Non-decoupling scalars at future detectors
[WIP with Dave Sutherland]

Graeme Crawford[1]

[1]School of Physics and Astronomy
University of Glasgow

July 15, 2024

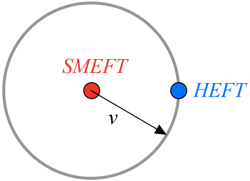
Primer on Effective Field Theory

EFT: offer a low energy description of an unknown/tough to calculate high energy theory.

New physics written as a perturbative expansion, e.g

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \mathcal{O}(\Lambda^{-3})$$

Two main EFTs of Higgs sector:



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 $\Rightarrow$ mass scales with Higgs coupling.
- Non-decoupling theories require **HEFT prescription**.
- We focus on simple scalar models $\begin{cases} \text{Neutral singlet} \\ \text{inert 2HDM} \\ \text{Real/Complex Triplet} \end{cases}$

The Loryon Mass Spectrum

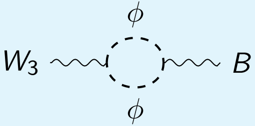
$$\mathcal{L}_{\text{mass}} = -\underbrace{\left(m_{\text{ex}}^2 + \lambda\,|\Phi|^2\right)}_{M^2}|H|^2 - \lambda'(H^\dagger T^a H)(\Phi^\dagger T^a \Phi) - \lambda''(\tilde{\Phi}^\dagger T^a \Phi)(H^\dagger T^a \tilde{H} + \text{h.c})$$

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

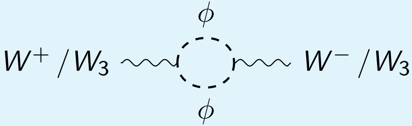
S and T: Oblique parameters

Calculating one-loop corrections and comparing to projected FCC-ee bounds in order to constrain each model (de Blas et.al 2022).

$$S = -\frac{4c_W s_W}{\alpha}\Pi'_{3B}(0)$$

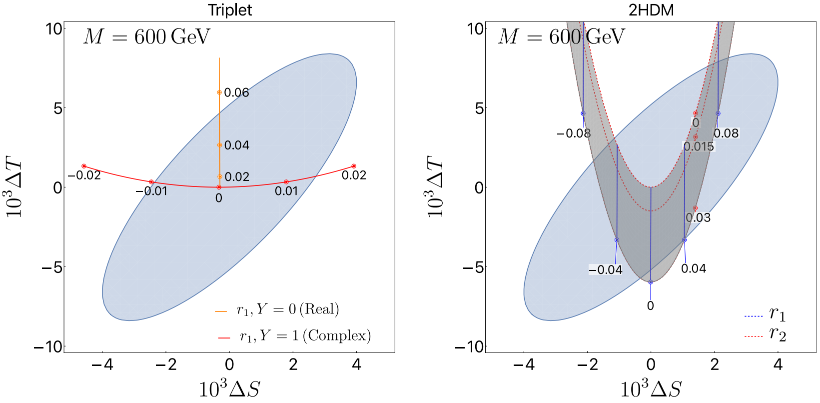


$$T = \frac{1}{\alpha m_W^2}\left(\Pi_{+-}(0) - \Pi_{33}(0)\right)$$



Mass splitting constraints at FCC-ee

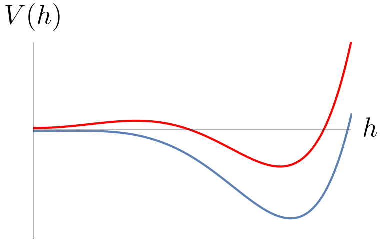
$$r_1 = \frac{\lambda' v^2}{4M^2} \qquad r_2 = \frac{\lambda'' v^2}{4M^2}$$



⇒ we have sensitivity to r_1 and r_2 at FCC-ee.

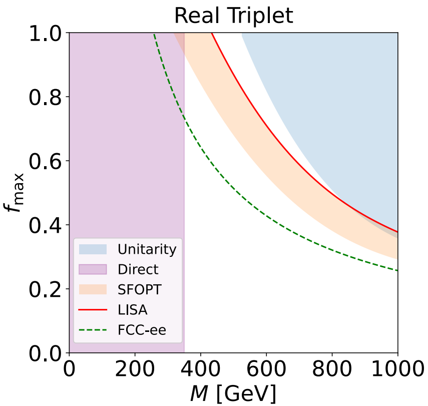
Electroweak Baryogenesis

- 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 changes the potential $V(h)$.
- During transition, bubbles of the new phase collide $\Rightarrow$ produce gravitational waves (GW).



SFOPT/GW constraints

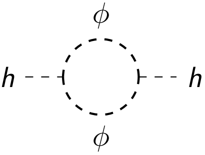
$$f = \frac{\lambda v^2}{2M^2} > 0.5 \qquad M^2 = m_{ex}^2 + \frac{1}{2}\lambda v^2$$



following (Banta 2022)

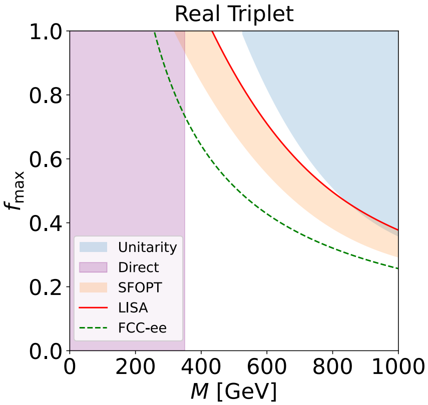
SFOPT/GW constraints

Wavefunction Renormalisation



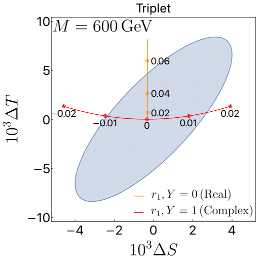
$$\delta\kappa_h = \frac{2(2j+1)}{3}\frac{1}{(4\pi)^2}\frac{M^2}{v^2}f^2$$

Projections: (Abada et.al 2019)

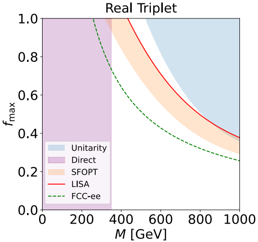


Conclusions

- FCC-ee will be sensitive to any Higgs-*Loryon* coupling.



- *Loryons* can induce a SFOPT, required for electroweak baryogenesis.
- Transition may produce a stochastic gravitational-wave background, detectable by LISA.



Backup – Effective Potential

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

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

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

Backup – SFOPT/GW conditions

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

$$S_3/T_{\rm nuc} \sim 140$$

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

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

for LISA: $\log(\beta/H_*) - 1.2\log(\alpha) \leq 8.8$

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

SFOPT/GW constraints