Long-lived particle searches at FASER and future machines

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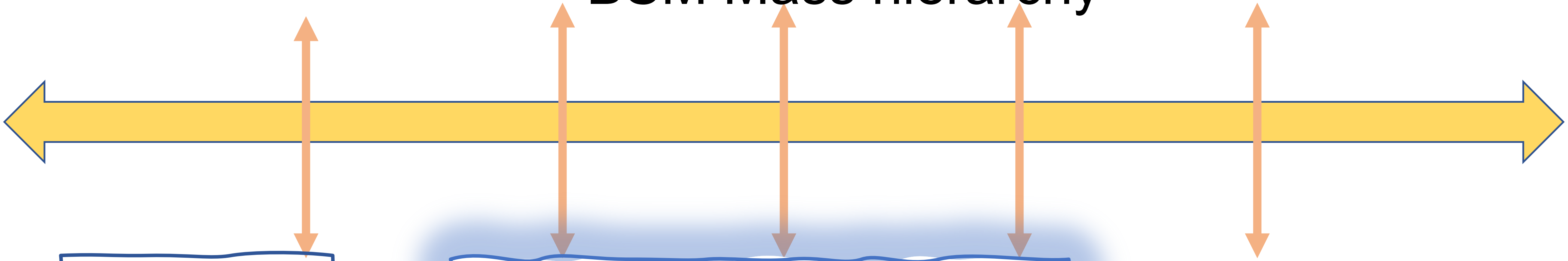
2606.XXXXX （YZ. Shi, WS, etc.）

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 $< m_{h_S} < 10$TeV
- 10 TeV $< m_{h_S}$

FASER

SHiP
Search for Hidden Particles

MUTHUSLA

$10^{17}\ \pi$, 10^{16} K, 10^{15} D, 10^{14} B

Heavy

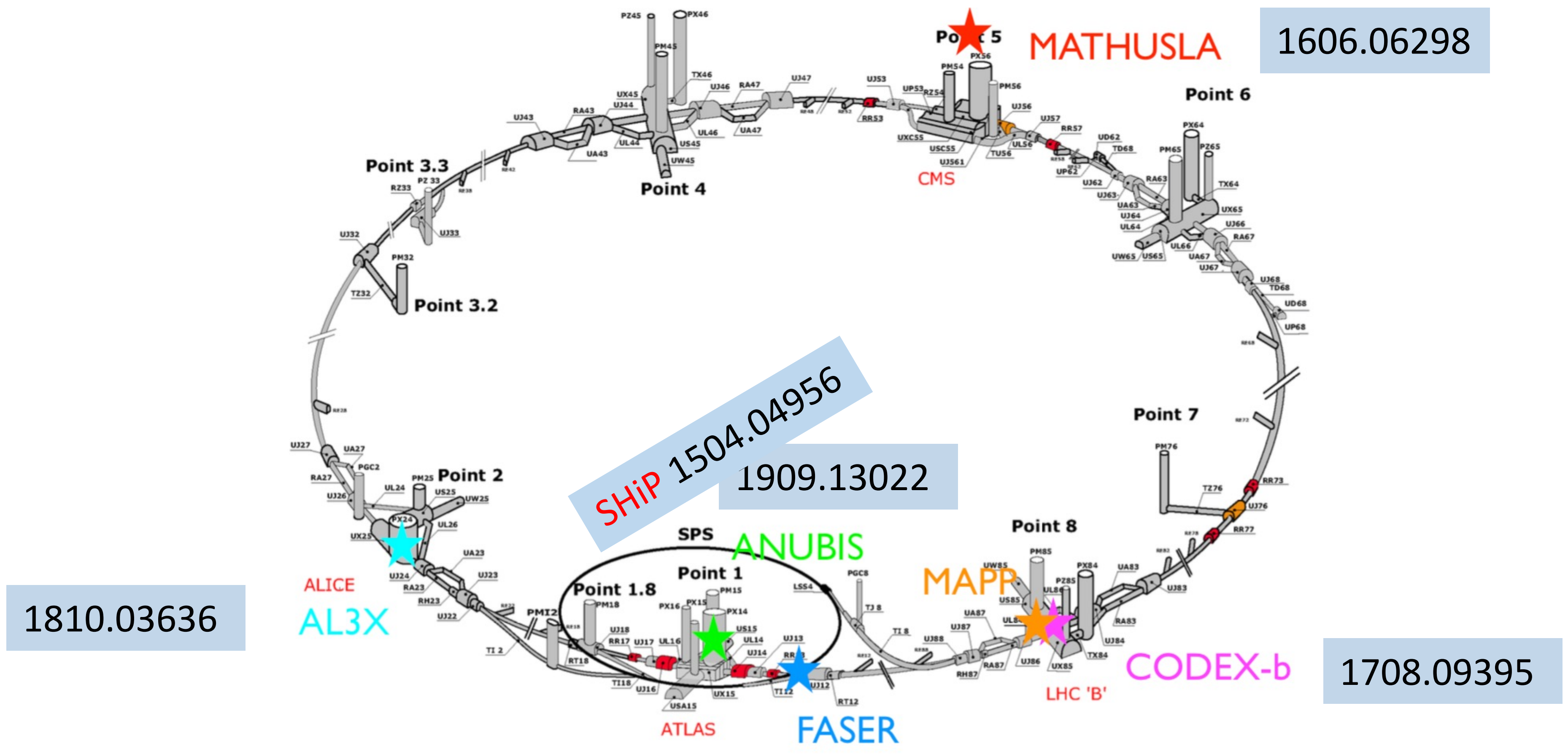
ATLAS EXPERIMENT

CEPC

CMS

Strongly interacting
Heavy Particle

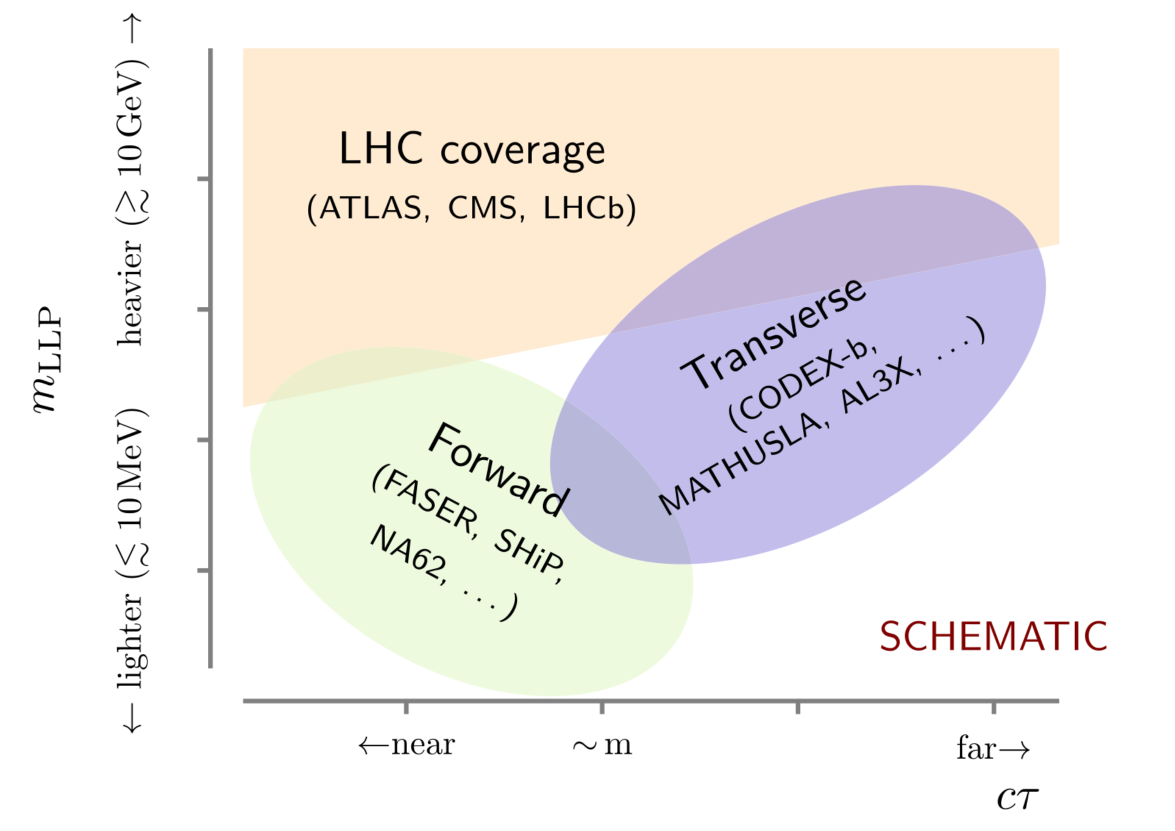
Proposals for LLP



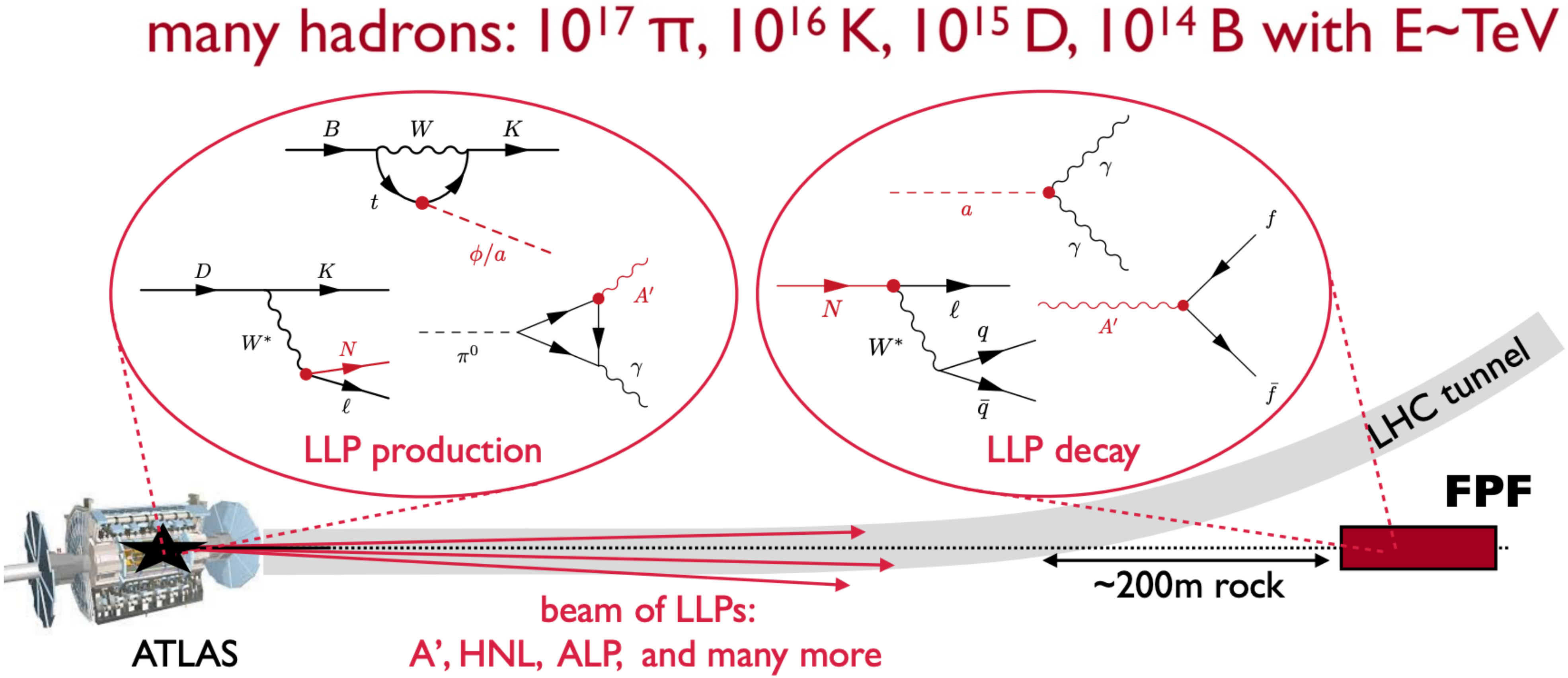
Light LLP searches

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

1. ATLAS and CMS: Heavy LLPs ($m_{\mathrm{LLP}} \gtrsim 10\,\mathrm{GeV}$) for all lifetimes ($c\tau \lesssim 10^7$ m).
2. LHCb: Short to medium lifetimes ($c\tau \lesssim 1$ 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 ($0.1 \lesssim c\tau \lesssim 10^7$ 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 ($1 \lesssim c\tau \lesssim 10^7$ m), and high $\sqrt{\hat{s}}$ production channels.



Eg: Production at FASER



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

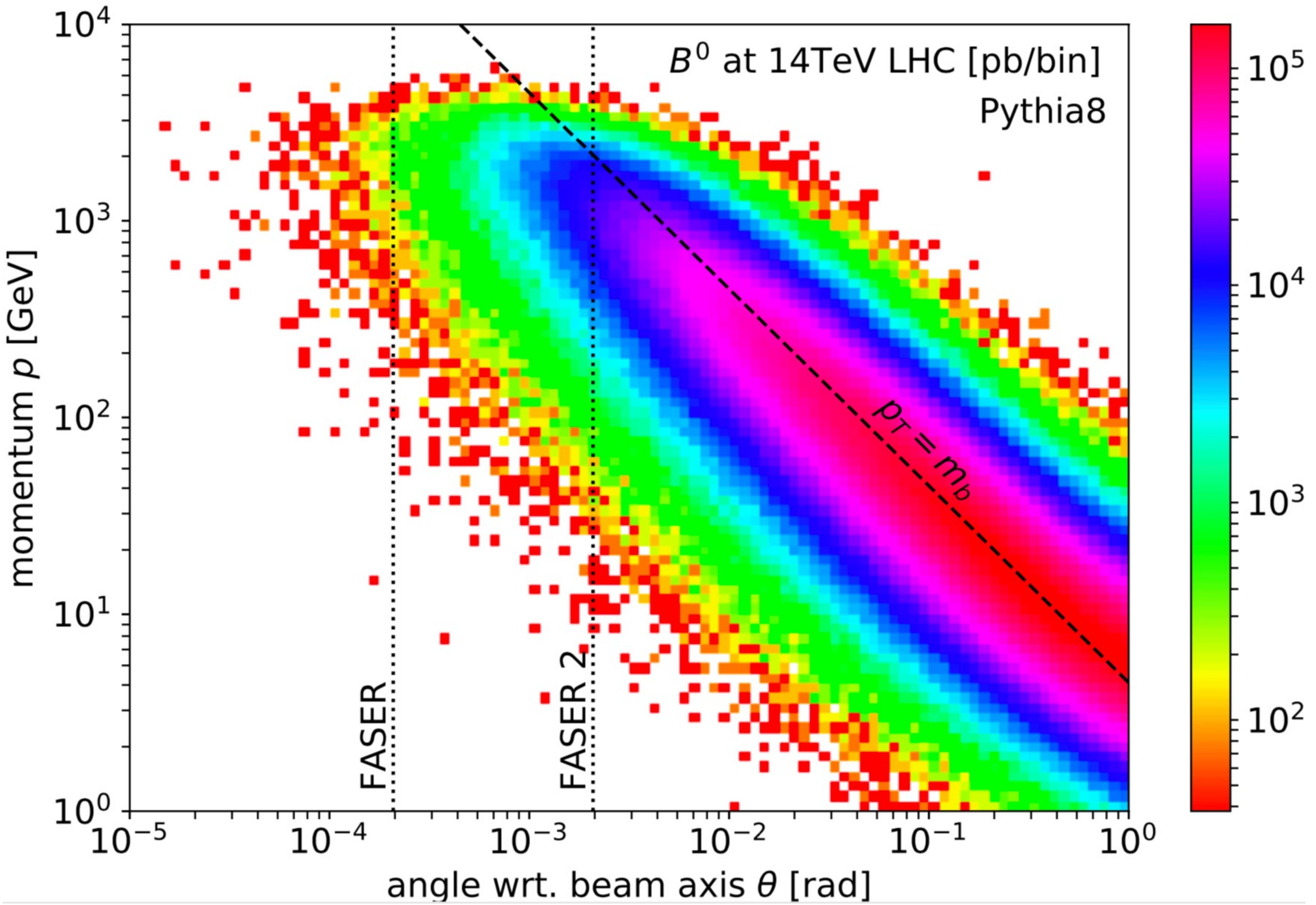
Production

B^0

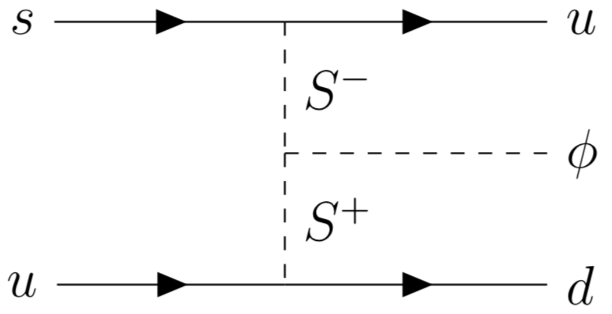
boosted mesons highly collimated

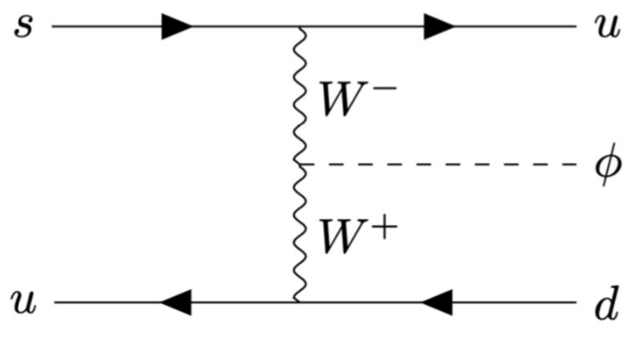
$p \cdot \theta = p_T \sim$ Mb

<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





Main contribution

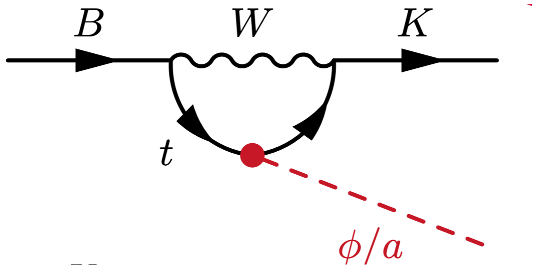
K$^{\pm}$: 493.677 ±0.016 MeV/

K^{0}: 497.611 ±0.013 MeV/

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

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

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



b: 4.18 GeV,   B: around 5.3 GeV,

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

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

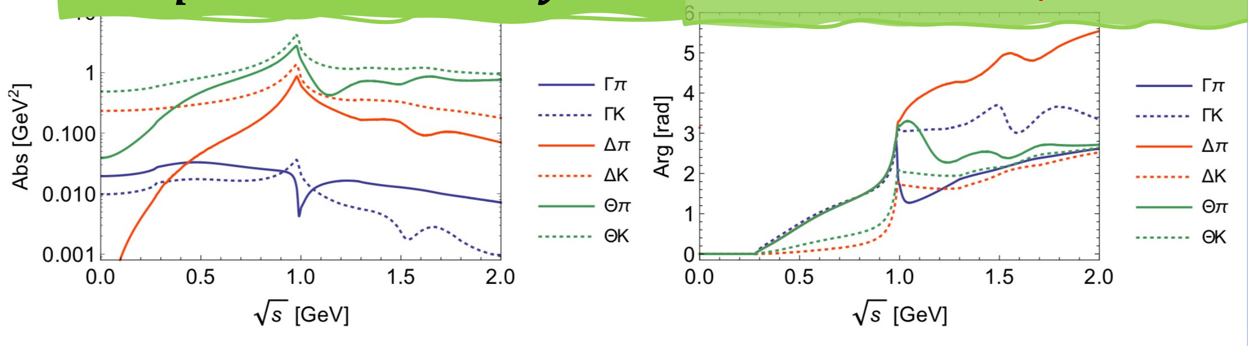
$$\Theta_\mu^\mu = -\frac{9\alpha_s}{8\pi} G_{\mu\nu}^a G^{a\mu\nu} + m_u\bar{u}u + m_d\bar{d}d + m_s\bar{s}s.$$

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

$m_\phi < 0.5$ GeV

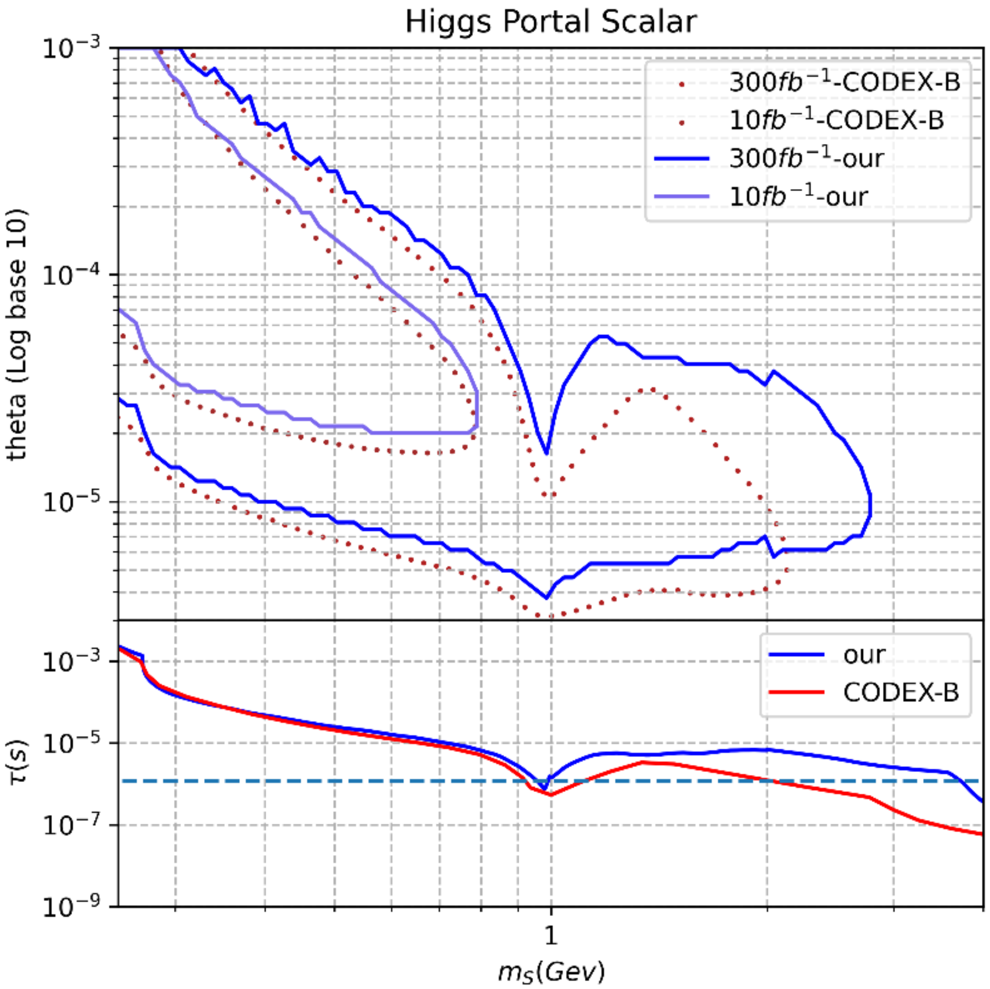
Leading order chiral perturbation theory

Dispersive Analysis 0.5GeV< m_ϕ < 2 GeV



Comparison

- SM+singlet



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

Complete Light Higgs

All constraints @ Type-I 2HDM

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

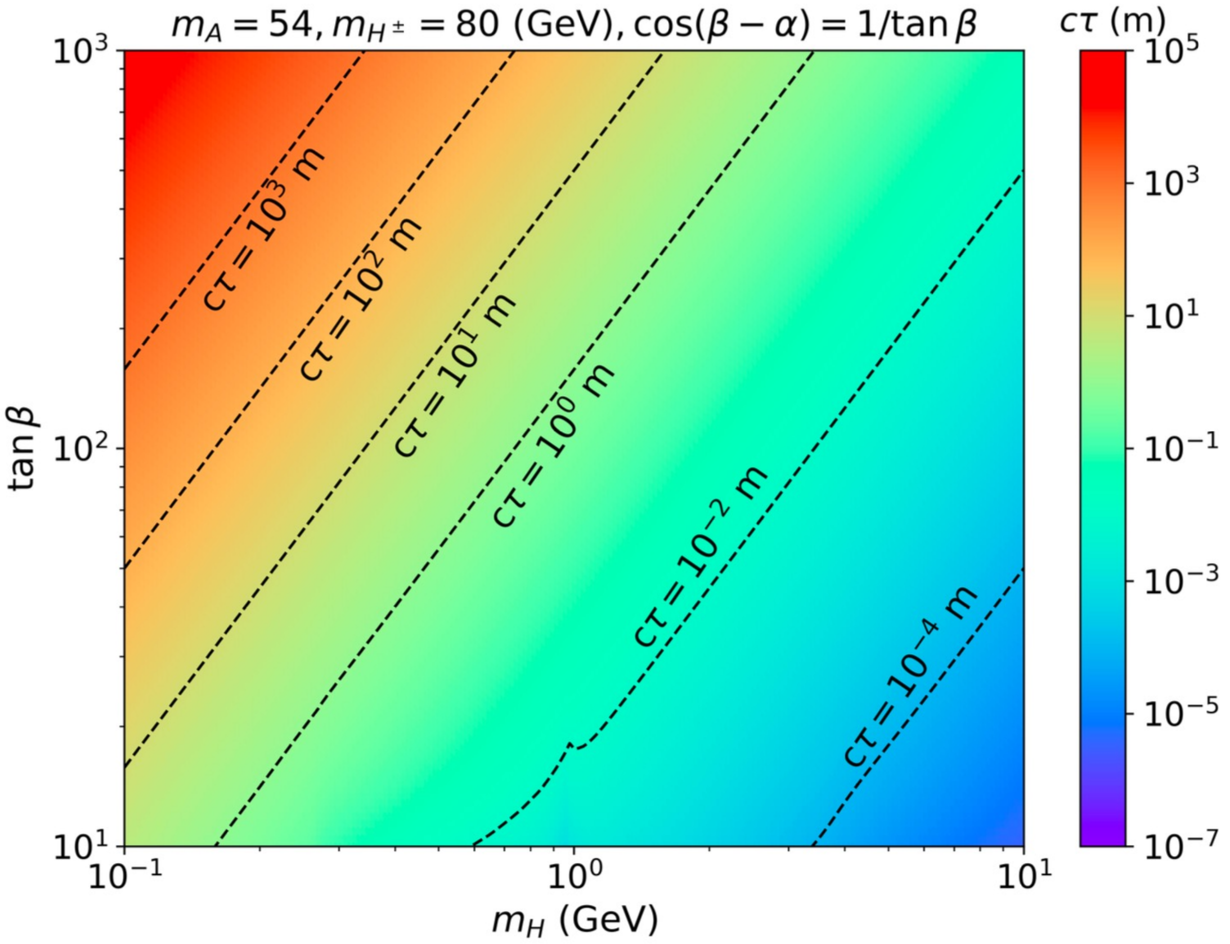
$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}\frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2}, \quad m_H \in (54, m_h)\ \mathrm{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.$$

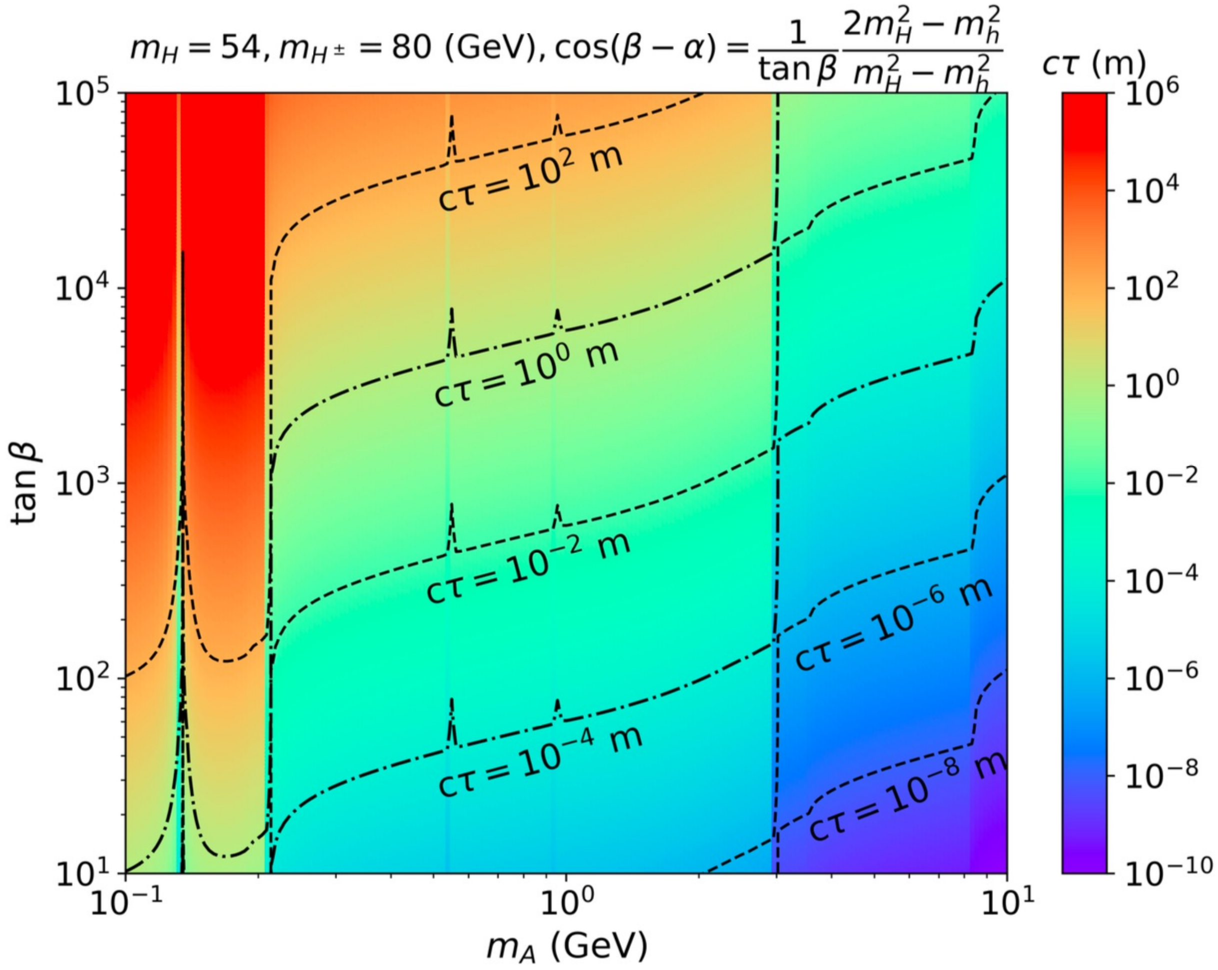
$$\cos(\beta-\alpha) = 0, \quad m_H \in (86.9, 90)\ \mathrm{GeV}, \quad m_{H^\pm} \sim m_H, \quad \lambda v^2 = 0,$$

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

Complete Light LLP

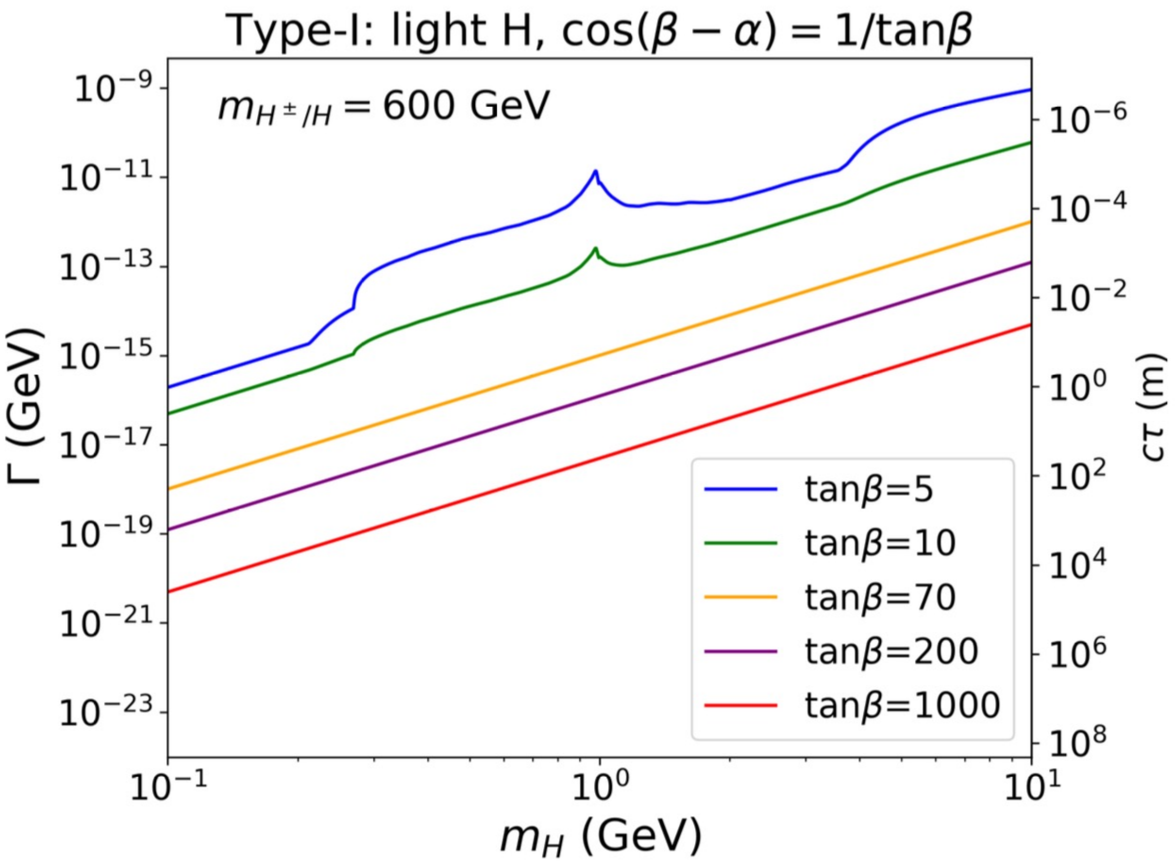
@ Type-I 2HDM

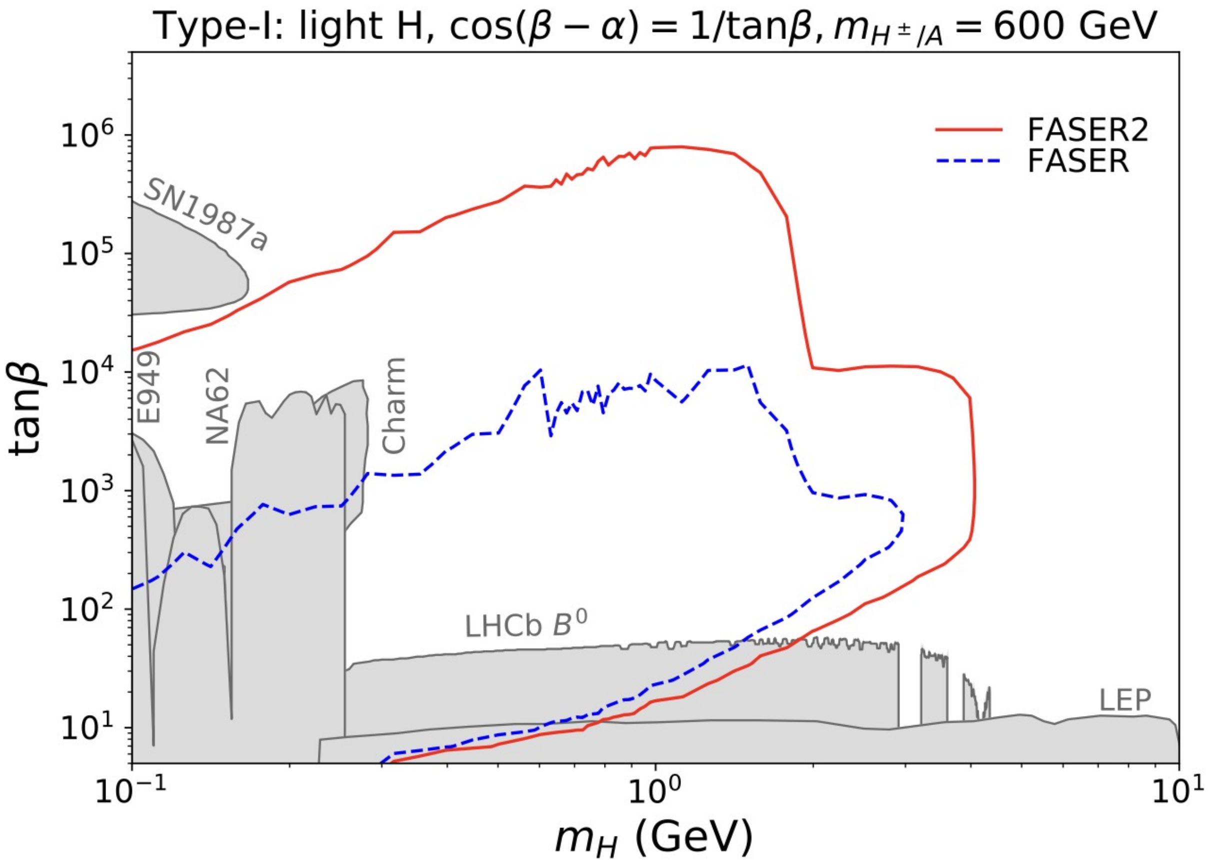




Results: CP even BM

@ Type-I 2HDM

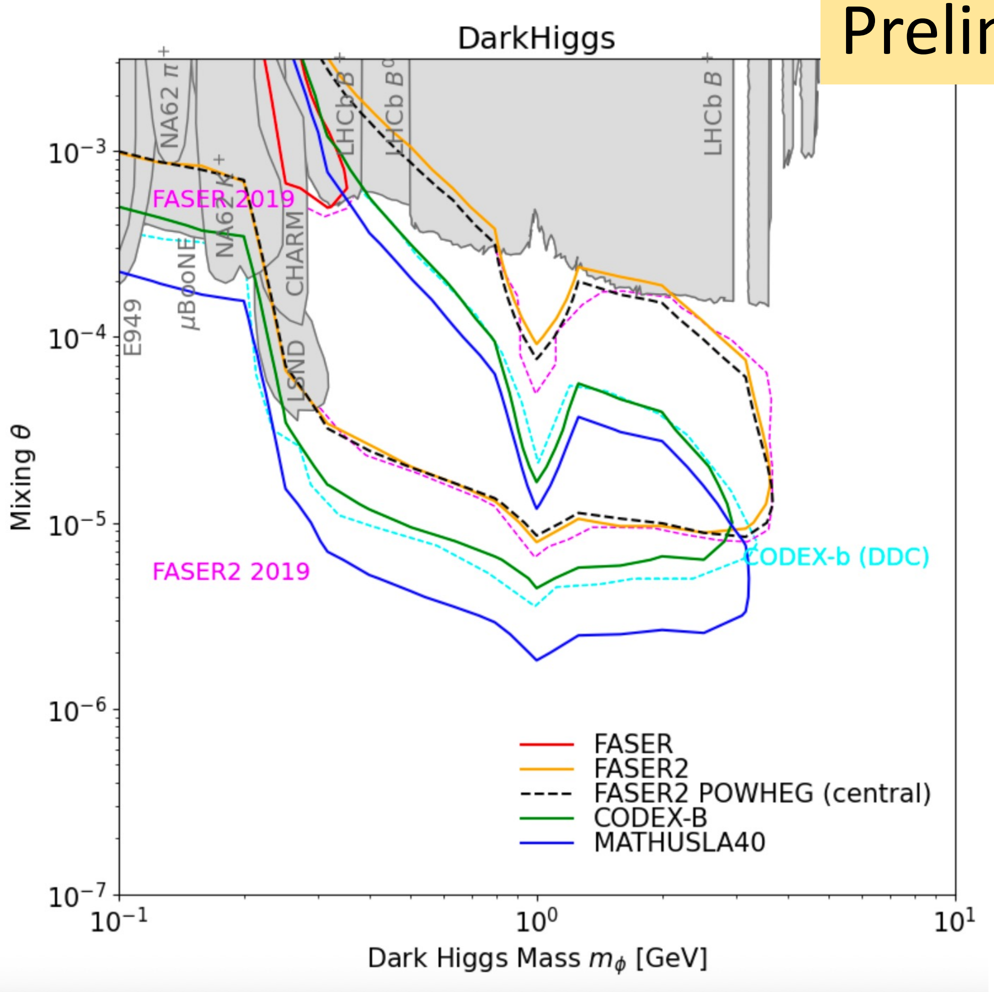


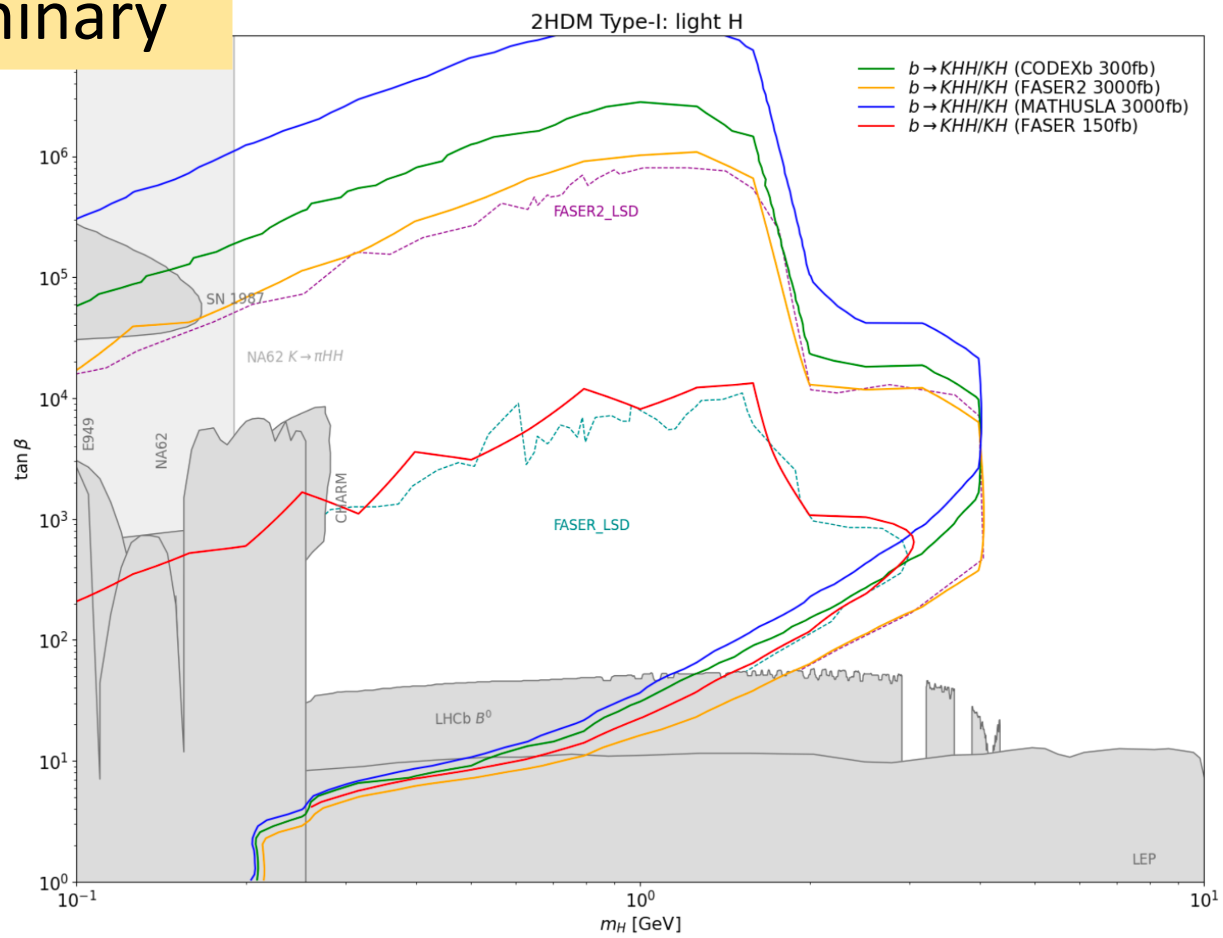


Future machines

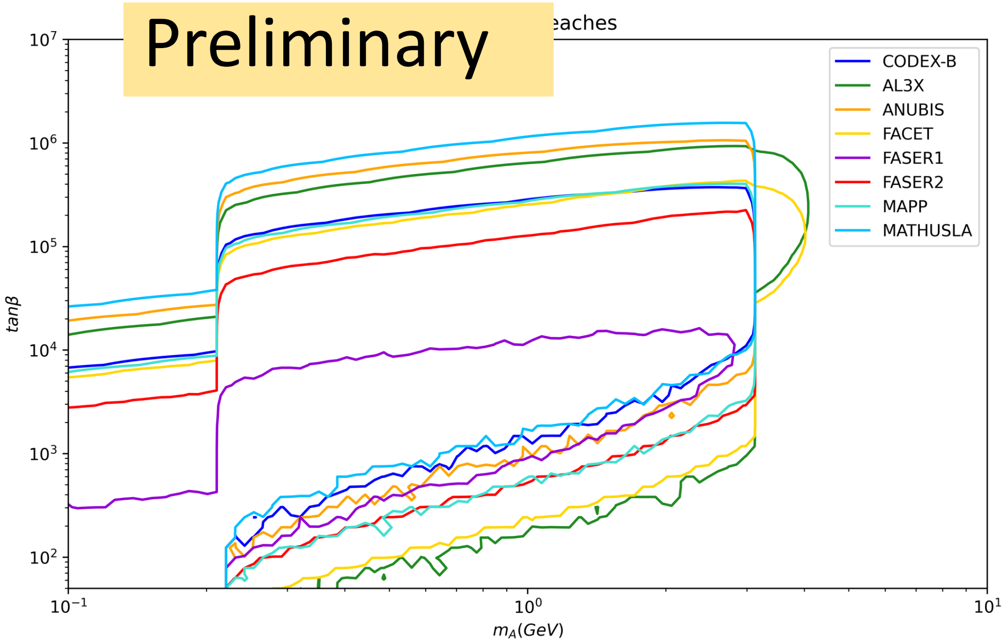
Experiment	Geometry	Luminosity	Energy	Color in Figu
MATHUSLA40	Box Max=[20, 93, 110], Box Min=[-20, 81, 70]	3 ab^{-1}	14TeV	Blue
CODEX-b	Box Max=[36, 3, 15], Box Min=[26, -7, 5]	300 fb^{-1}	14TeV	Green
FASER	Cylinder L=480m, h=1.5m, r=0.1m	150 fb^{-1}	14TeV	Red
FASER2	Cylinder L=480m, h=5m, r=1m	3 ab^{-1}	14TeV	Orange

Preliminary





Case study



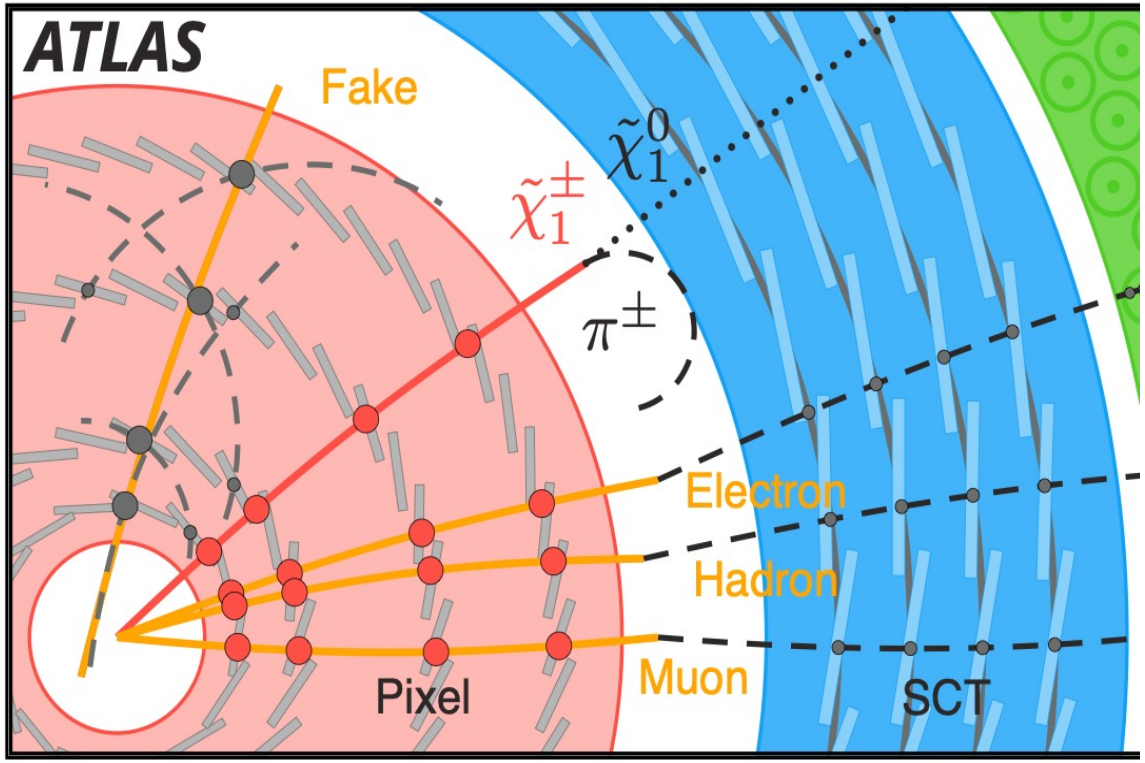
higher luminosity helps to reach the weaker coupling region.

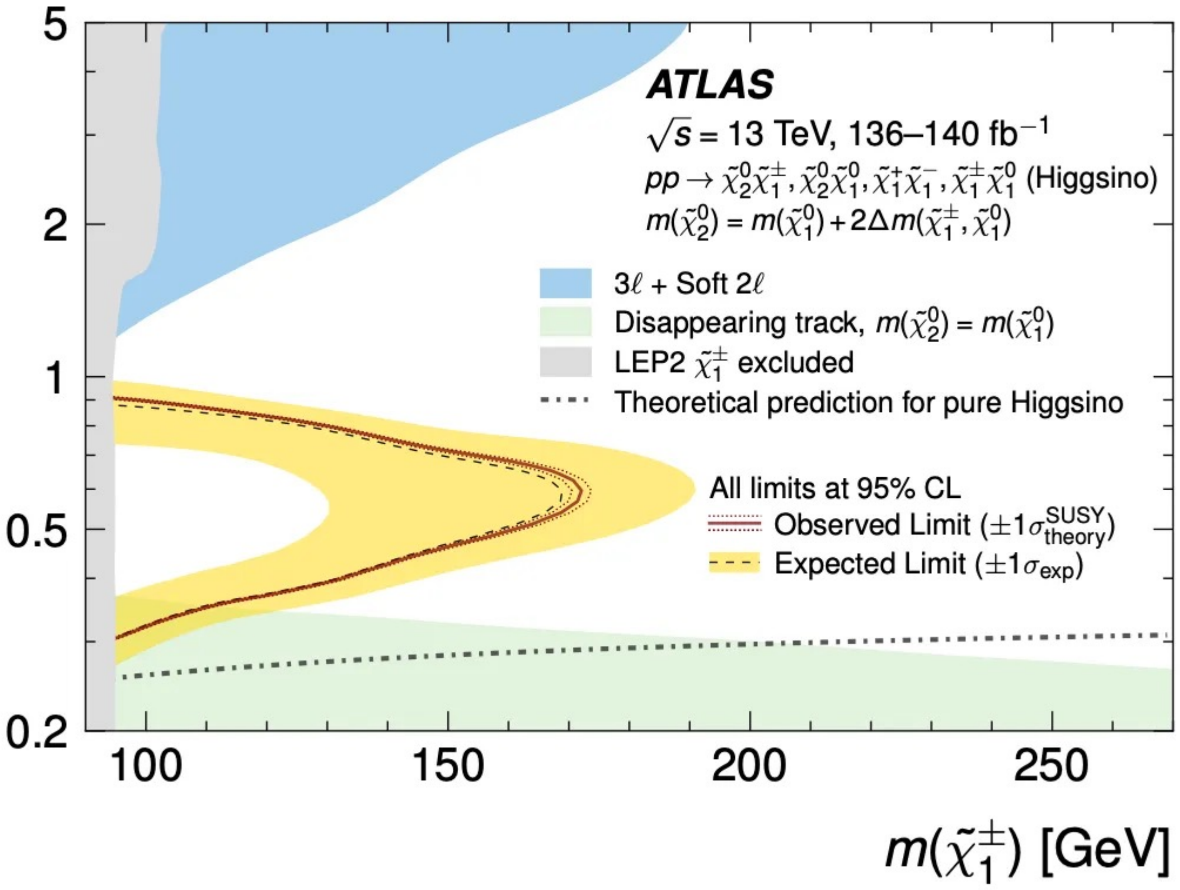
A larger detector, especially the radius helps to extend the reach in mA.

Q: possible to go beyond M_b @ FASER?

eg: Long-lived charginos $M_{LLP} > M_b$

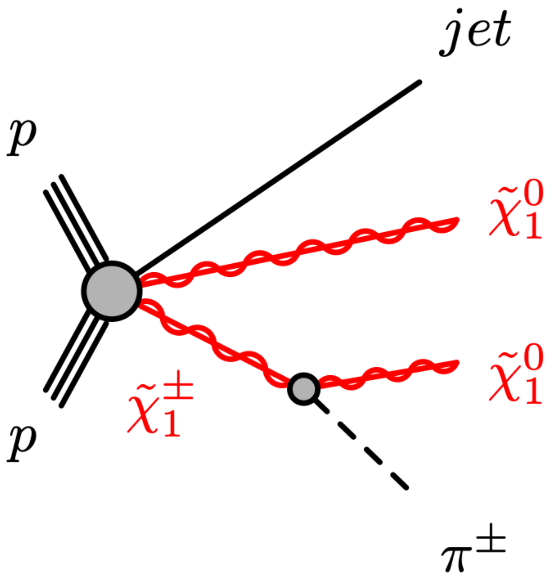
PhysRevLett.132.221801





$M_{LLP}>M_b$

Both the two methods, disappearing and displaced tracks, are focused on **charged LLP**



some assumptions

Disappearing track, $m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0)$

Displaced track :

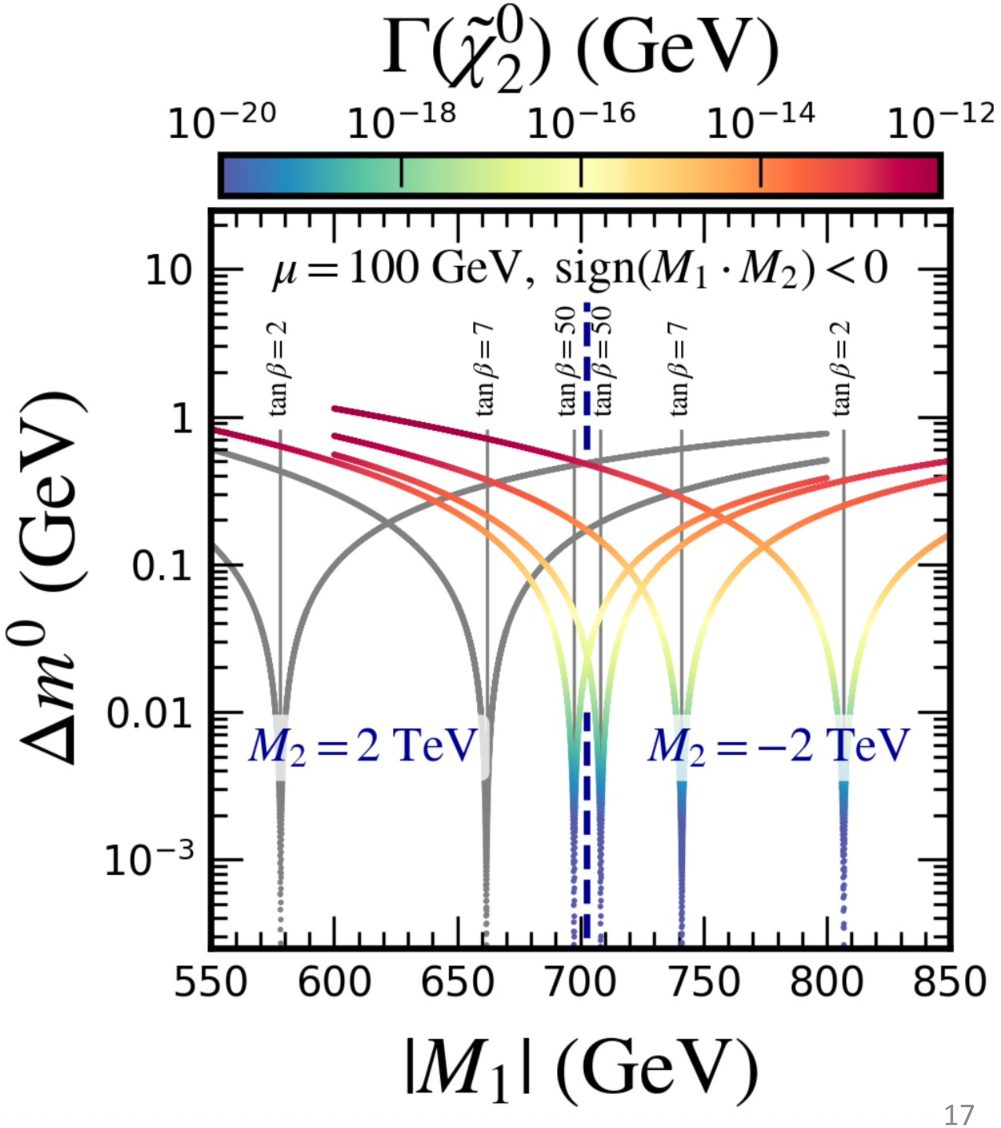
$$m(\tilde{\chi}_2^0) = m(\tilde{\chi}_1^0) + 2\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$$

$M_{LLP} > M_b$: Long-lived Higgsino

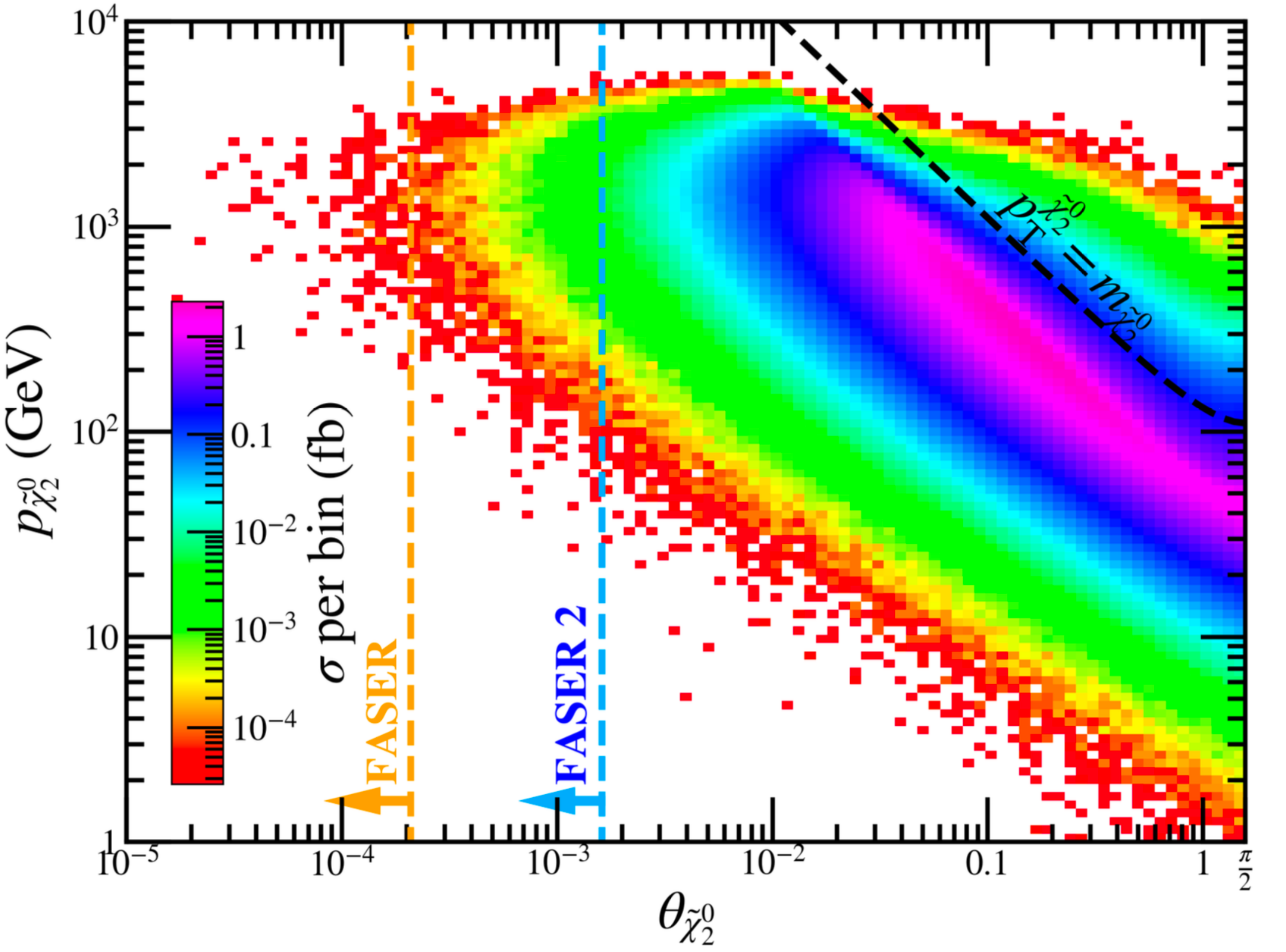
Higgsino-like neutralino @ MSSM

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \gamma,$$
$$\to \tilde{\chi}_1^0 + Z^* \to \tilde{\chi}_1^0 + f\bar{f}.$$

$$\Gamma(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma) = \frac{g^2_{\tilde{\chi}_2^0 \tilde{\chi}_1^0 \gamma}}{8\pi} \frac{\left(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_1^0}\right)^3}{m^5_{\tilde{\chi}_2^0}},$$

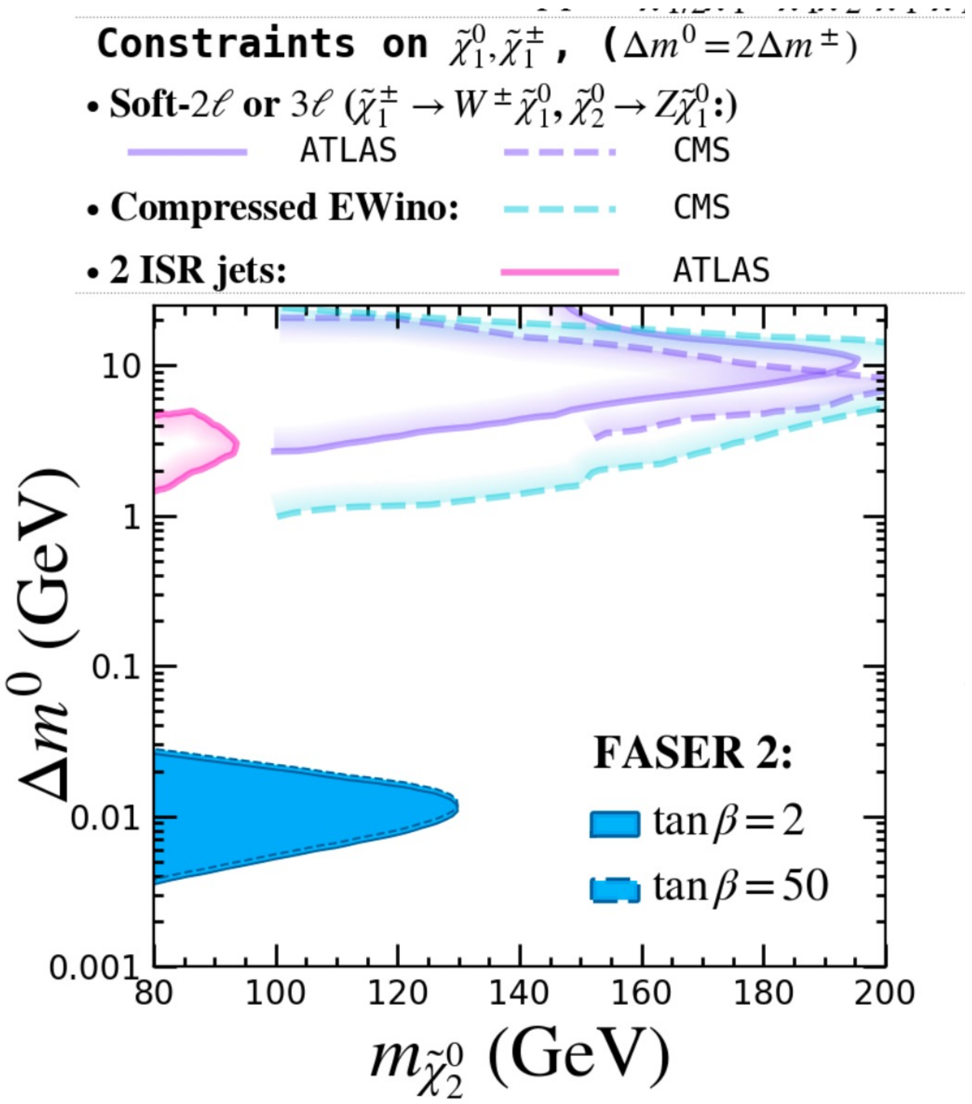


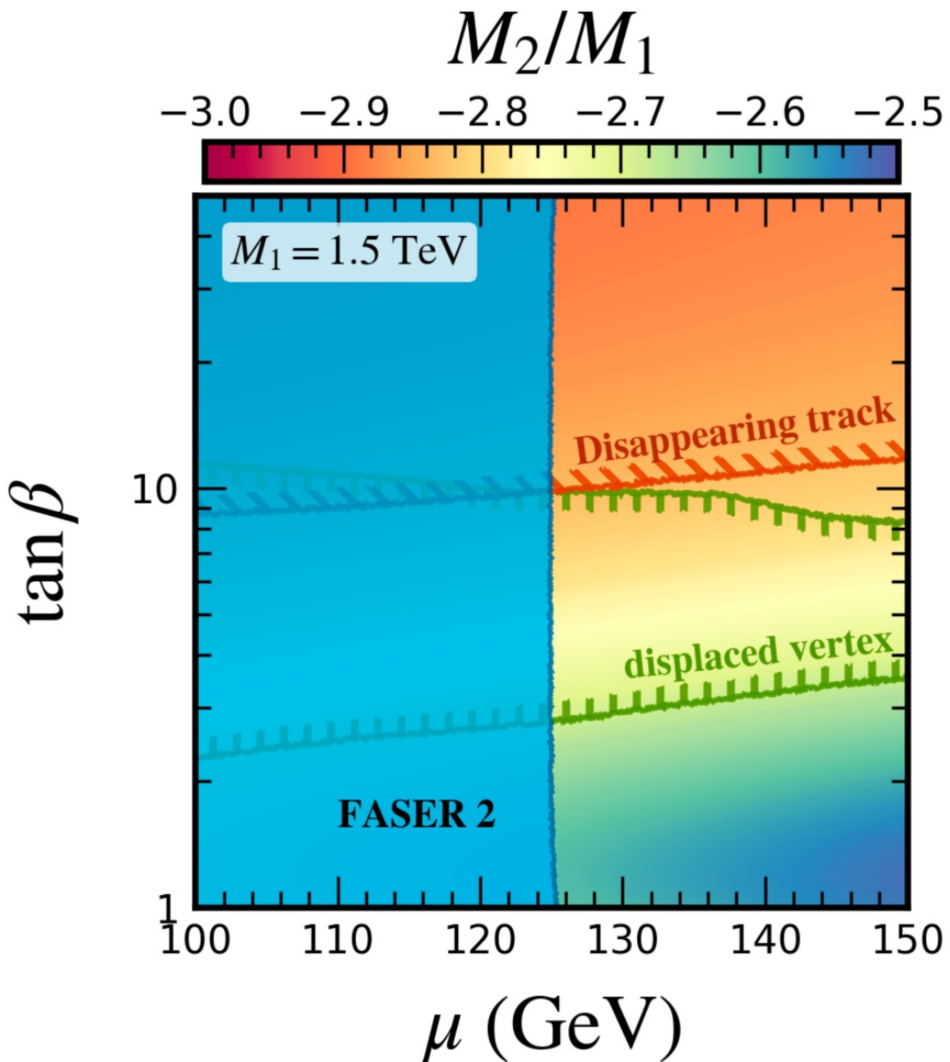
Production



$p_{\tilde{\chi}_2^0}$ (GeV)
$\theta_{\tilde{\chi}_2^0}$
σ per bin (fb)
FASER
FASER 2
$p_T^{\tilde{\chi}_2^0} = m_{\tilde{\chi}_2^0}$
10^4
10^3
10^2
10
1
10^{-5}
10^{-4}
10^{-3}
10^{-2}
0.1
1
$\frac{\pi}{2}$
1
0.1
10^{-2}
10^{-3}
10^{-4}

FASER for $\mathcal{O}(100)$ GeV LLP





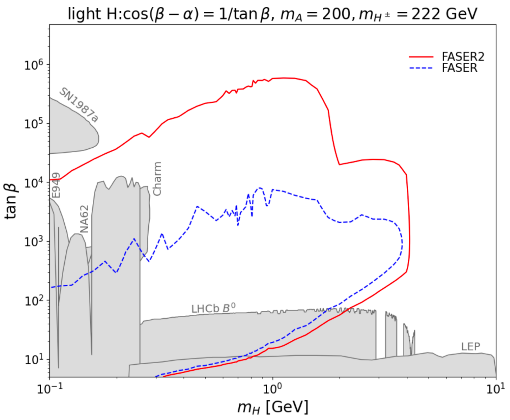
Conclusion

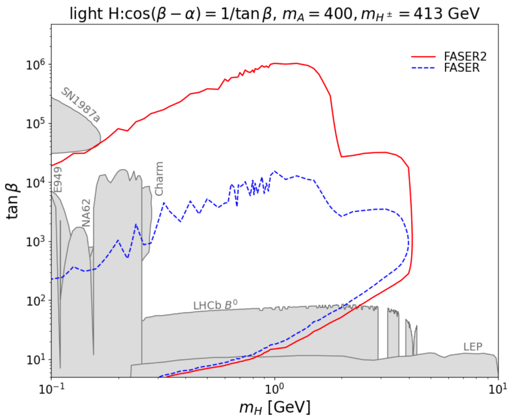
- Light scalar decay: GeV scale
- Complete LLP at Type-I 2HDM
- Various facilities
- $M_{LLP}>M_B$

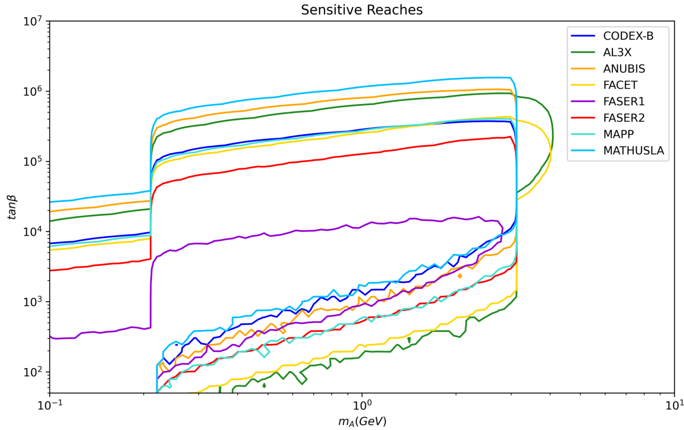
https://github.com/shiggs90/Light_scalar_decay.git.

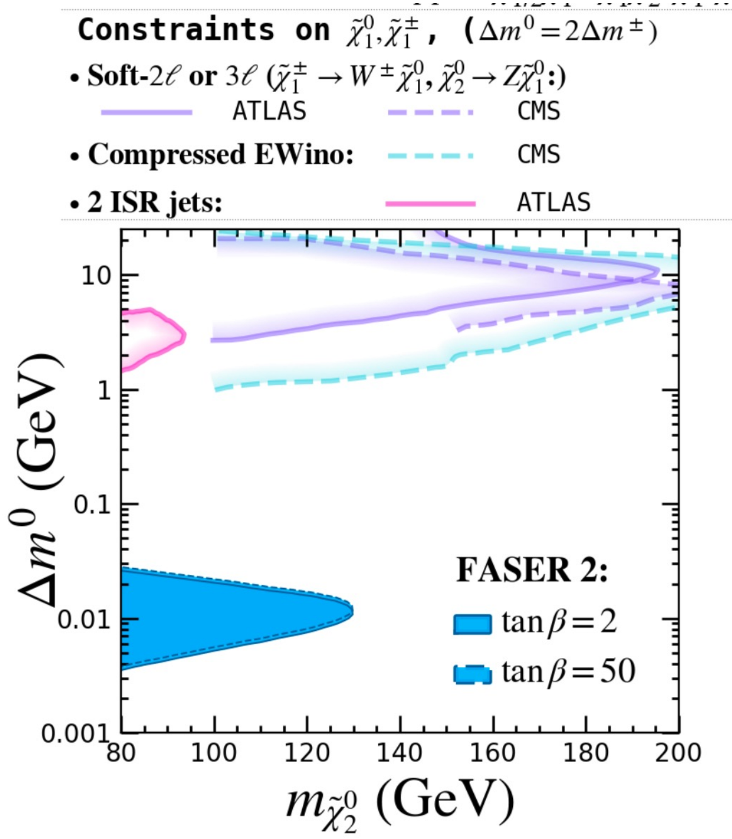
$$\boxed{\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}, \quad m_A \in (54, 600)\ \text{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.}$$

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









Thanks !

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

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

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

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

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

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

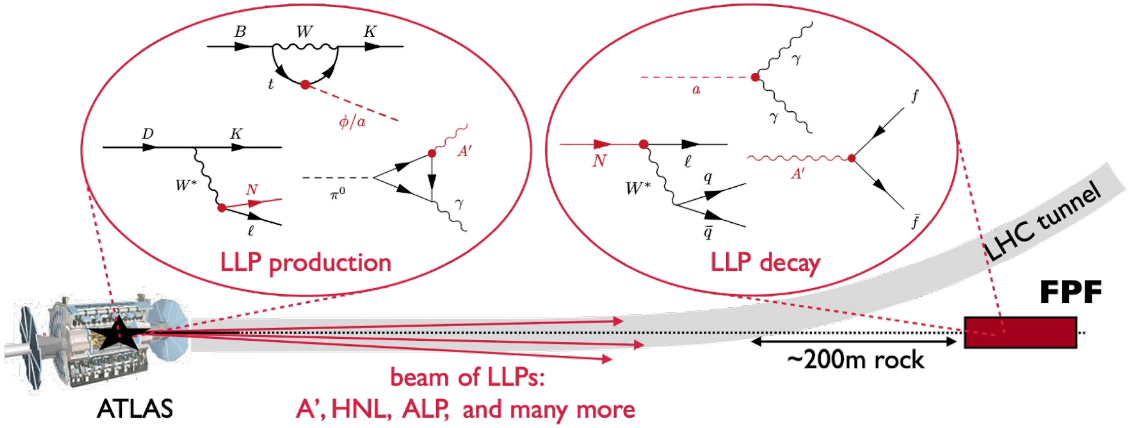
$$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \Rightarrow v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$$

v: 246 GeV

m_h: 125. GeV

Soft Z_2 symmetry breaking: m_{12}^2

Decay



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…

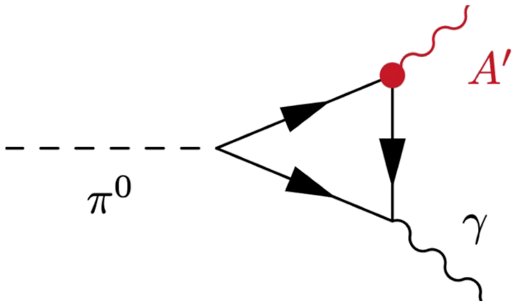
arXiv:1809.01876
arXiv:1612.06538

Production: CP even scalar

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

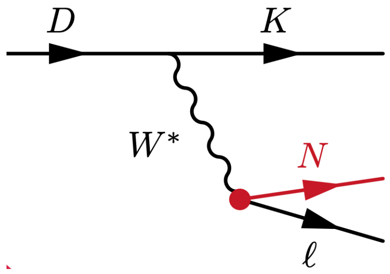
$$\xi_\phi^\gamma = \sum_{f\in q,\ell} N_c Q_f^2 \xi_\phi^f A_{1/2}^\phi\left(\tau_f^\phi\right) + \xi_\phi^V A_1^\phi\left(\tau_W^\phi\right)$$

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

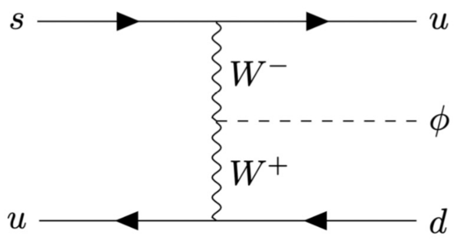


$$K \to \pi\phi,\ \eta^{(\prime)} \to \pi\phi,\ D \to X_u\phi\quad B \to X_s\phi$$

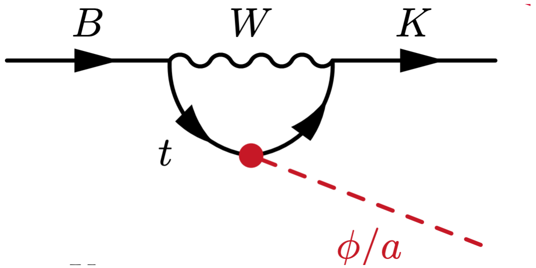
$$\pi^+ \to \ell\nu\phi \qquad K^+ \to \ell\nu\phi \qquad \Upsilon \to \phi\gamma$$



K



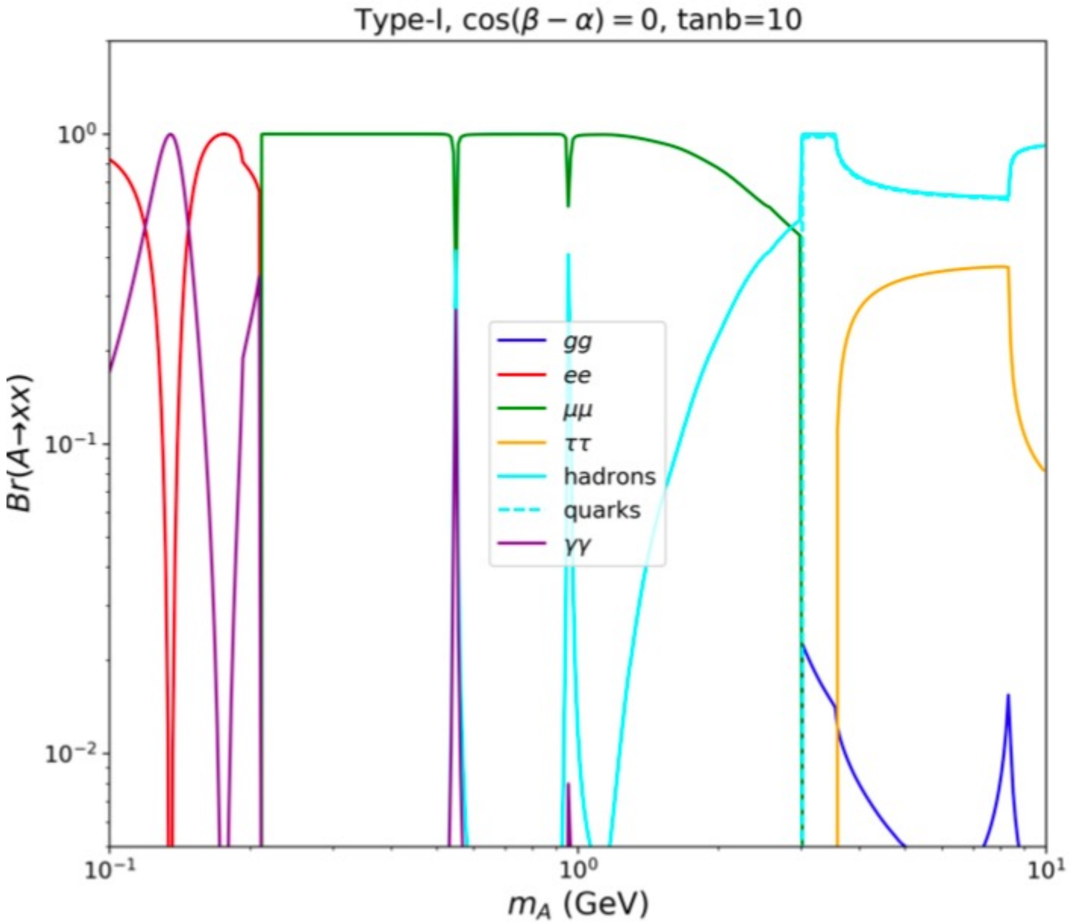
$$\frac{\mathrm{Br}(B\to X_s\phi)}{\mathrm{Br}(B\to X_c e\nu)} = \frac{\Gamma(b\to s\phi)}{\Gamma(b\to ce\nu)} = \frac{12\pi^2 v^2}{m_b^2}\left(1-\frac{m_\phi^2}{m_b^2}\right)^2 \frac{1}{f(m_c^2/m_b^2)}\left|\frac{\xi_\phi^{bs}}{V_{cb}}\right|^2$$

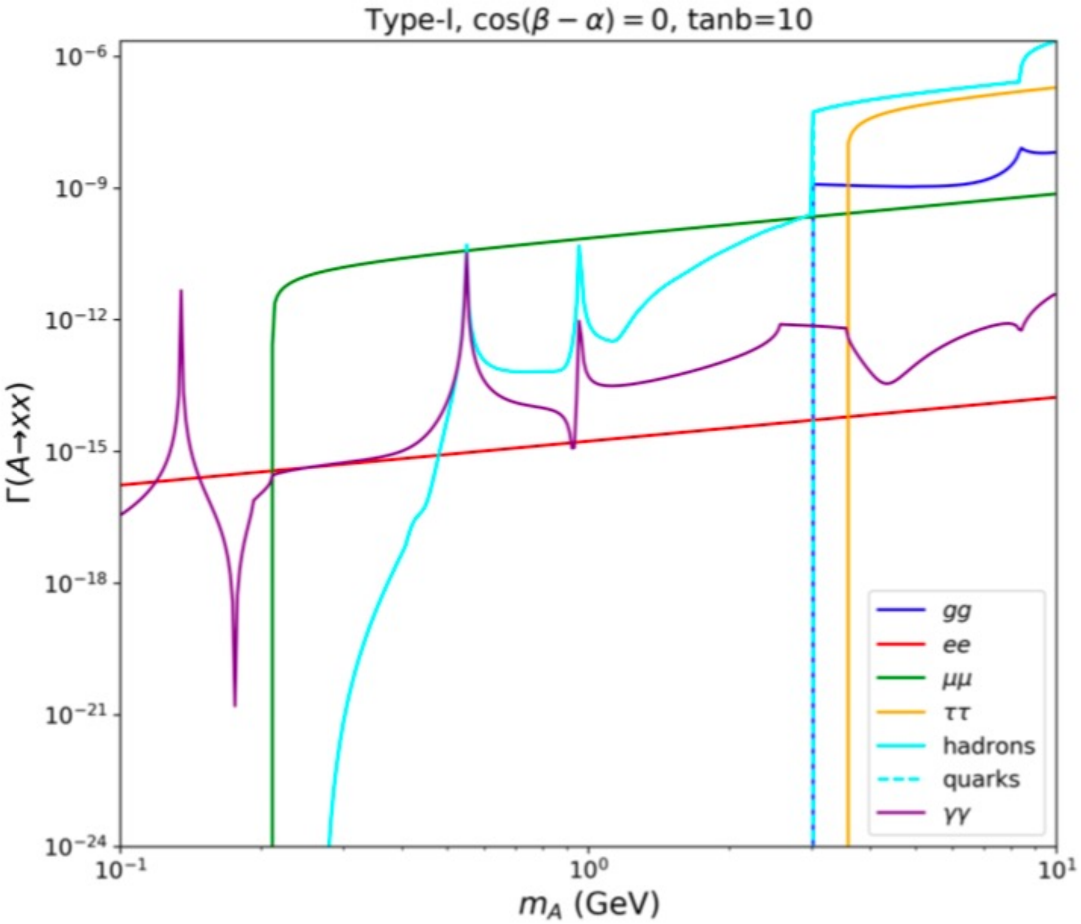


$$\mathrm{Br}(K^\pm \to \pi^\pm\phi) = \frac{1}{\Gamma_{K^\pm}}\frac{2p_\phi^0}{m_{K^\pm}}\frac{|\mathcal{M}|^2}{16\pi m_{K^\pm}},$$

Results: CP odd

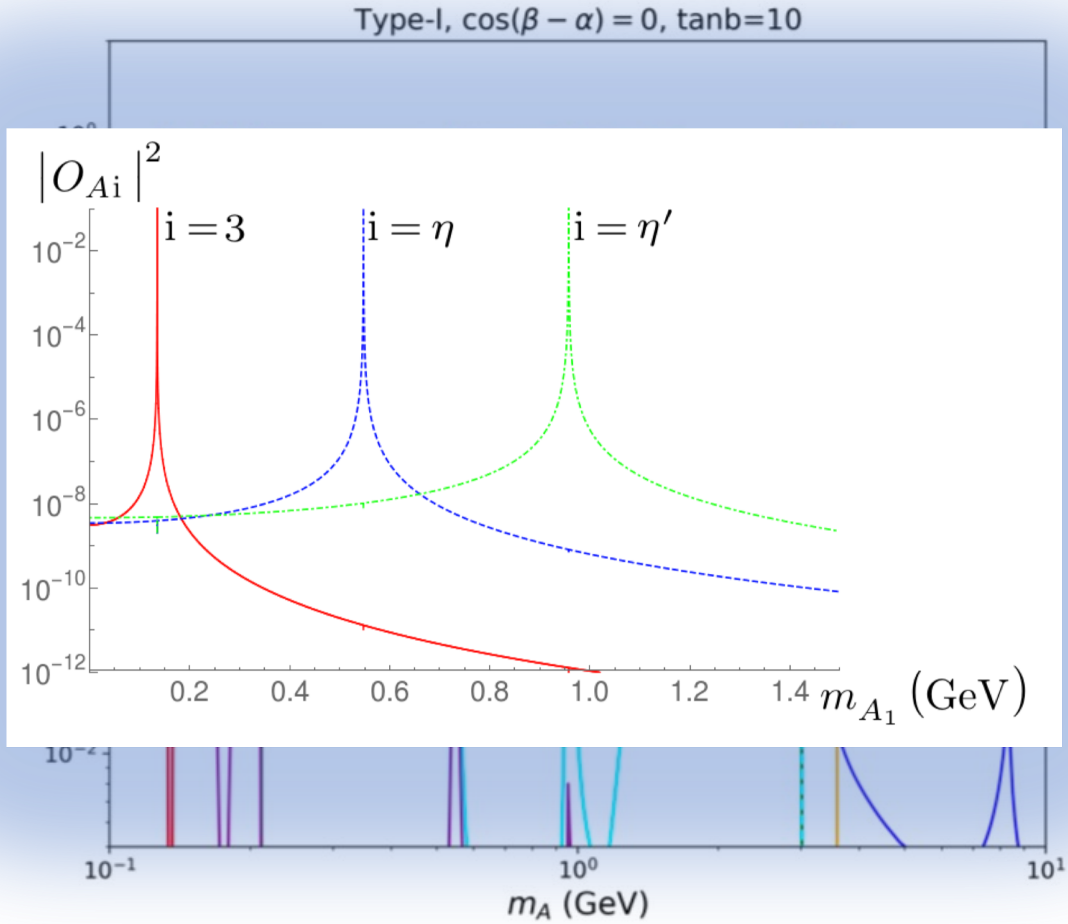
$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta$$

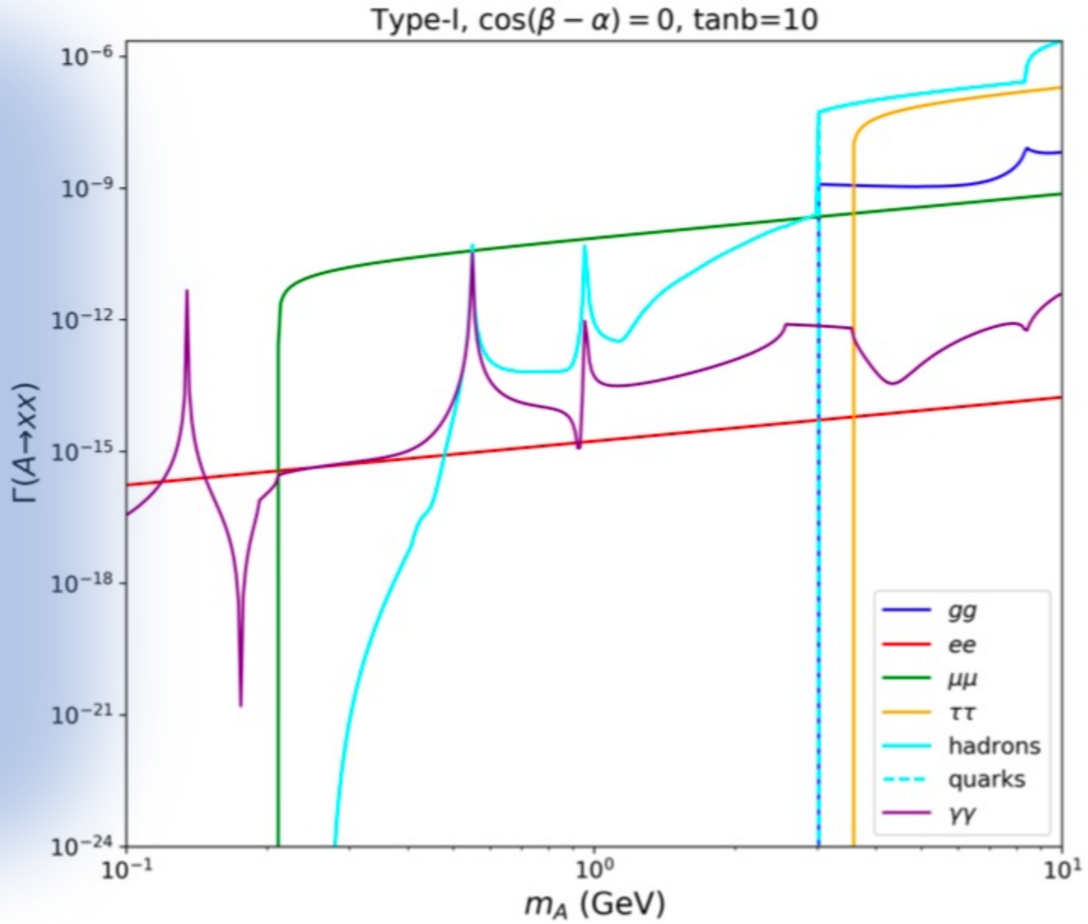




Results: CP odd

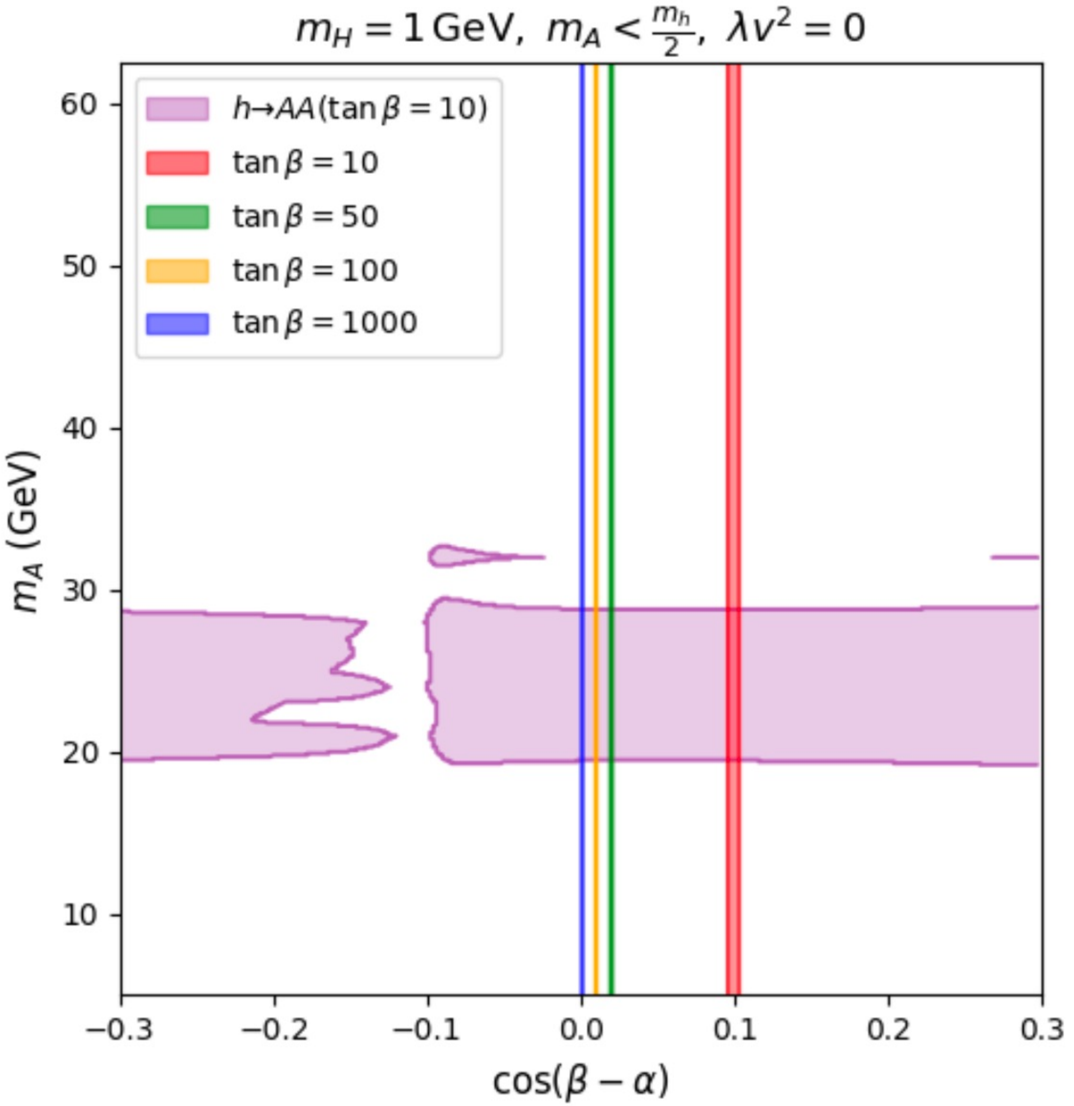
$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta$$

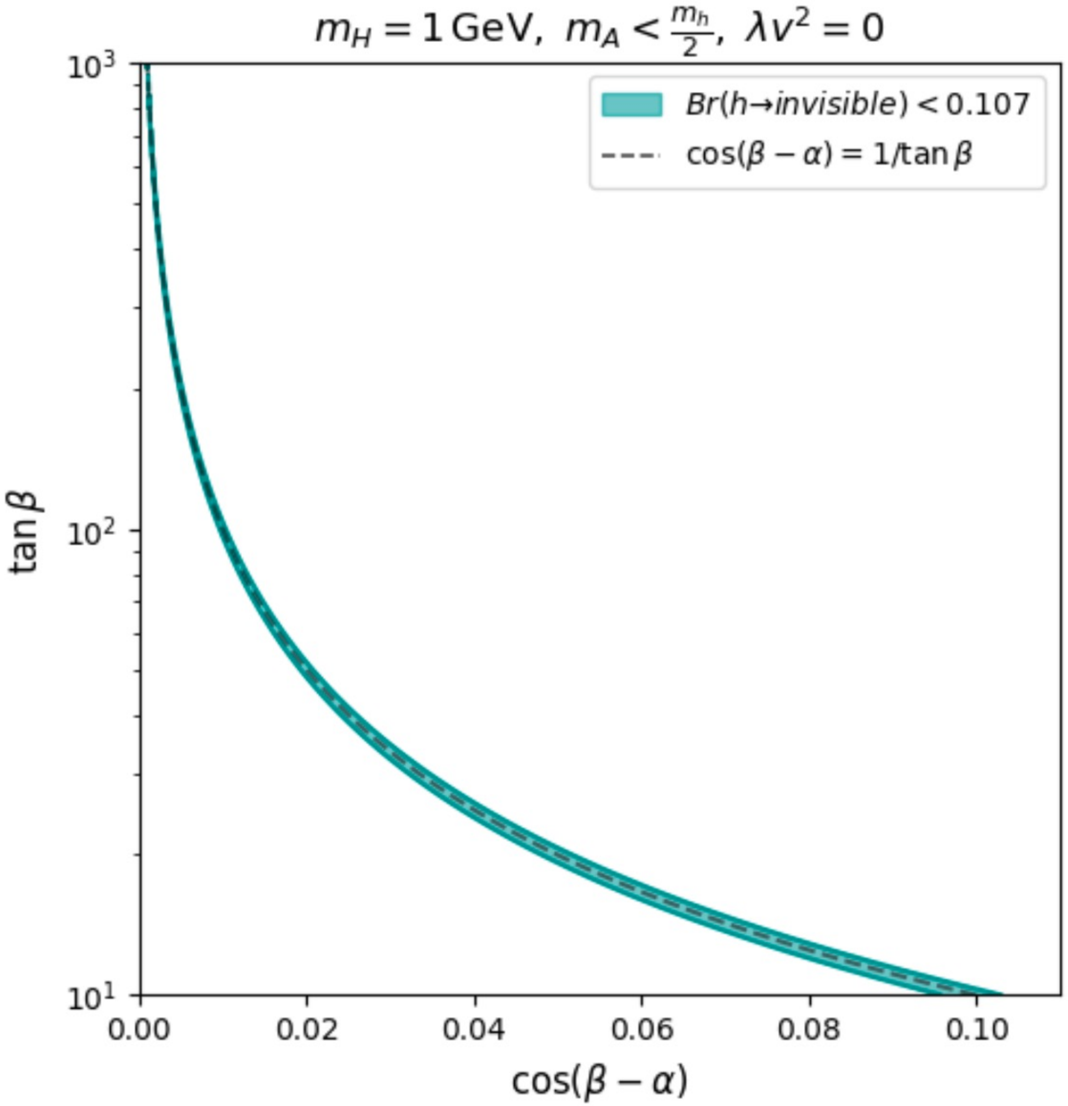




Light H

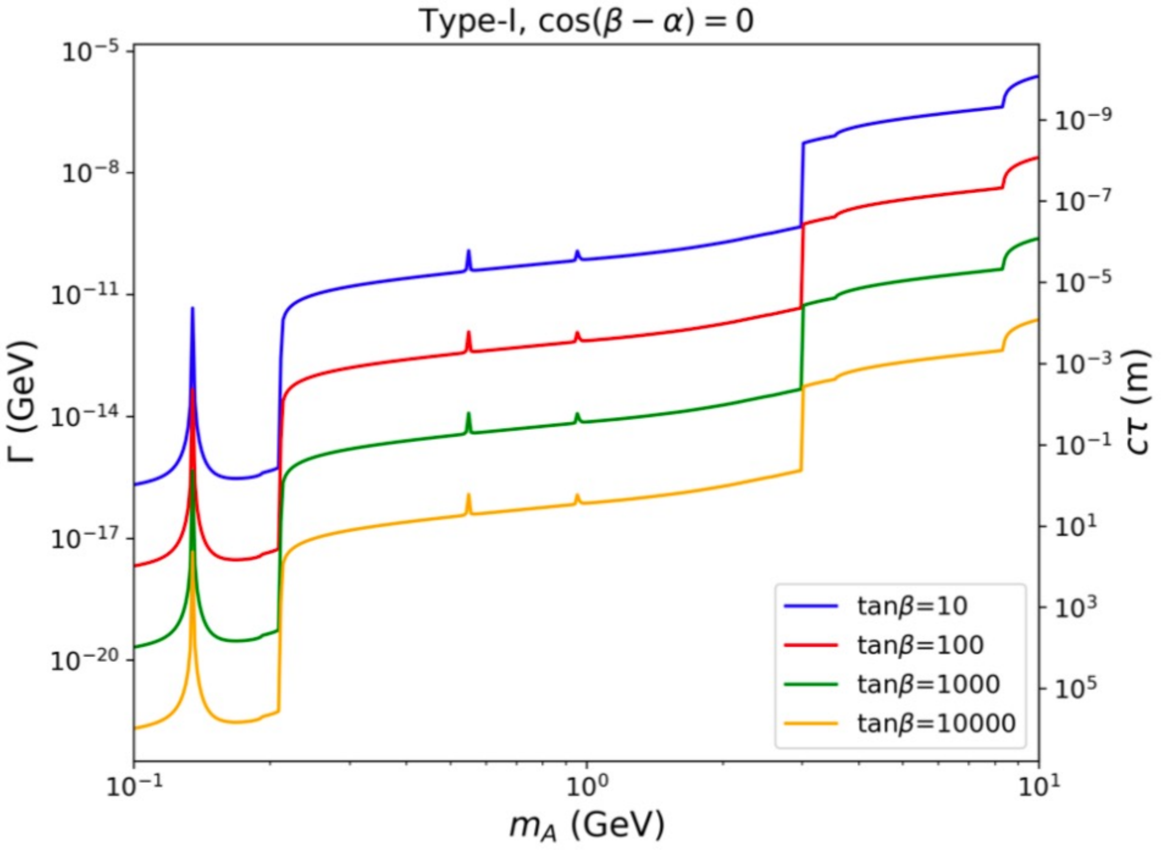
$$\cos(\beta-\alpha) \simeq \frac{1}{\tan\beta}, \quad m_A \in (54, 600)\ \mathrm{GeV}, \quad m_{H^\pm} \sim m_A, \quad \lambda v^2 = 0.$$

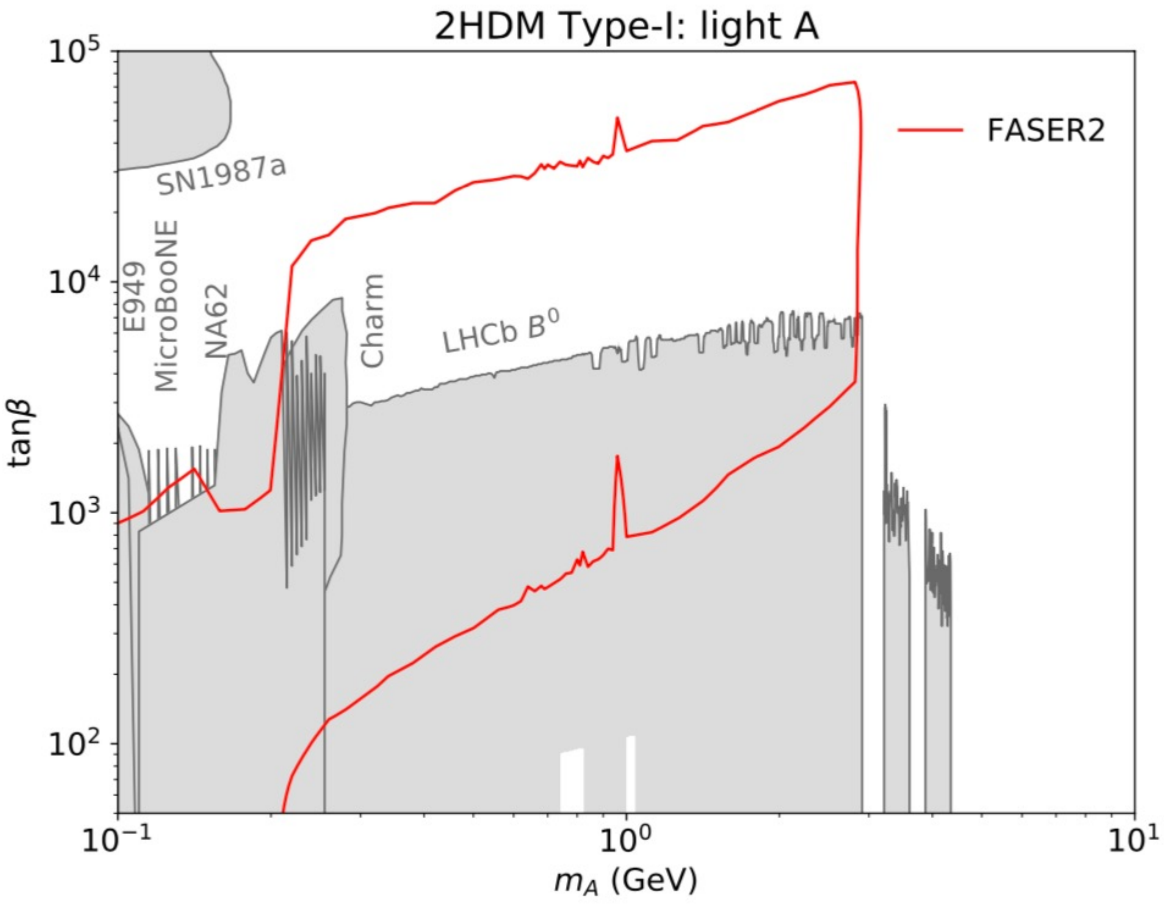




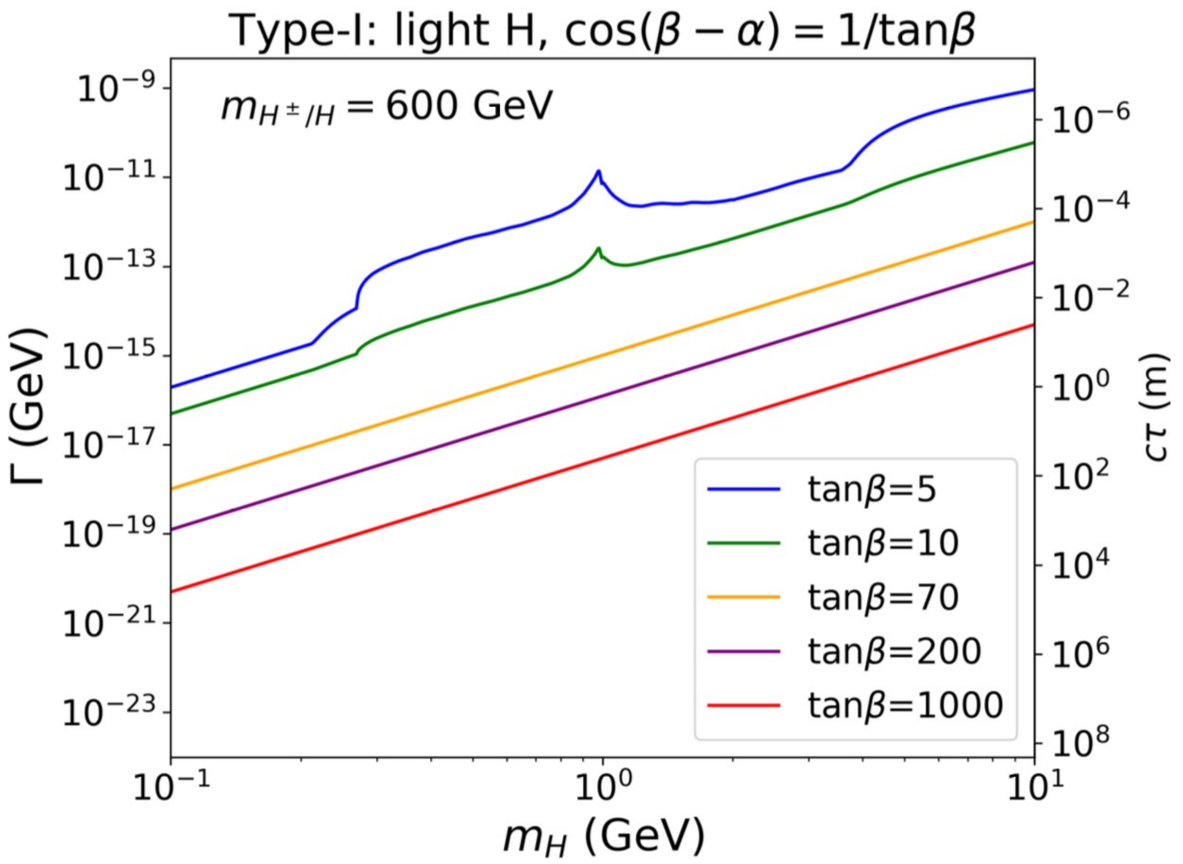
Results: CP odd

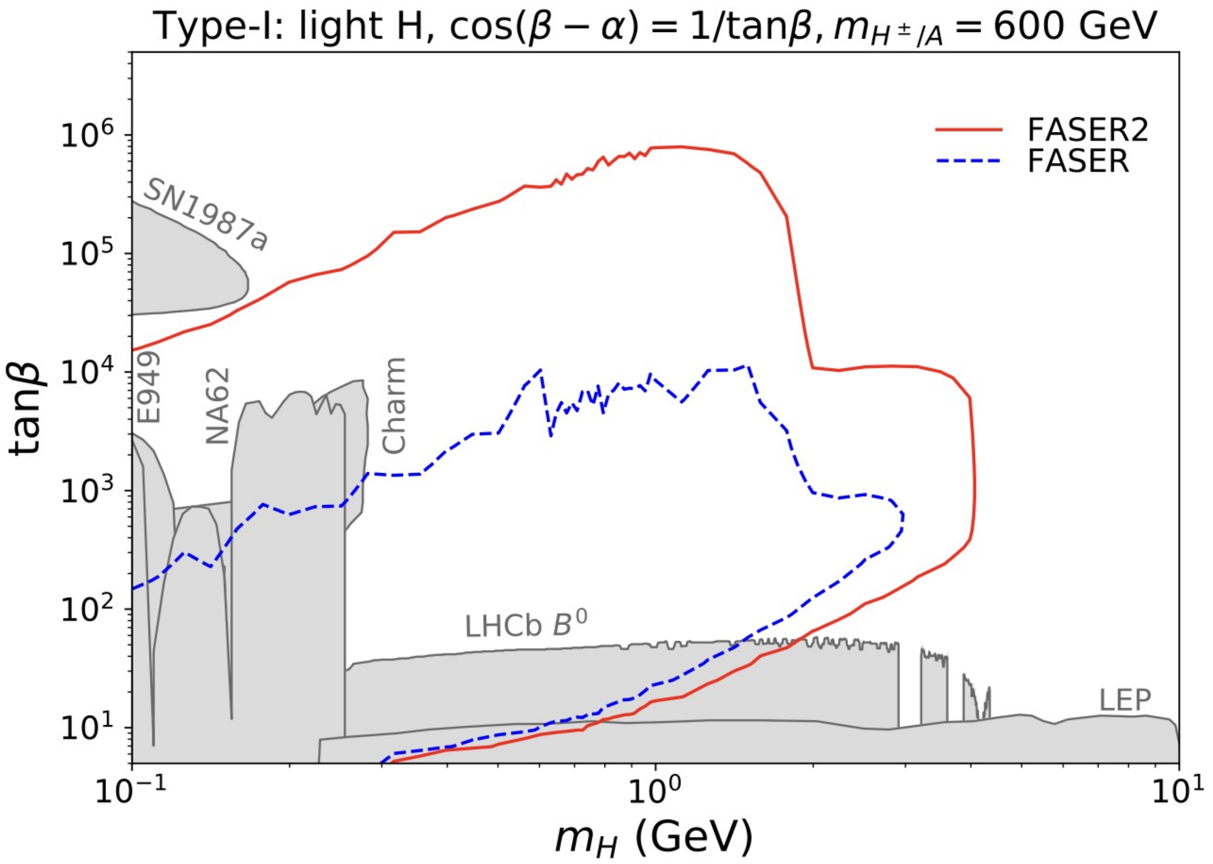
$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta$$





Results: CP even BM





Decay: CP even scalar

$m_\phi < 2$ GeV

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

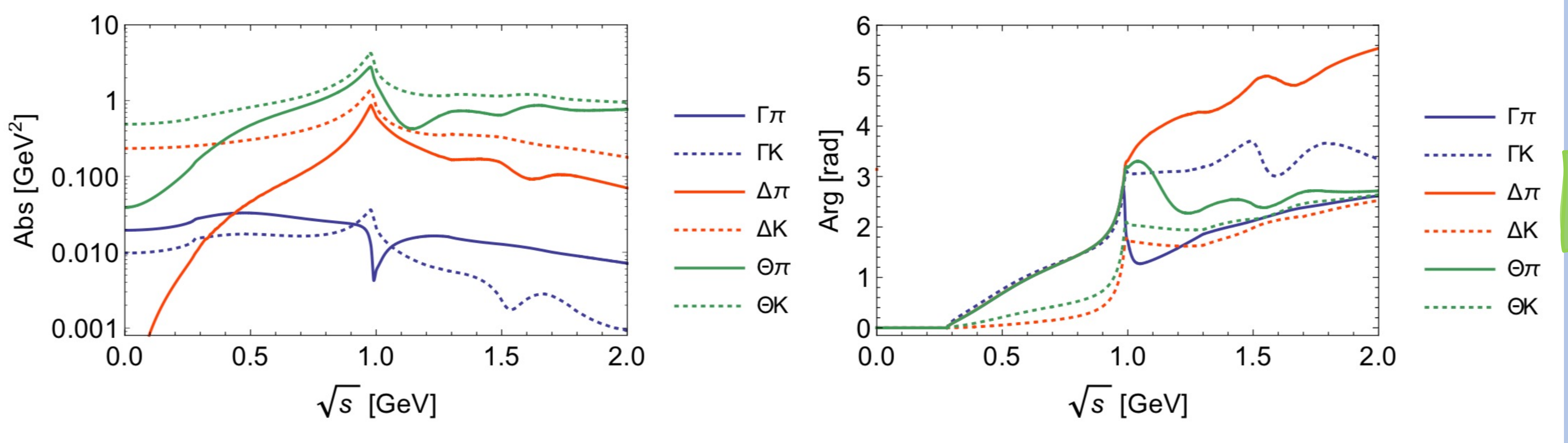
$$\Gamma_\pi = \langle \pi\pi \,| m_u \bar{u}u + m_d \bar{d}d |\, 0 \rangle \,, \qquad \Delta_\pi = \langle \pi\pi \,| m_s \bar{s}s |\, 0 \rangle \,, \qquad \Theta_\pi = \langle \pi\pi \,| \Theta^\mu_\mu |\, 0 \rangle$$

Leading order chiral perturbation theory

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

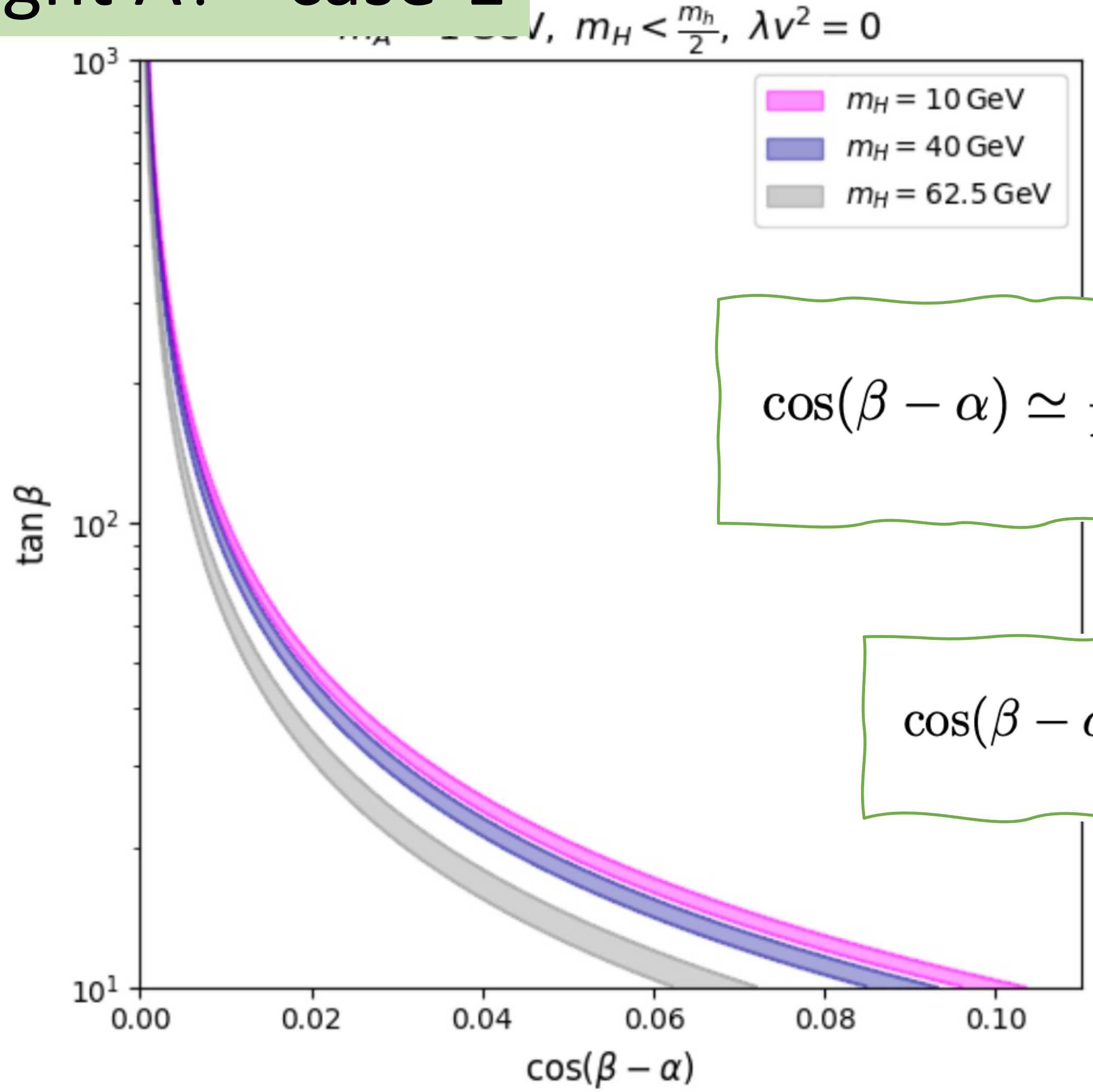
$m_\phi < 0.5$ GeV

Dispersive Analysis



0.5GeV$< m_\phi <$ 2 GeV

Light A： case-1



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

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