Non-Decoupling New Particles

based on JHEP 02 (2022) 029 [2110.02967] with N. Craig, T. Cohen, X. Lu, and D. Sutherland

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- Strongly first-order electroweak phase transition [IB '22]
- Unitarity constraints imply finite search space
- Good discovery prospects in the near future

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- Future directions

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- Scalars and vector-like fermions
- No new custodial symmetry violation to one-loop level
- $\mathbb{Z}_2$ symmetry on BSM Loryons, often weakly broken to allow decay
- All new charged particles promptly decay

For a scalar Φ in the custodial representation $[L, R]_Y$, we have

$$\begin{aligned}\mathcal{L} \supset &- \frac{m_{\text{ex}}^2}{2^\rho}\,\text{tr}\left(\Phi^\dagger \Phi\right) \\ &- \frac{\lambda_{h\Phi}}{2^\rho}\,\text{tr}\left(\Phi^\dagger \Phi\right)\frac{1}{2}\,\text{tr}\left(H^\dagger H\right) \\ &- \frac{\lambda'_{h\Phi}}{2^\rho}\,\text{tr}\left(\Phi^\dagger T_L^a \Phi T_R^{\dot{a}}\right)\frac{1}{2}\,\text{tr}\left(H^\dagger T_2^a H T_2^{\dot{a}}\right)\end{aligned}$$

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$$\begin{aligned}m_V^2 &= m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\Phi} v^2 + \frac{1}{2}\lambda'_{h\Phi} v^2 \left(C_2(L) + C_2(R) - C_2(V)\right) \\ &= m_{\text{ex}}^2 + \frac{1}{2}\lambda_V v^2,\end{aligned}$$

$$V \in \mathcal{V} = \{L + R - 1, L + R - 3, |L - R| + 1\}$$

For a pair of vector-like fermions Ψ_1, Ψ_2 in the custodial representations $[L_1, R_1]_Y, [L_2, R_2]_Y = [L_1 \pm 1, R_1 \pm 1]_Y$, we have

$$\mathcal{L} \supset -M_{\text{ex}1}\,\text{tr}\left(\bar{\Psi}_1\Psi_1\right) - M_{\text{ex}2}\,\text{tr}\left(\bar{\Psi}_2\Psi_2\right) - y_{12}\bar{\Psi}_1 \cdot H \cdot \Psi_2 + \text{ h.c.}$$

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$$M_V = M_{\text{ex}}, \qquad V \in \mathcal{V}_1 \cup \mathcal{V}_2 - \mathcal{V}_1 \cap \mathcal{V}_2$$

$$M_{\pm V} = M_{\text{ex}} \pm \frac{v}{\sqrt{2}}|y_V|, \qquad V \in \mathcal{V}_1 \cap \mathcal{V}_2$$

Integrating out a scalar Φ to all orders in H and two-derivative order gives [TC, NC, XL, DS '20]

$$\mathcal{L}_{\text{eff}} \supset \frac{1}{2^\rho(4\pi)^2} \sum_{V\in\mathcal{V}} V \left\{ \frac{m_V^4(H)}{2} \left[\ln \frac{\mu^2}{m_V^2(H)} + \frac{3}{2} \right] + \frac{\lambda_V^2}{6 m_V^2(H)} \frac{\left[\partial |H|^2\right]^2}{2} + \mathcal{O}\left(\partial^4\right) \right\},$$

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Expansion in $\lambda_V |H|^2 / m_{\text{ex}}^2$ (SMEFT) converges at $|H| = v/\sqrt{2}$ iff

$$\frac{1}{2} \lambda_V v^2 < m_{\text{ex}}^2 \qquad \forall V \in \mathcal{V}$$

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For fermions,

$$f_{\max} \equiv \max_{V \in \mathcal{V}_1 \cap \mathcal{V}_2} \frac{|y_V| v/\sqrt{2}}{M_{+V}} \geq \frac{1}{2}$$

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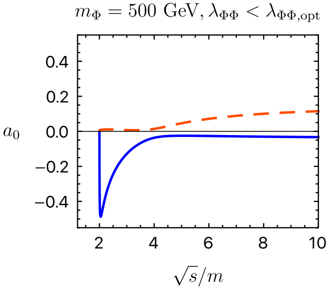
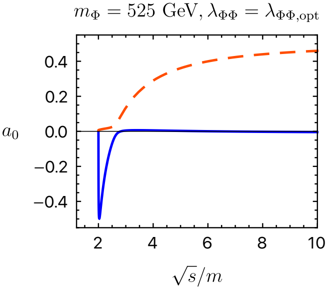
$$a_0\left(\sqrt{s}\right) = \sqrt{\frac{4\,|\vec{p}_i|\,|\vec{p}_f|}{2^{\delta_i+\delta_f}\,s}}\,\frac{1}{32\pi}\int_{-1}^{1} d(\cos\theta)\;\mathcal{M}(i \to f)$$

Can be considered not just in the high energy limit, but at all $\sqrt{s}$ [Goodsell, Staub '18]:

Strongest bound comes close to threshold, where the amplitude is dominated by *t*-channel exchange of a Higgs:





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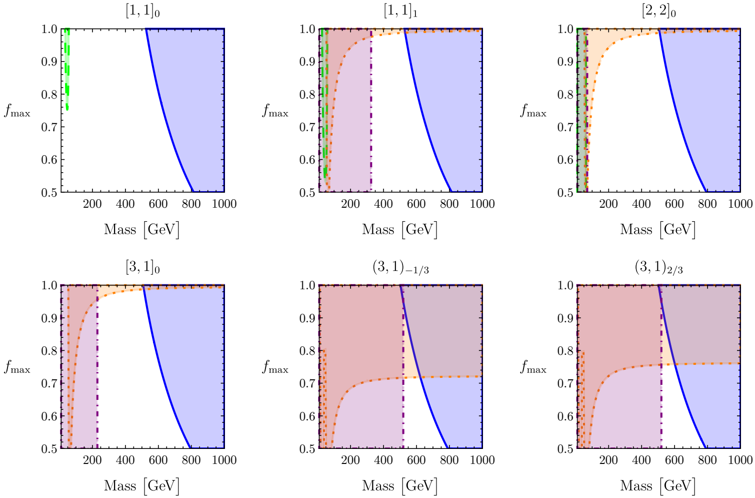
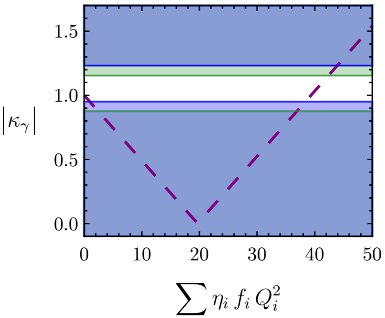
- Higgs couplings ($h\gamma\gamma$, hgg, Higgs decay) [ATLAS, arXiv:1909.02845; CMS, arXiv:1809.10733]
- Precision electroweak measurements (primarily the S parameter) [PDG, '18]
- Direct searches [various sources]


[1, 1]$_0$
[1, 1]$_1$
[2, 2]$_0$
[3, 1]$_0$
(3, 1)$_{-1/3}$
(3, 1)$_{2/3}$
$f_{\max}$
Mass [GeV]
1.0
0.9
0.8
0.7
0.6
0.5
200
400
600
800
1000

$m \gtrsim 500$ GeV



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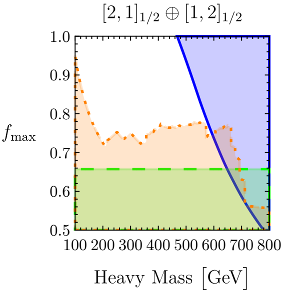
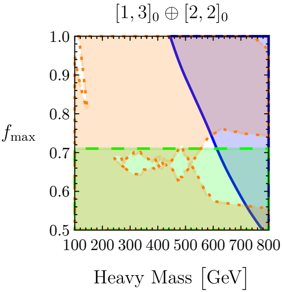
First noted by [Bizot, Frigerio '15]


$[2,1]_{1/2} \oplus [1,2]_{1/2}$
1.0
0.9
0.8
0.7
0.6
0.5
$f_{\max}$
100 200 300 400 500 600 700 800
Heavy Mass [GeV]


$[1,3]_0 \oplus [2,2]_0$
1.0
0.9
0.8
0.7
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0.5
$f_{\max}$
100 200 300 400 500 600 700 800
Heavy Mass [GeV]

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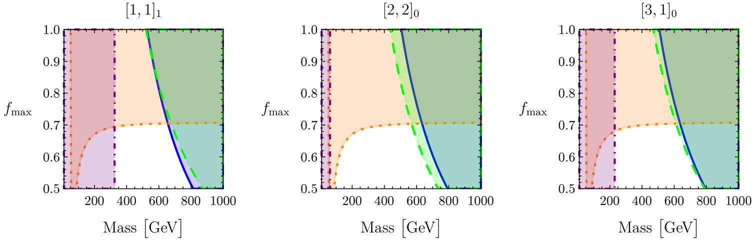
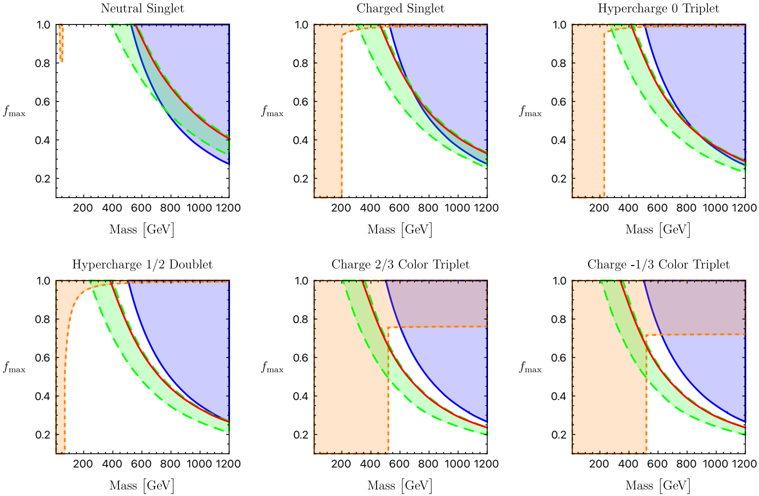
- Particularly $hZ\gamma$ and hhh


[1, 1]_1
[2, 2]_0
[3, 1]_0
f_max
Mass [GeV]
1.0
0.9
0.8
0.7
0.6
0.5
200
400
600
800
1000


Neutral Singlet
Charged Singlet
Hypercharge 0 Triplet
Hypercharge 1/2 Doublet
Charge 2/3 Color Triplet
Charge -1/3 Color Triplet
f_{max}
Mass [GeV]
1.0
0.8
0.6
0.4
0.2
200
400
600
800
1000
1200

[IB '22]

- Integrating out a particle acquiring most of its mass from the Higgs (a "Loryon") requires the use of HEFT.
- There are sizable viable regions of the Loryon parameter space.
- Improved measurements of Higgs properties would substantially narrow the allowed parameter space.
- Loryons' large coupling to the Higgs means that they are natural candidates for generating a strongly first-order electroweak phase transition.