Non-decoupling scalars at future detectors
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Motivation

- Extend SM with scalars that acquire more than half of their mass from the Higgs mechanism – ***"Loryons"*** (Banta et.al 2022).
- Loryons are non-decoupling $\Rightarrow$ capped at TeV scale.
- Non-decoupling theories require **HEFT prescription**.
- HEFT & SMEFT have different assumptions about **nature of EWSB**.

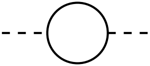
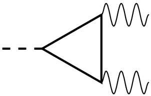
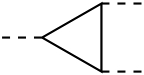
The Loryon Mass Spectrum

$$\mathcal{L}_{\text{mass}} = -\underbrace{\left(m_{\text{ex}}^2 + \lambda_{h\phi} \left|H\right|^2\right)}_{M^2} \left|\Phi\right|^2 - \{\text{mass-splitting terms}\}$$

- $f = \frac{\lambda_{h\phi} v^2}{2M^2}$ Fraction of mass obtained from Higgs.
- $M^2 = m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\phi} v^2$ Common mass of each component.
- Fermionic *Loryons* discoverable at HL-LHC (Banta et.al 2022).
- Consider loop level effects of $\mathbb{Z}_2$-symmetric scalars.

Indirect Bounds

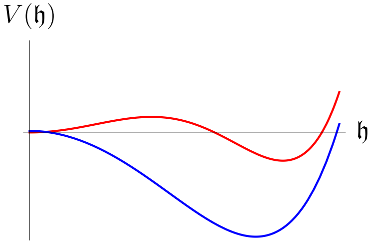
$$f = \frac{\lambda_{h\phi} v^2}{2M^2} > 0.5 \qquad M^2 = m_{\text{ex}}^2 + \frac{1}{2}\lambda_{h\phi} v^2$$

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		$M^4 f^3 d(j)$

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

Electroweak Baryogenesis

- Baryogenesis could be explained by a strong first order phase transition (SFOPT) in the early Universe (see Croon 2023 for review).
- Not possible in SM, but adding scalars induces potential barrier.
- During transition, bubbles of the new phase collide $\Rightarrow$ produce gravitational waves (GW).

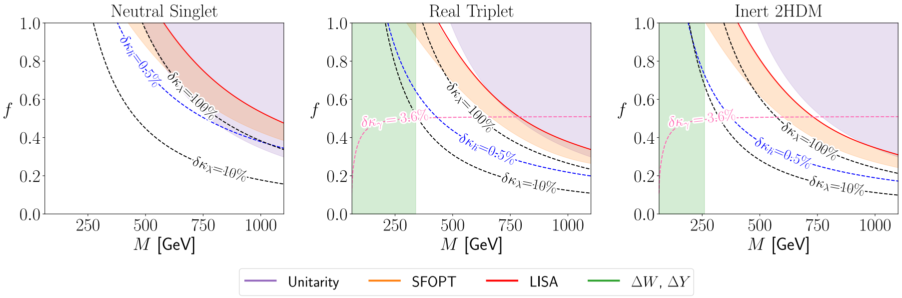


SFOPT: $\quad v_{\rm nuc}/T_{\rm nuc} \gtrsim 1$

$$100 < S_3/T_{\rm nuc} < 200$$

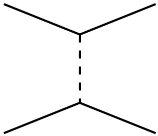
SFOPT / GW constraints

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



following (Banta 2022)

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 $\lambda_{h\phi}^2$.

Backup – W and Y parameters

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

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

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

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

Backup – Effective Potential

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

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

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

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

GW background determined by the energy released (α) and the duration of the phase transition ($\sim \beta$),

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

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

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

(Caprini et.al 2016, Caprini et.al 2020)

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,

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

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