The meaning of anomalous couplings

J. Wudka*

Department of Physics

University of California at Riverside

Riverside, California 92521–0413; U.S.A.

ABSTRACT

A prescription is presented for the interpretation of the coefficients in an effective lagrangian in terms of physical mass scales.

⋆ jose.wudka@ucr.edu

1. Introduction

During the last 15 years many papers have appeared which attempt to describe physics beyond the Standard Model in a model independent way using effective lagrangians [1]. Many of these papers present scenarios where enormous deviations from the Standard Model [2] are obtained. Given these situations one might reasonably ask whether there is *any* model that could generate such striking deviations, and, even in case where no such deviations are observed, what constraints on the underlying theory can be inferred from the experimental limits.

In this short note I want to describe how one can answer these questions. Since we have not observed yet any clear deviation from the Standard Model, the constraints on new physics are not completely unambiguous. Yet there are several statements that can be made irrespective of the kind of new physics which awaits us. The aim is to provide a sound recipe for extracting limits on the scale of new physics from the experimental bounds on the deviations from the Standard Model.

I will first motivate the results using electroweak physics as an example. Then I will discuss weakly and strongly interacting heavy physics concentrating on the interesting case of the vector-boson interactions.

Most of the contents in this paper have appeared in various publications; my purpose is to present a summary of the results.

2. Electroweak interactions as an example

When considering the low-energy limit of a given theory one has (inevitably) to deal with effective interactions produced by virtual heavy physics effects [1]. Thus, when we consider the low-energy limit of the electroweak sector [3] of the Standard Model, one obtains Fermi's theory of the weak interactions. QED for all light fermions is also generated, together with a host of other interactions such as those describing the weak contributions to the fermion's anomalous magnetic moments, the W and heavy quark contributions to the Euler-Heisenberg lagrangian, etc.

All these non-renormalizable interactions come with dimensional coefficients. For example, the term describing the weak contributions to the anomalous magnetic moment of the muon,

$$\bar{\mu}\sigma^{\alpha\beta}\mu\, F_{\alpha\beta}, \tag{2.1}$$

has dimension five and will appear multiplied by a constant of mass dimension -1. The four-fermion operators describing low-energy electroweak physics have dimension six and appear multiplied by a constant of mass dimension -2, etc.

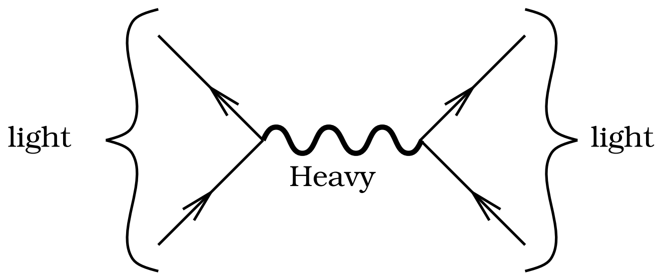
When considering a specific theory such as the Standard Model all these dimensional coefficients can be calculated in terms of the gauge coupling constants, the W and Z masses, etc. Such interactions inherit the symmetries of the Standard Model; not all possible Lorentz invariant terms occur.

With the benefit of hindsight, we may reinterpret the history of the Standard Model: when we were ignorant about the details of the electroweak theory what we did was write down the most general set of operators which

(i) Contained light fields (eg. leptons).

(ii) Respected the QED gauge symmetry (but not necessarily its global symmetries such as P and C!)

Such operators appeared multiplied by unknown coefficients which were constrained by the data. In this way we realized that the charged-current couplings were of the V–A type and not something else. We were also able to get an idea of the order of magnitude of the scale of the new physics, and for this we used the fact that the four-fermion operators could be generated by some heavy particle through a process such as the one in the figure below.



From such ideas we concluded that the coefficient of the four-fermion interactions would be of the form

$$\left(\frac{\text{coupling constant}}{\text{heavy mass}}\right)^2 . \tag{2.2}$$

If we assume that the theory underlying the weak interactions is weakly coupled, so that (coupling constant) $\lesssim 1$, we could get an estimate of the heavy mass from the observation of the processes mediated by the four-fermion interactions. We then designed colliders to probe physics at that energy.

Note also the two following points

- We did *not* expect the four-fermion interactions to be an accurate description of weak processes at energies close to the scale we just inferred. For example, the four-fermion theory cannot describe weak physics near the Z pole.
- Not all weak effects are so amenable to observation. For example, the weak contributions to the anomalous magnetic moments are very small (at the 10^{-9} level) and only now are being probed at the Brookhaven experiment AGS 821 [4] [1]. This is not because these weak contributions are accidentally suppressed, nor are they forbidden by some symmetry. The reason is simply that they are generated by loops, and thus are naturally small [6].

1 Extracting these effects from the data presents other problems, see [5] and references therein.

Thus when studying the weak interactions we took a very sensible approach: we selected those effects which are tree-level generated, and then restricted our interest to those processes forbidden by QED. By doing this we optimized the chances of obtaining information about the interactions ultimately responsible for Fermi's effective theory. This is, of course, an unfair oversimplification of the history, but it does emphasize the following points

(**a**) When we want to discover new physics through the virtual processes which it induces, the most sensible thing to do is to select the effects that can be generated at tree level, and leave the study of loop-generated effects for later[2].

(**b**) When describing the underlying theory through its low-energy manifestations, one should have an idea of which processes are responsible for the effective operators we are considering (eg. a Z mediating $e^+e^- \to \nu\bar{\nu}$). In this way we can obtain rough estimates of the **physical** scales involved in the theory.

(**c**) A description of new physics in terms of effective operators has a limited range of validity. One can derive from the formalism the scale at which such description will fail [1]. Applying the formalism beyond such scale will give **wrong** results.

Even if we had been unlucky and found no deviations from QED. The above process would have provided a lower bound for the scale of new physics.

These considerations, though somewhat self-evident, are regularly ignored when considering physics beyond the Standard Model through effective operators. It is not true that "anything can happen beyond the Standard Model": the fact that the Standard Model is so well measured puts very strong restrictions on the kinds of new physics that could be responsible for the virtual effects we are attempting to measure. This is true even if we have not probed all possible processes: a strong deviation from the Standard Model in, for example, the WWZ coupling cannot occur in isolation, a host of other effects must be present concurrently which are constrained by current data.

The main restriction on the underlying theory is that it should respect the Standard Model gauge symmetries. If we assume that this is not the case then, even if the deviations from gauge invariance occur at a scale Λ, they will induce gauge variant terms to which existing data is sensitive [7]. In this case the many consequences of gauge invariance, such as lepton universality, would be nothing more than amazing coincidences. It is also important to note that in *all* models studied to date low energy gauge invariance is respected by the underlying theory.

These restrictions do not extend to global symmetries. For example $SU(5)$ GUT does respect the Standard Model gauge symmetry but violates lepton and baryon numbers.

2 Though this is appropriate for weakly coupled theories similar considerations apply for strongly coupled ones, see below.

3. Weakly coupled theories

If the physics beyond the Standard Model were weakly coupled, and if we are interested in the virtual effects from the heavy particles, the relevant question is which of the manifold of terms generated at low energies could possibly be generated through tree-level graphs in the heavy theory. The list of such tree-induced processes is known [8] (provided we make the single mild assumption that the underlying theory is a gauge theory); the list of *all* terms of dimension 6 is also known [9]

All loop-generated terms are small, not necessarily unobservable, but harder to deal with. A reasonable strategy is to concentrate first on the observables that can get large contributions from the heavy physics.

To illustrate the consequences of these statements I will consider the possible modifications to the gauge-boson couplings induced by the heavy interactions.

3.1 Vector-boson interactions.

Any interaction among vector bosons not contained in the Standard Model appears as an operator of dimension six or higher [9]. In unitary gauge such an operator might appear to have dimension 4, but this is because in this gauge (and ignoring Higgs interactions) the scalar doublet is replaced by a number (= 246 GeV).

All dimension 6 operators mediating vector-boson interactions are generated by loops, operators of dimension 8 and higher can be generated at tree level. Again I emphasize that such operators may appear as if they were dimension 4 operators in some gauges, but fundamentally they are not.

Because of their origin such operators get a coefficient

$$\text{dimension } 6: \quad \sim \frac{1}{16\pi^2\Lambda^2} \qquad\qquad \text{dimension } 8: \quad \sim \left(\frac{v}{\Lambda}\right)^4, \tag{3.1}$$

where Λ denotes a *physical* mass scale, *i.e.*, the mass of a particle or other similar threshold.

The standard notation [2] is not derived from the effective lagrangian approach based on gauge invariant operators, but uses an effective Lagrangian restricted only through Lorentz and QED gauge invariances. Nonetheless the arguments described above can be used to interpret the couplings which appear in the standard approach.

Consider for example the WWZ interaction [2]

$$-ie\cot\theta_w \frac{\lambda}{M_w^2} W^+_{\alpha\beta} W^-_{\beta\mu} Z_{\mu\alpha} \tag{3.2}$$

where e denotes the proton charge, θ_w the weak-mixing angle, and $W^\pm_{\alpha\beta} = \partial_\alpha W^\pm_\beta - \partial_\beta W^\pm_\alpha$, $Z_{\alpha\beta} = \partial_\alpha Z_\beta - \partial_\beta Z_\alpha$ are the field strengths for the W and Z vector-boson fields. The coupling λ is unknown and parametrizes a certain type of new physics; the gauge invariant formalism provides the estimates [6]

$$\lambda \sim \begin{cases} \frac{6M_w^2 g^2}{16\pi^2\Lambda^2} & \text{for dim-6 operators },\\ \frac{M_w^4}{\Lambda^4} & \text{for dim-8 operators }, \end{cases} \tag{3.3}$$

where, as before, Λ denotes the mass of a heavy excitation, g is the $SU(2)$ gauge coupling constant and M_w the W mass (the factor of 6 is due to combinatorics).

Using the above estimate one can understand what the experimental limits imply with respect to the underlying theory (corresponding to dimension 6 and 8 terms respectively)

$$\lambda \sim \frac{1}{(100\Lambda_{\rm TeV})^2}, \quad \frac{1}{(12.5\Lambda_{\rm TeV})^4} \tag{3.4}$$

where $\Lambda_{\rm TeV}$ denotes the scale of new physics in TeV units. Thus the statement $|\lambda| < 0.1$ corresponds to $\Lambda > 150$ GeV while $|\lambda| < 10^{-4}$ implies $\Lambda > 1$ TeV.

This illustrates the power of the gauge invariant approach: we are able to interpret the results in terms of physical quantities and determine the implications on the scale of new physics[3]. For the case of the WWZ interactions if we wish to probe physics at the 1 TeV scale we must be able to measure λ to to a precision of $\sim 10^{-4}$. This should be done, of course, at colliders whose CM energies lie below 1 TeV, otherwise the heavy particles would be produced directly and the effective operator formalism fails, just as the four-fermion theory should not be used at energies $\gtrsim$80 GeV.

Similar considerations apply, for example, to the $Z\gamma\gamma$ couplings. Here it is known [9] that the operators responsible for such couplings are of dimension 8 or higher and can be generated via tree graphs [8]. The coefficients are then expected to be of the form $1/\Lambda^4$. The standard notation for this case [11] is based, again, on a lagrangian restricted only by Lorentz and QED gauge invariances. As an example consider the interactions

$$i\frac{h_3^Z}{M_z^2}\left[(\Box + M_z^2)Z_\mu\right]\tilde F^{\mu\nu}Z^\nu, \qquad i\frac{h_4^Z}{M_z^4}\left[(\Box + M_z^2)\partial_\alpha Z_{\mu\nu}\right]\tilde F^{\mu\nu}Z^\alpha, \tag{3.5}$$

denoting by Z_α the Z-boson field, $Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$ and $\tilde F_{\mu\nu}$ is the dual of the photon field strength. We then have the estimates

$$h_3^Z \sim \frac{v^2 M_z^2}{\Lambda^4} \simeq \frac{1}{(6.7\Lambda_{\rm TeV})^4}, \qquad h_4^Z \sim \frac{M_z^4}{\Lambda^4} \simeq \frac{1}{(11\Lambda_{\rm TeV})^4}, \tag{3.6}$$

so that a bound $|h_{3,4}^Z| < 1$ implies $\Lambda > 150$ GeV and $\Lambda > 92$ GeV respectively.

3 It has been shown argued [10] that any theory can be rendered gauge invariant by introducing spurious degrees of freedom. In this approach, however, all fermions (and scalars, when present) are assumed to be gauge singlets; nor is the gauge group uniquely fixed. Taking the Standard Model as an excellent approximation to the low energy physics excludes this approach; for a discussion see J. Wudka in Ref. 1.

3.1.1 Form factors

It has been customary to use form factors to insure the theory does not violate unitarity. I will not do this here for the following reasons:

(*i*) The effective lagrangian approach should not be extended to scales close to a threshold. All attempts at modifying the formalism to this end are *extremely* model dependent and no general conclusions can be derived from them.

(*ii*) The form factors are usually chosen so that there are no poles in *any* physical process. This is unreasonable: even if in certain processes no poles occur, they will appear in the crossed channels.

As an example, the (expected) bounds $h_3^Z \lesssim 0.005$, $h_4^Z \lesssim 10^{-4}$ have been obtained for the LHC [12] using the $p\bar{p} \rightarrow Z\gamma \rightarrow e^+e^-\gamma$ reaction assuming that the CM energy was 14 TeV while the scale of the form factor was 1.5 TeV. These values, however, imply that we have enough energy to observe directly the heavy physics ($1.5 \ll 14$). The effective lagrangian approach breaks down in this region and no reliable information can be derived from this approach, but this is of little importance: the new physics would be directly observable.

Similar statements can be made for all form-factor modifications of effective couplings. In fact there is an example from low-energy hadron physics which illustrates the above statements. Consider the decay $K \rightarrow \pi e \nu$ which is characterized by two form factors [13] parametrized in the form $1 + \lambda_{K\pi} q^2/m_\pi^2$; q is the difference between the K and π four-momenta, $\lambda_{K\pi} \sim 0.03$ is a constant and m_π is the pion mass. This, to the same order in q^2 is equivalent to $1/(1 - q^2/nM^2)^n$, $M \simeq 800$ GeV, which has poles at $q^2 = nM^2$. Of course we do find "new" physics (*i.e.* physics beyond the lightest pseudoscalar mesons) around M. It is also true that one cannot simply replace the form factor by the expression $1/(1 - q^2/nM^2)^n$ in order to describe this new physics entirely.

3.2 Large effects

As I mentioned above, some operators are generated at tree level; for the corresponding processes we do not expect an *a priori* suppression. In this subsection I will give some examples. I will write all operators in the unitary gauge.

3.2.1 Fermion-gauge-boson couplings

Certain kinds of new physics can induce *right*-handed couplings of the W to the quarks. The specific interaction is

$$\frac{1}{\Lambda^2}(v + H)^2 \bar{u}_R \not{W}^+ d_R,$$

where $v = 246$ GeV and H denotes the Higgs field. Similar terms can be generated for the $b - t$ and the $c - s$ quark pairs. Certain kinds of physics also generate terms which mix generations. Some such interactions are probed by the Michel-ρ parameter, as well as by the W lifetime and branching ratios. All the bounds derived in this way are relatively weak: $\Lambda \gtrsim 500$ GeV (for the first and second generations only).

The couplings of the fermions to the Z can be also modified. The bounds derived from the oblique ρ parameter as well as from the LEP1 data are stronger than the ones above, implying $\Lambda \gtrsim 2$ TeV [14].

3.2.2 Higgs couplings

The presence of new interactions can modify the couplings of the Higgs to the fermions, the Higgs self couplings and the fermion-V-Higgs coupling ($V = W, Z$). An example of the latter effects is the right handed current coupling described above.

3.2.3 Four-fermion interactions

Many different kinds of physics will generate four-fermion interactions, both CP violating and CP conserving. Such interactions are strongly bounded if they occur between first-family fermions. For the third family the bounds are generally weak (or non-existent).

The operators generated by vector exchange have been studied for NLC type of machines [15]. Similar studies exist for LHC and other hadron colliders [16]. I am not aware of a comprehensive study (including scalar and vector exchange possibilities) for the NLC.

4. Strongly coupled theories

When the underlying theory is strongly coupled[4] the calculational reliability is reduced for quantitative predictions. It is still possible, however, to provide some reliable estimates [17]. The idea is the following: let Λ be the scale of new physics and assume that the interactions of the particles lighter than Λ (the light excitations) is described by some effective theory which contains a series of (effective) coupling constants. Just as in other theories, one can use the effective theory to calculate the renormalization group evolution of these couplings. In the case of strong coupling one must work to all orders in perturbation theory, which is in general technically impossible. One can, however, estimate the renormalization group evolution and require that the running coupling constants do not diverge at lower energies[5]. This yields upper bounds on the various coefficients of the terms in the effective lagrangian. It is interesting to note that the *same* estimates for the WWZ, $WW\gamma$ and $ZZ\gamma$ couplings derived above are obtained, that is, the expressions (3.3) and (3.6) are valid also for strongly coupled underlying theories.

These arguments can be further specialized if it is assumed that there are no light scalar particles, *i.e.* that the low energy spectrum corresponds to the Standard Model without the Higgs excitation. In

4 This possibly is usually associated with the assumption that there is no light Higgs, I will comment on this later.

5 In this argument it is assumed that no cancellations occur between various graphs, *i.e.* the theory is assumed to be natural [18]—no fine tunings are required.

this case the scale of new physics Λ is constrained to be $\lesssim 4\pi v \sim 3$ TeV [19, 17] and some modifications occur which lead to refinements of the above bounds. For example (3.3) and (3.6) are replaced by

$$\lambda \sim \frac{6M_w^2 g^2}{16\pi^2\Lambda^2}, \qquad h_3^Z \sim \frac{v^2 M_z^2}{16\pi^2\Lambda^4}, \qquad h_4^Z \sim \frac{M_z^4}{16\pi^2\Lambda^4}, \qquad (\Lambda \lesssim 3 \text{ TeV}); \tag{4.1}$$

note that $h_{3,4}^Z$ acquire a strong suppression factor, now a constraint $|h_{3,4}^Z| < 1$ imply $\Lambda > 40$ GeV, 26 GeV respectively.

5. Rigidity of the bounds

I have argued above that there is a way of estimating the couplings which parametrize non-Standard Model effects using gauge-invariant effective lagrangians. The question is then how rigid are these bounds.

Consider first the weakly coupled theory. One can argue that under certain circumstances a given loop graph could be enhanced by having several particles in the loop. This gives an order of magnitude leeway in the above estimates (note that the same could be said about the tree-level graphs).

What one cannot say is that there could be hundreds of particles in the loop whose contributions cancel the $1/(4\pi)^2$ entirely. If this were the case the theory would be such that the one-loop effects would be as large as the tree-level ones and the theory would be, in fact, strongly coupled. One can study such situations in exactly-solvable toy models (J. Wudka, Ref. 1) and the result is that the effect of this type of effects significantly alters the theory: it is not possible (without significant fine-tuning) to maintain the scalar mass below the cutoff. But, if the Higgs is no longer in the light theory we must examine the model as a strongly coupled one. For this case we revert to the arguments given in section 4 above.

For strongly coupled theories the bounds, as I mentioned, are more qualitative. They are based on the assumption that no fine tuning should be required of the underlying theory. If one grants this, the bounds given hold (again with an order of magnitude uncertainty). I would also like to add that these arguments can be applied to the non-linear sigma model which describes low-energy hadron physics and they agree well with experiment [20].

For example, allowing for a factor of 10 enhancement in λ would imply that, in order to probe physics at the 1 TeV level one should measure λ to a precision of $\lesssim 10^{-3}$. Similarly $h_{3,4}^Z$ should be measured to a precision of $\lesssim 5 \times 10^{-3}$ and $\lesssim 7 \times 10^{-4}$ respectively.

While it is possible for some couplings to be thus enhanced, it is also possible for them to be suppressed, either accidentally or as a result of a symmetry. Thus a strong constraint on a given effective coupling might indicate either a large value of Λ or the fact that the underlying theory suppresses the coefficient under consideration. If *all* effective couplings expected *a priori* not to contain the (small) factors of $1/(4\pi)$ are measured to be very small, the simplest possibility is that this is a result of large Λ, still all possible scenarios should be considered when analyzing the data.

If one allows for fine tuning several of these statements can be obviated. In this case, however, consistency would allow us to fine tune anything we want, such models contain no information. Of course one could say that Nature has chosen to fine tune just those interactions which we have not probed directly, and while this is a logical possibility, I will not consider it.

6. Conclusion

From the arguments given one can conclude that there is a reliable method for extracting information about the scale of new physics from the existing and expected data. In deriving the dependence of the measurements on this scale one can work in a model independent way using effective lagrangians. This does *not* mean, however, that the coefficients can in principle have any values whatever: general consistency requirements forbid their being too large and provide estimates for their value. Using this input one can then determine the reach into the realm of heavy physics that a given experiment has.

I have also strived to show that triple boson couplings are not the best place to look for deviations from the standard model. Despite the fact that one can write down lagrangians which appear to generate easily observable deviations for these couplings, such "models" cannot be derived from *any* consistent theory, weakly or strongly coupled, with or without light scalars. The point is that one cannot state, by the mere fact that a coefficient is measured to be small compared to one, that the corresponding experiment is a sensitive probe of new physics. For example, measuring the anomalous magnetic moment of the muon to 10^{-7} says nothing about non-Standard Model physics [6] (taking chiral symmetry to be natural [18]).

The formalism presented determines the constraints an experiment should satisfy in order to probe new physics up to a given scale. For example in order for a 500 GeV collider to probe WWZ physics beyond 1 TeV, λ should be measured to a precision better than $\sim 10^{-4}$. Similar precision is required for the parameter $\Delta\kappa$ (related to the heavy physics contributions to the W magnetic and electric quadrupole moments [12]).

The processes which are worth measuring are those for which the coefficients of the effective operators are as large as possible. It is of course possible that the underlying theory will suppress precisely those couplings, but I believe it is better to look at these terms than to concentrate on terms which we are *certain* provide very small effects.

The interactions with the largest coefficients have been catalogued for the case of weakly-interacting heavy physics [8]. It is also possible to determine the kind of physics responsible for each of the tree-level generated operators. Examples of such interactions are the four-fermion interactions (generated by scalar of vector exchanges[6]), and the Z couplings to fermions; the particular case of the $Zb\bar{b}$ vertex can be shown to receive its largest contributions through either $Z - Z'$ mixing (where Z' denotes a heavy

6 Tensor exchanges are reduced using Fierz identities.

vector boson) or through mixing of b with some heavy fermions. Both of these possibilities have been studied in the literature [21]; it can be shown using the results of [8] that these are the *only* possibilities: no other kind of heavy physics can alter this vertex as significantly.

Thus the effective lagrangian approach can not only estimate coefficients, but can also exhibit the culprits responsible for any operator. It is precisely the insistence that the underlying physics should be described by a consistent model (whatever the details) that imposes the various constraints discussed above. If such consistency requirements are foregone, the coefficients can indeed take any values, but in this case the underlying physics is not described by *any* consistent theory.

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