SMEFT, HEFT, AND THE FCC

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(based on works w/ I. Banta, T. Cohen, N. Craig, X. Lu)

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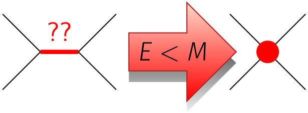
OUTLINE

- SMEFT encodes some untested assumptions
- Viable non-decoupling models break them
- They are a finite target for the FCC

WHAT ARE SMEFT AND HEFT?

A CHOICE OF TWO EFTS FOR THE STANDARD MODEL (SM)

Heavy new physics looks like new contact interactions.



Encode the contact interactions as EFT operators, either:

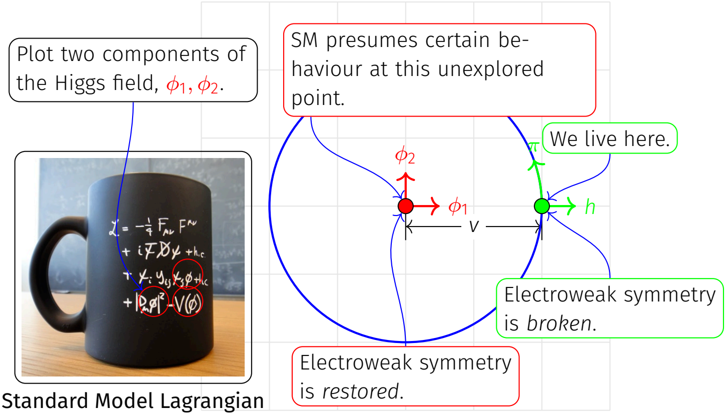
- SMEFT: built out of the Higgs doublet Φ

$$\kappa_f \sim |\Phi|^2 \overline{Q}_L \Phi d_R\,; \quad \kappa_V \sim |\Phi|^2 |D\Phi|^2\,; \quad \kappa_\lambda \sim |\Phi|^6\,.$$

- HEFT: built separately out of the Higgs h and Goldstones π_i

$$\kappa_f \sim h\bar{f}_L f_R\,; \quad \kappa_V \sim hW^+W^-\,; \quad \kappa_\lambda \sim h^3\,.$$

THE SM IS AN EXPANSION IN FIELD SPACE

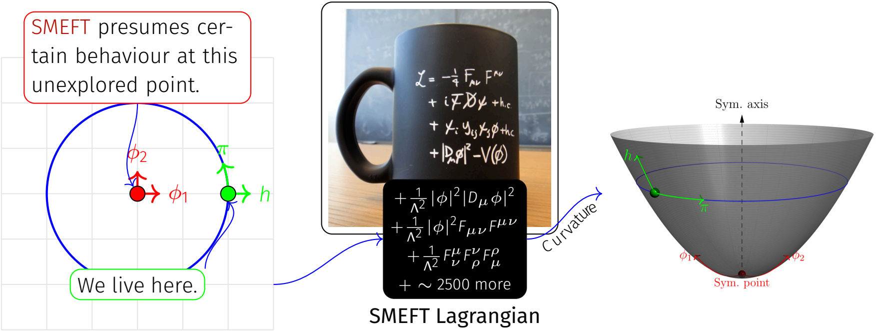


We observe that Higgs physics is SM-like at our vacuum.

We *assume* it is SM-like at the EW symmetric vacuum.

SMEFT is a Taylor expansion in Φ about $\Phi = 0$.

$$\mathcal{L} \approx |D\Phi|^2 + \frac{1}{\Lambda^2}|\Phi|^2|D\Phi|^2 + \frac{1}{\Lambda^4}|\Phi|^4|D\Phi|^2 + \ldots$$



SMEFT Lagrangian

Encode **deviations from the Standard Model** as **curvature**. (Alonso, Jenkins, and Manohar 2016)

SMEFT CORRELATES DIFFERENT HIGGS MULTIPLICITIES

$$\mathcal{L} \approx |D\Phi|^2 + \frac{1}{\Lambda^2}|\Phi|^2|D\Phi|^2 + \frac{1}{\Lambda^4}|\Phi|^4|D\Phi|^2 + \dots$$

As can be seen in the broken phase

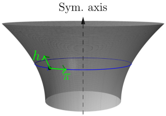
$$\begin{aligned}
\mathcal{L} \to & g_2^2 W^+ W^- \left[(v+h)^2 + \frac{1}{\Lambda^2}(v+h)^4 + \frac{1}{\Lambda^4}(v+h)^6 + \dots\right] \\
\to & g_2^2 W^+ W^- \left[v^2\left(1 + \frac{v^2}{\Lambda^2} + \frac{v^4}{\Lambda^4} + \dots\right)\right. \\
& + vh\left(1 + 2\frac{v^2}{\Lambda^2} + 4\frac{v^4}{\Lambda^4} + \dots\right) \\
& \left. + h^2\left(1 + \frac{v^2}{\Lambda^2} + 6\frac{v^4}{\Lambda^4} + \dots\right) + \dots\right]
\end{aligned}$$

Correlation: $\kappa_V \approx \kappa_{2V} \approx \frac{v^2}{\Lambda^2}$

WHAT NEW PHYSICS BREAKS SMEFT ASSUMPTIONS?

WHEN IS SMEFT NOT ENOUGH?

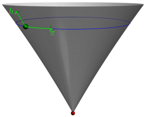
(Cohen, Craig, Lu, and Sutherland 2021)



Like a Laurent expansion

$$\mathcal{L} = \sum_{k=k_{\min}<0}^{\infty} c_k \frac{|\Phi|^{2k}}{\Lambda^{2k}} |D\Phi|^2$$

1) When electroweak symmetry is *broken* as $v \to 0$: there are **extra sources of electroweak symmetry breaking**



Like a non-convergent expansion

$$\mathcal{L} = \sum_{k=0}^{\infty} c_k \frac{|\Phi|^{2k}}{v^{2k}} |D\Phi|^2$$

2) When new physics effects are large when $v \to 0$: there are **new particles that get most of their mass from the Higgs.**

Both HEFTy cases have particles mass $m \lesssim 4\pi v$.

VIABLE HEFTY MODELS

Use HEFT when fraction of mass(-squared) from Higgs:

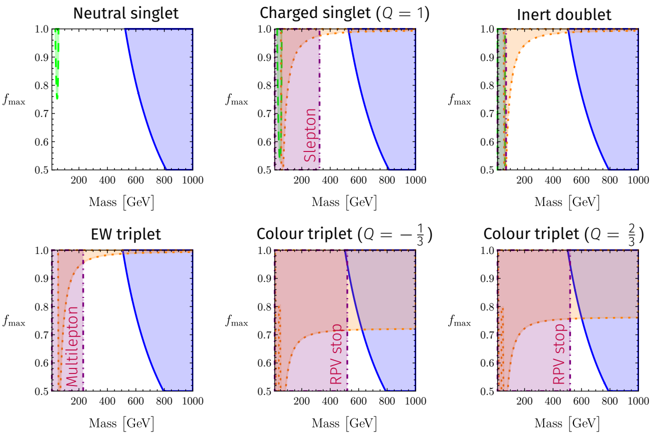
$$f_{\text{max}} > \frac{1}{2}$$

Study scalars and fermions in various electroweak irreps, with approximate $\mathbb{Z}_2$ symmetry. Consider

- κ_γ, κ_g
- perturbative unitarity constraints on coupling to Higgs
- Higgs decay
- Direct searches (charged components decay promptly via the least detectable lowest dimension operator)

THESE HEFTY MODELS ARE EXPERIMENTALLY VIABLE

(Banta, Cohen, Craig, Lu, and Sutherland 2021)



Disallowed regions in colour:

Orange, dotted: κ_γ or κ_g

Blue, solid: perturb. unitarity $\lambda_{h\Phi}$

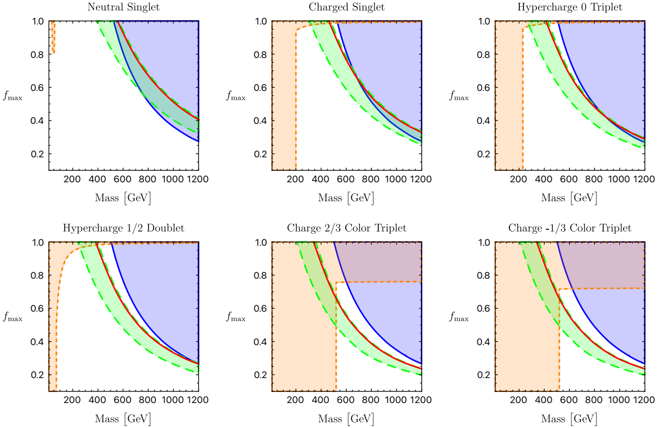
Green, dashed: Higgs decay

Purple, dot-dash: Direct search

Plots: fraction of mass squared from Higgs ($f_{\max}$) *vs.* total mass.

HEFTY MODELS PRODUCE A STRONGLY FIRST ORDER EWPT

(Banta 2022)



Orange, dotted: κ_γ or κ_g expt. constraints

Blue, solid: perturb. unitarity

Green, dashed: strongly first-order phase transition

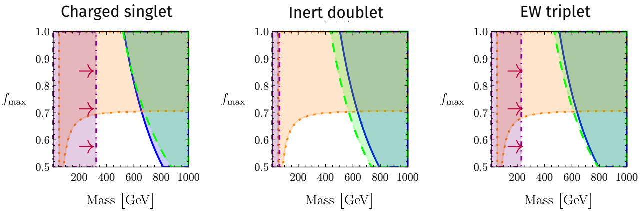
Red, solid lower bound for stochastic gravitational wave background @ LISA

…a necessary condition for electroweak baryogenesis.

THE FUTURE AND THE FCC

HL-LHC MAKES SLOW INROADS

HEFTy models have a finite parameter space. At HL-LHC, κ_g rules out coloured particles, κ_γ makes inroads, κ_λ approaches unitarity bound.



Orange, dotted: κ_γ or κ_g

Blue, solid: perturb. unitarity $\lambda_{h\Phi}$

Green, dashed: *Higgs cubic*

Purple, dot-dash: Direct search

Nightmare scenario of neutral scalar singlet remains open.

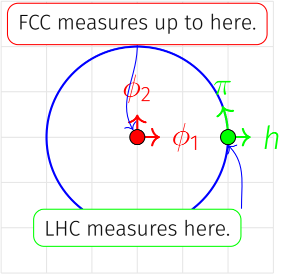
$\kappa_\lambda \sim 5\%$ measurement of FCC-hh closes off everything.

SUMMARY

The world is SM-like at $v = 246\,\text{GeV}$.

Extra sources of EWSB, or particles getting most their mass from the Higgs, make it wildly different at $v = 0$.

These models are poorly fit by SMEFT, and could precipate a strongly first order phase transition.



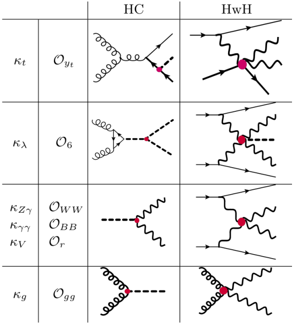
Such non-decoupling models present a finite parameter space, conclusively probed by the FCC.

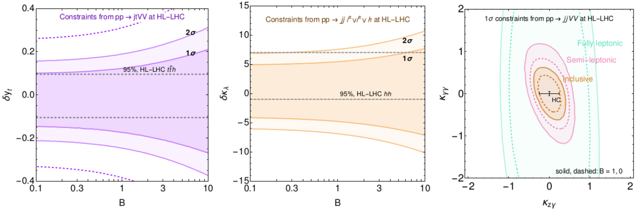
BACKUP

HEFTY MODELS POORLY FIT BY *DIMENSION 6* SMEFT

HL-LHC could probe the correlations of a single SMEFT operator across different Higgs multiplicities. (Henning, Lombardo, Riembau, and Riva 2019)

These correlations may be broken.





HEFTY PHYSICS BREAKS CORRELATIONS

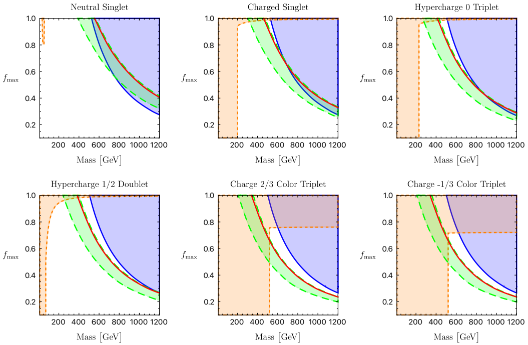
(Abu-Ajamieh, Chang, Chen, and Luty 2020)

$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\rm SM} &- \delta_3 \frac{m_h^2}{2v} h^3 - \delta_4 \frac{m_h^2}{8v^2} h^4 - \sum_{n=5}^{\infty} \frac{c_n}{n!} \frac{m_h^2}{v^{n-2}} h^n + \cdots \\
&+ \delta_{Z1} \frac{m_Z^2}{v} h Z^\mu Z_\mu + \delta_{W1} \frac{2m_W^2}{v} h W^{\mu+} W_\mu^- + \delta_{Z2} \frac{m_Z^2}{2v^2} h^2 Z^\mu Z_\mu + \delta_{W2} \frac{m_W^2}{v} h^2 W^{\mu+} W_\mu^- \\
&+ \sum_{n=3}^{\infty} \left[\frac{c_{Zn}}{n!} \frac{m_Z^2}{v^n} h^n Z^\mu Z_\mu + \frac{c_{Wn}}{n!} \frac{2m_W^2}{v^n} h^n W^{\mu+} W_\mu^- \right] + \cdots \\
&- \delta_{t1} \frac{m_t}{v} h \bar{t} t - \sum_{n=2}^{\infty} \frac{c_{tn}}{n!} \frac{m_t}{v^n} h^n \bar{t} t + \cdots
\end{aligned}
$$

Process	$\times \frac{E^4}{1152\pi^3 v^4}$
$hZ^2 \to hZ^2$	$[4\delta_{V1} - 2\delta_{V2} + \frac{1}{2}c_{V3}]$
$h^2Z \to Z^3$	$-\frac{\sqrt{3}}{2}[4\delta_{V1} - 2\delta_{V2} + \frac{1}{2}c_{V3}]$
$h^2W^+ \to Z^2W^+$	$-\frac{1}{2}[4\delta_{V1} - 2\delta_{V2} + \frac{1}{2}c_{V3}]$
$h^2Z \to ZW^+W^-$	$-\frac{1}{\sqrt{2}}[4\delta_{V1} - 2\delta_{V2} + \frac{1}{2}c_{V3}]$
$h^2W^+ \to W^+W^-W^+$	$-[4\delta_{V1} - 2\delta_{V2} + \frac{1}{2}c_{V3}]$
$hZW^+ \to hZW^+$	$[36\delta_{V1} - 13\delta_{V2} + 2c_{Vc}]$
$hW^+W^+ \to hW^+W^+$	$[36\delta_{V1} - 13\delta_{V2} + 2c_{V3}]$
$hW^+W^- \to hW^+W^-$	$-[28\delta_{V1} - 9\delta_{V2} + c_{V3}]$
$hZ^2 \to hW^+W^-$	$-\sqrt{2}[32\delta_{V1} - 11\delta_{V2} + \frac{3}{2}c_{V3}]$

Process	$\times \frac{\left(\frac{1}{2}c_{t2} - \delta_{t1}\right) m_t E^2}{32\pi^2 v^3}$
$\bar{t}_R t_R \to Zh^2$	$i\sqrt{N_c}$
$h^2 \to Z\bar{t}_L t_L$	$i\sqrt{\frac{N_c}{3}}$
$Zh \to h\bar{t}_L t_L$	$i\sqrt{\frac{2N_c}{3}}$
$t_R Z \to t_L h^2$	$\frac{i}{\sqrt{6}}$
$t_R h \to t_L Zh$	$\frac{i}{\sqrt{3}}$
$\bar{t}_R t_R \to Z^2 h$	$-\sqrt{N_c}$
$Z^2 \to \bar{t}_L t_L h$	$-\sqrt{\frac{N_c}{3}}$
$Zh \to \bar{t}_L t_L Z$	$-\sqrt{\frac{2N_c}{3}}$
$t_R h \to t_L Z^2$	$-\frac{1}{\sqrt{6}}$
$t_R Z \to t_L Zh$	$-\frac{1}{\sqrt{3}}$

(Banta 2022)



Orange, dotted: κ_γ or κ_g expt. constraints

Blue, solid: perturb. unitarity

Green, dashed: strongly first-order phase transition

Red, solid lower bound for stochastic gravitational wave background @ LISA

$$\frac{S_3}{T_n} \approx 140$$

$$\frac{v_n}{T_n} \gtrsim 1$$

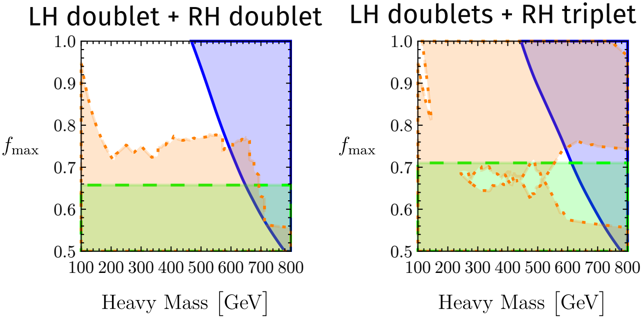
$$T_n > 10 \text{ GeV}$$

$$\alpha = \left(\Delta V_{\text{eff}} - \frac{T_n}{4}\Delta\frac{\mathrm{d}V_{\text{eff}}}{\mathrm{d}T}\right) \Bigg/ \frac{g_* \pi^2 T_n^4}{30} \,,$$

$$\beta/H_* = \left.\frac{\mathrm{d}S_3}{\mathrm{d}T}\right|_{T_n} - \frac{S_3}{T_n}.$$

$$\log(\beta/H_*) \lesssim 1.2 \log\alpha + 8.8$$

(Banta, Cohen, Craig, Lu, and Sutherland 2021)



Disallowed regions in colour:

Orange, dotted: Direct search

Blue, solid: perturb. unitarity

Green, dashed: EW precision test (*S*)

Purple, dot-dash: Direct search

Plots: fraction of mass from Higgs (f_{max}) *vs.* total mass.
Assuming no mass splitting among components of multiplet

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