New ideas for TeV-scale model building

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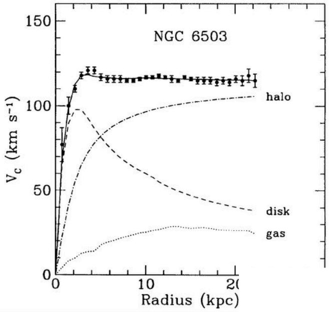
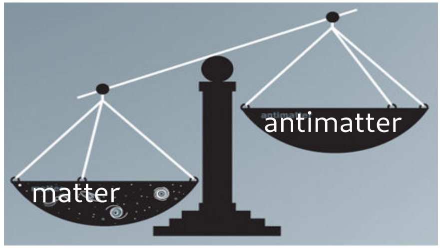
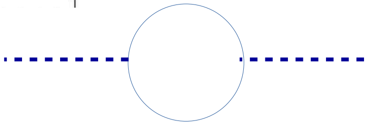
LHCP 2020
May 28, 2020
BSM-1 (TeV scale) Plenary session VII

Open Questions in the SM

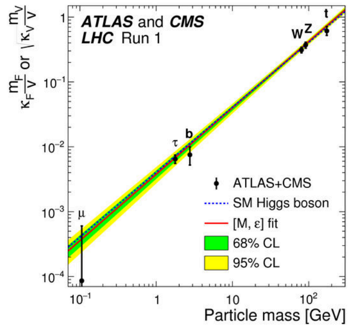
- Dark Matter
- Matter-antimatter asymmetry
- Hierarchy problem of Higgs mass
- Neutrino masses
- Flavour hierarchies

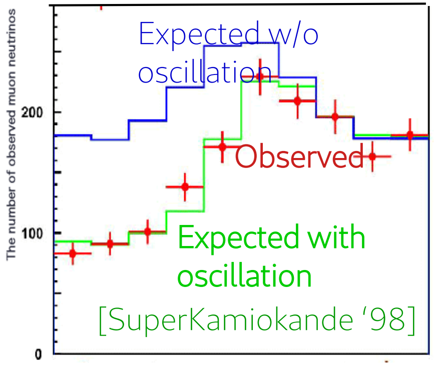






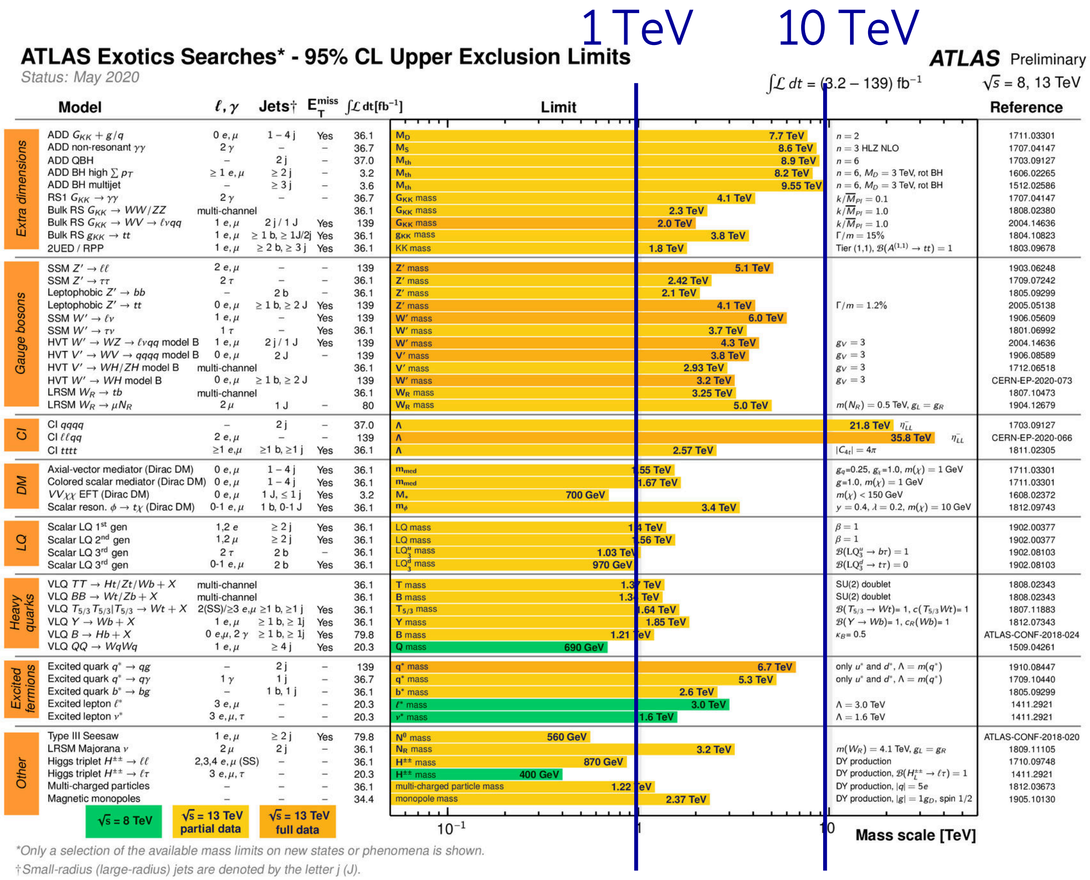
$$m_H \sim \mathcal{O}(10^{-16}) m_{\text{Planck}}$$





Need Physics beyond the SM: at which scale(s)?

Challenges for naturalness ~TeV scale



Ways out of the null-results of NP searches

Non-minimal versions of the investigated models, revisit simplified models, assumptions of spectra, new benchmarks…

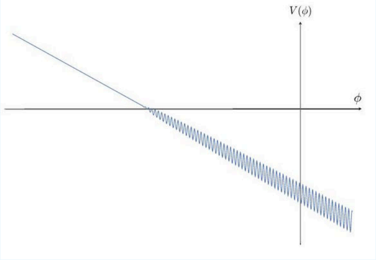
Conceptually **different models**, e.g. new dynamics instead of symmetries
- relaxion

Outline

Extended Higgs sectors

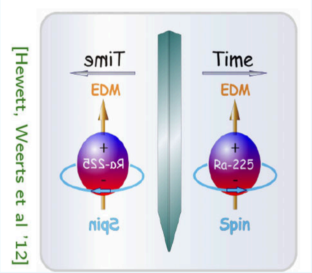
- Adding singlets
- Z_2 symmetry
- Role for e.w. phase transition

Relaxion framework



- Rolling and stopping
- Relaxion-Higgs mixing
- Relaxion vs any (pseudo)scalar

New sources of CP violation



- Time-varying phases
- CPV in Dark Sector
- Complex Yukawas in EFT

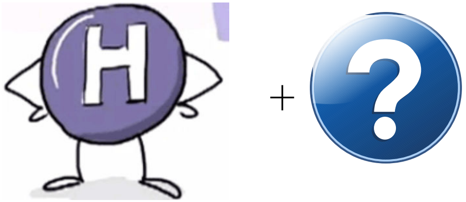
Disclaimer/strategy

- Picked complementary BSM models
  ~~No claim for completeness~~ → Claim for incompleteness
- BSM at TeV scale can also have effects at lower energies

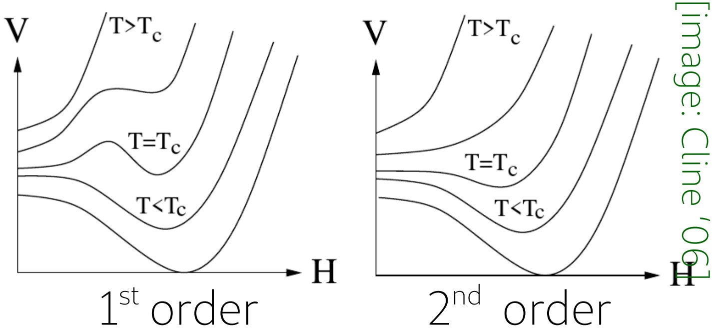
I. EXTENDED HIGGS SECTORS WITH SINGLETS

Non-minimal Higgs sectors

- Why more scalars?
  - SM with 1 Higgs just minimal solution
  - Different Higgses for up-/down-type masses?
  - Scalar potential needs to be modified to enable first-order electroweak phase transition
  - More parameter space



- Why scalar singlets?
  - Interact with SM particles via the Higgs
  - Minimal extensions with rich phenomenology
  - Can help with phase transition
  - Adding singlets to doublet models (→ N2HDM, NMSSM): can relax mass constraint of h_{125}



SM+S

- SM + 1 real singlet scalar: simplest extension of the SM

$$V = \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \mu_S^2 S^2 + \lambda S^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2$$

doublet　　　　new singlet

$$+ \mathbb{Z}_2 \text{ breaking terms}$$

- Well studied model with different scenarios:
  - Z_2 conserved or explicitely broken
  - S can be heavier or lighter than h_{125}

SM+S with spontaneous ~~Z_2~~

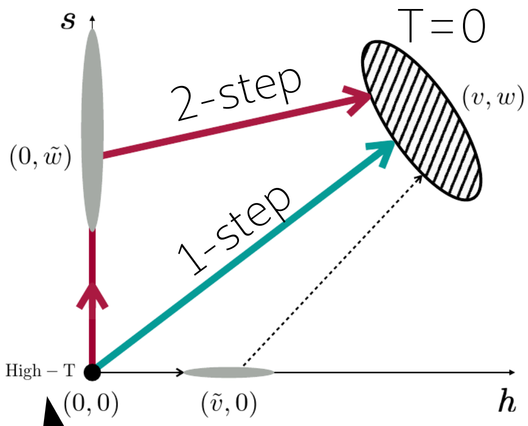
M. Carena, Z. Liu, Y. Wang '19

- Modification of **e.w. phase transition challenging**
  - modifications occur only at loop level due to cancellations by Z_2
- **Light singlet S**, possibly <S>~TeV at T=0
- Upper bound on singlet Higgs mixing quartic $\lambda_{hS}\Phi^\dagger\Phi S^2$
  - Need almost degenerate minima at T=0
- phase transition enhanced: **strongly 1st order possible**

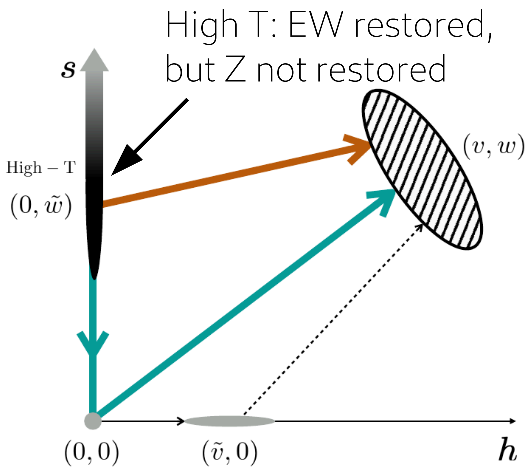
SM+S ~~Z_2~~: phase transition + collider

- 1- or 2-step phase transition

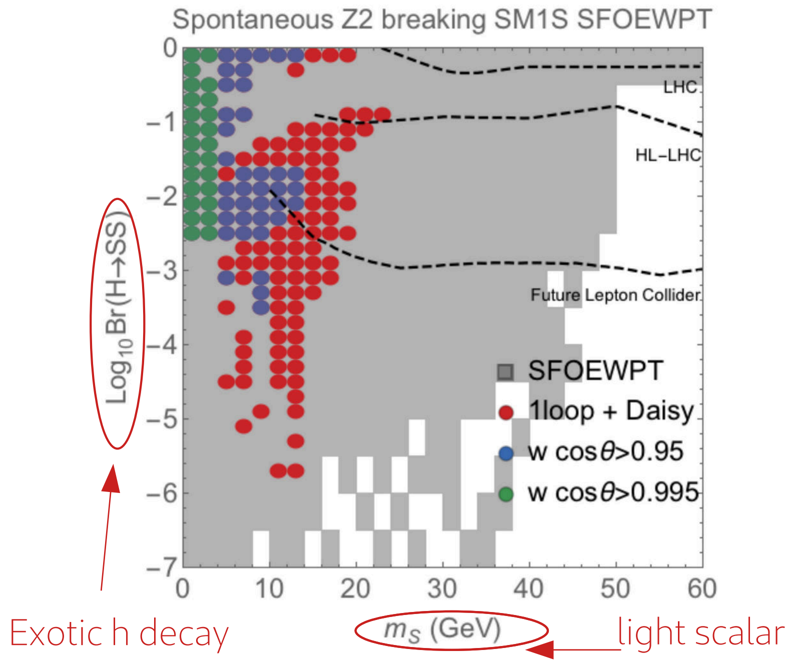
M. Carena, Z. Liu, Y. Wang '19



Thermal history starts in symmetric phase



Starts in Z_2 broken phase



Signatures: h→ SS decay, Higgs precision coupling measurements, Higgs self-coupling, gravitational waves

SM+2S with Z_2

→ talk by T. Stefaniak

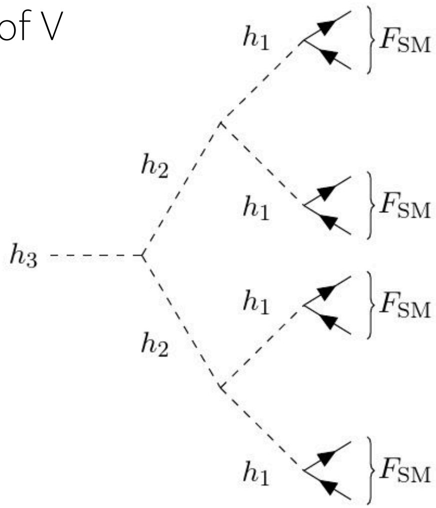
Robens, Stefaniak, Wittbrodt '19

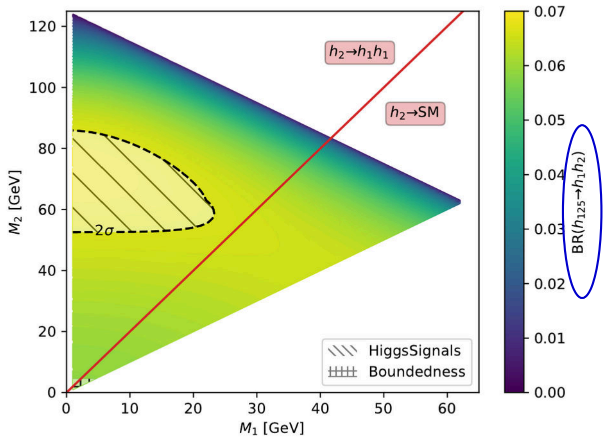
- **2 real singlets** S_i, 1 doublet **Φ** of $SU(2)_L$

$$V = \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_{12} S_1^2 S_2^2 + \sum_{i=1,2} \mu_i^2 S_i^2 + \lambda_i S_i^4 + \lambda_{\Phi,i} \Phi^\dagger \Phi S_i^2$$

  - Described by 3 masses, 3 vevs, 3 mixing angles → $h_{1,2,3}$
  - Perturbative unitarity constraints, boundedness of V
  - Sub-case of general 1 complex singlet extension

- $h_a \to h_b h_c$ decays:
  - cascades, multi-Higgs final states
  - rich (so far overlooked) signatures





Benchmark with $h_{125} = h_3$

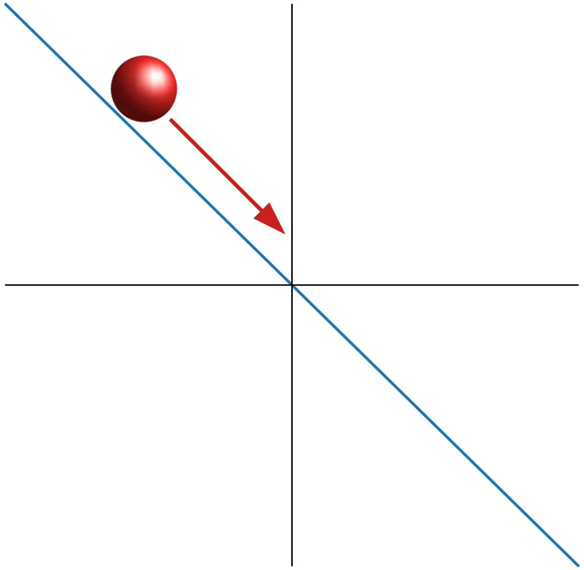
II. RELAXION MECHANISM

Relaxion and Higgs potential

Graham, Kaplan, Rajendran '15

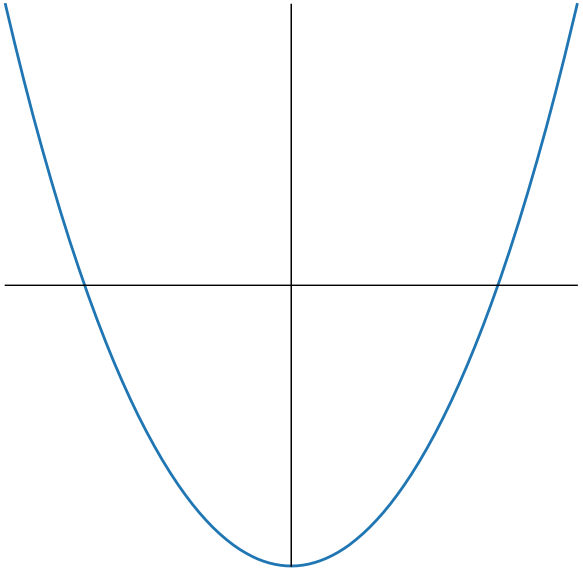
Potential plots by M. Schlaffer

Relaxion V(**Φ**)



slow-roll

Higgs V(**H**)

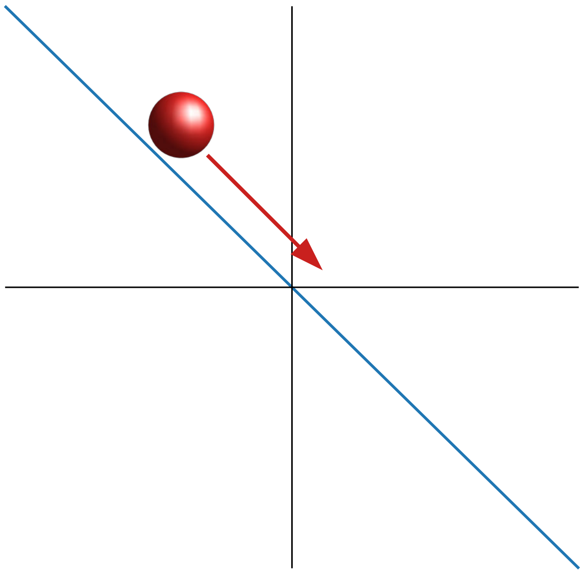


$v = 0$

Relaxion and Higgs potential

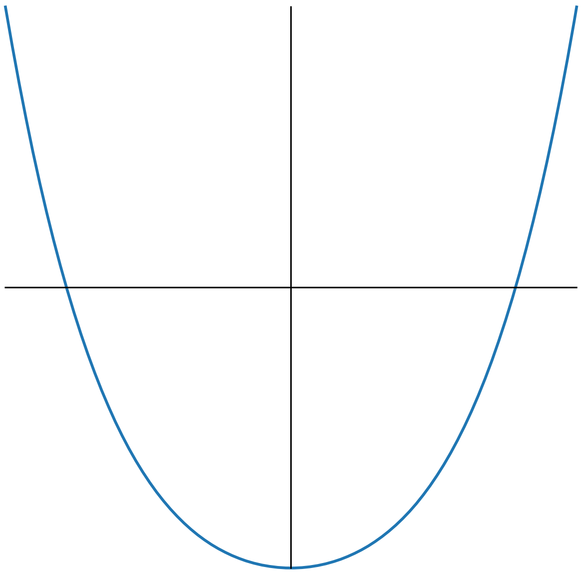
Graham, Kaplan, Rajendran '15

Relaxion V(**Φ**)



slow-roll

Higgs V(**H**)



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Relaxion and Higgs potential

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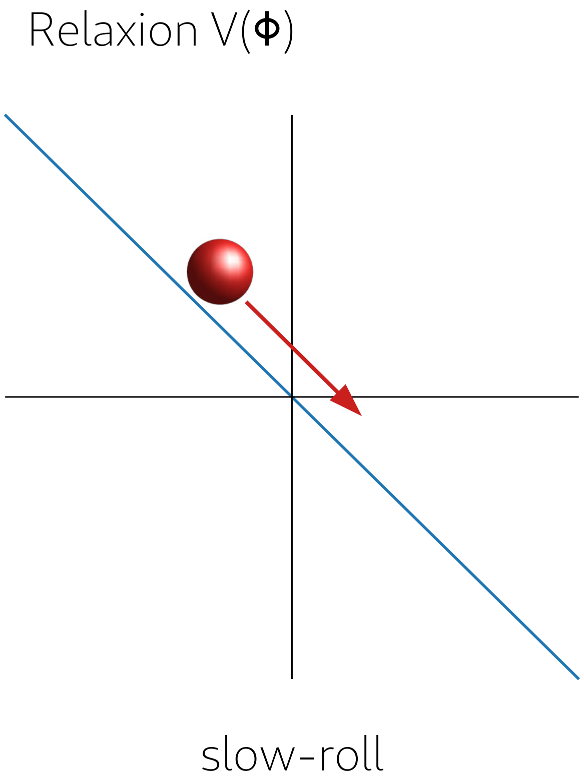
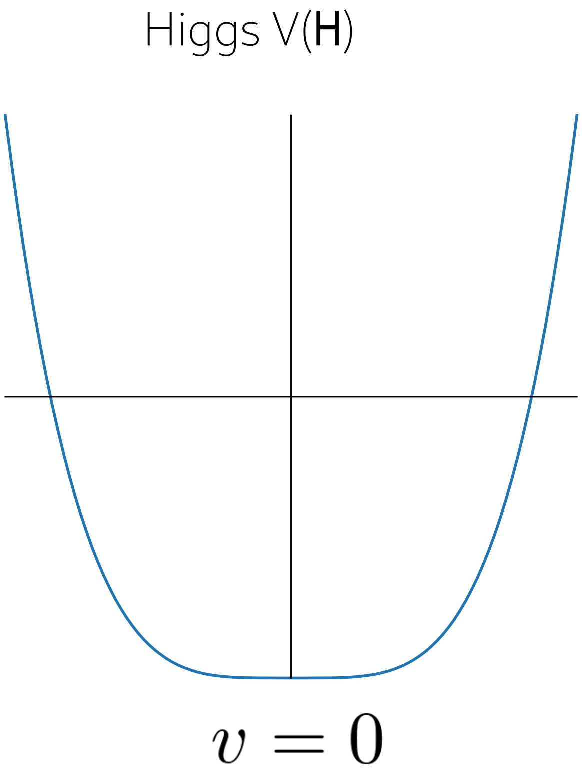
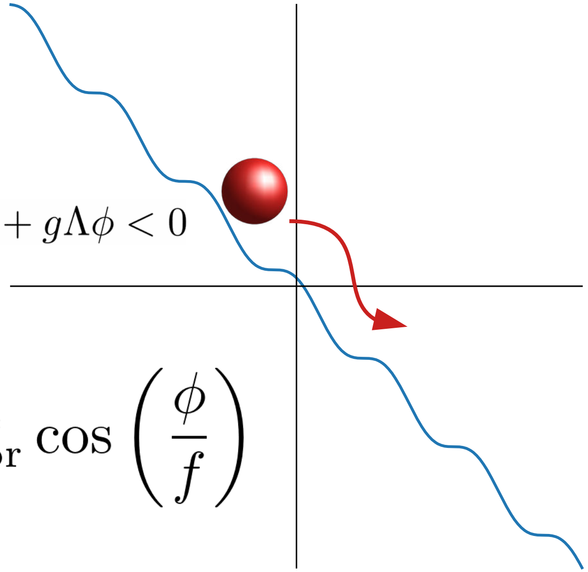




Relaxion and Higgs potential

Graham, Kaplan, Rajendran '15

Relaxion V(**Φ**)

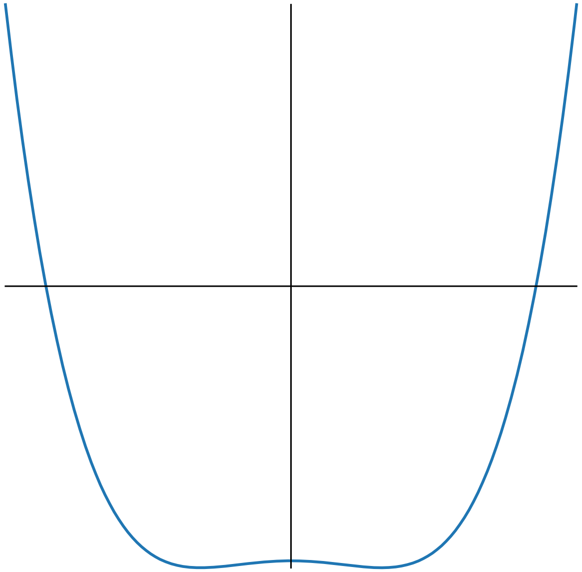


$$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi < 0$$

$$V_{\rm br} = \Lambda_{\rm br}^4 \cos\left(\frac{\phi}{f}\right)$$

Backreaction barrier→ wiggles grow

Higgs V(**H**)

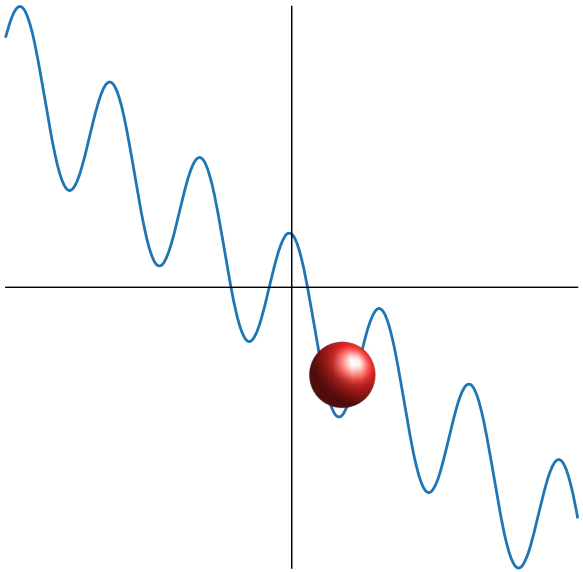


$$v \neq 0$$

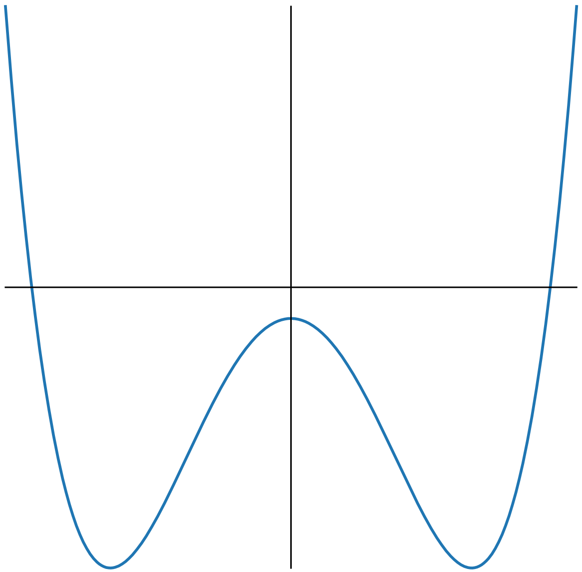
Relaxion and Higgs potential

Graham, Kaplan, Rajendran '15

Relaxion V(**Φ**)



Higgs V(**H**)



Backreaction: when

$V'_{\mathrm{roll}} = -V'_{br}$ → **relaxion stops**

$$v \neq 0$$
$$m_h = m_h^{\mathrm{obs}}$$

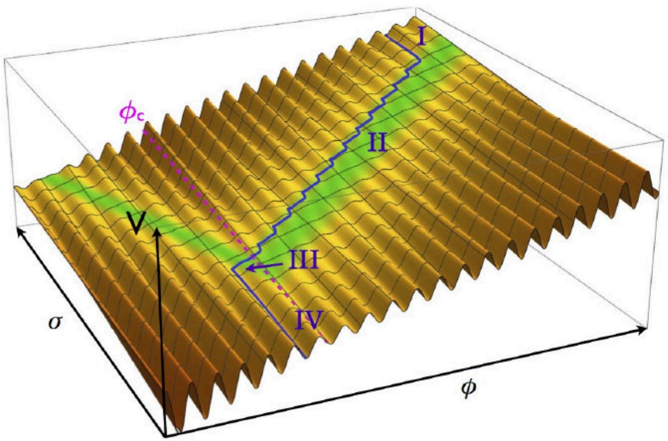
Various relaxion models

Not a complete list!

- Minimal model: QCD (rel)axion
- Non-QCD strong sector
- Double-field mechanism (ϕ, σ)
  Espinosa, Grojean, Pomarol, Pujolas, Servant '15
- Familon (pNGB of spontaneously broken flavor symmetry)
  Gupta, Komargodski, Perez, Ubaldi '15

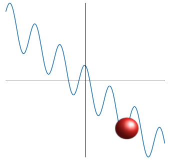
$$V(H) = \mu^2(\phi)H^\dagger H + \lambda(H^\dagger H)^2$$

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



Backreaction sector and scale Λ_{br} model-dependent

Models for relaxion stopping



- Standard: during **inflation**
- Alternative: friction via **particle production** $\frac{\phi}{f} V\tilde{V}$ Hook, Marques-Tavares '16
  - Relaxation mechanism independent of inflation
  - Friction from dark gauge boson production Choi, Kim Sekiguchi '16
- New proposal: **self-stopping** relaxion Fonseca, Morgante, Sato, Servant '19
  - Also independent of inflation
  - Relaxion quantum fluctuations → grow → relaxion production

What the relaxion can do for you

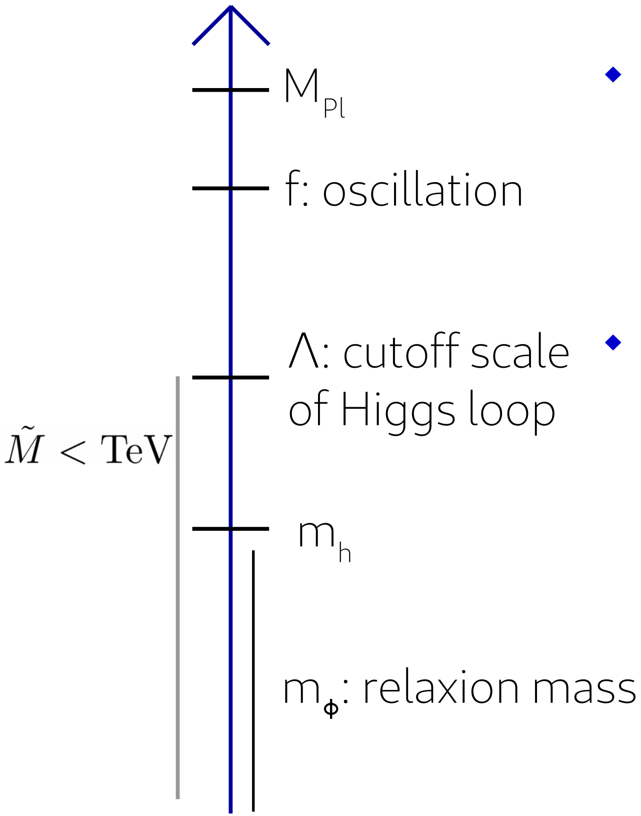
- DM
  - With particle production Fonseca, Morgante '18
  - Coherent oscillations of very light DM → earth/sun halo
    Banerjee, Kim, Perez '18; Banerjee, Budker, Eby, Kim, Perez '19
- Baryogenesis Abel, Gupta, Scholtz '18
  - CPT violation during slow-roll

Can be realized for same masses $\sim 10^{-10} - 10^{-5}$ eV

- "hierarchion"/ Nelson-Barr relaxion: **ew, strong CP, flavor hierarchies**
  Davidi, Gupta, Perez, Redigolo, Shalit '17 '18
- "All-in-one relaxion": m_H naturalness, DM, baryon asymmetry, m_ν and strong CP
  Gupta, Reiness, Spannowsky '19

Relaxion-Higgs mixing

Flacke, Frugiuele, EF, Gupta, Perez '16; Choi, Im '16



- Backreaction scale (wiggle height)

here j=2 (non-QCD)

$$\Lambda_{\rm br}^4 = \mu_{\rm br}^{4-j} v^j / \sqrt{2}^j \equiv r_{\rm br}^4 v^4$$

- CPV mixing term

$$V(\phi, h) \supset \frac{\mu_{\rm br}^{4-j} v^{j-1}}{\sqrt{2}^j f} \underbrace{\sin\left(\frac{\phi_0}{f}\right)}_{s_0} \boldsymbol{h\phi}$$

s_0 endpoint of rolling

Relaxion couples to SM via relaxion-Higgs mixing→ measure

Relaxion vs SM+S

$$\mathcal{L}_{\rm scalar} = V_\phi + \mu^2(\phi) H^\dagger H + \lambda_h \left(H^\dagger H\right)^2$$

General singlet

$$V_\phi = \frac{1}{2} m_0^2 \phi^2 + \frac{a_\phi}{3}\phi^3 + \frac{\lambda_\phi}{4}\phi^4$$

$$\mu^2(\phi) = -\mu_0^2 + 2a_{h\phi}\phi + \lambda_{h\phi}\phi^2$$

Naturalness

$$\sin\theta \lesssim m_\phi / m_h$$ Mixing angle

$$\lambda_{h\phi} \lesssim m_\phi^2 / v^2$$ Quartic coupling

Relaxion

$$V_\phi = r g \Lambda^3 \phi$$

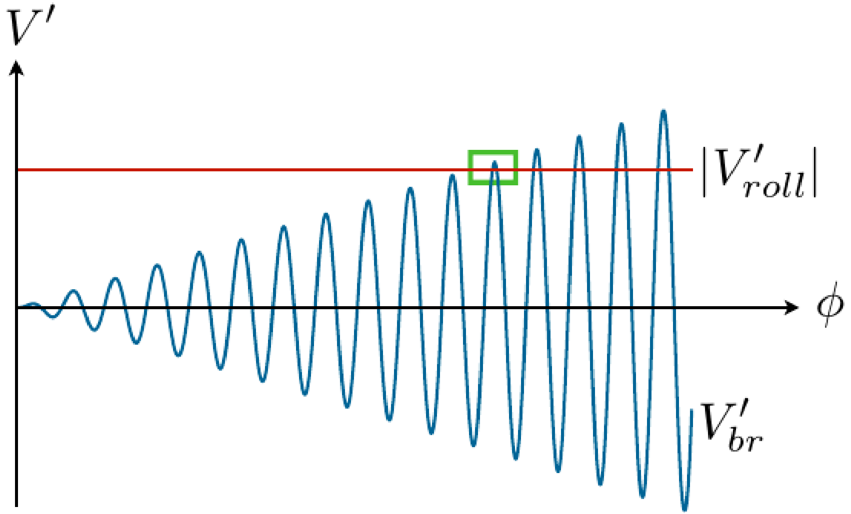
$$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi - \tilde{M}^2 \cos(\phi/f)$$

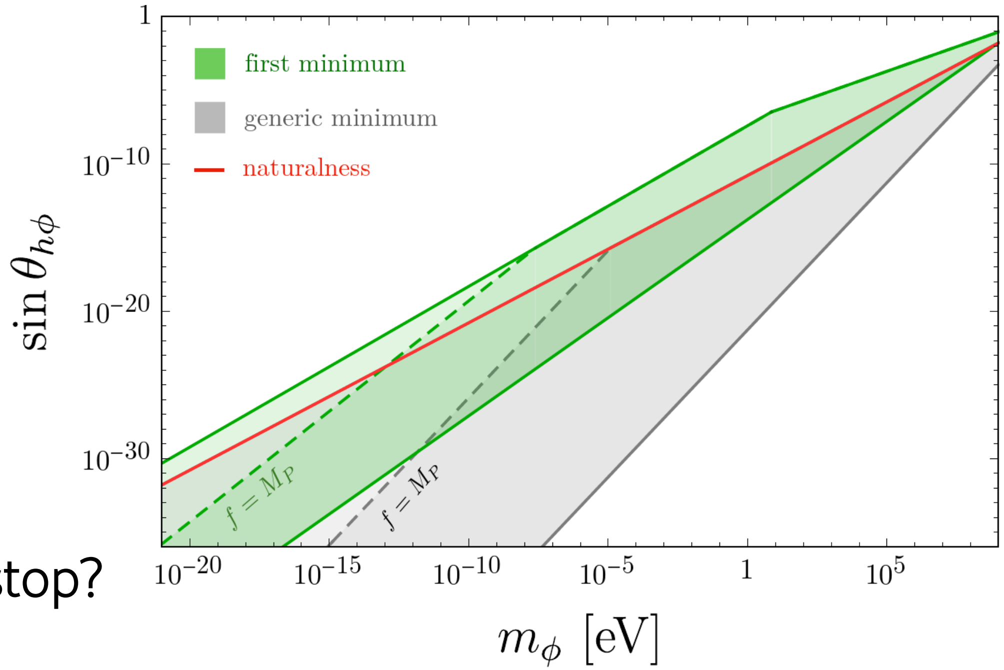
upper/lower bound on relaxion-Higgs mixing?

Also CP-odd couplings to SM (like axion)

Relaxed mass and mixing

Banerjee, Matsedonskyi, Kim, Perez, Safronova '20





- In which minimum (n) does the relaxion stop?
- Parametrically suppressed mass

$$m_\phi^2 \simeq \sqrt{n}\frac{\mu_b}{\Lambda}\frac{\Lambda_{\rm br}^4}{f^2}$$

Upper and lower limit on mixing angle

Relaxion hunting at multiple frontiers

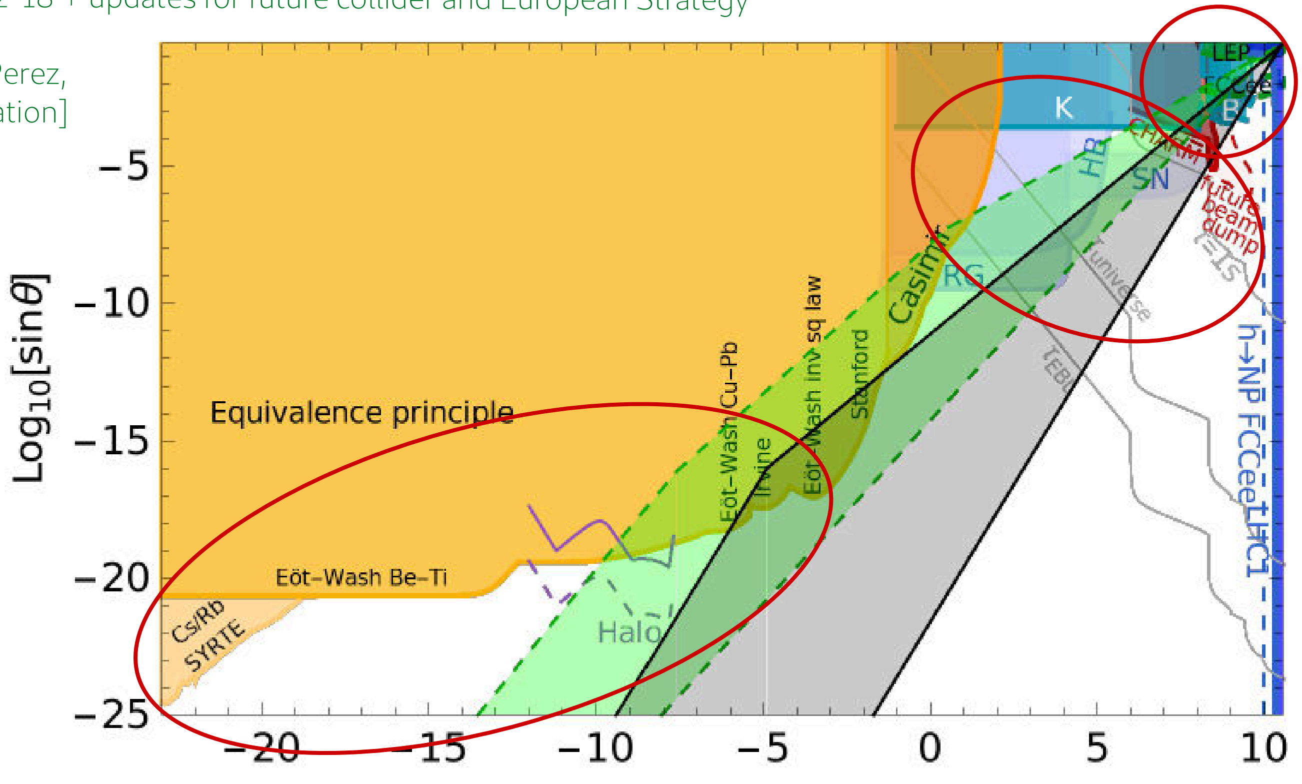
Frugiuele, EF, Schlaffer, Perez '18 + updates for future collider and European Strategy

EF, Grojean, Matsedonskyi, Perez, Savoray, Schlaffer [in preparation]

Banerjee, Budker, Eby, Kim, Perez '19

Flacke, Frugiuele, EF, Gupta, Perez '16

Banerjee, Kim, Matsedonskyi, Perez, Safronova '20



Collider → **Energy**

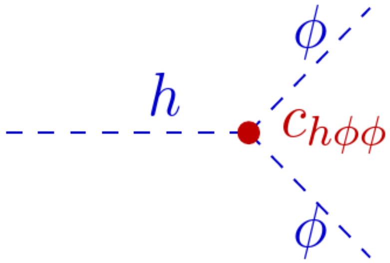
Beam dump, flavour → **Intensity**

Precision

New h decay: h→ ϕϕ, coupling modifier

invisible and untagged final states

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



total Higgs width

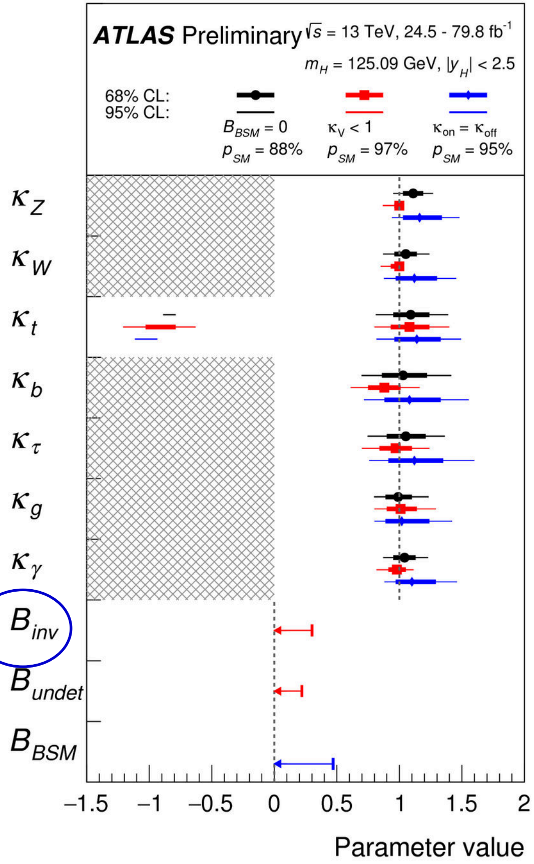
$$\Gamma_h = \kappa^2\, \Gamma_h^{\rm SM} + \Gamma_h^{\rm NP}$$

$$\kappa \equiv \cos\theta$$

$$\mu_{if} = \frac{\sigma_{i\to h}}{\sigma_{i\to h}^{\rm SM}} \frac{{\rm BR}(h\to f_{\rm SM})}{{\rm BR}^{\rm SM}(h\to f_{\rm SM})} = \kappa^2\,[1-{\rm BR_{NP}}]$$

→ talk by G. Petrucciani

Updated with VBF, 139/fb: $B_{\rm inv}<0.13$



Direct and indirect bounds: prompt

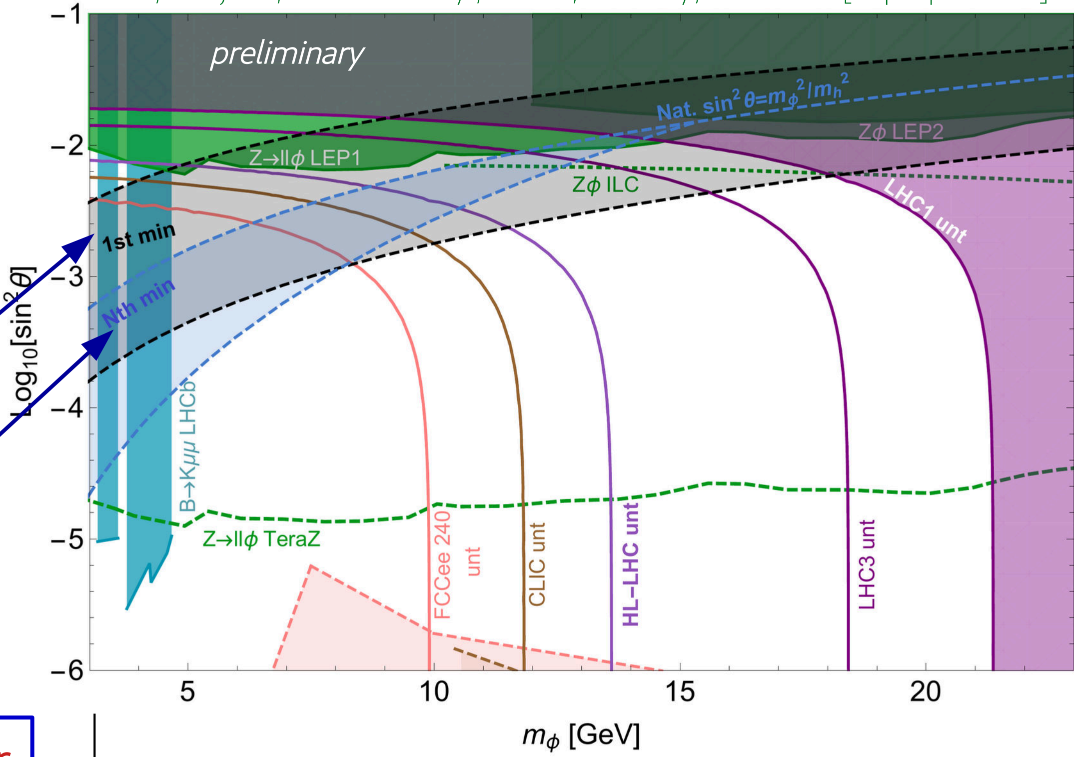
- h→ΦΦ indirect (untagged)
- h→ΦΦ →4f,...direct (not shown here)
- Z decay and production

Stops in 1st minumum

Stops in any minumum

Identify relaxion region

EF, Grojean, Matsedonskyi, Perez, Savoray, Schlaffer [in preparation]



Distinguish relaxion-region from any scalar
TeraZ could rule out heavy relaxion

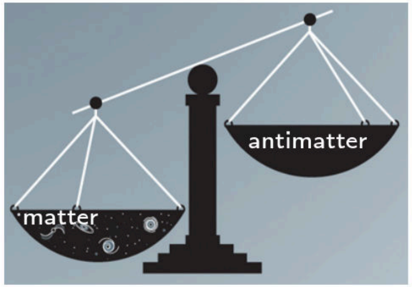
If sinθ even smaller
→ long-lived

→ talks by Z. Liu, A. Reinsvold Hall, M. Saito, M. Kucharczyk, B. Gomber, V. Mitsou; posters by E. Pastor, D. Wang

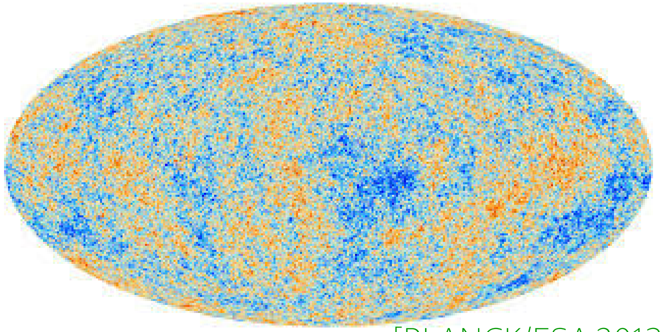
II. NEW SOURCES OF CP VIOLATION

CP violation for baryon asymmetry

Sakharov conditions for Baryogenesis
I. B number violation
II. CP violation
III. Out of thermal equilibrium



[adapted from quantumdiaries]


[PLANCK/ESA 2013]

- Observed baryon asymmetry $\eta = \dfrac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$
- SM: $\delta_{\rm CKM}$ and $\bar{\theta}_{\rm QCD} < 10^{-10}$ insufficient

Gavela, Hernandez, Orloff, Pene '93
Huet, Sather '94

Need CP violation beyond the SM

Leptogenesis:
L asymmetry to B asymmetry
→ high scales

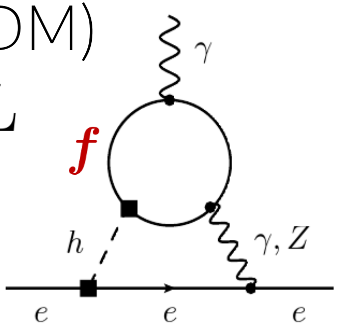
Electroweak baryogenesis:
during e.w. phase transition
→ connected to the Higgs
→ testable at colliders

Restrictions on BSM CP violation

- Discovered Higgs compatible with $J^{PC}=0^{++}$
  - Small CP-odd component possible
- Electron electric dipole moment (EDM)

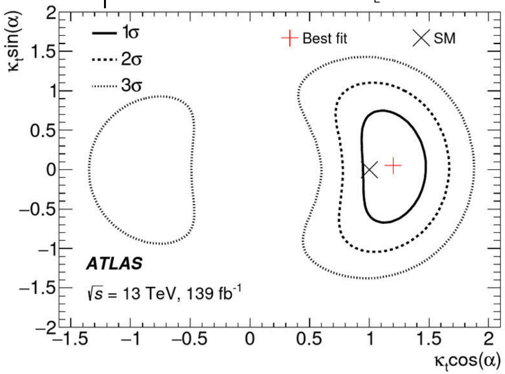
$$d_e \leq 1.1 \times 10^{-29}\, e\,\mathrm{cm\ at\ 90\%\ CL}$$

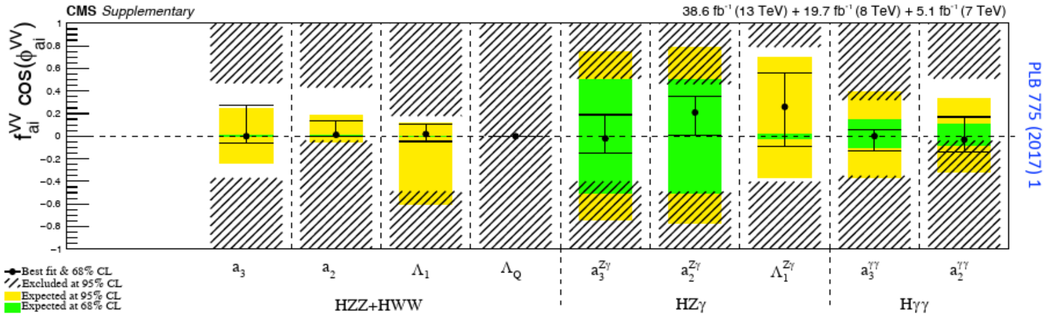
ACME [Nature '18]



ttH+tH, H→γγ → talk by L. Fiorini

top Yukawa CP [2004.04545]





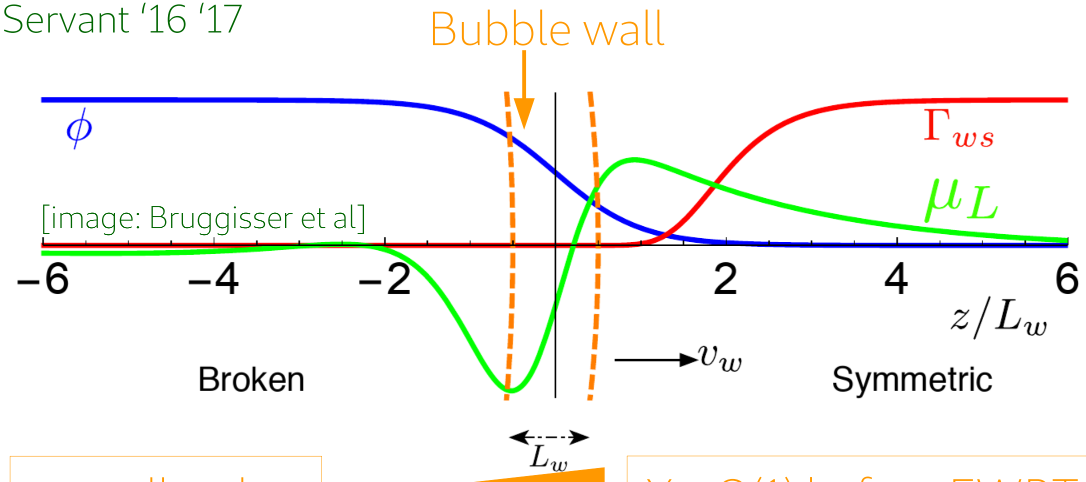
- Cancellations
- Time variation of CP phases
- CP suppressed in visible sector

Time-varying Yukawas

Bruggisser, Konstandin, Servant '17; Baldes, Konstandin, Servant '16 '17

- CPV only from CKM matrix
- Flavour   EWPT:
  - Embed in flavour model

    Frogatt-Nielsen, extra dimension, composite Higgs
- Scale of flavour structure can be near ew. scale
- New scalar between m_h and TeV



y small today → EDM suppressed

Yukawas vary

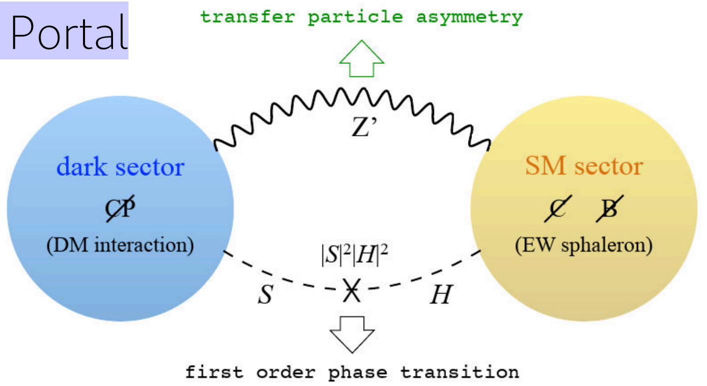
<h> varies

Y ~O(1) before EWPT → 1^{st} order phase transition, CP violation large

CP violation in dark sector

CPV in dark sector
→ EDM suppressed
→ provides DM

CP Portal



[image: Carena, Quiros, Zhang '19]

Different models, e.g.

- Cline, Kainulainen, Tucker-Smith '17: spontaneous CPV in renormalisable interaction of scalar with fermionic DM; CP restored at T=0
- Carena, Quiros, Zhang '18 '19: light Z' as messenger ~e.w. scale
- Hall, Konstandin, McGehee, Murayama, Servant '19: Dark 1st order phase transition, dark SU(2) with neutrino portal
- Azevedo, Ferreira, Mühlleitner, Patel, Santos '18; Okawa, Pospelov, Ritz '19; Keus '19; …

Signatures include
- Extra scalars
- Extra vectors
- DM
- Neutrino ΔN_{eff}

SMEFT: dim-6 complex Yukawas

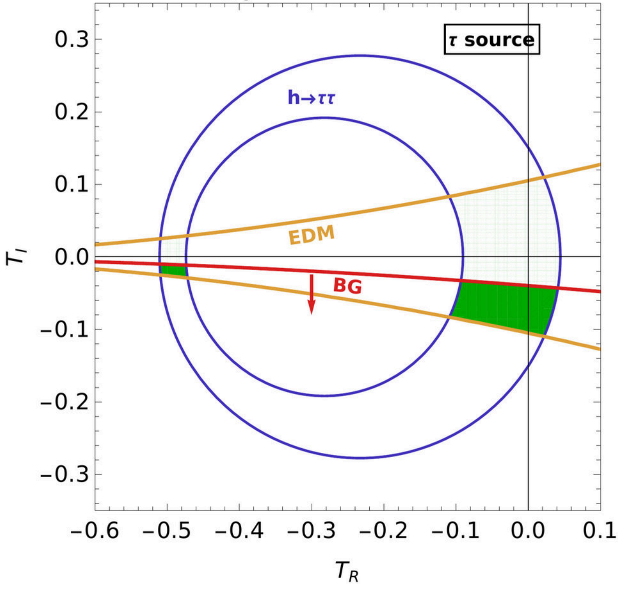
- Consider dim-6 Yukawa with real and imaginary part (*only 1 EFT term*)

→ for more general EFT see next talk by K. Mimasu

$$\mathcal{L}_{\rm Yuk} = Y_f \overline{F_L} F_R H + \frac{1}{\Lambda^2}(X_R^f + iX_I^f)|H|^2 \overline{F_L} F_R H. + {\rm h.c.}$$

EF, Losada, Nir, Viernik '19 '20 cf de Vries, Postma, van de Vies '18 where $X_R^f \equiv 0, X \equiv \pm i Y_f$

- Ratio of dim-6/dim-4: $T^f = \frac{m_f^{(6)}}{m_f^{(4)}} = \frac{v^2}{2\Lambda^2}\frac{X^f}{Y^f}$



sufficient baryon asymmetry within LHC & EDM limits?

τ: yes

t, b, μ: no

EDM μ(h→ μμ)<1.7

EFT Cut-off scales $\Lambda/\sqrt{X_{R,I}}$

Minimal scales maximally allowed T (collider, EDM)

τ, b: 1 - 3 TeV; t: 1 TeV (LHC), 9 TeV (EDM)

μ: 10 – 12 TeV

Maximal scales minimally required T_I (EWBG)

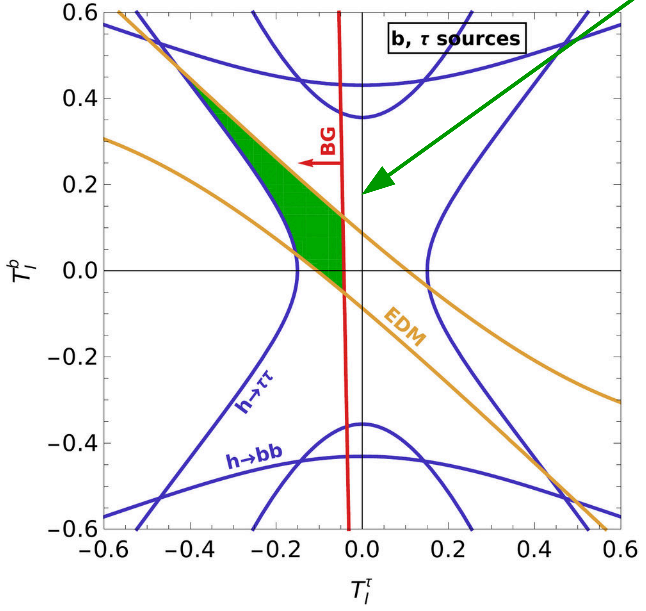
$\Lambda/\sqrt{X_I^\tau} \lesssim 18\ {\rm TeV}\ (0.01/T_I^\tau)^{1/2}$

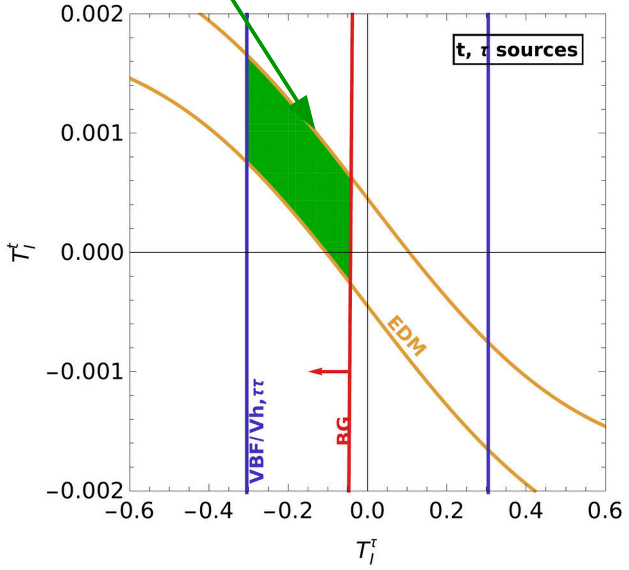
Several complex Yukawas

EF, Losada, Nir, Viernik '19 '20

$T_R^f = 0$

Allowed by all 3 constraints!





Further test these scenarios:

- Higgs production & decay: precise signal strength measurements
- angular distributions, especially h→ττ
- additional EDMs

Cancellations in EDM + enhancement of baryogenesis

- τ+b with nonzero T_R, T_I:

$$Y_B^{b+\tau,\max}(d_e = 0, \mu_b = \mu_\tau = 1) = 10.25 Y_B^{\rm obs}$$

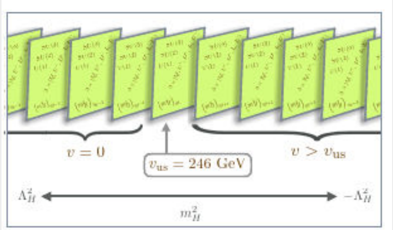
- EWBG possible with 0 CPV signals!

Many other (newer or older) models

Axion/ALPS

Neutral Naturalness
Twin Higgs
Folded SUSY
Hyperbolic Higgs

N-Naturalness



Arkani-Hamed, Cohen, D'Agnolo, Hook
Do Kim, Pinner '17

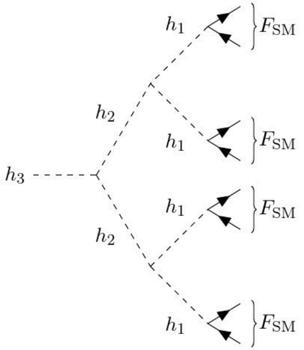
Clockwork

Giudice, McCullough '16

See other BSM talks at this conference!

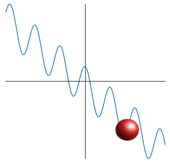
Conclusions

Adding singlets to the SM



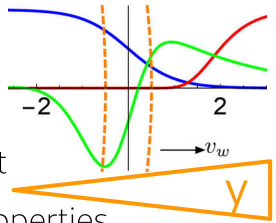
- Helps with e.w. phase transition
- 2S model: Higgs→ Higgs decays
- Broken or unbroken Z_2

Relaxion



- Dynamic solution to hierarchy of m_h
- CPV **h-Φ mixing**
- Mass range: from collider to table-top precision probes

BSM CP violation



- Need **large enough** CPV for baryogenesis
  - Enhanced asymmetry or suppressed washout
- **Small enough** to hide behind EDM & Higgs properties
  - e.g. cancellation, time variation, CPV in dark sector

Models and searches

- BSM possible despite SM-like data
- Some models solve several shortcomings
- Higgs precision, exotic Higgs decays, cosmology,...
  - Combine different methods → *hoping for discoveries*

THANK YOU

Invitation to further discussion on BSM models at the TeV scale:
Meeting ID: 962 5456 7705
Password: same as for this session

APPENDIX

Graham, Kaplan, Rajendran '15

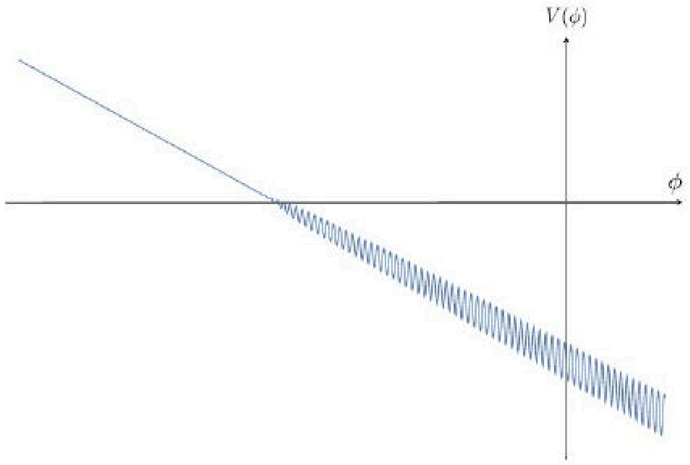
Relaxion mechanism

Λ: cutoff scale of Higgs loop

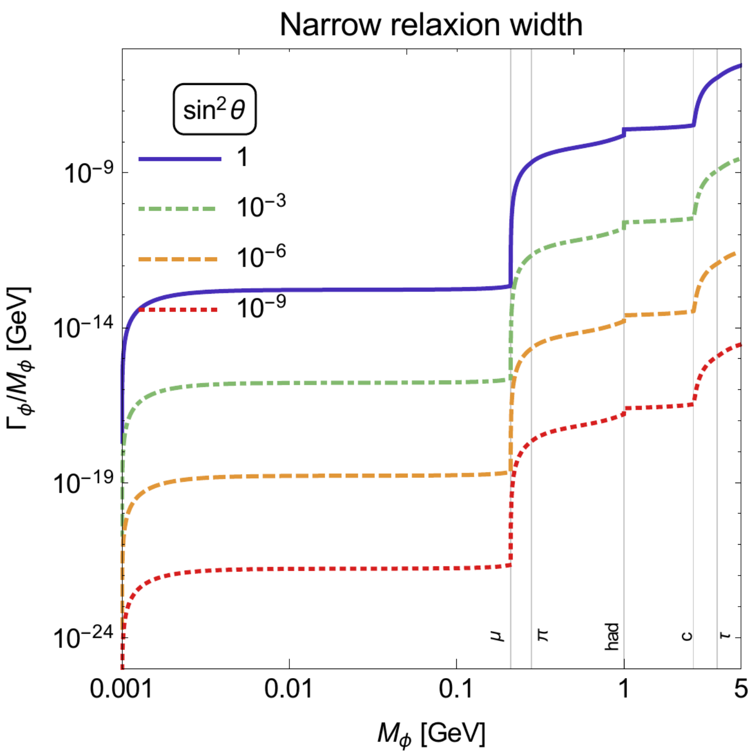
$$V(H) = \mu^2(\phi) H^\dagger H + \lambda (H^\dagger H)^2$$
$$V(\phi) = rg\Lambda^3 \phi + \ldots$$

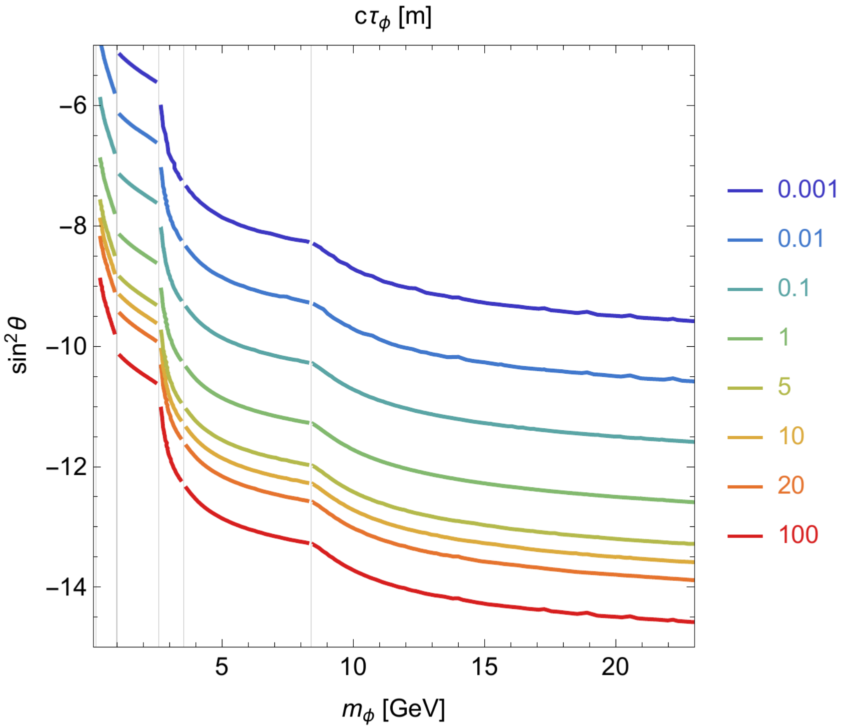
$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi$ scans m_h during inflation

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



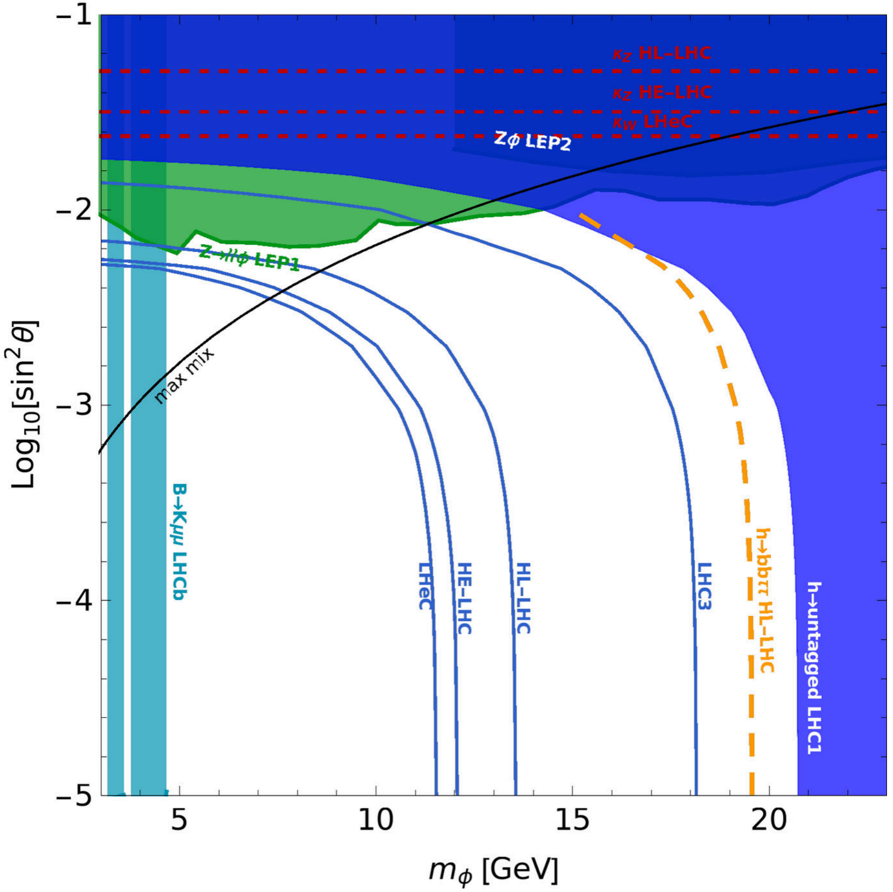


Flacke, Frugiuele, EF, Gupta, Perez '16;

Relaxion hunting at LHC+

- Z decay and production
- h→ΦΦ Prompt decays
  - "untagged" final state
  - Visible decay products
- K_Z from hZ xsec

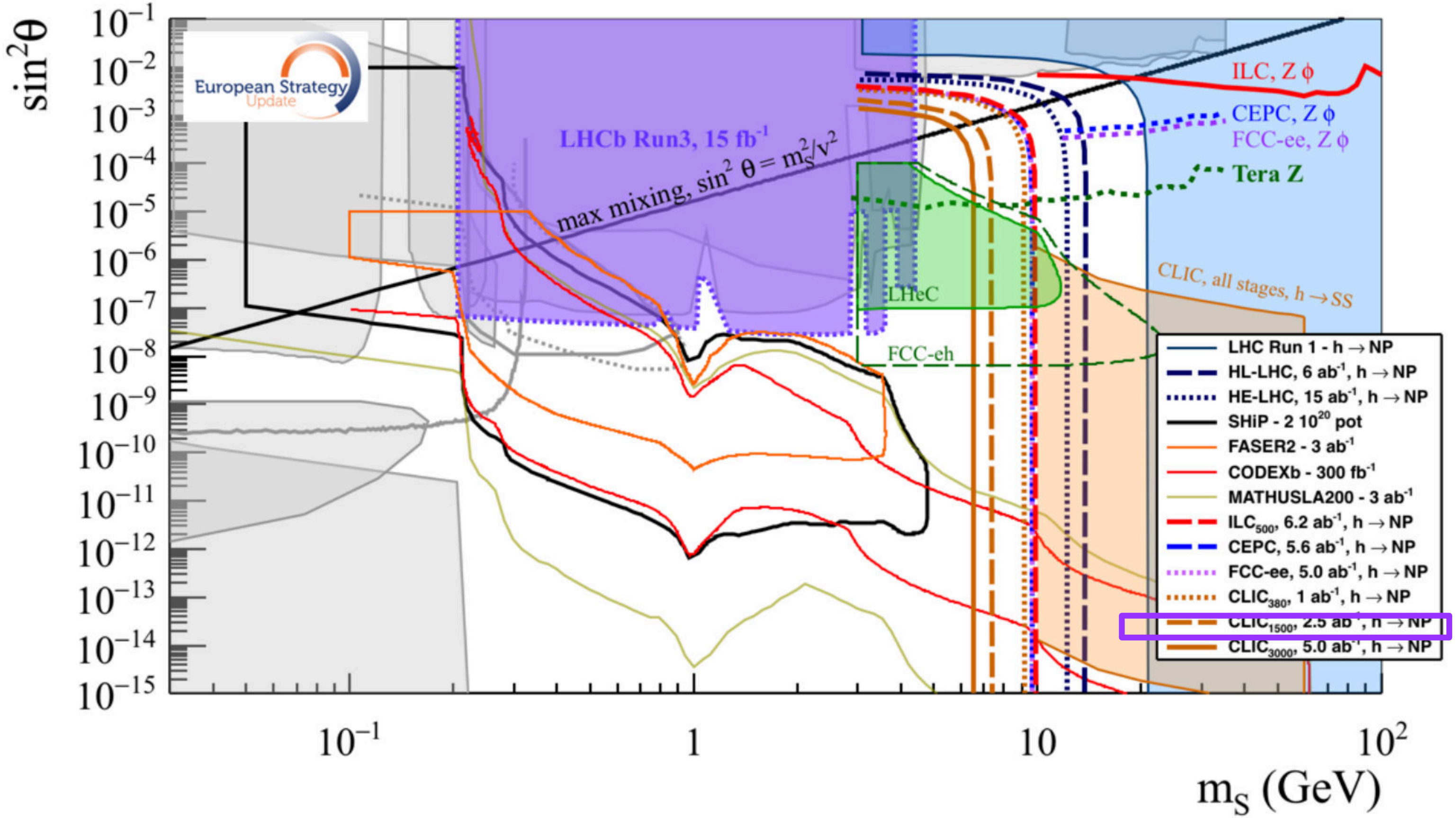
Frugiuele, EF, Schlaffer, Perez '18 + updates for European Strategy '19



Benchmark for European Strategy Update

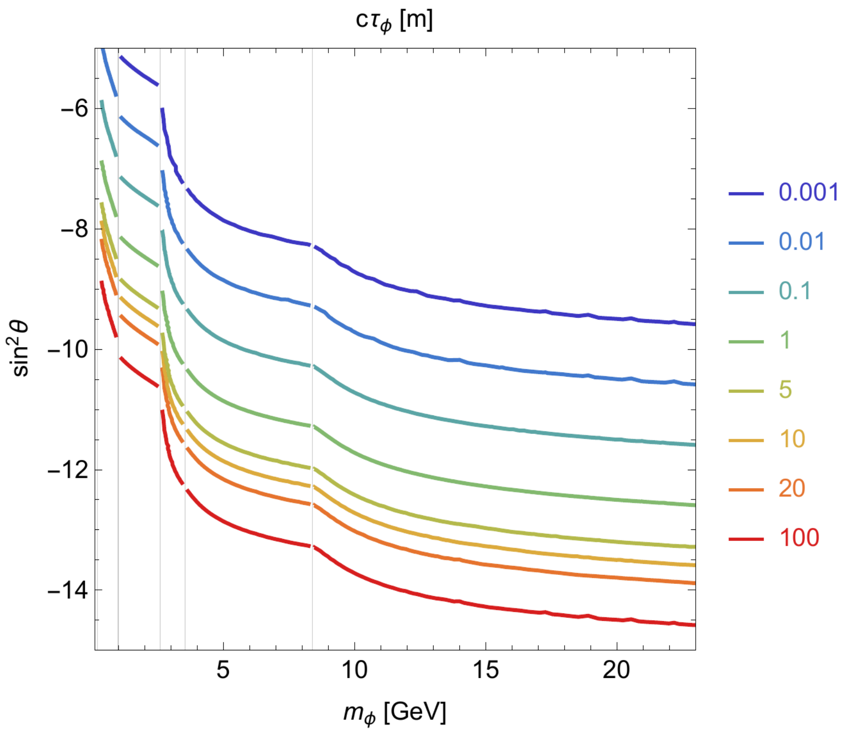
Ellis et al '19

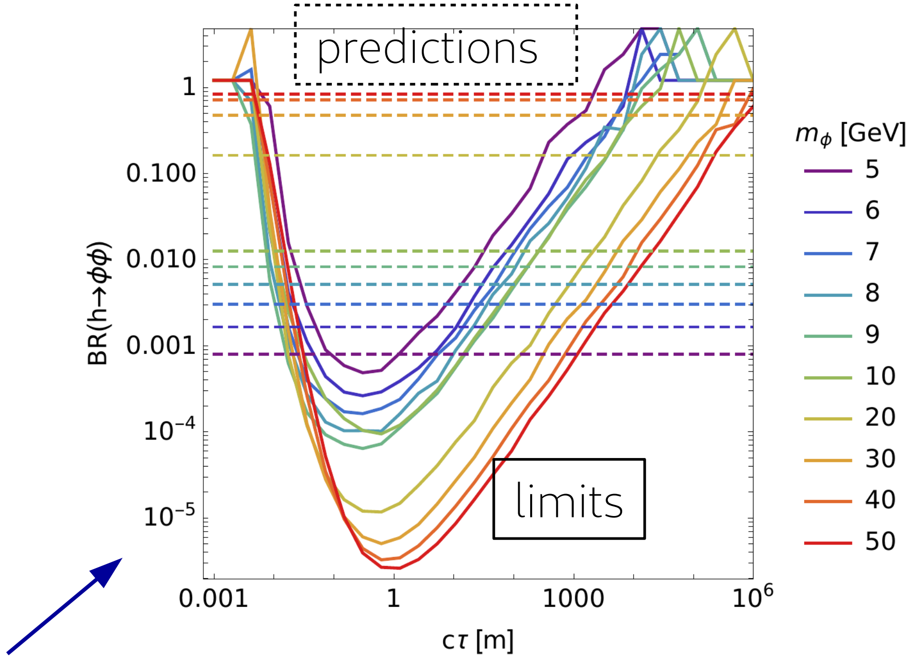
Relaxion as
NP benchmark
with light new scalar



Long-lived relaxions

EF, Perez, Savoray, Schlaffer, work in progress

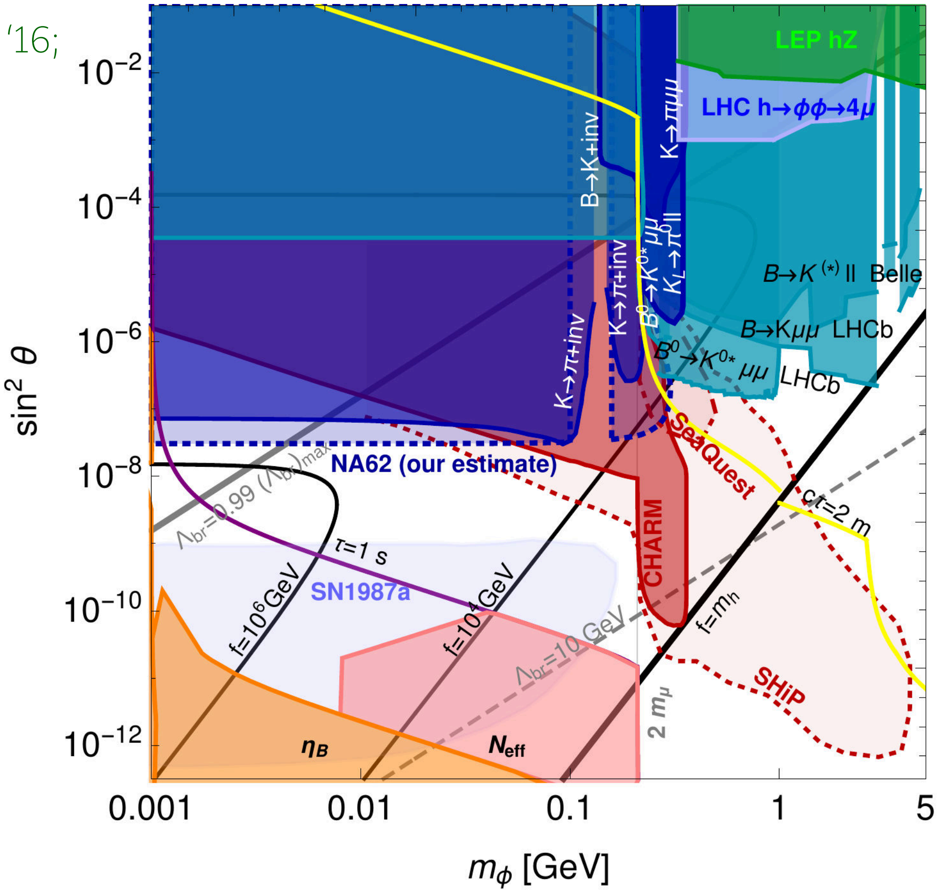




Using and reproducing J. Liu, Zh. Liu, L.T. Wang '19

MeV-GeV: B, K decays

Flacke, Frugiuele, EF, Gupta, Perez '16;



Coupling modifier, BR_{NP}, Br_{inv}

Collider	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [ab^{-1}]	BR_{NP} [%]	BR_{inv} [%]	$\delta\kappa$ [%]	Ref.
LHC1	7, 8	0.022	20	37	26	[14] Tab. 10,11
LHC3	13	0.3	12.3	17	8.6	
HL-LHC	14	6	4.1	1.9	1.3	[15] Tab. 24
HE-LHC	27	15	2.6	(2.6)	0.8	
LHeC	1.3	1	2.2	2.2	0.6	
ILC250	0.25	2	1.8	0.26	0.3	[15] Tab. 25
ILC500	0.25, 0.35, 0.5	2+0.2+4	1.4	0.23	0.24	
CEPC	$M_Z, 2M_W, 0.24$	16+2.6+5.6	1.1	0.28	0.18	[15] Tab. 25
FCCee240	0.24	5	1.2	0.22	0.21	[15] Tab. 25
FCCee365	0.365	1.7	1.1	0.19	0.18	
FCCee/eh/hh	100	30	1	0.024	0.24	
TeraZ	M_Z	$N_Z = 10^{12}$				
CLIC stage 1	0.38	1	2.7 (0.92)	0.64	0.4	[15] Tab. 25
CLIC stage 2	1.5	2.5	2.4 (0.39)	0.65	0.2	([16] Tab. 6c)
CLIC stage 3	3	5	2.4 (0.26)	0.65	0.1	

Table 1. Bounds in the $\kappa - 2$ scenario on the BR_{NP} and uncertainty in the determination of the most precise κ (namely κ_Z except for CLIC stage 2 and 3 and LHeC where κ_W is more precise) at different benchmarks of the LHC and future lepton colliders with given energy and luminosity. Assumptions on the polarization can be found in the original references. The LHC Run-3 bound at approximately 95% CL was obtained by multiplying the 68% CL bound from Ref. [14] by the ratio of the quantiles of a χ^2 distribution with 2 parameters assuming that a true 2-parameter (BR_{NP} and one global κ) fit will be dominated by the most precise κ.

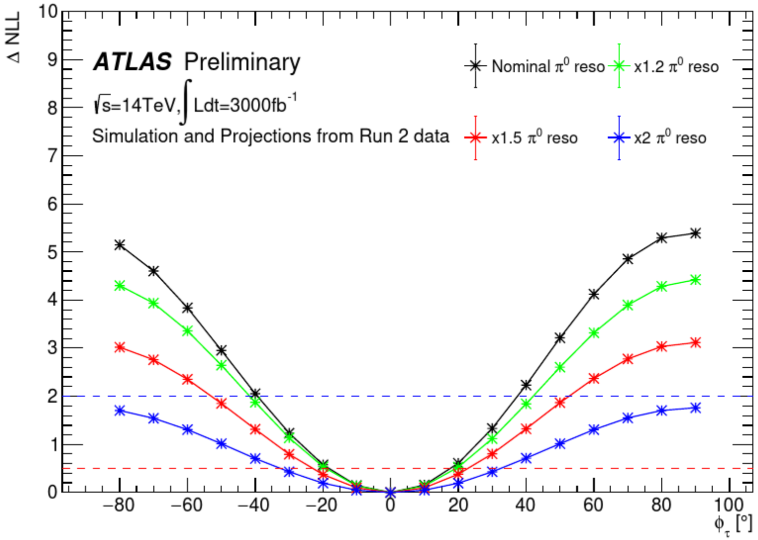
[14] Bechtle et al 1403.1582
[15] de Blas et al 1905.03764
[16] de Blas et al 1812.02093

LHC results used for EFT of Yukawa

channel	experiment	$\sqrt{s}$ / TeV	$\mathscr{L}$ / fb^{-1}	comment	μ	Ref
$h \to \tau^+\tau^-$	ATLAS+CMS	7+8	$5+20$		$1.11^{+0.24}_{-0.22}$	[16]
	ATLAS	13	36.1	ggF, VBF	$1.09^{+0.35}_{-0.30}$	[17]
	CMS	13	77	ggF, $\bar{b}b$, VBF, Vh	0.75 ± 0.17	[18]
	ATLAS+CMS	7+8+13		all prod., priv. comb.	0.91 ± 0.13	[16–18]
$h \to \mu^+\mu^-$	ATLAS	13	139	upper bound at 95% C. L.	< 1.7	[19]
	CMS		35.9		< 2.9	[20]
$h \to \bar{b}b$	ATLAS	13	79.8	VBF+VH	1.23 ± 0.26	[15]
				$t\bar{t}h + th$	$0.79^{+0.60}_{-0.59}$	
	CMS	7+8+13	41.3	VH (0-2ℓ, 2 b-tags+jets)	1.01 ± 0.22	[21]
				all prod.	1.04 ± 0.2	
	ATLAS+CMS	7+8+13	≤ 79.8	VH, priv. comb.	0.98 ± 0.15	[14, 21]
				all prod., priv. comb.	1.02 ± 0.14	

CPV ATLAS h→ ττ: Prospects for HL

This note presents a study for the prospective measurement of the $\mathcal{CP}$ quantum number of the Higgs boson coupling to τ leptons with 3000 fb^{-1} of proton–proton collisions at $\sqrt{s}$ = 14 TeV using the ATLAS detector at the HL-LHC. Only $H \to \tau\tau$ events where both τ leptons decay via the $\tau^{\pm} \to \rho^{\pm}\nu_{\tau} \to \pi^{0}\pi^{\pm}\nu_{\tau}$ chain are analysed and the acoplanarity angle $\varphi^{*}_{\mathcal{CP}}$, the angle between the planes spanned by the pion pairs, is used to determine the $\mathcal{CP}$-mixing angle. It is shown that considering only statistical uncertainties, a pseudoscalar Higgs boson can be excluded at 95% confidence level. The $\mathcal{CP}$-mixing angle can be measured with a statistical precision ranging between ±18° and ±33°, depending on the precision of the π^0 reconstruction



$$\mathcal{L} = g_{\tau\tau}(\cos(\phi_\tau)\bar{\tau}\tau + \sin(\phi_\tau)\bar{\tau}i\gamma_5\tau)h$$

ATLAS PHYS-PUB-2019-008