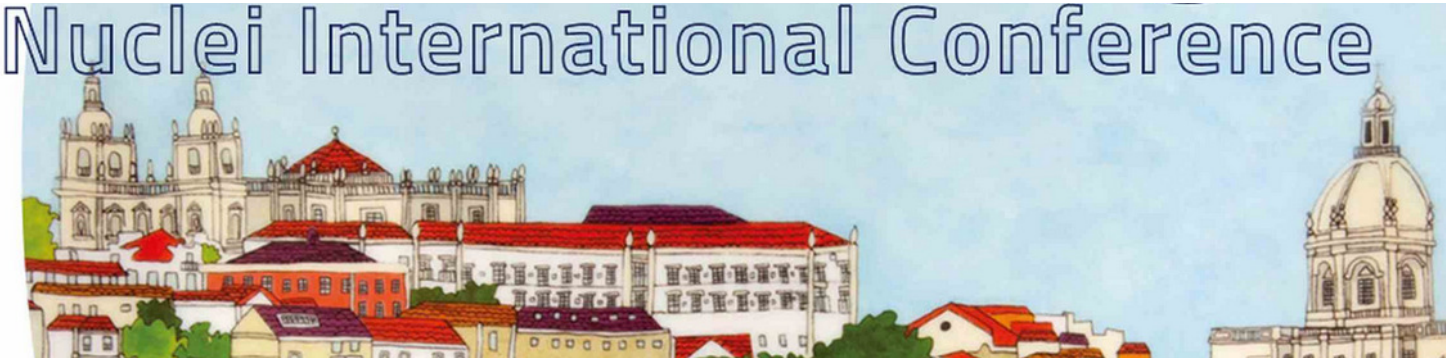
BSM vision



PANIC 2021 Lisbon, Portugal
September 5, 2021
Parallel session “Energy frontier physics beyond the standard model”

Elina Fuchs
CERN & LU Hannover & PTB

CERN

Leibniz Universität Hannover

PTB

QuantumFrontiers

Outline

1.) BSM challenges

2.) BSM theories – new and old paradigms

3.) BSM opportunities – looking for the unexpected

4.) Case: SM+singlet

This talk: incomplete & biased selection

1.) BSM challenges

BSM challenges

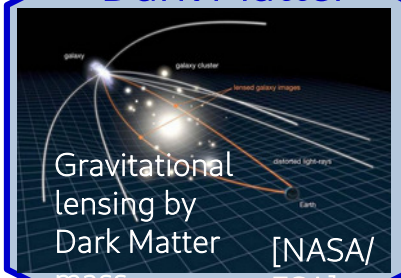
BSM must solve/ ameliorate

...and reproduce SM-like measurements

Baryon Asymmetry

[PLANCK/ESA 2013]

Dark Matter



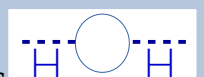
New Physics

Where? How? At which scale?

Higgs Mass Hierarchy Problem

10^{18} GeV: Planck scale

16 orders



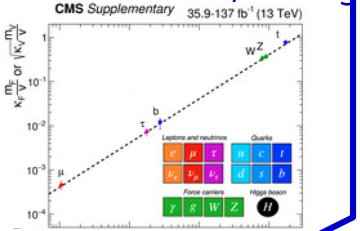
10^{2} GeV: Higgs mass

Strong CP problem

$$\bar{\theta} < 10^{-11}$$

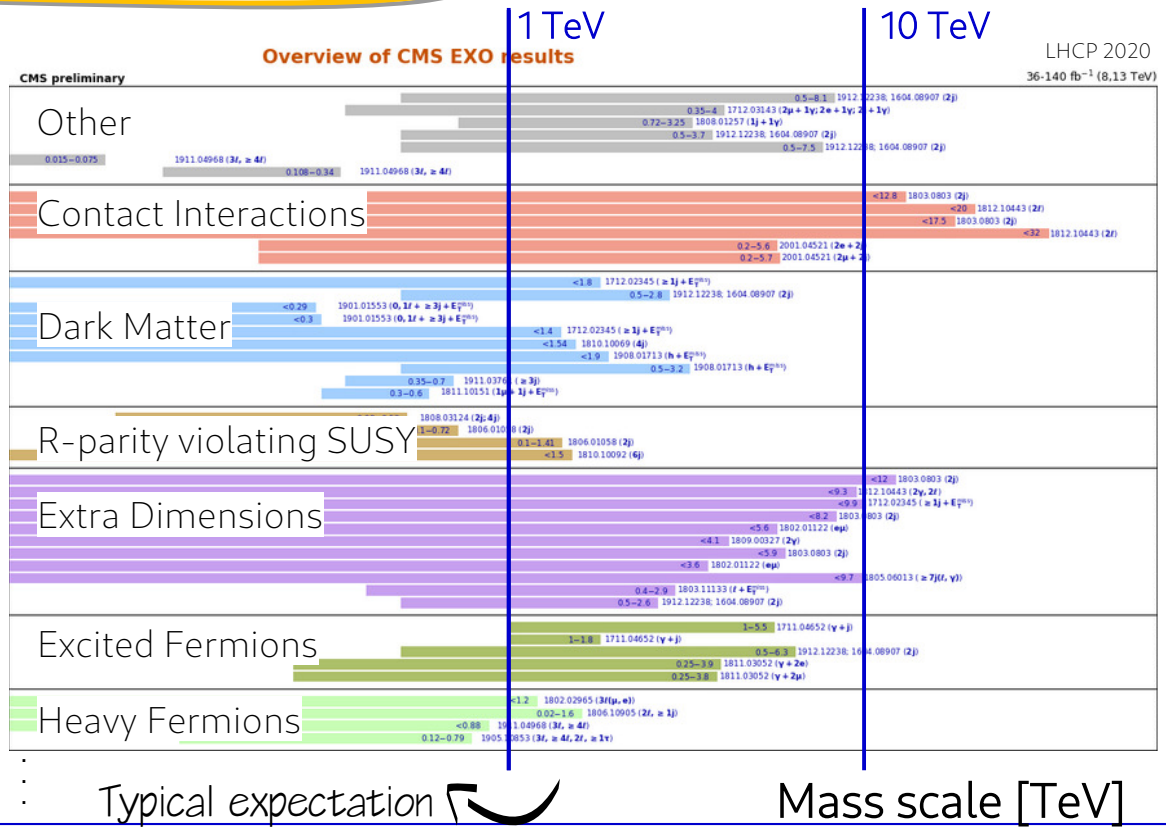
Flavor puzzle

fermion masses, mixing



Searches for New Physics

Direct LHC searches

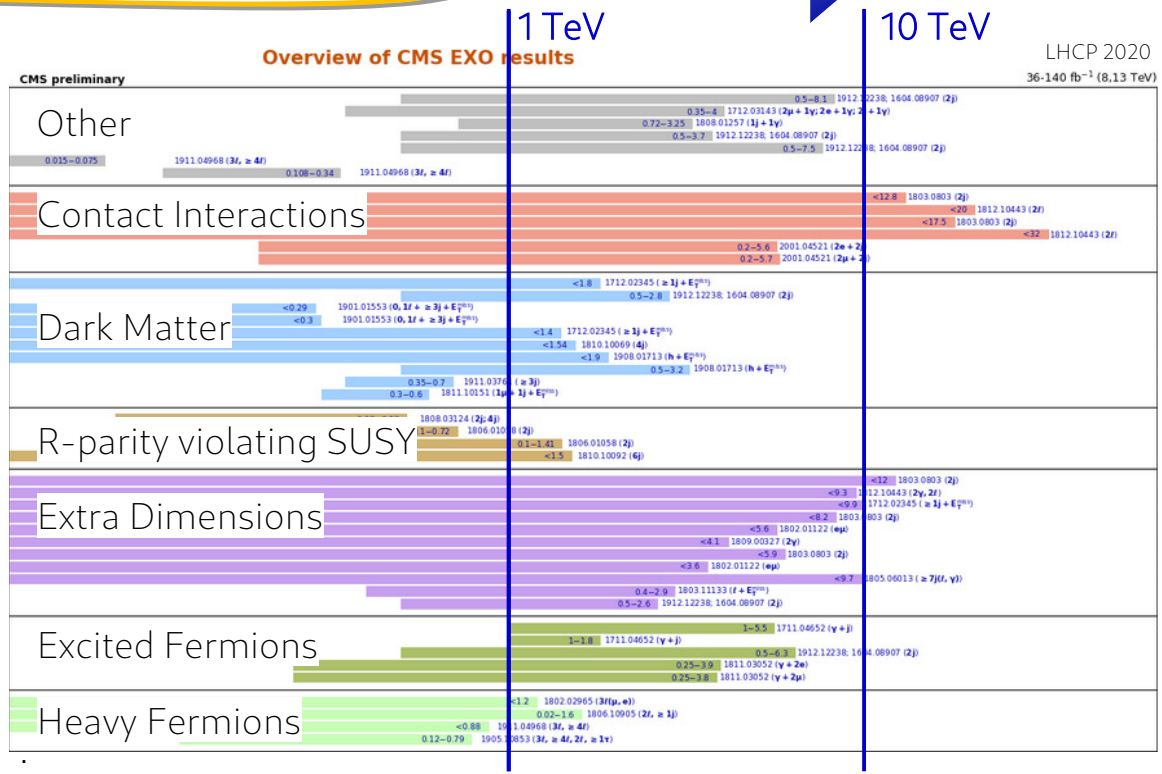


Plethora of models tested

Searches for New Physics

Direct LHC searches

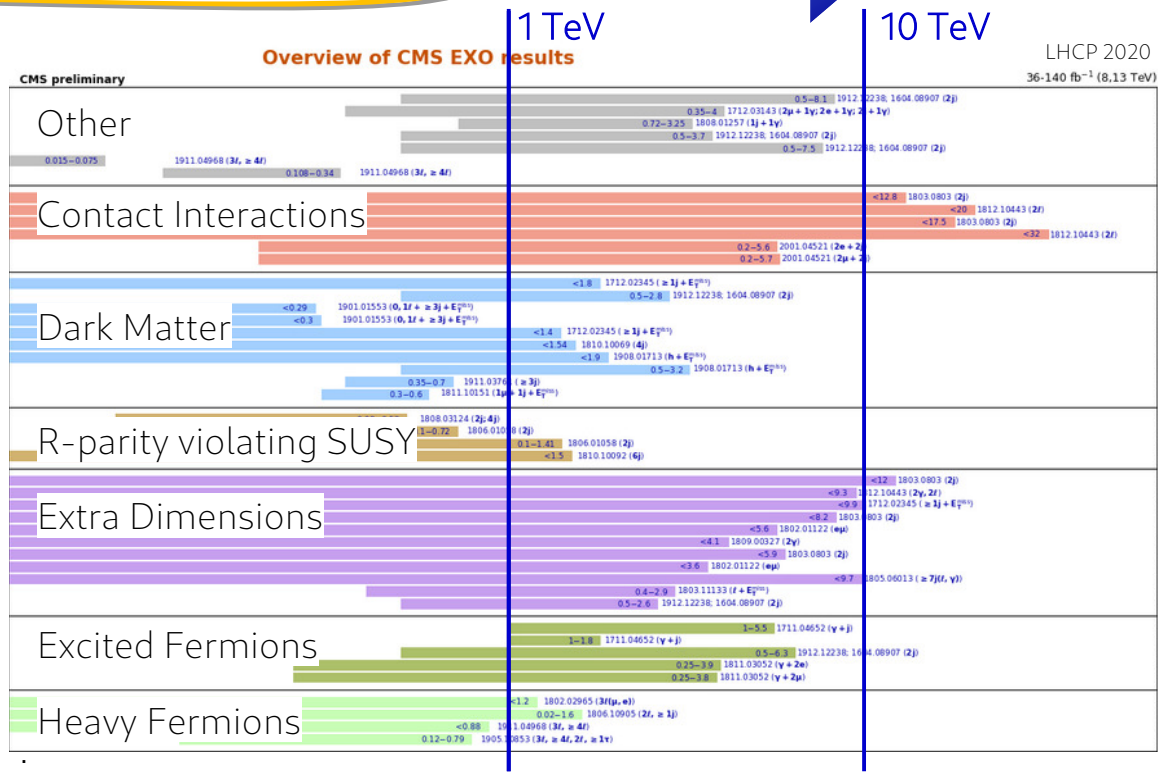
Pushing the limits



Searches for New Physics

Direct LHC searches

Pushing the limits



Plethora of models tested

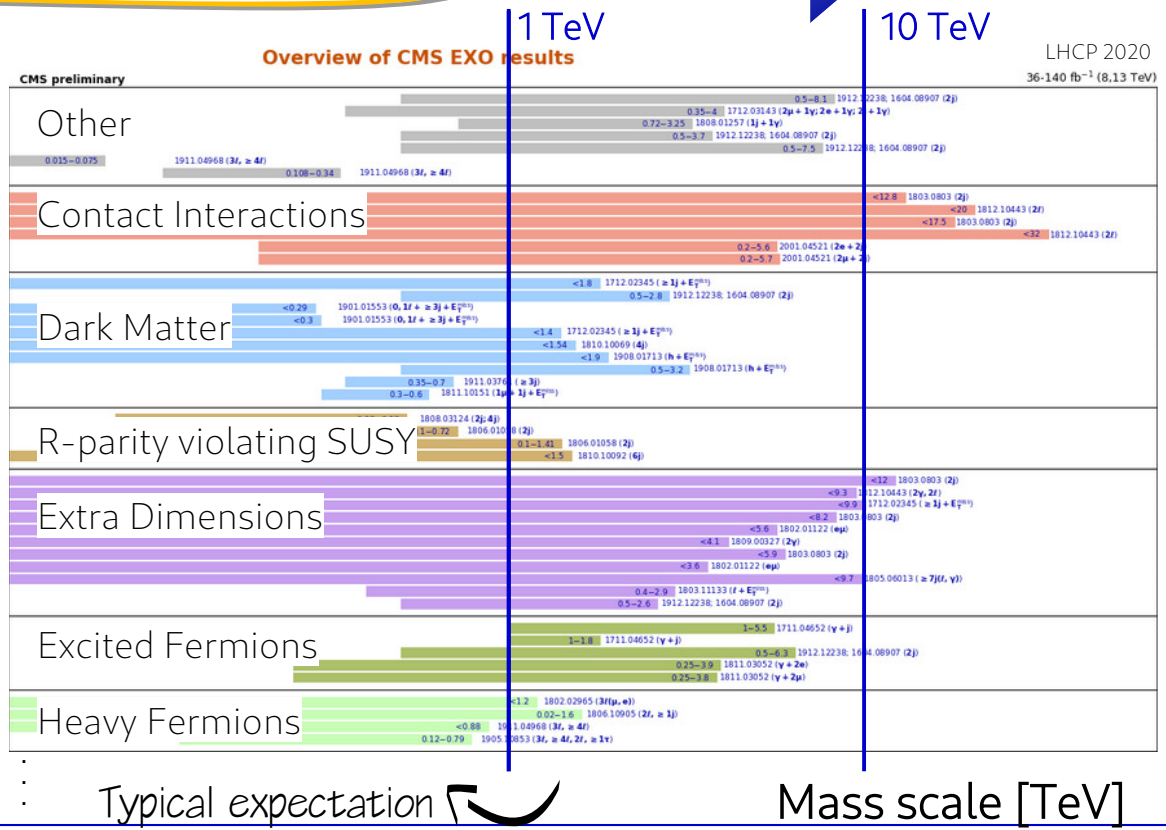
Interesting anomalies, e.g.

- Flavor: B-, K-, D-mesons
- muon magnetic moment → update 2021 [g-2 Fermilab]
- Dark Matter [XENON1T '20]
- Neutrinos [MiniBooNE '20]
- Stellar cooling beyond neutrinos

Searches for New Physics

Direct LHC searches

Pushing the limits



Interesting anomalies, e.g.

- Flavor: B-, K-, D-mesons
- muon magnetic moment
  → update 2021 [g-2 Fermilab]
- Dark Matter [XENON1T '20]
- Neutrinos [MiniBooNE '20]
- Stellar cooling beyond neutrinos

- No discovery (yet), but tensions
- Limits on particle masses and couplings stronger

→ inconclusive so far, more data and strategies needed

BSM through the Higgs window

Higgs discovery 2012

9 years later: How well do we now this Higgs boson?
Is it an elementary scalar? Is it responsible for the masses?

- ✔ It has spin 0 and is not a pure pseudoscalar
- ✔ It has no substructure down to 10^{-19}m
- ✔ It gives mass to the W and Z
- ✔ It gives mass to the 3rd generation via the Yukawa interaction
- ✔ There is some evidence (~2-3σ) for its coupling to the 2nd generation (μ,c).

ATLAS-CONF-2021-021
ATLAS-CONF-2019-028, CMS 2009.04363

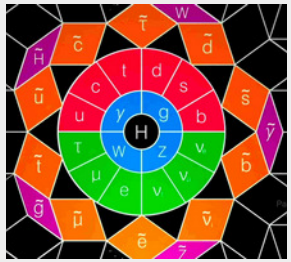
Many open questions:

- Does it couple to each of the lighter fermions?
- How does it couple to itself?
- Is it a pure scalar or does it have a CP structure?
- What stabilizes its mass much below the Planck scale?
- Are there additional light or heavy scalars?
- Are the couplings flavor-diagonal?

2.) BSM theory space

Naturalness concepts

Supersymmetry

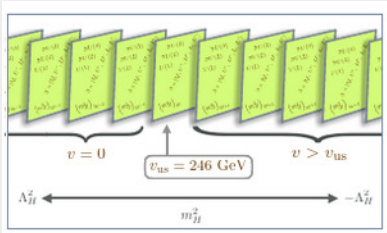


Particle Fever

Compositeness

Dimopoulos, Georgi, Kaplan '83

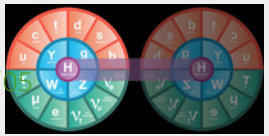
N-Naturalness



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

Neutral Naturalness

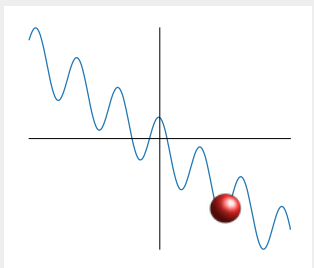
Twin Higgs
Chacko, Goh, Harnik '05



Folded SUSY
Burdman, Chacko, Goh, Harnik '07

Hyperbolic Higgs
Cohen, Craig, Giudice, McCullough '18

Relaxion



Graham, Kaplan, Rajendran '15

Clockwork

Giudice, McCullough '16

Self-organised localisation

Vacuum structure for criticality

Giudice, McCullough, You '21

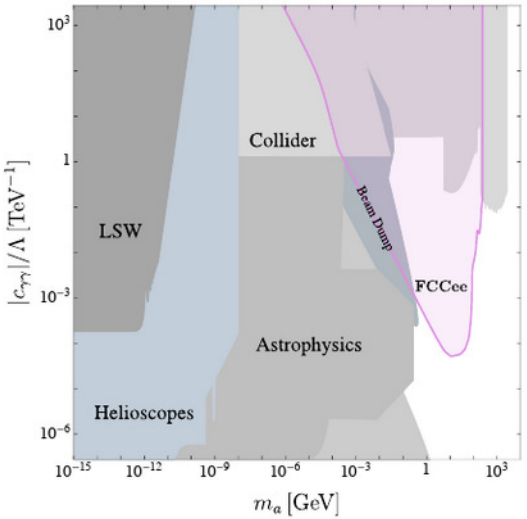
see also talk by Daniele Teresi

Extra scalars/pseudoscalars

MSSM → NMSSM

2HDM → N2HDM

SM+S



e.g. recent Knapen, Thamm '21

Axion, ALPS

see also talk by Andrea Thamm

SM+Singlet: General vs Relaxion

$$V(\Phi, H) = V_\phi + \mu^2(\phi) H^\dagger H + \lambda_h \left(H^\dagger H\right)^2$$

General renormalizable scalar singlet

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

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

→ Singlet-Higgs Mixing angle $\sin\theta \approx \frac{a_{h\phi}}{v\lambda_h}$

special case

Relaxion (pseudoscalar)

Graham, Kaplan, Rajendran '15

$$V_\phi = g\,\Lambda^3\phi + \mathcal{O}\left(g/\Lambda\right)$$

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

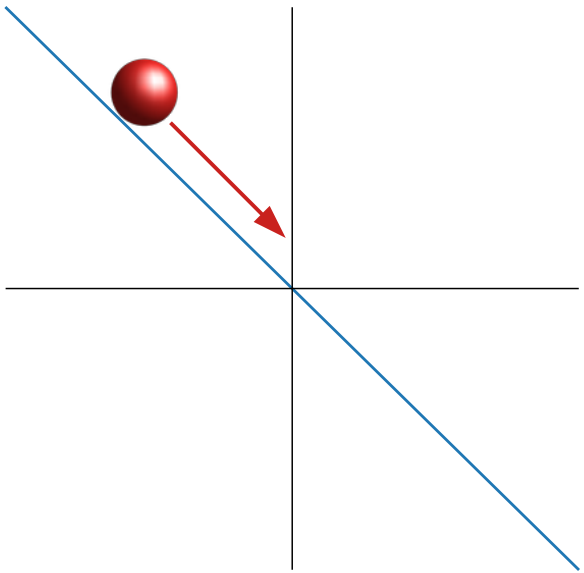
$$s_\theta \approx \frac{\tilde{M}^2}{2vf\lambda_h} \sin\left(\frac{\phi_0}{f}\right)$$

+ CP-odd couplings to SM (like axion)

Relaxion and Higgs potential

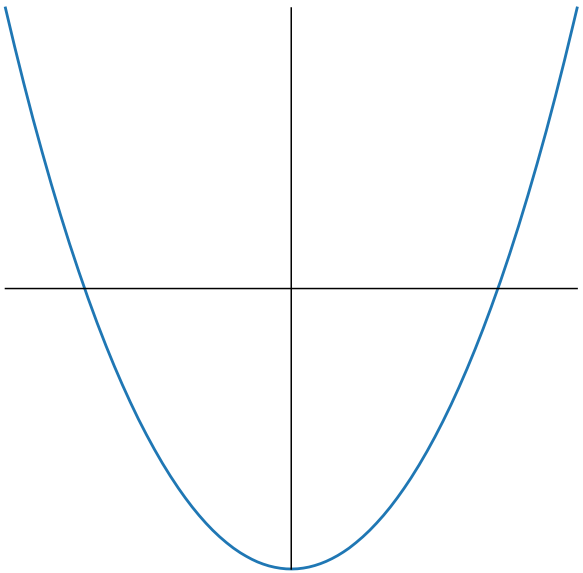
Graham, Kaplan, Rajendran '15

Relaxion V(Φ)



slow-roll

Higgs V(H)

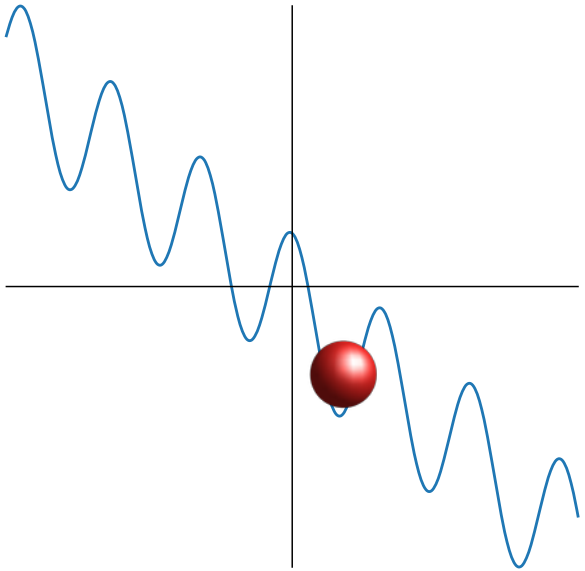


$v = 0$

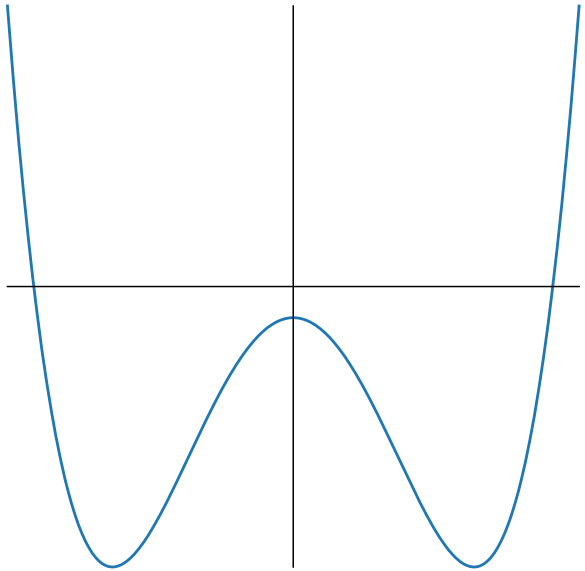
Relaxion and Higgs potential

Graham, Kaplan, Rajendran '15

Relaxion V(Φ)



Higgs V(H)



Backreaction: when

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

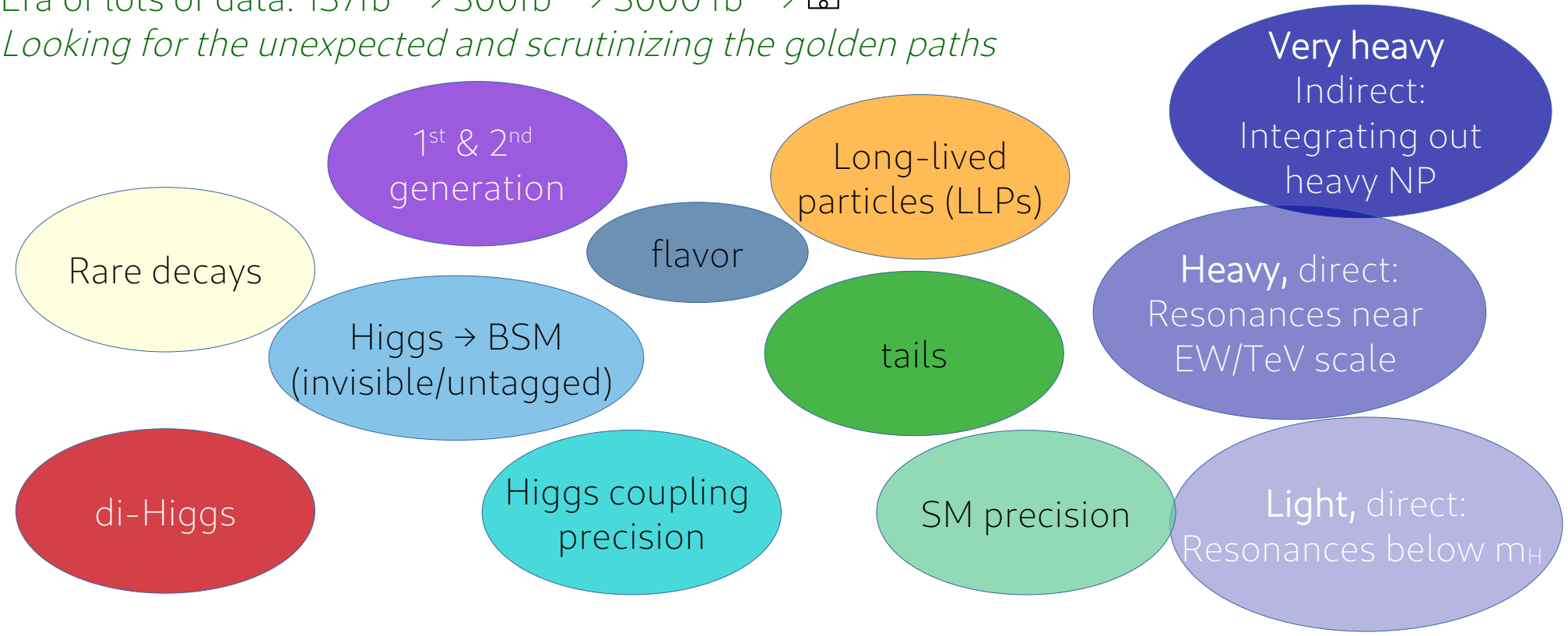
$$v \neq 0$$

$$m_h = m_h^{\text{obs}}$$

3.) BSM opportunities at the energy frontier

Era of lots of data: 137fb^{-1} → 300fb^{-1} → 3000 fb^{-1} → ⍰

Looking for the unexpected and scrutinizing the golden paths



Observables of fundamental properties

Examples of

High-energy collider opportunities

CP violation

Electroweak phase transition

Vacuum stability

Dark Matter/ Dark Sector

Higgs mass hierarchy

Examples of

Low-energy precision opportunities

Observables of fundamental properties

Higgs rates

CPV Higgs distributions

CP violation

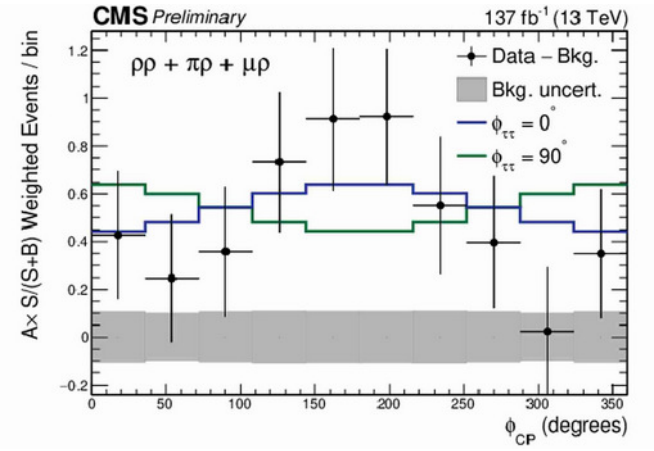
Electric dipole moments

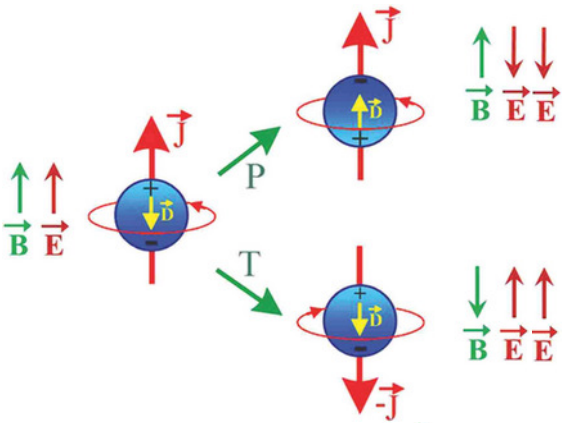
Electroweak phase transition

Vacuum stability

Dark Matter/ Dark Sector

Higgs mass hierarchy





Observables of fundamental properties

SM Higgs potential

$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$$

$\boxed{\mu^2 < 0}$

CP violation

Electroweak phase transition

Vacuum stability

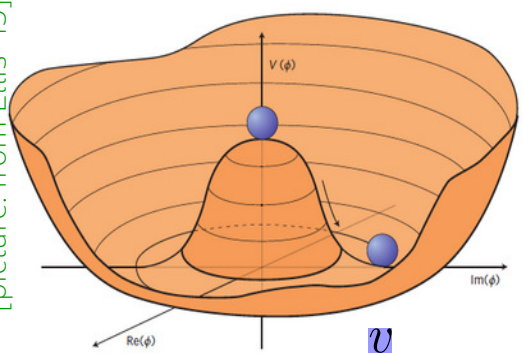
Dark Matter/ Dark Sector

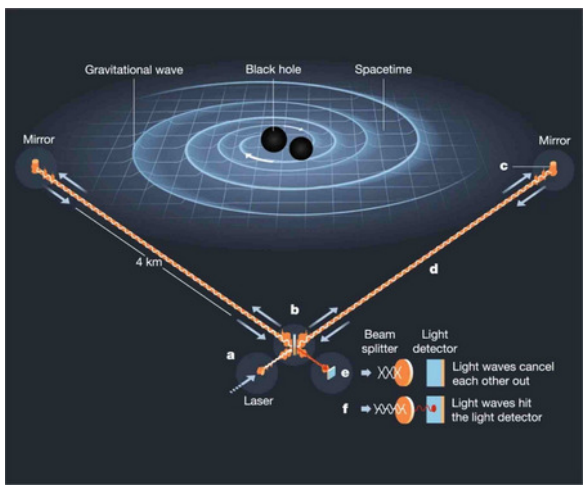
Higgs mass hierarchy

λ: Di-Higgs production

Gravit. waves: interferometry

[picture: from Ellis '15]





Observables of fundamental properties

SM Higgs potential

$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$$

$\boxed{\mu^2 < 0}$

CP violation

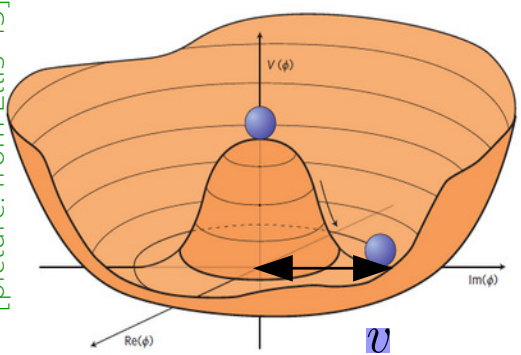
Electroweak phase transition

Vacuum stability

λ_H, y_t, M_H

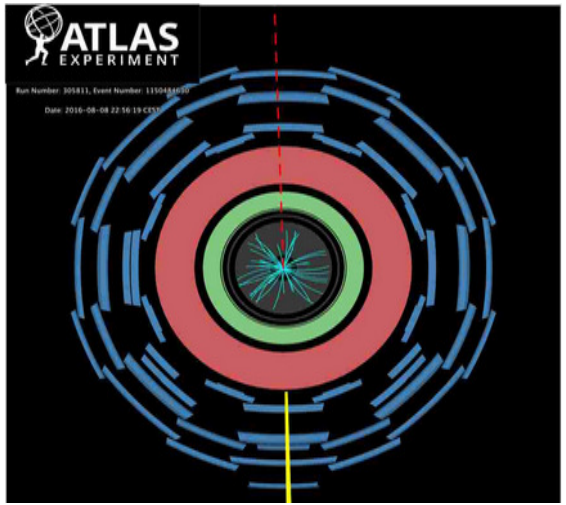
Dark Matter/ Dark Sector

Higgs mass hierarchy



[picture: from Ellis '15]

Observables of fundamental properties



CP violation

Electroweak phase transition

Vacuum stability

Dark Matter/ Dark Sector

Higgs mass hierarchy

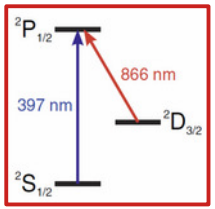
H→ inv

Mono-X searches

Spectroscopy

Variation of constants

Targeted exp.



Observables of fundamental properties

CP violation

Electroweak phase transition

Vacuum stability

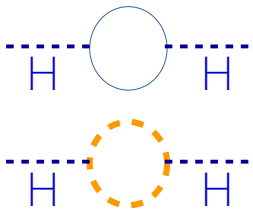
Dark Matter/ Dark Sector

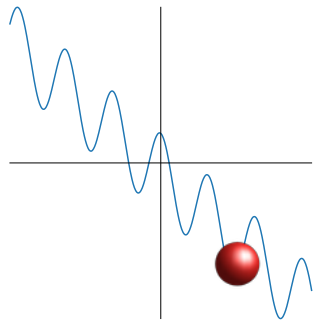
Higgs mass hierarchy

top partners

relaxion

relaxion



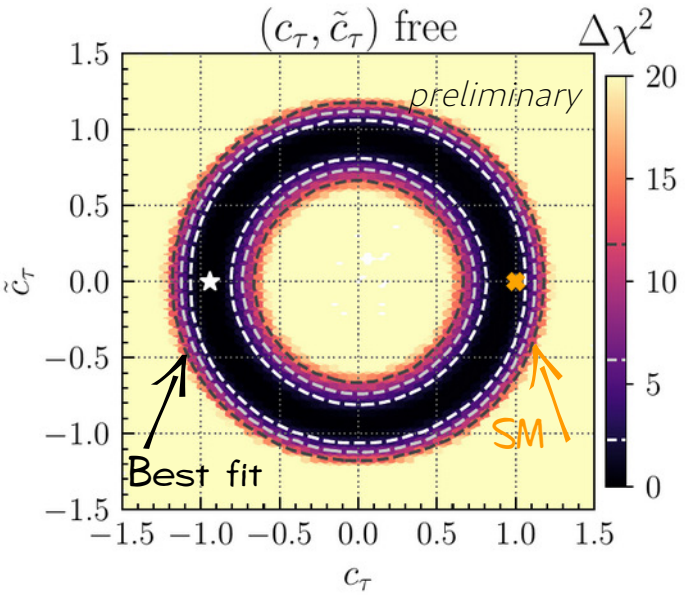


CP structure of Higgs couplings

$$\mathcal{L}_{\text{Yuk}} = -\sum_f \frac{y_f}{\sqrt{2}} \bar{f}\,(c_f + i\gamma_5 \tilde{c}_f)\, f h,$$

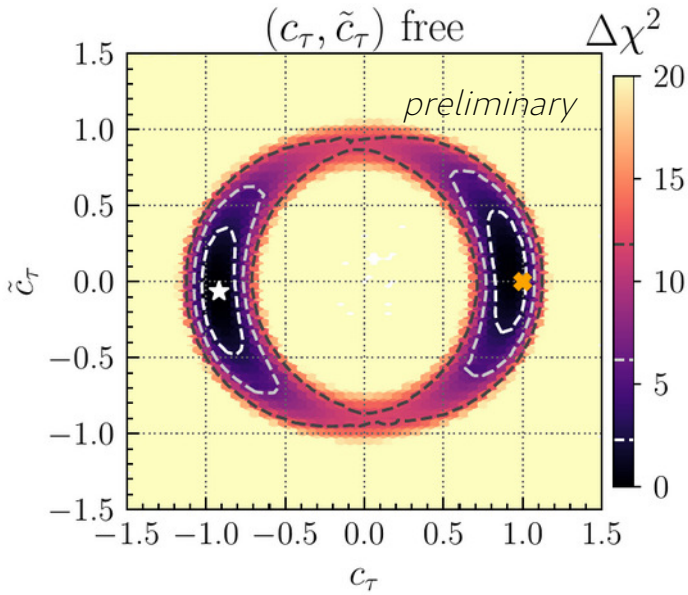
Bahl, Bechtle, EF, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein (in preparation)

can also be analyzed in EFT



CMS PAS HIG-20-06
h→ ττ CPV analysis

$c_\tau \simeq \pm 1$ almost degenerate minima of $\Delta\chi^2$



Ring-structure from upper/lower bound on BR

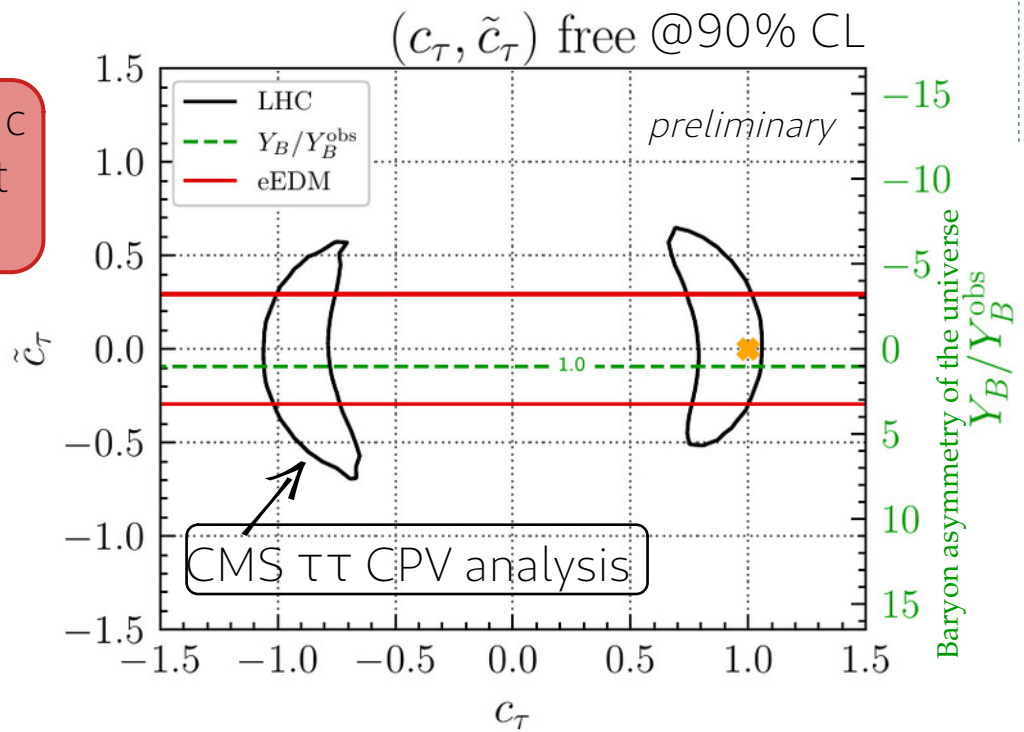
CMS analysis excludes large $\tilde{c}_\tau$

Complementary: LHC, EDM, EWBG

Bahl, Bechtle, EF, Heinemeyer, Katzy, Menen, Peters, Weiglein (in preparation)

See also
Brod, Haisch, Zupan '13
De Vries, Postma, van de Vis '18
EF, Losada, Nir, Viernik '19, '20, '20
Aharony-Shapira 2106..05338
Brod et al (in preparation)

Electron electric dipole moment
$d_e \propto \tilde{c}_f$



Electroweak baryogenesis
$Y_B \propto \tilde{c}_f$

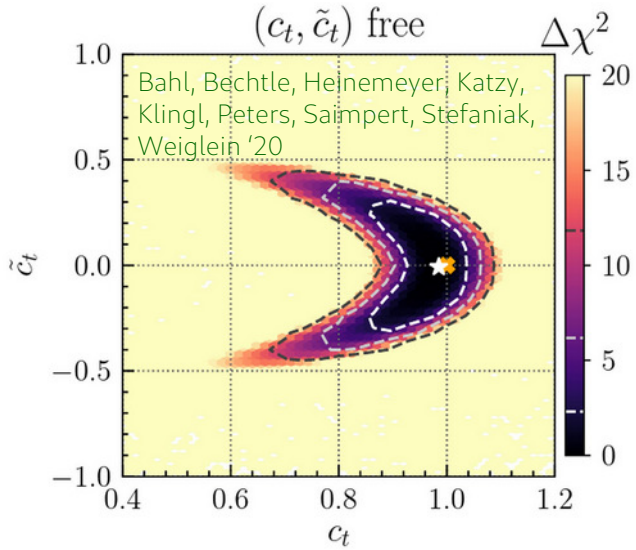
Caveat: "optimistic" scenario, large uncertainty (vev-insertion approximation)
→ almost upper bound

Cline, Kainulainen 2001.00568
Cline, Laurent 2108.04249
Postma 2107.05971
Kainulainen 2108.08336

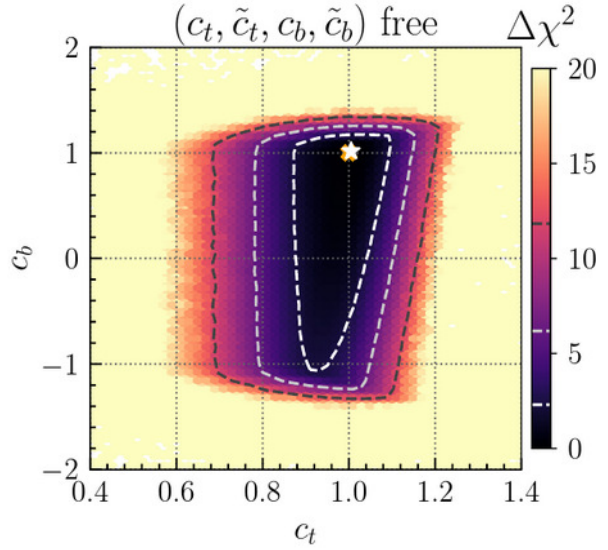
Different coupling models

Bahl, Bechtle, EF, Heinemeyer, Katzy, Menen, Peters, Saimpert, Weiglein (in preparation)

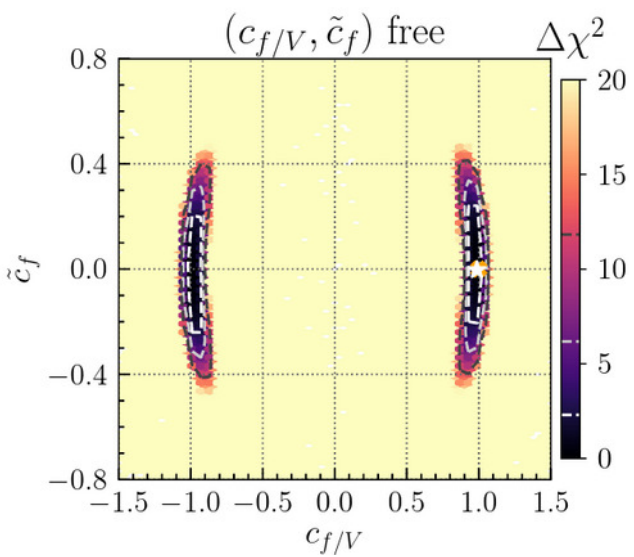
Floating several coupling modifiers simultaneously



Top: ellipse (ggF) cut off by $h \to \gamma\gamma$



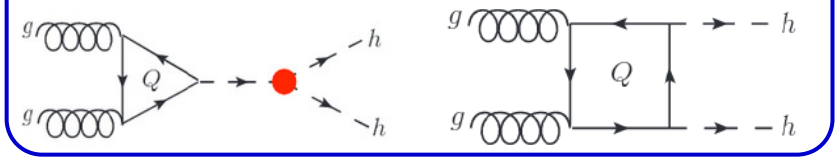
t+b: small c_b can be compensated by $\tilde{c}_b$



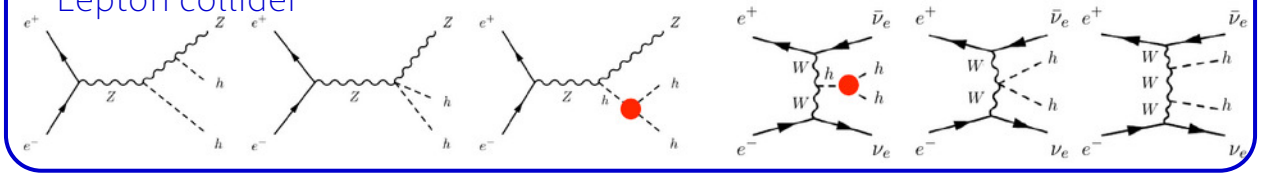
General mixing scenario
No CPV included in vector couplings

BSM wishlist for Di-Higgs

Hadron collider



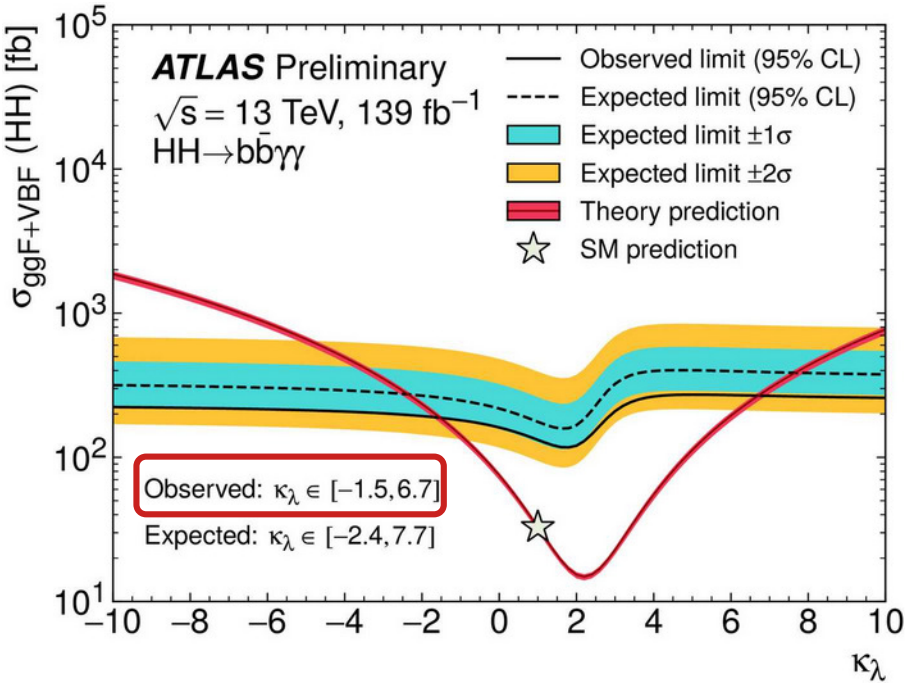
Lepton collider



from de Blas et al, Granada 1905.03764

- Electroweak phase transition → EW baryogenesis
  - Strong first order phase transition requires significant enhancement of triple Higgs coupling λ
  - → O(20%-100%) depending on model e.g. Grojean, Servant, Wells '04; Noble, Perelstein '07
- New heavy resonances
- New particles in triangle/ box (but compete with single Higgs)
- pp→ hh small in SM → challenging ⟶ BSM enhancement may have large effect

Di-Higgs status and prospects



Significant improvement compared to limit at 36 fb^{-1}

Prospects

$0.5 \leq \kappa_\lambda \leq 1.5$ HL-LHC [LHCHXSWG 1910.00012]

↘ Start testing the EW phase transitions

5% accuracy FCC [CDR '19]

↘ Distinguish models?

BSM with 1st & 2nd generation

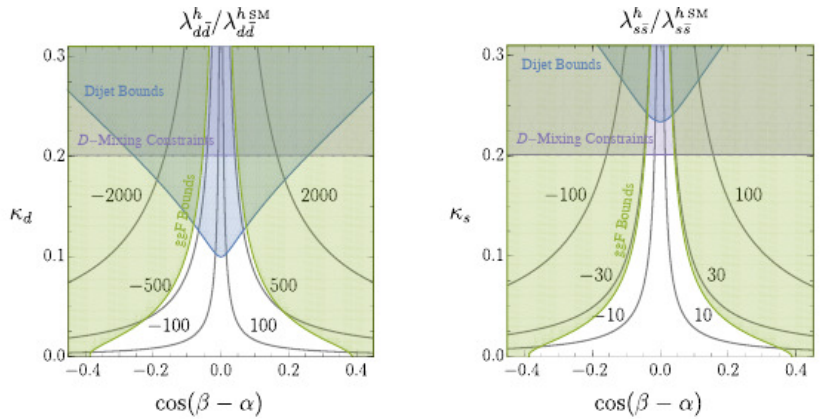
Bounds on light fermion Yukawas still loose → room for New Physics

UV Model: 2HDM with Aligned and Spontaneous Flavor Violation Egana-Ugrinovic, Homiller, Meade '18 '19 '21

Flavor alignment: 2nd doublet Yukawa matrices simultaneously diagonalible with first doublet

→ Additional heavy scalars can have large couplings to 1st & 2nd generation

→ via mixing with h_{125}: also its Yukawas enhanced, up to ~500 for d, 30 for s



Di-Higgs, triple Higgs, Zh enhanced

→ for h_{125}: $\lambda_{hd\bar{d}} \leq 30\lambda^{\mathrm{SM}}_{hd\bar{d}}$

This stringent bound only obtained for $\cos(\beta-\alpha) = 0.025$

Room for BSM in Higgs Decays

- Higgs width narrow in SM: $\Gamma_h = 4.1$ MeV, $\Gamma_h/M_h \approx O(10^{-5})$
  - **Loop**-suppressed: e.g. H→ **γγ**, Z**γ**
  - **Phase-space** suppressed: H→ WW*, ZZ*
  - **Coupling**-suppressed: even dominant channel BR(H→bb)≈58% has small $y_b \approx 10^{-2}$

Detailed overview: Curtin, Essig, Gori, Jaiswal, Katz, T. Liu, Zh. Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhon '13

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Detailed overview: Curtin, Essig, Gori, Jaiswal, Katz, T. Liu, Zh. Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhon '13

- 'exotic':  BSM decay modes can change Γ_h significantly
  - H→ BSM particles: **visible/ invisible**
    - **Long-lived** decay products
  - H→ SM decays which are suppressed/forbidden in the SM:
    - Flavor changing: H→ $f_1 f_2$ (e.g. μτ)
    - **Rare** decays e.g. to light fermions (μμ, ss, cc)

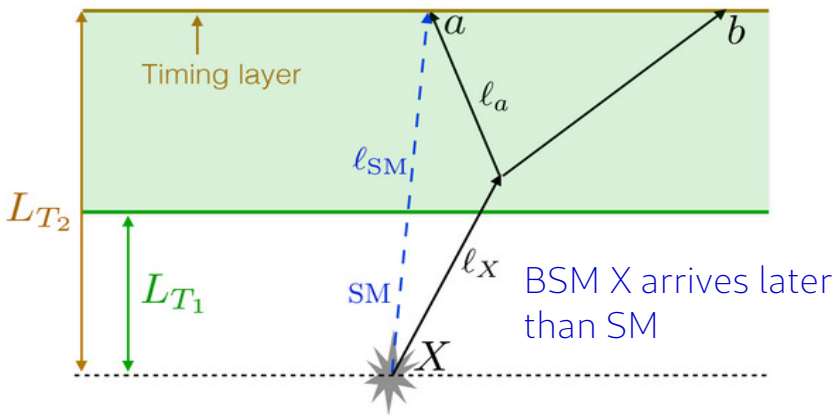
Lifetime Opportunities

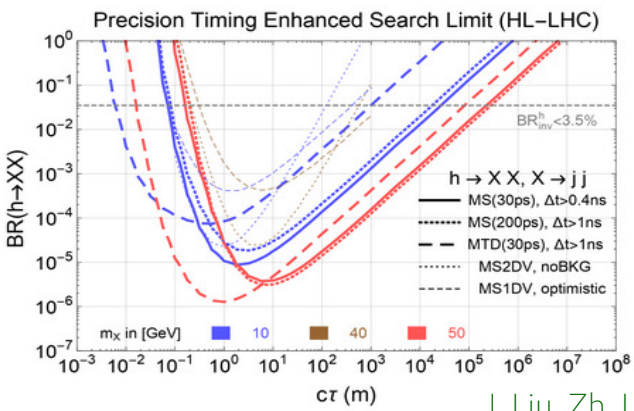
See e.g. Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider '19

Long-lived particles (LLPs) are common in BSM:

- Small coupling to SM particles
  - suppressed by mixing → Higgs portal, gauge portal to Dark Sector
  - Forbidden by (approximate) symmetry → R-parity
- Small phase space for decay → Compressed spectra, stealth/split SUSY

e.g.





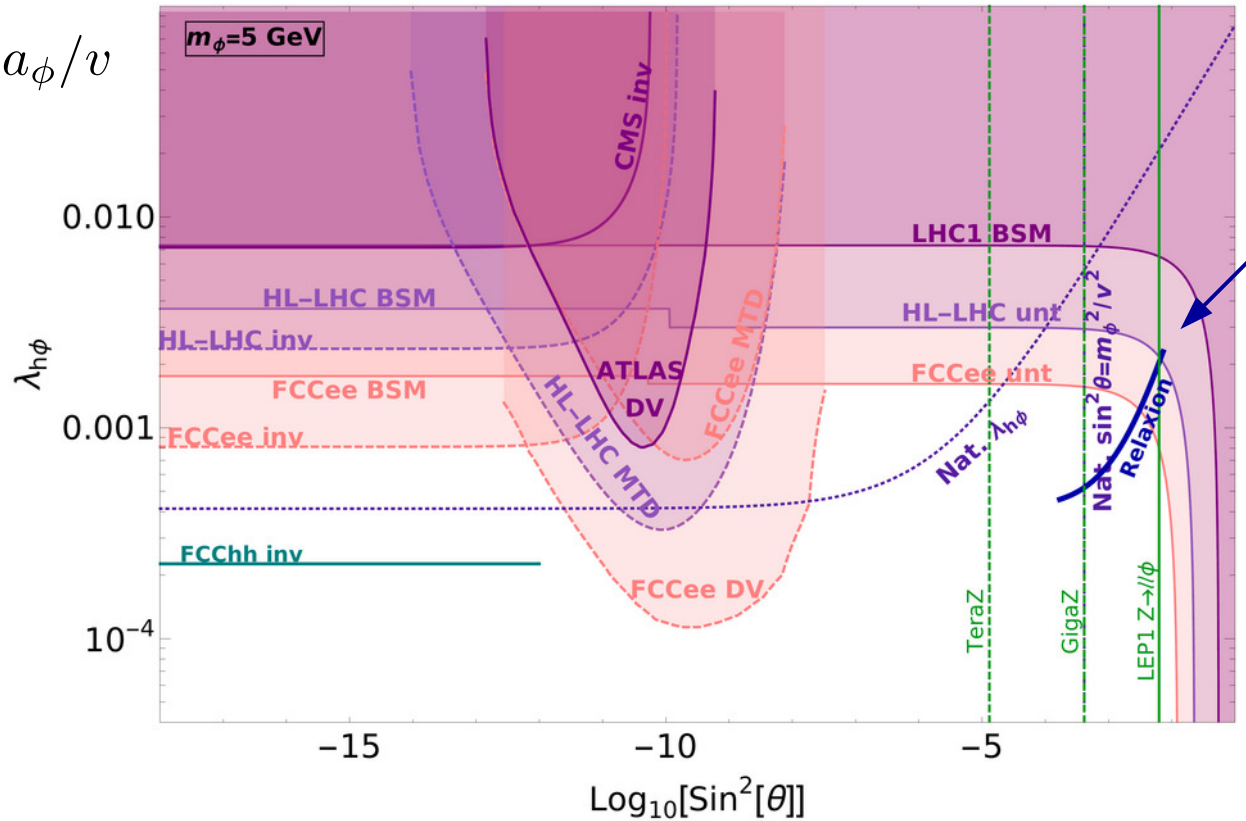
J. Liu, Zh. Liu, L.T. Wang '19

Lifetime, exotic Higgs decay &light scalar

EF, Matsedonskyi, Schlaffer, Savoray '20

$$\lambda_{h\phi} = \hat{\lambda}_{h\phi} + \sin\theta\, a_\phi / v$$

$\phi^2 h^2$



Relaxion space confined to this curve

Lifetime, exotic Higgs decay &light scalar

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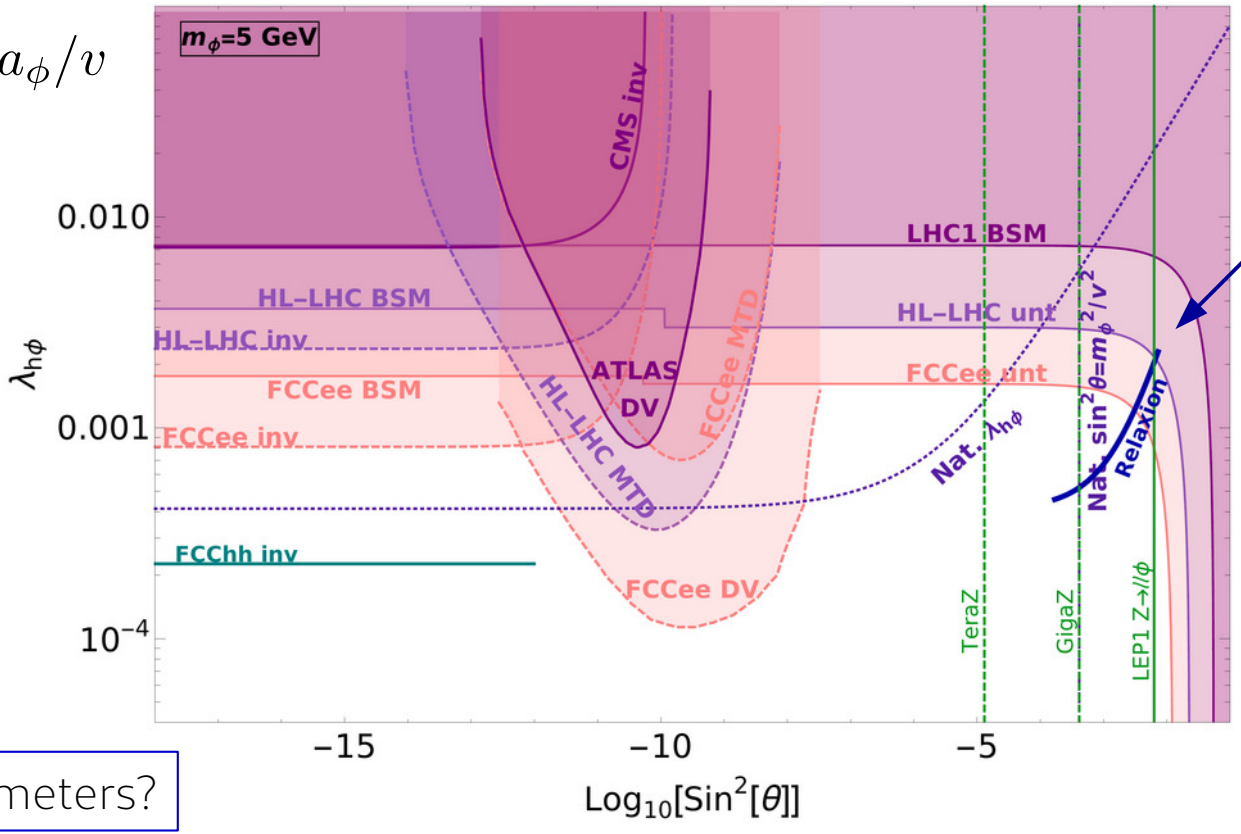


Relaxion space confined to this curve

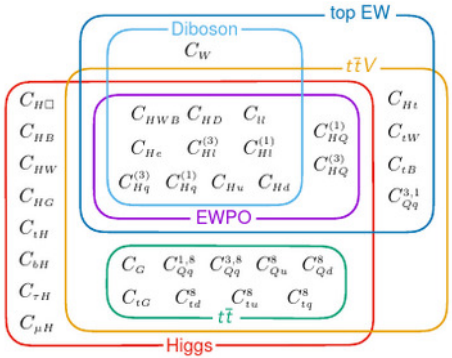
Probe natural parameters?

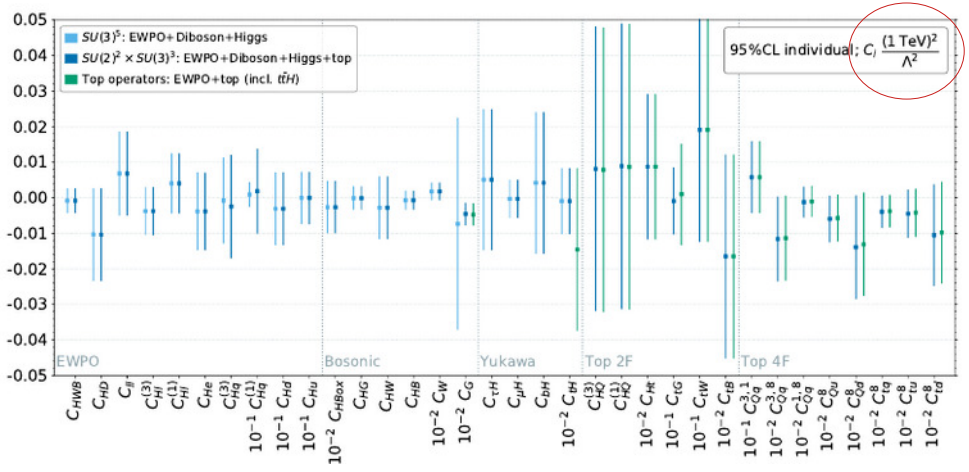
Heavy New Physics in SMEFT dim. 6

Ellis, Madigan, Mimasu, Sanz, You '21

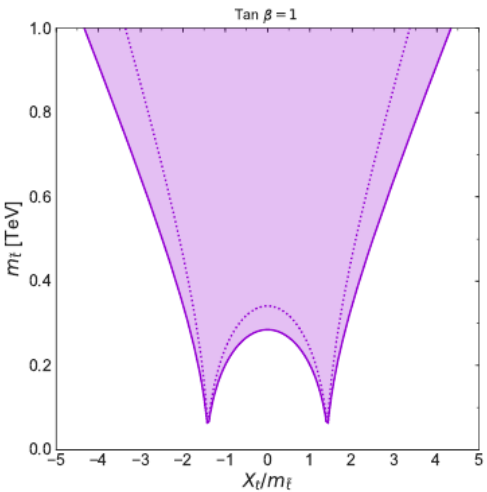
SMEFT: Standard Model Effective Field Theory

↳ Constrain operators in global fit, then interpret in models





SUSY stop squark



Combine data sets

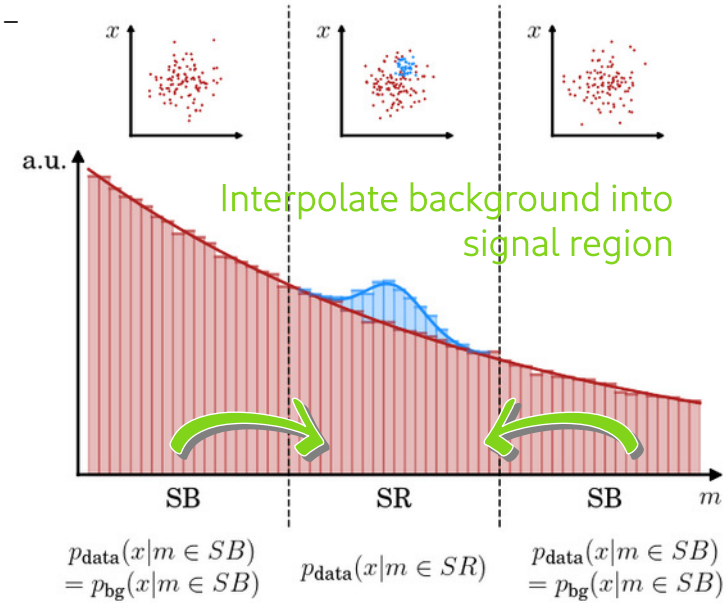
SMEFT: testing the TeV scale

What are we missing?

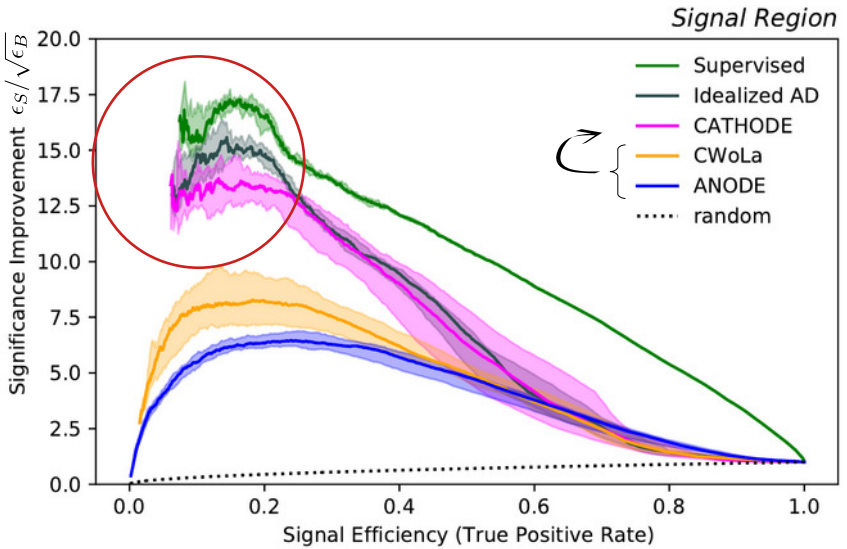
Model-driven → signature-driven searches
Overcome/ reduce theory bias → general anomaly detection (less model-dependent)

CATHODE: enhance signal resonance

Train conditional density estimators



CATHODE method
Hallin, Isaacson, Kasieczka, Krause, Nachman, Quadfasel, Schlaffer, Shih, Sommerhalder 2109.00546

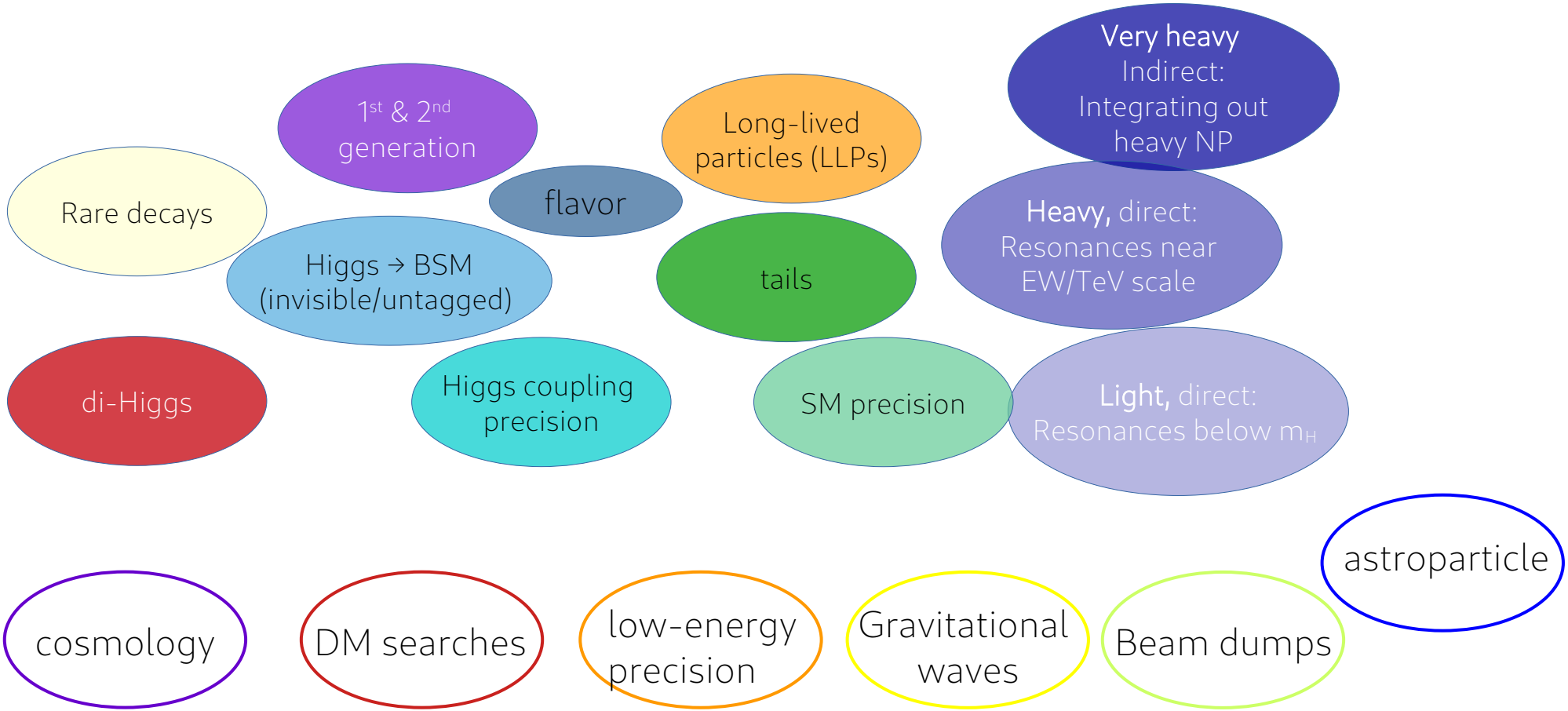


Near-optimal sensitivity improvement

BSM vision/hopes at the energy frontier

- A 2σ anomaly of today @137 fb^{-1} $\longrightarrow$ discovery @HL-LHC
- New, unexpected signal at the LHC
- Future collider approved & built
- Indirect hint at deviation from SM

Complementarity with other frontiers



Summary

→ Exciting times with lots of data, ideas, and opportunities

→ Di-Higgs: important information on self-coupling

→ No stone unturned: test all couplings of the Higgs, also light generations

→ Long-lived particles occur in many interesting models, testable

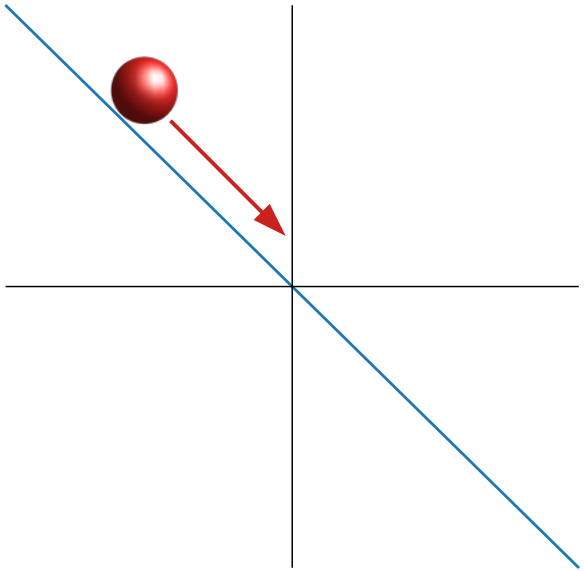
THANK YOU!

BACKUP

Relaxion and Higgs potential

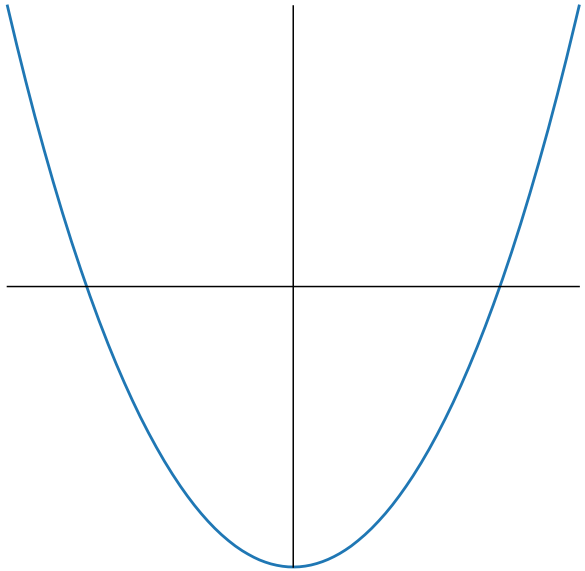
Graham, Kaplan, Rajendran '15

Relaxion V(Φ)



slow-roll

Higgs V(H)

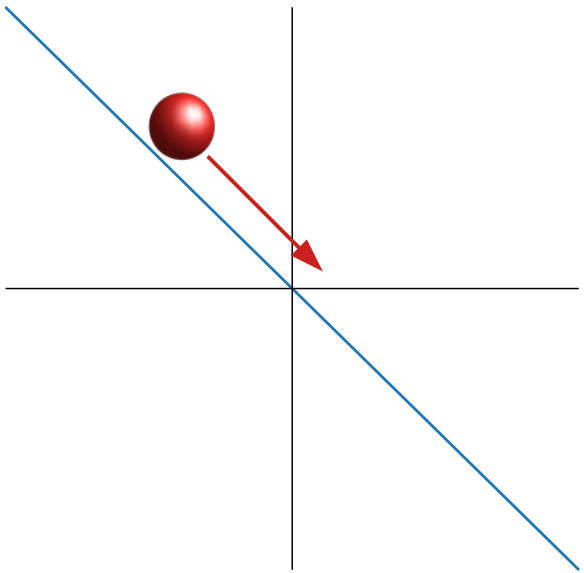


$v = 0$

Relaxion and Higgs potential

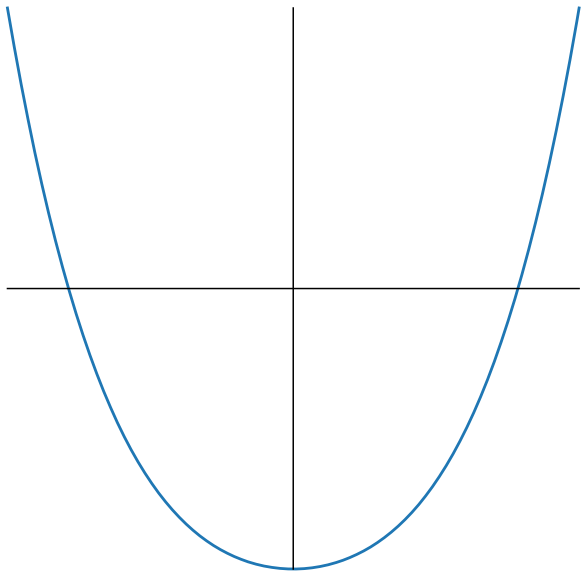
Graham, Kaplan, Rajendran '15

Relaxion V(Φ)



slow-roll

Higgs V(H)

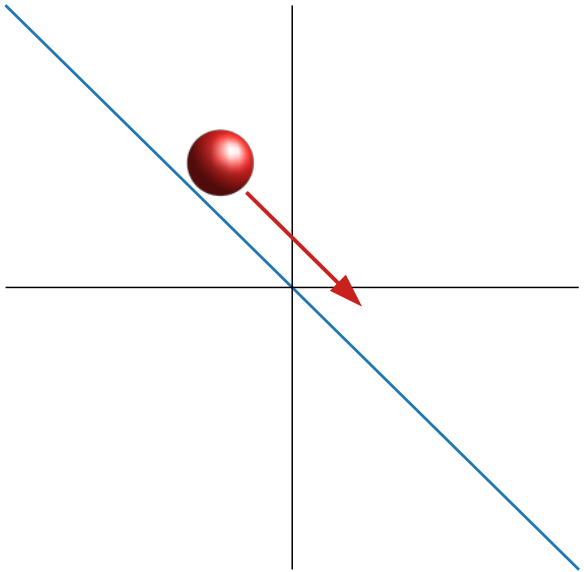


$v = 0$

Relaxion and Higgs potential

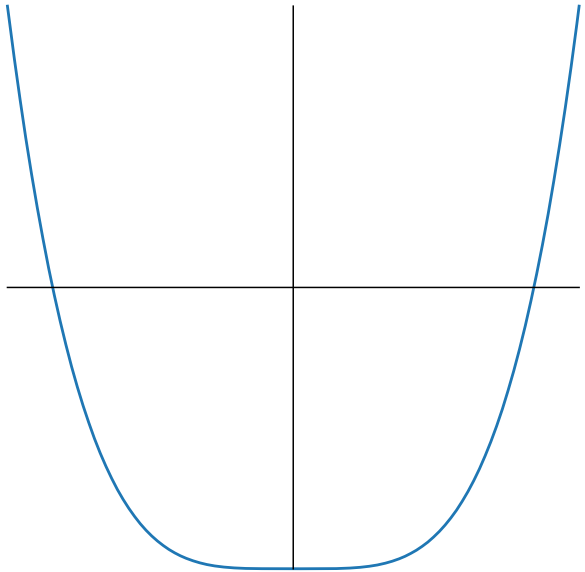
Graham, Kaplan, Rajendran '15

Relaxion V(Φ)



slow-roll

Higgs V(H)



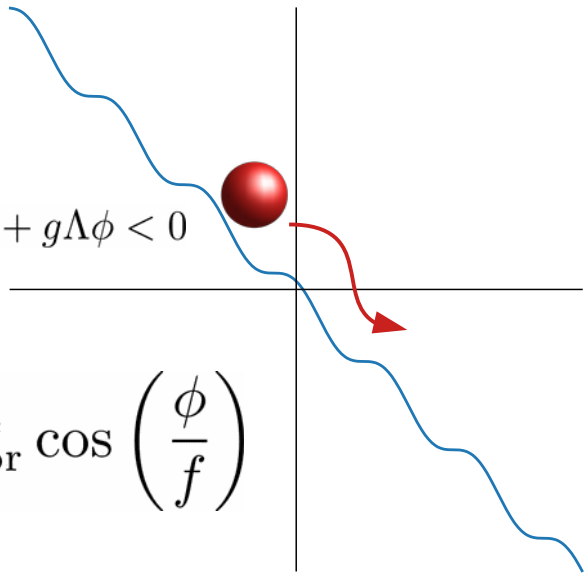
$v = 0$

Relaxion and Higgs potential

Graham, Kaplan, Rajendran '15

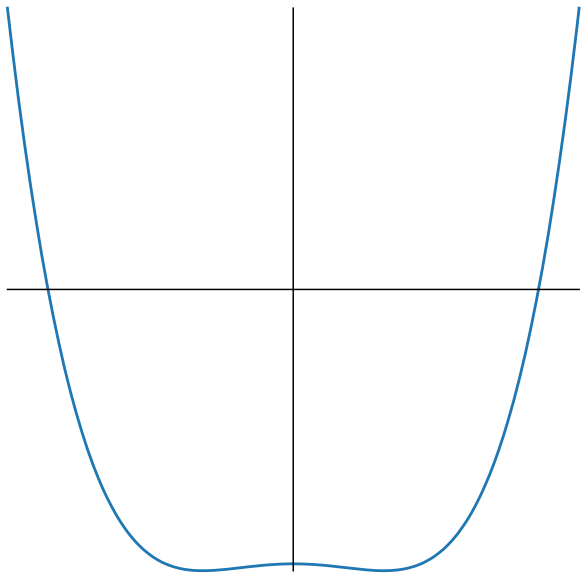
Relaxion V(**Φ**)

Higgs V(**H**)



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

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



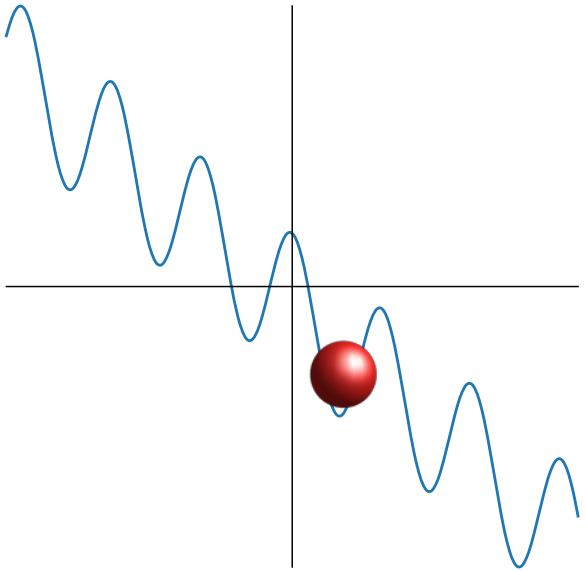
Backreaction barrier→ wiggles grow

$$v \neq 0$$

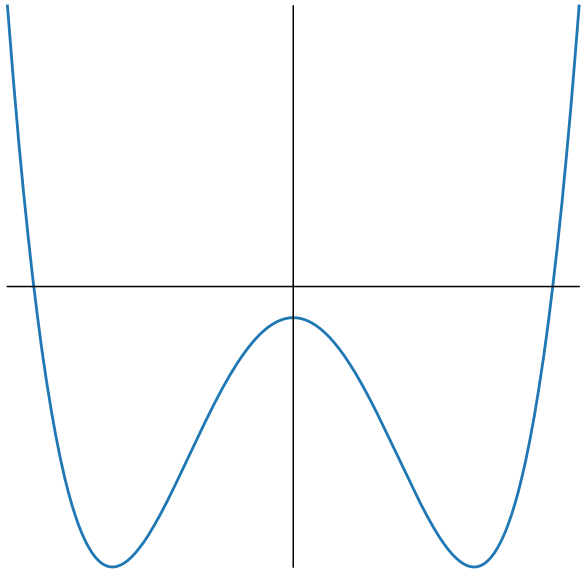
Relaxion and Higgs potential

Graham, Kaplan, Rajendran '15

Relaxion V(Φ)



Higgs V(H)



Backreaction: when
$V'_{\text{roll}} = -V'_{br}$ → relaxion stops

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

Relaxion hunting at multiple frontiers

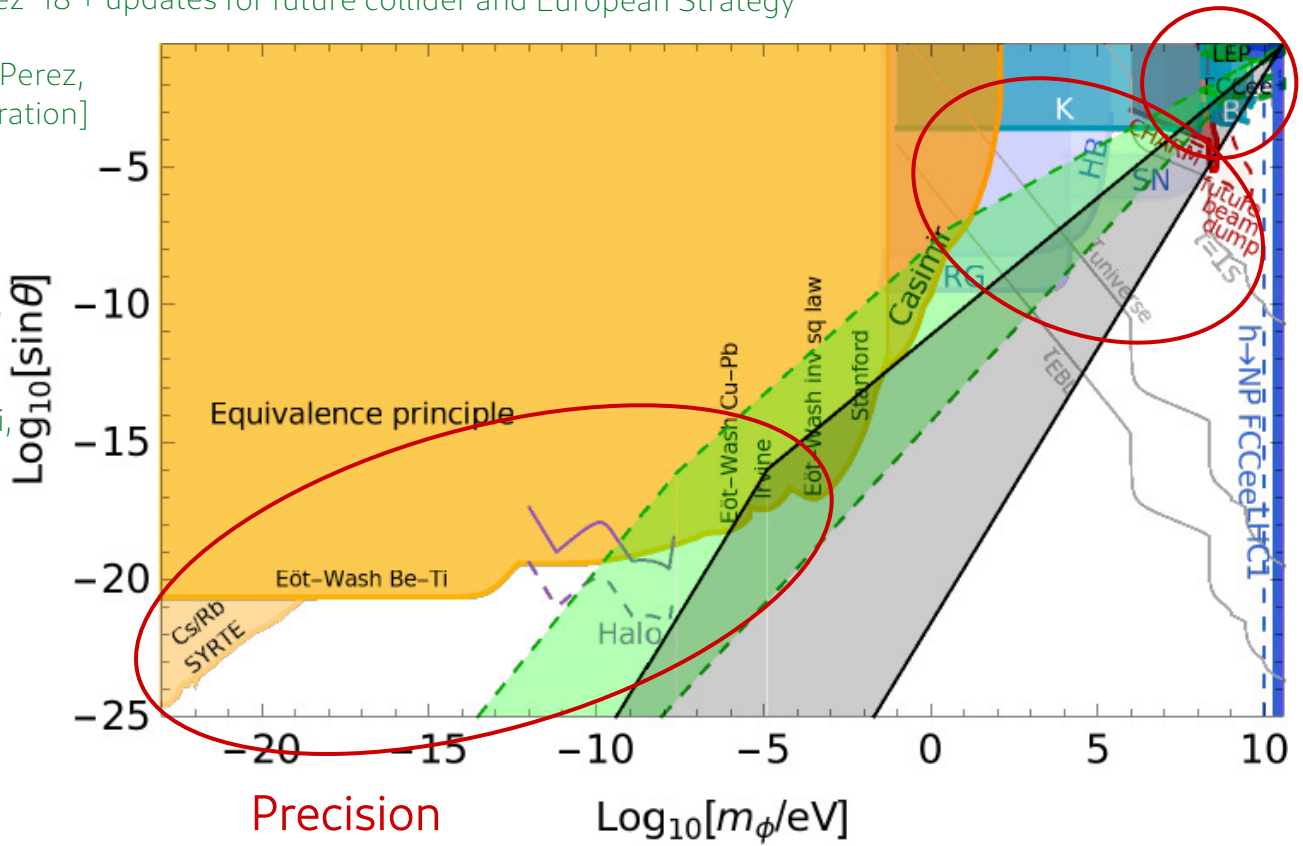
Frugiuele, EF, Schlaffer, Perez '18 + updates for future collider and European Strategy

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

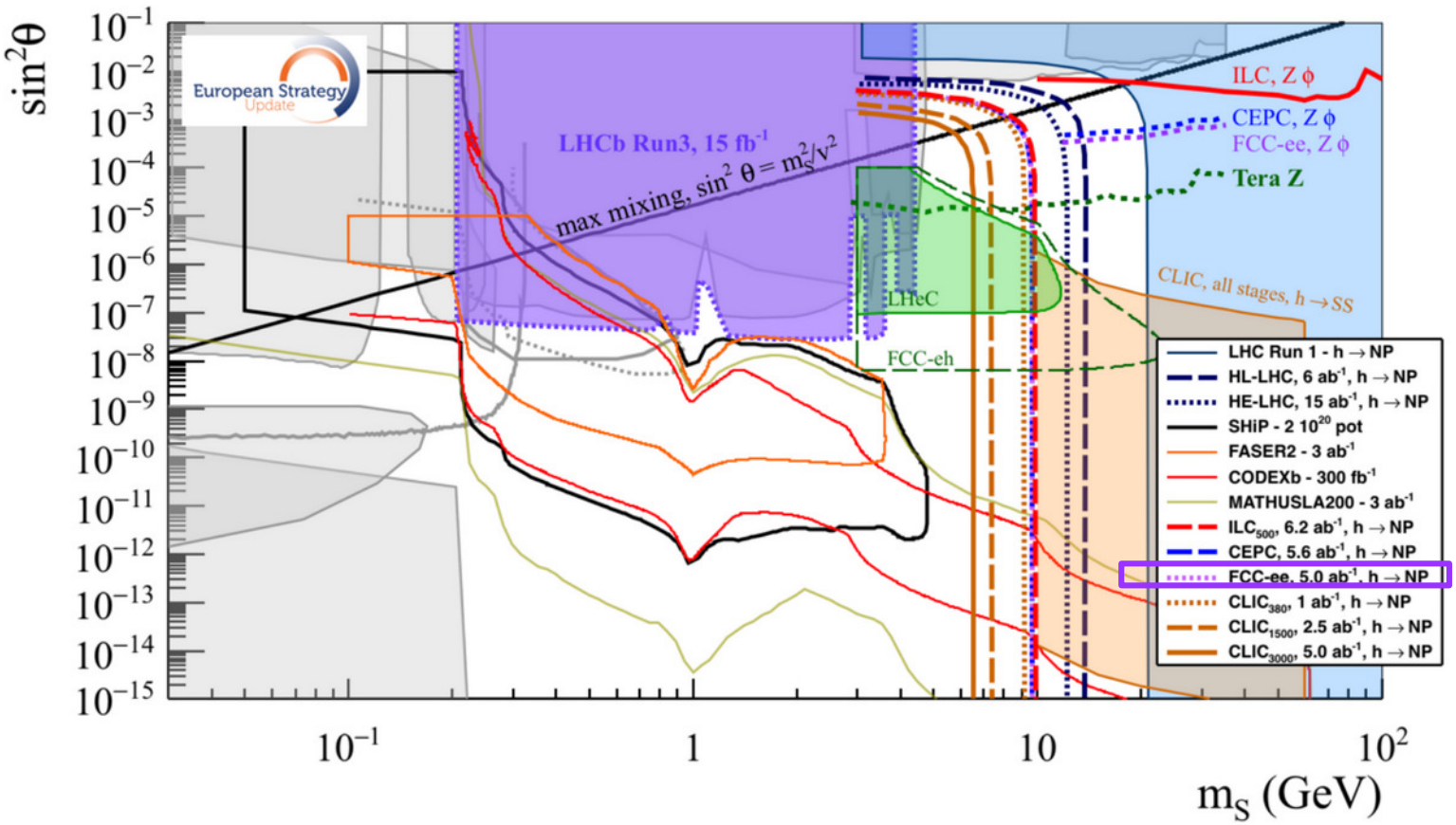
Beam dump, flavou
→ Intensity

Precision

Benchmark for European Strategy Update

Ellis et al '19

Relaxion as
NP benchmark
with light new scalar



MeV-GeV: B, K decays

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