BSM PATTERNS IN HVV, HHVV, AND HHH

Dave Sutherland
(based on work w/ C. Englert, W. Naskar)

6th July 2023 — **FCC phenomenology Workshop**

University of Glasgow

Viable non-decoupling new physics can make the scalar sector differ significantly from SM.

We consider $WW \to hh$ at future colliders and the pattern of NP effects in $\kappa_V : \kappa_{2V} : \kappa_\lambda$

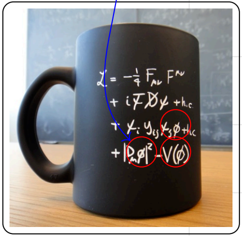
$$\mathcal{L} = m_W^2 \left(W_\mu^+ W^{-\mu} + \frac{1}{2c_W^2} Z_\mu Z^\mu \right) \left[1 + \kappa_V \frac{2h}{v} + \kappa_{2V} \frac{h^2}{v^2} \right] - \frac{m_h^2}{2v} \kappa_\lambda h^3$$

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

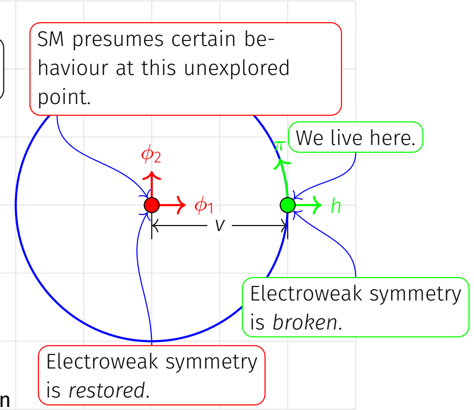
2σ precision(ish)	$\delta\kappa_V$	$\delta\kappa_{2V}$	$\delta\kappa_\lambda$
HL-LHC	2.5%	30%	100%

AN INVITATION TO NON-DECOUPLING NEW PHYSICS

THE SM IS AN EXPANSION IN FIELD SPACE



Standard Model Lagrangian



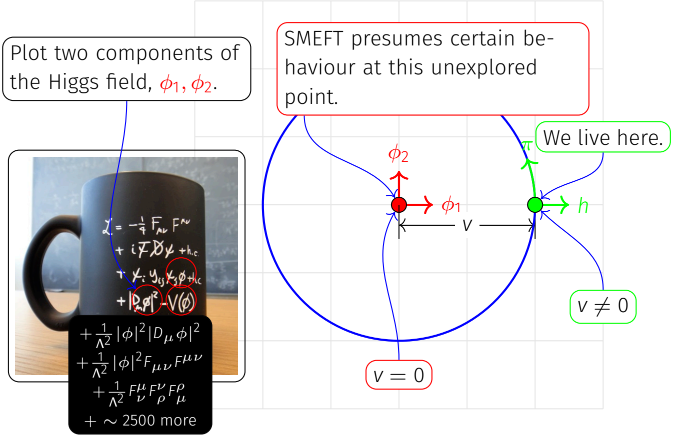
We observe that Higgs physics is SM-like at our vacuum.

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 $\Phi = 0$.

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

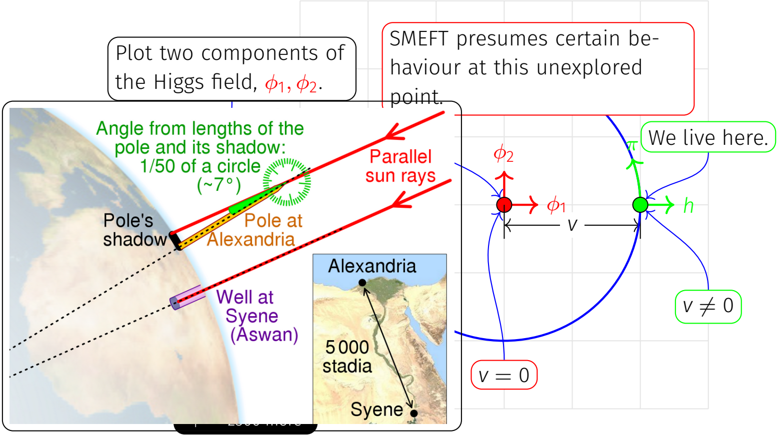


SMEFT Lagrangian

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.

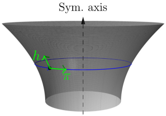
$$\mathcal{L} \approx |D\Phi|^2 + \frac{1}{\Lambda^2}|\Phi|^2|D\Phi|^2 + \frac{1}{\Lambda^4}|\Phi|^4|D\Phi|^2 + \dots$$

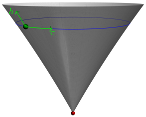
As can be seen in the broken phase

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

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

(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 NON-DECOUPLING MODELS

[See Tim's talk yesterday!]

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

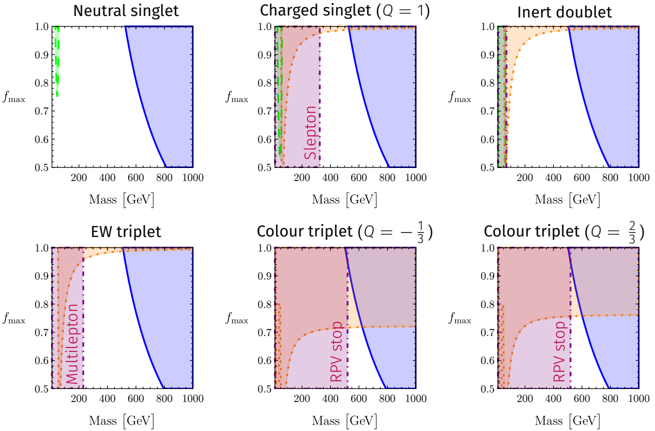
$$f_{\text{max}} > \frac{1}{2}$$

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)

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 $\lambda_{h\Phi}$

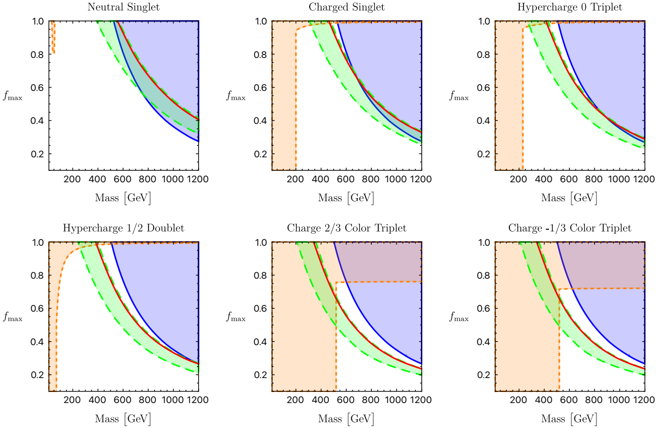
Green, dashed: Higgs decay

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

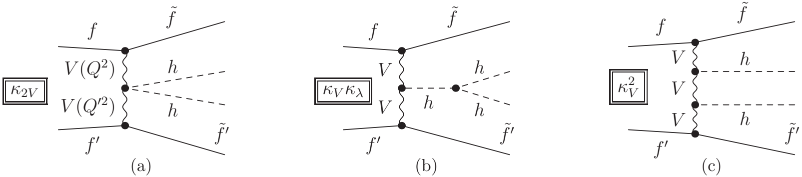
Red, solid lower bound for stochastic gravitational wave background @ LISA

...a necessary condition for electroweak baryogenesis.

$ww \to hh$

$ww \to hh$

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



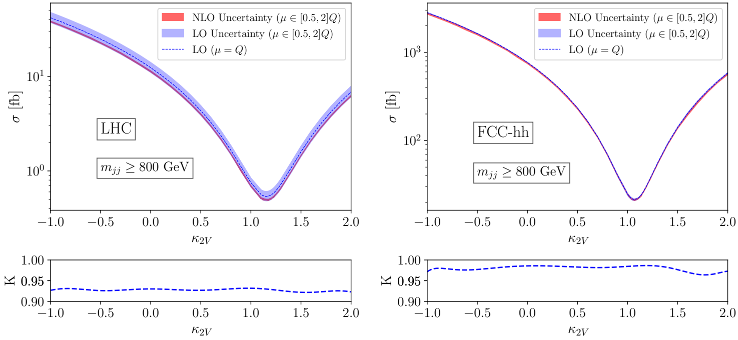
Helicity amps when $s \gg m_W^2$ (Contino, Grojean, Moretti, Piccinini, and Rattazzi 2010)

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

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

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

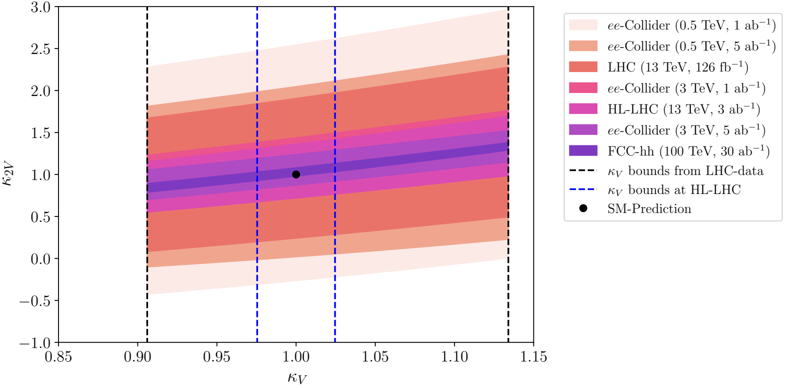
Mild NLO corrections to production



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. Syst. uncertainty $\sim$ 50%)

CAN FUTURE COLLIDERS DO BETTER WITH κ_{2V}?



$\kappa_{2V} \approx [0.95, 1.1]$ 95% CL FCC-hh. $\kappa_\lambda = 1$ above. Current κ_V limit from (Aad et al. 2022)

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

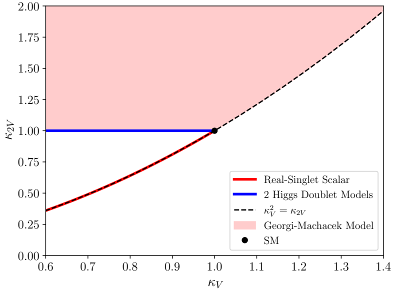
EXTENDED SCALAR SECTORS, TREE-LEVEL

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

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

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

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



Note $\kappa_{2V} \geq \kappa_V^2$, *always*. $\kappa_{2V} = \kappa_V^2$ in alignment limit $\hat{n}_i \propto v_i$.

κ_{2V} enhancement with triplets. Direct searches: (Ismail, Logan, and Wu 2020)

κ_λ ENHANCED IN ALIGNMENT + DECOUPLING LIMIT

In the presence of cubic interactions between multiplets, κ_λ free.

In their absence, if ϵ_a is a small angle denoting mixing into non-SM Higgses, masses m_a^2:

$$\begin{aligned}\kappa_V \approx& 1 - \mathrm{O}(\epsilon^2)\\ \kappa_{2V} \approx& 1 - \mathrm{O}(\epsilon^2)\\ \kappa_\lambda \approx& 1 - 2\sum_a \epsilon_a^2 \left(\frac{m_a^2}{m_h^2} - \frac{1}{4}\right) .\end{aligned}$$

EXTENDED SCALAR SECTORS, LOOP-LEVEL

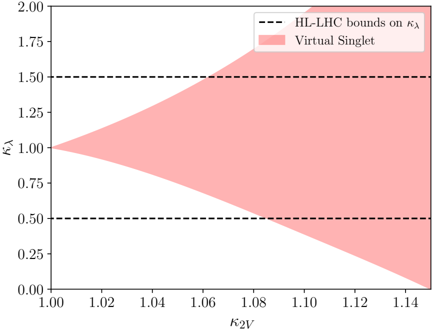
$$\mathcal{L} = |D\Phi_A|^2 - m_\varphi^2 |\Phi_A|^2 - 2\lambda |\Phi_A|^2 \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right) .$$

$$\kappa_V \approx 1 - D \, \frac{\lambda^2 v^2}{96\pi^2 m_\varphi^2}$$

$$\kappa_{2V} \approx 1 - D \, \frac{\lambda^2 v^2}{48\pi^2 m_\varphi^2}$$

$$\kappa_\lambda \approx 1 + D \, \frac{\lambda^2 v^2}{12\pi^2 m_\varphi^2} \frac{\lambda v^2}{m_h^2} .$$

($D = \#$ real d.o.fs)



Wavefunction normalisation corrections $\kappa_{2V} = \kappa_V^2$.

κ_λ enhanced in the non-decoupling limit $\lambda v^2 \sim m_\varphi^2 > m_h^2$.

(Note order $\frac{\lambda g^2 v^2}{16\pi^2 m_\varphi^2}$ contributions to $h^2 W_{\mu\nu}^2$ operator aka $\mathcal{A}(\pm\pm \to hh)$.)

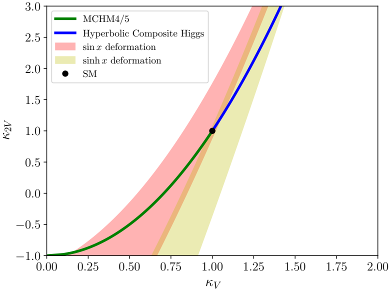
MCHM5

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

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

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

($\xi = \frac{v^2}{f^2}$, $\xi \to -\xi$ for hyperbolic)



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)

All decoupling physics (SMEFT) follows the blue/green line (Alonso and West 2022)

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

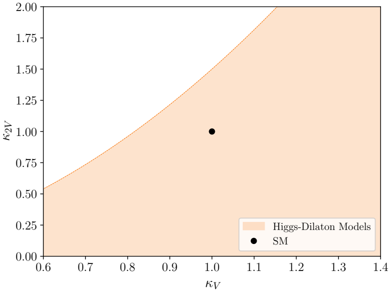
(Bruggisser, Harling, Matsedonskyi, and Servant 2022)

$$\kappa_V \approx \kappa_V^{\mathrm{MCHM}} c_\phi - s_\phi \sqrt{\zeta}$$

$$\kappa_{2V} \approx \kappa_{2V}^{\mathrm{MCHM}} c_\phi^2 - 4 s_\phi c_\phi \sqrt{\zeta(1-\xi)}$$

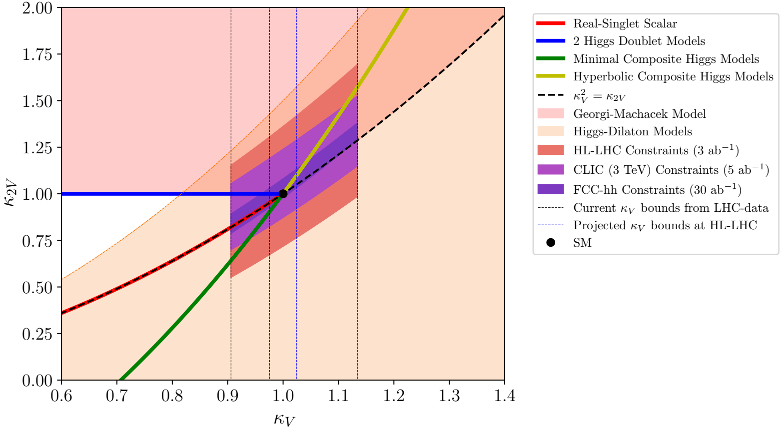
$$\kappa_\lambda \approx \kappa_\lambda^{\mathrm{MCHM}} c_\phi^3 - 4 c_\phi^2 s_\phi \sqrt{\zeta}$$

($\xi = \frac{v^2}{f^2}$, $\zeta = \frac{v^2}{\langle\chi\rangle^2}$, ϕ h–χ mixing)



($0 \leq \xi \leq 1$)

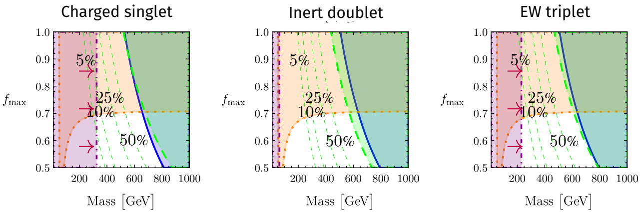
THE RESULT



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

κ_λ IS KING?

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.



Orange, dotted: κ_γ or κ_g

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

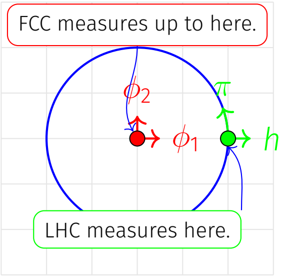
Green, dashed: *Higgs cubic*

Purple, dot-dash: Direct search

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

The world is SM-like at $v = 246\,\text{GeV}$, may be wildly different at $v = 0$.

$\delta\kappa_{2V} \sim 10\%$ at FCC-hh, $100\,\mathrm{TeV}$, $30\,\mathrm{ab}^{-1}$, but κ_λ often more interesting from BSM perspective.



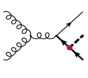
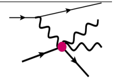
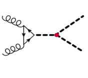
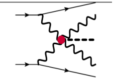
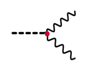
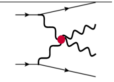
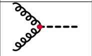
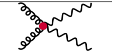
Non-decoupling NP is a finite target space for future colliders

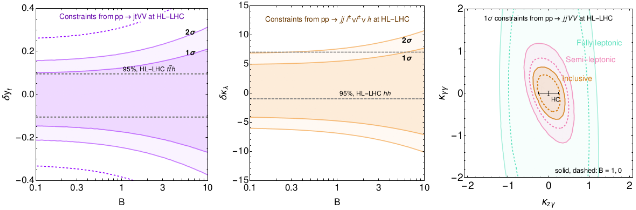
Thanks

BACKUP

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.

		HC	HwH
κ_t	$\mathcal{O}_{y_t}$		
κ_λ	$\mathcal{O}_6$		
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$		
κ_g	$\mathcal{O}_{gg}$		



HEFTY PHYSICS BREAKS CORRELATIONS

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

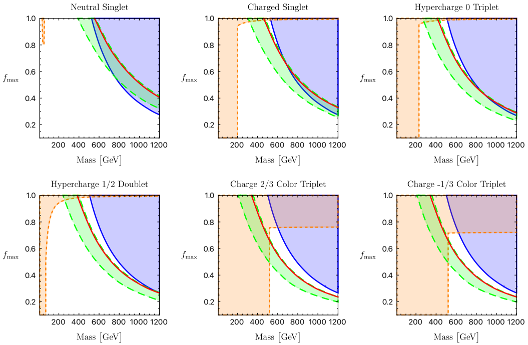
$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\text{SM}} &- \delta_3 \frac{m_h^2}{2v} h^3 - \delta_4 \frac{m_h^2}{8v^2} h^4 - \sum_{n=5}^{\infty} \frac{c_n}{n!} \frac{m_h^2}{v^{n-2}} h^n + \cdots \\
&+ \delta_{Z1} \frac{m_Z^2}{v} h Z^\mu Z_\mu + \delta_{W1} \frac{2m_W^2}{v} h W^{\mu+} W_\mu^- + \delta_{Z2}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

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

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

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

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

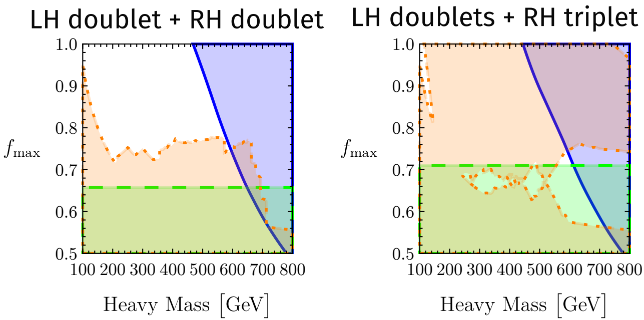
$$\alpha = \left(\Delta V_{\text{eff}} - \frac{T_n}{4}\Delta\frac{\mathrm{d}V_{\text{eff}}}{\mathrm{d}T}\right)\bigg/\frac{g_* \pi^2 T_n^4}{30} \ ,$$

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

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

HEFTY (CUSTODIALLY SYMMETRIC) FERMIONS

(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

Aad, Georges et al. (2022). “A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery”. In: *Nature* 607.7917. [Erratum: Nature 612, E24 (2022)], pp. 52–59. DOI: 10.1038/s41586-022-04893-w. arXiv: 2207.00092 [hep-ex].

Abu-Ajamieh, Fayez et al. (Sept. 2020). “Higgs Coupling Measurements and the Scale of New Physics”. In: arXiv: 2009.11293 [hep-ph].

Alonso, Rodrigo, Elizabeth E. Jenkins, and Aneesh V. Manohar (2016). “Geometry of the Scalar Sector”. In: *JHEP* 08, p. 101. DOI: 10.1007/JHEP08(2016)101. arXiv: 1605.03602 [hep-ph].

Alonso, Rodrigo and Mia West (2022). “Roads to the Standard Model”. In: *Phys. Rev. D* 105.9, p. 096028. DOI: 10.1103/PhysRevD.105.096028. arXiv: 2109.13290 [hep-ph].

Banta, Ian (Feb. 2022). “A Strongly First-Order Electroweak Phase Transition from Loryons”. In: arXiv: 2202.04608 [hep-ph].

Banta, Ian et al. (Oct. 2021). “Non-Decoupling New Particles”. In: arXiv: 2110.02967 [hep-ph].

Bruggisser, Sebastian et al. (Nov. 2022). “Dilaton at the LHC: Complementary Probe of Composite Higgs”. In: arXiv: 2212.00056 [hep-ph].

Cohen, Timothy et al. (2021). “Is SMEFT enough?” In: *JHEP* 03, p. 237. DOI: 10.1007/JHEP03(2021)237. arXiv: 2008.08597 [hep-ph].

Contino, Roberto et al. (2010). “Strong Double Higgs Production at the LHC”. In: *JHEP* 05, p. 089. DOI: 10.1007/JHEP05(2010)089. arXiv: 1002.1011 [hep-ph].

Durieux, Gauthier, Matthew McCullough, and Ennio Salvioni (2022). “Gegenbauer Goldstones”. In: *JHEP* 01, p. 076. DOI: 10.1007/JHEP01(2022)076. arXiv: 2110.06941 [hep-ph].