Two Higgs Doublets – with and without Dark Matter

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From Higgs to Dark Matter
Geilo, Norway, 2014-12-15

Outline

1. Two Higgs doublets
2. 2HDM with dark matter
3. 2HDM at the LHC (without dark matter)

Disclaimer: Not a review. Highly biased on my own work.

Extensive recent work on different aspects of this model:
Ferreira, Santos, Branco, Silva, Osland, Moretti, Lipniacka, Pruna, Haber, Kraml, Gunion, Grzadkowski, Krawczyk, Pich, Tuczon, Carena, Wagner, Yaguna, Lopez-Val, Plehn, Rathsman, Nierste, Wiebusch, Craig, Thomas, Reece, Mühlleitner, Spira, Harlander, Liebler, …, …

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

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

- Scalar potential:

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

- Complex phases on λ_5, λ_6, λ_7 and m_{12} can give rise to tree-level CP-violation (restricted by data). This talk: CP conservation.

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

Review: [arXiv:1106.0034]

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

- Introducing an explicit basis in (Φ_1, Φ_2) space: $\tan\beta = \dfrac{v_2}{v_1}$

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,(G^+ \cos\beta - H^+ \sin\beta) \\ v\cos\beta - h\sin\alpha + H\cos\alpha + \mathrm{i}\,(G^0\cos\beta - A\sin\beta) \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,(G^+ \sin\beta + H^+ \cos\beta) \\ v\sin\beta + h\cos\alpha + H\sin\alpha + \mathrm{i}\,(G^0\sin\beta + A\cos\beta) \end{pmatrix}$$

- Five physical Higgs states following EWSB:
  Two CP-even Higgs bosons: h, H
  $m_h < m_H$, mixing angle α
  One CP-odd Higgs boson: A
  One charged Higgs pair: H^{+-}

2HDM with Dark Matter

Mainly based on A. Goudelis, B. Herrmann, OS, [1303.3010]

The Higgs basis

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

$$H_1 = \cos\beta\Phi_1 + \sin\beta\Phi_2$$

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

$$\langle H_1^0\rangle = \frac{v}{\sqrt{2}} \qquad \langle H_2^0\rangle = 0$$

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

- Imposing an exact Z_2 symmetry in this basis there is *no mixing* between the doublets. The second doublet (without Yukawa couplings) becomes *inert*. Inert Doublet Model (IDM)

Ma, [hep-ph/0601255]; Barbieri, Hall, Rychkov, [hep-ph/0603188]

IDM at leading order

- Scalar potential:

$$V_0 = \mu_1^2|H|^2+\mu_2^2|\Phi|^2+\lambda_1|H|^4+\lambda_2|\Phi|^4+\lambda_3|H|^2|\Phi|^2+\lambda_4|H^\dagger\Phi|^2+\frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2+\mathrm{h.c.}\right]$$

- One doublet, H, is identified with SM Higgs

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v+h^0+\mathrm{i}G^0\right) \end{pmatrix} \qquad \Phi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^0+\mathrm{i}A^0\right) \end{pmatrix}$$

Here: $m_{h^0} \simeq 125\,\mathrm{GeV}$

- Lightest Z_2-odd particle (LOP) stable -> Dark Matter candidate
  - Neutral DM candidate can be either H^0 or A^0 (equivalent)

Beyond leading order

- Model parametrizations

$$\{\lambda_1, \quad \lambda_2, \quad \lambda_3, \quad \lambda_4, \quad \lambda_5, \quad \mu_2\} \quad \{m_{h^0}, \quad m_{H^0}, \quad m_{A^0}, \quad m_{H^\pm}, \quad \lambda_L, \quad \lambda_2\}$$

are equivalent at leading order:

$$m_{h^0}^2 = \mu_1^2 + 3\lambda_1 v^2, \qquad \lambda_L = \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)$$

$$m_{H^0}^2 = \mu_2^2 + \lambda_L v^2, \qquad \lambda_S = \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)$$

$$m_{A^0}^2 = \mu_2^2 + \lambda_S v^2, \qquad g_{h_{\rm SM} H^0 H^0} \propto \lambda_L$$

$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2. \qquad g_{h_{\rm SM} A^0 A^0} \propto \lambda_S$$

- Beyond tree-level should relate input parameters to (in principle) measureable quantities (e.g. on-shell masses, couplings, …)
  Here: 1-loop calculation of pole masses (MSbar ren.)

Model constraints

- Perturbativity

$$|\lambda_i|,\ |g_i|,\ |y_i|\ \leq\ K. \qquad\qquad K = 4\pi$$

- S-matrix unitarity for gauge/Higgs boson scattering

$$|f(\lambda_i(Q))| < C$$

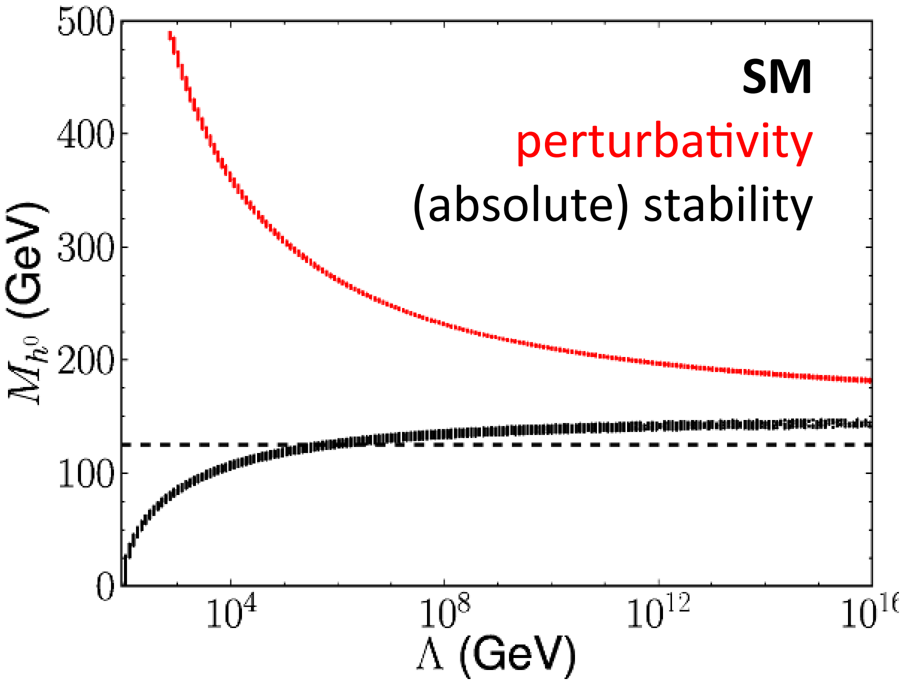
Ginzburg, Ivanov, PRD72 (2005) 115010

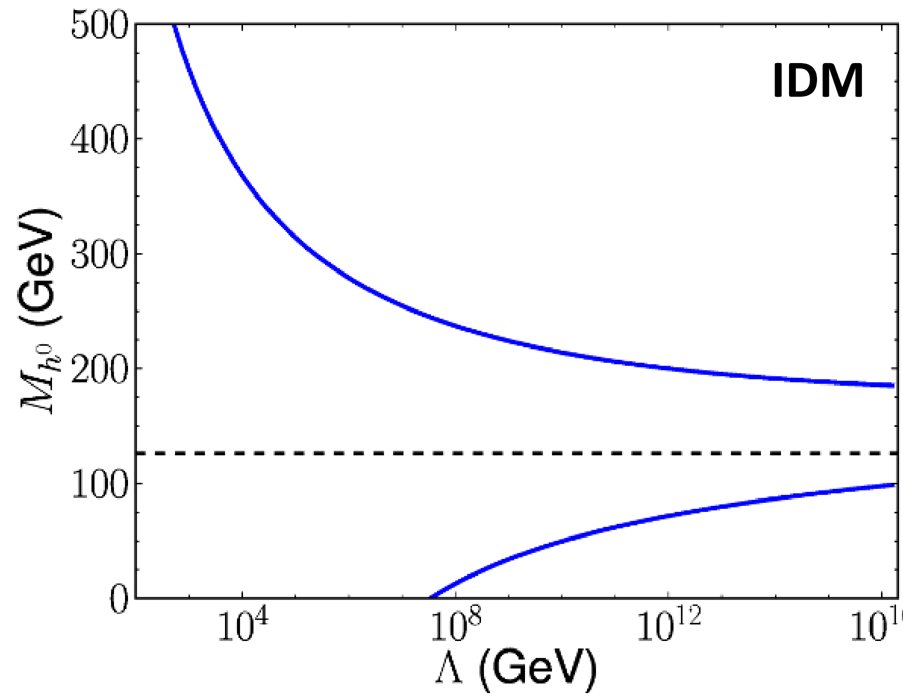
- Positivity of the potential (*absolute* stability)

$$\begin{aligned}\lambda_1(Q), \lambda_2(Q) &> 0,\\ \lambda_3(Q) &> -2\sqrt{\lambda_1(Q)\lambda_2(Q)},\\ \lambda_3(Q) + \lambda_4(Q) - |\lambda_5(Q)| &> -2\sqrt{\lambda_1(Q)\lambda_2(Q)}\end{aligned}$$

- Constraints at input scale Q = M_Z, or higher scales (RGE)

Stabilizing the vacuum



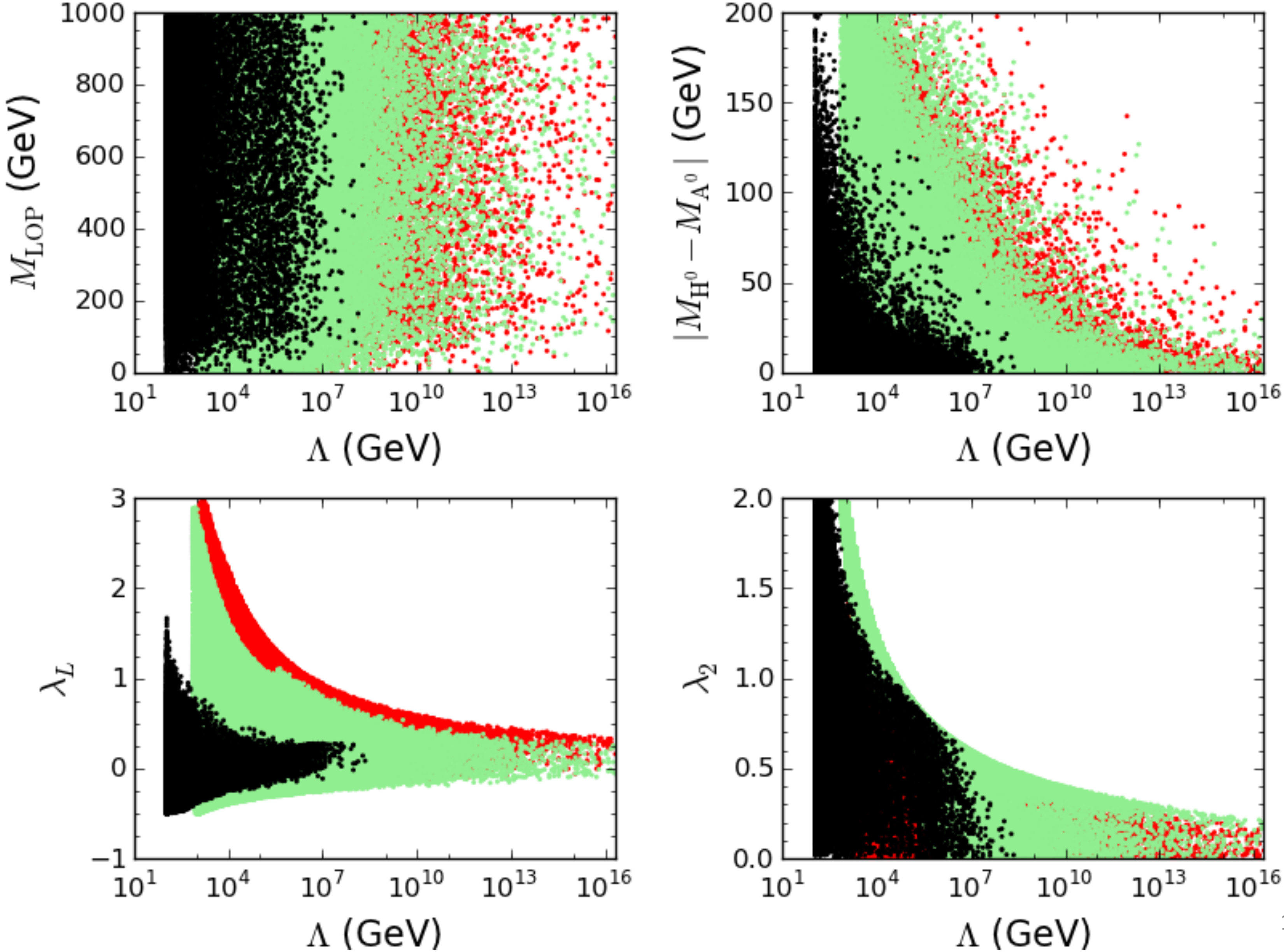


- Simple 1-loop RGE comparison, 1-loop pole masses (capital M_h)

- The second doublet can compensate top Yukawa coupling which drives the SM quartic negative
  -> Absolute stability for M_h = 125 GeV possible up to high scales
  (Beyond 1-loop SM somewhat improved) Degrassi et al, [1205.6497], [1307.3536]

1-loop RG analysis of the IDM

Pertubativity fails - Unitarity fails - Stability fails



DM Relic Density

- DM relic density calculated assuming thermal production MicrOMEGAS (incl. 3/4-body final states)

Bélanger, Boudjema, Pukhov, Semenov, [1305.0237]

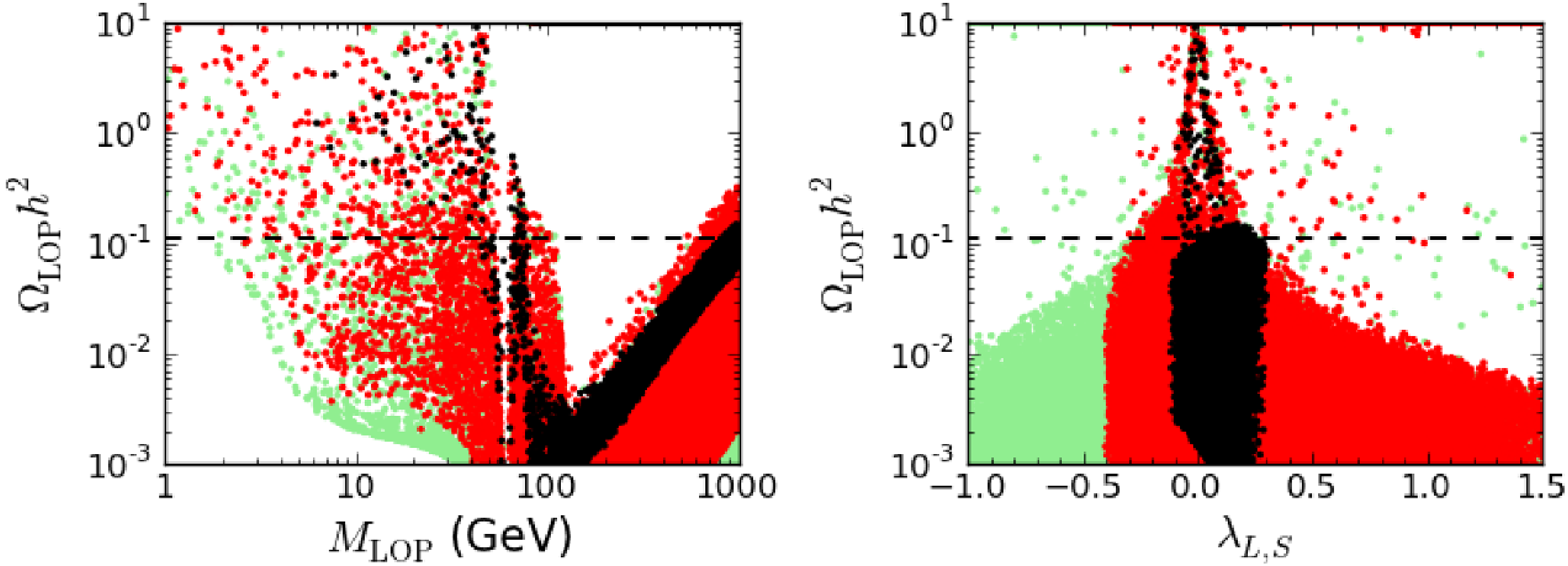
- Dotted line is WMAP 7-year limit (Planck similar)

$$0.1018 \leq \Omega_{\rm LOP} h^2 \leq 0.1234$$

Point valid at input (EW) scale

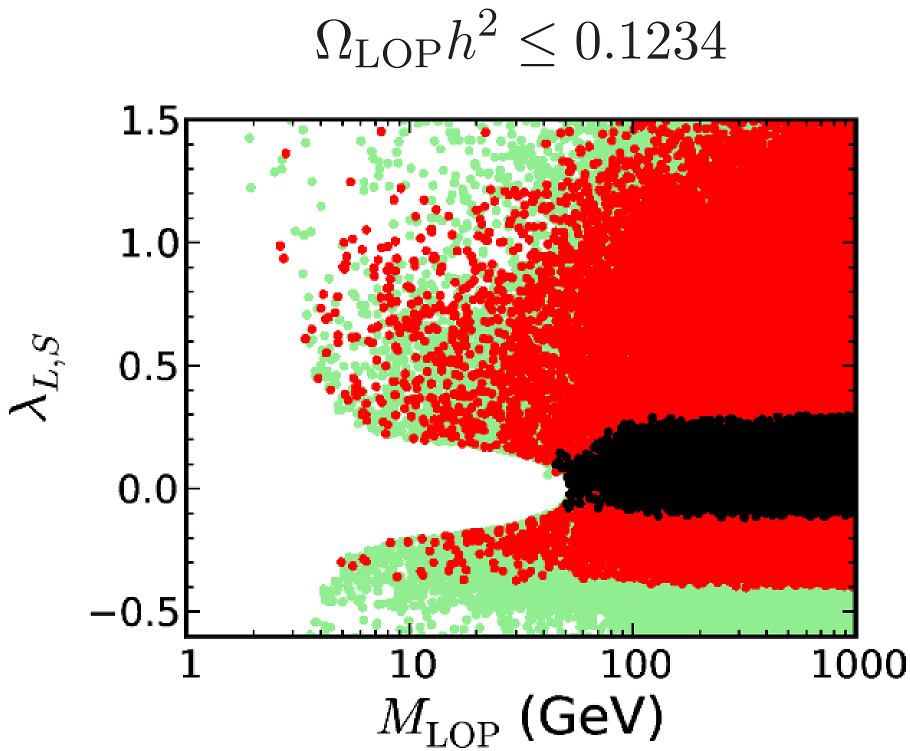
Point valid up to (at least) Λ = 10 TeV

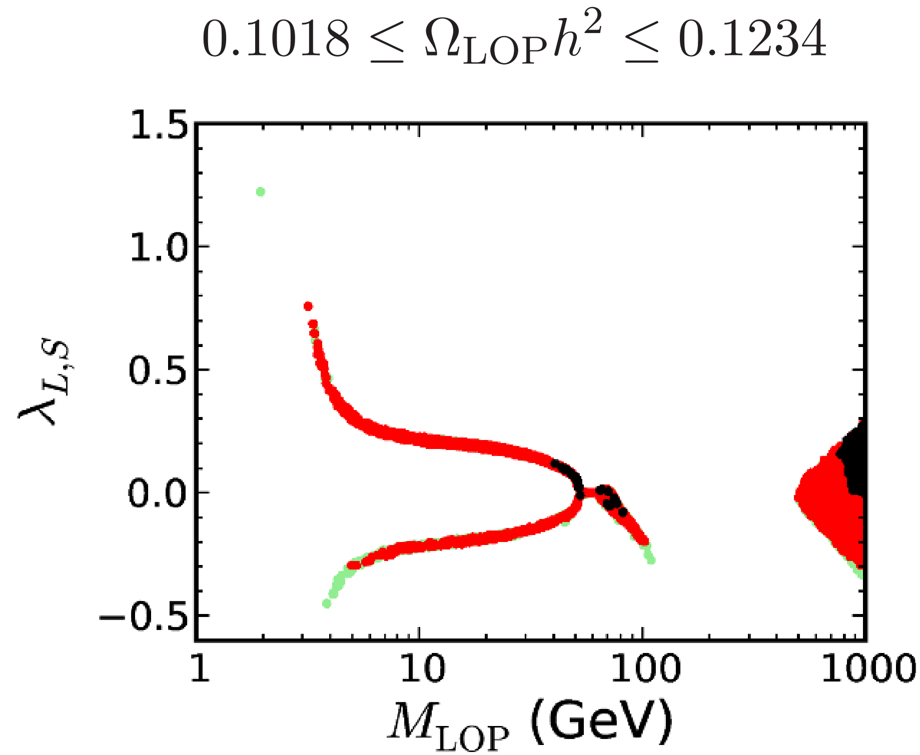
Point valid up to GUT scale (10^{16} GeV)



DM Relic Density

- Like in other models, the precise knowledge of the relic density effectively reduces dimensionality of parameter space



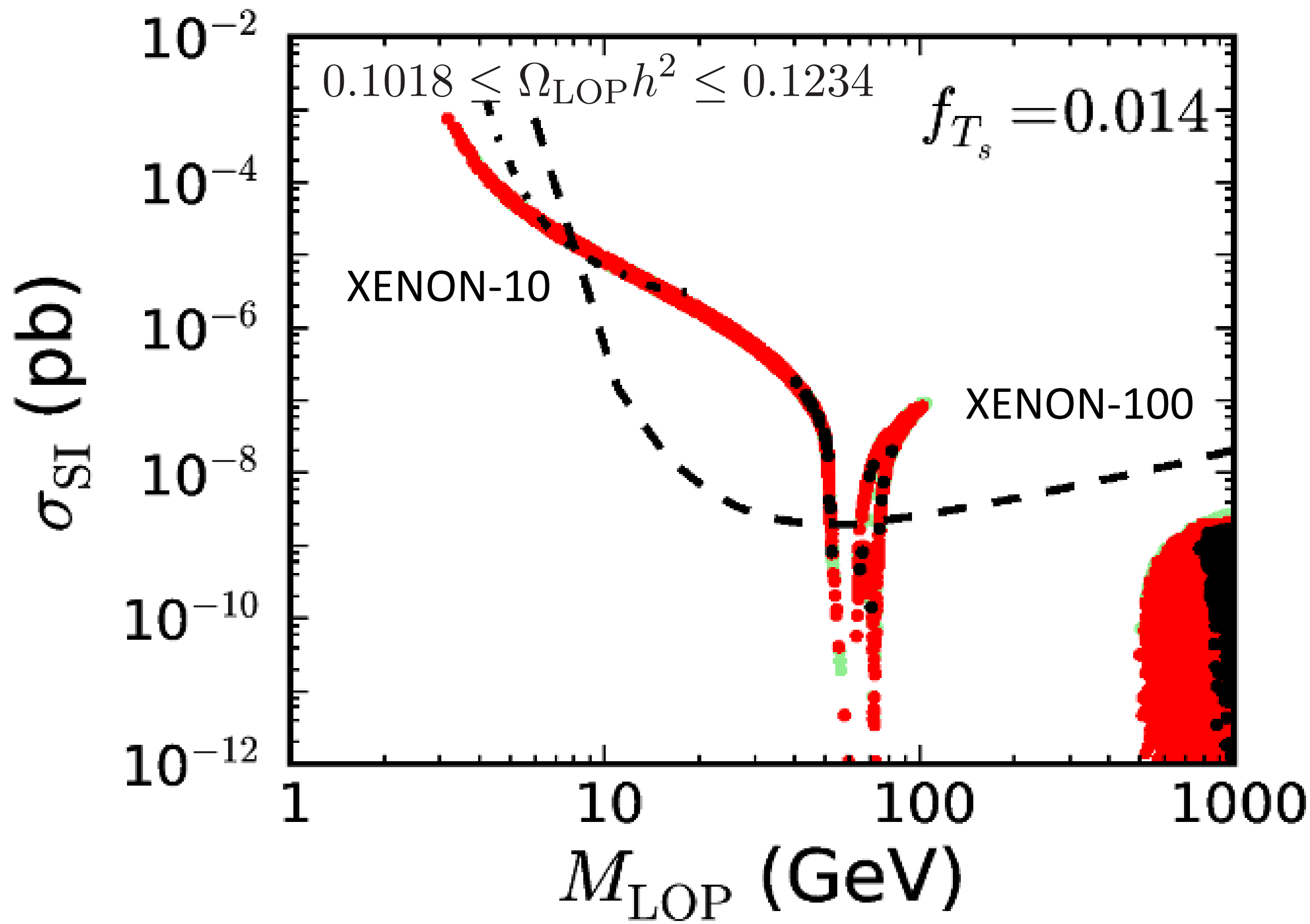


- Theoretical precision probably not comparable with current experimental knowledge of $\Omega_{\rm DM}$ (true for many models). Framework for inclusion of effects beyond LO in progress.

Direct detection

- Assuming that DM has not been observed in any direct detection experiment, we can use e.h. the XENON upper limit on σ_{SI}

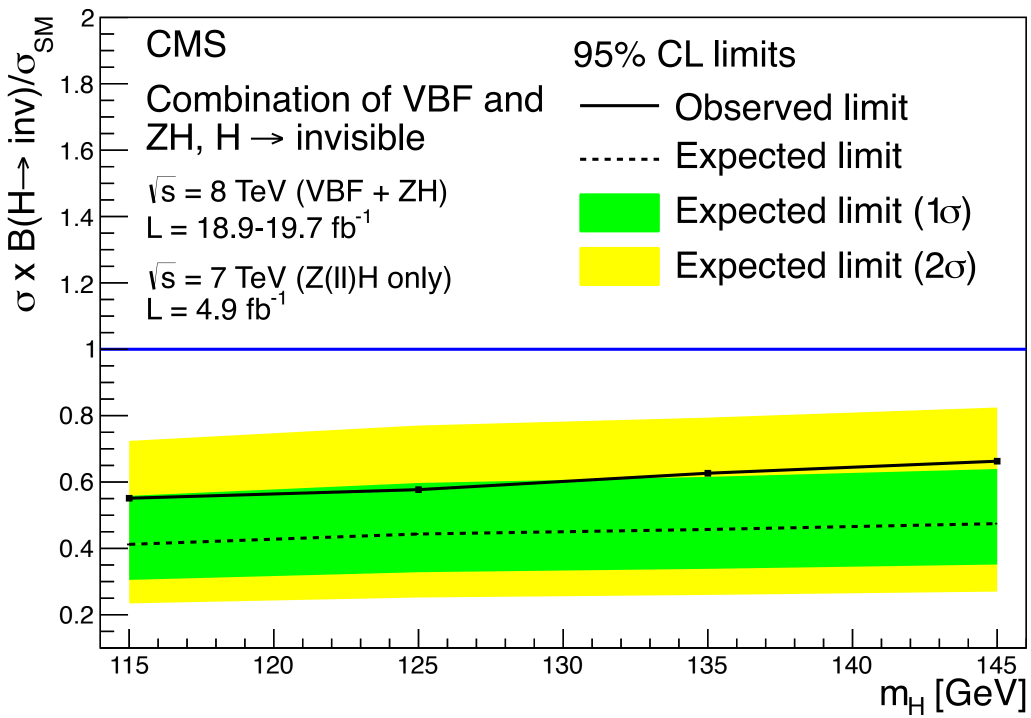
XENON Collaboration, [1104.2549], [1104.3088]



Invisible Higgs decays

- Both ATLAS and CMS have performed searches for "invisible" decays of the 125 GeV Higgs (invisible = missing E_T)

$$pp \to ZH, Z \to \ell^+\ell^-$$



ATLAS-CONF-
CMS-

Assuming SM production:

$$\mathrm{BR}(h^0 \to \mathrm{inv.}) \lesssim 0.6$$

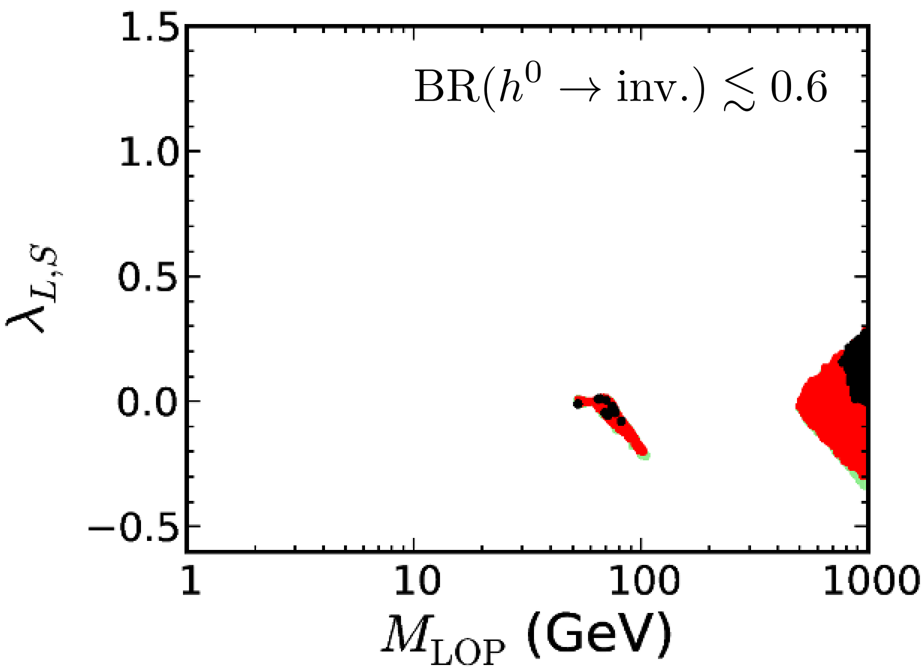
IDM constraints from invisible Higgs decays

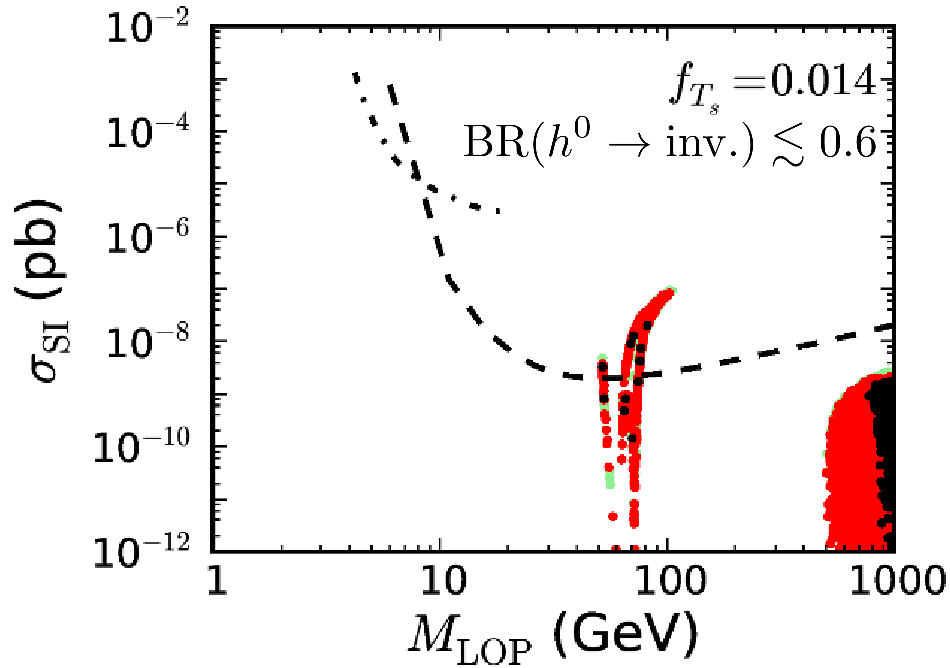
- In the IDM, this constraint would apply to the case

$$h \to H^0 H^0 \quad (h \to A^0 A^0)$$

- Remember:

$$g_{h_{\rm SM} H^0 H^0} \propto \lambda_L \qquad g_{h_{\rm SM} A^0 A^0} \propto \lambda_S$$

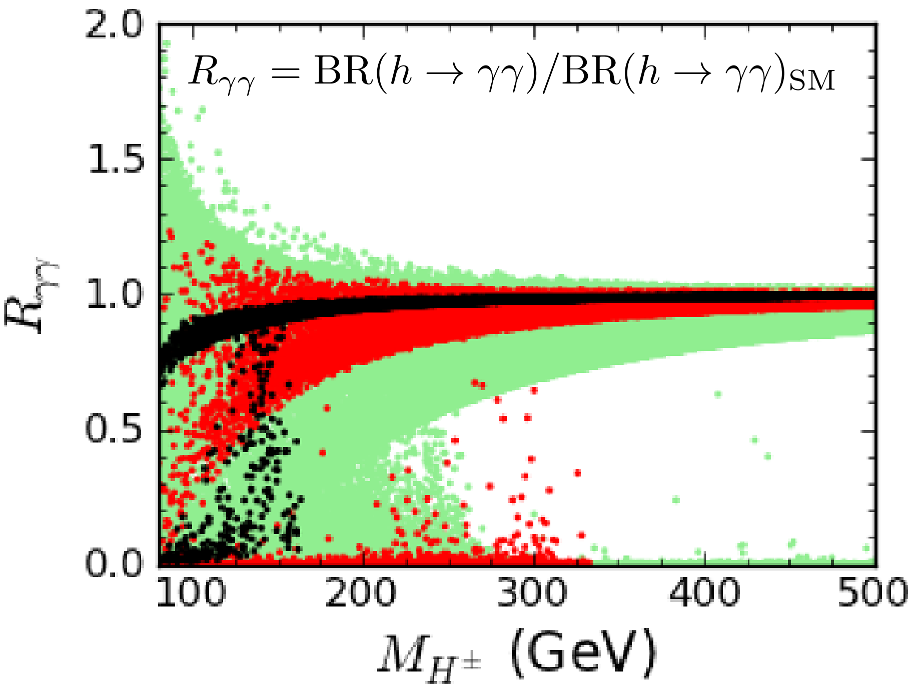


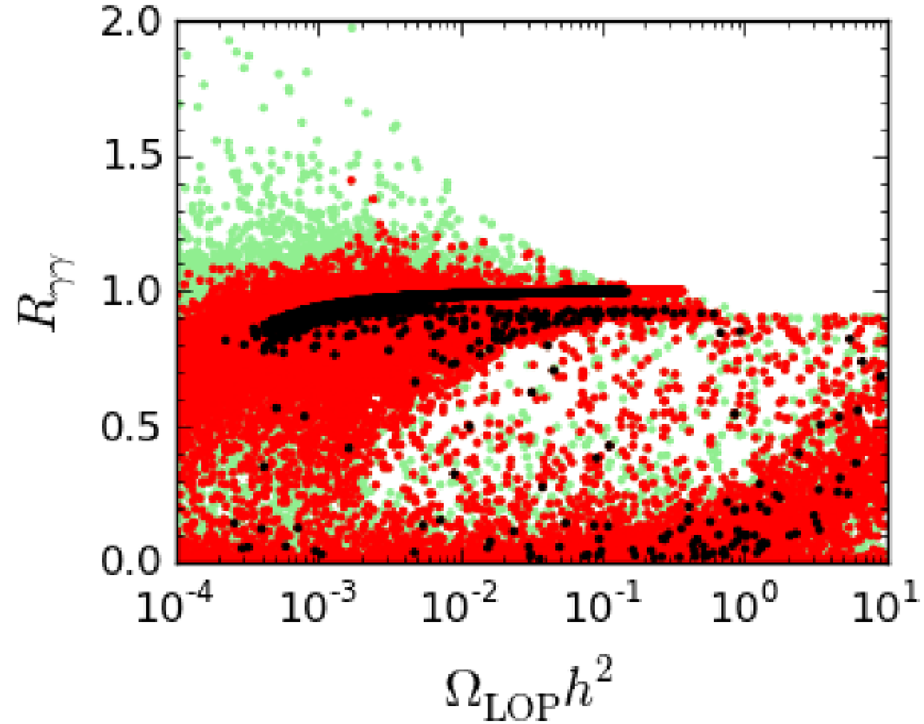


- IDM can live either close to Higgs resonance ($M_{\rm LOP} \simeq 50 - 80\,{\rm GeV}$) or at high mass, $M_{\rm LOP} \gtrsim 500\,{\rm GeV}$

Implications for 125 GeV Higgs at LHC

- Besides the invisible decays, H+ in the IDM can modify the loop-induced decays of a SM-like h^0





- When IDM makes up all DM, there is no enhancement of the two photon rate (even before constraints).
  In agreement with current experimental results ☺

LHC Signatures of IDM Dark Matter

- Two mass regions for IDM Dark Matter:

  M_{DM} = 50 – 80 GeV, M_{DM} > 500 GeV

- Direct production of DM pair possible only through Higgs channel

$$pp \to h^{(*)} \to H^0 H^0$$

  also production through gauge bosons of

$$pp \to Z^{(*)} \to H^0 A^0$$
$$pp \to W^{\pm(*)} \to H^0 H^{\pm}$$

- Only possible decays are within the inert doublet, i.e.

$$A^0 \to H^0 Z^{(*)} \qquad H^{\pm} \to H^0 W^{\pm(*)} \qquad H^{\pm} \to A^0 W^{\pm(*)}$$

- Weak-scale xsections with multi-lepton signatures + E_T-miss

2HDM at the LHC (without Dark Matter)

Higgs Couplings

- Couplings to vector bosons determined by mixing angle

$$\frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \sin(\beta-\alpha) \qquad \frac{g_{HVV}}{g_{HVV}^{\rm SM}} = \cos(\beta-\alpha) \qquad g_{AVV} = 0$$

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

- 2HDM Yukawa couplings in arbitrary basis

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

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 <u>at tree level</u>, broken by Δ_b corrections

Model predictions for the LHC

- Two bundles of codes provide complete 2HDM predictions of cross sections + branching ratios, including available higher-order (mostly QCD) corrections

SusHi + 2HDMC

Harlander, Mantler, Liebler, [1212.3249]
Eriksson, Rathsman, OS, [0902.0851]

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

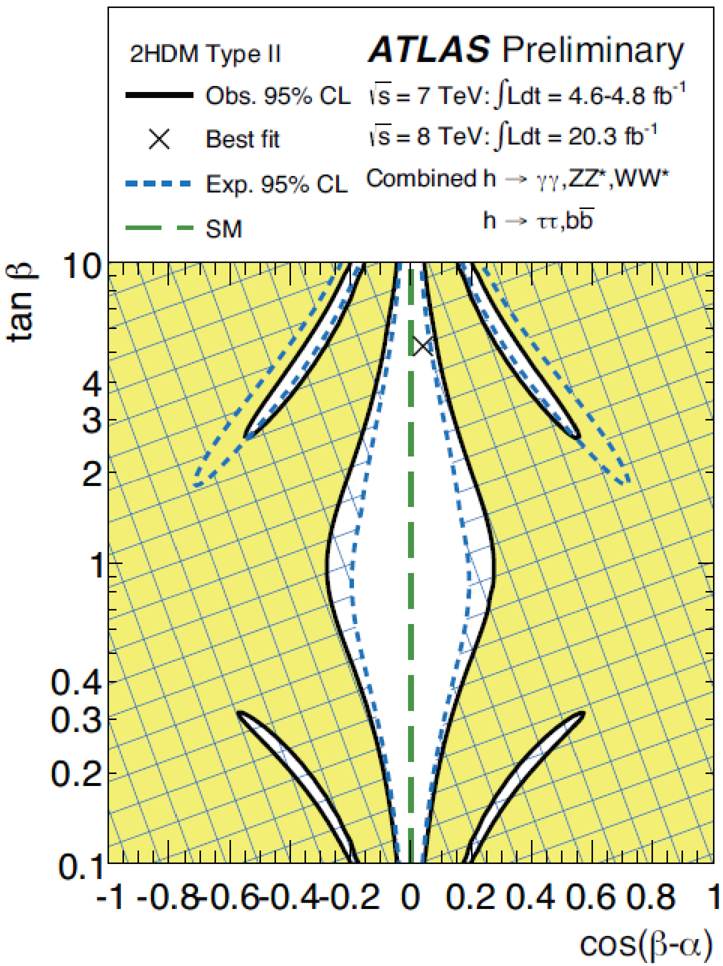
R. Harlander[1], M. Mühlleitner[2], J. Rathsman[3], M. Spira[4], O. Stål[5]

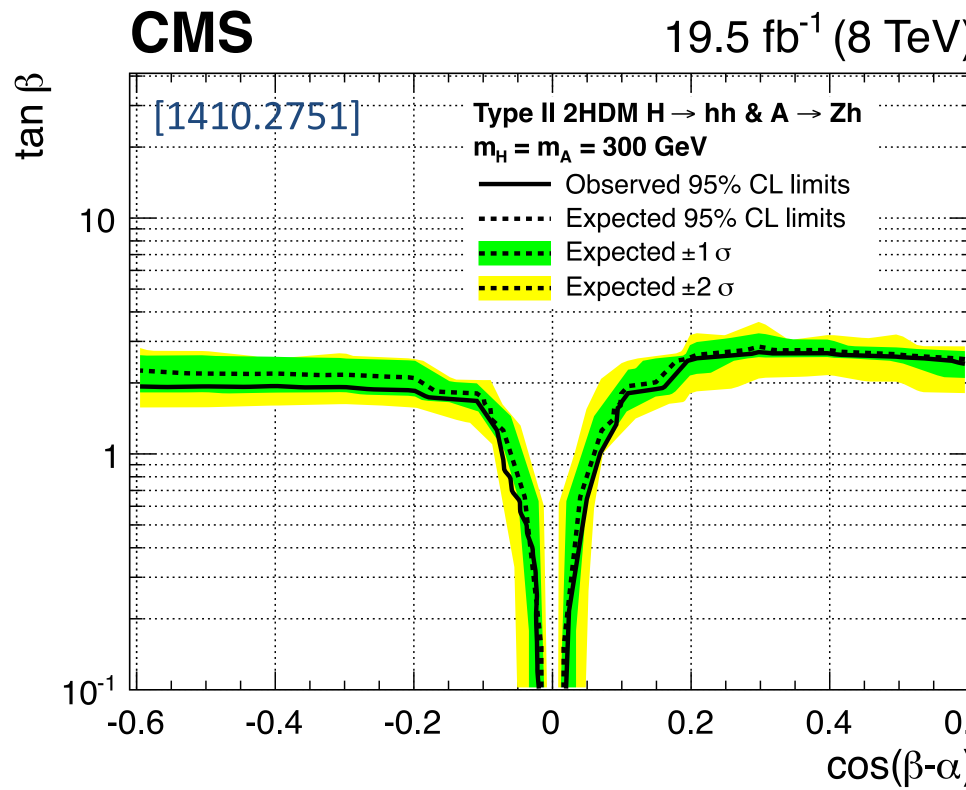
[LHCHXSWG-2013-001], [1312.5571]

First LHC analyses of 2HDM

- Reinterpretation of 125 GeV coupling measurements

ATLAS-CONF-2014-010





- Genuine 2HDM searches
- BR(H -> hh) sensitive to full model $M_H = M_A = 300$ GeV “best case”

Preparing for run-II: Benchmarks

In collaboration with H.E. Haber

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

- Still, in many situations it <u>also</u> 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
  - Combine different channels to improve sensitivity
  - Define unambiguous and complete sets of parameters
  - Be able to consider relevant model constraints
  - Provide language to compare exp <-> exp and exp <-> th

Model parametrization

- Even with restrictions to CP conservation and soft Z_2 (Types) there remains seven free parameters:

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

or

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

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

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

  + "Type" condition on the Yukawa couplings
- Higgs basis condition for soft Z_2-breaking:

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

- Symmetry manifest: ($\lambda_6 = \lambda_7 = 0$) in basis for specified $\tan\beta$

Mass relations

- Remaining masses fixed by the quartic Higgs basis couplings:

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

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

(Z_7 only enters in triple/quartic scalar interactions)

- Theoretical constraints:

$$|Z_i| \lesssim \mathcal{O}(1)$$

- Further constraints on the choice of benchmarks come from observed properties of 125 GeV Higgs and wishful(?) thinking about observable signatures

Benchmark scenarios

H.E. 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 GeV < M_H < M_A = M_{H+}.
  Useful for H searches in "standard" modes.

- Scenario B
  "Inverted" scenario with heavy CP-even Higgs at 125 GeV
  M_h < M_H = 125 GeV < M_A = M_{H+}. Useful for h searches.

- Scenario C
  Overlapping CP-even and CP-odd Higgses @ 125 GeV
  M_h = M_A = 125 GeV < M_H = M_{H+}. Test sensitivity to mixed CP.

Benchmark scenarios

- Scenario D
  Heavy CP-even Higgs with non-SM decays, e.g. $H \rightarrow A\,Z$, $H \rightarrow H^+W^-$
  $M_h = 125$ GeV $< M_A/M_{H+} < M_H$. Useful for H searches in cascades.

- Scenario E
  Scenario for heavy CP-odd / charged Higgs with
  $A \rightarrow H^+ W^-$ or $H^+ \rightarrow A\,W^+$. Useful for A (H+ searches) in cascades.

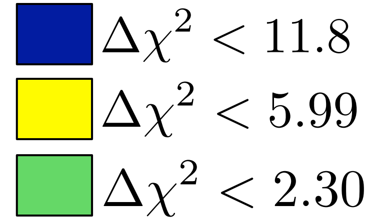
- Scenario F
  h with SM-like couplings to up-type fermions and vector bosons, but flipped sign of coupling to down-type fermions.

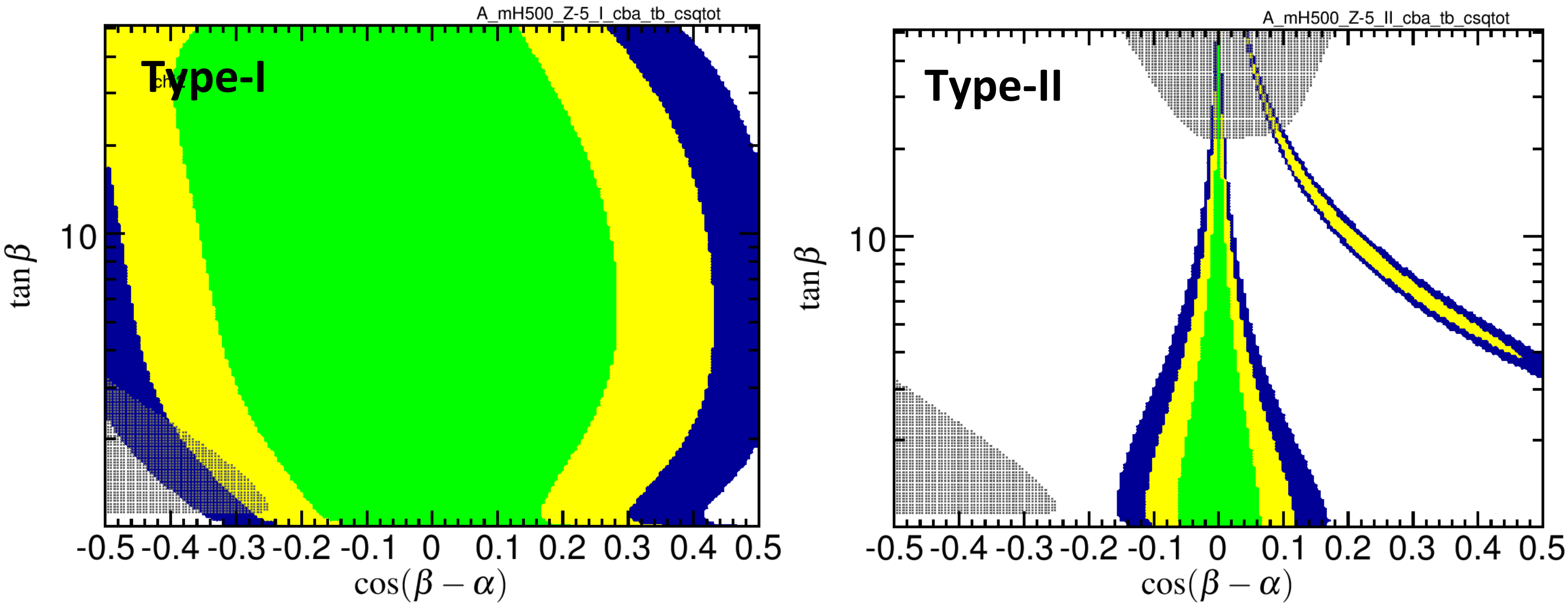
- Scenario G
  "MSSM"-like (mass-degenerate) scenario for heavy Higgs bosons
  $M_h = 125$ GeV $< M_H = M_A = M_{H+}$, decoupling as $M >> v$.

Scenario A: Lightest 2HDM Higgs@125 GeV

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

$M_H = 500\,\mathrm{GeV} < M_A = M_{H^\pm}$ -> Talk by P. Bechtle



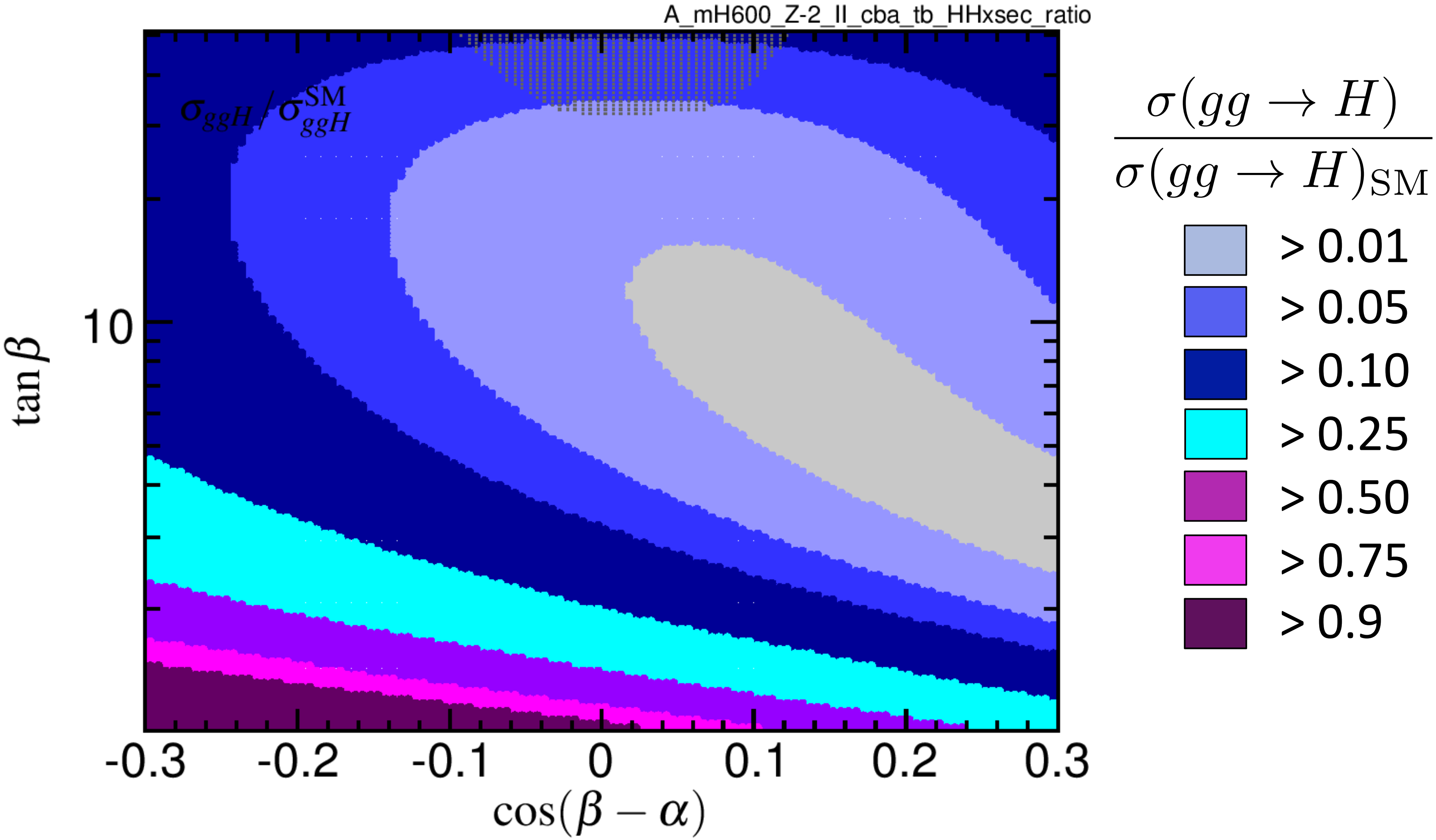


- Type-II couplings much more restricted around alignment, in particular for high tan β. Exception: flipped-sign scenario (F)

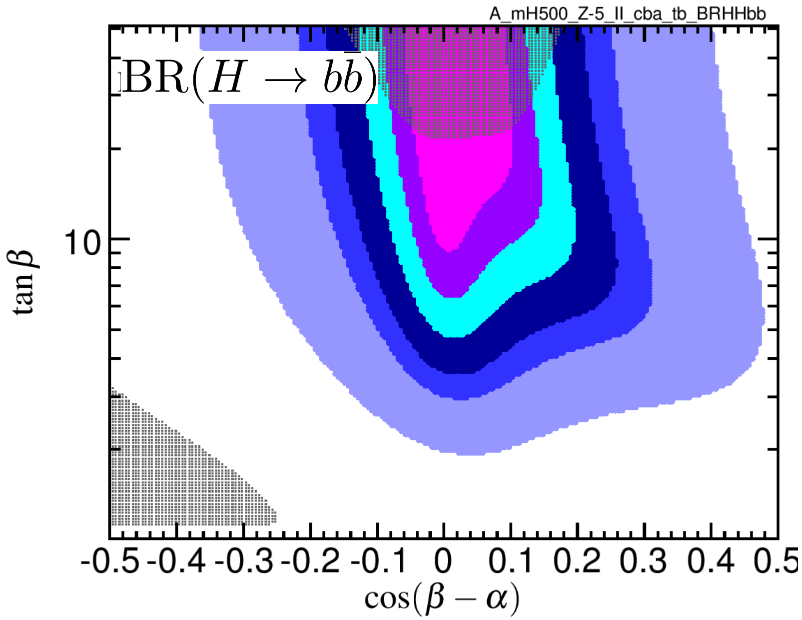
Ferreira, Haber, Gunion, Santos, [1403.4736]

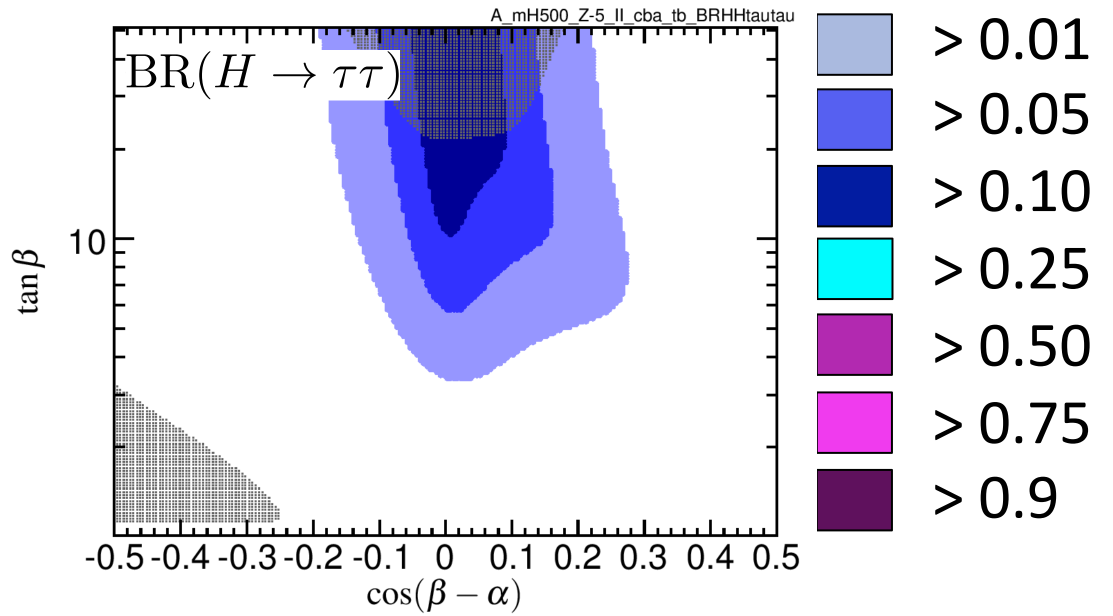
Type-II: Heavy Higgs production

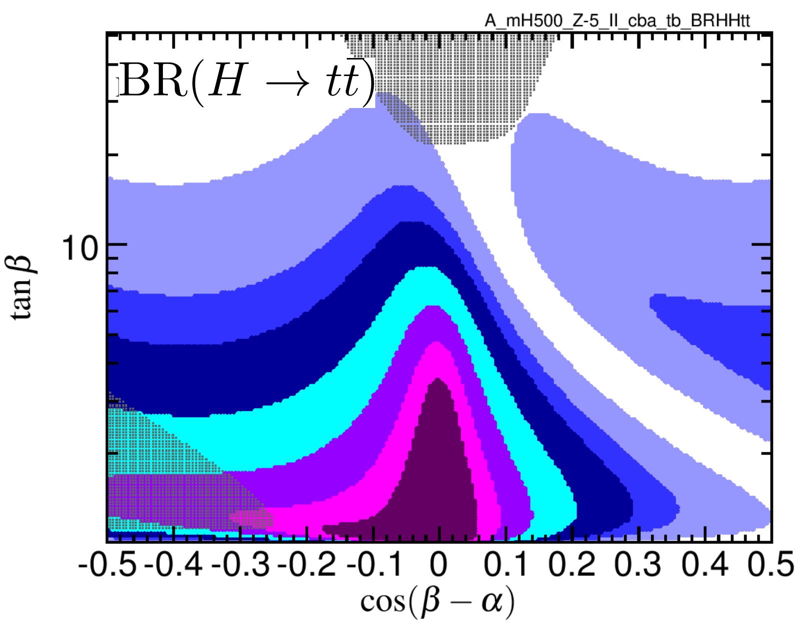
- Since the H must have suppressed couplings to gauge bosons, only $gg \to H$ and $b\bar{b} \to H$ (at high tan β)



Type-II: H decays to fermions



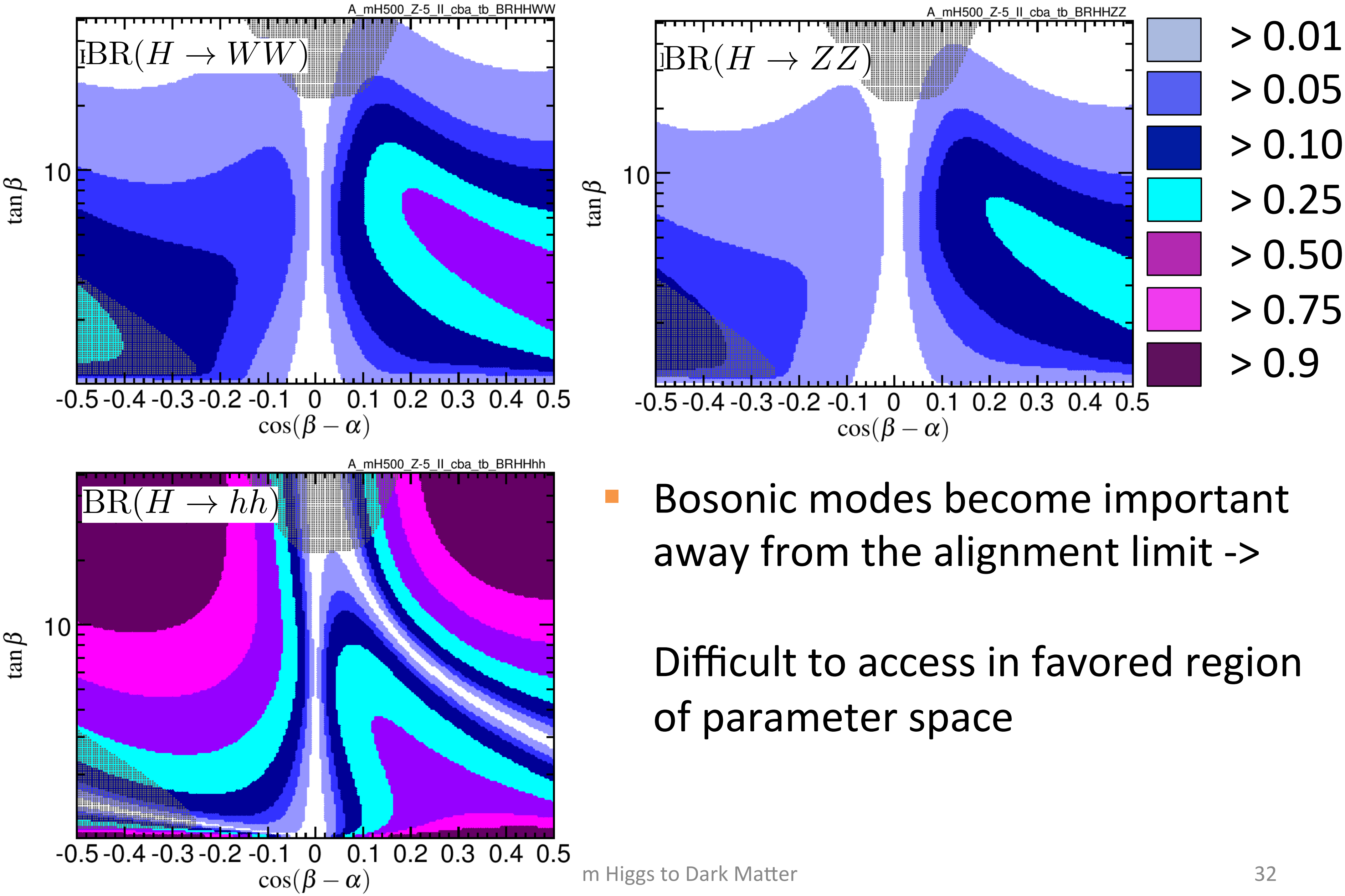




$$m_H = 500\,\mathrm{GeV}$$

- Fermions dominate close to alignment limit
- Complementarity between up- and down-type modes typical of Type-II

Type-II: H decays to bosons

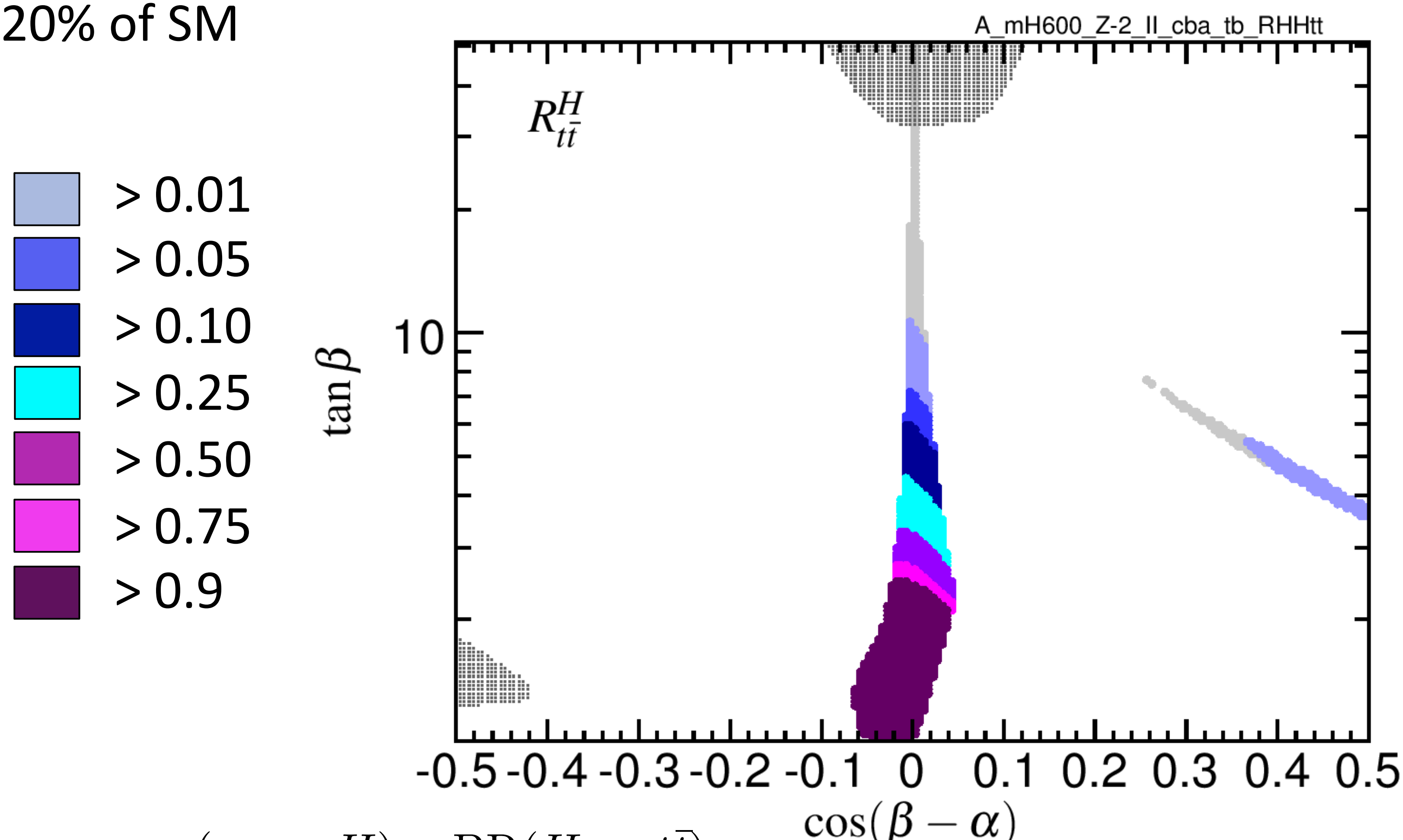


- Bosonic modes become important away from the alignment limit ->

  Difficult to access in favored region of parameter space

Type-II: The allowed parameter space

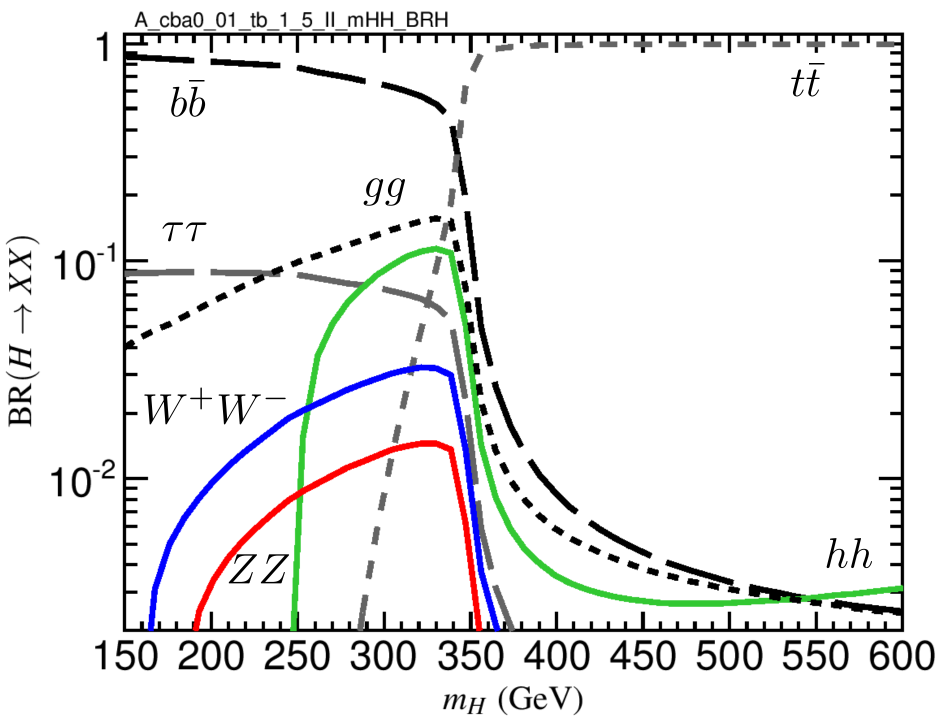
- Applying theory constraints and rates of 125 GeV Higgs within 20% of SM

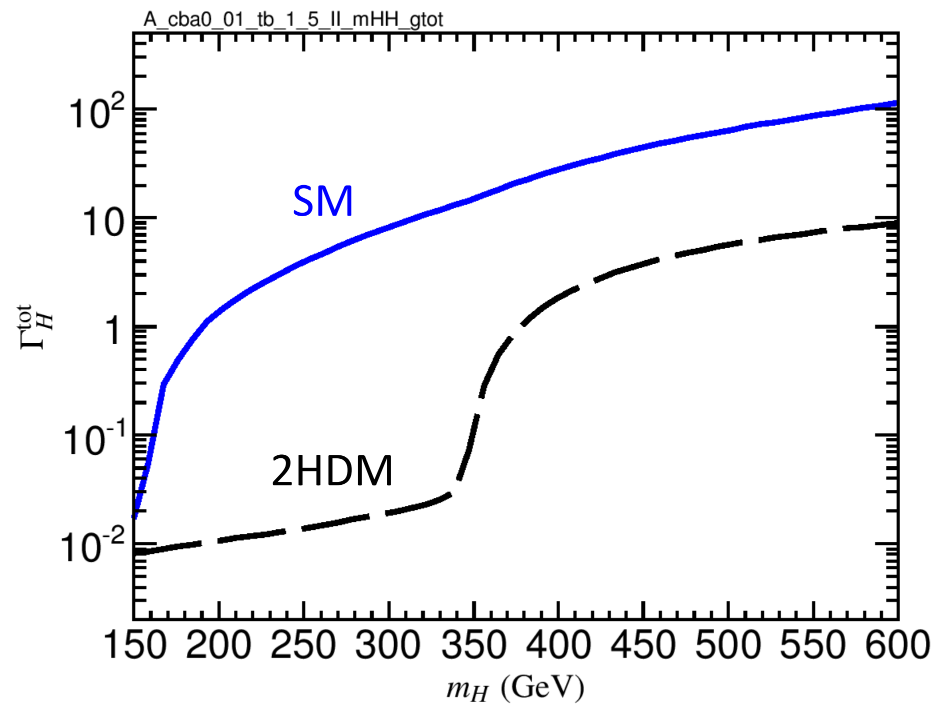


$$R^H_{t\bar{t}} = \frac{\sigma(gg \to H) \times \mathrm{BR}(H \to t\bar{t})}{[\sigma(gg \to H) \times \mathrm{BR}(H \to t\bar{t})]_{\mathrm{SM}}}$$

Scenario A: Type-II Benchmark

- 1D Benchmark can be defined 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

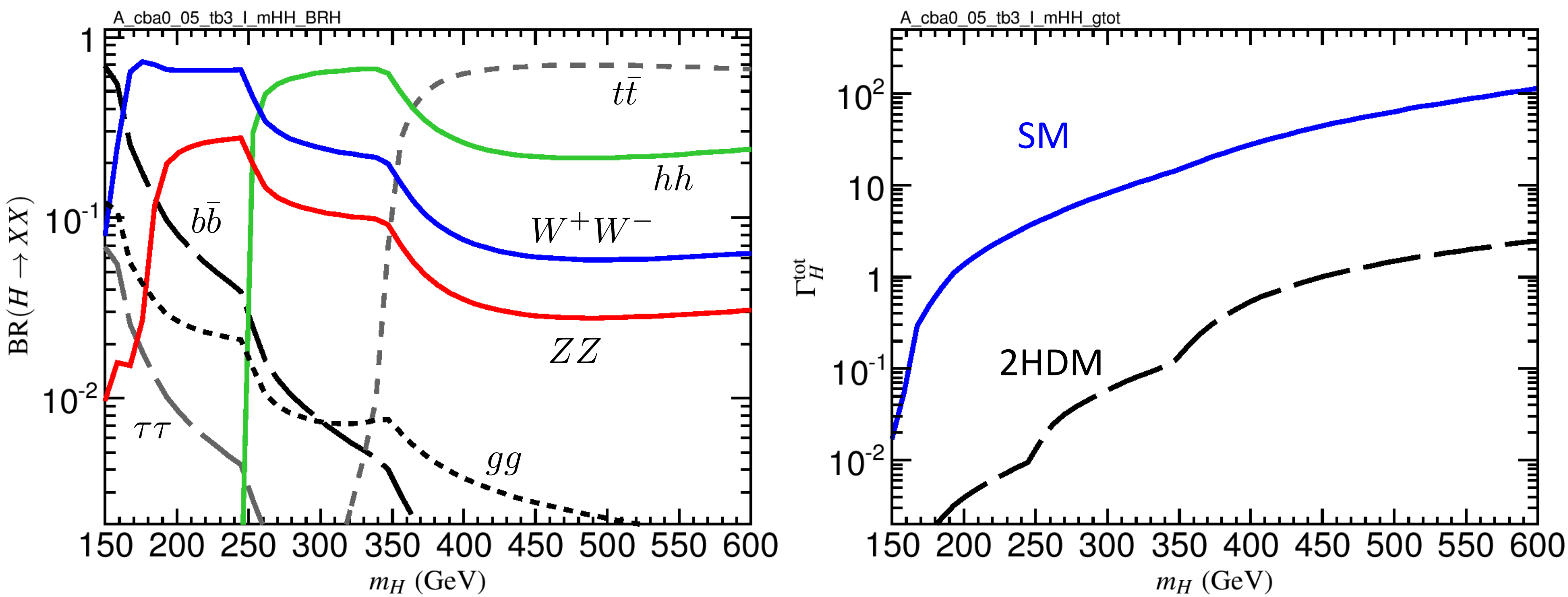




- Maximizes production and decay to tt
  Total H width remains relatively small, $\Gamma_H/\Gamma_{\mathrm{SM}} < 0.1$

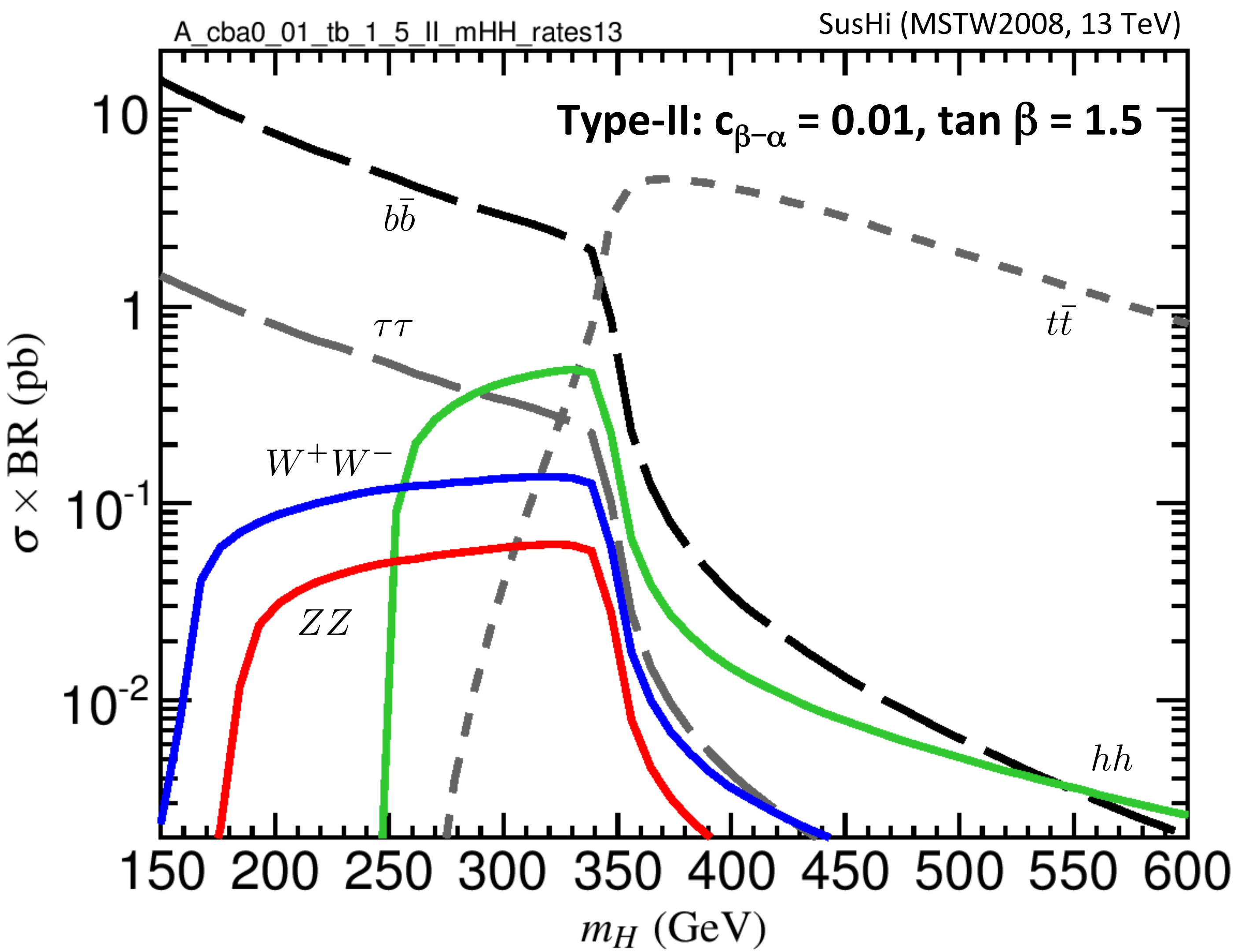
Scenario A: Type-I Benchmark

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

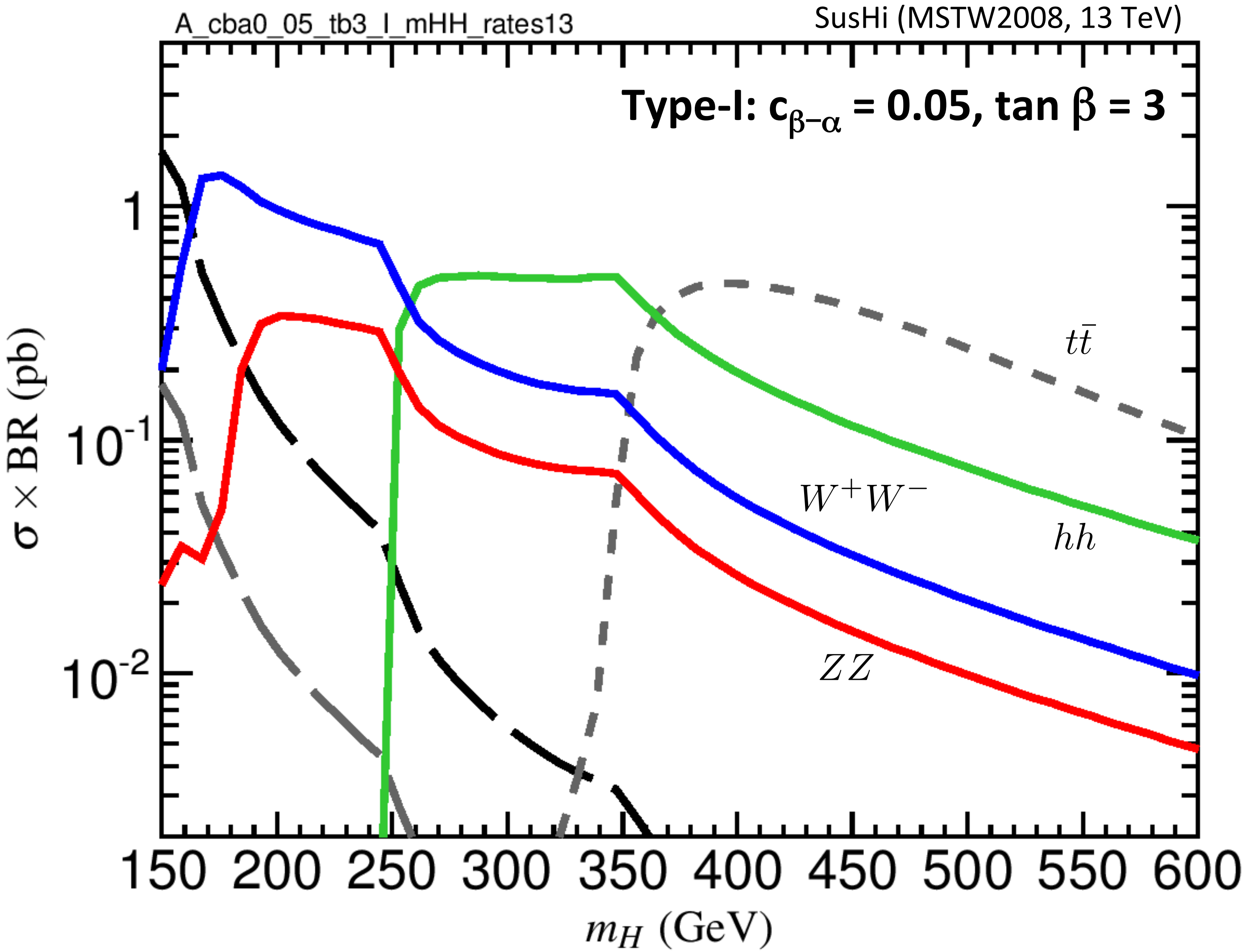


- Sizeable branching ratios to bosonic final states, total width small

Total rates for LHC-13



Total rates for LHC-13

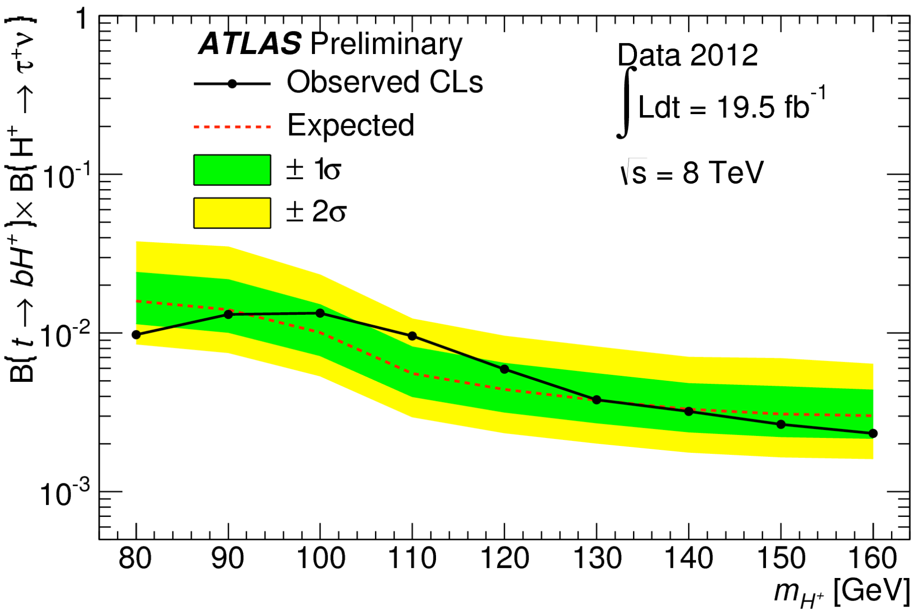


Charged Higgs

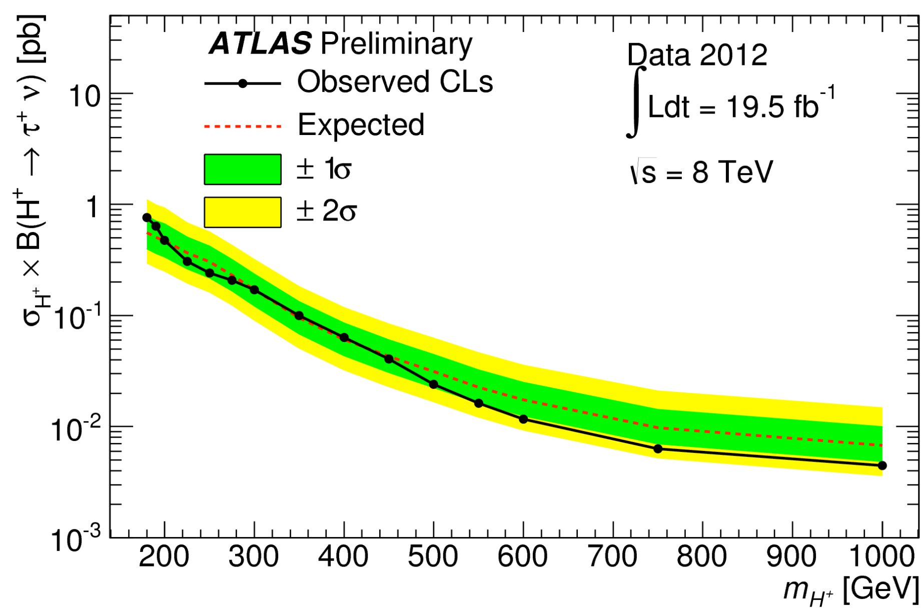
- Interesting component of all models with multiple Higgs doublets, mass related to neutral scalars through SU(2) (custodial) symmetry

- Fewer signatures to consider (if neutral Higgs channels closed)

$$M_{H^\pm} < m_t$$



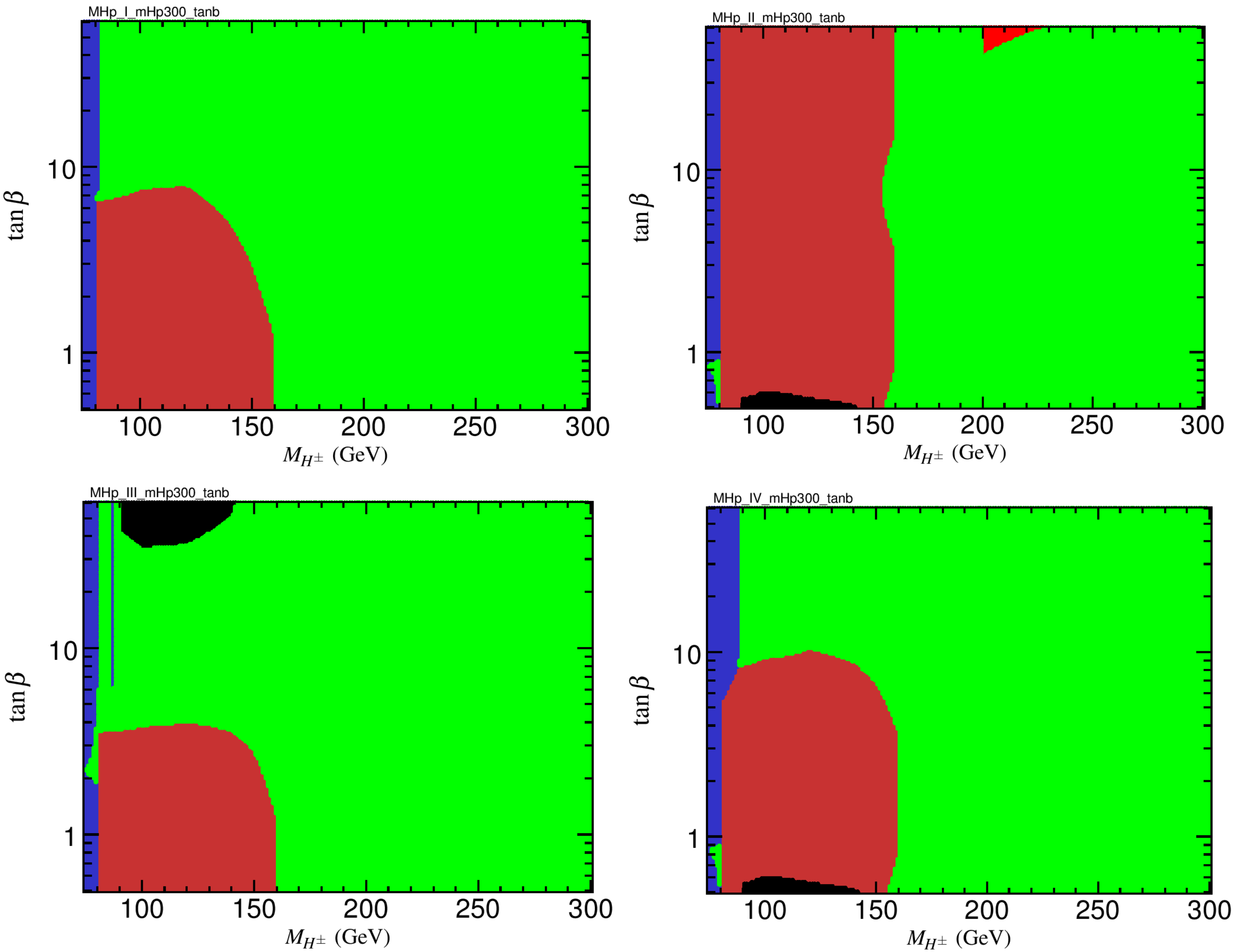
$$M_{H^\pm} > m_t$$



ATLAS-CONF-2014-050

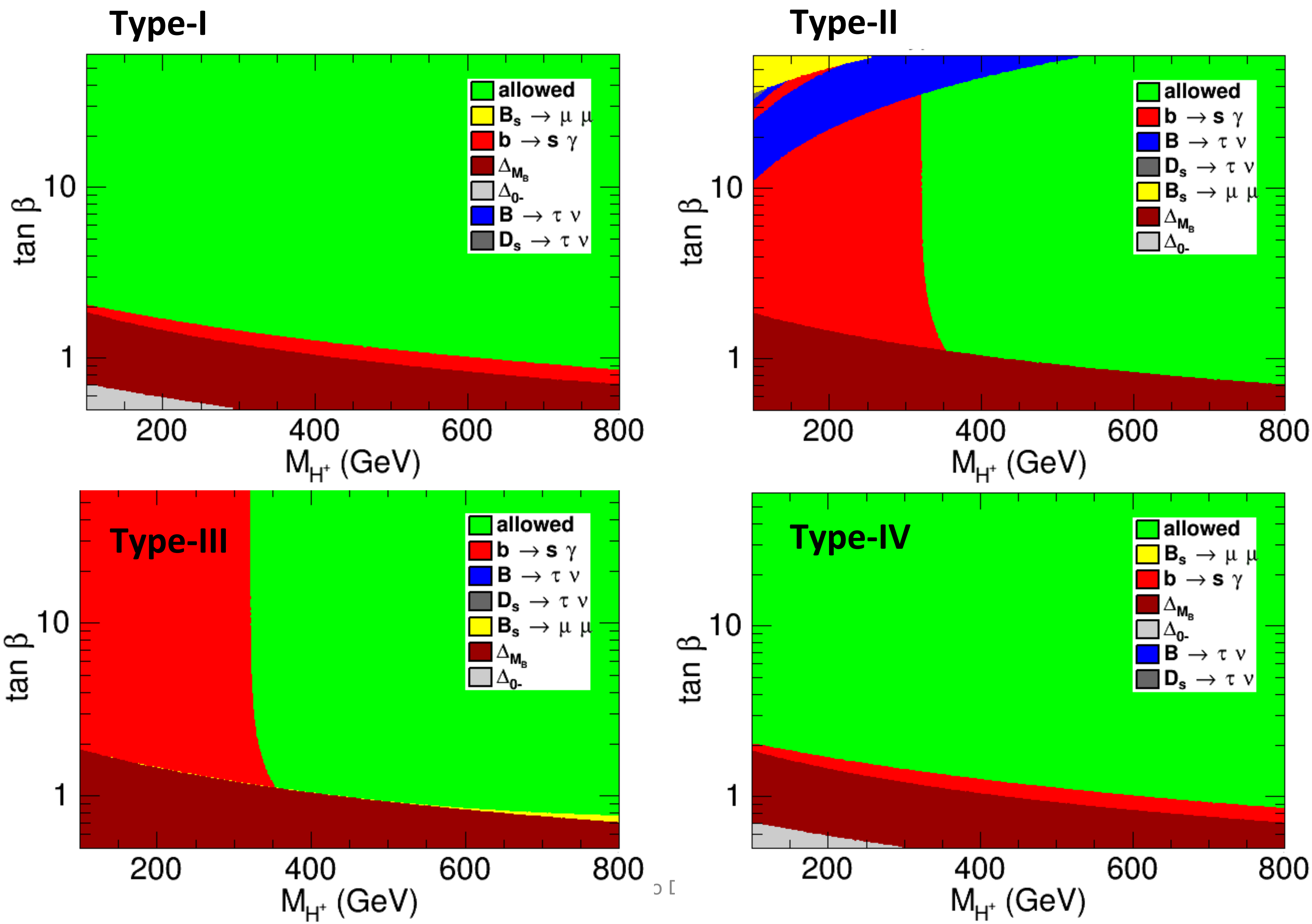
2HDM interpretation of Charged Higgs searches

F. Mahmoudi, OS, [to appear]



Low-energy constraints

F. Mahmoudi, OS, [to appear]



Conclusions

- The 2HDM remains a useful theoretical playground to study both phenomenology of scalar dark matter and searches for additional Higgs bosons at the LHC

- With all constraints taken into account, IDM dark matter restricted to Higgs pole: $M_{\mathrm{DM}} \simeq M_{h^0}/2$ or $M_{\mathrm{DM}} \gtrsim 500\,\mathrm{GeV}$

- First LHC analyses of 2HDM already there, preparing for run-II:
  - "Official" cross sections and branching ratios available for experimental collaborations using public tools
  - Benchmarks covering different interesting signatures

Geilo-2016

From the Second discovered Higgs boson to Dark Matter?

Backup

2HDMC (2-Higgs Doublet Model Calculator)

- Object-oriented C++ code implementing calculations for the general (CP-conserving) 2HDM in different parametrizations

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

[0902.0851]

http://2hdmc.hepforge.org

- First released in 2009, current public version is 1.6.5

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

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

Boring 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**

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:

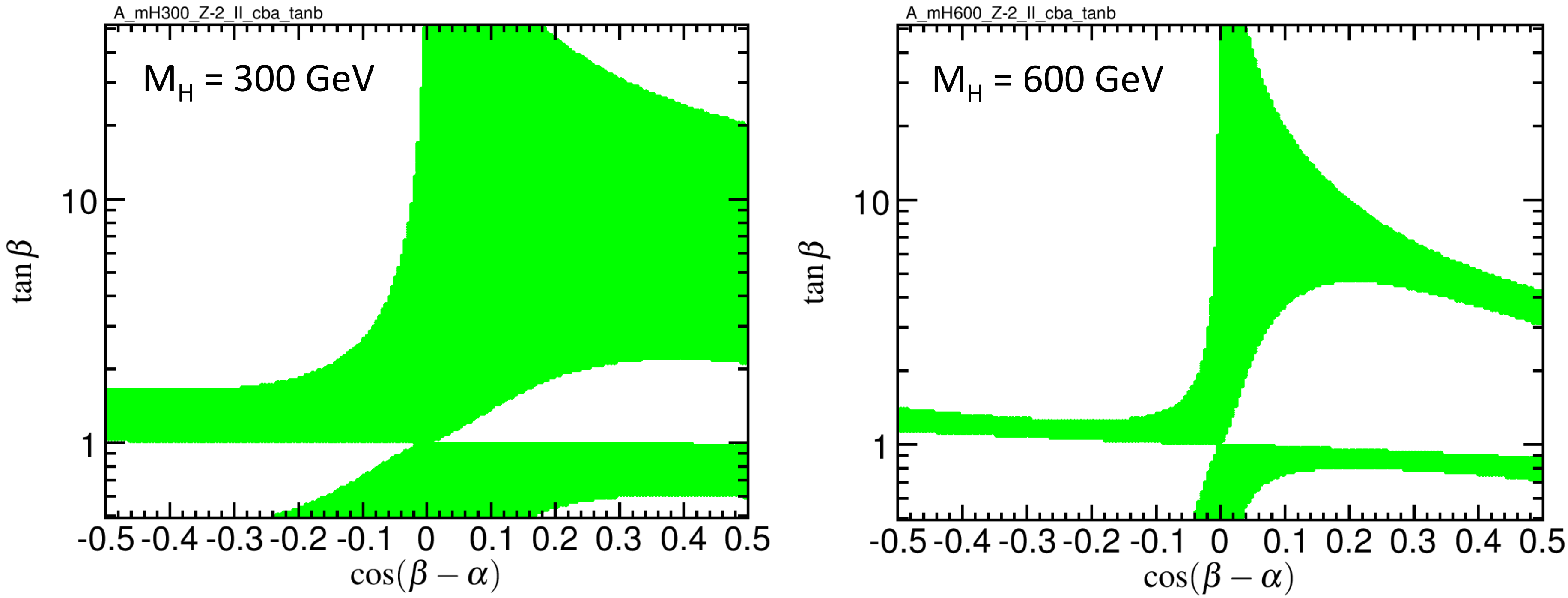
$$m_A^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 - Z_5 v^2$$
$$m_{H^\pm}^2 = m_A^2 - \frac{1}{2}(Z_4 - Z_5) v^2$$

Theoretical constraints restricts coupling space

- As before, S-matrix unitarity and positivity of Higgs potential:

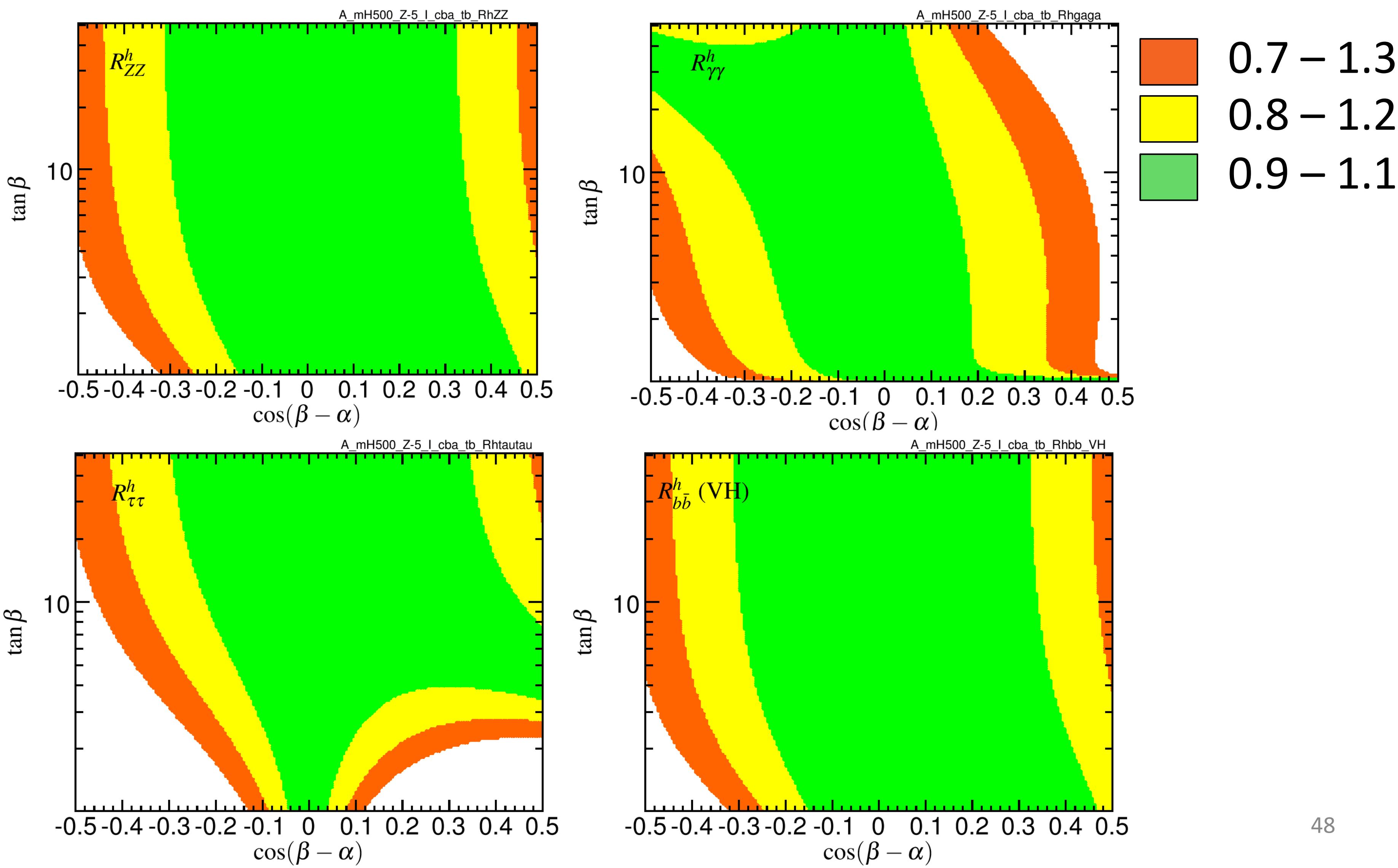
$$Z_i \sim \mathcal{O}(1)$$

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



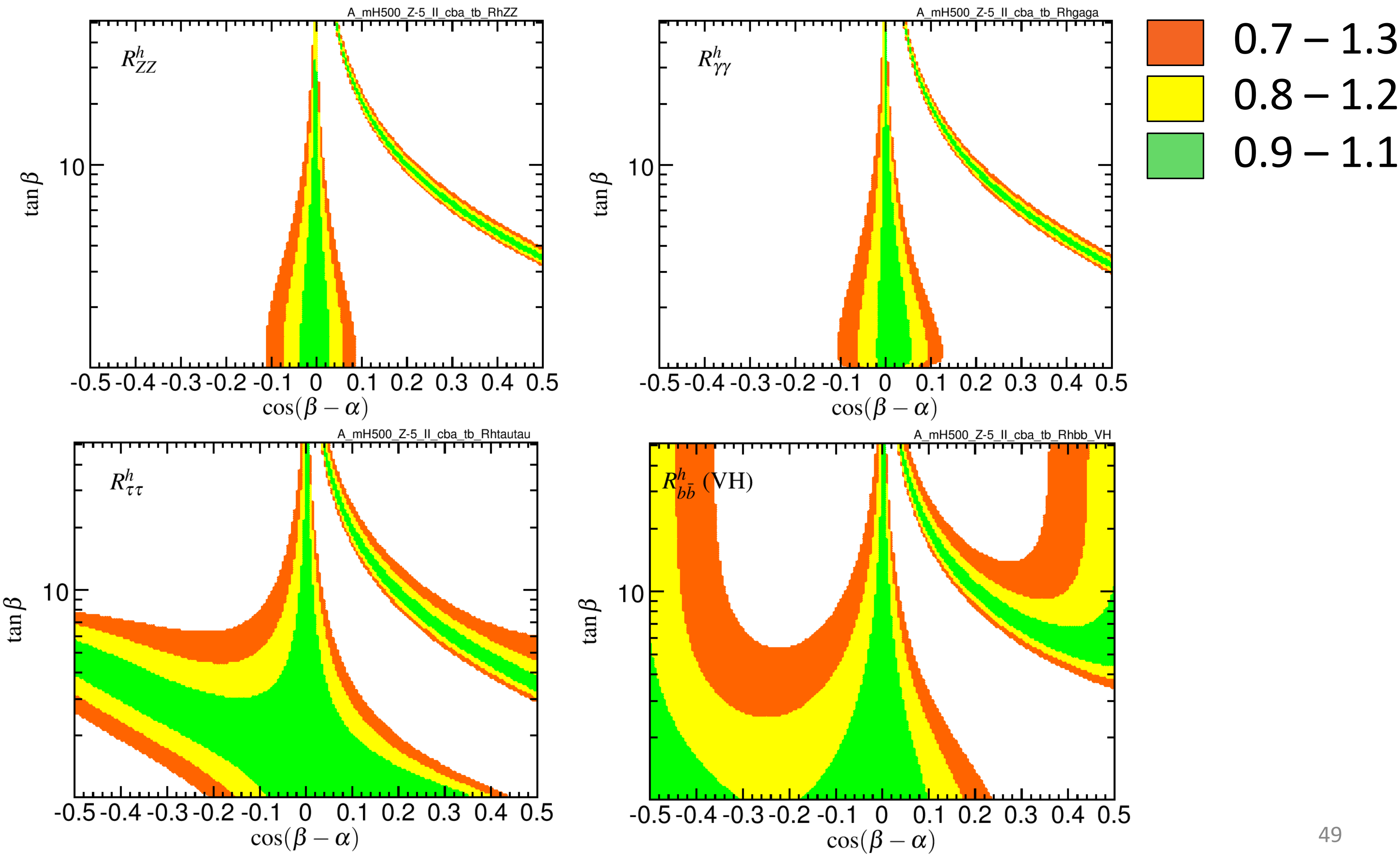
- Allowed parameter region tends towards alignment ($c_{\beta-\alpha} \to 0$) at high tan β, positive values of $c_{\beta-\alpha}$ preferred

Scenario A (Type-I): Light Higgs rates

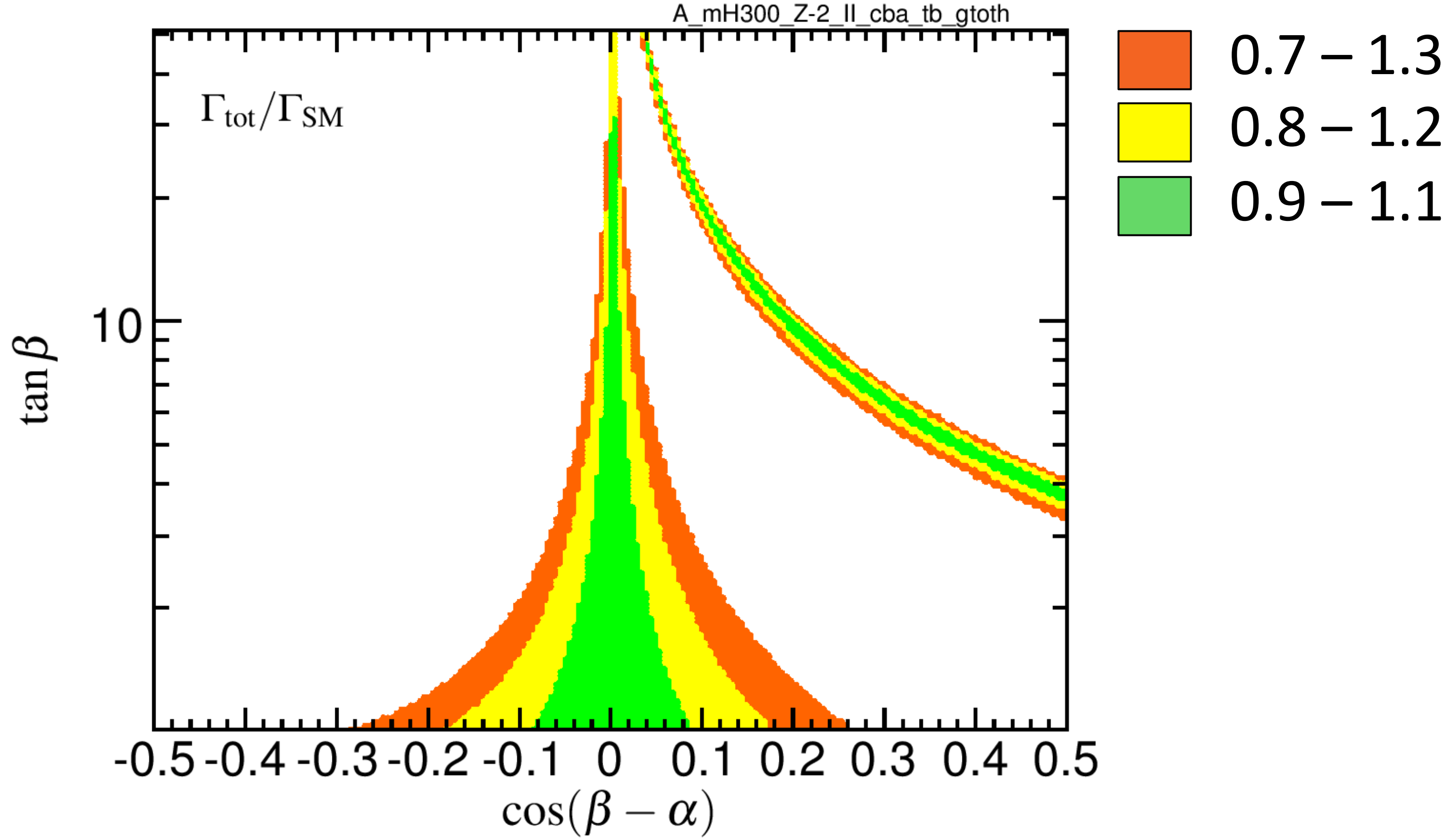


Scenario A (Type-II): Light Higgs rates

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



Total width

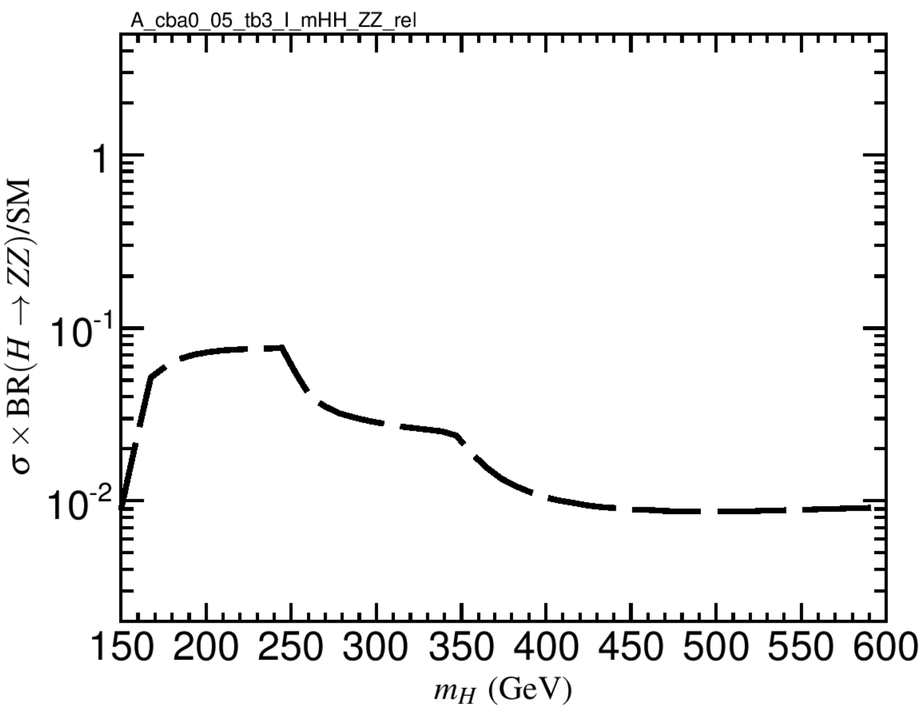


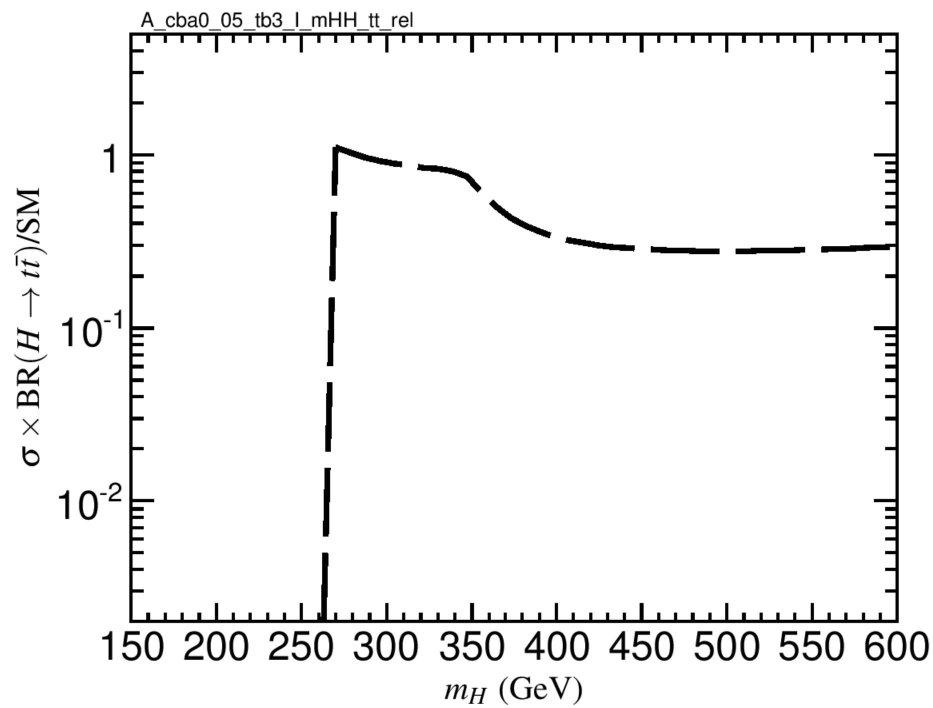
- The experimentally favored region is driven by the total h width, which in turns follow closely the coupling to b quarks

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

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

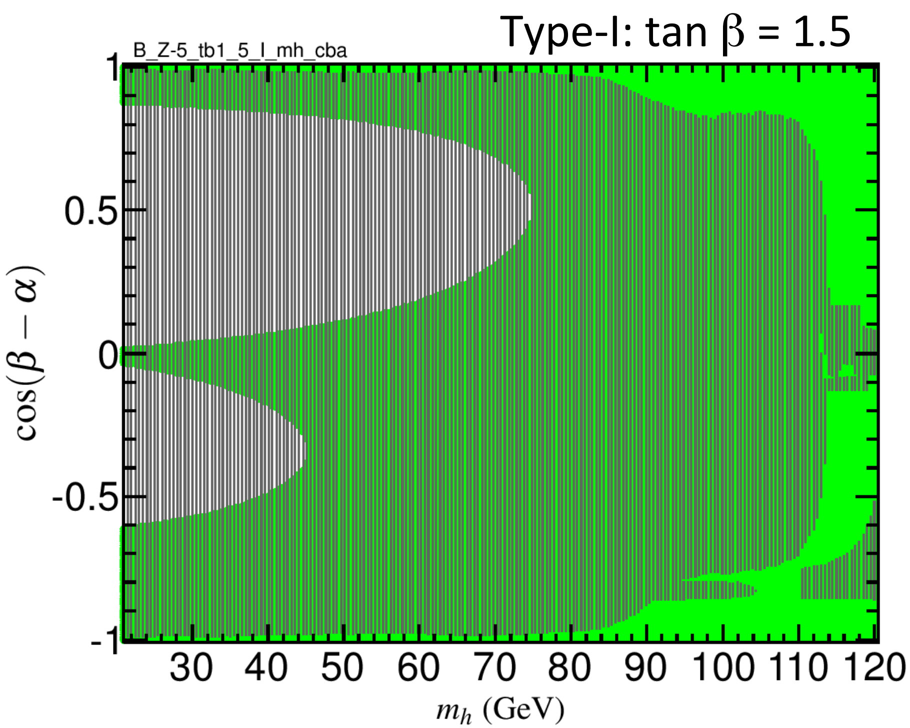
- Rates relative to SM for cos(β−α) = 0.05, tan β = 3 (Type-I)

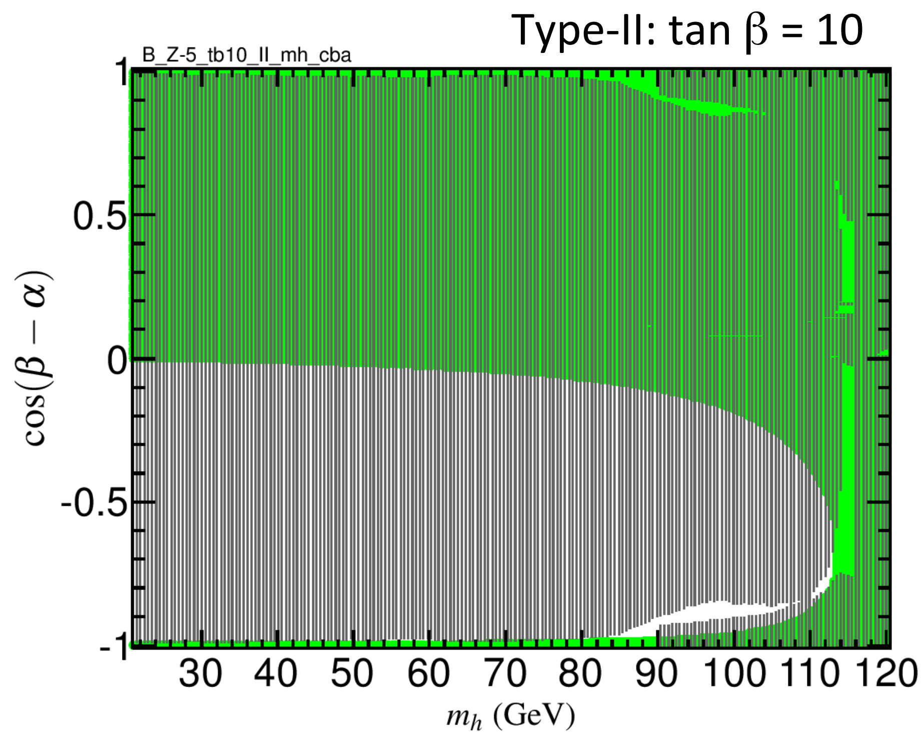




Scenario B

- "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)



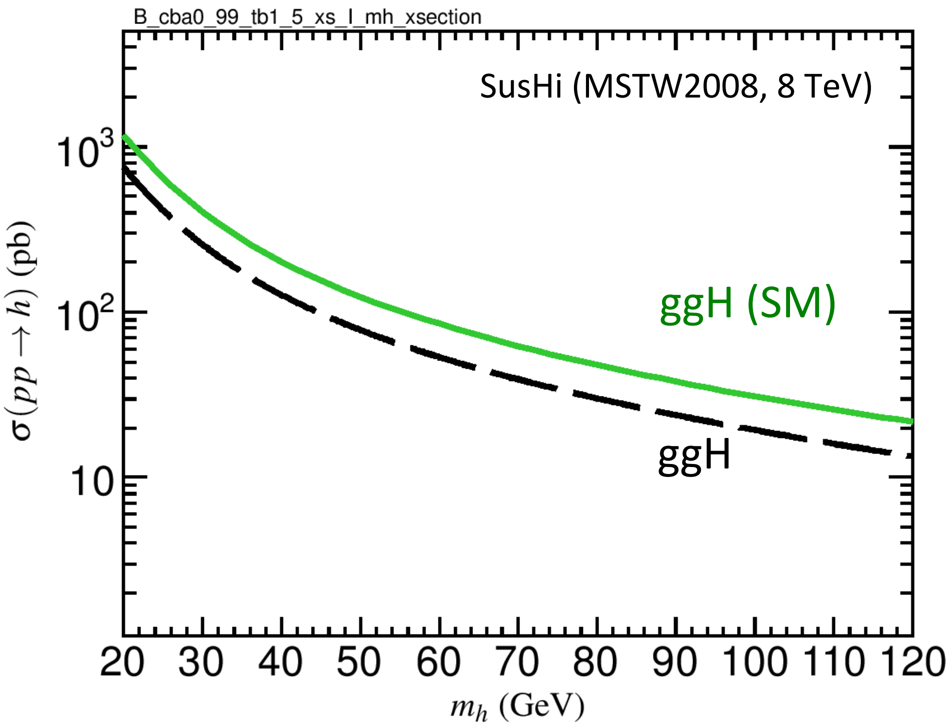


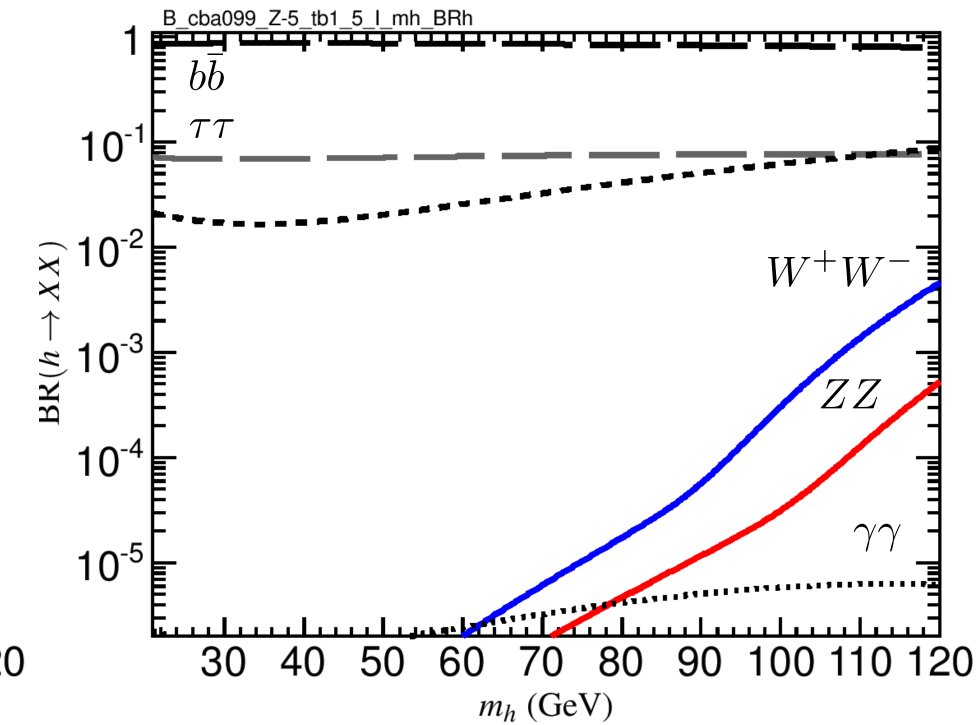
- Constraints from LEP/Tevatron/LHC (gray). Below 90 GeV only allowed solution is alignment of heavy Higgs: $|c_{\beta-\alpha}| \to 1$
  In Type-II also LHC constraints at higher tan β for m_h > 90 GeV.

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, $c_{\beta\text{-}\alpha}$ = 0.99, M_H = 125.5 GeV





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

Scenario C

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

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

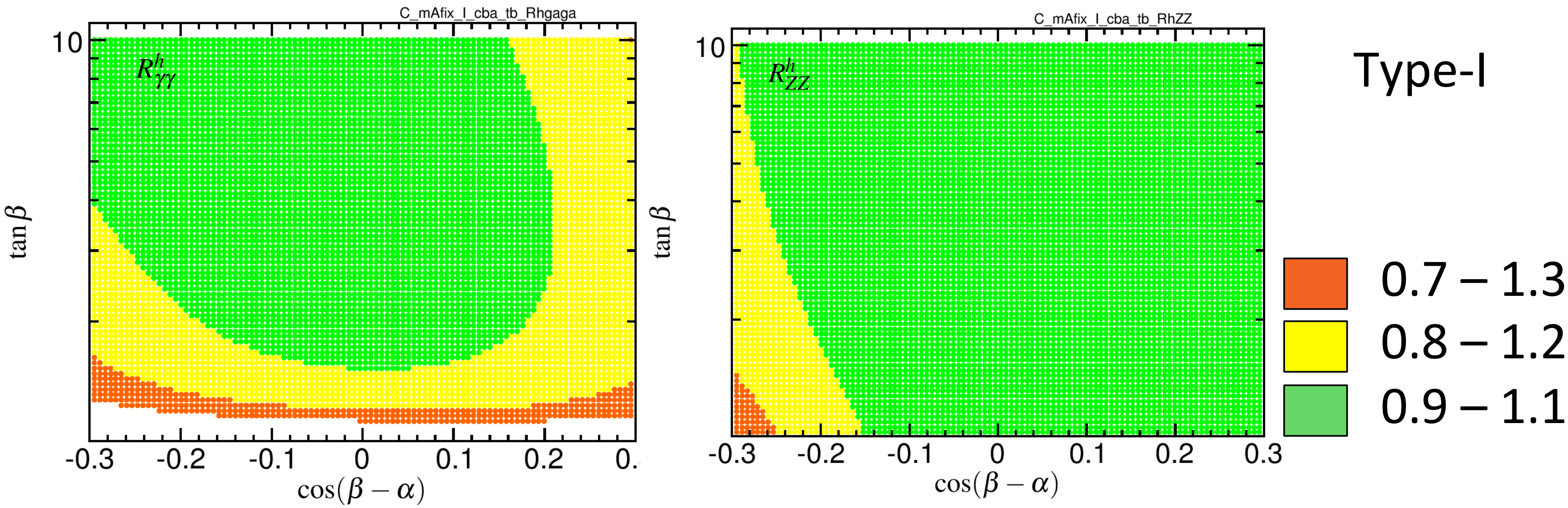
$$Z_5 = \frac{m_H^2 - m_h^2}{v^2} s_{\beta-\alpha}^2 \qquad Z_4 = -Z_5 - 2\frac{m_H^2 - m_h^2}{v^2} c_{\beta-\alpha}^2$$

$$Z_7 = -Z_5$$

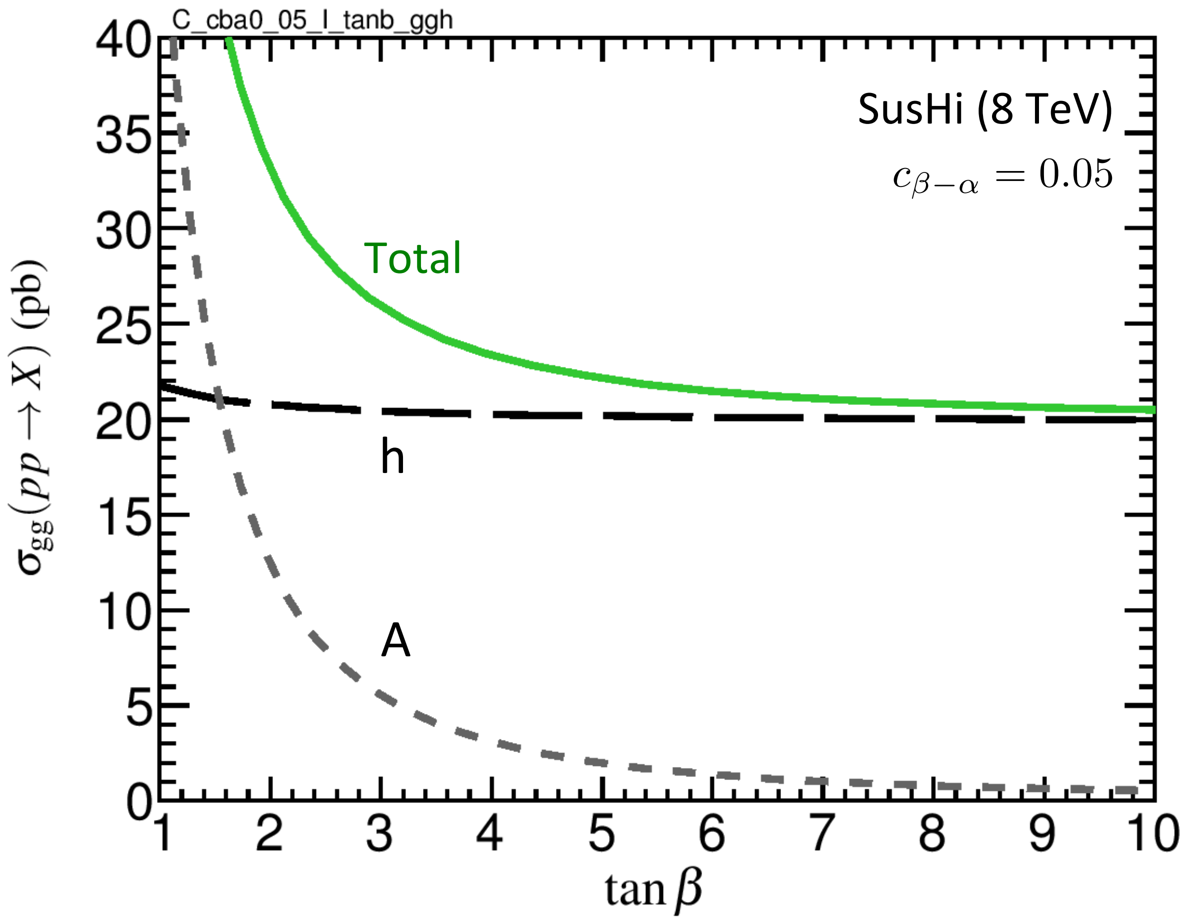
Scenario C: Degenerate states

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

  h/A -> $\gamma\gamma$ (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 -> $\tau\tau$ (inclusive) – similar h/A contributions possible



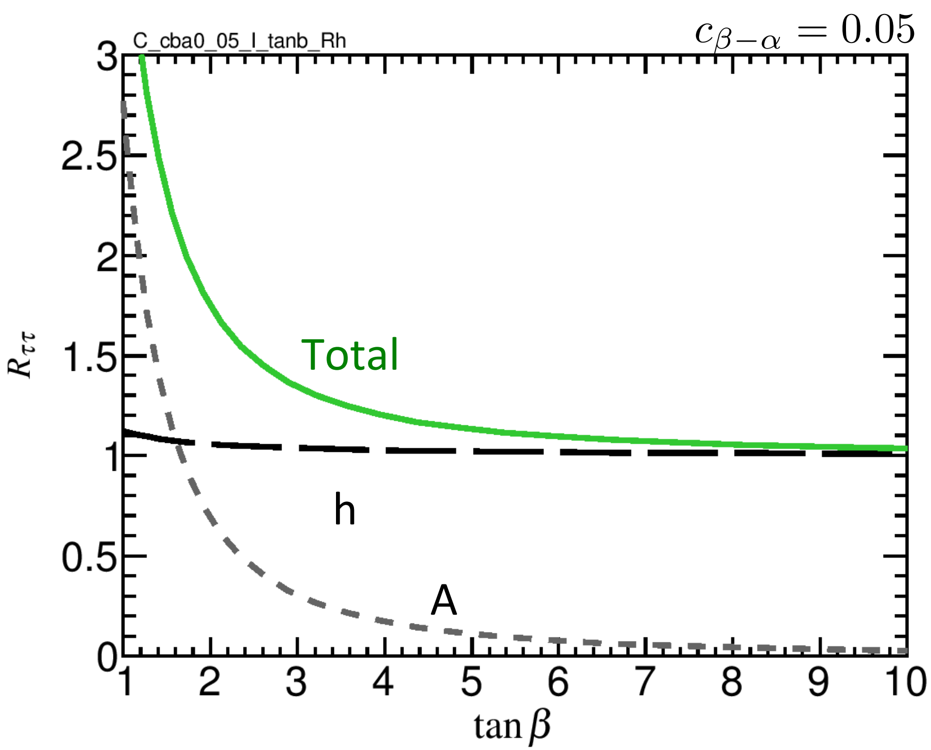
Scenario C: h/A production

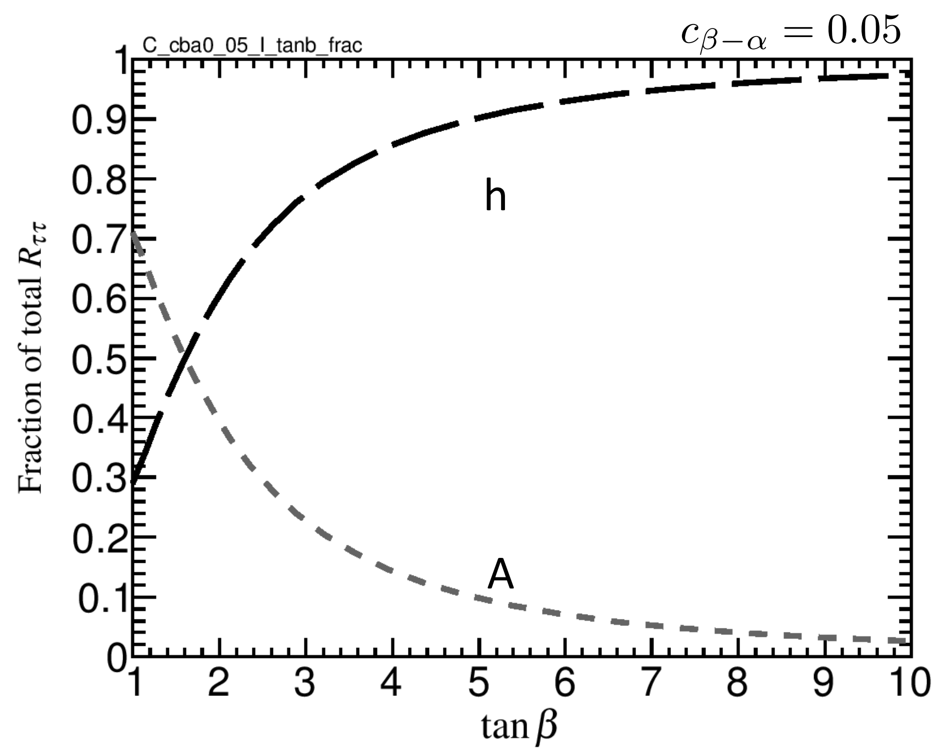


- Total cross section dominated by SM-like h for high tan β (Yukawa decoupling in Type-I)

Inclusive ττ signal composition

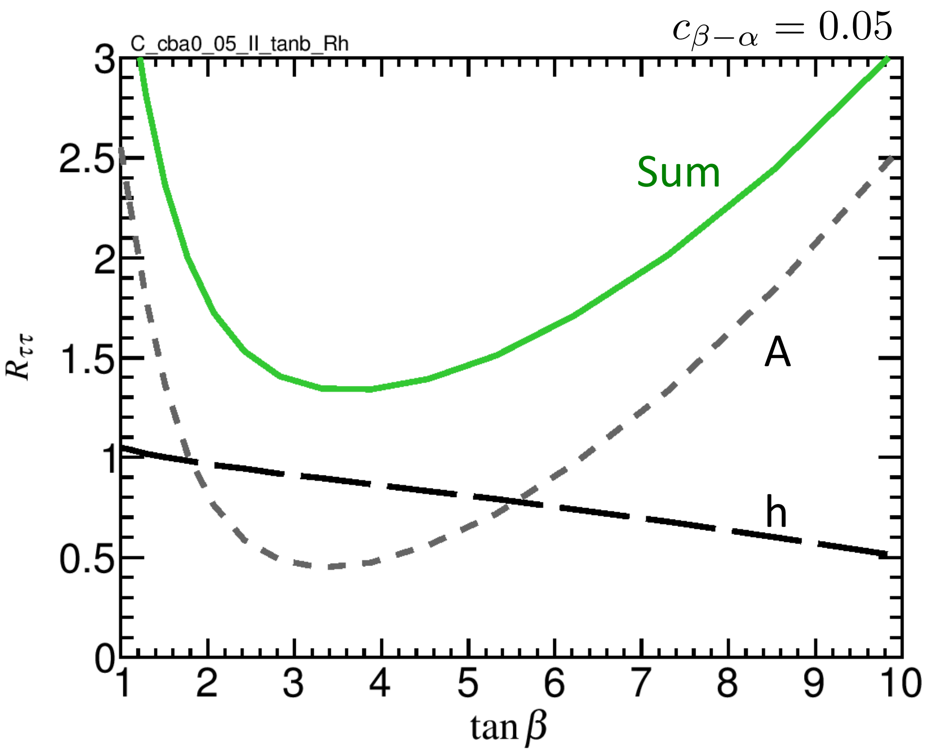
$$R_{\tau\tau}^{h/A} = \frac{\sigma(pp \to h/A) \times \mathrm{BR}(h/A \to \tau\tau)}{\sigma(pp \to H_{\mathrm{SM}}) \times \mathrm{BR}(H_{\mathrm{SM}} \to \tau\tau)}$$

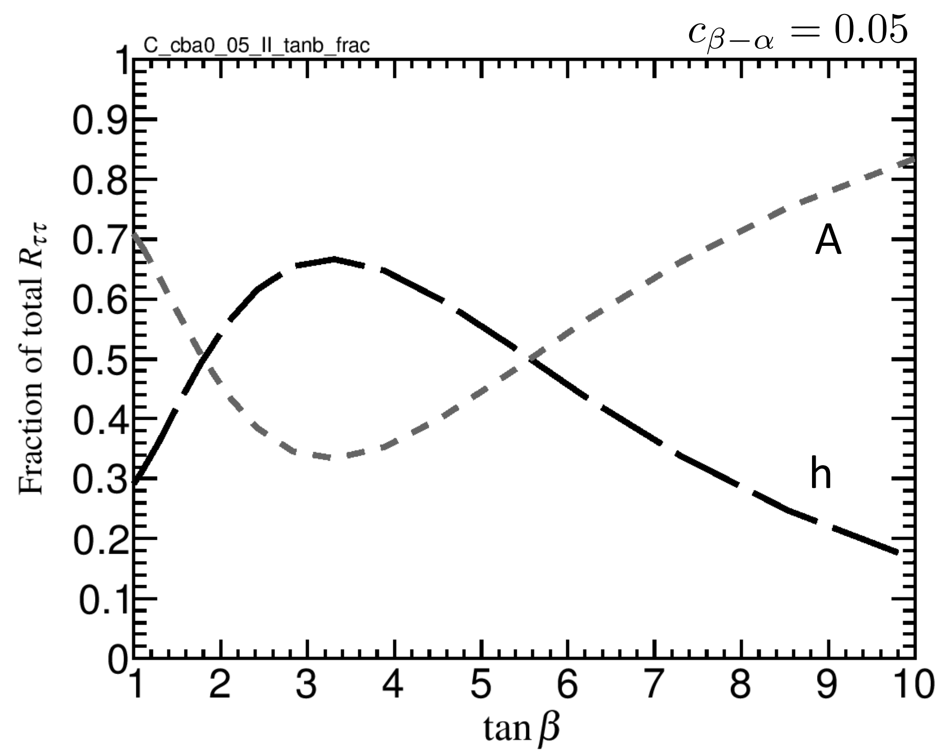




- The currently allowed value for the ττ rate (within errors) could easily accommodate for a large CP-odd contribution

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