$\mathcal{CP}$ violation in BSM Higgs sectors

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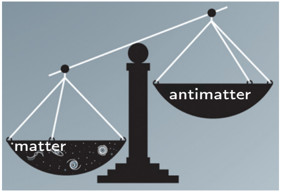
Necessity for BSM $\mathcal{CP}$ violation

Baryon asymmetry



[adapted from quantumdiaries]

$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$ observed

SM: phases $\delta_{\rm CKM}$ and $\bar{\theta}_{\rm QCD} < 10^{-10}$ insufficient

furthermore strong 1st order phase transition needed

$\rightsquigarrow$ need NP connected to Higgs sector

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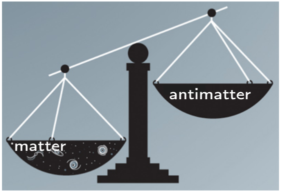

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Possible fingerprints of $\mathcal{CP}$ violation in the Higgs sector

- properties of the h^{125} $\longrightarrow$ precision, angular distributions
- additional (pseudo)scalars $\longrightarrow$ searches for new resonances

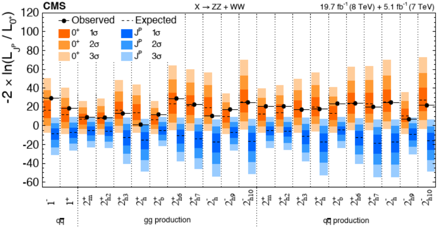
Outline

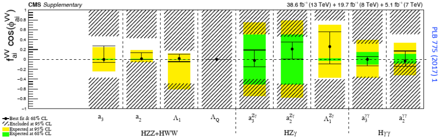
1. Motivation: baryogenesis
2. Observables to test the $\mathcal{CP}$ nature
3. Models with $\mathcal{CP}$ violation in the Higgs sector

Observables to test the $\mathcal{CP}$ nature

Status of the $h(125\,\mathrm{GeV})$

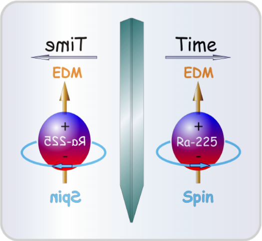
- the Higgs at 125 GeV is very SM-like
  - coupling strengths $\hookrightarrow$ talk by Zirui Wang
  - spin and $\mathcal{CP}$ compatible with $J^{\mathcal{CP}} = 0^{++}$
  - $J = 1, 2$ and pure pseudoscalar excluded
- $\mathcal{CP}$-odd admixture constrained but not completely ruled out



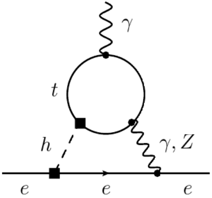


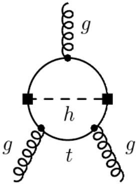
Bottleneck: Electric Dipole Moments (EDMs)

[Hewett, Weerts et al '12]



EDM violates $\mathcal{T}$ and $\mathcal{P}$
$\Rightarrow \not{\mathcal{CP}}$





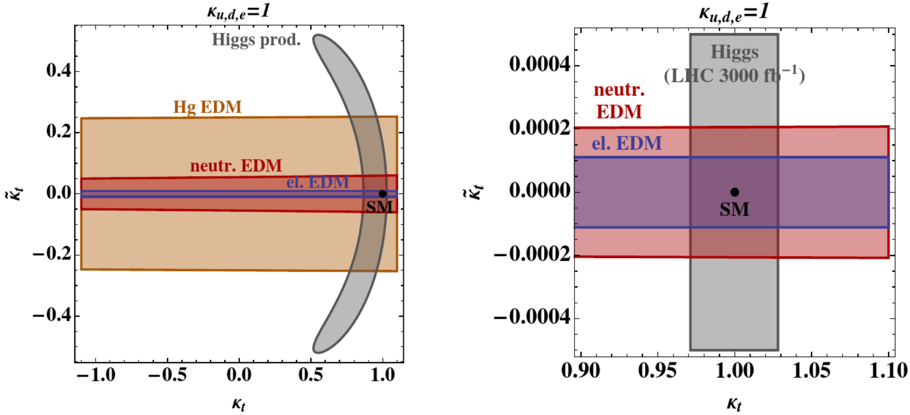
BSM: $h \rightarrow$ additional scalars,
$t \rightarrow$ additional electrically/ colour charged particles

EDM	95% CL upper limits [e cm]	Ref.
electron d_e	$8.7 \cdot 10^{-29}$	[ACME '14]
neutron d_n	$4.7 \cdot 10^{-26}$	[Baker et al '06]
mercury d_{Hg}	$3.5 \cdot 10^{-29}$	[Griffith et al '09]

anticipated improvement of d_e by factor 90 [Hewett, Weerts et al '12]

EDM and collider rates: top

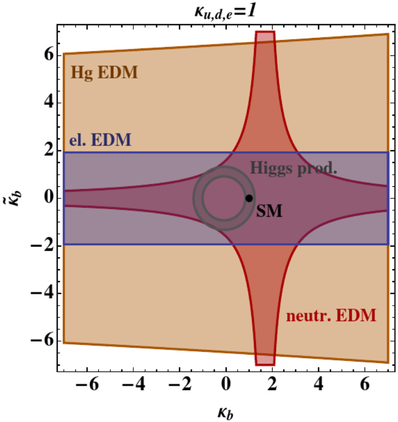
[Brod, Haisch, Zupan '13]

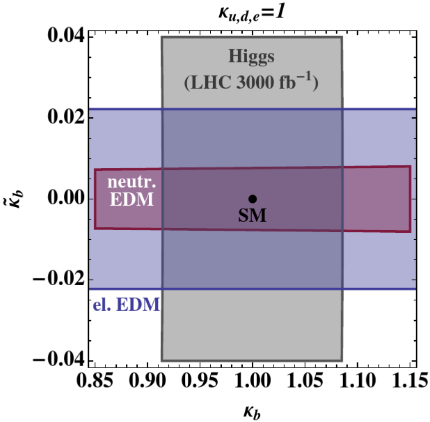


$\kappa_t, \tilde{\kappa}_t$ bounded by loop contribution to κ_g, κ_γ
all other couplings fixed to SM value

EDM and collider rates: bottom

[Brod, Haisch, Zupan '13]



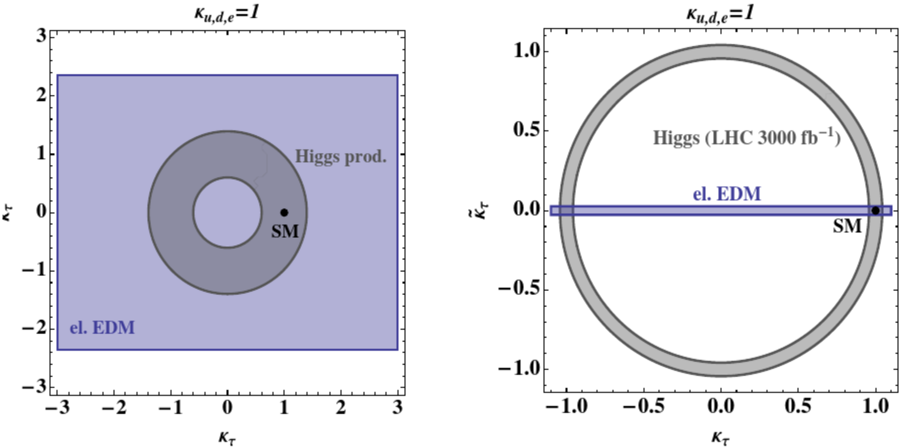


$\kappa_b, \tilde{\kappa}_b$ bounded by the total Higgs width
all other couplings fixed to SM value

EDM and collider rates: leptons

[Brod, Haisch, Zupan '13]

τ



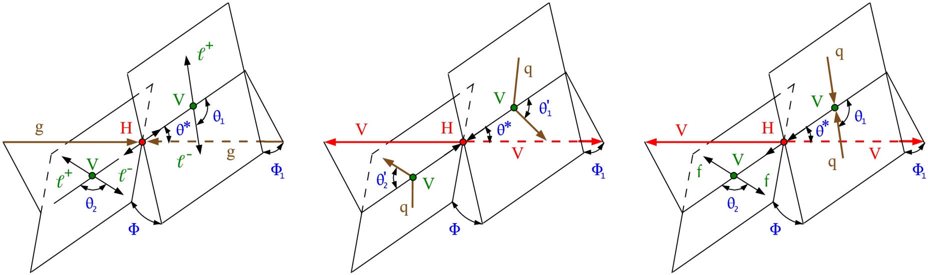
$\kappa_\tau, \tilde{\kappa}_\tau$ bounded by the total Higgs width via κ_γ (2% precision with $3\ \mathrm{ab}^{-1}$)
all other couplings fixed to SM value

e : $|\kappa_e| < 6.1 \times 10^2, |\tilde{\kappa}_e| < 1.7 \times 10^{-2}$ from eEDM [Dery, Frugiuele, Nir '17]

Differential distributions

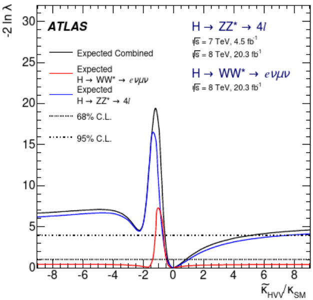
- total rates and EDM constraints on κ_f powerful, but depend on assumptions on the other couplings and EDM progress
- consider direct channels: angular distributions

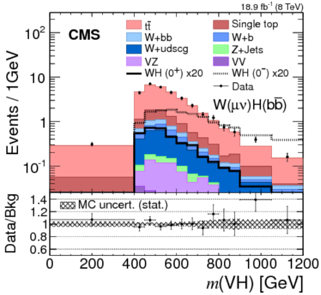
triple products $\vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$: $\mathcal{T}, \mathcal{P}$-odd, $\mathcal{C}$-even $\Rightarrow$ $\mathcal{CP}$-odd



Observables to decipher the $\mathcal{CP}$ nature: $h \to VV$

- $h \to VV$ in ggF, VBF, $qq \to V \to Vh$: 5 angles, 2 masses
- Vh
  - m_{Vh} larger for pseudoscalar
  - $h \to WW$ up-down $\mathcal{CP}$ asymmetry with $q/\bar{q}$ discriminating rapidity cuts [Delaunay, Perez, Sandes, Skiba '13]
- $h \to \gamma\gamma$ with converted photons [Bishara, Grossman, Harnik, Robinson, Shu, Zupan]
- $h \to Z\gamma$ with bkg interference [Farina, Grossman, Robinson]
- information geometry in VBF, Zh, $h \to 4l$ [Brehmer, Kling, Plehn, Tait '17]
- ...



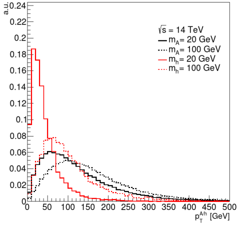


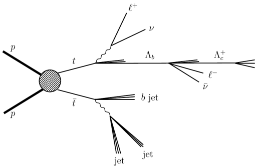
Observables to decipher the $\mathcal{CP}$ nature: $h \to f\bar{f}$

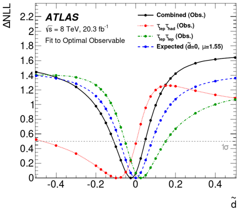
$$\mathcal{L} = -m_f \bar{f} f - \frac{y_f}{\sqrt{s2}} h \bar{f} \left(\cos\delta + i\gamma_5 \sin\delta\right) f,$$

δ: $\mathcal{CP}$ phase $\kappa_f = \cos\delta, \quad \tilde{\kappa}_f = \sin\delta$

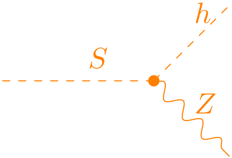
- $t\bar{t}$
  - $t\bar{t}h$, e.g. $p_T^{h,a}$ [Casolino, Farooque, Juste, Liu, Spannowsky '15] , dileptonic $t\bar{t}$ decay and $h \to b\bar{b}$ with jet substructure [Buckley, Goncalves '15]
  - tHj
- $b\bar{b}, c\bar{c}$ by Λ baryon polarization measurement in $W + c, t\bar{t}$ samples: $\mathcal{O}(10\%)$ at Run 2 [Galanti, Giammanco, Grossman, Kats, Stamou, Zupan '15] , [Kats '15 '15]
- $\tau^+\tau^-$: *optimal observable* (interference/SM)
- ...

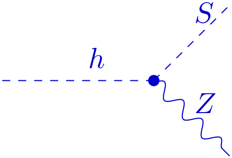


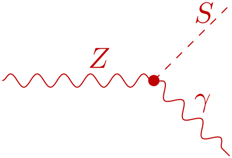




Characterize new spin-0 resonances







assume new singlet S:

1. $m_S > m_h + m_Z$
   - $S \to hZ$ allowed only if S has pseudoscalar coupling [Bauer, Neubert, Thamm '16] : mere observation of this process establishes presence of pseudoscalar coupling whereas processes allowed for scalars and pseudoscalar need angular analysis from the beginning
   - next step: scalar/pseudoscalar admixture requires angular analysis
2. $m_S < m_h - m_Z$
   - $h \to SZ$
3. $m_S < m_Z$
   - $Z \to S\gamma$ loop-induced in both cases of pseudoscalar and Higgs-like scalar: pseudoscalar less suppressed relative to scalar (in contrast to $Z^* \to ZS$)

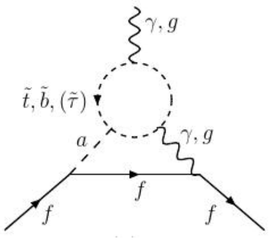
Models with $\mathcal{CP}$ violation in the Higgs sector

MSSM: higher-order $\not{CP}$ in the Higgs sector

Complex parameters of the model

- parameters from non-Higgs sectors can be **complex**
  - trilinear couplings A_f
  - higgsino mass parameter μ
  - gaugino mass parameters M_1, M_3
- most relevant for Higgs sector: $\phi_{A_{t,b}}, \phi_{M_3} \rightsquigarrow$ enter via **loops**

Constrained by EDMs see e.g. [Barger, Falk, Han, Jiang, Li, Plehn '01] [Ellis, Lee, Pilaftsis '09] [Li, Profumo, Ramsey-Musolf '10] [Arbey, Ellis, Godbole, Mahmoudi '14]



3×3 mixing among the neutral Higgs bosons

$\mathbb{C}$: $\mathcal{CP}$ eigenstates $\boldsymbol{h, H, A} \xrightarrow{\text{mix}}$ mass eigenstates $\boldsymbol{h_1, h_2, h_3}$

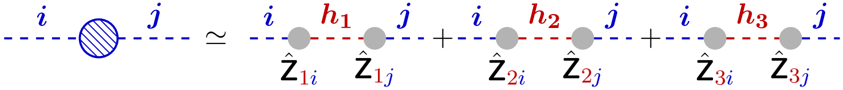
[Chankowski, Pokorski, Rosiek '93] [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '07] [Williams, Rzehak, Weiglein '11] , ...

- express full propagators in terms of mass eigenstates and mixing factors

$$\Delta_{ij}(p^2) \simeq \sum_{a=1,2,3} \hat{\mathbf{Z}}_{ai} \Delta_a^{\mathrm{BW}}(p^2) \hat{\mathbf{Z}}_{aj}$$

[EF, Weiglein '16]

full mixing — Breit-Wigner propagators — on-shell $\hat{\mathbf{Z}}$-factors approximate mixing



MSSM: $\mathcal{CP}$-violating interference

generally: $\Delta M \leq \Gamma_1 + \Gamma_2 \hookrightarrow$ overlapping resonances

MSSM: Higgs bosons can be quasi degenerate and interfere

$\mathbb{R}$	$\boldsymbol{h, H}$	$M_h \simeq M_H$ at high $\tan\beta$, low M_A
$\mathbb{C}$	$\boldsymbol{h_1, h_2, h_3}$	$M_{h_2} \simeq M_{h_3}$ in decoupling limit

if $\mathbb{C}$: *incoherent* sum $\sigma_H + \sigma_A$ not sufficient in heavy Higgs searches

need to include interference beyond NWA [Cacciapaglia, Deandrea, Curtis '09] [Blas, Lizana, Perez-Victoria '12] [Kauer '13] [EF, Thewes, Weiglein '14]

Factorisation: production $\times$ decay $\times$ interference factor [EF, Weiglein '17]

$$\sigma_{I\to h_a \to F} \simeq \sum_a \sigma_{I\to h_a} \times \boldsymbol{\eta_a^{IF}} \times \mathrm{BR}_{h_a\to F}, \qquad \boldsymbol{\eta_a^{IF}} \stackrel{2\times 2}{=} \frac{2\mathrm{Re}\left[\mathcal{A}_{h_2}\mathcal{A}_{h_3}^*\right]}{|\mathcal{A}_{h_2}|^2+|\mathcal{A}_{h_3}|^2}$$

- interference factor $\boldsymbol{\eta_a^{IF}}$ implemented in `SusHi`, provided with ROOT files for benchmark scenario

MSSM: $M_{h_1}^{125}$(CPV) benchmark with interference

[Bahl, EF, Hahn, Heinemeyer, Liebler, Patel, Slavich, Stefaniak, Wagner, Weiglein '18]

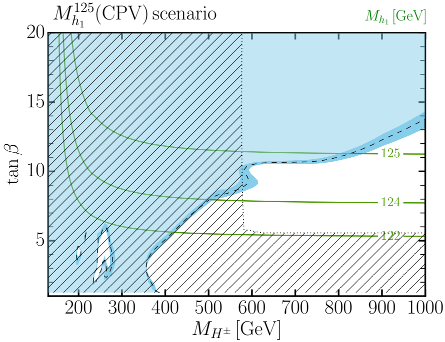
$M_{\text{SUSY}} = 2\,\text{TeV}, \mu = 1.65\,\text{TeV},$

$M_1 = M_2 = 1\,\text{TeV},\ M_3 = 2.5\,\text{TeV},$

$|A_t| = A_{b,\tau} = \mu \cot\beta + 2.8\,\text{TeV},$

$\phi_{A_t} = 2\pi/15$

- ✓ $M_{h_1} = 125.09 \pm 3\,\text{GeV}$ FeynHiggs
- ✓ h_1 SM-like HiggsSignals
- ✓ additional searches HiggsBounds
- ✓ EDMs



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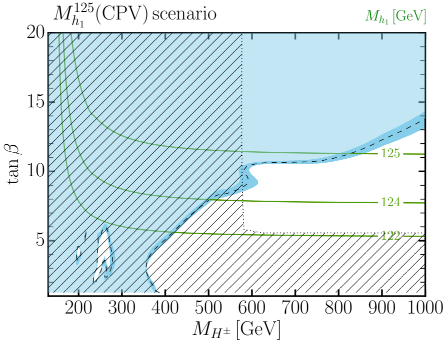
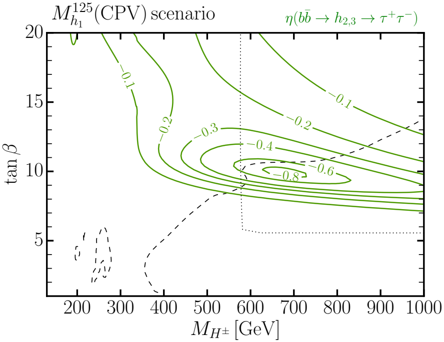


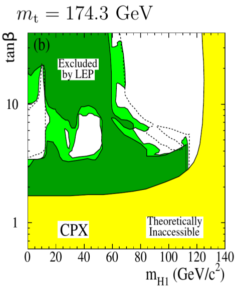


unexcluded "bay" due to destructive $h_2 - h_3$ interference of up to -95%

Further examples of $\mathcal{CP}$ violation in the MSSM

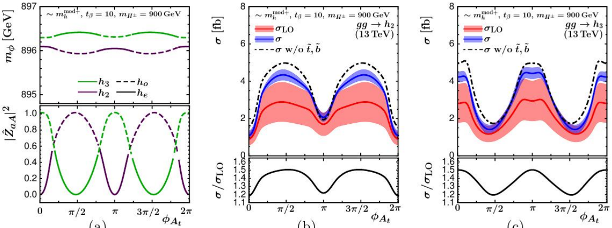
CPX scenario defined in [Carena, Ellis, Pilaftsis, Wagner '00]

- h_1VV coupling suppressed
- $h_2 \to h_1h_1$ difficult



On-shell neutral Higgs production with mixing
SusHiMi

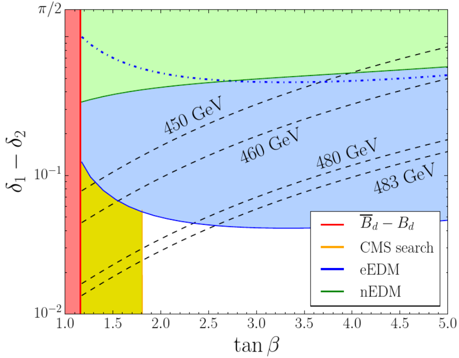
[Liebler, Patel, Weiglein '16]



(a) (b) (c)

2HDM: tree-level $\not{CP}$ in the Higgs sector

- phase in tree-level potential: $V \supset \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}$
- complex 2HDM at the LHC and for electroweak baryogenesis: e.g. [Keus, King, Moretti, Yagyu '15] [Dorsch, Huber, Konstandin, No '16] [Fontes, Mühlleitner, Romao, Santos, Silva, Wittbrodt '17]



$m_H = 200\,\text{GeV}$,
varying $m_A = m_{H^\pm}$
relative phase allowed AND sufficient for EWBG?

↪ talk by Margarethe Mühlleitner

Relaxion mechanism in a nutshell

[Graham, Kaplan, Rajendran '15]

New pseudoscalar ϕ:
the relaxion (a pNGB)

$$V(H) = \mu^2(\phi) H^\dagger H + \lambda (H^\dagger H)^2$$

$$V(\phi) = rg\Lambda^3\phi + ...$$

$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi$ 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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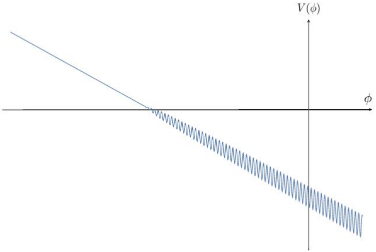
1. $\phi \geq \Lambda/g \Rightarrow \mu^2 > 0$, no vev
2. $\phi < \Lambda/g \Rightarrow \mu^2 < 0$, sign flip, EWSB
3. backreaction
   $V_{\rm br}(h,\phi) = \Lambda^4_{\rm br}(h) \cos\left(\frac{\phi}{f}\right)$
4. $\phi \searrow \Rightarrow |\mu^2(\phi)|, v^2(\phi) \nearrow$
   $\Rightarrow \Delta V_{\rm br} \nearrow$
5. until ϕ stopped by sufficient barrier
   $\rightsquigarrow m_h = 125\,\mathrm{GeV}$



dynamical solution to hierarchy problem w/O top partners at TeV scale

$\mathcal{CP}$-violating relaxion-Higgs mixing

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

backreaction $\Rightarrow$ ϕ stopped at ϕ_0 that breaks $\mathcal{CP}$

minimum of $V(\phi, h)$: $(\phi_0, v = 246\,\mathrm{GeV})$

$\boxed{\Lambda_{\rm br}^4\,(v(\phi_0)) = \tilde{M}^{4-j} v(\phi_0)^j / \sqrt{2}^j \equiv r_{\rm br}^4 v^4,}$ here $j = 2$ (non-QCD)

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?

Higgs as a window to relaxion: SM+S & beyond

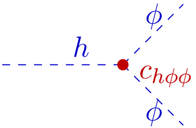
Relaxion-$f\bar{f}, VV$ interactions inherited from Higgs via mixing

$$m_\phi \simeq \frac{r_{\rm br}^2 v^2}{f}\sqrt{c_0 - 16 r_{\rm br}^4 s_0^2}\,, \quad \sin\theta \simeq 8 r_{\rm br}^4 s_0 \frac{v}{f} \leq 2\frac{m_\phi}{v}$$

"Relaxion line": maximal mixing depends linearly on mass

in addition: CP-odd couplings $\tilde{c}$ from backreaction sector

Triple-scalar coupling $h\phi\phi$



$\overset{\theta\to 0}{\sim} \frac{m_\phi^2}{v}$

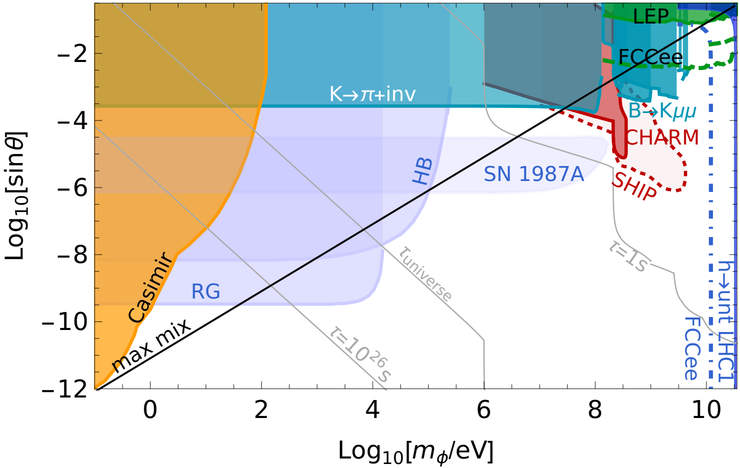
$$\mathrm{BR}(h \to \mathrm{NP}) = \mathrm{BR}(\boldsymbol{h \to \phi\phi})$$

- search for decay products, e.g. $bb\tau\tau$
- fit: new BR, universal modifier $\kappa \equiv \cos\theta$

exotic Higgs decay $h \to \phi\phi$ sensitive via precision Higgs couplings

Status of relaxion-Higgs mixing

[Frugiuele, EF, Schlaffer, Perez '18] [Flacke, Frugiuele, EF, Gupta, Perez '16]

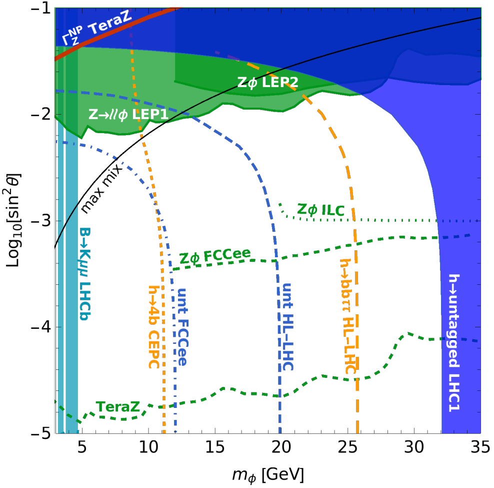


5th force astro cosmo meson decays beam dump lepton collider LHC

Relaxion mass and mixing span many orders of magnitude

Collider constraints on light scalars

[Frugiuele, EF, Perez, Schlaffer '18]



$e^+e^-Z \to \ell\ell\phi, e^+e^- \to Z\phi$

▷ production at TeraZ, FCCee: estimate from LEP1,2

▷ ILC [Drechsel, Moortgat-Pick, Weiglein '18]

$h \to \phi\phi$ (relaxion-specific)

▷ untagged final state

▷ searches for decay products

$B \to K\phi, \phi \to \mu\mu$

[Schmidt-Hoberg, Staub, Winkler '13]

complementary channels; future colliders probe relevant θ

Conclusions: BSM $\mathcal{CP}$-violating effects

Observables

- angular distributions of f/V couplings, EDMs, rates

Models with additional sources of $\not{\mathcal{CP}}$

- MSSM: e.g. CPV mixing and destructive interference of h_2, h_3
  $\Rightarrow$ unexcluded "bay" possibly not ruled out by next LHC run
  $\Rightarrow$ new $M_{h_1}^{125}(\mathrm{CPV})$ benchmark scenario via LHCHXSWG
- 2HDM: CPV already at tree-level
- relaxion: CPV mixing with $h \Rightarrow$ HL-LHC & lepton colliders sensitive
- many other models: SM+S, NMSSM, 2HDM+S, time-varying Yukawas and CKM phase,...

rich Higgs phenomenology, connection to cosmology

Possible points for discussion of $\not{\mathcal{CP}}$ aspects

- **experimental prospects** for a $\mathcal{CP}$-admixture in fermionic/ bosonic couplings?
- interplay of the (HL-)LHC with **future lepton colliders**?
- Higgs+DM (mono-V) $\hookrightarrow$ talk by Michele Gallinaro : distinguish **invisible** (pseudo)scalar decay?
- outlook for **EDM** constraints
- did not discuss **flavour** constraints
- treat **baryogenesis** as necessary constraint for $\mathcal{CP}$-violating BSM models or investigate Higgs phenomenology independently?

THANK YOU! TACK!

Appendix

$\mathcal{CP}$-odd component of couplings

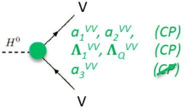
from talk by Senka Duric at ICHEP 2018

VVH couplings and parameters

Generic spin-0 HVV scattering amplitude:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

tree level scalar (0^+) — higher order scalar (0^+_h) — pseudoscalar (0^-)



$$f_{a3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \tilde{\sigma}_{\Lambda 1} / (\Lambda_1)^4 + \dots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

σ_i defined in decay

a_3 anomalous couplings: mixture of scalar and pseudo-scalar

there are also other parametrizations

Anomalous couplings (a_i , Λ_i) are universal parameters of nature

- However it is **more convenient to measure the effective cross-section ratios** (f_{ai}) rather than the anomalous couplings themselves
  - ⇒ **Measure fractions in defined convention with unique meaning along different channels**

f_{a3} = fractional pseudoscalar cross section

- value **$0 < |f_{a3}| < 1$** would indicate CP violation, with a possible mixture of scalar and pseudoscalar states
- **f_{a3} = 1 would indicate that the H boson is a pure pseudoscalar resonance**

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Prospects per channel

from talk by Senka Duric at ICHEP 2018

ggH, ffH and VVH sensitivity

expected precision of spin and CP-mixture measurements:

arXiv:1310.8361

Collider	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	250	350	500	1,000	126	126	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000	250		
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			$>5\sigma$
$VVH^\dagger$	0.07	0.02	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
$VVH^\ddagger$	$4\cdot 10^{-4}$	$1.2\cdot 10^{-4}$	$7\cdot 10^{-4}$	$1.1\cdot 10^{-4}$	$4\cdot 10^{-5}$	$8\cdot 10^{-6}$	–	–	$< 10^{-5}$
$VVH^\diamond$	$7\cdot 10^{-4}$	$1.3\cdot 10^{-4}$	✓	✓	✓	✓	–	–	$< 10^{-5}$
ggH	0.50	0.16	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	✓	✓	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

† estimated in $H \to ZZ^*$ decay mode

‡ estimated in $V^* \to HV$ production mode

$^\diamond$ estimated in $V^*V^* \to H$ (VBF) production mode

ggH and ffH experimental measurements are more challenging than VVH measurements

- **the focus with current LHC data is on VVH measurement**

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 $h\phi\phi$

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

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

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

Bounds on untagged/invisible Higgs decays

Collider	$\sqrt{s}$ [TeV]	$\mathcal{L}_{\rm int}$ [fb^{-1}]	$\mathrm{BR}_{\rm inv}$ [%]	$\mathrm{BR}_{\rm NP}$ [%]
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

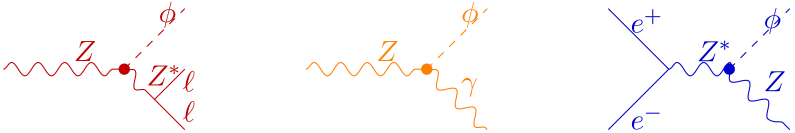
Searches for $h \to \phi\phi \to F$ at ATLAS and CMS

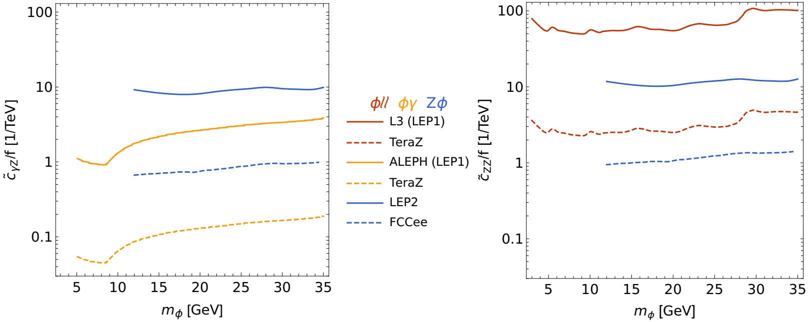
F	exp.	$\sqrt{s}$ [TeV]	$\mathcal{L}_{\text{int}}$ [fb^{-1}]	m_ϕ [GeV]	comment	m_ϕ^{HL} [GeV]
$bb\tau\tau$	CMS	13	35.9	15-60		26
$bb\mu\mu$	CMS	8	19.7	15-62.5		27
	ATLAS	13	36.1	20-60		30
$\tau\tau\mu\mu$	CMS	13	35.9	15-62.6		-
4τ	CMS	8	19.7	5-15		-
4μ	CMS	13	2.8	0.25-8.5	NMSSM, γ_D	-
	ATLAS	13	2.8	1-2.5, 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	-

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

[Frugiuele, EF, Perez, Schlaffer '18]

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





{LEP1, LEP2} → strong bounds expected at {TeraZ, FCCee}