NON-DECOUPLING NEW PHYSICS

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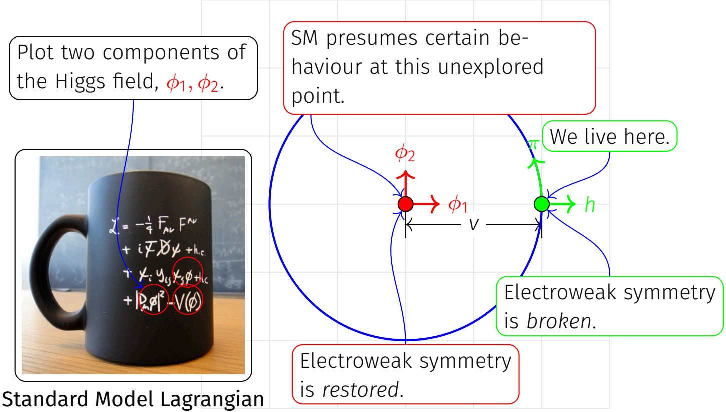
20th June 2024 — **CERN-CKC “Crossroads” workshop**

University of Glasgow

THE SM EXISTS IN FIELD SPACE



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

SM presumes certain behaviour at this unexplored point.

We live here.

Electroweak symmetry is *broken*.

Electroweak symmetry is *restored*.

Standard Model Lagrangian

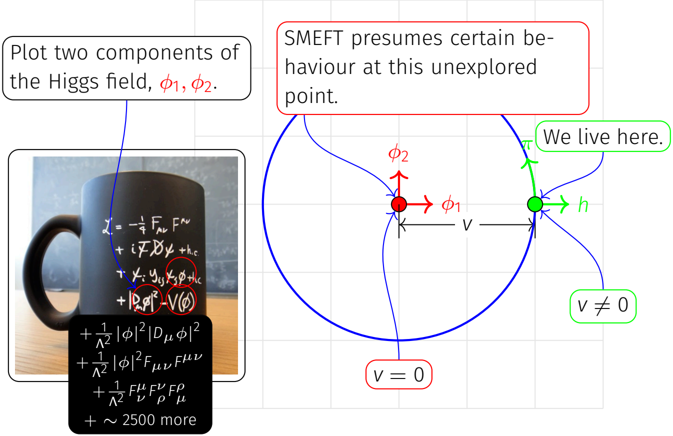
We observe that Higgs physics is SM-like at our vacuum.

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 $\Phi = 0$.

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



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

SMEFT presumes certain behaviour at this unexplored point.

We live here.

$v \neq 0$

$v = 0$

$$+\frac{1}{\Lambda^2}|\phi|^2|D_\mu\phi|^2$$
$$+\frac{1}{\Lambda^2}|\phi|^2 F_{\mu\nu}F^{\mu\nu}$$
$$+\frac{1}{\Lambda^2}F^{\mu}_{\nu}F^{\nu}_{\rho}F^{\rho}_{\mu}$$

$+ \sim$ 2500 more

SMEFT Lagrangian

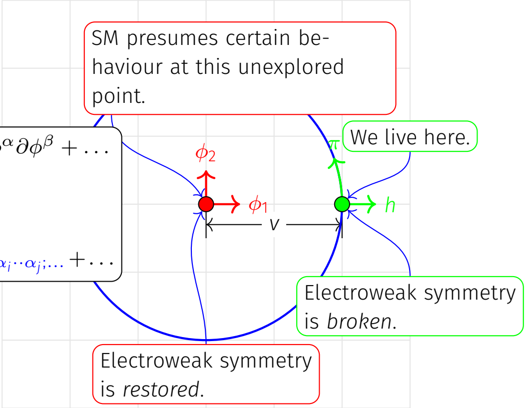
GEOMETRIC APPROACHES HELP HERE

(Alonso, Jenkins, and Manohar 2016)

$$\mathcal{L} = -V(\phi) + \tfrac{1}{2} g_{\alpha\beta}(\phi)\partial\phi^\alpha\partial\phi^\beta + \dots$$

$$\downarrow$$

$$\mathcal{A}_n \sim \overline{V}_{;(\alpha_1\dots\alpha_n)} + \textstyle\sum_{ij} s_{ij}\overline{R}_{\alpha_i\cdot\cdot\alpha_j;\dots} + \dots$$



SM presumes certain behaviour at this unexplored point.

We live here.

Electroweak symmetry is *broken*.

Electroweak symmetry is *restored*.

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

DECOUPLING NP (SMEFT) CORRELATES HIGGS OBS.

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

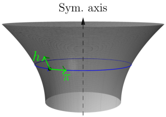
As can be seen in the broken phase

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

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

WHEN DOES PHYSICS NOT DECOUPLE?

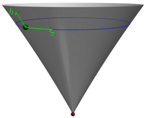
(Cohen, Craig, Lu, and Sutherland 2021)



Like a Laurent expansion

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

1) **Extra sources of electroweak symmetry breaking**



Like a non-convergent expansion

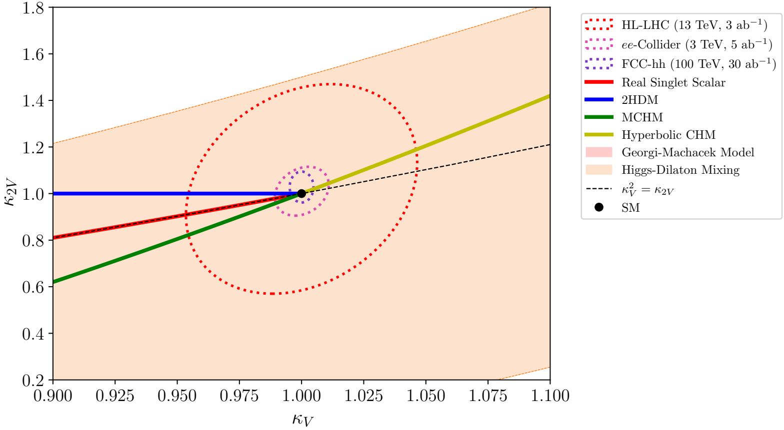
$$\mathcal{L} = \sum_{k=0}^{\infty} c_k \frac{|\Phi|^{2k}}{v^{2k}} |D\Phi|^2$$

2) **New particles getting most of their mass from the Higgs.**

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

EXTRA SOURCES OF EWSB

(Englert, Naskar, and Sutherland 2023)



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

MASS FROM EWSB: LOOP-LEVEL SINGLET EXAMPLE

$$\begin{aligned}\mathcal{L}_{\mathrm{UV}} =& |\partial\Phi|^2 + \frac{1}{2}(\partial S)^2 \\ &- \left(-\mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \frac{1}{2}\underbrace{\left(m^2 + \kappa|\Phi|^2\right)}_{\equiv m^2(|\Phi|^2)} S^2 + \frac{1}{4}\lambda_S S^4 \right)\end{aligned}$$

Choose $m^2, \kappa > 0$ so S does not get a vev

$$\begin{aligned}\mathcal{L}_{\mathrm{EFT}} =& |\partial\Phi|^2 + \frac{1}{384\pi^2}\frac{\kappa^2}{m^2(|\Phi|^2)}\left(\partial|\Phi|^2\right)^2 \\ &+ \mu_\Phi^2 |\Phi|^2 - \lambda_\Phi |\Phi|^4 + \frac{1}{64\pi^2} m^4(|\Phi|^2)\left(\ln\frac{\mu^2}{m^2(|\Phi|^2)} + \frac{3}{2}\right)\end{aligned}$$

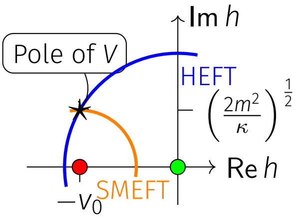
EFT CONVERGENCE

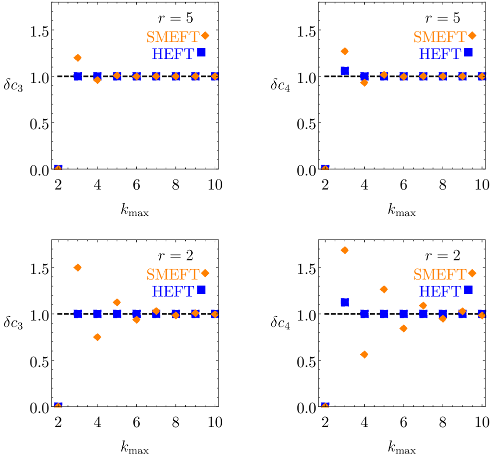
See also (Falkowski and Rattazzi 2019)

Expand Higgs potential, V, in SMEFT and HEFT

$$r \equiv \frac{m^2}{\frac{1}{2}\kappa v_0^2}$$

$$m^2(|\Phi|^2) = m^2 + \kappa|\Phi|^2$$

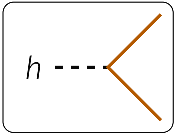




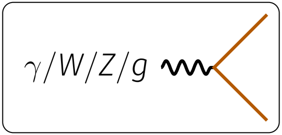
VIABLE NON-DECOUPLING MODELS

'Loryons' get most of their mass from the Higgs

Interactions:

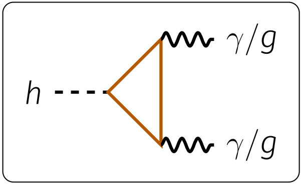


Higgs

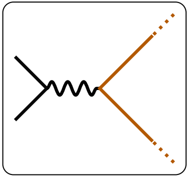


gauge bosons

Signals:



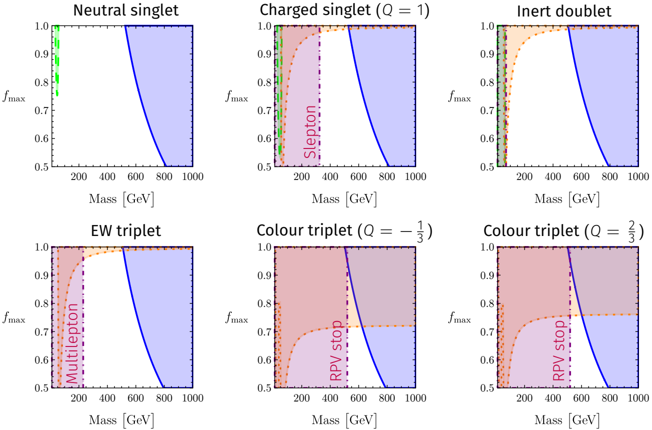
Higgs couplings



pair production

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 $\lambda_{h\Phi}$

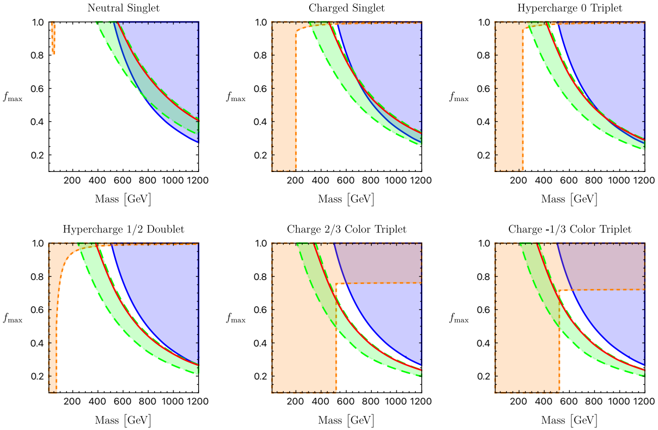
Green, dashed: Higgs decay

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

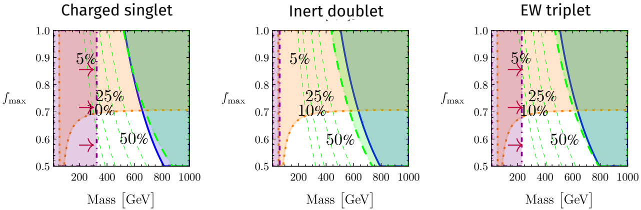
Green, dashed: strongly first-order phase transition

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

…a necessary condition for electroweak baryogenesis.

THE FUTURE: HADRONIC

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.

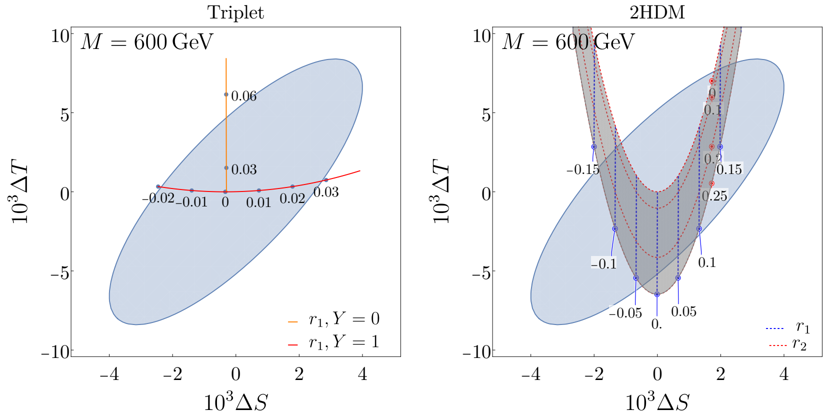
$\kappa_\lambda \sim 5\%$ measurement of FCC-hh closes off everything.

THE FUTURE: LEPTONIC (1)

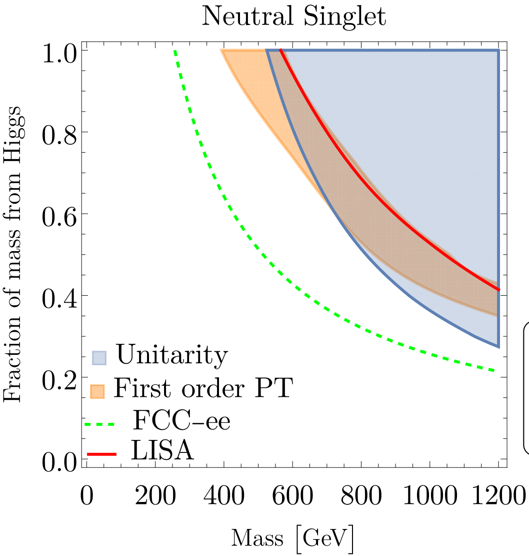
$$\boxed{f = \frac{\lambda v^2}{2M^2}} \qquad \boxed{r_1 = \frac{\lambda' v^2}{4M^2}} \qquad \boxed{r_2 = \frac{\lambda'' v^2}{4M^2}}$$

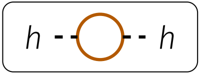
(Crawford and Sutherland to appear)

$$\mathcal{L} = |DL|^2 - \underbrace{\left(m_{\text{ex}}^2 + \lambda|\Phi|^2\right)}_{M^2} |L|^2 - \lambda'(L^\dagger T^a L)(\Phi^\dagger T^a \Phi) - \underbrace{\left\{\lambda''(\tilde{L}^\dagger T^a L)(\Phi^\dagger T^a \tilde{\Phi}) + \text{h.c.}\right\}}_{\text{iff. } |Y| = \frac{1}{2}}$$



THE FUTURE: LEPTONIC (2)





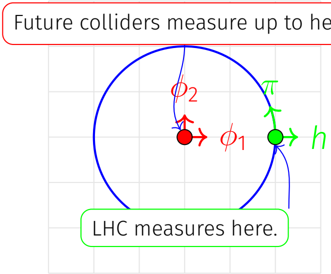
Wavefunction renormalisation

$$\delta\kappa_h = \frac{1}{12(4\pi)^2}\frac{1}{M^2}\left(\frac{\partial M^2}{\partial v}\right)^2 = \frac{2}{3(4\pi)^2}\frac{M^2}{v^2}f^2$$

SUMMARY

Nature is SM-like at $v = 246\,\text{GeV}$, but may be wildly different at $v = 0$, due to non-decoupling physics.

Gives generic signals in κ_h and κ_λ



Future colliders measure up to here.

LHC measures here.

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

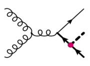
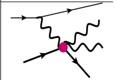
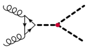
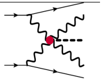
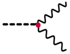
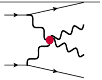
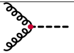
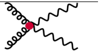
THANKS

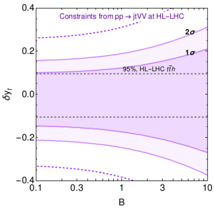
BACKUP

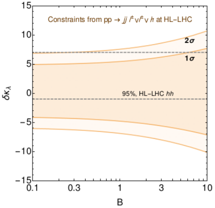
HEFTY MODELS POORLY FIT BY *DIMENSION 6* SMEFT

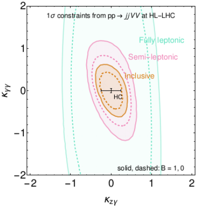
HL-LHC could probe the correlations of a single SMEFT operator across different Higgs multiplicities. (Henning, Lombardo, Riembau, and Riva 2019)

These correlations may be broken.

		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)

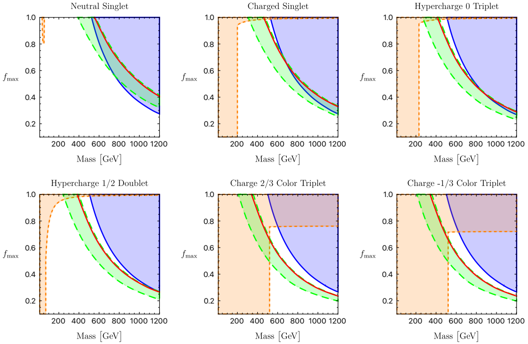
$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\text{SM}} &- \delta_3 \frac{m_h^2}{2v} h^3 - \delta_4 \frac{m_h^2}{8v^2} h^4 - \sum_{n=5}^{\infty} \frac{c_n}{n!} \frac{m_h^2}{v^{n-2}} h^n + \cdots \\
&+ \delta_{Z1} \frac{m_Z^2}{v} h Z^\mu Z_\mu + \delta_{W1} \frac{2m_W^2}{v} h W^{\mu +} W_\mu^- + \delta_{Z2}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

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

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

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

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

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

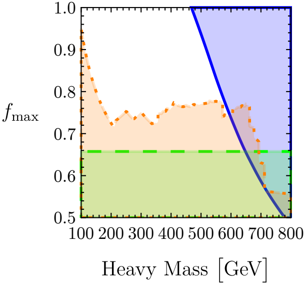
$$\beta / H_* = \left. \frac{\mathrm{d}S_3}{\mathrm{d}T} \right|_{T_n} - \frac{S_3}{T_n} .$$

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

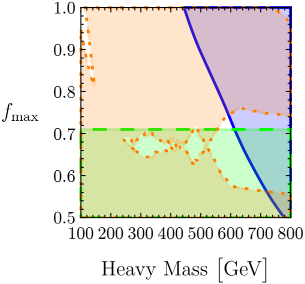
HEFTY (CUSTODIALLY SYMMETRIC) FERMIONS

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

LH doublet + RH doublet



LH doublets + RH triplet



Disallowed regions in colour:

Orange, dotted: Direct search

Blue, solid: perturb. unitarity

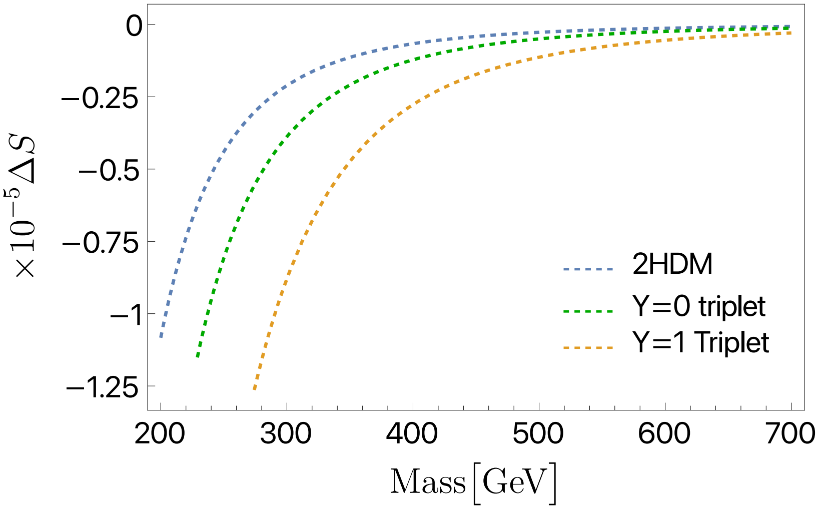
Green, dashed: EW precision test (S)

Purple, dot-dash: Direct search

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

Assuming no mass splitting among components of multiplet

m_z^2 PIECES IN S



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