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Rafael Delgado López

Study of the Electroweak Symmetry Breaking Sector for the LHC

Doctoral Thesis accepted by
the Complutense University of Madrid, Spain

Springer

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Supervisor's Foreword

The Electroweak Symmetry Breaking Sector (EWSBS) of the Standard Model (SM) is one of the major problems of our time and reinforcing its foundations is a very active field of scholarly work. Reconciling the concept of massive gauge bosons (induced from the weakness of beta decay that explains, for example, the long 30-yr life of dangerous nuclear waste such as ^{90}Sr or ^{137}Cs) with the electroweak gauge symmetry (induced from the flavor structure of weak decays) requires a Higgs-like mechanism. The resulting electroweak SM, that Dr. Delgado quickly recalls in Chap. 1 of this dissertation, has a spectrum which is now complete with the finding of the predicted Higgs boson, and might soon be a closed chapter in the quest for understanding of the physical world. Indeed, alternative theories and extensions are severely constrained by

- *LEP precision observables* that test the electroweak sector (W, Z, h) through loop corrections.
- *Quark-flavor observables, especially at the B-factories* that test the Yukawa and Cabibbo-Kobayashi-Maskawa sector coupling the Higgs to the SM fermions.
- *Low-energy experiments* such as the (null) searches for an electron or a neutron electric dipole moments, the agreement of the SM and the muon magnetic moment, etc. that constrain the existence of new particles and new sources of CP violation.
- And in the last years, *direct production of the Higgs boson at the LHC* that allows direct tree-level tests of the SM couplings in the electroweak sector.

Yet the SM is not entirely satisfactory. First, it needs well over 20 independent parameters (how many precisely, depends on how we count certain ones that seem to vanish such as the strong CP phase); this does not appear to be a very economic description. The balance of these parameters is in the Yukawa sector coupling the fermions to the Higgs boson, and thus, more detailed studies thereof are warranted. Second, there is ample consensus in the field of cosmology (and also in galactic astrophysics) that a modification of known physics, perhaps in the form of "Dark Matter" is necessary to understand various observables. A viable alternative happens to be provided by hypothetical *Weakly Interacting Massive Particles* whose mass and couplings are compatible with their existence at the electroweak scale ($\sim$TeV), so that the spectrum would be richer than in the minimum SM. Third, the SM also features a fundamental scalar boson, the Higgs, whose mass is sensitive to higher scales. But there are reasons to believe that there may be physics at energies yet higher than the electroweak sector: the seesaw explanation of neutrino masses, the convergence of running coupling constants, inflation, dark matter and generally gravity, all point out to unknown phenomena above our current energy reach. This scale "hierarchy problem" (why is the electroweak scale so much smaller than those other ones?) has motivated much of the research in particle physics for three decades. Yet, not knowing what, if any, new physics there is, it makes sense to adopt the tools of Effective Field Theory (EFT) for the particles that are known to be in the spectrum. Rafael dedicates Chaps. 2 and 3 of the dissertation to formulating the appropriate theory and reporting the computation of scattering amplitudes of the electroweak sector with it.

Unlike what has been dubbed SMEFT, that is an extension of the SM where the Higgs is a scalar particle remaining from an SU(2) complex doublet, Rafael has, upon our advice, adopted the more general approach of HEFT (Higgs-sector EFT), where the new Higgs-like scalar particle is coupled to the longitudinal gauge bosons and other particles without prior prejudice as to its belonging to a specific multiplet. We believe that this is the more general EFT approach that should be pursued.

If and when deviations from the SM are found in the HEFT parameters, by precision measurements carried out at the LHC, one will need tools to exploit that small separation from the SM to enlighten us about higher energy physics. Now, the SM is a carefully tuned theory, renormalizable and perturbatively computable; but any separations from it have a large chance (in the sense of overwhelming parameter-space volume) of turning the theory into a strongly coupled one. Perturbation theory will then be in question.

If that new physics appears at a scale f, then the EFT has a nominal range of validity $4\pi f$. But if resonances appear in that energy range, the EFT fails earlier at much lower energy. It is known since the work of Mandelstam, Truong, etc. in pion physics, and even earlier from the effective range expansion in nuclear physics dating back to Bethe and Schwinger, that the key to a successful description of data even at low energies is respecting unitarity. The methods that extend perturbation theory to comply with this very basic theory requirement are developed in Chap. 4 of this dissertation.

The resulting unitarized formulae can be used to predict new resonances after experiment provides the values of the low-energy constants of the HEFT deviating from the SM. The logic of the whole procedure is represented in the flow-chart of Fig. 1.

Without having actual separations from the SM at hand, as all current observations at the LHC are compatible with it, the present effort (middle column of the chart) should loop between more accurate measurements, further constraining the HEFT parameters, and improved theoretical computations. Chap. 5 of this dissertation provides an orientation on the current status of these parameters.

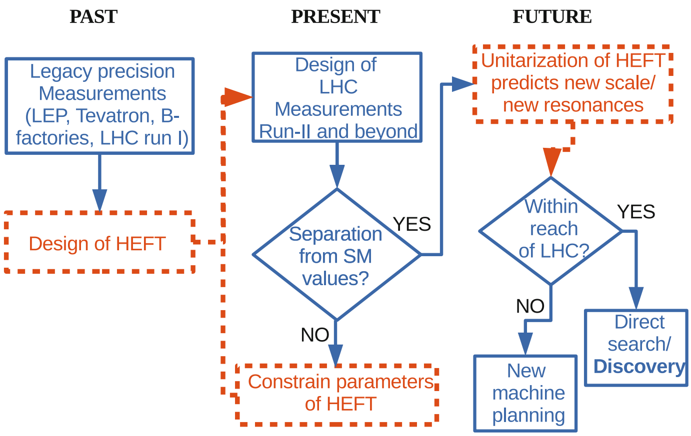

Fig. 1 This flow chart shows the discovery logic of Unitarized Effective Field Theory. The solid-delineated boxes (*blue online*) show necessary experimental effort. The *dashed-lined boxes* are the theory needed. While the formulation of the HEFT Lagrangian has already been reported in the literature, the computation of amplitudes thereof so that its parameters can be constrained, and their unitarization so that any new resonances can be parametrized, are not so widely known and have been the objects of study in this thesis

There is also space in the thesis to assess the coupling of the EWSBS to other particle pairs that interact sufficiently to it (top-antitop pairs, the fermions that have largest Yukawa matrix elements) or offer very clean reconstruction of initial and final states (photons). We hope to expand on the phenomenological applications of these in work that is soon to appear.

In summary, the thesis is a well rounded-off assessment of the Electroweak sector of the standard model in the event that new physics, generally strongly coupled, surfaces at the LHC or elsewhere, and in that case it provides amplitudes, both in perturbation theory and in several unitarization formalisms, that will be much needed.

We encourage you to browse through its pages and profit from the very detailed exposition that guides the reader from first principles to results and helps him by providing many intermediate steps of all computations.

Madrid, Spain
March 2017

Antonio Dobado
Felipe J. Llanes-Estrada

Abstract

In this dissertation, a strongly interacting Electroweak Symmetry Breaking Sector is considered. We use the framework of Effective Field Theories (EFT) and unitarization procedures, successfully deployed to study resonances in low energy QCD in the last decades. The EFT amplitudes are computed at the Next to Leading order (NLO).

If new resonances were discovered at the LHC run-II, different theoretical approaches could be used to study them. However, the framework that we follow here has several advantages. For instance, it only contains a few parameters. Seven in the case of scattering within the Electroweak Symmetry Breaking Sector ($W_L^{\pm}$, Z_L and h); a few more if the $\gamma\gamma$ and $t\bar{t}$ states are included. And, even more important, the masses and widths of the resonances emerge as a consequence of the low-energy behaviour of the theory. They are not free parameters of the model, we will derive them from the Lagrangian.

The EFTs for longitudinal gauge bosons plus Higgs are being actively investigated, because of their direct application to the experimental program of the LHC run-II. However, they are frequently considered only as a useful parameterization of slight deviations from the Standard Model behaviour. In other cases, they are extended to implement new resonances in an explicit way. Our approach shares with these models the use of an EFT in the very first steps, as well as the experimental bounds over the parameters of the Effective Lagrangian.

If we used only the EFT, the perturbative expansion would break down because it is derivative. But in our work below, the EFT is efficiently extended to cover the regime of saturation of unitarity. This is achieved by dispersion relations, whose subtraction constants and left cut contribution can be approximately obtained in different ways giving rise to different unitarization procedures.

Several unitarization procedures have been considered. We have studied three of them in finer detail, since they have the best properties. These chosen methods are the Inverse Amplitude Method, one version of the N/D method and another improved version of the K-matrix. An extended version of the first two is used for the coupling with $\gamma\gamma$ and $t\bar{t}$. In all the cases we get partial waves which are unitary, analytical with the proper left and right cuts and in some cases poles in the second Riemann sheet that can be understood as dynamically generated resonances. A new numerical method has been developed in order to look for such poles.

We also point out that the unitarization formalisms are also extendable to coupled channels. This is a novelty, and implies the possibility that a hypothetical resonance comes from a strongly process like $VV \to hh \to VV$ (V stands for a longitudinal gauge boson). Such a resonance would be triggered by the coupling $VVhh$ (parameter b of the EFT), which is less constrained that the coupling VVh (parameter a).

Finally, all this work is given in a form that it could be implemented in a Monte Carlo (MC) simulation program, in order to generate MC events for the LHC Run-II or future collider experiments.

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First of all, I would like to acknowledge the contributions of my Ph.D. supervisors, Profs. Antonio Dobado and Felipe J. Llanes-Estrada, to this work. I also acknowledge my coauthors Juan José Sanz Cillero and Maria José Herrero Solans, with whom I published the $\gamma\gamma$ computation, and who gave me very useful comments and advice while I was writing this thesis. And our collaborator Andrés Fernando Castillo, a Ph.D. student from Bogotá who visited us to collaborate on the $\omega\omega$, $hh \to t\bar{t}$ scattering.

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I have also worked with Prof. Domènec Espriu, with whom I published a congress contribution. Moreover, his group at Barcelona made an independent study of the a_4-a_5 parameter space of the $\omega\omega \to \omega\omega$ computation, which is an interesting check of part of this work, and they provided me in full detail.

I also would like to thank Prof. Thomas Hahn and the Theoretical Physics Division group at the Max-Planck-Institute for Physics (Werner-Heisenberg-Institute, Germany), who kindly welcomed me during a stay there. Prof. Thomas Hahn taught me the deep details of the programs FeynArts and FormCalc, which he develops actively and that I use for this thesis, and gave me good advice.

I also remember Prof. Stefano Moretti, who supervised me during my earlier stay at the SHEP group in the University of Southampton (UK). He introduced me to the usage of the Monte Carlo tool MadGraph. The graphs where I compare, for the Standard Model and at leading order, the Equivalence Theorem computations versus the exact ones has been obtained in collaboration with Prof. Stefano Moretti. As a host Ph.D. student in the SHEP group, I was allowed to use the facilities of both the NExT Institute and the South East Physics Network (SEPnet). As a result of this, I followed some Ph.D. lectures from the institutions which participate in the NExT Ph.D. School. Furthermore, I was allowed to contribute to both the NExT Meeting at Sussex and the UK HEP Forum 2014 “Future Collider” (STFC, Abingdon, Oxford).

As part of my Master and Ph.D. program, I collaborated with Profs. Fernando Sols Lucia, Pedro Bargueño de Retes and José Alberto Ruiz Cembranos. These collaborations are not directly related to the EWSBS. However, the collaboration with José Alberto Ruiz Cembranos is centered on the phenomenological study of BSM models at the LHC, and it helped me gain many computational skills.

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