Non-decoupling scalars at future detectors
[arXiv:2409.18177 w/ Dave Sutherland]

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VIA VERITAS VITA

What is the nature of electroweak symmetry breaking?

Models vastly different from SM prediction remain viable ...

non-decoupling particles

↙ extra EWSB source (Cohen et.al 2021)

↘ **Loryons** – acquire most of their mass from the Higgs (Banta et.al 2022)

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↘ **Loryons** – acquire most of their mass from the Higgs (Banta et.al 2022)

Loryons {
- are capped at the TeV scale by unitarity
- can be scalars or vector-like fermions
- are a finite target for future lepton colliders

The Loryon mass spectrum

$$\mathcal{L}_{\text{mass}} = -\underbrace{\left(m_{\text{ex}}^2 + \lambda_{h\phi}\,|H|^2\right)}_{M^2}|\Phi|^2$$
$$-\lambda'_{h\phi}(H^\dagger T^a H)(\Phi^\dagger T^a \Phi) - \lambda''_{h\phi}(\tilde{\Phi}^\dagger T^a \Phi)(H^\dagger T^a \tilde{H} + \text{h.c})$$

- $M^2 = m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\phi} v^2$ Common mass of each component
- $f = \frac{\lambda_{h\phi} v^2}{2M^2}$ Fraction of mass obtained from Higgs
- $r_1 = \frac{\lambda'_{h\phi} v^2}{4M^2}$ Mass splitting parameter
- $r_2 = \frac{\lambda''_{h\phi} v^2}{4M^2}$ Additional mass splitting for $|Y| = \frac{1}{2}$ irreps

m_{ex} is an explicit mass term

Non-decoupling theories require HEFT

$$\text{SM} \subset \text{SMEFT} \subset \text{HEFT}$$

$$\text{SMEFT} \Rightarrow \text{Expand about } |\Phi| = 0$$

$$\text{HEFT} \Rightarrow \text{ Expand about } |\Phi| = v$$

Integrate out a singlet S at tree-level,

$$\mathcal{L}_{\text{UV}} = \frac{1}{2}(\partial S)^2 - gSJ - \frac{1}{2}M^2(|\Phi|^2)S^2 \,.$$

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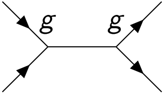
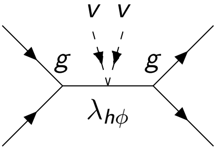
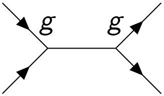


$$= \quad \frac{g^2 J^2}{M^2(|\Phi|^2)}$$



$$= \quad \frac{-g^2 J^2}{M^2(|\Phi|^2)}\left(\frac{\lambda_{h\phi} v^2}{M^2(|\Phi|^2)}\right)$$

Non-decoupling theories require HEFT



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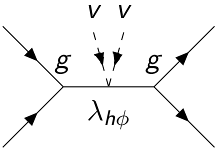


$$= \quad \frac{-g^2 J^2}{M^2(|\Phi|^2)}\left(\frac{\lambda_{h\phi} v^2}{M^2(|\Phi|^2)}\right)$$

Expand around $|\Phi| = 0$, à la SMEFT;

$$\Rightarrow \mathcal{L}_{\text{EFT}} = \frac{g^2 J^2}{M^2(|\Phi|^2)}\Big(1 - \frac{\lambda_{h\phi} v^2}{M^2(|\Phi|^2)} + \big(\frac{\lambda_{h\phi} v^2}{M^2(|\Phi|^2)}\big)^2 - \dots\Big)$$

$$\boxed{\Rightarrow 2f = \frac{\lambda_{h\phi} v^2}{M^2(|\Phi|^2)} < 1}$$

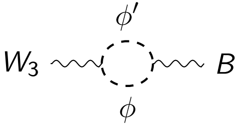
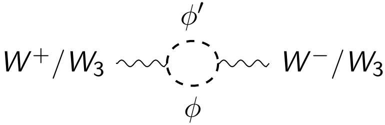
Mass spectrum of charged multiplets

	Real triplet ($Y = 0$)	Inert 2HDM ($Y = \frac{1}{2}$)
	$\begin{pmatrix} H^+ \\ H^0 \\ H^- \end{pmatrix}$	$\begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$
Masses	$m_{H^+}^2 = M^2(1 - r_1)$ $m_{H^0}^2 = M^2$ $m_{H^-}^2 = M^2(1 + r_1)$	$m_{H^\pm}^2 = M^2\left(1 - \frac{1}{2}r_1\right)$ $m_H^2 = M^2\left(1 + \frac{1}{2}r_1 + 2r_2\right)$ $m_A^2 = M^2\left(1 + \frac{1}{2}r_1 - 2r_2\right)$

Neutral singlet: $m_s^2 = M^2$

Oblique parameters measure mass splittings

$$M^2 = m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\phi} v^2 \qquad r_1 = \frac{\lambda'_{h\phi} v^2}{4M^2} \qquad r_2 = \frac{\lambda''_{h\phi} v^2}{4M^2}$$

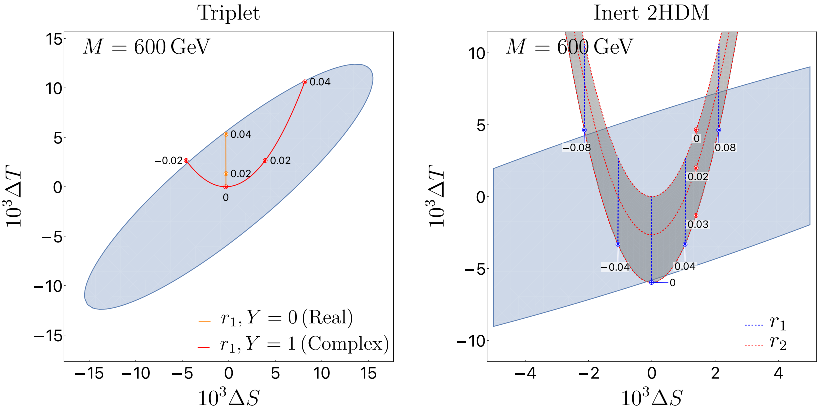
Observable	**Representative diagram**	**Scaling**
S		$r_1 YC(j)$ or $r_2^2 YC(j)$
T		$M^2 r_1^2 C(j)$ or $M^2 r_2^2 C(j)$

Impose $\mathbb{Z}_2$ symmetry: study deviations to gauge 2-pt functions at 1-loop.

$C(j) = [(T^3)^2] = \frac{2}{3} j(j+\frac{1}{2})(j+1)$

Constraining r_1 and r_2 at FCC-ee

$$r_1 = \frac{\lambda'_{h\phi} v^2}{4M^2} \qquad r_2 = \frac{\lambda''_{h\phi} v^2}{4M^2}$$

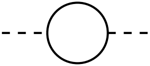
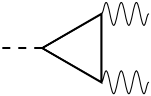
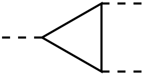


FCC-ee ellipse: (de Blas et.al 2021)

$\Rightarrow$ $\sim$ 10% sensitivity for 2HDM splittings, smaller for triplets.

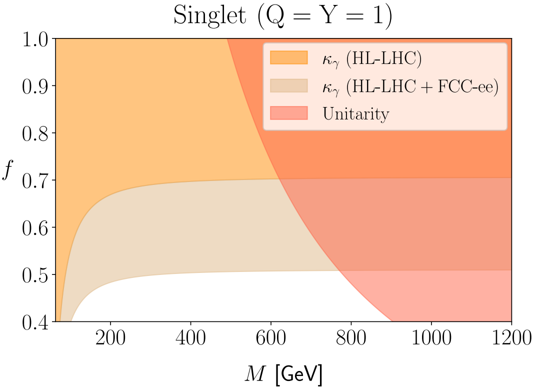
Higgs coupling modifiers provide indirect bounds

$$f = \frac{\lambda_{h\phi} v^2}{2M^2} > 0.5 \qquad M^2 = m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\phi} v^2$$

Observable	**Representative diagram**	**Scaling**
κ_h		$M^2 f^2 d(j)$
κ_γ		$f\left(C(j) + Y^2 d(j)\right)$
κ_λ		$M^4 f^3 d(j)$

$C(j) = [(T^3)^2] = \frac{2}{3} j(j+\frac{1}{2})(j+1), \qquad d(j) = 2j+1$

κ_γ – Any charged Loryon can be found at FCC-ee [1]

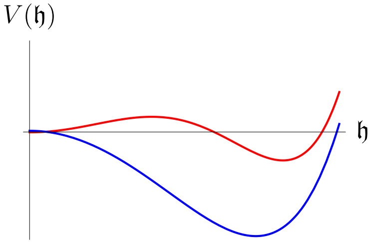


Using 2σ projected κ_γ sensitivities from (Tab. 4.2, Abada et.al 2022).
$\Rightarrow$ sensitive to everything above $f > 0.5$.

[1] or similar machine

Electroweak Baryogenesis

- Baryogenesis could be explained by a strong first order phase transition (SFOPT) in the early Universe (see Quiros 1999, Croon 2023 for reviews).
- Not possible in SM, but adding scalars induces potential barrier (enhances $\mathfrak{h}^3$ term).



SFOPT:

$$v_{\rm nuc}/T_{\rm nuc} \gtrsim 1\,,$$
$$100 < S_3/T_{\rm nuc} < 200\,,$$
$$S_3 \equiv \text{bounce action.}$$

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strong transition ensures baryon asymmetry not washed out at later time.

Gravitational wave production

- During transition, bubbles of the new phase collide
  $\Rightarrow$ produce gravitational wave (GW) background.

- Determined by the energy released (α) and the duration of the phase transition ($\sim \beta$),

$$\alpha = \left(\Delta V - \frac{T_{\rm nuc}}{4} \Delta \frac{\mathrm{d}V}{\mathrm{d}T} \right) \Big/ \frac{g_{\rm eff}\,\pi^2\, T_{\rm nuc}^4}{30} \,,$$

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

(Caprini et.al 2016, 2020)

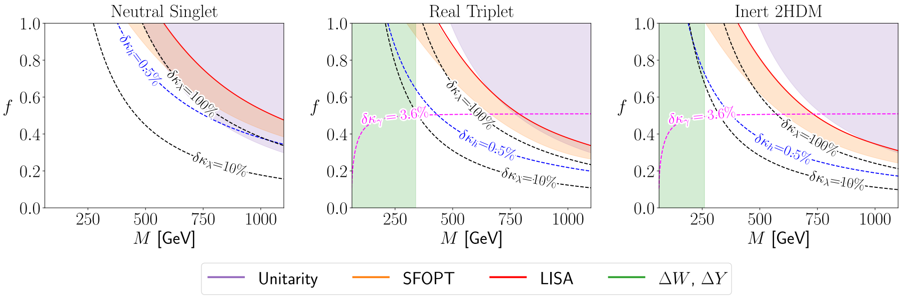
- Approx bounds for LISA: $\log(\beta/H_*) - 1.2\,\log(\alpha) < 8.8$

(Banta 2022)

$g_{\rm eff} \equiv$ effective relativistic d.o.f

SFOPT/GW constraints

$$f = \frac{\lambda_{h\phi} v^2}{2M^2} > 0.5 \qquad M^2 = m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\phi} v^2$$



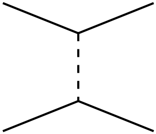
Bounds for multiplets with larger d.o.f will move towards the bottom left.

following (Banta 2022)

Summary

- Motivation: non-decoupling physics may have important implications in understanding the **nature of EWSB**.
- Pheno: scalar Loryons can **induce a SFOPT** in the early Universe – potential source of baryogenesis – and a residual GW background.
- Search: present a **finite target for future colliders** – virtually all of the parameter space accessible by FCC-hh.

Backup — Unitarity

Observable	Representative diagram	Scaling
Unitarity		$M^3 f^2$

Constraint dominated by $2 \to 2$ elastic scattering of Loryon with exchange of a Higgs – only tree-level diagram that grows as $\lambda_{h\phi}^2$.

Contributions of an arbitrary multiplet to the oblique parameters W and Y are given by;

$$\Delta W = \frac{1}{2^\rho} \underbrace{\frac{43}{180}\frac{g^2}{(4\pi)^2}\frac{m_W^2}{M^2}}_{\simeq 1.2\times 10^{-5}\left(\frac{600\text{ GeV}}{M}\right)^2} \times j(j+\frac{1}{2})(j+1)\,,$$

$$\Delta Y = \frac{1}{2^\rho} \underbrace{\frac{43}{60}\frac{g'^2}{(4\pi)^2}\frac{m_W^2}{M^2}}_{\simeq 1.0\times 10^{-5}\left(\frac{600\text{ GeV}}{M}\right)^2} \times Y^2(j+\frac{1}{2})\,.$$

A lower bound for the Real Triplet and Inert 2HDM models were found using 2d sensitivities for ΔW and ΔY (de Blas et.al 2016).

Backup – Effective Potential

$$V_{\text{eff}}(\mathfrak{h}) = V_0(\mathfrak{h}) + \underbrace{\sum_i n_i V_{\text{CW,bos}}(m_i^2(\mathfrak{h})) + n_t V_{\text{CW,fer}}(m_t^2(\mathfrak{h})) + n_\Phi V_{\text{CW,bos}}(m_\Phi^2(\mathfrak{h}))}_{\text{zero temperature corrections}} + \underbrace{\sum_i n_i V_{\text{T,bos}}(m_i^2(\mathfrak{h}), T) + n_t V_{\text{T,fer}}(m_t^2(\mathfrak{h}), T) + n_\Phi V_{\text{T,bos}}(m_\Phi^2(\mathfrak{h}))}_{\text{finite temperature corrections}}$$

$i = \{W_T, W_L, Z_T, Z_L, h, \chi, \gamma_L\}$

n_i (degrees of freedom) $= \{4, 2, 2, 1, 1, 3, 1\}$

$v \to \mathfrak{h} \equiv v + h$

Field-dependent masses are shifted by contributions of hard thermal loops;

$$\Pi_i = \frac{\partial^2 V_T}{\partial f_i^2} \,,$$

e.g, the Higgs and Goldstones shift by,

$$\Pi_h = \Pi_\chi = \frac{1}{24} T^2 \left(\frac{3}{2} g'^2 + \frac{9}{2} g^2 + 12\lambda_{hh} + 6y_t^2 + n_{\text{Loryons}} \lambda \right) \,.$$

We use the Parwani scheme, inserting $m_i^2(\mathfrak{h}) \to m_i^2(\mathfrak{h}) + \Pi_i(\mathfrak{h}, T)$ directly into $\mathrm{V}_{\mathrm{eff}}(\mathfrak{h})$ (Parwani 1991).