Constraints on New Physics in the Electroweak Bosonic Sector from Current Data and Future Experiments

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Abstract

Extensions of the Standard Model which involve a new scale, $Λ$, may, for energies sufficiently small compared to this new scale, be expressed in terms of operators with energy dimension greater than four. The coefficients of just four SU(2)$\times$U(1)-gauge-invariant energy-dimension-six operators are sufficient to parameterize the contributions of new physics in the electroweak bosonic sector to electroweak precision measurements. In this letter we update constraints on the coefficients of these four operators due to recent precision measurements of electroweak observables. We further demonstrate how such constraints may be improved by experiments at TRISTAN, LEP2 and at a future linear $e^+e^-$ collider. The relationship of these operators to the oblique parameters $S$, $T$ and $U$ is examined. Two of the operators contribute to a non-standard running of the electroweak charge form-factors $\bar{\tau}(q^2)$, $\bar{\tau}^2(q^2)$, $\bar{\tau}^L_Z(q^2)$ and $\bar{g}^2_{1W}(q^2)$; in the special case where the coefficients of these two vanish the operator analysis reduces to an analysis in terms of $S$, $T$ and $U$ with $U = 0$. 
If one assumes that the Standard Model (SM) is the low-energy approximation of some more general theory for which we lack a complete description, then it is possible to describe the full theory with an effective Lagrangian. The leading terms of the effective Lagrangian will be the energy-dimension-four operators of the SM, and correction terms will be operators of greater energy dimension suppressed by inverse powers of the scale of the additional physics, Λ. Under the assumption Λ ≫ v, where v = 246.22GeV is the vacuum expectation value (vev) of the SM Higgs field, one may write an effective Lagrangian of the full theory in the form

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{n \geq 5} \sum_i \frac{f_i^{(n)} O_i^{(n)}}{\Lambda^{n-4}}. \]  

(1)

The energy dimension of each operator is denoted by n, and the index i sums over all operators of the given energy dimension. Assuming that the correct low-energy theory is the SM and that the full theory is SU(2) × U(1) gauge invariant, these operators are constructed from SM fields and derivatives. An exhaustive list of energy-dimension-five and -six operators has been compiled in Refs. [1, 2].

By studying the consequences of these operators one may hope to acquire model-independent insight into the new physics. In general, however, even if the analysis is restricted to operators not exceeding energy-dimension-six, so many operators contribute that the effective Lagrangian lacks predictive power. Nevertheless there is a special class of new physics which may be effectively studied through the present precision electroweak measurements. All physics which contributes to precision measurements only via contributions to the two-point functions of SM gauge bosons belongs to this class [3–6]. It was first observed by Grinstein and Wise [7] that only four operators through energy-dimension-six contribute at the tree level. In the notation of Ref. [8] they are

\[ O_{DW} = -g^2 \text{Tr} \left( (\partial_\mu W_{\nu \rho}) (\partial^{\mu} W^{\nu \rho}) \right), \]  

(2a)

\[ O_{DB} = -g'^2 \left( (\partial_\mu B_{\nu \rho}) (\partial^{\mu} B^{\nu \rho}) \right), \]  

(2b)

\[ O_{BW} = -\frac{gg'}{2} \Phi^\dagger B_{\mu \nu} W^{\mu \nu} \Phi, \]  

(2c)
\[ O_{\Phi,1} = \left[ (D_\mu \Phi)^\dagger \Phi \right] \left[ \Phi^\dagger (D^\mu \Phi) \right]. \] (2d)

Here \( W_{\mu \nu} = W^a_{\mu \nu} T^a \), \( g \) is the SU(2) coupling with \( \text{Tr}(T^a T^b) = \frac{1}{2} \delta^{ab} \), and \( g' \) is the U(1) coupling. Their coefficients, the \( f_i^{(n)} \) of Eq. (1), are denoted by

\[ \{ f_{DW}, f_{DB}, f_{BW}, f_{\Phi,1} \} \] (3)

respectively.

**Oblique corrections:** To date precision electroweak measurements are restricted to those processes which involve four external light fermions and conserve both chirality and flavor. Those effects of the new physics which may be described by the operators (2) contribute to electroweak precision measurements via their contributions to the transverse components of the gauge-boson propagators. If the one-particle-irreducible two-point-function is separated into SM and new physics contributions according to \( \Pi = \Pi_{\text{SM}} + \Delta \Pi \), then, in the notation of Ref. [8], we find

\[ \Delta \Pi_Q^{QQ}(q^2) = 2 \frac{q^2}{\Lambda^2} \left[ (f_{DW} + f_{DB}) q^2 - f_{BW} v^2 \frac{v^2}{4} \right], \] (4a)

\[ \Delta \Pi_Q^{33}(q^2) = 2 \frac{q^2}{\Lambda^2} \left[ f_{DW} q^2 - f_{BW} v^2 \frac{v^2}{8} \right], \] (4b)

\[ \Delta \Pi_T^{33}(q^2) = 2 \frac{q^2}{\Lambda^2} f_{DW} q^2 - \frac{v^2}{\Lambda^2} f_{\Phi,1} \frac{v^2}{8}, \] (4c)

\[ \Delta \Pi_{11}^{11}(q^2) = 2 \frac{q^2}{\Lambda^2} f_{DW} q^2. \] (4d)

One immediately notices that these expressions contain terms which are constant and linear in \( q^2 \), but terms which are quadratic in \( q^2 \) appear as well [7,8]. For precisely this reason the dimension-six operator analysis does not reduce to the standard analysis in terms of a triplet of parameters such as \( S, T \) and \( U \) of Ref. [4], \( \epsilon_1, \epsilon_2 \) and \( \epsilon_3 \) of Ref. [5] or others of Ref. [6]. By contrast the standard three-parameter description is sufficient for an analysis based upon the effective Lagrangian with a non-linear realization of the gauge symmetry. (See Ref. [9] and references therein.)

It is convenient to introduce an additional parameter for which we choose the anomalous contribution to the running of \( \alpha_{\text{QED}} \) evaluated at \( m_Z^2 \). We define \( \Delta^{-1} \equiv \Delta_{\text{QED}}^{-1}(m_Z^2) \). Then
we may form a quartet of parameters given by

\[
\{\Delta S, \Delta T, \Delta U, \Delta \frac{1}{\alpha}\},
\]

where \( S = S_{SM} + \Delta S \), \( T = T_{SM} + \Delta T \) and \( U = U_{SM} + \Delta U \). The quartet (5) is related to (3) according to

\[
\Delta S \equiv 16\pi \text{Re}\left[ \Delta \Pi_{T,\gamma}^{3Q}(m_Z^2) - \Delta \Pi_{T,Z}^{33}(0) \right] = -4\pi \frac{v^2}{\Lambda^2} f_{BW},
\]

\[
\Delta T \equiv \frac{4\sqrt{2}G_F}{\alpha} \text{Re}\left[ \Delta \Pi_{T}^{33}(0) - \Delta \Pi_{T}^{11}(0) \right] = -\frac{1}{2\alpha} \frac{v^2}{\Lambda^2} f_{\phi,1},
\]

\[
\Delta U \equiv 16\pi \text{Re}\left[ \Delta \Pi_{T,Z}^{33}(0) - \Delta \Pi_{T,W}^{11}(0) \right] = 32\pi \frac{m_Z^2 - m_W^2}{\Lambda^2} f_{DW},
\]

\[
\Delta \frac{1}{\alpha} \equiv 4\pi \text{Re}\left[ \Delta \Pi_{T,\gamma}^{3Q}(m_Z^2) - \Delta \Pi_{T,\gamma}^{33}(0) \right] = 8\pi \frac{m_Z^2 - m_W^2}{\Lambda^2} (f_{DW} + f_{DB}).
\]

where the following short-hand notation [10] has been employed:

\[
\Pi_{AB}^{T,V}(q^2) = \Pi_{AB}^{T}(q^2) - \Pi_{AB}^{T}(m_V^2).
\]

Employing (6) one may calculate the charge form-factors of Ref. [10],

\[
\frac{1}{g_Z^2(0)} = 1 + \delta_G - \alpha T,
\]

\[
\frac{1}{g_V^2(0)} = \frac{\pi^2(m_Z^2)}{\pi^2(m_Z^2) - \frac{1}{16\pi} (S + U),
\]

which are intimately related to observable quantities. The SM vertex and box corrections to the muon lifetime are incorporated in \( \delta_G \approx 0.0055 \). The remaining effects of the operators (4) are expressed as a non-standard running of the charge form-factors:

\[
\Delta \left[ \frac{1}{\pi^2(q^2)} - \frac{1}{4\pi^2\alpha} \right] = 2\frac{q^2}{\Lambda^2} (f_{DW} + f_{DB}),
\]

\[
\Delta \left[ \frac{\pi^2(q^2)}{\pi^2(q^2)} - \frac{\pi^2(m_Z^2)}{\pi^2(m_Z^2)} \right] = 2\frac{q^2 - m_Z^2}{\Lambda^2} f_{DW},
\]

\[
\Delta \left[ \frac{1}{g_Z^2(q^2)} - \frac{1}{g_Z^2(0)} \right] = 2\frac{q^2}{\Lambda^2} (\hat{c}^4 f_{DW} + \hat{s}^4 f_{DB}),
\]

\[
\Delta \left[ \frac{1}{g_V^2(q^2)} - \frac{1}{g_V^2(0)} \right] = 2\frac{q^2}{\Lambda^2} f_{DW}.
\]
In the limit where $f_{DB} = f_{DW} = 0$ all non-standard contributions to the running of the charge form-factors vanish, and the operator analysis is equivalent to an analysis in terms of $S$, $T$ and $U$ with $U = 0$.

Combining Eq. (8) with Eq. (9) the results may be stated compactly as

\begin{align}
\Delta \alpha(q^2) & = -8\pi\hat{\alpha}^2 \frac{q^2}{\Lambda^2} (f_{DW} + f_{DB}) , \\
\Delta g_Z^2(q^2) & = -2\hat{g}_Z^4 \frac{q^2}{\Lambda^2} (\hat{c}^4 f_{DW} + \hat{s}^4 f_{DB}) - \frac{1}{2} \hat{g}_Z^2 v^2 f_{\Phi,1} , \\
\Delta s^2(q^2) & = \frac{\hat{s}^2 \hat{c}^2}{\hat{c}^2 - \hat{s}^2} \left[ 8\pi\hat{\alpha} \frac{m_Z^2}{\Lambda^2} (f_{DW} + f_{DB}) + \frac{m_Z^2}{\Lambda^2} f_{BW} - \frac{1}{2} \frac{v^2}{\Lambda^2} f_{\Phi,1} \right] \\
& \quad + 8\pi\hat{\alpha} \frac{q^2 - m_Z^2}{\Lambda^2} (\hat{c}^2 f_{DW} - \hat{s}^2 f_{DB}) , \\
\Delta g_W^2(q^2) & = -8\pi\hat{\alpha} \hat{g}_W^2 m_Z^2 f_{DB} - \hat{g}^2 \Delta s^2(m_Z^2) - \frac{1}{4} \hat{g}_W^4 \frac{v^2}{\Lambda^2} f_{BW} - 2\hat{g}_W^4 \frac{q^2}{\Lambda^2} f_{DW} .
\end{align}

The ‘hatted’ couplings satisfy the tree-level relationships $\hat{e} \equiv \hat{g}\hat{s} \equiv \hat{g}_Z\hat{s}\hat{c}$ and $\hat{e}^2 \equiv 4\pi\hat{\alpha}$. For numerical results we use $\hat{\alpha} = 128.72$ and $\hat{s}^2 = 0.2312$.

**Low-energy constraints:** In the calculation of electroweak observables we use the vertex and box corrections of the SM, but the charge form-factors of the SM are modified according to (10). We then perform a $\chi^2$ analysis of all available electroweak data to place constraints upon the four coefficients of (3) for $\Lambda = 1$ TeV. Included in the analysis are the recent LEP data [11] and the SLC measurement of the left-right asymmetry [12]. We present the central values and one-sigma uncertainties of the four coefficients along with the correlation matrix:

\[
\begin{pmatrix}
1 & -0.323 & 0.151 & -0.228 \\
1 & -0.979 & -0.806 \\
1 & 0.905 \\
1 &
\end{pmatrix}
\]

\[
\begin{pmatrix}
f_{DW} = -0.35 + 0.012 \ln x_H - 0.14 x_t \pm 0.62 \\
f_{DB} = -11 \pm 11 \\
f_{BW} = 3.1 + 0.072 \ln x_H \pm 2.6 \\
f_{\Phi,1} = 0.23 - 0.031 \ln x_H + 0.36 x_t \pm 0.17
\end{pmatrix}
\]

where

\[
x_t = \frac{m_t - 175\text{GeV}}{100\text{GeV}} , \quad x_H = \frac{m_H}{100\text{GeV}} .
\]
The parameterization is good to better than 2% of the one-sigma errors in the range \(140\text{GeV} < m_t < 220\text{GeV}\) and \(60\text{GeV} < m_H < 800\text{GeV}\).

For all four parameters the dependencies upon \(m_H\) and \(m_t\) arise from SM contributions only. For \(m_t = 175\text{GeV}\) and \(m_H = 100\text{GeV}\) we find \(f_{BW} = 3.1 \pm 2.6\) and \(f_{\Phi,1} = 0.23 \pm 0.17\). A value of \(f_{\Phi,1}\) which is more consistent with zero indicates a lower value for \(m_t\) and/or a larger value for \(m_H\). In particular \(f_{\Phi,1}\) and \(m_t\) are correlated via the linear contribution of the former and the quadratic contribution of the latter to the \(T\) parameter. The dependence of \(f_{BW}\) upon \(m_H\) is weak, and the dependence on \(m_t\) is negligible, hence it is difficult to make \(f_{BW}\) more consistent with zero.

We note, however, that \(f_{DB}\) is not well constrained by the present data, and there are strong correlations among the coefficients \(f_{DB}\), \(f_{BW}\) and \(f_{\Phi,1}\). The accurate measurement of \(\pi^2(m_Z^2)\) from asymmetries leads to a strong \(f_{DB}-f_{BW}\) anti-correlation as well as an \(f_{BW}-f_{\Phi,1}\) correlation. The precise measurement of the Z-boson width tightly constrains \(\mathcal{F}_Z^2(m_Z^2)\), which in turn favors a strong \(f_{DB}-f_{\Phi,1}\) anti-correlation. The measurement of \(\mathcal{F}_W^2(0)\), via the measurement of \(m_W\), strengthens the \(f_{BW}-f_{\Phi,1}\) correlation. See Eqn. (10). The individual measurements produce correlations between \(f_{DW}\) and the other parameters, but these effects tend to cancel in the overall analysis.

We next add the constraint \(f_{DW} = f_{DB} = 0\) and perform a two-parameter fit where \(f_{BW}\) and \(f_{\Phi,1}\) are free parameters. The results are given by

\[
\begin{align*}
    f_{BW} &= -0.04 + 0.11 \ln x_H \pm 0.28 \\
    f_{\Phi,1} &= 0.00 - 0.027 \ln x_H + 0.33 x_t \pm 0.05
\end{align*}
\]

Employing (6) the fit (13) may be rewritten in terms of a fit of \(S\) and \(T\) with \(U\) constrained to zero, and we find good agreement with the results of Ref. [13]. Comparing (13) with (11) we notice several common features with regard to the parameters \(f_{BW}\) and \(f_{\Phi,1}\); both fits show a strong \(f_{BW}-f_{\Phi,1}\) correlation, and both fits possess similar dependence upon \(m_t\) and \(m_H\). However, in the two-parameter fit the errors are significantly reduced, and both parameters are completely consistent with zero. The precise measurement of \(f_{BW}\) and \(f_{\Phi,1}\),
or, equivalently, the precise measurement of $S$ and $T$, is subject to the assumption that $f_{DW}$ and $f_{DB}$, which are poorly constrained by the data, are small.

Fig. 1(a) illustrates the possible contribution of the new physics to the running of the charge form-factors as described by (10) subject to the constraints of the fit (11). Due to the running with $q^2$, effects which are small at low-energies may be appreciably enhanced at higher energies. Alternatively, experiments at higher $q^2$ are more sensitive to $O_{DW}$ and $O_{DB}$. Examine, for instance, the running of $1/\alpha(q^2)$. Near $q^2 = 0$, where a direct precision measurement exists, little deviation is possible. However, for $q^2 = m_Z^2$, the possible deviations are fairly large, and for energies relevant to LEP II the constraints are quite poor. Similar comments apply to the remaining form-factors. In particular $\bar{s}^2(q^2)$ is very well constrained at $q^2 = m_Z^2$ and fairly well measured at $q^2 = 0$. Away from these points the constraints are poor. This behavior is also exhibited by $\bar{g}_Z^2(q^2)$, and $\bar{g}_W^2(q^2)$ is directly constrained only at $q^2 = 0$.

It is possible to improve these constraints via the increased precision of existing measurements. An alternative method is via measurements at different energy scales. In the latter case the absence of high precision may be compensated by enhancements proportional to $q^2/\Lambda^2$. Those effects of the new physics which are proportional to $q^2/\Lambda^2$ decouple at low energies, but, in some cases, at high energies ($|q^2| \geq v^2$) they may be more important than non-decoupling effects.

The operators $O_{DW}$ and $O_{BW}$ also contribute to $WWZ$ and $WW\gamma$ vertices, hence one might hope to achieve additional constraints by studying processes such as W-boson pair production at LEP II. However, three additional operators which are very poorly constrained at present also contribute to these same vertices [8]. Therefore, without making additional assumptions, this line of analysis is not useful for the current discussion.

**TRISTAN:** Consider the measurement of $\bar{\alpha}(q^2)$ at TRISTAN [14] which is especially interesting because it is the first precision measurement of this quantity near $q^2 = m_Z^2$.

$$\bar{\alpha}^{-1}((58\text{GeV})^2) = 128.9 \pm 0.6(\text{stat.}) \pm 2.0(\text{syst.}) . \quad (14)$$
Fig. 1: Deviations from the SM predictions for the charge form-factors as allowed by (a) present constraints (11) and as allowed by (b) current data combined with anticipated data from LEP II (16). Both figures assume $m_t = 175$ GeV and $m_H = 100$ GeV. The SM predictions are given by the solid lines. When the effects of energy-dimension-six operators are included the best-fit values are represented by the dashed lines. The dot-dashed lines and dotted lines denote the deviations allowed at the 1-$\sigma$ and 2-$\sigma$ levels respectively.
The combined error of 1.6% is systematics dominated. The largest contribution, arising from the measurement of the luminosity, is expected to decrease further. Currently the results of the fit (11) and the TRISTAN measurement (14) are consistent, but with a reduced error this measurement will provide an additional constraint on the coefficients of the dimension-six operators. We assume that the combined error of (14) can be reduced to \( \approx \pm 0.8 \). For the central value of the improved measurement we adopt the SM prediction, \( \alpha^{-1}(58\text{GeV})^2 = 129.46 \), and repeat the analysis with the following results:

\[
\begin{align*}
    f_{DW} &= -0.46 + 0.013 \ln x_H - 0.14x_t \pm 0.61 \\
    f_{DB} &= -4.2 \pm 7.4 \\
    f_{BW} &= 1.4 + 0.090 \ln x_H \pm 1.8 \\
    f_{\Phi,1} &= 0.14 - 0.030 \ln x_H + 0.35x_t \pm 0.13
\end{align*}
\]

The measurement of \( \alpha(q^2) \) is a direct constraint upon \( f_{DW} + f_{DB} \), but the primary effect is a reduced one-sigma limit for \( f_{DB} \). Because of the strong correlations this in turn leads to smaller errors for \( f_{BW} \) and \( f_{\Phi,1} \).

The fit (15) does not qualitatively alter the running of the charge form-factors from the scenario illustrated in Fig. 1(a), but numerically the results are non-negligible. The allowed deviations in \( \alpha^{-1}(q^2) \) have, at \( \sqrt{q^2} = 200\text{GeV} \), been reduced by a factor of two. The corresponding deviations in \( s^2(q^2) \) and \( g_2^Z(q^2) \) are reduced by a similar factor, but there is minimal improvement for \( g_2^W(q^2) \).

**LEP II:** Further improvement will likely await results from LEP II. We assume that 500pb\(^{-1}\) of data will be collected at \( \sqrt{s} = 175\text{GeV} \) and, assuming errors dominated by statistics, perform a fit using the following observables: \( \sigma(e^+e^- \rightarrow \mu^+\mu^-) \), \( \sigma(e^+e^- \rightarrow \text{hadrons}) \) and the forward-backward asymmetries \( A_{FB}^\mu, A_{FB}^h \) and \( A_{FB}^c \). Additionally we should expect an improved measurement of \( m_W \). We employ \( \Delta m_W \approx 50\text{MeV} \). In the absence of actual experimental results we choose for the central values of the hypothetical data the predictions of the SM. This will bias the central values of the \( f_i \)'s which we obtain in our fit, but the estimation of the errors and correlations will provide useful information.
Combining the hypothetical LEP II data described above with the current data we repeat the \( \chi^2 \) analysis and summarize the results:

\[
\begin{align*}
    f_{DW} &= -0.52 + 0.043 \ln x_H - 0.43 x_t \pm 0.27 \\
    f_{DB} &= 1.5 + 0.10 \ln x_H - 0.52 x_t \pm 2.1 \\
    f_{BW} &= 0.07 + 0.055 \ln x_H + 0.41 x_t \pm 0.54 \\
    f_{\Phi,1} &= 0.09 - 0.033 \ln x_H + 0.39 x_t \pm 0.05
\end{align*}
\]

The errors are greatly reduced for all four coefficients. The correlation matrix now exhibits a strong \( f_{DW} - f_{DB} \) anti-correlation, but the \( f_{DB} - f_{BW} - f_{\Phi,1} \) correlations are weakened. These new features are the result of improved knowledge of \( \alpha^{-1}(q^2) \) well above the Z peak, especially through the measurement of \( \sigma(e^+e^- \rightarrow \mu^+\mu^-) \). We present Fig. 1(b). Note that Fig. 1(a) and Fig. 1(b) employ different scales for the vertical axes. At 175GeV it is possible to fit \( \alpha^{-1}, \sigma^2, g_Z^2 \) and \( g_W^2 \) with a precision of 1.2%, 0.9%, 0.5% and 0.7% respectively.

**NLC:** Finally we consider a Next Linear Collider (NLC) with an integrated luminosity of 50fb\(^{-1} \) at \( \sqrt{s} = 500 \text{GeV} \). We assume that the errors in \( R_h, A_{FB}^\mu, A_b^\mu \) and \( A_c^\mu \) are dominated by statistics, and hence can be measured to within approximately one percent. For the measurement of \( \sigma(e^+e^- \rightarrow \mu^+\mu^-) \) we assume that systematics are relevant and estimate a three percent error. We choose for the central values the predictions of the SM. The combination of the current data and the NLC data yields

\[
\begin{align*}
    f_{DW} &= -0.04 + 0.0092 \ln x_H - 0.082 x_t \pm 0.06 \\
    f_{DB} &= -0.04 - 0.0087 \ln x_H \pm 0.22 \\
    f_{BW} &= 0.16 + 0.099 \ln x_H \pm 0.27 \\
    f_{\Phi,1} &= -0.08 - 0.030 \ln x_H + 0.36 x_t \pm 0.04
\end{align*}
\]

All four coefficients are now measured to the same level of precision, and the strong anti-correlations between \( f_{DB} \) and the remaining coefficients disappear.

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