Standard Model Extended by a Heavy Singlet: Linear vs. Nonlinear EFT

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Motivation

The discovery of the Higgs boson together with the absence of new-physics has triggered interest in effective field theories (EFTs) at the electroweak scale.

Effective Field Theory

the basic idea...

- right degrees of freedom
- description of low-energy physics
- valid up to some cut-off

- With the right degrees of freedom, build the most general effective Lagrangian.
- ∞ terms $\rightarrow$ some ordering principle needed: power counting

Motivation

Building a bottom-up EFT for the electroweak sector involves some assumptions about the nature of the underlying dynamics

If new-physics appears at a high scale $\Lambda \gg v$ and decouples:

Standard Model Effective Field Theory or **linear EFT**

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^{n_i-4}} \mathcal{O}_i \,,$$

with n_i the canonical dimension of $\mathcal{O}_i$.

New physics effects are encoded in higher dimensional operators that enter suppressed by the appropriate power of Λ.

The EFT expansion is organized by canonical dimensions.

Motivation

If EWSB occurs due to some strong dynamics (around the scale $f \gtrsim v$) and new-physics effects in the Higgs sector do not decouple:

Electroweak Chiral Lagrangian (EWChL) or **nonlinear EFT**

The LO EWChL is non-renormalisable

$$\mathcal{L}_{\rm LO} \supset \frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle\,(1+F_U(h)) - V(h)\,,$$

where $U = \exp(2i\varphi^a T^a/v)$ is the Goldstone-boson matrix and

$$F_U(h) = \sum_{n=1}^{\infty} f_{U,n}\left(\frac{h}{v}\right)^n\,, \quad V(h) = v^4\sum_{n=2}^{\infty} f_{V,n}\left(\frac{h}{v}\right)^n$$

The EFT is organized as a loop expansion

NLO operators suppressed by $\Lambda^2 \sim (4\pi f)^2$

Motivation

Linear vs. Nonlinear EFT, a bottom-up view

- **linear EFT:** deviations from the SM in the Higgs and electroweak gauge sectors at the level of $v^2/\Lambda^2 \ll 1$.

- **nonlinear EFT:** deviations from the SM in the Higgs sector expected at the level of $v^2/f^2 \lesssim 1$ while the gauge sector is SM-like up to corrections of order $v^2/(16\pi^2 f^2) \ll 1$.

A simple UV model can be used to illustrate the systematics of these two EFTs.

Model

Consider the SM extended with a real scalar singlet

$$\mathcal{L} = (D^\mu \Phi)^\dagger (D_\mu \Phi) + \partial^\mu S \partial_\mu S - V(\Phi, S) + \mathcal{L}_{Yukawa}\,,$$

with

$$V(\Phi, S) = -\frac{\mu_1^2}{2}\Phi^\dagger\Phi - \frac{\mu_2^2}{2}S^2 + \frac{\lambda_1}{4}(\Phi^\dagger\Phi)^2 + \frac{\lambda_2}{4}S^4 + \frac{\lambda_3}{2}\Phi^\dagger\Phi S^2\,.$$

We impose a Z_2 symmetry under which $S \to -S$.

$$\Phi = \frac{v + h_1}{\sqrt{2}} U \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \qquad S = \frac{v_s + h_2}{\sqrt{2}}\,.$$

Here we write Φ in polar coordinates, U is the Goldstone-boson matrix

Model

The physical states are given by

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{bmatrix} \cos\chi & -\sin\chi \\ \sin\chi & \cos\chi \end{bmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \quad \tan(2\chi) = \frac{2\lambda_3 v v_s}{\lambda_2 v_s^2 - \lambda_1 v^2},$$

with $M_h \equiv m < M_H \equiv M$ by convention. Fixing $m = 125$ GeV, the model depends only on three combinations of parameters

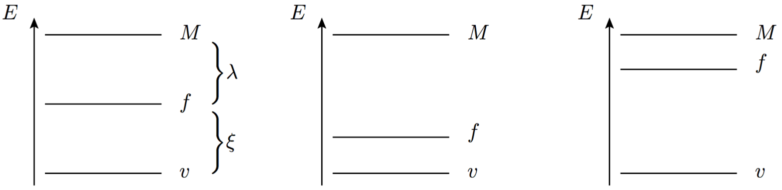
$$r \equiv \frac{m^2}{M^2}, \quad \xi \equiv \frac{v^2}{f^2}, \quad \omega \equiv \sin^2\chi, \qquad \text{with } f \equiv \sqrt{v^2 + v_s^2}.$$

We assume an approximate $SO(5)$ symmetry in the scalar sector.

In the strict $SO(5)$ symmetric limit, we have

$$\lambda_1 = \lambda_2 = \lambda_3 \equiv \lambda = 2M^2/f^2, \qquad r = 0, \qquad \omega = \xi$$

Model



(a) generic singlet model (b) nonlinear EFT (c) linear EFT

(b) strongly-coupled regime (nonlinear EFT)

$$|\lambda_i| \leq 32\pi^2, \quad m \sim v \sim f \ll M \quad \Rightarrow \quad \xi, \omega = \mathcal{O}(1)$$

(c) weakly-coupled regime (linear EFT)

$$\lambda_i = \mathcal{O}(1), \quad m \sim v \ll f \sim M \quad \Rightarrow \quad \xi, \omega \ll 1$$

Linear vs. Nonlinear EFT, a top-down view

The heavy field is integrated out at tree level by solving its equation of motion via an expansion in powers of $1/M$.

In the strongly-coupled regime the resulting EFT takes the form of the nonlinear EFT with

$$H = H_0 + \frac{H_1}{M} + \cdots\,, \qquad H_0 = H_{0,2}\left(\frac{h}{v}\right)^2 + H_{0,3}\left(\frac{h}{v}\right)^3 + \cdots$$

$$F_U(h) = 2\sqrt{1-\xi}\left(\frac{h}{v}\right) + (1-2\xi)\left(\frac{h}{v}\right)^2 - \frac{4}{3}\xi\sqrt{1-\xi}\left(\frac{h}{v}\right)^3 + \mathcal{O}(h^4)$$

$$V(h) = m^2 v^2\left[\frac{1}{2}\left(\frac{h}{v}\right)^2 + \frac{1-2\xi}{2\sqrt{1-\xi}}\left(\frac{h}{v}\right)^3 + \mathcal{O}(h^4)\right]$$

Linear vs. Nonlinear EFT, a top-down view

In the weakly-coupled limit, integrating out the heavy scalar gives rise to an EFT organized by canonical dimensions of the fields. The only dimension six operator generated is $(\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$.

$$H = H_0 + \frac{H_1}{M} + \cdots\,, \qquad\qquad H_0 = 0\,,$$

$$\mathcal{L}_{D=6} = -\frac{1}{4}\frac{\lambda_3^2}{\lambda_2 M^2}(\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$$

The resulting linear EFT can also be derived by expanding the leading order nonlinear effective Lagrangian through $\mathcal{O}(\omega,\xi)$.

Conclusions

- A simple model has been used to illustrate the systematics of the **linear and nonlinear EFTs.**
- These two EFTs possess the same degrees of freedom and symmetries, yet they are organized by **different power counting principles.**
- The toy model allows to understand the different organization principles based on the character of the underlying dynamics.
- **In the non-decoupling regime the low-energy EFT approaches the nonlinear EFT formulation organized as a loop expansion.**
- **In the decoupling regime, the low-energy EFT falls into the linear EFT paradigm and is organized via canonical dimensions.**

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