Effective Theory of Electroweak Symmetry Breaking

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INTRODUCTION

The recent discovery of a Higgs-like boson at the LHC has been one of the most important breakthroughs of the last decades in particle physics. Within uncertainties of typically 20–30%, the properties of the new particle appear so far consistent with the Standard Model. However, the Standard-Model solution for electroweak symmetry breaking is extremely fine-tuned and should be deemed unsatisfactory. More natural solutions typically call for new-physics states at the TeV scale, for which there is still no evidence at present. Their existence would induce deviations from the Standard-Model Higgs parameters, which would be of profound significance for the high-energy behaviour of the theory and, more generally, for our understanding of the dynamics of electroweak symmetry breaking.

There exists a large number of alternatives to the minimal Higgs model, which provide different dynamical explanations of electroweak symmetry breaking. From a phenomenological viewpoint it is however more efficient to test these potential deviations from the Standard Model with a broader framework. Given the large energy gap between the electroweak scale $v = 246$ GeV and the expected new physics scale $\Lambda \sim$ few TeV, this broader framework can be conveniently cast in an effective field theory (EFT) language. This EFT should provide, by construction, the most general description of the electroweak interactions in the presence of a light scalar h, and therefore provide the right framework to test its dynamical nature. The most general formulation should include the possibility of strong dynamics at the natural cut-off $\Lambda = 4\pi v$.

The starting point for such an EFT requires a parameterization of the minimal coset $SU(2)_L \times U(1)_Y/U(1)_{em}$, which can be done using a nonlinear realization (*chiral Lagrangian*). The resulting Goldstone bosons provide the longitudinal components of the gauge bosons. The new scalar h is then introduced in full generality as a singlet under $SU(2)_L \times U(1)_Y$. Such a theory is nonrenormalizable in general. A systematic approximation scheme can then be constructed based on a *loop expansion*.

This path has been pursued before, and partial sets of the resulting effective-theory operators have been listed and their phenomenological consequences explored. However, the previous papers lacked a careful discussion of the foundations of the EFT, including essential aspects in the construction of the operator basis such as power-counting arguments. The major goal of our work in the past year has been, first, to fill this gap and to put the EFT on a more systematic basis (see [1] and references therein), and second, to apply the theory to important processes in electroweak and Higgs-boson physics.

RECENT WORK

A basic achievement was the detailed discussion of the power counting for effective field theories valid at a scale v and with strong dynamics at their cut-off $\Lambda \gg v$ [2]. This counting is the key element for organizing the possible terms in the effective Lagrangian according to their order in powers of v^2/Λ^2. The basic assumptions can be stated as follows:

- The degrees of freedom at the low scale v are, in general, (chiral) fermions $\psi_{L,R}$, gauge fields A_μ and (pseudo-) Goldstone bosons φ.
- A mass gap separates the scale v from the high scale Λ, which has been integrated out in the low-energy effective theory.
- At the scale Λ (part of) the dynamics is strongly coupled, the natural cut-off is then $\Lambda = 4\pi v \gg v$.
- The Goldstone sector is strongly coupled, with couplings $\sim 4\pi$, to the strong interactions at Λ.
- Chiral fermions and gauge fields are weakly coupled to the dynamics at Λ, that is with couplings of order unity (or smaller).

Important examples for such a scenario are the chiral perturbation theory for pions and kaons in the presence of electromagnetism, or, in particular, the electroweak chiral Lagrangian with a light (pseudo-Goldstone) Higgs. In the latter case the actual cut-off may be at a scale $4\pi f$, with $f > v$. When the parameter $\xi \equiv v^2/f^2$ is taken to zero, the ordinary Standard Model is recovered. Expanded to first order in ξ, the electroweak chiral Lagrangian contains [1] the SILH framework [3]. The full chiral Lagrangian amounts to a resummation of terms to all orders in ξ, which is parametrically viewed as a quantity of order one.

We have emphasized the importance of specifying the leading-order Lagrangian consistently with the assumptions above. The leading-order Lagrangian provides the basis for the power-counting analysis of loop corrections and their divergence structure. The latter determines the required classes of counterterms, which yield the higher-order operators in the effective Lagrangian.

Previous treatments of power counting appear to have followed one of two different lines of approach, the first employing naive dimensional analysis (NDA) [4, 5], the second using the concept of chiral dimensions [6, 7, 8]. We have shown how the two methods are related. In particular, we have demonstrated how chiral dimensions follow from standard power counting and we have clarified the physical assumptions that are needed in addition to the chiral dimensions in order to construct effective Lagrangians. We have shown that chiral dimensions simply count the loop order of diagrams, and in that sense they have a topological nature. Our approach is also in agreement with the basic philosophy of NDA and shows how the simple NDA rules need to be modified in order to be fully consistent.

The power counting discussed in [1, 2] provides a general and unified framework for constructing low-energy effective theories of a strong sector. Based on this approach, the complete electroweak chiral Lagrangian, including a light Higgs, has been constructed at next-to-leading order, $\mathcal{O}(v^2/\Lambda^2)$ [1]. This Lagrangian is the most general effective description of the Standard Model containing a light scalar boson, in general with strong dynamics of electroweak symmetry breaking. The dimension-6 Lagrangian of a linearly realized Higgs sector can be recovered essentially as a special case.

The general effective field theory formulation has been applied to the phenomenology of several processes of interest: $e^+e^- \to W^+W^-$ at a linear collider [9], ZZ and γZ production [10], and nonstandard Higgs couplings from angular distributions in $h \to Z\ell^+\ell^-$ decays [11].

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Publications

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2. O. Catà, *Revisiting ZZ and γZ Production with Effective Field Theories*, arXiv:1304.1008 [hep-ph].

3. G. Buchalla, O. Catà, C. Krause, *Complete Electroweak Chiral Lagrangian with a Light Higgs at NLO*, Nucl. Phys. **B 880**, (2014), 552, [arXiv:1307.5017 [hep-ph]].

4. G. Buchalla, O. Catà, G. D'Ambrosio, *Nonstandard Higgs Couplings from Angular Distributions in $h \to Z\ell^+\ell^-$*, arXiv:1310.2574 [hep-ph], to appear in Eur. Phys. J.

5. G. Buchalla, O. Catà, C. Krause, *On the Power Counting in Effective Field Theories*, arXiv:1312.5624 [hep-ph], to appear in Phys. Lett. B

Conference Contributions

1. O. Catà, *Searches for Strong Dynamics Signals in Gauge Boson Pair Production*, PoS CD 12, (2013), 032, [arXiv:1305.2785 [hep-ph]].

2. O. Catà, *EWSB from Strongly-Coupled Dynamics: An EFT Approach and Implications for W^+W^- Production*, PoS Confinement X, (2012), 280, [arXiv:1305.5431 [hep-ph]].

3. O. Catà, *Recent Developments in Nonleptonic Kaon Decays*, PoS KAON 13, (2013), 026, [arXiv:1308.0254 [hep-ph]].

Theses

1. C. Krause, *An Effective Field Theory for Electroweak Symmetry Breaking Including a Light Higgs*, Master thesis, LMU 2013.

2. N. Schäfer, *Higgs-Boson Decays*, Bachelor thesis, LMU 2013.