Long-lived neutral scalar searches at FASER

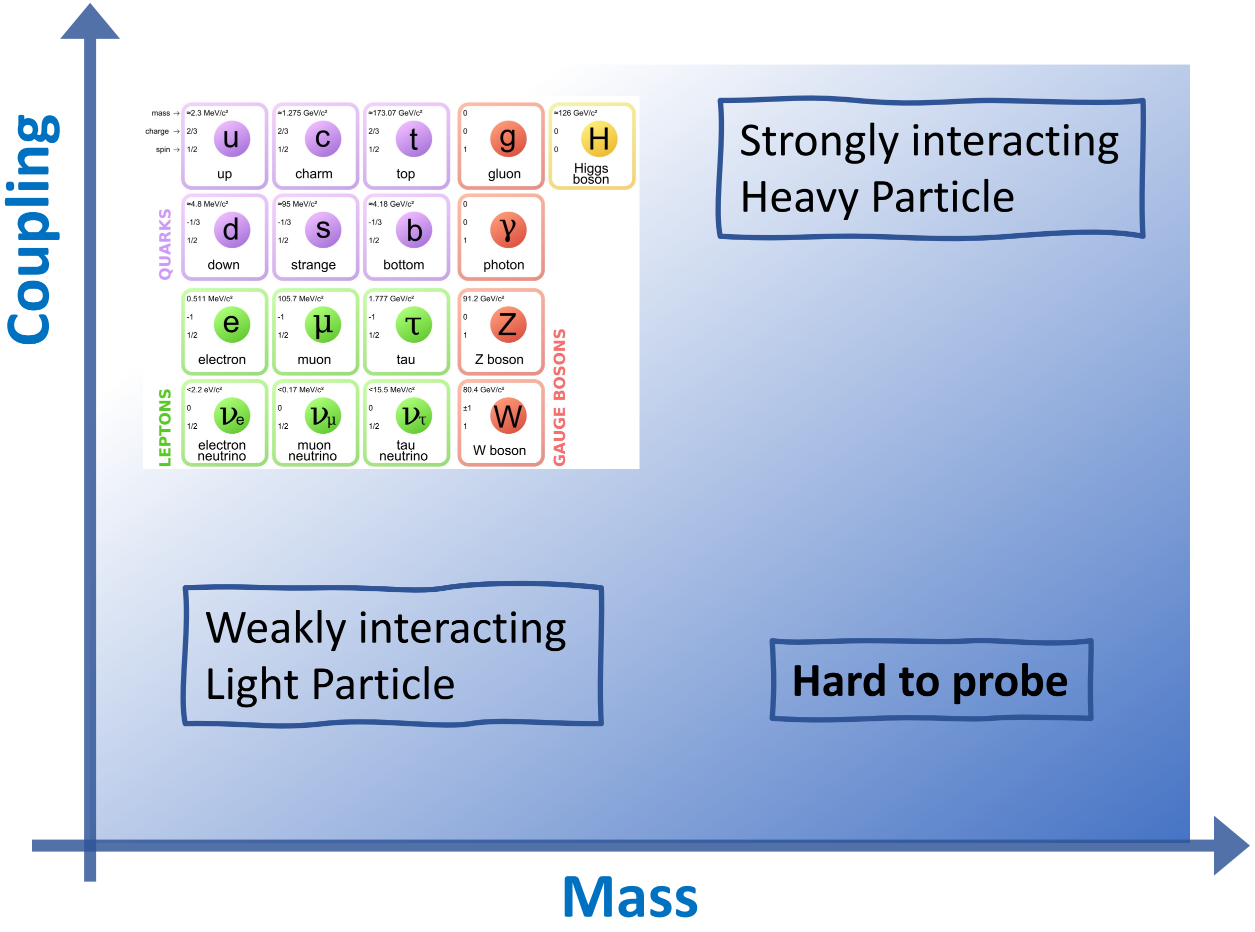
Wei Su

2212.06186 (F. Kling, S. Li, S. Su, H.Song, WS)

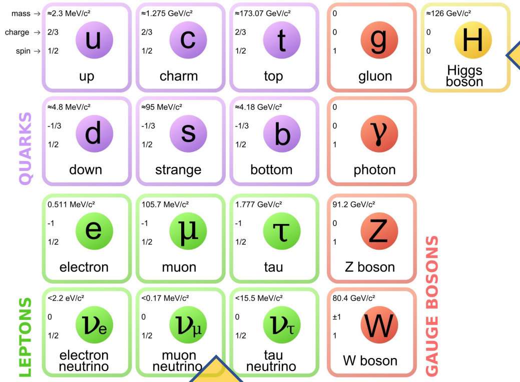
outline

- Motivation: Brief introduction to LLP
- Method: Brief introduction to FASER
- General study
    - Production
    - Decay
    - Constraints
- Case study: 2HDM results

Motivation: LLP

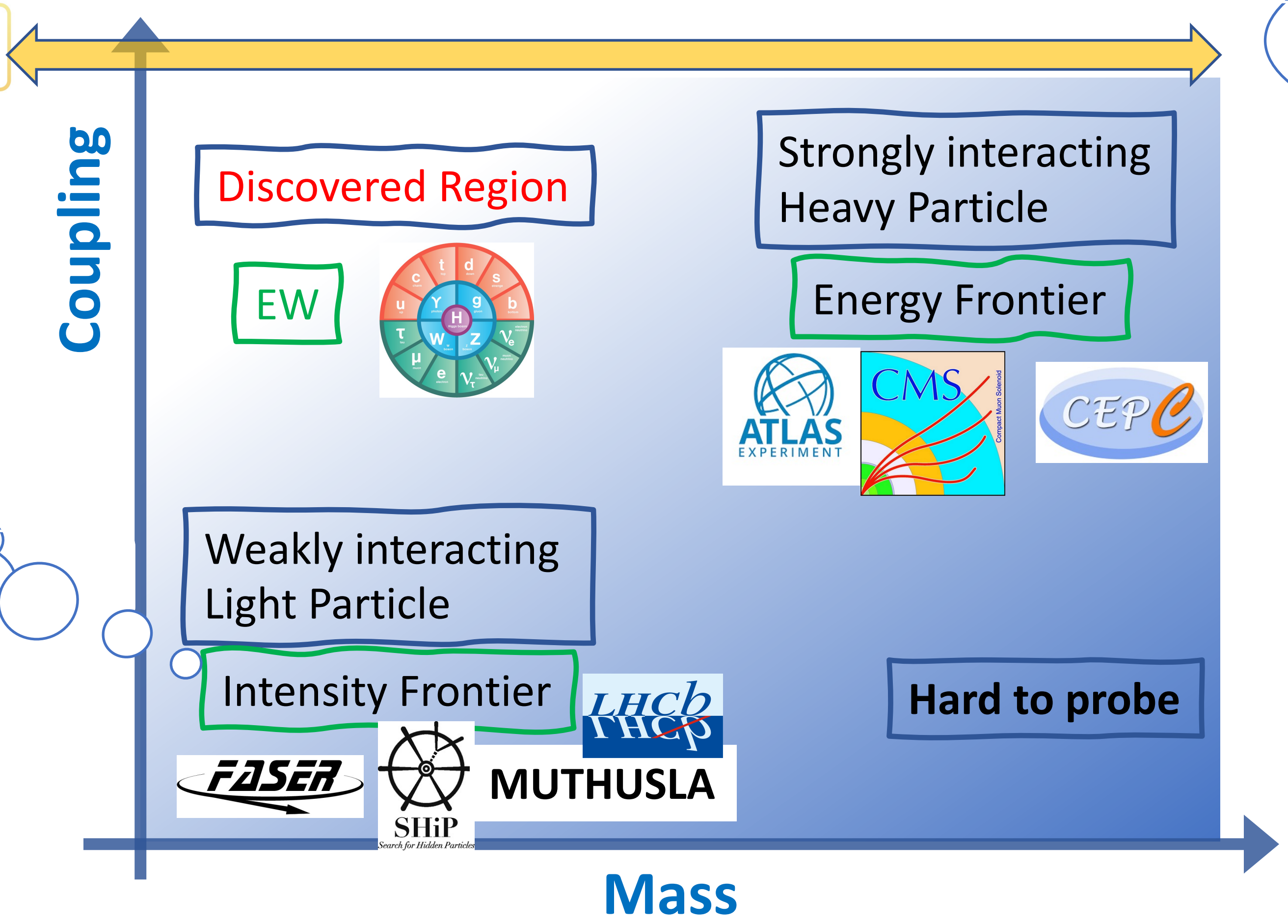


Motivation: LLP



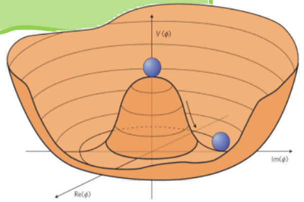
WIMP, Dark Photon ..

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



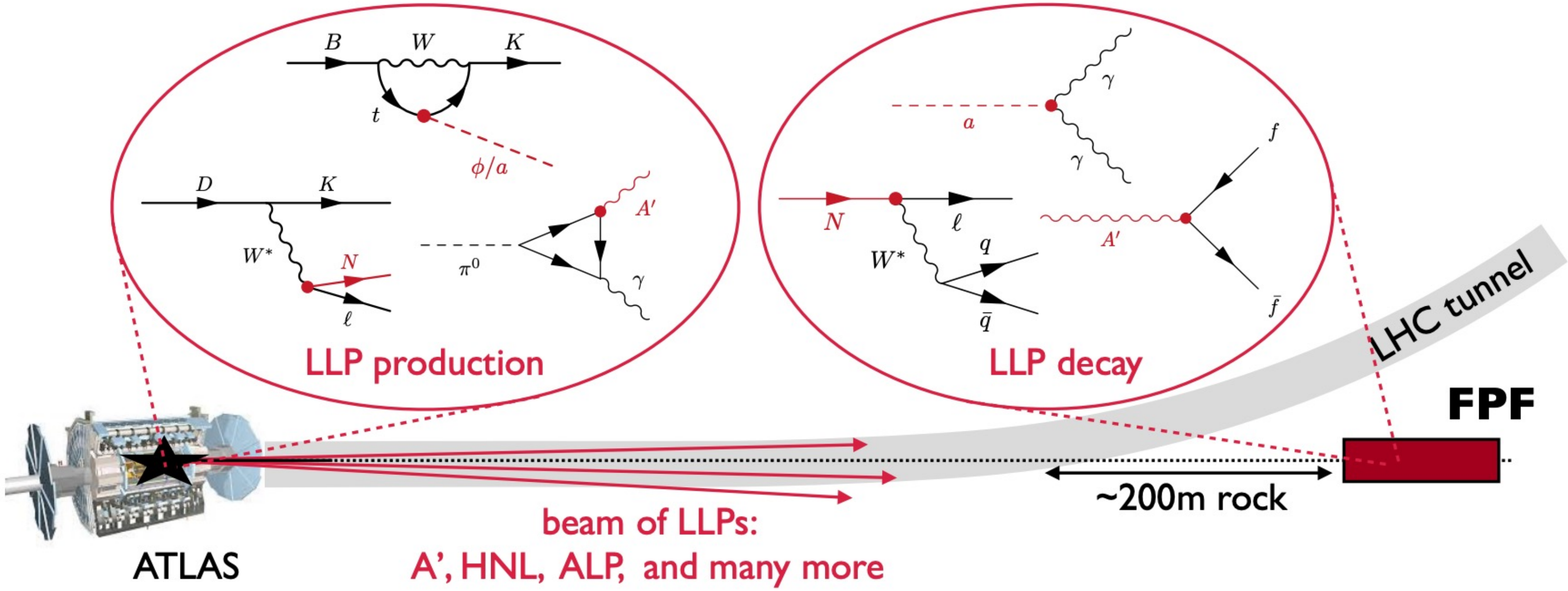
DM, Dark Photon …

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



FASER: ForwArd Search ExpeRiment

$pp \to$ LLP + X, LLP travels ~480 m, LLP $\to$ charged tracks + X



many hadrons: 10^{17} π, 10^{16} K, 10^{15} D, 10^{14} B with E~TeV

More details: K. Li 's Talk

Production

PP → mesons → LLP + X, LLP → charged tracks + X

Data base: FORESEE : 2105.07077 F. Kling and S. Trojanowski,

Particle category	Particles	Generators			
		EPOS-LHC	QGSJET II-04	SIBYLL 2.3c	Pythia 8.2
Photons	γ	✓	✓	✓	
Light hadrons	π^0, π^+, η, η', ω, ρ, ϕ, n, p K^+, K_L, K_S, K_0^*, K^{*+}, Λ	✓	✓	✓	
Charm hadrons	D^+, D^0, D_s^+, Λ_c			✓	✓
Beauty hadrons	B^0, B^+, B_s, B_c^+, Λ_b				✓
Heavy quarks	c, b				✓
Quarkonia	J/Ψ, $\psi(2S)$, $\Upsilon(nS)$				✓
Weak bosons	W^+, Z, h				✓

Production

Data base: FORESEE

- the `distance` from the IP in meter (default: 480)
- the `length` in meter (default: 5)
- the `luminosity` in units of fb^-1 (default: 3000)
- the `selection` : (default: `np.sqrt(x.x**2 + x.y**2)< 1`)
- the decay `channels` which the detector can see

Particle category	Particles	Generators			
		EPOS-LHC	QGSJET II-04	SIBYLL 2.3c	Pythia 8.2
Photons	γ	✓	✓	✓	
Light hadrons	π^0, π^+, η, η', ω, ρ, ϕ, n, p K^+, K_L, K_S, K_0^*, K^{*+}, Λ	✓	✓	✓	
Charm hadrons	D^+, D^0, D_s^+, Λ_c			✓	✓
Beauty hadrons	B^0, B^+, B_s, B_c^+, Λ_b				✓
Heavy quarks	c, b				✓
Quarkonia	J/Ψ, $\psi(2S)$, $\Upsilon(nS)$				✓
Weak bosons	W^+, Z, h				✓

Production

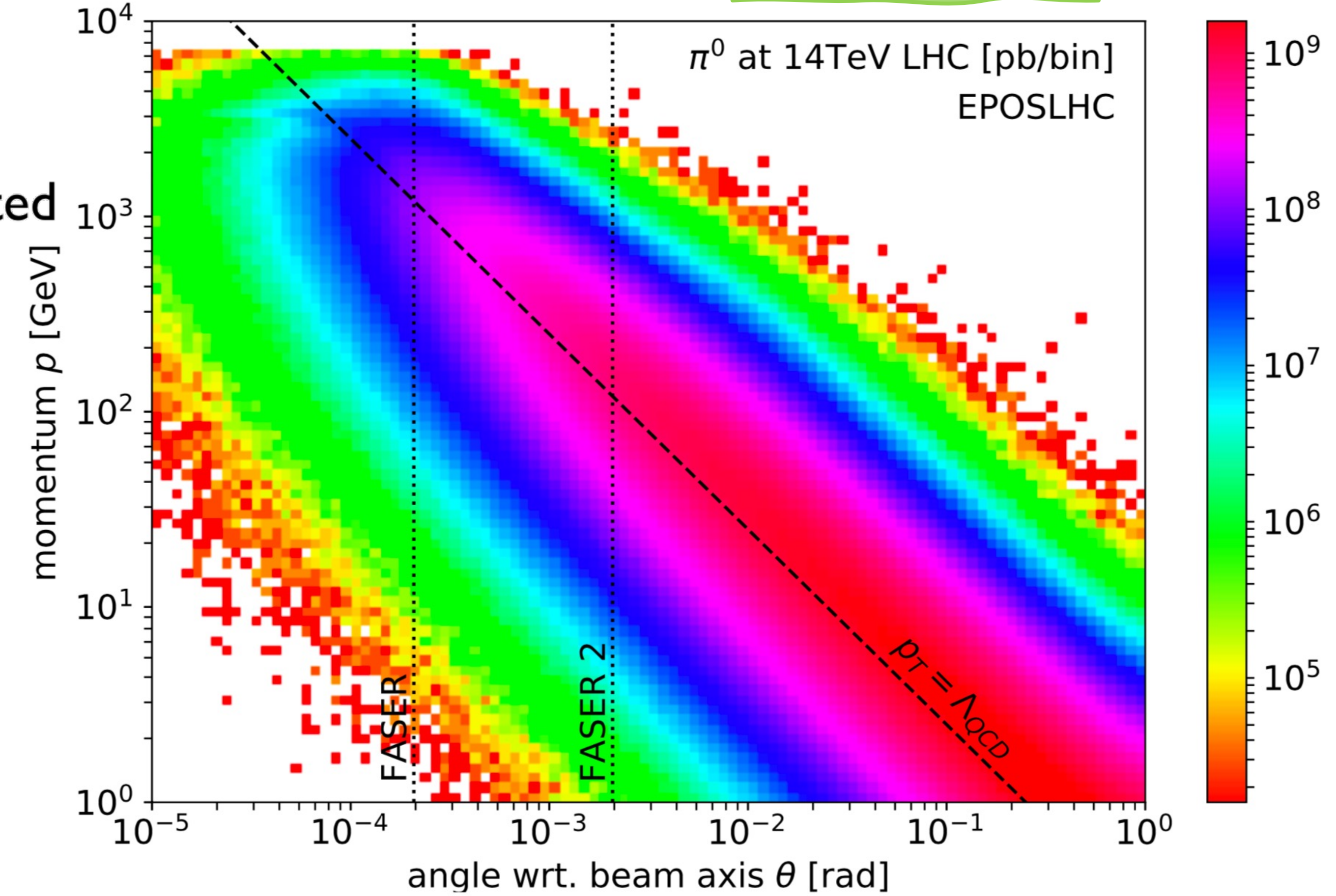
FORESEE

Pion

boosted mesons highly collimated

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

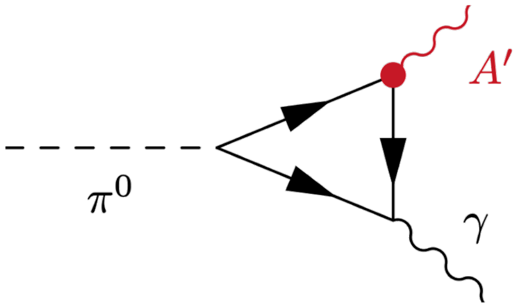
$$N_\pi = 10^{18} \quad \text{at } 3000 \text{ fb}^{-1}$$



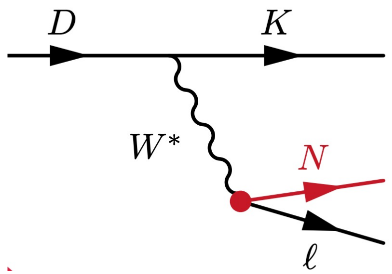
<u>FASER</u>: radius R = 10 cm,
lenght D = 1.5 m,
<u>FASER 2</u>: radius R = 1m,
lenght D = 5 m.

Production: CP even scalar

$$\mathcal{L} = -\frac{1}{2} m_\phi^2 \phi^2 - \sum_f \xi_\phi^f \frac{m_f}{v} \phi \bar{f} f + \xi_\phi^W \frac{2m_W^2}{v} \phi W^{\mu +} W_\mu^- + \xi_\phi^Z \frac{m_Z^2}{v} \phi Z^\mu Z_\mu + \xi_\phi^g \frac{\alpha_s}{12\pi v} \phi G_{\mu\nu}^a G^{a\mu\nu} + \xi_\phi^\gamma \frac{\alpha}{4\pi v} \phi F_{\mu\nu} F^{\mu\nu}.$$



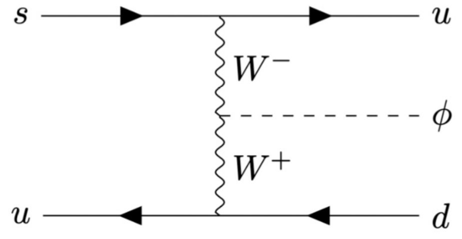
$K \to \pi\phi$, $\eta^{(\prime)} \to \pi\phi$, $D \to X_u\phi$ $B \to X_s\phi$

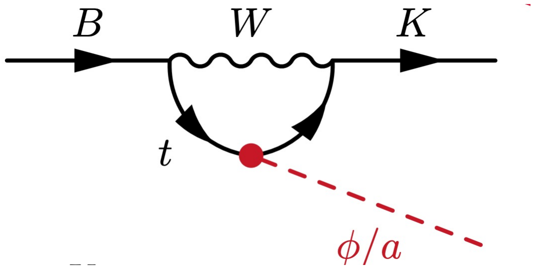


$\pi^+ \to \ell\nu\phi$ $K^+ \to \ell\nu\phi$ $\Upsilon \to \phi\gamma$

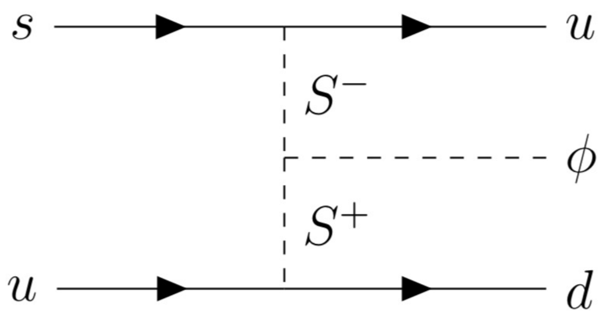
meson	quark content	mass (MeV)
$\pi^\pm$	$u\bar{d}$	139.57018 ± 0.00035
π^0	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$ [a]	134.9766 ± 0.0006
η	$\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}$ [a]	547.853 ± 0.024
η'	$\frac{u\bar{u}+d\bar{d}+s\bar{s}}{\sqrt{3}}$ [a]	957.66 ± 0.24

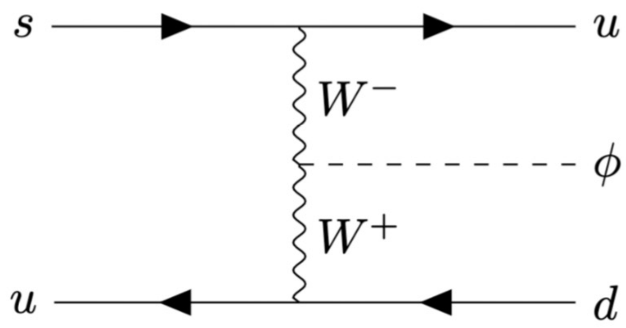
K





Production: CP even scalar





Main contribution

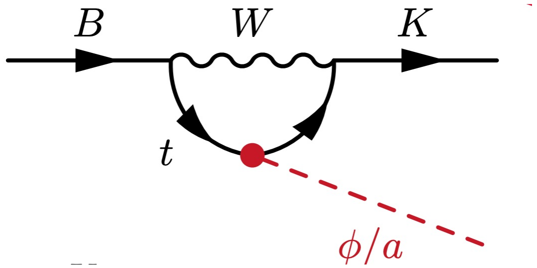
K$^{\pm}$: 493.677 ±0.016 MeV/

K^{0}: 497.611 ±0.013 MeV/

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

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

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



b: 4.18 GeV, B: around 5.3 GeV,

Production: CP odd scalar

$$\mathcal{L}_A = -\frac{1}{2}m_A^2 A^2 + \sum_{f=u,d,e} \xi_A^f \frac{i m_f}{v} \bar{f}\gamma_5 f A + \xi_A^g \frac{\alpha_s}{4\pi v} A G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \xi_A^\gamma \frac{\alpha}{4\pi v} A F_{\mu\nu}\tilde{F}^{\mu\nu}$$

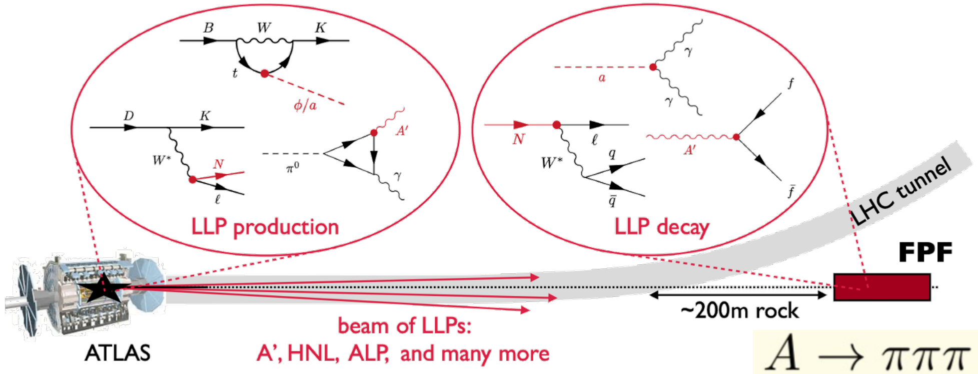
CP-odd particle mixing production: contribute mainly at mass peak

$$\begin{aligned} A &= O_{A3}\pi_3 + O_{A8}\pi_8 + O_{A9}\pi_9 + O_{AA}A \\ &\approx O_{A3}\pi_3 + O_{A\eta}\eta + O_{A\eta'}\eta' + O_{AA}A \end{aligned}$$

$$\mathcal{L}_\chi \ni -\frac{1}{2}(\pi_3\ \pi_8\ \pi_9\ A)\begin{pmatrix} m_\pi^2 & 0 & 0 & \delta m_3^2 \\ 0 & m_{\pi_8}^2 & \Delta & \delta m_8^2 \\ 0 & \Delta & m_{\pi_9}^2 & \delta m_9^2 \\ \delta m_3^2 & \delta m_8^2 & \delta m_9^2 & \bar{m}_A^2 \end{pmatrix}\begin{pmatrix} \pi_3 \\ \pi_8 \\ \pi_9 \\ A \end{pmatrix}$$

$$\sigma_A \approx O^2_{A\pi^0}\sigma_{\pi^0} + O^2_{A\eta}\sigma_\eta + O^2_{A\eta'}\sigma_{\eta'},$$

Decay : CP even scalar



Well studied

$A \to \gamma\gamma$	$H \to \gamma\gamma$
$A \to e^+e^-$	$H \to e^+e^-$
$A \to \mu^+\mu^-$	$H \to \mu^+\mu^-$
$A \to \tau^+\tau^-$	$H \to \tau^+\tau^-$
$A \to q\bar{q}$	$H \to c\bar{c}$
$A \to gg$	$H \to s\bar{s}$
	$H \to gg$

Scale-ind

Scale > 2/3 GeV

?

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

$A \to \pi\pi\pi$
$A \to \eta\pi\pi$
$A \to \eta'\pi\pi$
$A \to \eta\eta\pi$
$A \to KK\pi$
$A \to \gamma\pi\pi$
$A \to \eta\eta'\pi$
$A \to \eta'\eta'\pi$
$A \to \eta\eta\eta$
$A \to \eta\eta\eta'$
$A \to \eta\eta'\eta'$
$A \to \eta'\eta'\eta'$
$A \to \eta KK$
$A \to \eta' KK$

Chiral Perturbativity…

arXiv:1809.01876
arXiv:1612.06538

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

$m_\phi < 2$ GeV

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

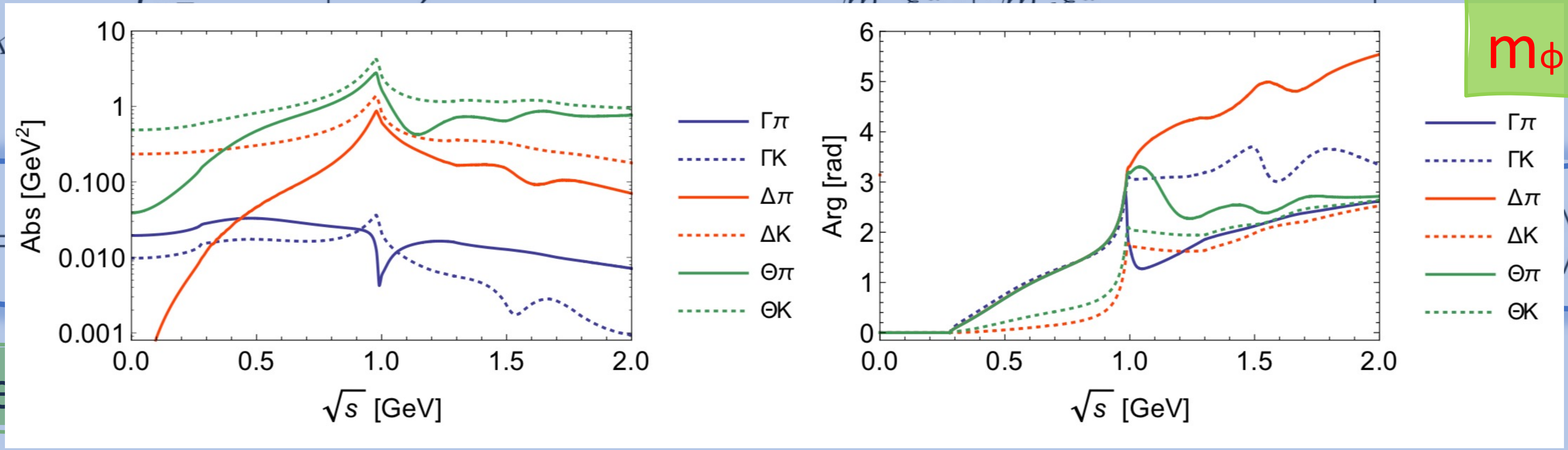
$\Gamma_{\pi\pi}$ … $3G_F$ … β … $\left| \xi^{gg} \right|^2$ … $\frac{m_u \xi^u_\Phi + m_d \xi^d_\Phi}{\ldots} \Gamma_\pi + (\xi^s_\Phi) \Delta_\pi \Big|^2$

Dispersive Analysis

Γ_{KK} … $m_u \xi^u + m_d \xi^d$ … $|^2$

$\Gamma_\pi =$ …

Le…



$m_\phi > 0.5$ GeV

$$\Gamma^0_\pi = m_\pi^2, \qquad \Delta^0_\pi = 0, \qquad \Theta^0_\pi = s + 2m_\pi^2$$

$$\Gamma^0_K = \frac{1}{2} m_\pi^2, \qquad \Delta^0_K = m_K^2 - \frac{1}{2} m_\pi^2, \qquad \Theta^0_K = s + 2m_K^2$$

Decay: CP odd scalar

arXiv:1612.06538

Hadronic decays into Tri-meson for $\mathbf{m_A \lesssim 1.3}$ GeV

Radiative Hadronic Decays for $\mathbf{m_A \lesssim 1.3}$ GeV

hadronic decays for 1.3 GeV $\lesssim \mathbf{m_A} \lesssim$ 3 GeV (Spectator Model)

$A \to \pi\pi\pi$
$A \to \eta\pi\pi$
$A \to \eta'\pi\pi$
$A \to \eta\eta\pi$
$A \to KK\pi$
$A \to \gamma\pi\pi$
$A \to \eta\eta'\pi$
$A \to \eta'\eta'\pi$
$A \to \eta\eta\eta$
$A \to \eta\eta\eta'$
$A \to \eta\eta'\eta'$
$A \to \eta'\eta'\eta'$
$A \to \eta KK$
$A \to \eta' KK$

Constraints

- current experiments (typically considered)

SN1987a

LEP $\bar{e}e \to Z^* \phi$

CHARM *dipoton*

NA62 $K \to \pi\Phi$

E949 $K^+ \to \pi^+ + \bar{\nu}\nu$

KTeV $K_L \to \pi + \bar{\mu}\mu$

LHCb $B \to K^{(*)} + \bar{\mu}\mu$

MicroBooNE $K^+ \to \pi^+ \chi\,(e^+ e^-)$

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)

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

(v → 246 GeV; m_h → 125. GeV)

Soft Z_2 symmetry breaking: m_{12}^2

Case study: 2HDM

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

	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	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$\cot\beta$	$\tan\beta$	$-\cot\beta$

Small couplings

- Type-I: easy at large $\tan\beta$ for both A and H
- A: impossible for other 3 types
- H: hard for other 3 types (fine-tunned)

Constraint and 2HDM

Benchmark Scenario:
theoretical constraints, Z-pole direct search, invisible h decay

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

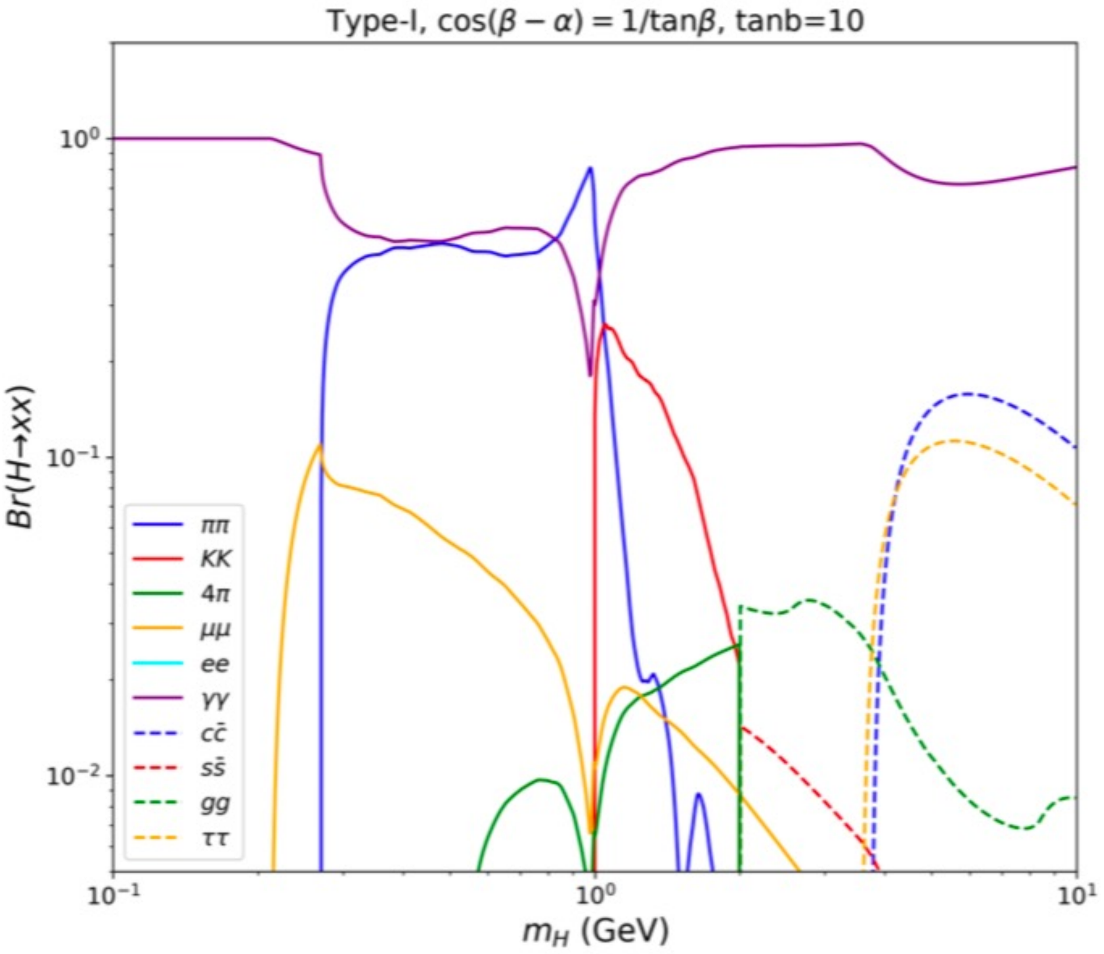
$$Light\ A : \cos(\beta-\alpha) = 0,\ m_H = m_{H^\pm} = 90\ \text{GeV},\ \lambda v^2 = 0\ \text{GeV}^2\ .$$

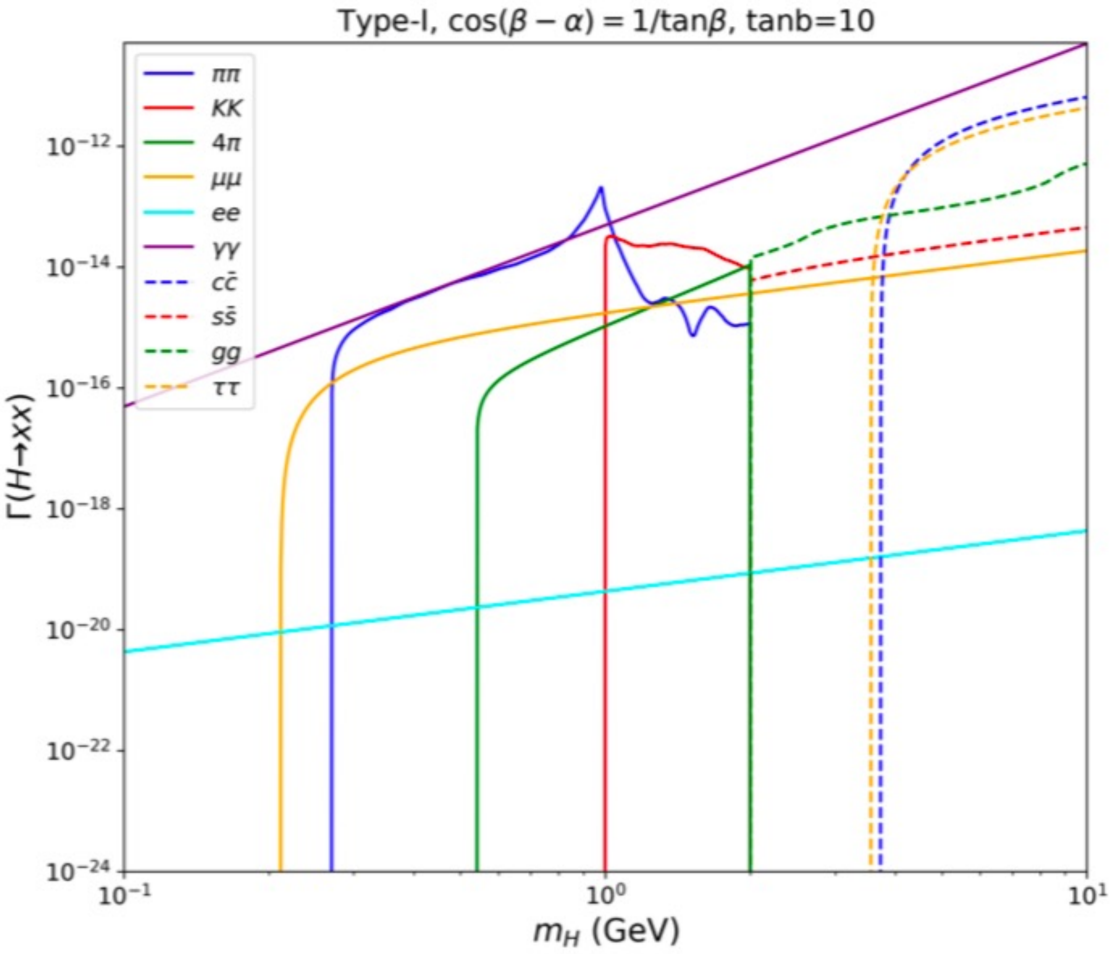
$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta,$$
$$\xi_H^V = c_{\beta-\alpha} = 1/\tan\beta,$$
$$\xi_H^f = c_{\beta-\alpha}(1-s_{\beta-\alpha}) \approx 1/(2\tan^3\beta) + \mathcal{O}(c^5_{\beta-\alpha})$$

Light H is easier to be long-lived

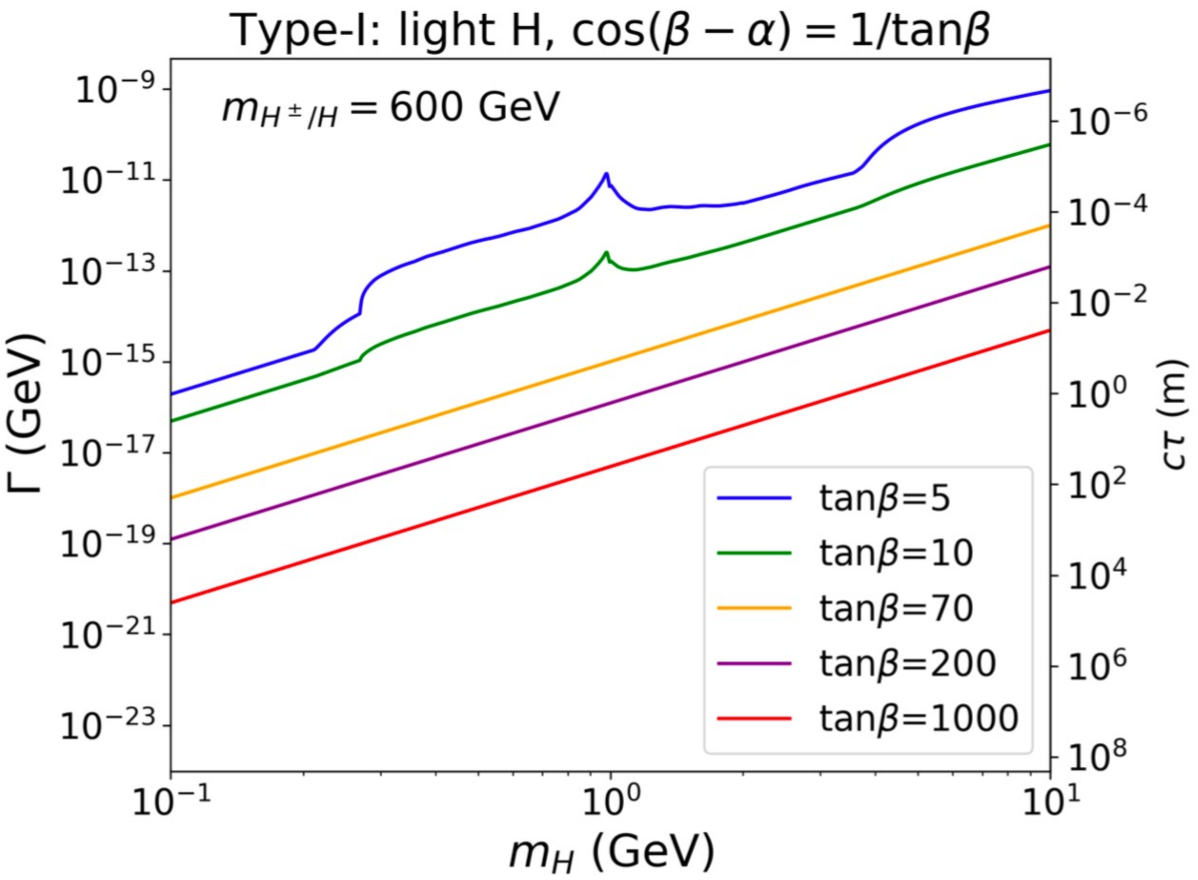
Results: CP even

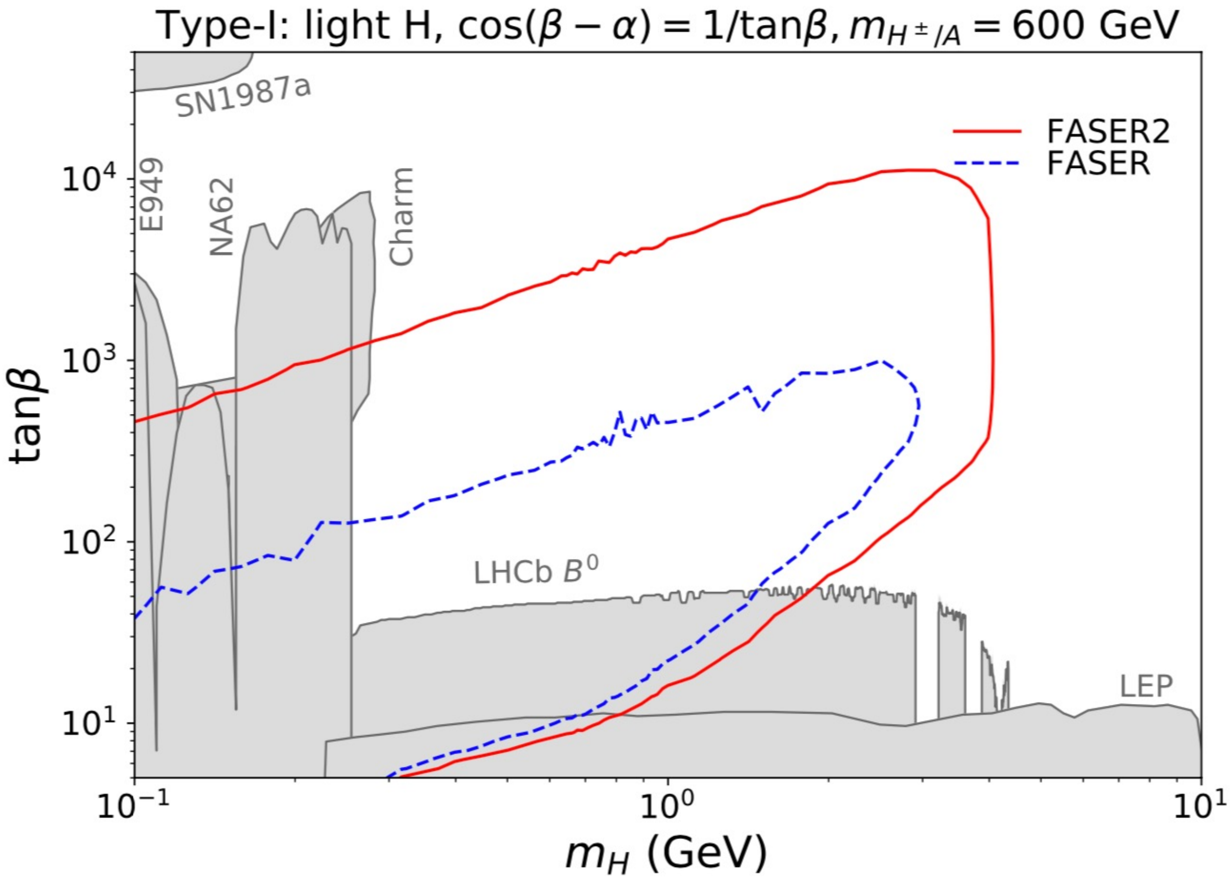
$$\xi_H^V = c_{\beta-\alpha} = 1/\tan\beta,$$
$$\xi_H^f = c_{\beta-\alpha}(1 - s_{\beta-\alpha}) \approx 1/(2\tan^3\beta) + \mathcal{O}(c_{\beta-\alpha}^5)$$





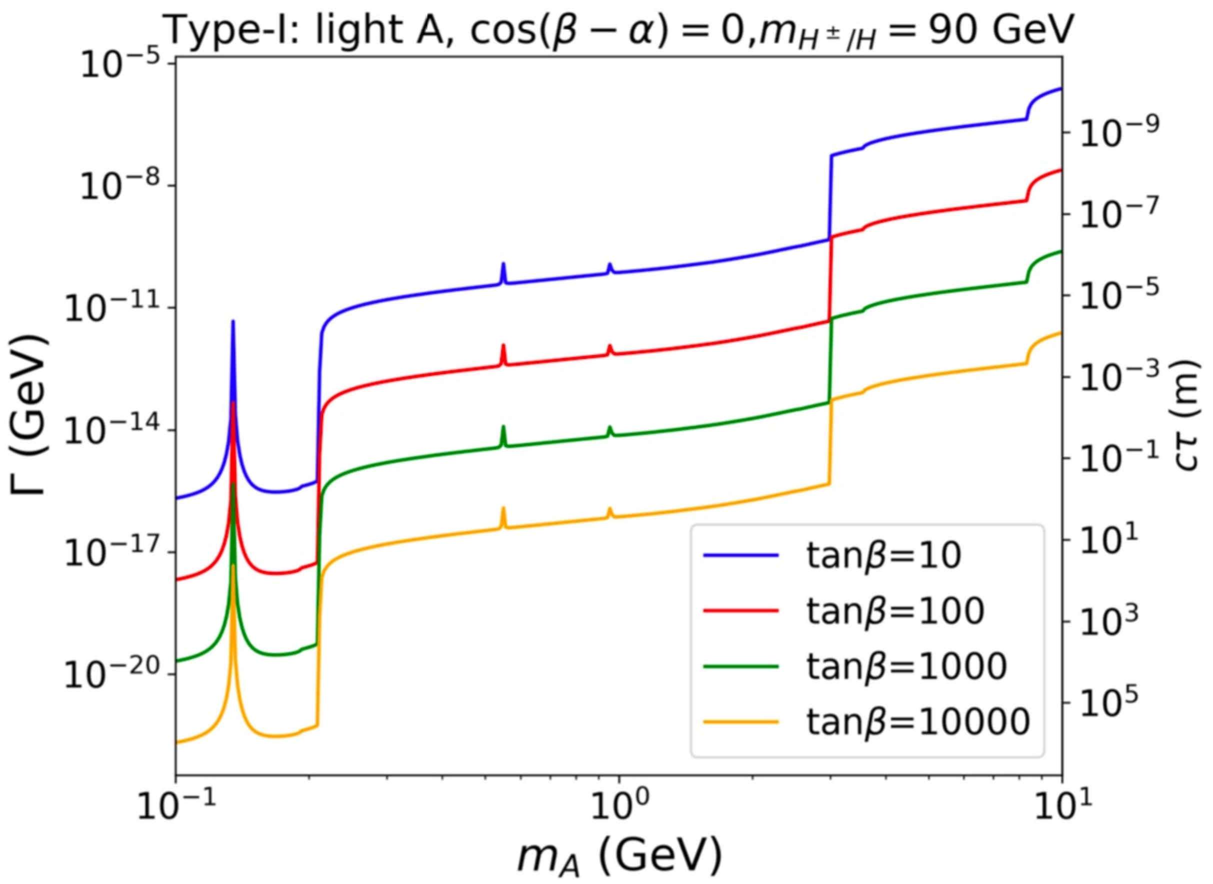
Results: CP even

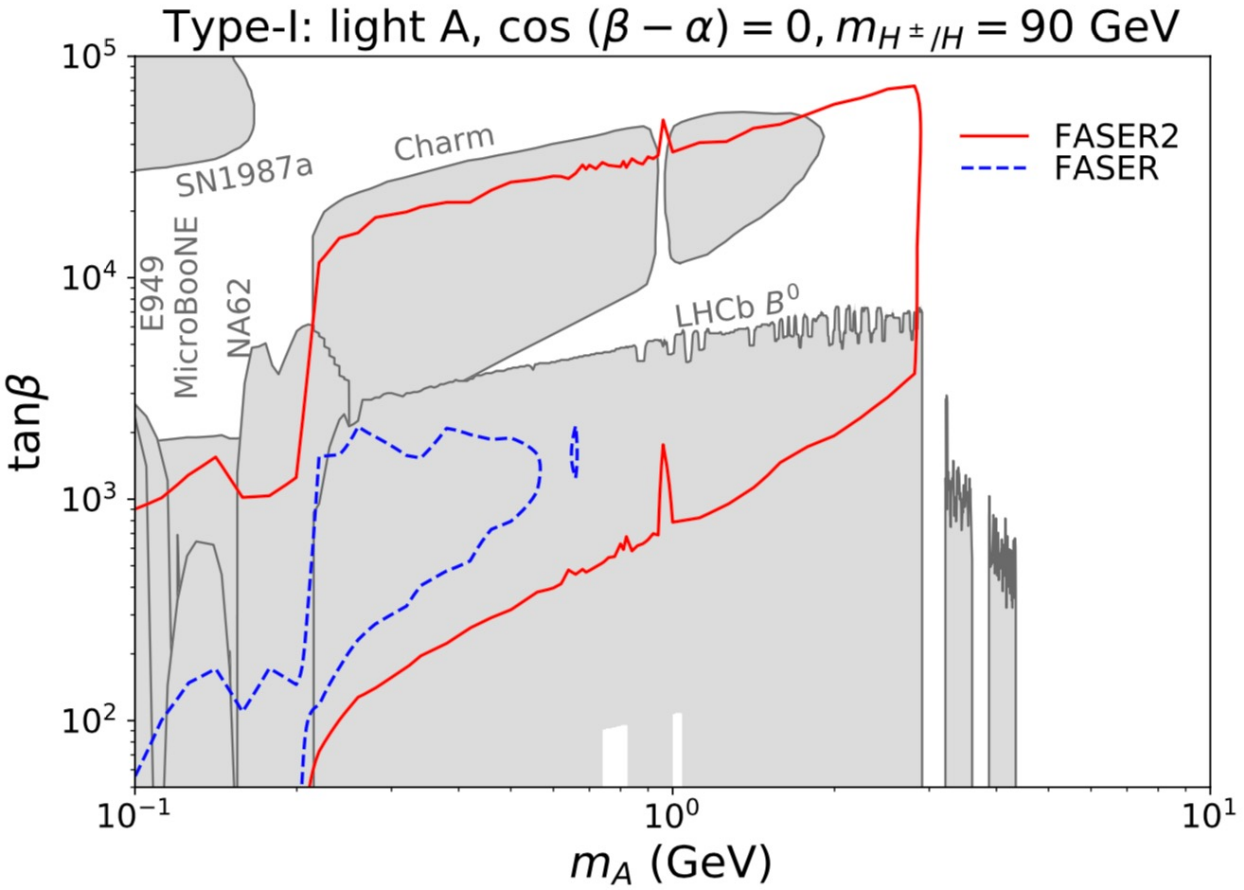




Results: CP odd

$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta$$



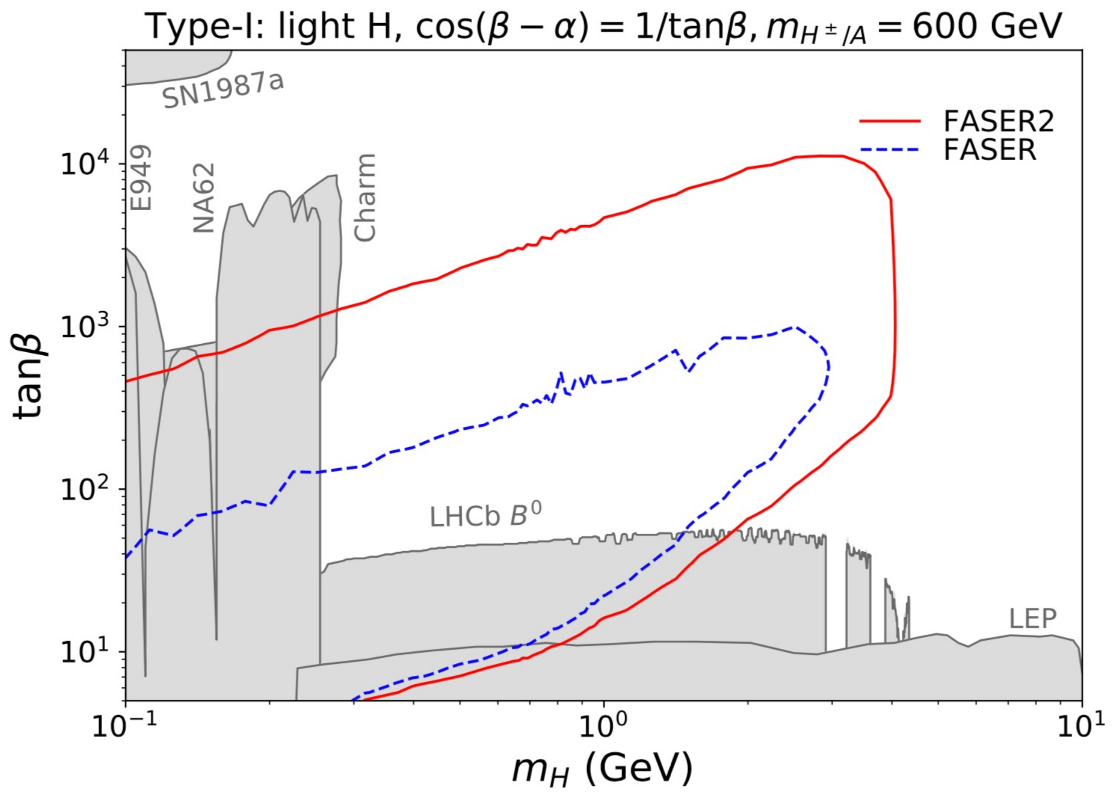


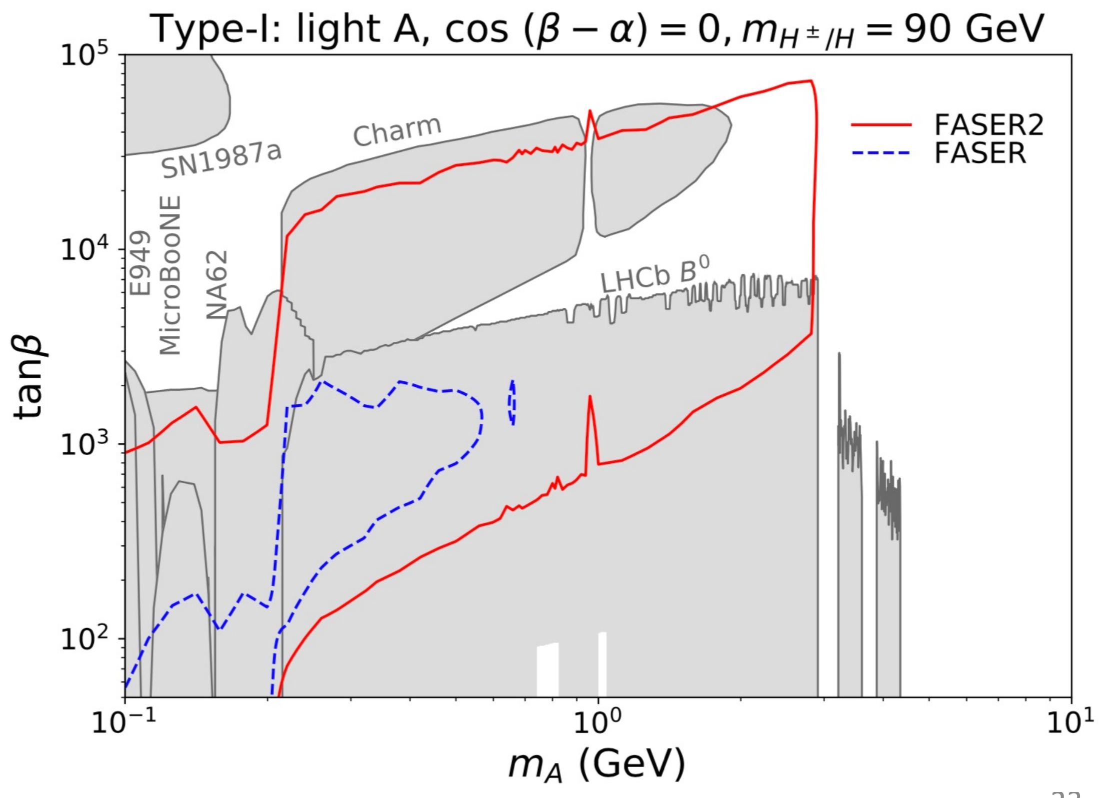
Results: for case study

- higher luminosity helps to reach the weaker coupling region.
- A larger detector, especially the radius helps to extend the reach in mA.

Summary

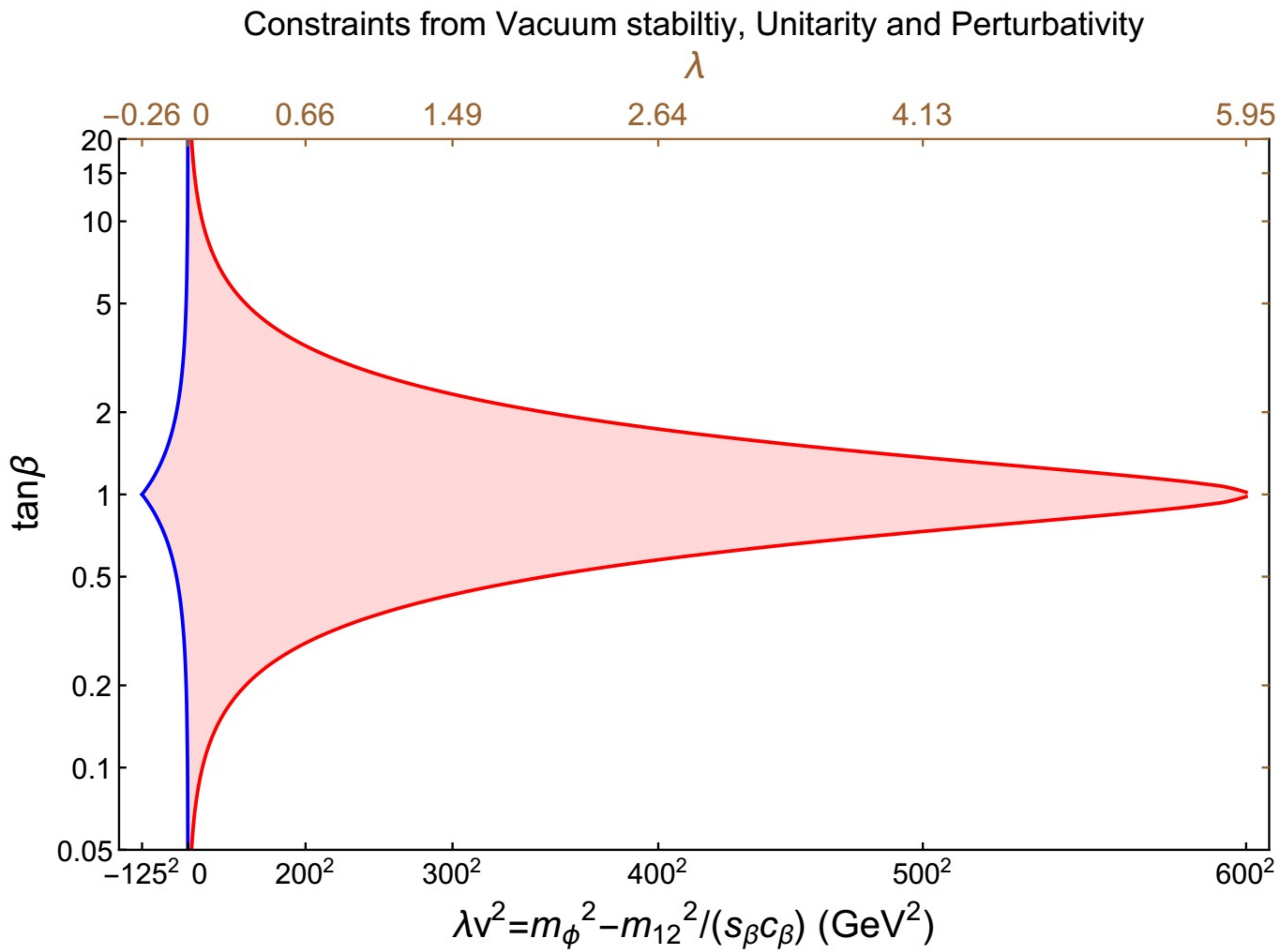
- General study
  - Production
  - Decay : public code
  - Constraints
- Case study: 2HDM results





Thanks !

Constraint



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

Theoretical constraints

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

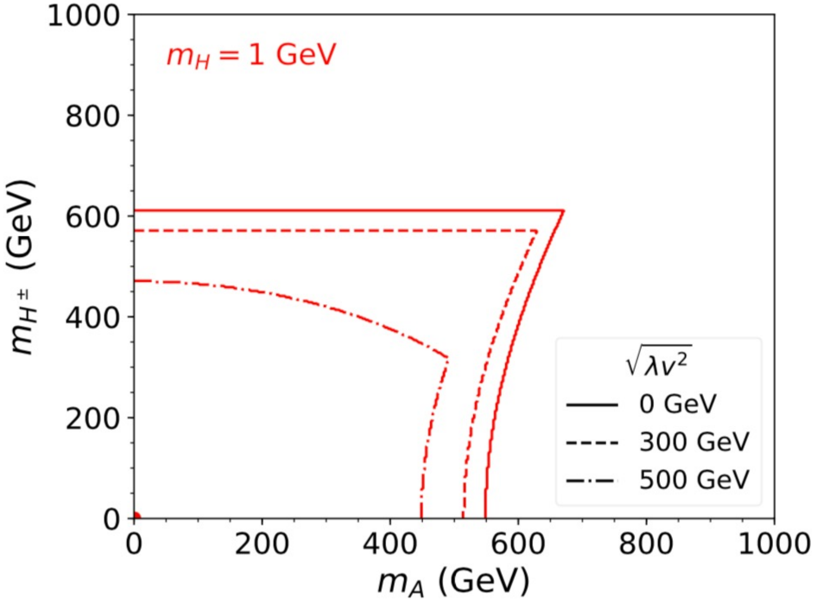
$-125^2 \mathrm{GeV}^2 < \lambda v^2 < 600^2 \mathrm{GeV}^2$

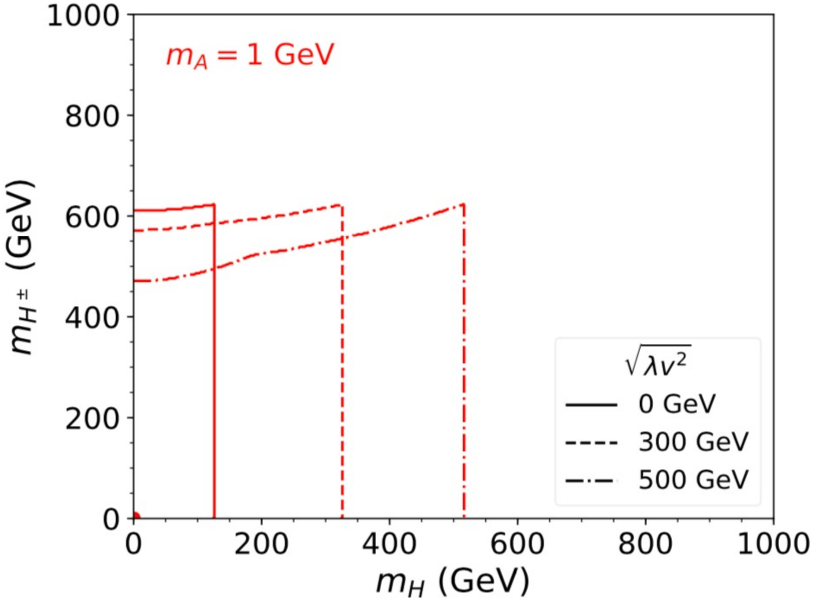
$\lambda \in (-0.26, 5.95)$
$\lambda_4 = \lambda_5 = \lambda_3 - 0.258 = -\lambda$

Constraint

Theoretical constraints

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





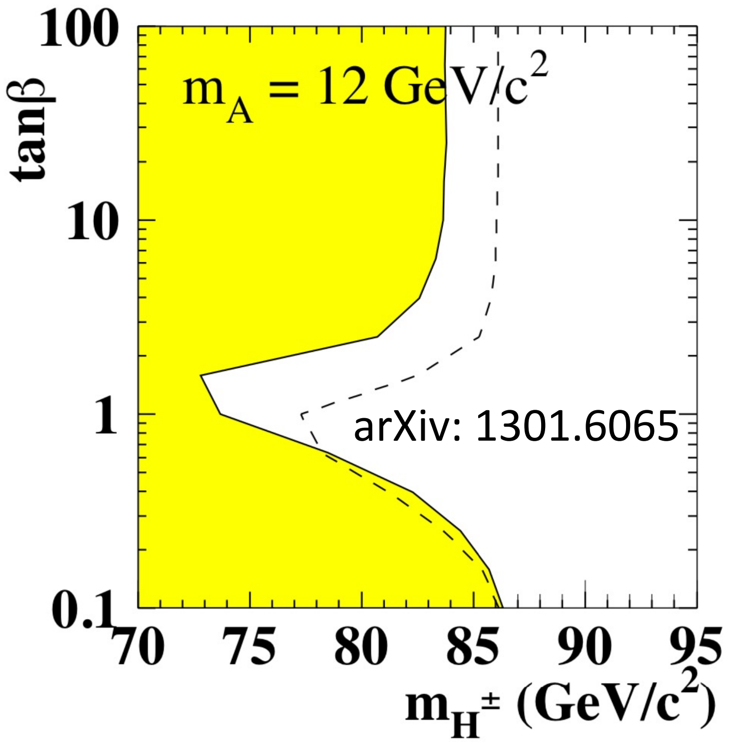
$$m_H \sim 0 : \quad m_{A/H^\pm} \lesssim 600 \text{ GeV}$$

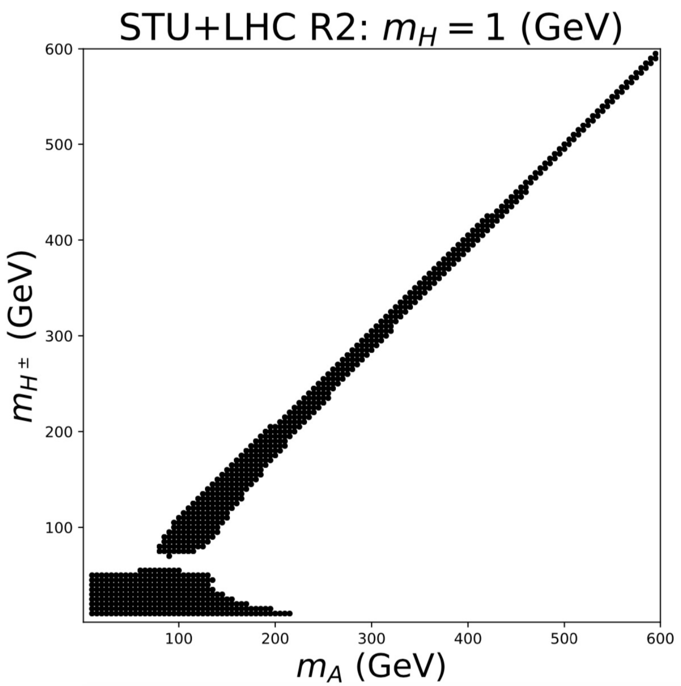
$$m_A \sim 0 : \quad m_{H^\pm} \lesssim 600 \text{ GeV}, \qquad m_H \lesssim m_h$$

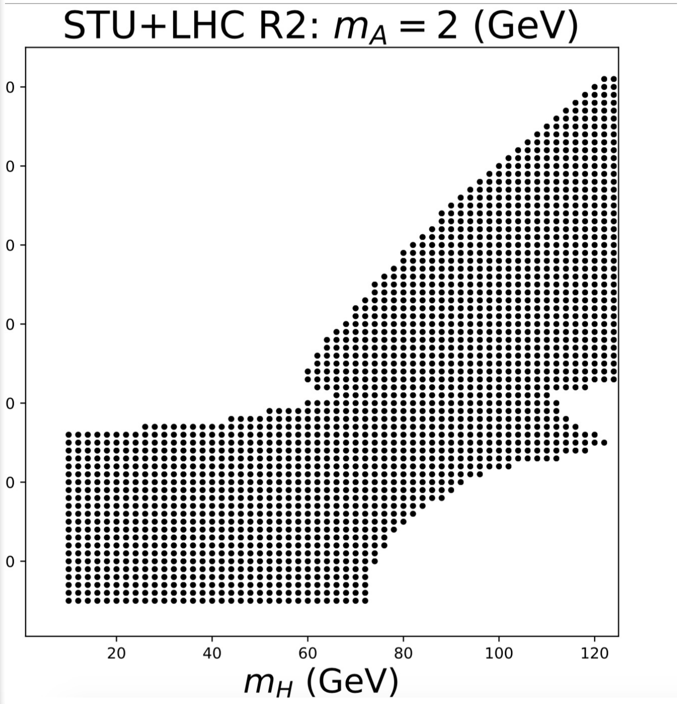
Constraint

Oblique constraints: Z pole

Direct search at LEP







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

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

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

Constraint

Invisible Higgs decays

$$\mathrm{Br}(h \to \phi\phi) = \frac{\Gamma(h \to \phi\phi)}{\Gamma_h} \approx \frac{1}{\Gamma_h^{\mathrm{SM}}} \frac{g_{h\phi\phi}^2}{8\pi m_h^2} \left(1 - \frac{4m_H^2}{m_h^2}\right)^{1/2} \simeq 4700 \cdot \left(\frac{g_{h\phi\phi}}{v}\right)^2 < 0.24$$

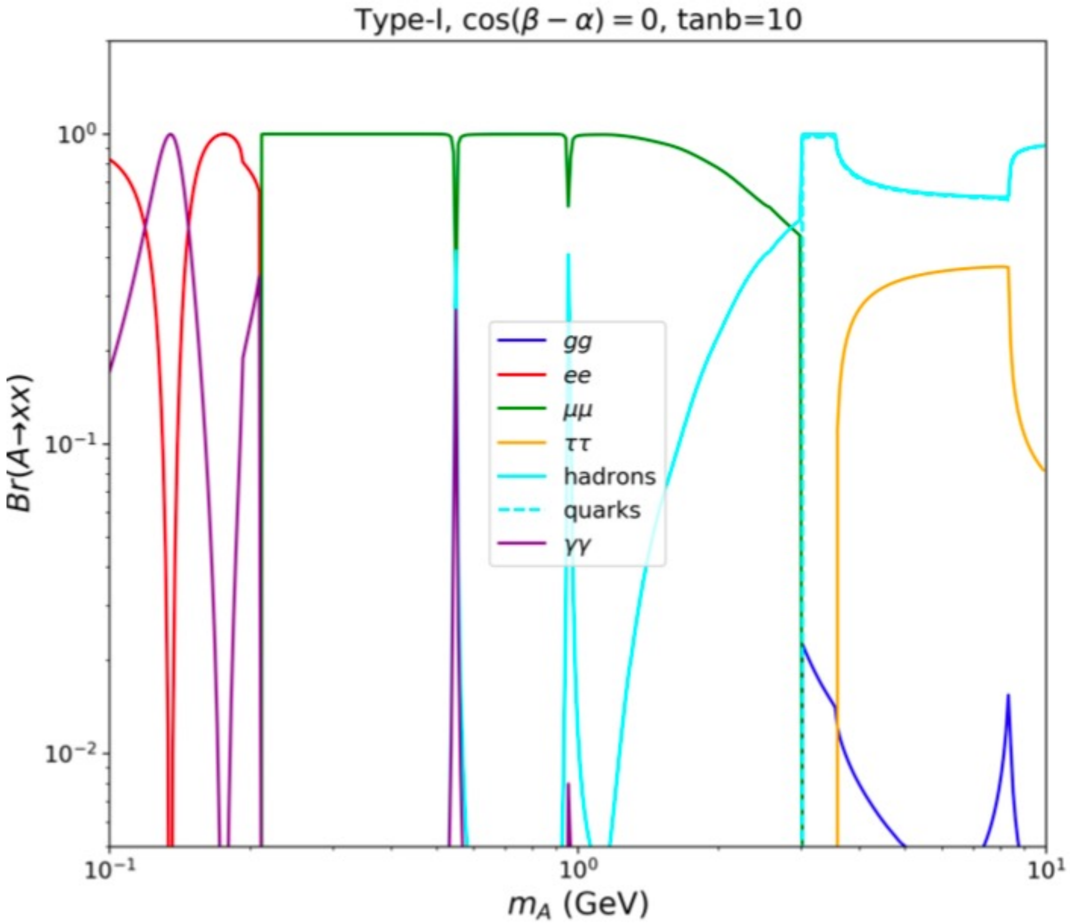
$$\mathrm{Br}(h \to \phi\phi) = 0$$

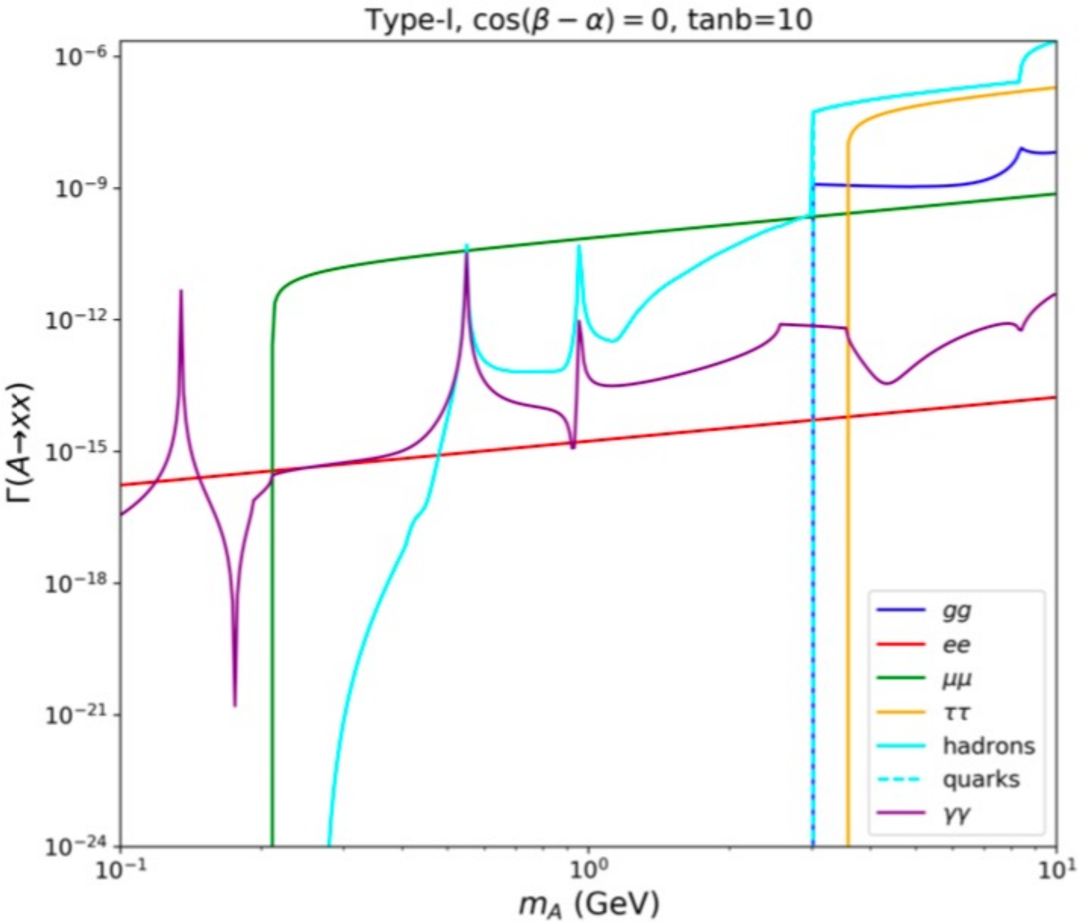
$$Light\ H : \cos(\beta - \alpha) = \tan 2\beta \frac{2\lambda v^2 + m_h^2}{2(m_H^2 - 3\lambda v^2 - m_h^2)} \approx \frac{1}{\tan\beta} ,$$

$$Light\ A : \cos(\beta - \alpha) = \tan 2\beta \frac{2\lambda v^2 + m_h^2 + 2m_A^2 - 2m_H^2}{2(m_H^2 - \lambda v^2 - m_h^2)} \approx \frac{1}{\tan\beta} \frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2} ,$$

Results: CP odd

$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta$$





Decay: CP even scalar

$m_\phi < 2$ GeV

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

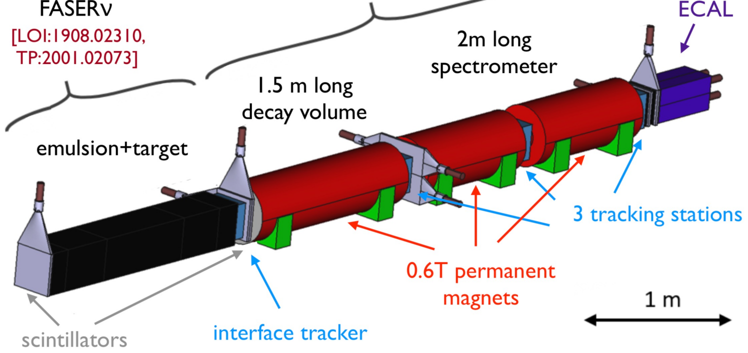
$$\mathcal{L} \supset \frac{\Phi}{v}\left(\xi_\Phi^g \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\mu\nu} - \xi_\Phi^u m_u \bar{u}u - \xi_\Phi^d m_d \bar{d}d - \xi_\Phi^s m_s \bar{s}s\right)$$
$$= -\frac{\Phi}{v}\left\{\xi_\Phi^g\left[\frac{2}{27}\Theta^\mu_\mu - \frac{2}{27}(m_u\bar{u}u + m_d\bar{d}d + m_s\bar{s}s)\right] + (\xi_\Phi^u m_u\bar{u}u + \xi_\Phi^d m_d\bar{d}d + \xi_\Phi^s m_s\bar{s}s)\right\}$$

$$\Theta^\mu_\mu = -\frac{9\alpha_s}{8\pi} G^a_{\mu\nu} G^{a\mu\nu} + m_u\bar{u}u + m_d\bar{d}d + m_s\bar{s}s.$$

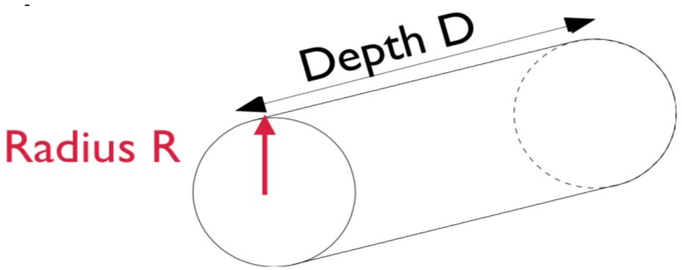
$$\Gamma_\pi = \langle \pi\pi | m_u\bar{u}u + m_d\bar{d}d | 0\rangle\,, \qquad \Delta_\pi = \langle \pi\pi | m_s\bar{s}s | 0\rangle\,, \qquad \Theta_\pi = \langle \pi\pi | \Theta^\mu_\mu | 0\rangle$$

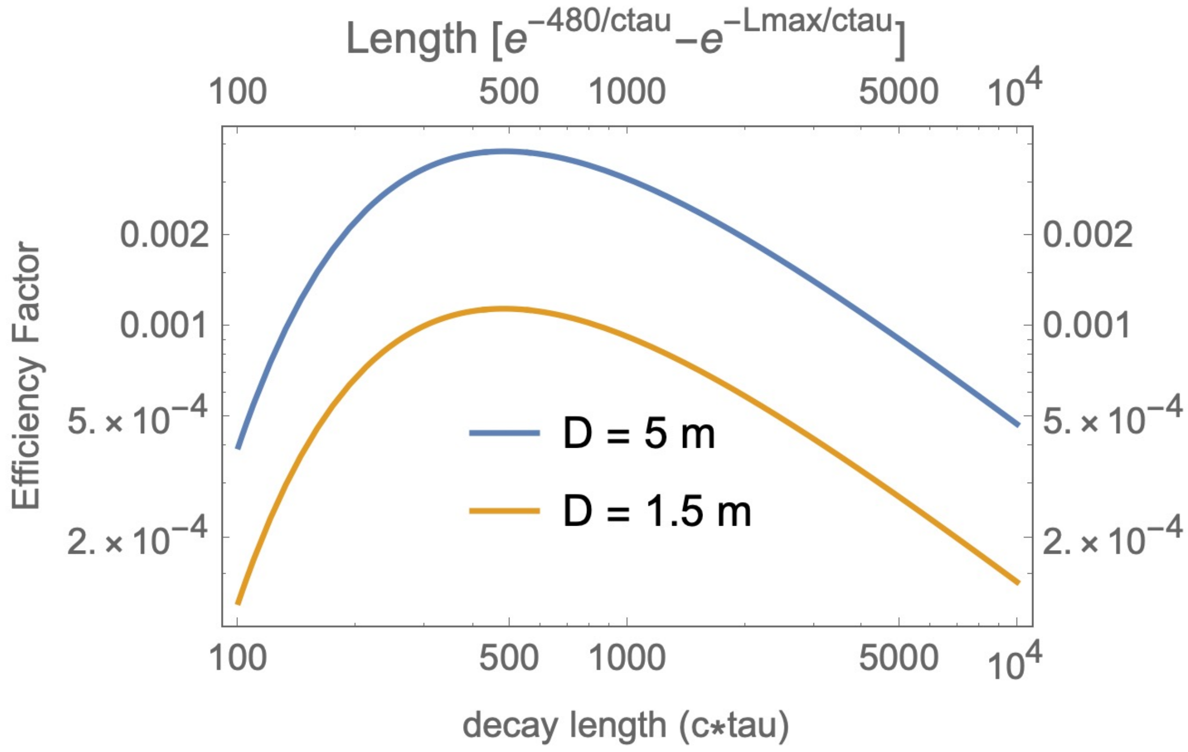
$$\Gamma_{\pi\pi} = \frac{3G_F}{16\sqrt{2}\pi m_\Phi}\beta_\pi \left|\xi_\Phi^{gg}\frac{2}{27}(\Theta_\pi - \Gamma_\pi - \Delta_\pi) + \frac{m_u\xi_\Phi^u + m_d\xi_\Phi^d}{m_u + m_d}\Gamma_\pi + (\xi_\Phi^s)\Delta_\pi\right|^2$$
$$\Gamma_{KK} = \frac{G_F}{4\sqrt{2}\pi m_\Phi}\beta_K \left|\xi_\Phi^{gg}\frac{2}{27}(\Theta_K - \Gamma_K - \Delta_K) + \frac{m_u\xi_\Phi^u + m_d\xi_\Phi^d}{m_u + m_d}\Gamma_K + (\xi_\Phi^s)\Delta_K\right|^2$$

FASER: Detector



***pp* → LLP + X, LLP travels ~480 m, LLP → charged tracks + X**





<u>FASER</u>: radius R = 10 cm, lenght D = 1.5 m, luminosity L = 150 fb^{-1},

<u>FASER 2</u>: radius R = 1m, lenght D = 5 m, luminosity L = 3 ab^{-1}.