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Through precision straits to next standard model heights[☆]

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ABSTRACT

After the LHC Run 1, the standard model (SM) of particle physics has been completed. Yet, despite its successes, the SM has shortcomings vis-à-vis cosmological and other observations. At the same time, while the LHC restarts for Run 2 at 13 TeV, there is presently a lack of direct evidence for new physics phenomena at the accelerator energy frontier. From this state of affairs arises the need for a consistent theoretical framework in which deviations from the SM predictions can be calculated and compared to precision measurements. Such a framework should be able to comprehensively make use of all measurements in all sectors of particle physics, including LHC Higgs measurements, past electroweak precision data, electric dipole moment, $g-2$, penguins and flavor physics, neutrino scattering, deep inelastic scattering, low-energy e^+e^- scattering, mass measurements, and any search for physics beyond the SM. By simultaneously describing all existing measurements, this framework then becomes an intermediate step, pointing us toward the next SM, and hopefully revealing the underlying symmetries. We review the role that the standard model effective field theory (SMEFT) could play in this context, as a consistent, complete, and calculable generalization of the SM in the absence of light new physics. We discuss the relationship of the SMEFT with the existing kappa-framework for Higgs boson couplings characterization and the use of pseudo-observables, that insulate experimental results from refinements due to ever-improving calculations. The LHC context, as well as that of previous and future accelerators and experiments, is also addressed.

1. The Higgs boson

During the LHC Run 1 a new resonance was discovered in 2012 [1,2]. That resonance, with a mass measured to be $125.09 \pm 0.24\,\text{GeV}$ [3], is a candidate to be the Higgs boson of the standard model (SM). The spin-0 nature of the resonance is well established [4–6], all the available studies on the couplings of the new resonance conclude it to be compatible with the Higgs boson of the SM within present precision [7,8], and, as of yet, there is no direct evidence for new physics phenomena beyond the SM (BSM).

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Inevitably, after the LHC Run 1 results comes a need for a better understanding of the current “we haven’t seen anything (yet)” theoretical *zeitgeist*. Is the SM with a 125 GeV Higgs boson the final theory, or indeed can it be? The associated problems with the SM are known and include the neutrino masses as well as cosmological evidence for dark matter.

The discovery of a scalar resonance and the absence of direct evidence for new physics forces us to change perspectives and to redefine the problem. In this review, the starting point is to assume quantum field theory (QFT) as the framework with which to study the basic constituents of matter. The parameters of QFT Lagrangians describe the dynamics, something that is at the heart of the needed change of perspective. At LEP, the dynamics were fixed by the SM Lagrangian, with the unknowns being parameters such as the Higgs mass M_{H}, the strong coupling constant $\alpha_{\mathrm{s}}(M_{\mathrm{Z}})$, etc. [9]. In other words, at LEP the SM was the hypothesis and bounds on M_{H} were derived from a comparison with high-precision data. At the LHC, after the 2012 discovery, the unknowns are deviations from the SM, given that the SM is fully specified and constrained by experimental measurements of increasing precision and accuracy. The definition of SM deviations requires a characterization of the underlying dynamics. Whereas (concrete) BSM models represent specific roads toward the Planck scale, it would be of great interest to employ a (more) model-independent approach, a framework that could describe a whole class of paths to the Planck scale.

While studies performed with limited precision may only claim the discovery of a SM-like Higgs boson, as soon as greater precision is available, it may be possible to decipher the nature of the Higgs through the accurate determination of its couplings [10–13].

Given the precision that was expected for LHC Run 1 results, it was natural to begin exploring the couplings using the (original) κ-framework [14,15]. There is no need to repeat here the main argument, of splitting and scaling different loop contributions in the amplitudes of processes mediated by Higgs bosons. The main shortcoming is that the original κ-framework is only an intuitive language that lacks internal consistency when moving beyond leading order (LO). In parallel, recent years have witnessed an increasing interest in Higgs effective Lagrangians and SM effective field theory (EFT); see in particular Refs. [11,16–42]. EFTs can be used to describe the full set of deviations from the SM and therefore a better name is certainly SMEFT, as used in Ref. [19,43–45].

It is worth noting that there is no formulation which is completely model-independent and the SMEFT, as any other approach, is based on a given set of (well-defined) assumptions. In full generality we can distinguish a top-down approach (model-dependent) and a bottom-up approach (with fewer assumptions).

The top-down approach is based on several steps. First one has to classify BSM models, possibly respecting custodial symmetry and decoupling of high mass states, then the corresponding SMEFT can be constructed, e.g. via a covariant derivative expansion [43]. Once the SMEFT is derived one can construct the corresponding SM deviations, that may be different for each BSM model or class of BSM models. In a recent example, Ref. [46] studied the adequateness of $\dim = 6$ operators to describe LHC observables for a comprehensive set of BSM models. The authors succinctly summarized their results as “Forcing the EFT approach into a spectacular breakdown was the original aim [. . .], but to our surprise this did not happen.”

The bottom-up approach starts with the determination of a basis of $\dim = 6$ (or higher) operators and proceeds directly to the classification of SM deviations, possibly respecting the analytic structure of the SM amplitudes. The synthesis is that $\dim = 6$ operators are supposed to arise from a local Lagrangian, containing heavy degrees of freedom decoupled from the presently-probed energy scales. Of course, the correspondence between Lagrangians and effective operators is not bijective because different Lagrangians can give rise to the same operator. For recent developments on the classification of SMET operators with $\dim > 6$, see Refs. [47,48].

The change of perspective after the LHC Run 1 is equivalent to saying that we have moved from a fully predictive (SM) phase to a “partially predictive (fitting)” one. The predictive phase is defined as follows: in any (strictly) renormalizable theory with n parameters we need to match n data points, and the $(n+1)$th calculation is a prediction, e.g. as can be done in the SM. In the fitting (partially predictive) phase there will be $(N_6 + N_8 + \cdots = \infty)$ renormalized Wilson coefficients to be fitted, e.g. by measuring the SM deformations due to a single $\mathcal{O}^{(6)}$ insertion. This represents a departure from the use of a strictly renormalizable theory, with the compromise of gaining, order-by-order, the ability to explore deviations that can only be constrained by fitting to data. As the number of parameters increases it becomes inevitable that only combinations of the parameters can be constrained.

There is a conceptual difference between Higgs physics at the LHC, for which the UV completion is unknown, and other scenarios where EFT techniques are applied and for which there are known UV completions. When the UV completion is known, we consider a theory with both light and heavy particles; the Lagrangian is $\mathcal{L}(m)$ where m is the mass of the heavy degree of freedom. Next, we introduce the corresponding $\mathcal{L}_{\mathrm{eff}}$, the effective theory valid up to a scale $\Lambda = m$. We renormalize the two theories, say in the $\overline{\mathrm{MS}}$-scheme, taking care that loop-integration and heavy limit are operations that do not commute, and impose matching conditions among renormalized “light” one-particle irreducible (1PI) Green’s functions.

When we compare the present situation with the past an analogy can be drawn. Consider the QED Lagrangian and complement it with $\dim = 6$ Fermi operators $\overline{\mathrm{e}}_{\mathrm{L}}\,\gamma^{\mu}\,\mathrm{e}_{\mathrm{L}}\,\overline{\mathrm{e}}_{\mathrm{L}}\,\gamma_{\mu}\,\mathrm{e}_{\mathrm{L}}$, etc. This EFT can be used to study the muon decay but also $\nu_{\mathrm{e}}(\nu_{\mu})\mathrm{e}$ scattering in the approximation of zero momentum transfer. Using data on $\sigma_{\overline{\nu}_{\mathrm{l}}\mathrm{e}}/\sigma_{\nu_{\mathrm{l}}\mathrm{e}}$, one can derive predictions for the Z couplings [49], e.g. for the ratio $g^{\mathrm{e}}_{\mathrm{V}}/g^{\mathrm{e}}_{\mathrm{A}}$. In principle, one could have realized the possibility of having neutral currents. Understanding that the Yang–Mills theory could match this EFT at very low energy scales took longer [50], and pretending to use this theory to describe the Z-lineshape is not feasible as the Z boson mass is beyond the validity of this EFT.

One could ask: would there be a way to take the Fermi theory and show how this theory would have pointed to massive vector bosons? The answer is yes, due to unitarity violations at large energies (pure S-wave unitarity); for instance, with