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

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What is the nature of electroweak symmetry breaking?

Models with a vastly different prediction from SM remain viable ...
they must be **non-decoupling**

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extra EWSB source (see, e.g, Cohen et al. 2021)

- extended scalar sectors, composite Higgs
- predict deviations to hWW and hZZ
- constrained to small regions of parameter space

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

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

The Loryon Model

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

$M^2 = m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\phi} v^2$ Common mass component for any scalar

$f = \frac{\lambda_{h\phi} v^2}{2M^2}$ Fraction of mass obtained via Higgs

$r_1 = \frac{\lambda'_{h\phi} v^2}{4M^2}$ Splits mass based on isospin

$r_2 = \frac{\lambda''_{h\phi} v^2}{4M^2}$ Mixes and splits mass for $|Y| = \frac{1}{2}$ irreps

m_{ex} is a *small* explicit mass term

Non-decoupling theories require HEFT

Integrate out a singlet S at tree-level,

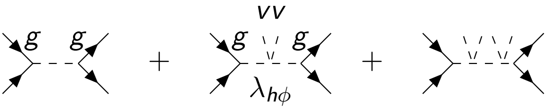
$$\mathcal{L}_{\text{UV}} = \frac{1}{2}(\partial S)^2 - gSJ - \frac{1}{2}M^2(|\Phi|^2)S^2$$

$$\Rightarrow \mathcal{L}_{\text{EFT}} = \frac{g^2 J^2}{m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\phi}|\Phi|^2}$$

$M^2(|\Phi|^2) = m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\phi}|\Phi|^2$

Non-decoupling theories require HEFT

Expand around $|\Phi| = 0$, à la SMEFT. Then move to broken phase.



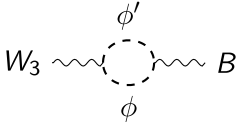
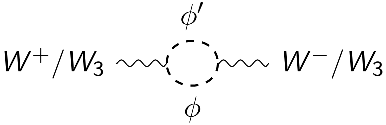
$$+ \ldots = \frac{g^2 J^2}{m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\phi} v^2}$$

$$\Rightarrow \mathcal{L}_{\text{EFT}} = \frac{g^2 J^2}{m_{\text{ex}}^2}\left(1 - \frac{\lambda_{h\phi} v^2}{2\, m_{\text{ex}}^2} + \left(\frac{\lambda_{h\phi} v^2}{2\, m_{\text{ex}}^2}\right)^2 - \ \ldots\right)$$

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

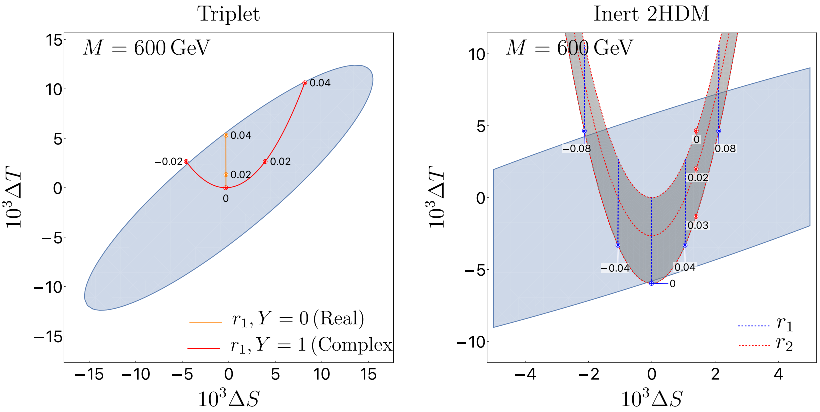
Oblique parameters measure mass splittings

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

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

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

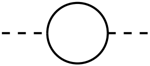
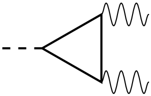
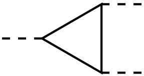
Constraining r_1 and r_2 at FCC-ee



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

$\Rightarrow$ ~ 10% sensitivity to 2HDM splittings, ~ 10GeV for triplets.

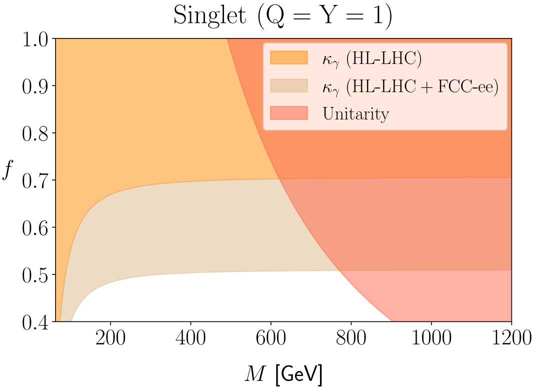
Higgs coupling modifiers provide indirect bounds

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

(kappa framework – LHCHXSWG et al. 2011)

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

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

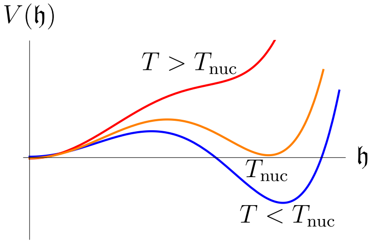


Using 2σ projected κ_γ sensitivities from (Tab. 4.2, Abada et al. 2022).
$\Rightarrow$ sensitive to everything above $f > 0.5$.

[1] or similar machine

Electroweak Phase Transition (EWPT)

- Particles at TeV scale with strong Higgs couplings modify EWPT.
- EW baryogenesis requires strong first order phase transition (SFOPT).
- $V = V_{\mathrm{tree}} + V_{1-\mathrm{loop}} + V_{\mathrm{thermal}}$



SFOPT:

$$v_{\mathrm{nuc}}/T_{\mathrm{nuc}} \gtrsim 1\,,$$

$$100 < S_3/T_{\mathrm{nuc}} < 200\,,$$

$$S_3 \equiv \text{bounce action.}$$

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 ($\sim \beta$),

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

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

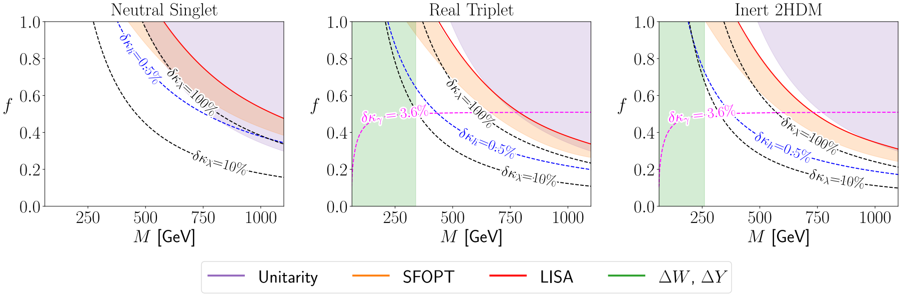
(Caprini et al. 2016, 2020)

- 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 (see ESPP update 2026)



2-loop effects on oblique parameters at Z-pole can close window on neutral singlet (Maura, Stefanek, You 2024)

following on from (Banta 2022)

Summary

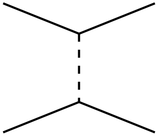
- Motivation: non-decoupling physics may have important implications in understanding the **nature of EWSB**.
- Pheno: scalar Loryons can **induce a SFOPT** in the early Universe – potential source of baryogenesis – and a residual GW background.
- Search: present a **finite target for future colliders**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

Backup — 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: $m_s^2 = M^2$

Backup – Perturbative Unitarity

Observable	Representative diagram	Scaling
Perturbative 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 $\lambda_{h\phi}^2$.

For $f = 0.5$, $\lambda_{h\phi}$ will run into non-perturbative regime at $\sim 30,000$ TeV (must be accompanied by extra states).

Backup – W and Y parameters

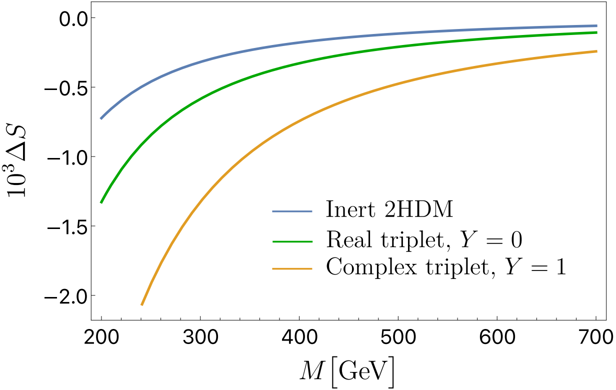
Contributions of an arbitrary multiplet to the oblique parameters W and Y are given by;

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

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

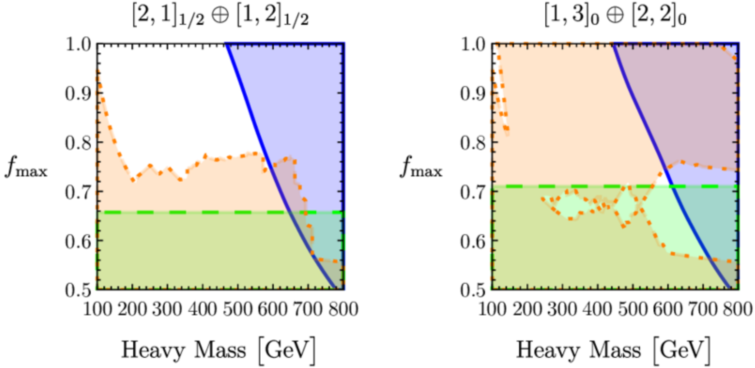
A lower bound for the Real Triplet and Inert 2HDM models were found using 2d sensitivities for ΔW and ΔY (de Blas et al. 2016).

Backup – m_Z^2 dependent shift to S



For each scalar multiplet, the m_Z^2 shift in S up to $\mathcal{O}(m_Z^2)$ is negligible.

Backup – Fermionic Constraints



Green: EWPO Blue: Perturbative Unitarity Orange: Direct Search

Adding in κ_γ constraints rule out each individual fermion; extra fermions or scalars are required (plot from Banta et al. 2022).

Backup – Effective Potential

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

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

Degrees of freedom: $n_i = \{4, 2, 2, 1, 1, 3, 1\}$

Field-dependent masses: $v \to \mathfrak{h} \equiv v + h$

Backup — Daisy Resummation

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).