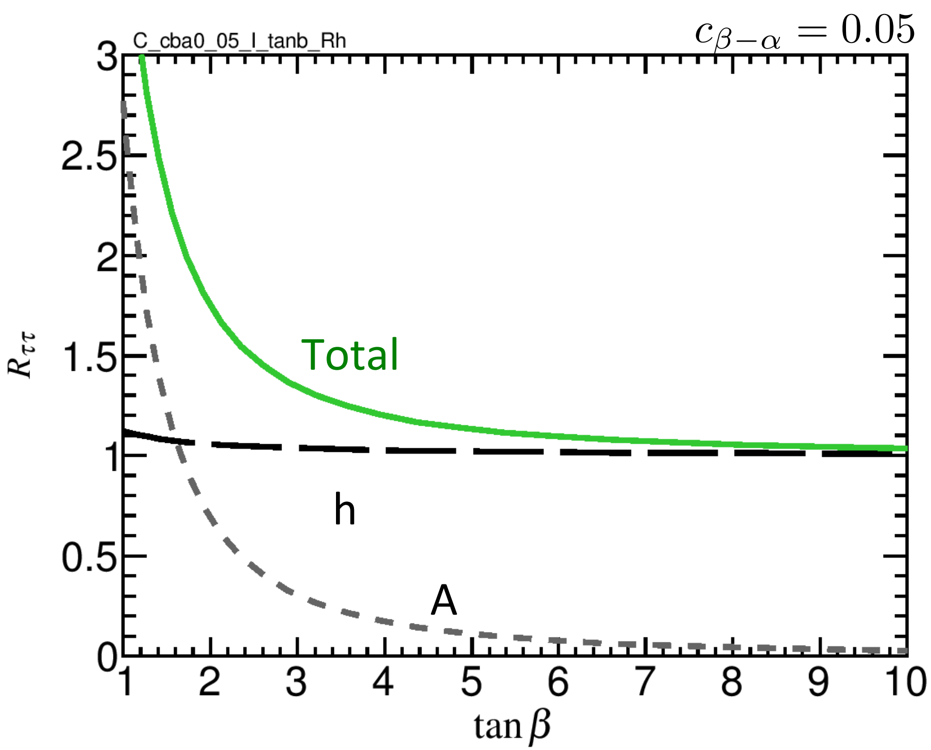
Scenario C: h/A production

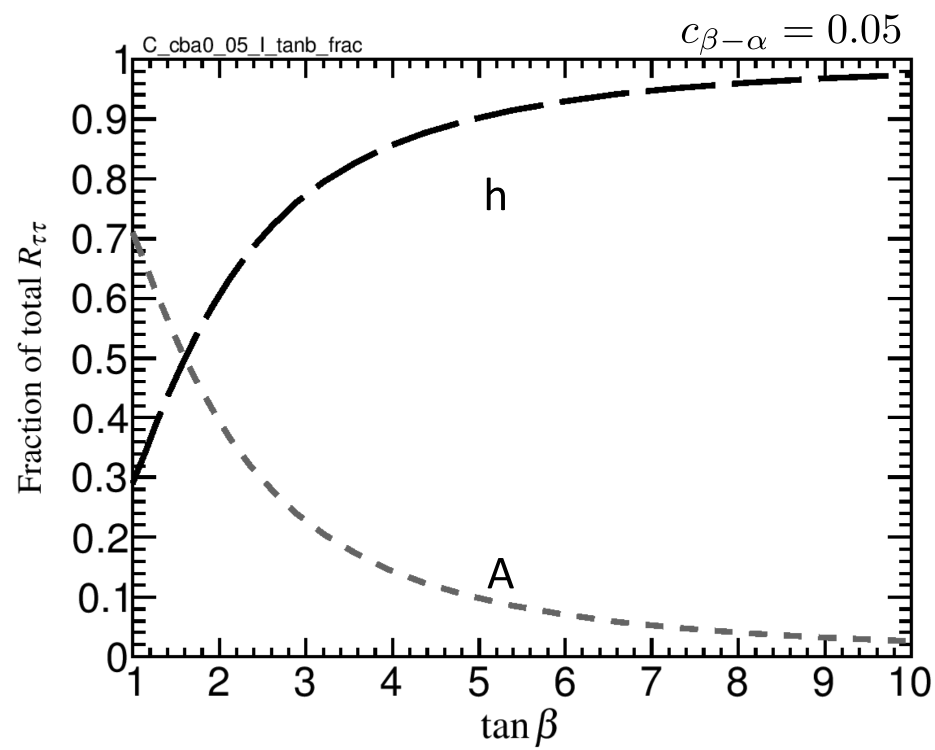


- Total cross section dominated by SM-like h for high tan β (Yukawa decoupling in Type-I)

Inclusive ττ signal composition

$$R_{\tau\tau}^{h/A} = \frac{\sigma(pp \to h/A) \times \mathrm{BR}(h/A \to \tau\tau)}{\sigma(pp \to H_{\mathrm{SM}}) \times \mathrm{BR}(H_{\mathrm{SM}} \to \tau\tau)}$$





- The currently allowed value for the ττ rate (within errors) could easily accommodate for a large CP-odd contribution

Conclusions

- The 2HDM is a useful theoretical framework to discuss the searches for additional Higgs bosons at the LHC
- Model-dependent interpretations of results often require benchmark scenarios to reduce complexity of full parameter space and to ensure consistent communication of results
- We propose a set of 2HDM scenarios for LHC Higgs searches capturing different model capabilities
- For the 125 GeV signal we include options for the light CP-even, heavy CP-even or overlapping CP-even/CP-odd states
- The scenarios are defined in new “hybrid basis” implemented in the public 2HDMC code. Predictions for total cross sections and branching ratios available.


Truth
NEXT EXIT

Backup

Theoretical constraints

- Unitarity
  Perturbative unitarity of the S-matrix for longitudinal vector boson/Higgs scattering, saturated with tree-level contribution.

$$Z_i \sim \mathcal{O}(1)$$

Ginzburg, Ivanov, PRD72 (2005) 115010

- Positivity of the potential
  In the case with CP-conservation and $\lambda_6 = \lambda_7 = 0$:

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

$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}$$

From Hybrid basis to Higgs basis

- Higgs basis condition for soft Z_2-breaking:

$$(Z_1 - Z_2)\big[Z_1 Z_7 + Z_2 Z_6 - Z_{345} Z_{67}\big] + 2Z_{67}^2 (Z_6 - Z_7) = 0$$

- Preferred basis in which soft Z_2-breaking is manifest:

$$\tan 2\beta = \pm \frac{|Z_6| + \varepsilon_6 \varepsilon_7 |Z_7|}{Z_2 - Z_1}$$

- Remaining quartic couplings (in the Higgs basis) determine the CP-odd and charged Higgs mases:

$$m_A^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 - Z_5 v^2$$

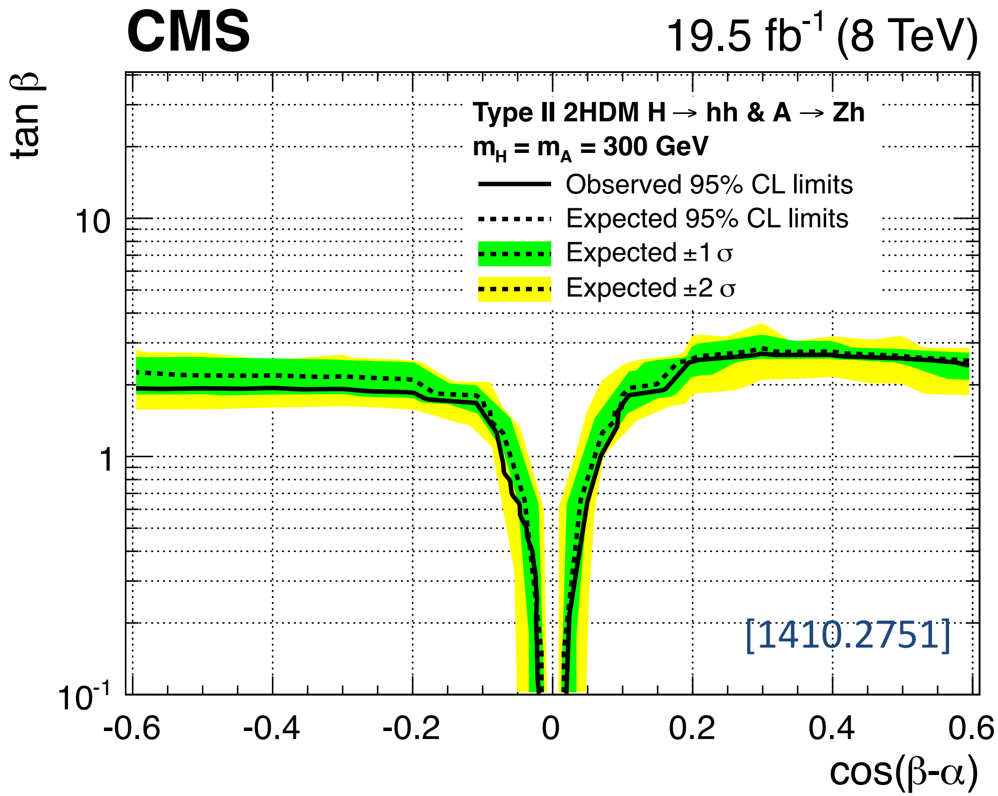
$$m_{H^\pm}^2 = m_A^2 - \frac{1}{2}(Z_4 - Z_5) v^2$$

Numerical comparisons

[1312.5571]

		2HDMC		HDECAY		
		BR	Γ (GeV)	BR	Γ (GeV)	Γ_{2H}/Γ_{HD}
$h \to$	$b\bar{b}$	0.6812	3.790×10^{-3}	0.6827	3.820×10^{-3}	0.992
	$\tau^+\tau^-$	6.587×10^{-2}	3.664×10^{-4}	6.548×10^{-2}	3.664×10^{-4}	1.000
	$\mu^+\mu^-$	2.332×10^{-4}	1.297×10^{-6}	2.318×10^{-4}	1.297×10^{-6}	1.000
	$s\bar{s}$	2.484×10^{-4}	1.382×10^{-6}	2.503×10^{-4}	1.400×10^{-6}	0.987
	$c\bar{c}$	3.059×10^{-2}	1.701×10^{-4}	2.976×10^{-2}	1.665×10^{-4}	1.022
	gg	8.110×10^{-2}	4.511×10^{-4}	8.166×10^{-2}	4.569×10^{-4}	0.987
	$\gamma\gamma$	1.130×10^{-3}	6.284×10^{-6}	1.117×10^{-3}	6.250×10^{-6}	1.006
	$Z\gamma$	8.728×10^{-4}	4.855×10^{-6}	8.677×10^{-4}	4.855×10^{-6}	1.000
	W^+W^-	0.1233	6.859×10^{-4}	0.1226	6.860×10^{-4}	1.000
	ZZ	1.540×10^{-2}	8.569×10^{-5}	1.531×10^{-2}	8.566×10^{-5}	1.000
Total width			$\mathbf{5.563 \times 10^{-3}}$		$\mathbf{5.595 \times 10^{-3}}$	**0.994**
$H \to$	$b\bar{b}$	8.492×10^{-5}	1.536×10^{-4}	8.526×10^{-5}	1.542×10^{-4}	0.996
	$\tau^+\tau^-$	9.667×10^{-6}	1.748×10^{-5}	9.667×10^{-6}	1.748×10^{-5}	1.000
	$\mu^+\mu^-$	3.419×10^{-8}	6.182×10^{-8}	3.419×10^{-8}	6.183×10^{-8}	1.000
	$s\bar{s}$	3.070×10^{-8}	5.552×10^{-8}	3.115×10^{-7}	5.636×10^{-8}	0.985
	$c\bar{c}$	3.787×10^{-6}	6.848×10^{-6}	3.706×10^{-6}	6.706×10^{-6}	1.021
	$t\bar{t}$	5.976×10^{-6}	1.081×10^{-5}	5.986×10^{-6}	1.082×10^{-5}	0.998
	gg	8.382×10^{-5}	1.516×10^{-4}	8.669×10^{-5}	1.568×10^{-4}	0.967
	$\gamma\gamma$	1.642×10^{-5}	2.969×10^{-5}	1.653×10^{-5}	2.989×10^{-5}	0.993
	$Z\gamma$	5.300×10^{-5}	9.584×10^{-5}	5.300×10^{-5}	9.584×10^{-5}	1.000
	W^+W^-	0.5872	1.062	0.5872	1.062	1.000
	ZZ	0.2606	0.4713	0.2606	0.4712	1.000
	hh	0.1493	0.2699	0.1493	0.2700	1.000
	$W^\pm H^\mp$	2.658×10^{-3}	4.806×10^{-3}	2.663×10^{-3}	4.815×10^{-3}	0.998
Total width			**1.808**		**1.808**	**1.000**

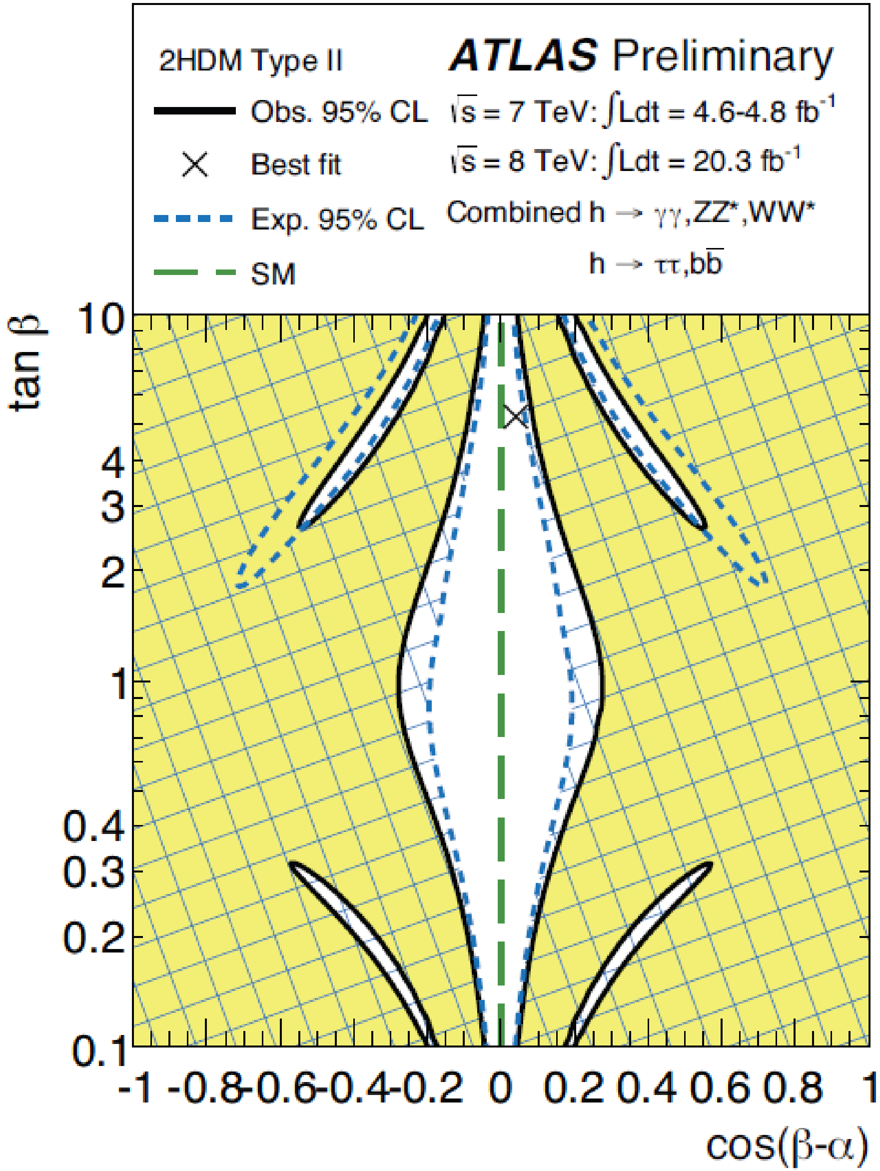
Experimental results



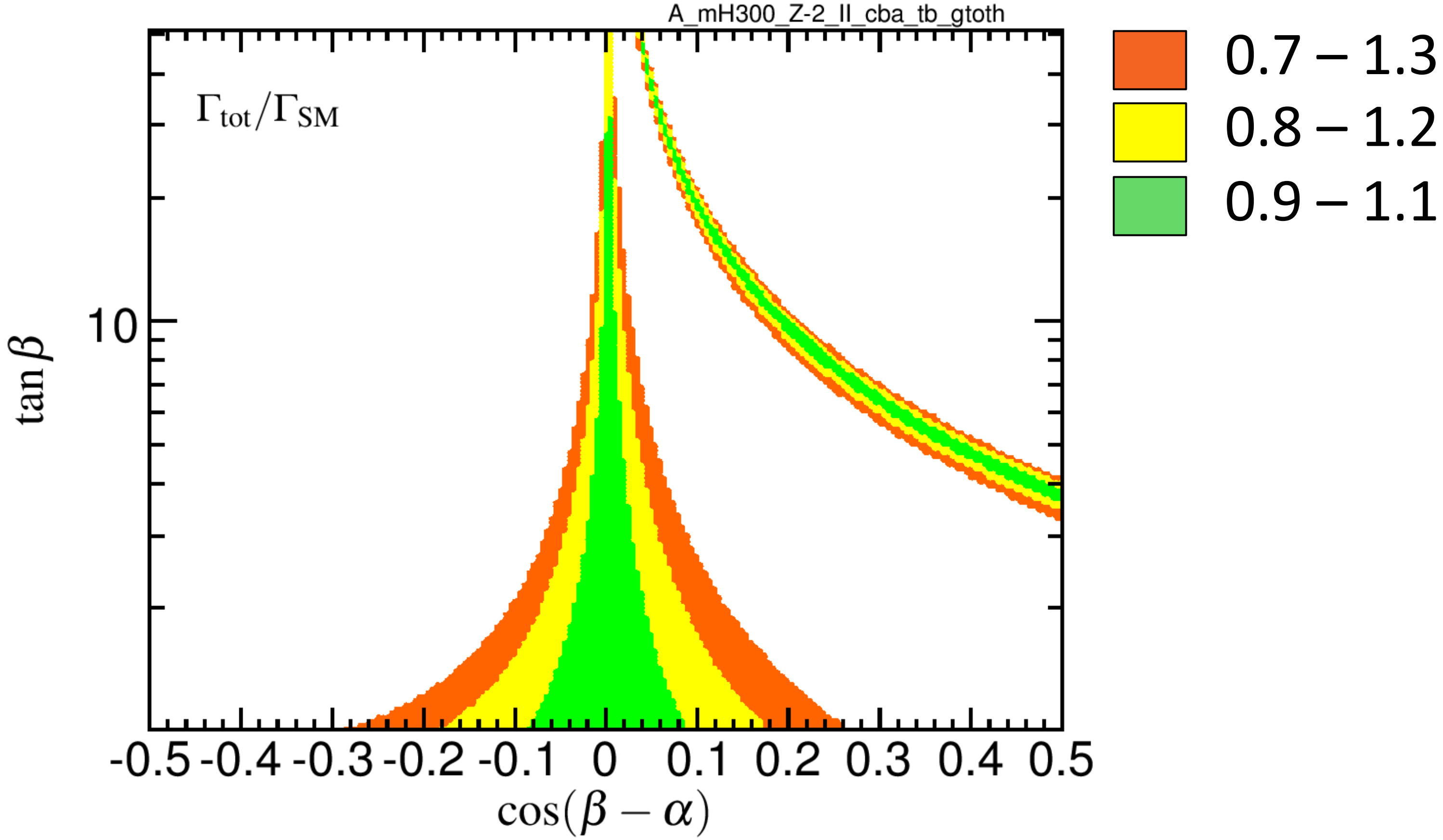
$$g_{Hhh} = \frac{\cos(\beta-\alpha)}{v}\Bigg[\left(3m_A^2 + 3\lambda_5 v^2 - 2m_h^2 - m_H^2\right)\left(\cos(2\beta-2\alpha) - \frac{\sin(2\beta-2\alpha)}{\tan(2\beta)}\right) - m_A^2 - \lambda_5 v^2 + \frac{\lambda_6 v^2}{2}\left(-\cot\beta + 3\sin(2\beta-2\alpha) + 3\cot\beta\cos(2\beta-2\alpha)\right) + \frac{\lambda_7 v^2}{2}\left(-\tan\beta - 3\sin(2\beta-2\alpha) + 3\tan\beta\cos(2\beta-2\alpha)\right)\Bigg] \quad \text{(A.6)}$$

Experimental results

ATLAS-CONF-2014-010



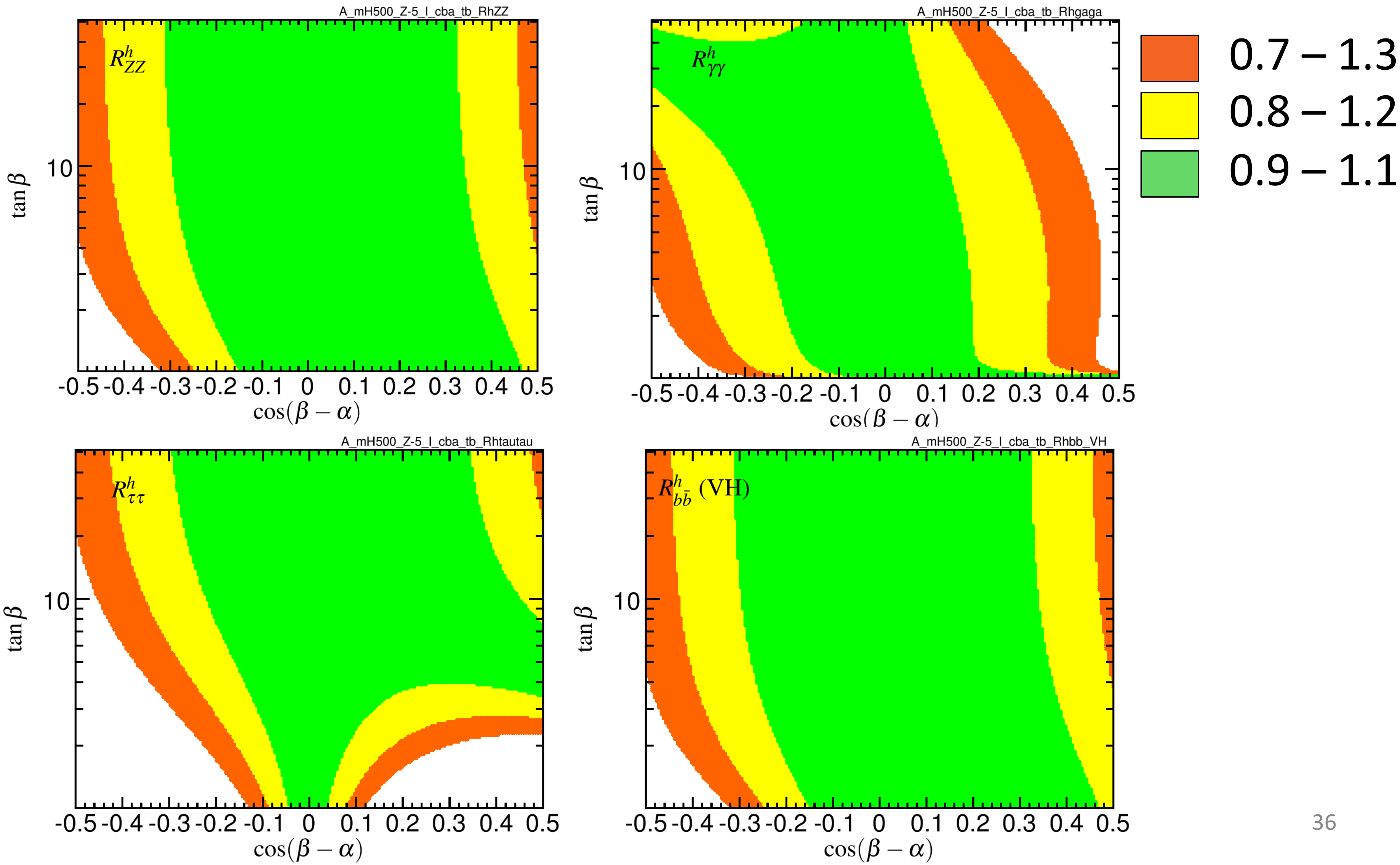
Total width



- The experimentally favored region is driven by the total h width, which in turns follow closely the coupling to b quarks

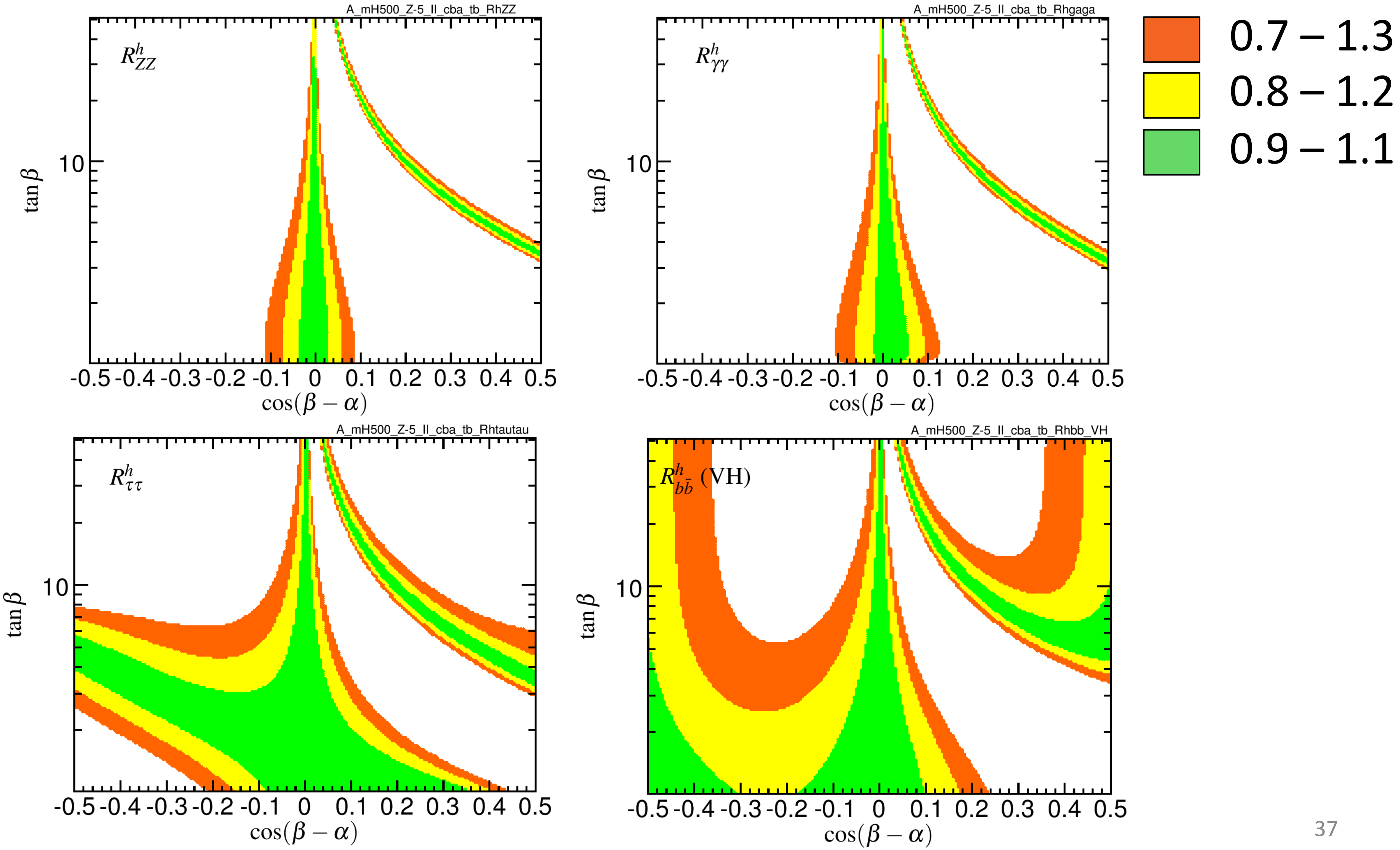
$$\frac{g_{hd\bar{d}}}{g_{hd\bar{d}}^{\rm SM}} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$$

Scenario A (Type-I): Light Higgs rates



Scenario A (Type-II): Light Higgs rates

- Allowed region driven by total width (h -> bb)

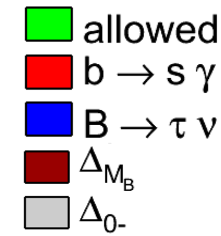


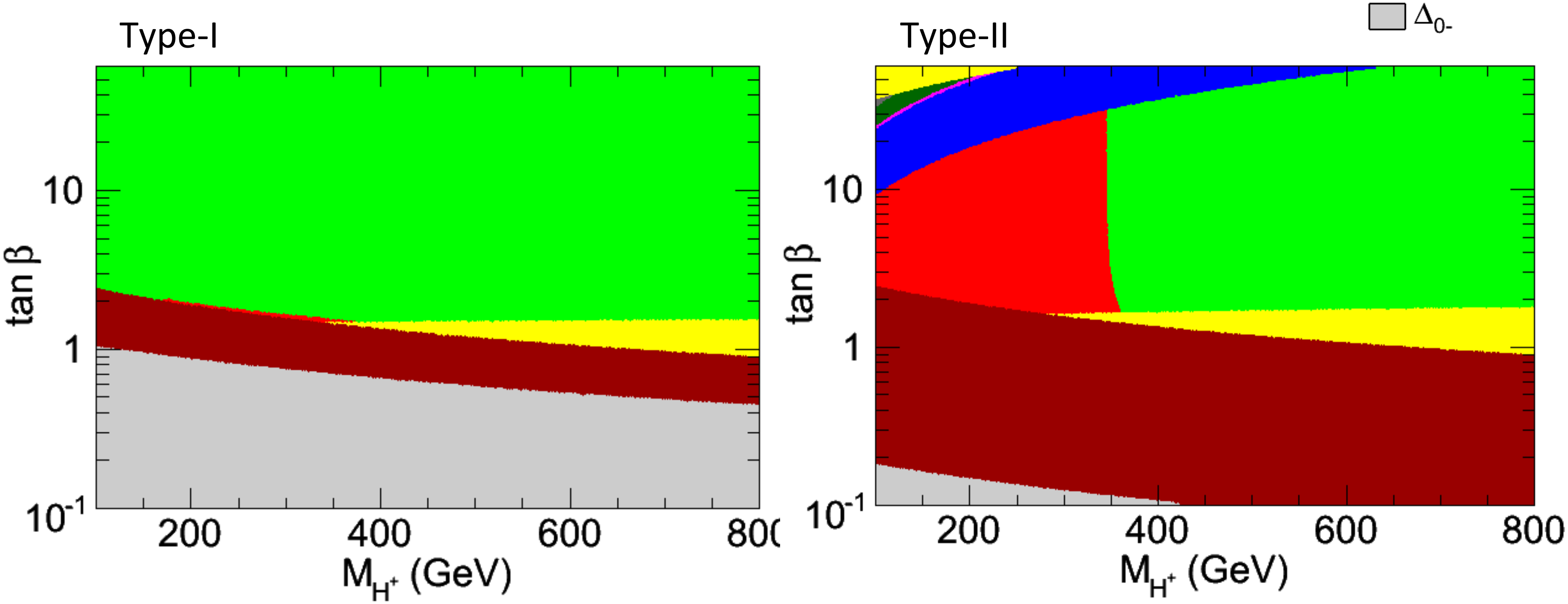
Flavor constraints

- The most important constraints from flavor physics can be summarized as follows:

Type-I/II Yukawa couplings: $\tan\beta > 1$

Type-II Yukawa couplings: $M_{H+} > 350$ GeV

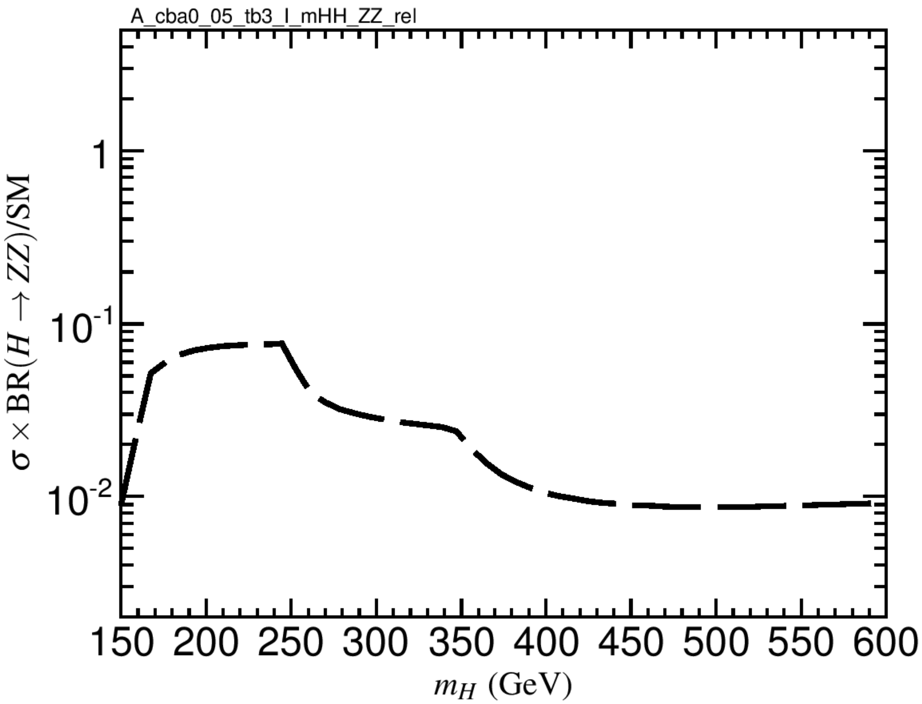


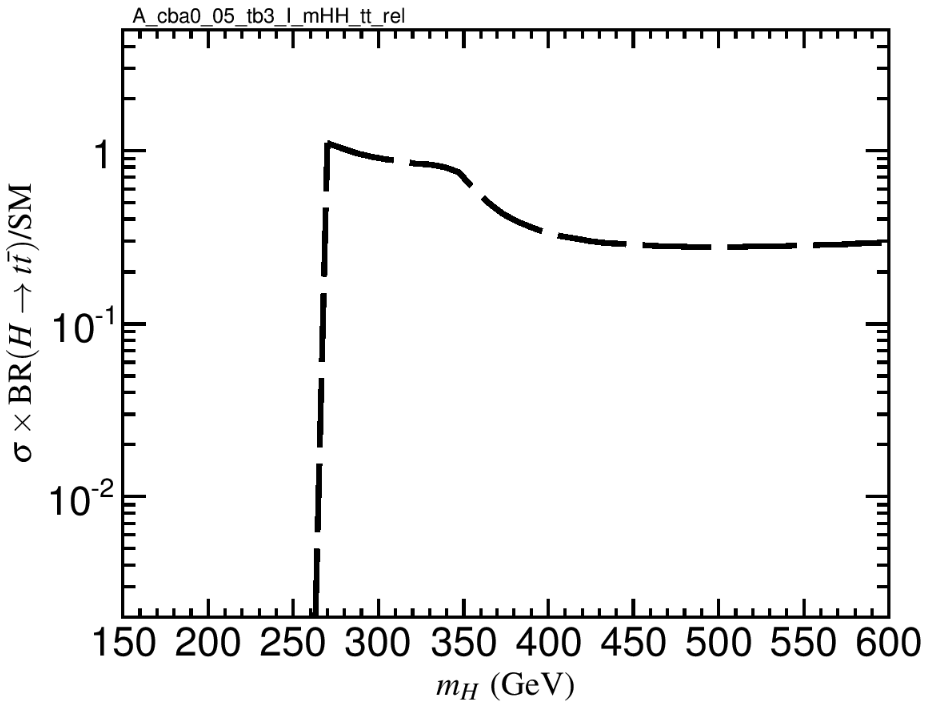


F. Mahmoudi, OS
[0907.1791] and work in progress

Scenario A (Type-I): Rates relative to SM

- Rates relative to SM for $\cos(\beta-\alpha) = 0.05$, $\tan\beta = 3$ (Type-I)

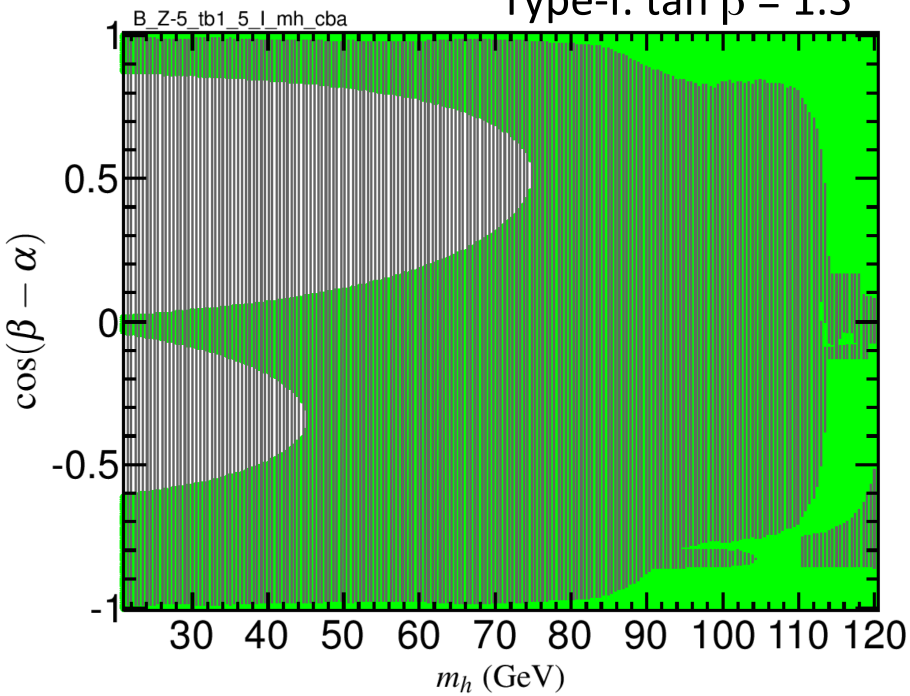




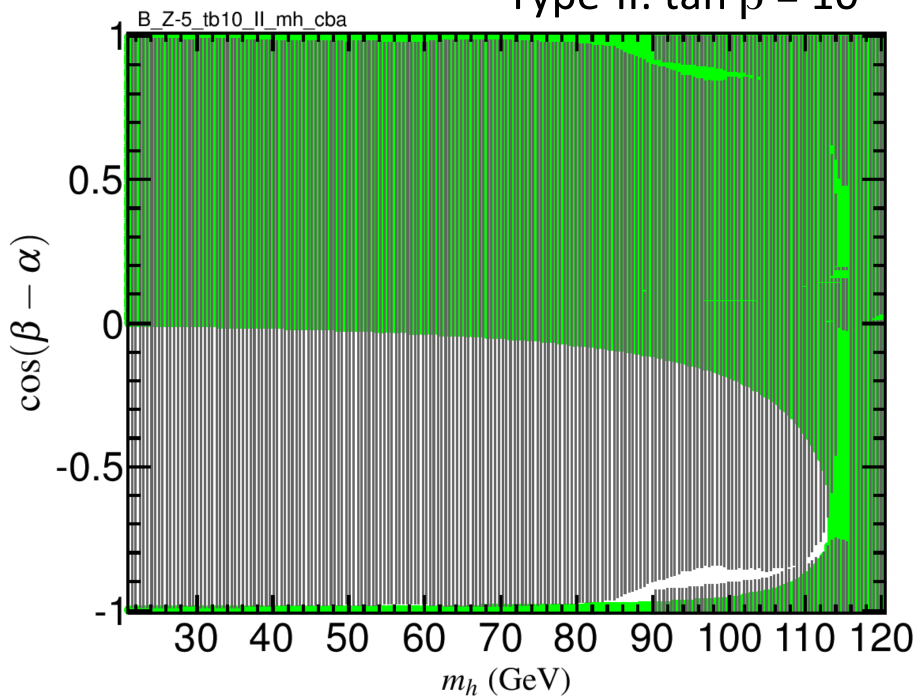
Scenario B

- "Inverted" scenario with lightest Higgs below 125 GeV, second CP-even Higgs, H, as the SM-like Higgs at 125
  $M_h < M_H = 125$ GeV $< M_A = M_{H+}$ (M_{H+} above 350 GeV for Type-II)

Type-I: tan β = 1.5



Type-II: tan β = 10

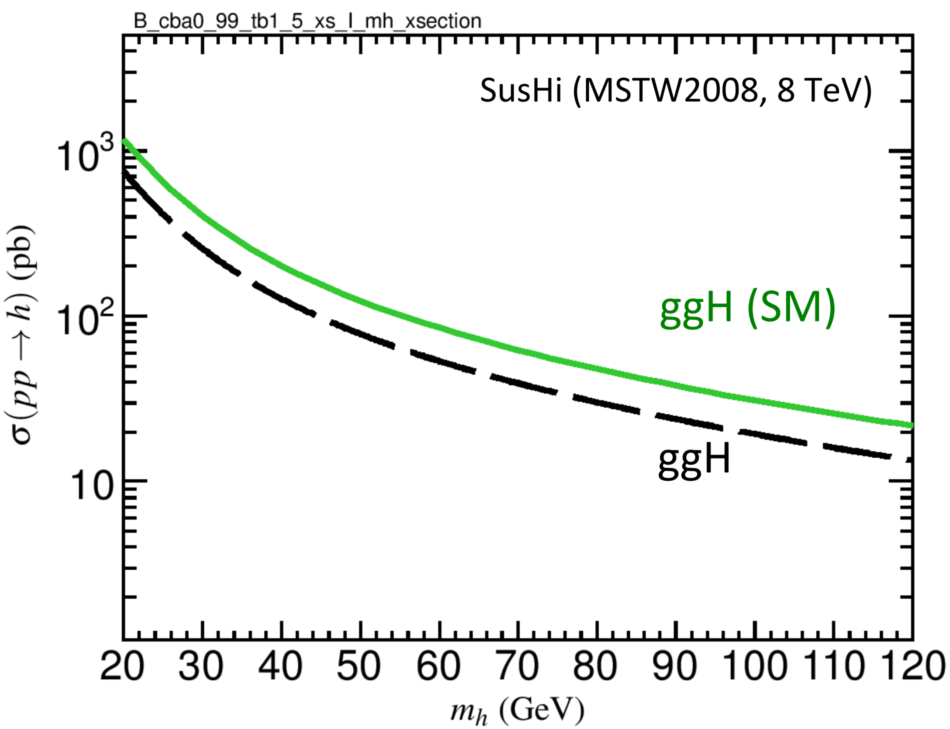


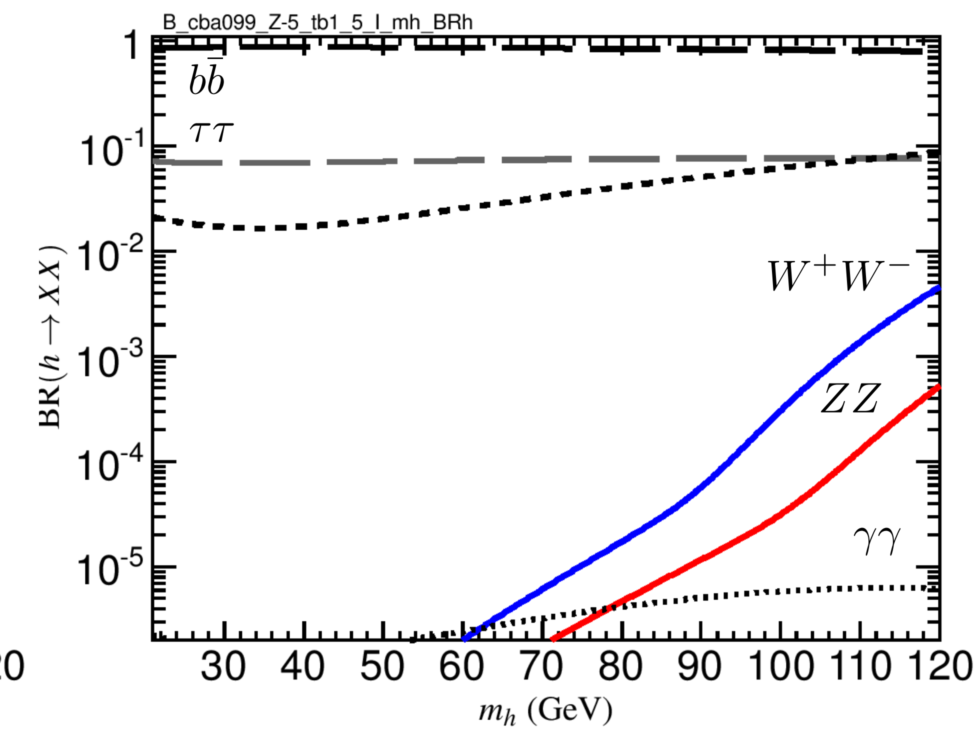
- Constraints from LEP/Tevatron/LHC (gray). Below 90 GeV only allowed solution is alignment of heavy Higgs: $|c_{\beta-\alpha}| \to 1$
  In Type-II also LHC constraints at higher tan β for m_h > 90 GeV.

Scenario B (Type-I): Decays

- Fix the remaining free parameter $c_{\beta-\alpha}$ to ensure H SM-like, get predictions for varying M_h

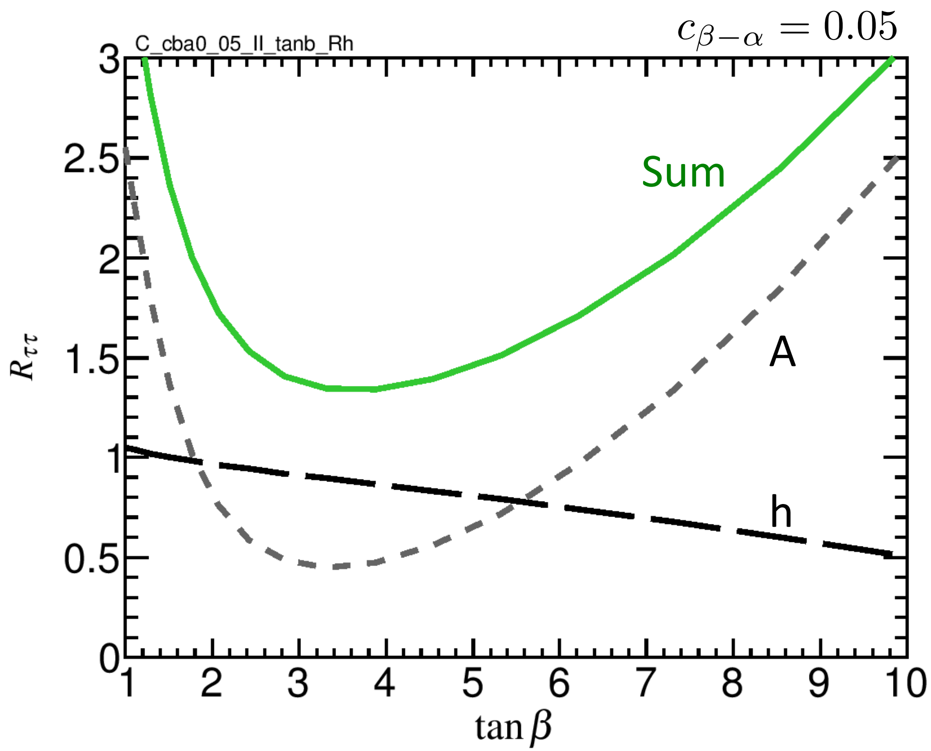
Type-I: tan β = 1.5, $c_{\beta-\alpha}$ = 0.99, M_H = 125.5 GeV

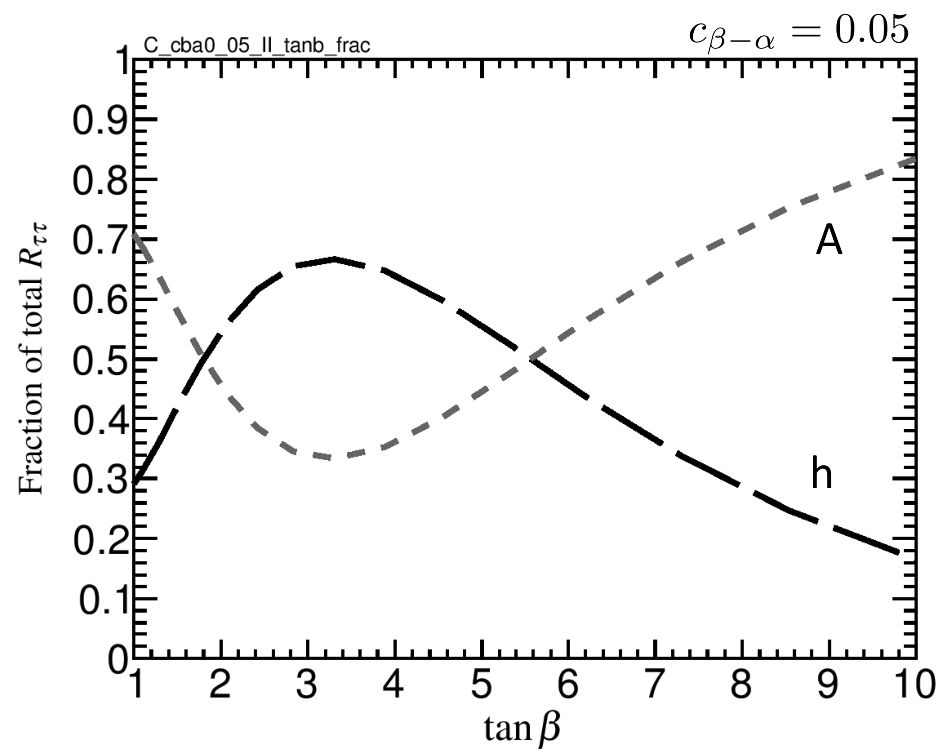




- gg cross section similar to SM, which modes could be used?

Scenario C (Type-II): ττ composition





- Larger variation in h rate from BR(h -> ττ) (non-zero $c_{\beta-\alpha}$)
  Relative contribution of CP-odd Higgs always above 35%

- Low/high tan β in principle excluded from direct searches / rates
  Define benchmark at minimum of combined rate