Light Scalars at FASER

FPF Theory Workshop

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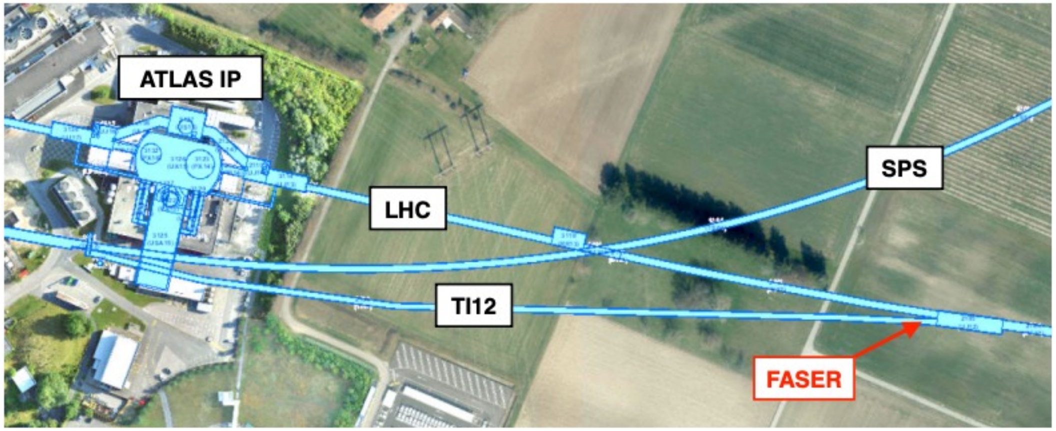
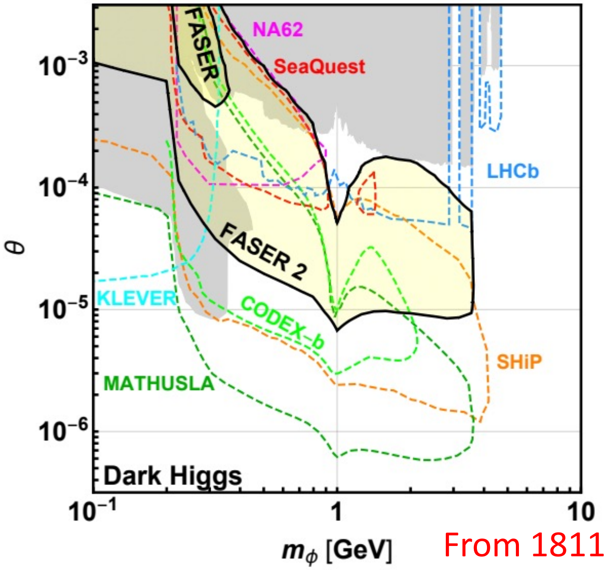
Light Scalars @ FASER

Many Beyond Standard Models including extended Higgs sector permit the light and weakly coupled scalars, such as Dark Higgs (SM+Singlet), 2HDM, 2HDM+(P)S, NMSSM, ….

Simplest prototype model:
Dark Higgs

$$\mathcal{L} = -m_\phi^2 \phi^2 - \sin\theta \frac{m_f}{v} \phi \bar{f} f - \lambda v h \phi\phi + \dots$$





From 1811.12522

Light Scalars @ FASER

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

Light CP-even Scalar

Effective Lagrangian

$$\mathcal{L} = -\frac{1}{2}m_\phi^2\phi^2 - \sum_f \xi_\phi^f \frac{m_f}{v}\phi \bar{f} f + \xi_\phi^W \frac{2m_W^2}{v}\phi W^{\mu+}W_\mu^- + \xi_\phi^Z \frac{m_Z^2}{v}\phi Z^\mu Z_\mu$$
$$+ \xi_{\phi\phi}^W \frac{g^2}{4}\phi\phi W^{\mu+}W_\mu^- + \xi_{\phi\phi}^Z \frac{g^2}{8\cos^2\theta_W}\phi\phi Z^\mu Z_\mu + \xi_\phi^g \frac{\alpha_s}{12\pi v}\phi G_{\mu\nu}^a G^{a\mu\nu} + \xi_\phi^\gamma \frac{\alpha_{ew}}{4\pi v}\phi F_{\mu\nu}F^{\mu\nu}$$

coupling modifiers

loop generated

Production

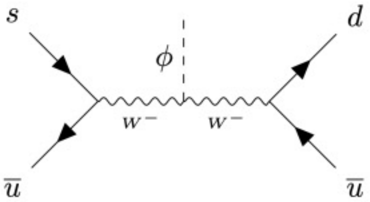
- **decay of mesons, hadrons, radiative bottomonium**
- **Bremsstrahlung: small for high beam energies**
- **photon/gluon fusion: smaller, small in forward region**
- **h/Z/W decay: small in forward region**

$$\mathcal{L}_{eff} = \frac{\phi}{v}\sum \xi_\phi^{ij} m_{f_j} \bar{f}_i P_R f_j + h.c. \qquad \mathcal{L} \supset \xi_{\phi\phi}^{ij} \frac{\phi^2}{v^2} m_j \bar{f}_i P_R f_j + h.c.$$

effective coupling for flavor changing quark interactions

ϕ Production

- **Heavy B meson decay** $B \to X_s \phi$ ξ_ϕ^{bs}
- **Semileptonic decay of mesons** $X \to \phi e \nu$ ξ_ϕ^{W}
- **Kaon decay** $K \to \pi \phi$ ξ_ϕ^{ds} ξ_ϕ^{W}



- **$\eta^{(\prime)}$ decay** $\eta^{(\prime)} \to \pi \phi$ $g_{\phi \eta^{(\prime)} \pi}$
- **Radiative bottomonium decay** $\Upsilon \to \gamma \phi$ ξ_ϕ^{b}
- **Double scalar procution** $B \to X_s \phi\phi$ $K \to \pi \phi\phi$ $\xi_{\phi\phi}^{ij}$

ϕ Decay

Decay into a pair of photons, leptons, pair of quarks (gluons)/multiple hadrons

- **Decay into diphoton** $\Gamma_{\gamma\gamma} = \frac{G_F \alpha_{\rm ew}^2 m_\phi^3}{32\sqrt{2}\pi^3} \left|\xi_\phi^\gamma\right|^2$
- **Decay into dilepton** $\Gamma_{\ell^+\ell^-} = \frac{G_F m_\phi m_\ell^2 \beta_\ell^3}{4\sqrt{2}\pi} |\xi_\phi^\ell|^2$

$m_\phi > 2$ GeV: perturbative spectator model

- **Decay into diquark** $\Gamma_{\ell^+\ell^-} : \Gamma_{s\bar{s}} : \Gamma_{c\bar{c}} : \Gamma_{b\bar{b}} = |\xi_\phi^\ell|^2 m_\ell^2 \beta_\ell^3 : 3|\xi_\phi^s|^2 m_s^2 \beta_K^3 : 3|\xi_\phi^c|^2 m_c^2 \beta_D^3 : 3|\xi_\phi^b|^2 m_b^2 \beta_B^3$
- **Decay into digluon** $\Gamma_{gg} = \frac{G_F \alpha_s^2 m_\phi^3}{36\sqrt{2}\pi^3} |\xi_\phi^g|^2$

$m_\phi < 2$ GeV: dispersive analyses

- **Hadronic decay into pions and kaons** $\Gamma_\pi \quad \Delta_\pi \quad \Theta_\pi$ $\quad \xi_\phi^u \quad \xi_\phi^d \quad \xi_\phi^s \quad \xi_\phi^d$
- **Further hadronic decays** $\phi \to 4\pi, \eta\eta, KK\pi\pi, \rho\rho \ldots$ $\quad \Gamma_{4\pi,\eta\eta,\rho\rho,\ldots} = C \left|\xi_\phi^g\right|^2 m_\phi^3 \beta_{2\pi}$

Light CP-odd Scalar

Effective Lagrangian

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

loop generated

coupling modifiers

Mixing

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

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** $K \to \pi A \quad B \to X_s A \qquad \xi_A^{ij}$
- **Bottomonium decay** $\Upsilon \to \gamma A \quad J/\psi \to \gamma A \qquad \xi_A^f$
- **Double pseudoscalar production** $B \to X_s AA \qquad K \to \pi AA \qquad \xi_{AA}^{ij}$

A Decay

Decay into a pair of photons, leptons, pair of quarks (gluons)/multiple hadrons

- **Decay into diphoton**

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

- **Decay into dilepton**

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

$m_A > 3$ GeV: perturbative spectator model

- **Decay into diquark**

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

- **Decay into digluon**

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

1.3 GeV $< m_A <$ 3 GeV: spectator model with partonic dynamic and hadronic kinematics

- **Hadronic decay**

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

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

A Decay continued

$m_A < 1.3$ GeV: chiral perturbation theory

- **Hadronic decay into tri-meson**

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

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

- **Radiative hadronic decay**

$$A \to \pi^+ \pi^- \gamma$$

$$\Gamma(A \to \pi^+\pi^-\gamma) = \int_{4m_\pi^2}^{m_A^2} ds \Gamma_0(s) |O_{A\eta} B_\eta(s) + O_{A\eta'} B_{\eta'}(s)|^2$$

2HDM

Two Higgs Doublet Model (CP-conserving): $\phi_{1,2}$

After EWSB, 5 physical Higgses:
CP-even Higgses: h, H, CP-odd Higgs: A, 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 Z_2 breaking: m_{12}^2

Alignment limit: h is 125 GeV Higgs, $\cos(\beta-\alpha) \sim 0$

- Type I: ϕ_1 couples quarks and leptons
  all fermion couplings suppressed at large $\tan\beta \Longrightarrow$ LLP
- Type II, L, F: $\phi_{1,2}$ 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 $\tan\beta \Longrightarrow$ difficult to realize very weakly coupled long-lived scalars

constraints

- Theoretical constraints: unitarity, perturbativity, vacuum stability
- EW precision constraints
- Flavor constraints
- Invisible Higgs decay
- LEP & LHC $H^{\pm}$ search

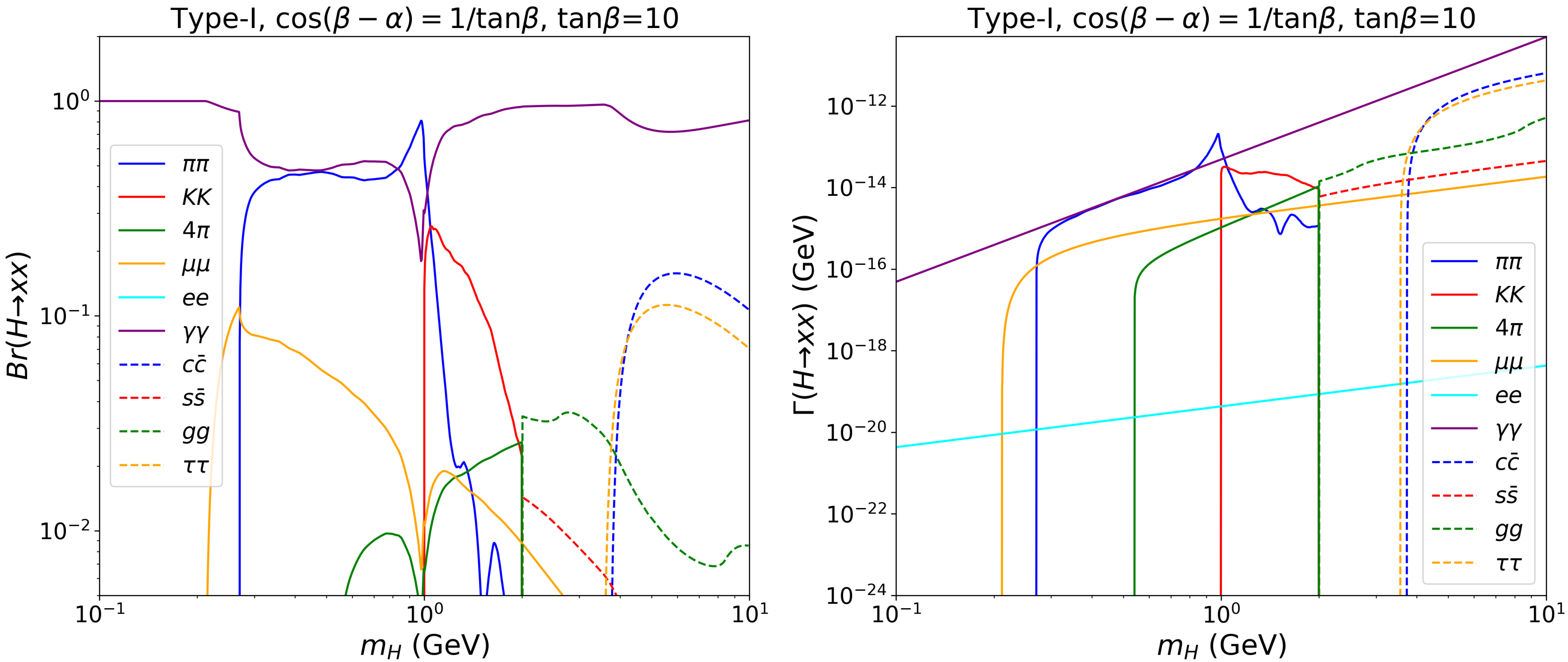
Two benchmark scenarios

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

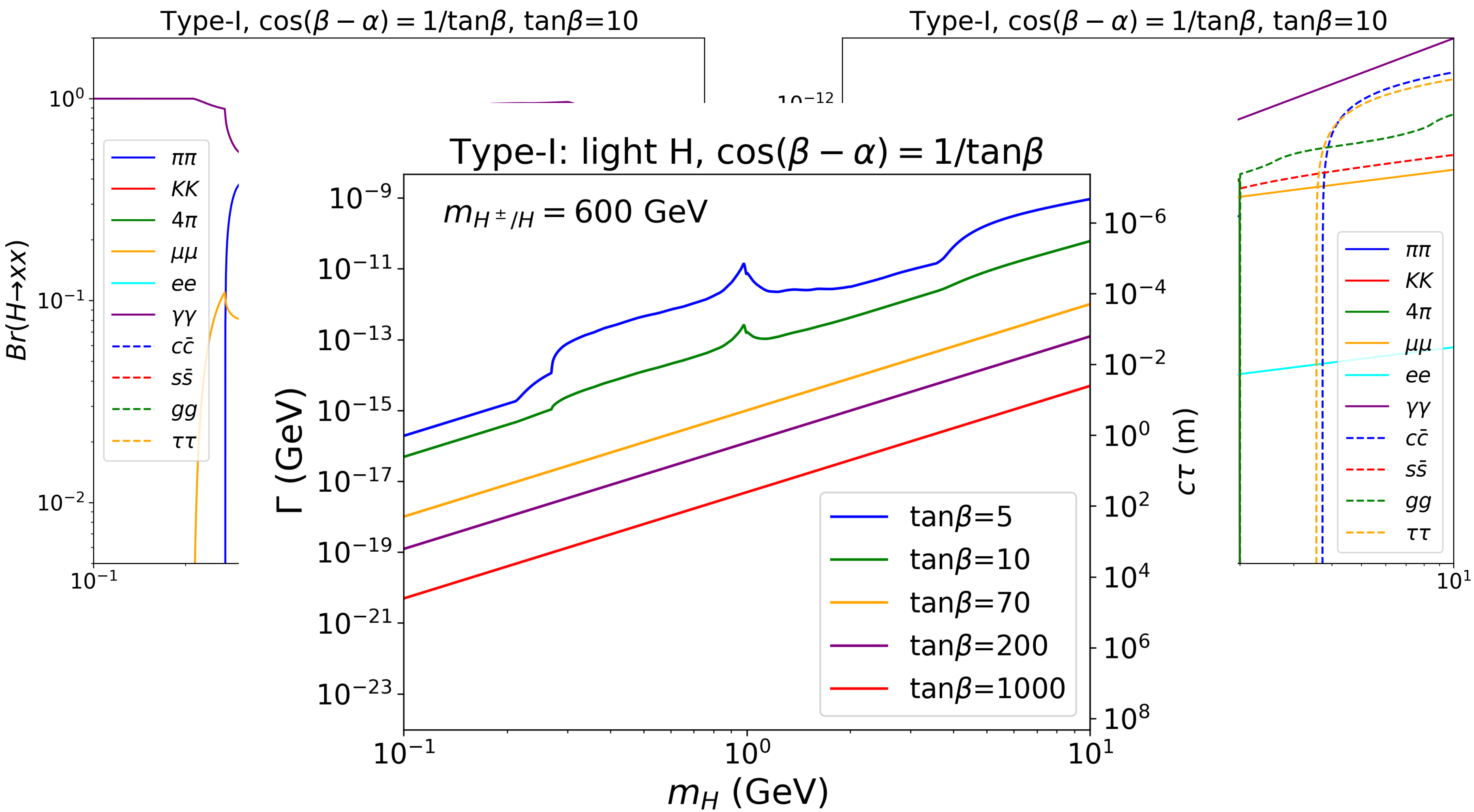
$$\text{Light } A: \quad \cos(\beta-\alpha) = 0, \; m_H = m_{H^\pm} = 90 \text{ GeV}, \; \lambda v^2 = 0 \; ,$$

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

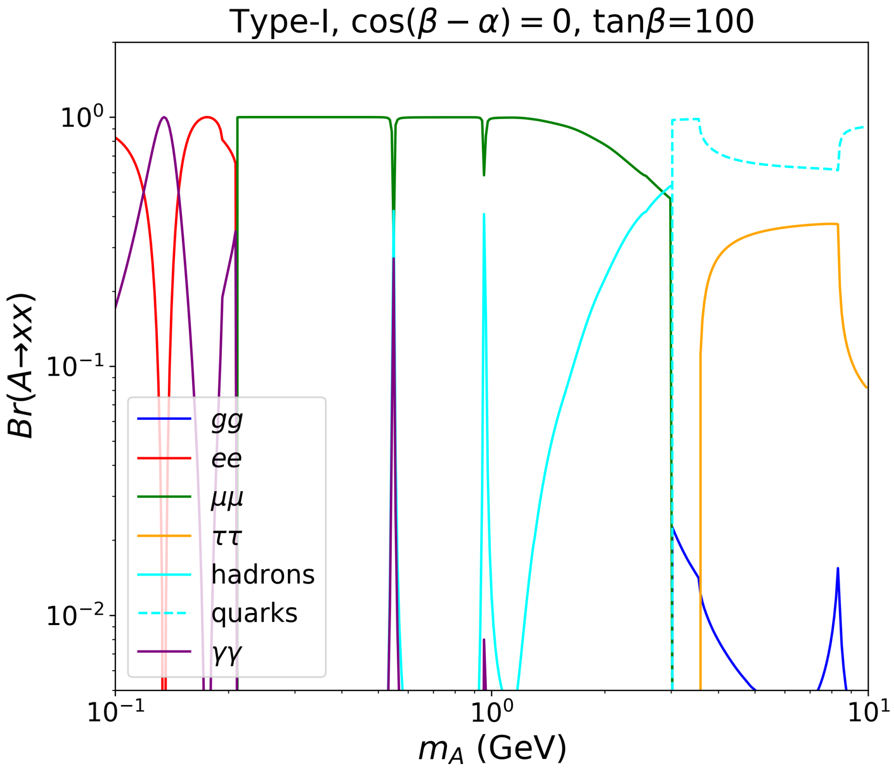
Light CP-even Scalar

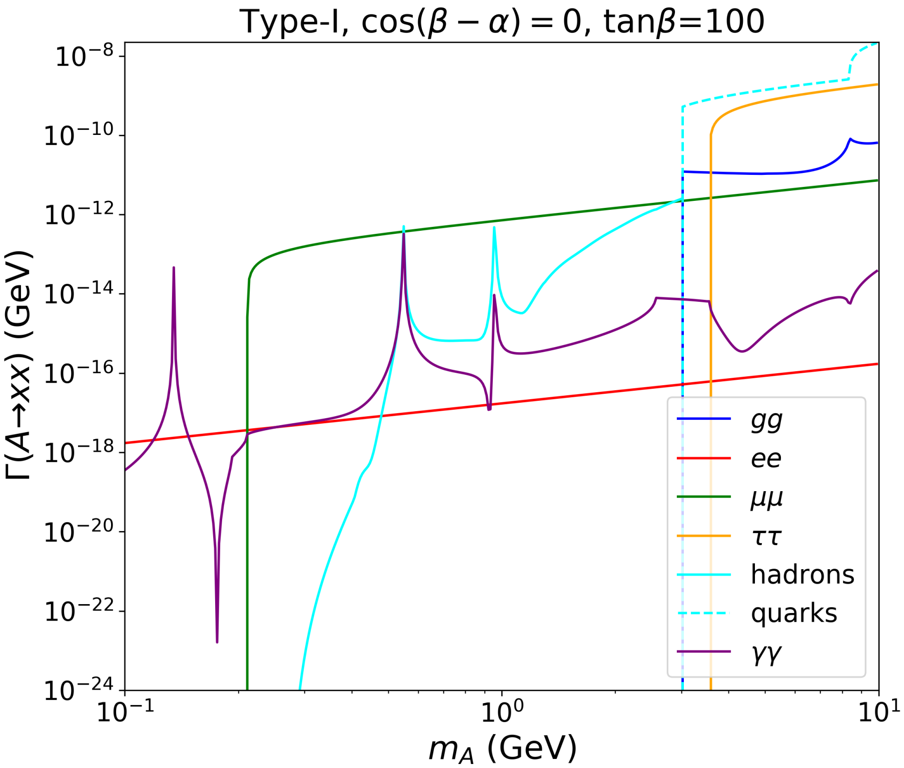


Light CP-even Scalar

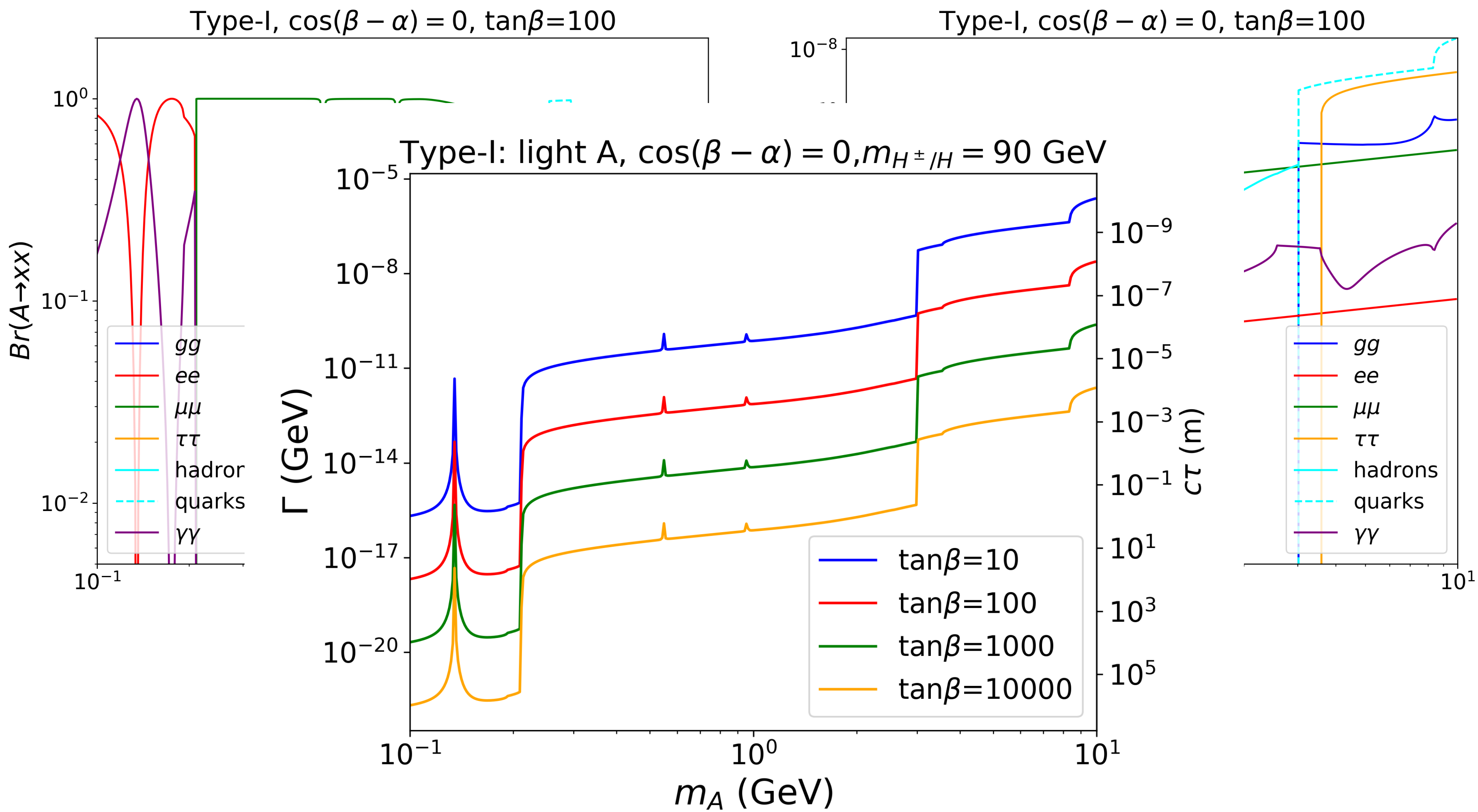


Light CP-odd Scalar





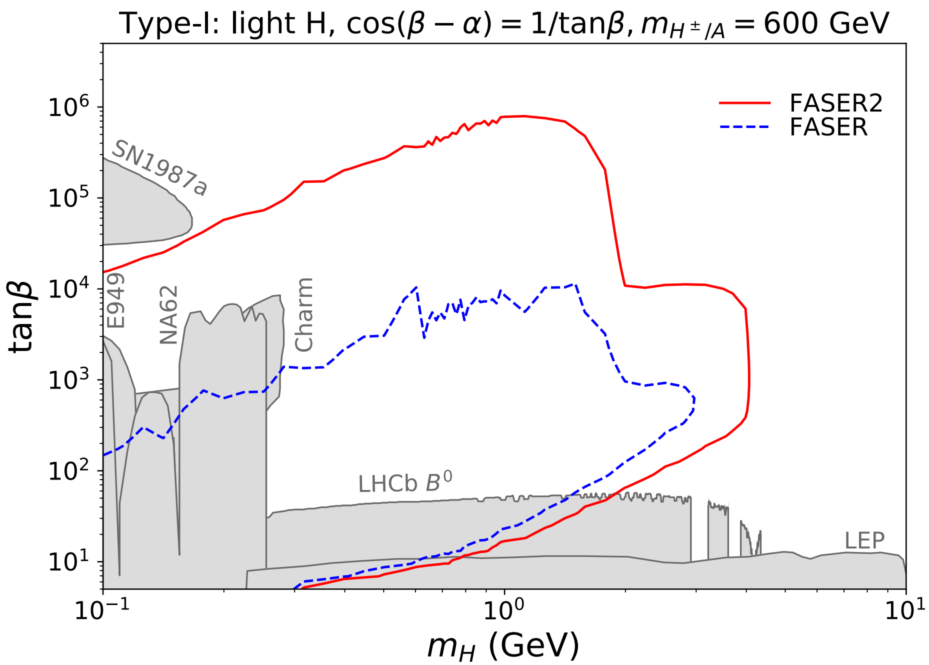
Light CP-odd Scalar

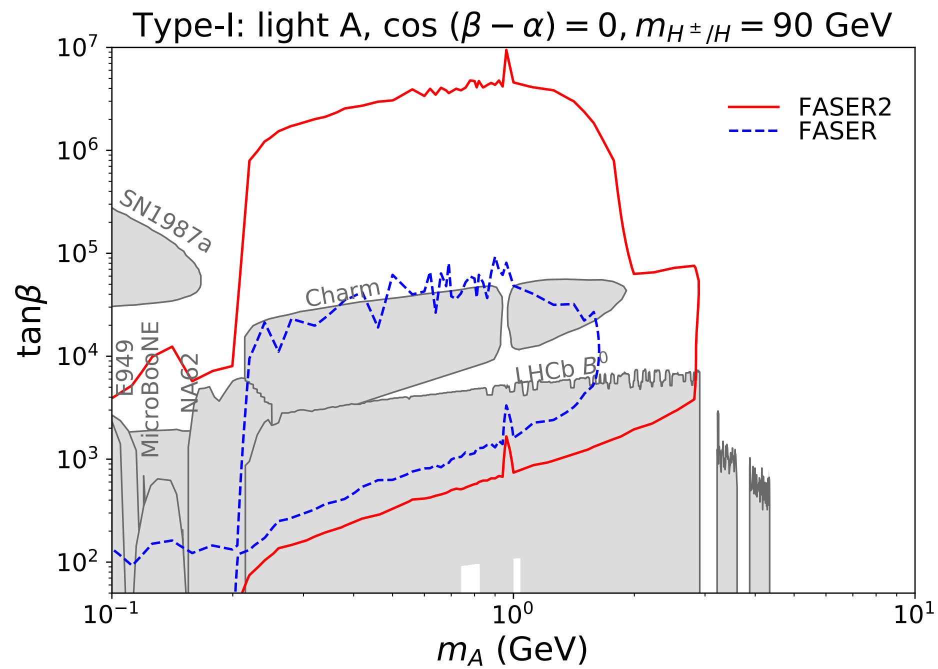


Other constraints on Light Scalar Searches

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

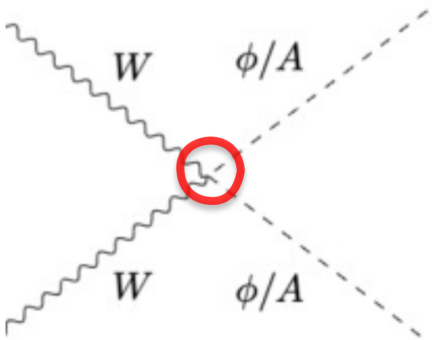
Light Scalars Reaches at FASER





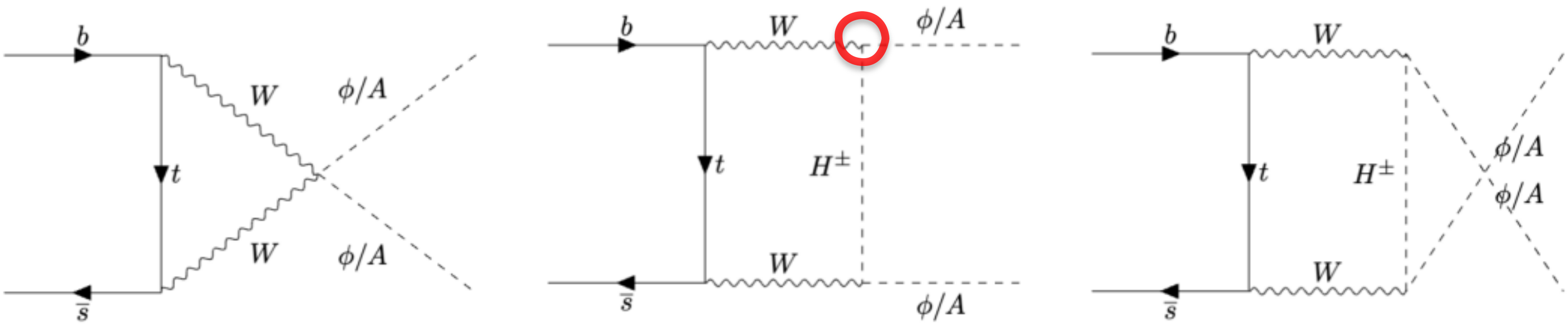
$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta,$$
$$\xi_H^V = c_{\beta-\alpha} = 1/\tan\beta,$$
$$\xi_H^f = c_{\beta-\alpha}(1 - s_{\beta-\alpha}) \approx 1/(2\tan^3\beta) + \mathcal{O}(c_{\beta-\alpha}^5)$$

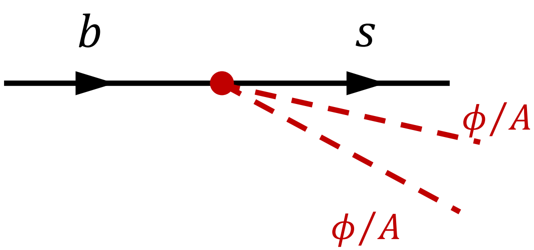
Double Scalar Production



$\sim g^2$

Governed by gauge symmetry and not suppressed





$$\mathcal{L} \supset \xi^{ij}_{\phi\phi} \frac{\phi^2}{v^2} m_j \bar{f}_i P_R f_j + \xi^{ij}_{AA} \frac{A^2}{v^2} m_j \bar{f}_i P_R f_j + h.c.$$

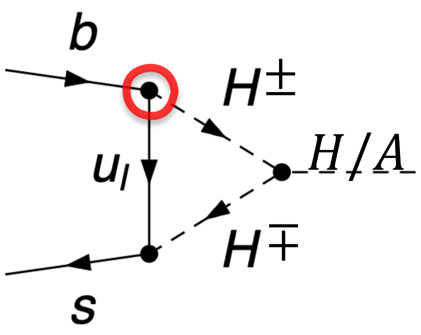
conclusion

- Light LLP appear in many new physics scenarios
- Light particle copiously produced in the forward region of LHC, and FASER/FASER2 (FPF): new experiments to detect light LLP
- Light (pseudo)scalar
  - Model-independent framework, coupling modified in EFT
  - Scalar production and decay (hadronic)
  - Public code to calculate decay (https://github.com/shiggs90/Light_scalar_decay.git)
- 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: higher Lum, larger detector
- Complementary to LHC prompt search, LLP search in transverse region, and fixed target exp at low energies, or other astrophysical processes (e.g. supernova)

Backup Slides

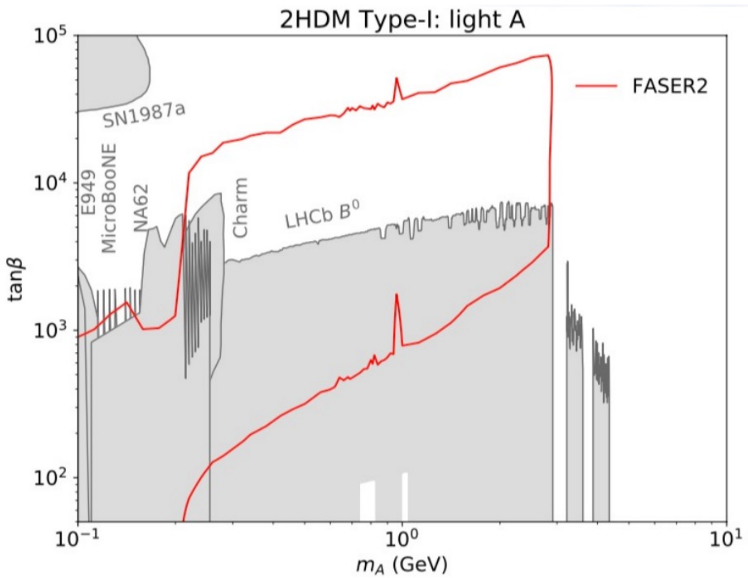
Without Double Scalar Production

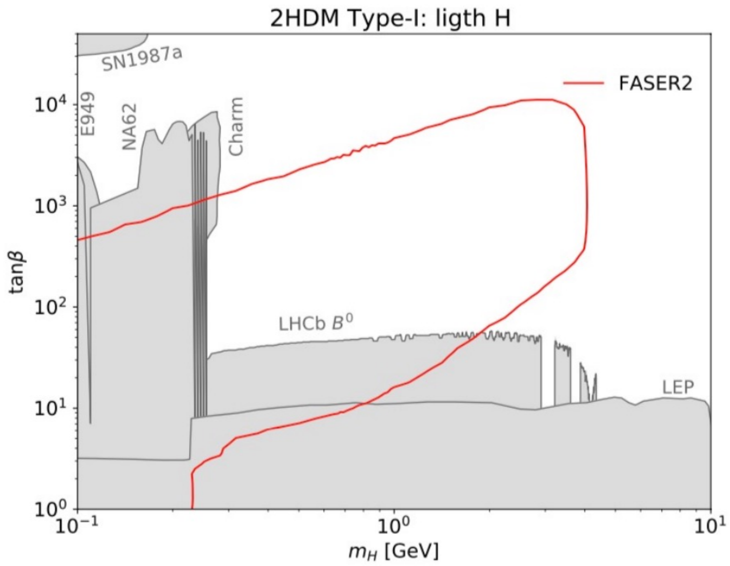
In Type-I 2HDM



$\sim \tan^{-1}\beta$

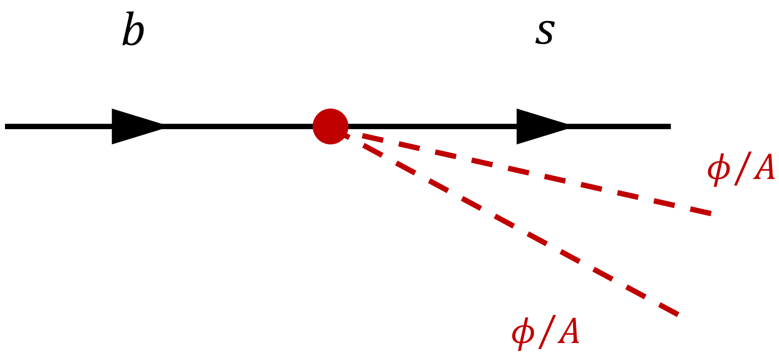
Similar to mimimal model (Dark Higgs)





Effective couplings

In Type-I 2HDM



$$\mathcal{L} \supset \xi^{ij}_{\phi\phi} \frac{\phi^2}{v^2} m_j \bar{f}_i P_R f_j + \xi^{ij}_{AA} \frac{A^2}{v^2} m_j \bar{f}_i P_R f_j + h.c.$$

$$s^2 H^{\dagger i} (d_{cp}{}^a Q_{r\,ai})$$

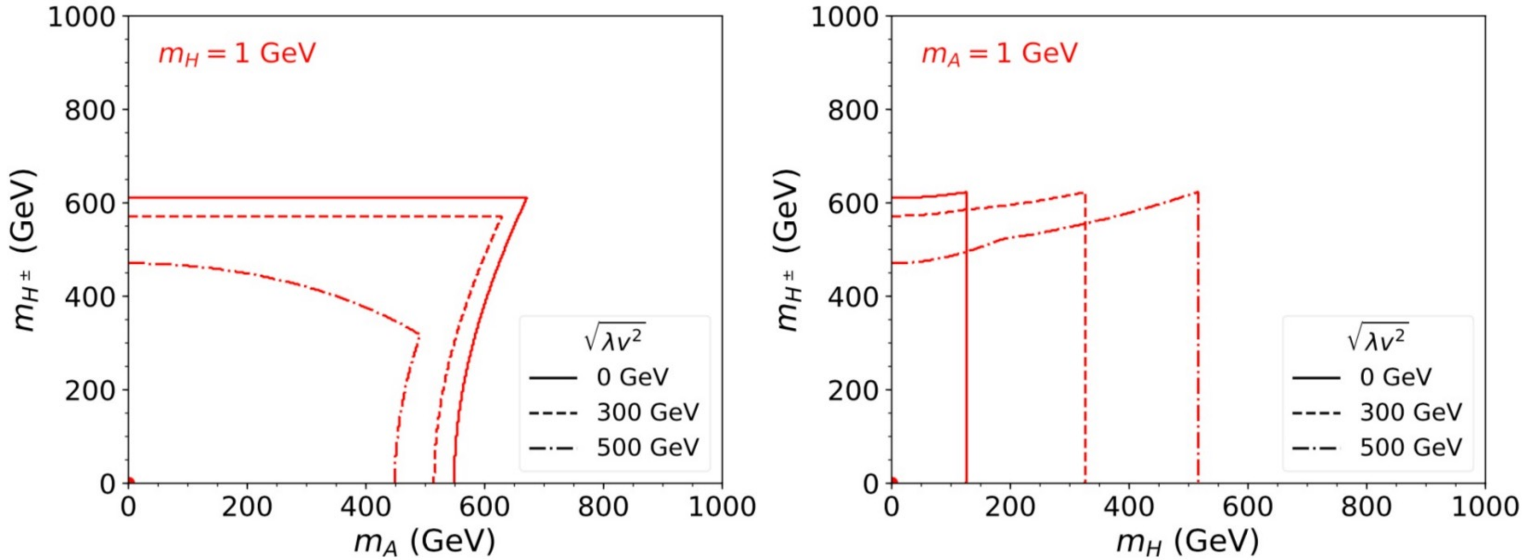
HS, Sun, Yu [2306.05999]
HS, Sun, Yu [2305.16770]

$$\xi^{ij}_{\phi\phi} \simeq \xi^{ij}_{AA} \simeq \frac{g^2}{64\pi^2} \sum_k V^*_{ki} \left[f_0(x_k, x_{H^\pm}) + f_1(x_k, x_{H^\pm}) \log x_k \right.$$
$$\left. + f_2(x_k, x_{H^\pm}) \log x_{H^\pm} \right] V_{kj} + \mathcal{O}(\cos(\beta - \alpha), 1/\tan\beta)$$

constraints

Theoretical constraints

$$\lambda v^2 \equiv m_H^2 - m_{12}^2/s_\beta c_\beta = 0$$



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

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

constraints

Invisible Higgs decays

$$\mathrm{Br}(h \to \phi\phi) = \frac{\Gamma(h \to \phi\phi)}{\Gamma_h} \approx \frac{1}{\Gamma_h^{\mathrm{SM}}} \frac{g_{h\phi\phi}^2}{8\pi m_h^2} \left(1 - \frac{4m_H^2}{m_h^2}\right)^{1/2} \simeq 4700 \cdot \left(\frac{g_{h\phi\phi}}{v}\right)^2 \quad < 0.24$$

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

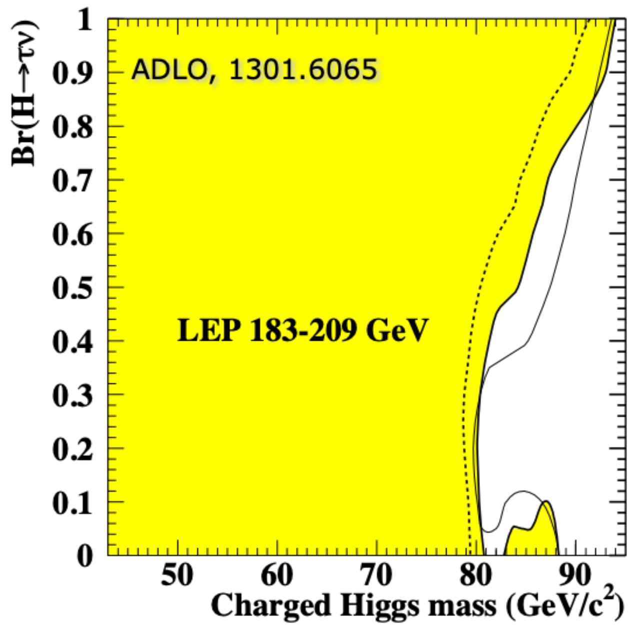
$$Light\ H : \cos(\beta - \alpha) = \tan 2\beta \frac{2\lambda v^2 + m_h^2}{2(m_H^2 - 3\lambda v^2 - m_h^2)} \approx \frac{1}{\tan\beta},$$

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

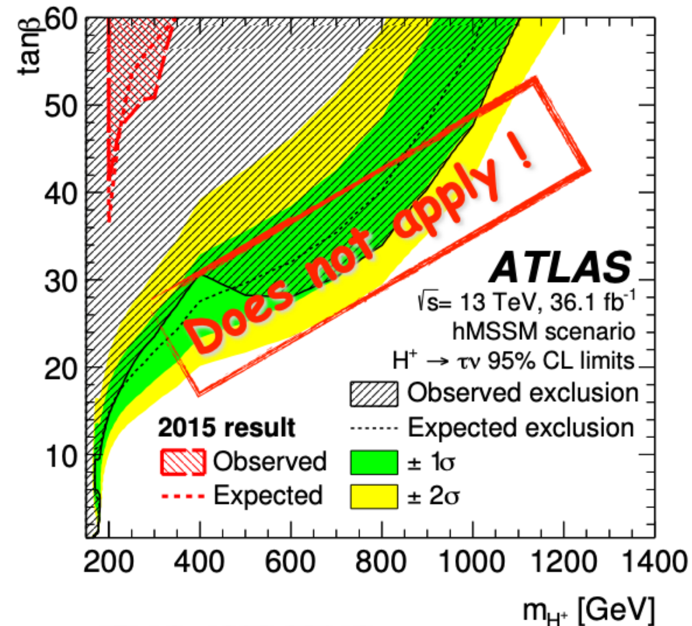
constraints

LEP H± search:

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



LHC H± search

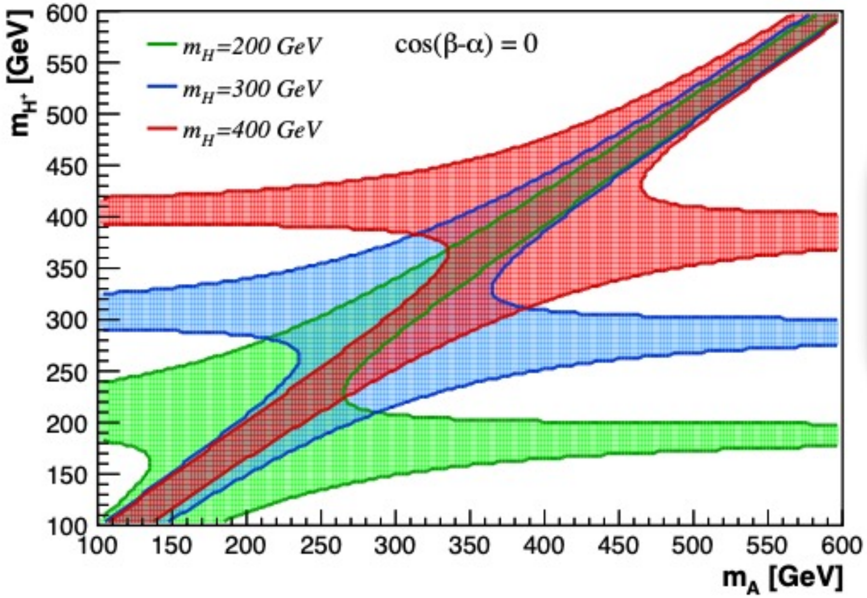


ATLAS, 1807.07915

constraints

- **EW precision constraints:**

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



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

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

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