PPG BSM: Dark Higgs

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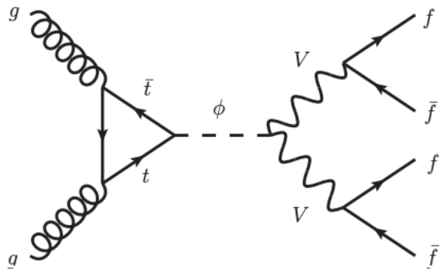
Dark scalar (or dark Higgs)

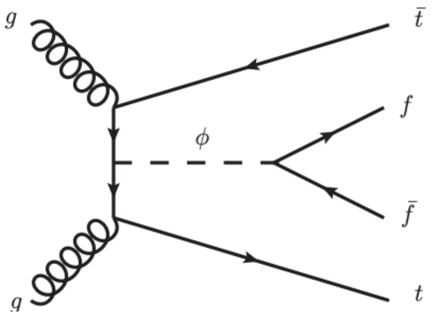
- a complex scalar field:
  - a singlet under the SM gauge group
  - carries charge under a new U(1)’ gauge group
- φ in general couples linearly to other fields in the theory
- generally expected to be unstable and decay into any pair of particles, allowed by their masses
- typically considered to be the lightest dark sector particle and decays into visible final states only

$$L = H^\dagger H(c_1 S^2 + c_2 S) \Rightarrow L_{\text{eff}} = \theta m_h^2 hS + \frac{\alpha}{2} hSS$$

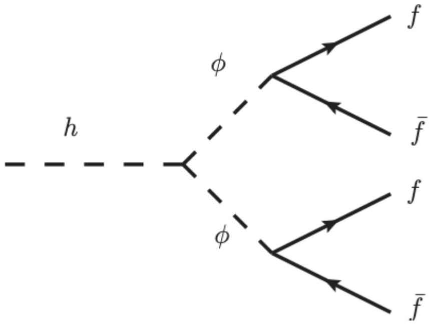
Production and decays at colliders



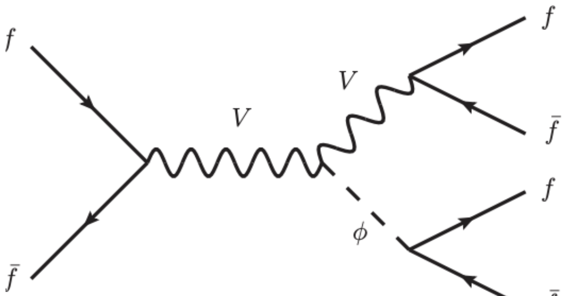
(a) Gluon fusion production.



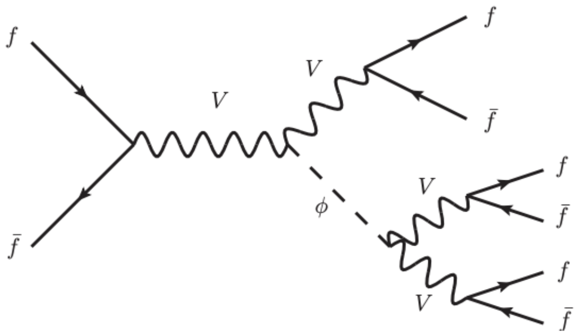
(b) Top-associated production.



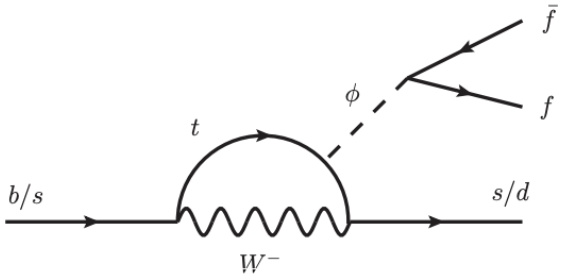
(c) Decay of the SM-like Higgs boson.



(d) Dark Higgs-strahlung.



(e) Dark Higgs-strahlung and decay into two dark photons.

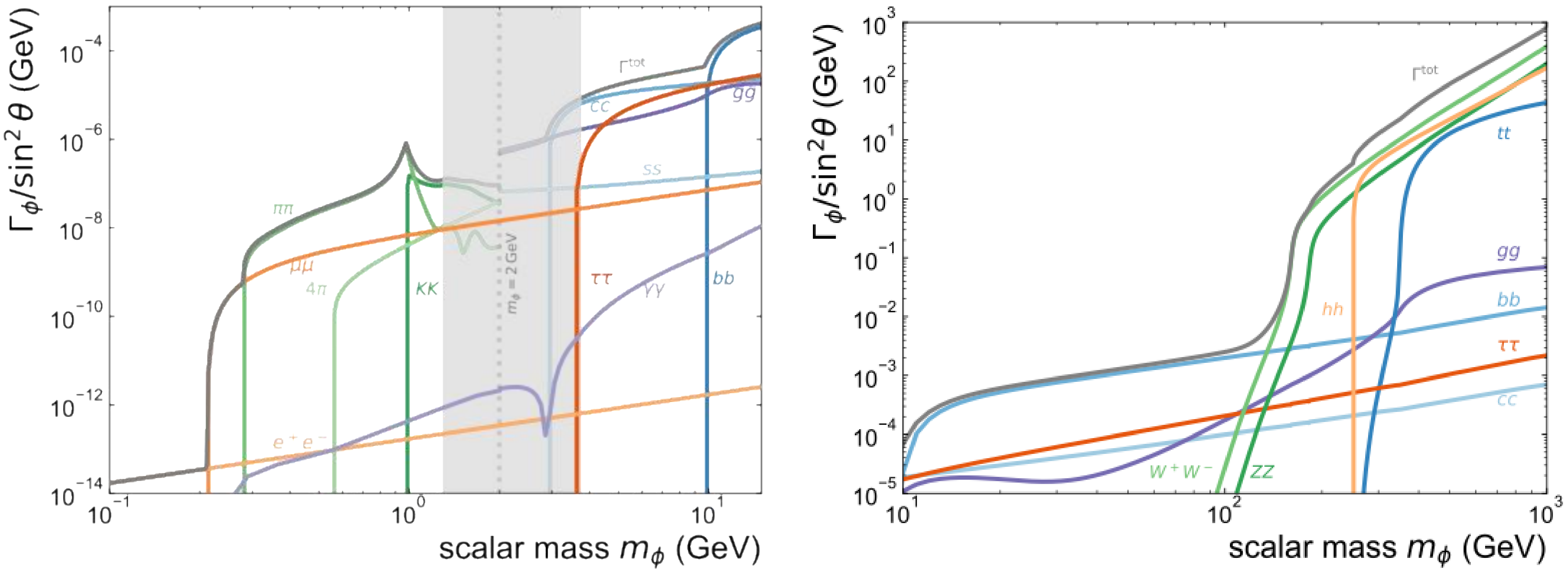


(f) Rare K and B decays.

Ferber, Grohsjean, Kahlhoefer'23

Dark scalar decay widths

Various decay channels can be targeted, depending on mass:



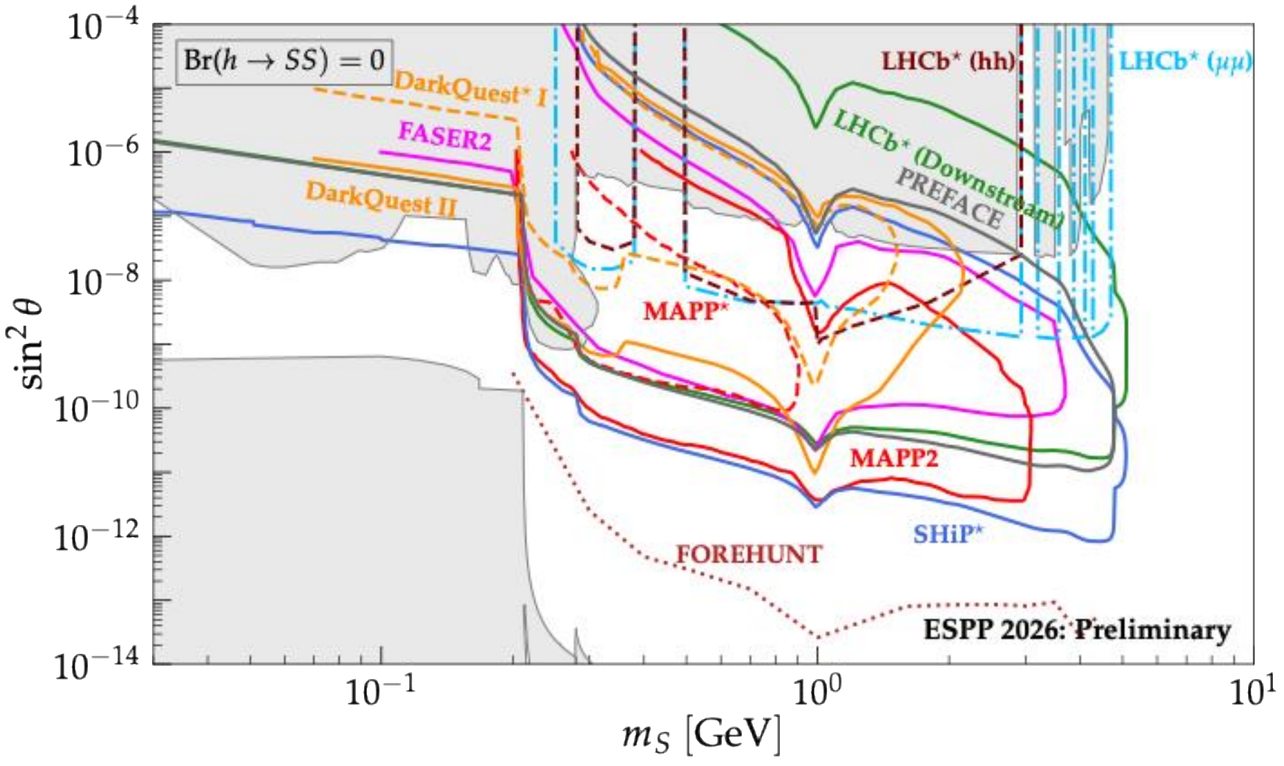
GeV mass range has large theoretical uncertainties (grey band)

Ferber, Grohsjean, Kahlhoefer'23

BC4: no quartic coupling (λ=0), Br(h→SS)=0

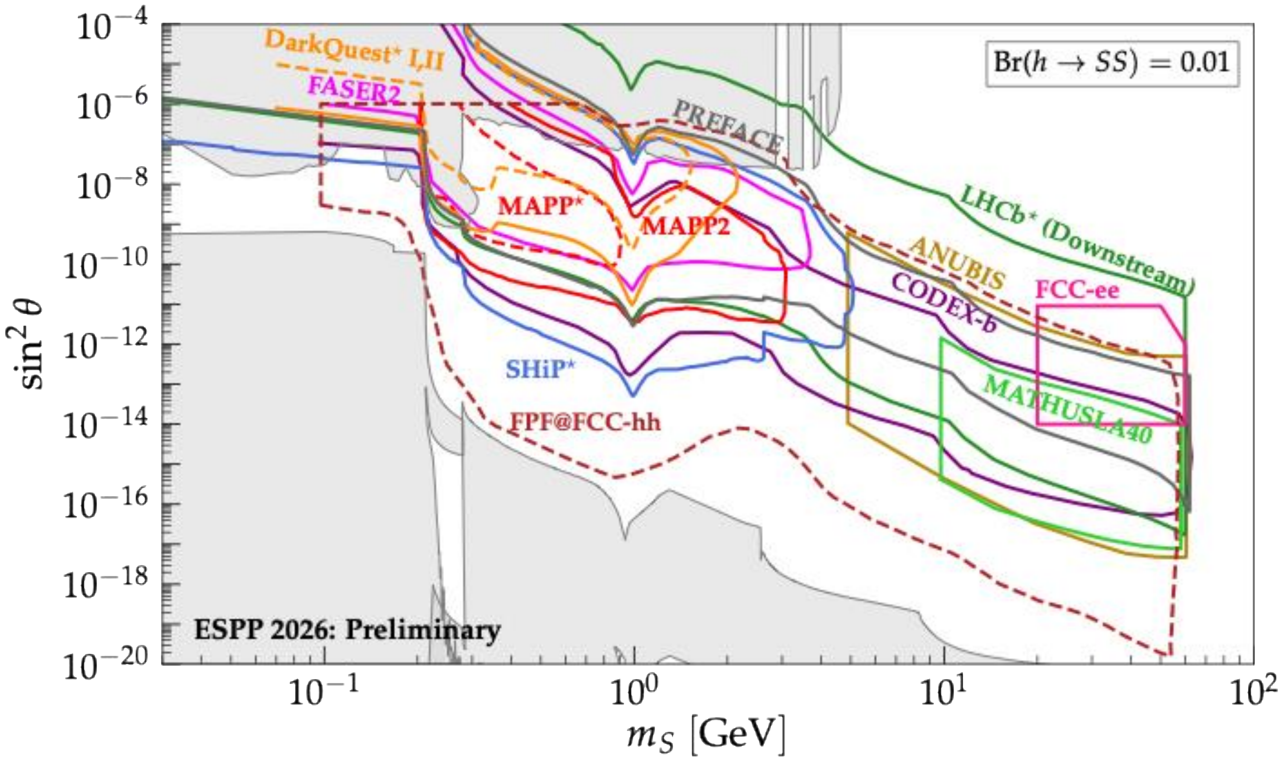
- production through hadron decays
- at low masses, sensitivity is dominated by the beam-dump:
  - SHiP, DarkQuest

  and forward/shielded experiments:
  - LHCb, MAPP, PREFACE
- large potential for dedicated experiments at FCC-hh:
  - FOREHUNT



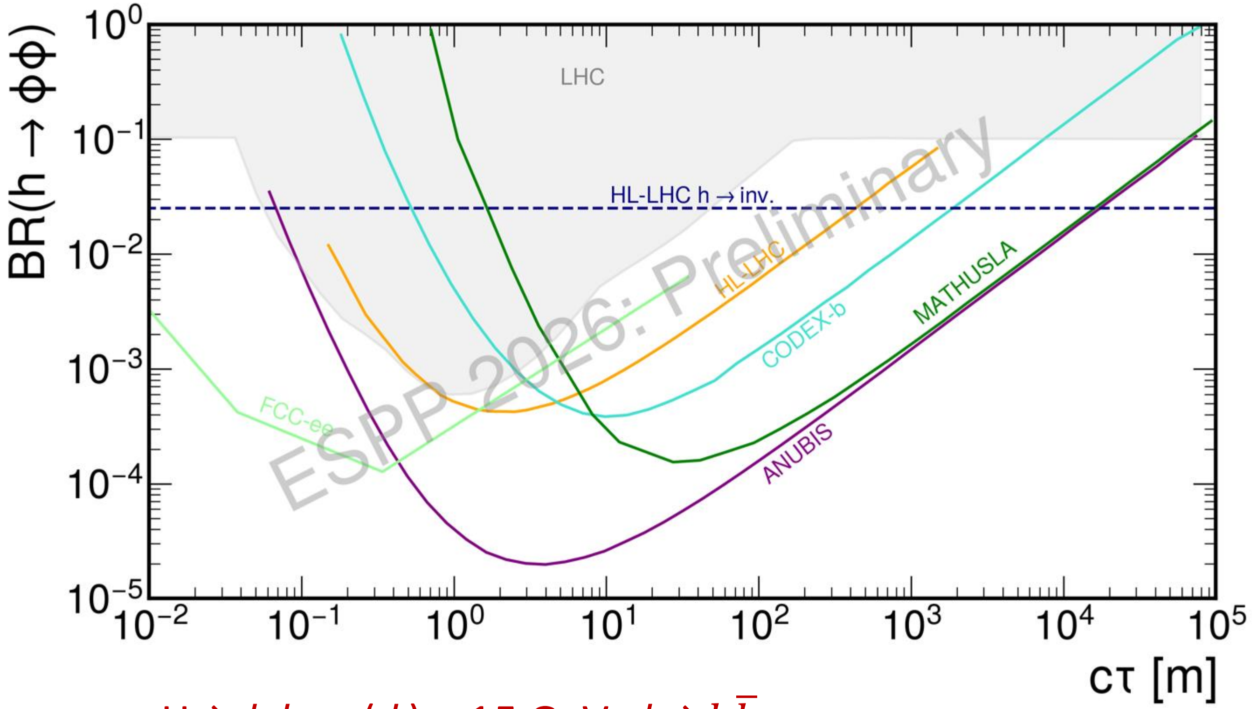
BC5: Br(h→SS)=0.01

- $B \to K^{(*)}SS, B \to SS$ for light S
- in addition, production through Higgs boson decays
- dedicated LHC-based experiments:
  - ANUBIS, CODEX-b, MATHUSLA, PREFACE
- FCC-ee experiments are sensitive to much lower BF:
  - the results are rescaled to Br(h→SS)=1% for comparison
- FPF-like facility at the FCC-hh can lead to a significant improvement



LLP interpretation: exotic H boson decay

- Additional interpretation to demonstrate LLP exploration
- H boson decay to two dark scalars
- dedicated detectors at (HL-)LHC are sensitive to larger lifetimes:
  - ANUBIS, CODEX-b, MATHUSLA
- shorter lifetimes are uniquely probed at FCC-ee: clean environment for purely hadronic decays



H→$\phi\phi$, m(ϕ) = 15 GeV, ϕ→$b\bar{b}$

Summary

- Dark scalar searches require a range of complementary approaches
- **Low masses** (below *b* quark) will be comprehensively explored by the running LHC experiments and can be complemented by dedicated LLP detectors. Ultimately, **SHiP** will cover the smallest couplings.
  - **Shorter-lived** hadronically decaying scalars are accessible at the **FCC-ee**
- **Intermediate masses** (below H boson) can be best explored by the dedicated LHC experiments, and LHCb. In the future, by the Higgs factories, as FCC-ee
  - Also, large potential for the dedicated FCC-hh facilities
- Sensitivity to **high-mass scalars** is explored under different model assumptions. Comes from associated dark Higgs boson production in high-energy colliders

Considered inputs

- 19: The Forward Physics Facility at the Large Hadron Collider
- 44: Proposal for a shared transverse LLP detector for FCC-ee and FCC-hh and a forward LLP detector for FCC-hh
- 61: MATHUSLA: An External Long-Lived Particle Detector to Maximize the Discovery Potential of the HL-LHC
- 81: Discovery potential of LHCb Upgrade II
- 140: LC vision: different model assumptions
- 141: The ECFA Higgs/Electroweak/Top Factory Study
- 145: SHiP experiment at the SPS Beam Dump Facility
- 235: Summary Report of the Physics Beyond Colliders Study at CERN
- 214: The Large Hadron electron Collider (LHeC) as a bridge project for CERN: different model assumptions
- 227: Prospects for physics at FCC-hh
- 233: FCC Integrated Programme Stage 1: The FCC-ee
- 242: Prospects in BSM physics at FCC
- 247: FCC Integrated Programme Stage 2: The FCC-hh

140: LC vision

Input in different coordinates

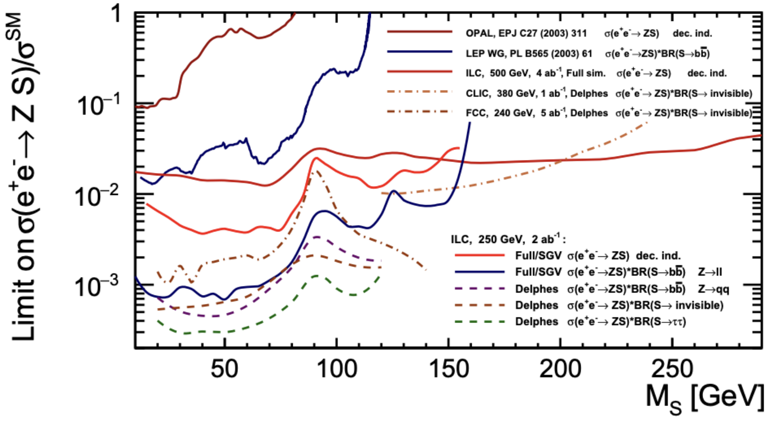


Figure 26: Comparison of expected exclusion limits for exotic light scalar production searches in the scalar-strahlung processes, for different search strategies and scalar decay channels considered. When particular decay channel is indicated, limits are set on the cross section ratio times the branching fraction [41].

Model assumptions: arXiv:1807.04743

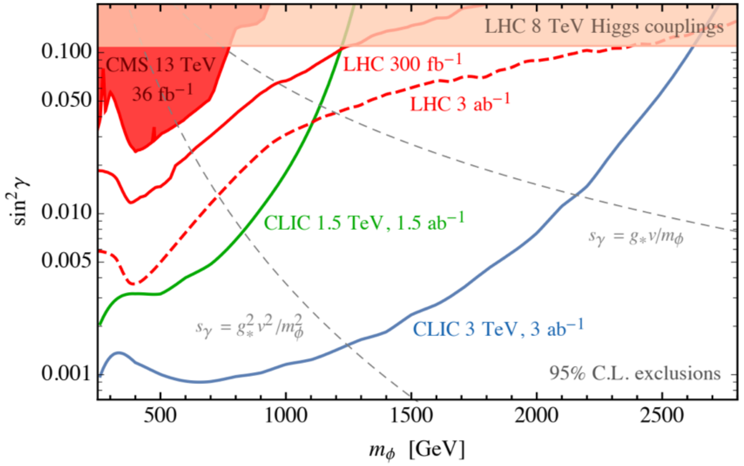


Figure 6. Exclusions at 95% C.L. in the plane $(m_\phi, \sin^2\gamma)$. The shaded regions are the present constraints from LHC direct searches for $\phi \to ZZ$ (red) and Higgs couplings measurements (pink). The reach at CLIC Stage II (green) and Stage III (blue) in $\phi \to hh(4b)$ is compared with the projections for LHC in $\phi \to ZZ$ with a luminosity of 300 fb^{-1} (solid red) and 3 ab^{-1} (dashed red). We have fixed $\mathrm{BR}_{\phi\to hh} = \mathrm{BR}_{\phi\to ZZ} = 25\%$. The dashed grey lines show two different scalings of s_γ with m_ϕ, as described in Section 2.1 ($g_* = 1$ in both cases).

arXiv:1807.10842

Direct searches

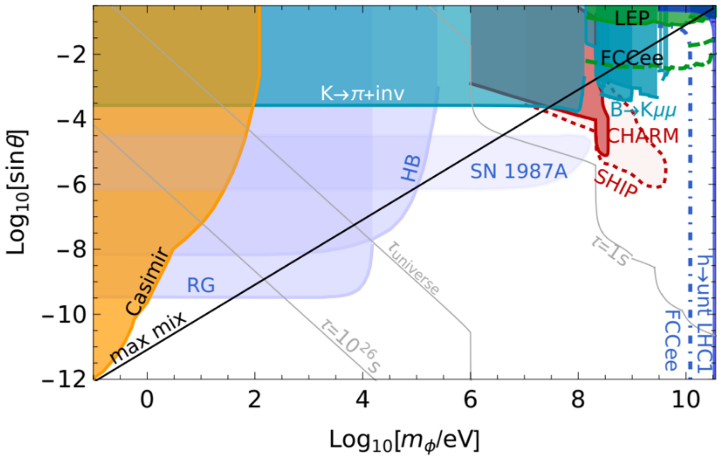


Figure 1. Summary of present bounds and few projections on the relaxion mass m_ϕ and the mixing angle $\sin\theta$ (for details see Ref. [10]): Fifth force via the Casimir effect (orange) [45, 46], astrophysical probes (light blue) [55–60] such as red giants (RG), horizontal branch stars (HB) and the Supernova (SN) 1987A, rare meson decays (turquoise) where the strongest bounds stem from $K \to \pi +$ invisible at E949 [64], $K_L \to \pi l^+ l^-$ at KTeV/E799 [70, 71] and $B \to K\mu^+\mu^-$ at LHCb [65, 66]. Beam dump experiment for ϕ production from K- and B-decays at CHARM [61–63] and a projection from SHiP [72] (red dotted). Constraints from the ϕZ interaction (green) via $Z \to Z^*\phi$ and $e^+e^- \to Z\phi$ at LEP [67, 68] and projections for the same processes at the FCCee (green dashed). Untagged Higgs decays (blue) at the LHC Run-1 [10] and projections for the FCCee and TeraZ (blue, dash-dotted, see Sect. 4.1.1). The gray contours of the relaxion lifetime of $\tau_\phi = 1\,\text{s}$, $10^{17}\,\text{s}$ and $10^{26}\,\text{s}$ indicate the beginning of BBN, the lifetime of the universe and safety from constraints of extragalactic background light, respectively. The black line shows the upper bound on the mixing according to Eq. (2.12).

Indirect constraints

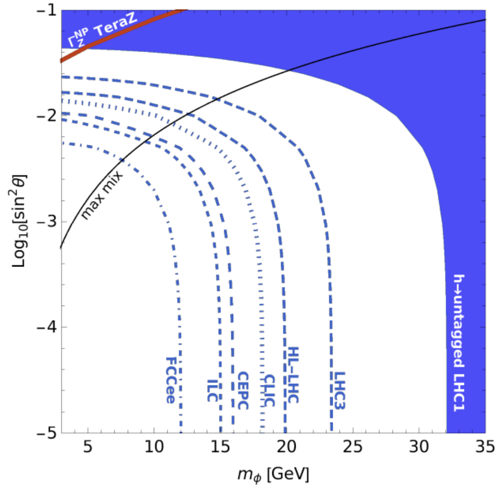


Figure 2. *Precision* bounds on $\sin^2\theta$ and m_ϕ: Upper limit on the untagged branching ratio of the Higgs boson, here $h \to \phi\phi$ (blue), obtained via the precision of Higgs couplings. Current (solid, blue area) and projected (blue, dashed) exclusion from the (HL-)LHC, CLIC at $\sqrt{s} = 380\,\text{GeV}$ with $500\,\text{fb}^{-1}$, CEPC at $250\,\text{GeV}$ with $5\,\text{ab}^{-1}$, ILC with $250\,\text{GeV}$ with $2\,\text{ab}^{-1}$ and FCCee at $240\,\text{GeV}$ with $10\,\text{ab}^{-1}$. The energies, luminosities and upper bounds on $\text{BR}(h \to \text{NP})$ of the collider benchmarks are summarized in Tab. 1. The contours represent the 95% CL, except for LHC3 and HL-LHC which are at 68% CL. Projection of the constraint on the NP contribution $\Gamma(Z \to \phi f\bar{f})$ to the total Z-width, assuming the experimental precision of the FCCee running at the Z-pole with $10^{12} Z$ and an improved theory uncertainty (red). The black line shows the upper bound on the mixing according to Eq. (2.12).

arXiv:1807.10842

Final plot: direct and indirect

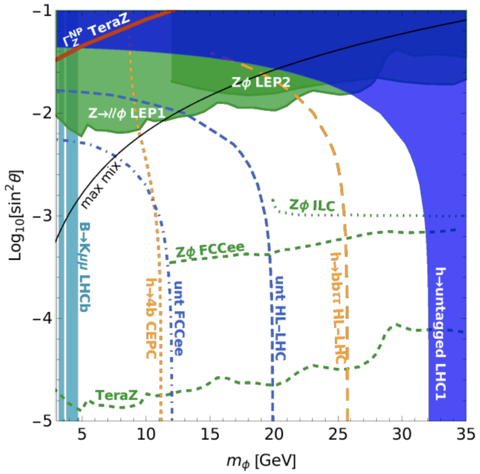


Figure 5. *Direct* and *indirect* bounds and projections for processes at hadron and lepton colliders. $Z \to Z^*\phi \to \ell\bar{\ell}\phi$ at LEP1 with $\sqrt{s} = M_Z$ [67] and $e^+e^- \to Z\phi$ at LEP2 with $\sqrt{s} = 192$–202 GeV [68]; projections for the same processes at the FCCee (green, dashed) running at $\sqrt{s} = M_Z$ with 10^{12} Zs produced (TeraZ) and $\sqrt{s} = 240$ GeV with 10 ab^{-1}. Projection for $e^+e^- \to Z\phi$ at the ILC with $\mathcal{L}_{\rm int} = 2$ ab^{-1} [132] (green, dotted). Bound from $B^+ \to K^+\mu^+\mu^-$ at LHCb [65, 66]. Direct searches for exotic Higgs decays at the HL-LHC in the $bb\tau\tau$ channel inferred from Ref. [113] (orange, dashed) and at CEPC with 5 ab^{-1} in the $4b$ channel from the BR bound of Ref. [112]. Untagged Higgs decays (blue) at the LHC Run-1 (blue area) and projections for the HL-LHC with 3 ab^{-1} (blue, dashed) and the FCCee with 10 ab^{-1} (blue, dash-dotted) according to Tab. 1. The NP contribution to the total Z-width will be bounded by TeraZ (red). The maximal mixing according to Eq. (2.12) is indicated by the black line.

Low mass

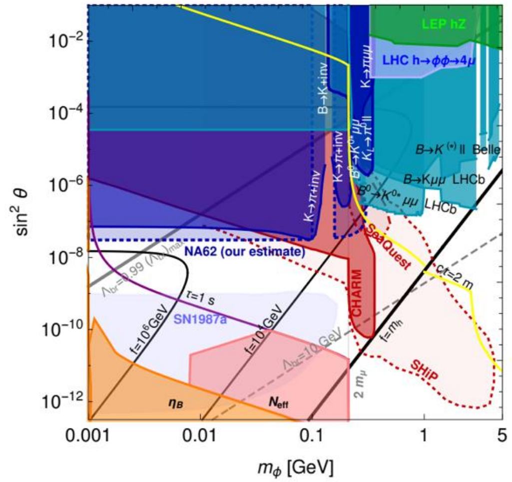
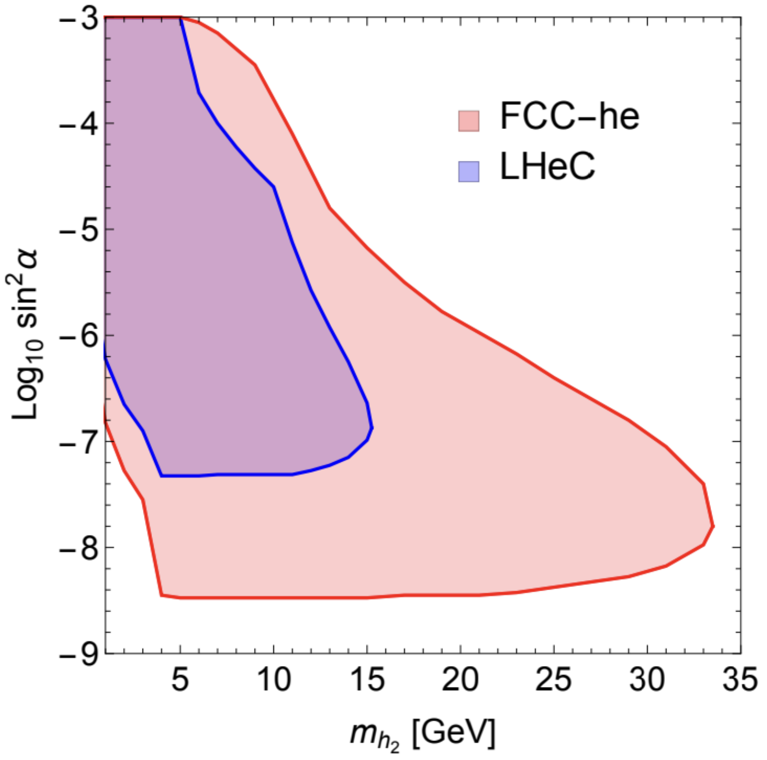


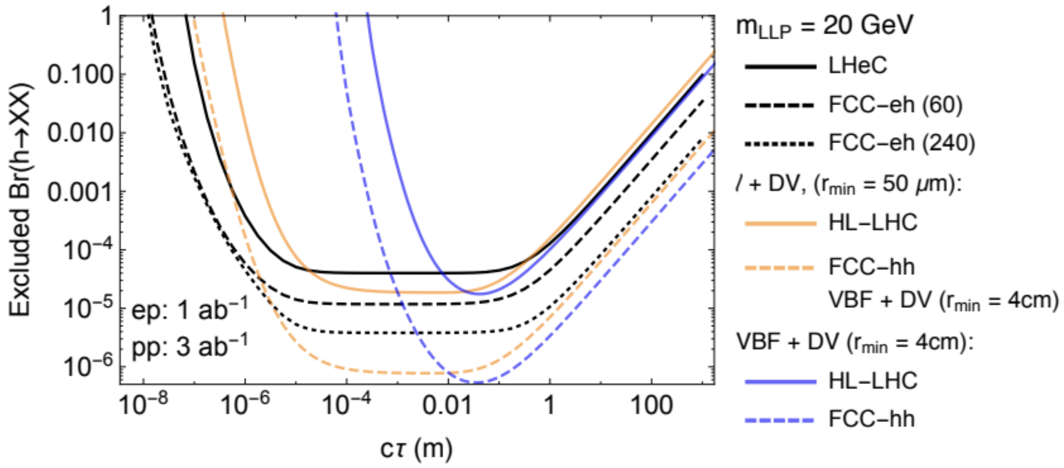
Figure 3. Constraints on the relaxion-Higgs mixing $\sin^2\theta$ for relaxions with m_ϕ between MeV and 5 GeV. The laboratory probes include: proton beam dump experiments (red for CHARM, light red for the projected sensitivity for SHIP and SeaQuest), K-meson decays (blue, our conservative projection from NA62 in a lighter shade of blue), B-meson decays (turquoise), LHC search for $h \to 4\mu$ (light blue) and LEP (green). Astrophysical and cosmological probes include the Supernova 1987a (pale violet, labelled as SN), η_b (orange) and $N_{\rm eff}$(pink). Contours for $\Lambda_{\rm br} = 0.99\Lambda_{\rm br}^{\rm max} \simeq$ 104 GeV (gray, thick, solid), $\Lambda_{\rm br} = 10$ GeV (gray, dashed), $f/$GeV $= 10^6, 10^4, 125$ (black, solid) are presented. Here $\Lambda_{\rm br}^{\rm max}$ is the upper bound on $\Lambda_{\rm br}$ arising from the requirement of a non-tachyonic ϕ in Eq. (3.12) for $\sin(\phi_0/f) = 1/\sqrt{2}$. The vertical light gray line corresponds to the contour for the relaxion mass at the muon threshold; the yellow contour corresponds to $c\tau = 2$ m and the purple one to $\tau = 1$ s.

214: LHeC and FCC-eh

arXiv:2007.14491



arXiv:1712.07135



The considered model has varying Br(h→SS), hence not directly compatible with the BC5