Hunting relaxions and light (pseudo)scalars

at LEP, the (HL)LHC and future lepton colliders

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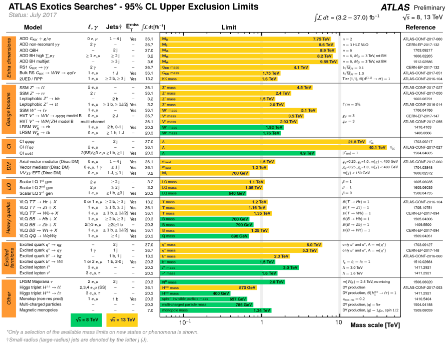
[1610:02025] Flacke, Frugiuele, EF, Gupta, Perez
[1807.10842] Frugiuele, EF, Perez, Schlaffer

Beyond Standard Model: Where do we go from here?
GGI Firenze, August 28, 2018

Challenges for naturalness at the TeV-scale

- symmetry-based theories of naturalness: New Physics $\sim$ TeV
  - e.g. SUSY, composite Higgs
- under pressure by null-results at LHC
  - how much tuning acceptable?
  - still some blind spots survive
- novel ideas for naturalness with light NP
  - instead of symmetry protection of Higgs mass: dynamical evolution $\rightsquigarrow$ **Relaxion**



Outline

I. Brief introduction: relaxion for naturalness

Relaxion mechanism

[Graham, Kaplan, Rajendran '15]

$$V(H) = \mu^2(\phi) H^\dagger H + \lambda (H^\dagger H)^2$$
$$V(\phi) = rg\Lambda^3 \phi + ...$$

$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi$ scans m_h during inflation

1. $\phi \geq \Lambda/g \;\Rightarrow \mu^2 > 0$, no vev
2. $\phi < \Lambda/g \;\Rightarrow \mu^2 < 0$, sign flip, EWSB

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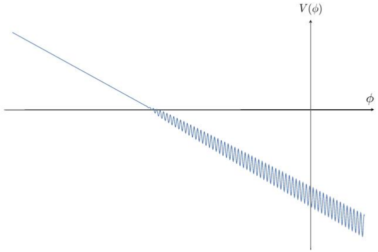
1. $\phi \geq \Lambda/g \;\Rightarrow \mu^2 > 0$, no vev
2. $\phi < \Lambda/g \;\Rightarrow \mu^2 < 0$, sign flip, EWSB
3. backreaction $V_{\rm br} = \Lambda_{\rm br}^4 \cos\left(\frac{\phi}{f}\right)$
4. $\phi \searrow \;\Rightarrow |\mu^2(\phi)|, v^2 \nearrow \;\Rightarrow \Delta V_{\rm br} \nearrow$
5. until ϕ stopped by sufficient barrier



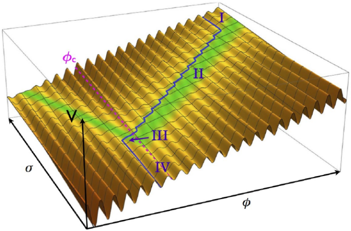
Relaxion models (examples)

- minimal model: QCD (rel)axion,
  $\Lambda_{\rm br}^4 = 4\pi f_\pi^3 y_u v/\sqrt{2} \not\leftrightarrow \theta_{\rm QCD}$ ×
- non-QCD strong sector,
  $\Lambda_{\rm br}^4 \simeq y v'^3 v_H/\sqrt{2}$
- double-field mechanism (ϕ, σ)

  [Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15]
- familon (PNGB of spontaneously broken flavour symmetry) with vector-like leptons in the backreaction sector

  [Gupta, Komargodski, Perez, Ubaldi '15]
- friction via particle production

  [Hook, Marques-Tavares '16]
- ...



backreaction sector and scale $\Lambda_{\rm br}$ model-dependent

II. Relaxion Phenomenology

Relaxion-Higgs mixing

[Flacke, Frugiuele, EF, Gupta, Perez '16] [Choi, Im '16]

considering $\boxed{\Lambda_{\rm br}^4 = \tilde{M}^{4-j} v^j / \sqrt{2}^j \equiv r_{\rm br}^4 v^4,}$ here $j = 2$ (non-QCD)

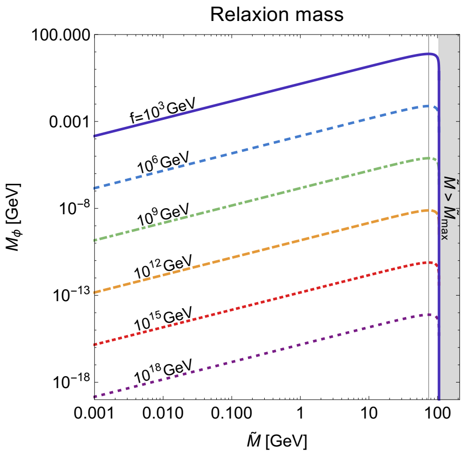
minimum of $V(\phi, h)$: $(\phi_0, v = 246\,\mathrm{GeV})$,
ϕ_0: endpoint of rolling, $s_0 \equiv \sin(\phi_0/f)$ can be $\mathcal{O}(1)$ or smaller

Mixing term in the relaxion-Higgs potential

$$V(\phi, h) \supset \frac{\tilde{M}^{4-j} v^{j-1}}{\sqrt{2}^j f} \sin\left(\frac{\phi_0}{f}\right) \boldsymbol{h\phi} \rightarrow \text{diagonalise}$$

$\boldsymbol{V(h, \phi) \supset h\phi}$ **:** Measurable consequences of relaxion-Higgs mixing?

Relaxion properties I: mass & mixing



$$m_\phi \simeq \frac{r_{\rm br}^2 v^2}{f}\sqrt{c_0 - 16 r_{\rm br}^4 s_0^2}$$

$$\sin\theta \simeq 8 r_{\rm br}^4 s_0 \frac{v}{f} \leq 2\frac{m_\phi}{v}$$

(for $f \gg r_{\rm br}^2 v$, $16\, r_{\rm br}^4 s_0^2 \ll c_0$)

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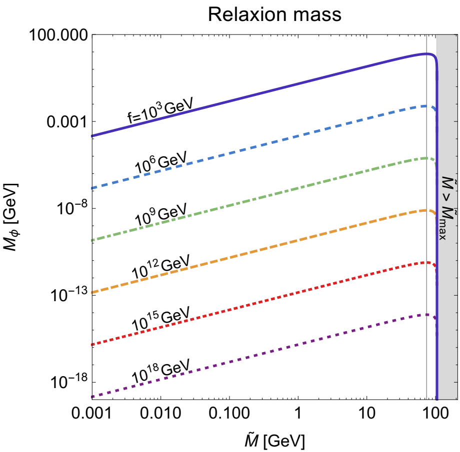

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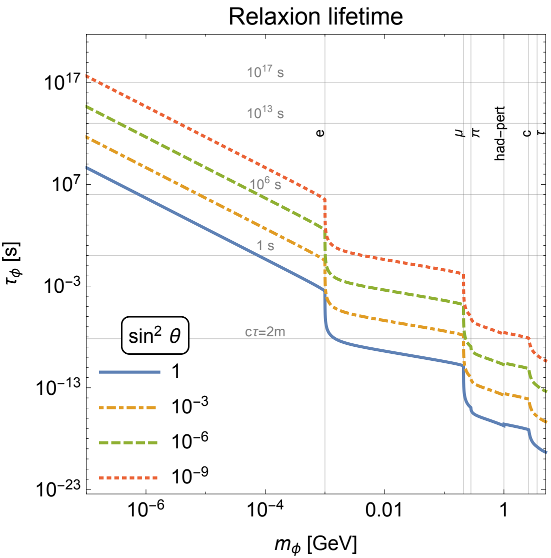
"Relaxion line": maximal mixing depends linearly on mass

Relaxion properties II: lifetime

[Clarke, Foot, Volkas '13] [Flacke, Frugiuele, EF, Gupta, Perez '16]



- ▷ threshold effects
- ▷ $c\tau_\phi \propto (\sin\theta)^{-2}$
- ▷ displaced vertex?
- ▷ decay outside detector?
- ▷ cosmological time scales?

ϕ possibly long-lived

Relaxion couplings to SM: $\mathcal{CP}$-even and -odd

$\mathcal{CP}$-even

$$g_{hX} = \sin\theta\, g_{hX}, X = f\bar{f}, VV$$

Relaxion inherits SM Higgs couplings suppressed by mixing
$\Leftrightarrow$ Higgs portal (applicable to other light-scalar models)

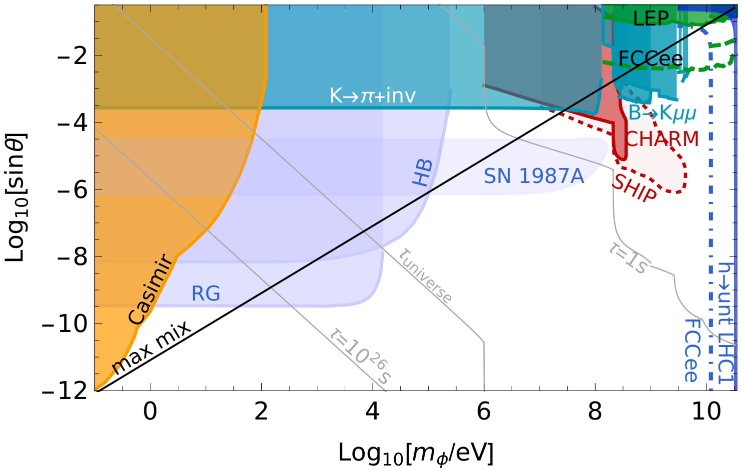
$\mathcal{CP}$-odd

$$\mathcal{L} \supset \frac{\phi}{4\pi f}\left(\frac{\tilde{c}_{\gamma\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu} + \frac{\tilde{c}_{Z\gamma}}{2}Z_{\mu\nu}\widetilde{F}^{\mu\nu} + \frac{\tilde{c}_{ZZ}}{4}Z_{\mu\nu}\widetilde{Z}^{\mu\nu} + \frac{\tilde{c}_{WW}}{4}W_{\mu\nu}\widetilde{W}^{\mu\nu} + \frac{\tilde{c}_{GG}}{4}G_{\mu\nu}\widetilde{G}^{\mu\nu}\right)$$

$\tilde{c}$ model-dependent: backreaction sector

III. Relaxion Searches

Status ($\mathcal{CP}$-even interaction)



5th force astro cosmo meson decays beam dump lepton collider LHC

Relaxion mass and mixing span many orders of magnitude

Precision probes

- Higgs couplings
  - sensitivity to $\mathrm{BR}(h \to \mathrm{NP})$?
  - deviation from self-coupling λ?

- Z total width?

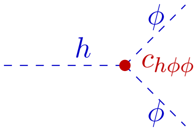
New decay mode of the Higgs

invisible and untagged final states

$$\Gamma_h^{\rm NP} = \Gamma_h^{\rm inv} + \Gamma_h^{\rm unt}$$

total Higgs width

$$\Gamma_h = \kappa^2\, \Gamma_h^{\rm SM} + \Gamma_h^{\rm NP}$$



relaxion: 2 parameters → fit (as SM+singlet)

- $\mathrm{BR}(h \to \mathrm{NP}) = \mathrm{BR}(h \to \mathrm{unt}) = \mathrm{BR}(h \to \phi\phi)$ (GeV-scale relaxion decays inside detector)
- $\kappa \equiv \cos\theta$: universal coupling modifier

Triple-scalar coupling $h\phi\phi$

$$c_{\phi\phi h} = \frac{r_{\rm br}^4 v^3}{f^2} c_0 c_\theta^3 - \frac{2 r_{\rm br}^4 v^2}{f} s_0 c_\theta^2 s_\theta - \frac{r_{\rm br}^4 v^4}{2 f^3} s_0 c_\theta^2 s_\theta - \frac{2 r_{\rm br}^4 v^3}{f^2} c_0 c_\theta s_\theta^2 + 3 v \lambda c_\theta s_\theta^2 + \frac{r_{\rm br}^4 v^2}{f} s_0 s_\theta^3$$

$$\xrightarrow{\theta \to 0} \frac{r_{\rm br}^4 v^3}{f^2} c_0 c_\theta^3 \simeq \frac{m_\phi^2}{v}$$

where $s_0, c_0 \equiv \sin, \cos(\phi_0/f)$

Untagged Higgs decays

- Global Higgs coupling fits allow (under model assumptions) to bound BR($h \to$NP), in particular $h \to$untagged
- here $h \to \phi\phi \implies$ bound on $g_{h\phi\phi}$ containing term $\propto \cos^3\theta$
  $\rightsquigarrow$ does not vanish at $\theta \to 0$

expect $\sin\theta$-independent bound on m_ϕ for $\theta \to 0$: relaxion-specific

Upper bounds on $\mathrm{BR}(h \to \mathrm{NP})$

- $\mathrm{BR}(h \to \mathrm{inv})$ available for all colliders
- $\mathrm{BR}(h \to \mathrm{NP})$ often not available for suitable assumptions

Estimate via precision of couplings

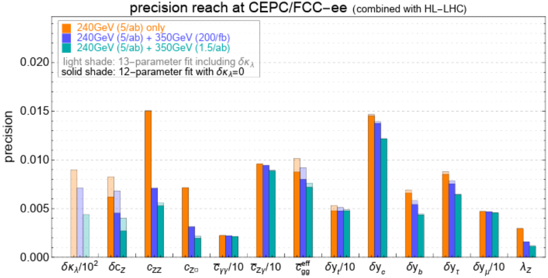
- κ_Z most precise $\to$ approximation of global κ
- rates constrain combination of κ and $\mathrm{BR}(h \to \mathrm{NP})$

$$\mathrm{BR}(h \to \mathrm{NP}) \leq 1 - \left(\frac{1-n\cdot\delta_\kappa}{\kappa}\right)^2$$

Conservative estimate; 2-parameter fit would be stronger than multi-κ

Higgs self-coupling λ

$$\lambda \simeq \frac{f^2 - 4r_{\rm br}^4\,\left(c_0 + 16 r_{\rm br}^4 s_0^2\right)\,v^2}{8\left(f^2 - 4c_0\,r_{\rm br}^4 v^2\right)}$$



[Di Vita, Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon '17]

- HL-LHC, FCCee, CLIC, ILC may reach a sensitivity of $10 - 50\%$

  [Di Vita et al '17, Abramowicz et al '16]

- relaxion-induced deviations from SM prediction $< 10\%$ for $\sin^2\theta < 0.1$

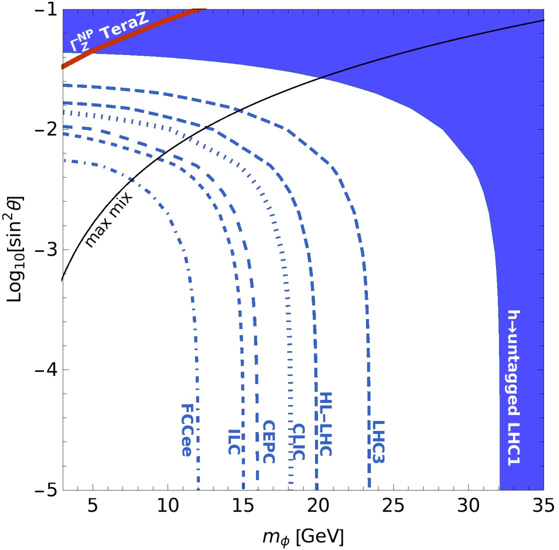
$\Longrightarrow$ too small to be resolved

Z precision measurements

Precision measurements at the Z-pole

- relaxion opens NP contribution: $\Gamma_Z^{\rm NP} = \Gamma(Z \to \phi f \bar{f})$
- bounded by $\delta\Gamma_Z^{\rm LEP1} = 2.3\,{\rm MeV} \to \delta\Gamma_Z^{\rm TeraZ} = 0.1\,{\rm MeV}$ [Bicer et al '14]
- $\leadsto$ theory improvement needed:
  $\delta\Gamma_Z^{\rm th} = 0.5\,{\rm MeV} \to \delta\Gamma_Z^{\rm th,3loop} = 0.2\,{\rm MeV}$ [Freitas '14]

Resulting indirect bounds



- Z and Higgs precision measurements
- lepton colliders powerful

$h \to$ untagged: bound on mass independent of $\sin\theta$ for small mixing

Direct probes: ϕ production as a light Higgs

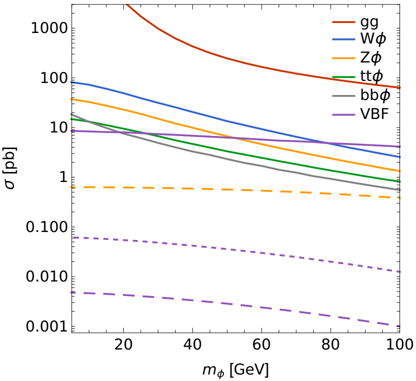
Production at the LHC

- $pp \to \phi$ (gg)
- $pp \to Z\phi, W\phi$
- $pp \to t\bar{t}\phi, b\bar{b}\phi$
- $pp \to \phi jj$ (VBF)

Production at lepton colliders

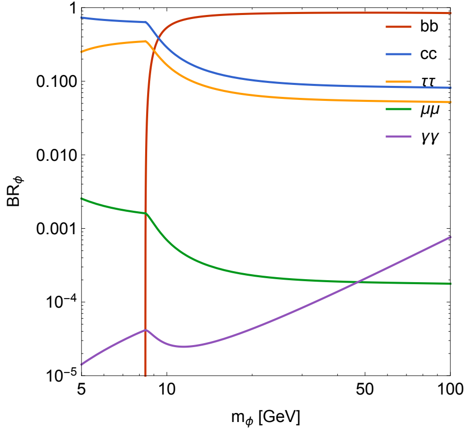
- $e^+e^- \to Z\phi$
- $Z \to Z^*\phi$, $Z^* \to ff$

measurements at and above Z-pole



Hadronic cross sections at 13 TeV (solid) and leptonic ones at 240 GeV (dashed) for $\sin^2\theta = 1$.

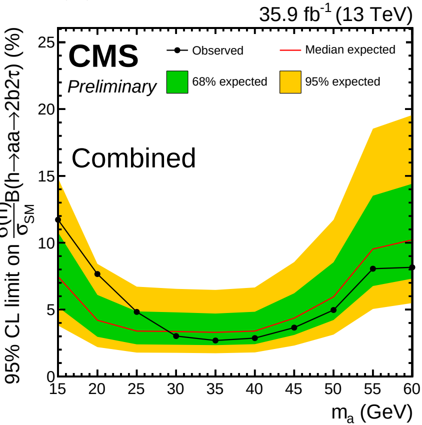
Branching ratios

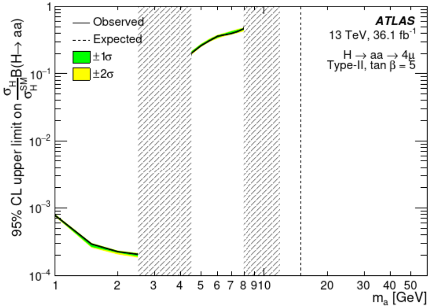


exploit all final states: suitable at lepton/hadron colliders

Searches for exotic Higgs decays

$h \to \phi\phi \to XXYY$ [e.g. CMS-PAS-HIG-17-024, ATLAS 1802.03388]



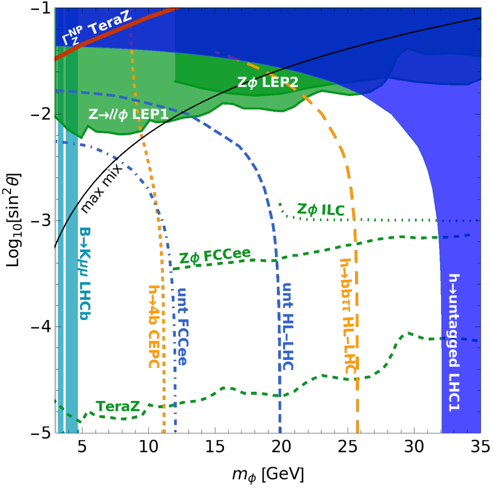


(b) $H \to aa$

- $\mathrm{BR}(h \to \phi\phi \to 4b) \lesssim \mathcal{O}(10^{-3})$ at CEPC with $\sqrt{s} = 240\,\mathrm{GeV}$

  [Liu. Wang, Zhang '17]

Comparison of direct and indirect bounds



- production at TeraZ, FCCee: rough estimate by rescaling LEP1,2
- ILC: light Higgs study applicable

  [Drechsel, Moortgat-Pick, Weiglein '18]

- $\Delta\Gamma_Z$ not competitive

direct & indirect bounds complementary

future colliders probe relevant mixing

$\mathcal{CP}$-violating nature of the relaxion

- so far: assumed dominating $\mathcal{CP}$-even couplings $(\sin\theta)$
- constraints on $\mathcal{CP}$-odd couplings:
  - $f/\tilde{c}_{\gamma\gamma} > 500\,\mathrm{GeV}$ from Pb-Pb collisions [Knapen, Lin, Lou, Melia '17]
  - $f/\tilde{c}_{Z\gamma} > 1\,\mathrm{TeV}$ from rare Z decays [Bauer, Neubert, Thamm '17]
  - $f/\tilde{c}_{\gamma\gamma} > 2.5 \times 10^4 \sin\theta\,\mathrm{GeV}$ from e-EDM [Flacke, Frugiuele, EF, Gupta, Perez '16]
- ALP at colliders studied, e.g. [Bauer, Neubert, Thamm '17] [Brivio et al '17] [Buttazzo, Redigolo, Sala, Tesi '18] ,...

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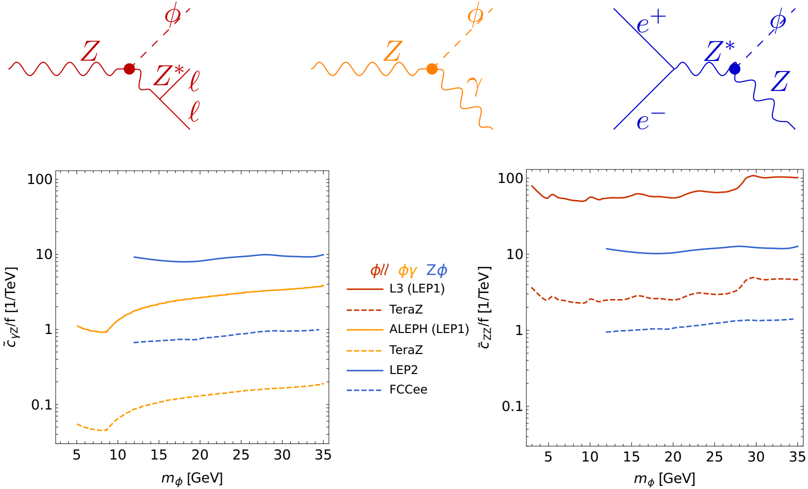
Possible hints of $\mathcal{CP}$-violating interaction

- observation of $\phi\gamma$ and ϕZ production
  - $\phi\gamma$ loop-suppressed both for $\mathcal{CP}$-even and -odd coupling
    $\rightsquigarrow$ possibly of similar order
- angular analyses of $\phi \to f\bar{f}$ decays which can be realised by $\mathcal{CP}$-even and -odd couplings

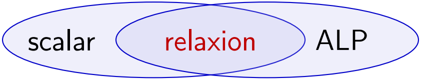
goal: distinction between pure H portal/ SM+singlet, pure axion-like and genuine relaxion signatures

New bounds on $\tilde{c}_{\gamma Z}$ and $\tilde{c}_{ZZ}$



{LEP1, LEP2} $\rightarrow$ strong bounds expected at {TeraZ, FCCee}

Summary



- relaxion attractive framework for naturalness without NP at TeV scale
- relaxion mass, mixing and lifetime: many orders of magnitude possible
  $\rightsquigarrow$ searches via 5th force, astro, cosmo, flavour and colliders
- $\mathcal{CP}$-violating relaxion-Higgs mixing $\rightsquigarrow$ close connection to Higgs physics
- $\mathcal{CP}$-even and -odd couplings for model distinction
- LEP, LHC probe already "high-mass" region,
  (future) colliders such as HL-LHC, FCCee/TLEP, ILC, CLIC:
  promising sensitivity esp. via ϕ-strahlung and Higgs couplings

Outlook/discussion

- background studies for the proposed processes
- higher-order corrections
- systematic investigation of interplay of $\mathcal{CP}$-even and -odd couplings
- further experimental searches for scalars of $5 - 35\,\mathrm{GeV}$ needed
- collider information for $h \to \mathrm{NP}$ (in addition to $h \to \mathrm{inv}$)

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pushing the low-mass collider frontier = high-mass relaxion region

relaxion as a benchmark – applicable to other models

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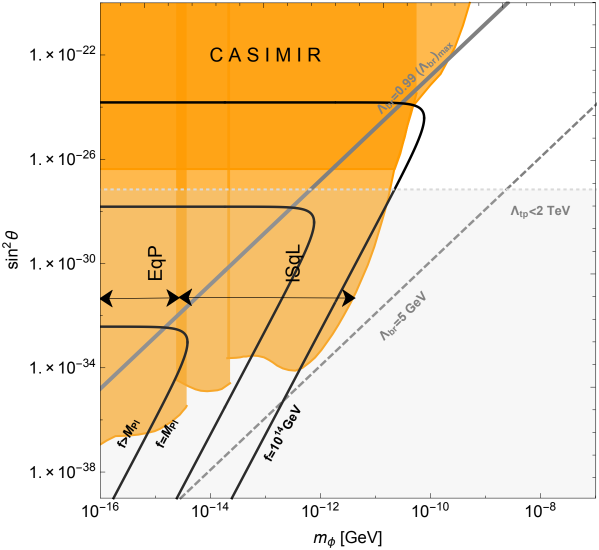
THANK YOU!

APPENDIX

Low-energy: 5th force



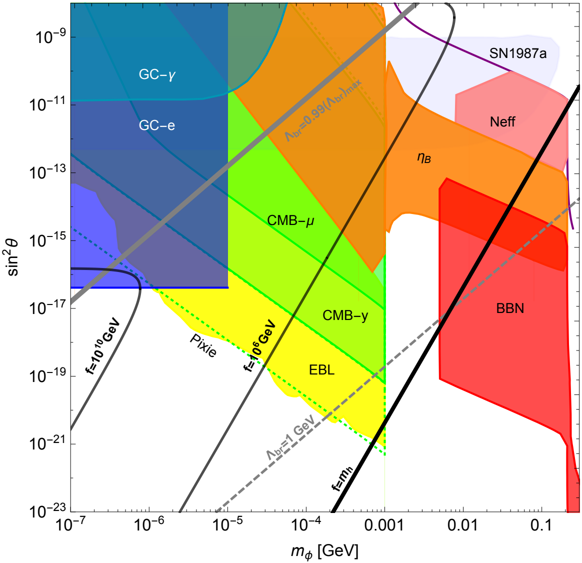
[Flacke, Frugiuele, EF, Gupta, Perez '16]

- torsion balance experiments:
  - weak equivalence principle (EqP)
  - inverse square law (ISqL)
- Casimir force

re-interpreted from
[Eöt-Wash group (Adelberger et al.)] [Bordag, Mohideen, Mostepanenko '01] [Piazza, Pospelov '10] [...]

Cosmological and astrophysical bounds

[Flacke, Frugiuele, EF, Gupta, Perez '16]

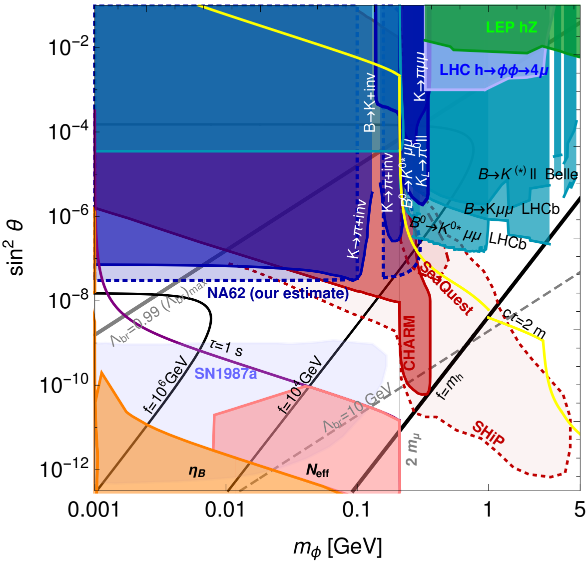


some bounds re-interpreted from

[Kolb, Turner] [Cadamuro, Redondo '12] [Arias, Cadamuro, Goodsell, Jäckel, Redondo, Ringwald '12] [...]

Meson decays (mass range of MeV – few GeV)

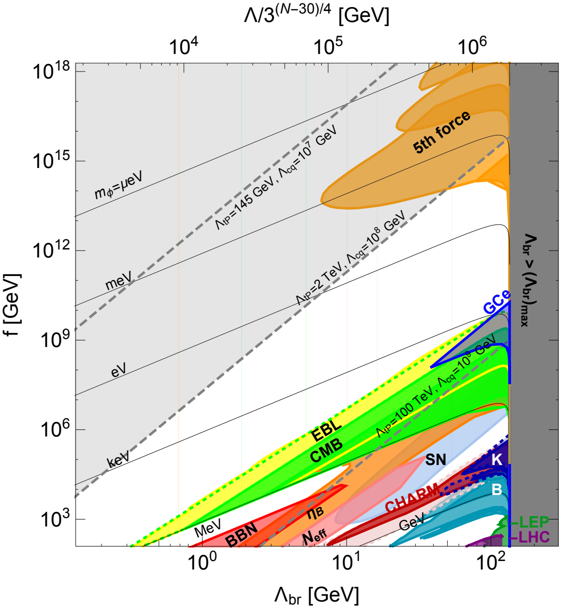
[Flacke, Frugiuele, EF, Gupta, Perez '16]



some bounds re-interpreted from [Clarke, Foot, Volkas '13] [Schmidt-Hoberg, Staub, Winkler '13]] [Dolan, Kahlhoefer, McCabe, Schmidt-Hoberg '14] [Krnjaic '15]

Relaxion parameter space

[Flacke, Frugiuele, EF, Gupta, Perez '16]



Bounds on untagged/invisible Higgs decays

Collider	$\sqrt{s}$ [TeV]	$\mathcal{L}_{\text{int}}$ [fb^{-1}]	BR_{inv} [%]	BR_{NP} [%]
LHC1	$7, 8$	22	37	20
LHC3	13	300	8.8 (68%)	7.6 (68%)
HL-LHC	13	3 000	5.1 (68%)	4.3 (68%)
CLIC	0.38	500	0.97 (90%)	3.1
CEPC	0.25	5 000	1.2	1.9
ILC	0.25	2 000	0.3	1.5
FCCee	0.24	10 000	0.19	0.64

Searches for $h \to \phi\phi \to F$ at ATLAS and CMS

F	exp.	$\sqrt{s}$ [TeV]	$\mathcal{L}_{\rm int}$ [fb^{-1}]	m_ϕ [GeV]	comment	$m_\phi^{\rm HL}$ [GeV]
$bb\tau\tau$	CMS	13	35.9	15-60		26
$bb\mu\mu$	CMS	8	19.7	15-62.5		27
	ATLAS	13	36.1	20-60		30
$\tau\tau\mu\mu$	CMS	13	35.9	15-62.6		-
4τ	CMS	8	19.7	5-15		-
4μ	CMS	13	2.8	0.25-8.5	NMSSM, γ_D	-
	ATLAS	13	2.8	1-2.5, 4.5-8	2HDMS, Z_D	
$4b$	ATLAS	13	36.1	20-60	Zh	27
					Wh	29
$\gamma\gamma gg$	ATLAS	13	36.7	20-60	VBF	-

Approximation of $\mathrm{BR}(h \to \mathrm{NP})$

Dilution of the BR of the h into SM:

$$\mathrm{BR}(h \to F) = \mathrm{BR}^{\mathrm{SM}}(h \to F) \cdot [1 - \mathrm{BR}(h \to \mathrm{NP})]$$

SM-like at $n\,\sigma$:

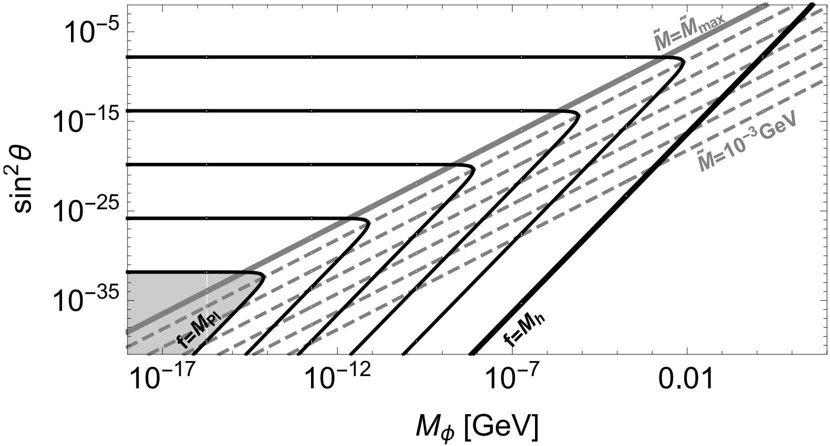
$$(1 - n \cdot \delta_\kappa)^2 \leq \kappa^2 \cdot [1 - \mathrm{BR}(h \to \mathrm{NP})]$$

upper bound on $\mathrm{BR}(h \to \mathrm{NP})$:

$$\mathrm{BR}(h \to \mathrm{NP}) \leq 1 - \left(\frac{1 - n \cdot \delta_\kappa}{\kappa}\right)^2$$

"Higgs portal" vs relaxion

translation $(m_\phi, s_\theta) \longleftrightarrow (\tilde{M}, f)$



given $(m_\phi, f) \longrightarrow$ 2 solutions of $\tilde{M}$

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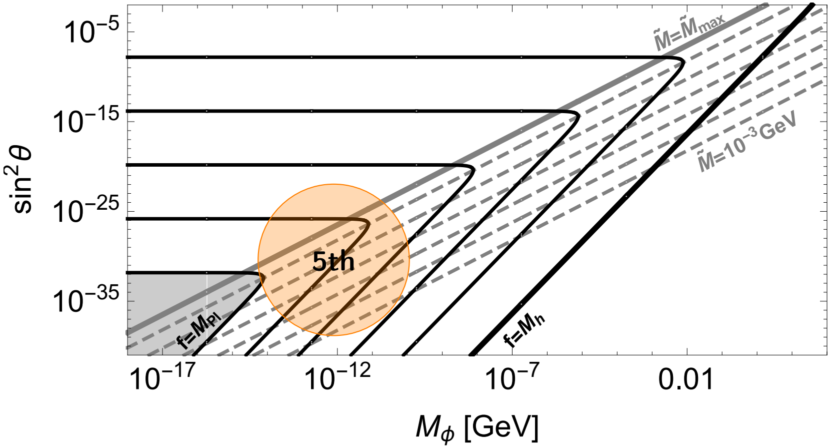

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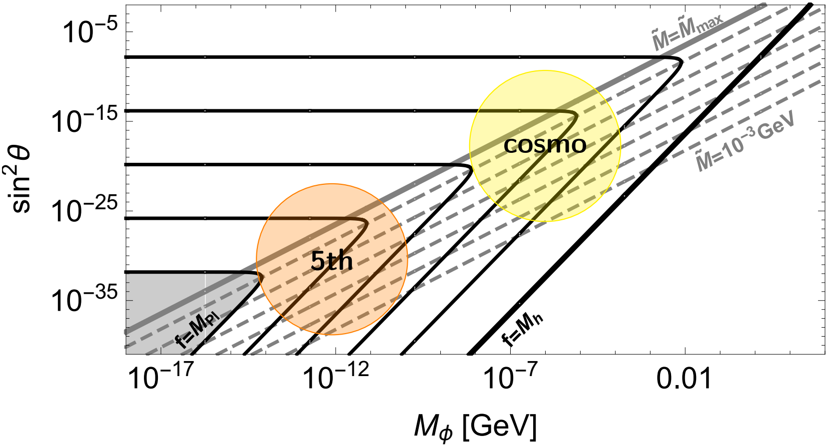
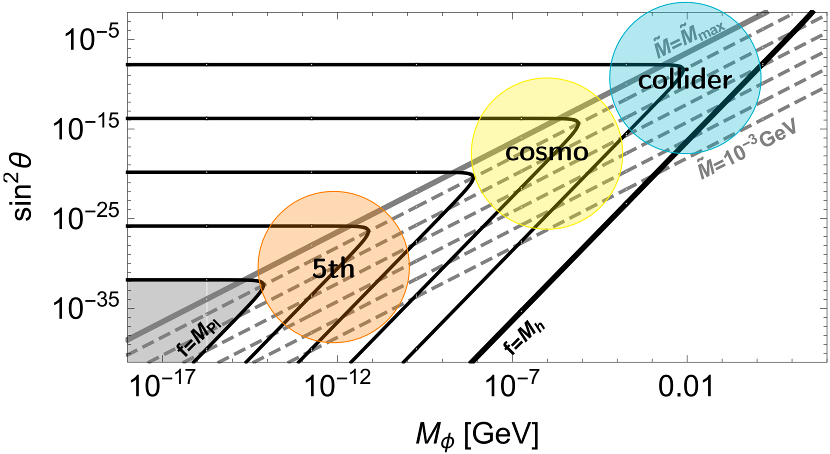


given $(m_\phi, f) \longrightarrow$ 2 solutions of $\tilde{M}$

"Higgs portal" vs relaxion

translation $(m_\phi, s_\theta) \longleftrightarrow (\tilde{M}, f)$



given $(m_\phi, f) \longrightarrow$ 2 solutions of $\tilde{M}$