高能物理学术年会, 8月9日

Long-lived neutral scalar searches at FASER

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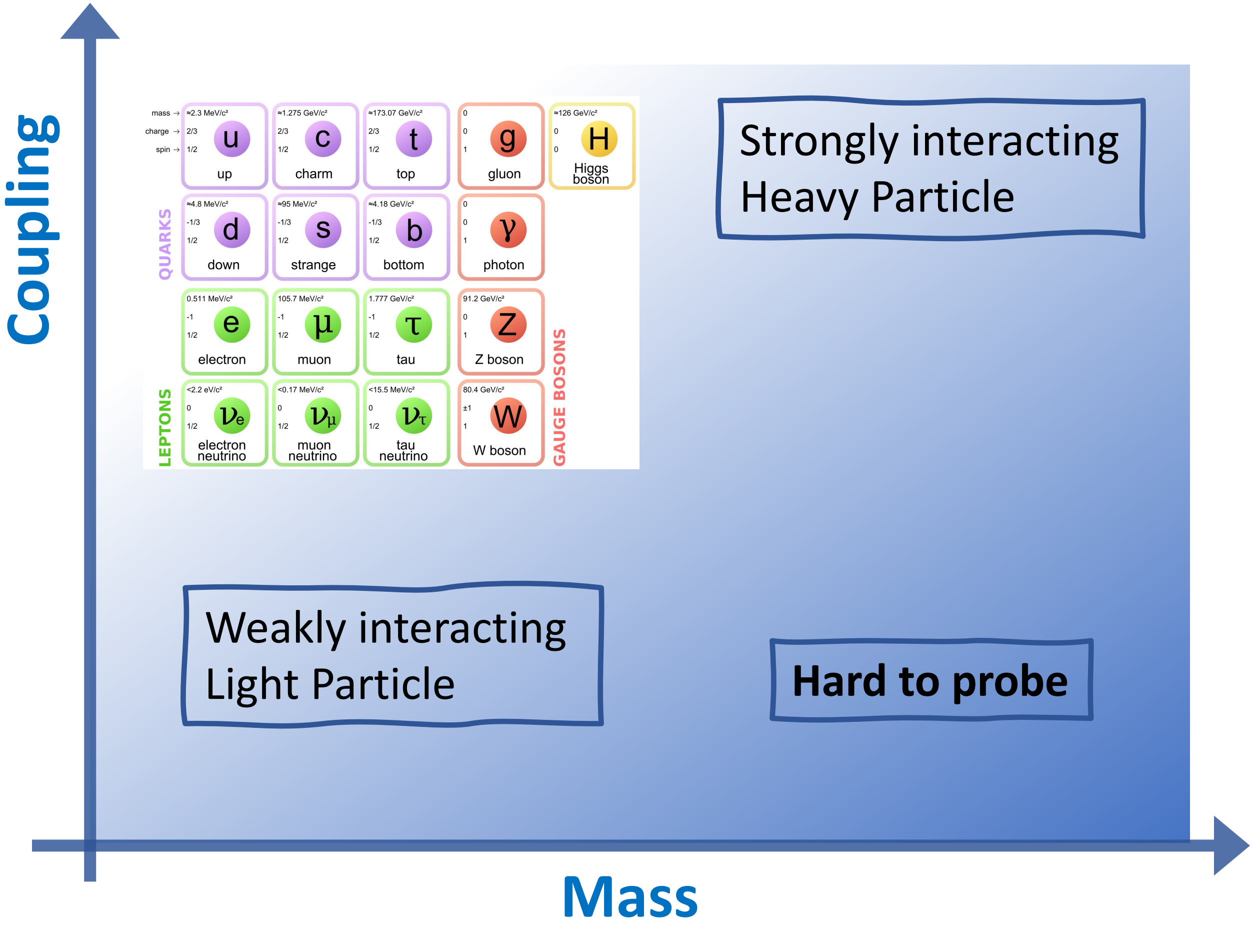
2022.09xxx (F. Kling, S. Li, S. Su, H.Song, WS)

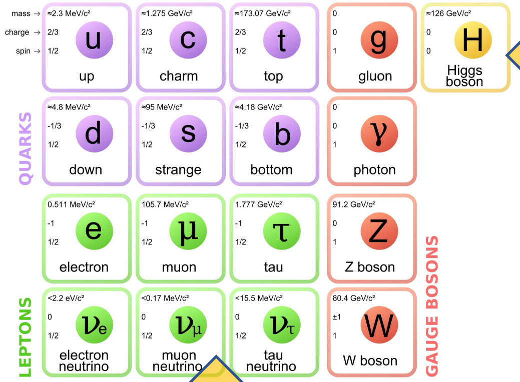
outline

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

Motivation: LLP



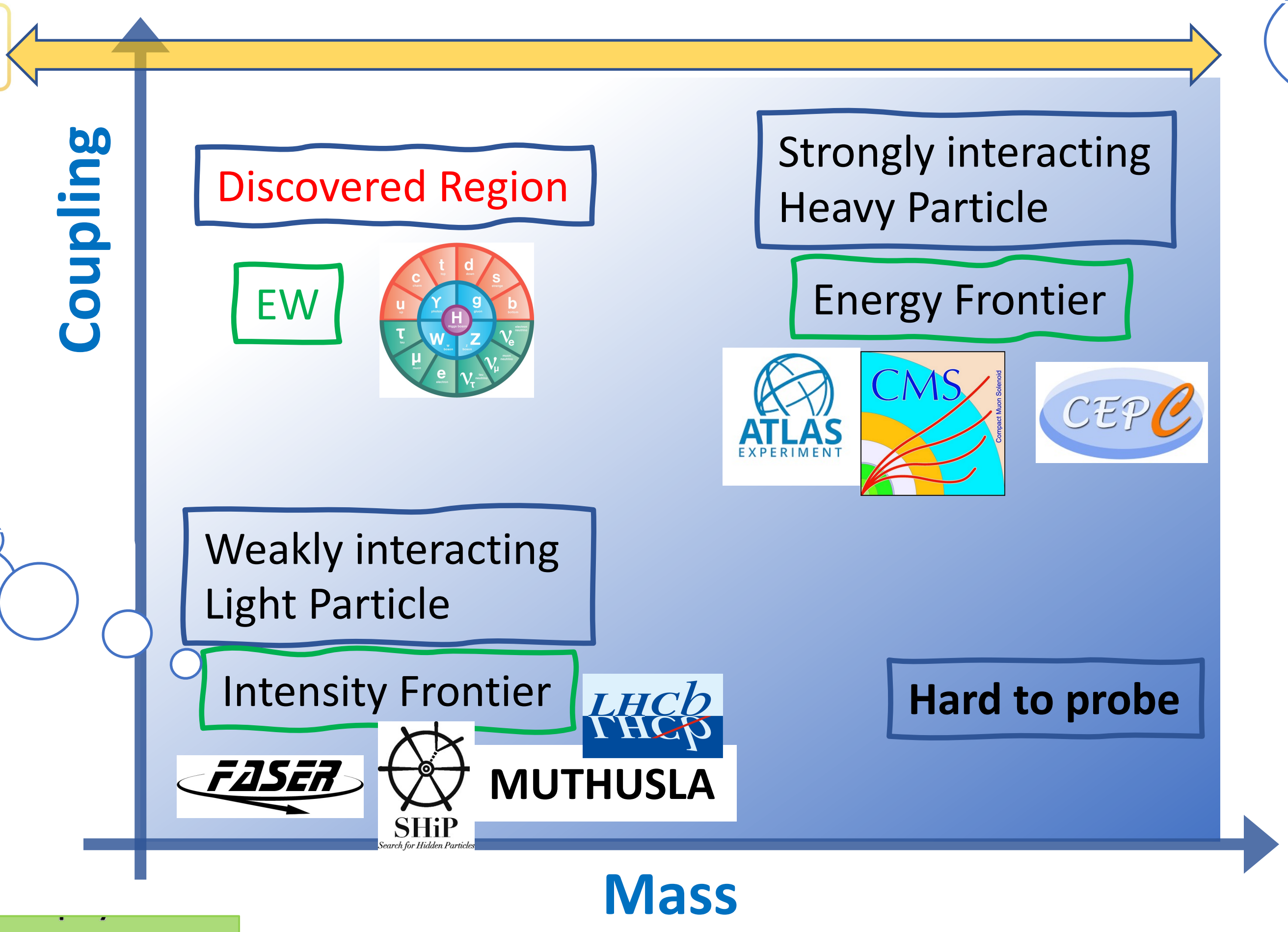
Motivation: LLP



$WIMP, Dark\ Photon\ ..$

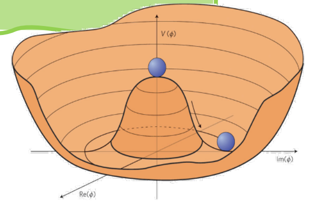
- Naturalness
- Muon g-2
- B anomaly
- …

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

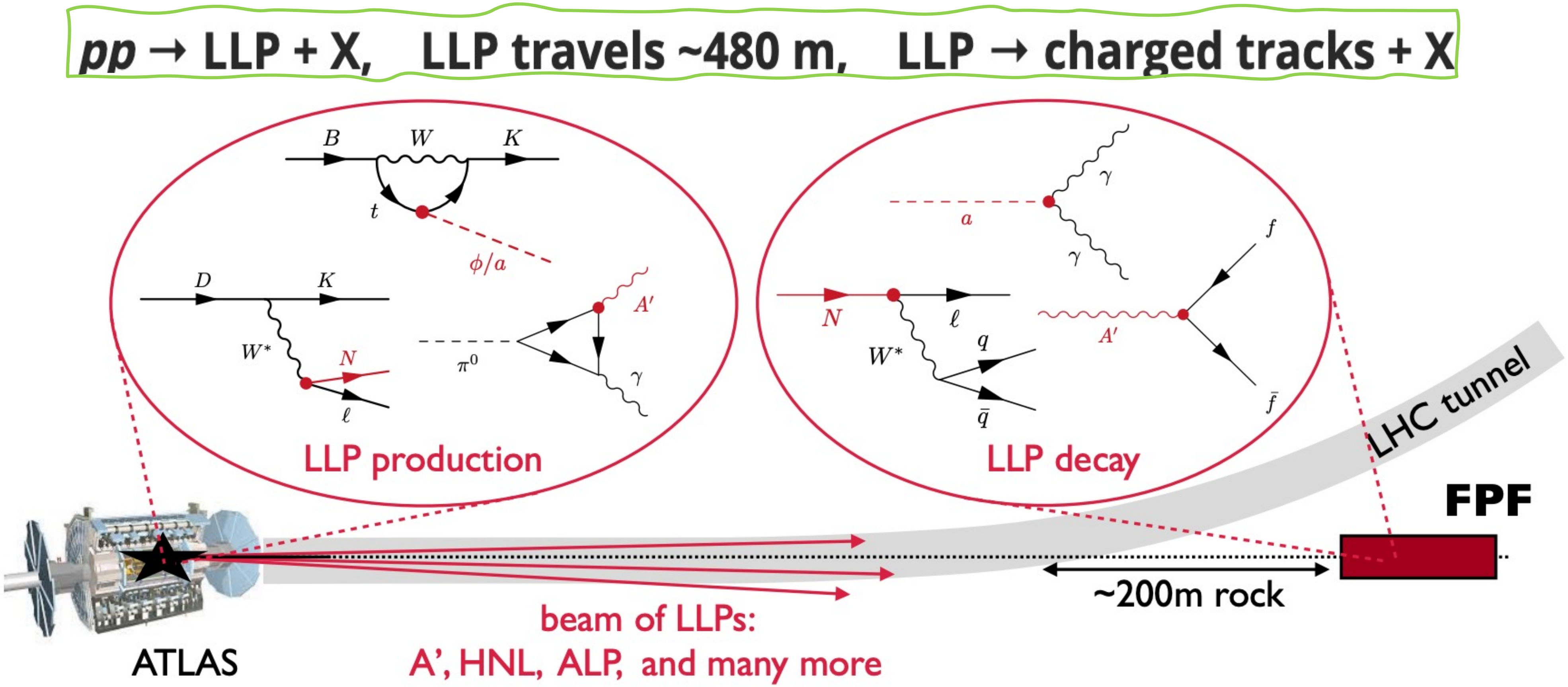


$DM, Dark\ Photon\ \ldots$

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



FASER: ForwArd Search ExpeRiment



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

Production

FORESEE

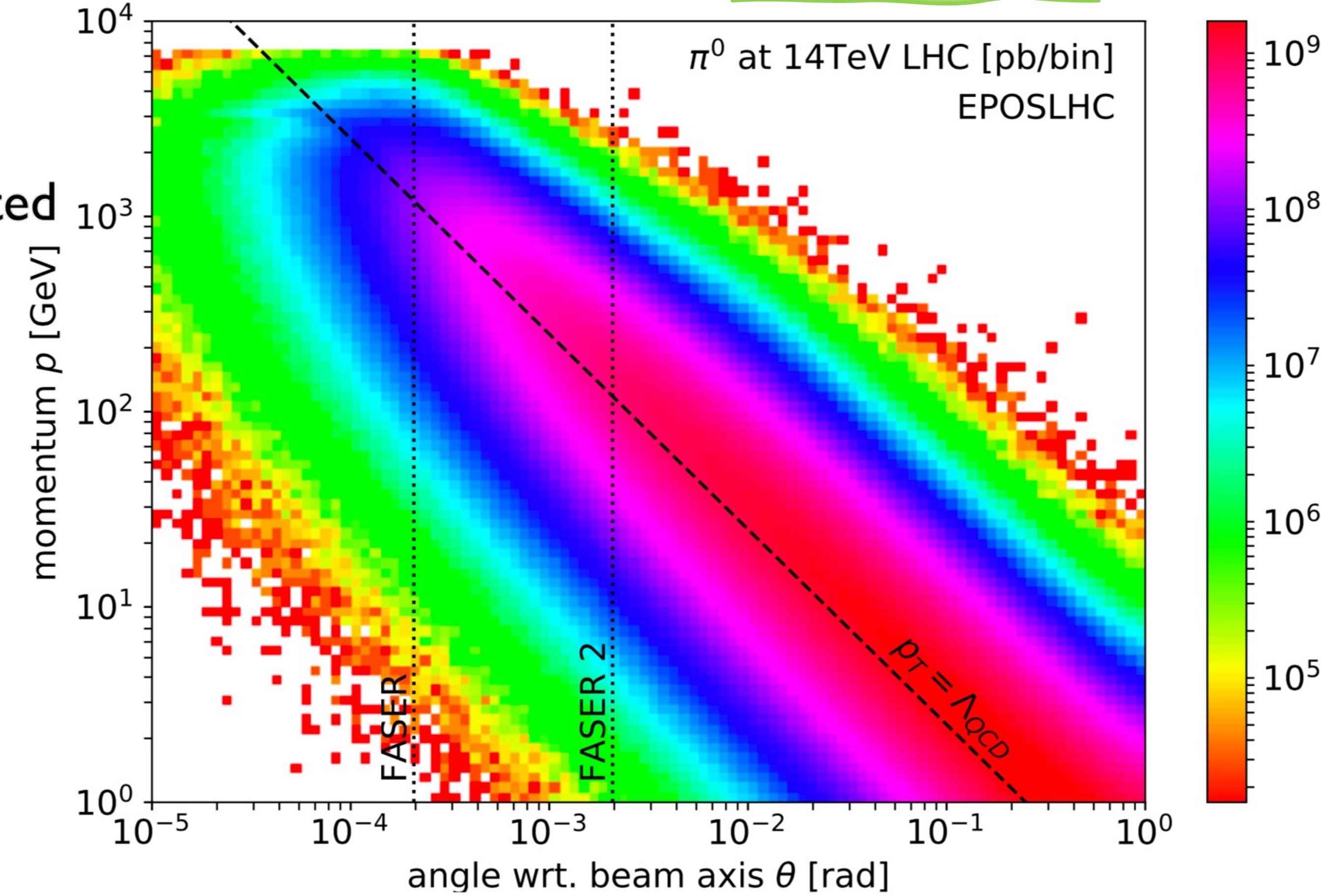
Pion

boosted mesons highly collimated

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

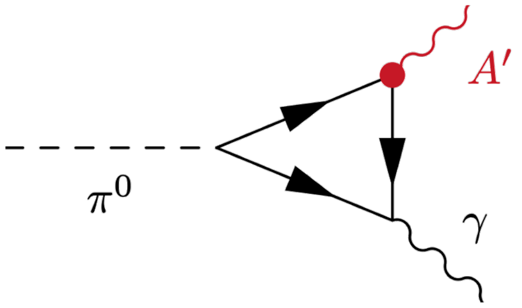
$$N_\pi = 10^{18} \quad \text{at } 3000 \text{ fb}^{-1}$$

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



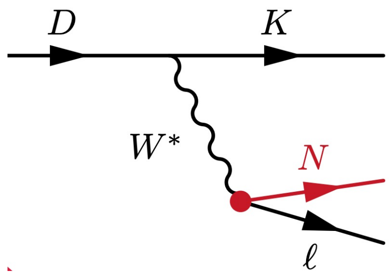
Production: CP even scalar

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



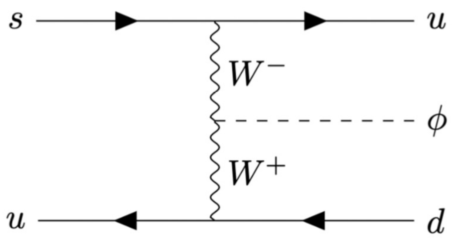
$$K \to \pi\phi,\ \eta^{(\prime)} \to \pi\phi,\ D \to X_u\phi\quad B \to X_s\phi$$

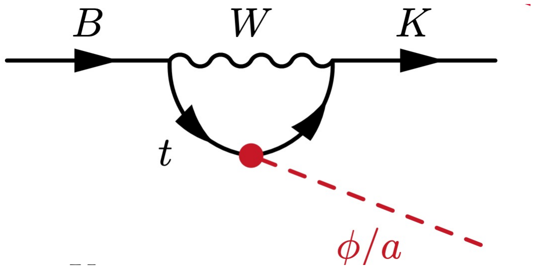
$$\pi^+ \to \ell\nu\phi \qquad K^+ \to \ell\nu\phi \qquad \Upsilon \to \phi\gamma$$



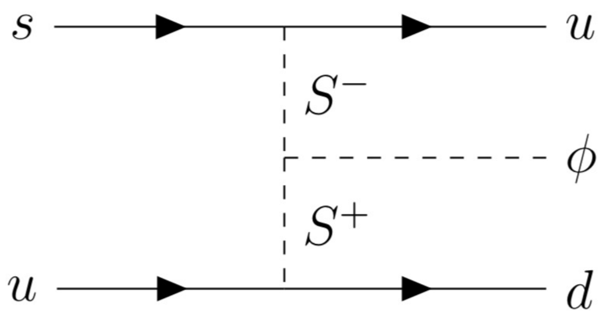
meson	quark content	mass (MeV)
$\pi^\pm$	$u\bar{d}$	139.57018 ± 0.00035
π^0	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$ [a]	134.9766 ± 0.0006
η	$\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}$ [a]	547.853 ± 0.024
η'	$\frac{u\bar{u}+d\bar{d}+s\bar{s}}{\sqrt{3}}$ [a]	957.66 ± 0.24

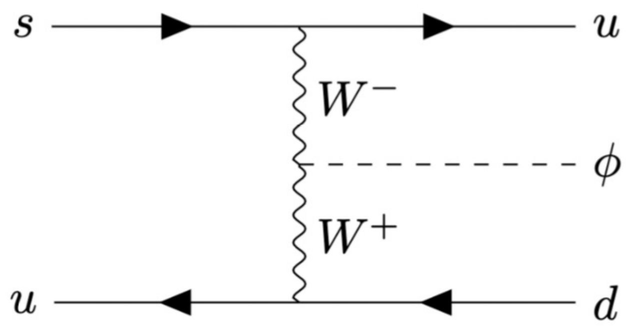
K





Production: CP even scalar





Main contribution

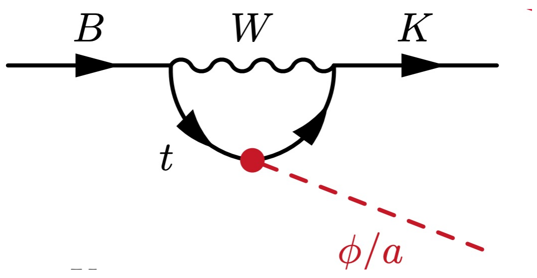
$K^{\pm}$: 493.677 ±0.016 MeV/

K^0: 497.611 ±0.013 MeV/

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

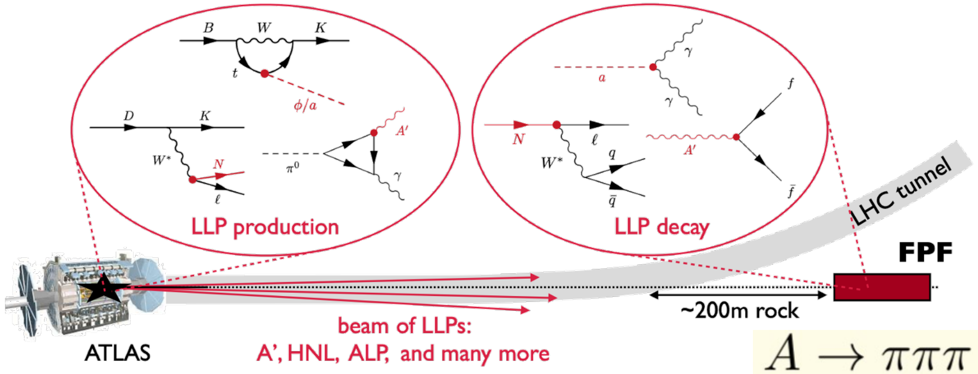
$$\mathcal{M}(K^{\pm} \to \pi^{\pm}\phi) = G_F^{1/2} 2^{1/4} \xi_{\phi}^{W} \left[\frac{7\lambda(m_{K^{\pm}}^2 + m_{\pi^{\pm}}^2 - m_{\phi}^2)}{18} - \frac{7Am_{K^{\pm}}^2}{9} \right] + \frac{\xi_{\phi}^{ds}}{2v} m_s \frac{m_{K^{\pm}}^2 - m_{\pi^{\pm}}^2}{m_s - m_d} f_0^{K^{\pm}\pi^{\pm}}(q^2)$$

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



b: 4.18 GeV,   B: around 5.3 GeV,

Decay : CP even scalar



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

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

$m_\phi < 2$ GeV

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

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

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

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

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

$$\Gamma_{\pi\pi} \quad 3G_F \quad \beta \left| \xi^{gg} \; 2 \; (\Theta \quad \Gamma \quad \Delta) + \frac{m_u \xi_\Phi^u + m_d \xi_\Phi^d}{\quad} \Gamma_\pi + (\xi_\Phi^s) \Delta_\pi \right|^2$$

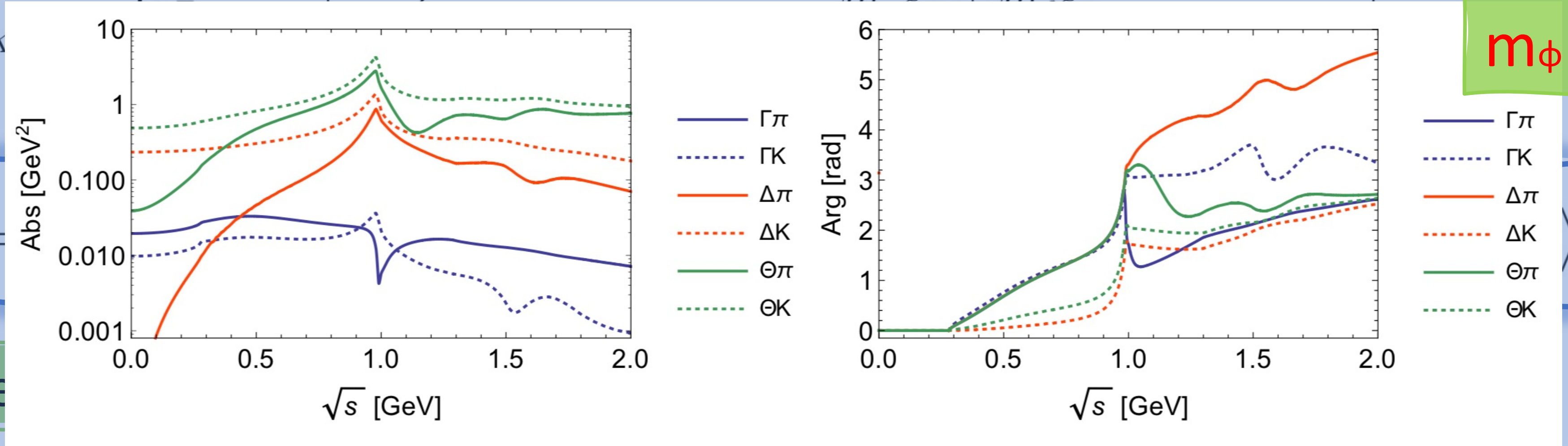
Dispersive Analysis

$$\Gamma_{KK}$$

m_ϕ >0.5 GeV

$$\Gamma_\pi =$$

Le



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

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

Constraint and 2HDM

Benchmark Scenario

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

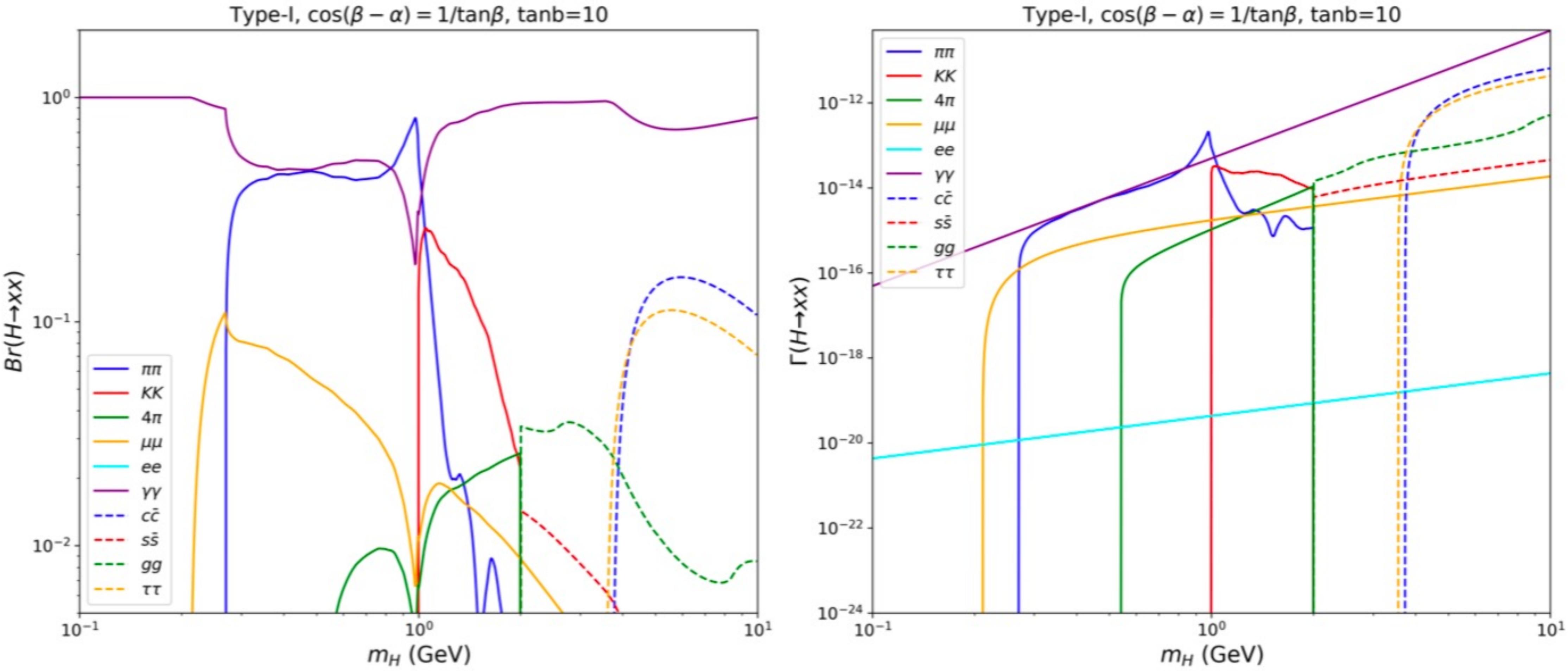
$$Light\ A : \cos(\beta-\alpha) = 0,\ m_H = m_{H^\pm} = 90\ \text{GeV},\ \lambda v^2 = 0\ \text{GeV}^2\ .$$

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

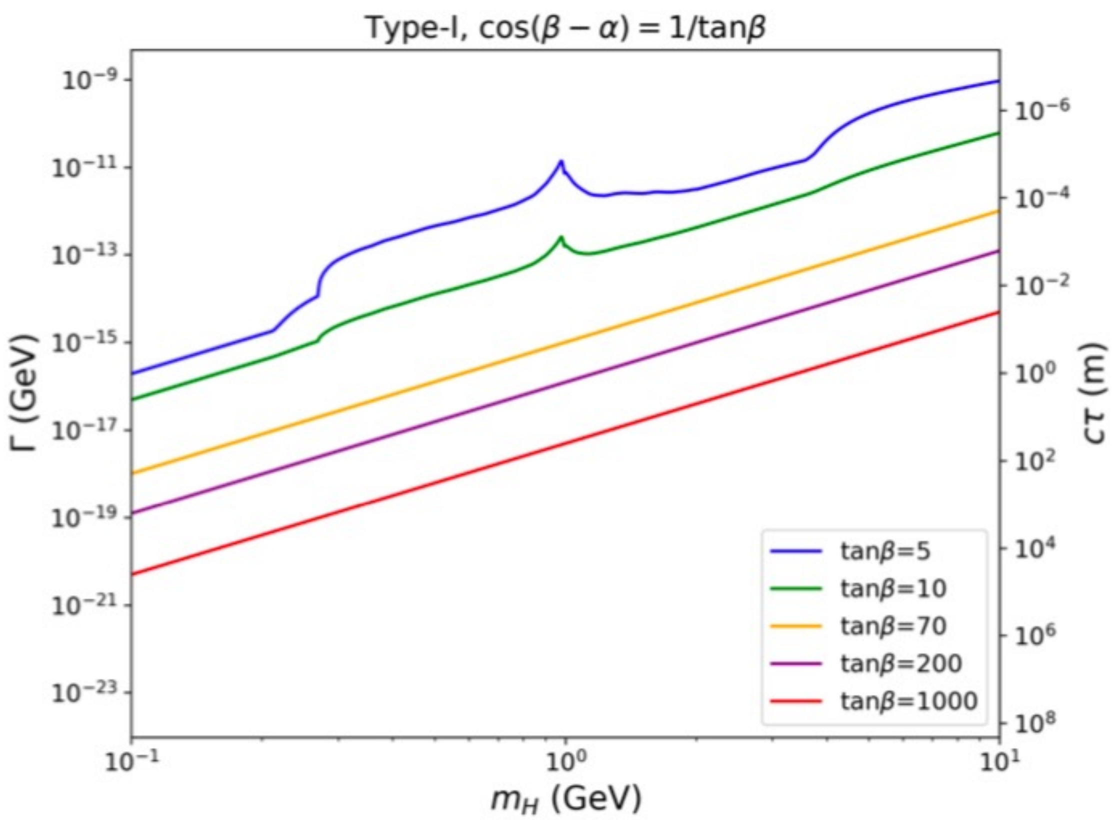
Light H is easier to be long lived

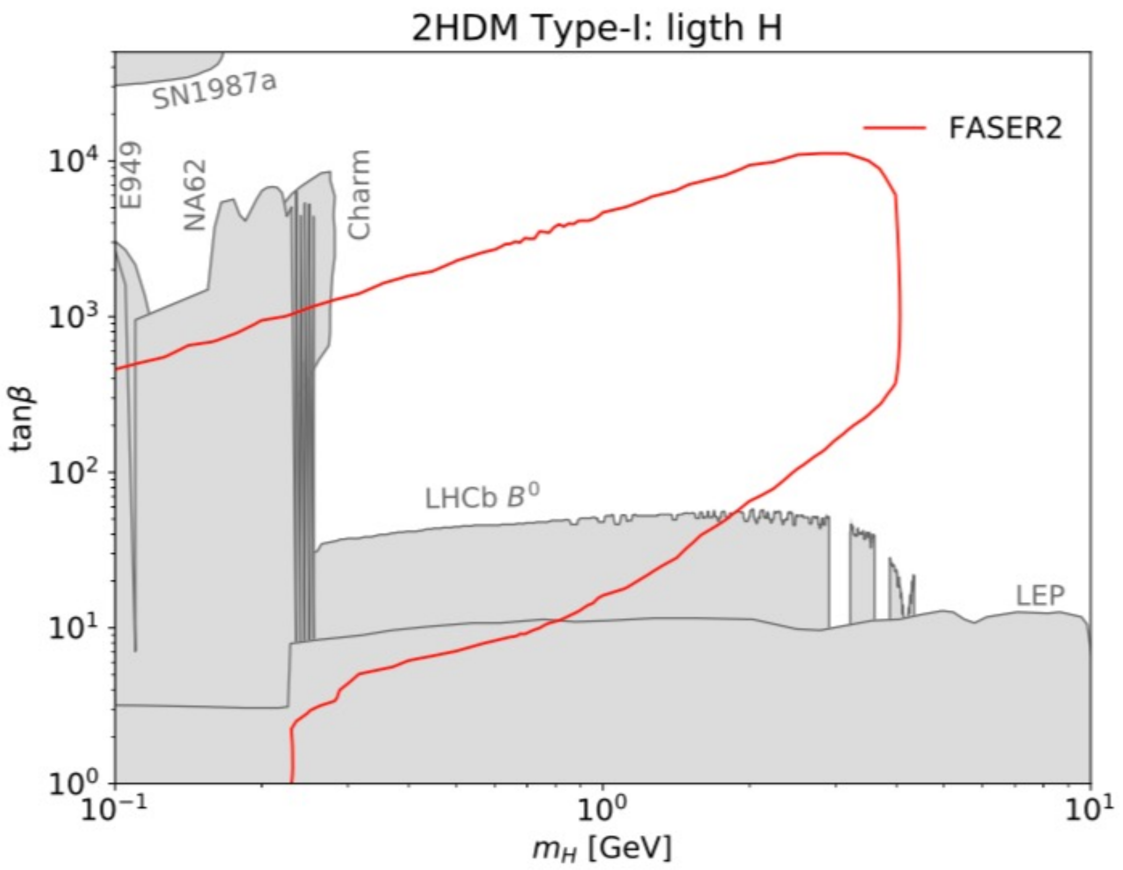
Results: CP even

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



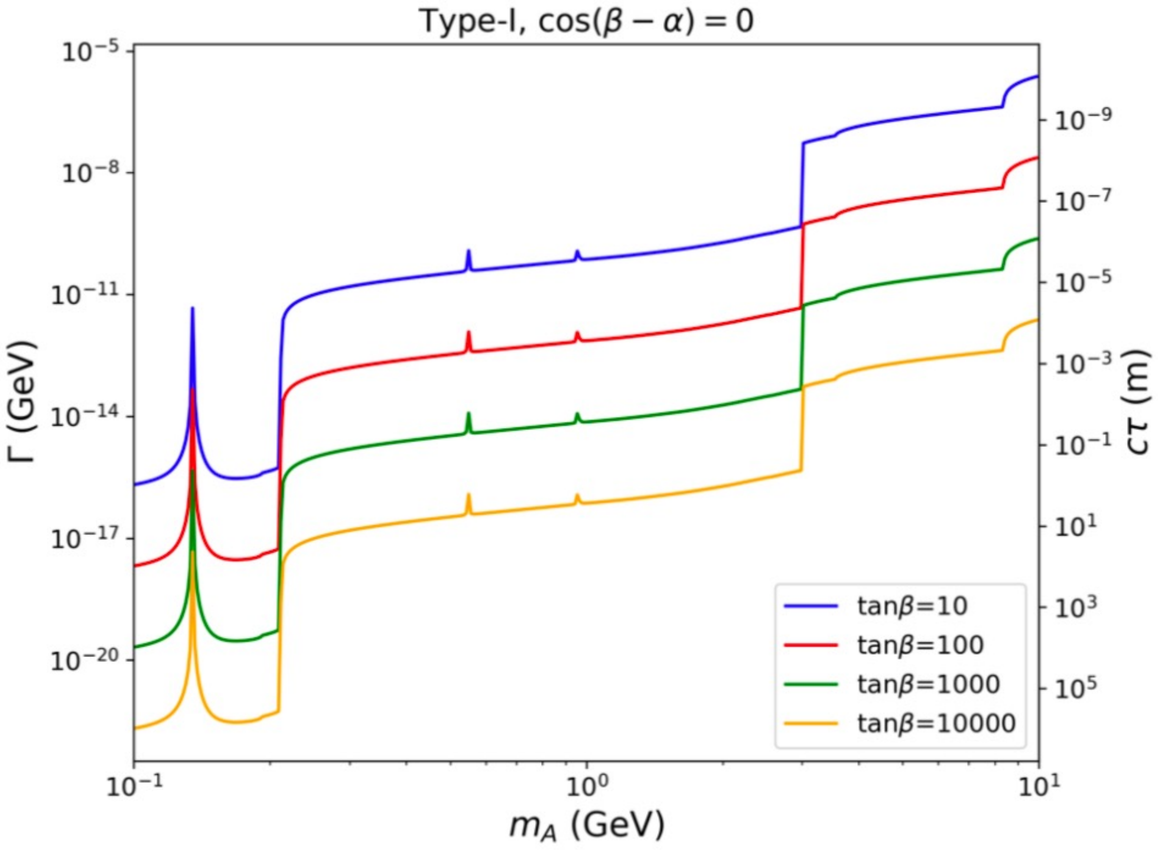
Results: CP even

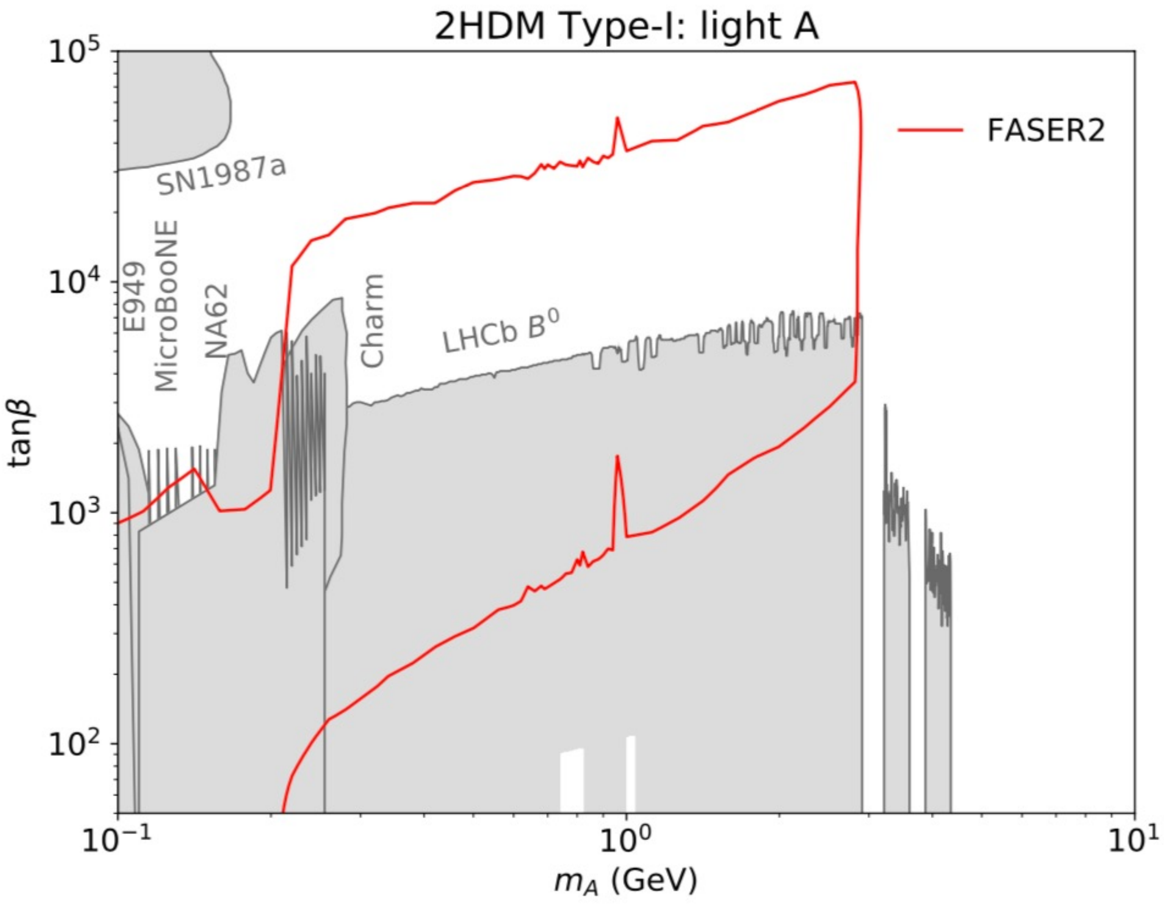




Results: CP odd

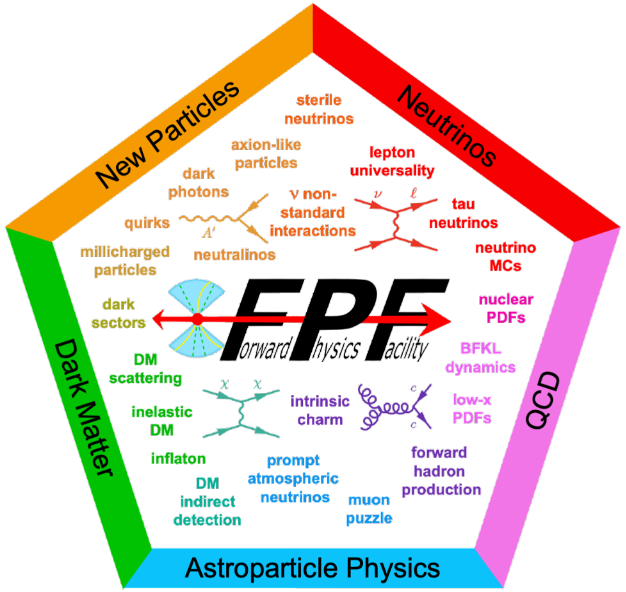
$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta$$

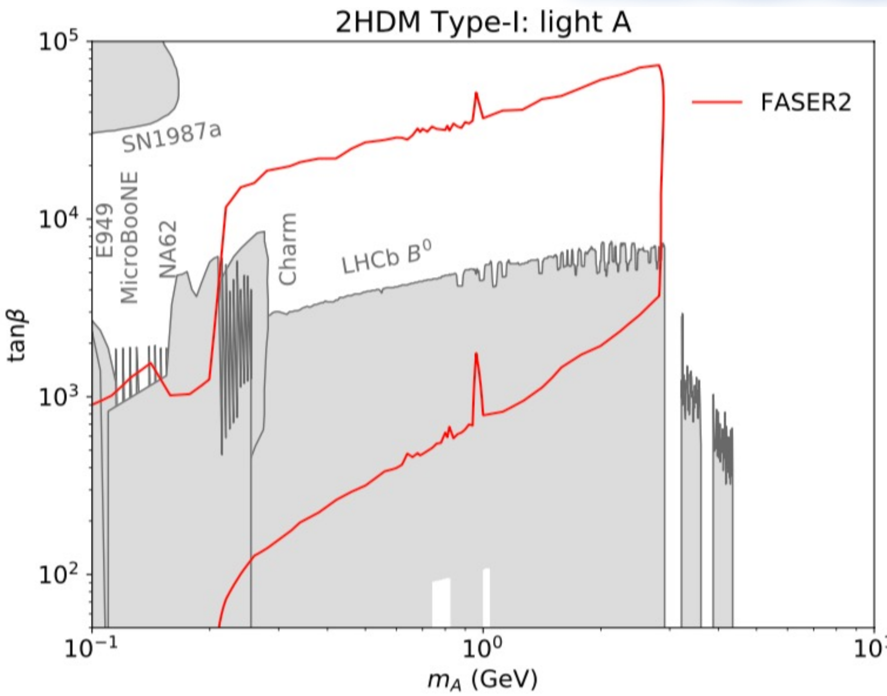


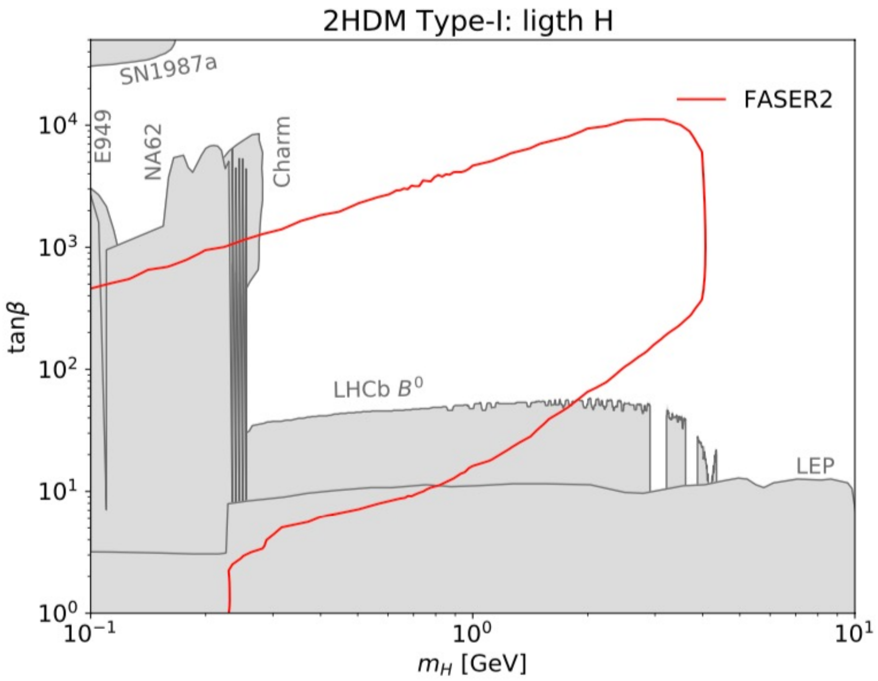


Summary

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



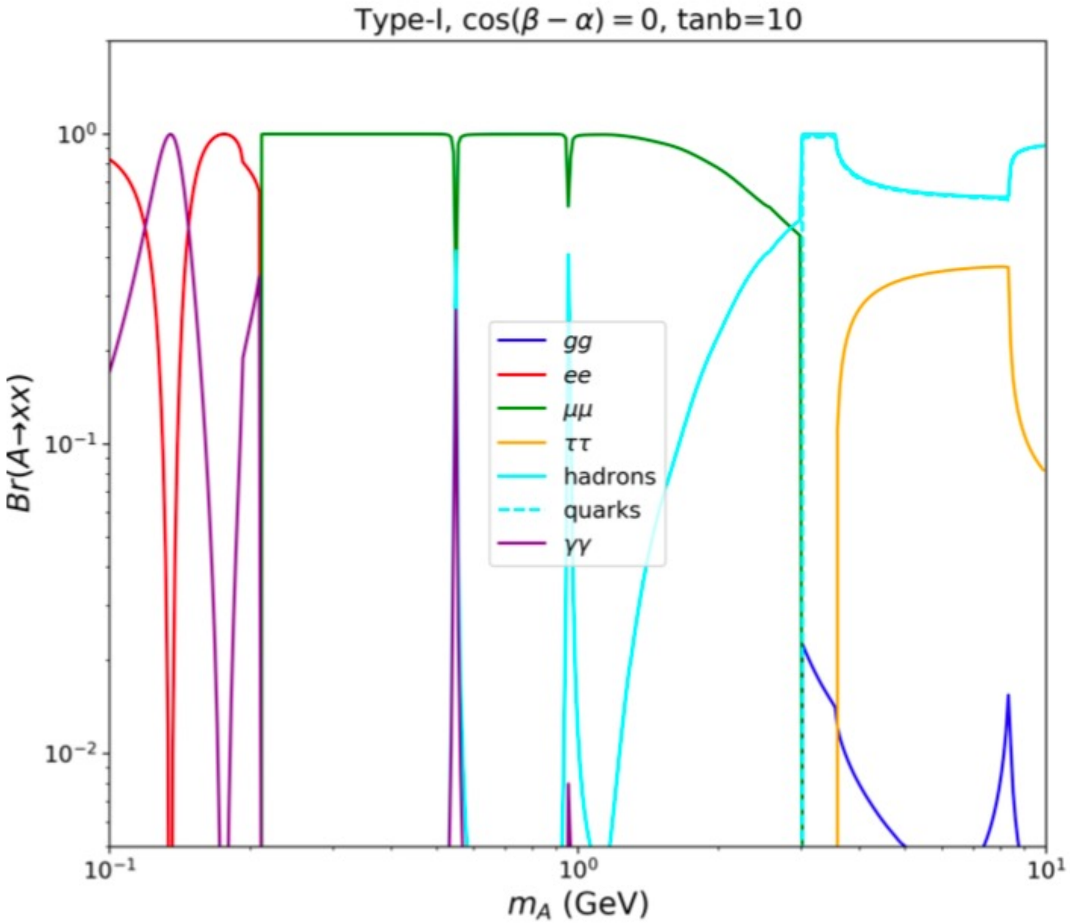


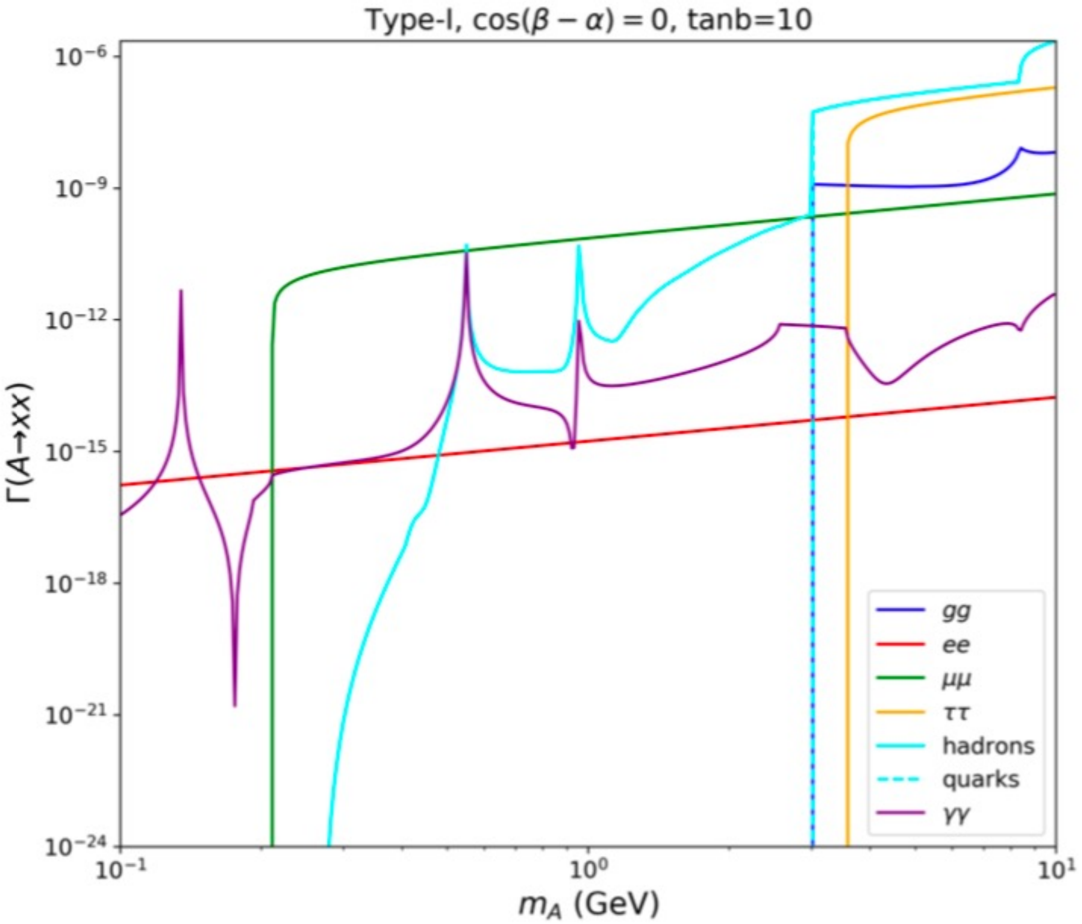


Thanks !

Results: CP odd

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





Decay: CP even scalar

$m_\phi < 2$ GeV

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

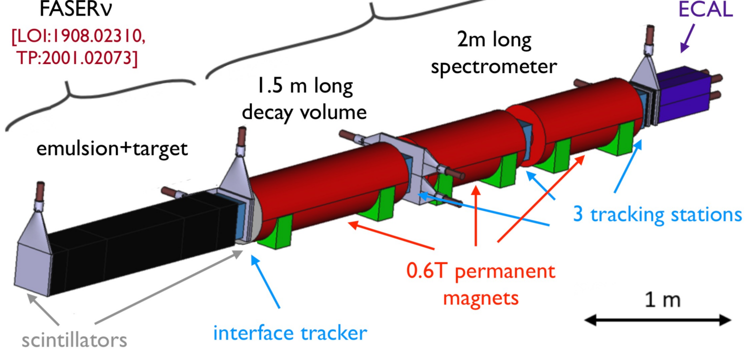
$$\mathcal{L} \supset \frac{\Phi}{v}\left(\xi_\Phi^g \frac{\alpha_s}{12\pi} G^a_{\mu\nu} G^{a\mu\nu} - \xi_\Phi^u m_u \bar{u}u - \xi_\Phi^d m_d \bar{d}d - \xi_\Phi^s m_s \bar{s}s\right)$$
$$= -\frac{\Phi}{v}\left\{\xi_\Phi^g \left[\frac{2}{27}\Theta^\mu_\mu - \frac{2}{27}(m_u\bar{u}u + m_d\bar{d}d +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

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

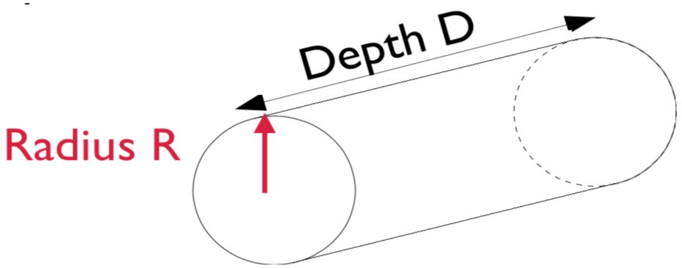
$$\boxed{\Gamma_\pi = \left\langle \pi\pi \left| m_u\bar{u}u + m_d\bar{d}d \right| 0 \right\rangle, \qquad \Delta_\pi = \left\langle \pi\pi \left| m_s\bar{s}s \right| 0 \right\rangle, \qquad \Theta_\pi = \left\langle \pi\pi \left| \Theta^\mu_\mu \right| 0 \right\rangle}$$

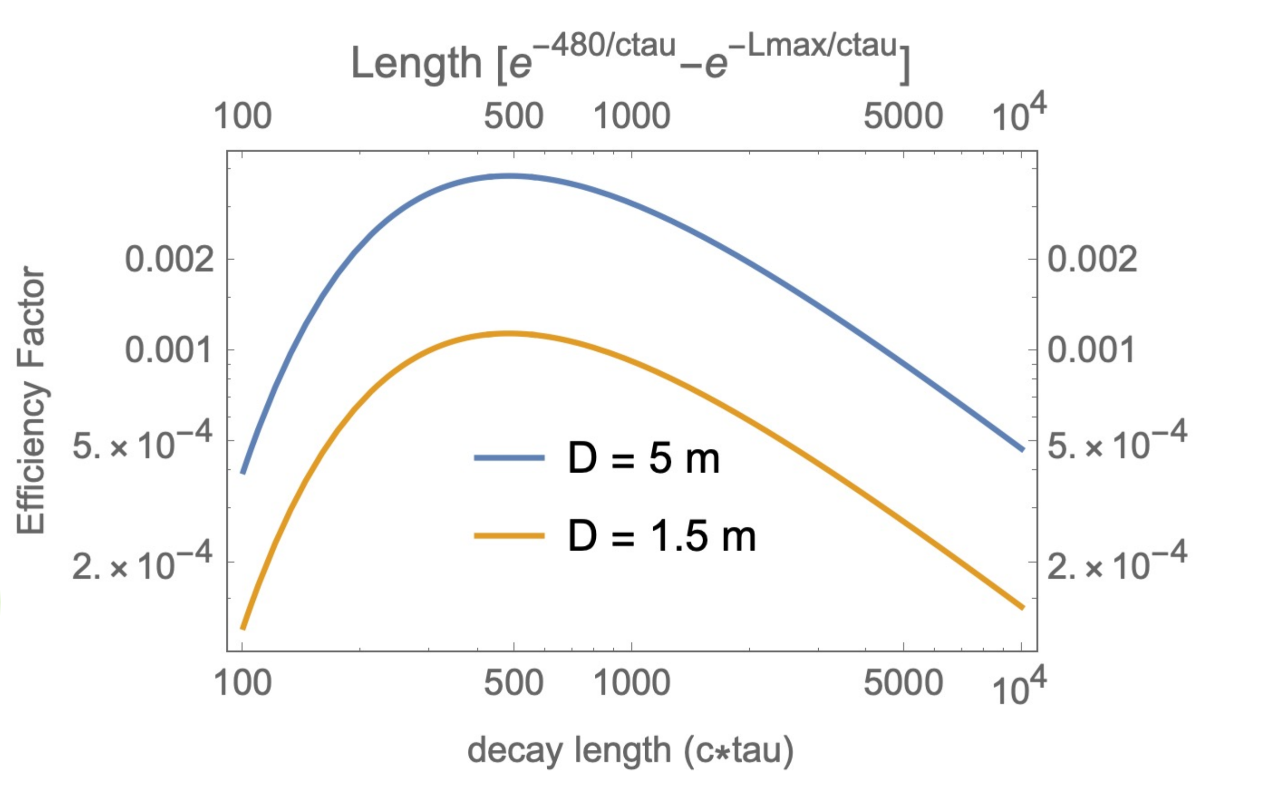
$$\Gamma_{\pi\pi} = \frac{3G_F}{16\sqrt{2}\pi m_\Phi}\beta_\pi \left| \xi_\Phi^{gg}\frac{2}{27}(\Theta_\pi - \Gamma_\pi - \Delta_\pi) + \frac{m_u\xi_\Phi^u + m_d\xi_\Phi^d}{m_u + m_d}\Gamma_\pi + (\xi_\Phi^s)\Delta_\pi \right|^2$$
$$\Gamma_{KK} = \frac{G_F}{4\sqrt{2}\pi m_\Phi}\beta_K \left| \xi_\Phi^{gg}\frac{2}{27}(\Theta_K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

FASER: Detector



***pp* → LLP + X, LLP travels ~480 m, LLP → 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}.