Light Scalars @ FASER

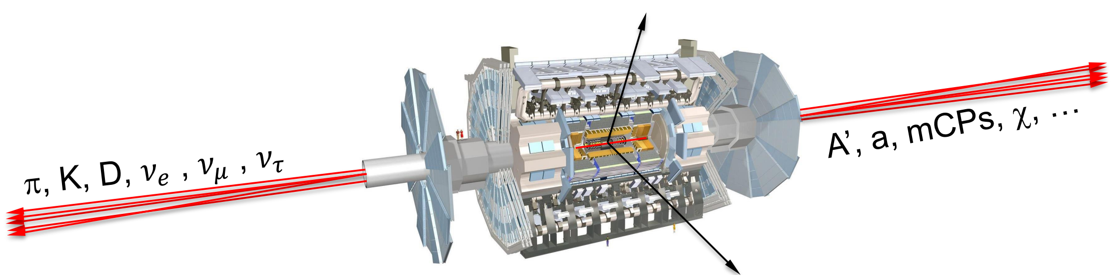
Shufang Su • U. of Arizona

Talk based on work:
2212.06186 (F. Kling, S. Li, H. Song, SS, W. Su)

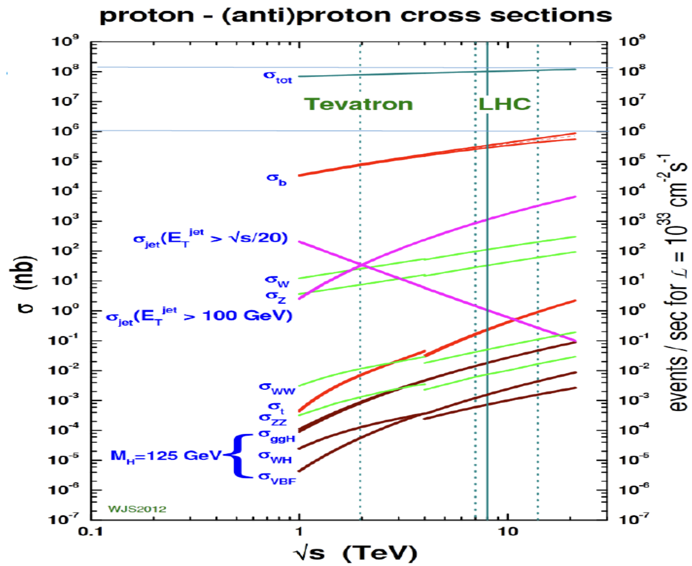
PASCOS
June 30, 2023

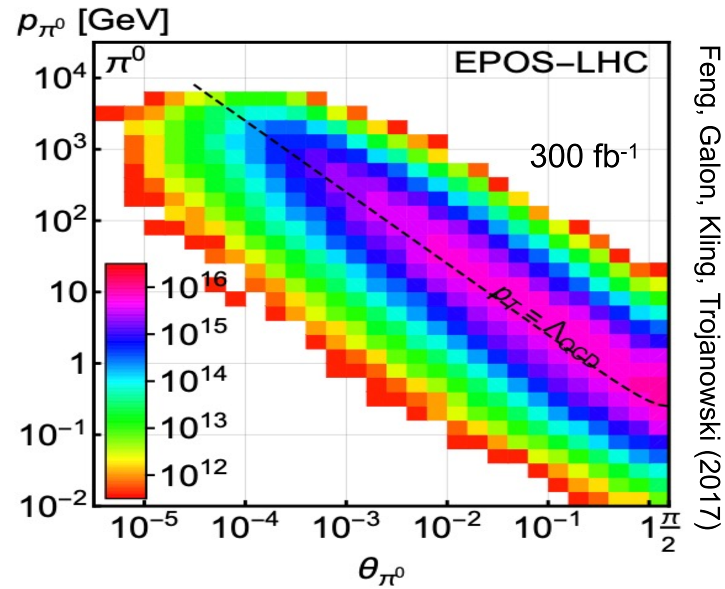
Motivation: FASER Searches

- Traditional resonance searches @ LHC main detector
  prompt decay, EW mass, O(1) couplings
- Long-lived particle (LLP) searches
  ATLAS main detector, MATHUSLA, CodexB, ANUBIS
  particle produced in the transverse region (heavy)
- Light LLP
  ➡ predicted in many new physics scenarios: DM, hidden valley, dark photon, ALP, heavy neutral lepton
  ➡ Current/proposed light LLP searches (low energy): Belle-II, HPS, SHiP, Spinquest/DarkQuest/…
  ➡ Copiously produced in the forward region of colliders



Motivation: Light LLP



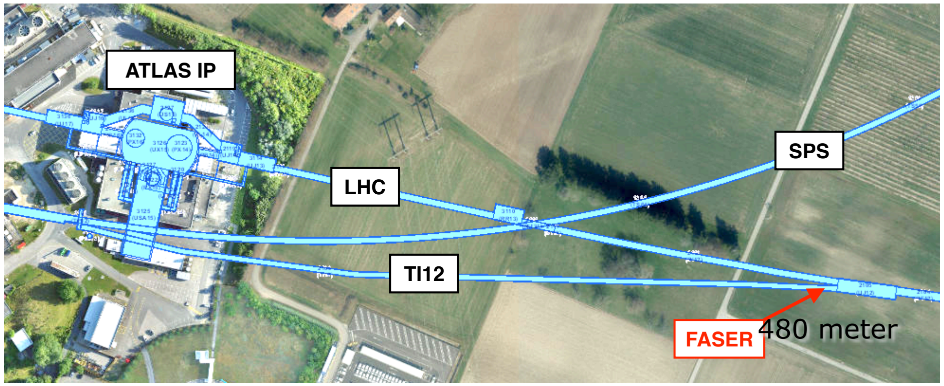


$N_{\pi^0} \approx 4.6 \times 10^{18}, \quad N_\eta \approx 5.0 \times 10^{17}, \quad N_D \approx 2.2 \times 10^{16}, \quad \text{and} \quad N_B \approx 1.4 \times 10^{15}$ LHC 150 fb^{-1}

- light → can be produced in the decay of light SM particles
- weakly interacting → need large numbers
- consider σ_{tot} ~ 100 mb, typically wasted CS for BSM searches
- low p_T~m, possible high p, $\theta \sim p_T/E < 1$ mrad ($\eta > 7.6$)

FASER

Feng, Galon, Kling, Trojanowski, 1708.09389
FASER LOI, 1811.10243
FASER Technical Proposal, 1812.09139
FASER Physics Reach, 1811.12522



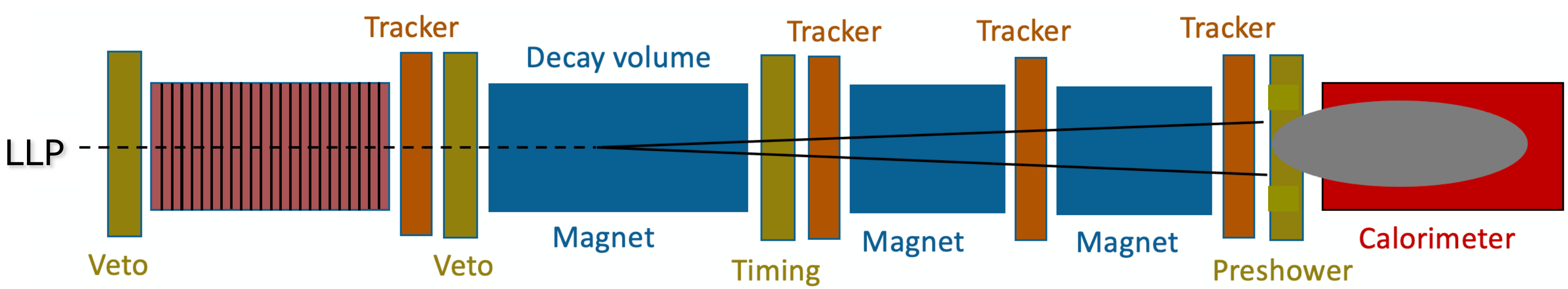
Run: 2021 - 2023

$\mathrm{FASER}: \Delta = 1.5\ \mathrm{m}, \quad R = 10\ \mathrm{cm}, \quad \mathcal{L} = 150\ \mathrm{fb}^{-1}$

Run: 2026 - 2035

$\mathrm{FASER\ 2}: \Delta = 5\ \mathrm{m}, \quad R = 1\ \mathrm{m}, \quad \mathcal{L} = 3\ \mathrm{ab}^{-1}$

10^4 increase in sensitivity

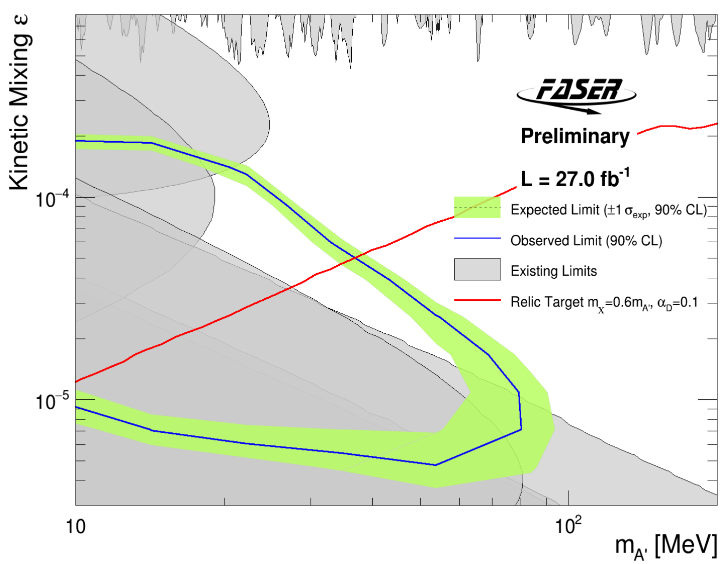


$pp \to \mathrm{LLP} + X, \quad \mathrm{LLP\ travels}\ \sim 480\ \mathrm{m}, \quad \mathrm{LLP} \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots,$

θ~ mrad, Δd~1 mm for 1m long detector
need magnetic field to split the opposite charged tracks.

FASER 1st Physics Result

- signature: 2 oppositely charged tracks or 2 photons with TeV energy from a common vertex inside the detector and combined momentum points back to IP.
- background: negligible after veto (charged particle muon from IP)

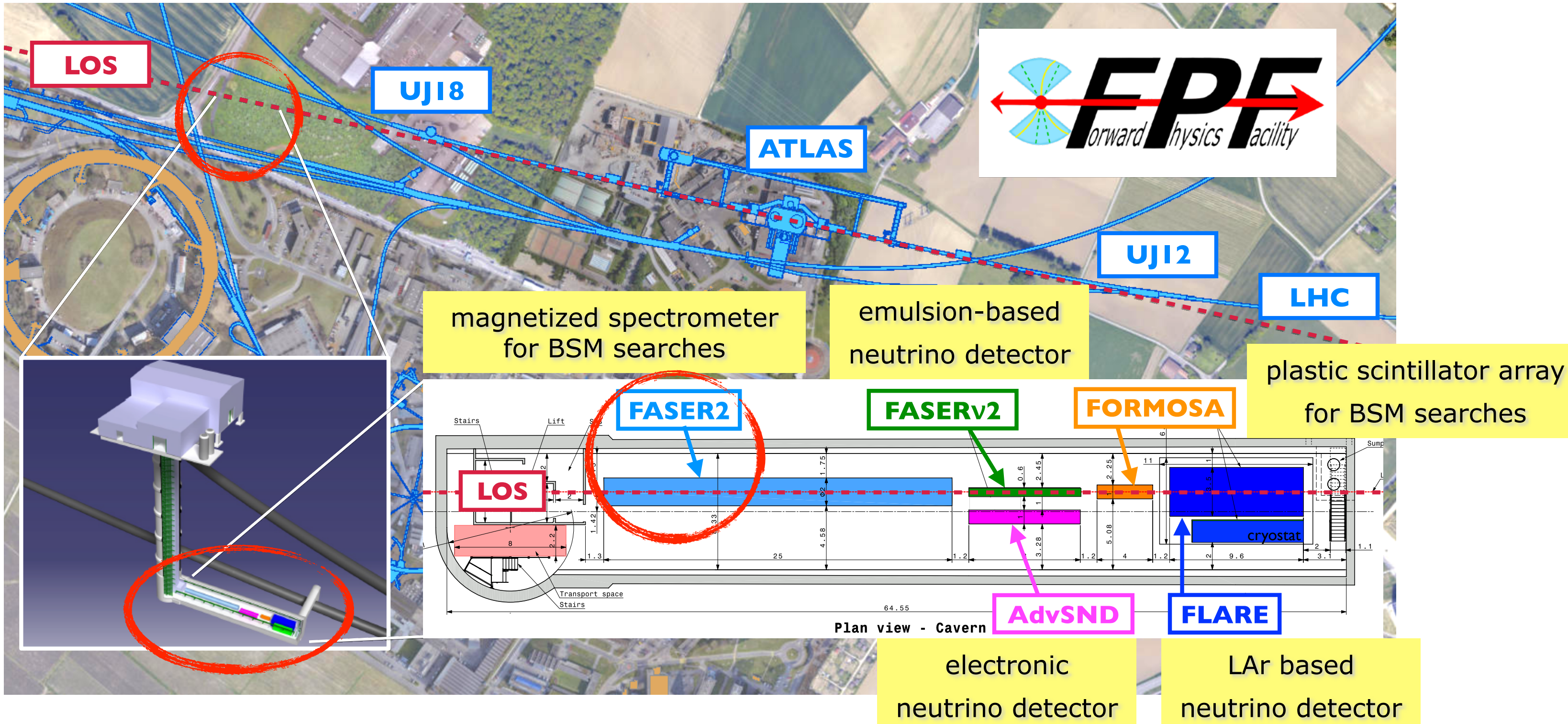


CERN-FASER-CONF-2023-001

- Installed 2021
- Taking data 2022
- No signal observed

FPF

FPF: 2109.10905, 2203.05090



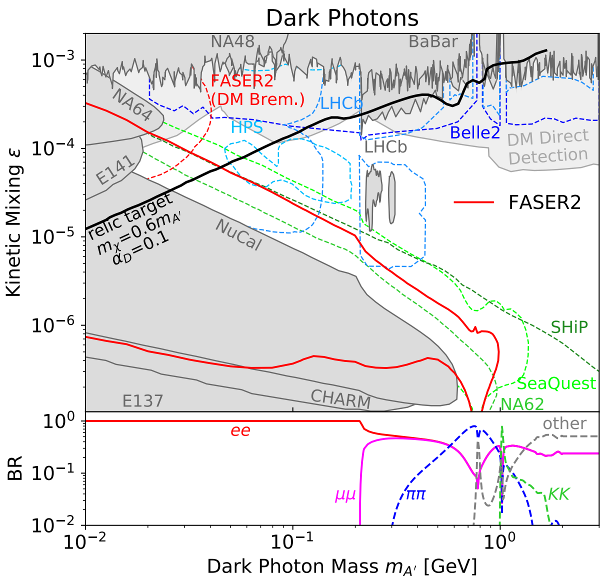
- 600 m west of ATLAS
- Cavern 65m x 9 m
- shield from ATLAS by 200m of rock
- disconnect from LHC tunnel
- vibration, safety studies: construct FPF without disrupt LHC operation
- Radiation studies: work in FPF while LHC is running

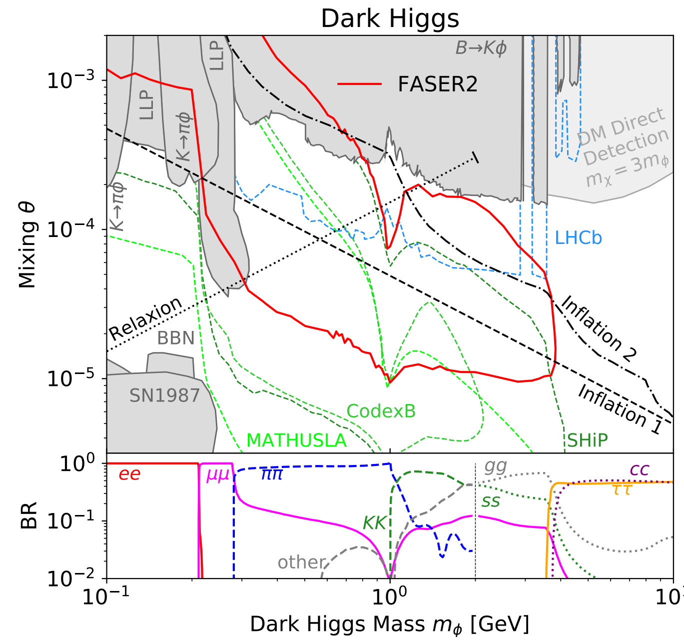
Run: 2026 - 2035

$\text{FASER 2}: \Delta = 5 \text{ m}, \quad R = 1 \text{ m}, \quad \mathcal{L} = 3 \text{ ab}^{-1}$

10^4 increase in sensitivity

FASER Reach





- currently studied (simple) scenario: singlet S mix with SM H mixing angle θ
- all couplings SM structure, scaled with sinθ

Light Scalar LLP

Model-independent framework with the most general interactions for CP-even and CP-odd scalar under EFT/coupling modifier.

- developed general formalism for scalar production and decay
- more complicated comparing to the simplest scenario
- CP-odd A mix with light meson states
- developed a program to calculate scalar decay, can be used for other new physics models.
- case study of 2HDM.

Outline

- Motivation
- Interaction/production/decay
  - ➡ CP-even
  - ➡ CP-odd (special feature due to mixing)
- Type-I 2HDM case study
- Results
- Conclusion

Light CP-even Scalar

Effective Lagrangian

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

$$+\xi_{\phi\phi}^W \frac{g^2}{4}\phi\phi W^{\mu+}W_\mu^- + \xi_{\phi\phi}^Z \frac{g^2}{8\cos^2\theta_W}\phi\phi Z^\mu Z_\mu + \xi_\phi^g \frac{\alpha_s}{12\pi v}\phi G_{\mu\nu}^a G^{a\mu\nu} + \xi_\phi^\gamma \frac{\alpha_{\rm ew}}{4\pi v}\phi F_{\mu\nu}F^{\mu\nu}$$

coupling modifier

loop generated

Production

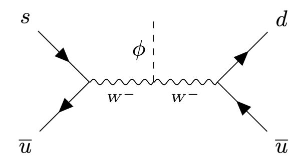
- Decay of hadrons, mesons, radiative bottomium decay
- h/Z/W decay: small in forward region

$$\mathcal{L}_{eff} = \frac{\phi}{v}\sum \xi_\phi^{ij} m_{f_j}\bar{f}_i P_R f_j + h.c.$$

effective coupling for flavor changing quark interactions

ϕ production

- **Heavy B meson decay** $B \to X_s \phi$ ξ_ϕ^{bs}
- **Kaon decay** $K \to \pi \phi$ ξ_ϕ^{ds} ξ_ϕ^{W}



- **$\eta^{(\prime)}$ decay** $\eta^{(\prime)} \to \pi \phi$ $g_{\phi \eta^{(\prime)} \pi}$
- **semileptonic decay of mesons** $X \to \phi e \nu$ ξ_ϕ^{W}
- **radiative bottomium decay** $\Upsilon \to \gamma \phi$ ξ_ϕ^{b}
- **double scalar production** $B \to X_s \phi\phi$ $K \to \pi \phi\phi$

ϕ Decay

Decay into pair of photons, leptons, multiple hadrons/pair of quarks

- Decay into diphotons

$$\Gamma_{\gamma\gamma} = \frac{G_F \alpha_{\rm ew}^2 m_\phi^3}{32\sqrt{2}\pi^3}\left|\xi_\phi^\gamma\right|^2$$

- Decay into dileptons

$$\Gamma_{\ell^+\ell^-} = \frac{G_F m_\phi m_\ell^2 \beta_\ell^3}{4\sqrt{2}\pi}|\xi_\phi^\ell|^2$$

m_ϕ < 2 GeV: dispersive analyses

- Hadronic decay into pions and kaons $\xi_\phi^u \quad \xi_\phi^d \quad \xi_\phi^s \quad \xi_\phi^g$
- Further hadronic decay $\phi \to 4\pi, \eta\eta, KK\pi\pi, \rho\rho \ldots$

m_ϕ > 2 GeV: perturbative spectator model

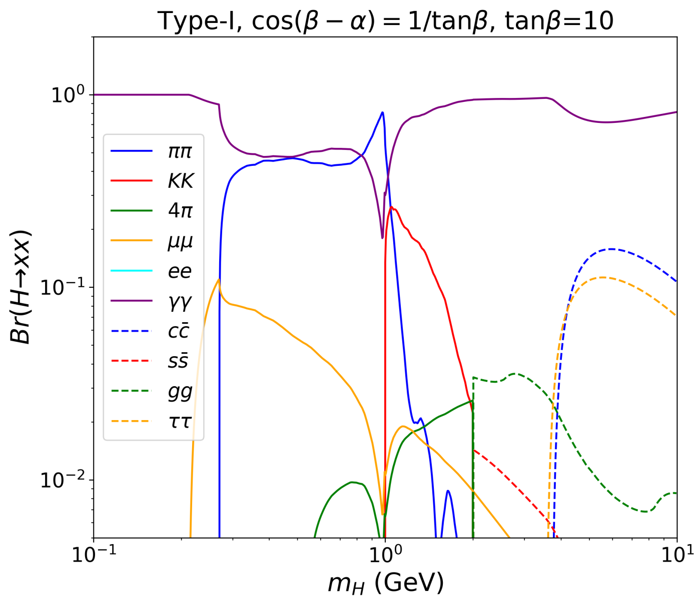
- Decays into quarks

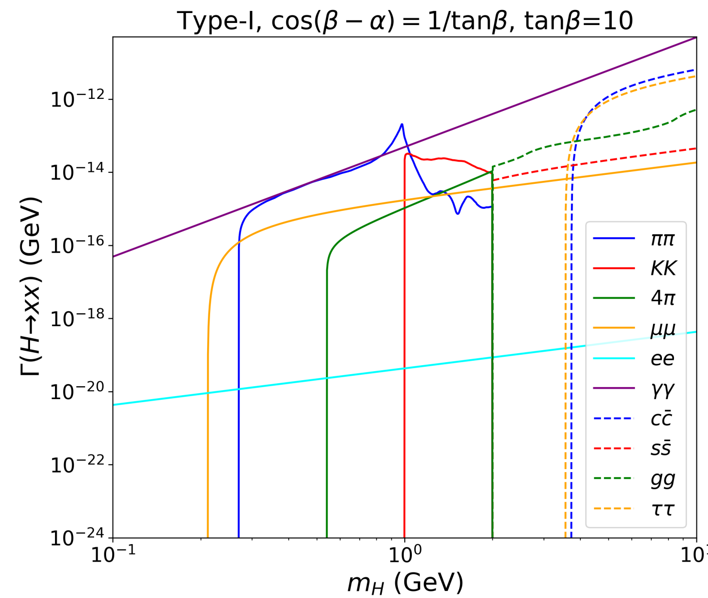
$$\Gamma_{\ell^+\ell^-} : \Gamma_{s\bar{s}} : \Gamma_{c\bar{c}} : \Gamma_{b\bar{b}} = |\xi_\phi^\ell|^2 m_\ell^2 \beta_\ell^3 : 3|\xi_\phi^s|^2 m_s^2 \beta_K^3 : 3|\xi_\phi^c|^2 m_c^2 \beta_D^3 : 3|\xi_\phi^b|^2 m_b^2 \beta_B^3$$

- Decays into gluons

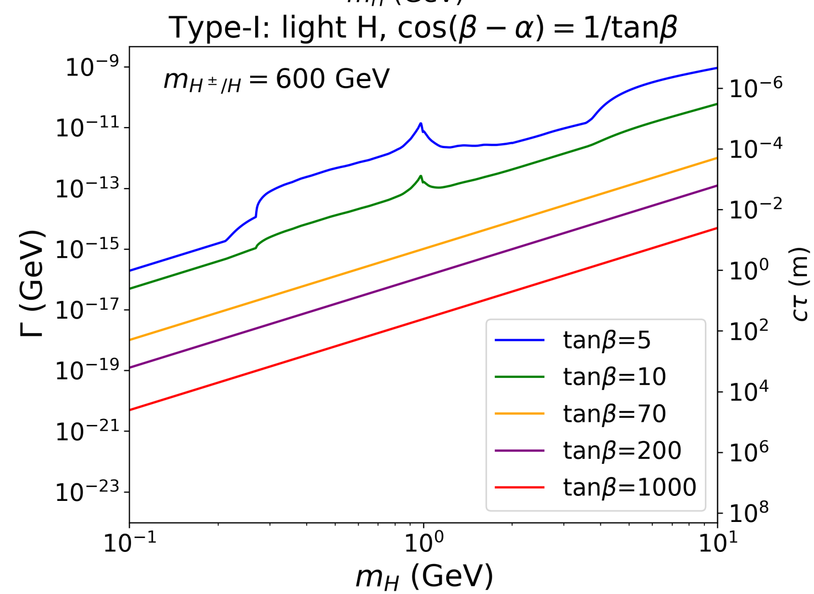
$$\Gamma_{gg} = \frac{G_F \alpha_s^2 m_\phi^3}{36\sqrt{2}\pi^3}|\xi_\phi^g|^2$$

Light CP-even Scalar





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



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Light CP-odd Scalar

Effective Lagrangian

$$\mathcal{L}_A = -\frac{1}{2}m_A^2 A^2 + \sum_{f=u,d,e} \xi_A^f \frac{i m_f}{v} \bar{f}\gamma_5 f A + \xi_{AA}^W \frac{g^2}{4} AAW^{\mu+}W_\mu^- + \xi_{AA}^Z \frac{g^2}{8\cos^2\theta_W} AAZ^\mu Z_\mu$$
$$+\xi_A^g \frac{\alpha_s}{4\pi v} AG_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \xi_A^\gamma \frac{\alpha_{\rm ew}}{4\pi v} AF_{\mu\nu}\tilde{F}^{\mu\nu},$$

loop generated

Mixing effects $A \approx O_{A\pi^0}\pi^0 + O_{A\eta}\eta + O_{A\eta'}\eta' + O_{AA}A_{\rm CP-odd}$

typically small except in the resonant region $m_A \sim m_i$

Production

- production via meson mixing $\sigma_A \approx |O_{A\pi^0}|^2\sigma_{\pi^0} + |O_{A\eta}|^2\sigma_\eta + |O_{A\eta'}|^2\sigma_{\eta'}$
- B meson and kaon decay $K \to \pi A$ $B \to X_s A$ $\mathcal{L}_{eff} = -i\frac{A}{v}\sum \xi_A^{ij} m_{f_j}\bar{f}_i P_R f_j + h.c.$
- radiative bottomium and charmonium decay $\Upsilon \to \gamma A$ $J/\psi \to \gamma A$ ξ_A^b
- double pseudoscalar production $B \to X_s AA$ $K \to \pi AA$

A Decay

Decay into pair of photons, leptons, multiple hadrons/pair of quarks

- Decay into diphotons

$$\Gamma(A \to \gamma\gamma) = \frac{\alpha_{\rm ew}^2 m_A^3}{64\pi^3}\left|O_{AA}C_A^\gamma + O_{A\pi^0}C_{\pi^0}^\gamma + O_{A\eta}C_\eta^\gamma + O_{A\eta'}C_{\eta'}^\gamma\right|^2.$$

- Decay into dileptons

$$\Gamma(A \to \ell^+\ell^-) = \frac{G_F m_A m_\ell^2 \beta_\ell}{4\sqrt{2}\pi}|\xi_A^\ell|^2$$

m_A < 1.3 GeV: chiral perturbation theory

- Hadronic decay into tri-mesons

$$\Gamma(A \to \Pi_i\Pi_j\Pi_k) = \frac{1}{256 S_{ijk}\pi^3 m_A}\int_{(m_j+m_k)^2}^{(m_A-m_i)^2} ds|\mathcal{M}_A^{ijk}|^2 \sqrt{1-\frac{2(m_j^2+m_k^2)}{s}+\frac{(m_j^2-m_k^2)^2}{s^2}} \times \sqrt{\left(1+\frac{s-m_i^2}{m_A^2}\right)^2-\frac{4s}{m_A^2}}$$

$$\mathcal{M}_A^{ijk} \propto O_{AA}\mathcal{A}_A^{ijk} + \sum_l O_{Al}\mathcal{A}^{ijkl}$$

- radiative hadronic decay $A \to \pi^+\pi^-\gamma$

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A Decay

1.3 GeV < m_A < 3 GeV:
spectator model partonic dynamics with hadronic kinematics

- hadronic decay

$$\mathcal{L}_{\text{spect.}} = \frac{i}{\sqrt{2}} A_1 (\mathcal{Y}_u^A \bar{u}\gamma_5 u + \mathcal{Y}_d^A \bar{d}\gamma_5 d + \mathcal{Y}_s^A \bar{s}\gamma_5 s)$$

$$\mathcal{Y}_u^A \approx \frac{\sqrt{2}B}{\sqrt{3} v f_\pi^2} m_u \xi_A^u$$

m_A > 3 GeV: spectator model at parton level

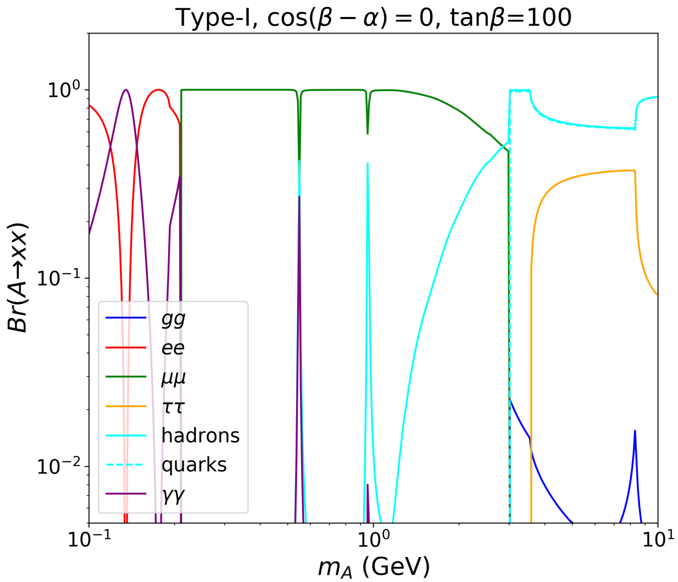
- Decays into quarks

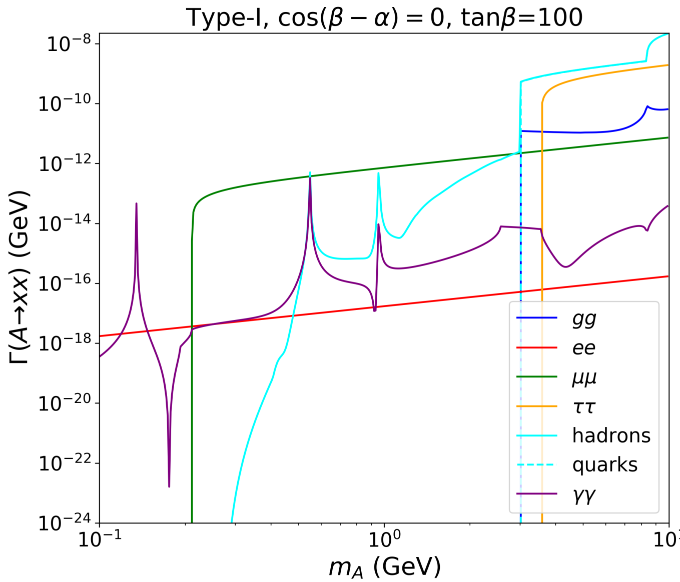
$$\Gamma_{\bar{\ell}\ell} : \Gamma_{\bar{s}s} : \Gamma_{\bar{c}c} : \Gamma_{\bar{b}b} = (\xi_A^\ell)^2 m_\ell^2 \beta_\ell : 3(\xi_A^s)^2 m_s^2 \beta_s : 3(\xi_A^c)^2 m_c^2 \beta_c : 3(\xi_A^b)^2 m_b^2 \beta_b.$$

- Decays into gluons

$$\Gamma(A \to gg) = \frac{G_F \alpha_s^2 m_A^3}{4\sqrt{2}\pi^3} |\xi_A^g|^2$$

Light CP-odd Scalar





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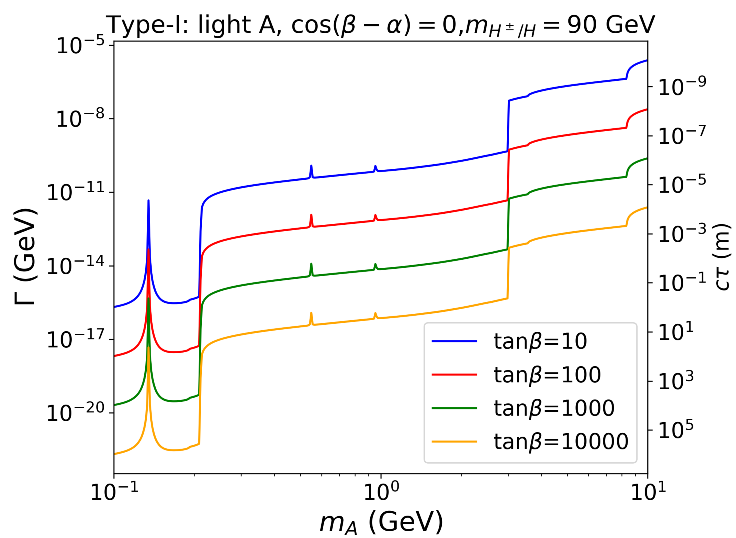

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2HDM

- Two Higgs Doublet Model (CP-conserving)

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

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

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

after EWSB, 5 physical Higgses

CP-even Higgses: h^0, H^0 , CP-odd Higgs: A^0, Charged Higgses: $H^\pm$

- parameters (CP-conserving, flavor limit, Z_2 symmetry)

$$v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$$

soft Z2 breaking: m_{12}^2

Types of 2HDM

- Type I: ϕ_1, quarks and leptons

  all fermion couplings suppressed at large tanβ ⇒ LLP

- Type II, L, F: ϕ_1,ϕ_2 couples to at least one type of quarks or leptons.

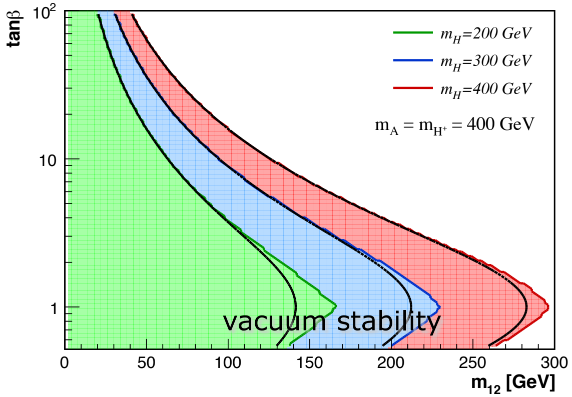
  unsuppressed couplings of scalars to at least one type of fermions for the entire region of tanβ.

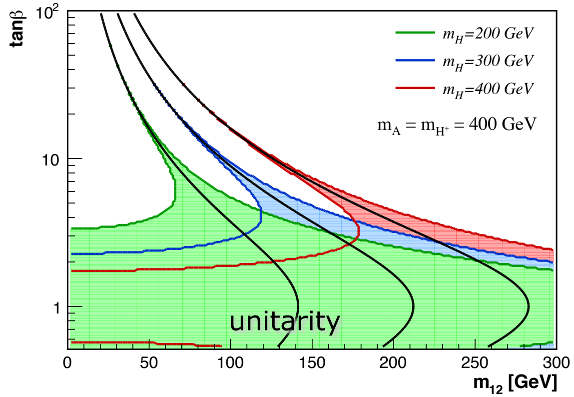
⇒ difficult to realize very weakly coupled long-lived scalars

Alignment limit　　h^0 125 GeV, cos(β-α)~0, H^0 non-SM like

Constraints

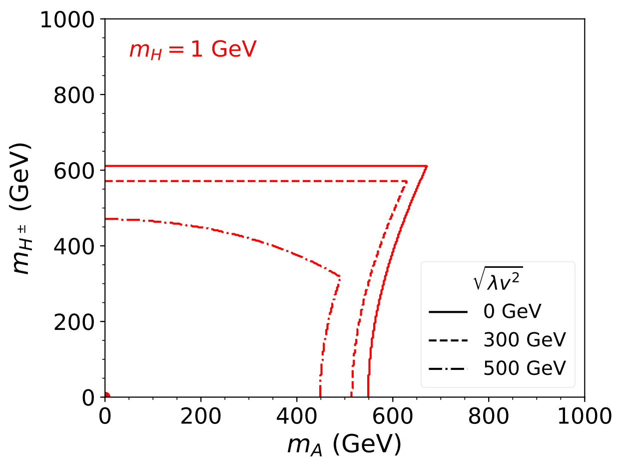
- **Theoretical constraints: unitarity, perturbativity, vacuum stability**

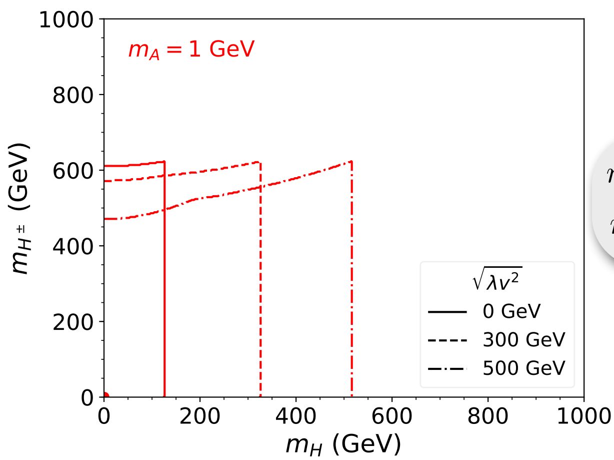




Kling, Miguel No, SS, 1604.01406

$$\lambda v^2 \equiv m_H^2 - \frac{m_{12}^2}{\sin\beta\cos\beta} \approx 0$$



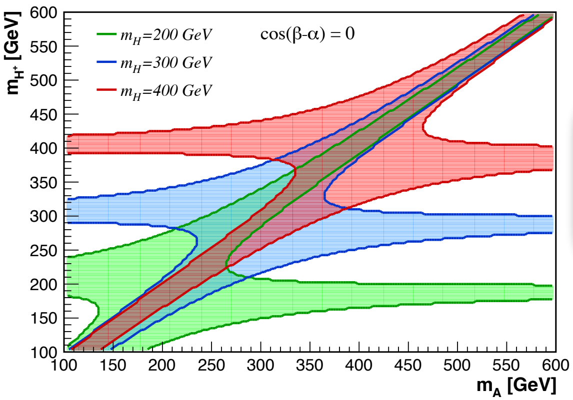


$$m_H \sim 0: \quad m_{A/H^\pm} \lesssim 600 \text{ GeV}$$
$$m_A \sim 0: \quad m_{H^\pm} \lesssim 600 \text{ GeV}, \quad m_H \lesssim m_h$$

Constraints

- **EW precision constraints:**

  $m_{H\pm} \sim m_H$ or m_A

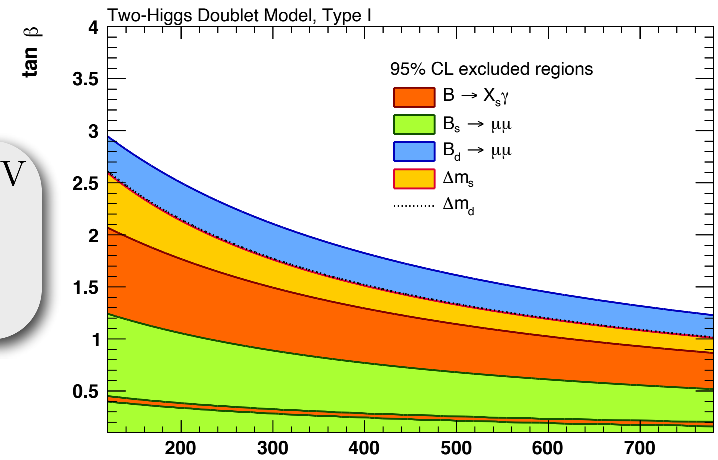


$$m_H \sim 0: \quad m_A \sim m_{H\pm} \lesssim 600 \text{ GeV}$$

$$m_A \sim 0: \quad m_{H\pm} \sim m_H \lesssim m_h,$$

$$\lambda v^2 \approx 0 \quad |\cos(\beta-\alpha)| \sim 0.$$

- **Flavor constraints**



Haller, Hoecher, Kogler, Monig, Peiffer, Stelzer, 1803.01853

- **Invisible Higgs decay** $\text{Br}(h \to \text{invisible}) < 0.24$

$$\text{Br}(h \to HH/AA) \approx \frac{1}{\Gamma_h^{SM}} \frac{g^2_{hHH/hAA}}{8\pi m_h^2}\left(1 - \frac{4m^2_{H/A}}{m_h^2}\right)^{1/2} \simeq 4700 \cdot \left(\frac{g_{hHH/hAA}}{v}\right)^2$$

$$\text{Light } H: \quad \cos(\beta-\alpha) \approx \frac{1}{\tan\beta}$$

$$\text{Light } A: \quad \cos(\beta-\alpha) \approx \frac{1}{\tan\beta}\frac{2m_H^2 - m_h^2}{m_H^2 - m_h^2}$$

exp bound satisfied for

$c_{\beta-\alpha} < 0.25 \qquad \tan\beta > 4$

Benchmarks

Two benchmark scenarios

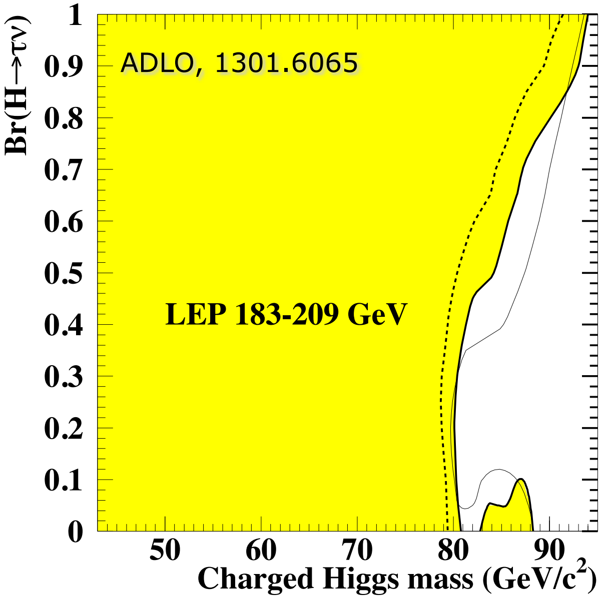
$$\text{Light } H: \quad \cos(\beta-\alpha) = \frac{1}{\tan\beta}, \; m_A = m_{H^\pm} = 600 \text{ GeV}, \; \lambda v^2 = 0$$

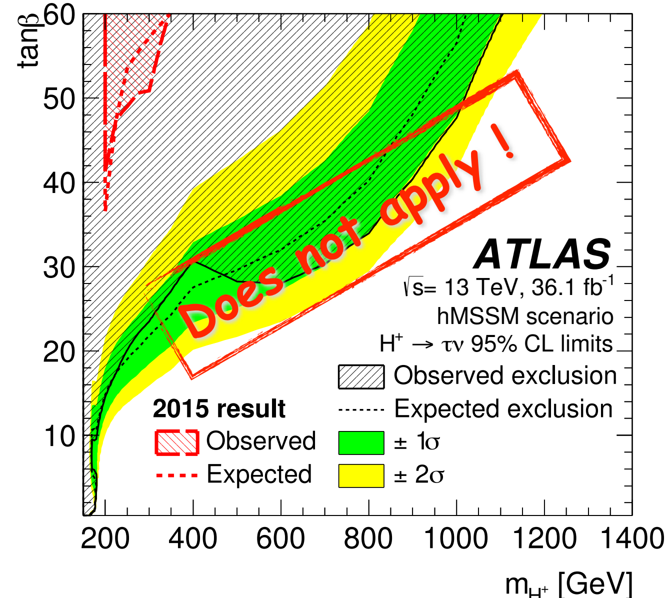
$$\text{Light } A: \quad \cos(\beta-\alpha) = 0, \; m_H = m_{H^\pm} = 90 \text{ GeV}, \; \lambda v^2 = 0 \;,$$

LEP $H^\pm$ search:

$m_{H\pm}$ > 85 GeV viable

LHC $H^\pm$ search





ATLAS, 1807.07915

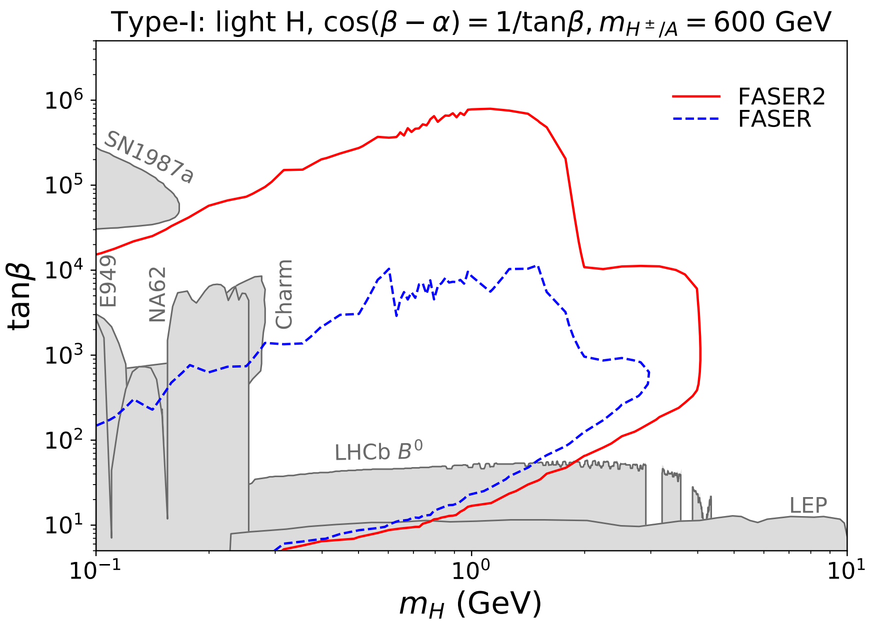
Constraints

Other light scalar searches

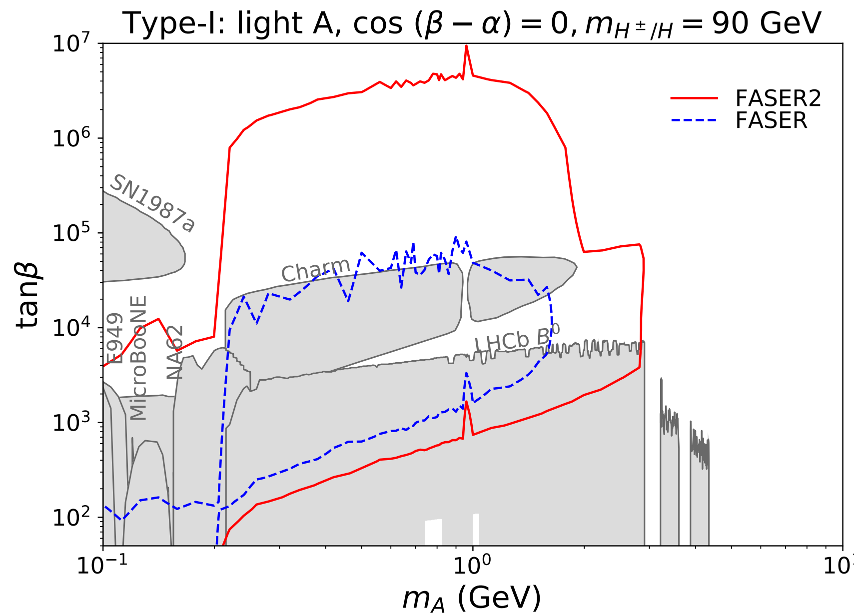
- CHARM bounds: light ALP — CHARM, PLB 157 (1985) 458
- Supernova $NN \to NNS(A)$ — Turner, PRL 60 (1988) 1797
- B meson decays: LHCb $B \to K^* \phi$ — LHCb, 1508,04094, 1612.07818
- kaon decays: NA62, MicroBooNE, E949 $K^+ \to \pi^+ X$ — NA62, 2103.15389; MicroBooNE, 2106.00568; BNL-E949, 0903.0030
- D meson decays: LHCb — PDG, LHCb, 2011.00217
- LEP: $e^+e^- \to Z^* \phi$ — Winkler, 1809.01876; Clarke, Foot, and Volkas, 1310.8042

Light Scalar

CP-even



CP-odd



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

Conclusion

- light LLP appear in many new physics scenario
- light particle copiously produced in the forward region of LHC
- FASER/FASER2: new experiments to detect light LLP
- light CP-even and CP-odd scalar
  - ➡ model-independent framework, coupling modified in EFT
  - ➡ scalar production and decay (hadronic)
  - ➡ general program to calculate decay
- 2HDM case study: large tanβ region of Type-I 2HDM
  - ➡ decay length: 10^{-8} to 10^{5} m, probe very large tanβ
  - ➡ FASER2 vs. FASER: more Lum, larger detector.
- Complementary to LHC prompt search, LLP search in transverse region, and fixed target exp at low energies