ITP, Beijing, 9 Jun

Long-lived neutral scalar searches at FASER

Wei Su

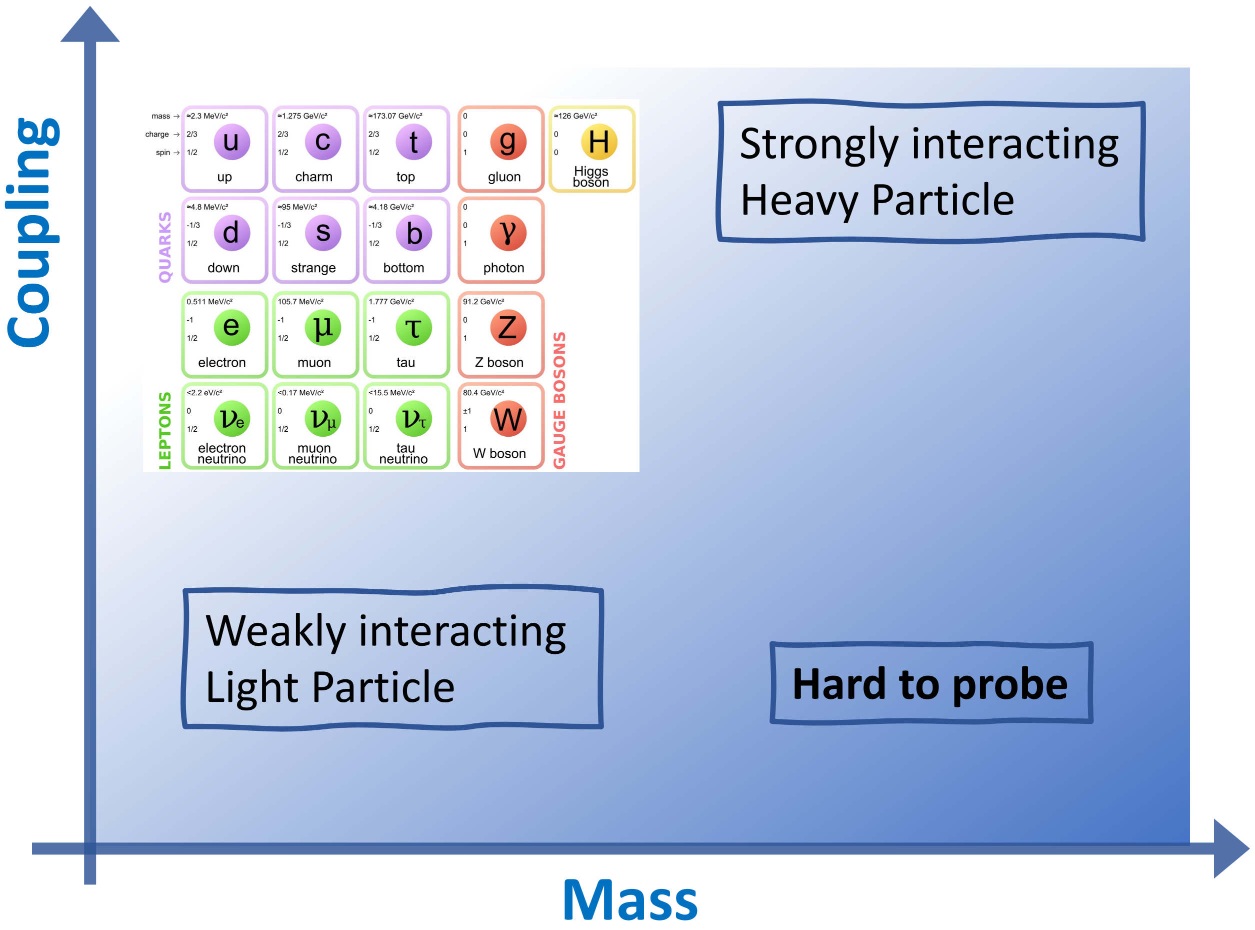
2022.06xxx (F. Kling, S. Li, S. Su, H.Song, WS)

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

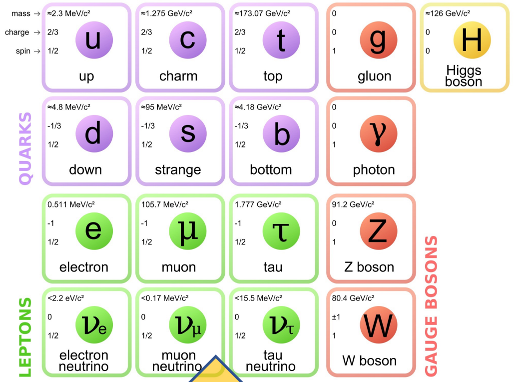
outline

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

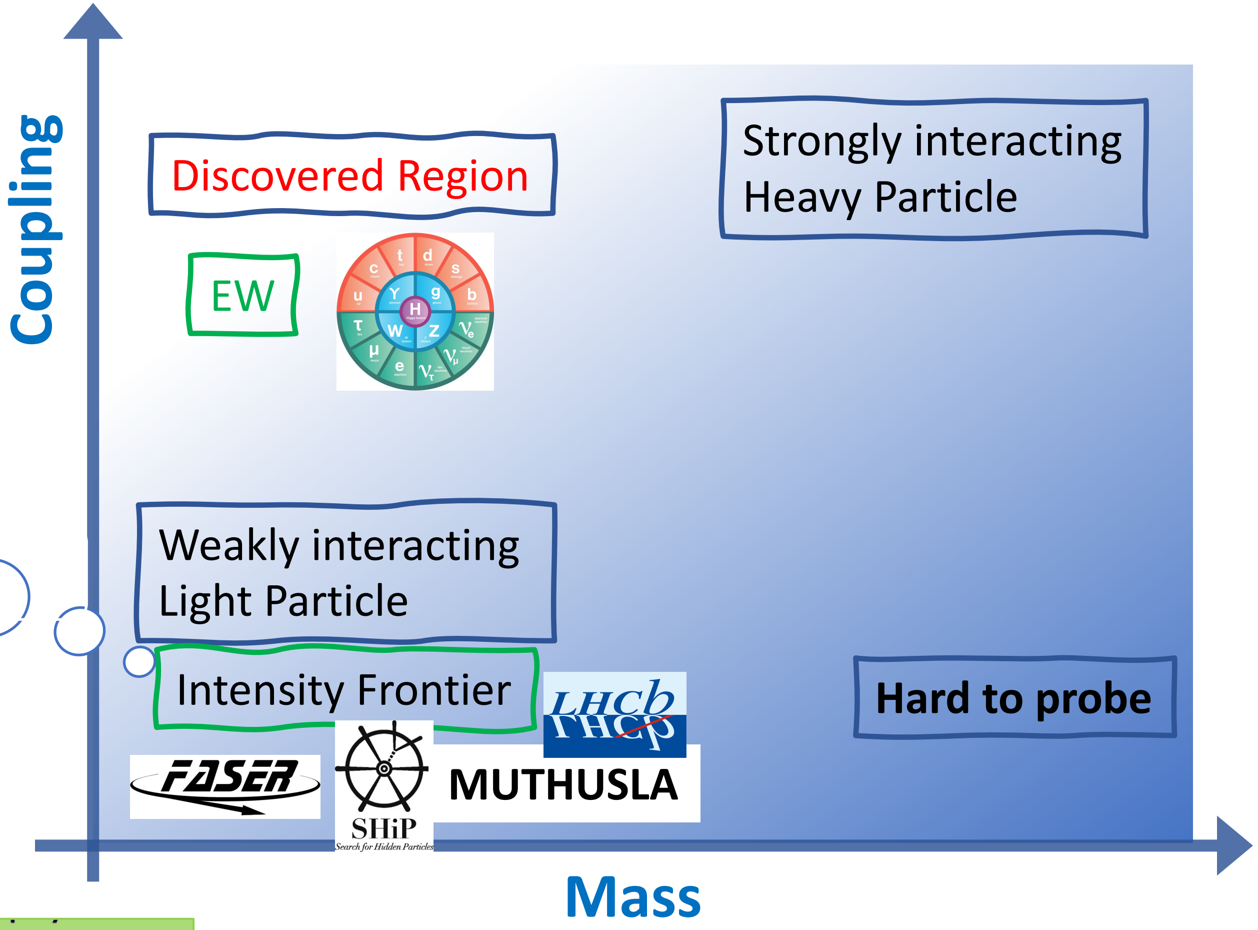
Motivation: LLP



Motivation: LLP



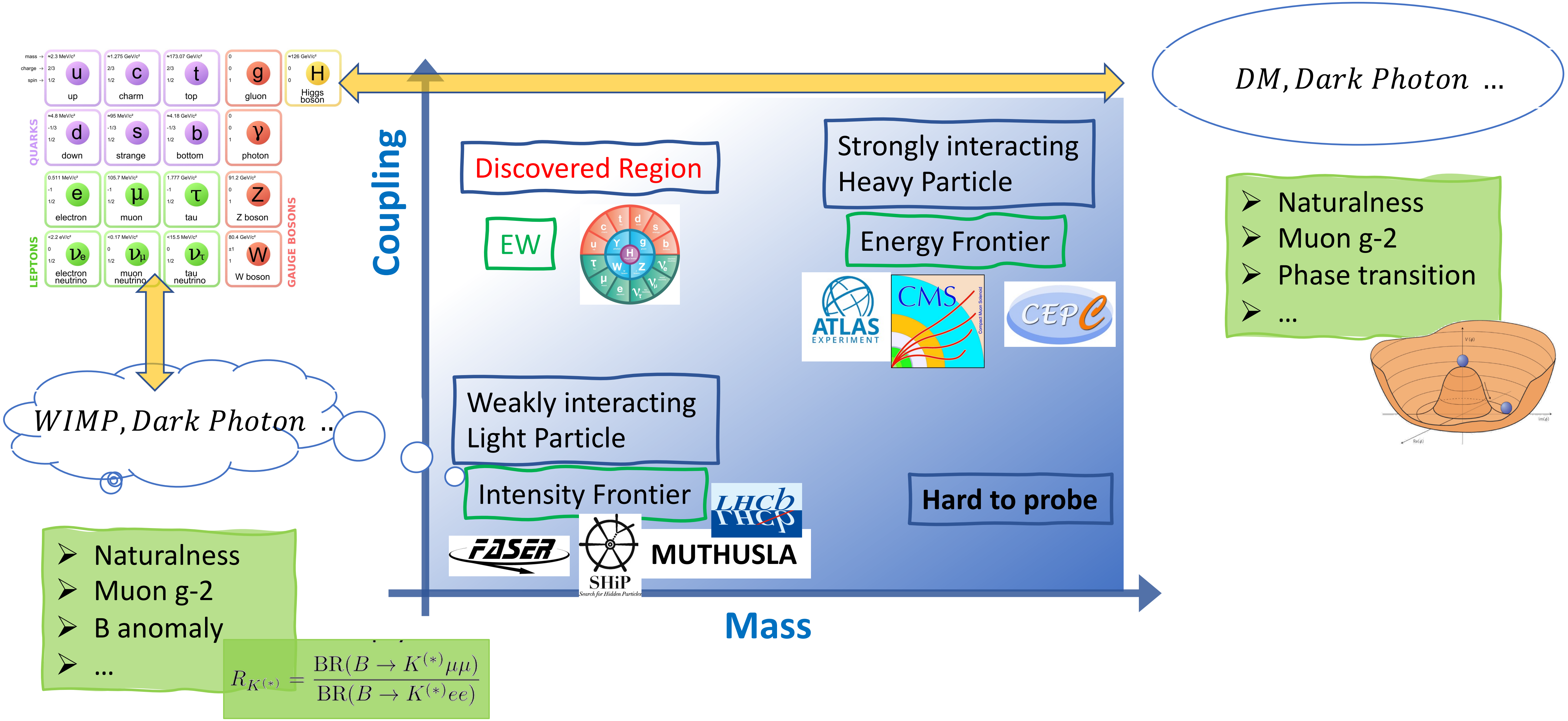
WIMP, Dark Photon …



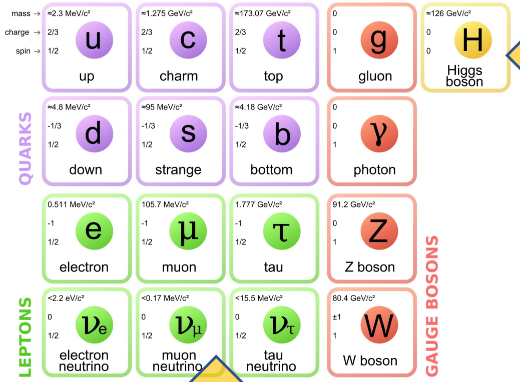
- ➢ Naturalness
- ➢ Muon g-2
- ➢ B anomaly
- ➢ …

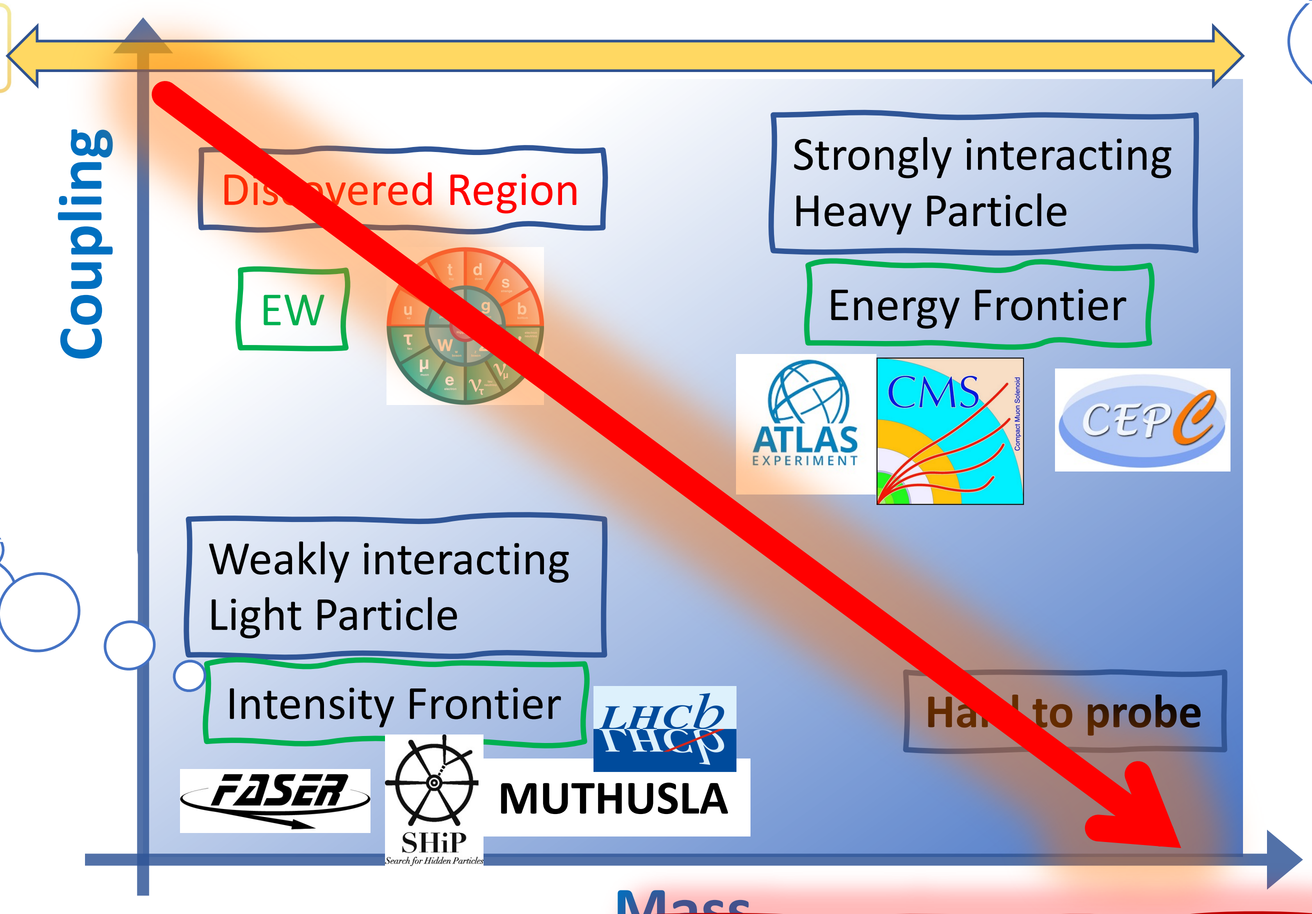
$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$$

Motivation: LLP



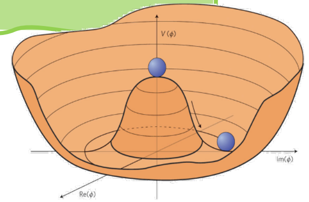
Motivation: LLP





DM, Dark Photon …

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



WIMP, Dark Photon ..

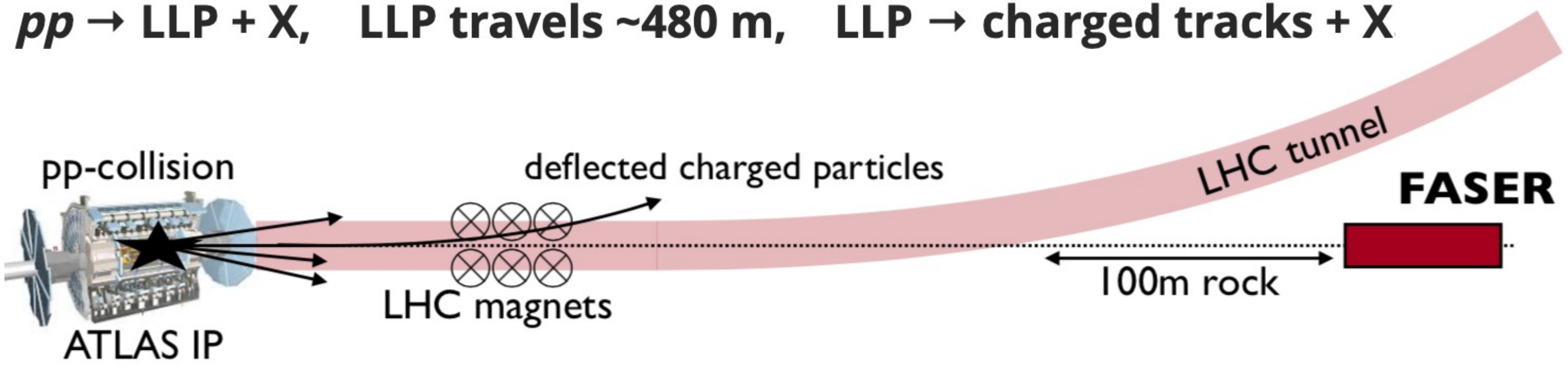
- Naturalness
- Muon g-2
- B anomaly
- …

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

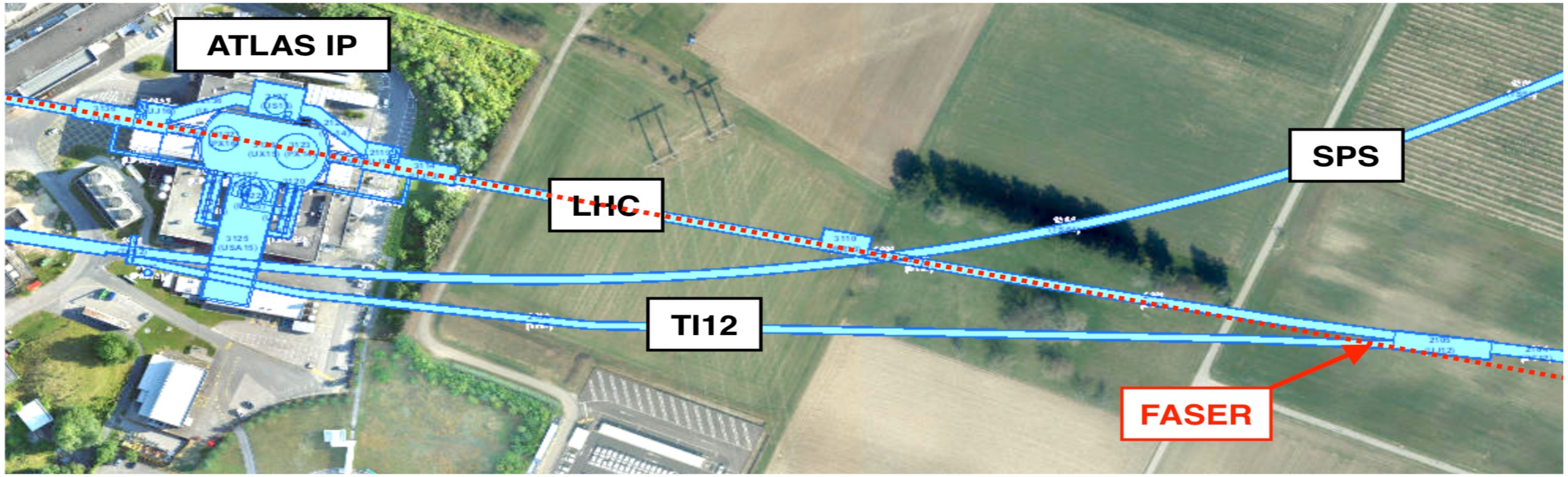
We are now searching for BSM discovery

FASER: ForwArd Search ExpeRiment

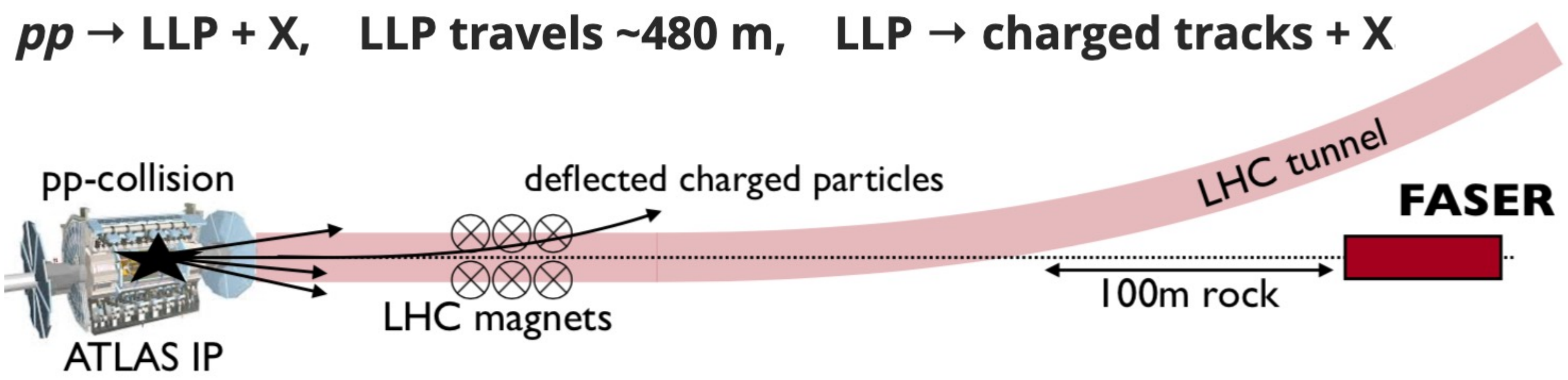
$pp \rightarrow$ LLP + X, LLP travels ~480 m, LLP $\rightarrow$ charged tracks + X



Weakly
interacting
Light Particle



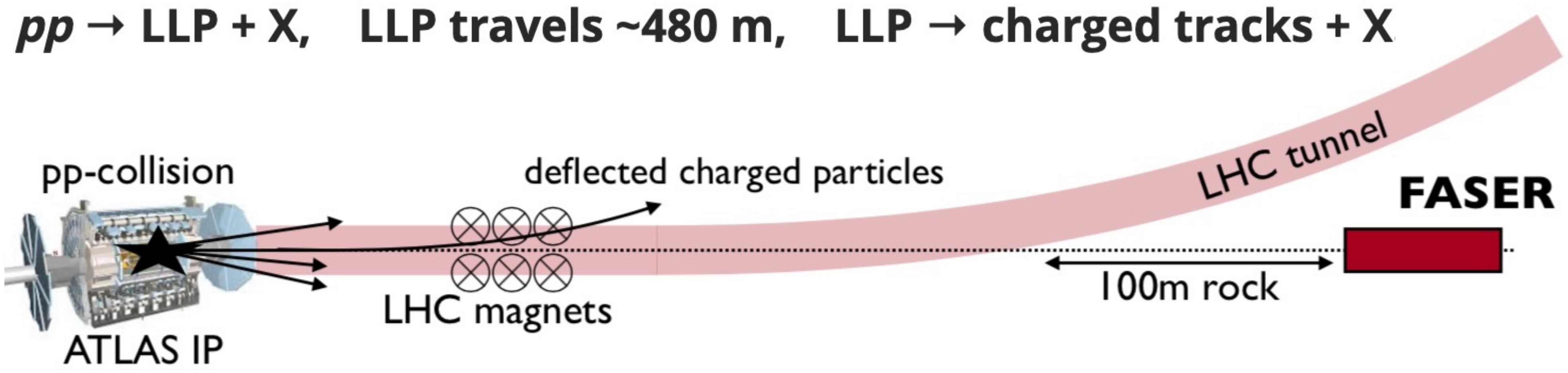
FASER



Production

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

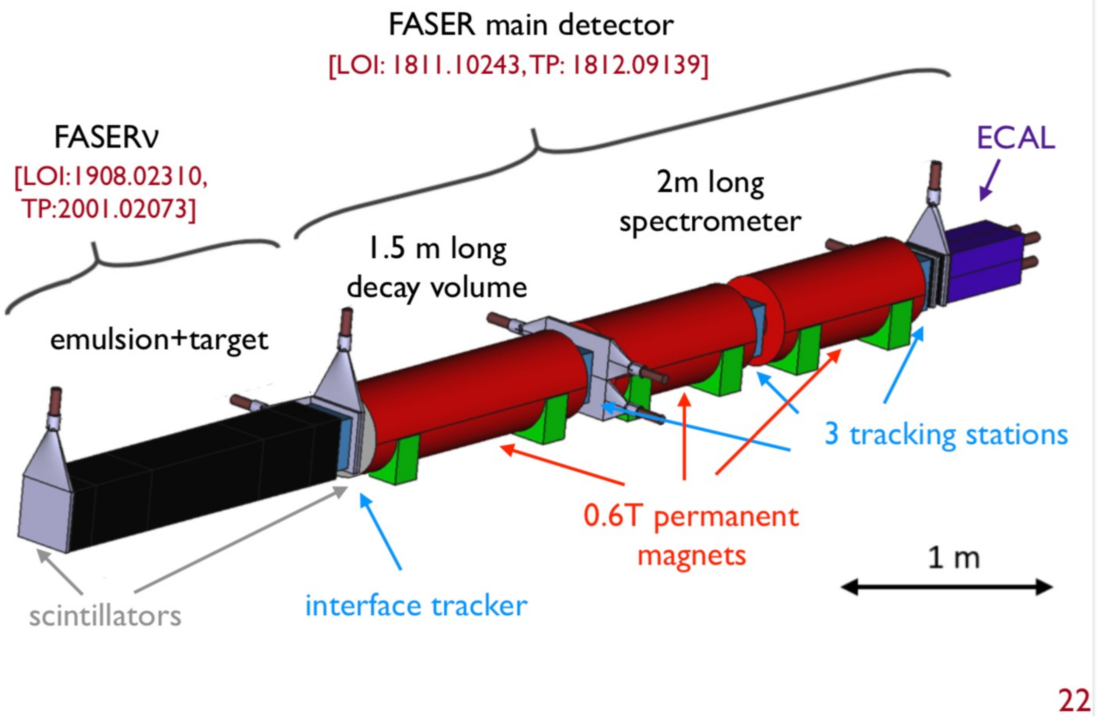
FASER

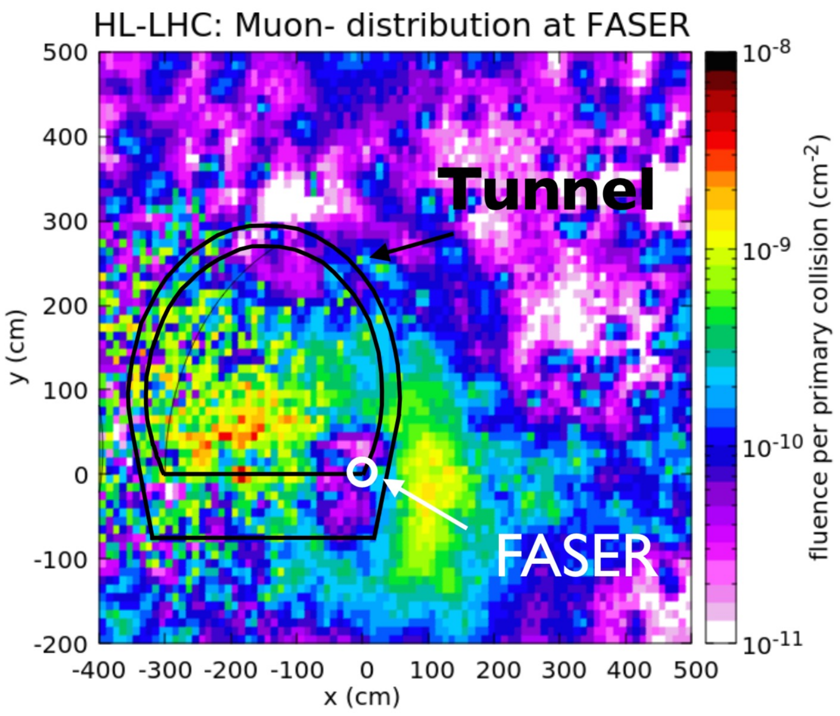


Travel

- Outside the LHC tunnel: a few hundred meters
- LHC infrastructure acts and rock act as shielding
- particles are still highly collimated

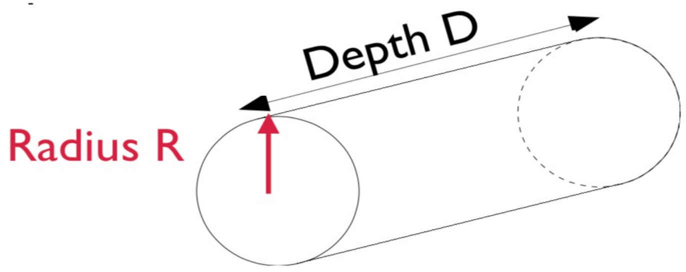
FASER: Detector





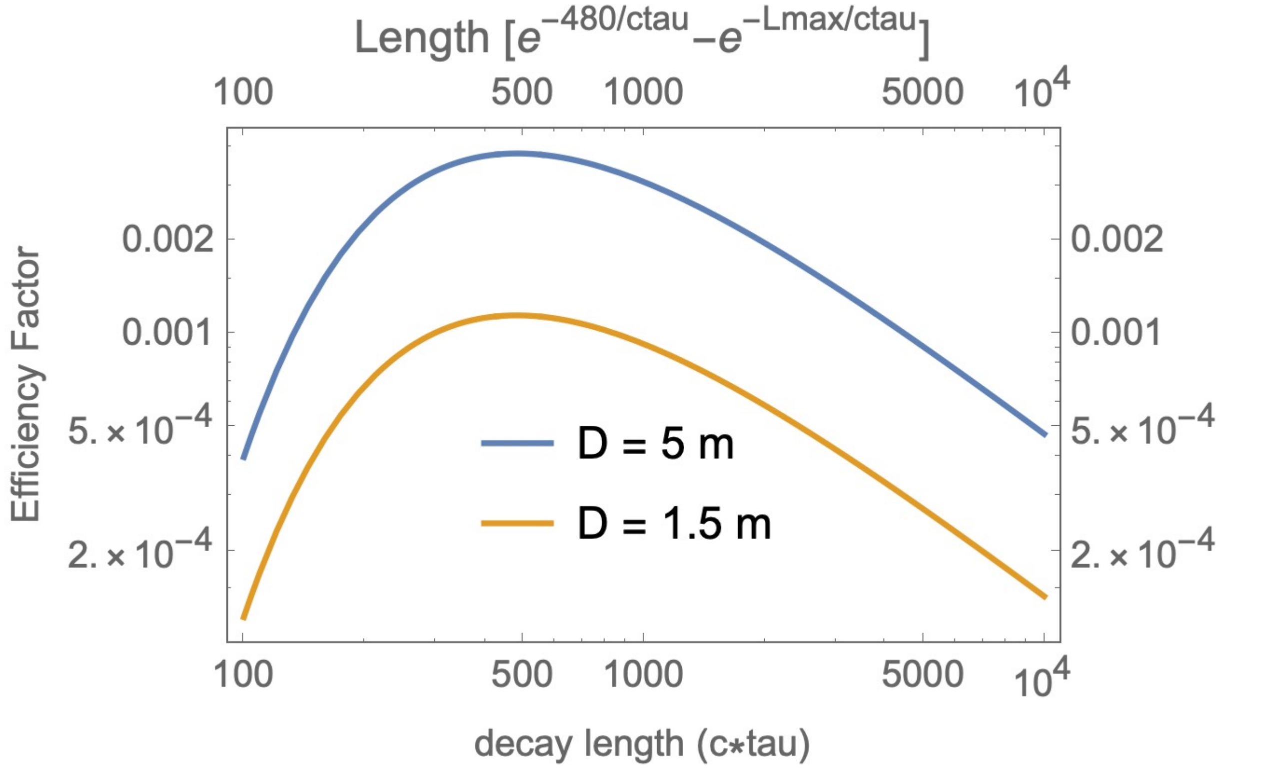
FASER: Detector

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

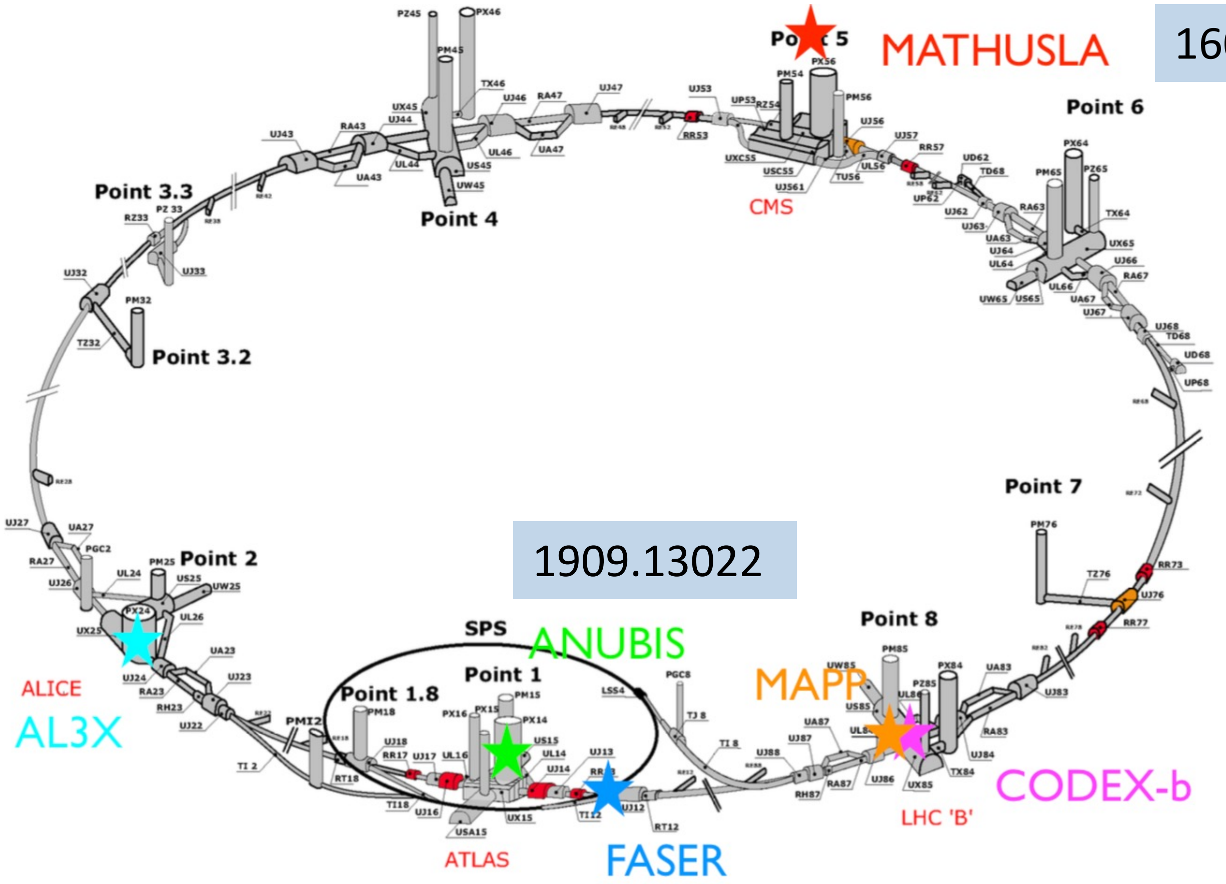


<u>FASER</u>: radius R = 10 cm, lenght D = 1.5 m, luminosity L = 150 fb^{-1},

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



Other proposals for LLP



1606.06298

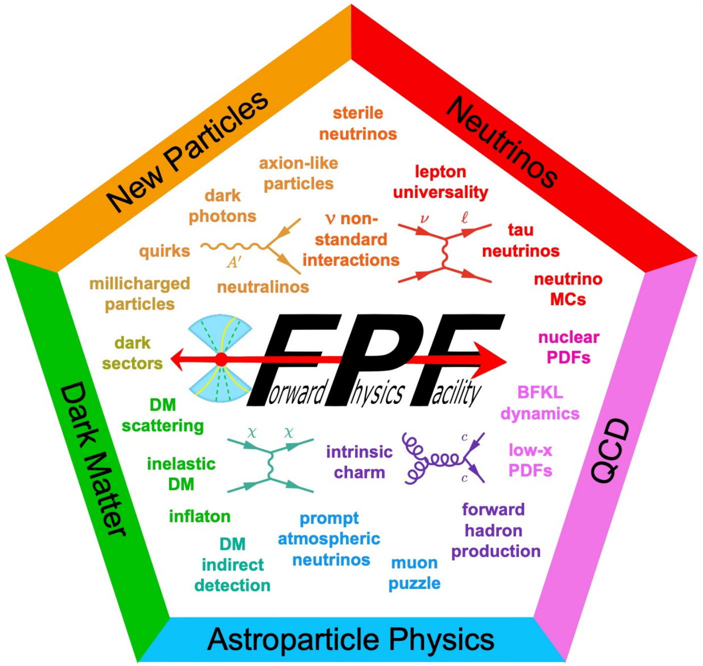
1909.13022

1810.03636

1708.09395

BSM @ FASER

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



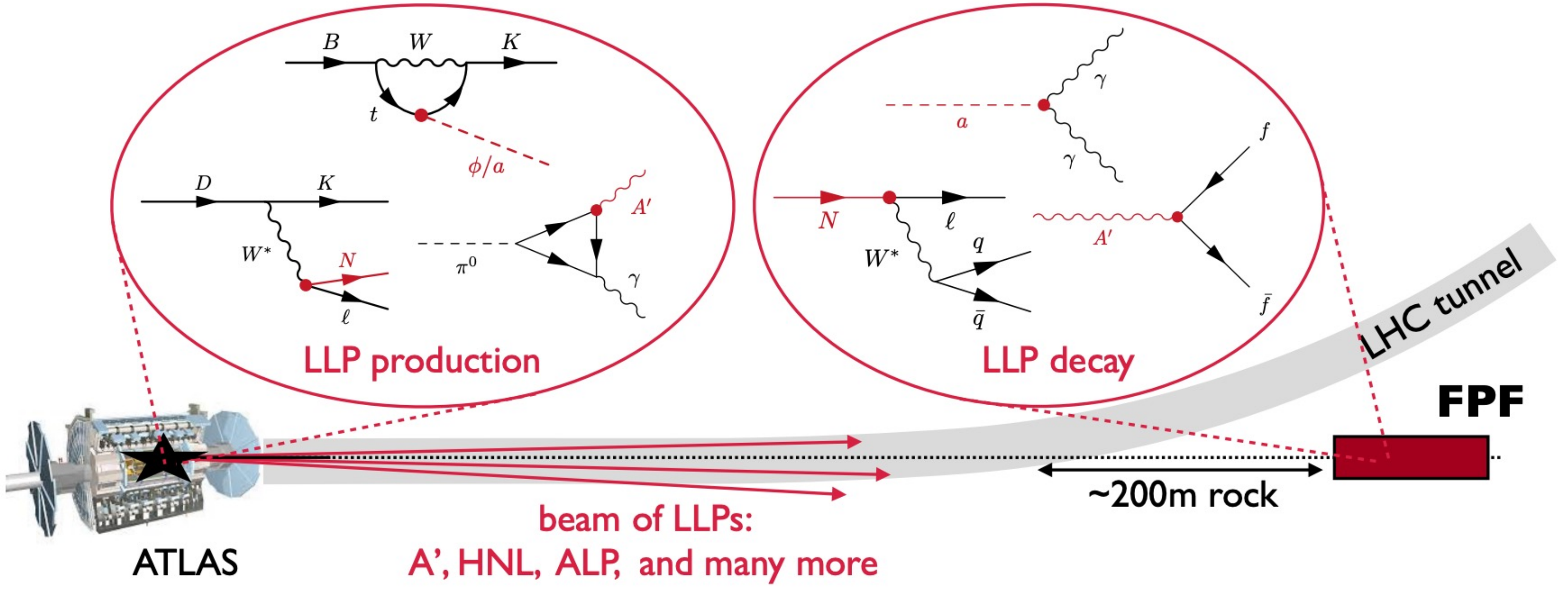
- Heavy Neutral Leptons arXiv: 1801.08947
- Heavy Neutral Fermions arXiv: 1803.02212
- dark photons arXiv: 1708.09389
- Long-lived bivo arXiv: 2103.01251
- Dark Higgs Bosons arXiv: 1710.09387
- Axion like Particle arXiv: 1806.02348
- …

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

2022 Snowmass Summer Study 2203.05090

Production

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



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

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` depending in `x.x` and `x.y` (default: `np.sqrt(x.x**2 + x.y**2)< 1`
- the decay `channels` which the detector can see (default: None, meaning all of t

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

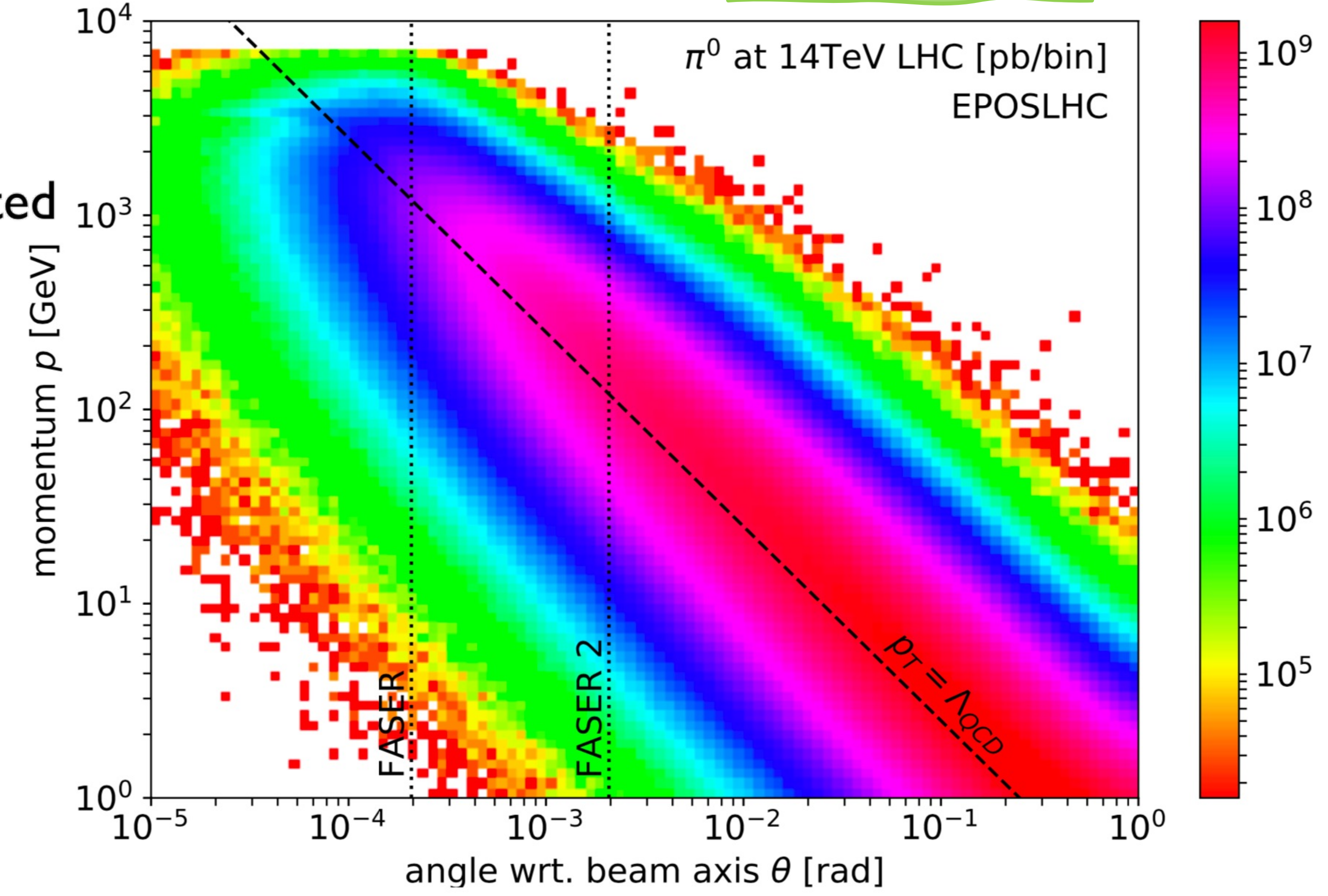
FORESEE

Pion

boosted mesons highly collimated

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

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

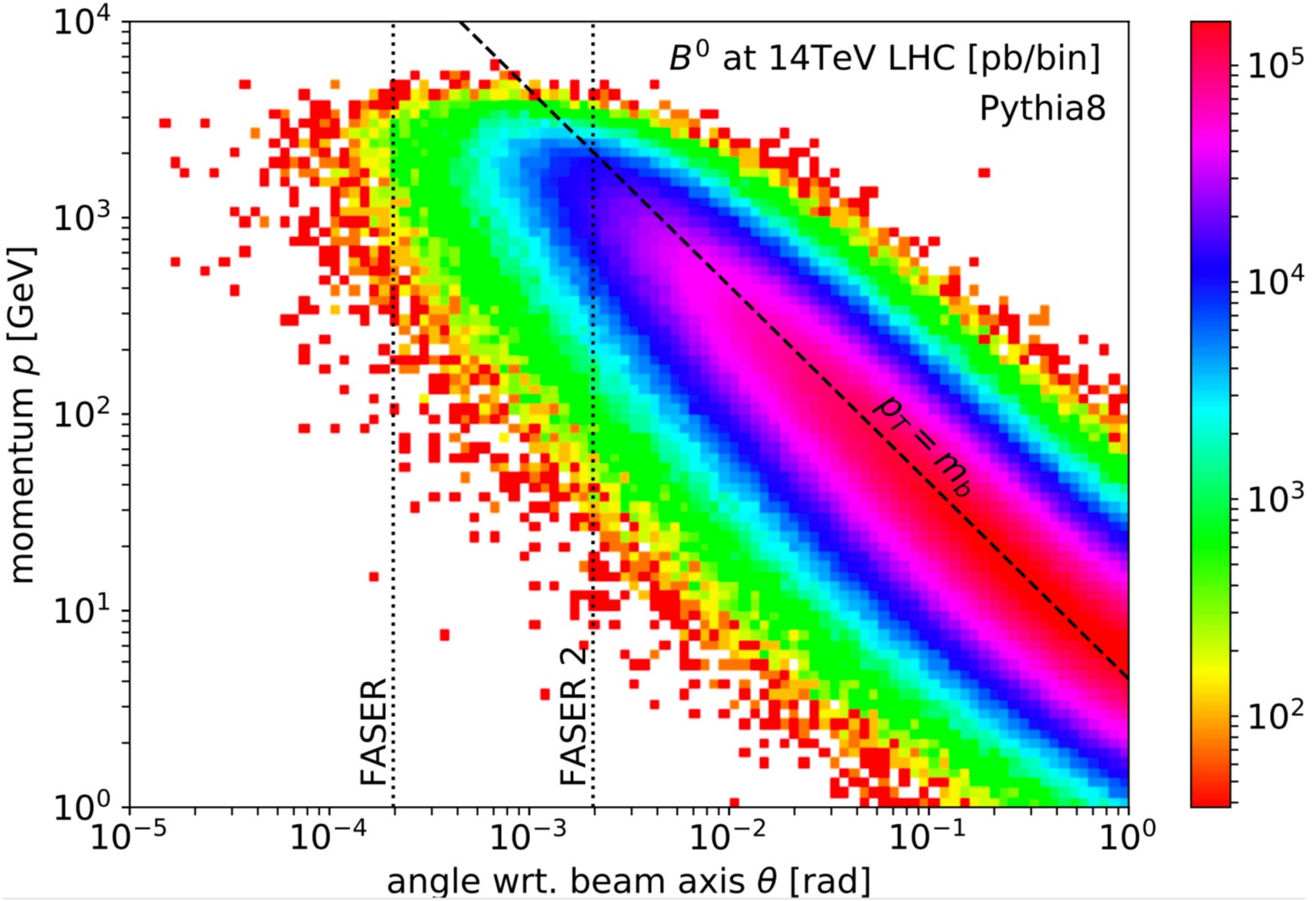


Production

B^0

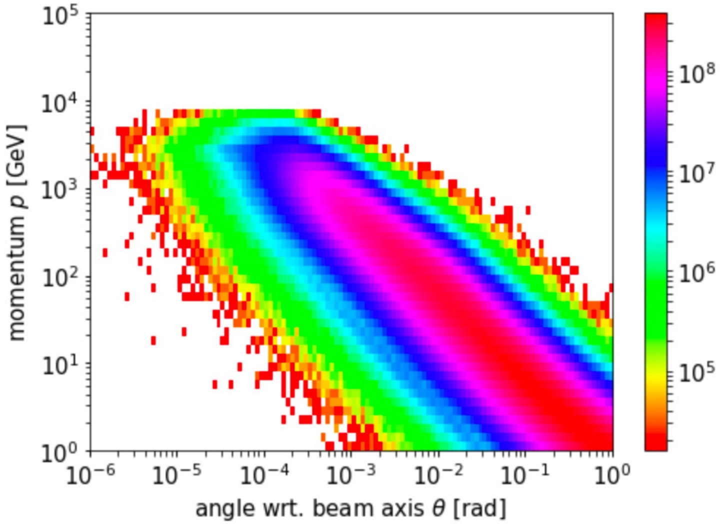
boosted mesons highly collimated

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

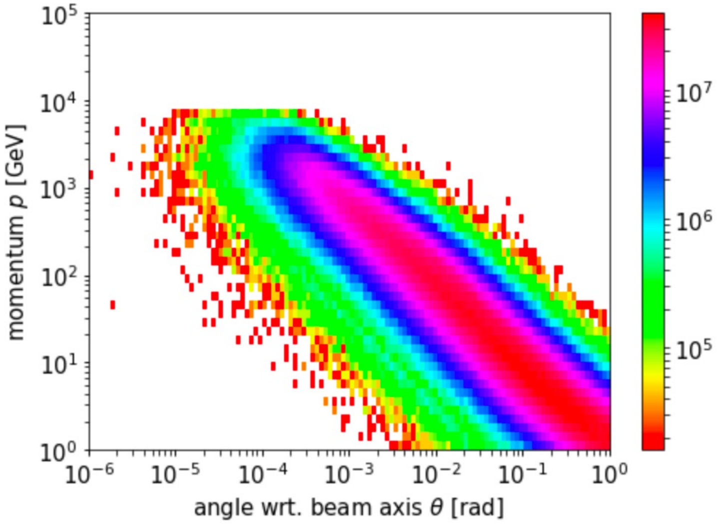


Production

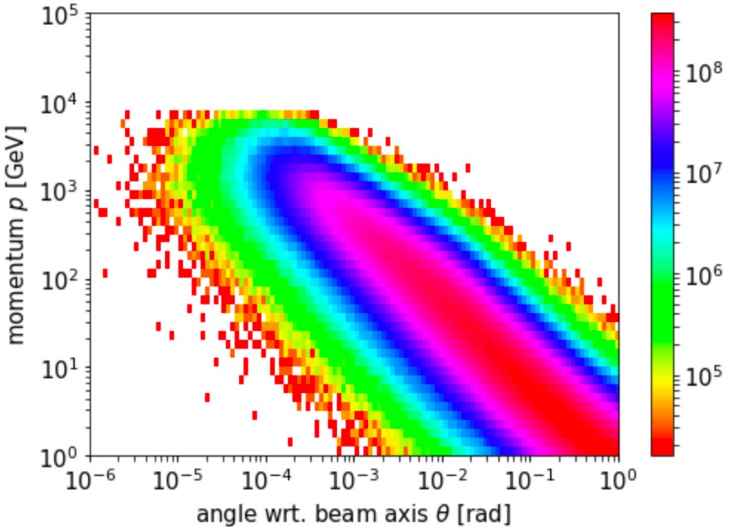
$\boldsymbol{\eta}$



$\boldsymbol{\eta'}$

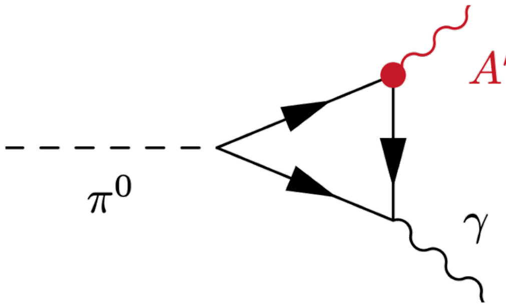


$\boldsymbol{K^+}$

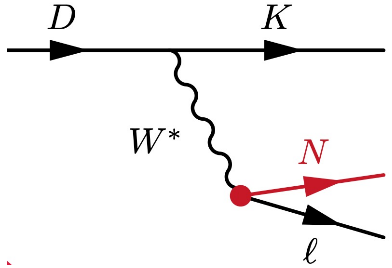


Production: CP even scalar

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

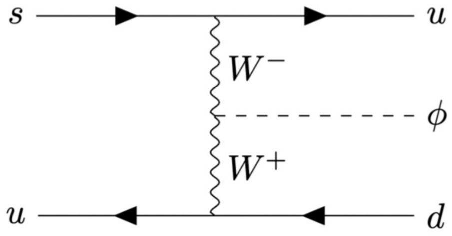


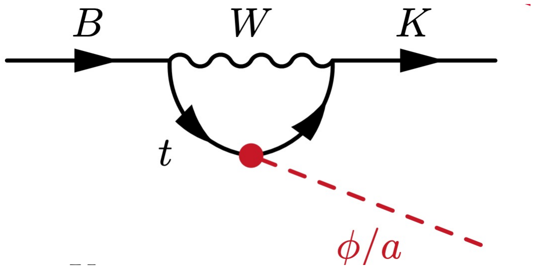
$$K \to \pi\phi,\ \eta^{(\prime)} \to \pi\phi,\ D \to X_u\phi \quad B \to X_s\phi$$



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

K

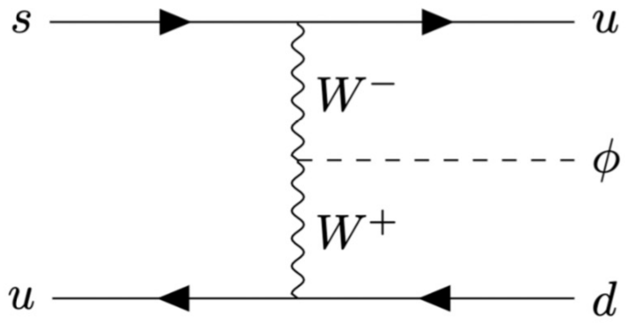




Production: CP even scalar

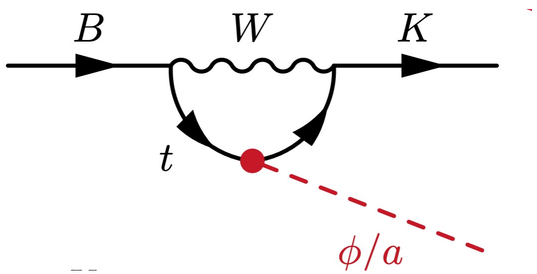
Main contribution

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



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

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



Production: CP even scalar

$$\mathrm{Br}(X \to \phi e\nu) = \frac{\sqrt{2} G_F m_X^4 {\xi_\phi^W}^2}{96\pi^2 m_\mu^2 (1 - m_\mu^2/m_X^2)^2} \times \mathrm{BR}(X \to \mu\nu) f(\frac{m_\phi^2}{m_X^2}) \left(1 - \frac{2n_h}{33 - 2n_l}\right)$$

$$\frac{\mathrm{Br}_{\Upsilon \to \gamma\phi}}{\mathrm{Br}_{\Upsilon \to \bar{e}e}} = \frac{{\xi_\phi^b}^2 G_F m_b^2}{\sqrt{2}\pi\alpha} (1 - \frac{m_\phi^2}{m_\Upsilon^2}) \times \frac{2}{3} \left(1 - \frac{m_\phi^6}{m_\Upsilon^6}\right)$$

Weak contribution

$$\mathrm{Br}(\eta^{(\prime)} \to \pi\phi) = \frac{1}{\Gamma_{\eta^{(\prime)}}} \frac{2p_\phi^0}{m_{\eta^{(\prime)}}} \frac{g_{\phi\eta^{(\prime)}\pi}^2}{16\pi m_{\eta^{(\prime)}}}$$

$$g_{\phi\eta^{(\prime)}\pi} = -\frac{1}{v} \left[m_u \xi_\phi^u - m_d \xi_\phi^d + \frac{2}{9} (m_u - m_d) \left(\xi_\phi^g + \sum_{q=c,b,t} \xi_\phi^q \right) \right] c_{\phi\eta^{(\prime)}\pi} B$$

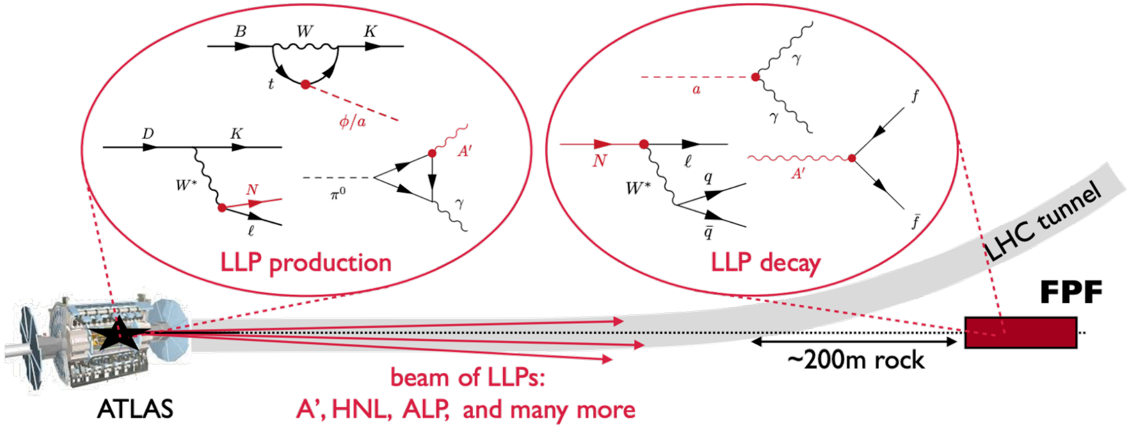
Production: CP odd scalar

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

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

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

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

Decay: CP even scalar

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

$$\xi_\phi^g = \sum_{f\in q} \frac{3}{2}\xi_\phi^i \mathcal{A}_{1/2}^\phi(\tau_f^\phi),$$
$$\xi_\phi^\gamma = \sum_{f\in q,\ell} N_c Q_f^2 \xi_\phi^f A_{1/2}^\phi\left(\tau_f^\phi\right) + \xi_\phi^V A_1^\phi\left(\tau_W^\phi\right)$$

Decay: CP even scalar

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

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

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

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

Decay: CP even scalar

$m_\phi < 2$ GeV

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

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

$$= -\frac{\Phi}{v}\left\{\xi_\Phi^g \left[\frac{2}{27}\Theta^\mu_\mu - \frac{2}{27}(m_u\bar{u}u + m_d\bar{d}d + m_s\bar{s}s)\right] + (\xi_\Phi^u m_u\bar{u}u + \xi_\Phi^d m_d\bar{d}d + \xi_\Phi^s m_s\bar{s}s)\right\}$$

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

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

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

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

Decay: CP even scalar

$m_\phi < 2$ GeV

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

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

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

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

Leading order chiral perturbation theory

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

Decay: CP even scalar

$m_\phi < 2$ GeV

$H \to \pi\pi$

$H \to KK$

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

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

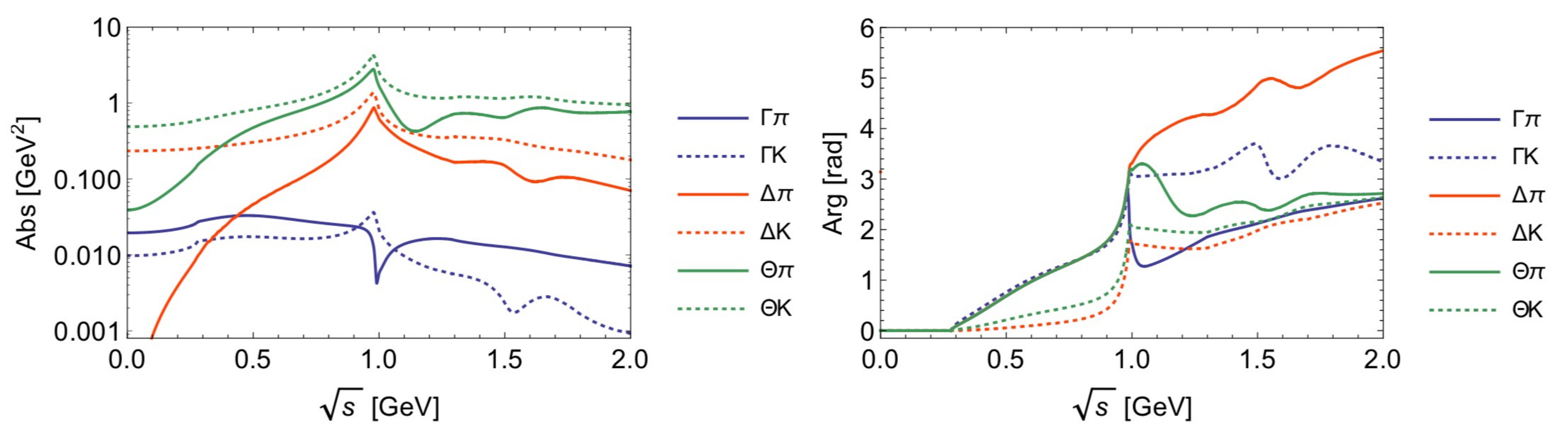
Dispersive Analysis

$$= \ldots m_u \bar{u}u + \xi_\Phi^d m_d \bar{d}d + \xi_\Phi^s m_s \bar{s}s) \Big\}$$

Θ^μ_μ

Γ_π … $0\rangle$

L



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

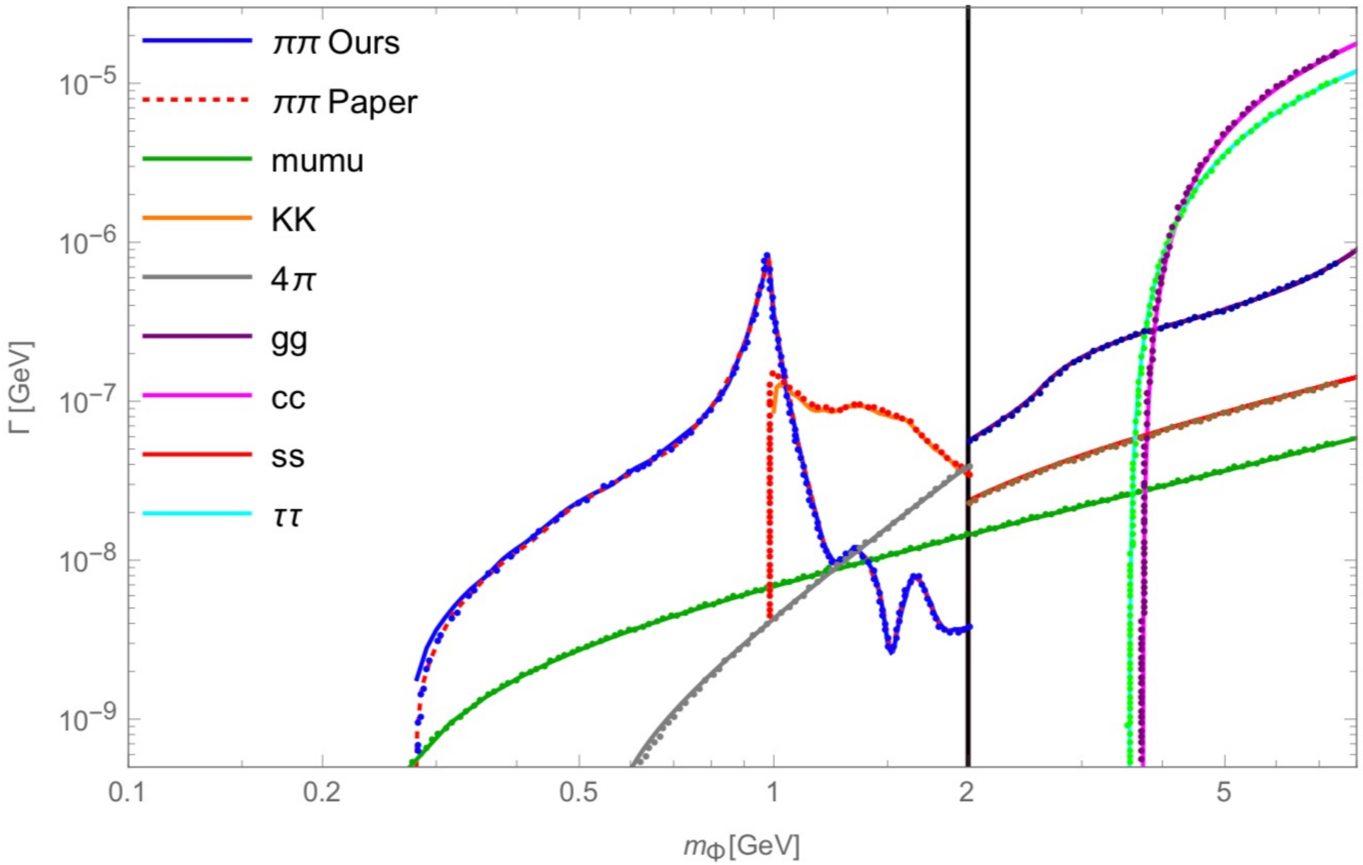
$$\Gamma^0_K = \frac{1}{2}m_\pi^2, \qquad \Delta^0_K = m_K^2 - \frac{1}{2}m_\pi^2, \qquad \Theta^0_K = s + 2m_K^2$$

Decay: CP even scalar

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

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

fig.3/4 of 1809.01876



SM + *singlet*

$H \to \pi\pi$

$H \to KK$

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

$$\phi \to 4\pi, \eta\eta, KK\pi\pi, \rho\rho \cdots$$

$$\Gamma_{4\pi,\eta\eta,\rho\rho,\ldots} = C(\xi_\phi^g)^2 m_\phi^3 \beta_{2\pi}$$

Match at m=2 GeV

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

4 Constraints

There are a variety of constraints on light scalars, and here we have a brief list including the relevant experiments.

CHARM bounds The CHARM Collaboration has searched for light axion-like particles at LHC with a 400 GeV proton beam-dump experiment on a copper target [41]. Its results can be transmitted to the light scalar constraints [25, 42].

SuperNova A light, weakly coupled scalar can affect astrophysical processes. During supernova (SN) explosion, the scalar emission can significantly contribute to the energy loss [43], shortening the neutrino pulse duration. Such an observable would place constraints on the light scalar [44–46].

B meson decays Below the B threshold, searches for semi-leptonic B decays become relevant in our study region. The leading constraints come from LHCb measurements B meson decays $B \to K^*\phi$ with $\phi \to \mu\mu$ at Ref. [47] and $B^+ \to K^+\chi(\mu^+\mu^-)$ at Ref. [48]. We digitized the provided constraints for further model study.

Kaon decays Kaon decays aso contribute to the searches for light scalar region. The latest important experiments of K^+ decays are $K^+ \to \pi^+ X$ with X scalar or pseudo-scalar particle to $\nu\bar{\nu}$, NA62 [49](90% C.L.), $K^+ \to \pi^+\chi(e^+e^-)$ at MicroBooNE [50] (95% C.L.), and $\mathcal{B}(K^+ \to \pi^+ X)$ at E949 [51] (90% C.L.). All of them provides constraints based on the light scalar decay lifetime hypotheses.

D meson decays Those are typically not considered, since in most models $\mathrm{BR}(D^+ \to \pi\phi)$ (corresponding to $\mathrm{BR}(c \to u\phi)$) is rather small. You can find the current limits in PDG, but also this really recent LHCb paper [52].

LEP Wei: add...

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

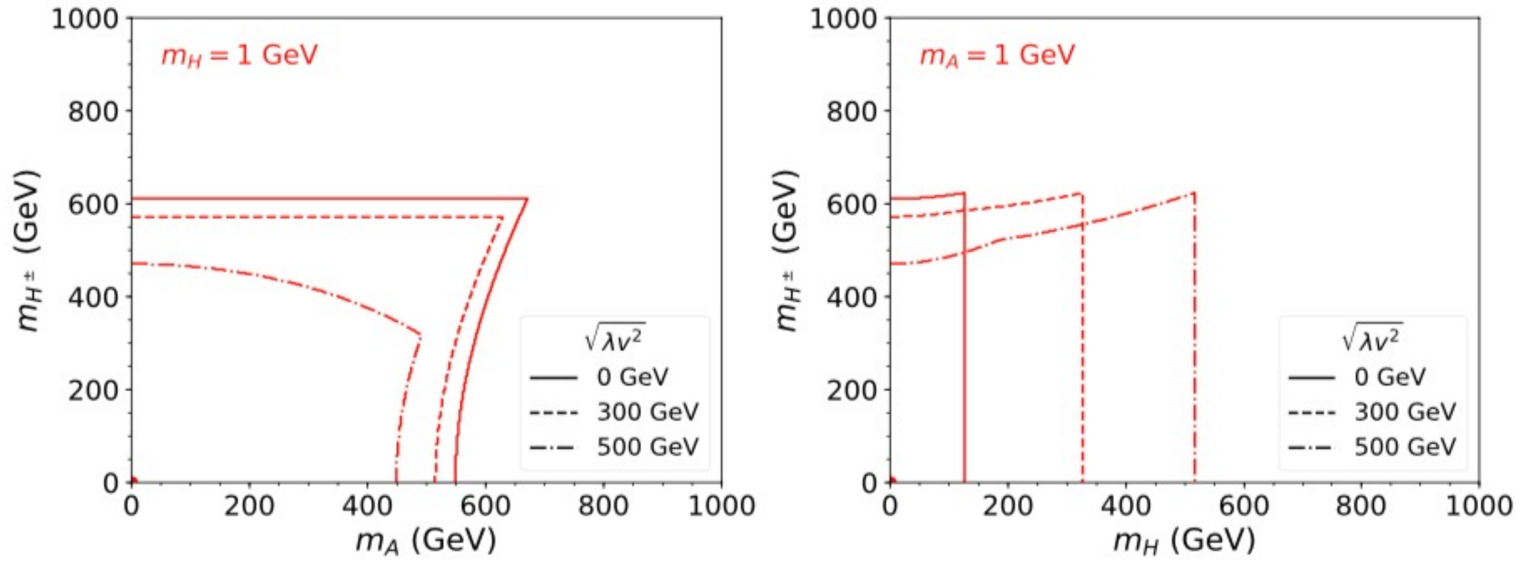
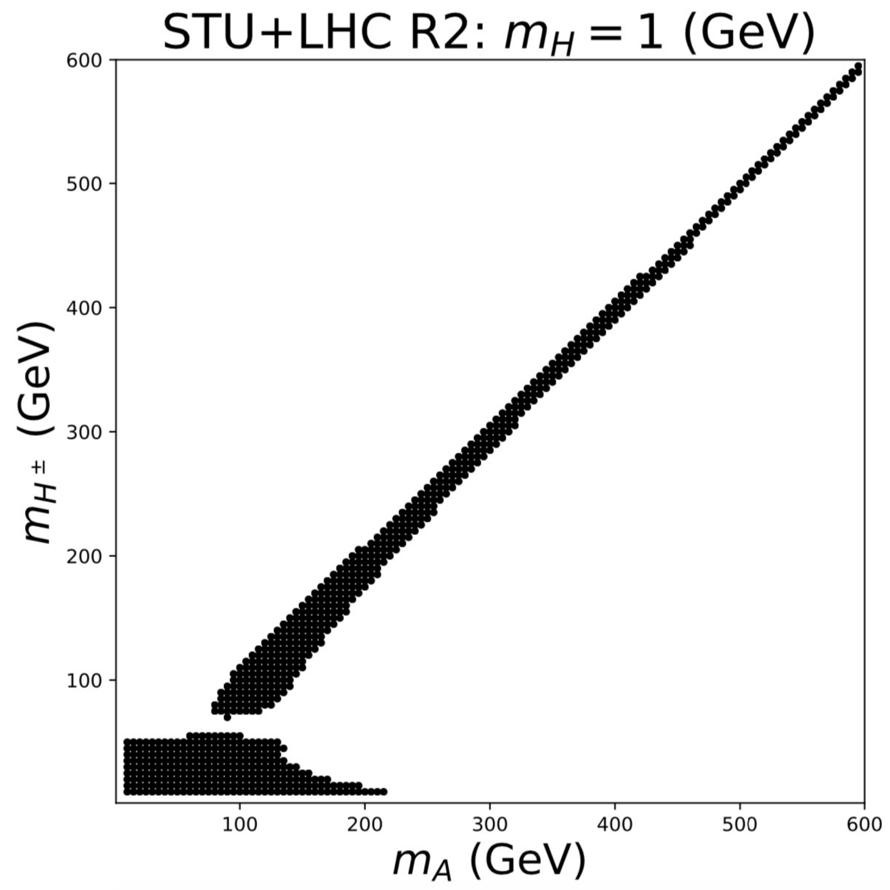
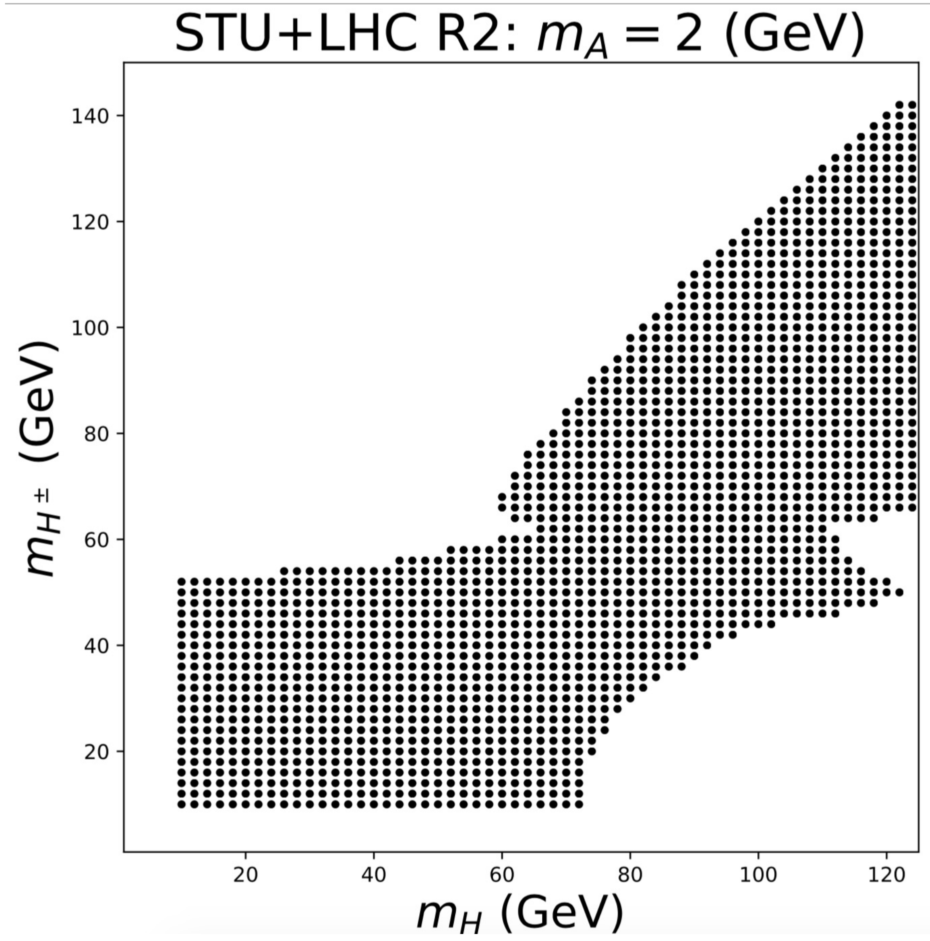


Figure 2. Allowed region by theoretical constraints for $m_H = 1$ GeV (left panel) and $m_A = 1$ GeV (right panel) for various values of λv^2.


STU+LHC R2: $m_H = 1$ (GeV)
600
500
400
300
200
100
$m_{H^\pm}$ (GeV)
100
200
300
400
500
600
m_A (GeV)


STU+LHC R2: $m_A = 2$ (GeV)
140
120
100
80
60
40
20
$m_{H^\pm}$ (GeV)
20
40
60
80
100
120
m_H (GeV)

5.2.4 Invisible Higgs decays

For a light H/A with long lifetime, $h \to HH/AA$ is constrained from the invisible Higgs decay of $\mathrm{Br}(h \to \phi\phi) < 0.24$ [61–63] The Branch fraction of Higgs invisible decay is given by [10]

$$\mathrm{Br}(h \to \phi\phi) = \frac{\Gamma(h \to \phi\phi)}{\Gamma_h} \approx \frac{1}{\Gamma_h^{\mathrm{SM}}} \frac{g_{h\phi\phi}^2}{8\pi m_h^2} \left(1 - \frac{4m_H^2}{m_h^2}\right)^{1/2} \simeq 4700 \cdot \left(\frac{g_{h\phi\phi}}{v}\right)^2 \tag{5.9}$$

here ϕ is light H or A.

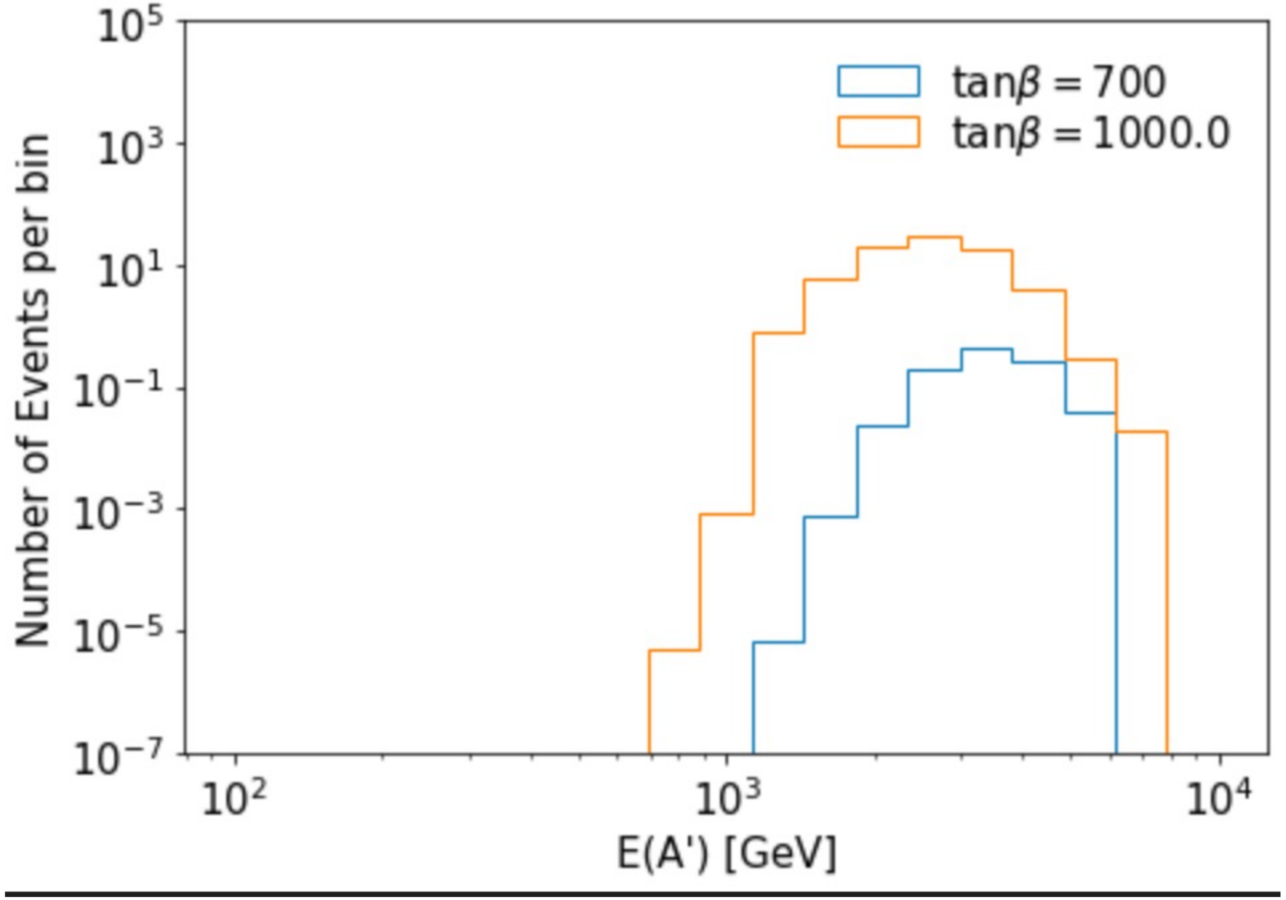
$$\begin{aligned} \mathit{Light}\ H : \cos(\beta - \alpha) &= \tan 2\beta \frac{2\lambda v^2 + m_h^2}{2(m_H^2 - 3\lambda v^2 - m_h^2)} \approx \frac{1}{\tan\beta}\,, \\ \mathit{Light}\ A : \cos(\beta - \alpha) &= \tan 2\beta \frac{2\lambda v^2 + m_h^2 + 2m_A^2 - 2m_H^2}{2(m_H^2 - \lambda v^2 - m_h^2)} \approx \frac{1}{\tan\beta} \frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2}\,, \end{aligned}$$

Benchmark Scenario

$$Light\ H : \cos(\beta - \alpha) = \frac{1}{\tan\beta},\ m_A = m_{H^\pm} = 600\ \text{GeV},\ \lambda v^2 = 0\ \text{GeV}^2\,,$$
$$Light\ A : \cos(\beta - \alpha) = 0,\ m_H = m_{H^\pm} = 90\ \text{GeV},\ \lambda v^2 = 0\ \text{GeV}^2\ .$$

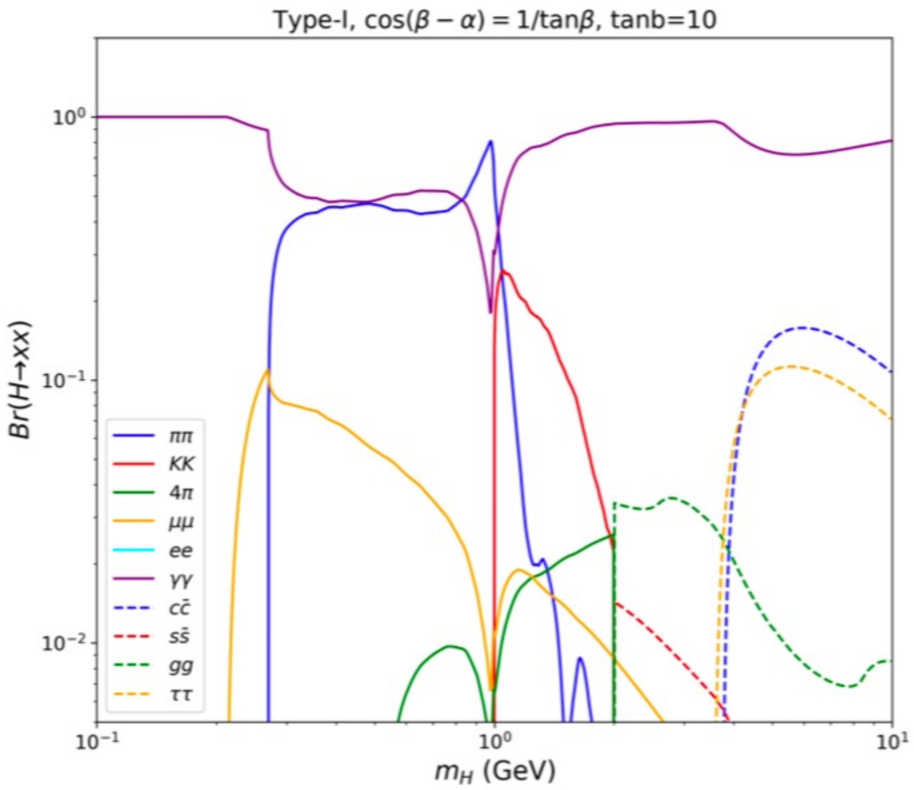
$$\xi_H^V = c_{\beta-\alpha} = 1/\tan\beta,$$
$$\xi_H^f = c_{\beta-\alpha}(1 - s_{\beta-\alpha}) \approx \tfrac{1}{2}c_{\beta-\alpha}^3 + \mathcal{O}(c_{\beta-\alpha}^5).$$

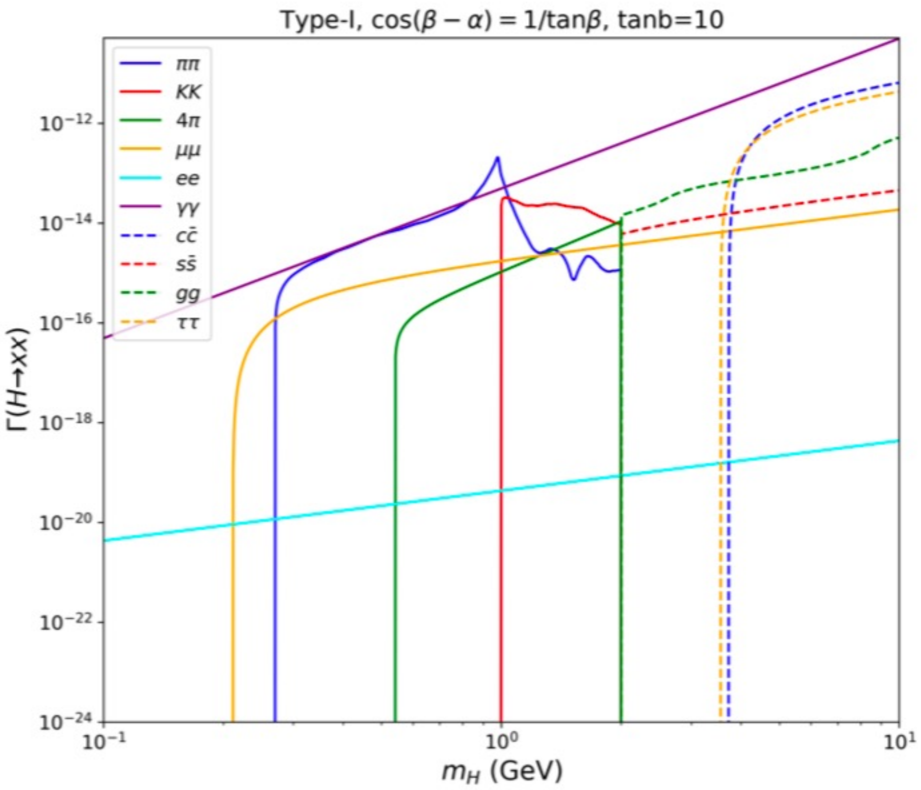
production

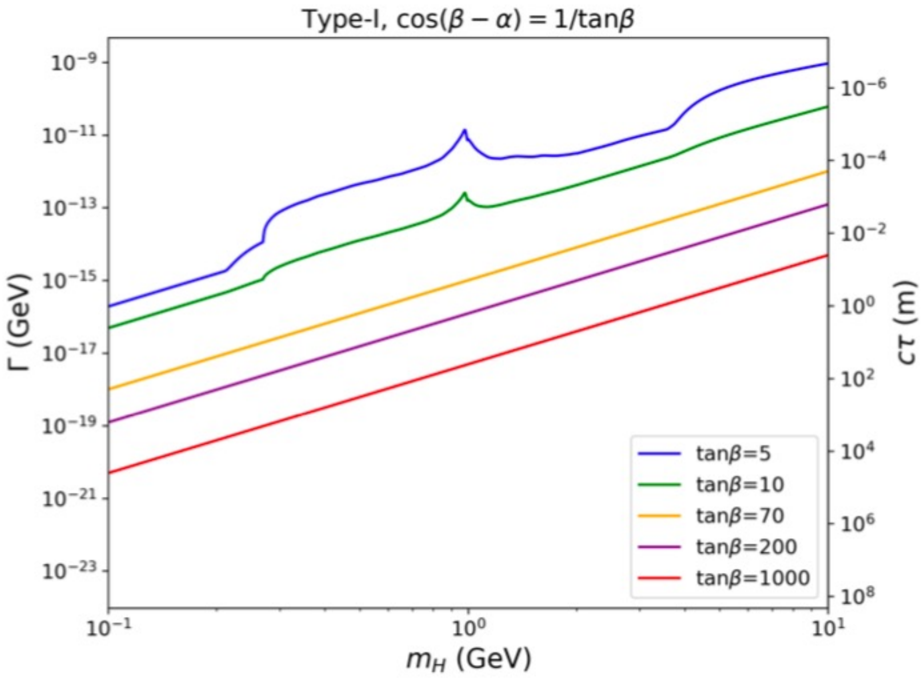


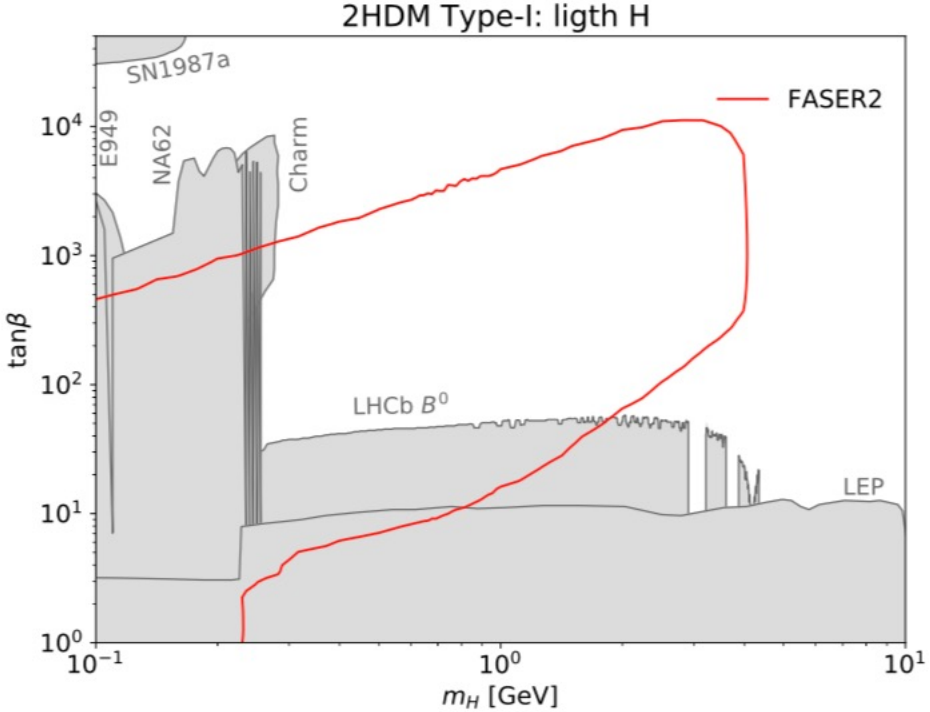
$\tan\beta = 700$
$\tan\beta = 1000.0$
Number of Events per bin
10^{5}
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{2}
10^{3}
10^{4}
E(A') [GeV]

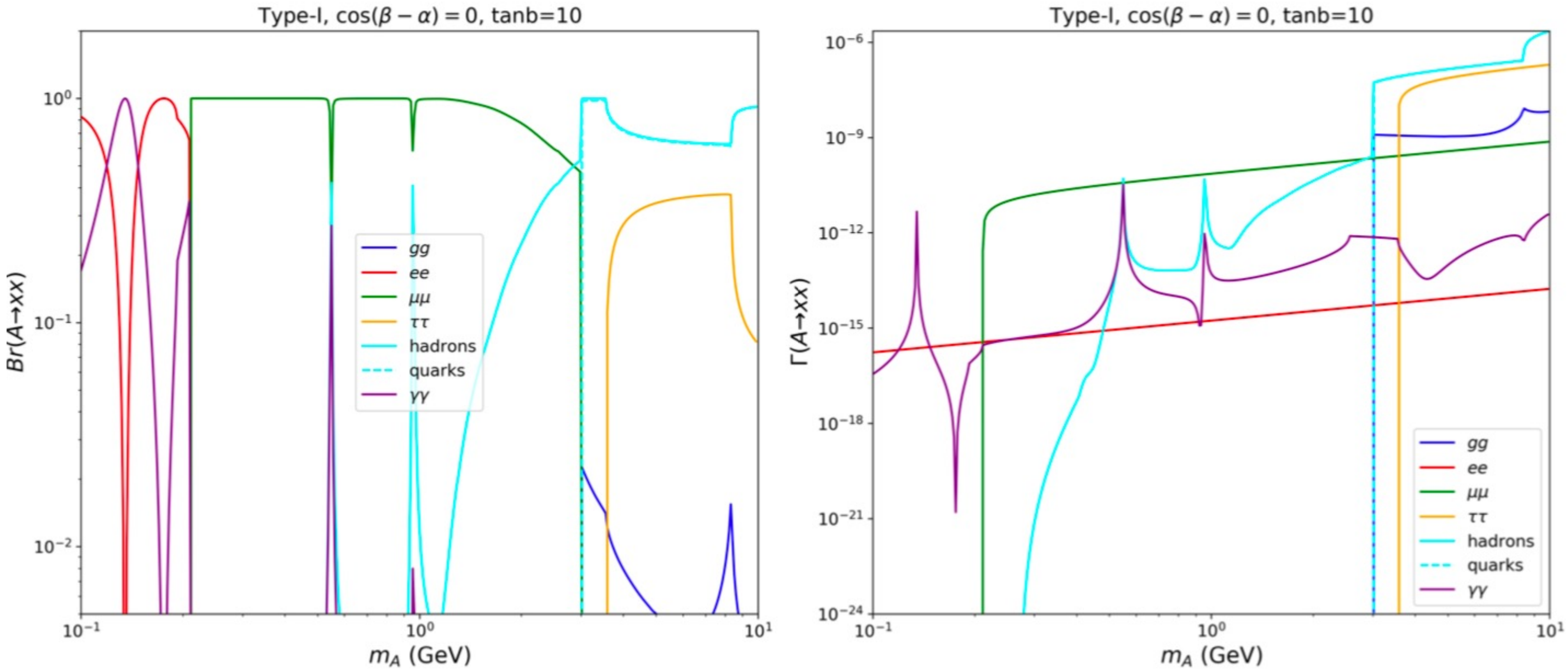
decay


Type-I, cos(β − α) = 1/tanβ, tanb=10
Br(H→xx)
m_H (GeV)
10⁰
10⁻¹
10⁻²
10⁻¹
10⁰
10¹
ππ
KK
4π
μμ
ee
γγ
cc̄
ss̄
gg
ττ

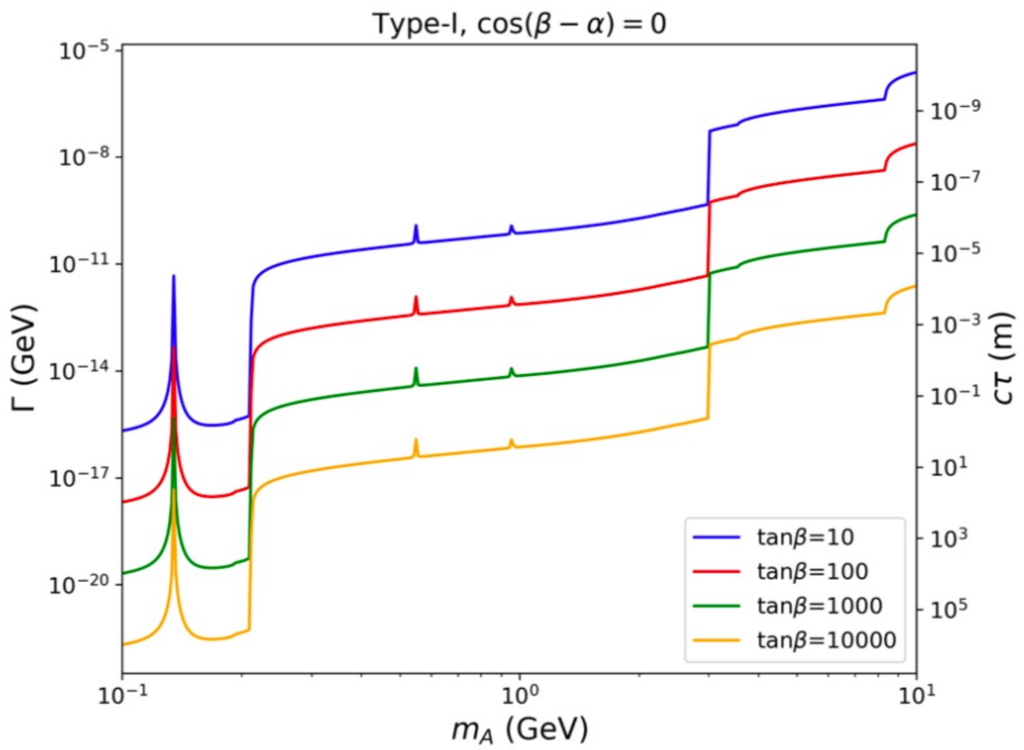

Type-I, cos(β − α) = 1/tanβ, tanb=10
Γ(H→xx)
m_H (GeV)
10⁻¹²
10⁻¹⁴
10⁻¹⁶
10⁻¹⁸
10⁻²⁰
10⁻²²
10⁻²⁴
10⁻¹
10⁰
10¹
ππ
KK
4π
μμ
ee
γγ
cc̄
ss̄
gg
ττ

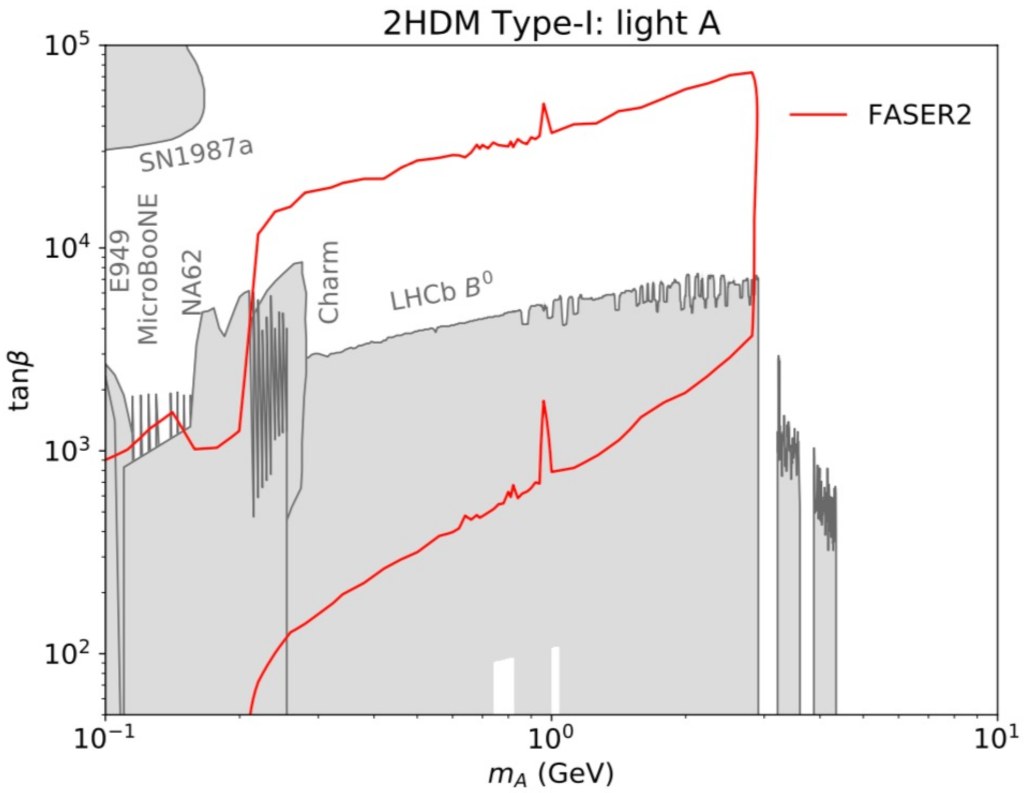

Type-I, cos(β − α) = 1/tanβ
Γ (GeV)
cτ (m)
m_H (GeV)
tanβ=5
tanβ=10
tanβ=70
tanβ=200
tanβ=1000


2HDM Type-I: ligth H
FASER2
SN1987a
E949
NA62
Charm
LHCb B^0
LEP
tanβ
m_H [GeV]



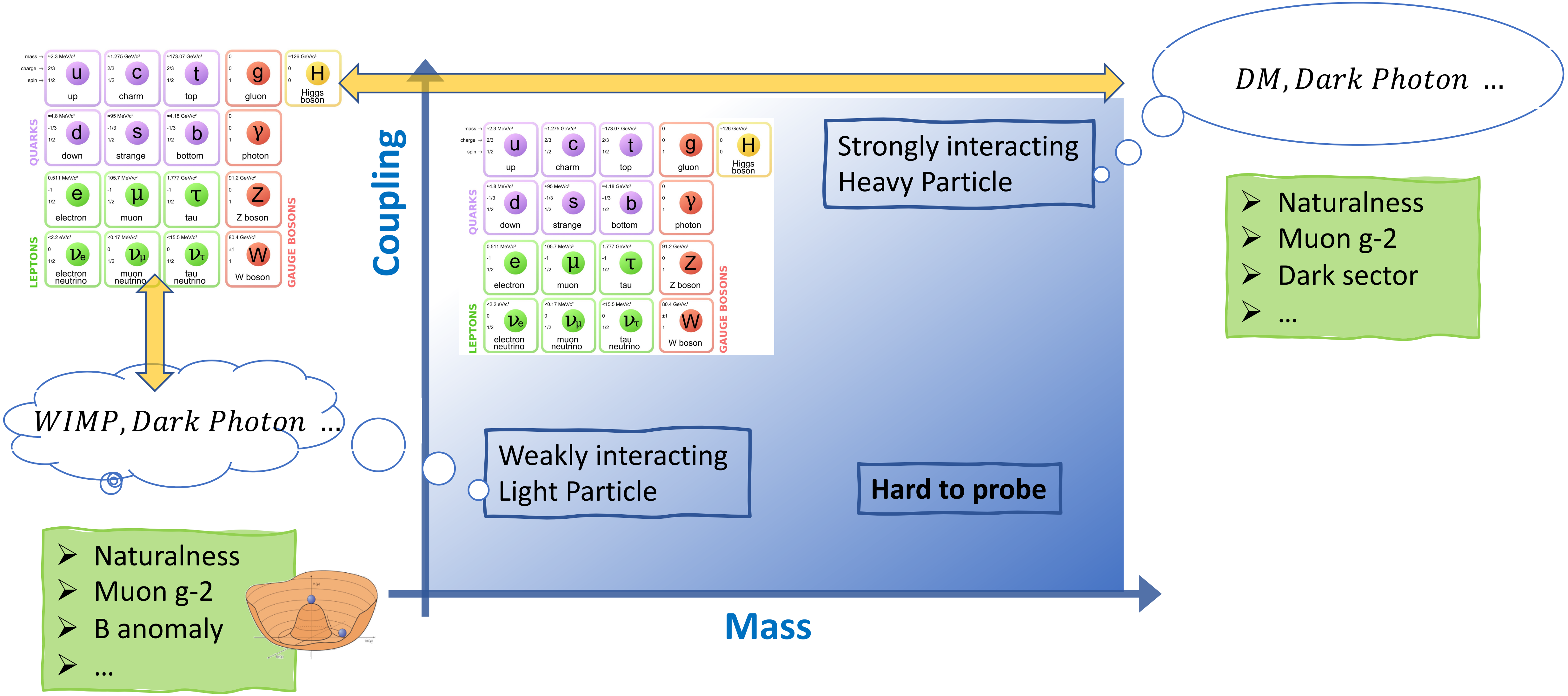
Type-I, cos(β − α) = 0, tanb=10
Br(A→xx)
m_A (GeV)
gg
ee
μμ
ττ
hadrons
quarks
γγ
Type-I, cos(β − α) = 0, tanb=10
Γ(A→xx)
m_A (GeV)
gg
ee
μμ
ττ
hadrons
quarks
γγ


Type-I, cos(β − α) = 0
Γ (GeV)
cτ (m)
m_A (GeV)
tanβ=10
tanβ=100
tanβ=1000
tanβ=10000


2HDM Type-I: light A
tanβ
m_A (GeV)
FASER2
SN1987a
E949
MicroBooNE
NA62
Charm
LHCb B^0

Thanks !

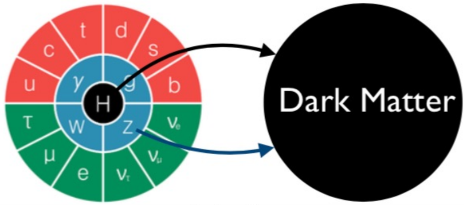
Motivation: LLP



Motivation: BSM hints

Strongly Interacting Heavy Particles

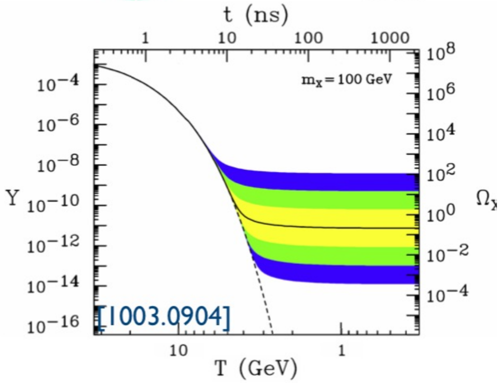
WIMP Miracle
- dark matter solid evidence for new particles
- thermal freeze out: $\Omega_{DM} \sim 1/\langle\sigma v\rangle \sim m^2/g^4$
- WIMP miracle: $m \sim m_{weak}, \;\; g \sim g_{weak}$



Electroweak Hierarchy Problem
- Why is Higgs mass small? $m_h \ll M_{Pl}$
- Higgs mass seems fine tuned

$$m_h^2 = m_{h0}^2 + \Delta m^2, \quad \Delta m^2 \sim \Lambda^2$$

- avoided if $\Lambda \lesssim 1$ TeV



Anomalies
- muon g-2
- anomalies in B-physics

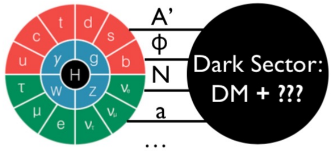
$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)} \qquad R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}$$

6

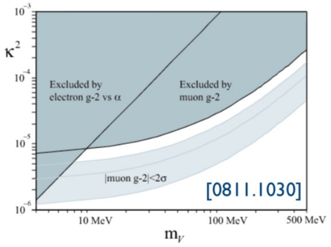
Motivation

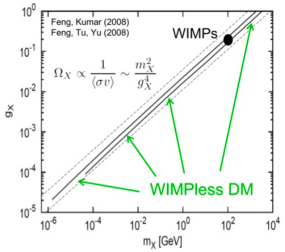
Weakly Interacting Light Particles

WIMPless Miracle
- thermal freeze out: $\Omega_{DM} \sim 1/\langle\sigma v\rangle \sim m^2/g^4$
- "broader" WIMP: $m < m_{weak}, \;\; g < g_{weak}$
- new mediators
  → dark sector



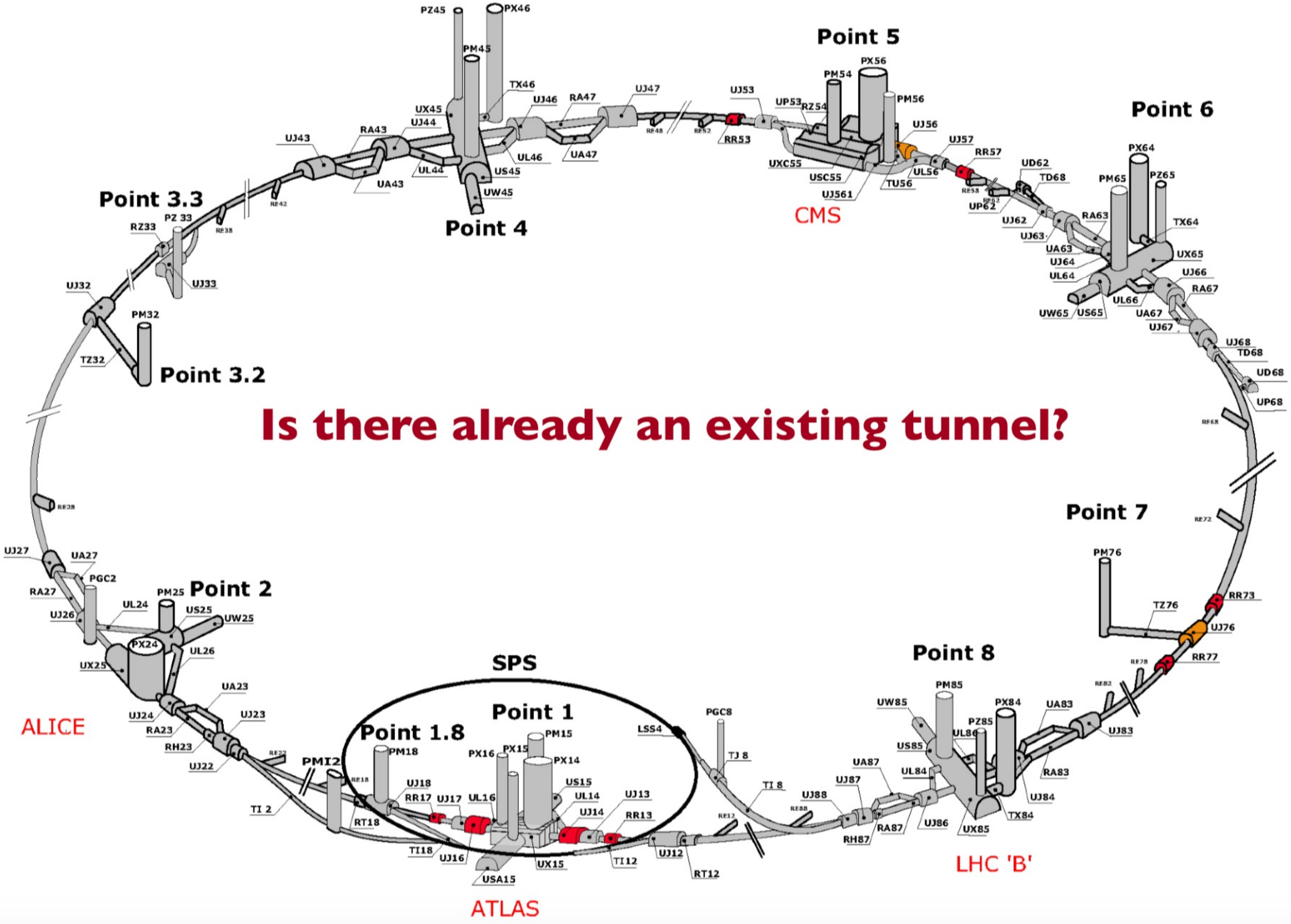
Anomalies
- muon g-2
- Be-8 anomaly



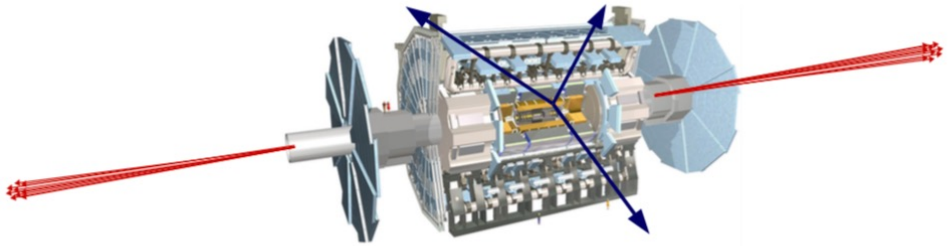


We are now searching for BSM discovery

Is there already an existing tunnel?



- LHC searches/experiments focus on **central region**, which is motivated by heavy, strongly interacting particles
  * small rates: σ ~ fb - pb or $N_H \sim 10^7$ at $\mathcal{L} = 300$ fb^{-1}
  * high pT, produced ~ isotropical



- For light and weakly interacting particles, this may be completely misguided
  * light: we can produce them in π, K, D, B decays
  * weakly-interacting: need extremely large SM event rate to see them

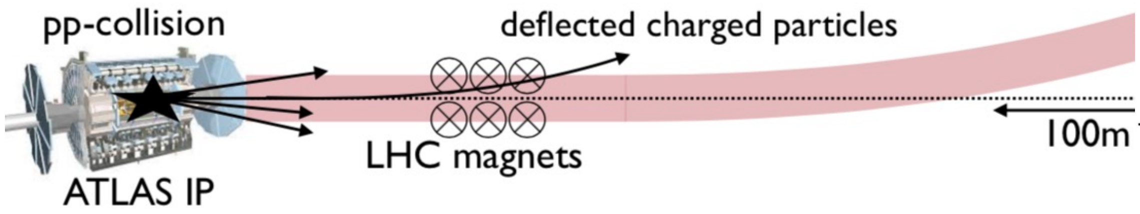
- We should go where the pions are: **forward region** along the beam line
  * enormous event rates: σ_{inel} ~ 100mb or $N_\pi \sim 10^{17}$ at $\mathcal{L} = 300$ fb^{-1}
  * highly energetic beam remnants: E ~ TeV
  * low pT ~ Λ_{QCD} → particles are collimated θ ~ Λ_{QCD}/E ~ mrad

Introduction

- We can't place a reasonably-sized detector on the beam line r
  * blocks the proton beams, subject to large radiation

- However, weakly-interacting particles do not interact with ma
  → place detector few 100m away along the "collision axis" aft
  * LHC infrastructure acts and rock act as shielding

- At this location, particles are still highly collimated
  * 100m x mrad ~ 10cm spread in transverse plane



- This motivates small, fast and cheap inexpensive detector
  FASER: Forw**A**rd **S**earch **E**xpe**R**iment at the LHC

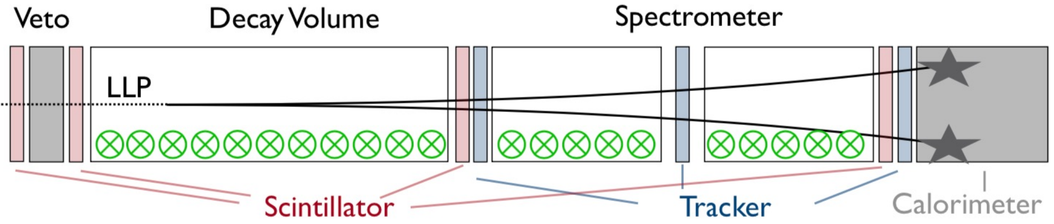
- Applications for light long-lived particles searches and neutrinos

Detector Design

$$pp \to \text{LLP} + X, \quad \text{LLP travels} \sim 480 \text{ m}, \quad \text{LLP} \to \text{charged tracks} + X$$

Features of the Signal:
- two oppositely charged energetic tracks: E>500 GeV
- vertex inside detector volume
- combined momentum points towards IP
- no incoming tracks

Proposed Detector Design:
- FASER needs tracking, charge identification, rough energy estimate, timing
  → tracking based technology, with a magnet, scintillators and a calorimeter

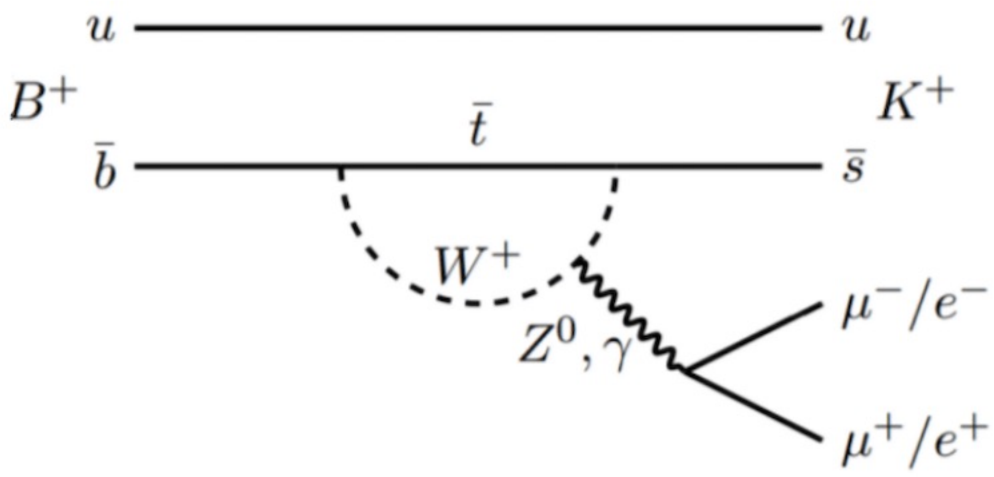


The effective Lagrangian involving CP-odd scalar A and its interaction with SM
be expressed as[2] [14]

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

where $\tilde{F}_{\mu\nu} \equiv 1/2\varepsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$ for completely anti-symmetric symbol $\varepsilon^{\mu\nu\rho\sigma}$, and
similarly. The SM contributions to loop-induced effective couplings, ξ_A^γ and ξ
by [14, 33]

$$\xi_A^g = -\frac{1}{4}\sum_{f\in q} \xi_A^f \mathcal{A}_{1/2}^A(\tau_f^A),$$
$$\xi_A^\gamma = -\frac{1}{2}\sum_{f\in q,\ell} N_c^f Q_f^2 \xi_A^f \mathcal{A}_{1/2}^A(\tau_f^A).$$



The pseudoscalar A shares its quantum numbers with some of the mesons (e.g. π^0, η and η'), which typically induces a mixing among these states as shown in Appendix C. We will still use the notation A to refer to the mass eigenstate which contains mostly of original CP-odd state $A_{\text{CP}-\text{odd}}$ (denoted as A in the Lagrangian of Eq. (3.1)) and can be approximately expressed as:

$$A \approx O_{A\pi^0}\pi^0 + O_{A\eta}\eta + O_{A\eta'}\eta' + O_{AA}A_{\text{CP}-\text{odd}}, \tag{3.4}$$

Here O_{Ai} is the orthogonal transition matrix from gauge state to mass state, whose expressions are given in Appendix C. O_{Ai} are typically small, except in the resonance region when $m_A \sim m_i$ for $i = \pi^0, \eta$, and η'.