Physics Letters B 724 (2013) 259–263

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Effective field theory of precision electroweak physics at one loop

Harrison Mebane [a,*], Nicolas Greiner [a,b], Cen Zhang [a,c], Scott Willenbrock [a]

[a] Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, IL 61801, United States
[b] Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
[c] Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium

ARTICLE INFO

Article history:
Received 8 April 2013
Received in revised form 6 June 2013
Accepted 8 June 2013
Available online 11 June 2013
Editor: B. Grinstein

ABSTRACT

The one loop effects of two dimension-six operators on gauge boson self-energies are computed within an effective field theory framework. These self-energies are translated into effects on precision electroweak observables, and bounds are obtained on the operator coefficients. The effective field theory framework allows for the divergences that arise in the loop calculations to be properly handled, and for unambiguous bounds on the coefficients to be obtained. We find that the coefficients are only weakly bounded, in contrast to previous calculations that obtained much stronger bounds. We argue that the results of these previous calculations are specious.

In addition to searching for direct evidence of new physics, data can be probed for the indirect effects of new heavy particles. The most general, model-independent framework for considering the indirect effects of new physics is effective field theory [1–3]. The new physics is parameterized by effective operators not present in the Standard Model. The power of effective field theory is particularly on display when dealing with one-loop calculations. The effective field theory framework provides a systematic means to deal with the divergences that arise in loop calculations, yielding a finite and unambiguous result.

In this Letter, we continue an analysis begun in Refs. [4–6] on the loop-level effects of effective operators on precision electroweak observables. Those papers focused on the divergent portions of the loop diagrams and a subset of the finite parts, and did not appreciate that unambiguous bounds could be obtained on the coefficients of the effective operators.[1] We use the full (finite plus divergent) expressions in order to obtain unambiguous bounds on a particular pair of effective operator coefficients. These calculations involve only weak boson self-energies, also called oblique corrections. Methods for organizing and applying such corrections to observables are well known [8,9] and will be used throughout the analysis.

Because we are dealing with loops of gauge or Higgs bosons, which are not significantly heavier than the W mass, the S, T, U, parametrization of Ref. [9] may not be accurate. This is in contrast to an analysis of top-quark loops in which the S, T, U, parameters are useful due to the large mass of the top quark [10]. Here we instead use the "star" formalism of Ref. [8], as in Ref. [11] which involves both top and bottom loops.

When used to extend the Standard Model, a general effective field theory can be written in the form

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots \tag{1}$$

where the c_i are dimensionless coefficients, Λ is the energy scale of new physics, and the $\mathcal{O}_i$ are effective operators with mass dimension six. We have not included a dimension-five term in the above expression because there is only one such operator, and it does not involve weak bosons [12].

In the basis of Ref. [6], there are nine dimension-six operators involving only weak bosons and/or Higgs doublets that affect precision electroweak measurements at tree or one-loop level. Four of these operators affect weak boson self-energies at tree level. Of the remaining five, three affect triple gauge couplings and can be bounded at tree level from weak boson pair production at high-energy colliders. This Letter will focus on the remaining two operators,

$$\begin{aligned}\mathcal{O}_{WW} &= \phi^\dagger \hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\phi,\\ \mathcal{O}_{BB} &= \phi^\dagger \hat{B}^{\mu\nu}\hat{B}_{\mu\nu}\phi\end{aligned} \tag{2}$$

where $\hat{B}_{\mu\nu} = \frac{ig'}{2}B_{\mu\nu}$, $\hat{W}_{\mu\nu} = ig\frac{\sigma^a}{2}W^a_{\mu\nu}$ (σ^a are the Pauli matrices), and ϕ is the Standard Model Higgs doublet.

The above two operators affect precision electroweak observables only through oblique corrections. When the Higgs field takes

* Corresponding author.
E-mail address: mebane1@illinois.edu (H. Mebane).

[1] A similar calculation, with the same shortcomings, is performed for a model with no Higgs field in Ref. [7].

0370-2693/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physletb.2013.06.021

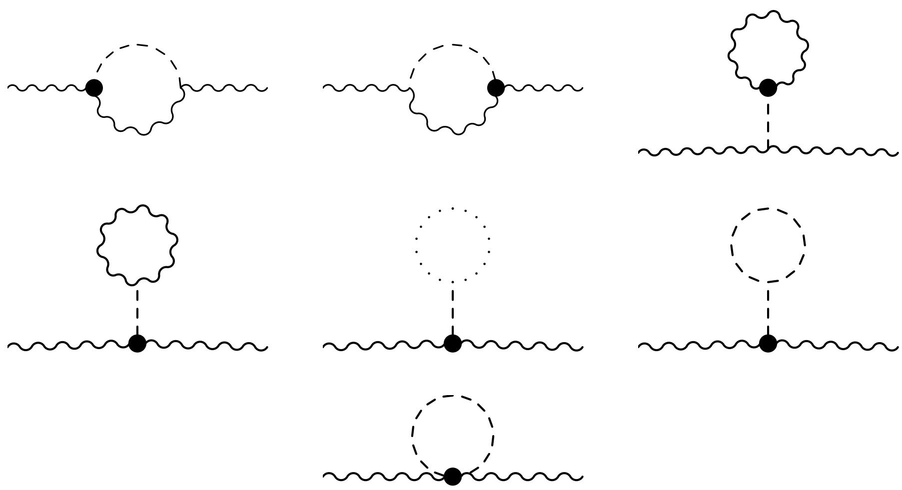

Fig. 1. Loop-level contributions of the operators $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$. Wavy lines represent gauge bosons, dashed lines represent Higgs or Goldstone bosons, dotted lines represent ghost fields, and the black dots represent effective operator interactions.

its vacuum expectation value, both operators appear to affect the weak boson self-energies at tree level; however, because the operators have the same form as the Standard Model gauge kinetic terms, all corrections generated by these operators that involve only gauge bosons can be absorbed into the Standard Model through field and coupling redefinitions. Thus, the only observable corrections from these operators arise from effective interactions involving gauge bosons and at least one Higgs boson or Goldstone boson. For this reason, these operators cannot be bounded from processes involving only vector bosons.

Explicitly, the new interactions generated by the operators $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$ that contribute at the one-loop level are

$$\begin{aligned}\mathcal{L}_{eff} = \mathcal{L}_{SM} &- \frac{c_{WW}}{\Lambda^2}\frac{g^2}{8}\big(2W^+_{\mu\nu}W^{-\mu\nu} + c^2 Z_{\mu\nu}Z^{\mu\nu} \\ &+ s^2 A_{\mu\nu}A^{\mu\nu} + 2sc A_{\mu\nu}Z^{\mu\nu}\big) \\ &\times \big(2\phi^+\phi^- + 2vH + HH + \phi^0\phi^0\big) \\ &- \frac{c_{BB}}{\Lambda^2}\frac{g'^2}{8}\big(s^2 Z_{\mu\nu}Z^{\mu\nu} + c^2 A_{\mu\nu}A^{\mu\nu} - 2sc A_{\mu\nu}Z^{\mu\nu}\big) \\ &\times \big(2\phi^+\phi^- + 2vH + HH + \phi^0\phi^0\big). \end{aligned} \tag{3}$$

These interactions induce several contributions to the gauge boson self-energies at the one-loop level. The general structure of the relevant diagrams appears in Fig. 1, and the explicit self-energies can be found in Appendix A.

The self-energies contain divergences that must be eliminated in order to arrive at meaningful results. Because of the gauge-invariant structure of the effective field theory, divergences arising from operators of a given dimension can always be absorbed by some other operator of the same dimension. As shown in Ref. [6], the operator

$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}^{\mu\nu}\hat{W}_{\mu\nu}\phi \tag{4}$$

contributes to gauge boson self-energies at tree level and is able to absorb all oblique divergences arising from the operators $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$. Thus the operator $\mathcal{O}_{BW}$ must be included in our analysis. An analogous situation arises for top-quark loops [10].

Electroweak boson self-energies contribute to precision electroweak data through corrections to the input variables α, m_Z, and s^2. The correction to α depends upon the type of vertex; these corrections will be labeled $\delta\alpha_\gamma$, $\delta\alpha_Z$, or $\delta\alpha_W$, depending on the mediating boson. The self-energy between bosons X and Y is denoted Π_{XY} in the expressions below:

$$\alpha + \delta\alpha_\gamma = \alpha\big(1 + \Pi'_{\gamma\gamma}(q^2) - \Pi'_{\gamma\gamma}(0)\big), \tag{5}$$

$$\begin{aligned}\alpha + \delta\alpha_Z = {}&\alpha\big(1 + \Pi'_{\gamma\gamma}(q^2) - \Pi'_{\gamma\gamma}(0)\big) \\ &\times \bigg(1 + \frac{d}{dq^2}\Pi_{ZZ}(m_Z^2) - \Pi'_{\gamma\gamma}(q^2) \\ &- \frac{c^2 - s^2}{cs}\Pi'_{\gamma Z}(q^2)\bigg),\end{aligned} \tag{6}$$

$$\begin{aligned}\alpha + \delta\alpha_W = {}&\alpha\big(1 + \Pi'_{\gamma\gamma}(q^2) - \Pi'_{\gamma\gamma}(0)\big) \\ &\times \bigg(1 + \frac{d}{dq^2}\Pi_{WW}(m_W^2) - \Pi'_{\gamma\gamma}(q^2) - \frac{c}{s}\Pi'_{\gamma Z}(q^2)\bigg),\end{aligned} \tag{7}$$

$$\begin{aligned}m_Z^2 + \delta m_Z^2 = {}&m_Z^2 - \Pi_{ZZ}(m_Z^2) + \Pi_{ZZ}(q^2) \\ &- (q^2 - m_Z^2)\frac{d}{dq^2}\Pi_{ZZ}(m_Z^2),\end{aligned} \tag{8}$$

$$\begin{aligned}s^2 + \delta s^2 = s^2\bigg[&1 - \frac{c}{s}\Pi'_{\gamma Z} - \frac{c^2}{c^2 - s^2}\bigg(\Pi'_{\gamma\gamma}(0) + \frac{1}{m_W^2}\Pi_{WW}(0) \\ &- \frac{1}{m_Z^2}\Pi_{ZZ}(m_Z^2)\bigg)\bigg]\end{aligned} \tag{9}$$

where $\Pi'_{XY}(q^2) = (\Pi_{XY}(q^2) - \Pi_{XY}(0))/q^2$. Explicit expressions for the self-energies are given in Appendix A.

The correction to any electroweak observable X measured at an energy at or above the Z-pole is given by

$$\delta X = \frac{\delta X}{\delta\alpha}\delta\alpha + \frac{\delta X}{\delta m_Z^2}\delta m_Z^2 + \frac{\delta X}{\delta s^2}\delta s^2. \tag{10}$$

In contrast, low-energy observables are affected by corrections to s^2 and by changes to the ρ parameter

$$\delta X = \frac{\delta X}{\delta s^2}\delta s^2 + \frac{\delta X}{\delta\rho}\delta\rho \tag{11}$$

where $\delta\rho = \frac{1}{m_W^2}\Pi_{WW}(0) - \frac{1}{m_Z^2}\Pi_{ZZ}(0)$ and the Standard Model value of ρ is unity.

In our calculations, we used the following values for input parameters: