Long lived Particle of Higgs sector

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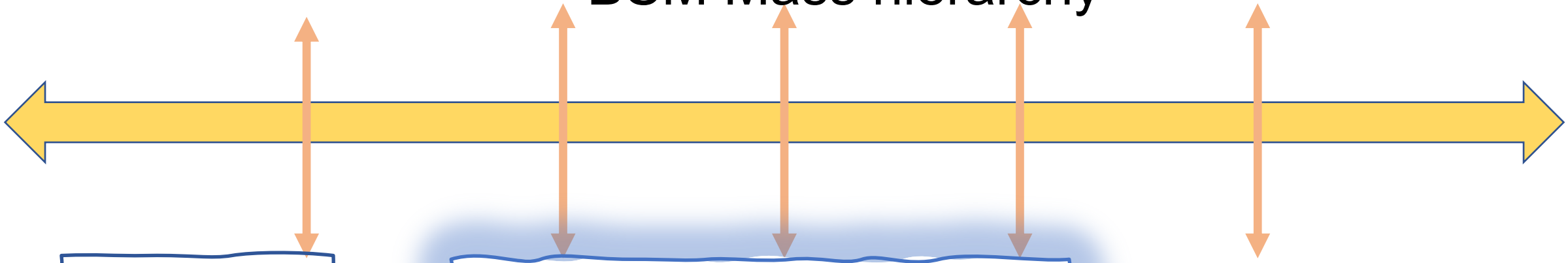
outline

- Motivation: LLP and FASER
- 2HDM: complete Type-I study
- Study method: EFT and BMs
- Conclusion

Motivation:LLP

BSM Mass hierarchy



LLP

Weakly interacting Light Particle

- $m_{h_S} < 0.1$ 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 $< m_{h_S}$

FASER

SHiP
Search for Hidden Particles

MUTHUSLA

10^{17} π, 10^{16} K, 10^{15} D, 10^{14} B

Heavy

ATLAS EXPERIMENT

CEPC

CMS

Strongly interacting Heavy Particle

Production

Pion

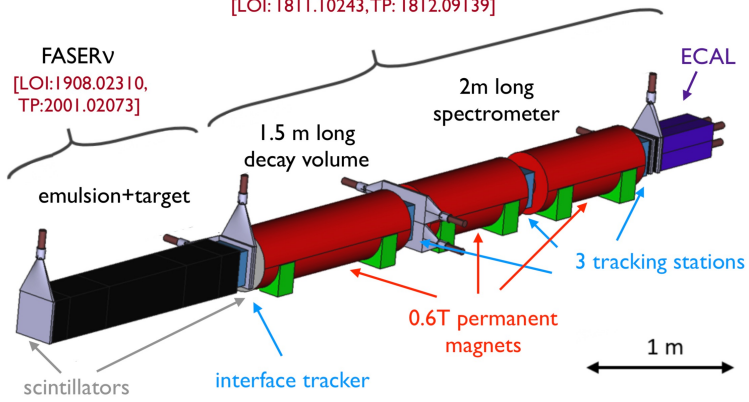
boosted mesons highly collimated

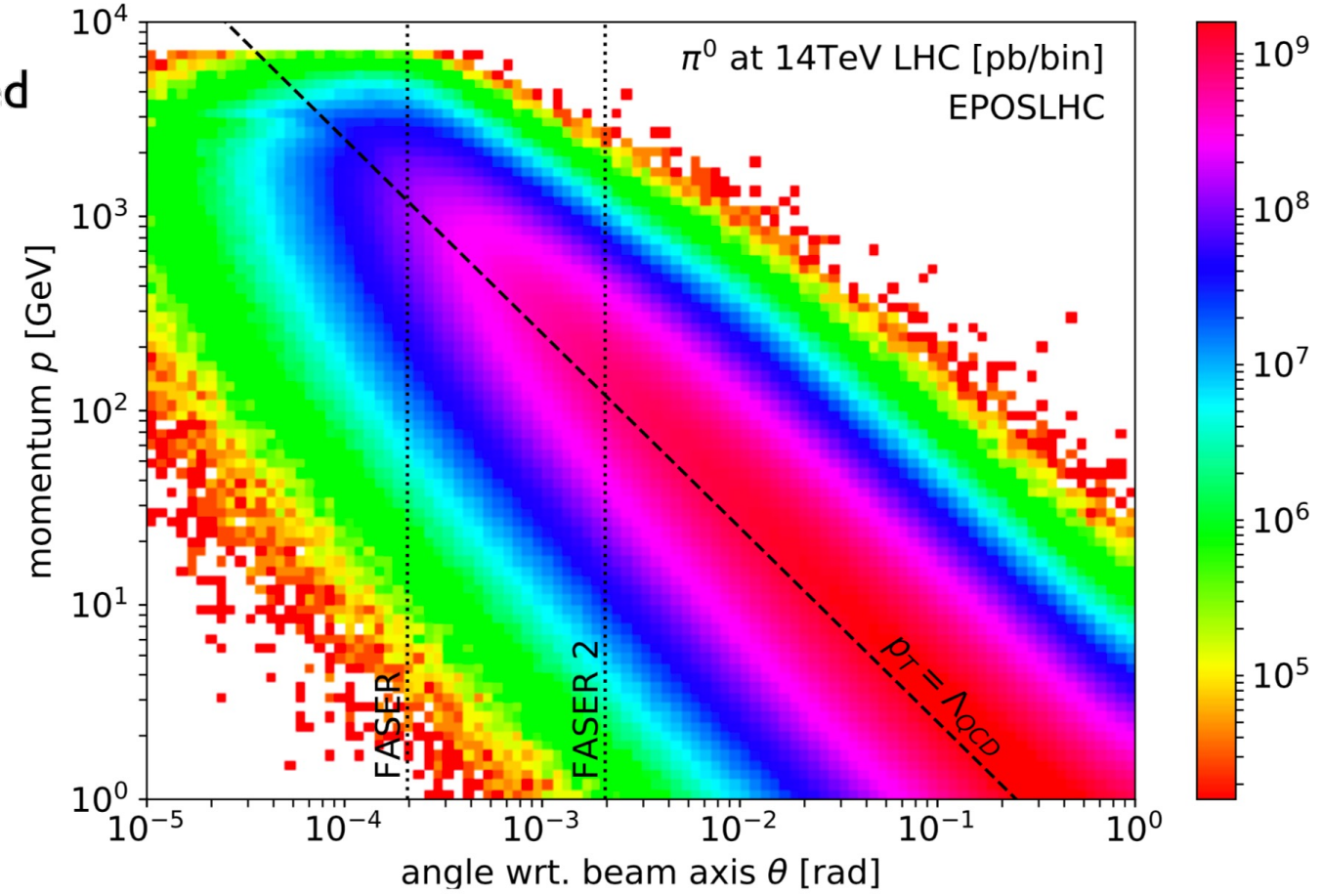
$$p \cdot \theta = p_T \sim \Lambda_{QCD}$$

$$N_\pi = 10^{18} \quad \text{at } 3000 \text{ fb}^{-1}$$

FASER: radius R = 10 cm,
lenght D = 1.5 m,
FASER 2: radius R = 1m,
lenght D = 5 m.

FORESEE





Case study: 2HDM

- 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

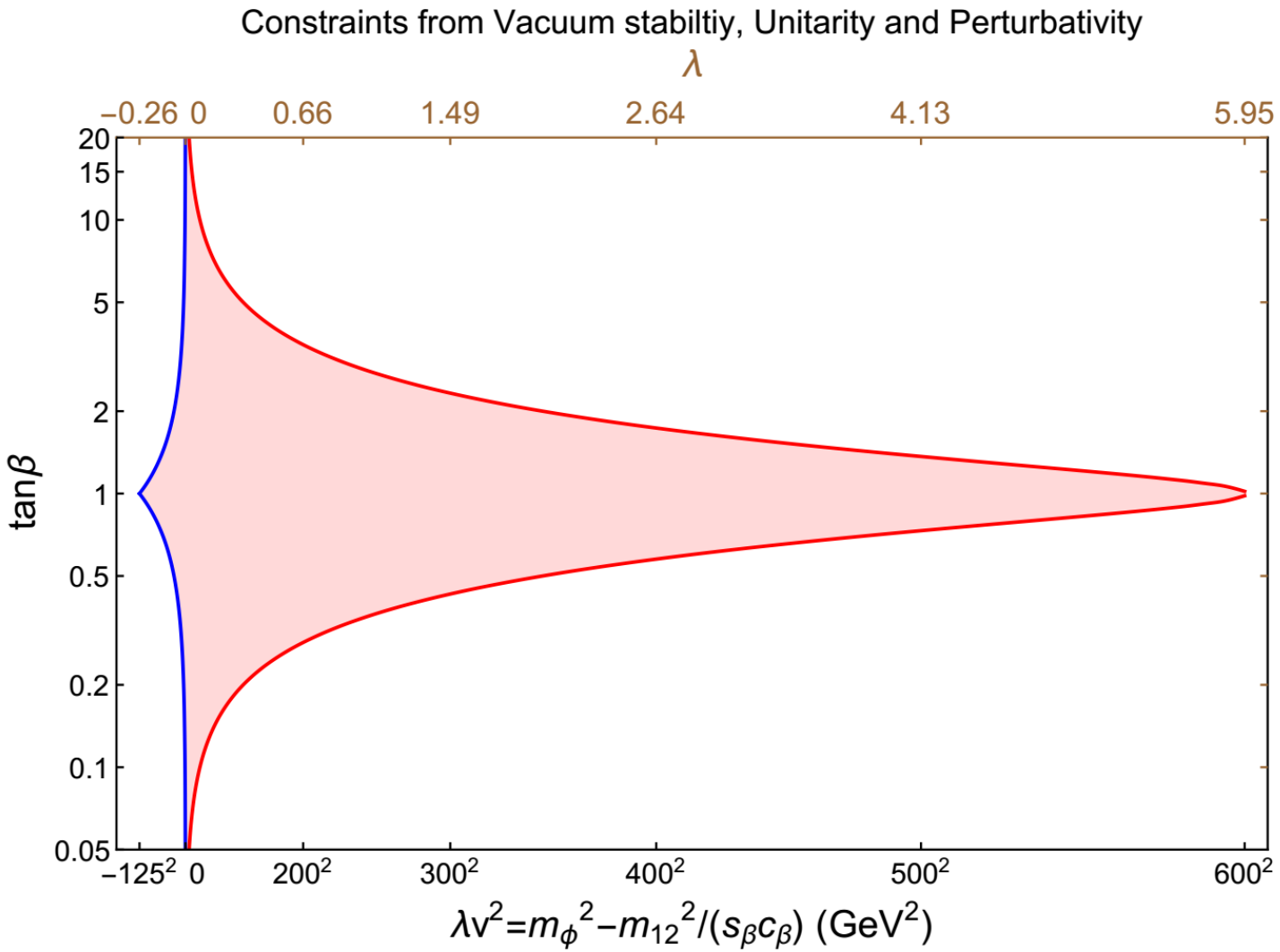
- Parameters (CP-conserving, Flavor Limit, Z_2 Symmetry)

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

Soft Z_2 symmetry breaking: m_{12}^2

246 GeV 125. GeV light

Constraint



$$\cos(\beta-\alpha)=0,$$
$$m_\Phi \equiv m_H = m_A = m_{H^\pm}$$

Theoretical constraints

$$\lambda v^2 \equiv m_\Phi^2 - m_{12}^2/s_\beta c_\beta$$

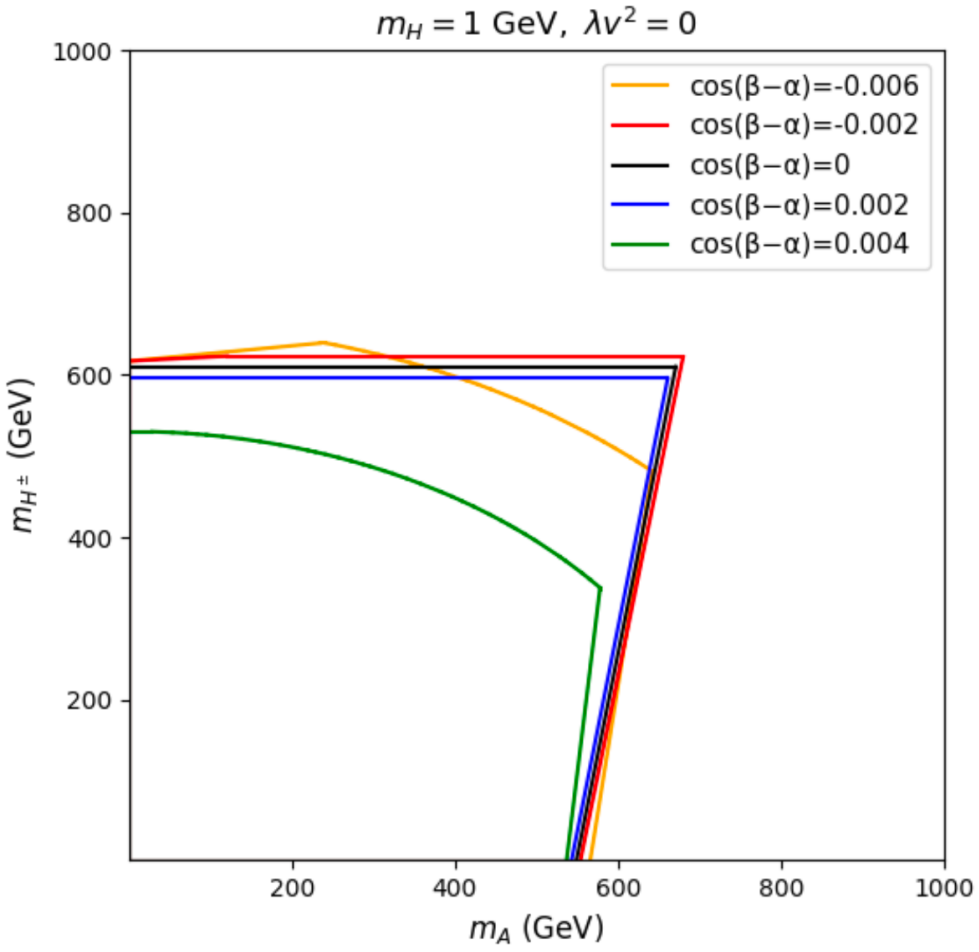
$$-125^2\mathrm{GeV}^2 < \lambda v^2 < 600^2\mathrm{GeV}^2$$

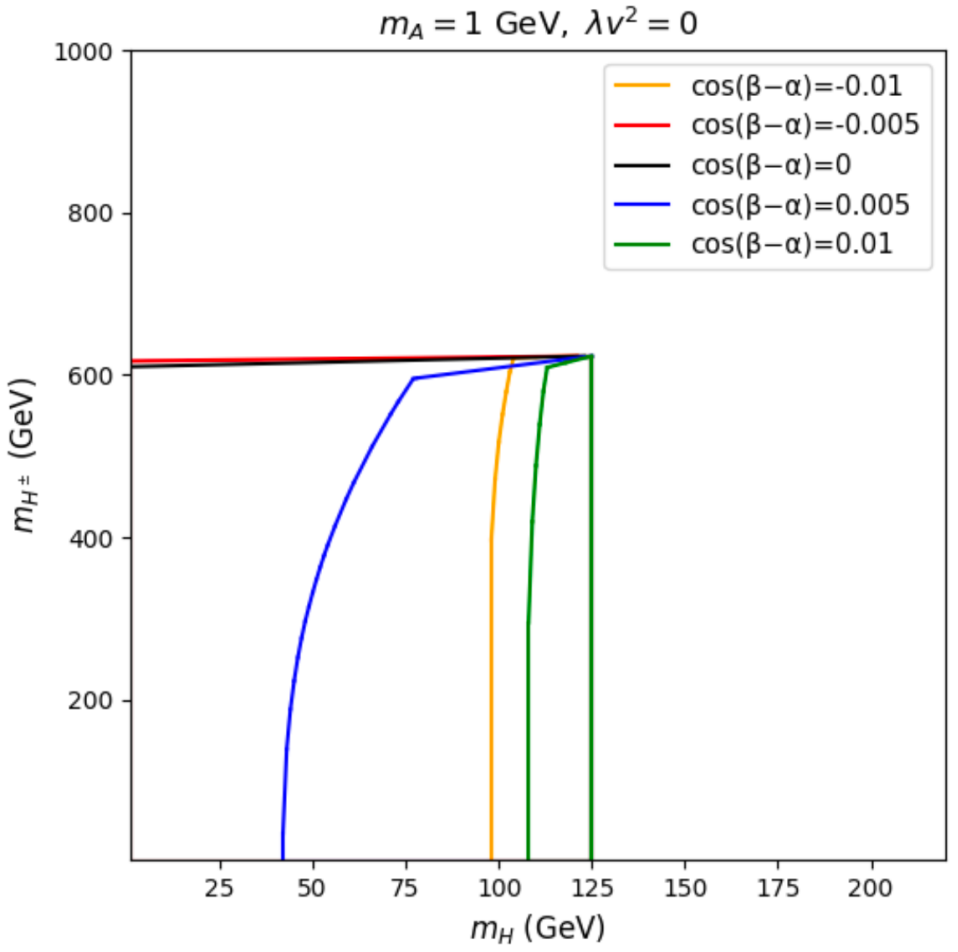
$$\lambda \in (-0.26, 5.95)$$
$$\lambda_4 = \lambda_5 = \lambda_3 - 0.258 = -\lambda$$

Constraint

Theoretical constraints

$$\lambda v^2 \equiv m_H^2 - m_{12}^2/s_\beta c_\beta = 0$$



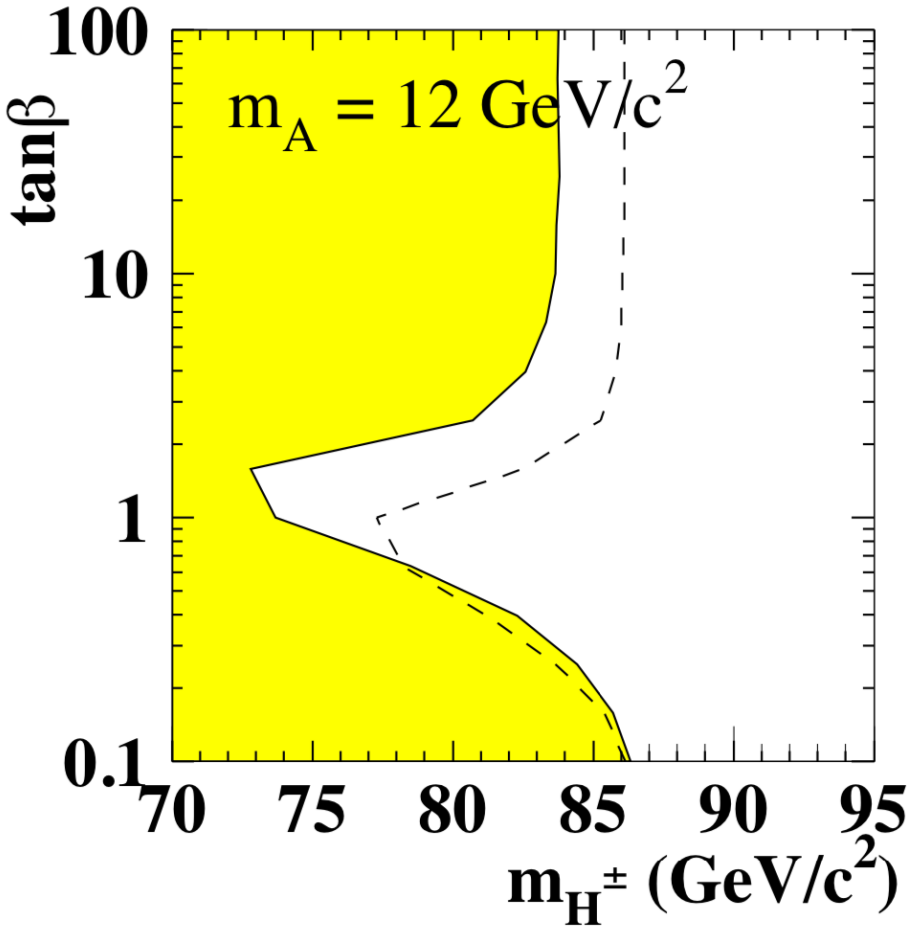


$$m_H \sim 0: \quad m_{A/H^\pm} \lesssim 600 \text{ GeV}$$

$$m_A \sim 0: \quad m_{H^\pm} \lesssim 600 \text{ GeV}, \quad m_H \lesssim m_h$$

Constraint

Direct search at LEP



arXiv: 1301.6065

$$m_H \sim 0: \qquad m_A \sim m_{H^\pm} \lesssim 600\ \text{GeV}$$

$$m_A \sim 0: \qquad m_{H^\pm} \sim m_H \lesssim m_h$$

$$m_A \sim 10\ \text{GeV}: \qquad 72\ \text{GeV} \lesssim m_{H^\pm} \sim m_H \lesssim 116\ \text{GeV}$$

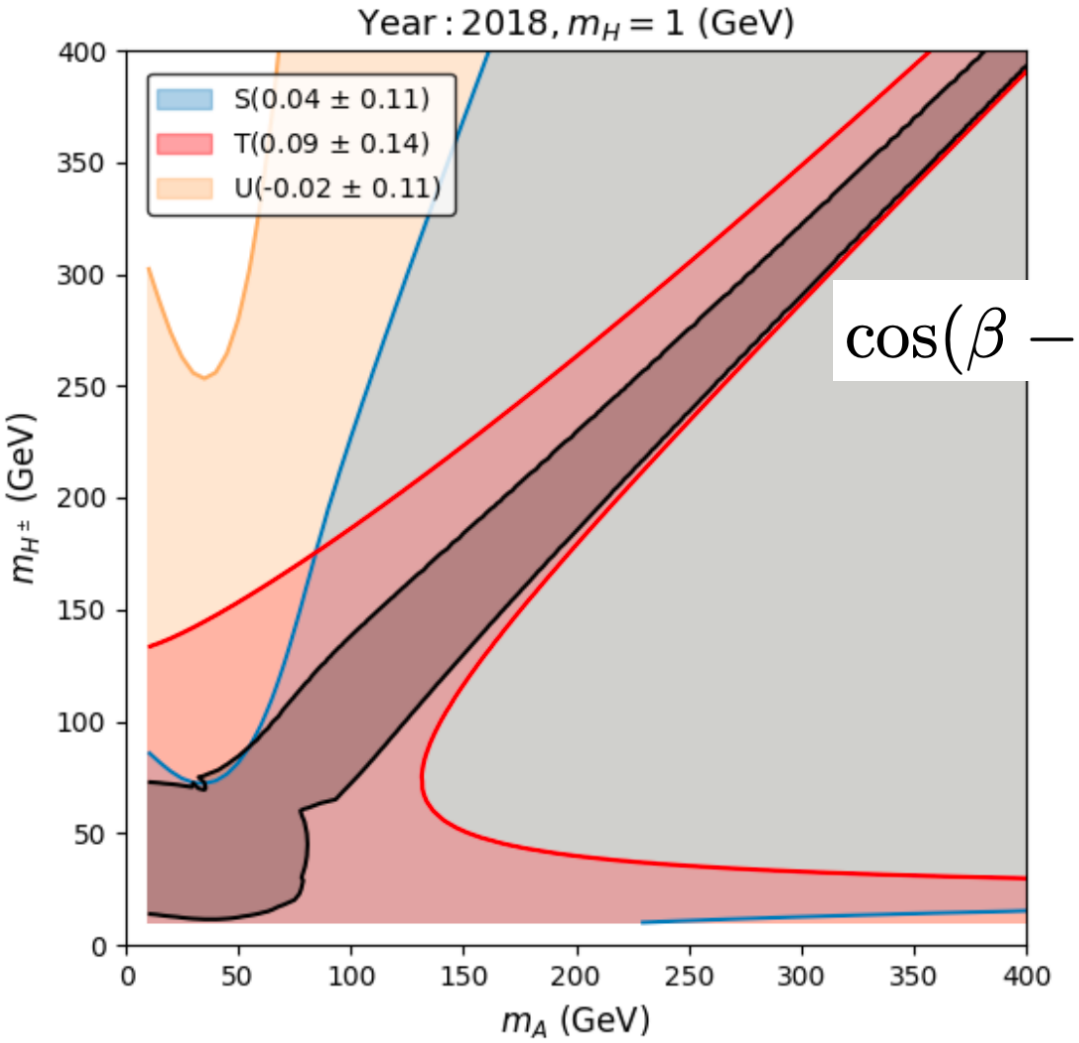
Constraint

Oblique constraints: Z pole

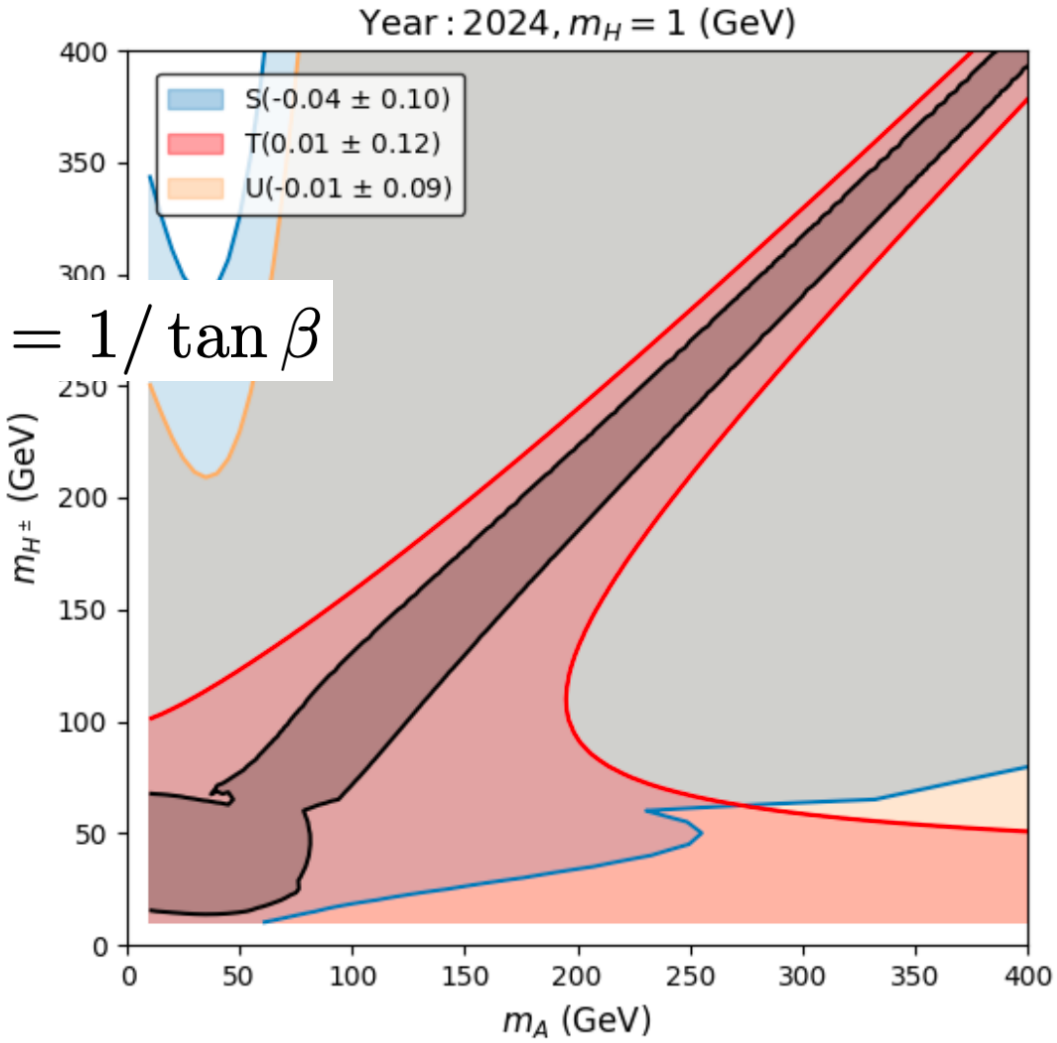
	2018 [96]				2024 [99]			
	σ	correlation			σ	correlation		
		S	T	U		S	T	U
S	0.04 ± 0.11	1	0.92	-0.68	-0.04 ± 0.10	1	0.93	-0.70
T	0.09 ± 0.14	–	1	-0.87	0.01 ± 0.12	–	1	-0.87
U	-0.02 ± 0.11	–	–	1	-0.01 ± 0.09	–	–	1

Constraint

Oblique constraints: Z pole

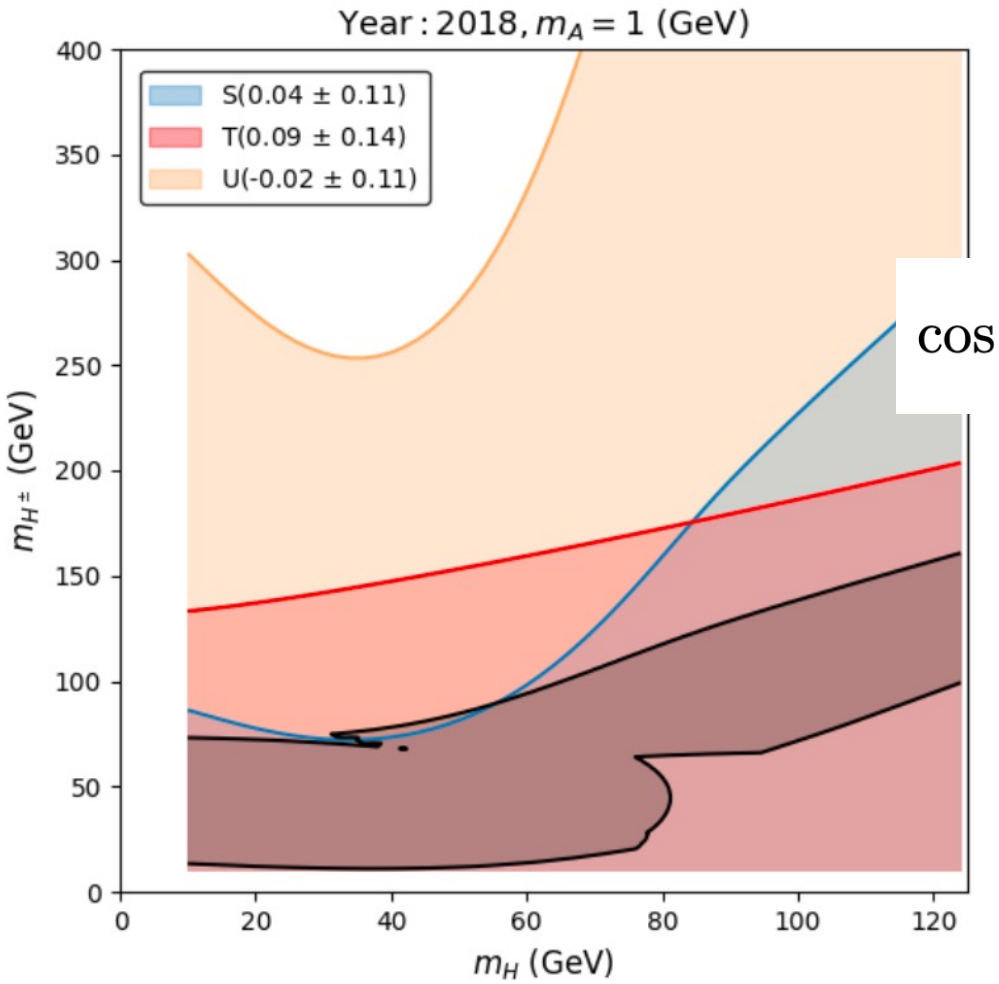


$$\cos(\beta - \alpha) = 1/\tan\beta$$

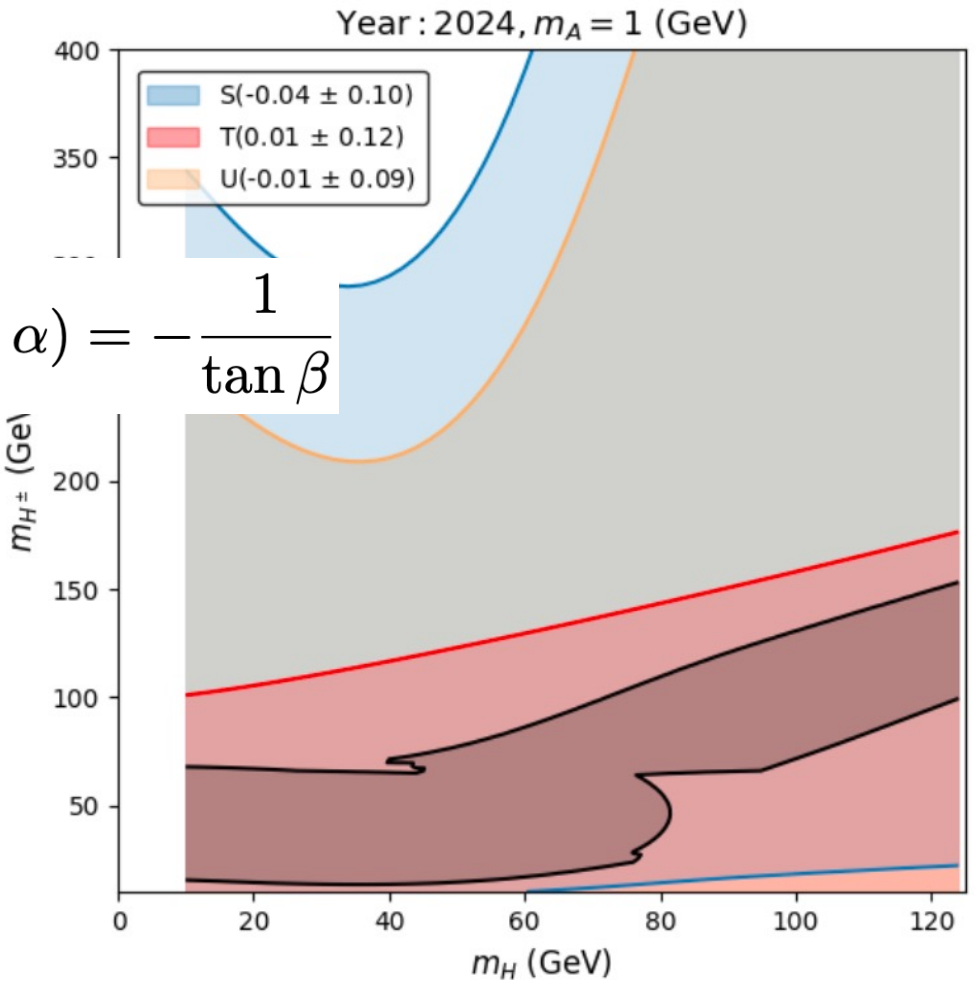


Constraint

Oblique constraints: Z pole



$$\cos(\beta - \alpha) = -\frac{1}{\tan\beta}$$



Constraint

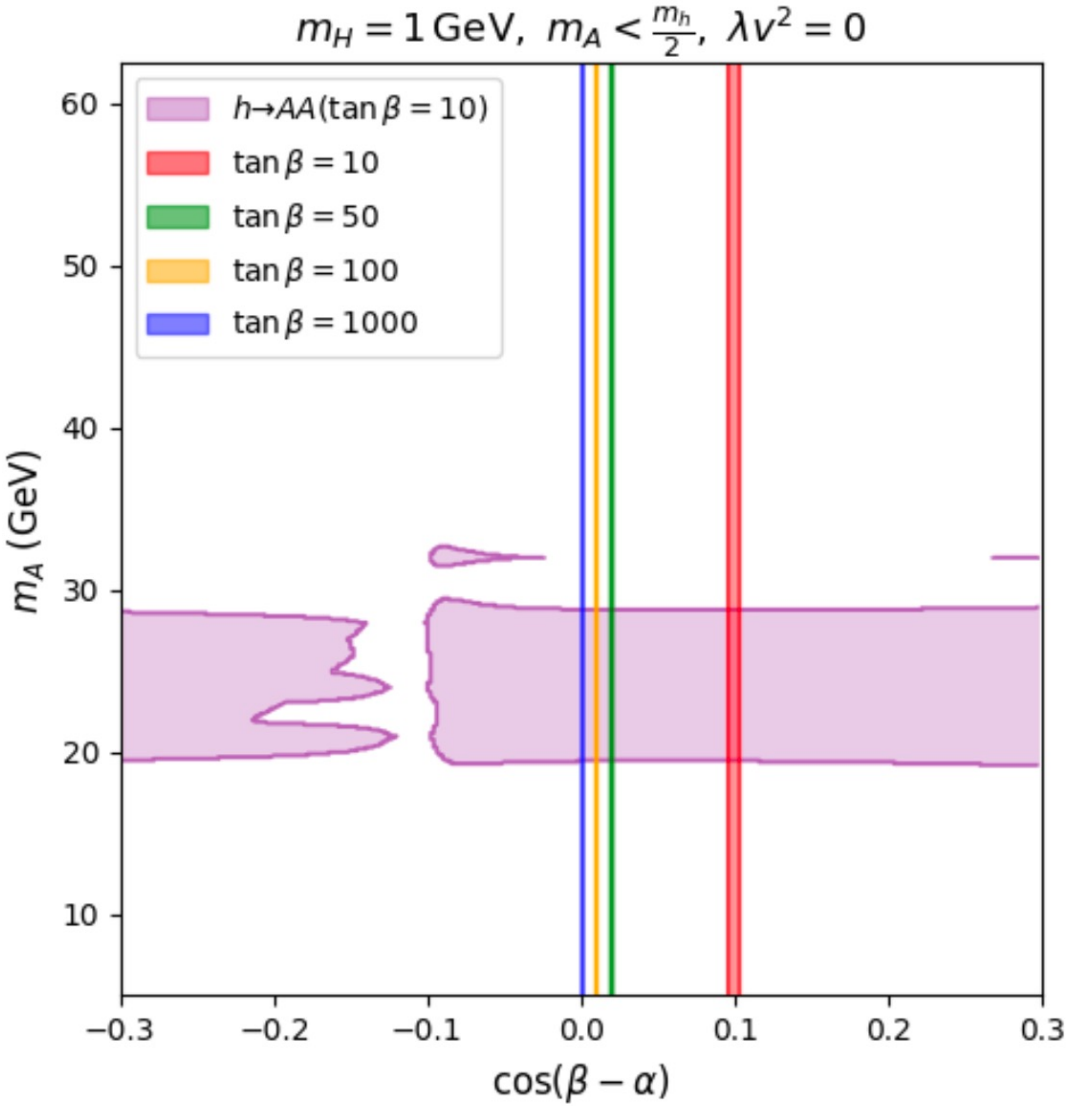
Invisible Higgs decays

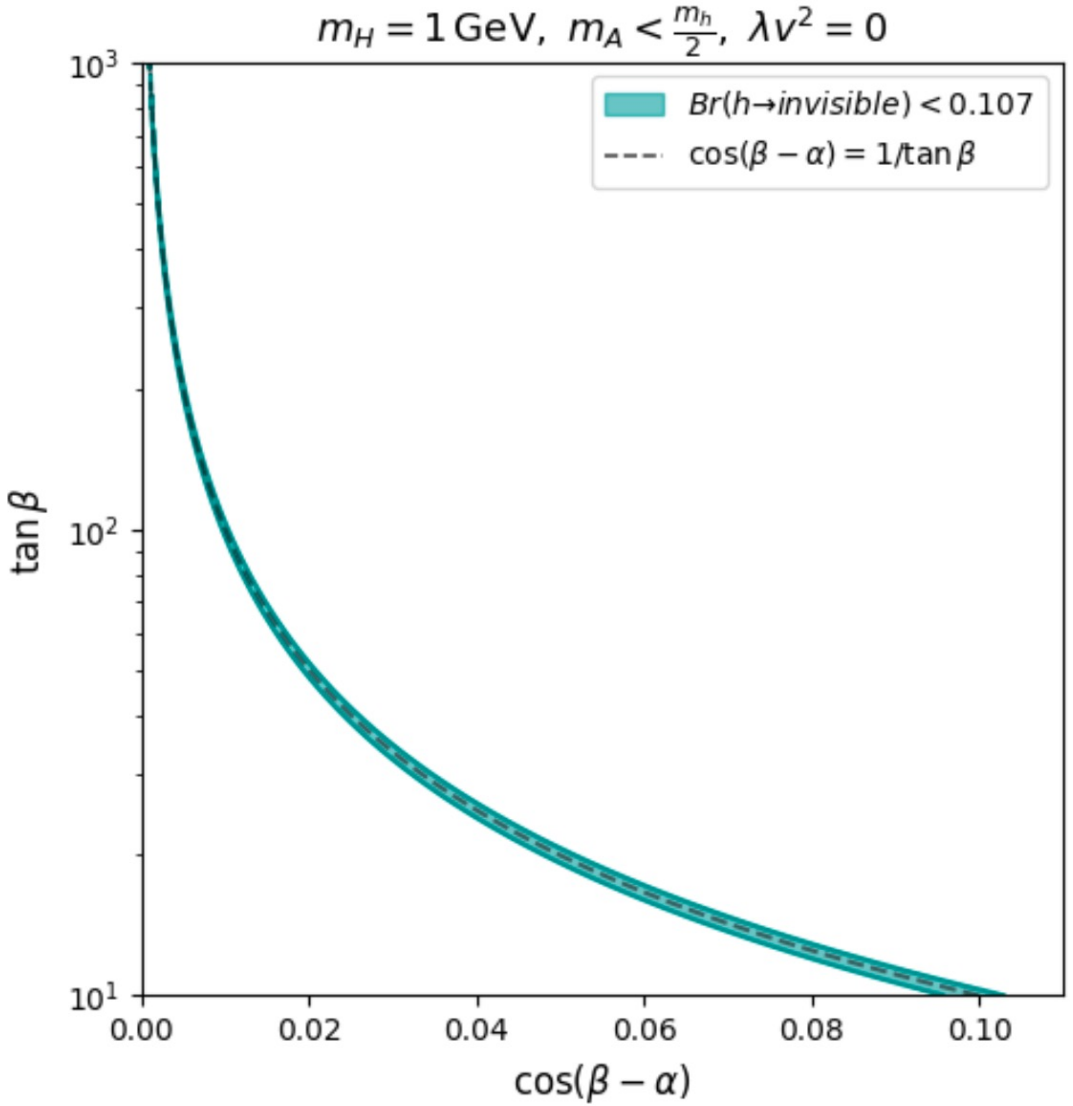
$$\mathrm{Br}(h \to \phi\phi) = \frac{\Gamma(h \to \phi\phi)}{\Gamma_h} \approx \frac{1}{\Gamma_h^{\mathrm{SM}}} \frac{g_{h\phi\phi}^2}{8\pi m_h^2} \left(1 - \frac{4m_H^2}{m_h^2}\right)^{1/2} \simeq 4700 \cdot \left(\frac{g_{h\phi\phi}}{v}\right)^2 < 0.107$$

$$g_{hHH} = \frac{s_{\beta-\alpha}}{2v}\left[\left(m_H^2 - 3\lambda v^2 - m_h^2\right)\left(2t_{2\beta}^{-1} s_{\beta-\alpha} c_{\beta-\alpha} - c_{\beta-\alpha}^2 + s_{\beta-\alpha}^2\right) + \left(\lambda v^2 - m_H^2\right)\right],$$

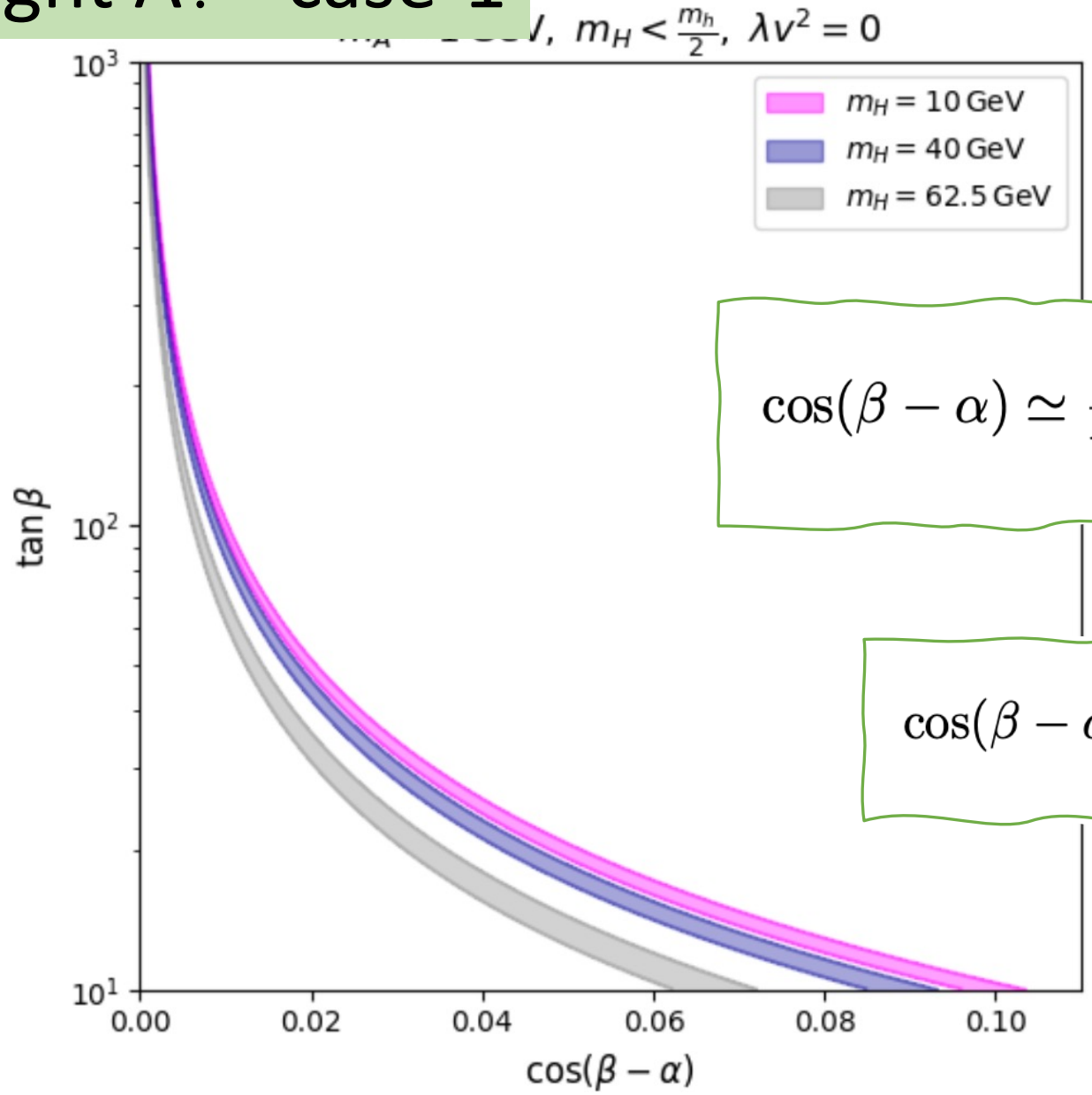
$$g_{hAA} = \frac{1}{2v}\left[\left(2m_H^2 - 2\lambda v^2 - 2m_A^2 - m_h^2\right) s_{\beta-\alpha} + 2\left(m_H^2 - \lambda v^2 - m_h^2\right) t_{2\beta}^{-1} c_{\beta-\alpha}\right].$$

Light H $\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}, \quad m_A \in (54, 600)\ \text{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.$





Light A： case-1



$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}\frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2}, \quad m_H \in \left(5, \frac{m_h}{2}\right) \text{ GeV}.$$

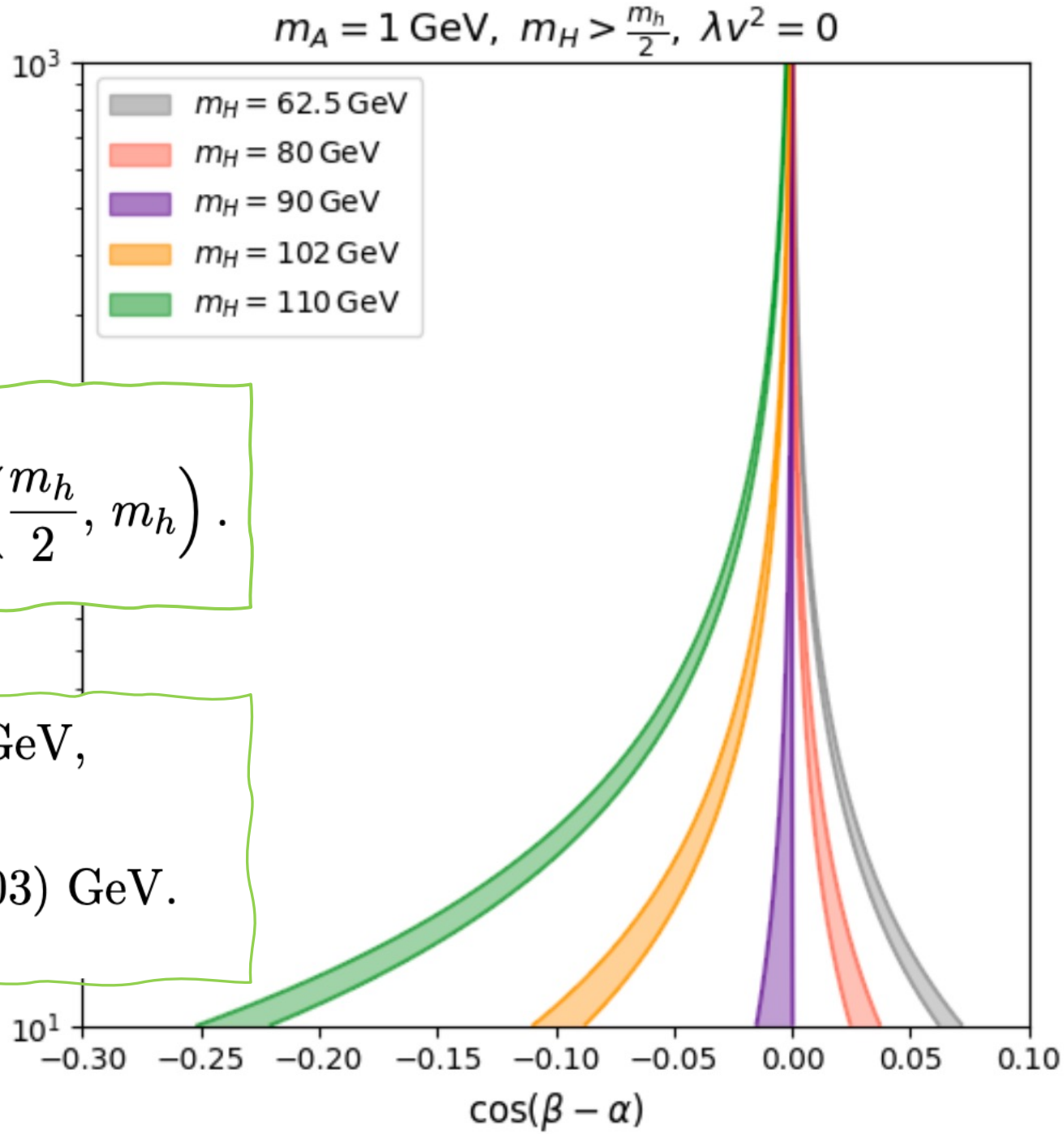
$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}, \quad m_H \in (5, 25) \text{ GeV}.$$

Light A：　case-2

$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}\frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2}, \quad m_H \in \left(\frac{m_h}{2}, m_h\right).$$

$$\cos(\beta-\alpha) \simeq 0, \quad m_H \in (86.9,\ 90)\ \text{GeV},$$

$$\cos(\beta-\alpha) \simeq -\frac{1}{\tan\beta}, \quad m_H \in (101.2,\ 103)\ \text{GeV}.$$



All constraints: allowed LLP at Type-I 2HDM

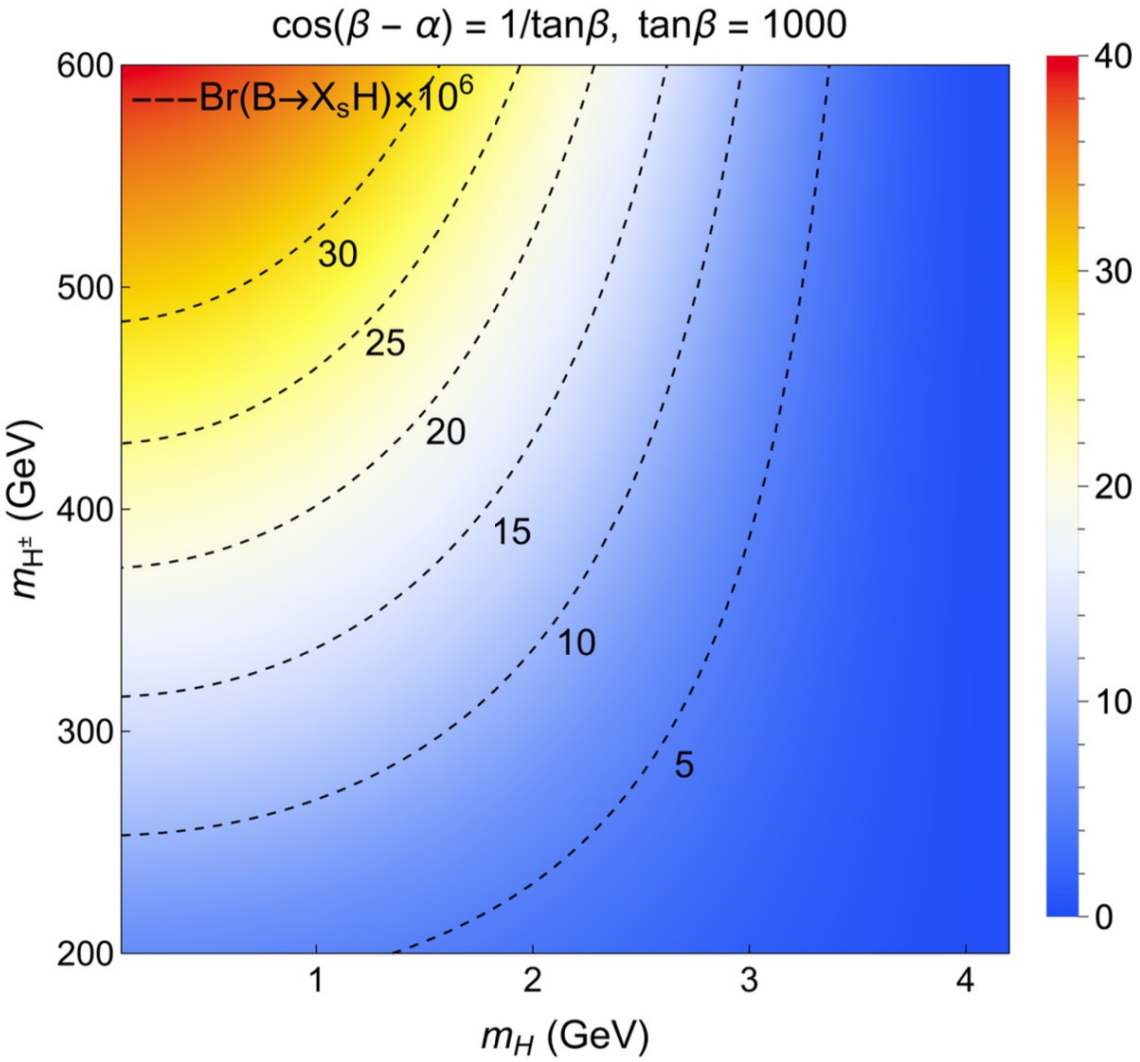
$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}, \quad m_A \in (54, 600)\ \text{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.$$

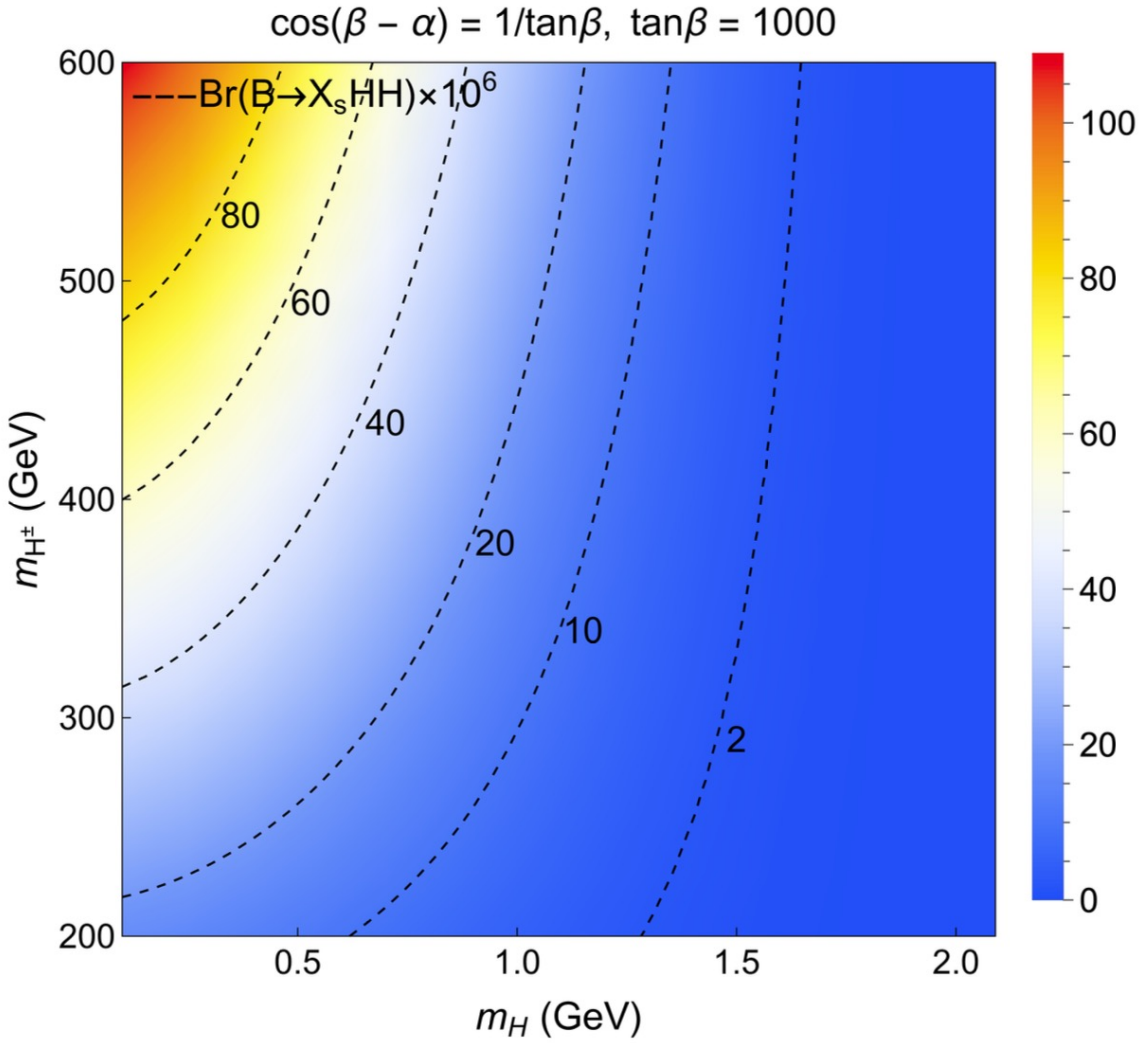
$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}\frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2}, \quad m_H \in (54, m_h)\ \text{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.$$

$$\cos(\beta-\alpha) = 0, \quad m_H \in (86.9, 90)\ \text{GeV}, \quad m_{H^\pm} \sim m_H, \quad \lambda v^2 = 0,$$

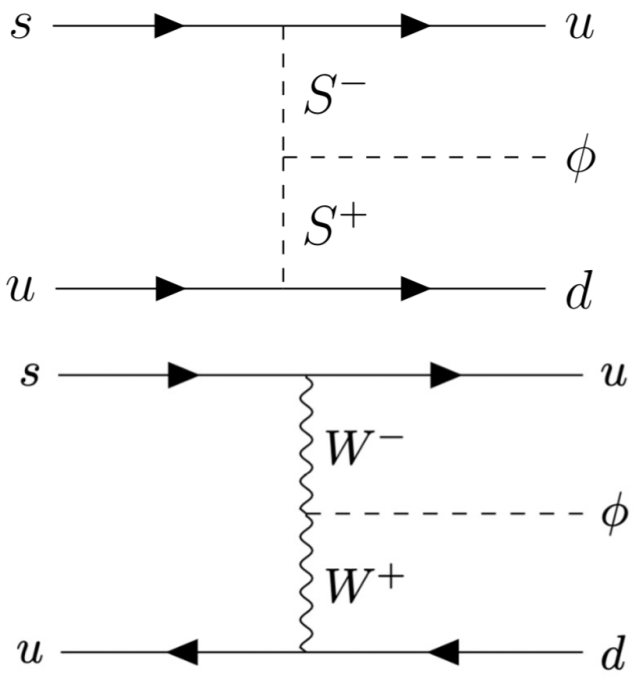
$$\cos(\beta-\alpha) = -\frac{1}{\tan\beta}, \quad m_H \in (101.2, 103)\ \text{GeV}, \quad m_{H^\pm} \sim m_H, \quad \lambda v^2 = 0.$$

Collider analysis





Production: CP even scalar



$$\mathcal{L} = -\frac{1}{2}m_\phi^2\phi^2 - \sum_f \xi_\phi^f \frac{m_f}{v}\phi\bar{f}f + \xi_\phi^W \frac{2m_W^2}{v}\phi W^{\mu+}W_\mu^- + \xi_\phi^Z \frac{m_Z^2}{v}\phi Z^\mu Z_\mu$$

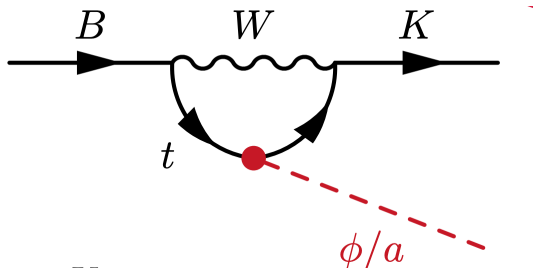
$$+\xi_{\phi\phi}^W \frac{g^2}{4}\phi\phi W^{\mu+}W_\mu^- + \xi_{\phi\phi}^Z \frac{g^2}{8\cos^2\theta_W}\phi\phi Z^\mu Z_\mu + \xi_\phi^g \frac{\alpha_s}{12\pi v}\phi G_{\mu\nu}^a G^{a\mu\nu} + \xi_\phi^\gamma \frac{\alpha_{\rm ew}}{4\pi v}\phi F_{\mu\nu}F^{\mu\nu}$$

$$\mathrm{Br}(K^\pm \to \pi^\pm\phi) = \frac{1}{\Gamma_{K^\pm}}\frac{2p_\phi^0}{m_{K^\pm}}\frac{|\mathcal{M}|^2}{16\pi m_{K^\pm}},$$

Main contribution

$$\mathcal{M}(K^\pm \to \pi^\pm\phi) = G_F^{1/2}2^{1/4}\xi_\phi^W \left[\frac{7\lambda(m_{K^\pm}^2 + m_{\pi^\pm}^2 - m_\phi^2)}{18} - \frac{7Am_{K^\pm}^2}{9}\right] + \frac{\xi_\phi^{ds}}{2\sqrt{}}m_s\frac{m_{K^\pm}^2 - m_{\pi^\pm}^2}{m_s - m_d}f_0^{K^\pm\pi^\pm}(q^2)$$

$$\frac{\mathrm{Br}(B \to X_s\phi)}{\mathrm{Br}(B \to X_c e\nu)} = \frac{\Gamma(b \to s\phi)}{\Gamma(b \to ce\nu)} = \frac{12\pi^2v^2}{m_b^2}(1 - \frac{m_\phi^2}{m_b^2})^2\frac{1}{f(m_c^2/m_b^2)}\left|\frac{\xi_\phi^{bs}}{V_{cb}}\right|^2$$



b: 4.18 GeV, B: around 5.3 GeV,

Decay: CP even scalar

$m_\phi < 2$ GeV

$$H \to \pi\pi$$
$$H \to KK$$
$$H \to \pi\pi\pi\pi$$

$$\Gamma_{\pi\pi} = \frac{3G_F}{16\sqrt{2}\pi m_\Phi}\beta_\pi \left| \xi_\Phi^{gg}\frac{2}{27}(\Theta_\pi - \Gamma_\pi - \Delta_\pi) + \frac{m_u\xi_\Phi^u + m_d\xi_\Phi^d}{m_u + m_d}\Gamma_\pi + (\xi_\Phi^s)\Delta_\pi \right|^2$$

$$\Gamma_{KK} = \frac{G_F}{4\sqrt{2}\pi m_\Phi}\beta_K \left| \xi_\Phi^{gg}\frac{2}{27}(\Theta_K - \Gamma_K - \Delta_K) + \frac{m_u\xi_\Phi^u + m_d\xi_\Phi^d}{m_u + m_d}\Gamma_K + (\xi_\Phi^s)\Delta_K \right|^2$$

$$\Gamma_\pi = \left\langle \pi\pi \left| m_u\bar{u}u + m_d\bar{d}d \right| 0 \right\rangle, \qquad \Delta_\pi = \left\langle \pi\pi \left| m_s\bar{s}s \right| 0 \right\rangle, \qquad \Theta_\pi = \left\langle \pi\pi \left| \Theta_\mu^\mu \right| 0 \right\rangle$$

Leading order chiral perturbation theory

$$\Gamma_\pi^0 = m_\pi^2, \qquad \Delta_\pi^0 = 0, \qquad \Theta_\pi^0 = s + 2m_\pi^2$$
$$\Gamma_K^0 = \frac{1}{2}m_\pi^2, \qquad \Delta_K^0 = m_K^2 - \frac{1}{2}m_\pi^2, \qquad \Theta_K^0 = s + 2m_K^2$$

$m_\phi < 0.5$ GeV

Decay: CP even scalar

$$H \to \pi\pi$$
$$H \to KK$$
$$H \to \pi\pi\pi\pi$$

$m_\phi < 2$ GeV

$$\Gamma_{\pi\pi} = \frac{3G_F}{\beta} \left| \xi^{gg}_\Phi \, 2 \, (\Theta \quad \Gamma \quad \Delta_\pi) + \frac{m_u \xi^u_\Phi + m_d \xi^d_\Phi}{} \Gamma_\pi + (\xi^s_\Phi)\Delta_\pi \right|^2$$

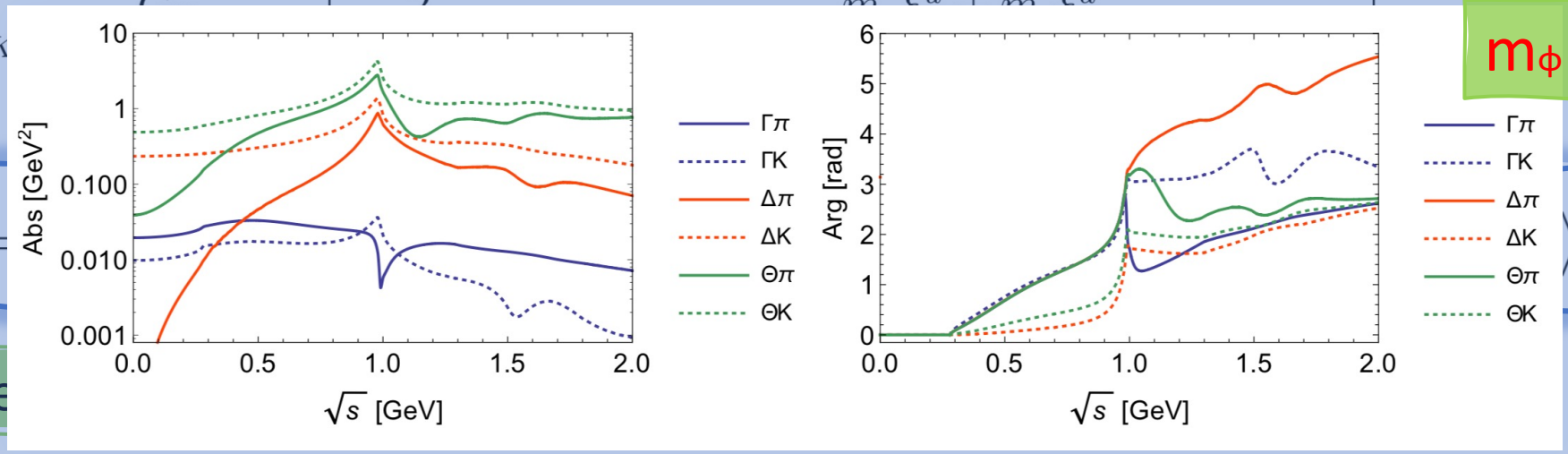
$$\Gamma_{KK} = \left| \quad 2 \quad m \quad \xi^u + m \quad \xi^d \right|^2$$

$$\Gamma_\pi =$$

Le

Dispersive Analysis

$m_\phi > 0.5$ GeV



$$\Gamma_\pi^0 = m_\pi^2, \qquad \Delta_\pi^0 = 0, \qquad \Theta_\pi^0 = s + 2m_\pi^2$$

$$\Gamma_K^0 = \frac{1}{2} m_\pi^2, \qquad \Delta_K^0 = m_K^2 - \frac{1}{2} m_\pi^2, \qquad \Theta_K^0 = s + 2m_K^2$$

https://github.com/shiggs90/Light_scalar_decay.git.

BMs

For light H:

$$\cos(\beta-\alpha)=\frac{1}{\tan\beta},\quad m_A=200\ \text{GeV},\quad m_{H^\pm}=222.35\pm0.95\ \text{GeV},\quad \lambda v^2=0,$$

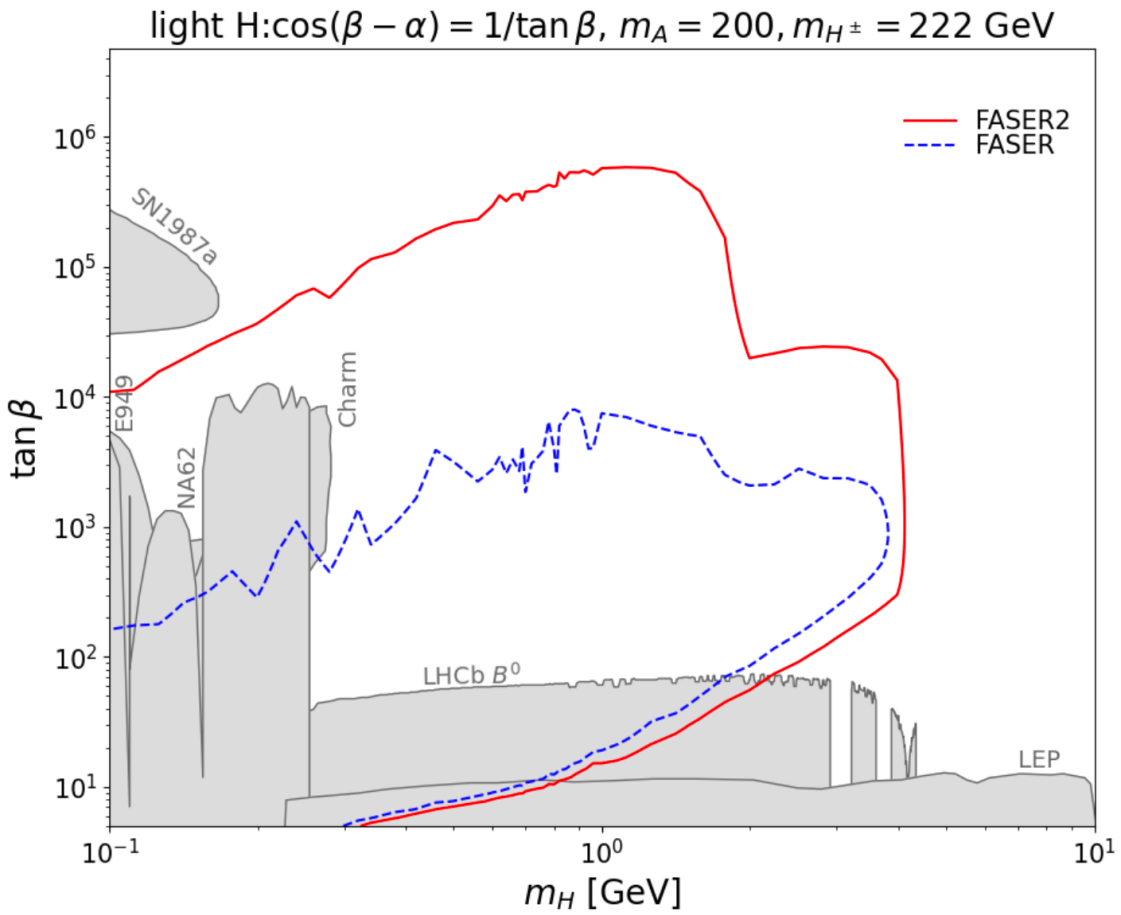
$$\cos(\beta-\alpha)=\frac{1}{\tan\beta},\quad m_A=400\ \text{GeV},\quad m_{H^\pm}=413.15\pm0.45\ \text{GeV},\quad \lambda v^2=0,$$

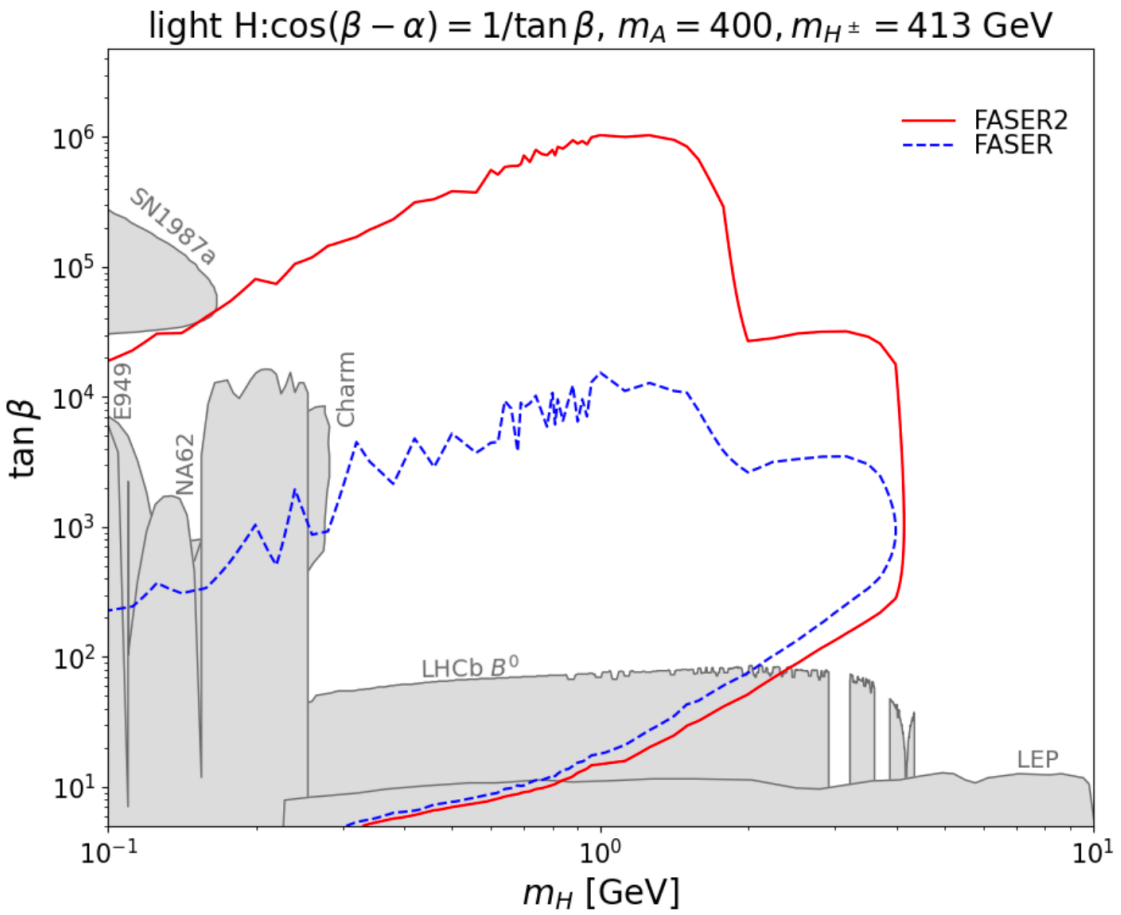
For light A:

$$\cos(\beta-\alpha)=0,\quad m_H=90\ \text{GeV},\quad m_{H^\pm}=118.75\pm2.25\ \text{GeV},\quad \lambda v^2=0,$$

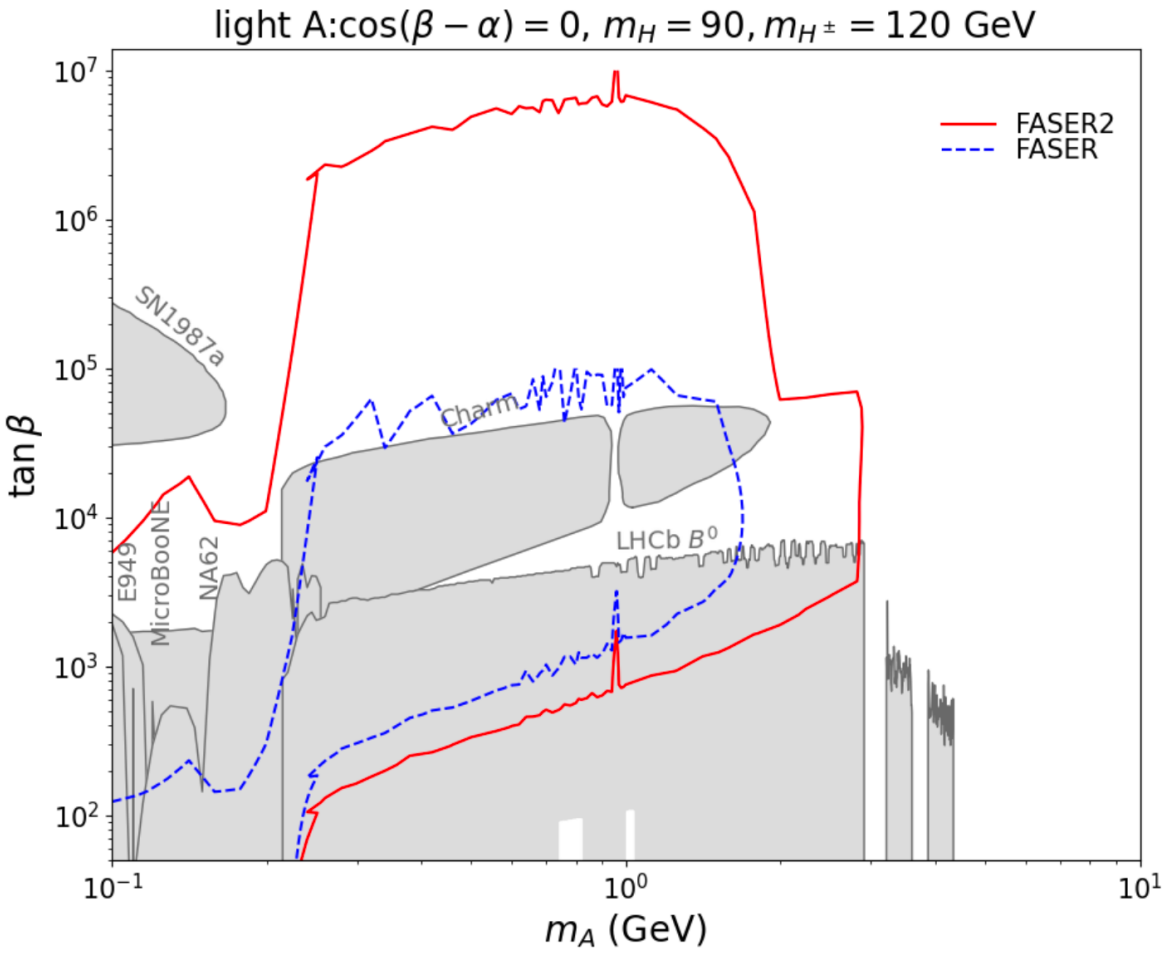
$$\cos(\beta-\alpha)=-\frac{1}{\tan\beta},\quad m_H=102\ \text{GeV},\quad m_{H^\pm}=131.05\pm1.95\ \text{GeV},\quad \lambda v^2=0.$$

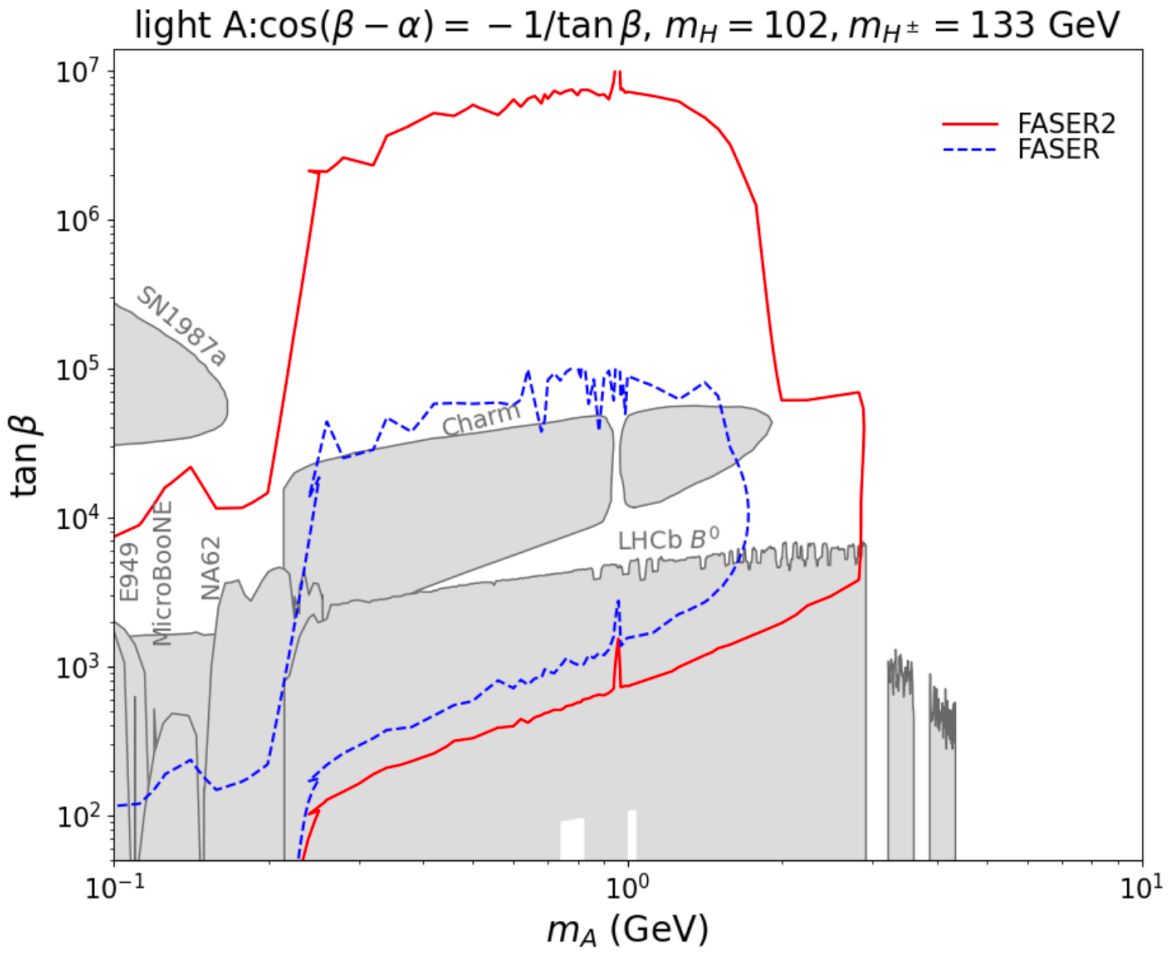
BMs


light H:cos(β − α) = 1/tan β, m_A = 200, m_H± = 222 GeV
FASER2
FASER
SN1987a
E949
NA62
Charm
LHCb B⁰
LEP
tan β
m_H [GeV]


light H:cos(β − α) = 1/tan β, m_A = 400, m_H± = 413 GeV
FASER2
FASER
SN1987a
E949
NA62
Charm
LHCb B⁰
LEP
tan β
m_H [GeV]

BMs


light A:cos(β − α) = 0, $m_H = 90$, $m_{H^\pm} = 120$ GeV
FASER2
FASER
SN1987a
Charm
LHCb B^0
E949
MicroBooNE
NA62
tan β
m_A (GeV)

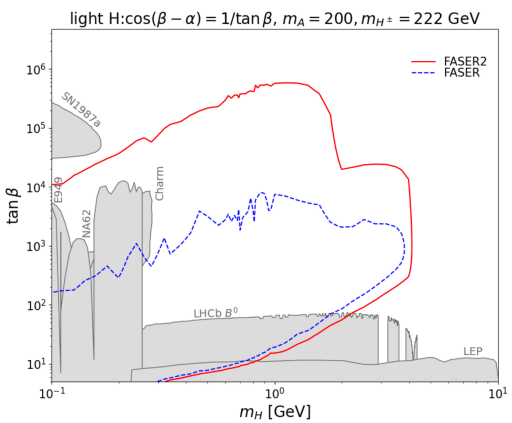

light A:cos(β − α) = − 1/tan β, $m_H = 102$, $m_{H^\pm} = 133$ GeV
FASER2
FASER
SN1987a
Charm
LHCb B^0
E949
MicroBooNE
NA62
tan β
m_A (GeV)

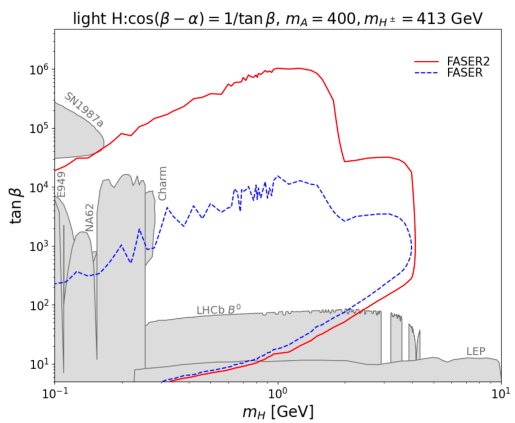
Conclusion

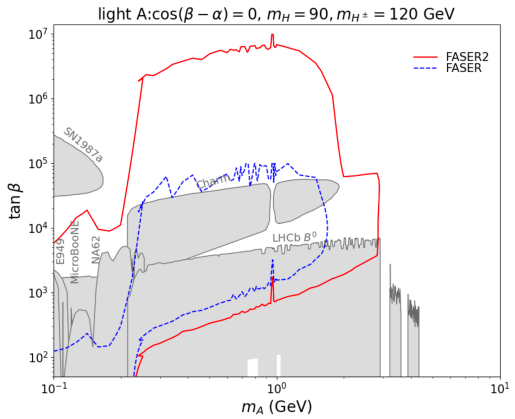
- Complete allowed LLP at Type-I 2HDM

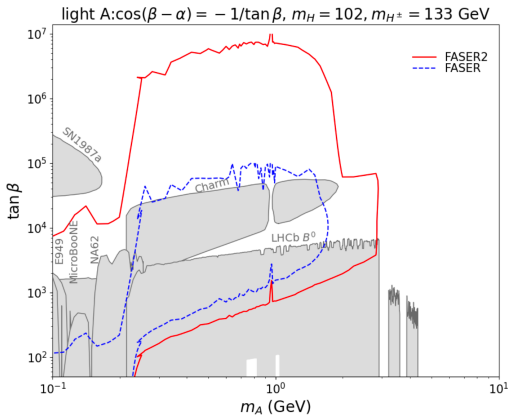
$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}, \quad m_A \in (54, 600)\ \text{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.$$

$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}\frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2}, \quad m_H \in (54, m_h)\ \text{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.$$









Thanks !