Light Scalars at Future Collider

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Based on work with F. Kling, S. Li, S. Su, W. Su

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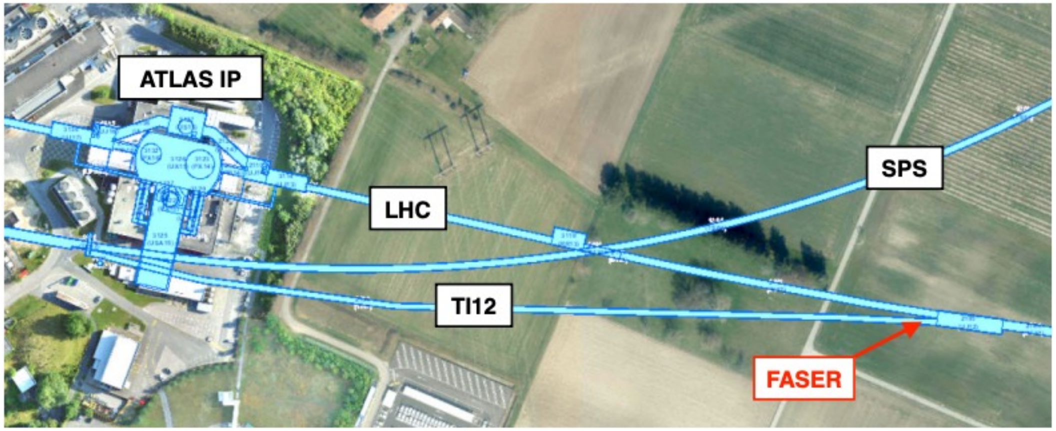
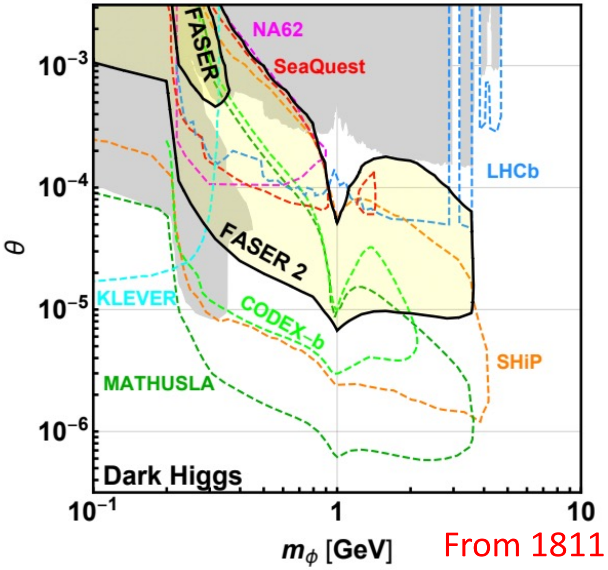
Light Scalars @ LHC

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

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





From 1811.12522

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 at Hadron Collider

- 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

Numbers of Mesons Produced at (Future) colliders

b-hadrons	Belle II	LHCb (300 fb^{-1})	Tera-Z
B^0, $\bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	1.2×10^{11}
$B^\pm$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	1.2×10^{11}
B_s^0, $\bar{B}_s^0$	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	3.1×10^{10}
$B_c^\pm$	-	1×10^{11}	1.8×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	2×10^{13}	2.5×10^{10}

Wang *et a*l. 2208.08327

Forward Region at ATLAS (FASER) for LHC Run 3 (150 fb^{-1})

$$N_{\pi^0} \approx 2.3 \times 10^{17}, \quad N_\eta \approx 2.5 \times 10^{16}, \quad N_D \approx 1.1 \times 10^{15}, \quad \text{and} \quad N_B \approx 7.1 \times 10^{13}$$

For HL-LHC (a ab^{-1}), 20-fold increase can be expected.

At FCC-hh, the amount of produced B mesons at FCC-hh will be at least 30 times larger, assuming 20 ab^{-1} total integrated luminosity.

Boyarsky *et al*. 2204.01622

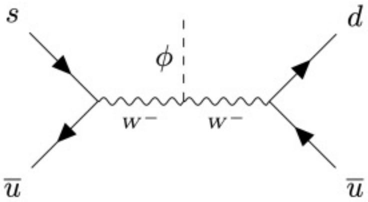
Light Scalars @ Forward Physics Facility (FPF)

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.

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** $\phi \to 4\pi, \eta\eta, KK\pi\pi, \rho\rho \ldots$ $$\Gamma_{4\pi,\eta\eta,\rho\rho,\ldots} = C \left|\xi_\phi^g\right|^2 m_\phi^3 \beta_{2\pi}$$

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

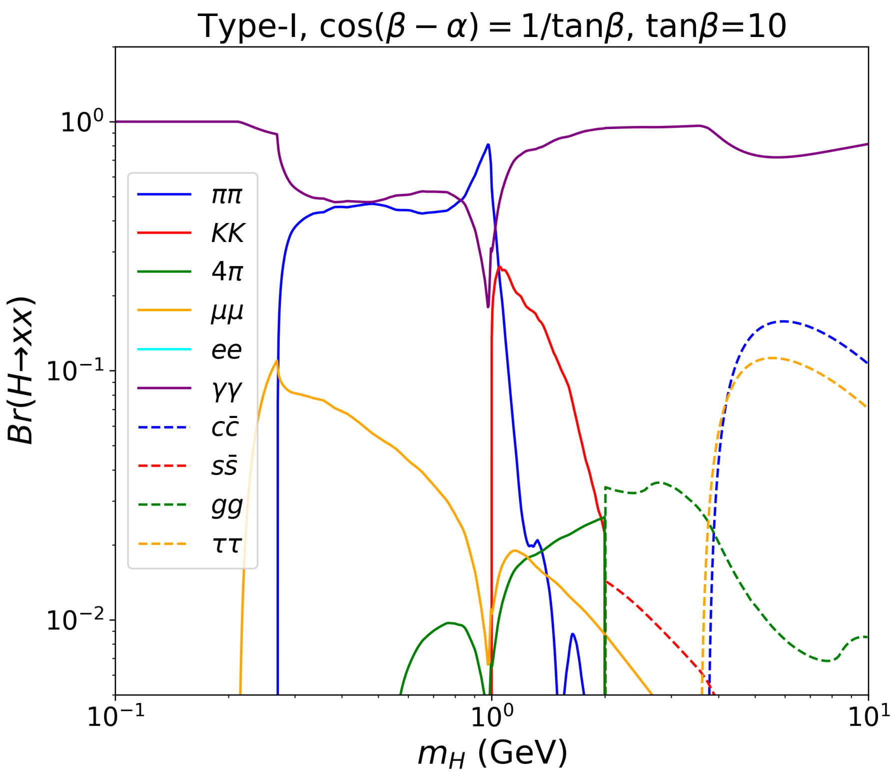
- Theoretical constraints: unitarity, perturbativity, vacuum stability
- EW precision constraints
- Flavor constraints
- Invisible Higgs decay
- LEP & LHC $H^{\pm}$ search

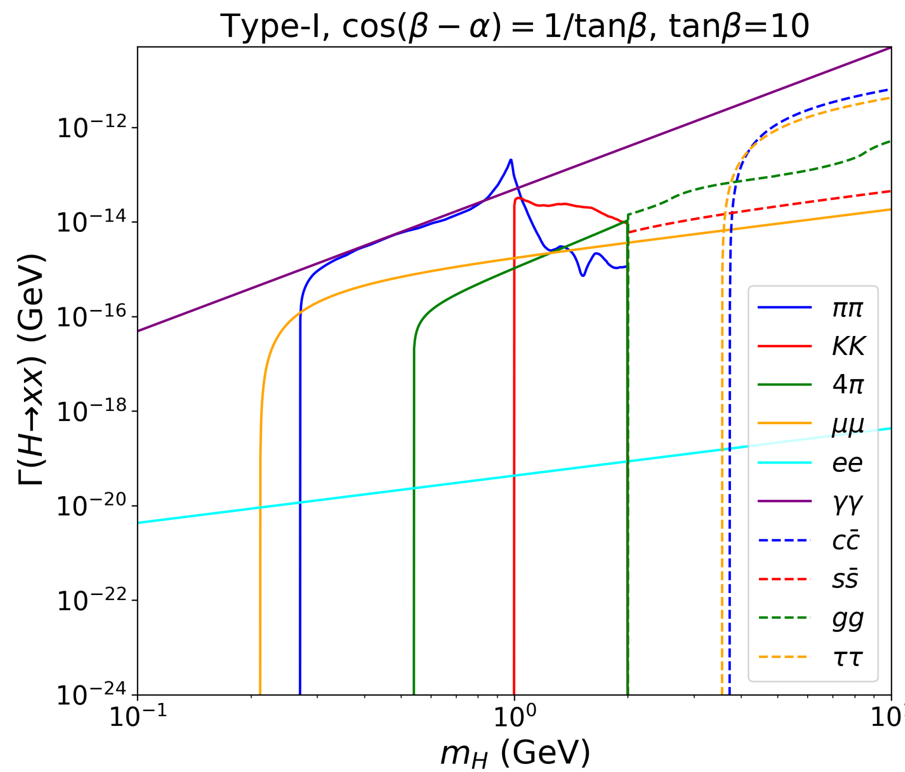
Two benchmark scenarios

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

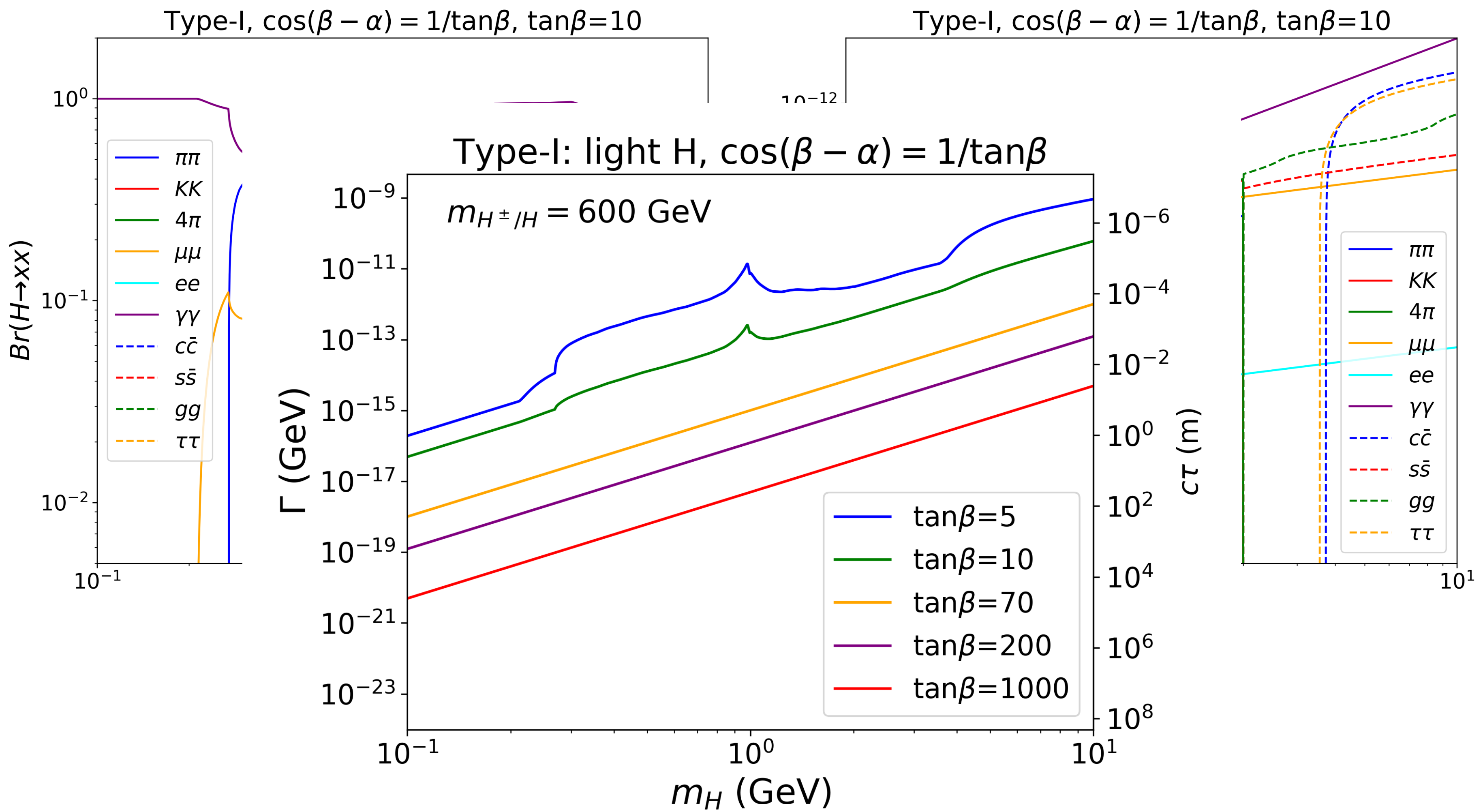
$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta,$$
$$\xi_H^V = c_{\beta-\alpha} = 1/\tan\beta,$$
$$\xi_H^f = c_{\beta-\alpha}(1-s_{\beta-\alpha}) \approx 1/(2\tan^3\beta) + \mathcal{O}(c_{\beta-\alpha}^5)$$

Light CP-even Scalar





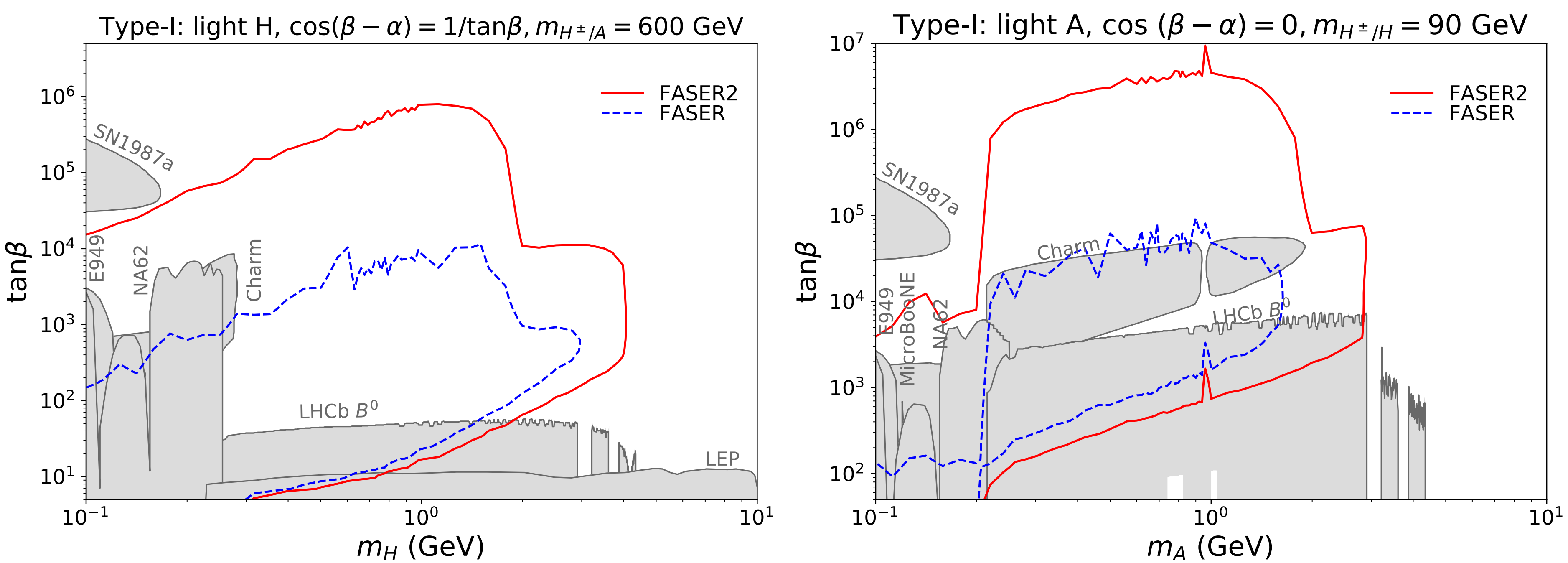
Light CP-even Scalar



Other constraints on Light Scalar Searches

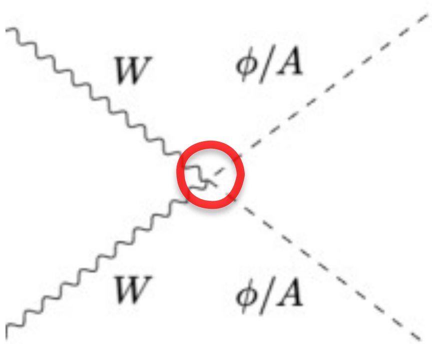
- CHARM bounds: light ALP — CHARM, PLB 157 (1985) 458
- Supernova: $NN \longrightarrow NNS(A)$ — Turner, PRL 60 (1988) 1797
- B meson decays: $B \longrightarrow K^{*}\phi$ (LHCb) — LHCb, 1508,04094, 1612.07818
- D meson decays: $D^{+} \longrightarrow \pi^{+}\phi$ (LHCb) — PDG, LHCb, 2011.00217
- Kaon 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 FPF



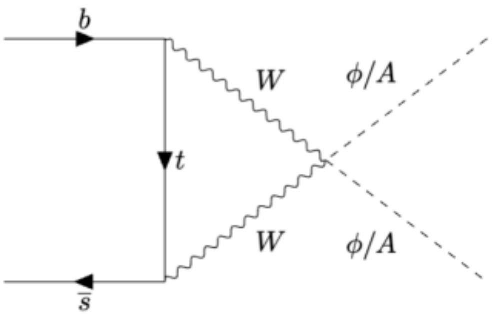
$$\xi_A^f|_{\cos(\beta-\alpha)=0} = 1/\tan\beta,$$
$$\xi_H^V = c_{\beta-\alpha} = 1/\tan\beta,$$
$$\xi_H^f = c_{\beta-\alpha}(1-s_{\beta-\alpha}) \approx 1/(2\tan^3\beta) + \mathcal{O}(c_{\beta-\alpha}^5)$$

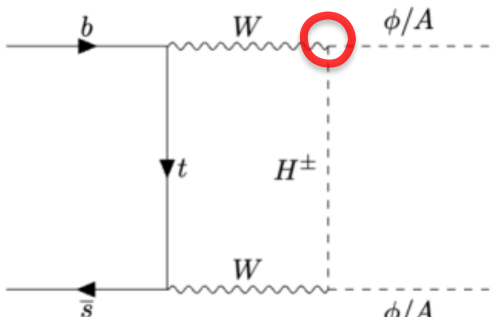
Double Scalar Production

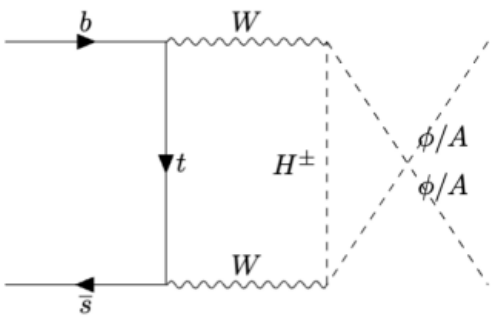


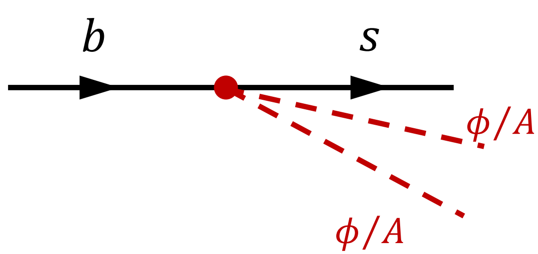
$\sim g^2$

Governed by gauge symmetry and not suppressed









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

More on Lepton colliders

- **Z associated production (like LEP $e^-e^+ \longrightarrow Z^*\phi$)**
- **h/Z/W decay (isotropic, commonly considered)**
- **decay of mesons, hadrons, radiative bottomonium (from h/Z/W decay)**
- **photon fusion (not important)**

New detectors: HErmetic CAvern TrackEr (HECATE)

Chrząszcza *et al.* 2011.01005

A large volume cavern is needed for FCC-hh/SppC detectors, while the detectors at the ee phase are rather small. Thus a MATHUSLA-like detector can be installed.

- Origins of the LLPs: two bottoms or charms, one of which can be tagged in the standard detector

- Complementary to MET search at the main detector

- More sensitive to lighter and longer lifetime particles, compared to displaced vertices search at the main detector in the

More on Scalar EFTs

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

Dark Higgs: $\xi = \sin\theta$

2HDM (Type-I):

$$\xi_H^V = \cos(\beta-\alpha) = \cot\beta, \quad \xi_H^f = \cot^3\beta, \quad \xi_{HH}^V = 1$$

$$\xi_A^V = \cos(\beta-\alpha) = 0, \quad \xi_A^f = \cot\beta, \quad \xi_{AA}^V = 1$$

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

2HDM (Type-II)+a:
HS, Wei Su, 2311.xxxxx

$$\xi_a^V = \cos(\beta-\alpha)\sin\theta$$
$$\xi_A^u = \cot\beta\sin\theta\,, \xi_A^d = \tan\beta\sin\theta$$

D meson physics?

Scalar (singlet) extension of the SMEFT ⟶ ϕEFT

HS, Sun, Yu, 2305.16770
HS, Sun, Yu, 2306.05999

- CHARM (FASER-like) bounds: reinterpretation
- Supernova bound: $NN \longrightarrow NNS(A)$ suppressed, $NN \longrightarrow NNSS(AA)$?

conclusion

- Light LLP appear in many new physics scenarios
- Light particle copiously produced in the forward region of Hadron colliders (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 prompt search, LLP search in transverse region, and fixed target exp at low energies, or other astrophysical processes (e.g. supernova)

Backup Slides

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

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

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

A Decay continued

$m_A < 1.3$ GeV: chiral perturbation theory

- **Hadronic decay into tri-meson**

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

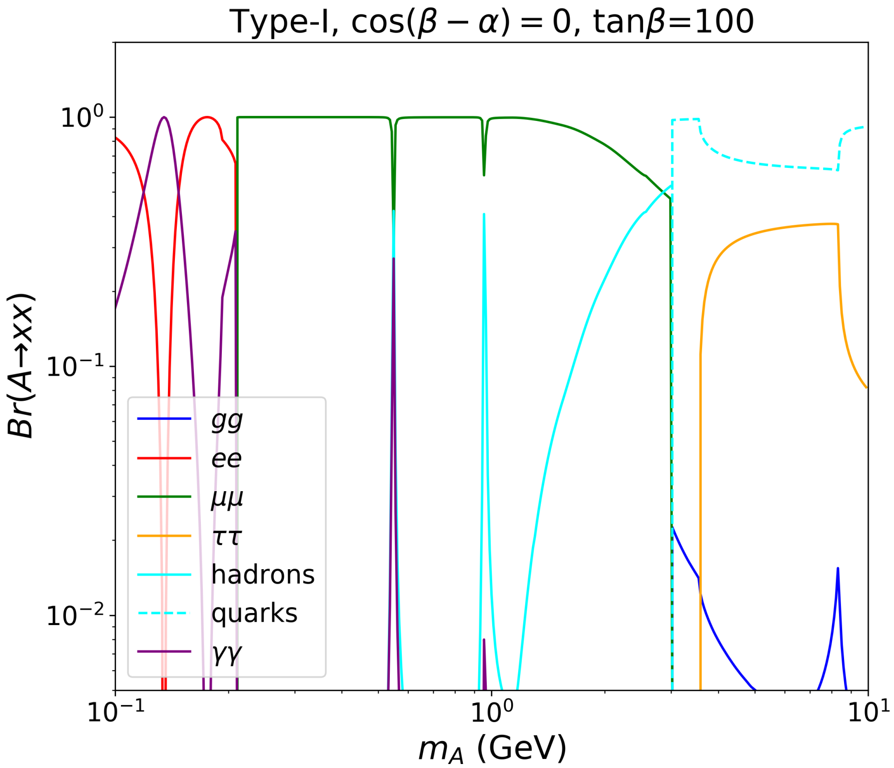
$$\mathcal{M}_A^{ijk} \propto O_{AA} \mathcal{A}_A^{ijk} + \sum_l O_{Al} \mathcal{A}^{ijkl}$$

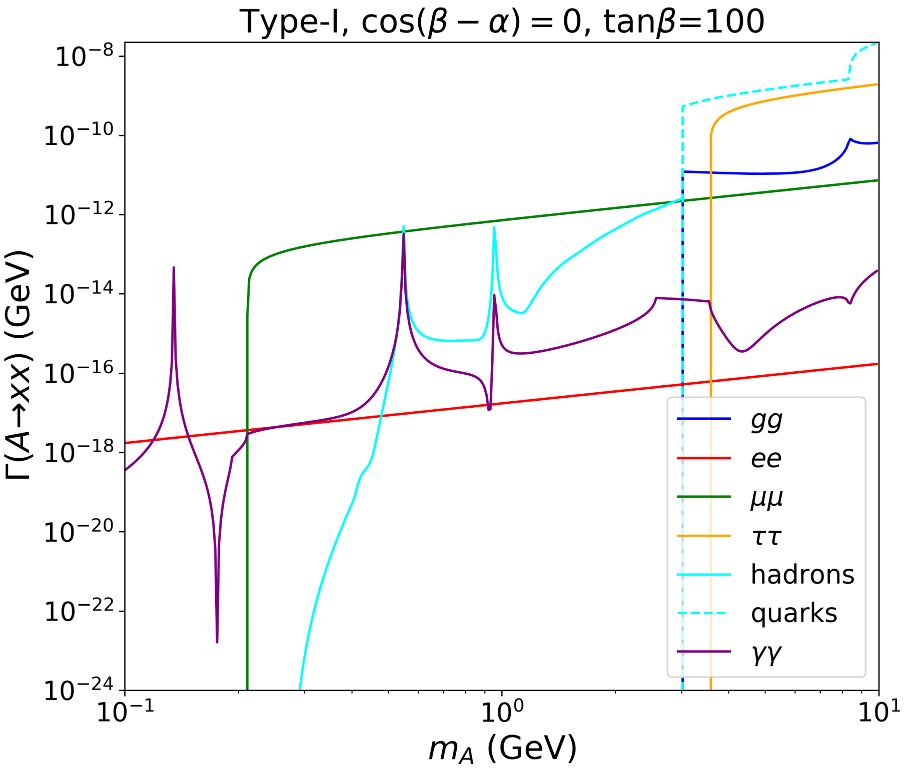
- **Radiative hadronic decay**

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

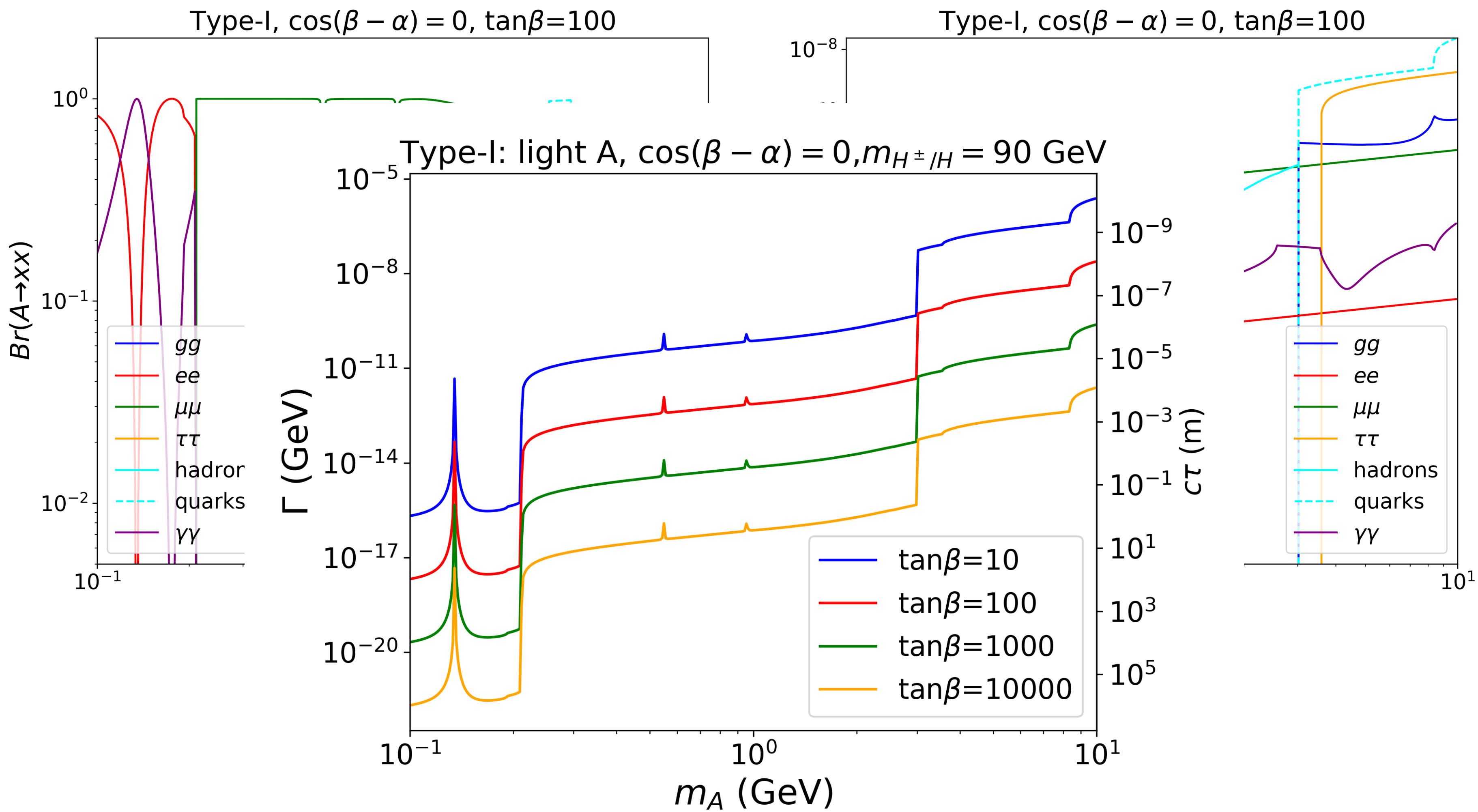
$$\Gamma(A \to \pi^+\pi^-\gamma) = \int_{4m_\pi^2}^{m_A^2} ds \Gamma_0(s) |O_{A\eta} B_\eta(s) + O_{A\eta'} B_{\eta'}(s)|^2$$

Light CP-odd Scalar



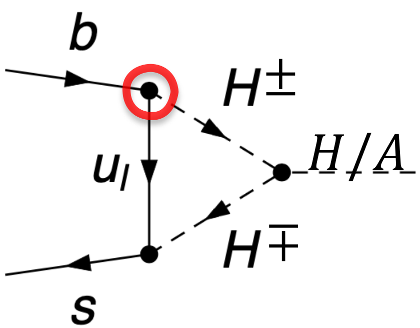


Light CP-odd Scalar



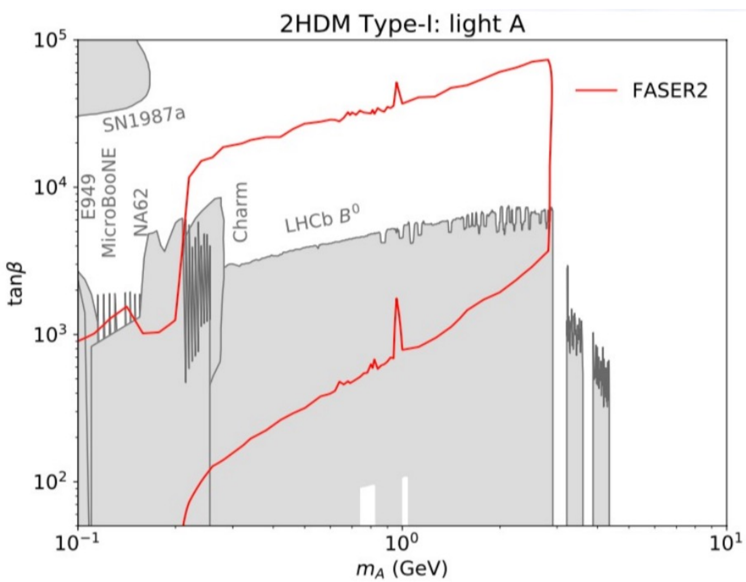
Without Double Scalar Production

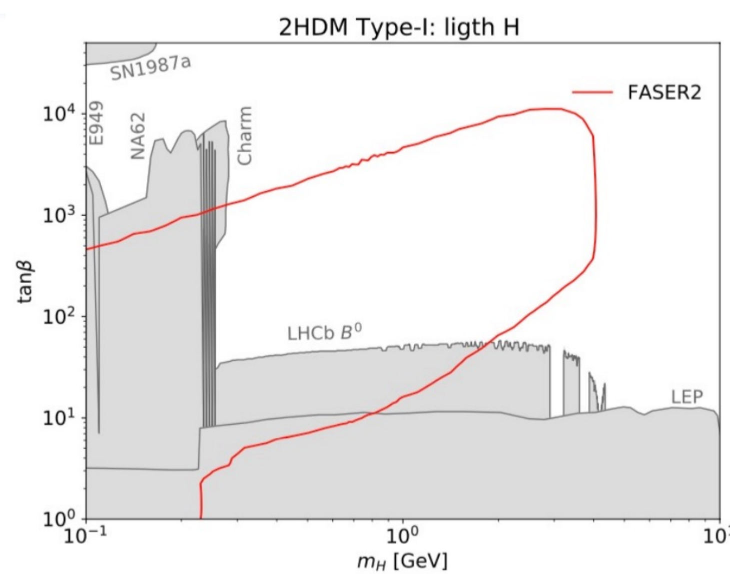
In Type-I 2HDM



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

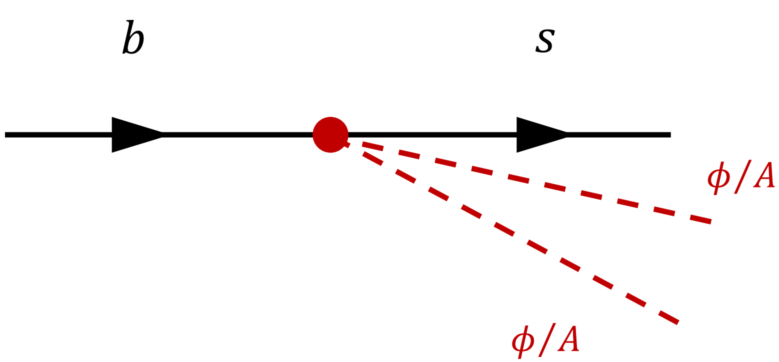
Similar to mimimal model
(Dark Higgs)





Effective couplings

In Type-I 2HDM



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

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

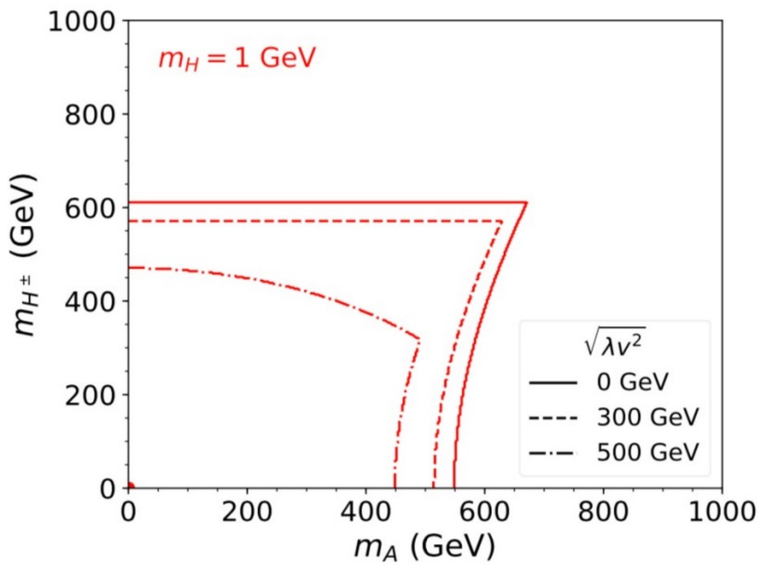
HS, Sun, Yu [2306.05999]
HS, Sun, Yu [2305.16770]

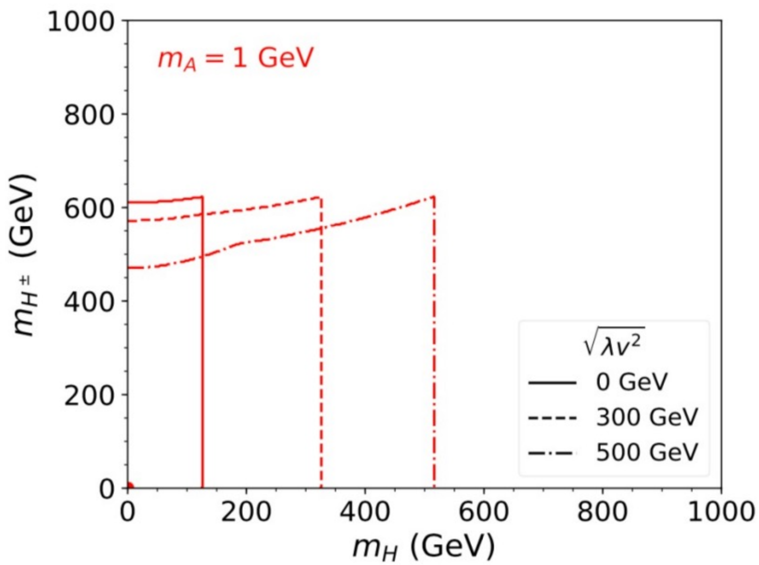
$$\xi^{ij}_{\phi\phi} \simeq \xi^{ij}_{AA} \simeq \frac{g^2}{64\pi^2}\sum_k V^*_{ki}\left[f_0(x_k, x_{H^\pm}) + f_1(x_k, x_{H^\pm})\log x_k + f_2(x_k, x_{H^\pm})\log x_{H^\pm}\right]V_{kj} + \mathcal{O}(\cos(\beta-\alpha), 1/\tan\beta)$$

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

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

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

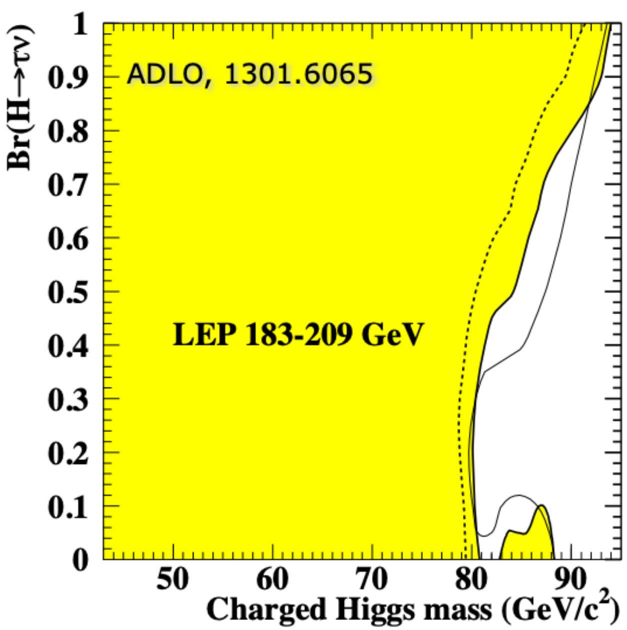
$$Light\ H : \cos(\beta - \alpha) = \tan 2\beta \frac{2\lambda v^2 + m_h^2}{2(m_H^2 - 3\lambda v^2 - m_h^2)} \approx \frac{1}{\tan\beta},$$

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

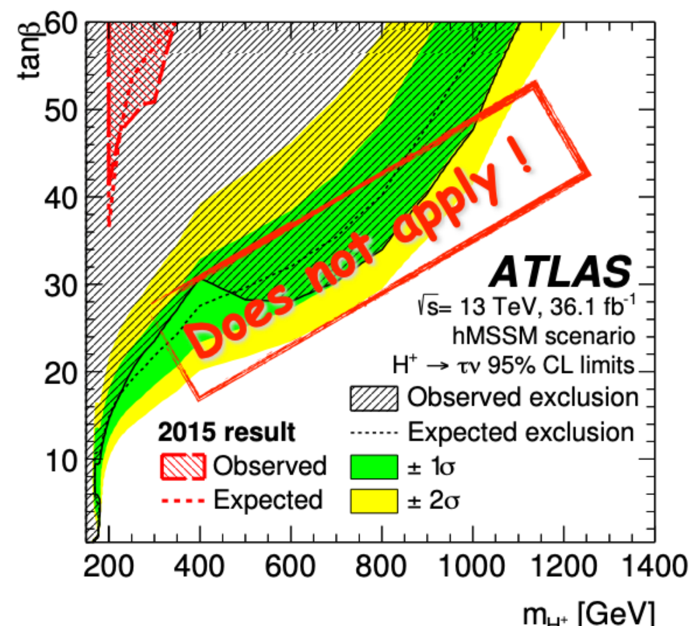
constraints

LEP H± search:

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



LHC H± search

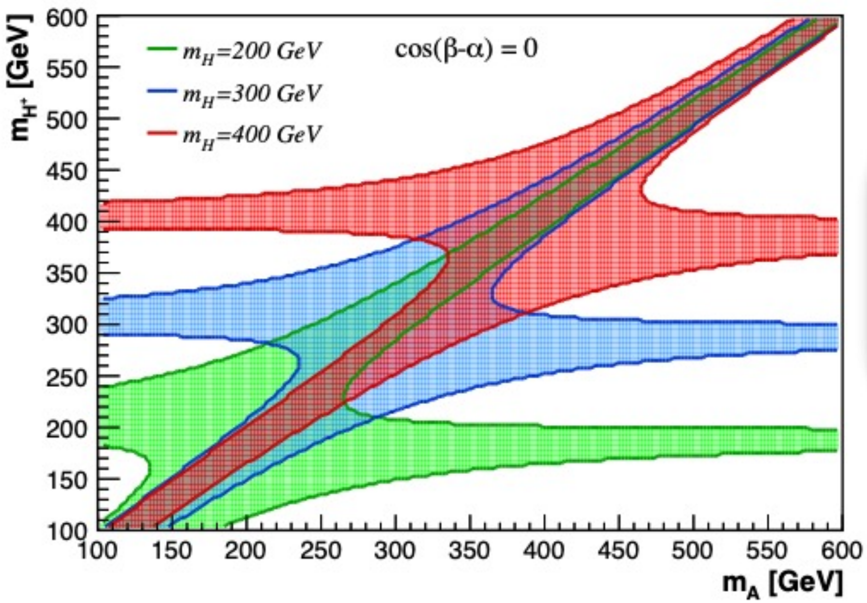


ATLAS, 1807.07915

constraints

- **EW precision constraints:**

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



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

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

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