FUTURE SIGNATURES OF A NON-DECOUPLING HIGGS SECTOR

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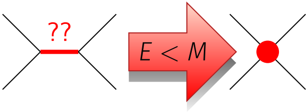
OUTLINE

- Heavy(ish) non-decoupling physics has a distinct pattern of effects
- There are currently viable non-decoupling models of new physics
- They are a finite target for future colliders

DECOUPLING VS NON-DECOUPLING PHYSICS

DECOUPLING VS NON-DECOUPLING PHYSICS

Heavy new physics looks like new contact interactions.



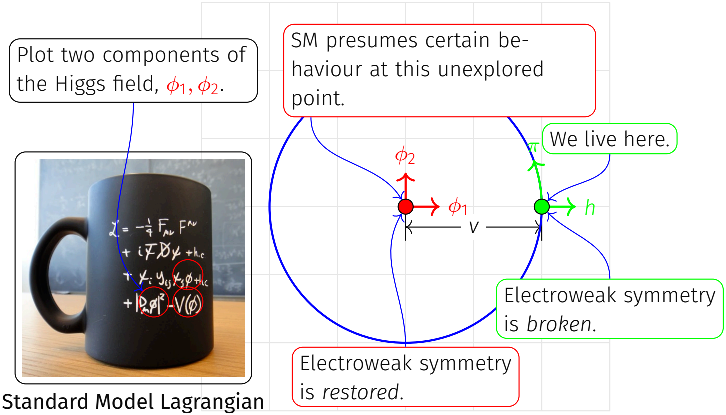
Encode the contact interactions as EFT operators, either:

- 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

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



Standard Model Lagrangian

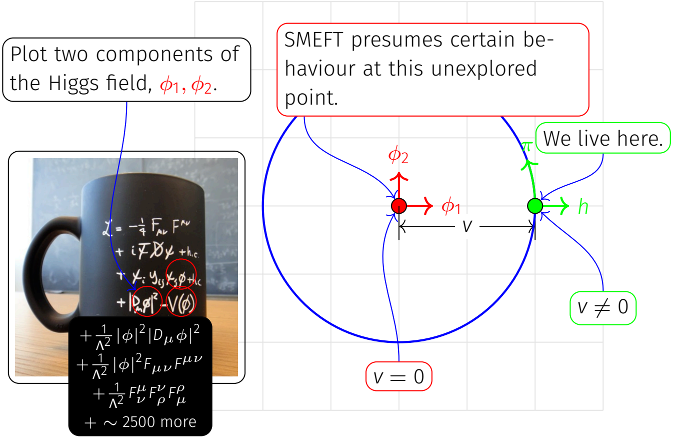
We observe that Higgs physics is SM-like at our vacuum.

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 $\Phi = 0$.

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



SMEFT Lagrangian

DECOUPLING NP (SMEFT) CORRELATES HIGGS OBS.

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

As can be seen in the broken phase

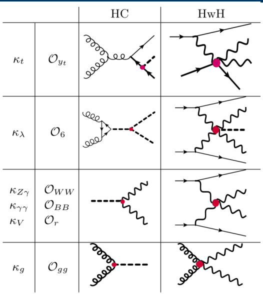
$$\begin{aligned}\mathcal{L} \to& \frac{1}{4}g_2^2 W^+W^- \left[(v+h)^2 + \frac{1}{2\Lambda^2}(v+h)^4 + \frac{1}{4\Lambda^4}(v+h)^6 + \ldots\right] \\ \to& \frac{1}{4}g_2^2 W^+W^- \left[v^2\left(1 + \frac{v^2}{2\Lambda^2} + \frac{v^4}{4\Lambda^4} + \ldots\right)\right. \\ &\qquad + 2vh\left(1 + \frac{v^2}{\Lambda^2}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

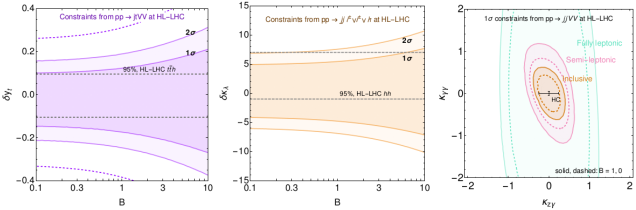
Note $m_W \to 0$ when $v \to 0$; correlation ($\kappa_V \approx \kappa_{2V} \approx 1 + \frac{v^2}{\Lambda^2}$).

OBSERVABLE DIMENSION 6 SMEFT CORRELATIONS

HL-LHC probes correlations of a single SMEFT operator across different Higgs multiplicities. (See also Ilaria's talk)

These correlations may be broken.

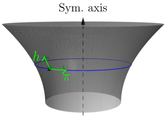




(Henning, Lombardo, Riembau, and Riva 2019)

(Alonso, Jenkins, and Manohar 2016) (Falkowski and Rattazzi 2019)

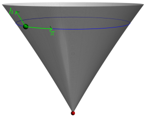
(Cohen, Craig, Lu, and Sutherland 2021)



Like a Laurent expansion

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

1) EW symmetry *broken* as $v \to 0$: there are **extra sources of EWSB**



Like a non-convergent expansion

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

2) Large effects when $v \to 0$: there are **new particles that get most of their mass from EWSB.**

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

MODELS WITH EXTRA SOURCES OF SYMMETRY BREAKING

$ww \to hh$

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

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

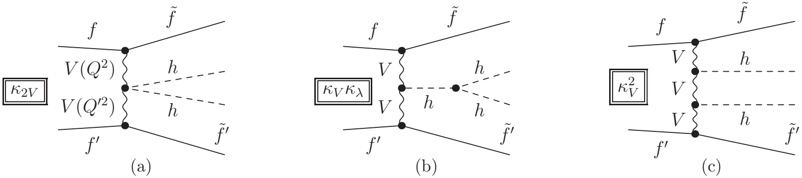
$$\mathcal{L} = m_W^2 \left(W_\mu^+ W^{-\mu} + \frac{1}{2c_W^2} Z_\mu Z^\mu \right) \left[1 + \kappa_V \frac{2h}{v} + \kappa_{2V} \frac{h^2}{v^2} \right] - \frac{m_h^2}{2v} \kappa_\lambda h^3$$

(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%

$WW \to hh$

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



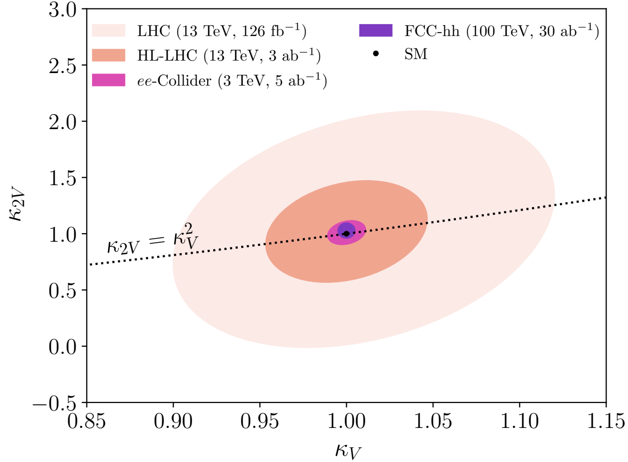
Helicity amps when $s \gg m_W^2$ (Contino, Grojean, Moretti, Piccinini, and Rattazzi 2010)

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

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

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

CAN κ_{2V} GIVE NEW INFORMATION?



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

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

Mixing between neutral components

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

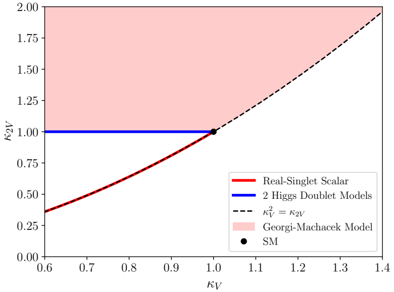
In general

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

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

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

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

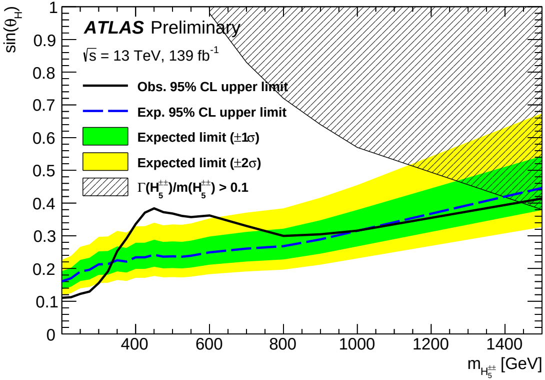


Models have a characteristic pattern in κ_V–κ_{2V} plane.

$\kappa_{2V} \geq \kappa_V^2$, *always*. $\kappa_{2V} = \kappa_V^2$ (SMEFTy) when aligned ($\hat{n}_i \propto v_i$).

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)



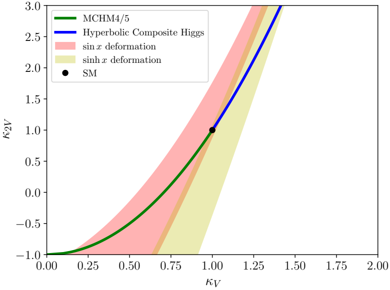
MCHM5 (green)

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

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

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

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

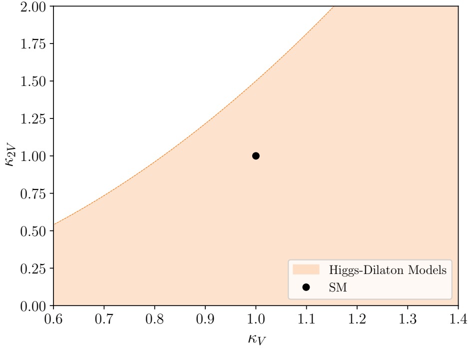


All custodial G/H models with compact G have $1-\kappa_V^2, \kappa_V^2 - \kappa_{2V} \geq 0$. (Alonso, Jenkins, and Manohar 2016)

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

NON-DECOUPLING: COMPOSITE HIGGS-DILATON MIXING

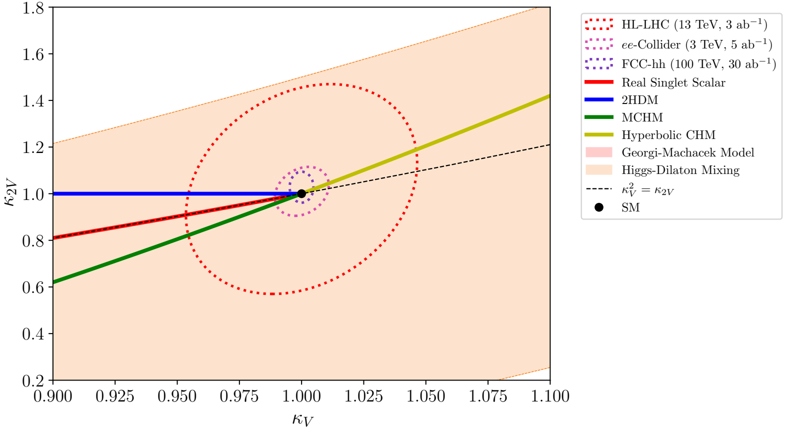
$$\mathcal{L} = \frac{g_W^2 f^2}{4} W^+ W^- \left(\frac{\chi}{\langle\chi\rangle}\right)^2 \sin^2\left(\frac{h}{f}\right) - \left(\frac{\chi}{\langle\chi\rangle}\right)^4 V_{\mathrm{MCHM}}\left(\frac{h}{f}\right) .$$



Dilaton most likely discoverable in $gg \to \chi \to WW, ZZ$

(Bruggisser, Harling, Matsedonskyi, and Servant 2022)

THE RESULT



To get an interesting signal in κ_{2V} before κ_V, require significant mixing with $\lesssim 1\,\mathrm{TeV}$ 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 and Higgs coupling. E.g., for scalars:

$$\mathcal{L} = |D\Phi|^2 - m_{\text{ex}}^2 |\Phi|^2 - \lambda_{h\Phi} |H|^2 |\Phi|^2$$

We also consider other $\Phi^2 H^2$ mass splitting terms.

Assume charged components decay promptly via a small amount of $\mathbb{Z}^2$ breaking.

[1] From *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:

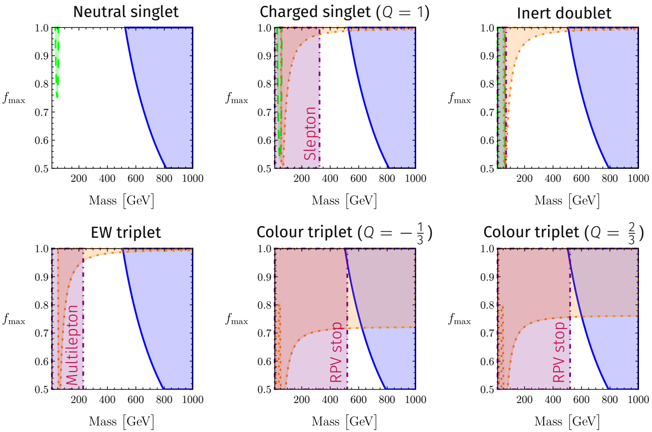
$$f_{\max} = \frac{\frac{1}{2}\lambda_{h\Phi} v^2}{m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\Phi} v^2} > \frac{1}{2}$$

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 $\lambda_{h\Phi}$

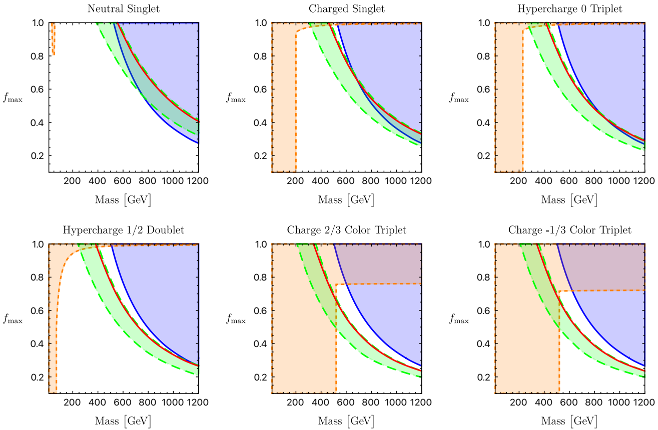
Green, dashed: Higgs decay

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

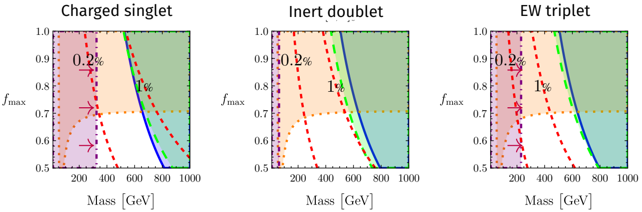
…a necessary condition for electroweak baryogenesis.

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.

At FCC-ee Higgs run, a uniform shift in single Higgs couplings could rule everything out.



Orange, dotted:
κ_γ, HL-LHC

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

Green, dashed:
Higgs cubic, HL-LHC

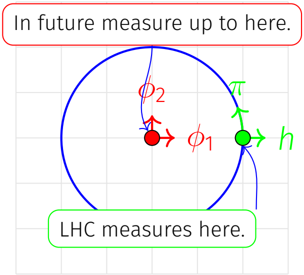
Purple, dot-dash:
Direct search, current

Red, dashed:
h coupling shift

Best we can tell, 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 have a distinct (unSMEFTy) pattern of Higgs couplings, and could precipitate a strongly first order phase transition.



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

Thank you

BACKUP

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HEFTY PHYSICS BREAKS CORRELATIONS

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

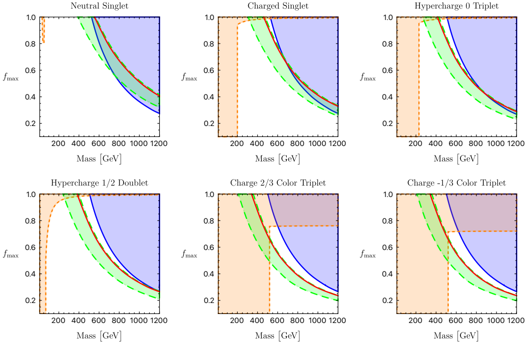
$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\rm SM} &- \delta_3 \frac{m_h^2}{2v} h^3 - \delta_4 \frac{m_h^2}{8v^2} h^4 - \sum_{n=5}^{\infty} \frac{c_n}{n!} \frac{m_h^2}{v^{n-2}} h^n + \cdots \\
&+ \delta_{Z1} \frac{m_Z^2}{v} h Z^\mu Z_\mu + \delta_{W1} \frac{2m_W^2}{v} h W^{\mu+} W_\mu^- + \delta_{Z2}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

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

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

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

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

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

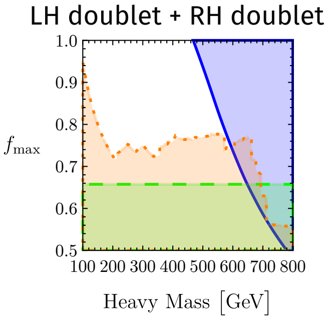
$$T_n > 10 \text{ GeV}$$

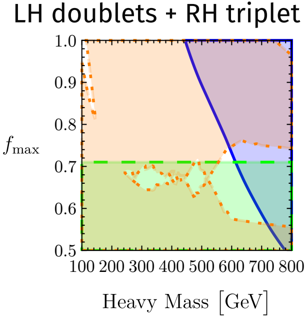
$$\alpha = \left(\Delta V_{\text{eff}} - \frac{T_n}{4}\Delta\frac{\mathrm{d}V_{\text{eff}}}{\mathrm{d}T}\right) \Big/ \frac{g_* \pi^2 T_n^4}{30} ,$$

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

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

(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)

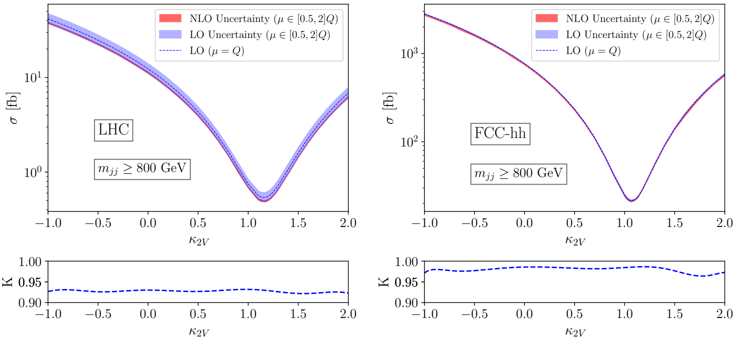
Purple, dot-dash: Direct search

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

Assuming no mass splitting among components of multiplet

ANALYSIS

Mild NLO corrections to production



From $pp \to bbbbjj, bb\tau\tau jj$ or $ee \to bbbbee, bbbb\nu\nu$.

Binned analysis in m_{hh}.

(70% b-tagging/100% τ-tagging eff.)