Hunting relaxions

in the lab, in the sky and at colliders .

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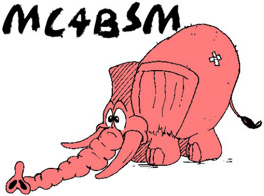
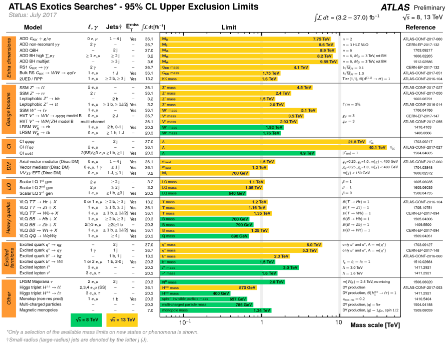
[1610:02025] Flacke, Frugiuele, EF, Gupta, Perez
[1804:XXXXX] Frugiuele, EF, Perez, Schlaffer

MC4BSM, IPPP Durham
April 21, 2018



Challenges for naturalness at the TeV-scale

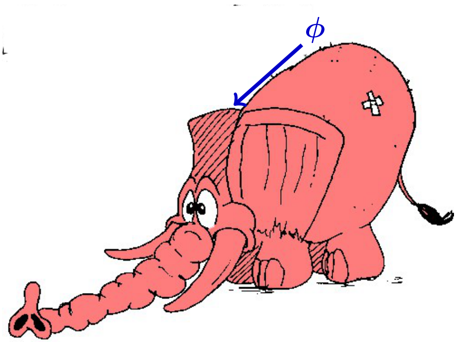
- symmetry-based theories of naturalness: NP $\sim$ TeV
  - e.g. SUSY, composite Higgs
  - various other models
- under pressure by null-results at LHC
  - how much tuning acceptable?
  - still some blind spots survive
- novel ideas for naturalness with light NP
  - instead of symmetry protection of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



Outline

Relaxion framework

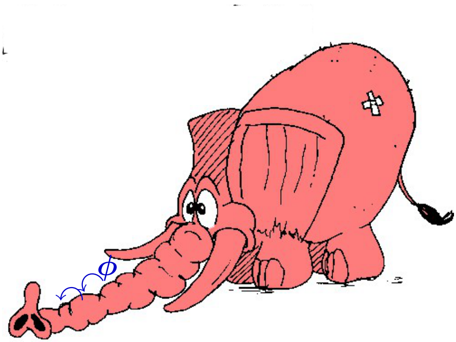
[Graham, Kaplan, Rajendran '15]



1. relaxion ϕ slowly rolls down potential, μ^2 evolves

Relaxion framework

[Graham, Kaplan, Rajendran '15]



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2. backreaction switched on for $\mu^2 < 0$, relaxion oscillates

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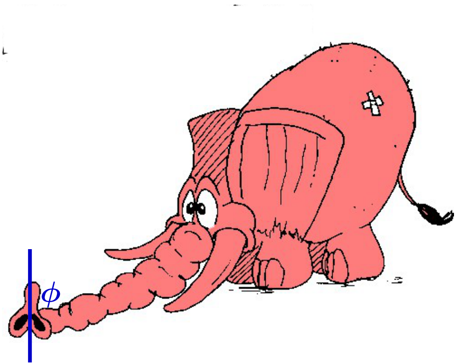
[Graham, Kaplan, Rajendran '15]



1. relaxion ϕ slowly rolls down potential, μ^2 evolves
2. backreaction switched on for $\mu^2 < 0$, relaxion oscillates
3. relaxion stopped $\rightsquigarrow$ Higgs mass $m_h = 125\,\mathrm{GeV}$

Relaxion mechanism

[Graham, Kaplan, Rajendran '15]

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

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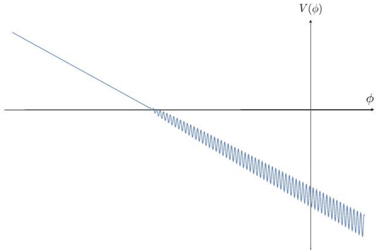
1. $\phi \geq \Lambda/g \Rightarrow \mu^2 > 0$, no vev
2. $\phi < \Lambda/g \Rightarrow \mu^2 < 0$, sign flip, EWSB
3. backreaction $V_{\rm br} = \Lambda_{\rm br}^4 \cos\left(\frac{\phi}{f}\right)$
4. $\phi \searrow \Rightarrow |\mu^2(\phi)|, v^2 \nearrow \Rightarrow \Delta V_{\rm br} \nearrow$
5. until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

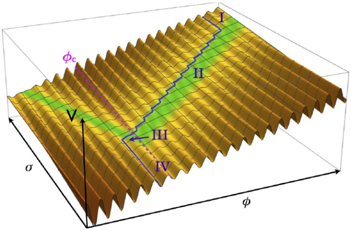


Relaxion models (examples)

- minimal model: QCD (rel)axion, $\Lambda_{\rm br}^4 = 4\pi f_\pi^3 y_u v/\sqrt{2}$, challenge to achieve small QCD phase
- 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

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)

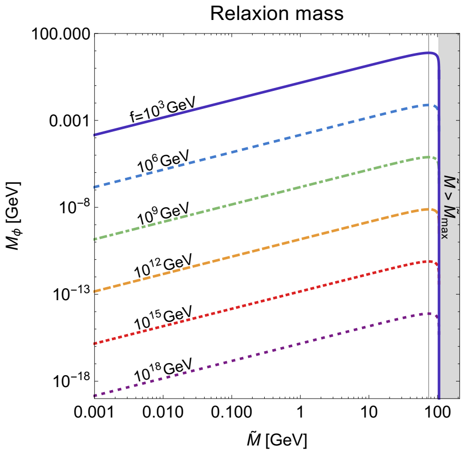
minimum of $V(\phi, h)$: $(\phi_0, v = 246\,\mathrm{GeV})$,
ϕ_0: endpoint of rolling, $s_0 \equiv \sin(\phi_0/f)$ can be $\mathcal{O}(1)$ or smaller

Mixing term in the relaxion-Higgs potential

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

$\boldsymbol{V(h, \phi) \supset h\phi}$ **:** 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 $f \gg r_{\rm br}^2 v$, $16\, r_{\rm br}^4 s_0^2 \ll c_0$)

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

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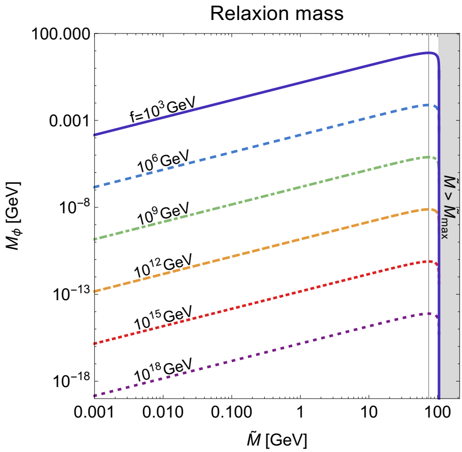

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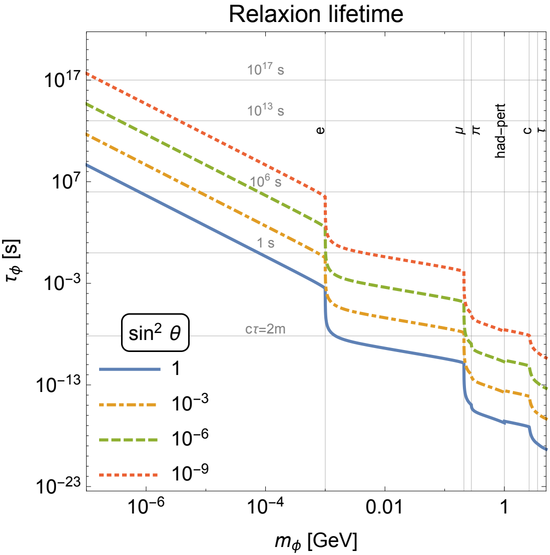
"Relaxion line": maximal mixing depends linearly on mass

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

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)

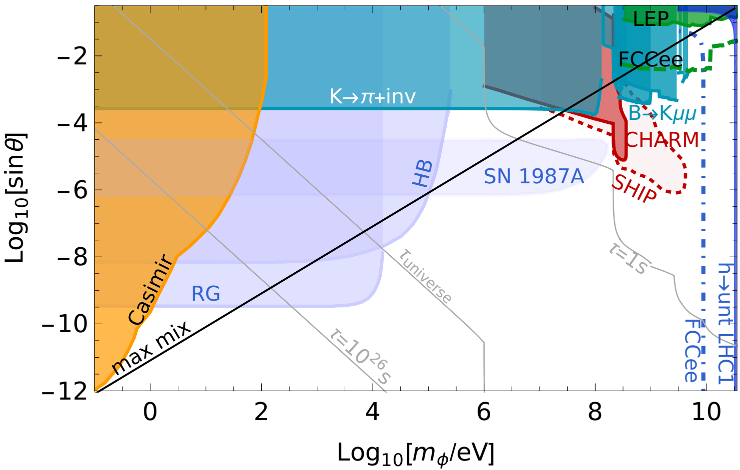
$\mathcal{CP}$-odd

$$\mathcal{L} \supset \frac{\phi}{4\pi f}\left[\tilde{c}_{\gamma\gamma} F_{\mu\nu}\widetilde{F}^{\mu\nu} + \tilde{c}_{Z\gamma} Z_{\mu\nu}\widetilde{F}^{\mu\nu} + \tilde{c}_{ZZ} Z_{\mu\nu}\widetilde{Z}^{\mu\nu} + \tilde{c}_{WW} W_{\mu\nu}\widetilde{W}^{\mu\nu}\right]$$

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

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

[Frugiuele, EF, Schlaffer, Perez '18 (in preparation)] [Flacke, Frugiuele, EF, Gupta, Perez '16]



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

Relaxion mass and mixing span many orders of magnitude

Indirect probes I: Higgs couplings

Untagged Higgs decays

- Higgs coupling fits allow (under model assumptions) to bound the BR($h \to$NP), in particular $h \to$untagged
- interpret as $h \to \phi\phi \implies$ bound on $g_{h\phi\phi}$, which contains term $\propto \cos^3\theta$ $\rightsquigarrow$ does not vanish at $\theta \to 0$
- stronger bound than direct searches for $h \to \phi\phi \to 4f, 2f2\gamma$ [ATLAS, CMS]

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Higgs self-coupling λ

- 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 $\sin^2\theta < 0.1$ $\implies$ too small to be resolved

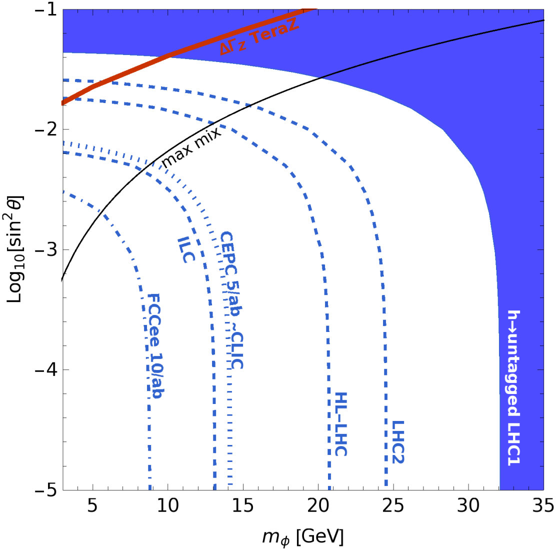
Indirect probes II: Z precision

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]
  $\rightsquigarrow$ 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]

Indirect probes III: resulting bounds

[Frugiuele, EF, Schlaffer, Perez '18 (in preparation)]



- 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

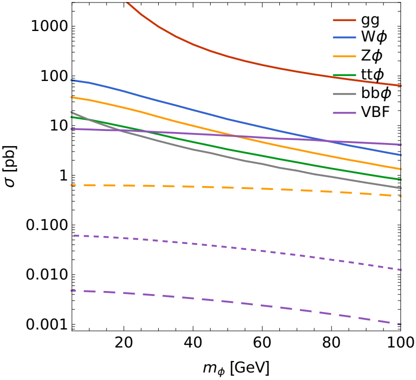
- $pp \to \phi$ (gg)
- $pp \to Z\phi, W\phi$
- $pp \to t\bar{t}\phi, b\bar{b}\phi$
- $pp \to \phi jj$ (VBF)

Production at lepton colliders

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

measurements at and above Z-pole

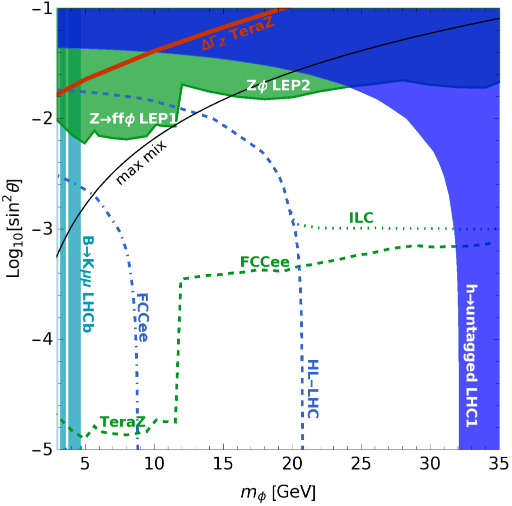
[Frugiuele, EF, Schlaffer, Perez '18 (in preparation)]



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

Comparison of direct and indirect bounds

[Frugiuele, EF, Schlaffer, Perez '18 (in preparation)]



- 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:
  - $f/\tilde{c}_{\gamma\gamma} > 1800\,\mathrm{GeV}$ from Pb-Pb collisions [Knapen, Lin, Lou, Melia '17]
  - $f/\tilde{c}_{Z\gamma} > 650\,\mathrm{GeV}$ from rare Z decays [Bauer, Neubert, Thamm '17]
  - $f/\tilde{c}_{\gamma\gamma} > 10^5 \sin\theta\,\mathrm{GeV}$ from e-EDM [Flacke, Frugiuele, EF, Gupta, Perez '16]

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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, pure axion-like and genuine relaxion signatures

Summary

- relaxion attractive framework for naturalness without NP at TeV scale, different realisations of backreaction
- 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 $\rightsquigarrow$ constraints/discovery
- $\mathcal{CP}$-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

- background studies for the proposed processes
- higher-order corrections
- full implementation of couplings, option for various backreaction sectors
- systematic investigation of interplay of $\mathcal{CP}$-even and -odd couplings
- further experimental searches for scalars of $5 - 35\,\mathrm{GeV}$ needed

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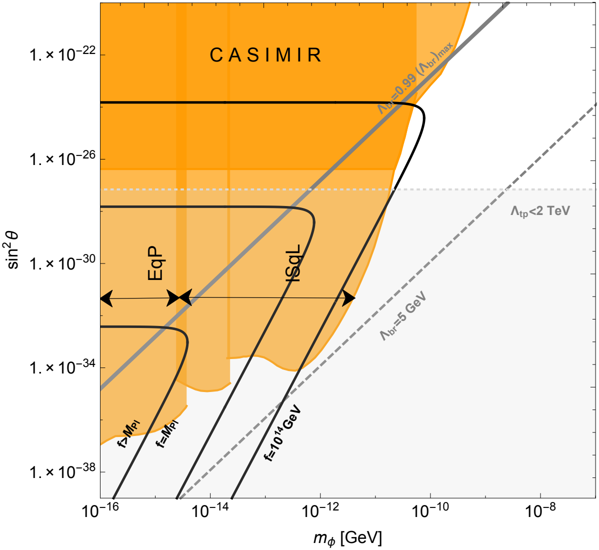
THANK YOU!

APPENDIX

Low-energy: 5th force



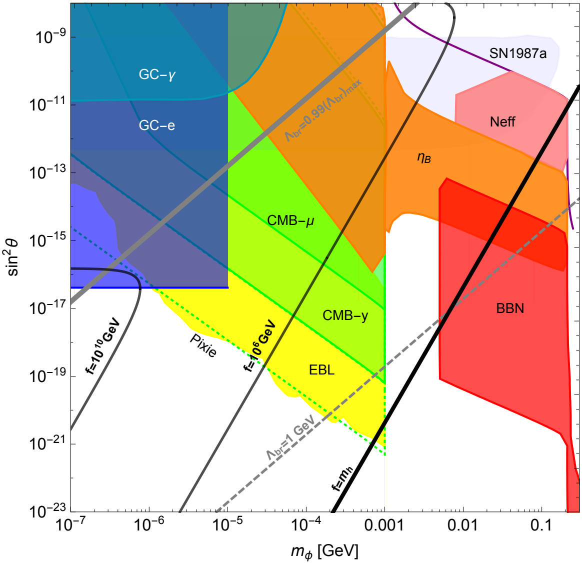
[Flacke, Frugiuele, EF, Gupta, Perez '16]

- 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

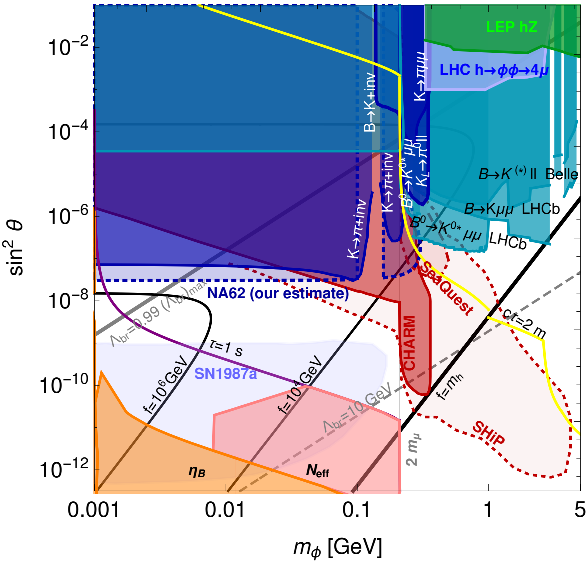
[Flacke, Frugiuele, EF, Gupta, Perez '16]



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)

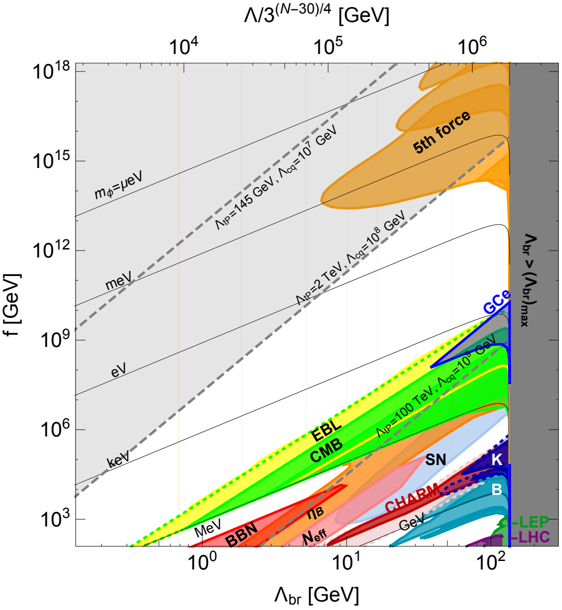
[Flacke, Frugiuele, EF, Gupta, Perez '16]



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 Higgs decays

Collider	$\sqrt{s}$	$\mathcal{L}_{\rm int}$ [fb^{-1}]	BR($h \to$ unt.) [%]	Ref.
LHC	$7, 8\,\text{TeV}$	22	20	[Bechtle et al '14, Belanger et al '13]
LHC	$7, 8, 14\,\text{TeV}$	300	8.9	[Bechtle et al]
HL-LHC	$7, 8, 14\,\text{TeV}$	3 000	5	[Bechtle et al]
CEPC	250 GeV	5 000	1.2	[Chen et al '16]
CLIC	380 GeV	500	0.97 at 90% C.L.	[Abramowicz et al '16, CLIC '16]
ILC	250 GeV	250	0.9	[Dawson et al '13]
ILC	250 GeV	2 000	0.3	[Fujii et al '17]
FCCee	240 GeV	10 000	0.19	[Dawson et al '13, Gomez-C. et al '13]

Current upper bound and projections on the branching ratio of $h \to$untagged at various colliders running at the given centre-of-mass energies $\sqrt{s}$ and assuming an integrated luminosity of $\mathcal{L}_{\rm int}$. All bounds are given at the 95% C.L. apart from CLIC for which the limit is reported at the 90% C.L.

The $h\phi\phi$ and Higgs self-coupling

[Flacke, Frugiuele, EF, Gupta, Perez '16] [Frugiuele, EF, Schlaffer, Perez (in preparation)]

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

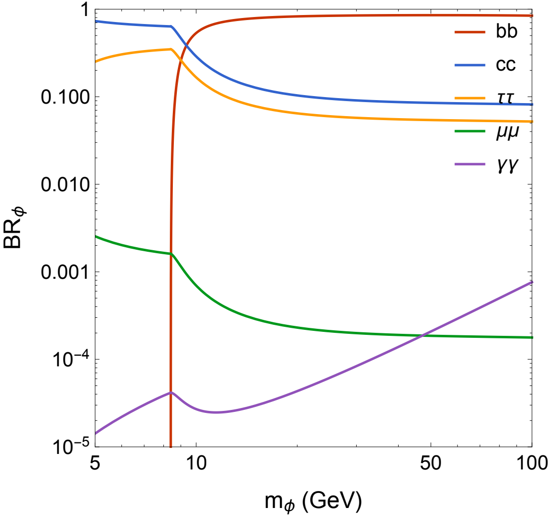
$$\xrightarrow{\theta\to 0} \frac{r_{\rm br}^4 v^3}{f^2} c_0 c_\theta^3 \simeq \frac{m_\phi^2}{v}$$

$$\lambda = \frac{-f^2 m_h^4 + c_0\, m_h^2\, r_{\rm br}^4 v^4 + 4 r_{\rm br}^8\, s_0^2\, v^6}{-2 f^2 m_h^2 v^2 + 2 c_0\, r_{\rm br}^4 v^6} \simeq \frac{f^2 - 4 r_{\rm br}^4 \left(c_0 + 16 r_{\rm br}^4 s_0^2\right) v^2}{8\left(f^2 - 4 c_0\, r_{\rm br}^4 v^2\right)}$$

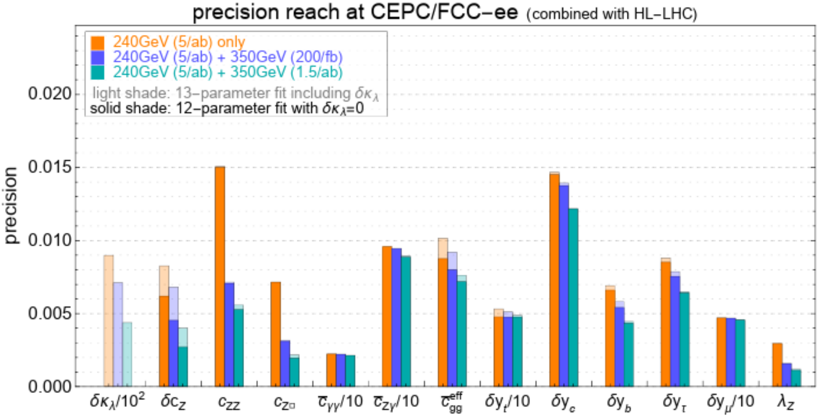
where $s_0, c_0 \equiv \sin, \cos\left(\phi_0/f\right)$

Branching ratios

[Flacke, Frugiuele, EF, Gupta, Perez '16] [Frugiuele, EF, Schlaffer, Perez (in preparation)]



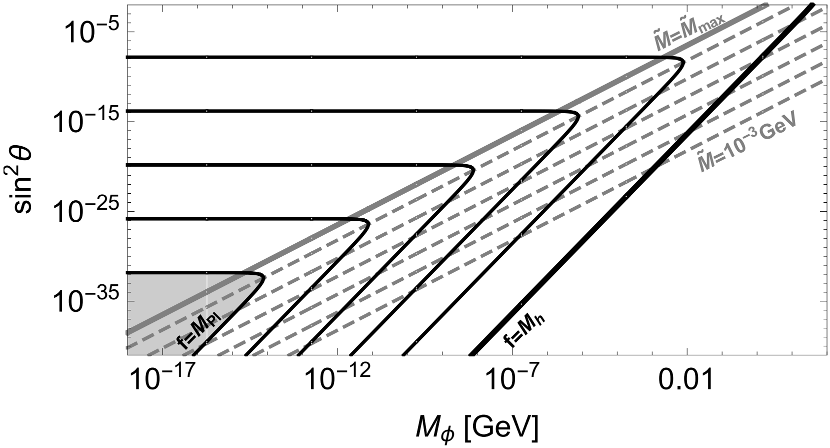
Projections for Higgs coupling precision



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

"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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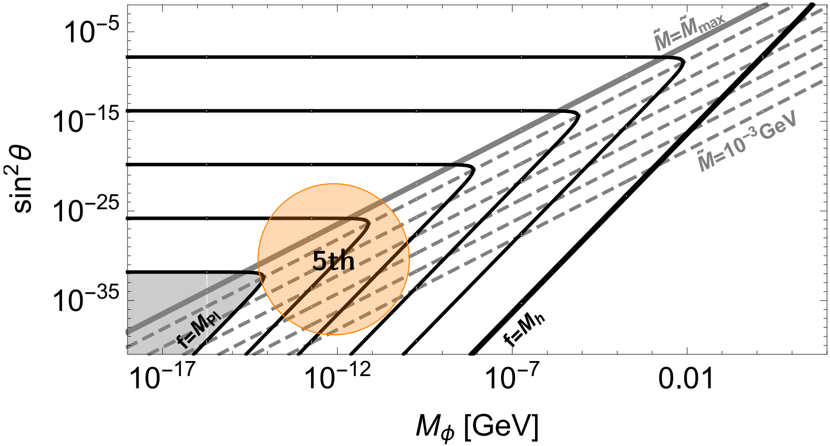

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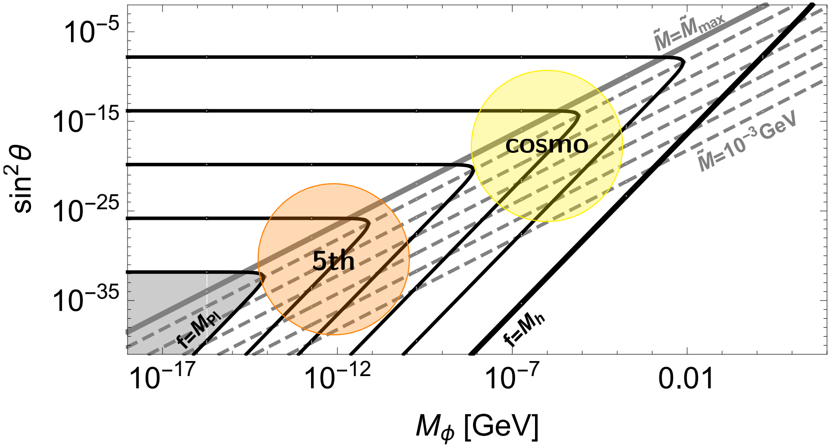

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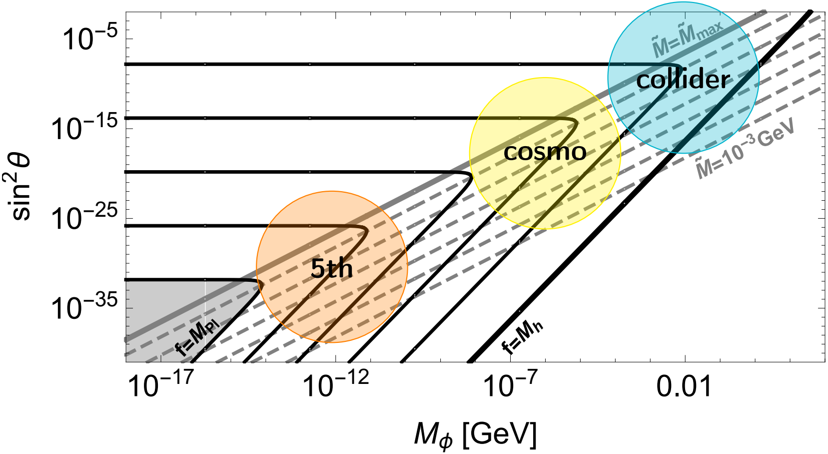

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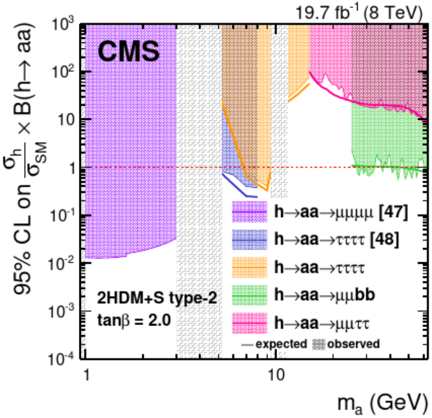
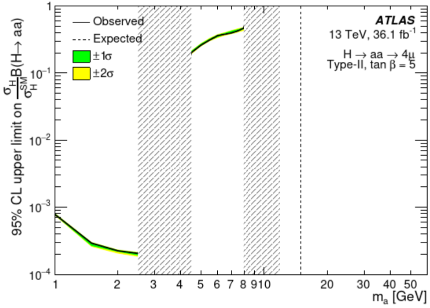
Exotic Higgs decays

[CMS 1701.02032, ATLAS 1802.03388]





(b) $H \to aa$