



University
of Glasgow

DI-HIGGS: EFT BEYOND SMEFT

Dave Sutherland

(work w/ I. Banta, T. Cohen, C. Englert, N. Craig, X. Lu, W. Naskar)

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University of Glasgow

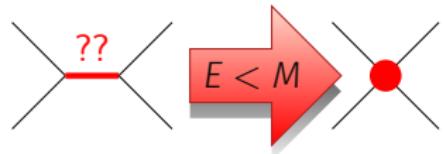
OUTLINE

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

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:

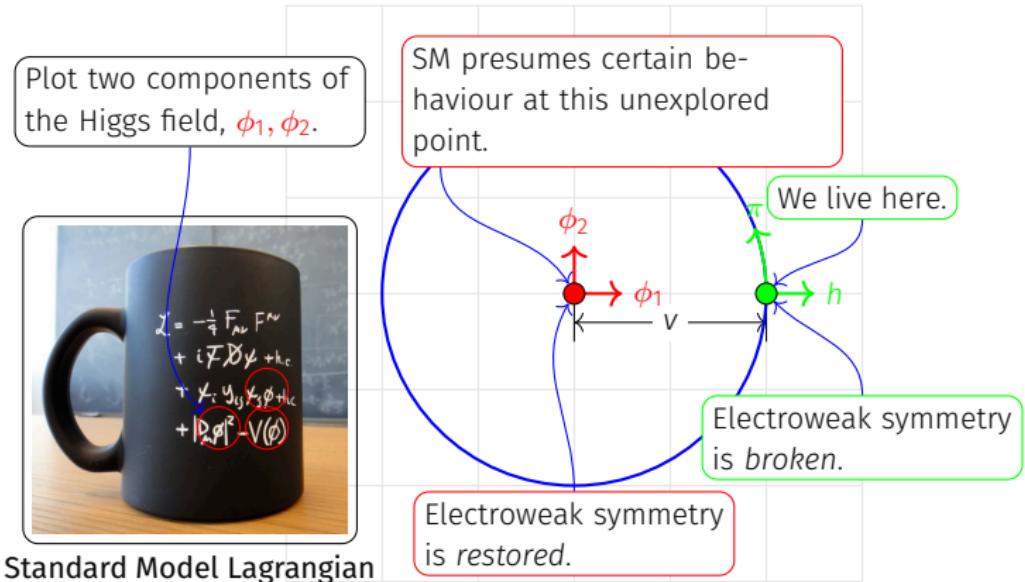
- **SMEFT**: built out of the Higgs doublet Φ

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

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

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

THE SM IS AN EXPANSION IN FIELD SPACE



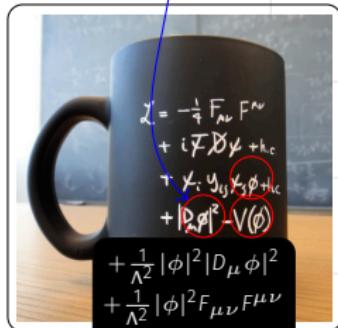
We observe that Higgs physics is SM-like at our vacuum.
We assume it is SM-like at the EW symmetric vacuum.

DECOUPLING NP GIVES SMALL EFFECTS EVERYWHERE

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

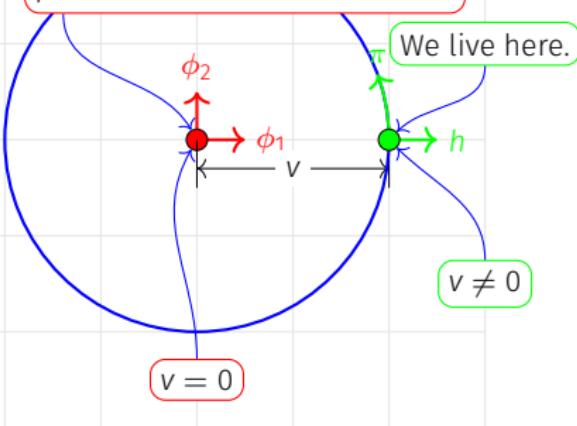
$$\mathcal{L} \approx |D\Phi|^2 + \frac{1}{\Lambda^2} |\Phi|^2 |D\Phi|^2 + \frac{1}{\Lambda^4} |\Phi|^4 |D\Phi|^2 + \dots$$

Plot two components of the Higgs field, ϕ_1, ϕ_2 .



SMEFT Lagrangian

SMEFT presumes certain behaviour at this unexplored point.



DECOUPLING NP (SMEFT) CORRELATES HIGGS OBS.

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

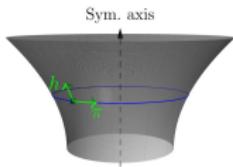
As can be seen in the broken phase

$$\begin{aligned}\mathcal{L} \rightarrow & \frac{1}{4} g_2^2 W^+ W^- \left[(v+h)^2 + \frac{1}{2\Lambda^2} (v+h)^4 + \frac{1}{4\Lambda^4} (v+h)^6 + \dots \right] \\ \rightarrow & \frac{1}{4} g_2^2 W^+ W^- \left[v^2 \left(1 + \frac{v^2}{2\Lambda^2} + \frac{v^4}{4\Lambda^4} + \dots \right) \right. \\ & + 2vh \left(1 + \frac{v^2}{\Lambda^2} + \frac{3}{4} \frac{v^4}{\Lambda^4} + \dots \right) \\ & \left. + h^2 \left(1 + 3 \frac{v^2}{\Lambda^2} + \frac{15}{4} \frac{v^4}{\Lambda^4} + \dots \right) + \dots \right]\end{aligned}$$

Note $m_W \rightarrow 0$ when $v \rightarrow 0$; correlation ($\kappa_V \approx \kappa_{2V} \approx 1 + \frac{v^2}{\Lambda^2}$).

WHEN IS SMEFT NOT ENOUGH?

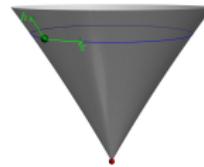
(Cohen, Craig, Lu, and Sutherland 2021)



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 $v \rightarrow 0$: 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 $v \rightarrow 0$: there are new particles that get most of their mass from the Higgs.

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

MODELS WITH EXTRA SOURCES OF SYMMETRY BREAKING

$WW \rightarrow hh$

Consider $WW \rightarrow hh$ and the pattern of NP effects in

$$\kappa_V : \kappa_{2V} : \kappa_\lambda$$

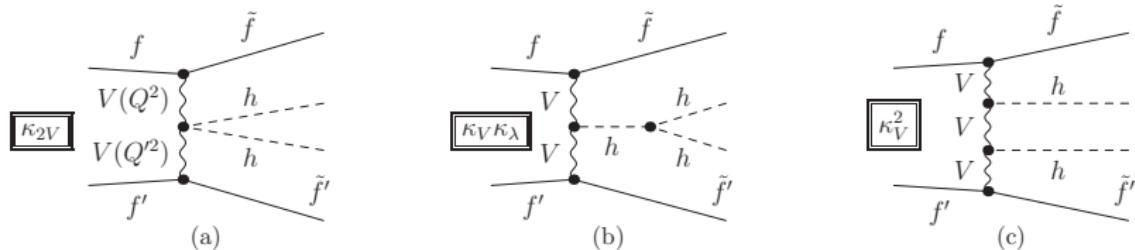
$$\mathcal{L} = m_W^2 \left(W_\mu^+ W^{-\mu} + \frac{1}{2c_W^2} Z_\mu Z^\mu \right) \left[1 + \color{red} \kappa_V \frac{2h}{v} + \color{red} \kappa_{2V} \frac{h^2}{v^2} \right] - \frac{m_h^2}{2v} \color{red} \kappa_\lambda h^3$$

(Note custodial symmetry $\kappa_W = \kappa_Z$ etc.)

2σ precision(ish)	$\delta\kappa_V$	$\delta\kappa_{2V}$	$\delta\kappa_\lambda$
HL-LHC	2.5%	30%	100%

$$WW \rightarrow hh$$

VBF di-Higgs production sensitive to $\kappa_V, \kappa_{2V}, \kappa_\lambda$



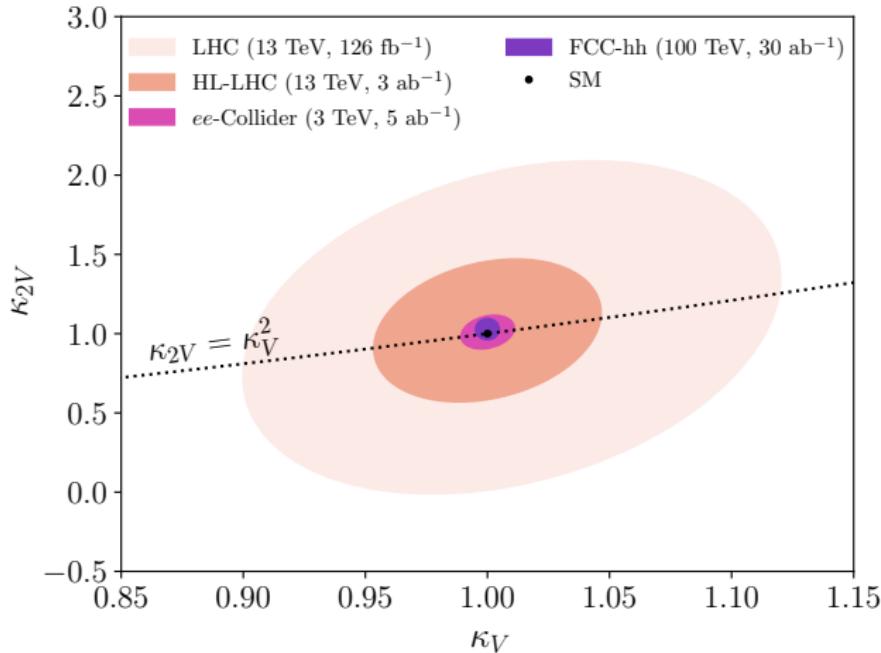
Helicity amps when $s \gg m_W^2$ (Contino, Grojean, Moretti, Piccinini, and Rattazzi 2010)

$$\mathcal{A}(++ \rightarrow hh) = \frac{1}{2} g^2 (\kappa_{2V} - \kappa_V^2)$$

$$\mathcal{A}(+- \rightarrow hh) = -\frac{1}{2} g^2 \kappa_V^2$$

$$\begin{aligned} \mathcal{A}(LL \rightarrow hh) = & \frac{s}{v^2} (\kappa_{2V} - \kappa_V^2) + \frac{1}{2} g^2 (2\kappa_V^2 - \kappa_{2V}) + \frac{m_h^2}{v^2} (3\kappa_V \kappa_\lambda - 2\kappa_V^2) \\ & + \frac{1}{2} g^2 \kappa_V^2 \left(\frac{s}{u - m_W^2} + \frac{s}{t - m_W^2} \right) \end{aligned}$$

CAN κ_{2V} GIVE NEW INFORMATION?



95% CL. $\kappa_\lambda = 1.$

POPULATING $\kappa_V, \kappa_{2V}, \kappa_\lambda$ SPACE

EXTENDED SCALAR SECTORS, TREE-LEVEL

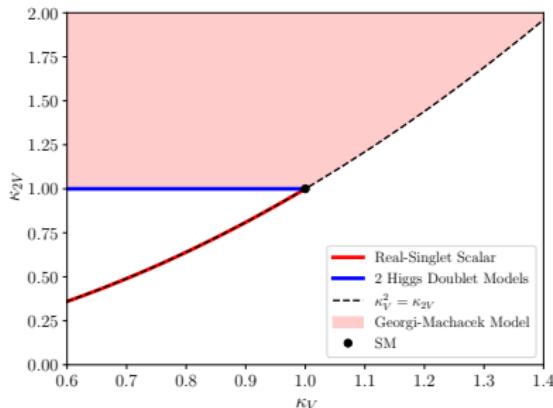
$$\mathcal{L} = \sum_i \frac{1}{2} (\partial h_i)^2 - \frac{1}{2} M_{ij}^2 h_i h_j + \frac{1}{4} g^2 W^+ W^- [C_{ij} v_i v_j + 2C_{ij} v_i h_j + C_{ij} h_i h_j]$$

$$\kappa_V = \frac{C_{ij} v_i \hat{n}_j}{(C_{ij} v_i v_j)^{\frac{1}{2}}},$$

$$\kappa_{2V} = C_{ij} \hat{n}_i \hat{n}_j,$$

$$\kappa_\lambda = ??.$$

where $M_{ij}^2 \hat{n}_j = m_h^2 \hat{n}_i$.



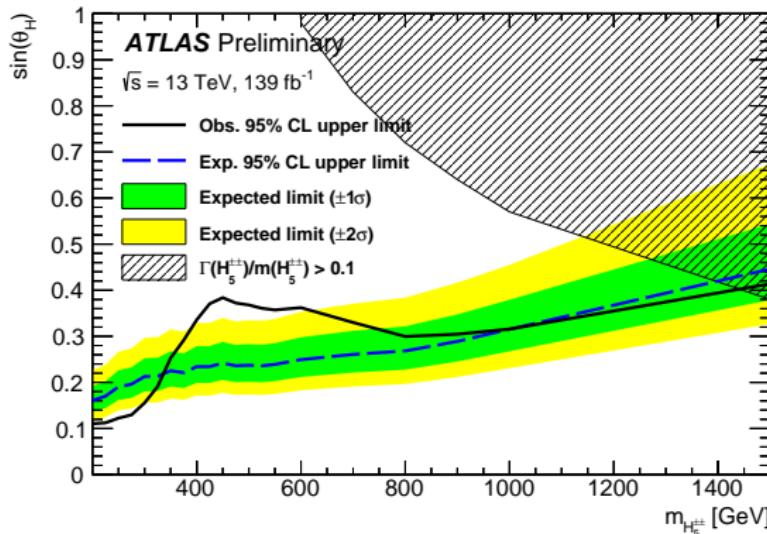
Note $\kappa_{2V} \geq \kappa_V^2$, always.

$\kappa_{2V} = \kappa_V^2$ (SMEFTy) in alignment limit $\hat{n}_i \propto v_i$.

GEORGI-MACHACEK MODEL

Lots of direct searches for neutral/charged Higgses: (Ismail, Logan, and Wu 2020)

If these fail, the doubly charged Higgs search bounds
 $|\sin \beta| \lesssim 0.2 \implies 1 \leq \kappa_{2V} \lesssim 1.5$. (ATLAS 2023)



COMPOSITE HIGGS

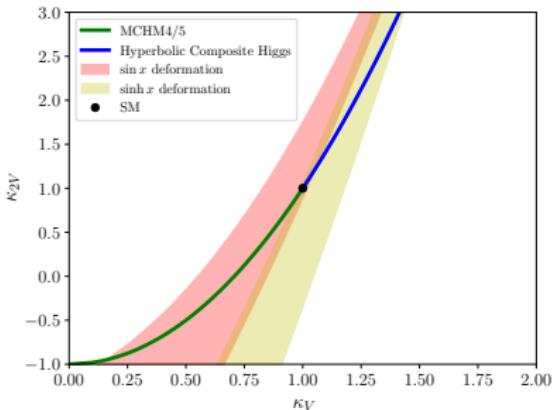
MCHM5 (green)

$$\kappa_V = \sqrt{1 - \xi}$$

$$\kappa_{2V} = 1 - 2\xi$$

$$\kappa_\lambda = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$$

$$(\xi = \frac{v^2}{f^2})$$



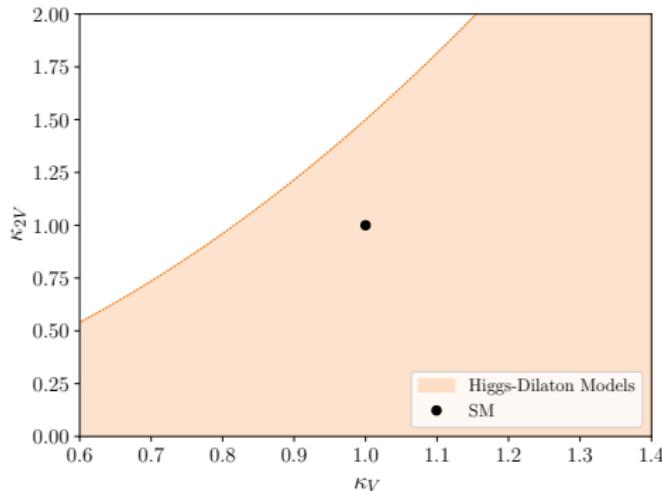
All custodial G/H models with compact G have

$1 - \kappa_V^2, \kappa_V^2 - \kappa_{2V} \geq 0$. (Alonso, Jenkins, and Manohar 2016)

κ_λ could be enhanced (Durieux, McCullough, and Salvioni 2022)

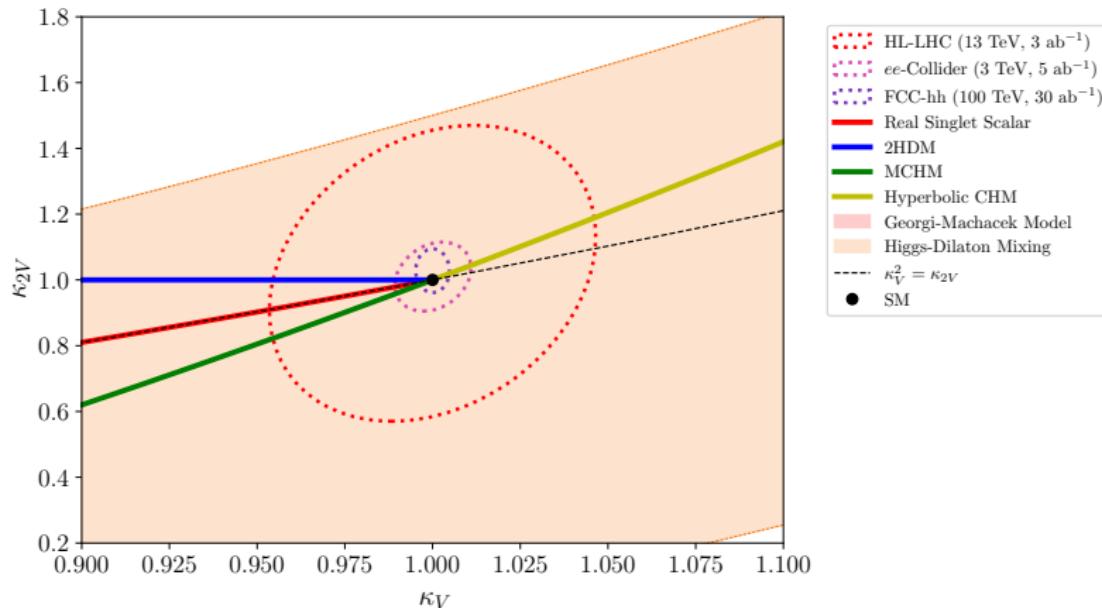
NON-DECOPLING: COMPOSITE HIGGS-DILATON MIXING

$$\mathcal{L} = \frac{g_W^2 f^2}{4} W^+ W^- \left(\frac{\chi}{\langle \chi \rangle} \right)^2 \sin^2 \left(\frac{h}{f} \right) - \left(\frac{\chi}{\langle \chi \rangle} \right)^4 V_{\text{MCHM}} \left(\frac{h}{f} \right).$$



Dilaton most likely discoverable in $gg \rightarrow \chi \rightarrow WW, ZZ$
(Bruggisser, Harling, Matsedonskyi, and Servant 2022)

THE RESULT



To get an interesting signal in κ_{2V} before κ_V , require significant mixing with $\lesssim 1$ TeV states.

NEW PARTICLES THAT GET MOST OF THEIR MASS FROM THE HIGGS

VIABLE NON-DECOUPLING MODELS

'Loryon':¹ new particle that gets most of its mass from the Higgs (Banta, Cohen, Craig, Lu, and Sutherland 2021)

Study scalars and fermions with approximate \mathbb{Z}_2 symmetry.

$$\mathcal{L} = \frac{1}{2^\rho} \text{tr} \left(D\Phi^\dagger D\Phi \right) - \frac{m_{\text{ex}}^2}{2^\rho} \text{tr} \left(\Phi^\dagger \Phi \right) - \frac{\lambda_{h\Phi}}{2^\rho} \text{tr} \left(\Phi^\dagger \Phi \right) \frac{1}{2} \text{tr} \left(H^\dagger H \right)$$

(Consider various custodial irreps $[L, R]_X$ under $SU(2)_L \times SU(2)_R \times U(1)_X$. Hypercharge of components $Y = T_R^3 + X$.)

¹From *Finnegan's Wake*, "with Pa's new heft...see Loryon the comaleon."

VIABLE NON-DECOUPLING MODELS

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

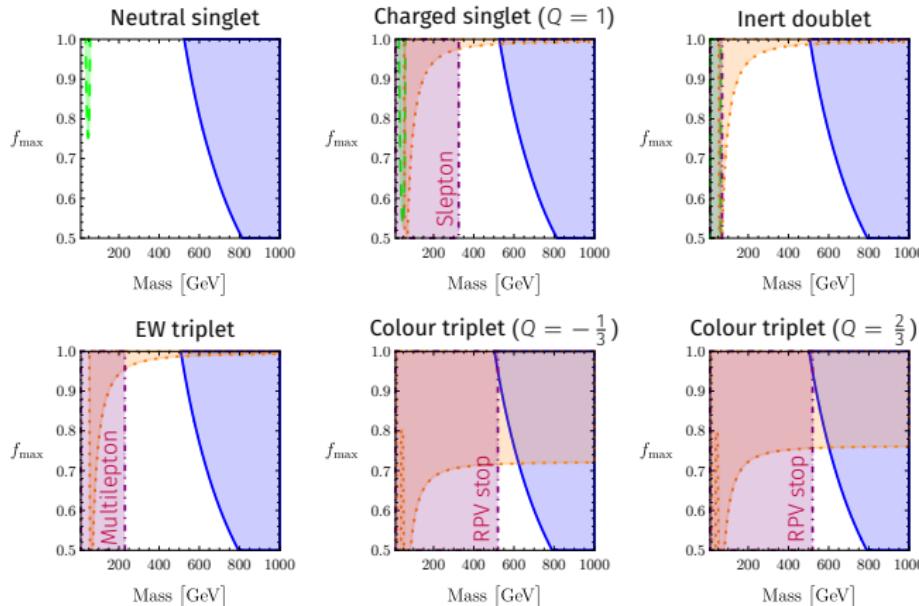
$$f_{\max} > \frac{1}{2}$$

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)

WHITE SPACE MEANS 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

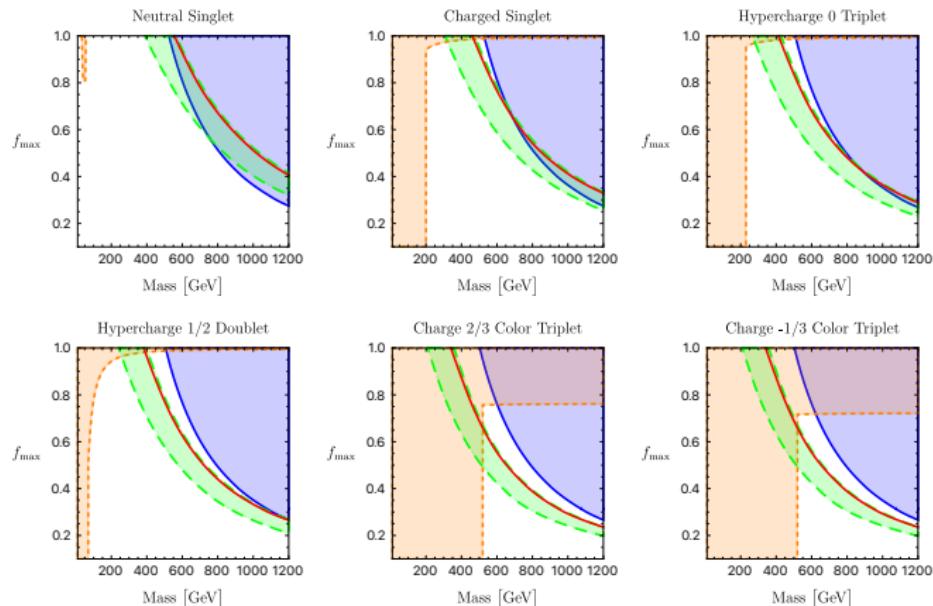
Purple, dot-dash:

Direct search

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

THESE MODELS PRODUCE A STRONGLY FIRST ORDER EWPT

(Banta 2022)



Orange, dotted:
 κ_γ or κ_g expt. constraints

Blue, solid:
perturb. unitarity

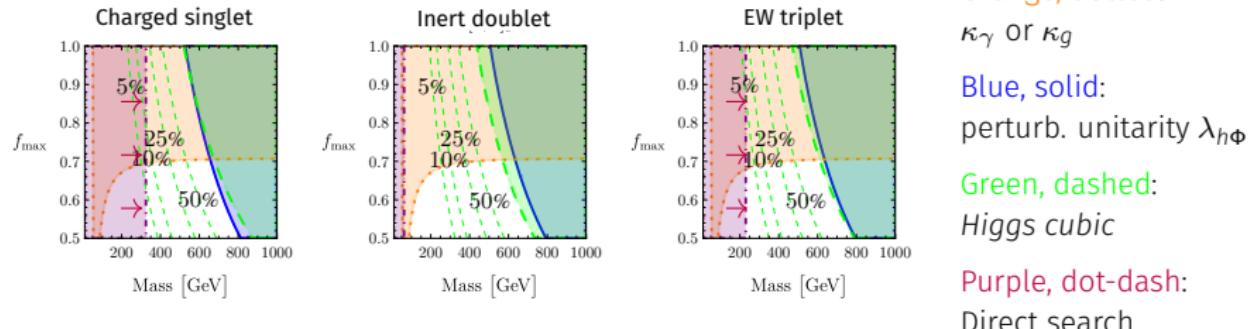
Green, dashed:
strongly first-order
phase transition

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

...a necessary condition for electroweak baryogenesis.

NEXT GENERATION COLLIDERS CAN RULE THIS OUT

Non-decoupling NP has a finite parameter space. At HL-LHC, κ_g rules out coloured particles, κ_γ makes inroads, κ_λ approaches unitarity bound.



Nightmare scenario of neutral scalar singlet remains open.
 $\kappa_\lambda \sim 5\%$ measurement of FCC-hh closes off everything.

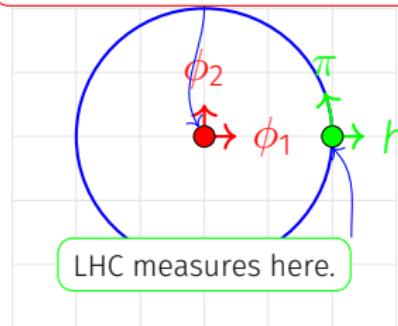
SUMMARY

The world is SM-like at $v = 246$ 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 precipitate a strongly first order phase transition.

In future measure up to here.



Non-decoupling NP is a finite target space for future colliders

THANK YOU

BACKUP

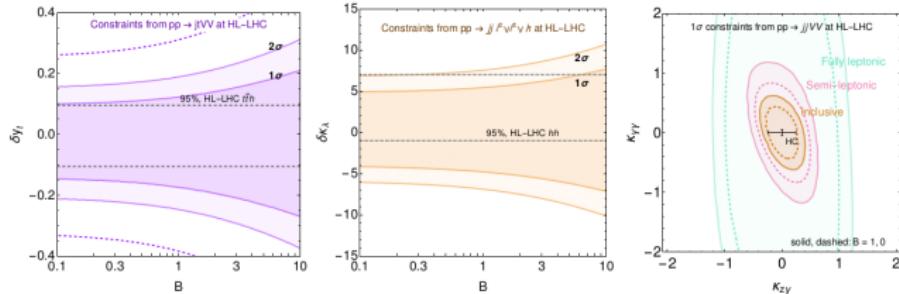
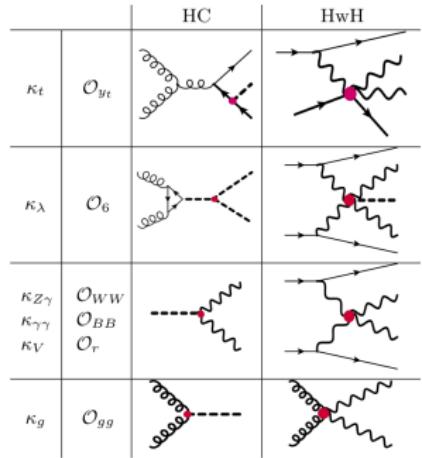
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HEFTY MODELS POORLY FIT BY DIMENSION 6 SMEFT

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)

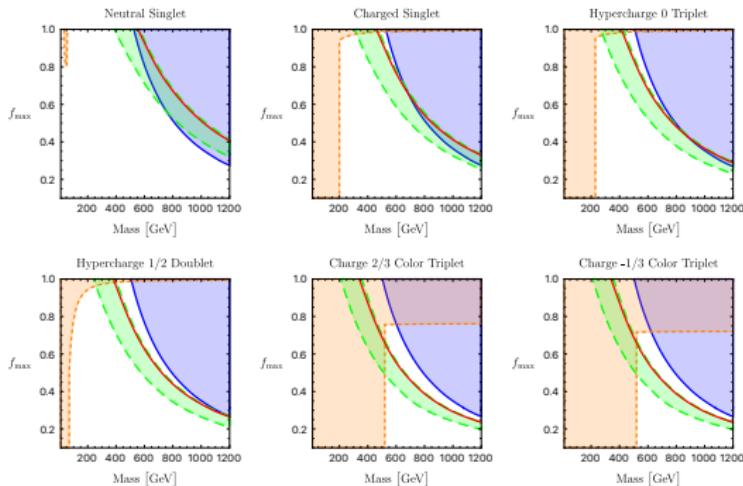
$$\begin{aligned}
 \mathcal{L} = & \mathcal{L}_{\text{SM}} - \delta_3 \frac{m_h^2}{2v} h^3 - \delta_4 \frac{m_h^2}{8v^2} h^4 - \sum_{n=5}^{\infty} \frac{c_n}{n!} \frac{m_h^2}{v^{n-2}} h^n + \dots \\
 & + \delta_{Z1} \frac{m_Z^2}{v} h Z^\mu Z_\mu + \delta_{W1} \frac{2m_W^2}{v} h W^{\mu+} W_\mu^- + \delta_{Z2}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

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

Process	$\times \frac{(\frac{1}{2}c_{02} - \delta_{11}) m_t E^2}{32\pi^2 v^3}$
$\bar{t}_R t_R \rightarrow Zh^2$	$i\sqrt{N_c}$
$h^2 \rightarrow Z \bar{t}_L t_L$	$i\sqrt{\frac{N_c}{3}}$
$Zh \rightarrow h \bar{t}_L t_L$	$i\sqrt{\frac{2N_c}{3}}$
$t_R Z \rightarrow t_L h^2$	$\frac{i}{\sqrt{6}}$
$t_R h \rightarrow t_L Z h$	$\frac{i}{\sqrt{3}}$
$\bar{t}_R t_R \rightarrow Z^2 h$	$-\sqrt{N_c}$
$Z^2 \rightarrow \bar{t}_L t_L h$	$-\sqrt{\frac{N_c}{3}}$
$Zh \rightarrow \bar{t}_L t_L Z$	$-\sqrt{\frac{2N_c}{3}}$
$t_R h \rightarrow t_L Z^2$	$-\frac{i}{\sqrt{6}}$
$t_R Z \rightarrow t_L Z h$	$-\frac{i}{\sqrt{3}}$

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

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

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

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

$$\alpha = \left(\Delta V_{\text{eff}} - \frac{T_n}{4} \Delta \frac{dV_{\text{eff}}}{dT} \right) \Big/ \frac{g_* \pi^2 T_n^4}{30} ,$$

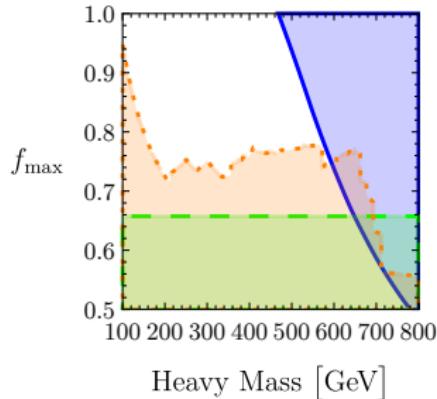
$$\beta/H_* = \left. \frac{dS_3}{dT} \right|_{T_n} - \frac{S_3}{T_n} .$$

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

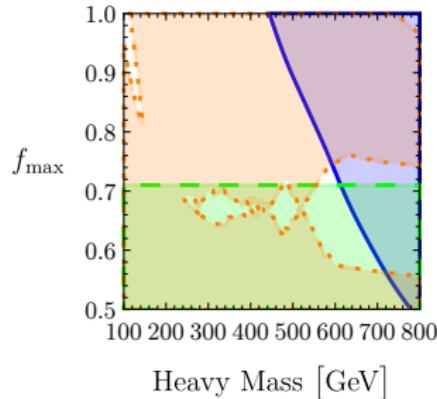
HEFTY (CUSTODIALLY SYMMETRIC) FERMIONS

(Banta, Cohen, Craig, Lu, and Sutherland [2021](#))

LH doublet + RH doublet



LH doublets + RH triplet



Disallowed regions in colour:

Orange, dotted:
Direct search

Blue, solid:
perturb. unitarity

Green, dashed:
EW precision test (S)

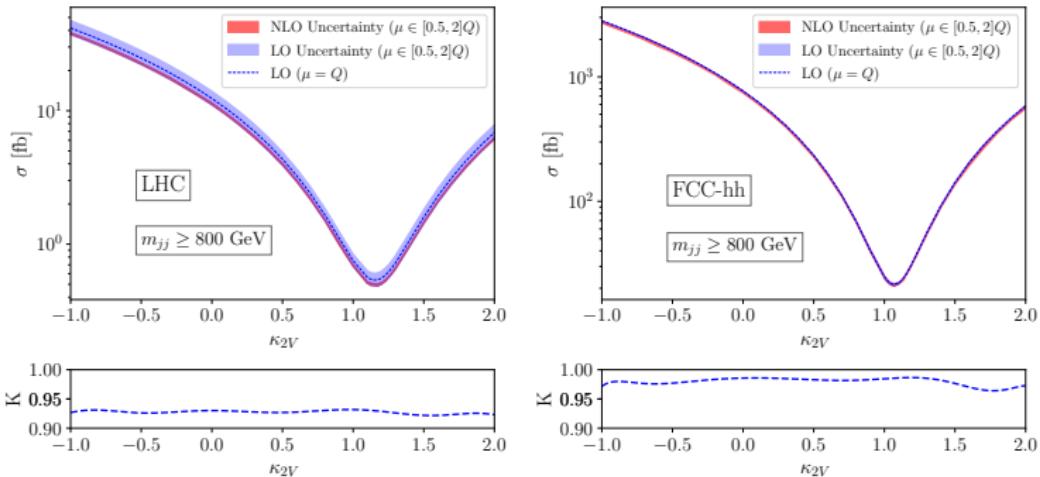
Purple, dot-dash:
Direct search

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

Assuming no mass splitting among components of multiplet

ANALYSIS

Mild NLO corrections to production



From $pp \rightarrow bbbbjj, bb\tau\tau jj$ or $ee \rightarrow bbbb ee, bbbb\nu\nu$.
Binned analysis in m_{hh} .

(70% b -tagging/100% τ -tagging eff.)