The 10th China LHC Physics Conference (CLHCP2024), Qingdao

Direct charged and neutral Higgs searches with LHC

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outline

- Brief introduction
- Charged Higgs @ 2HDM
- Neutral Higgs @ 2HDMS scenarios
- Summary

Brief Introduction

- Two Higgs Doublet Model

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

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

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

	Φ_1	Φ_2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

- Parameters (CP-conserving, Flavor Limit, Z_2 Symmetry)

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

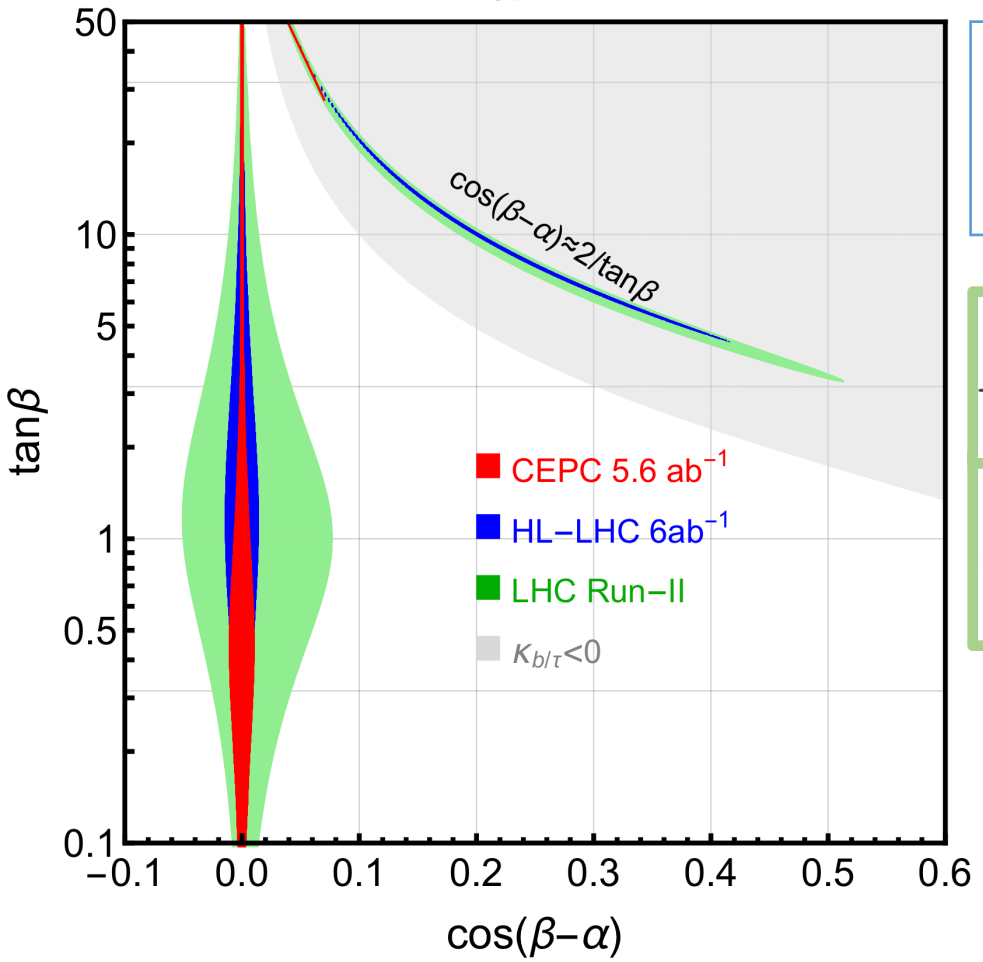
Soft Z_2 symmetry breaking: m_{12}^2

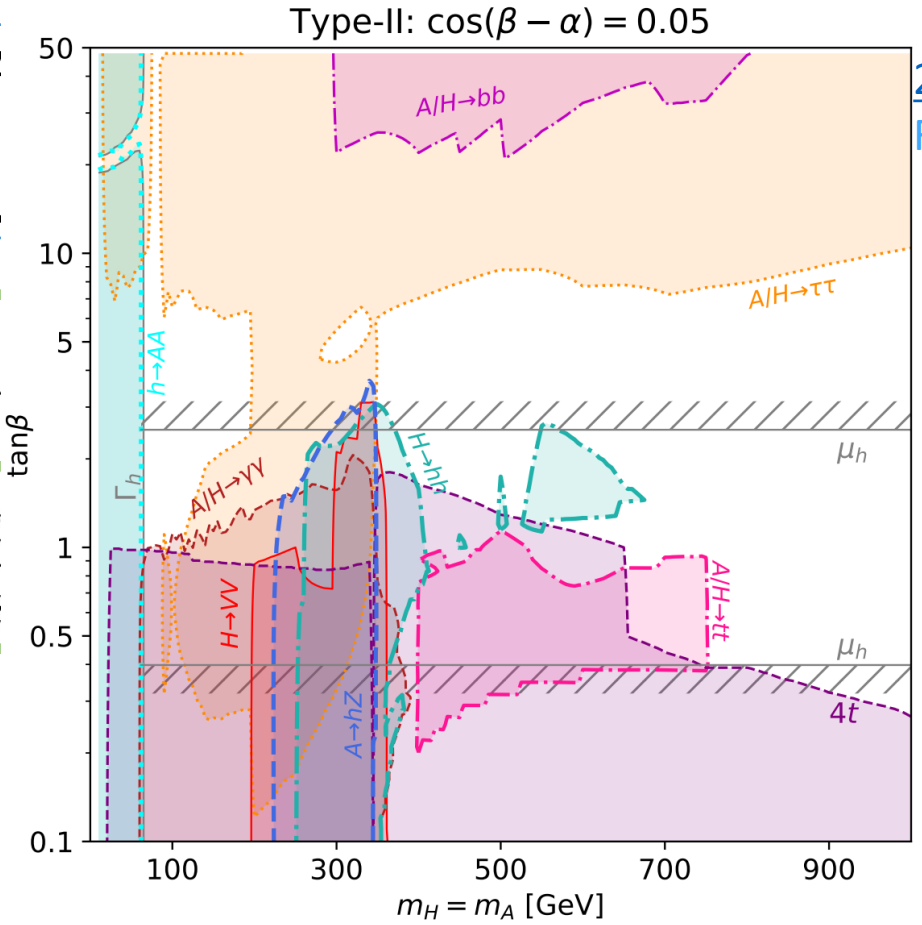
246 GeV 125. GeV

Brief Introduction

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM Type-II





2004.04172
F. Kling, S. Su, WS

$\alpha) \times \tan\beta$

$\alpha)$

Charged Higgs

- LEP search channels : $e^+ e^- \rightarrow H^+ H^-$
- Flavour searches
- LHC search results

  - ❖ light and heavy,
  - ❖ conventional and exotic decays

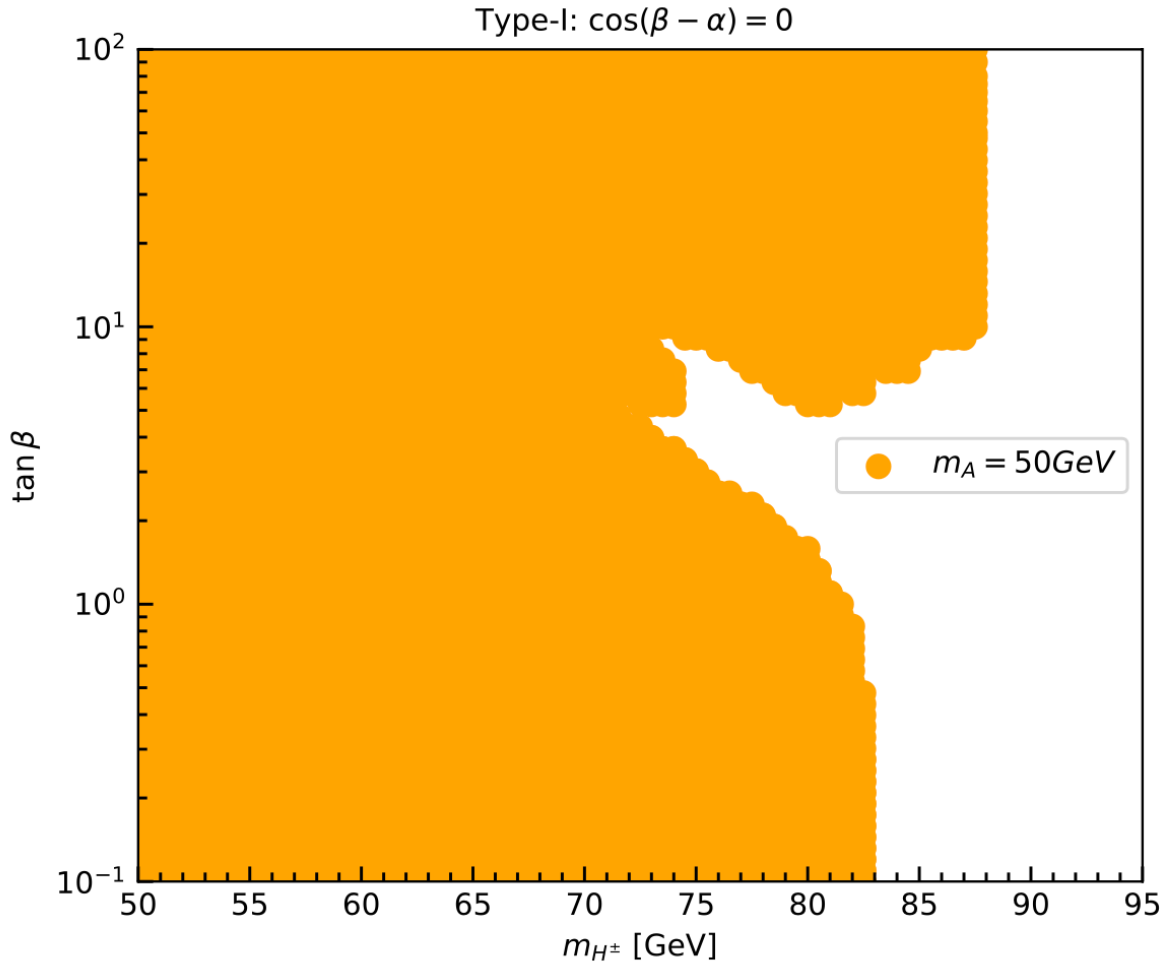
LEP searches: $e^+ e^- \rightarrow H^+ H^-$

$$H^{\pm} \rightarrow \tau\nu$$

$$H^{\pm} \rightarrow cs$$

$$H^{\pm} \rightarrow AW^{\pm}$$

Type-I 2HDM: $m_{H^+} > 87$ GeV

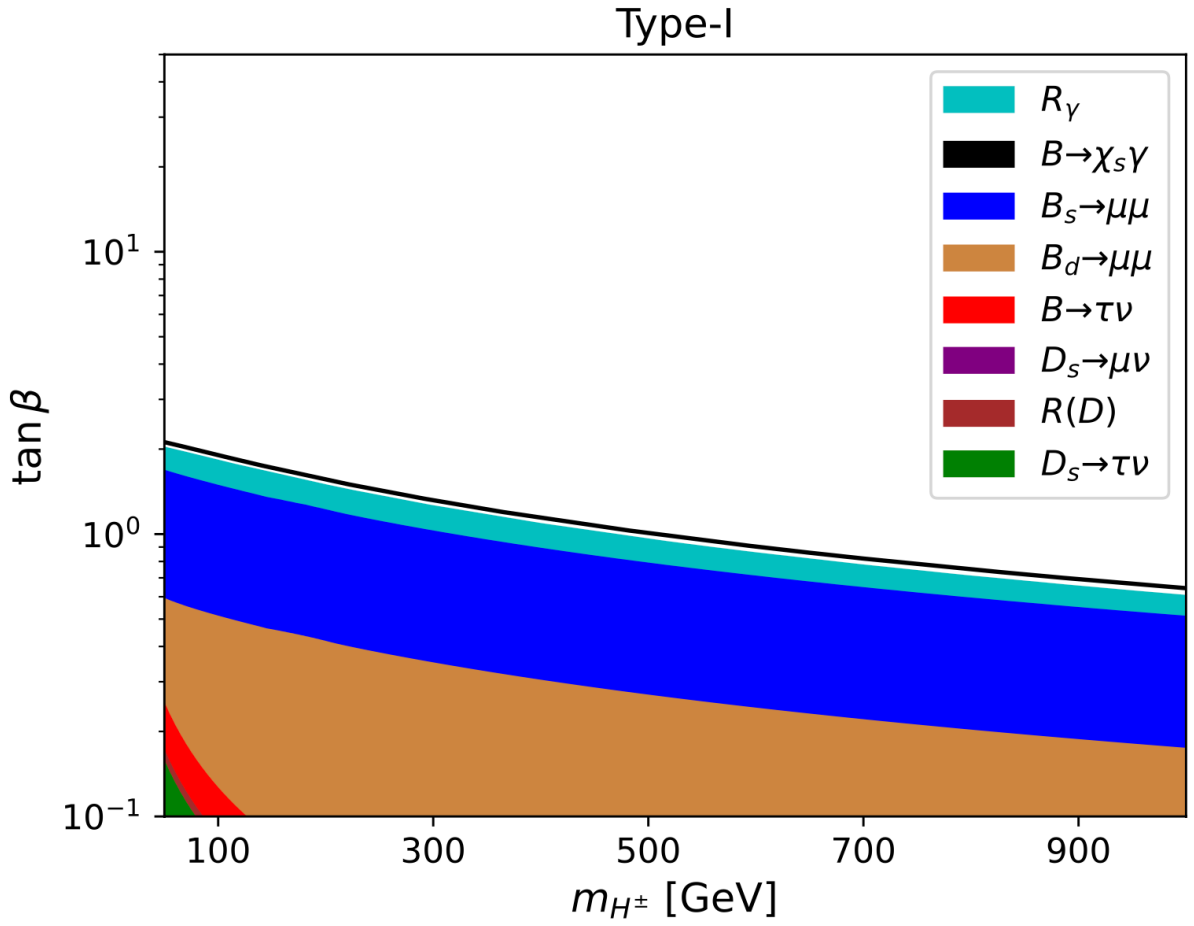


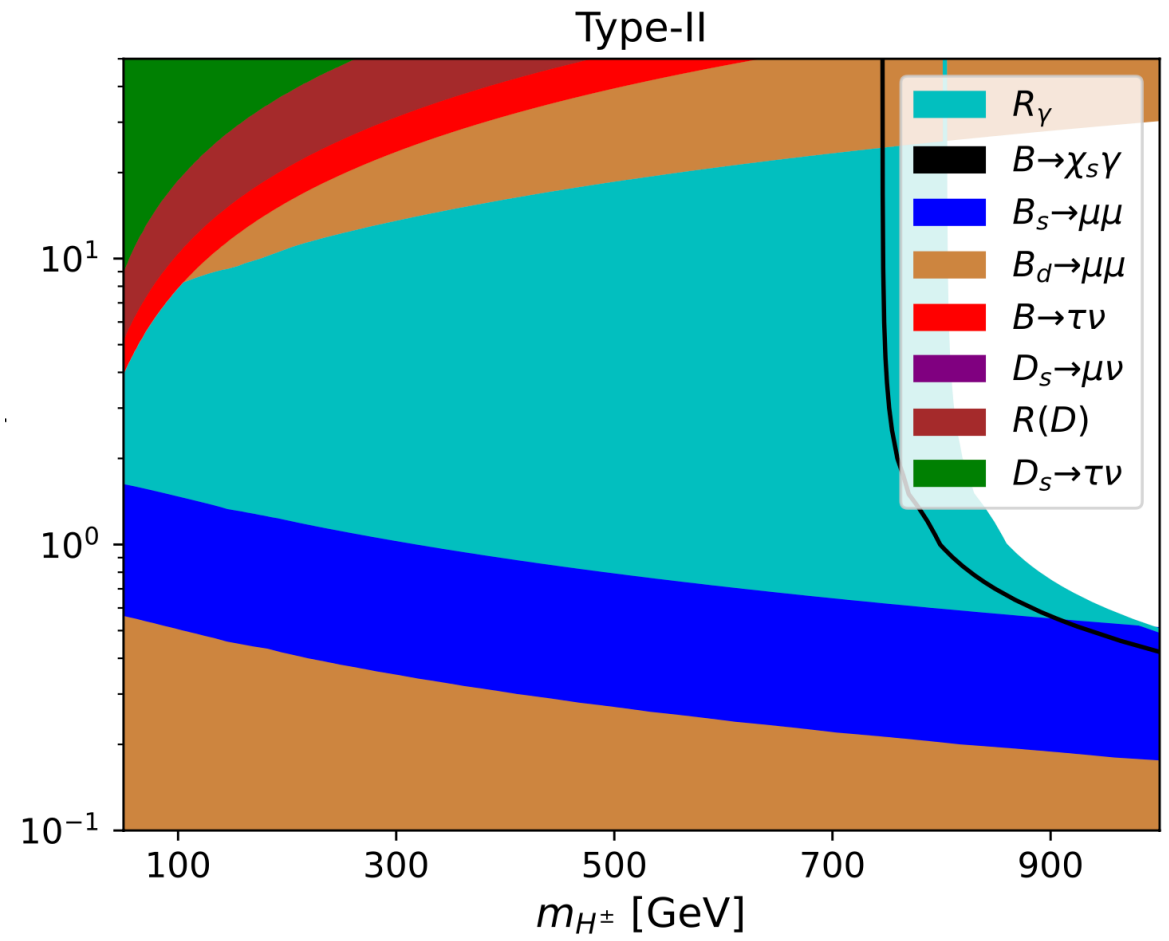
Flavour searches

Observable	Experimental result	SM prediction
R_γ	$(3.22 \pm 0.15) \times 10^{-3}$ [69]	$(3.35 \pm 0.16) \times 10^{-3}$ [70]
$BR(B \to \chi_s \gamma)$	$(3.32 \pm 0.15) \times 10^{-4}$ [15]	$(3.40 \pm 0.17) \times 10^{-4}$ [70]
$BR(B \to \tau\nu)$	$(1.09 \pm 0.24) \times 10^{-4}$ [16]	$(9.24 \pm 11.3) \times 10^{-5}$
$BR(B_s \to \mu^+\mu^-)$	$(2.93 \pm 0.35) \times 10^{-9}$ [16]	$(3.48 \pm 0.26) \times 10^{-9}$
$BR(B_d \to \mu^+\mu^-)$	$(3.9 \pm 1.5) \times 10^{-10}$ [17]	$(1.08 \pm 0.13) \times 10^{-10}$
$BR(D_s \to \tau\nu)$	$(5.48 \pm 0.23) \times 10^{-2}$ [16]	$(5.22 \pm 0.04) \times 10^{-2}$
$BR(D_s \to \mu\nu)$	$(5.49 \pm 0.16) \times 10^{-3}$ [16]	$(5.31 \pm 0.04) \times 10^{-3}$
$R(D)$	(0.34 ± 0.03) [15]	(0.303 ± 0.006)

Table 4. Experimental results for certain flavor physics observables and their corresponding SM values.

Flavour searches





LHC search results

- ❖ light and heavy,
- ❖ conventional and exotic decays

mass	channel	ATLAS	CMS
		13TeV	13TeV
$m_{H^\pm} < m_t$	$H^\pm \to AW \to W\mu\mu$	[53]	[52]
$m_{H^\pm} > m_t$	$H^\pm \to HW \to W\tau\tau$	-	[54]

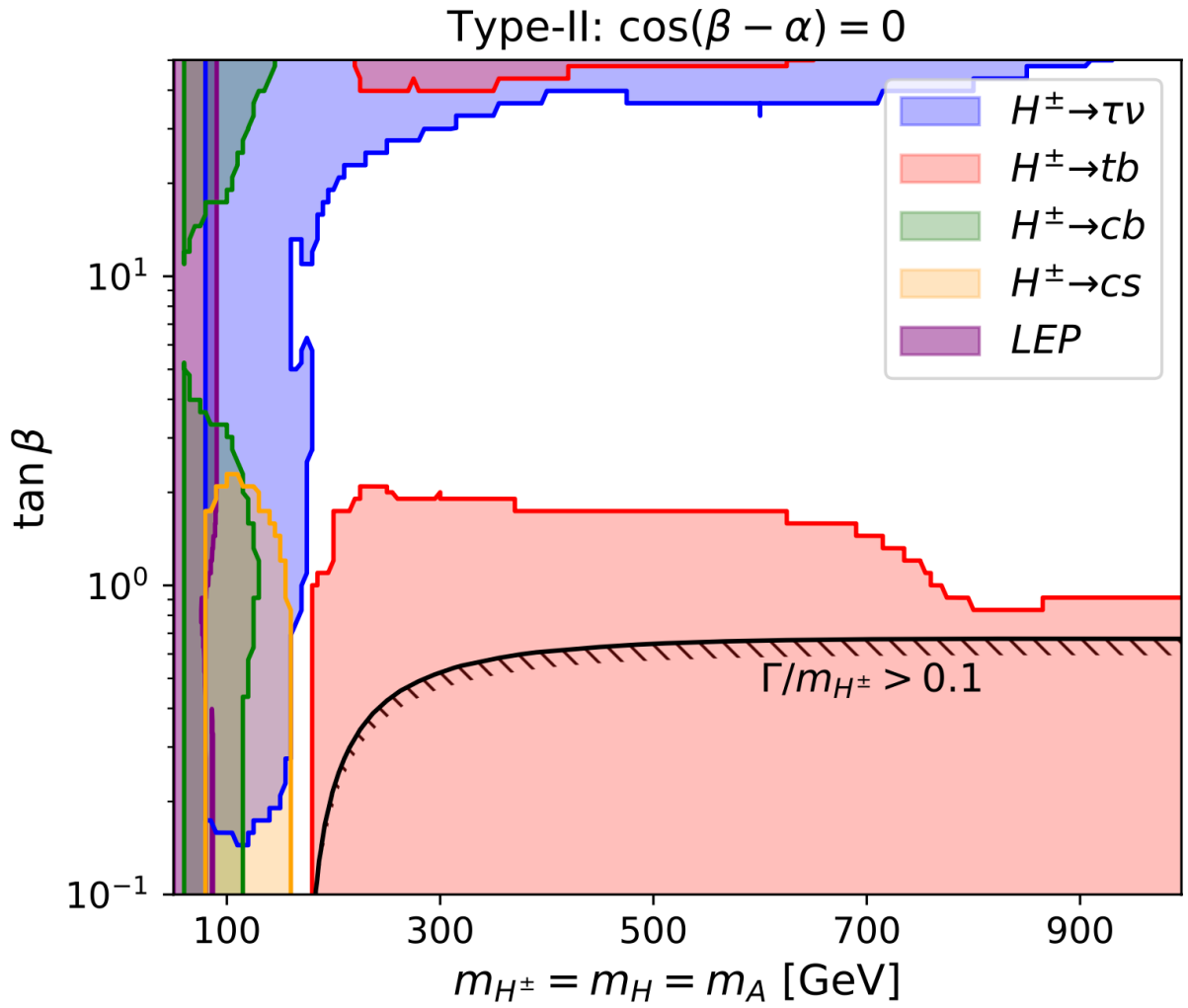
Table 3. Charged Higgs searches with $H^\pm \to HW/AW$ at LHC.

channel	ATLAS			CMS		
	7TeV	8TeV	13TeV	7TeV	8TeV	13TeV
$H^\pm \to \tau\nu$	[30, 31]	[32]	[33, 34]	[35]	[36–38]	[39, 40]
$H^\pm \to cs$	[41]	-	-	-	[42]	[43]
$H^\pm \to cb$	-	-	[44]	-	[45]	-
$pp \to tbH^\pm \to ttbb$	-	[46]	[47, 48]	-	[38, 49]	[50, 51]

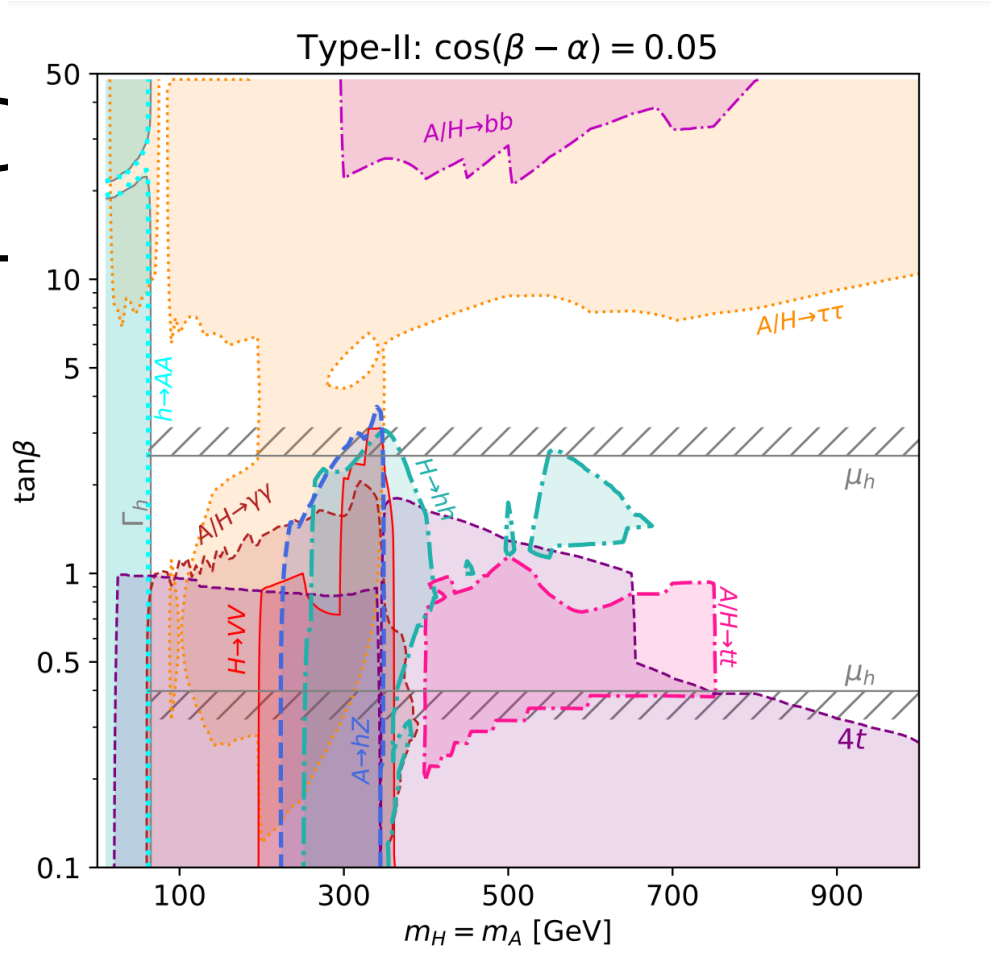
Table 2. Charged Higgs searches with $H^\pm \to ff'$ at LHC.

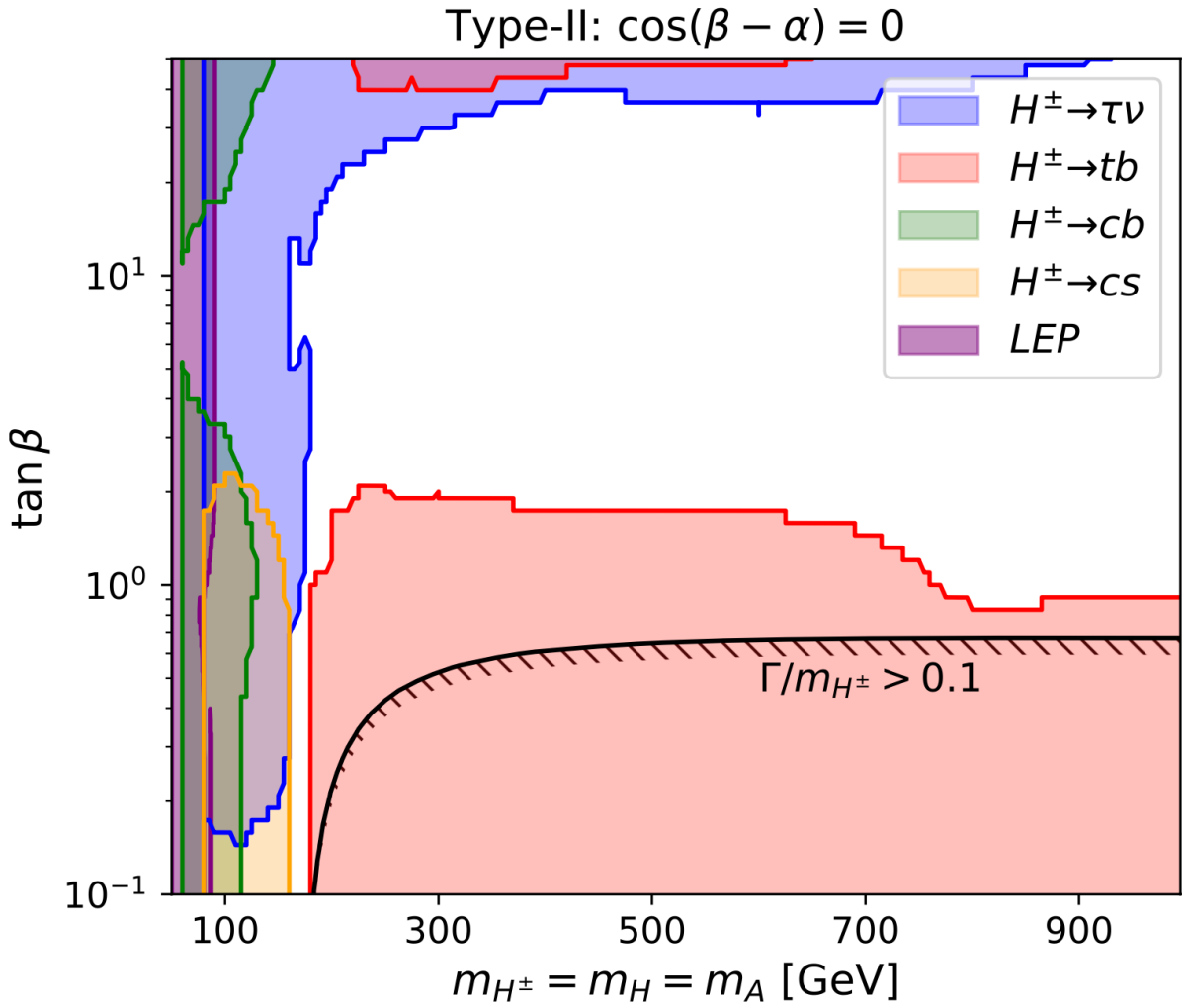
LHC search results

Degenerate Higgs masses

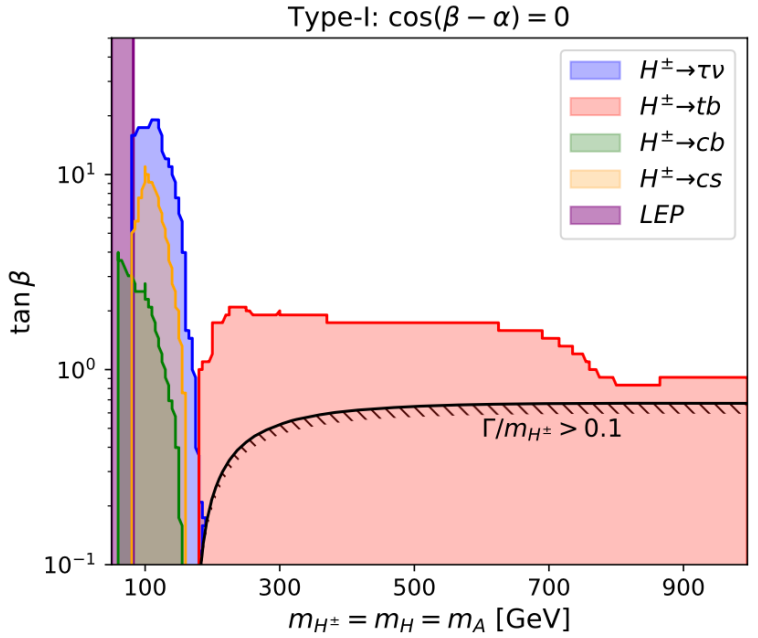


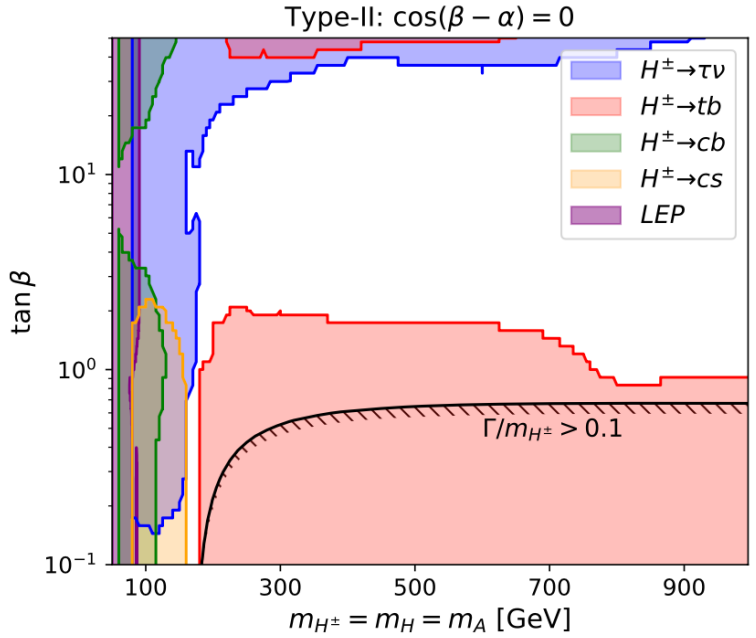
LHC search results

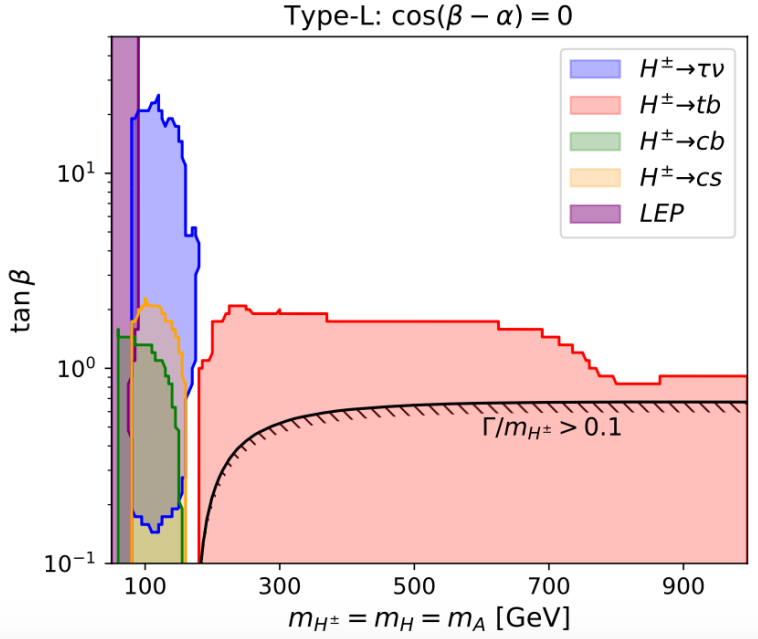


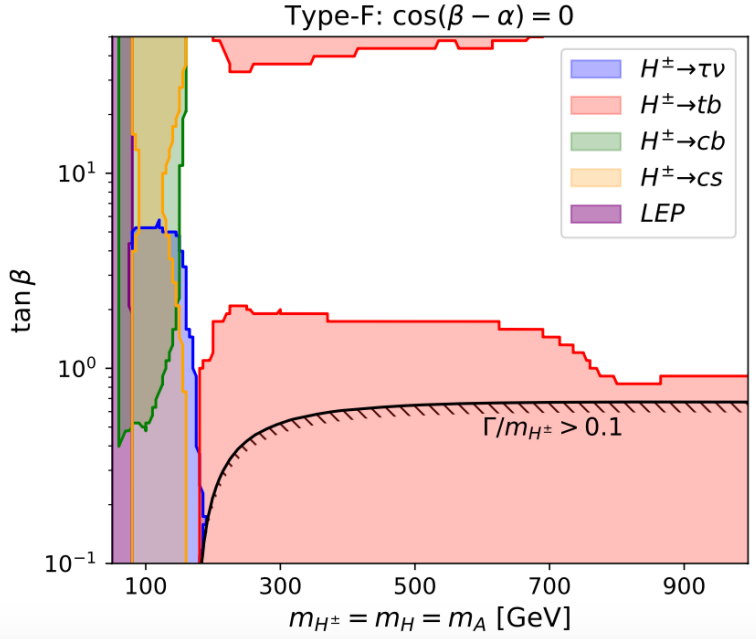


Degenerate Higgs masses





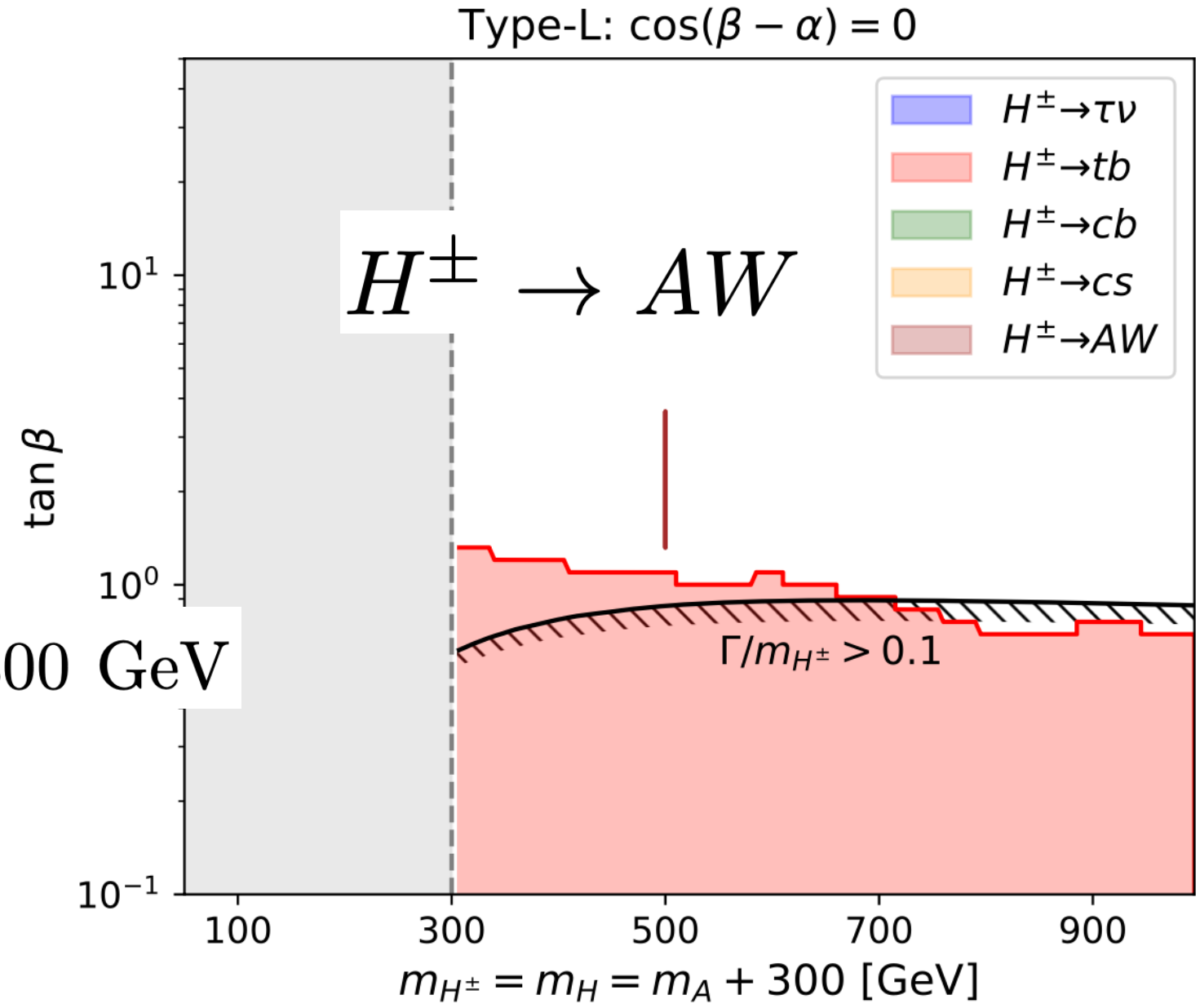




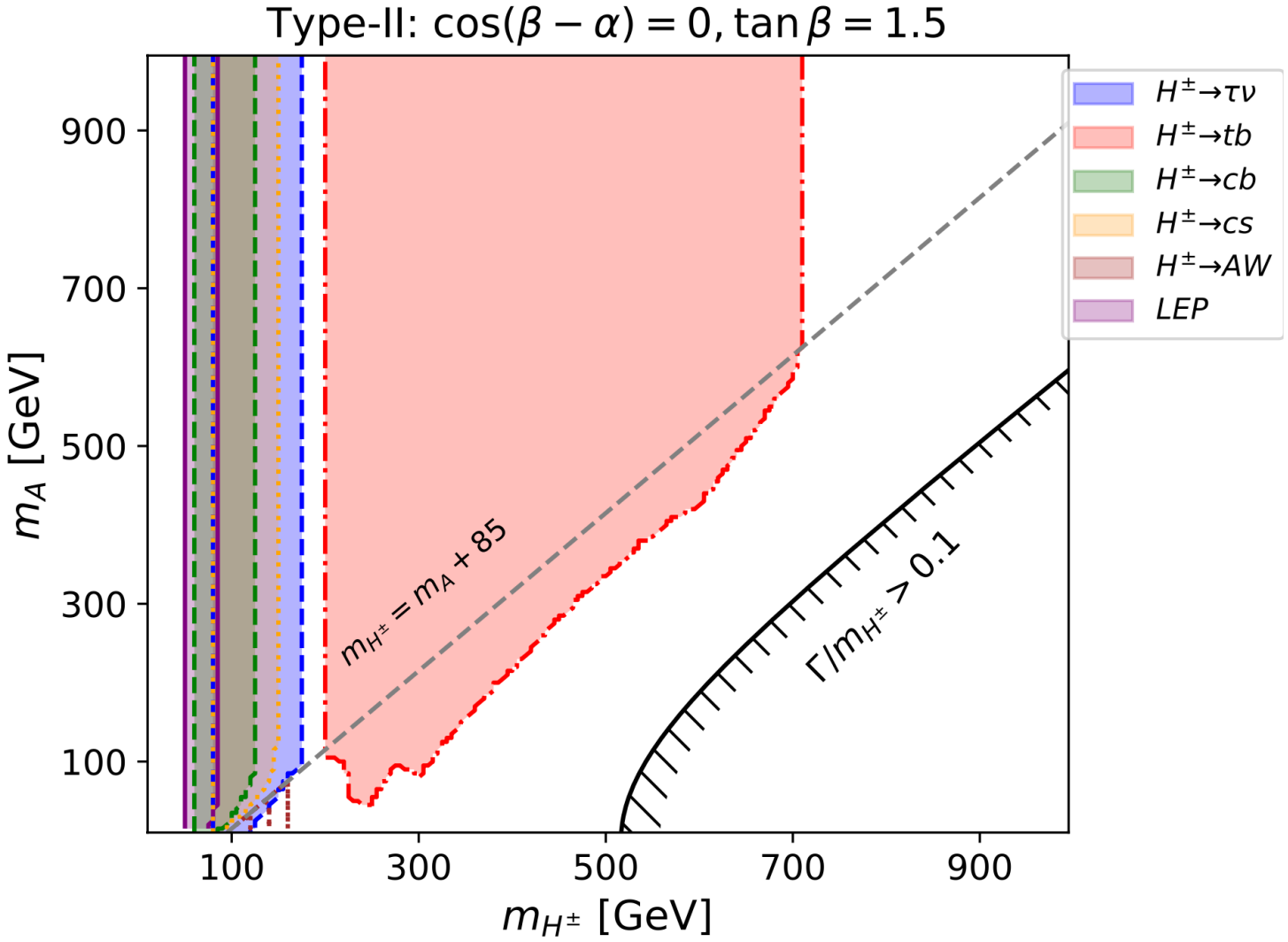
Non-Degenerate Higgs masses

$$m_{H^\pm} = m_H$$

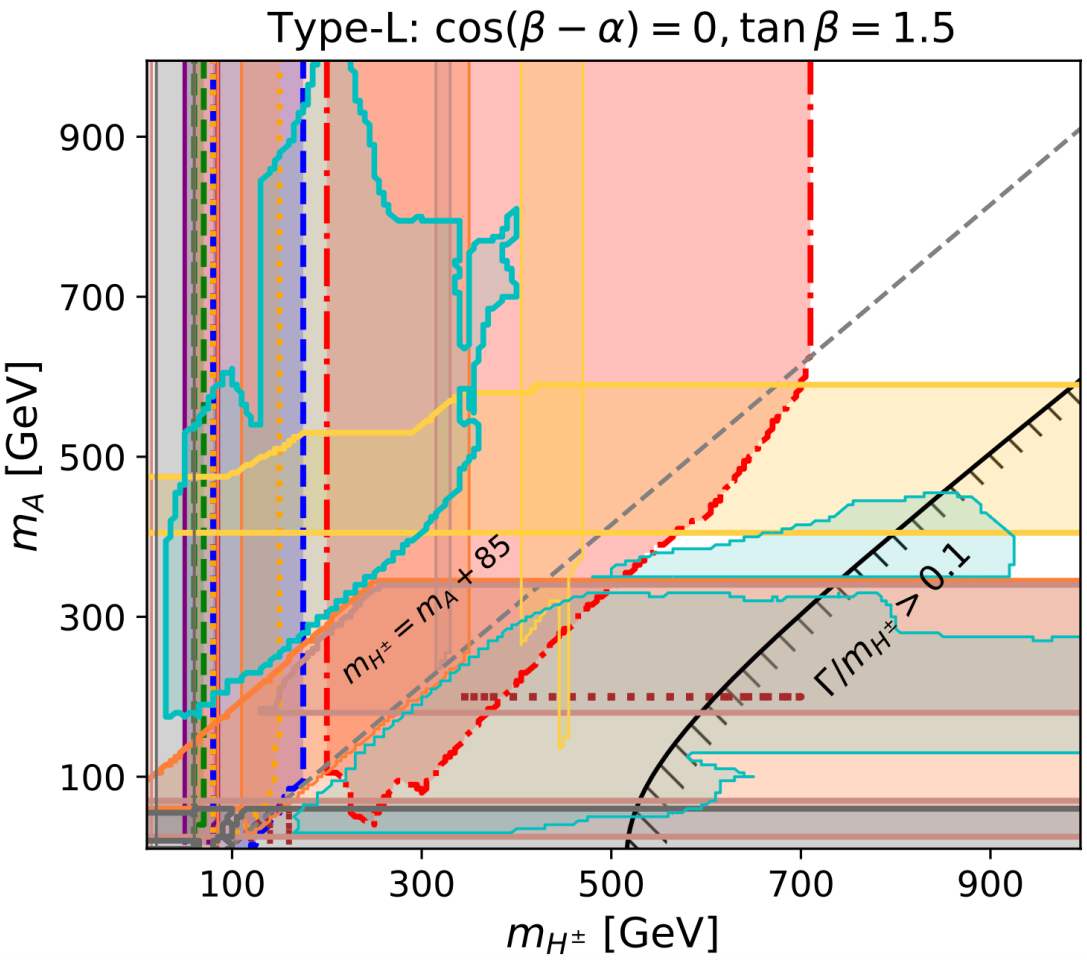
$$\Delta m_A = m_{H^\pm} - m_A = 300 \text{ GeV}$$

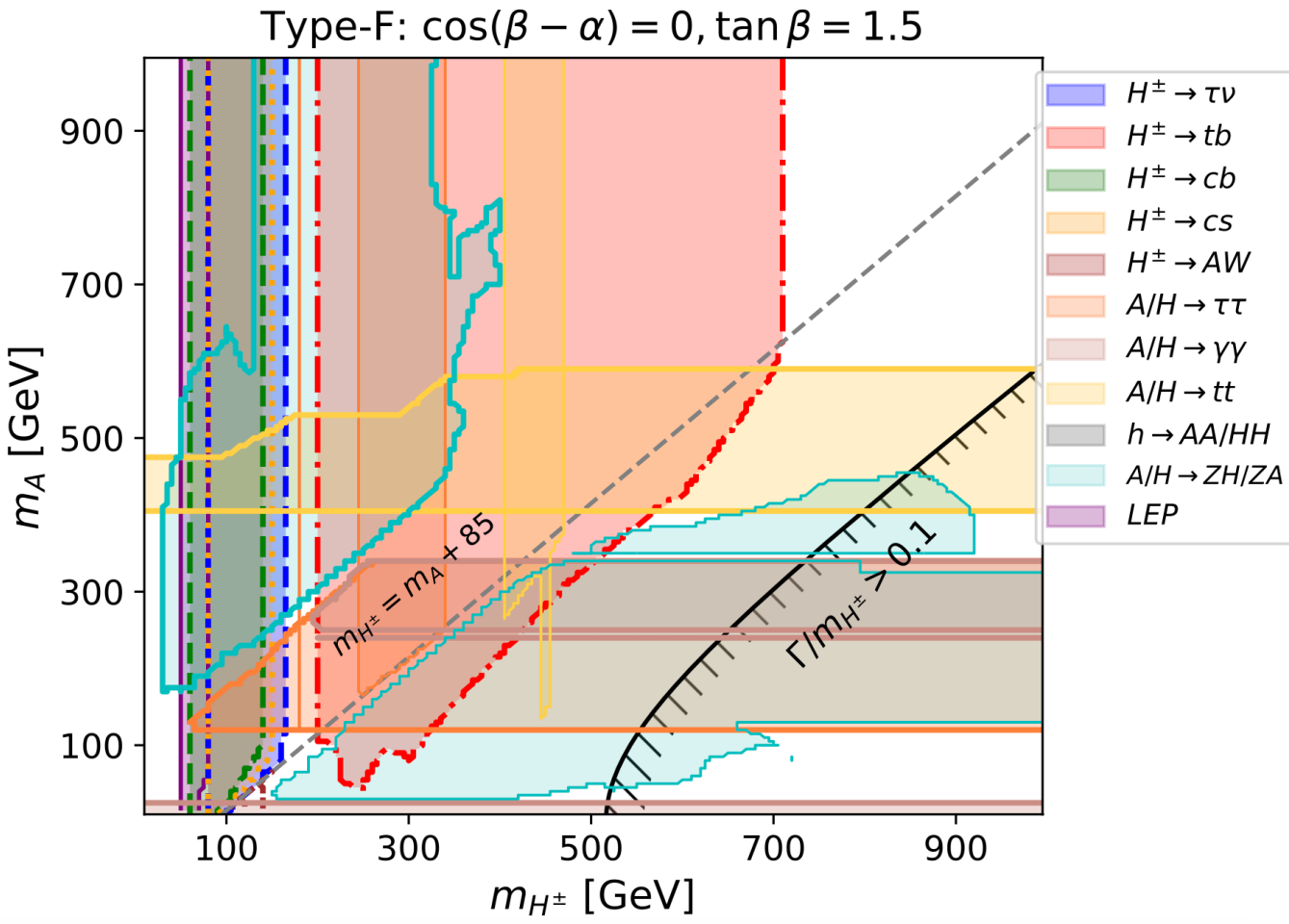


Non-Degenerate Higgs masses

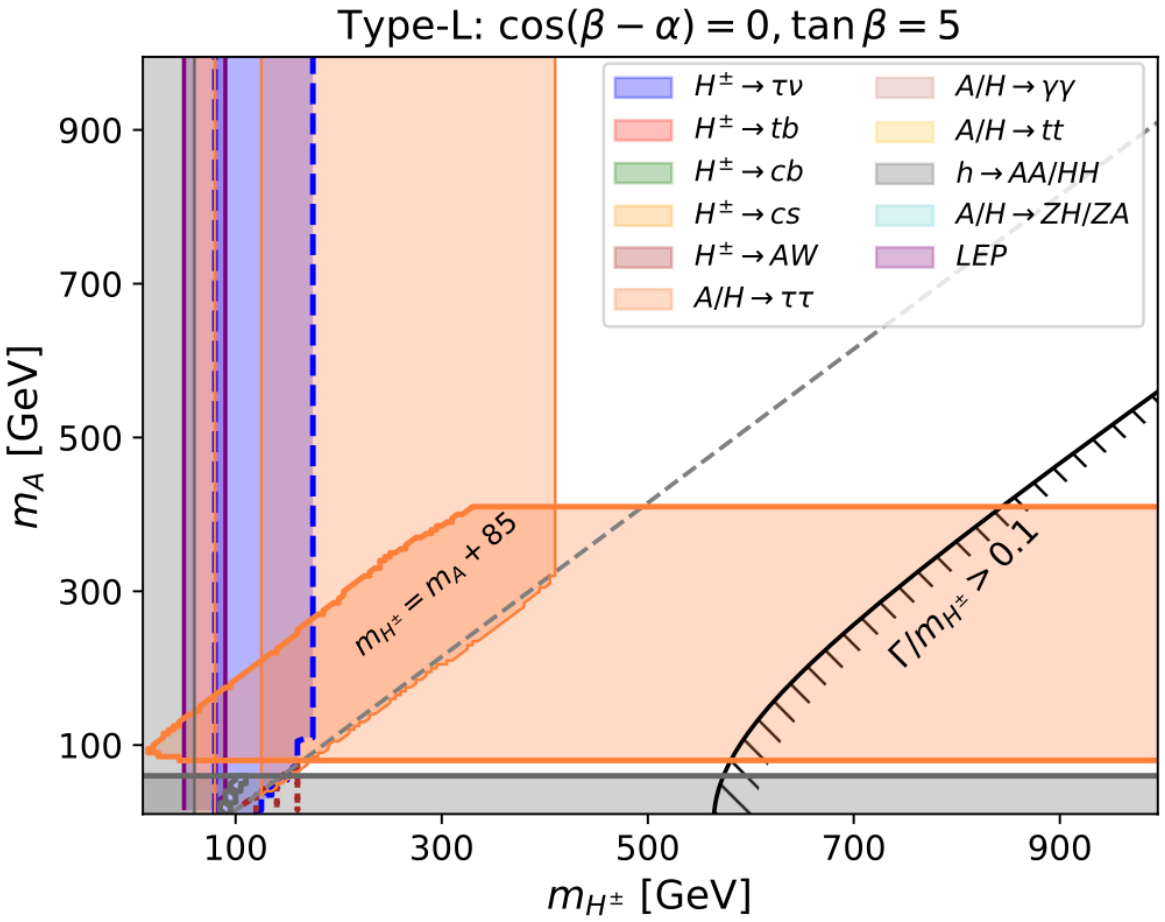


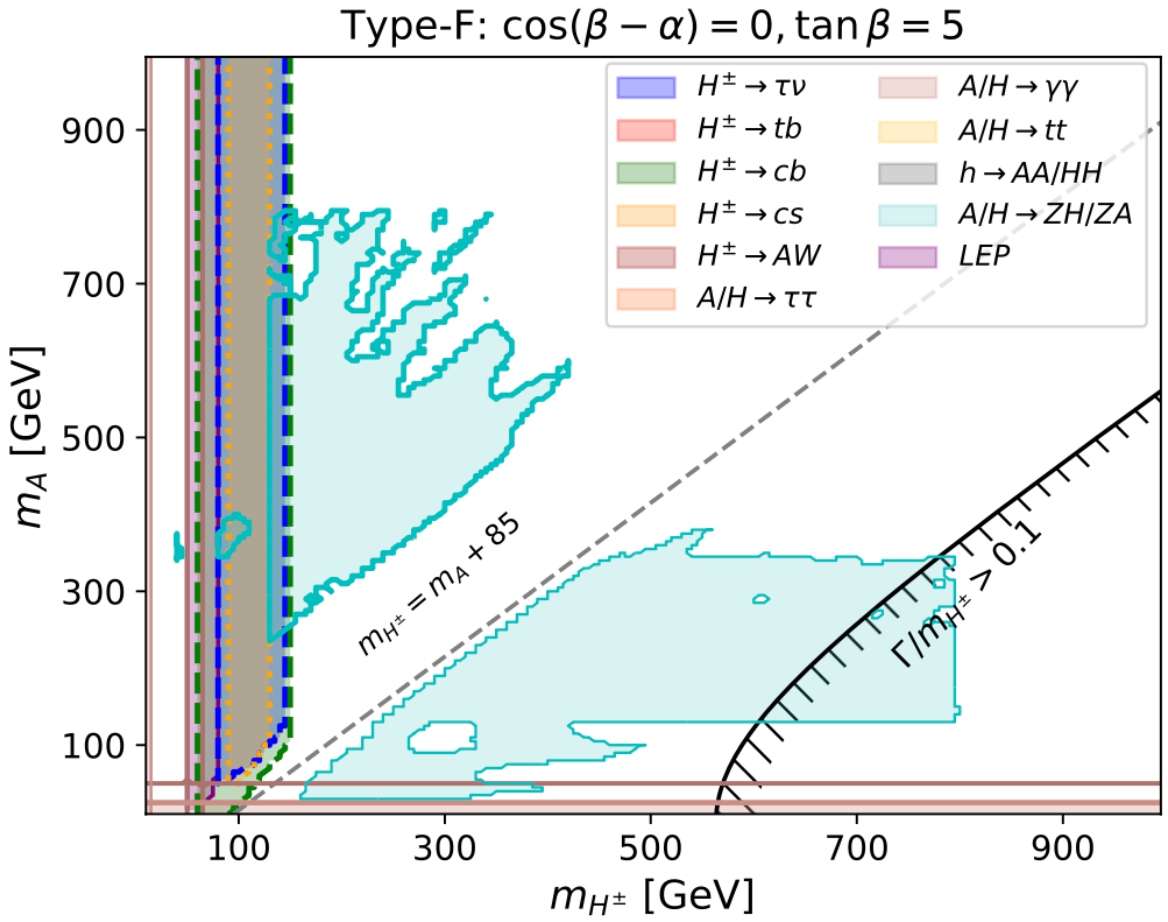
Non-Degenerate Higgs masses



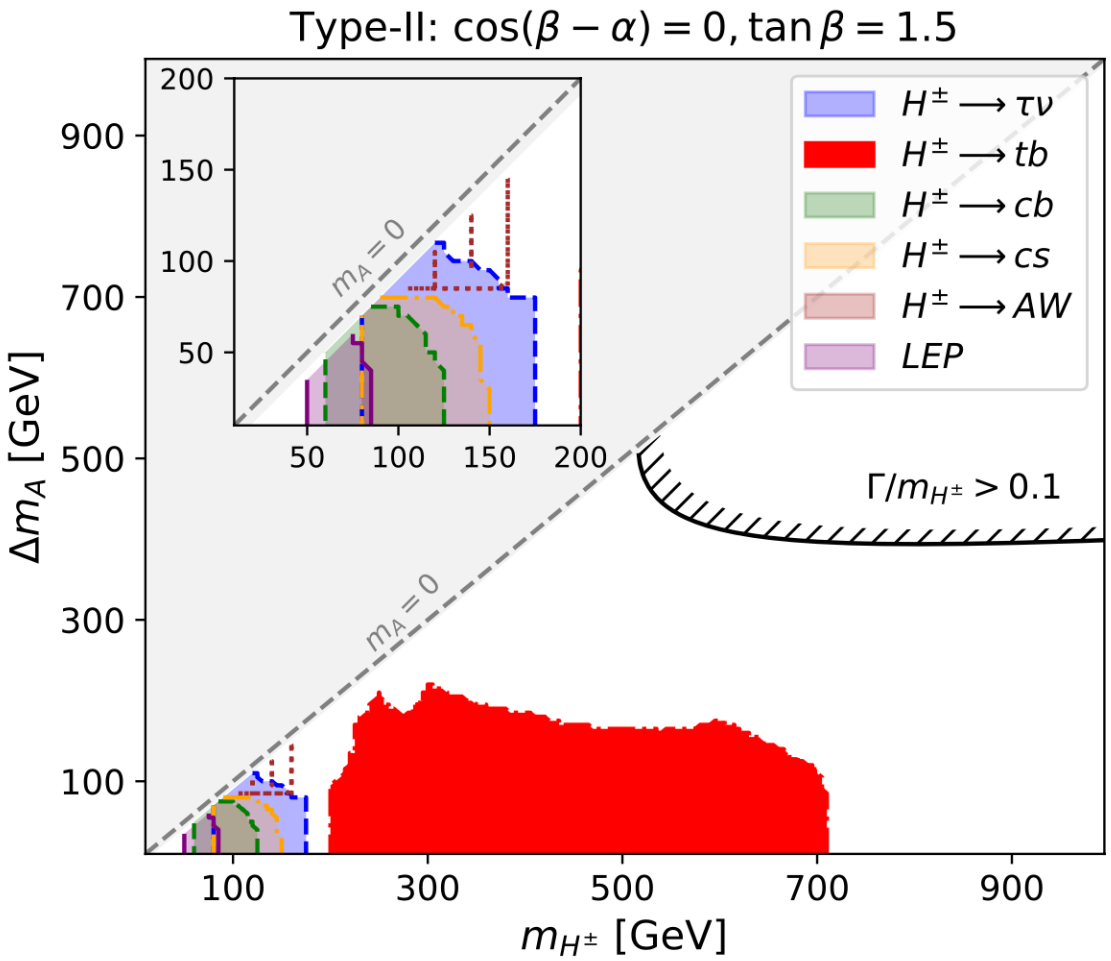


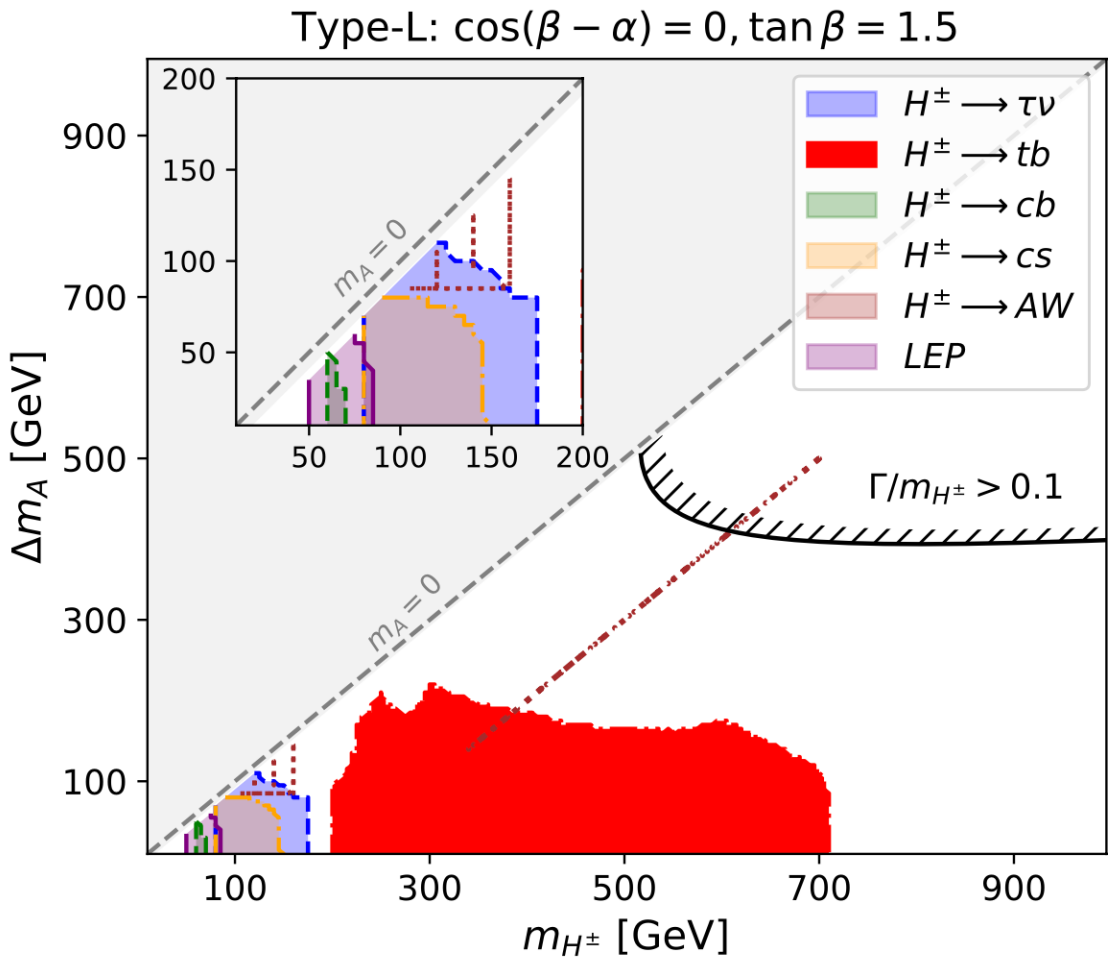
Non-Degenerate Higgs masses





Non-Degenerate Higgs masses





2HDM+singlet

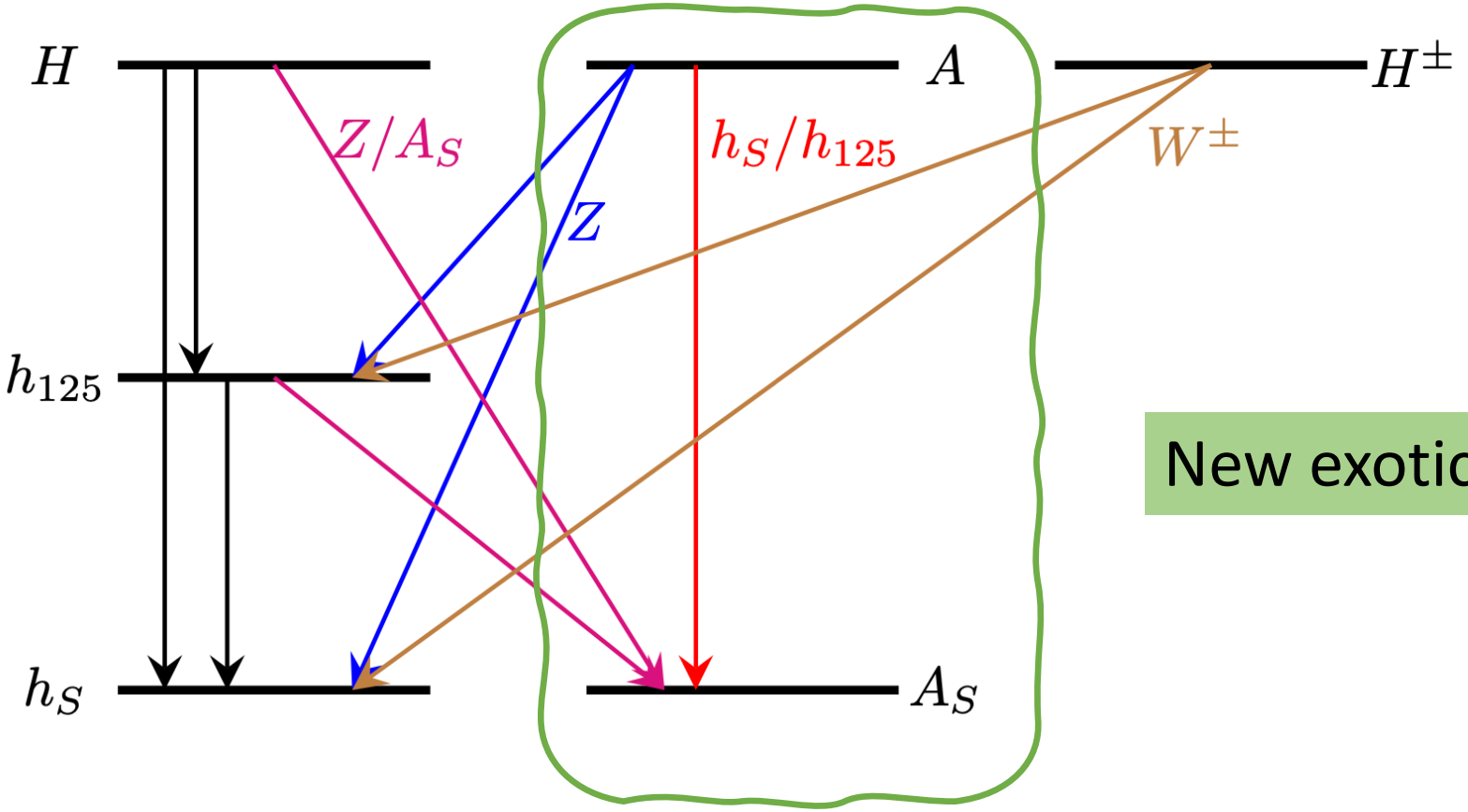
$$
\begin{aligned}
V = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\
& + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} \left((\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right) \\
& + m_S^2 S^\dagger S + \frac{m_S'^2}{2} (S^2 + \text{h.c.}) + \left(\frac{\mu_{S1}}{3!} S^3 + \mu_{12} S \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) \\
& + S^\dagger S \left(\lambda_1' (\Phi_1^\dagger \Phi_1) + \lambda_2' (\Phi_2^\dagger \Phi_2) \right) + \left[S^2 \left(\lambda_4' (\Phi_1^\dagger \Phi_1) + \lambda_5' (\Phi_2^\dagger \Phi_2) \right) + \text{h.c.} \right] \\
& + \left(\frac{\lambda_1''}{4!} S^4 + \frac{\lambda_2''}{3!} S^2 (S^\dagger S) + \text{h.c.} \right) + \frac{\lambda_3''}{4} (S^\dagger S)^2 .
\end{aligned}
$$

Models	Symmetries	
$\mathbb{Z}_2'$[11]	$S \to -S$	$\mu_{S1} = \mu_{12} = 0$
U(1)[17]	$S \to e^{i\delta} S$	$\lambda_1'' = \lambda_2'' = \lambda_4' = \lambda_5' = \mu_{S1} = \mu_{12} = 0$
$\mathbb{Z}_3$[18]	$\Phi_2 \to e^{i2\pi/3} \Phi_2, \ S \to e^{-2i\pi/3} S$	$\lambda_5 = m_S' = \lambda_1'' = \lambda_2'' = \lambda_4' = \lambda_5' = 0$

Table 1. Matching conditions to various singlet extended 2HDM

2HDM+singlet

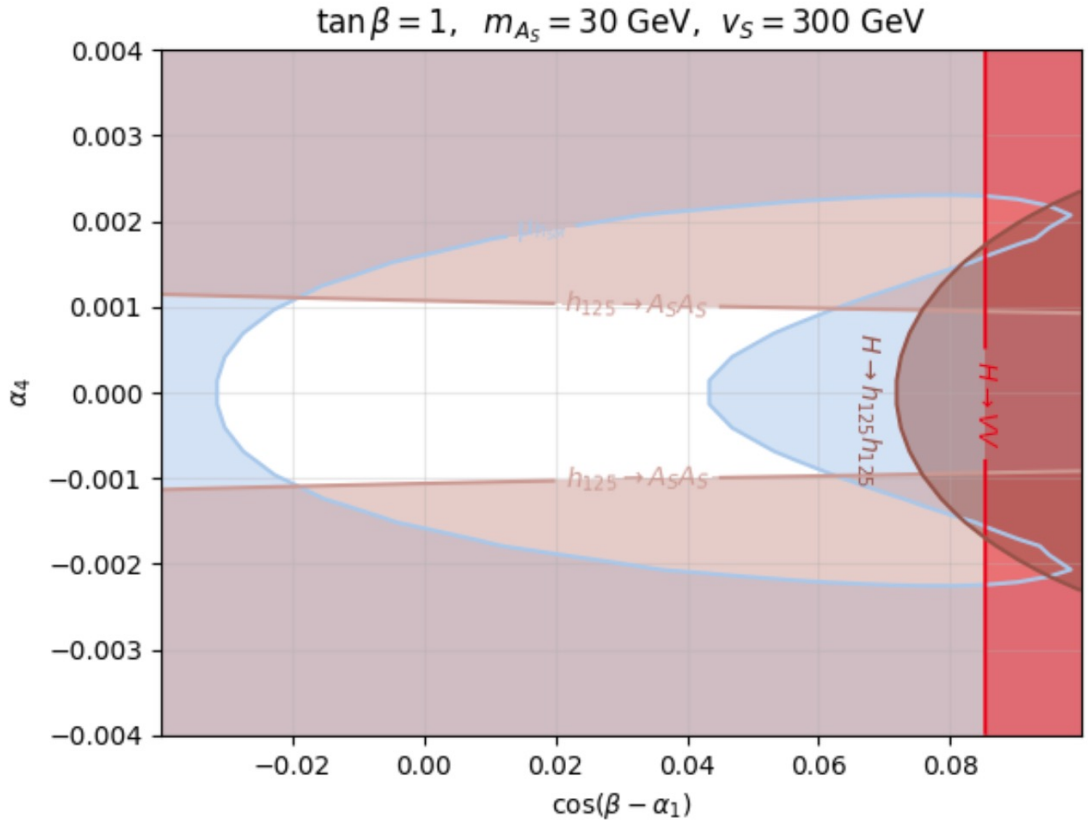
- The scenario with lighter singlet Higgs

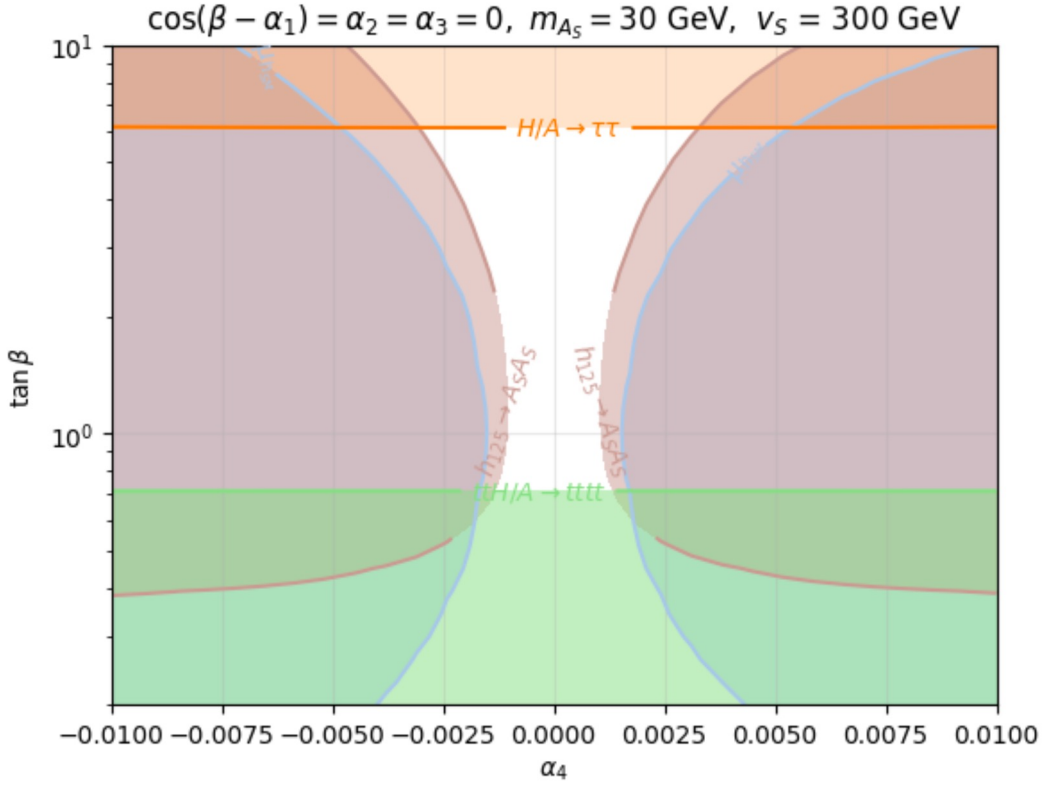


New exotic channels

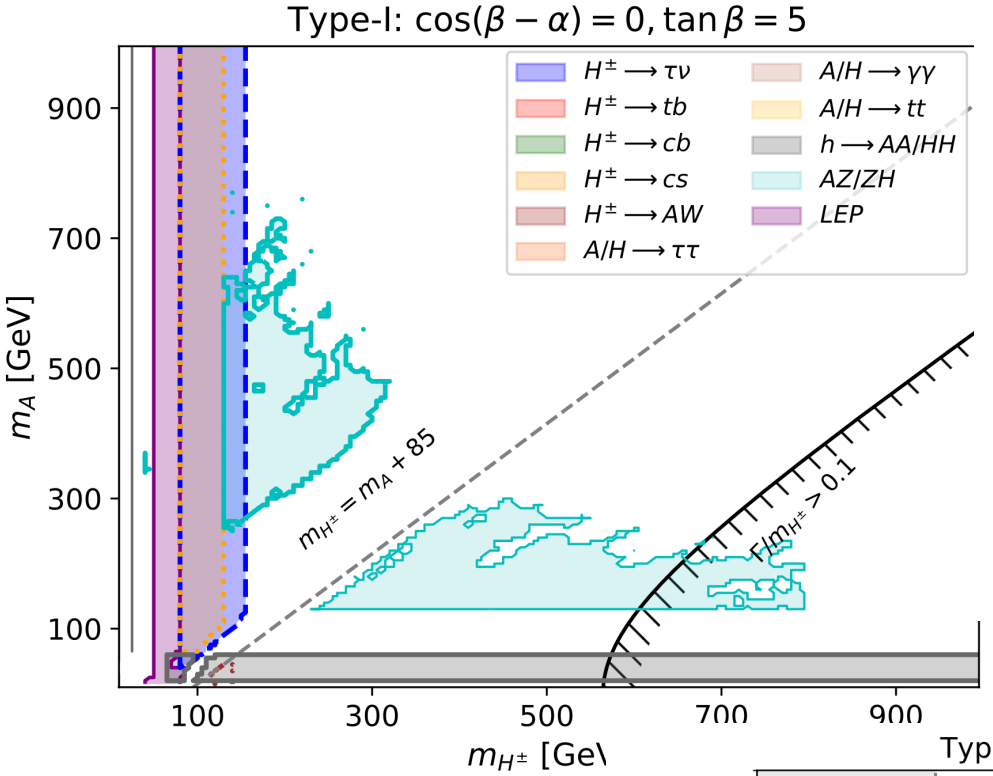
2HDM+singlet

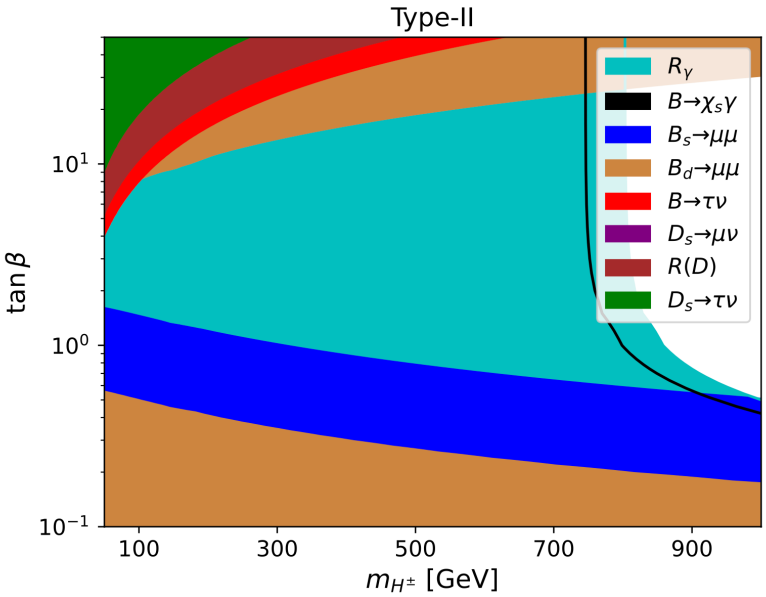
Preliminary

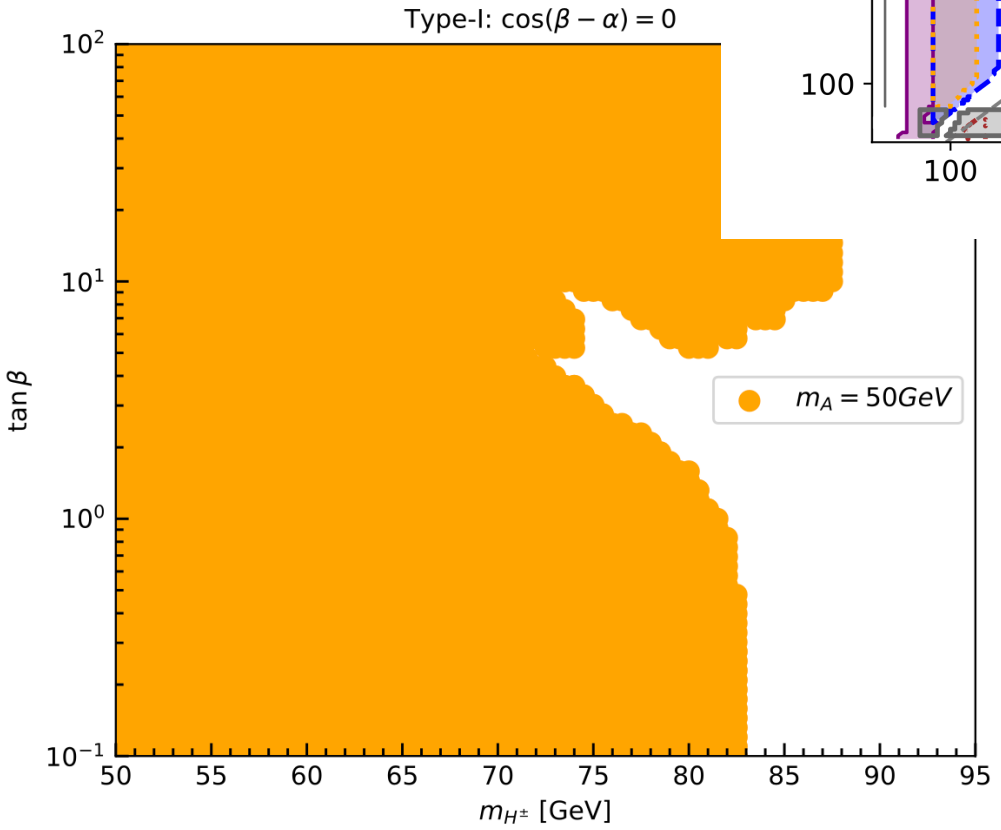


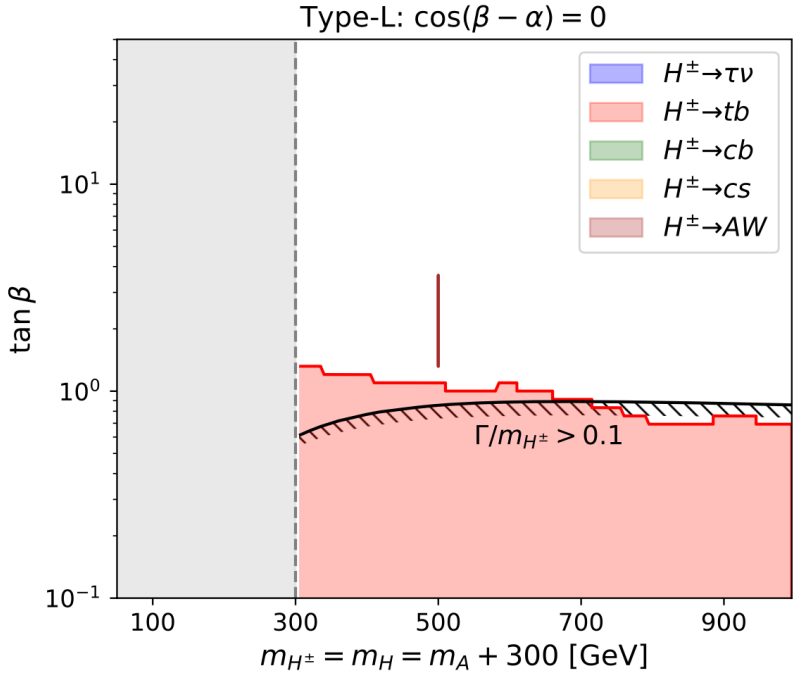


Summary


Type-I: cos(β − α) = 0, tan β = 5
H± → τν
H± → tb
H± → cb
H± → cs
H± → AW
A/H → ττ
A/H → γγ
A/H → tt
h → AA/HH
AZ/ZH
LEP
m_H± = m_A + 85
Γ/m_H± > 0.1
m_A [GeV]
m_H± [GeV]


Type-II
R_γ
B→χ_sγ
B_s→μμ
B_d→μμ
B→τν
D_s→μν
R(D)
D_s→τν
tan β
m_H± [GeV]


Type-I: cos(β − α) = 0
m_A = 50GeV
tan β
m_H± [GeV]


Type-L: cos(β − α) = 0
H±→τν
H±→tb
H±→cb
H±→cs
H±→AW
Γ/m_H± > 0.1
tan β
m_H± = m_H = m_A + 300 [GeV]

Thanks !

backup

2HDM+singlet

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\alpha_3} & s_{\alpha_3} \\ 0 & -s_{\alpha_3} & c_{\alpha_3} \end{pmatrix} \begin{pmatrix} c_{\alpha_2} & 0 & s_{\alpha_2} \\ 0 & 1 & 0 \\ -s_{\alpha_2} & 0 & c_{\alpha_2} \end{pmatrix} \begin{pmatrix} c_{\alpha_1} & s_{\alpha_1} & 0 \\ -s_{\alpha_1} & c_{\alpha_1} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

SM – singlet

Non-SM – singlet

Doublet mixing

SM limit of 2HDMS

$$\cos(\beta - \alpha_1) = 0, \ \alpha_3 = 0.$$

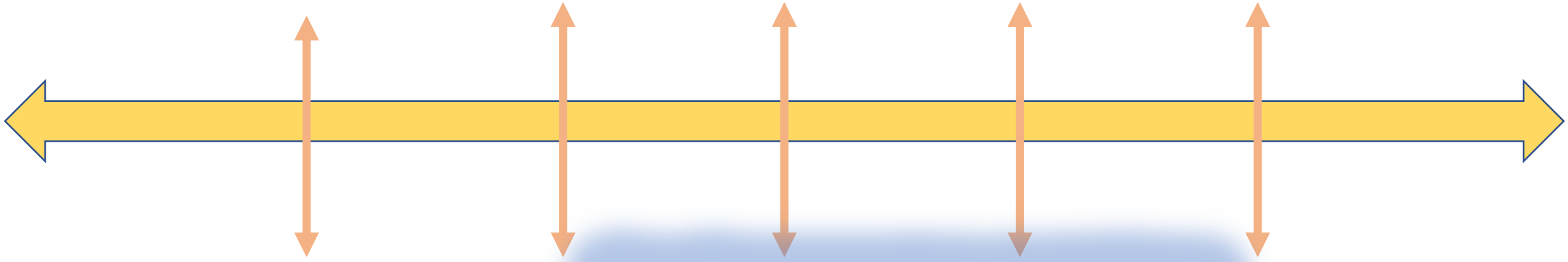
$$R^A = \begin{pmatrix} c_{\alpha_4} & s_{\alpha_4} \\ -s_{\alpha_4} & c_{\alpha_4} \end{pmatrix}$$

A - A_S

2HDM limit of 2HDMS

$$\alpha_2 = \alpha_3 = \alpha_4 = 0$$

Scenarios



Mass hierarchy

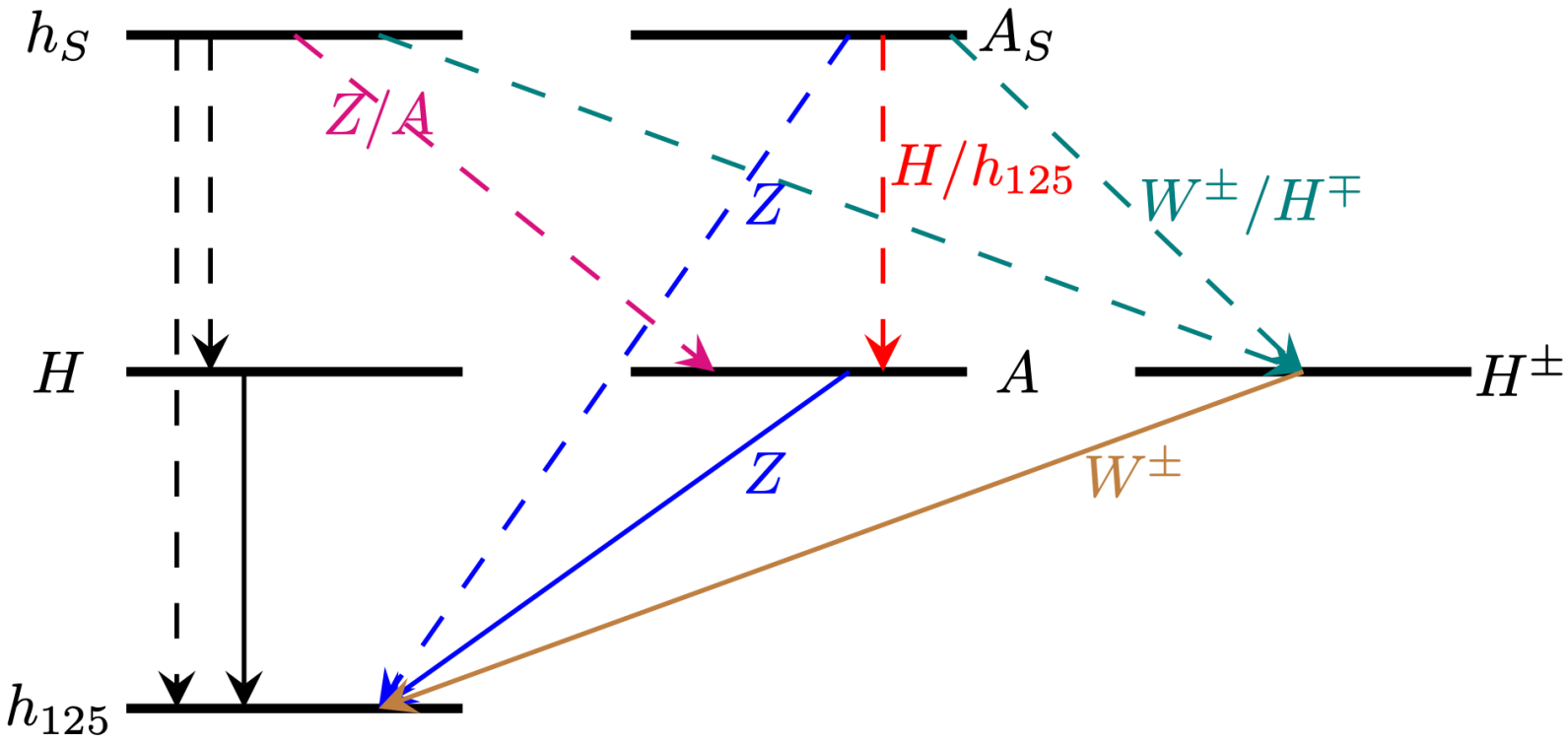
- $m_{h_S} < 0.1$ GeV
- 0.1 GeV$< m_{h_S} <$ 10 GeV
- 10 GeV $< m_{h_S} <$ 62.5 GeV
- 62.5 GeV $< m_{h_S} <$ 1 TeV
- 1 TeV $< m_{h_S} <$ 10TeV
- 10 TeV $< m_{h_S}$

LHC era

2HDM+singlet: Higgs sector

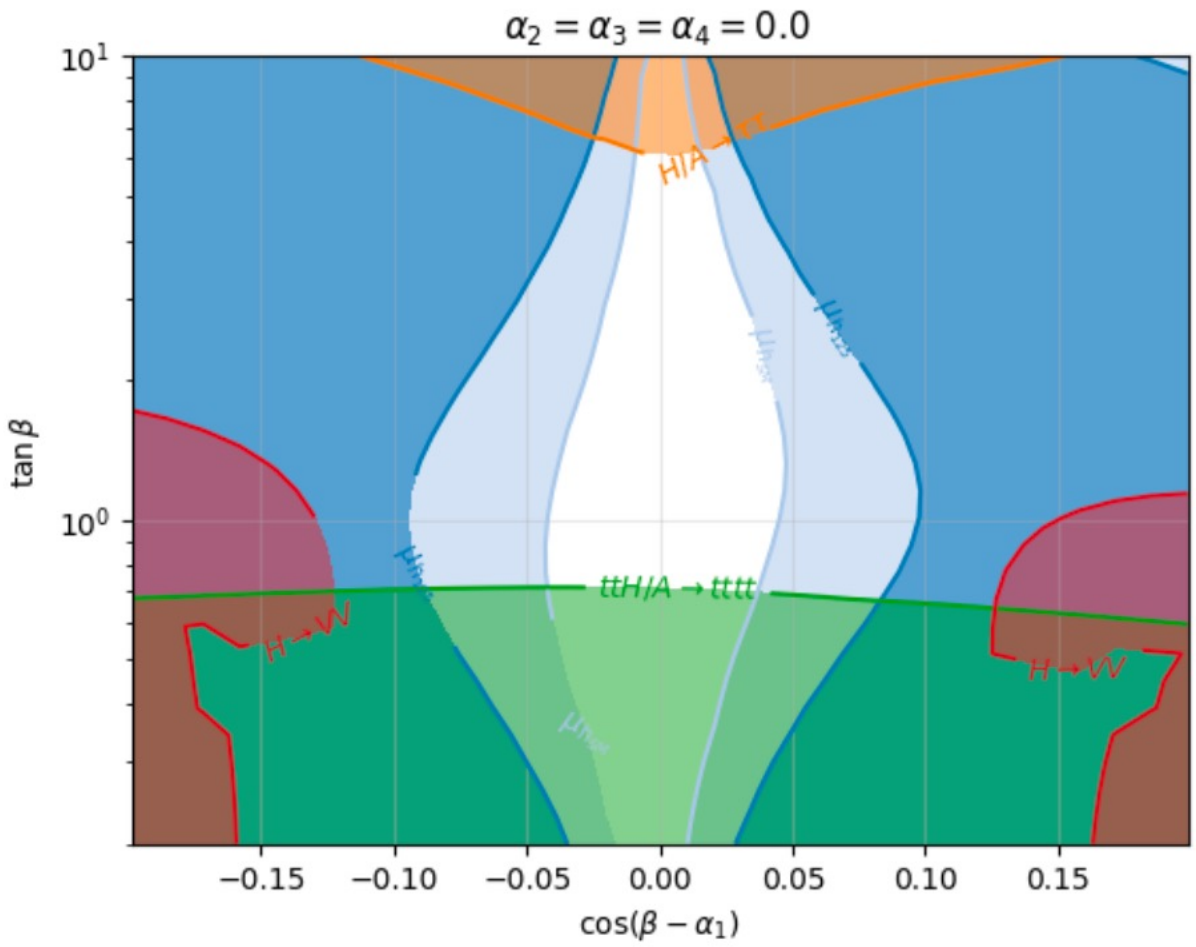
- The scenario with heavier singlet Higgs

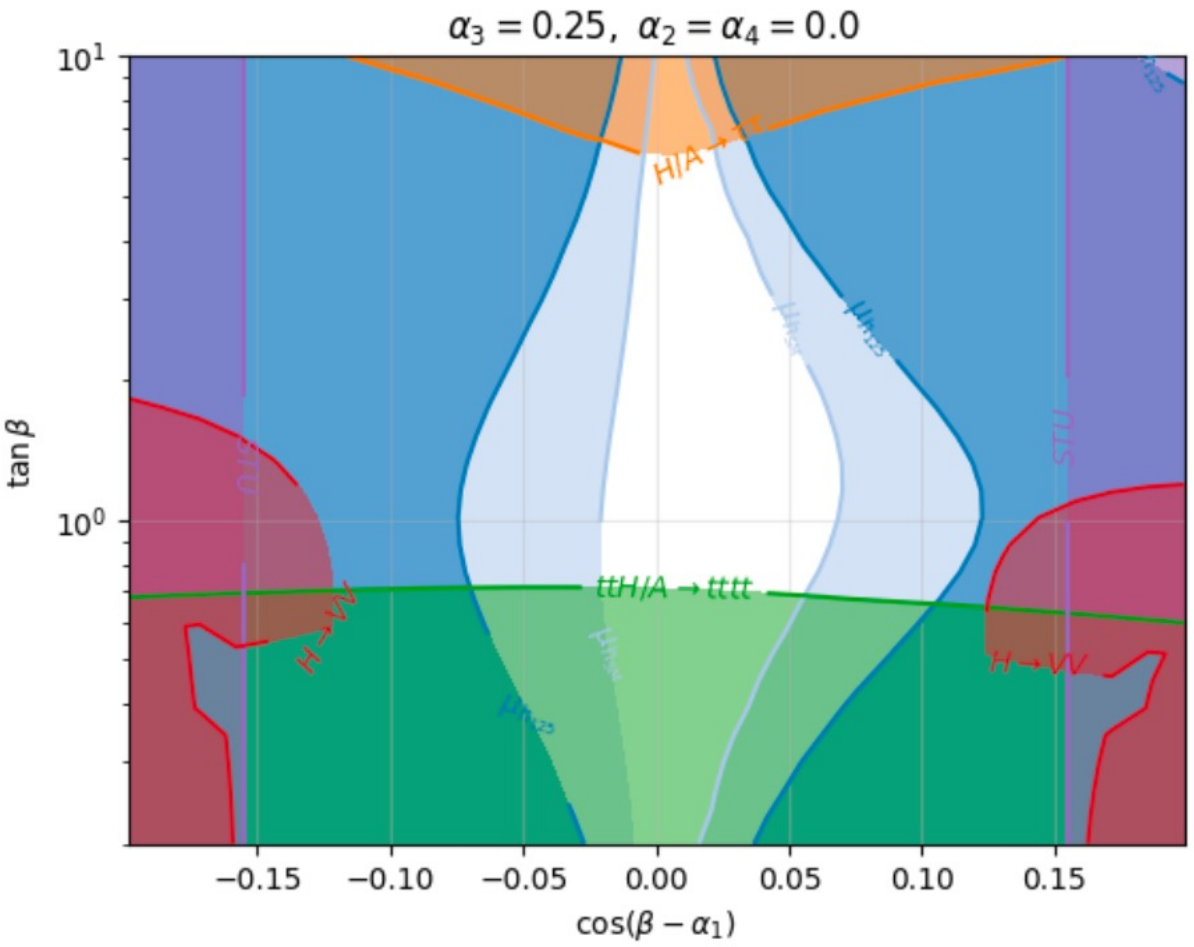
Type-II like 2HDMS



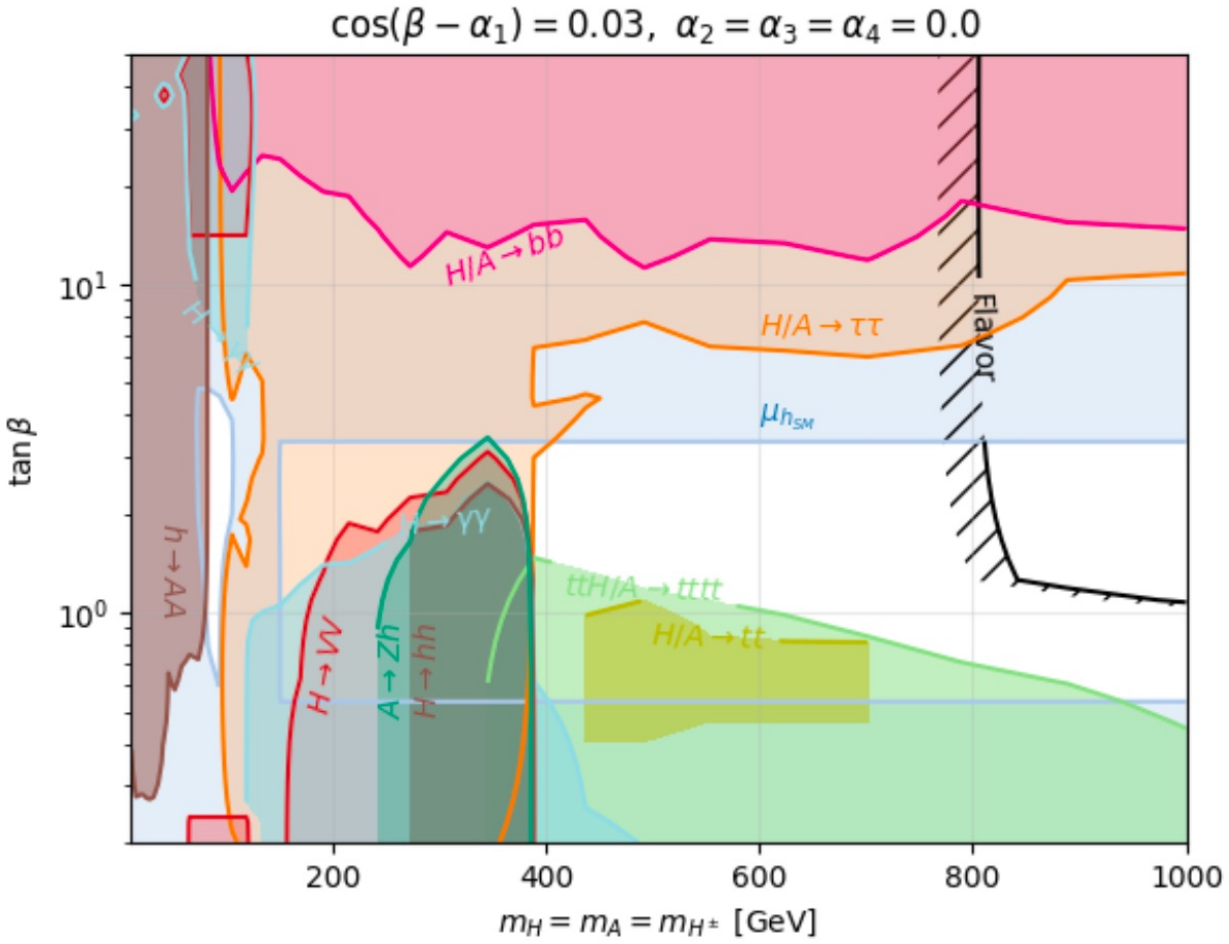
2HDM+singlet

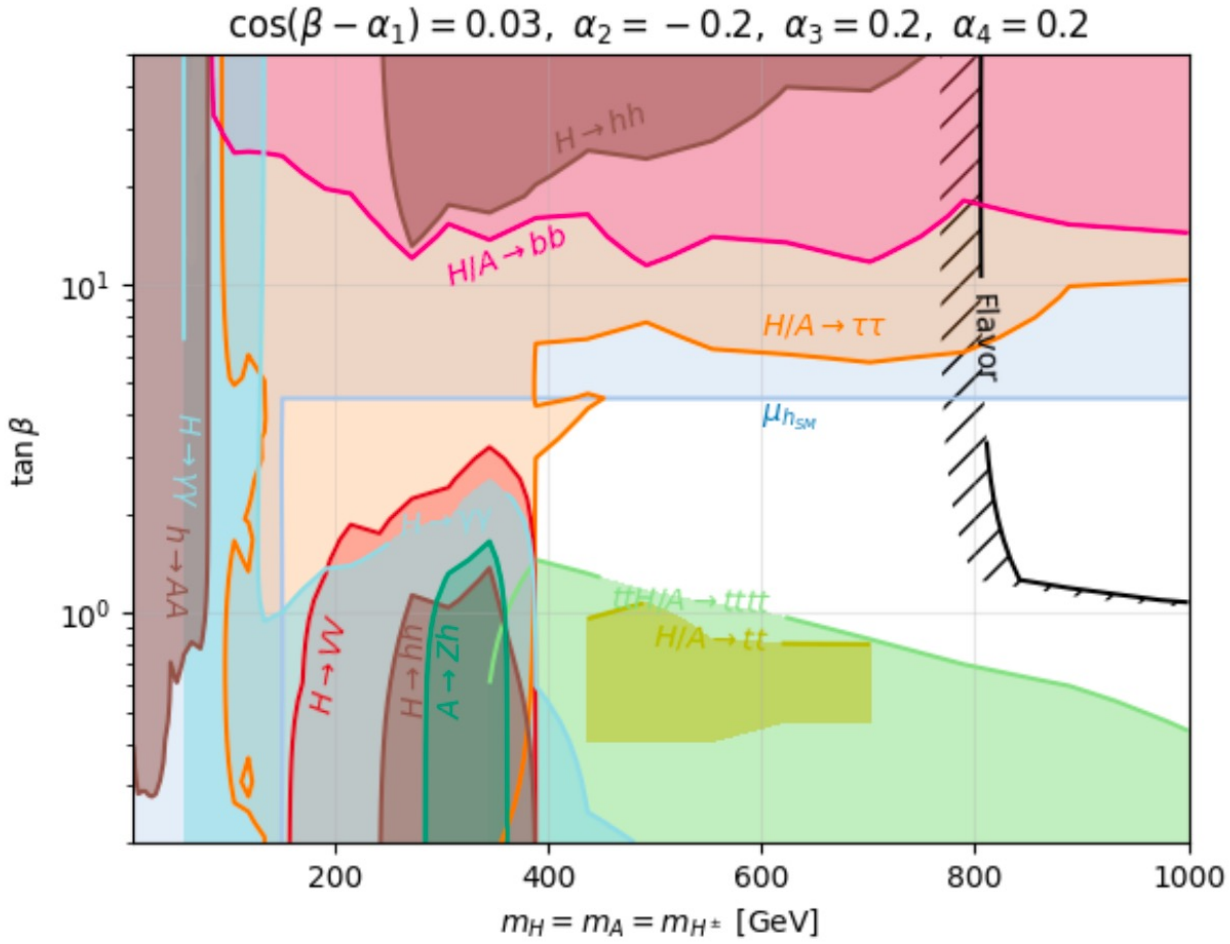
$$m_{h_S} = m_{a_S} = 1500 \text{ GeV}$$



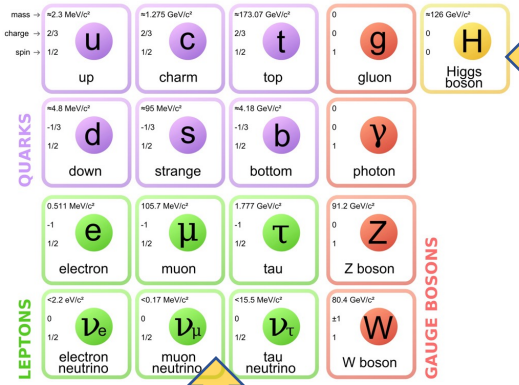


2HDM+singlet





Summary



$WIMP, Dark\ Photon$ ..

- Naturalness
- Muon g-2
- B anomaly
- …

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$$

Coupling

Discovered Region

EW

Strongly interacting Heavy Particle

Energy Frontier

ATLAS EXPERIMENT

CMS

CEPC

Weakly interacting Light Particle

Intensity Frontier

LHCb

FASER

SHiP

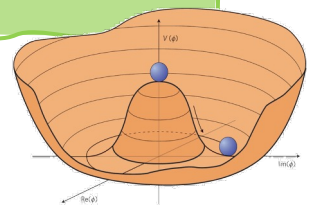
MUTHUSLA

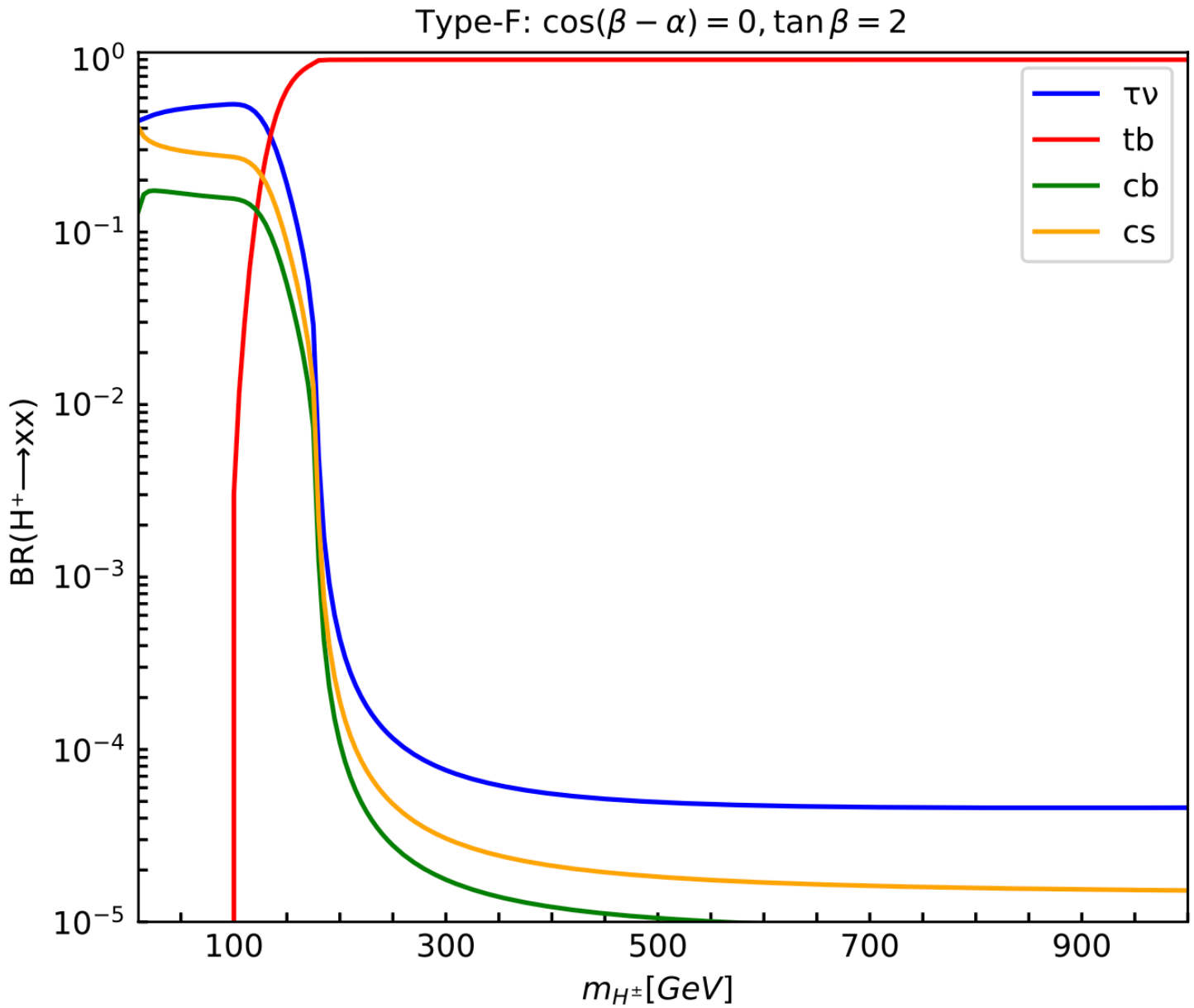
Hard to probe

Mass

$DM, Dark\ Photon$ …

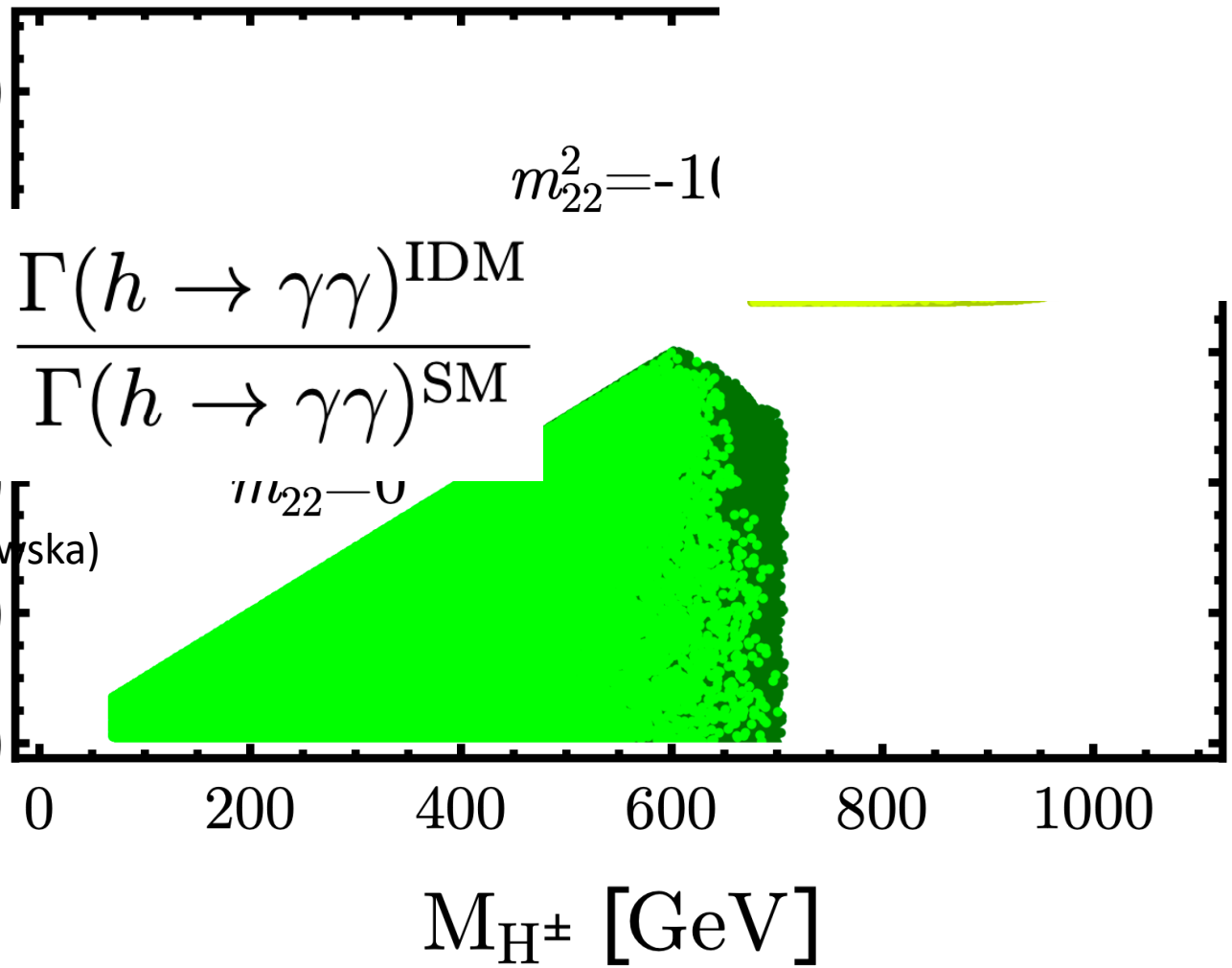
- Naturalness
- Muon g-2
- Phase transition
- …




Type-F: cos(β − α) = 0, tan β = 2
BR(H⁺⟶XX)
$m_{H^{\pm}}[GeV]$
τν
tb
cb
cs
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
100
300
500
700
900

$$\Gamma(h \to \gamma\gamma)^{\rm IDM} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \Big| \underbrace{\frac{4}{3} A_{1/2}\left(\frac{4M_t^2}{M_h^2}\right) + A_1\left(\frac{4M_W^2}{M_h^2}\right)}_{\mathcal{M}^{\rm SM}} + \underbrace{\frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right)}_{\delta\mathcal{M}^{\rm IDM}} \Big|^2,$$

$$\widetilde{R}_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)^{\rm IDM}}{\Gamma(h \to \gamma\gamma)^{\rm SM}}$$

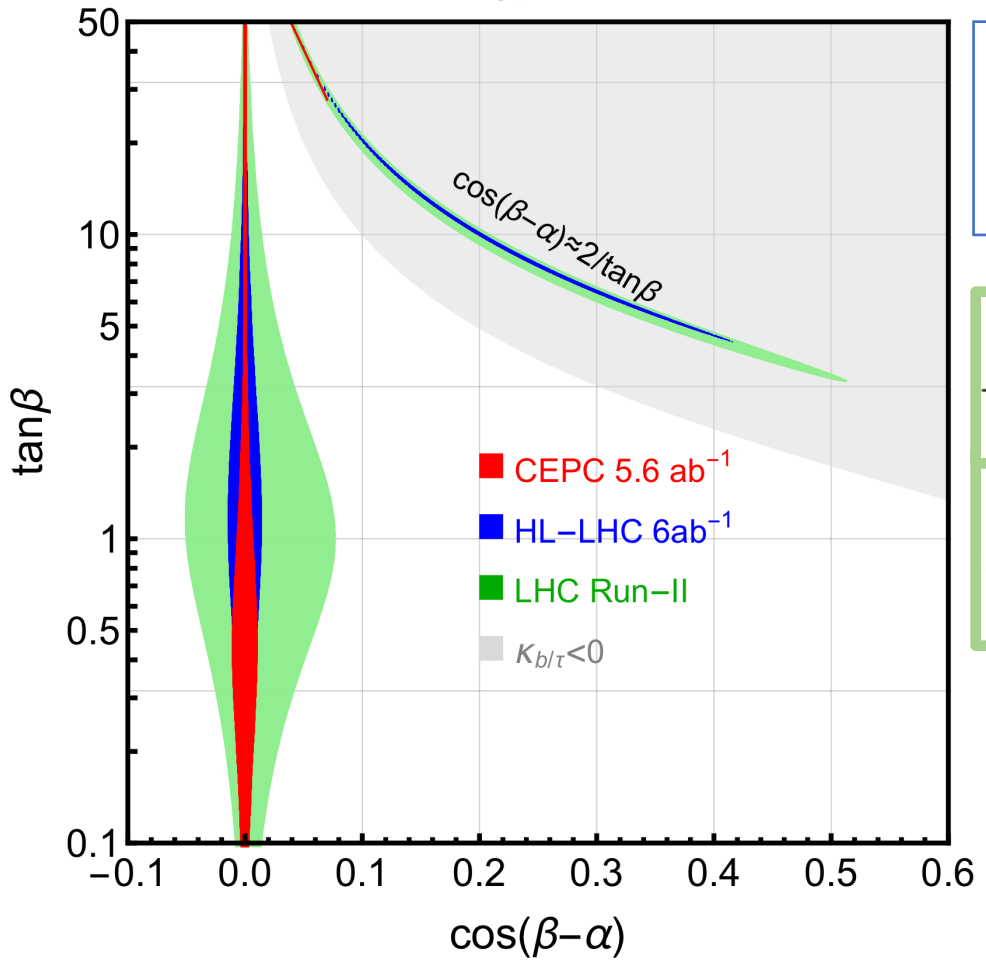


By B-N. Swiezewska)

2HDM: Tree Level

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM Type-II



Alignment limit :

$\cos(\beta-\alpha)=0$

$g(2HDM)=g(SM)$

1910.06269

WS

$$-\frac{\sin\beta}{\cos\alpha}-1=-\frac{1}{2}\cos^2(\beta-\alpha)-\cos(\beta-\alpha)\times\tan\beta$$

$$\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$

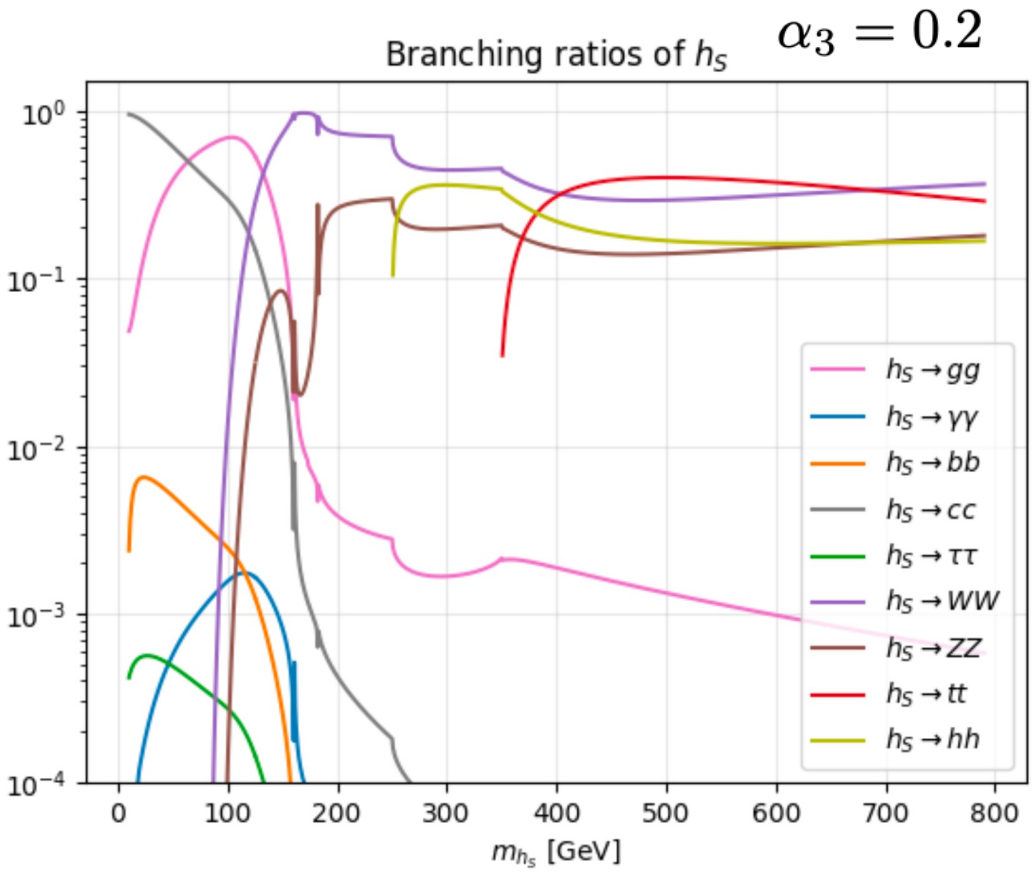
m_{h_1}	m_{h_2}	m_{h_3}	m_A	m_{A_S}
95 GeV	125.09 GeV	900 GeV	900 GeV	325.86 GeV
$m_{H^\pm}$	$m_S'^2$	δ'_{14}	δ'_{25}	$\tan(\beta)$
900 GeV	-4.809×10^4 GeV^2	-9.6958	0.2475	10
v_S	c_{h_1bb}	c_{h_1tt}	$alignm$	$\tilde{\mu}^2$
239.86 GeV	0.2096	0.4192	0.9998	8.128×10^5 GeV^2

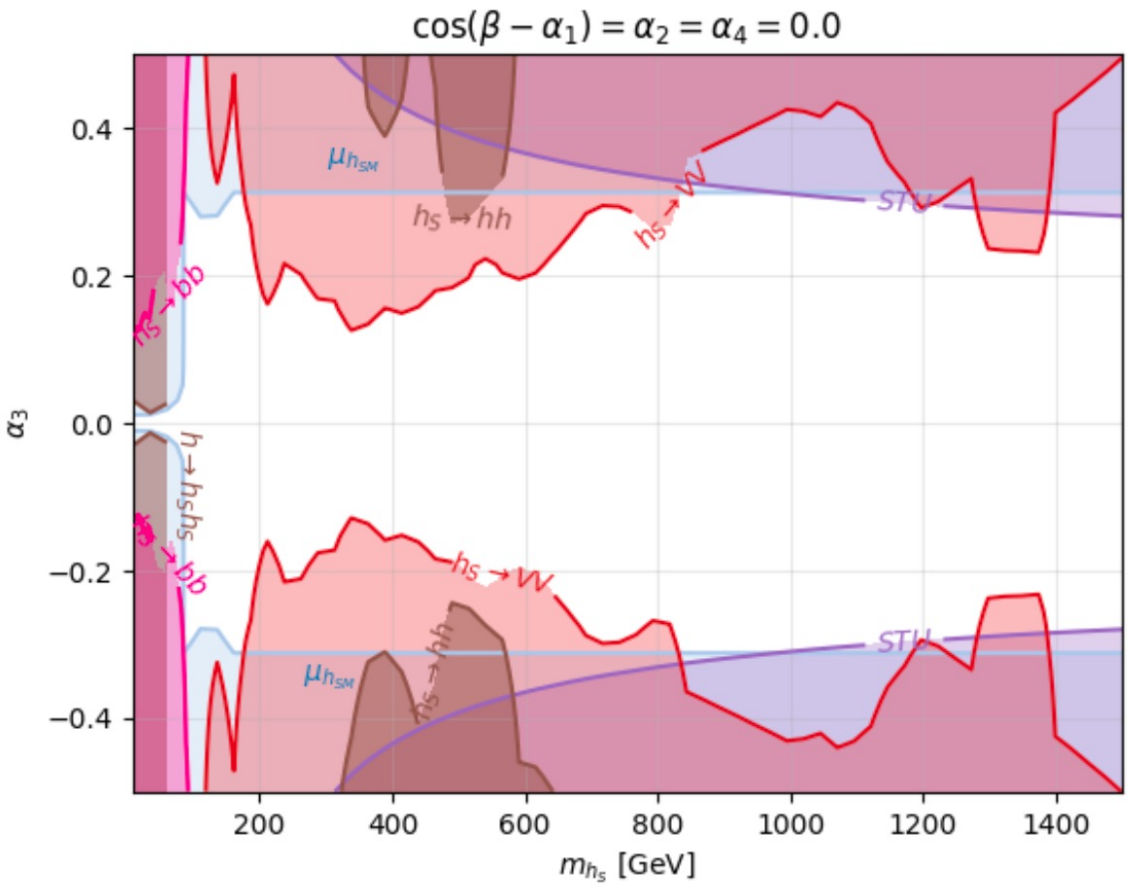
Table 3. The benchmark point **BP1** in the mass basis.

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

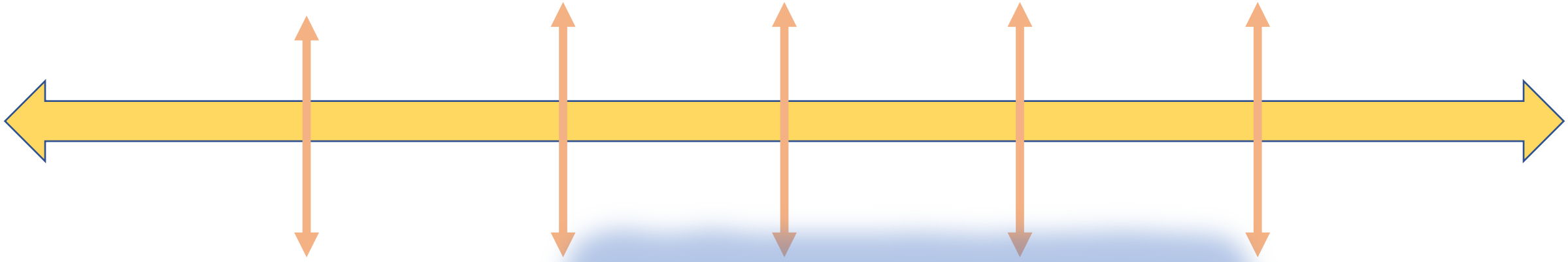
$$S = \frac{1}{\sqrt{2}}(v_S + \rho_S + iA_S)$$

2HDM+singlet:h_S





Scenarios



- $m_{h_S} < 0.1$ GeV
- 0.1 GeV$< m_{h_S} <$ 10 GeV
- 10 GeV $< m_{h_S} <$ 62.5 GeV
- 62.5 GeV $< m_{h_S} <$ 1 TeV
- 1 TeV $< m_{h_S} <$ 10TeV
- 10 TeV $< m_{h_S}$

Mass hierarchy

LHC era