2HDM Neutral Scalars @ LHC

Shufang Su • U. of Arizona

Talk based on work:
2004.04172 (F. Kling, SS, W. Su)

HPNP 2021
March 25-27, 2021

Motivation

Started as recast of LHC search: $A \to HZ$, $H \to AZ$

- limited interpretation of 2HDM parameter space
- mostly for Type-II

➡ comprehensive study of current direct/indirect constraints (LHC + more) on 2HDM parameter space

- complementarity between direct and indirect search
- complementarity between different direct search channel
- degenerate mass/mass hierarchy
- Type-I & Type-II (easily extend to other types)

Outline

- Why 2HDM
- Basics of 2HDM
- Various constraints
- Degenerate case
- Mass Hierarchy case
- Conclusion

Why 2HDM?

Models with extended Higgs sector: arise in natural theories of EWSB

- Higgs sector of MSSM/NMSSM
- Generic 2HDM
- Little Higgs, twin Higgs ...
- Composite Higgs models ...

- SM+singlet: parametrized by a simple mixing parameter
- 2HDM: covers board class of known models
- Allow for convenient parametrization
- Many features shared by many extended EWSB sectors

2HDM Higgs Sector

- Two Higgs Doublet Model (CP-conserving)

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}$$

$$v_1^2 + v_2^2 = v^2 \quad v = 246 \text{ GeV}$$

$$t_\beta = v_2/v_1$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \quad \begin{aligned} A &= -G_1 \sin\beta + G_2 \cos\beta \\ H^\pm &= -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta \end{aligned}$$

after EWSB, 5 physical Higgses

CP-even Higgses: h, H , CP-odd Higgs: A, Charged Higgses: $H^\pm$

Parametrization

- parameters (CP-conserving, flavor limit, Z_2 symmetry)

246 GeV (→ v) 125 GeV (→ m_h)

$$m_{11}^2,\ m_{22}^2,\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5 \longrightarrow v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$$

soft Z2 breaking: m_{12}^2

tanβ, cos(β-α),
control tree level h couplings

- Search for extra Higgses
  - ➡ Precision Higgs study: couplings of the SM-like Higgs
  - ➡ Direct search of extra Higgses: direct evidence for BSM new physics

Higgs Couplings

- **h/H VV coupling**

$$g_{H^0VV} = \frac{m_V^2}{v}\cos(\beta-\alpha), \quad g_{h^0VV} = \frac{m_V^2}{v}\sin(\beta-\alpha)$$

Alignment limit: h 125 GeV, cos(β-α)~0

LEP limit: no $e^+e^- \to Z \to ZH$, H could still be light.

- **Higgs-Higgs-V coupling**

$$g_{AH^0Z} = -\frac{g\sin(\beta-\alpha)}{2\cos\theta_w}(p_{H^0}-p_A)^\mu, \quad g_{Ah^0Z} = \frac{g\cos(\beta-\alpha)}{2\cos\theta_w}(p_{h^0}-p_A)^\mu,$$

$$g_{H^\pm H^0 W^\mp} = -\frac{g\sin(\beta-\alpha)}{2}(p_{H^0}-p_{H^\pm})^\mu, \quad g_{H^\pm h^0 W^\mp} = \frac{g\cos(\beta-\alpha)}{2}(p_{h^0}-p_{H^\pm})^\mu,$$

$$g_{H^\pm A W^\mp} = \frac{g}{2}(p_A-p_{H^\pm})^\mu,$$

Two non-SM like Higgses have unsuppressed couplings to gauge boson.

LEP limit: $e^+e^- \to Z \to AH$, $m_H + m_A > E_{cm}$

Higgs Couplings

- Yukawa couplings

	ϕ_1	ϕ_2
Type I		u,d,l
Type II	d,l	u
Type L	l	u,d
Type F	d	u,l

	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
Type-I	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-L	$\cot\beta$	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-F	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$\cot\beta$	$\tan\beta$	$-\cot\beta$

Alignment limit: hff, hVV coupling ⇒ SM

- tri-Higgs couplings

Alignment limit: no $H\to AA$, $H\to hh$

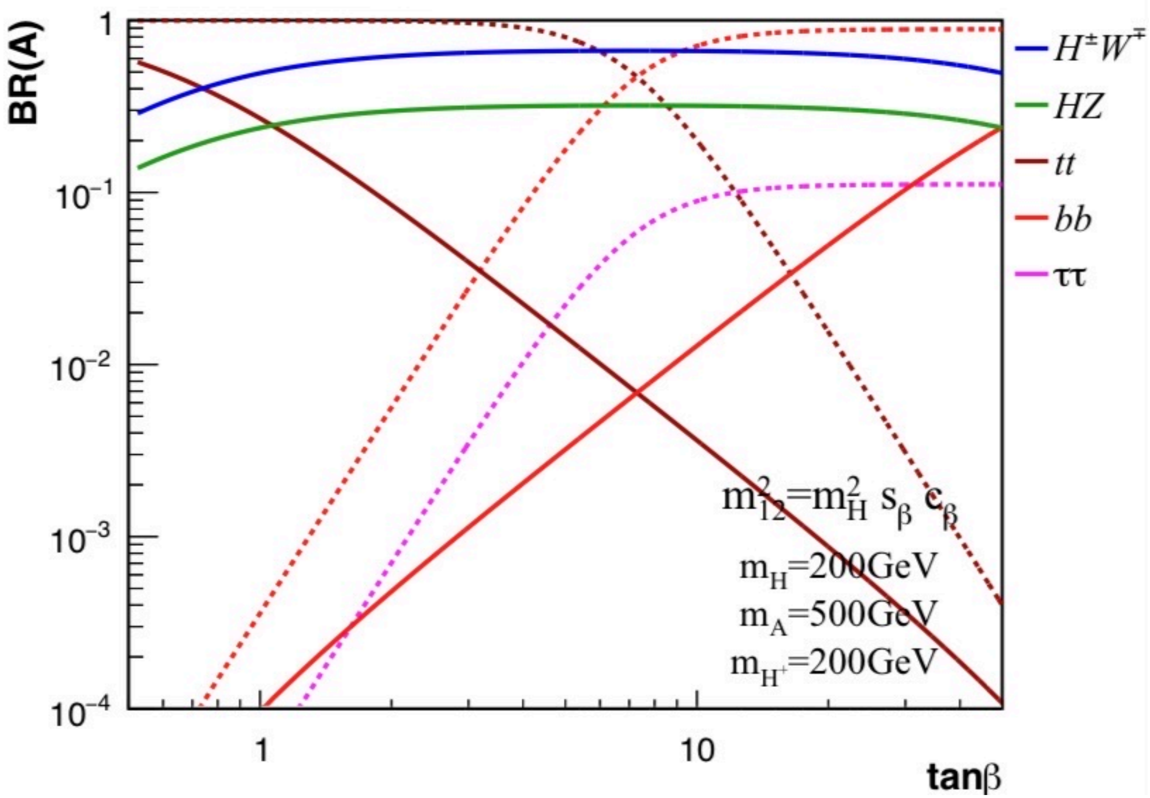
unsuppressed: $h\to AA$

Decay

- Conventional search channel (even for non-SM Higgs):

  γγ, ZZ, WW, ττ, μμ, bb, tt

- Exotic search channel (→ 2 light Higgs, light Higgs+V)



Constraints

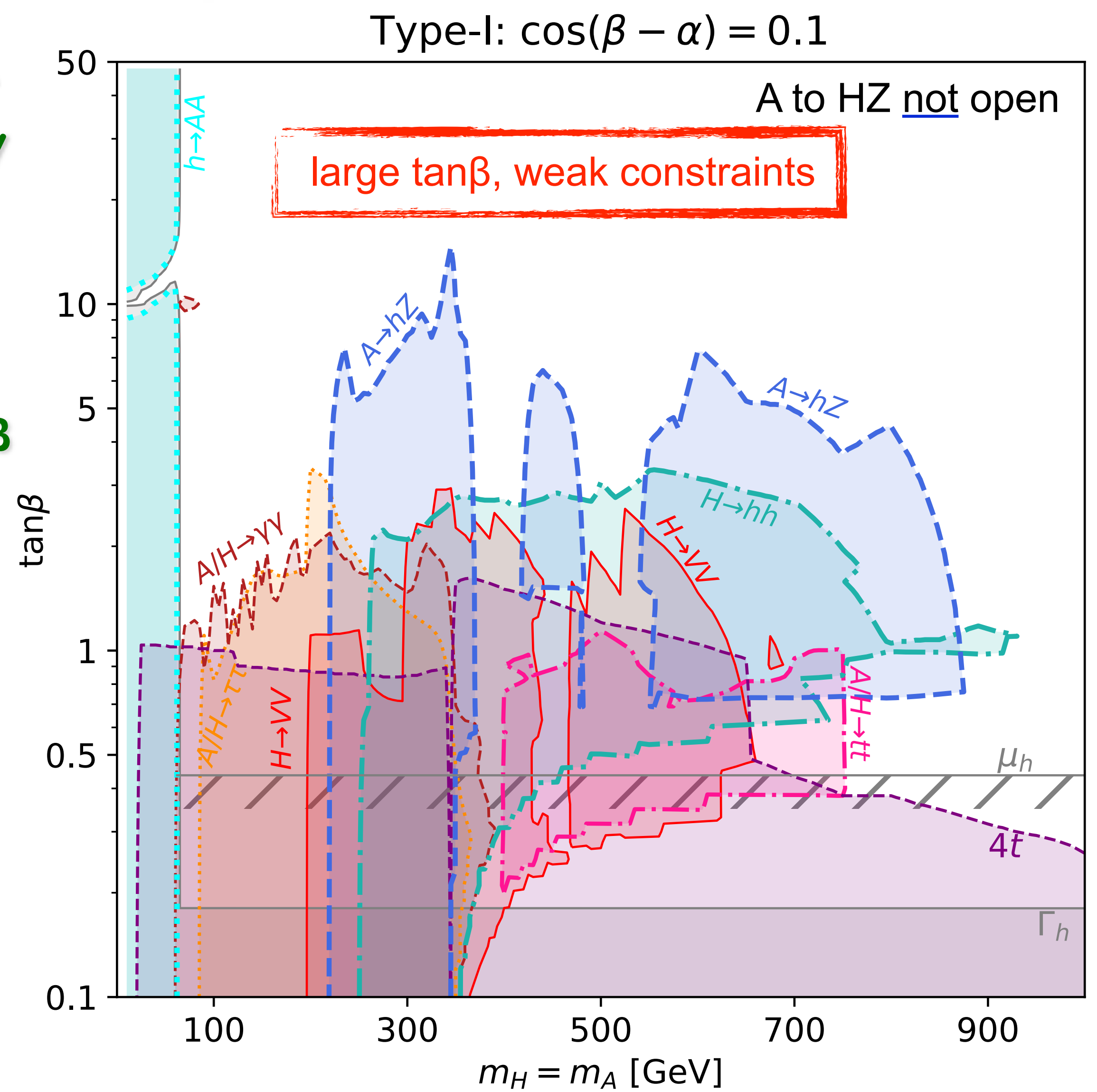
Neutral scalars

- theoretical constraints

  vacuum stability/Unitarity/perturbativity/... $m_{12}^2 = m_H^2 \sin\beta \cos\beta$
- Precision Higgs measurements (μ, Γ_h)
- Conventional channels: $\gamma\gamma$, ZZ, WW, $\tau\tau$, $\mu\mu$, bb, tt
- Exotic decay into h: $A\to hZ$, $H\to hh$
- Exotic decay of hSM: $h\to AA$, $h\to HH$
- Exotic decay of BSM sector: $A\to HZ$, $H\to AZ$
- LEP searches: $e^+e^-\to Z\to HA$, $e^+e^-\to Z\to ZH$
- SM non-resonant processes: ttZ, tttt

Degenerate Case: Type I

- **degenerate:** $m_{Hpm} = m_H = m_A$
  no BSM sector exotic decay
  allow A→Zh, H→hh, H→VV
  (away from alignment)
- **Type I: ϕ_2, u/d/l**
  BSM Higgs Yukawa ~ 1/tan β



Degenerate Case: Type I

- **degenerate:** $m_{Hpm} = m_H = m_A$

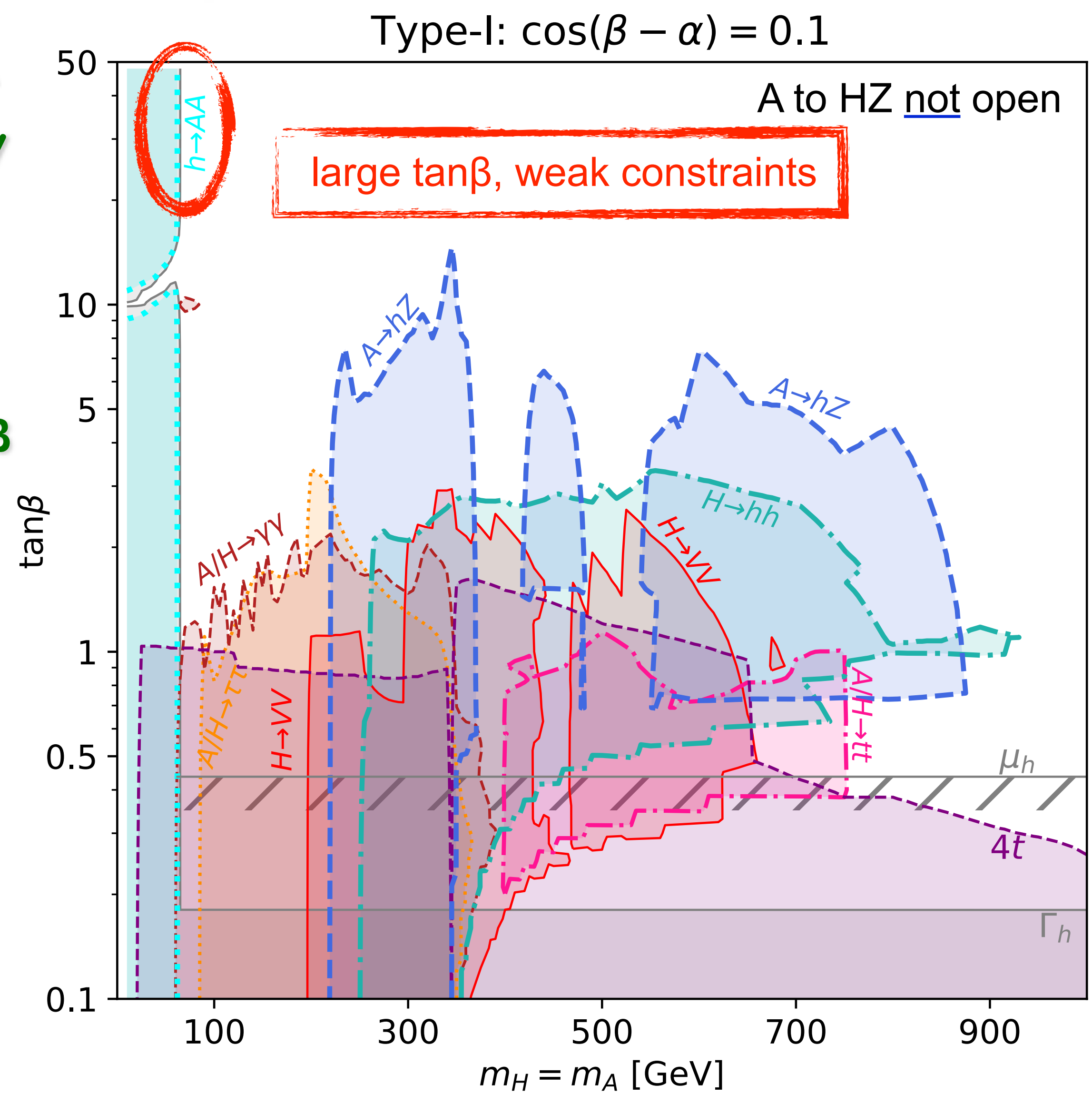
  no BSM sector exotic decay

  allow A→Zh, H→hh, H→VV

  (away from alignment)

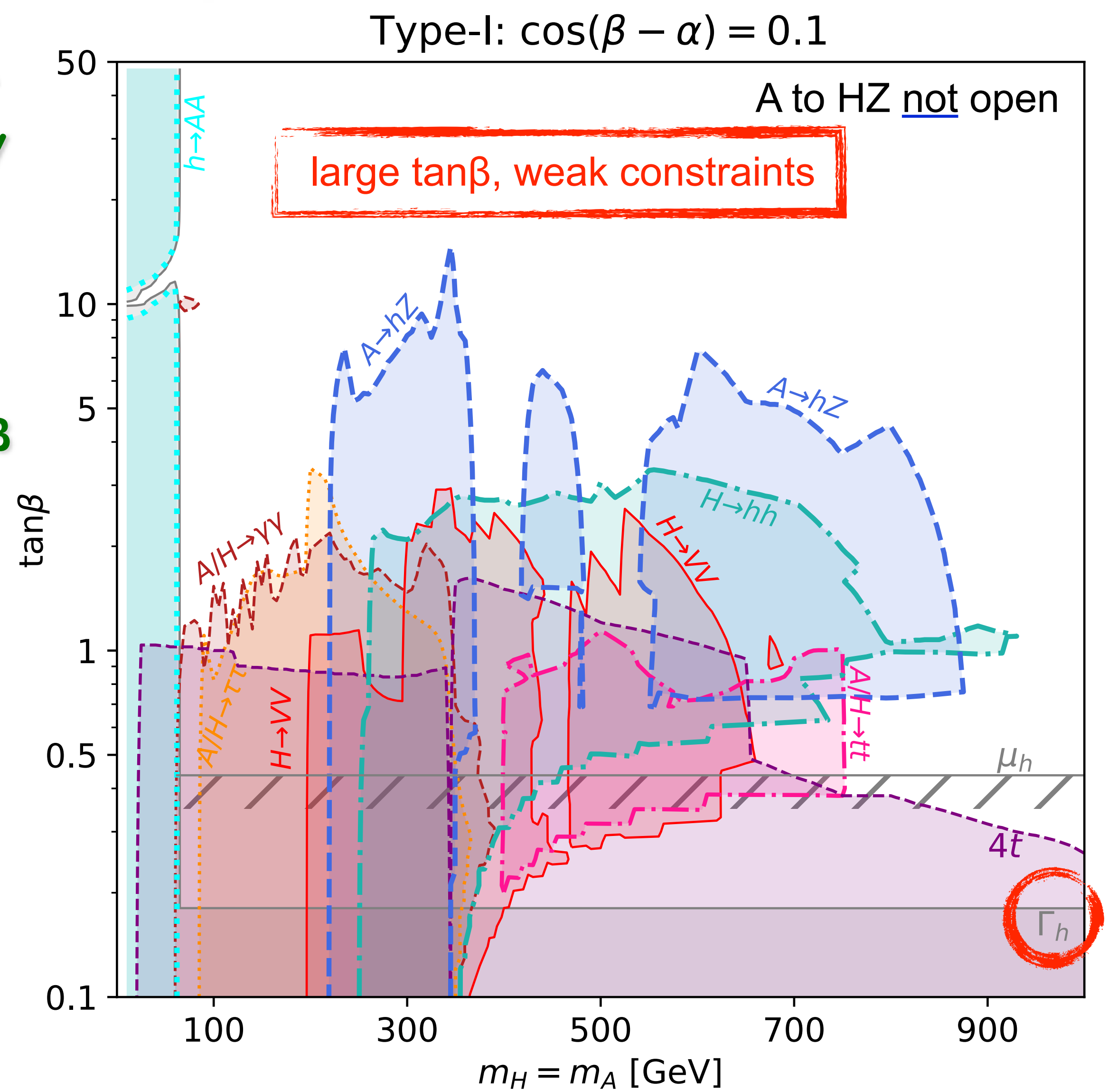
- **Type I: ϕ_2, u/d/l**

  BSM Higgs Yukawa ~ 1/tan β



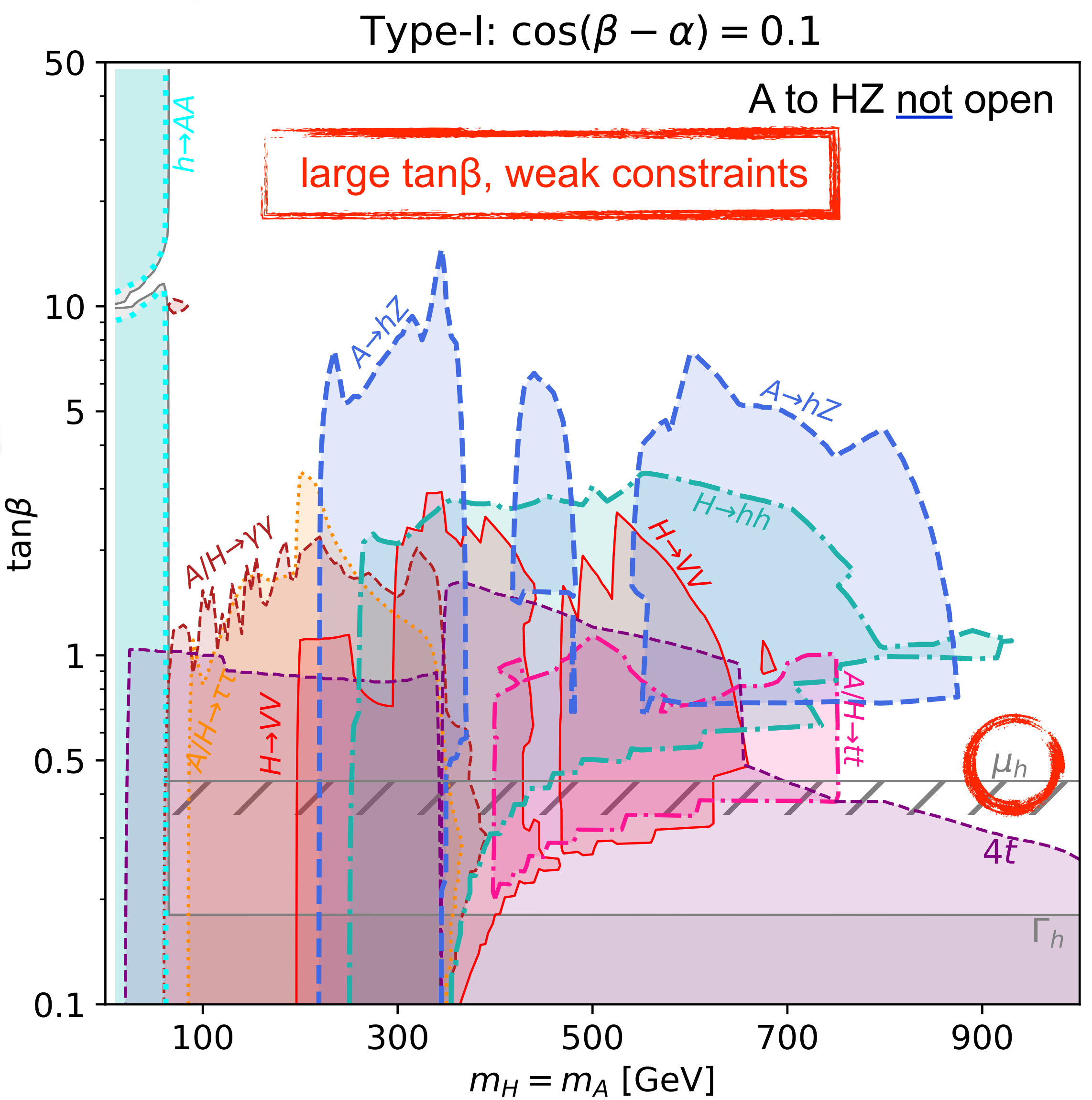
Degenerate Case: Type I

- **degenerate:** $m_{Hpm} = m_H = m_A$
  no BSM sector exotic decay
  allow A→Zh, H→hh, H→VV
  (away from alignment)
- **Type I: ϕ_2, u/d/l**
  BSM Higgs Yukawa ~ 1/tan β

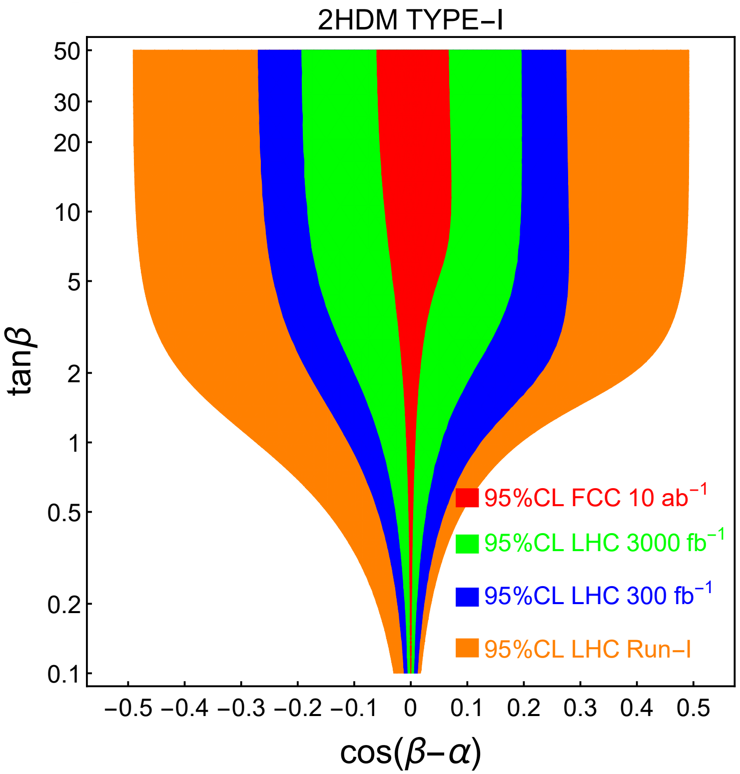


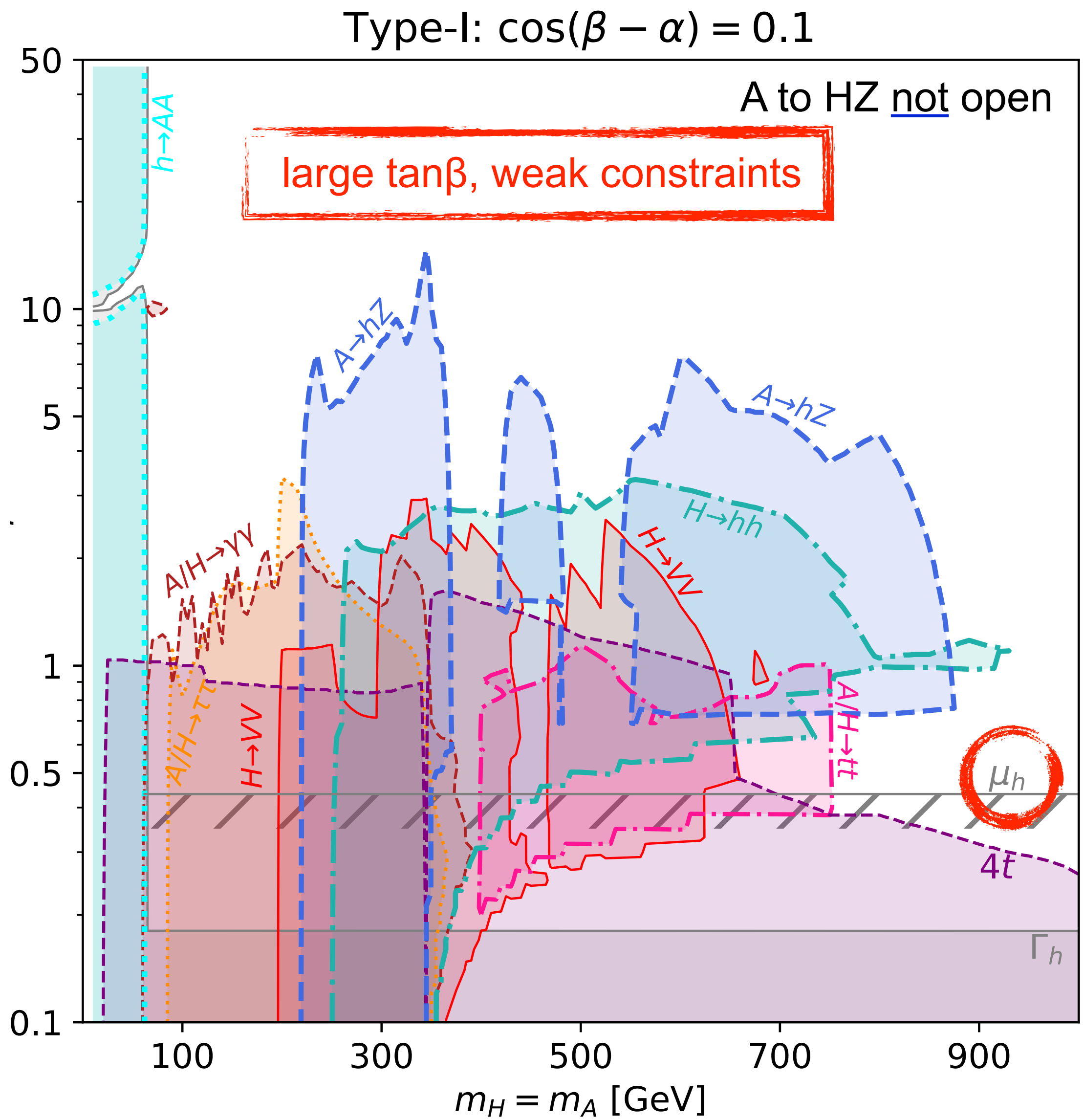
Degenerate Case: Type I

- **degenerate:** $m_{Hpm} = m_H = m_A$
  no BSM sector exotic decay
  allow $A \to Zh$, $H \to hh$, $H \to VV$
  (away from alignment)
- **Type I: ϕ_2, u/d/l**
  BSM Higgs Yukawa ~ 1/tan β



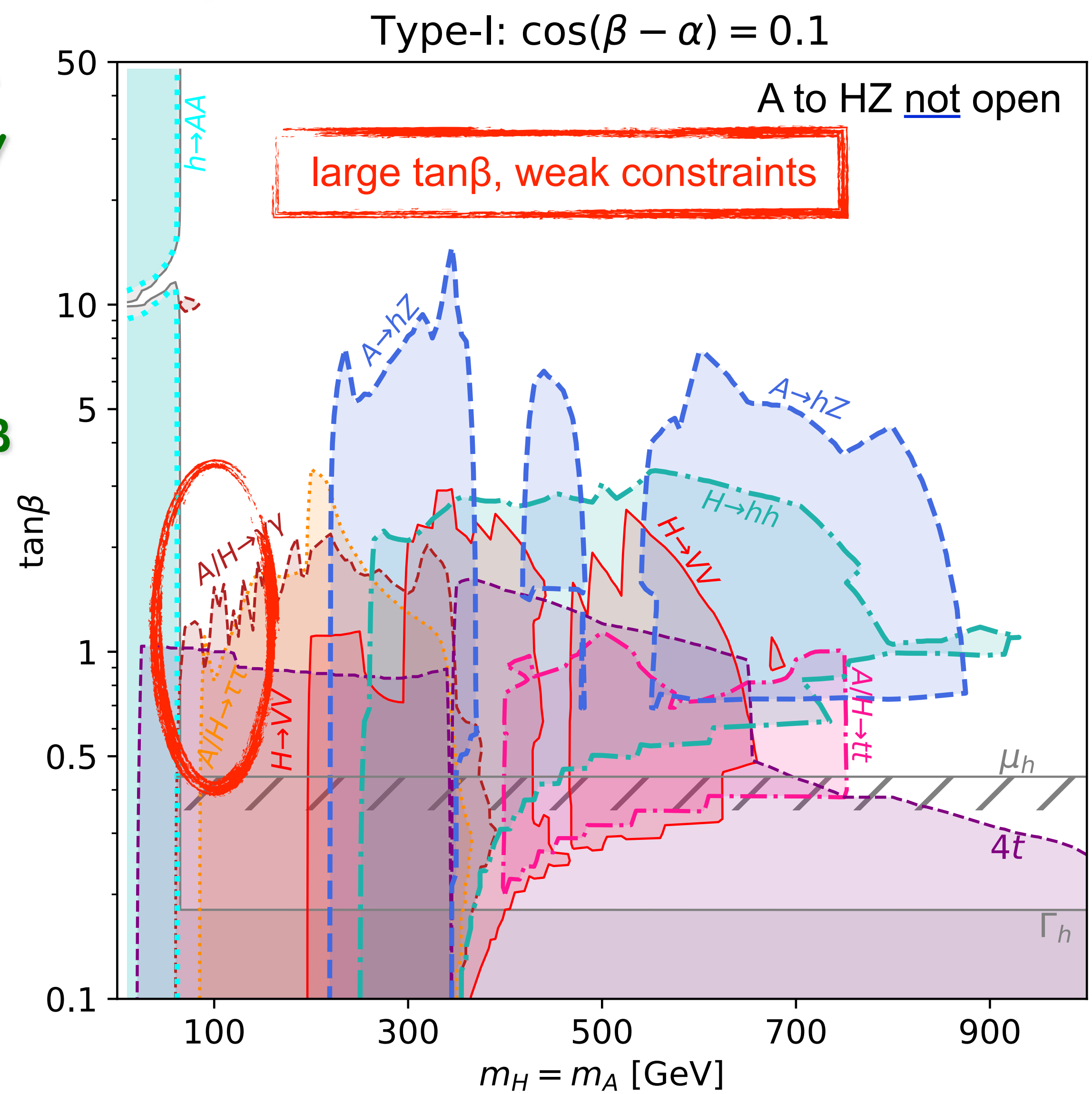
Degenerate Case: Type I





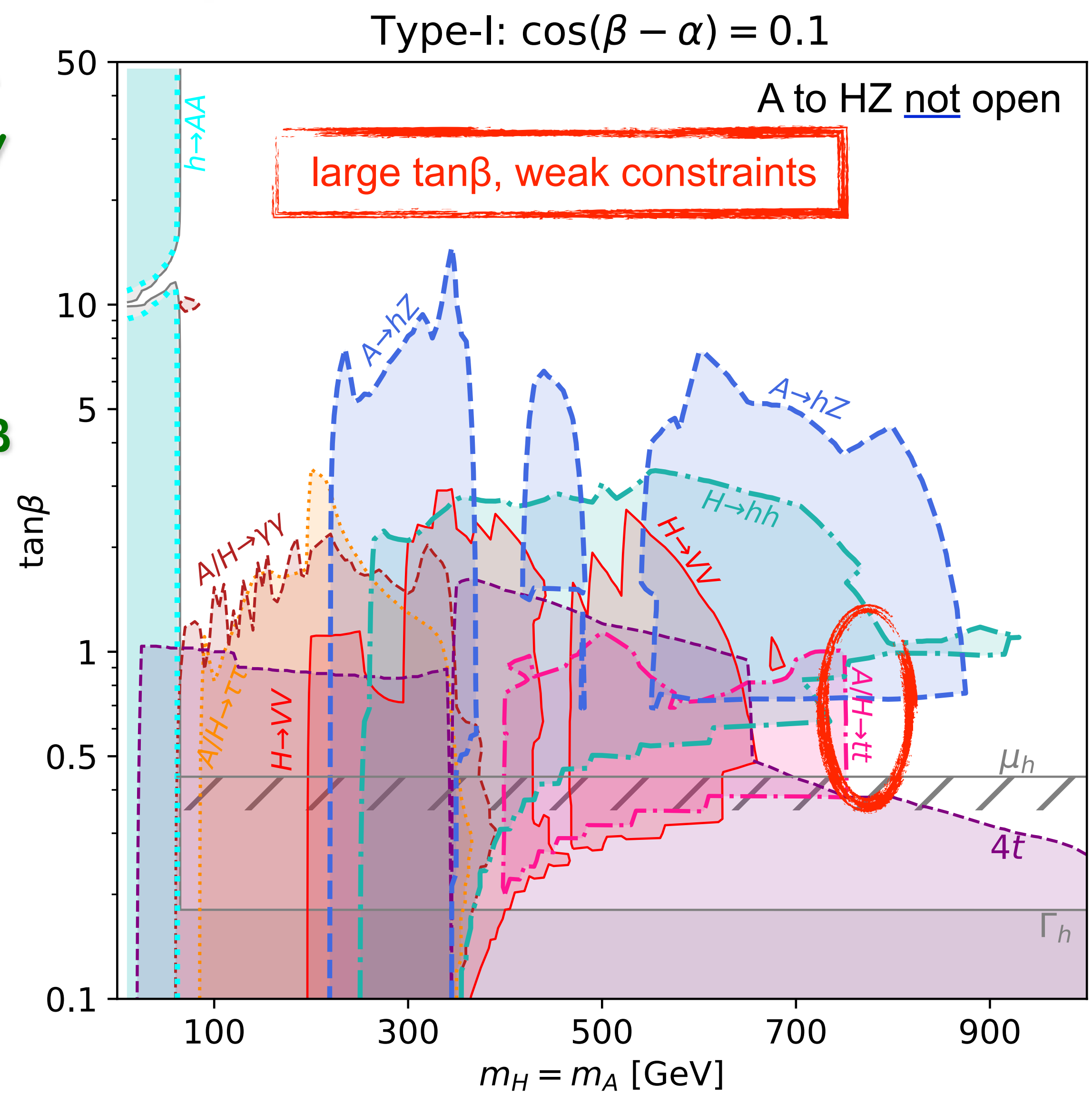
Degenerate Case: Type I

- **degenerate:** $m_{Hpm} = m_H = m_A$
  no BSM sector exotic decay
  allow A→Zh, H→hh, H→VV
  (away from alignment)
- **Type I: ϕ_2, u/d/l**
  BSM Higgs Yukawa ~ 1/tan β



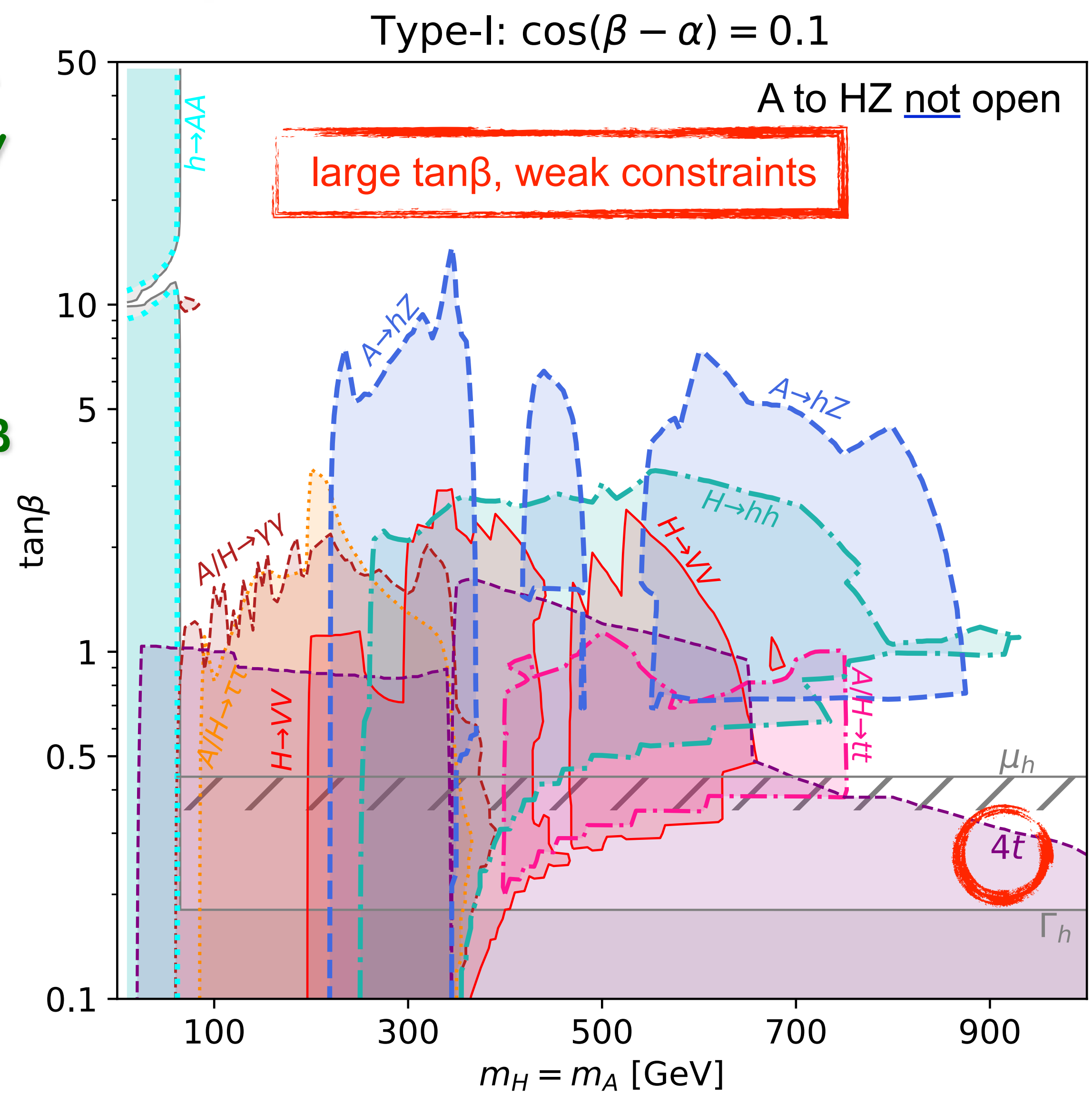
Degenerate Case: Type I

- **degenerate:** $m_{Hpm} = m_H = m_A$
  no BSM sector exotic decay
  allow A→Zh, H→hh, H→VV
  (away from alignment)
- **Type I: ϕ_2, u/d/l**
  BSM Higgs Yukawa ~ 1/tan β



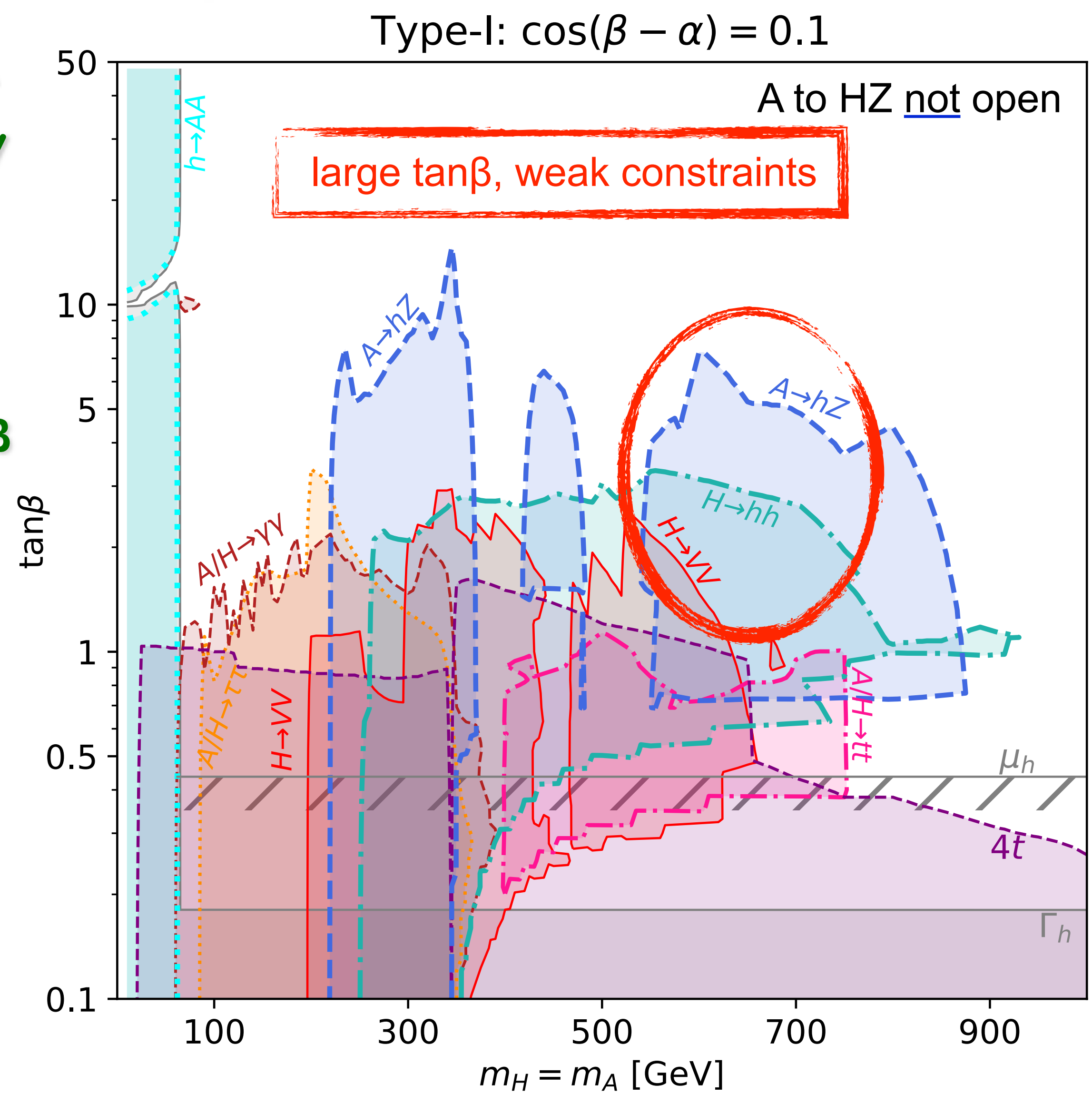
Degenerate Case: Type I

- **degenerate:** $m_{Hpm} = m_H = m_A$
  no BSM sector exotic decay
  allow A→Zh, H→hh, H→VV
  (away from alignment)
- **Type I:** ϕ_2, u/d/l
  BSM Higgs Yukawa ~ 1/tan β



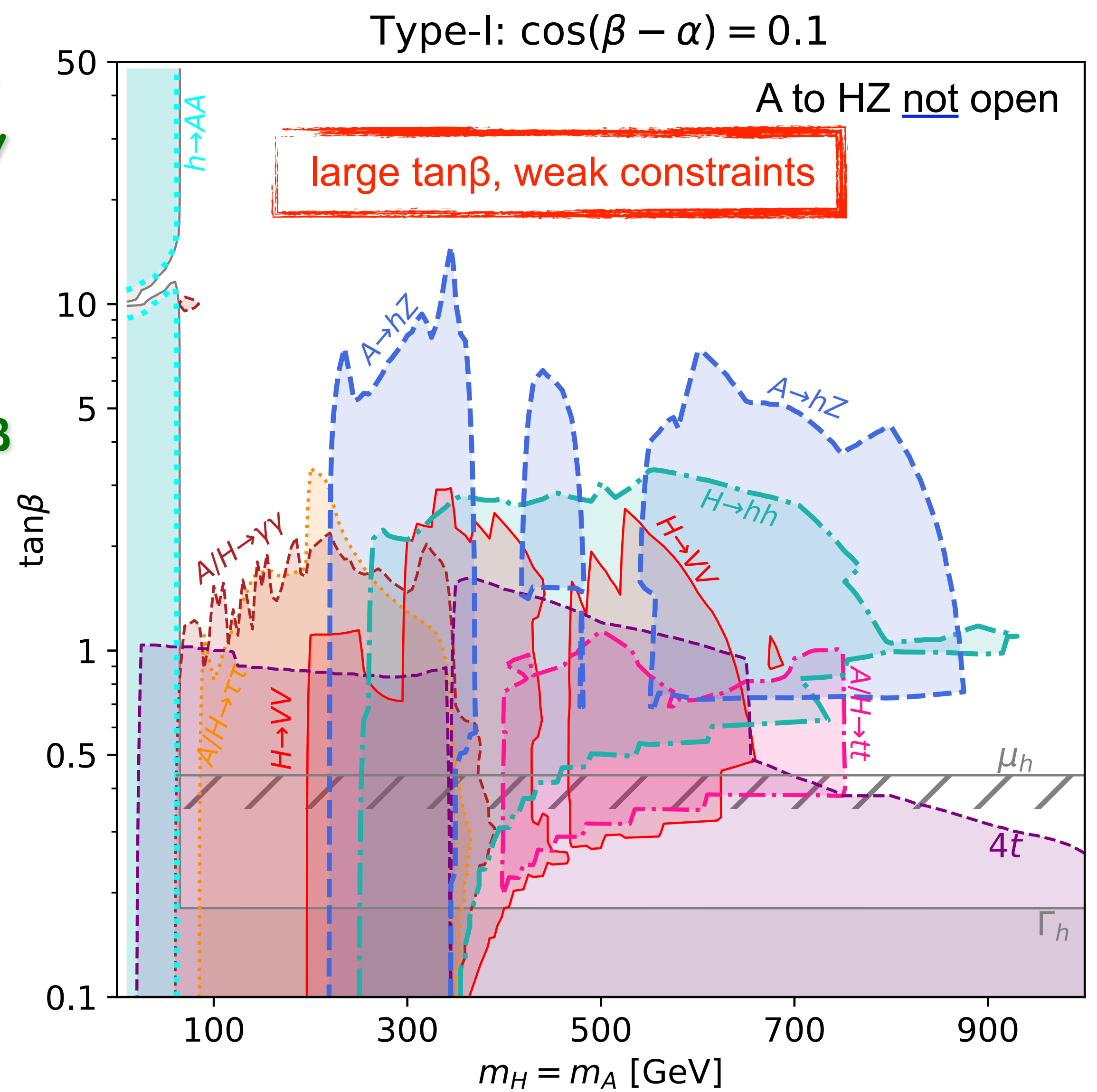
Degenerate Case: Type I

- **degenerate:** $m_{Hpm} = m_H = m_A$
  no BSM sector exotic decay
  allow A→Zh, H→hh, H→VV
  (away from alignment)
- **Type I: ϕ_2, u/d/l**
  BSM Higgs Yukawa ~ 1/tan β



Degenerate Case: Type I

- **degenerate: $m_{Hpm} = m_H = m_A$**
  no BSM sector exotic decay
  allow A→Zh, H→hh, H→VV
  (away from alignment)
- **Type I: ϕ_2, u/d/l**
  BSM Higgs Yukawa ~ 1/tan β



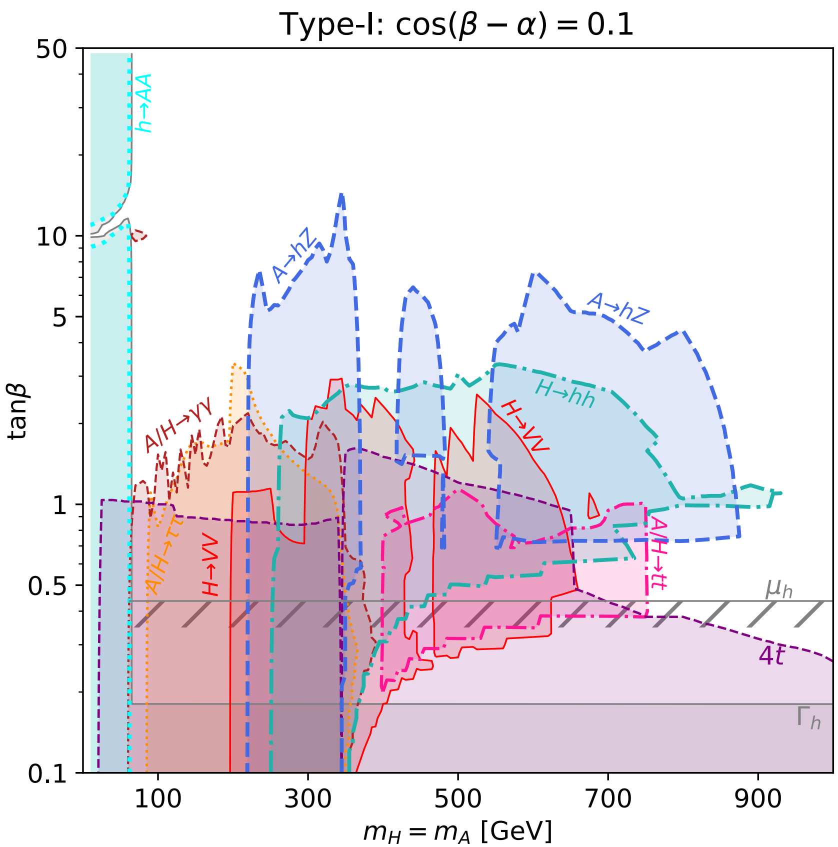
Degenerate Case: Type I & Type II

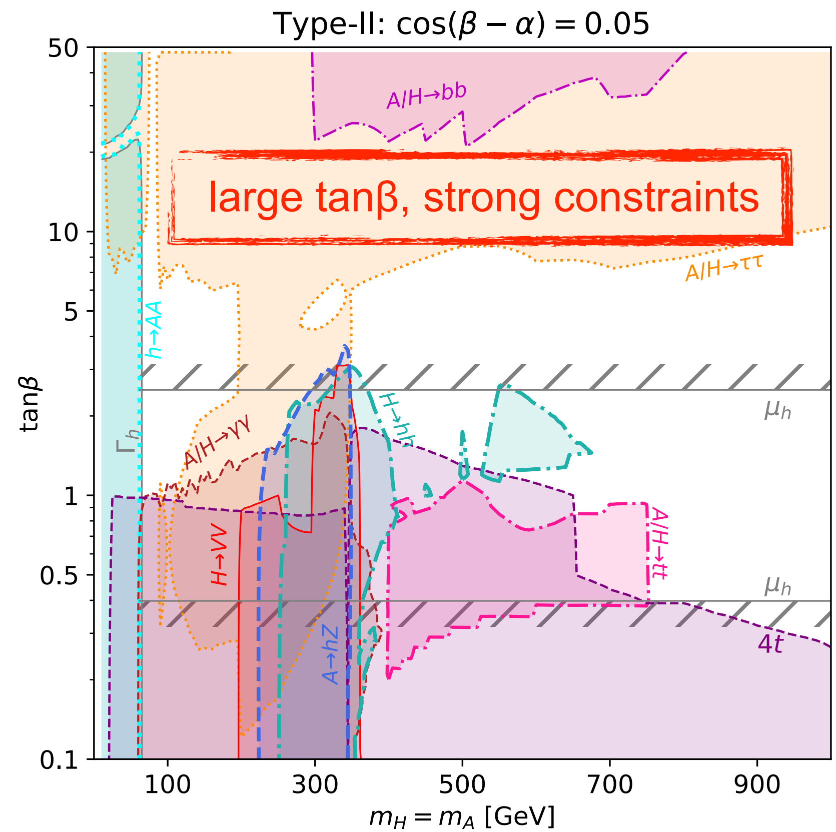
- **Type I: ϕ_1, u/d/l**

  BSM Higgs Yukawa ~ 1/tan β

- **Type II ϕ_1,u; ϕ_2,d/l**

  BSM H/A,u ~ 1/tan β; d/l ~ tan β





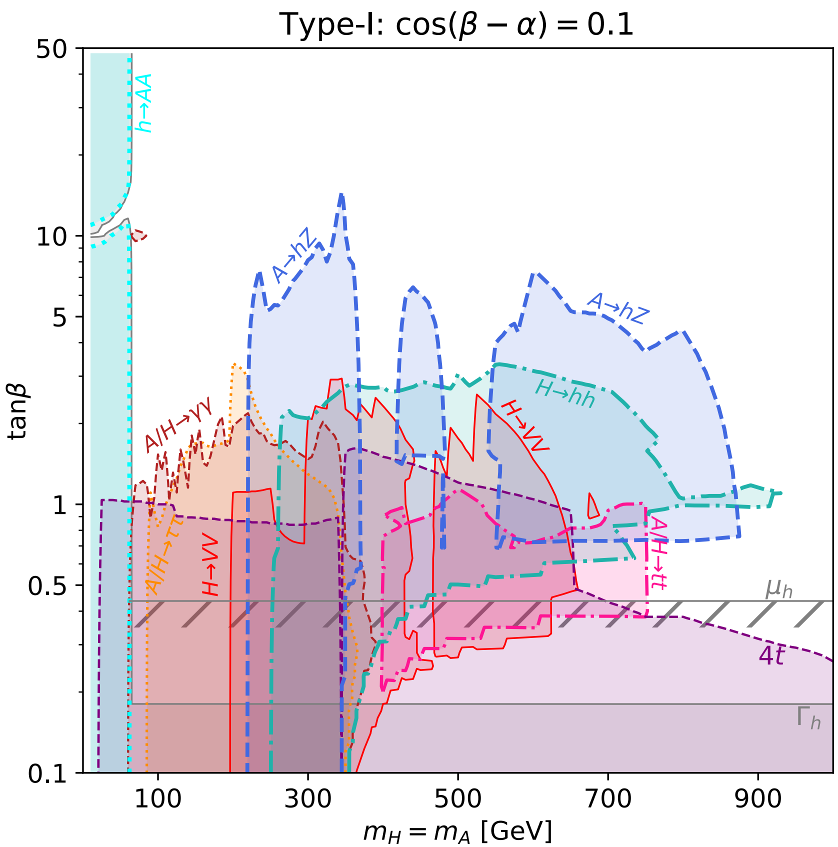
Degenerate Case: Type I & Type II

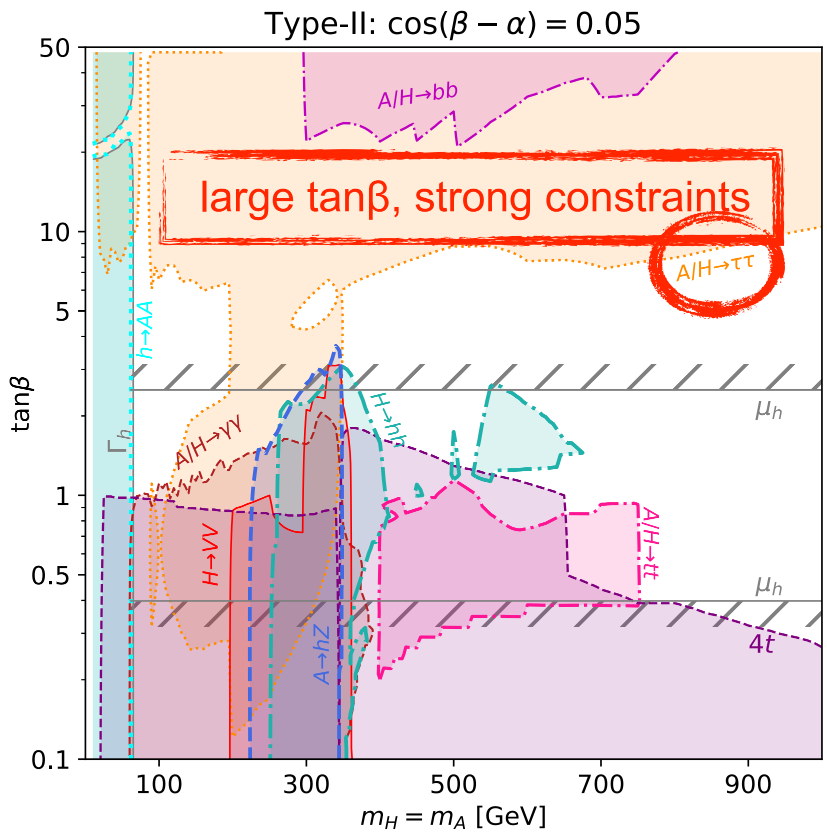
- **Type I: ϕ₁, u/d/l**

  BSM Higgs Yukawa ~ 1/tan β

- **Type II ϕ₁,u; ϕ₂,d/l**

  BSM H/A,u ~ 1/tan β; d/l ~ tan β





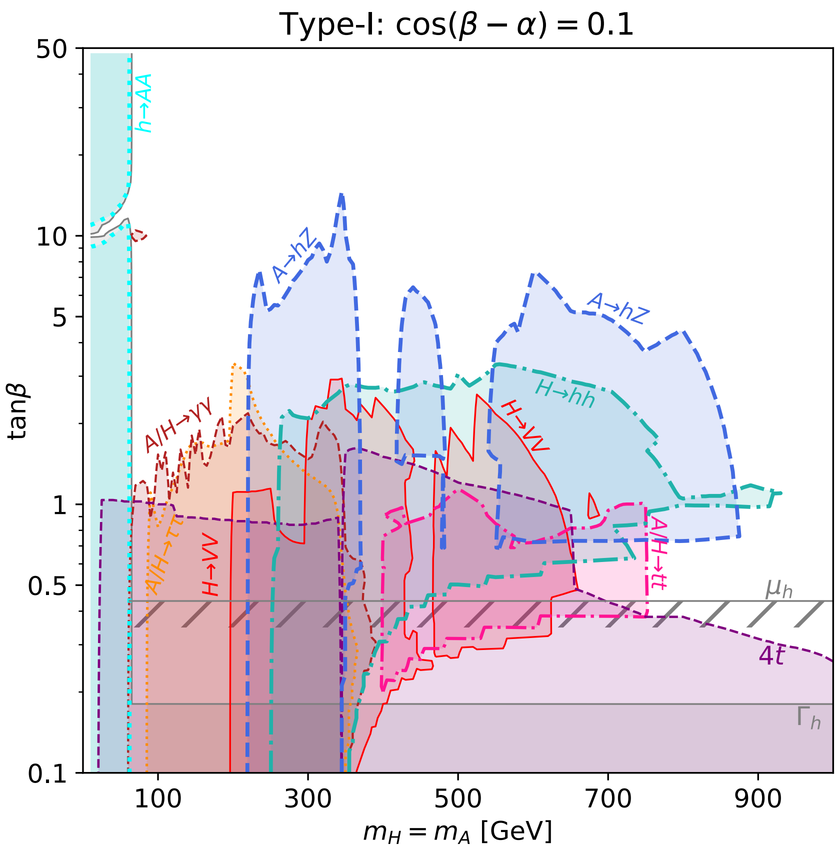
Degenerate Case: Type I & Type II

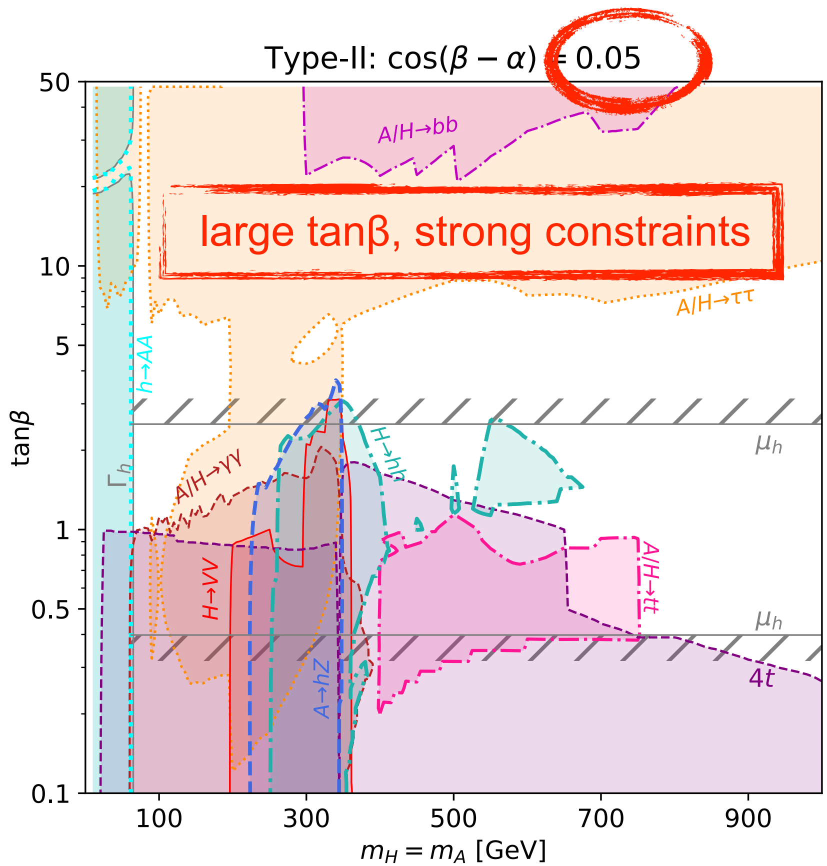
- **Type I: ϕ₁, u/d/l**

  BSM Higgs Yukawa ~ 1/tan β

- **Type II ϕ₁,u; ϕ₂,d/l**

  BSM H/A,u ~ 1/tan β; d/l ~ tan β

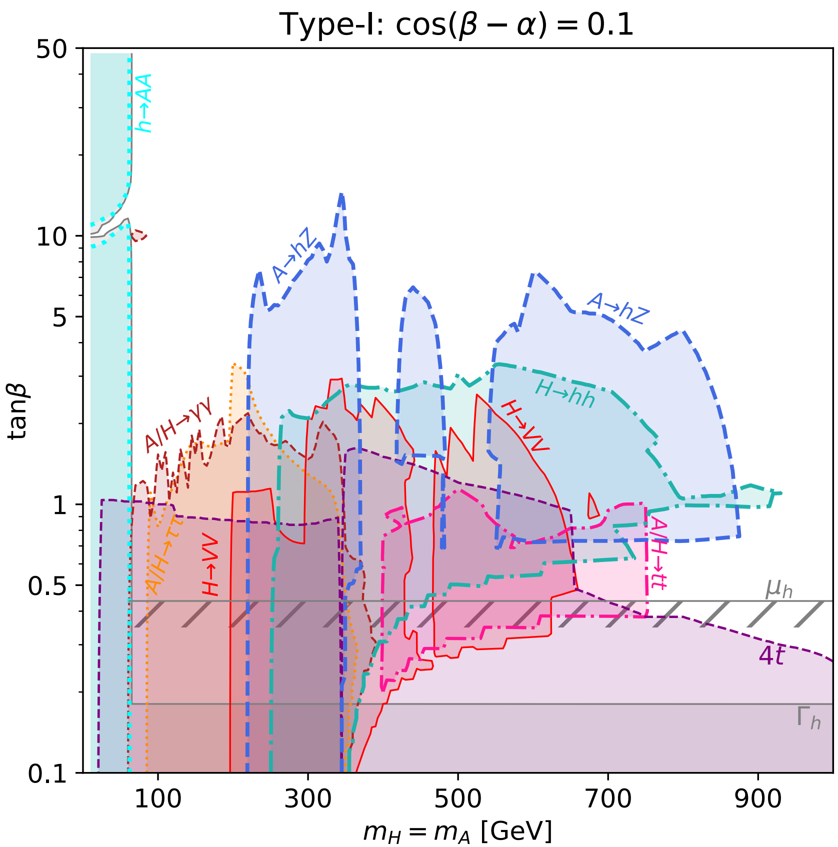


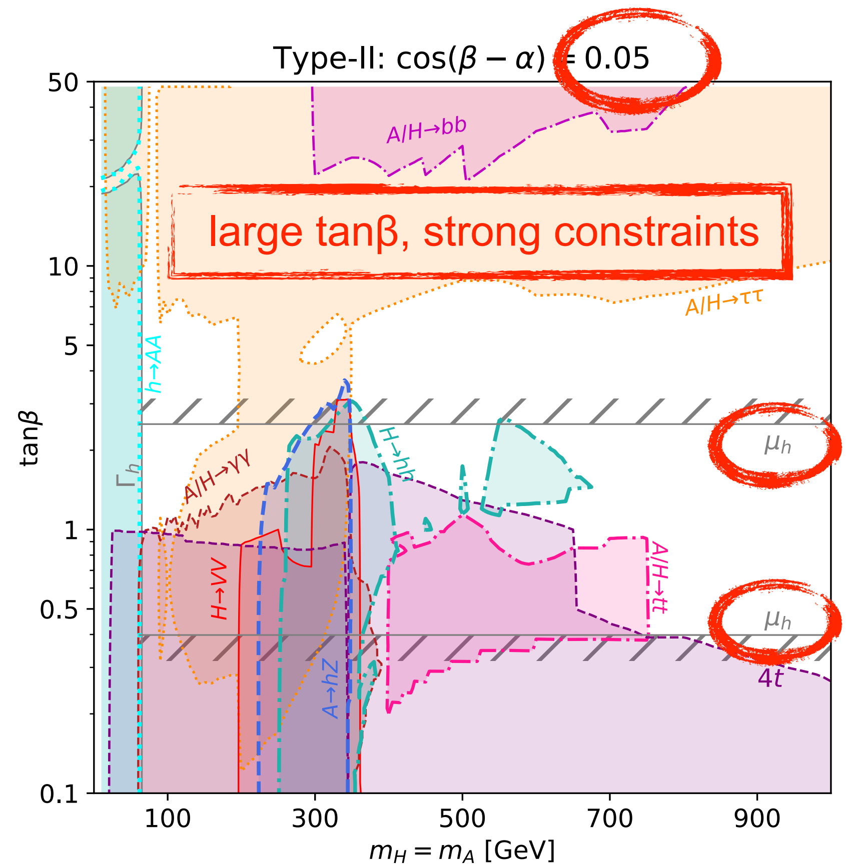


Degenerate Case: Type I & Type II

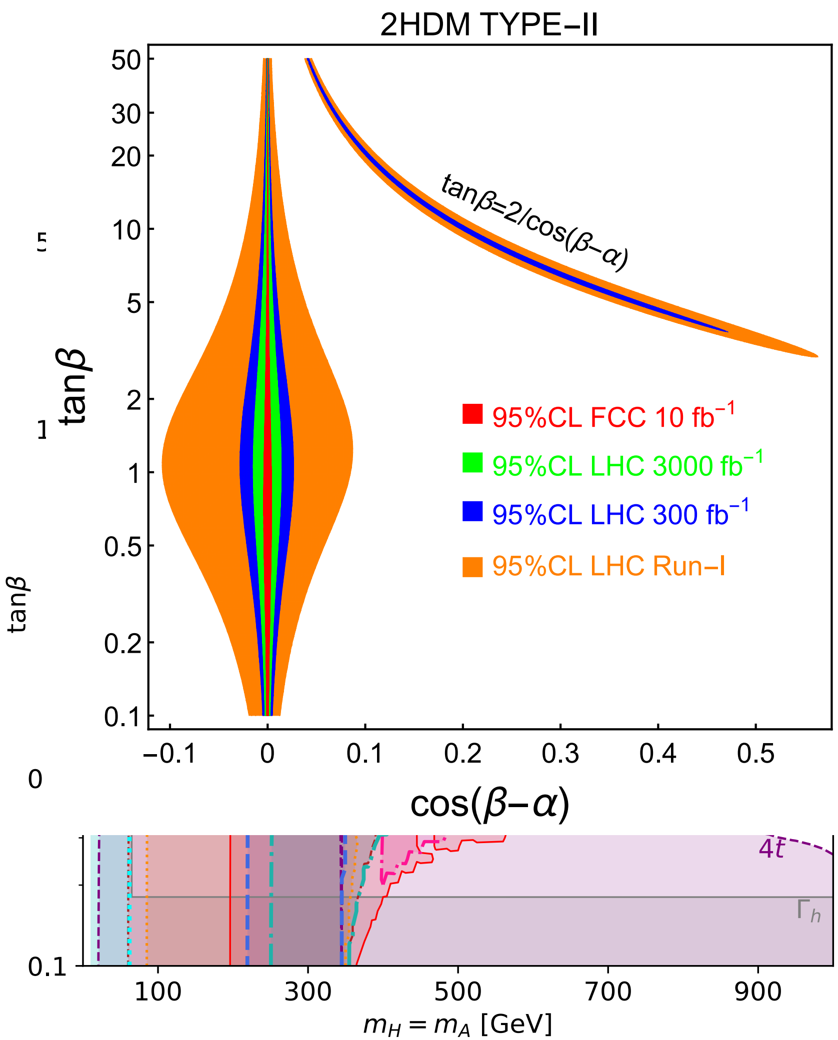
- **Type I: ϕ_1, u/d/l**
  BSM Higgs Yukawa ~ 1/tan β

- **Type II ϕ_1,u; ϕ_2,d/l**
  BSM H/A,u ~ 1/tan β; d/l ~ tan β



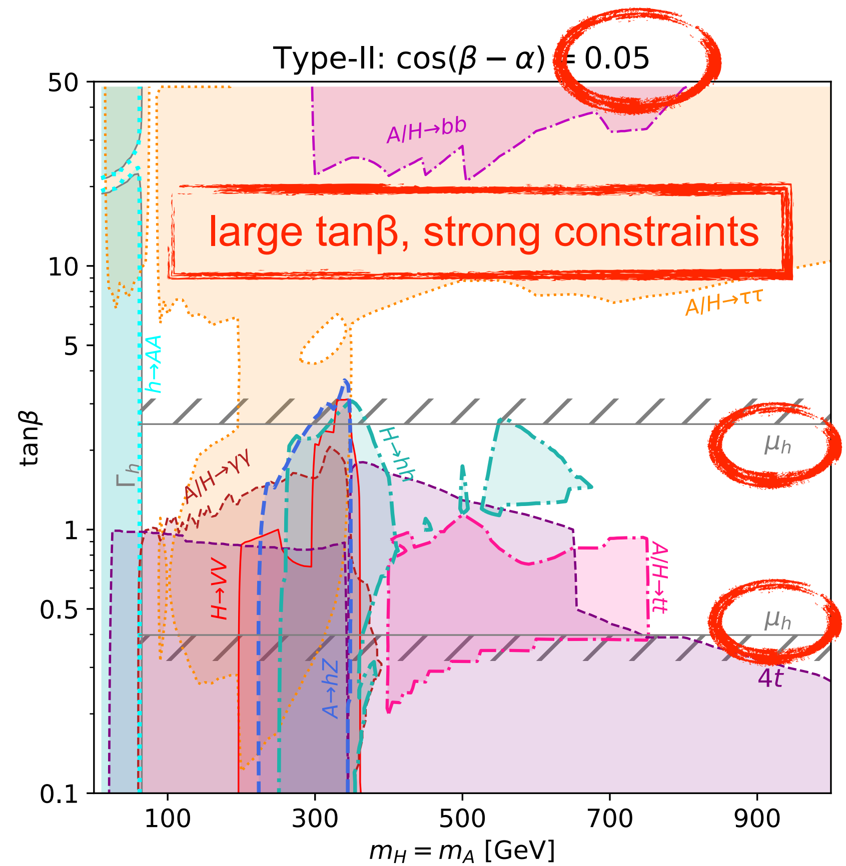


Degenerate Case: Type I & Type II



- **Type II** ϕ_1, u; ϕ_2, d/l

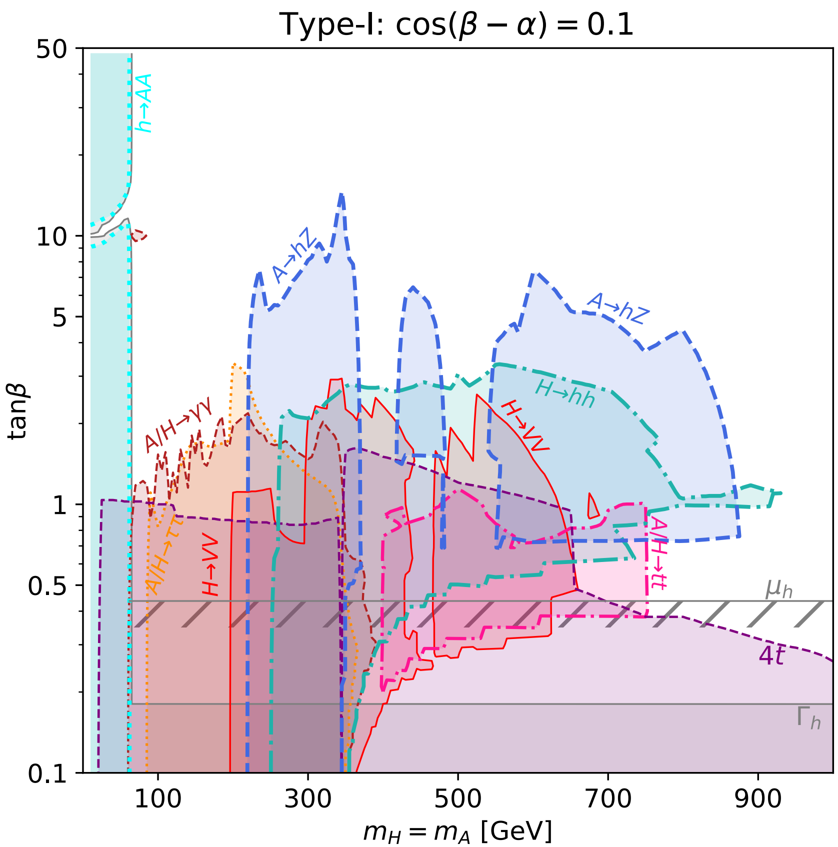
BSM H/A, u ~ 1/tan β; d/l ~ tan β



Degenerate Case: Type I & Type II

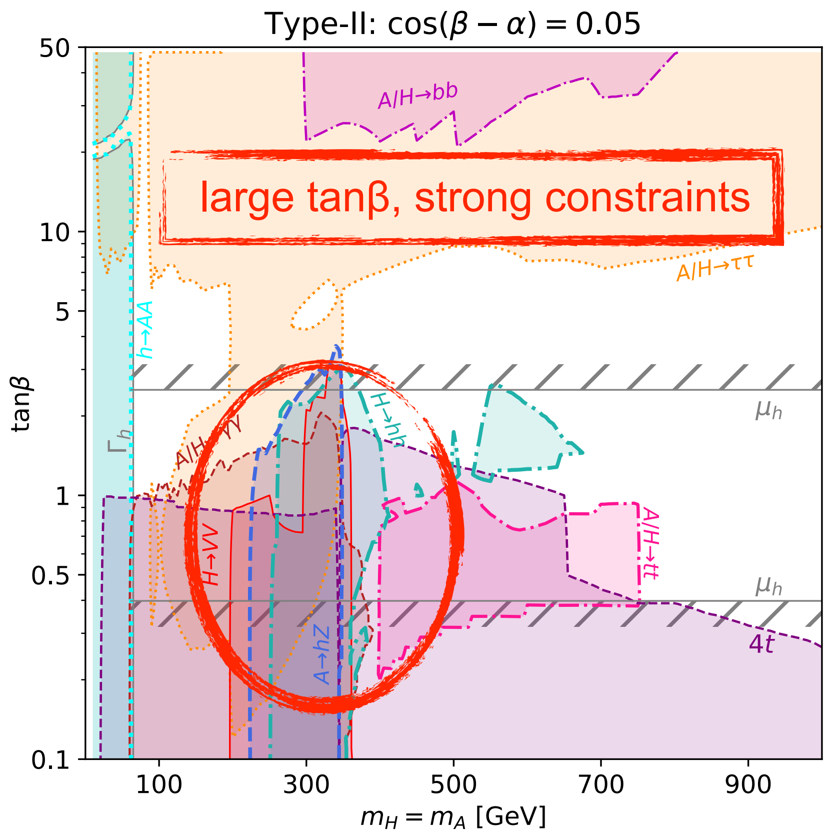
- **Type I: ϕ_1, u/d/l**

  BSM Higgs Yukawa ~ 1/tan β



- **Type II ϕ_1,u; ϕ_2,d/l**

  BSM H/A,u ~ 1/tan β; d/l ~ tan β



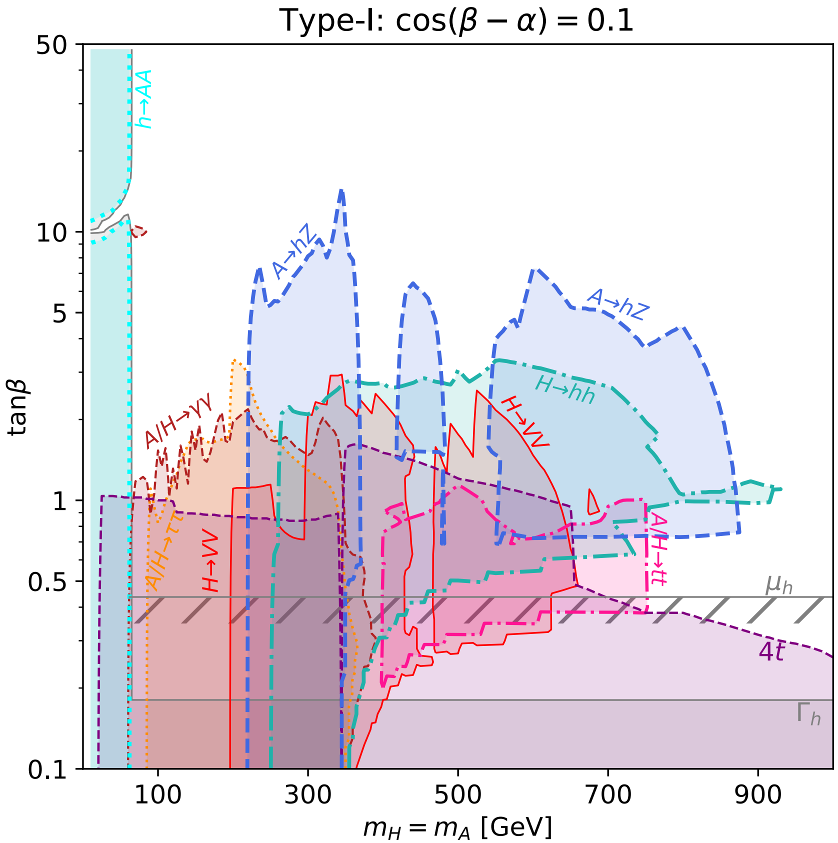
Degenerate Case: Type I & Type II

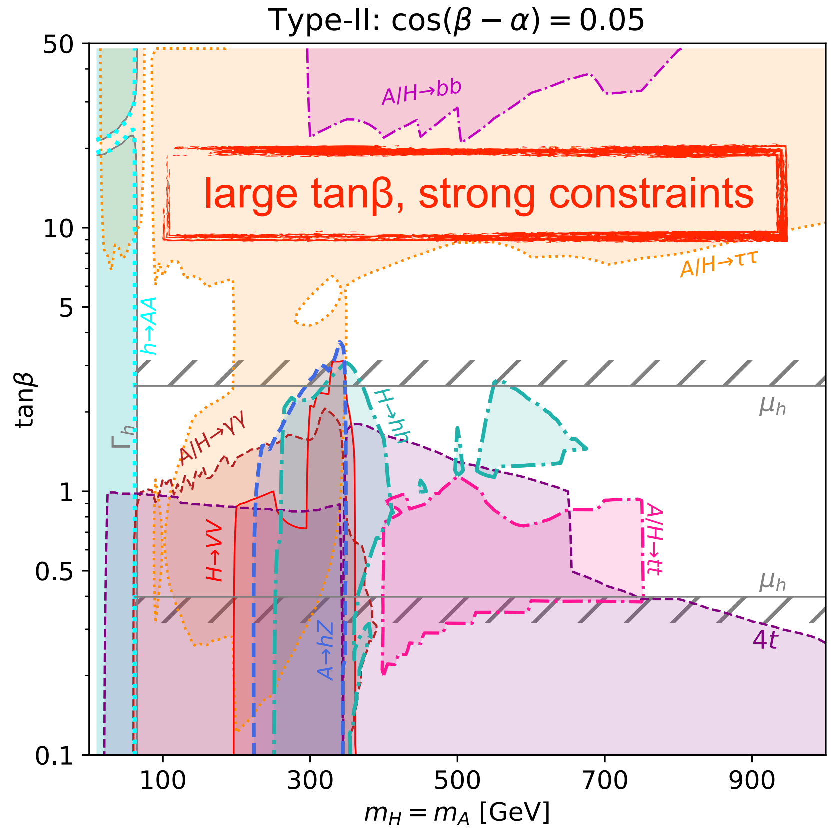
- **Type I: ϕ_1, u/d/l**

  BSM Higgs Yukawa ~ 1/tan β

- **Type II ϕ_1, u; ϕ_2, d/l**

  BSM H/A, u ~ 1/tan β; d/l ~ tan β

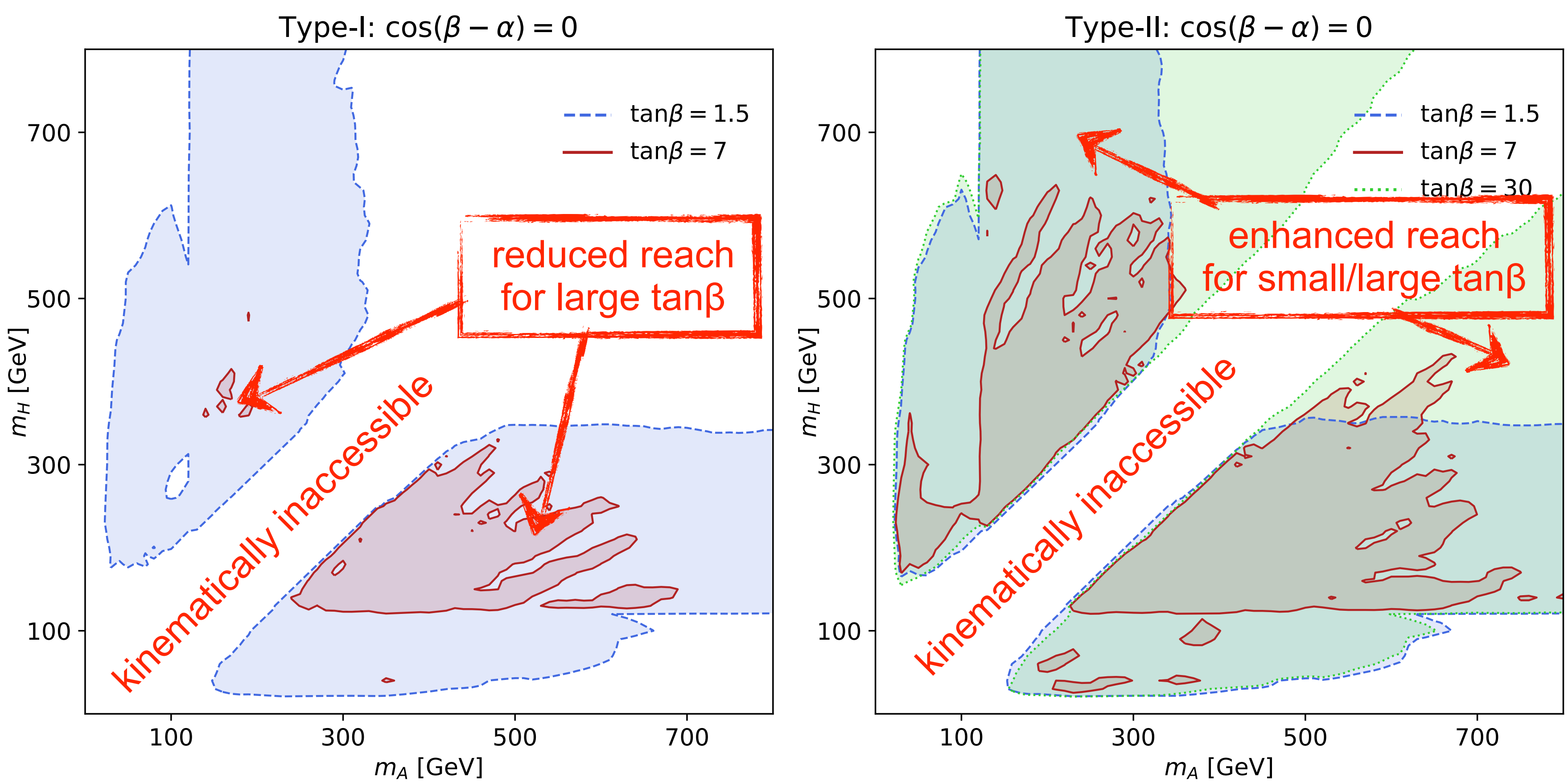




Non-Degenerate Case: Type I & Type II

- **Non-degenerate: A→ZH, H→ZA**

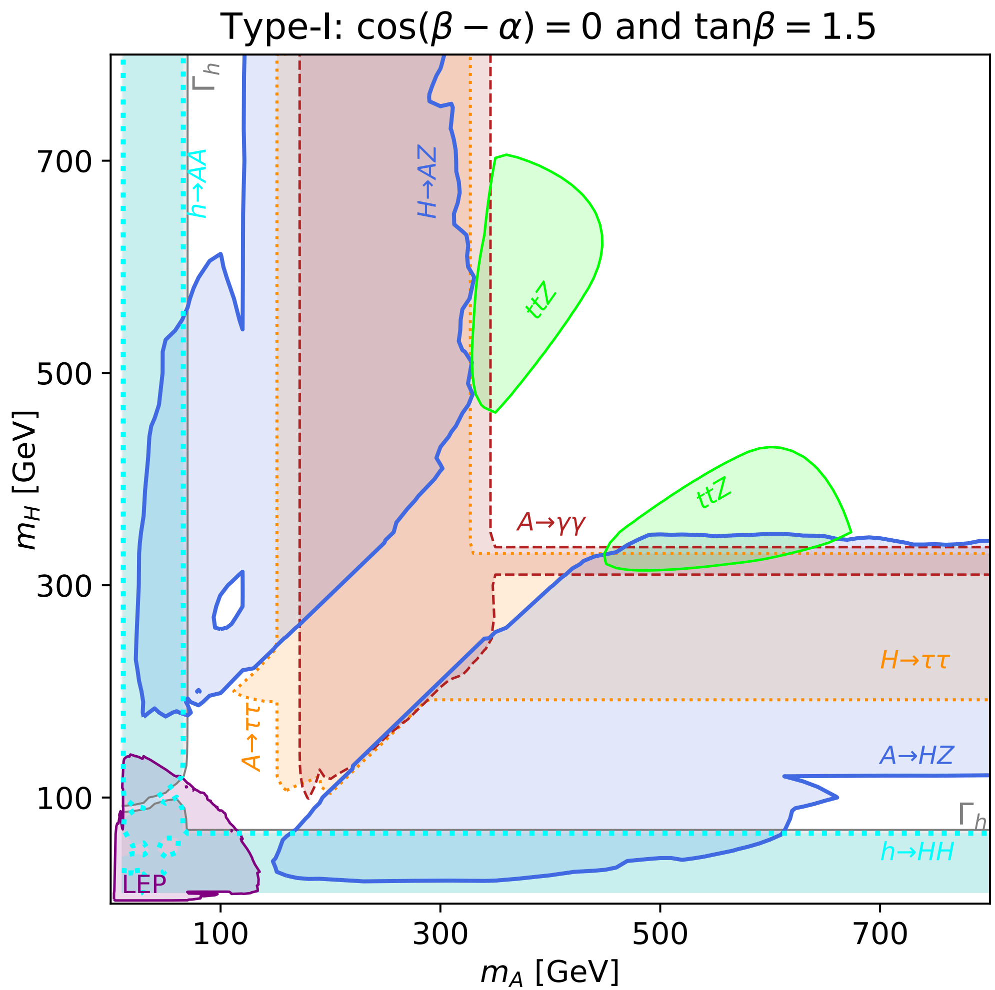
m_A vs. m_H



Non-Degenerate Case: Type I

- **Non-degenerate: A→ZH, H→ZA**

m_A vs. m_H

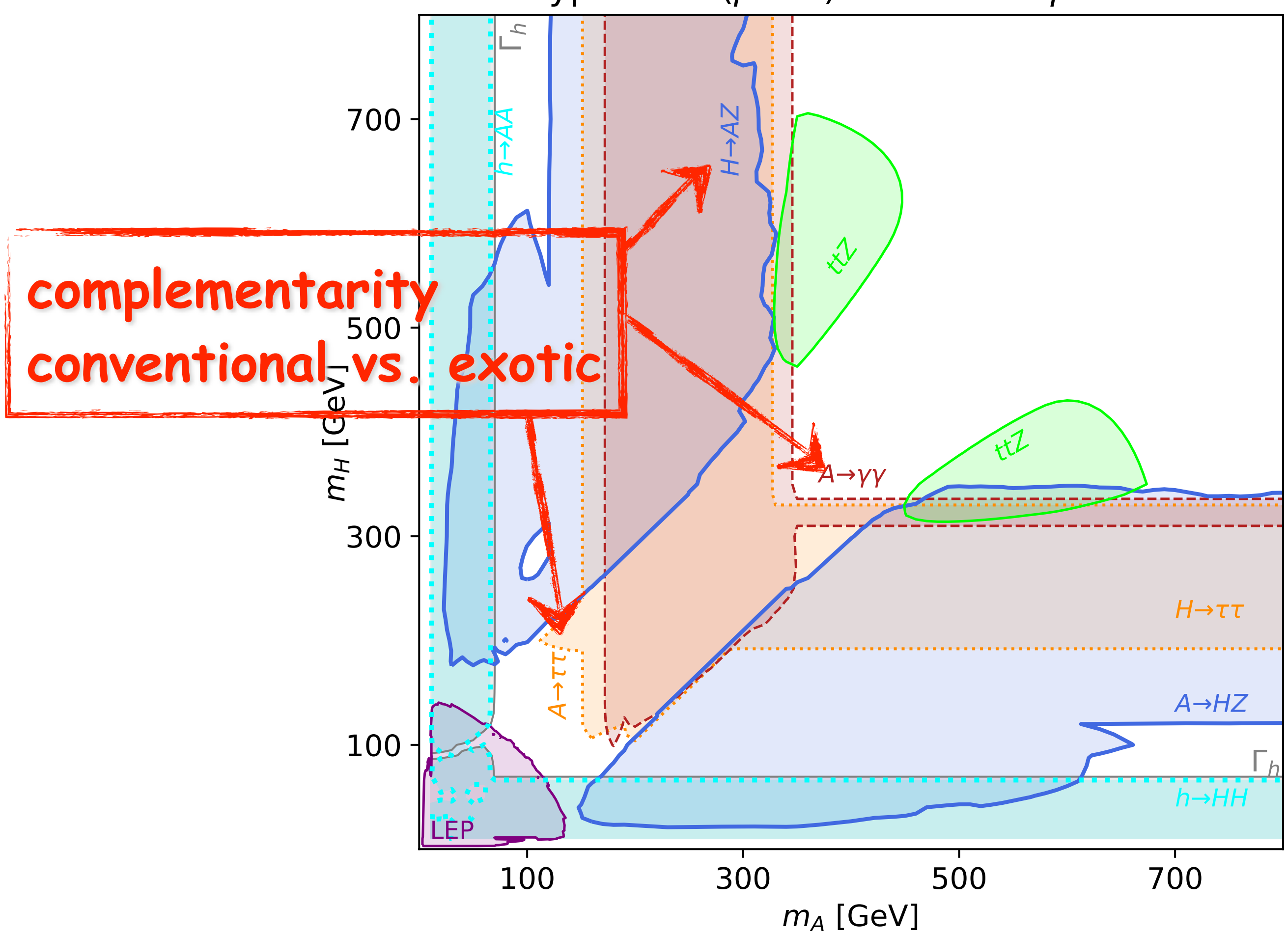


Non-Degenerate Case: Type I

- **Non-degenerate: A→ZH, H→ZA**

m_A vs. m_H

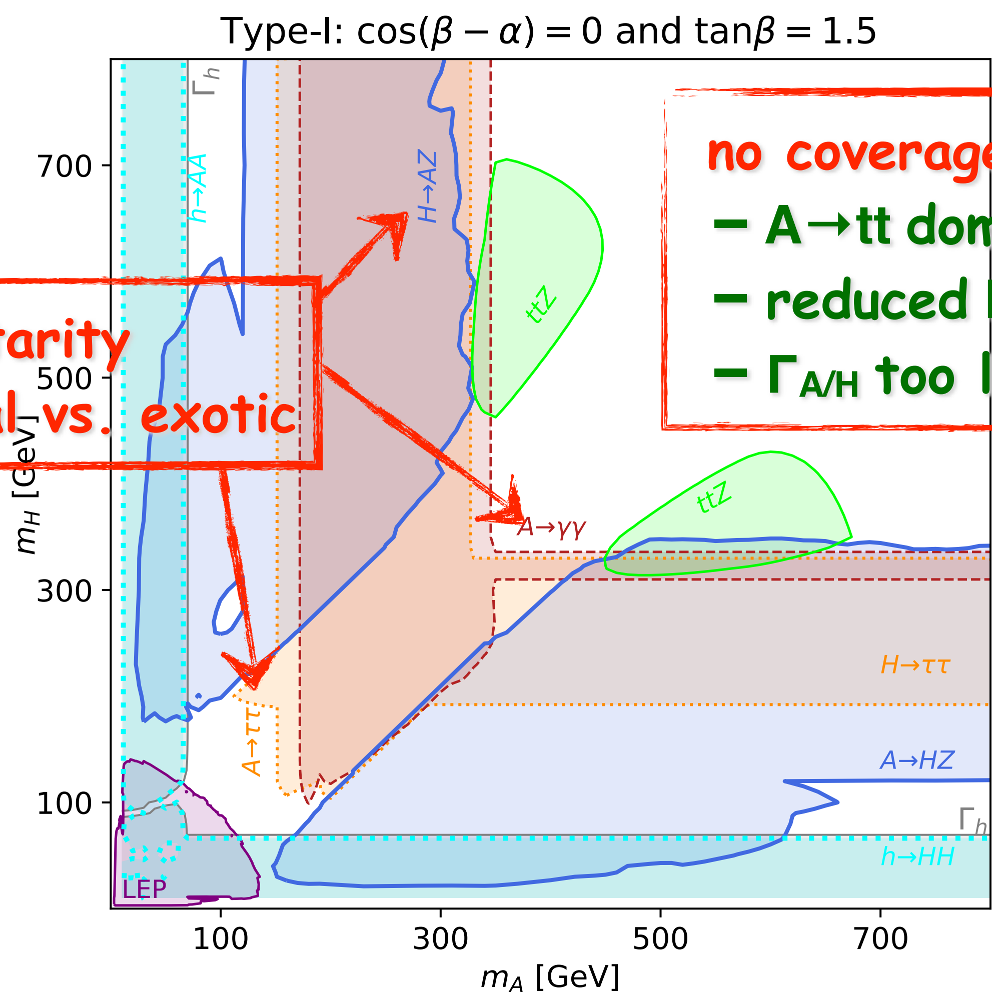
Type-I: $\cos(\beta-\alpha)=0$ and $\tan\beta=1.5$



Non-Degenerate Case: Type I

- **Non-degenerate: A→ZH, H→ZA**

m_A vs. m_H



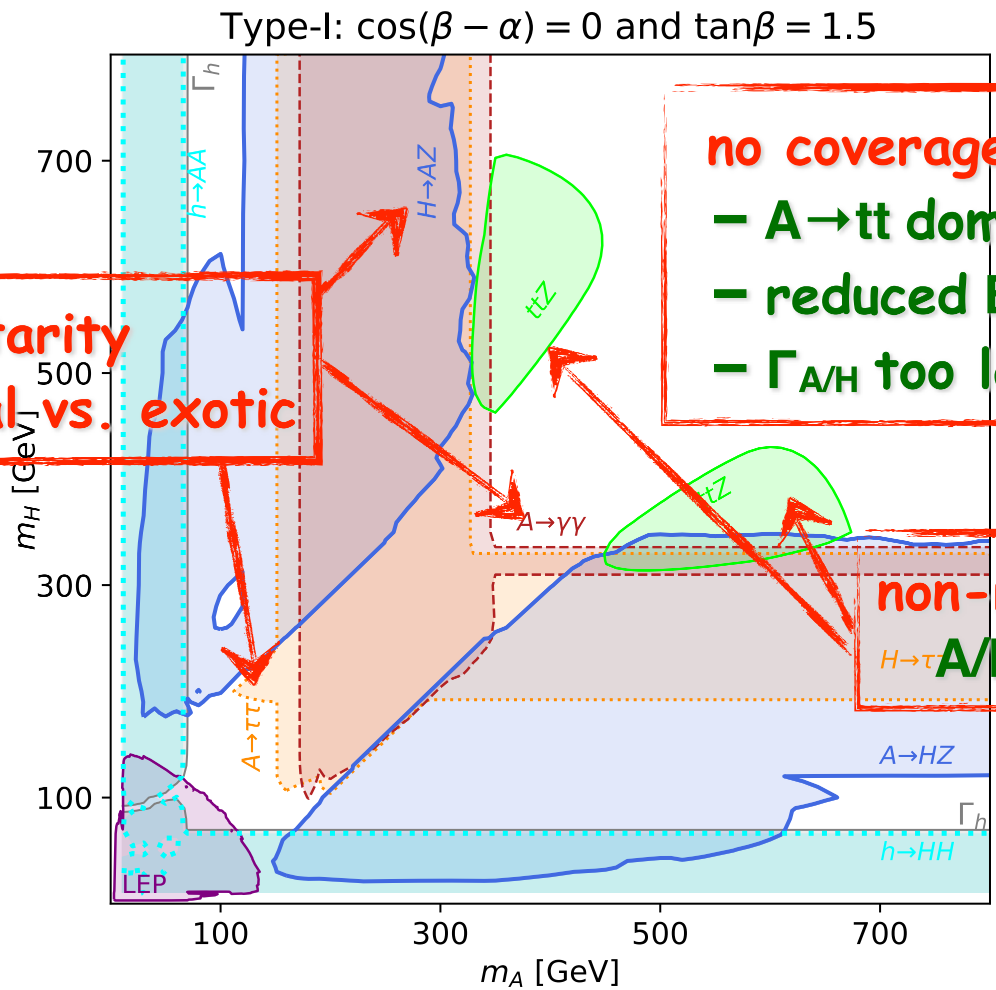
complementarity
conventional vs. exotic

no coverage above $m_{A/H} > 2\, m_t$
- A→tt dominant
- reduced Br (A/H→ZH/ZA)
- $\Gamma_{A/H}$ too large

Non-Degenerate Case: Type I

- **Non-degenerate: A→ZH, H→ZA**

m_A vs. m_H



complementarity
conventional vs. exotic

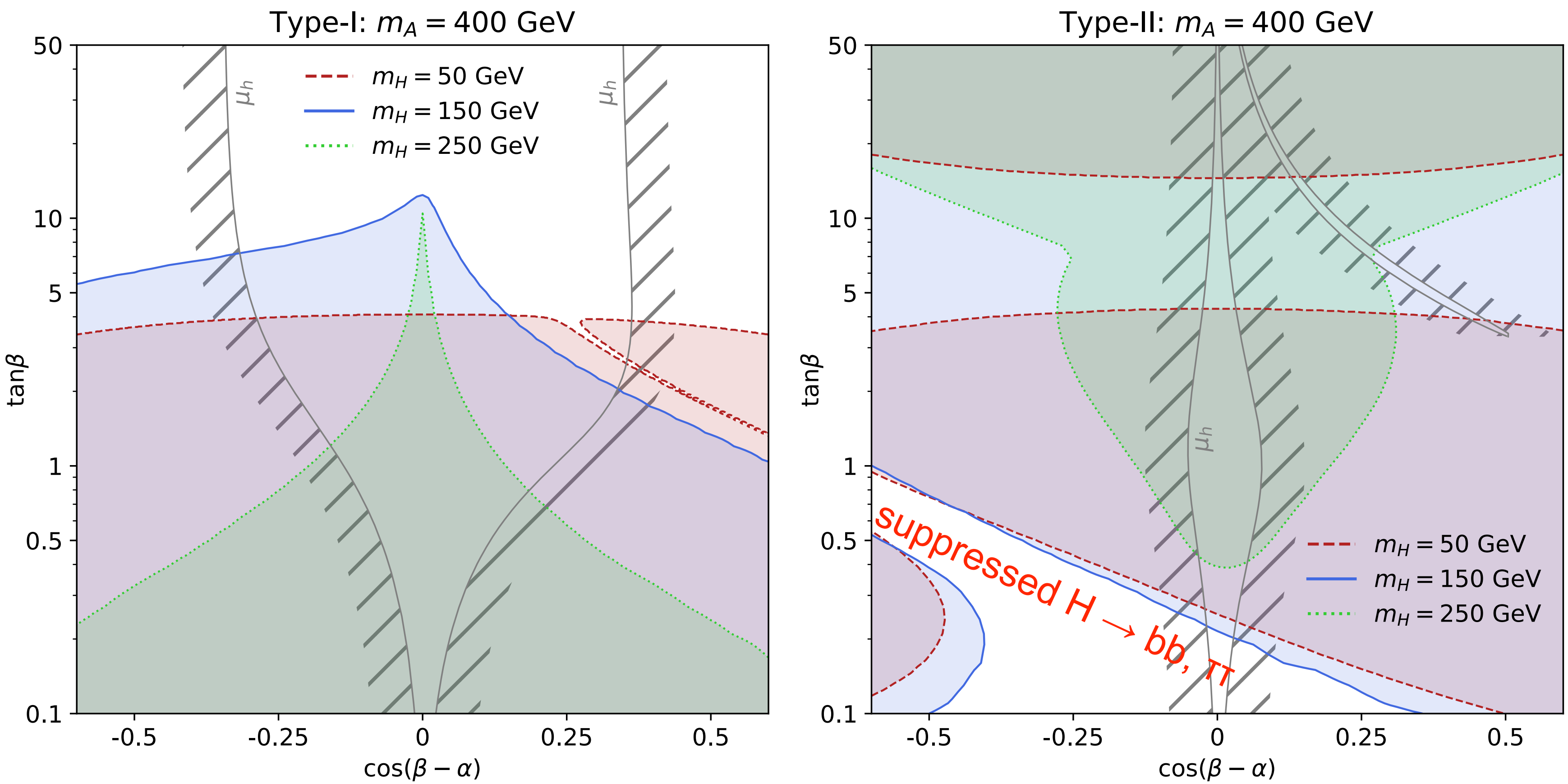
no coverage above $m_{A/H} > 2\, m_t$
- A→tt dominant
- reduced Br (A/H→ZH/ZA)
- $\Gamma_{A/H}$ too large

non-resonant search ttZ
A/H→ZH/ZA→ttZ

Non-Degenerate Case: Type I & Type II

- **Non-degenerate: A→ZH, H→ZA**

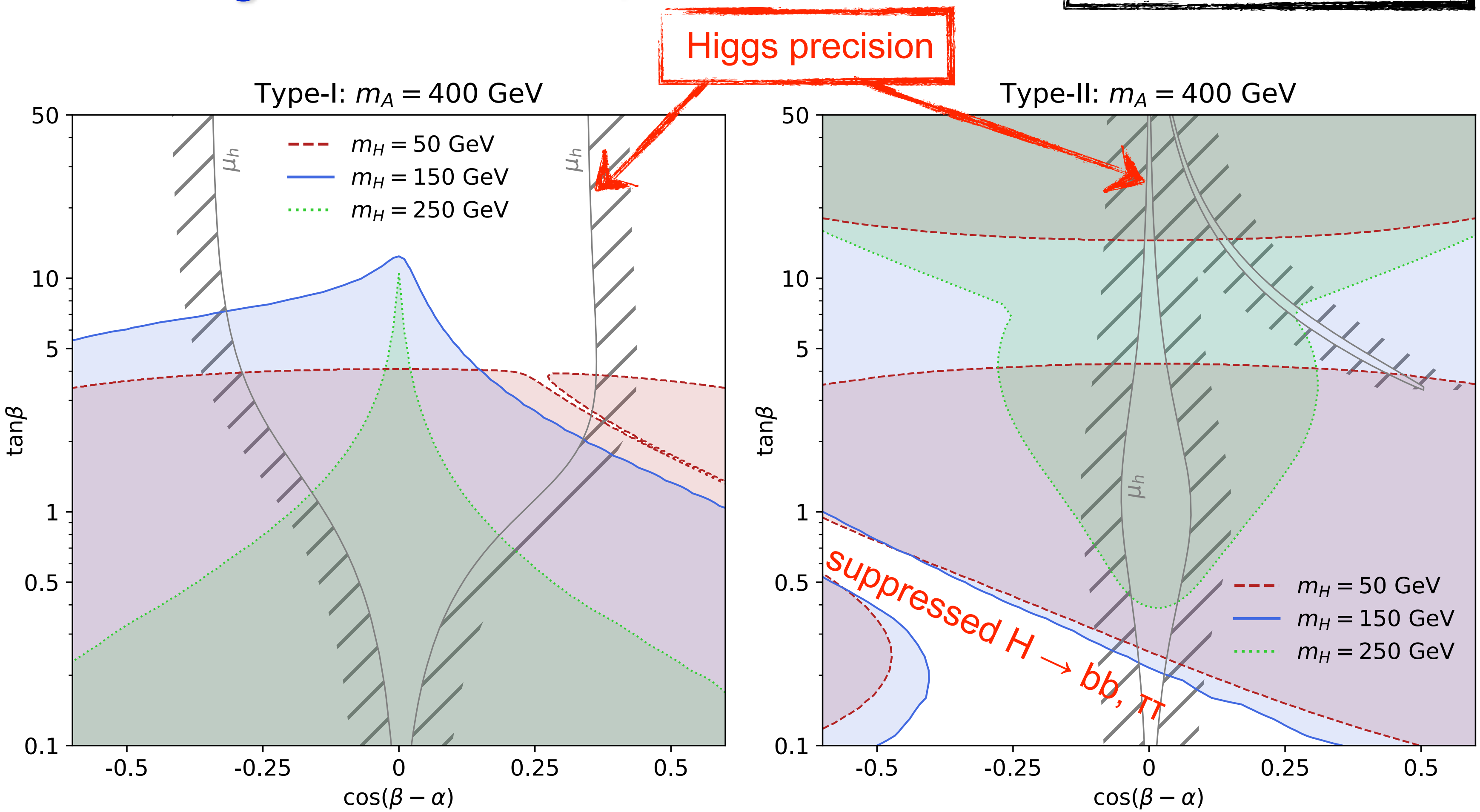
cos(β-α) vs. tanβ



Non-Degenerate Case: Type I & Type II

- **Non-degenerate: A→ZH, H→ZA**

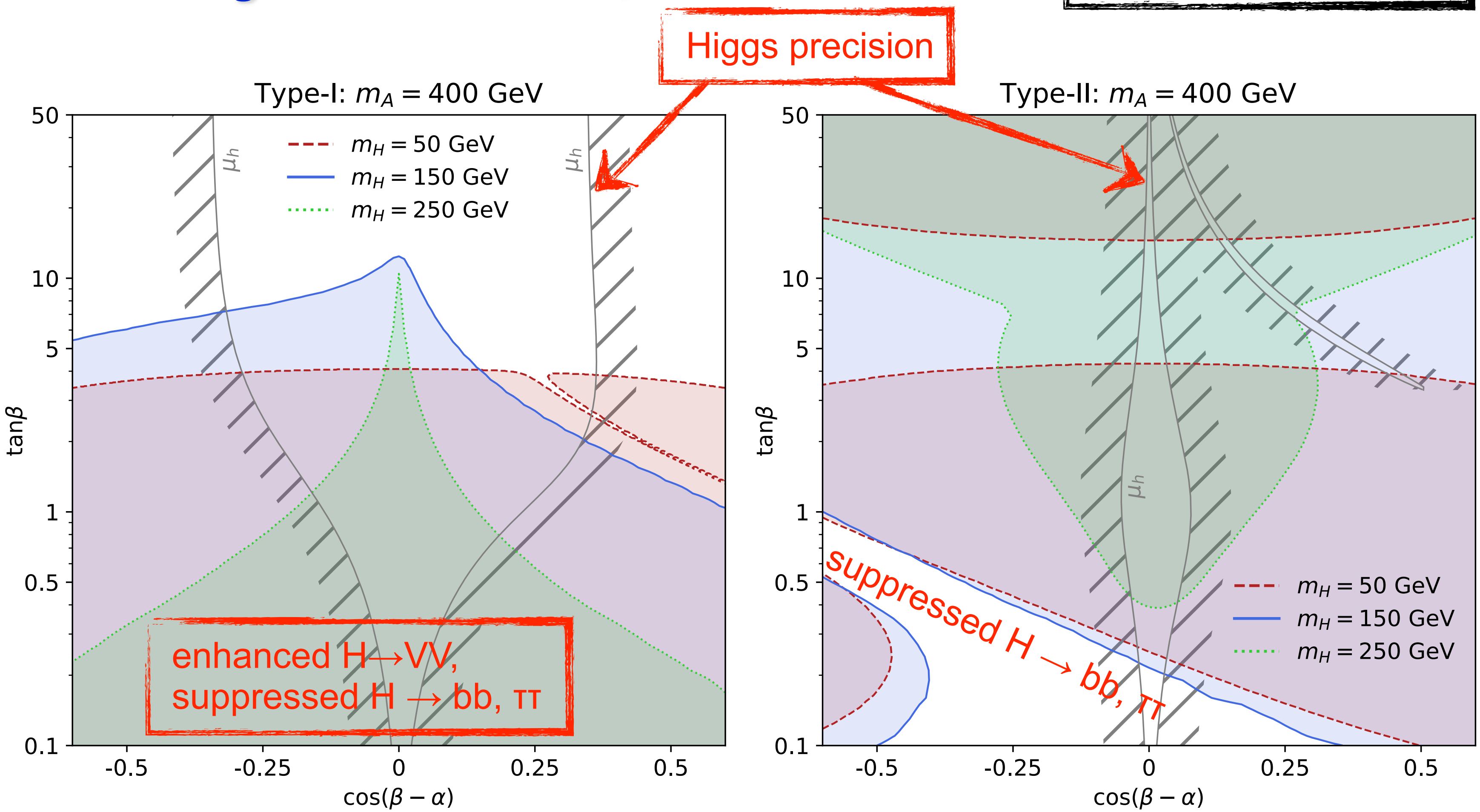
cos(β-α) vs. tanβ



Non-Degenerate Case: Type I & Type II

- **Non-degenerate: A→ZH, H→ZA**

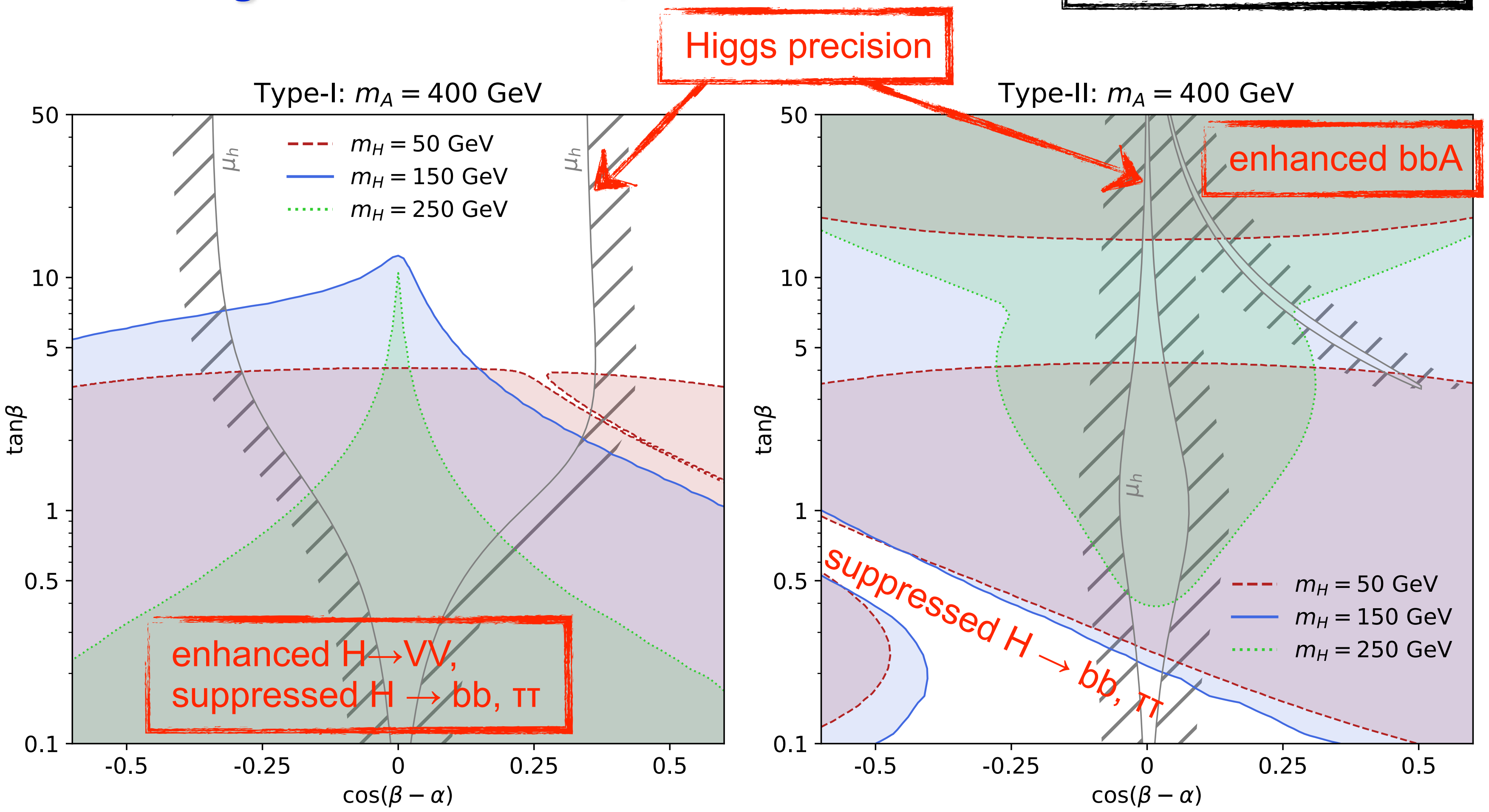
cos(β-α) vs. tanβ



Non-Degenerate Case: Type I & Type II

- **Non-degenerate: A→ZH, H→ZA**

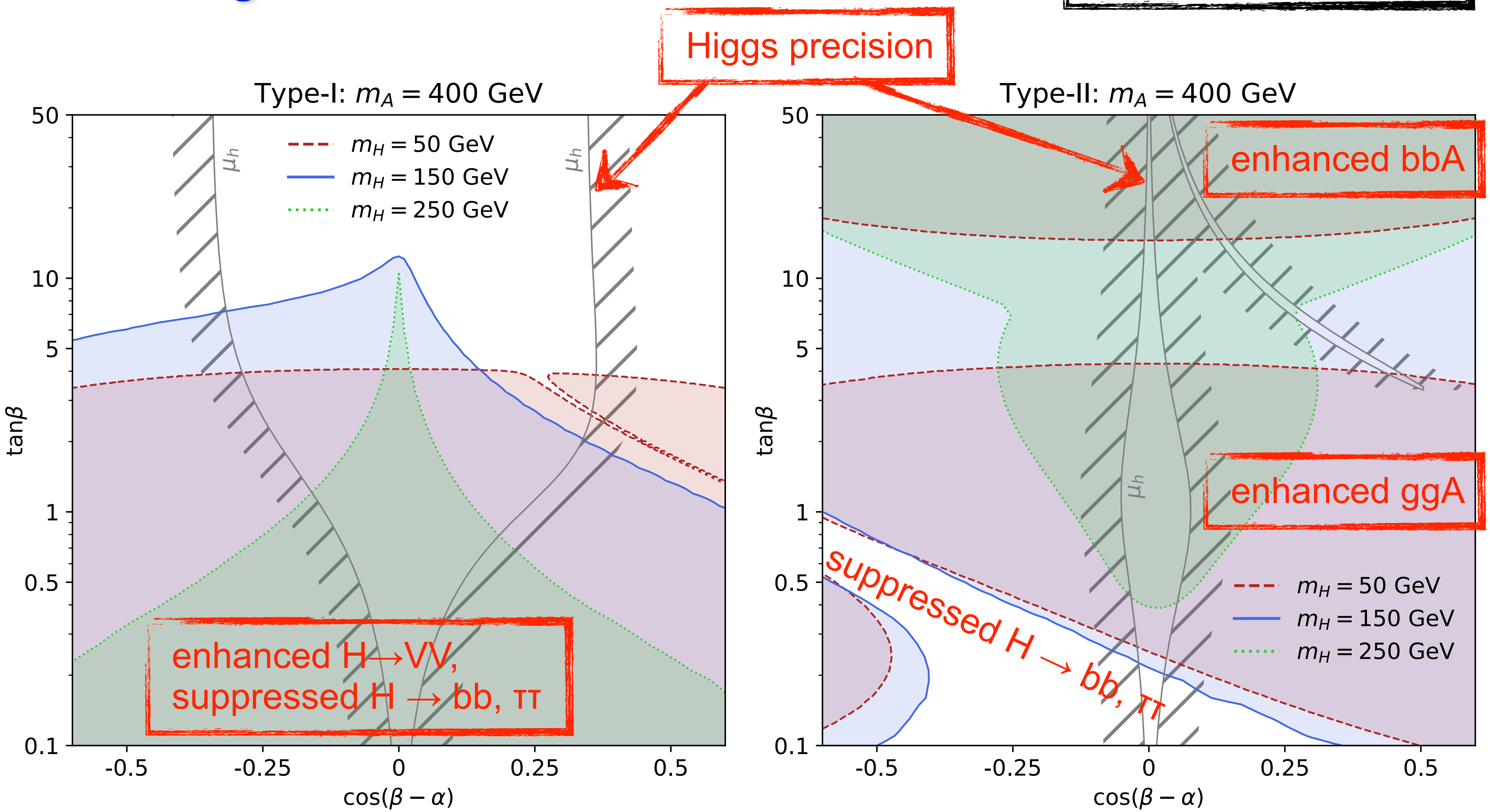
cos(β-α) vs. tanβ



Non-Degenerate Case: Type I & Type II

- **Non-degenerate: A→ZH, H→ZA**

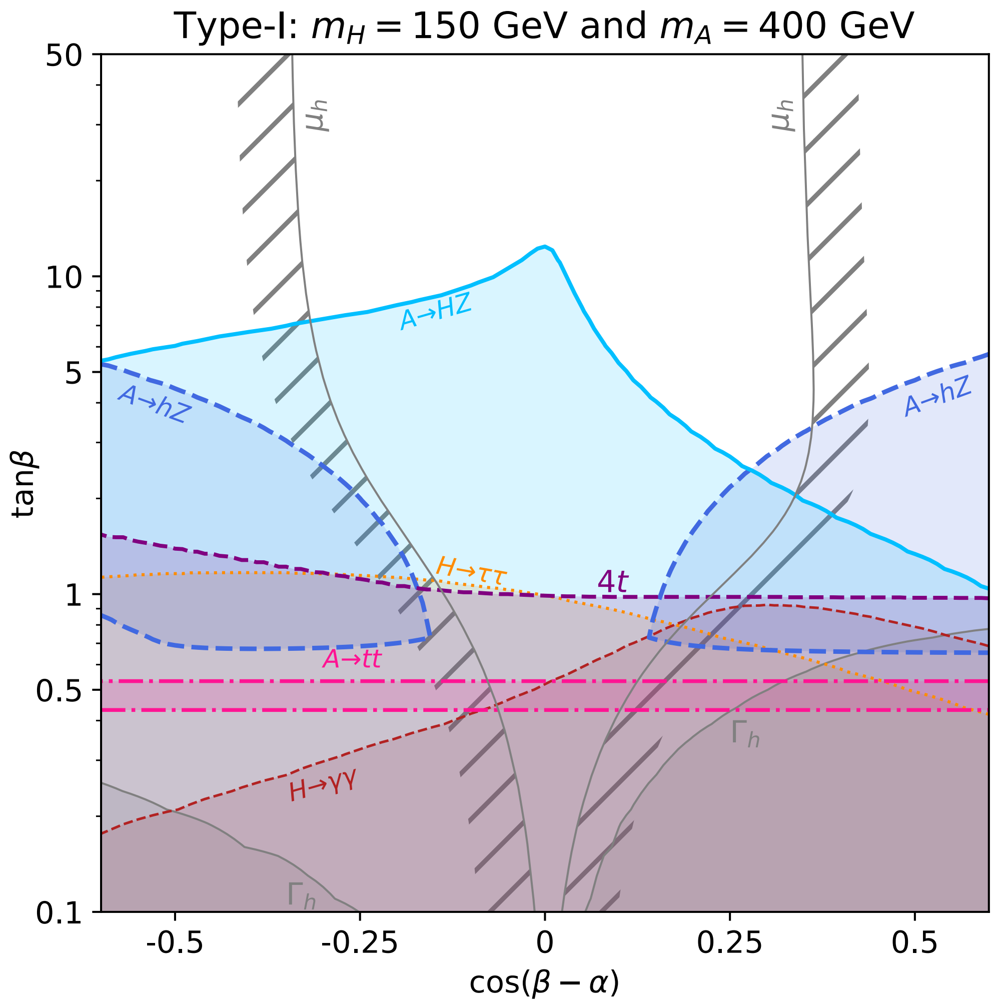
cos(β-α) vs. tanβ



Non-Degenerate Case: Type I

- **Non-degenerate: A→ZH, H→ZA**

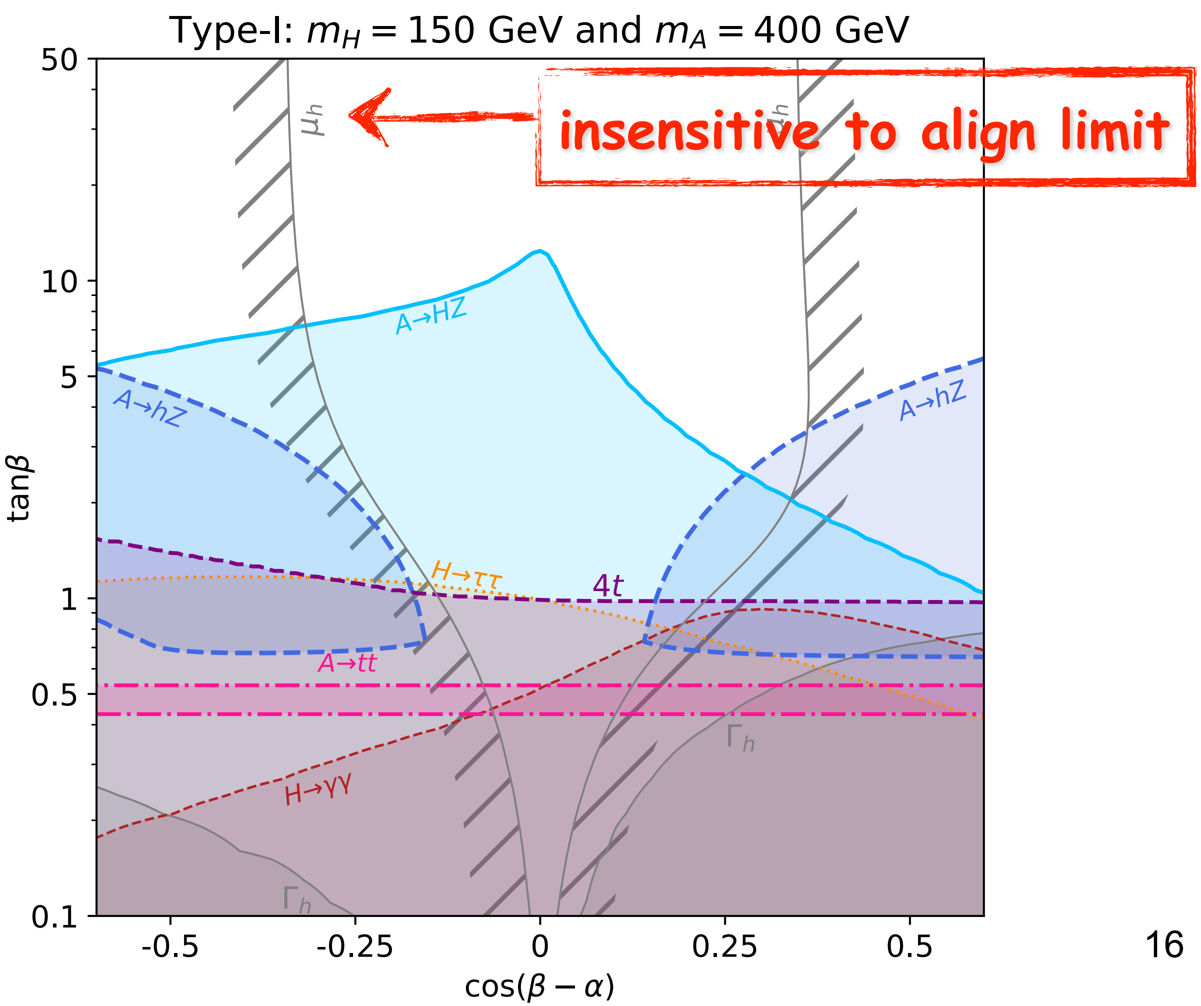
cos(β-α) vs. tanβ



Non-Degenerate Case: Type I

- **Non-degenerate: A→ZH, H→ZA**

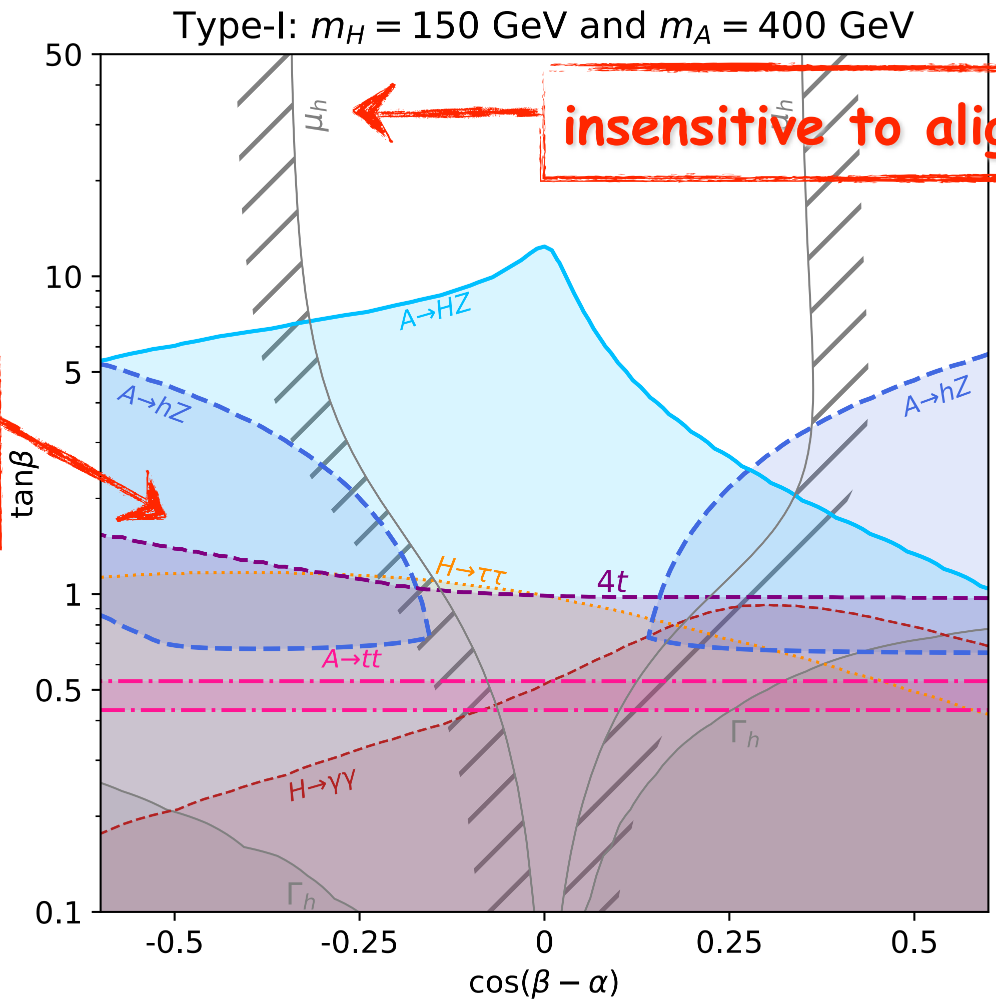
cos(β-α) vs. tanβ



Non-Degenerate Case: Type I

- Non-degenerate: A→ZH, H→ZA

cos(β-α) vs. tanβ



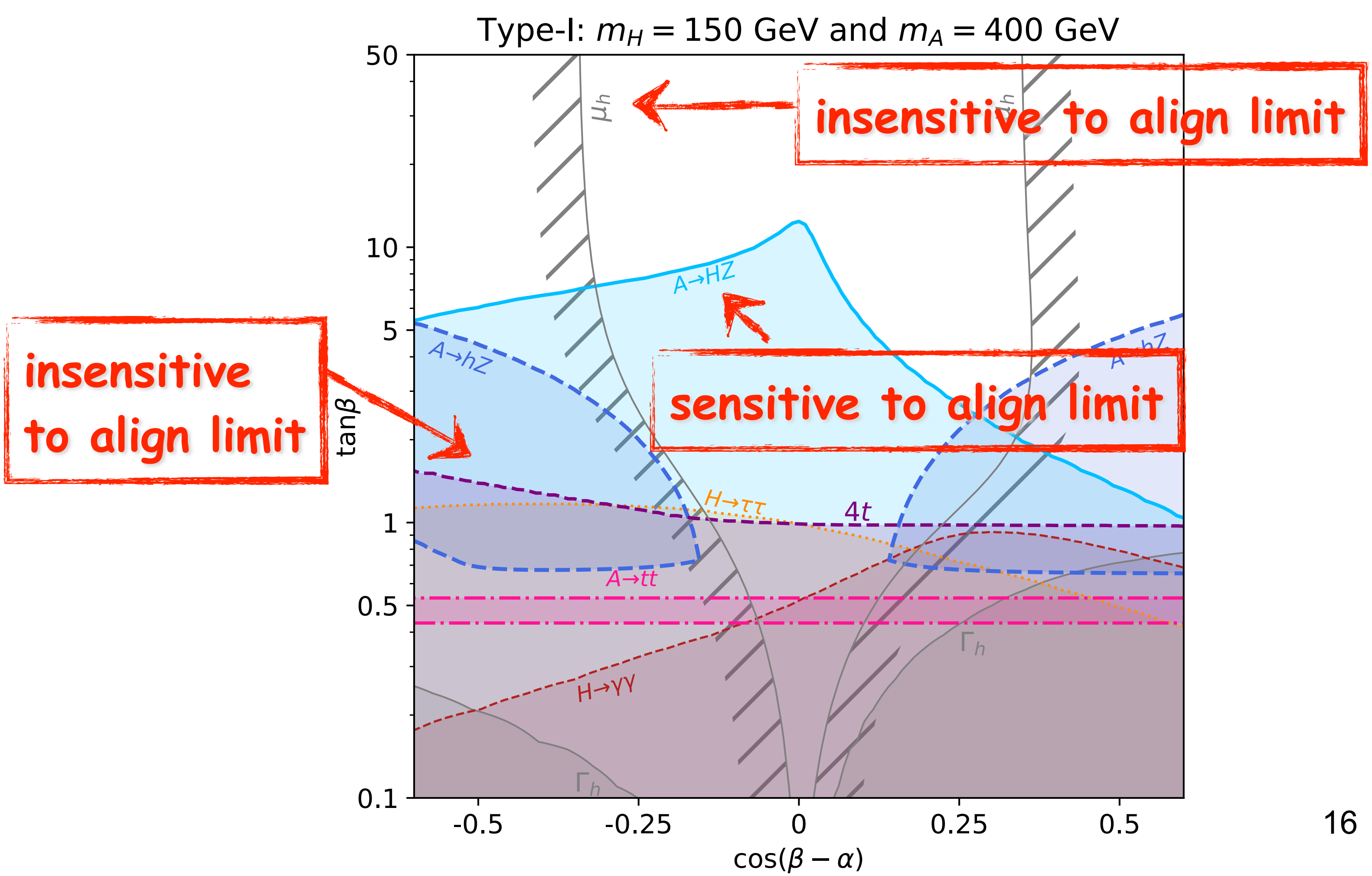
insensitive to align limit

insensitive to align limit

Non-Degenerate Case: Type I

- **Non-degenerate: A→ZH, H→ZA**

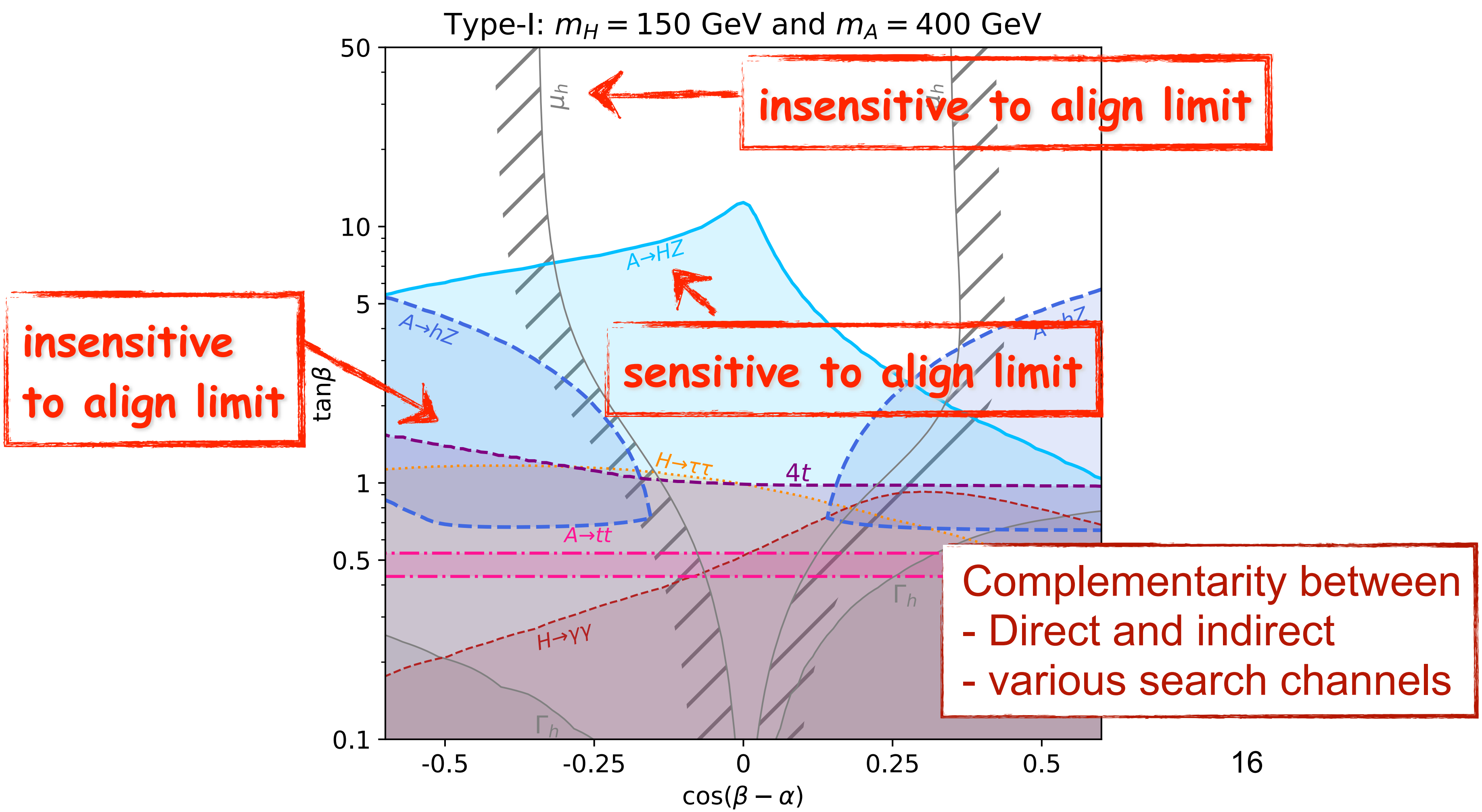
cos(β-α) vs. tanβ



Non-Degenerate Case: Type I

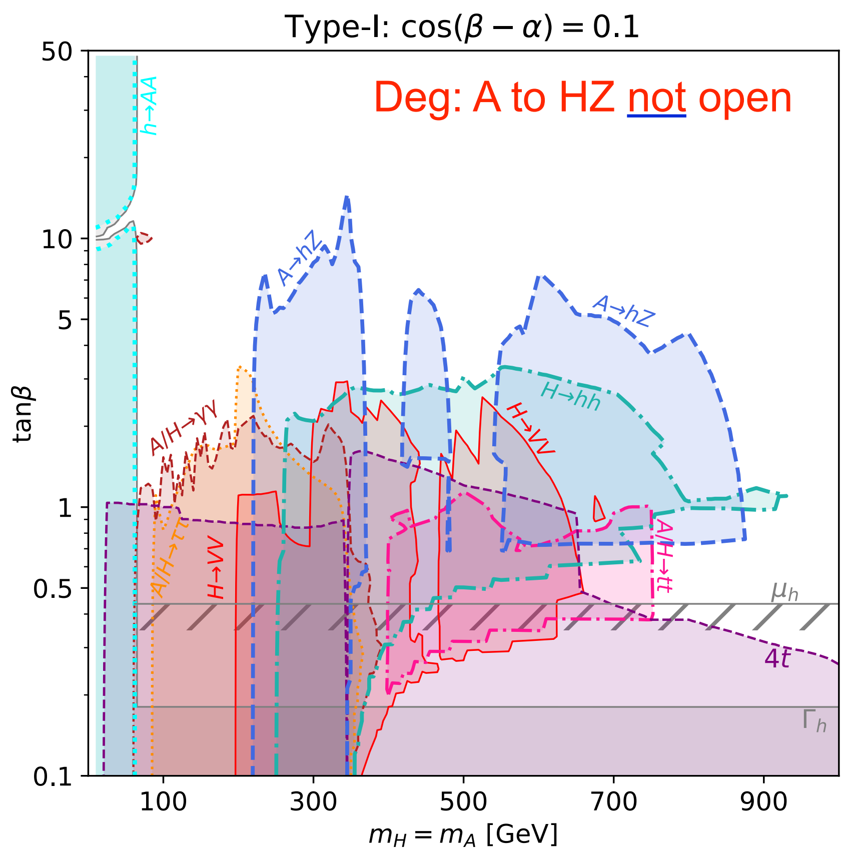
- **Non-degenerate: A→ZH, H→ZA**

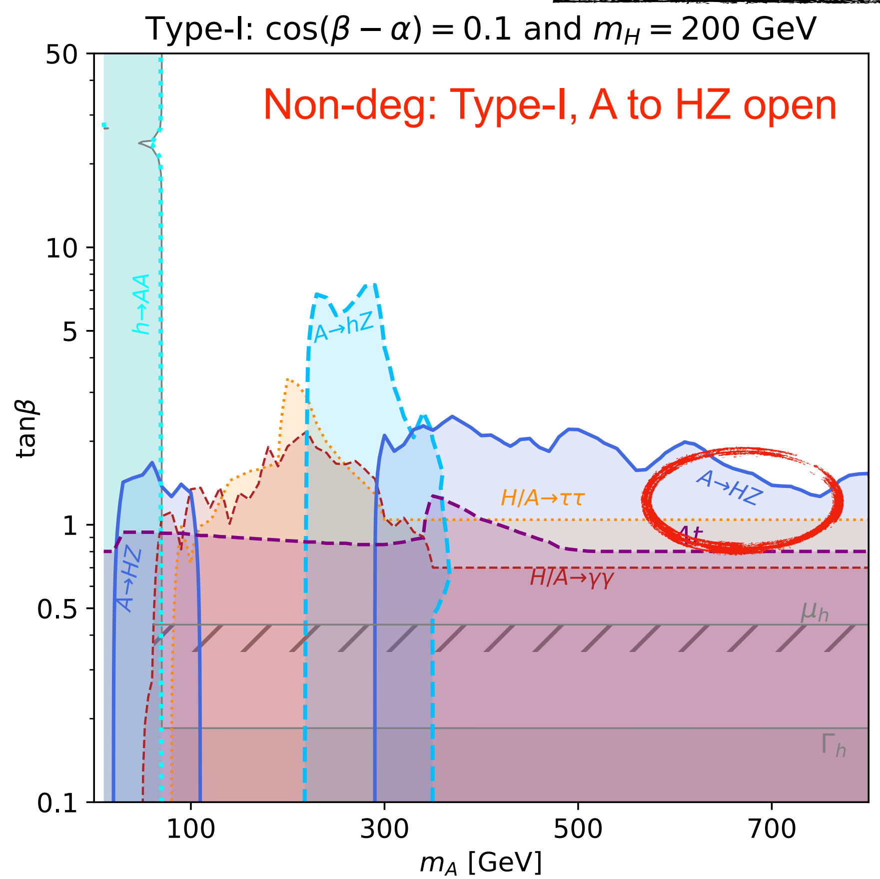
cos(β-α) vs. tanβ



Degenerate vs. non-Deg: Type I

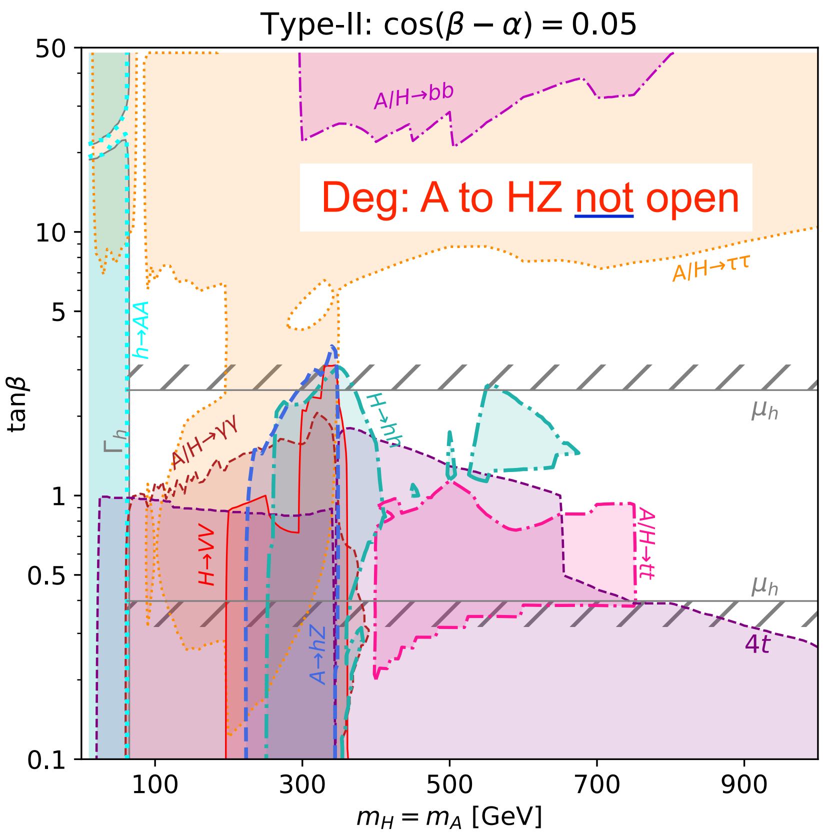
m_A vs. tanβ

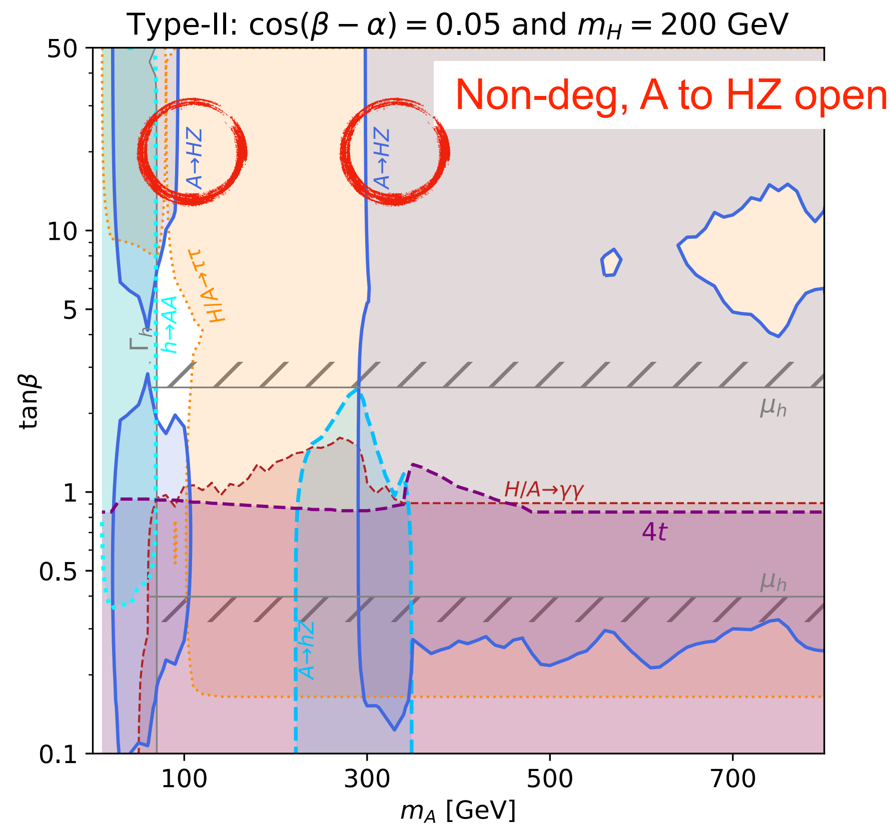




Degenerate vs. non-Deg: Type II

m_A vs. tanβ



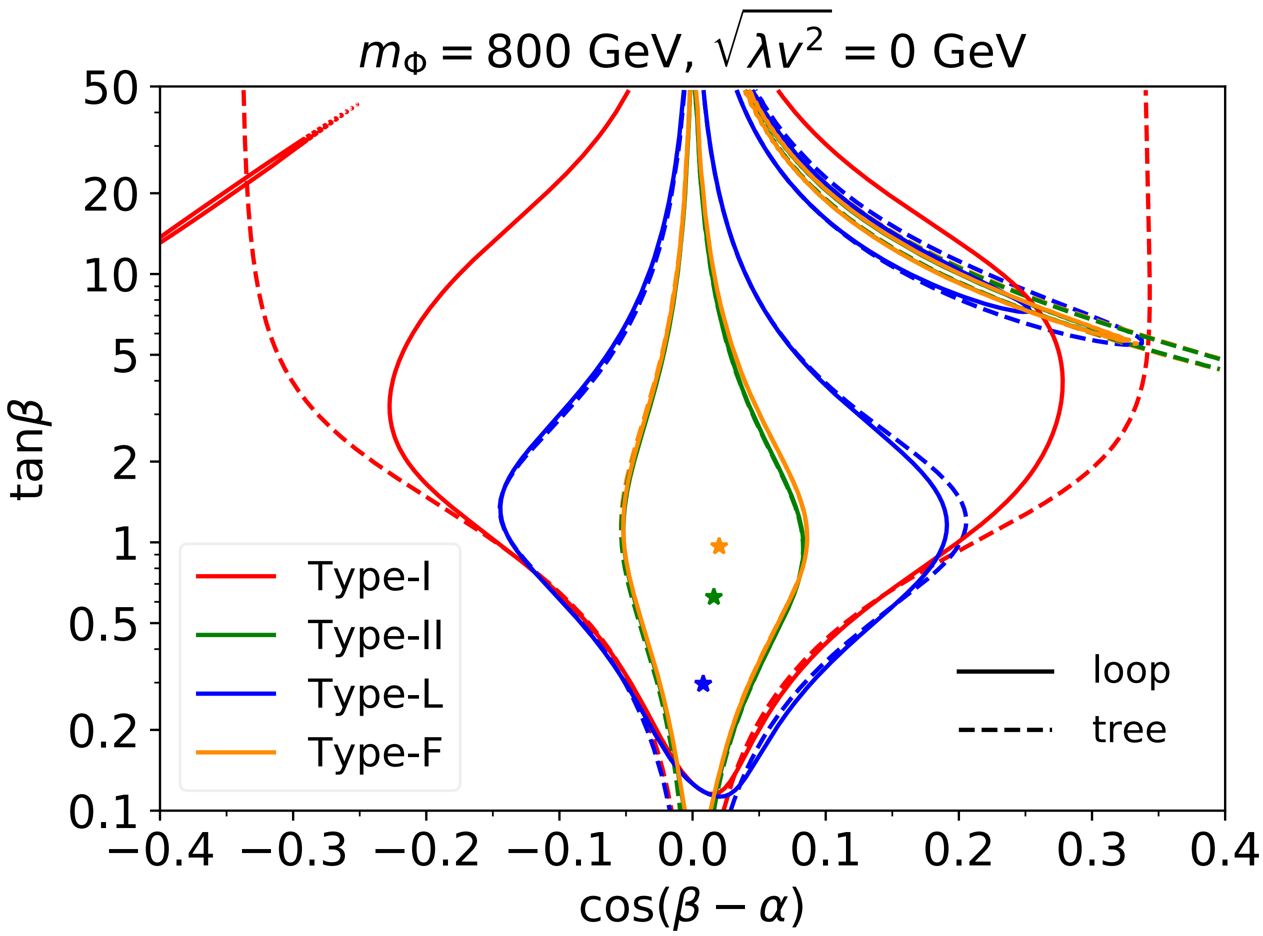


Conclusion

- exotic mode such as $A \to ZH$, $H \to ZA$
  - ➡ once open, dominate
  - ➡ limits from conventional searches relaxed.
  - ➡ offer alternative discovery channels
- theoretical considerations + EW: $\Delta m > 200$ GeV difficult for $m > 1$ TeV
  - ➡ LHC most relevant machine for probing non-degenerate case
- $H/A \to \tau\tau, \gamma\gamma$ most sensitive
- $m_{A/H} \sim 100$ GeV still challenge
- non-resonant search ttZ, tttt relevant
- exotic decay complementary to
  - ➡ Higgs precision: insensitive to alignment limit
  - ➡ $A \to Zh$, $H \to hh$, $H \to VV$: vanish under the alignment limit
- other exotic mode: $H^\pm \to AW/HW$, $A/H \to H^\pm W^\mp$

Backup Slides

Higgs Precision Constraints

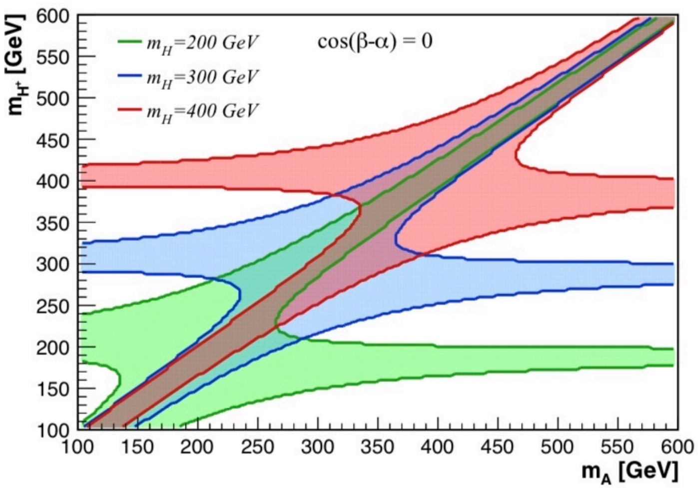


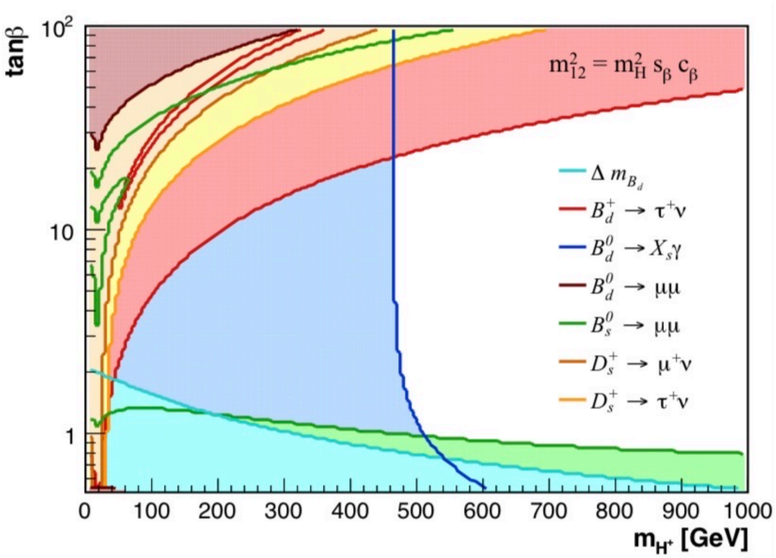
Charged Higgs

- EW precision constraints

  $m_{Hpm} \sim m_H, m_A, m_h$
- direct searches

  $H^\pm \to cs, \tau\nu, tb$
- flavor constraints



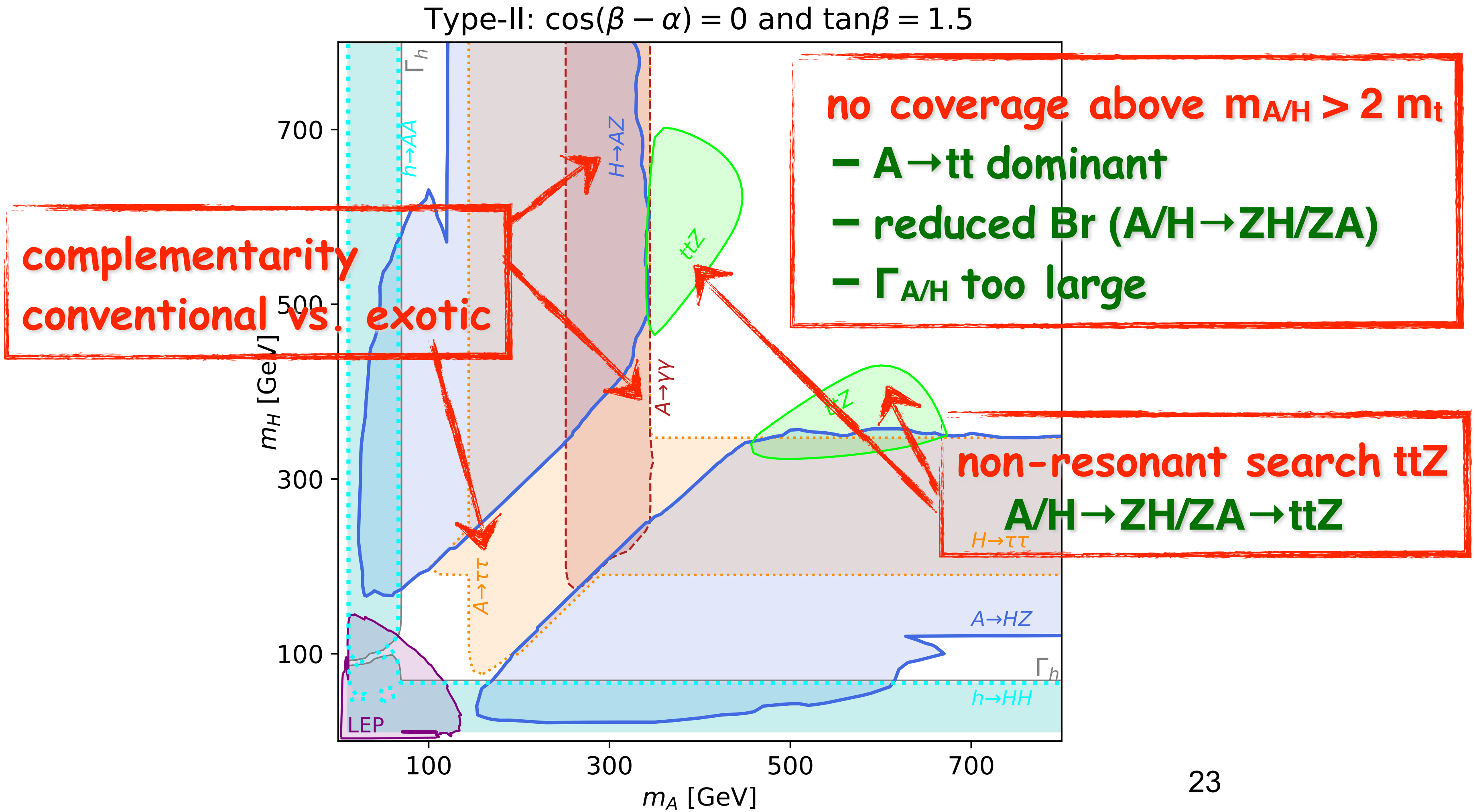


S. Su

Non-Degenerate Case: Type II

- **Non-degenerate: A→ZH, H→ZA**

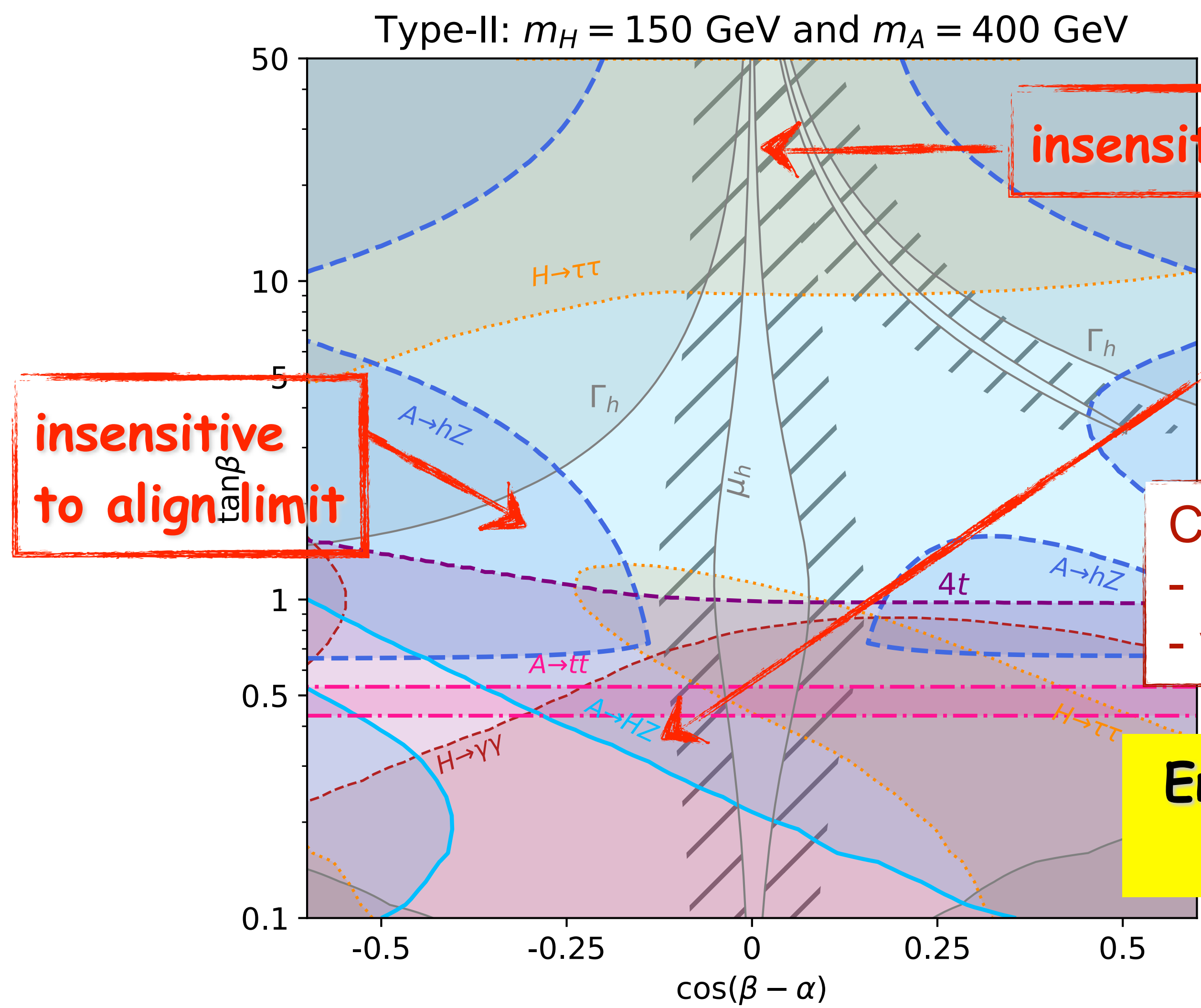
m_A vs. m_H



Non-Degenerate Case: Type II

- Non-degenerate: A→ZH, H→ZA

cos(β-α) vs. tanβ



Complementarity between
- Direct and indirect
- various search channels

Entire parameter region covered!