The 2025 Beijing Particle Physics and Cosmology Symposium:
early Universe, gravitational-wave templates, collider phenomenology

Long-lived Particle searches of Higgs sector

Wei Su

BPCS 2025.09.27

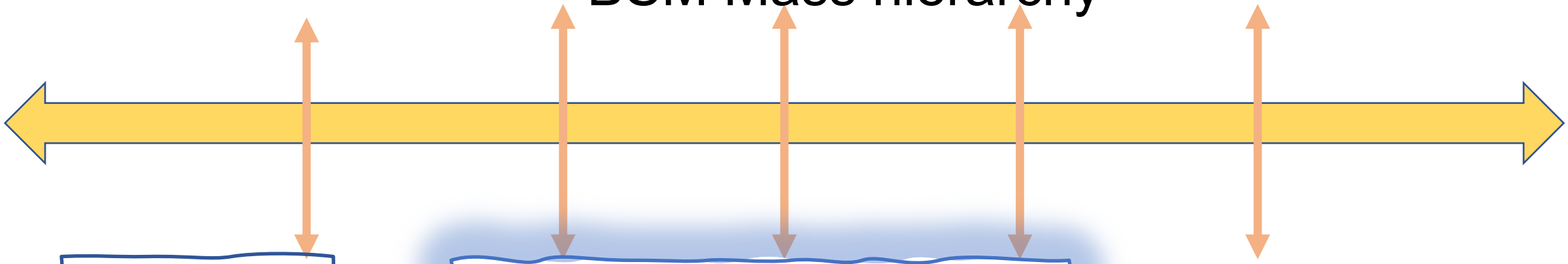
2212.06186 (F. Kling, S. Li, S. Su, H.Song, WS)
2508.12309 (XY Qi, HY Song, WS)
2510.XXXXX (X.Liu, H.Mo, Y.Shi, WS, L.Wang,J.Xue, Y.Yu)

outline

- Motivation: Brief introduction to LLP
- Higgs candidate
  - Production
  - Decay
  - Constraints
- Cases: 2HDM results

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

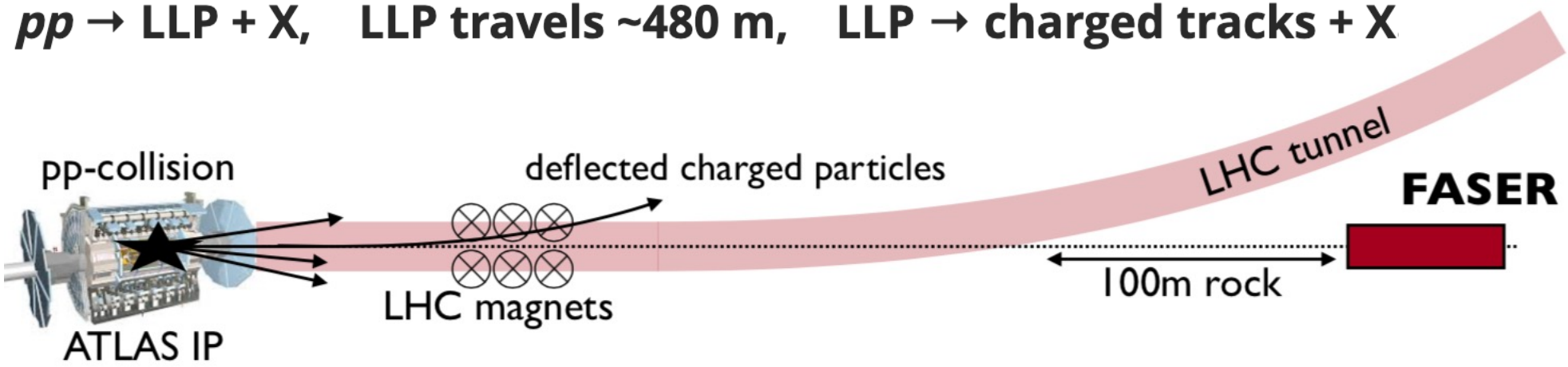
CEPC

CMS

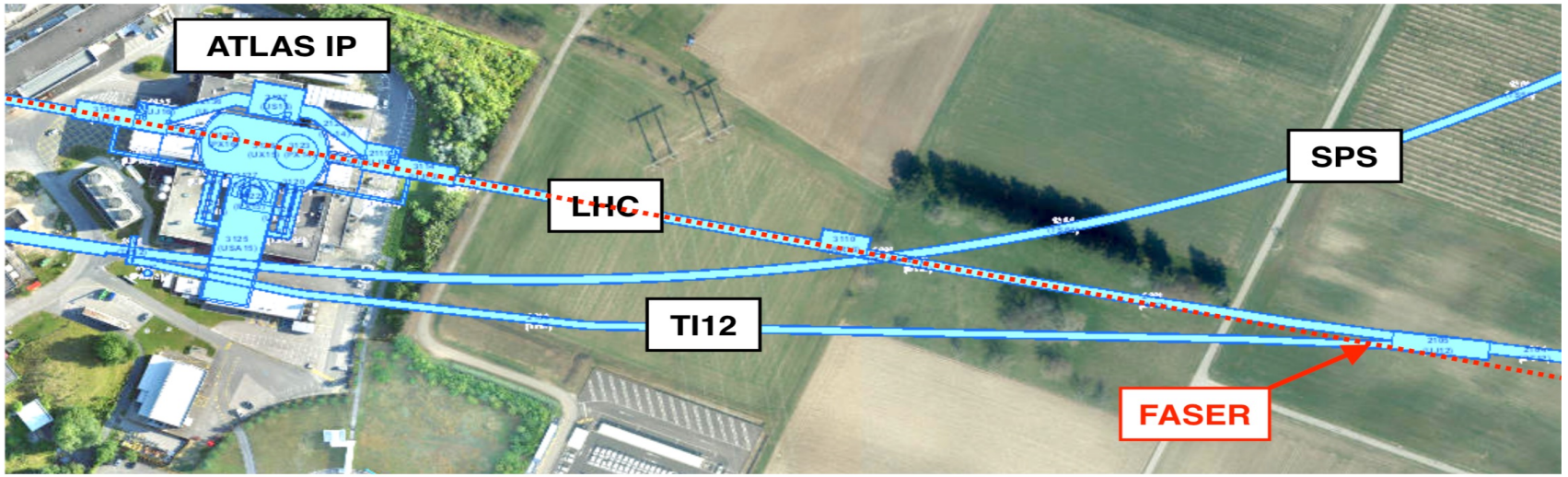
Strongly interacting Heavy Particle

FASER: ForwArd Search ExpeRiment

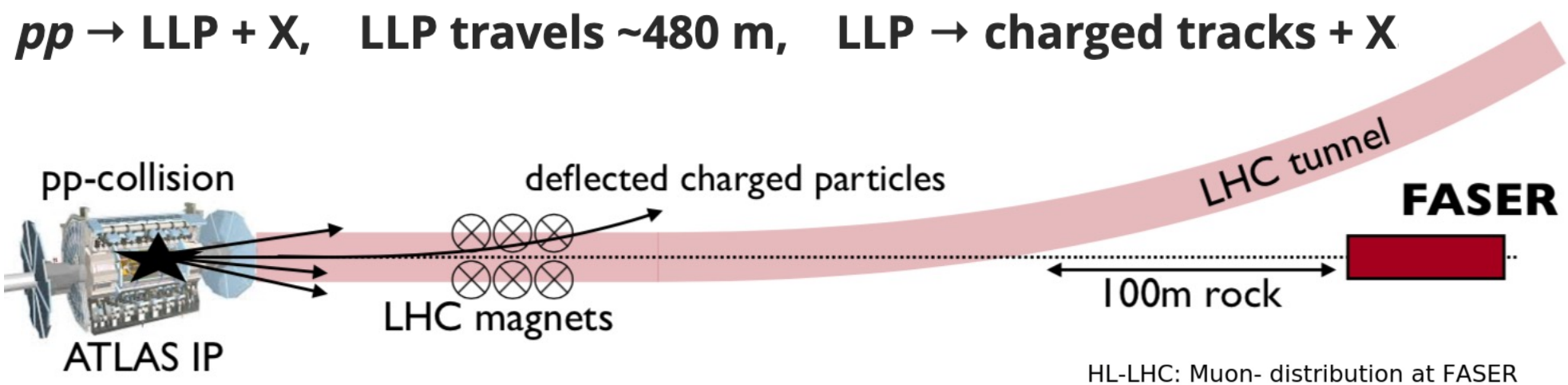
***pp* → LLP + X, LLP travels ~480 m, LLP → charged tracks + X**



Weakly interacting Light Particle

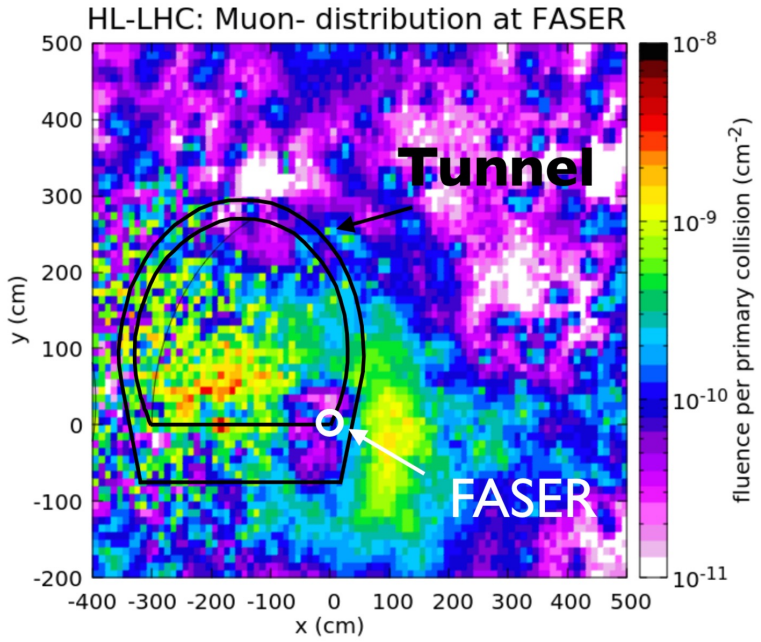


FASER



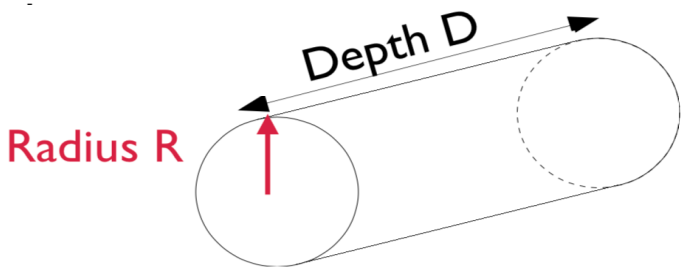
Production Weakly interacting Light Particle

- many hadrons: 10^17 π, 10^16 K, 10^15 D, 10^14 B with E~TeV
- low PT is not covered
- particles are collimated θ ~ ΛQCD/E

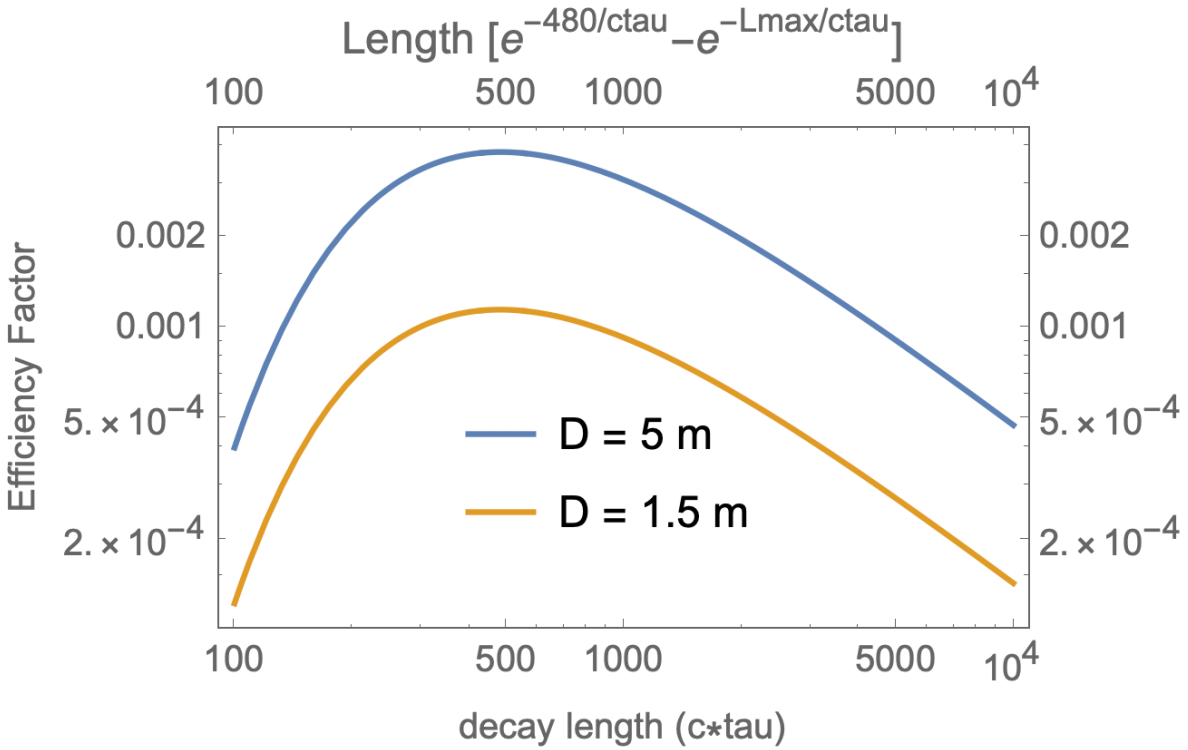


FASER: Detector

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



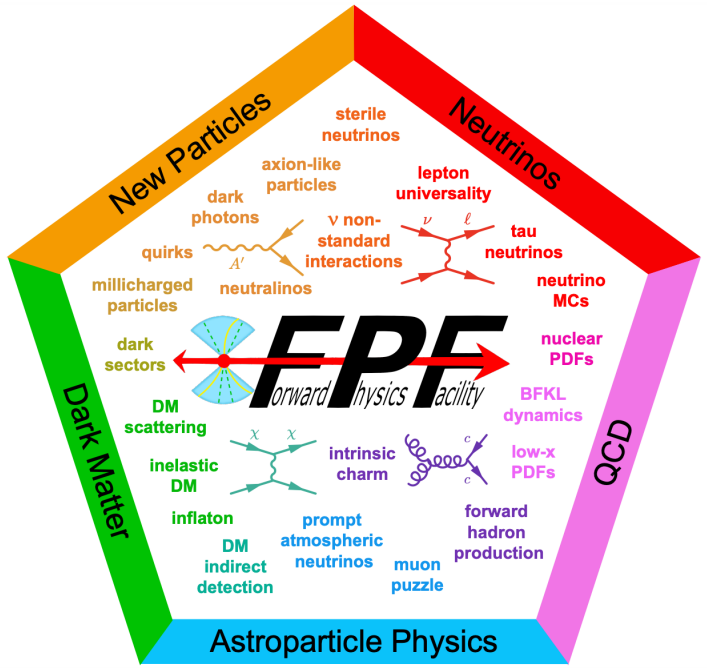
FASER: radius R = 10 cm, lenght D = 1.5 m,
luminosity L = 150 fb^{-1},
FASER 2: radius R = 1m, lenght D = 5 m,
luminosity L = 3 ab^{-1}.



BSM @ FASER

https://faser.web.cern.ch/physics

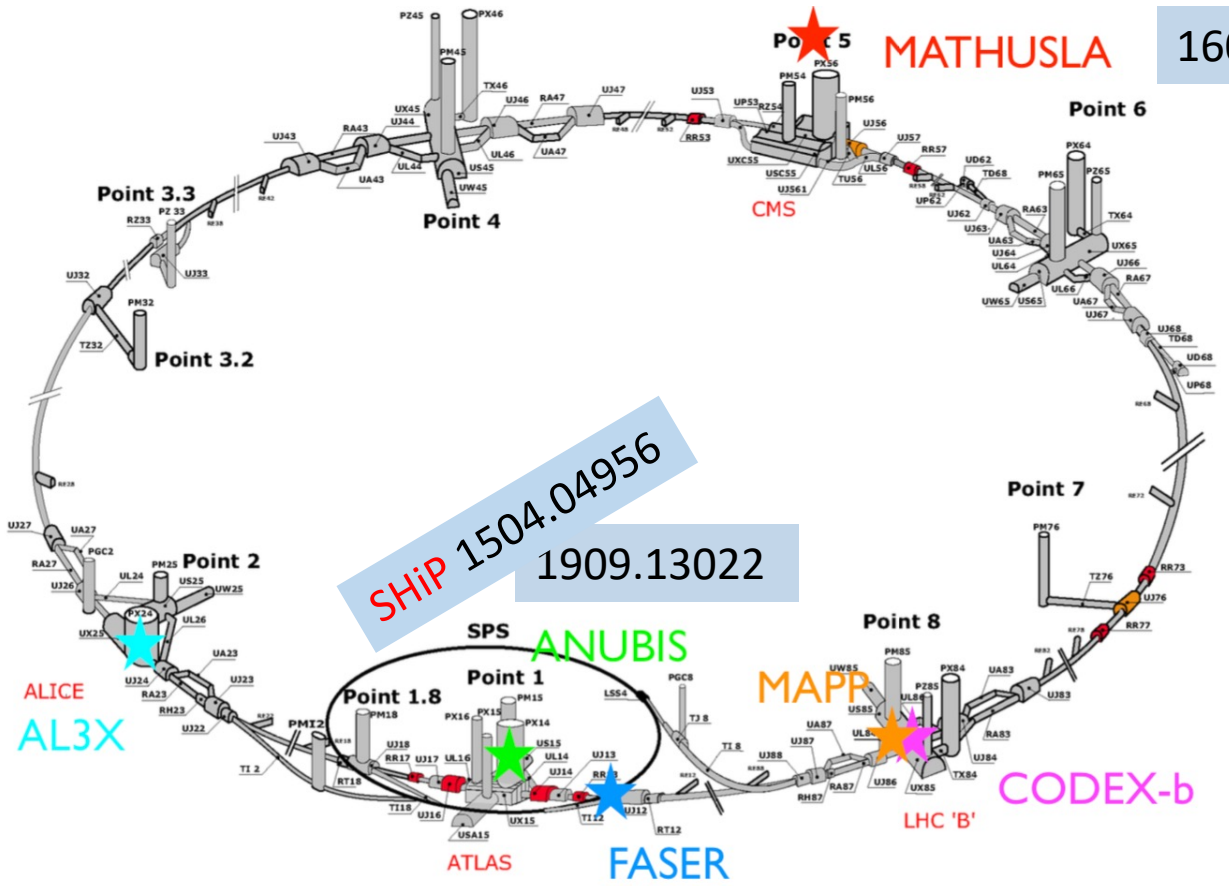
- Heavy Neutral Leptons arXiv: 1801.08947
- Heavy Neutral Fermions arXiv: 1803.02212
- dark photons arXiv: 1708.09389
- Long-lived bivo arXiv: 2103.01251
- Dark Higgs Bosons arXiv: 1710.09387
- Axion like Particle arXiv: 1806.02348
- …



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

2022 Snowmass Summer Study 2203.05090

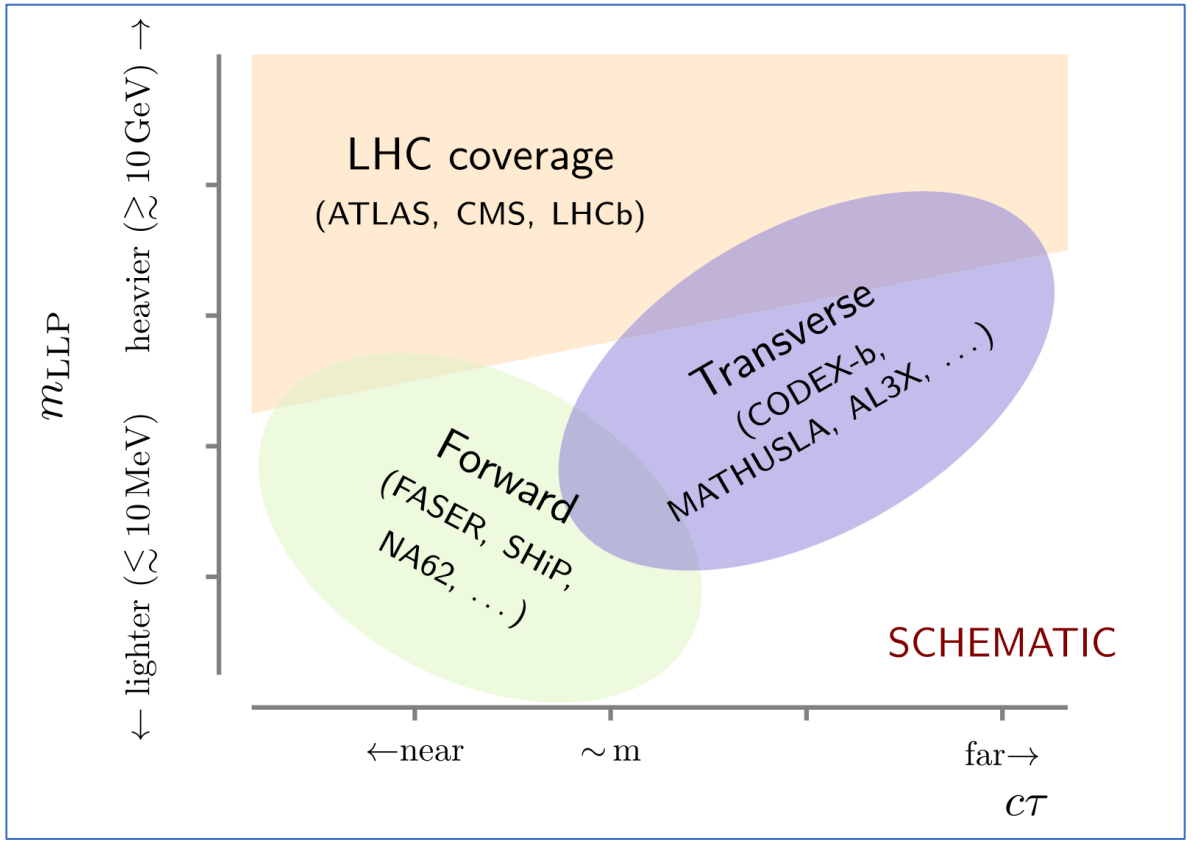
Other proposals for LLP



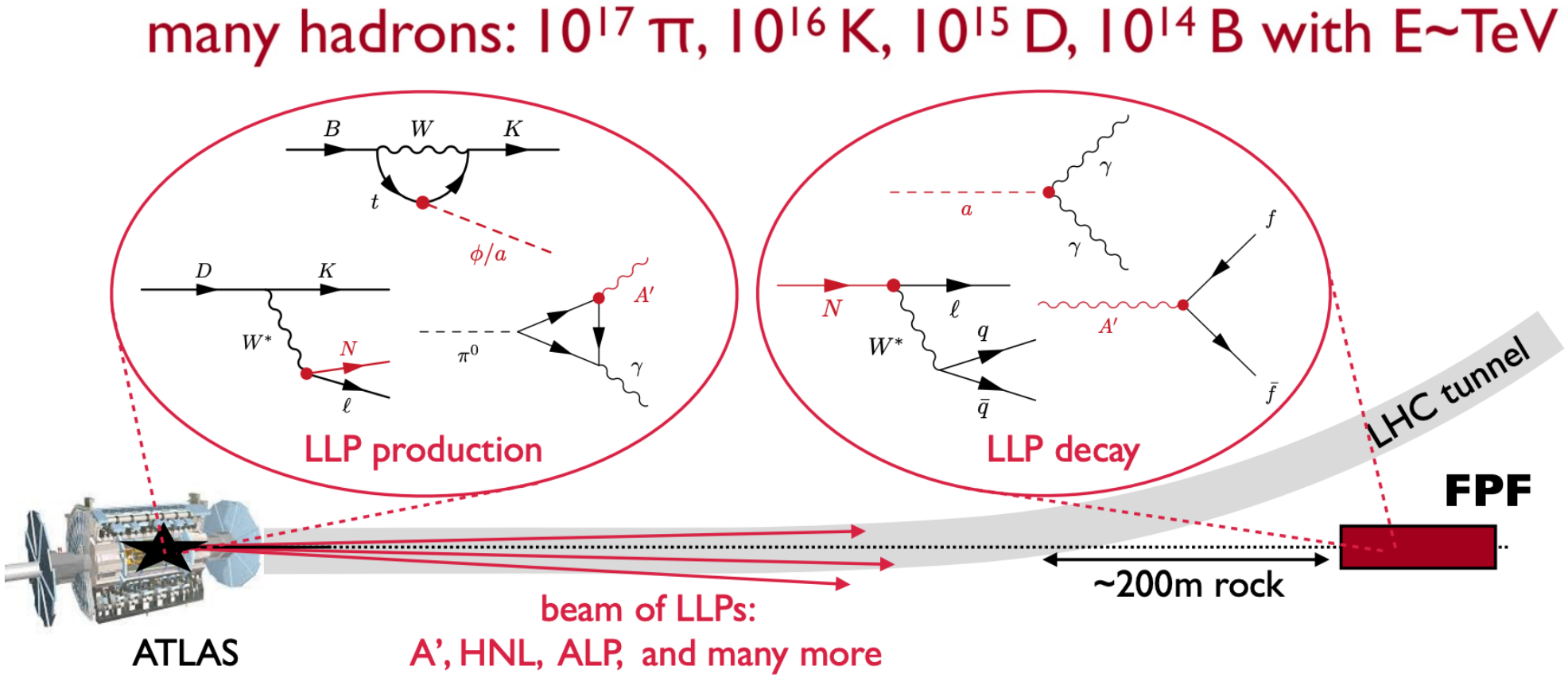
Light LLP searches

1. ATLAS and CMS: Heavy LLPs ($m_{\mathrm{LLP}} \gtrsim 10\,\mathrm{GeV}$) for all lifetimes ($c\tau \lesssim 10^7\,\mathrm{m}$).
2. LHCb: Short to medium lifetimes ($c\tau \lesssim 1\,\mathrm{m}$) for light LLPs ($0.1\,\mathrm{GeV} \lesssim m_{\mathrm{LLP}} \lesssim 10\,\mathrm{GeV}$).
3. Forward/beam dump detectors (FASER, NA62, SHiP): Medium to long lifetime regime ($0.1 \lesssim c\tau \lesssim 10^7\,\mathrm{m}$) for light LLPs ($m_{\mathrm{LLP}} \lesssim$ few GeV), for low $\sqrt{\hat{s}}$ production channels.
4. Shielded, transversely displaced detectors (MATHUSLA, CODEX-b, AL3X): Relatively light LLPs[2] ($m_{\mathrm{LLP}} \lesssim 10$–$100\,\mathrm{GeV}$) in the long lifetime regime ($1 \lesssim c\tau \lesssim 10^7\,\mathrm{m}$), and high $\sqrt{\hat{s}}$ production channels.

Eur. Phys. J. C (2020) 80:1177



Production at FASER



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

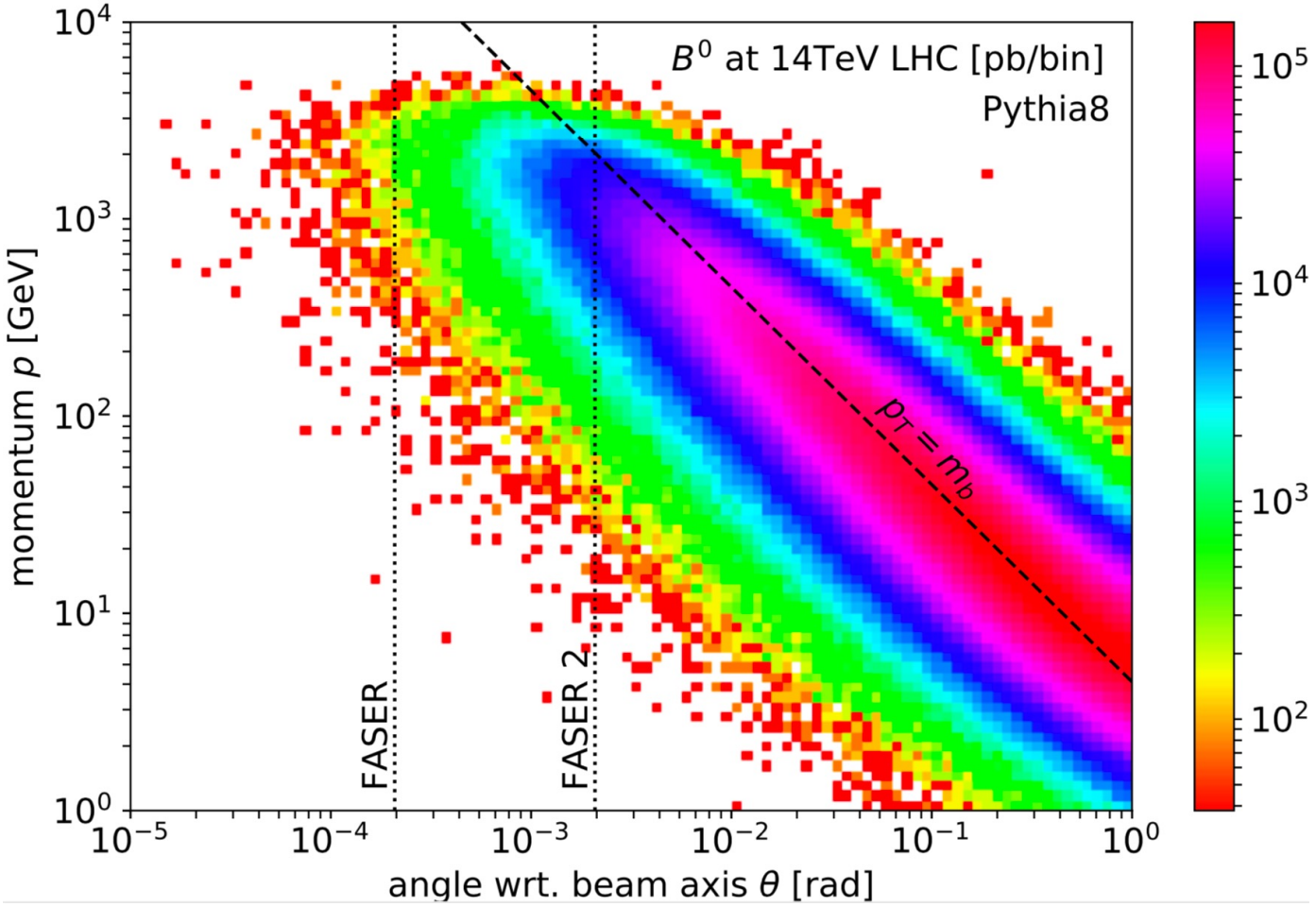
Production

B^0

boosted mesons highly collimated

$p \cdot \theta = p_T \sim$ Mb

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



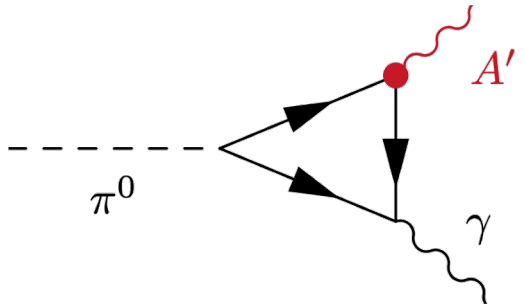
Production: CP even scalar

$$\xi_\phi^g = \sum_{f\in q} \frac{3}{2}\xi_\phi^i \mathcal{A}_{1/2}^\phi(\tau_f^\phi),$$

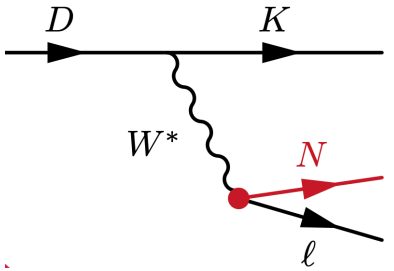
$$\xi_\phi^\gamma = \sum_{f\in q,\ell} N_c Q_f^2 \xi_\phi^f A_{1/2}^\phi\left(\tau_f^\phi\right) + \xi_\phi^V A_1^\phi\left(\tau_W^\phi\right)$$

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

$$+\xi_\phi^g \frac{\alpha_s}{12\pi v}\phi G_{\mu\nu}^a G^{a\mu\nu} + \xi_\phi^\gamma \frac{\alpha}{4\pi v}\phi F_{\mu\nu}F^{\mu\nu}.$$

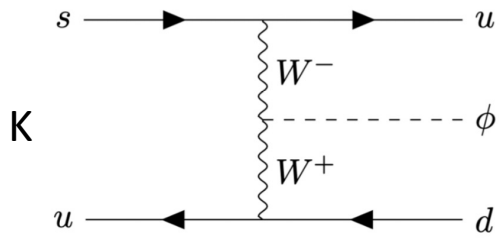


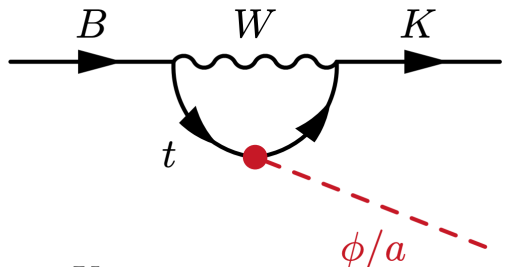
$$K \to \pi\phi,\ \eta^{(\prime)} \to \pi\phi,\ D \to X_u\phi \quad B \to X_s\phi$$



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

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



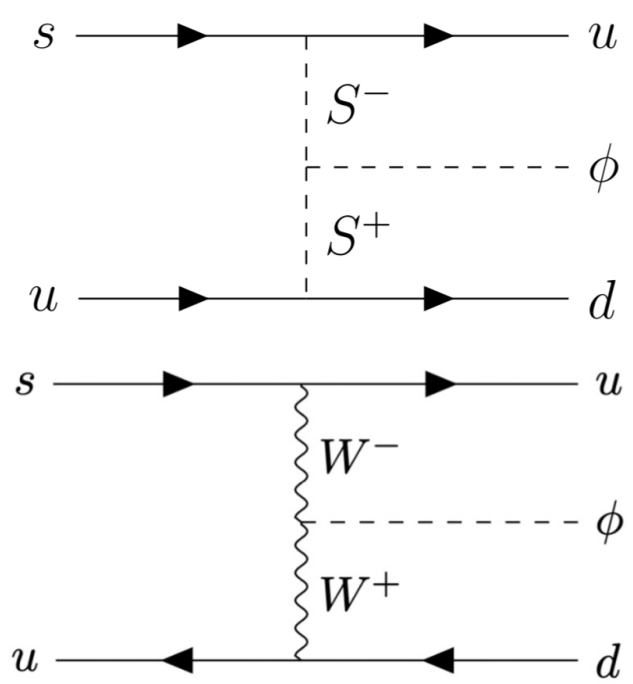


Production: CP even scalar

Main contribution

$K^{\pm}$: 493.677 ±0.016 MeV/

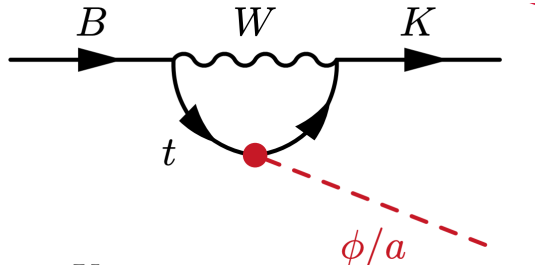
K^{0}: 497.611 ±0.013 MeV/



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

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

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



b: 4.18 GeV, B: around 5.3 GeV,

Decay: CP even scalar

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

Hadronic decays into pions and kaons for $m_\Phi < 2$ GeV

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

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

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

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

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

Decay: CP even scalar

$m_\phi < 2$ GeV

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

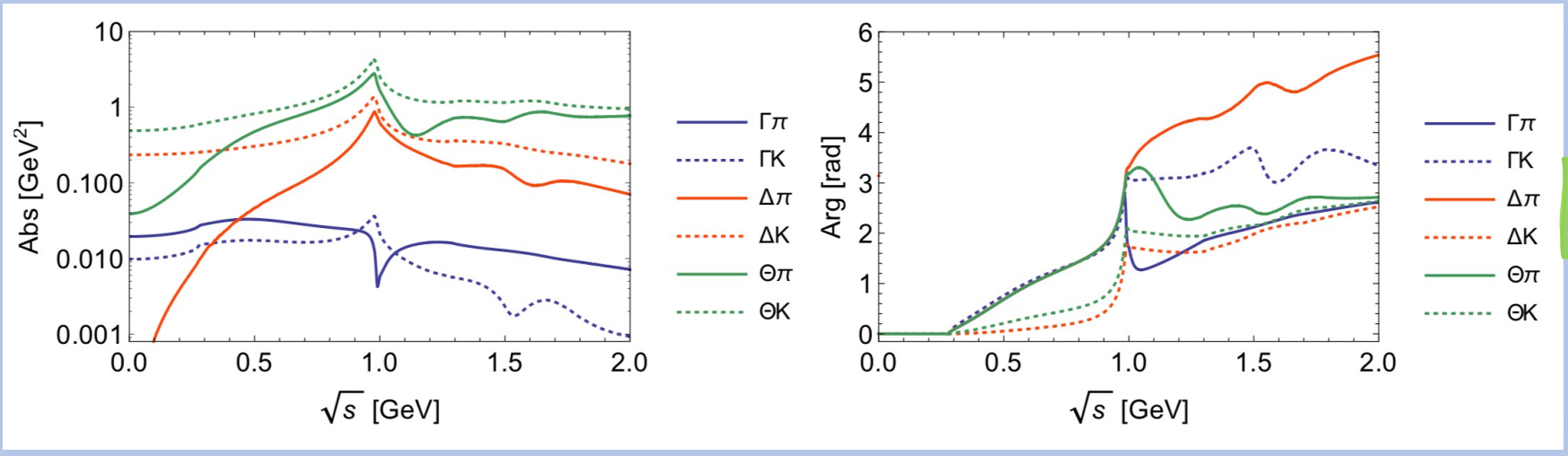
$$\Gamma_\pi = \langle \pi\pi \left| m_u \bar{u}u + m_d \bar{d}d \right| 0 \rangle, \qquad \Delta_\pi = \langle \pi\pi \left| m_s \bar{s}s \right| 0 \rangle, \qquad \Theta_\pi = \langle \pi\pi \left| \Theta^\mu_\mu \right| 0 \rangle$$

Leading order chiral perturbation theory

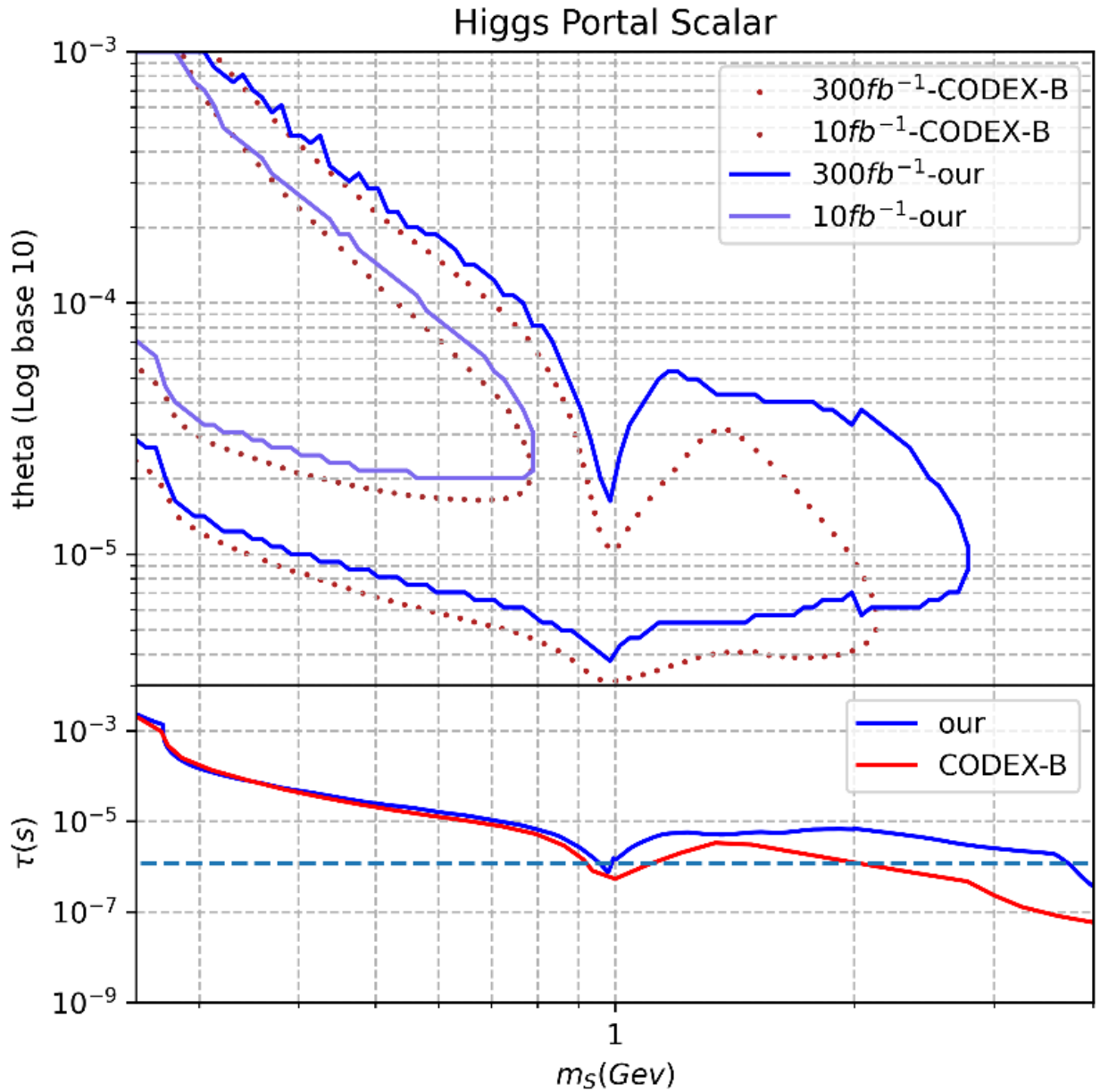
$$\Gamma^0_\pi = m^2_\pi, \qquad \Delta^0_\pi = 0, \qquad \Theta^0_\pi = s + 2m^2_\pi$$
$$\Gamma^0_K = \frac{1}{2} m^2_\pi, \qquad \Delta^0_K = m^2_K - \frac{1}{2} m^2_\pi, \qquad \Theta^0_K = s + 2m^2_K$$

$m_\phi < 0.5$ GeV

Dispersive Analysis



0.5GeV<m_ϕ< 2 GeV


Higgs Portal Scalar
theta (Log base 10)
10^{-3}
10^{-4}
10^{-5}
$300fb^{-1}$-CODEX-B
$10fb^{-1}$-CODEX-B
$300fb^{-1}$-our
$10fb^{-1}$-our
$\tau(s)$
10^{-3}
10^{-5}
10^{-7}
10^{-9}
our
CODEX-B
1
$m_S(Gev)$

Decay: CP odd scalar

Similar but different production and decay modes

Case study: 2HDM

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

- 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

Constraint

LEP, theoretical physics, Oblique …

LHCb, MicroBooNE, SN1987a, NA62…

Invisible Higgs decays

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

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

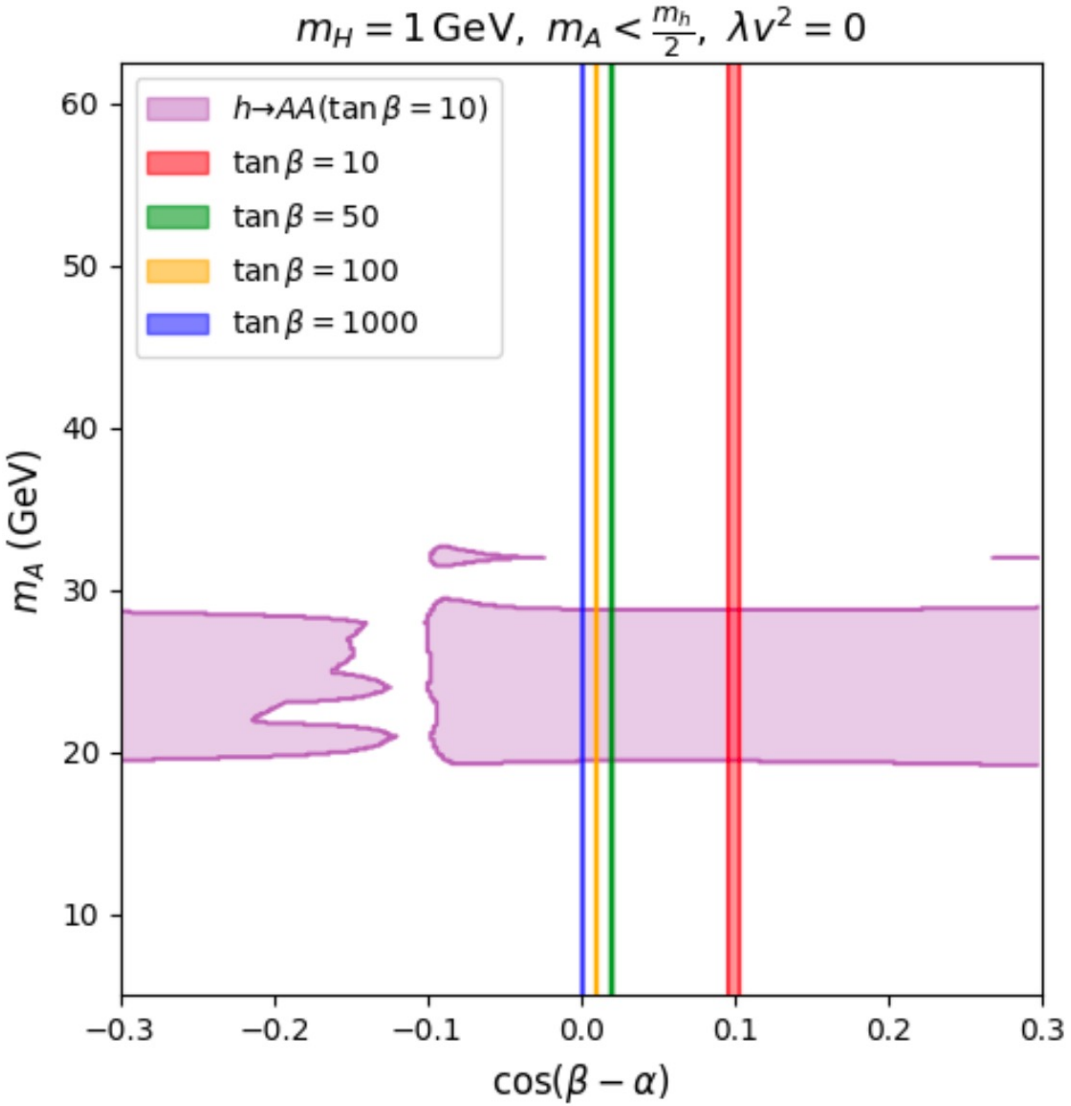
$$g_{hAA} = \frac{1}{2v}\left[\left(2m_H^2 - 2\lambda v^2 - 2m_A^2 - m_h^2\right) s_{\beta-\alpha} + 2\left(m_H^2 - \lambda v^2 - m_h^2\right) t_{2\beta}^{-1} c_{\beta-\alpha}\right].$$

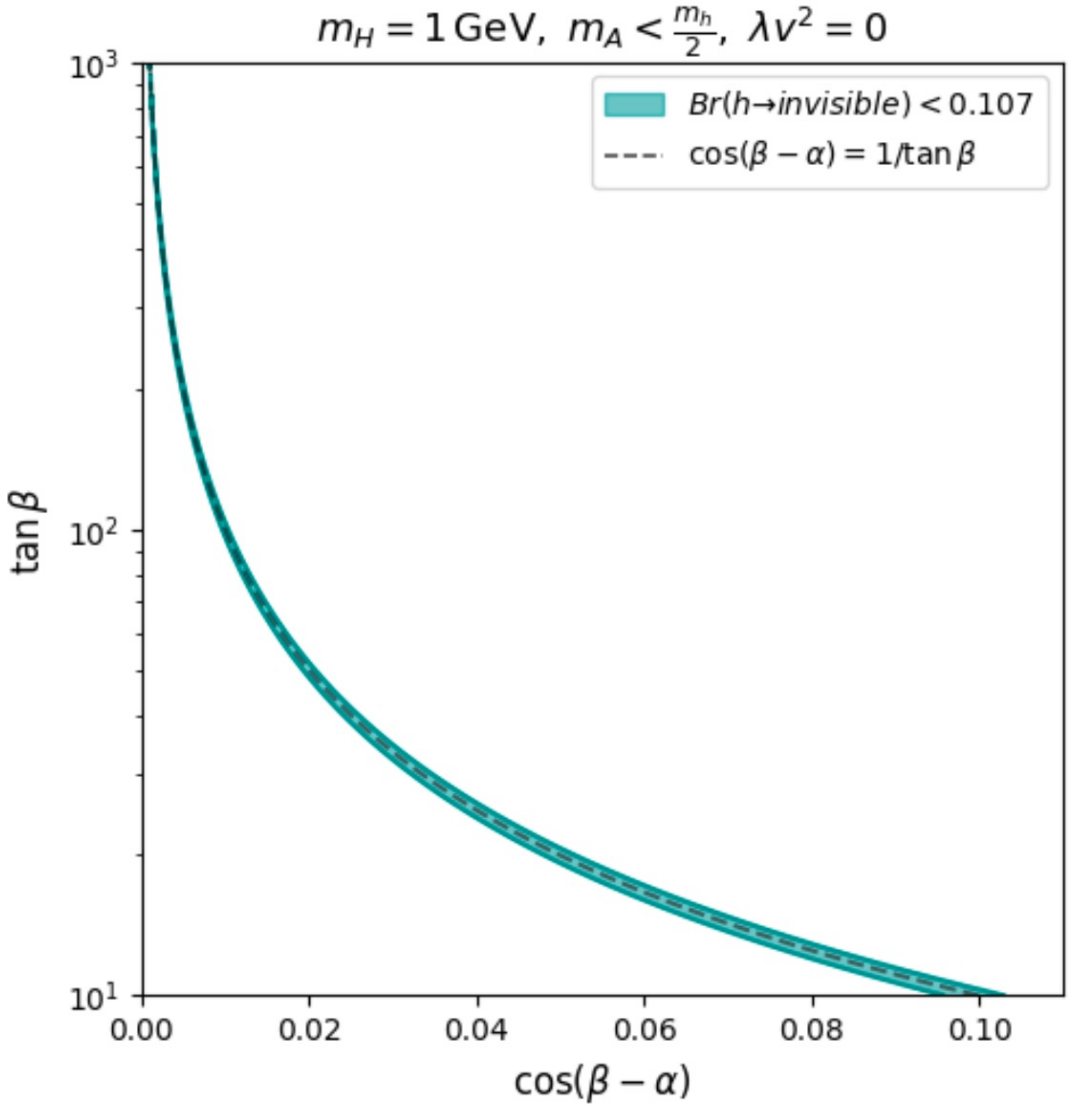
$$\mathrm{Br}(h \to \phi\phi) = 0$$

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

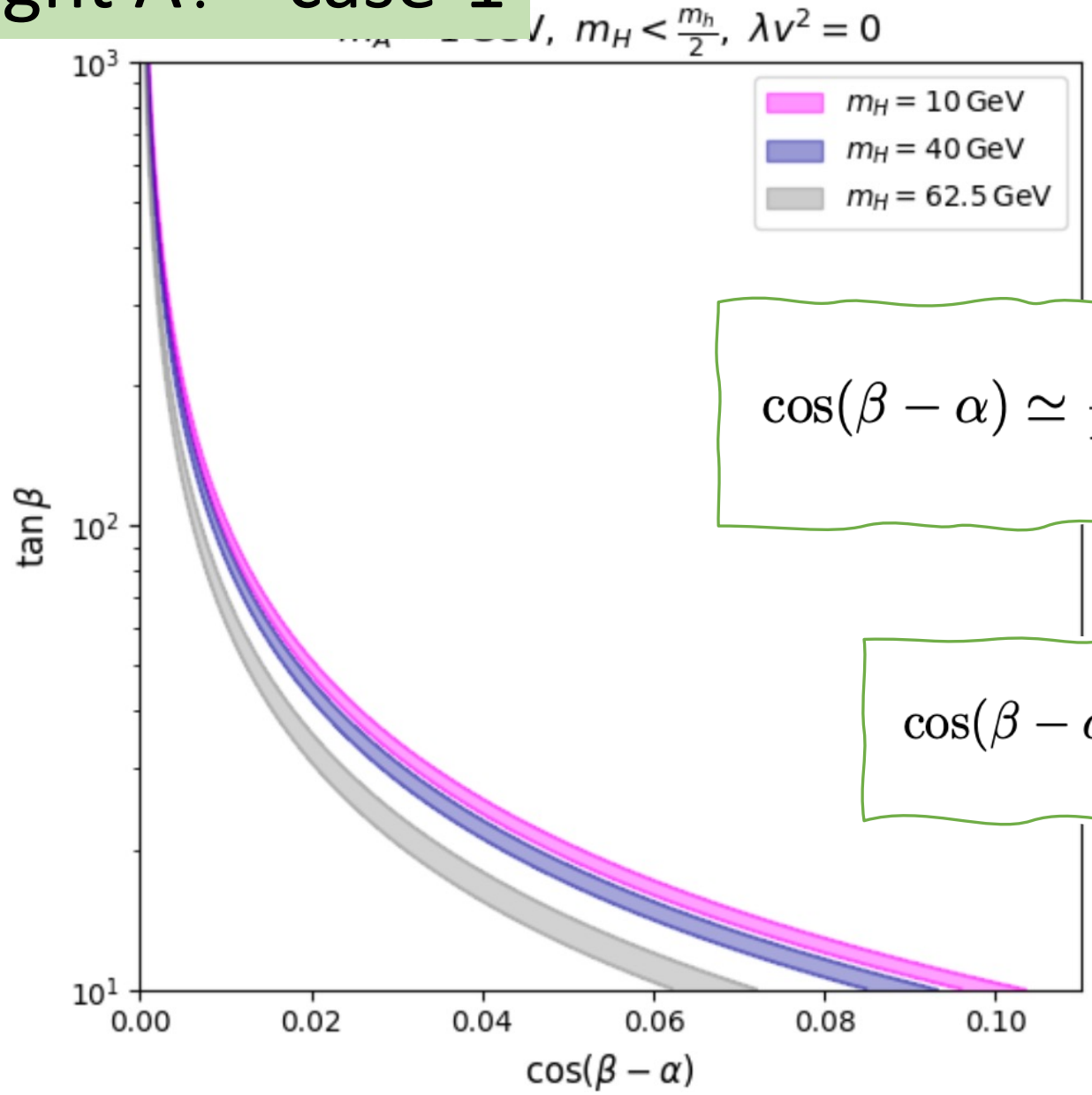
$$Light\ A : \cos(\beta-\alpha) = \tan 2\beta \frac{2\lambda v^2 + m_h^2 + 2m_A^2 - 2m_H^2}{2(m_H^2 - \lambda v^2 - m_h^2)} \approx \frac{1}{\tan\beta}\frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2},$$

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



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

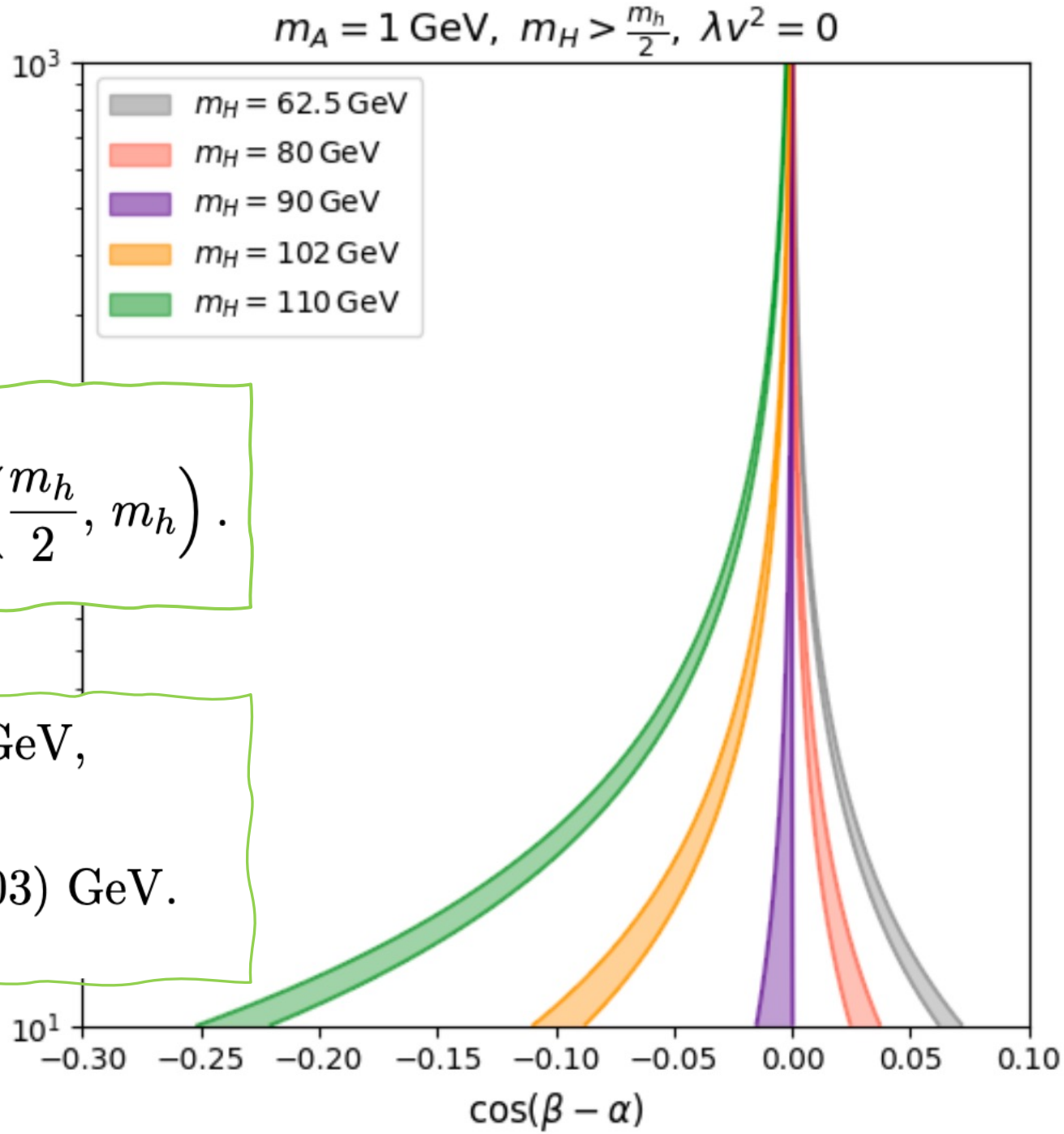
$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}, \quad m_H \in (5, 25) \text{ GeV}.$$

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: Complete Light Higgs

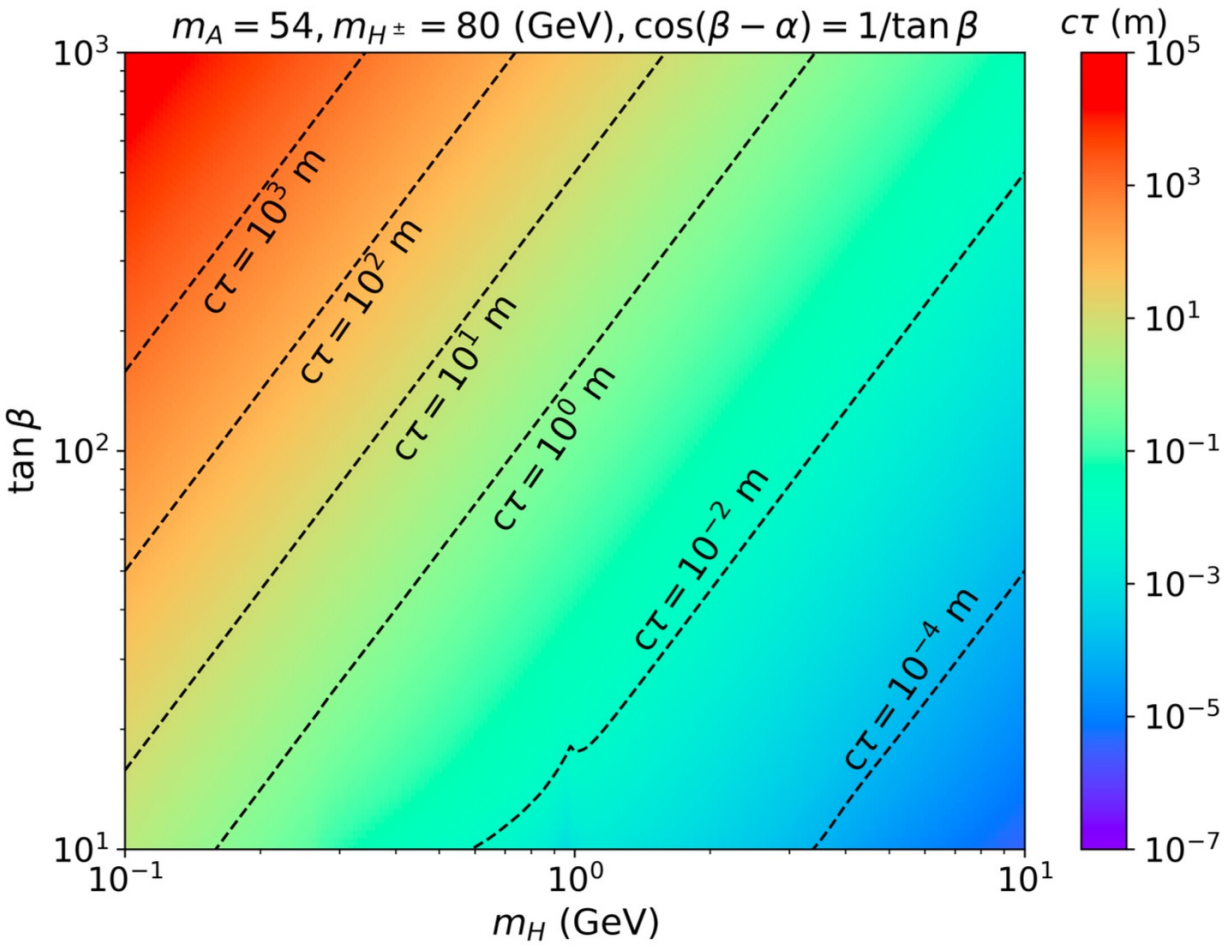
$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}, \quad m_A \in (54, 600)\ \text{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.$$

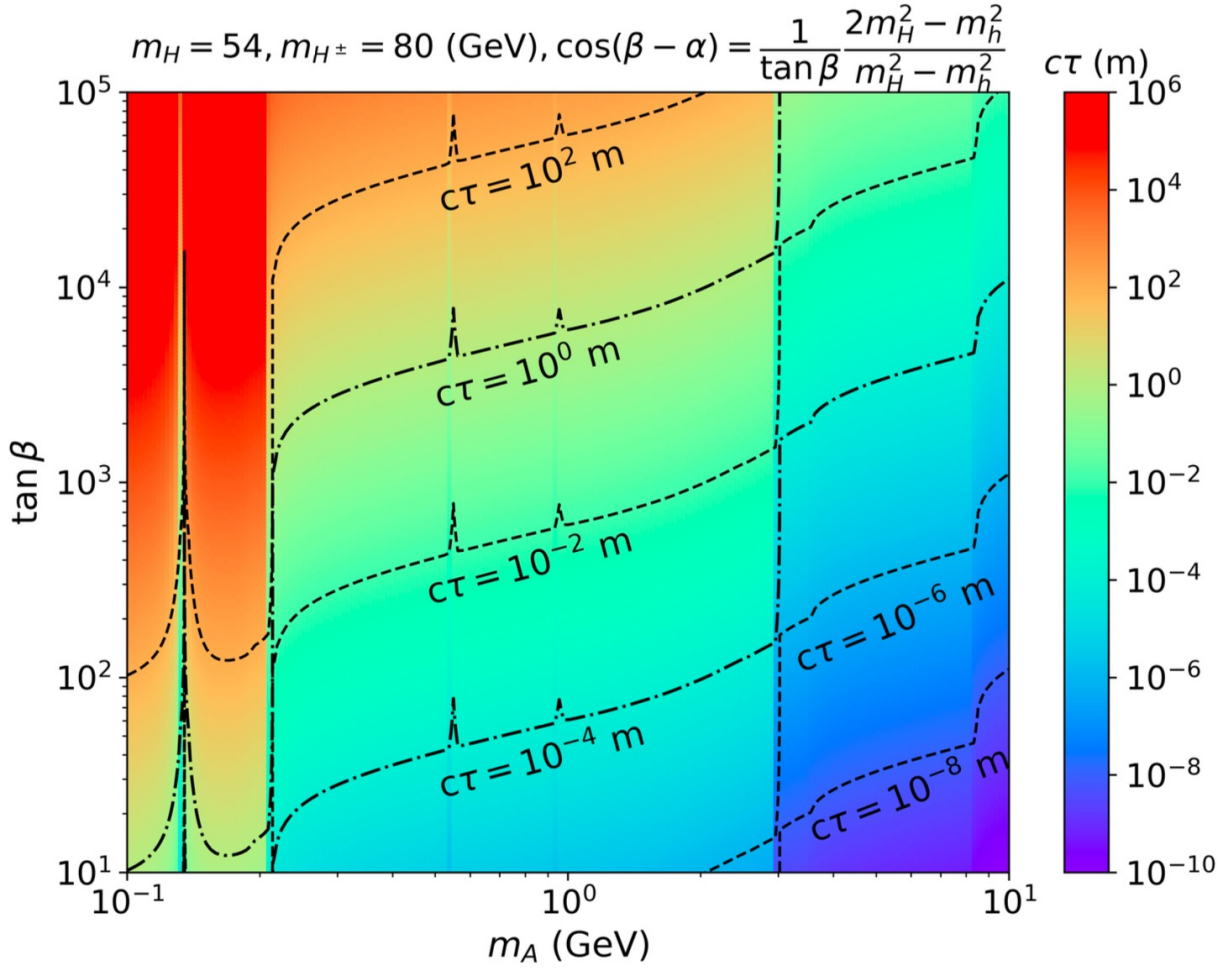
$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}\frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2}, \quad m_H \in (54, m_h)\ \text{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.$$

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

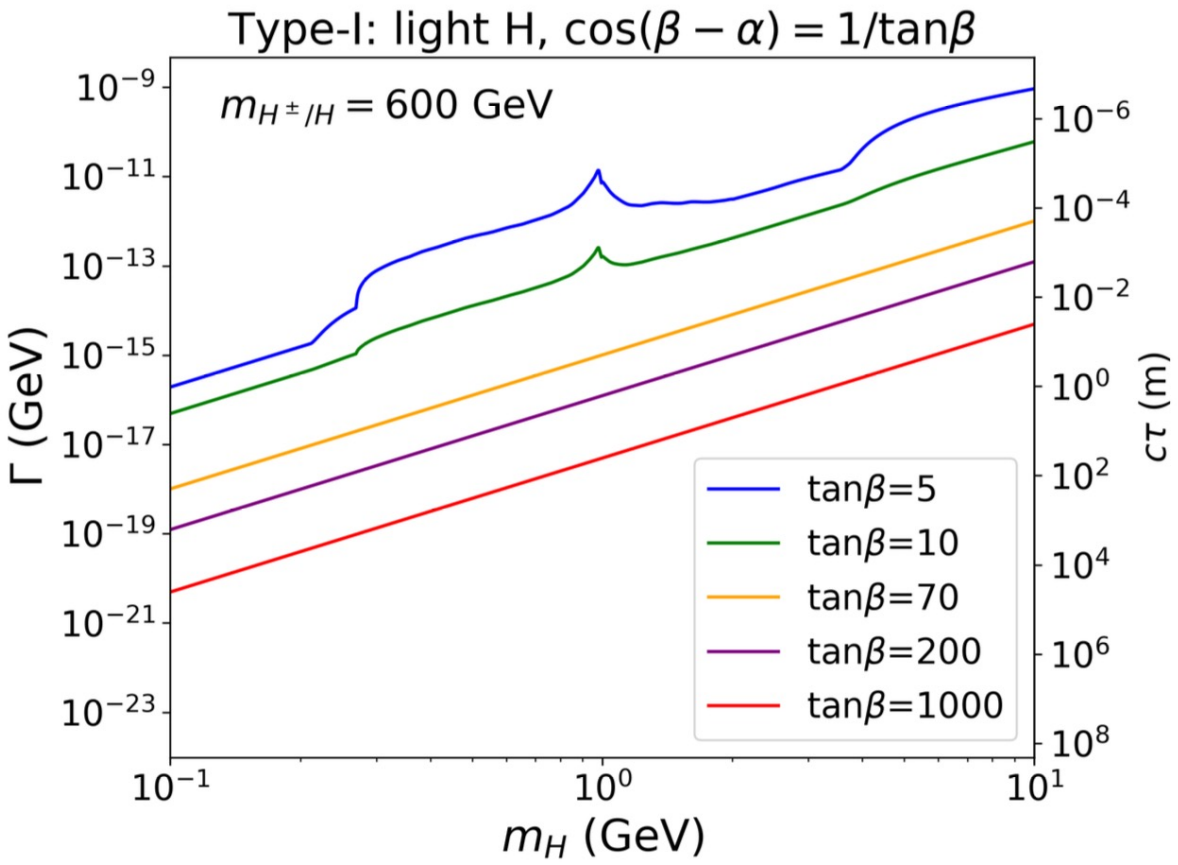
$$\cos(\beta-\alpha) = -\frac{1}{\tan\beta}, \quad m_H \in (101.2, 103)\ \text{GeV}, \quad m_{H^\pm} \sim m_H, \quad \lambda v^2 = 0.$$

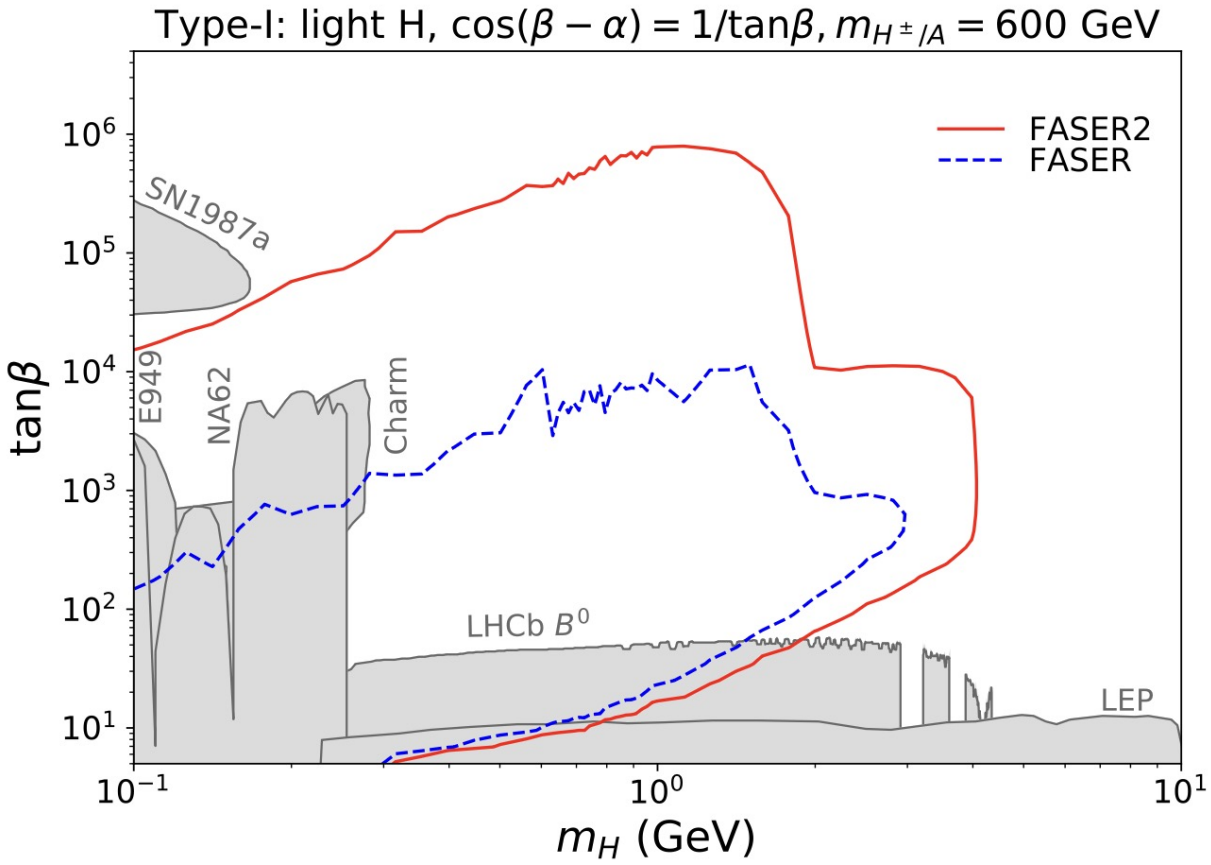
Complete Light LLP of Type-I 2HDM





Results: CP even BM





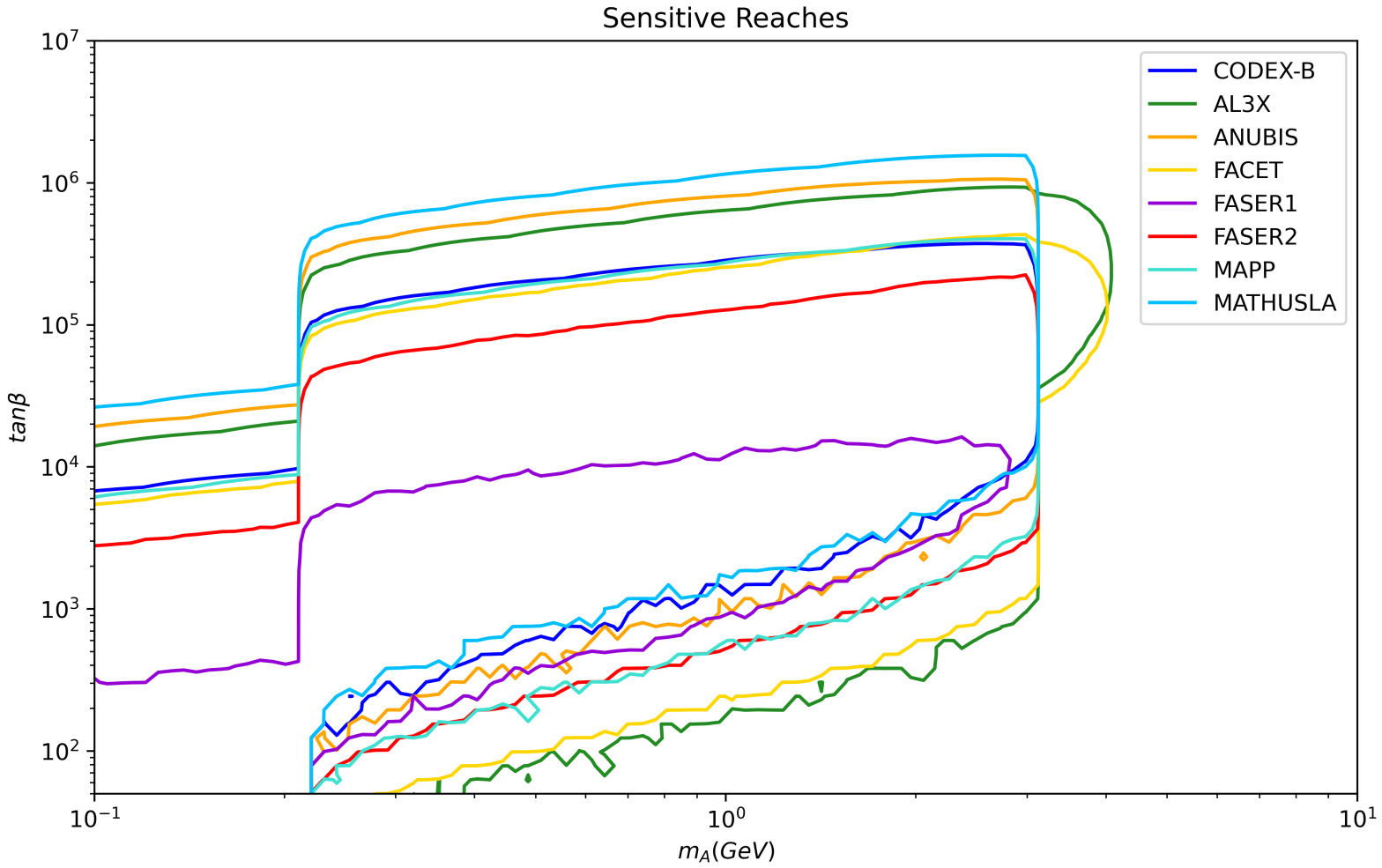
Results: for case study

higher luminosity helps to reach the weaker coupling region.

A larger detector, especially the radius helps to extend the reach in mA.

Facilities comparison

Preliminary



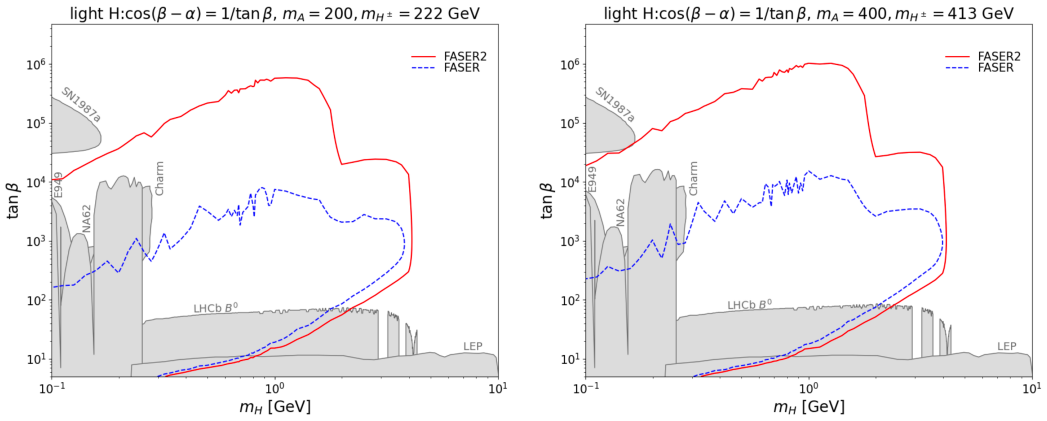
Conclusion

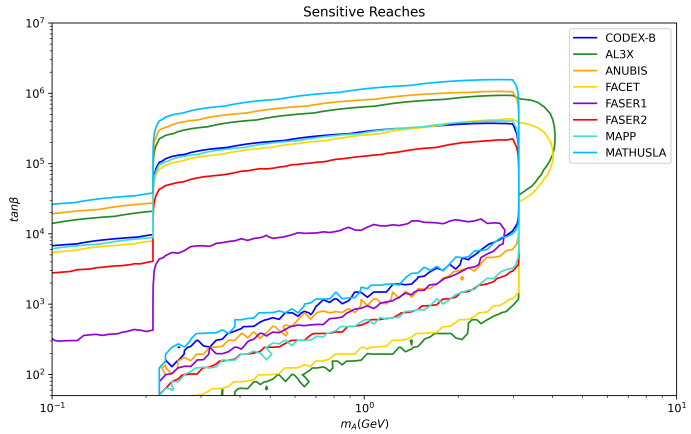
- Light scalar decay: GeV scale
- Complete LLP at Type-I 2HDM
- Various facilities

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

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

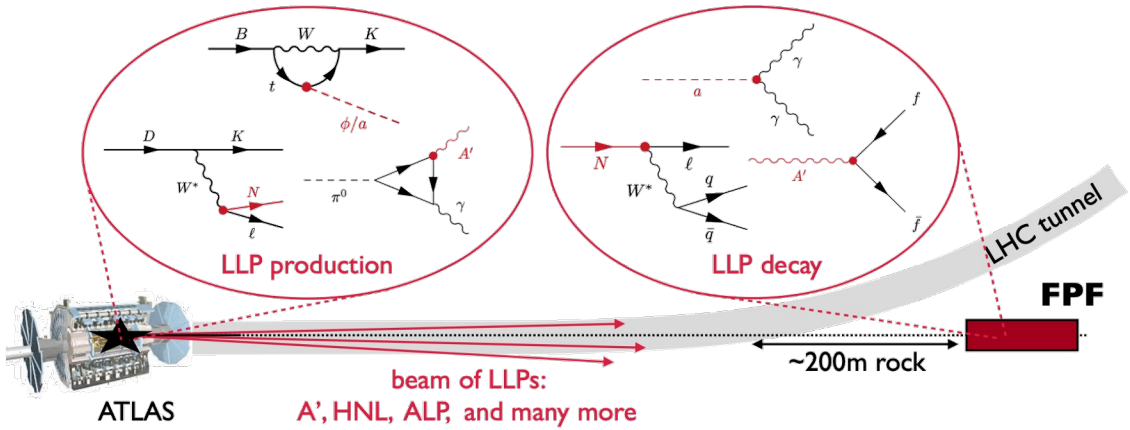
$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}\frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2}, \quad m_H \in (54, m_h)\ \text{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.$$





Thanks !

Decay



Well studied

?

Scale-ind

Scale > 2/3 GeV

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

$H \to \pi\pi$

$H \to KK$

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

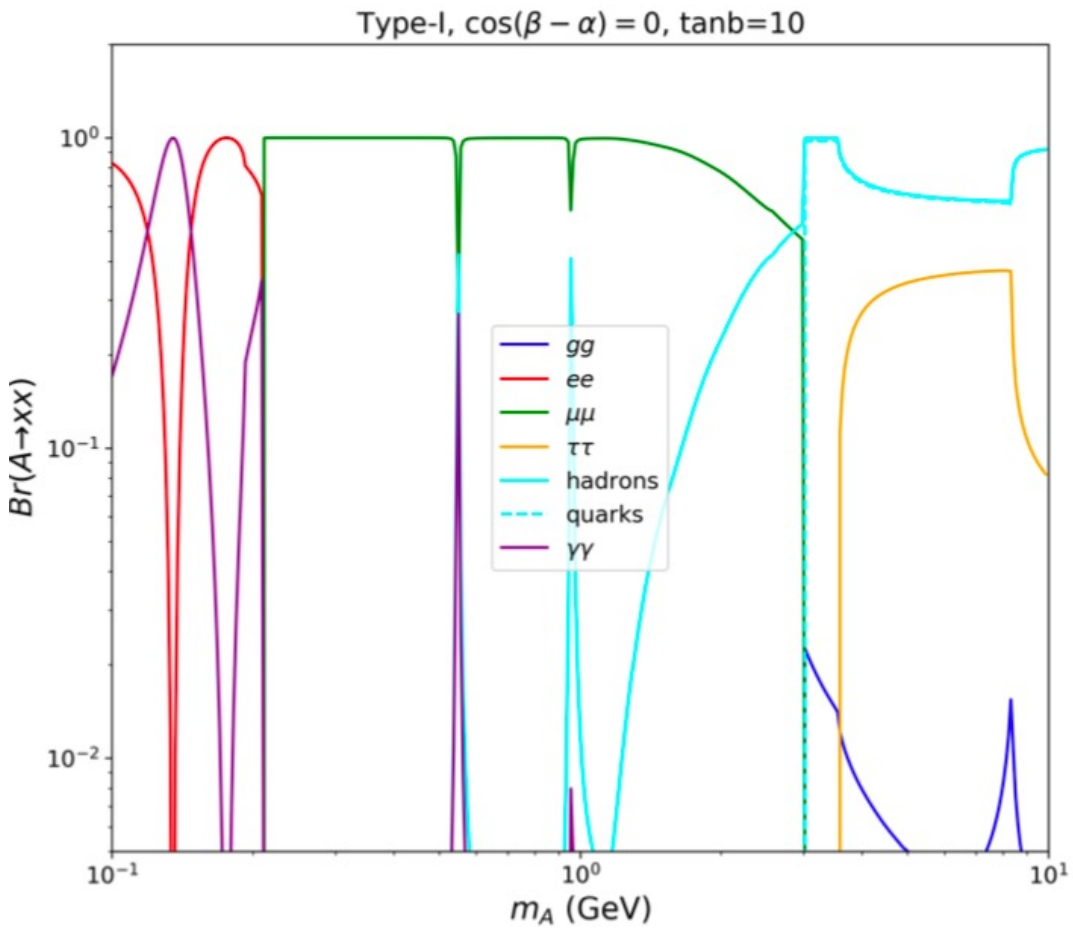
Chiral Perturbativity…

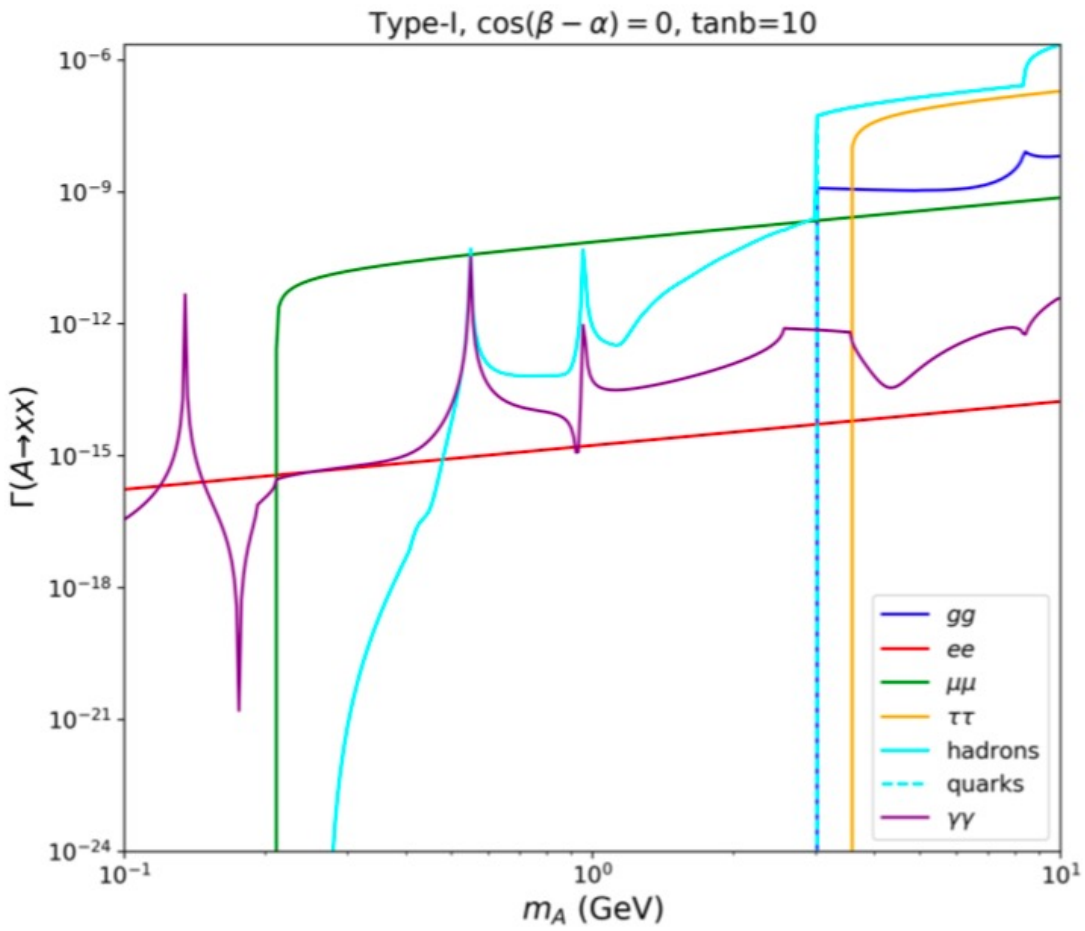
arXiv:1809.01876
arXiv:1612.06538

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

Results: CP odd

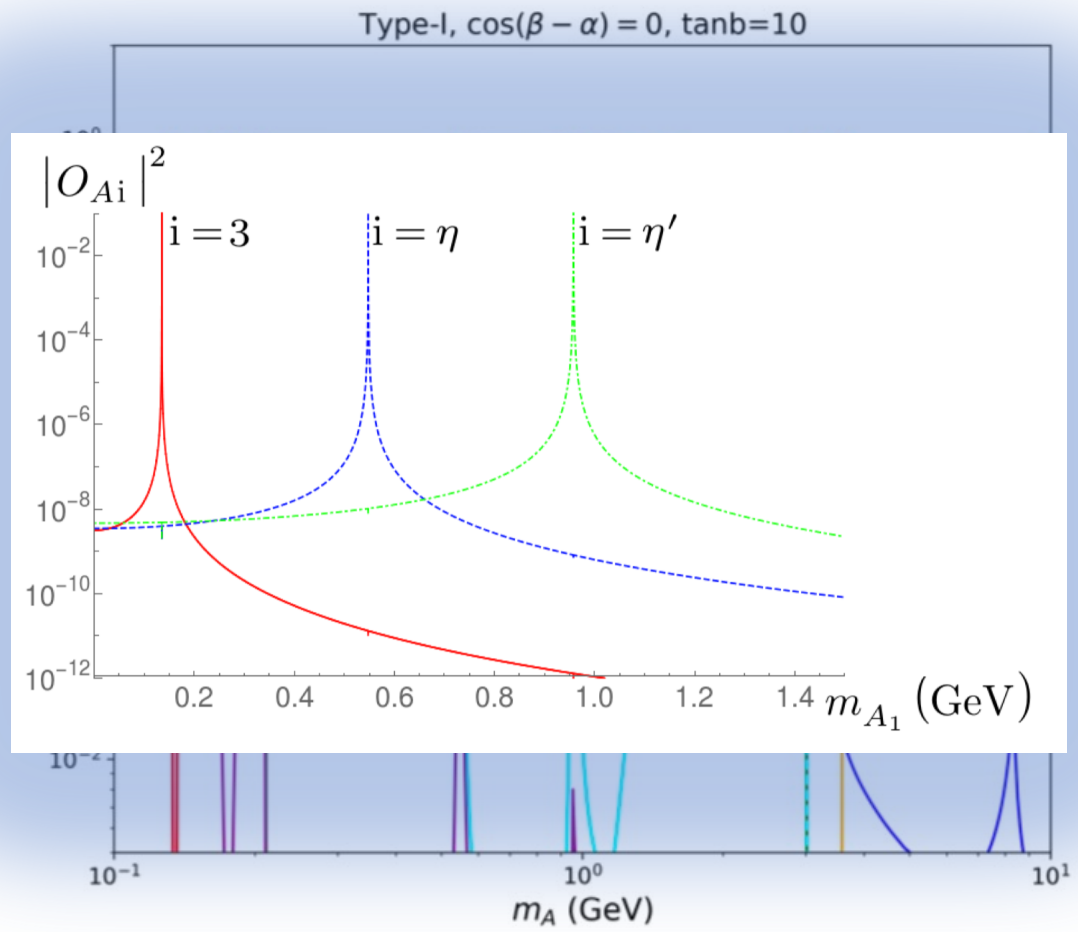
$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta$$

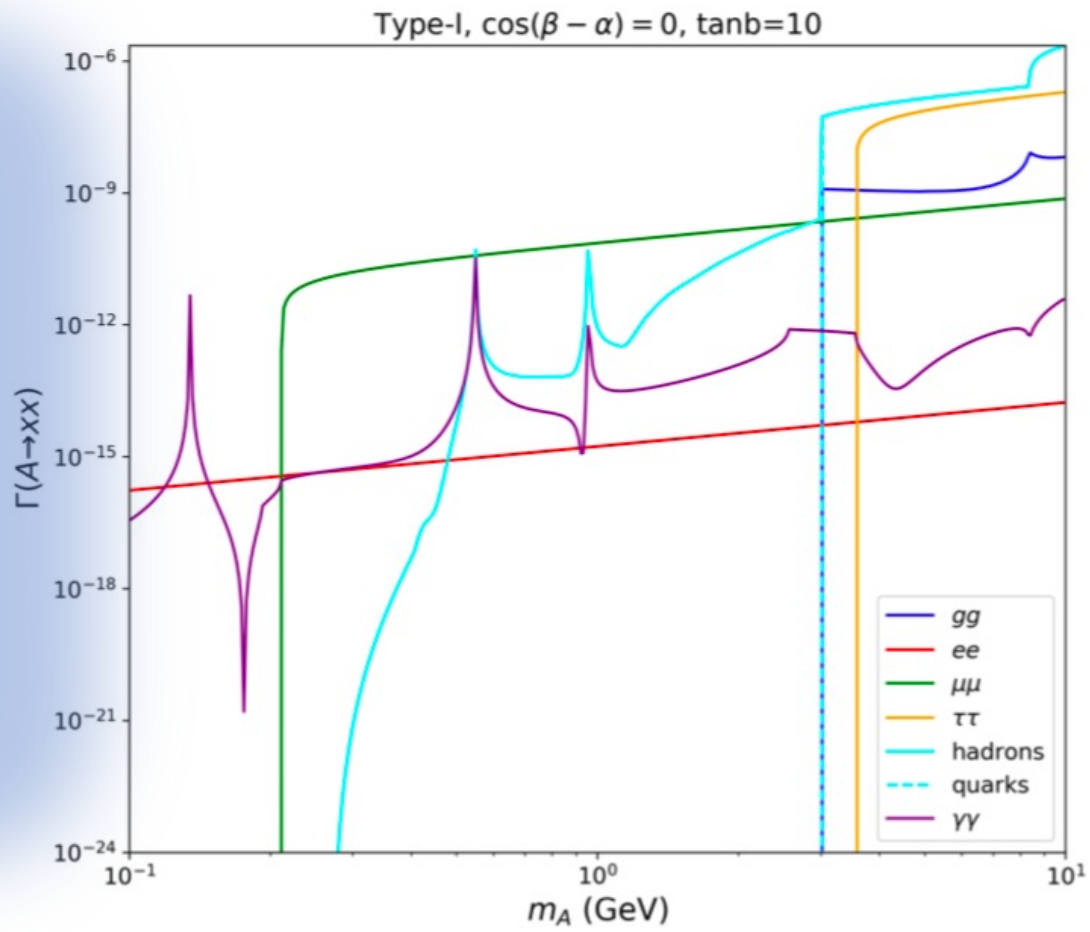




Results: CP odd

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





Results: CP odd

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