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Nuclear and Particle Physics Proceedings 270–272 (2016) 237–241

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# Heavy Resonances in the Electroweak Effective Lagrangian*

J. Santos[a,1], A. Pich[a], I. Rosell[b], J.J. Sanz-Cillero[c]

[a] *Departament de Física Teòrica, IFIC, Universitat de València - CSIC, Apt. Correus 22085, 46071, Valencia, Spain*
[b] *Departamento de Ciencias Físicas, Matemáticas y de la Computación, Universidad CEU Cardenal Herrera c/ Sant Bartomeu 55, 46115 Alfara del Patriarca, Valencia, Spain*
[c] *Departamento de Física Teórica and Instituto de Física Teórica, IFT-UAM/CSIC Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain*

## Abstract

As a first step towards the construction of a general electroweak effective Lagrangian incorporating heavy states, we present here a simplified version where only vector and axial-vector spin-1 triplets are involved. We adopt an effective field theory formalism, implementing the electroweak chiral symmetry breaking $SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$, which couples the heavy states to the SM fields. At low energies, the heavy degrees of freedom are integrated out from the action and their effects are hidden in the low-energy couplings of the Electroweak Effective Theory, which can be tested experimentally. Short-distance constraints are also implemented, requiring a proper behaviour in the high-energy regime. We analyze the phenomenological constraints from the oblique parameters $S$ and $T$, at the next-to-leading order. Our results show that present data allow for strongly-coupled scenarios with massive bosons above the TeV scale.

*Keywords:* Higgs Physics, BEH Physics, Beyond Standard Model, Composite Models, Electroweak Resonances

## 1. Introduction

The LHC found a Higgs boson with the properties predicted by the Standard Model (SM). This discovery has completed the last piece of the puzzle, confirming the SM paradigm in particle physics. At the moment, there is no clear evidence of new physics below the TeV scale and the possibility of an energy gap gains importance. For this reason, effective field theories turn out to be a proper approach to search for new physics. The information on the high-energy degrees of freedom stays in the Low-Energy Constants (LECs) of the effective theory and they can be tested experimentally.

The Electroweak Effective Theory (EWET) provides a powerful framework to study many of the open questions which remain unanswered within the SM. In this direction, one obvious next step consists in adding new heavier states to the effective theory and investigate their possible signals at low energies.

In this article we study a simplified scenario with massive spin-1 triplets interacting with the bosonic sector of the electroweak theory. A more complete analysis can be found in [1, 2]. In section 2 we build the corresponding effective description which is then matched to the low-energy EWET in section 3, and hence the LECs are determined. Another kind of conditions come from the ultraviolet (UV) completion of the effective theory. Thus, in section 4 some high-energy constraints must be imposed so that the theory is well-behaved. Phenomenology is analyzed in section 5, where the oblique parameters $S$ and $T$ become a key factor in order to set bounds on the Resonance Theory parameters. Finally, some brief conclusions are given in section 6.

*Talk given at 18th International Conference in Quantum Chromodynamics (QCD 15, 30th anniversary), 29 June - 3 July 2015, Montpellier - FR

*Email addresses:* Joaquin.Santos@ific.uv.es (J. Santos), pich@ific.uv.es (A. Pich), rosell@uch.ceu.es (I. Rosell), juanj.sanz@uam.es (J.J. Sanz-Cillero)

[1] Speaker.

http://dx.doi.org/10.1016/j.nuclphysbps.2016.02.047
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## 2. Building the Resonance Theory

We call Resonance Theory to the effective field theory description which includes the SM particle content plus the additional massive states. We assume the SM pattern of Electroweak Symmetry Breaking (EWSB), so the theory is symmetric under $G \equiv SU(2)_L \times SU(2)_R$ and gets spontaneously broken to the custodial subgroup $H \equiv SU(2)_{L+R}$. In this article, we perform a simplified analysis of the resonance theory:

- Only the bosonic sector is studied. We consider the SM gauge bosons, the electroweak Goldstone bosons $\varphi^a$ and one Higgs-like scalar field $h$, with mass $m_h = 125$ GeV, which is singlet under $H$.
- The resonance content is reduced to one vector and one axial-vector triplets, $V_{\mu\nu}$ and $A_{\mu\nu}$. We will use the antisymmetric formalism to describe these spin-1 fields [3–5].
- We assume that parity is a good symmetry of the strongly-coupled underlying theory.

According to these considerations, the lowest-order (LO) resonance interaction Lagrangian is

$$\begin{aligned}\mathscr{L} &= \frac{v^2}{4}\langle u_\mu u^\mu \rangle \left(1 + \frac{2\kappa_W}{v} h\right) + \frac{F_A}{2\sqrt{2}}\langle A_{\mu\nu} f_-^{\mu\nu}\rangle \\ &+ \frac{F_V}{2\sqrt{2}}\langle V_{\mu\nu} f_+^{\mu\nu}\rangle + \frac{iG_V}{2\sqrt{2}}\langle V_{\mu\nu}[u^\mu, u^\nu]\rangle \\ &+ \sqrt{2}\,\lambda_1^{hA}\,\partial_\mu h \langle A^{\mu\nu} u_\nu \rangle ,\end{aligned} \tag{1}$$

where the brackets stand for the SU(2) trace, and $u_\mu$, $f_{\pm\,\mu\nu}$ are chiral building blocks that involve Goldstone and gauge bosons, in agreement with the notation of Refs. [6, 7]. The constant $\kappa_W$ measures the deviation from the SM in the Higgs coupling to the electroweak Goldstones. A more complete analysis of the Resonance Theory, including the fermion sector, can be found in Ref. [1].

## 3. Constraining the EWET: Determination of the LECs

The EWET is the low-energy effective field theory with the same pattern of EWSB, but with only the SM particle content. It can be obtained from the underlying Resonance Theory by integrating out the heavy fields from the action. The information on the high-energy degrees of freedom (the resonances) is encoded in the free parameters of the theory, the so-called LECs.

In order to estimate these parameters, we calculate the solution of the resonance equations of motion at LO in the momentum expansion, *i.e.*, chiral $O(p^2)$. Replacing the resonance fields in Eq. (1) by these solutions, we obtain an $O(p^4)$ EWET Lagrangian. As an example, we provide the resulting subset of low-energy operators for the parity even, purely bosonic sector without Higgs fields (the Longhitano's Lagrangian [8]):

$$\begin{aligned}\mathscr{L} \supset\ & \frac{1}{4}\,a_1 \langle f_+^{\mu\nu} f_{+\mu\nu} - f_-^{\mu\nu} f_{-\mu\nu}\rangle \\ &+ \frac{i}{2}(a_2 - a_3)\langle f_+^{\mu\nu}[u_\mu, u_\nu]\rangle \\ &+ a_4 \langle u_\mu u_\nu\rangle\langle u^\mu u^\nu\rangle + a_5 \langle u_\mu u^\mu\rangle^2 \\ &+ \frac{1}{2} H_1 \langle f_+^{\mu\nu} f_{+\mu\nu} + f_-^{\mu\nu} f_{-\mu\nu}\rangle .\end{aligned} \tag{2}$$

Once the resonances are integrated out, we obtain the following estimation for these LECs:

$$\begin{aligned} a_1 &= -\frac{F_V^2}{4M_V^2} + \frac{F_A^2}{4M_A^2}, \\ a_2 - a_3 &= -\frac{F_V G_V}{2M_V^2}, \\ a_4 &= -a_5 = \frac{G_V^2}{4M_V^2}, \\ H_1 &= -\frac{F_V^2}{8M_V^2} - \frac{F_A^2}{8M_A^2}. \end{aligned} \tag{3}$$

The adopted procedure is completely analogous to the one developed in QCD to perform the matching between Chiral Perturbation Theory [9–12] and Resonance Chiral Theory [3–5, 13].

## 4. High-energy constraints

Although the true fundamental electroweak theory remains still unknown, we can use the Resonance Theory as an effective framework which allows us to interpolate between the low-energy EWET description of Green functions and its assumed UV behaviour. We can then impose some properties that well-behaved high-energy theories must satisfy. As a consequence, new constrains arise.

### 4.1. Form factors

If we consider the interaction Lagrangian in Eq. (1) and we calculate the two Goldstone boson vector form factor we obtain [3, 4]:

$$\begin{aligned}\langle \varphi^+(p_1)\,\varphi^-(p_2)|\, J_V^\mu \,|0\rangle &= (p_1 - p_2)^\mu\, F_{\varphi\varphi}^V(s), \\ F_{\varphi\varphi}^V(s) &= 1 + \frac{F_V G_V}{v^2}\,\frac{s}{M_V^2 - s}.\end{aligned} \tag{4}$$

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