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Low Energy Manifestations of a New Interaction Scale: Operator Analysis

C. N. Leung, S. T. Love*,
and
S. Rao
Fermi National Accelerator Laboratory
P. O.Box 500
Batavia, IL 60510

ABSTRACT

We list all dimension six $SU(3)\times SU(2)\times U(1)$ invariant operators which can be used in a phenomenological analysis of deviations from the standard model due to a new interaction scale Λ. Modifications to the masses of the W and Z bosons due to the new interaction are obtained and used to estimate a crude lower bound on Λ. Operators that could enhance nonstandard events are scrutinized.

*Address after August 1, 1984, Department of Physics, Purdue University, West Lafayette, IN. 47907.

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The standard model has enjoyed a remarkable success in explaining experimental data, culminating in the discovery of the W and Z bosons.[1] However, the very same experiments that discover the W and Z also provide us with surprises; namely, events that are difficult to understand within the context of the standard model. We shall refer to these as nonstandard events. They consist of, for exampe, $Z \to \ell^+ \ell^- \gamma$, monophoton events, monojet events, and events with an electron and associated jets.[2] This may be our first glimpse of the new physics beyond the standard model. Numerous suggestions have been made about the possible origin(s) of these nonstandard events, [3] none of which is particularly compelling.

In the absence of any compelling model, it would be useful to have a model independent parametrization of the new physics. This can be done from an effective operator point of view, in the same spirit as the classification of baryon and lepton number violating processes by Weinberg and Wilczek and Zee.[4] If the new physics is characterized by a certain energy scale Λ larger than the electroweak scale, its effects at low energy (small compared to Λ) can be described by higher (>4) dimensional effective operators which are scaled by appropriate inverse powers of Λ. Furthermore, based on the success of the standard model in low energy phenomenology, it is natural to attempt to describe all physics at energies below Λ by the (spontaneously broken) symmetry of the standard model. We are therefore only interested in effective operators that are $SU(3)\times SU(2)\times U(1)$ invariant.

In this note we list all baryon and lepton number conserving and $SU(3)\times SU(2)\times U(1)$ invariant dimension six hermitian operators involving the scalars, fermions and vector bosons of the standard model. There are no dimension five operators consistent with these requirements and operators with dimension higher than six are not considered since we are only interested in effects of leading order in $1/\Lambda$.

Some of the effective operators listed here have been considered before.[5] These operators indicate a new interaction scale, not through dramatic new processes, [4,6] but through enhancement (or suppression) of processes already present in the standard model. Our goal is to provide a useful classification and parametrization scheme for future phenomenological studies of the possible new interaction. It is not our interest here to perform a detailed phenomenological analysis to obtain limits on various coefficients associated with some of the operators. We simply point out what type of effects one might expect and which operators can contribute to some of the observed nonstandard events. For instance, there will be corrections to the masses of the W and Z bosons, which can be tested in future precise measurements of the W and Z masses.

Before listing the operators, let us define our conventions and notations. The operators are divided into seven classes depending on whether they contain vector fields only (V), fermion fields only (F), scalar fields only (S), vectors and fermions only (VF), vectors and scalars only (VS), fermions and scalars only (FS), or vectors, fermions and scalars (VFS). Vector fields and their field strengths are Lie algebra valued. Thus,

$$G_{\mu\nu} = \sum_{a=1}^{8} \frac{\lambda^a}{2} G^a_{\mu\nu} \quad , \quad W_{\mu\nu} = \sum_{a=1}^{3} \frac{\sigma^a}{2} W^a_{\mu\nu} \quad ,$$

and $B_{\mu\nu}$ are, respectively, the SU(3), SU(2), and U(1) field strengths, and $\tilde{G}_{\mu\nu}$, $\tilde{W}_{\mu\nu}$, and $\tilde{B}_{\mu\nu}$ are their respective duals;

$$\tilde{G}_{\mu\nu} = \frac{1}{2}\,\epsilon_{\mu\nu\lambda\tau}\,G^{\lambda\tau}, \quad \text{etc.}$$

Here λ^a ($a=1,\ldots,8$) are the Gell-Mann matrices and σ^a($a=1,2,3$) the Pauli matrices. To be explicit, trace over SU(3) indices is denoted by Tr and trace over SU(2) indices by tr. The covariant derivative is defined in the fundamental representation by

$$\mathcal{D}_\mu \equiv \partial_\mu - ig_3 G_\mu - ig_2 W_\mu - ig_1 \mathcal{B}_\mu \quad , \tag{1}$$

where g_3, g_2, and g_1 are, respectively, the SU(3), SU(2), and U(1) couplings. For the fermions,

$$Q^{\alpha i} = \begin{pmatrix} u^\alpha{}_L \\ d^\alpha{}_L \end{pmatrix} \text{ and } \quad L^i = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

denote left-handed SU(2) doublet quarks and leptons, respectively, and $U^\alpha = u^\alpha{}_R$, $D^\alpha = d^\alpha{}_R$, and $E = e_R$ denote, respectively, the right-handed u quark, d quark, and electron which are SU(2) singlets. SU(3) indices are denoted by α, β,... and SU(2) indices by $i,j,\ldots$ The charge conjugate of a fermion field ψ is $\psi^c = C\bar{\psi}^T$ and has the opposite handedness - e.g., $u^c{}_L = C\bar{u}_R{}^T$ is left-handed. The fermions implicitly carry a generation index. We list all operators that exist in the general multi-generation case, though some of them may disappear in the one generation case due to the anti-symmetry of the fermion fields in the bilinears. Finally,

$$\phi^i = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

are the SU(2) doublet scalar fields and $\tilde{\phi} = i\ \sigma_2\ \phi^*$.

We now list the dimension six operators.

I.) Vectors

$$O_1^{(V)} = Tr\left(G_\mu{}^\nu G_\nu{}^\lambda G_\lambda{}^\mu\right)$$

$$O_2^{(V)} = Tr\left(\tilde{G}_\mu{}^\nu G_\nu{}^\lambda G_\lambda{}^\mu\right)$$

$$O_3^{(V)} = tr\left(W_\mu{}^\nu W_\nu{}^\lambda W_\lambda{}^\mu\right)$$

$$O_4^{(V)} = tr\left(\tilde{W}_\mu{}^\nu W_\nu{}^\lambda W_\lambda{}^\mu\right)$$

$$O_5^{(V)} = Tr\left[(D_\mu G_{\nu\lambda})(D^\mu G^{\nu\lambda})\right]$$

$$O_6^{(V)} = Tr\left[(D_\mu \tilde{G}_{\nu\lambda})(D^\mu G^{\nu\lambda})\right]$$

$$O_7^{(V)} = Tr\left[(D_\mu G^{\mu\nu})(D^\lambda G_{\lambda\nu})\right]$$

$$O_8^{(V)} = tr\left[(D_\mu W_{\nu\lambda})(D^\mu W^{\nu\lambda})\right]$$

$$O_9^{(V)} = tr\left[(D_\mu \tilde{W}_{\nu\lambda})(D^\mu W^{\nu\lambda})\right]$$

$$O_{10}^{(V)} = tr\left[(D_\mu W^{\mu\nu})(D^\lambda W_{\lambda\nu})\right]$$

$$O_{11}^{(V)} = (\partial_\mu B_{\nu\lambda})(\partial^\mu B^{\nu\lambda})$$

$$O_{12}^{(V)} = (\partial_\mu \tilde{B}_{\nu\lambda})(\partial^\mu B^{\nu\lambda})$$

$$O_{13}^{(V)} = (\partial_\mu B^{\mu\nu})(\partial^\lambda B_{\lambda\nu})$$

II.) Fermions

$$O_1^{(F)} = (\bar{L}_i E)(\bar{E} L^i)$$

$$O_2^{(F)} = (\bar{L}_i U^\alpha)(\bar{U}_\alpha L^i)$$

$$O_3^{(F)} = (\bar{L}_i D^\alpha)(\bar{D}_\alpha L^i)$$

$$O_4^{(F)} = (\bar{Q}_{\alpha i} E)(\bar{E} Q^{\alpha i})$$

$$O_5^{(F)} = (\bar{Q}_{\alpha i} U^\alpha)(\bar{U}_\beta Q^{\beta i})$$

$$O_6^{(F)} = (\bar{Q}_{\alpha i} U^\beta)(\bar{U}_\beta Q^{\alpha i})$$

$$O_7^{(F)} = (\bar{Q}_{\alpha i} D^\alpha)(\bar{D}_\beta Q^{\beta i})$$

$$O_8^{(F)} = (\bar{Q}_{\alpha i} D^\beta)(\bar{D}_\beta Q^{\alpha i})$$

$$O_9^{(F)} = (\bar{L}_i E)(\bar{D}_\alpha Q^{\alpha i}) + h.c.$$

$$O_{10}^{(F)} = \epsilon_{ij} \epsilon^{kl} (\overline{L^{ci}} L^j)(\bar{L}_k L^c_l)$$

$$O_{11}^{(F)} = (\overline{L^{ci}} L^j)(\bar{L}_i L^c_j + \bar{L}_j L^c_i)$$

$$O_{12}^{(F)} = \epsilon_{ij} \epsilon^{kl} (\overline{Q^{c}}^{\alpha i} L^j)(\bar{L}_k Q^c_{\alpha l})$$

$$O_{13}^{(F)} = (\overline{Q^{c}}^{\alpha i} L^j)(\bar{L}_i Q^c_{\alpha j} + \bar{L}_j Q^c_{\alpha i})$$

$$O_{14}^{(F)} = \epsilon_{\alpha\beta\rho} \epsilon^{\lambda\tau\rho} \epsilon_{ij} \epsilon^{kl} (\overline{Q^{c}}^{\alpha i} Q^{\beta j})(\bar{Q}_{\lambda k} Q^c_{\tau l})$$

$$O_{15}^{(F)} = \epsilon_{\alpha\beta\rho} \epsilon^{\lambda\tau\rho} (\overline{Q^{c}}^{\alpha i} Q^{\beta j})(\bar{Q}_{\lambda i} Q^c_{\tau j} + \bar{Q}_{\lambda j} Q^c_{\tau i})$$

$$O_{16}^{(F)} = \epsilon_{ij}\epsilon^{kl}(\overline{Q^{c}}^{\alpha i}Q^{\beta j})(\overline{Q}_{\alpha k}Q^{c}_{\beta l} + \overline{Q}_{\beta k}Q^{c}_{\alpha l})$$
$$O_{17}^{(F)} = (\overline{Q^{c}}^{\alpha i}Q^{\beta j})(\overline{Q}_{\alpha i}Q^{c}_{\beta j} + \overline{Q}_{\beta i}Q^{c}_{\alpha j} + \overline{Q}_{\alpha j}Q^{c}_{\beta i} + \overline{Q}_{\beta j}Q^{c}_{\alpha i})$$
$$O_{18}^{(F)} = (\overline{E^{c}}E)(\overline{E}E^{c})$$
$$O_{19}^{(F)} = (\overline{E^{c}}U^{\alpha})(\overline{U}_{\alpha}E^{c})$$
$$O_{20}^{(F)} = (\overline{E^{c}}D^{\alpha})(\overline{D}_{\alpha}E^{c})$$
$$O_{21}^{(F)} = \epsilon_{\alpha\beta\rho}\epsilon^{\lambda\tau\rho}(\overline{U^{c}}^{\alpha}U^{\beta})(\overline{U}_{\lambda}U^{c}_{\tau})$$
$$O_{22}^{(F)} = (\overline{U^{c}}^{\alpha}U^{\beta})(\overline{U}_{\alpha}U^{c}_{\beta} + \overline{U}_{\beta}U^{c}_{\alpha})$$
$$O_{23}^{(F)} = \epsilon_{\alpha\beta\rho}\epsilon^{\lambda\tau\rho}(\overline{D^{c}}^{\alpha}D^{\beta})(\overline{D}_{\lambda}D^{c}_{\tau})$$
$$O_{24}^{(F)} = (\overline{D^{c}}^{\alpha}D^{\beta})(\overline{D}_{\alpha}D^{c}_{\beta} + \overline{D}_{\beta}D^{c}_{\alpha})$$
$$O_{25}^{(F)} = \epsilon_{\alpha\beta\rho}\epsilon^{\lambda\tau\rho}(\overline{U^{c}}^{\alpha}D^{\beta})(\overline{D}_{\lambda}U^{c}_{\tau})$$
$$O_{26}^{(F)} = (\overline{U^{c}}^{\alpha}D^{\beta})(\overline{D}_{\alpha}U^{c}_{\beta} + \overline{D}_{\beta}U^{c}_{\alpha})$$

III). Scalars

$$O_{1}^{(S)} = (\phi^{+}\phi)^{3}$$
$$O_{2}^{(S)} = \partial_{\mu}(\phi^{+}\phi)\partial^{\mu}(\phi^{+}\phi)$$

IV.) Vectors and Fermions

$$O_1^{(VF)} = i\bar{Q}\gamma_\mu G^{\mu\nu}\overleftrightarrow{D}_\nu Q \equiv i\bar{Q}\gamma_\mu G^{\mu\nu}D_\nu Q - i(\overline{D_\nu Q})\gamma_\mu G^{\mu\nu}Q$$

$$O_2^{(VF)} = i\bar{Q}\gamma_\mu \tilde{G}^{\mu\nu}\overleftrightarrow{D}_\nu Q$$

$$O_3^{(VF)} = i\bar{U}\gamma_\mu G^{\mu\nu}\overleftrightarrow{D}_\nu U$$

$$O_4^{(VF)} = i\bar{U}\gamma_\mu \tilde{G}^{\mu\nu}\overleftrightarrow{D}_\nu U$$

$$O_5^{(VF)} = i\bar{D}\gamma_\mu G^{\mu\nu}\overleftrightarrow{D}_\nu D$$

$$O_6^{(VF)} = i\bar{D}\gamma_\mu \tilde{G}^{\mu\nu}\overleftrightarrow{D}_\nu D$$

$$O_7^{(VF)} = i\bar{L}\gamma_\mu W^{\mu\nu}\overleftrightarrow{D}_\nu L$$

$$O_8^{(VF)} = i\bar{L}\gamma_\mu \tilde{W}^{\mu\nu}\overleftrightarrow{D}_\nu L$$

$$O_9^{(VF)} = i\bar{Q}\gamma_\mu W^{\mu\nu}\overleftrightarrow{D}_\nu Q$$

$$O_{10}^{(VF)} = i\bar{Q}\gamma_\mu \tilde{W}^{\mu\nu}\overleftrightarrow{D}_\nu Q$$

$$O_{11}^{(VF)} = i\bar{L}\gamma_\mu B^{\mu\nu}\overleftrightarrow{D}_\nu L$$

$$O_{12}^{(VF)} = i\bar{L}\gamma_\mu \tilde{B}^{\mu\nu}\overleftrightarrow{D}_\nu L$$

$$O_{13}^{(VF)} = i\bar{E}\gamma_\mu B^{\mu\nu}\overleftrightarrow{D}_\nu E$$

$$O_{14}^{(VF)} = i\bar{E}\gamma_\mu \tilde{B}^{\mu\nu}\overleftrightarrow{D}_\nu E$$

$$O_{15}^{(VF)} = i\,\bar{Q}\gamma_\mu B^{\mu\nu}\overleftrightarrow{D}_\nu Q$$

$$O_{16}^{(VF)} = i\,\bar{Q}\gamma_\mu \tilde{B}^{\mu\nu}\overleftrightarrow{D}_\nu Q$$

$$O_{17}^{(VF)} = i\,\bar{U}\gamma_\mu B^{\mu\nu}\overleftrightarrow{D}_\nu U$$

$$O_{18}^{(VF)} = i\,\bar{U}\gamma_\mu \tilde{B}^{\mu\nu}\overleftrightarrow{D}_\nu U$$

$$O_{19}^{(VF)} = i\,\bar{D}\gamma_\mu B^{\mu\nu}\overleftrightarrow{D}_\nu D$$

$$O_{20}^{(VF)} = i\,\bar{D}\gamma_\mu \tilde{B}^{\mu\nu}\overleftrightarrow{D}_\nu D$$

$$O_{21}^{(VF)} = \bar{Q}\gamma_\mu (D_\nu G^{\mu\nu}) Q$$

$$O_{22}^{(VF)} = \bar{U}\gamma_\mu (D_\nu G^{\mu\nu}) U$$

$$O_{23}^{(VF)} = \bar{D}\gamma_\mu (D_\nu G^{\mu\nu}) D$$

$$O_{24}^{(VF)} = \bar{L}\gamma_\mu (D_\nu W^{\mu\nu}) L$$

$$O_{25}^{(VF)} = \bar{Q}\gamma_\mu (D_\nu W^{\mu\nu}) Q$$

$$O_{26}^{(VF)} = \bar{L}\gamma_\mu (\partial_\nu B^{\mu\nu}) L$$

$$O_{27}^{(VF)} = \bar{E}\gamma_\mu (\partial_\nu B^{\mu\nu}) E$$

$$O_{28}^{(VF)} = \bar{Q}\gamma_\mu (\partial_\nu B^{\mu\nu}) Q$$

$$O_{29}^{(VF)} = \bar{U}\gamma_\mu (\partial_\nu B^{\mu\nu}) U$$

$$O_{30}^{(VF)} = \bar{D}\gamma_\mu (\partial_\nu B^{\mu\nu}) D$$

V.) Vectors and Scalars

$$O_1^{(VS)} = (\phi^\dagger\phi)\, Tr\,(G_{\mu\nu} G^{\mu\nu})$$

$$O_2^{(VS)} = (\phi^\dagger\phi)\, Tr\,(\tilde{G}_{\mu\nu} G^{\mu\nu})$$

$$O_3^{(VS)} = (\phi^\dagger\phi)\, tr\,(W_{\mu\nu} W^{\mu\nu})$$

$$O_4^{(VS)} = (\phi^\dagger\phi)\, tr\,(\tilde{W}_{\mu\nu} W^{\mu\nu})$$

$$O_5^{(VS)} = (\phi^\dagger\phi)\, B_{\mu\nu} B^{\mu\nu}$$

$$O_6^{(VS)} = (\phi^\dagger\phi)\, \tilde{B}_{\mu\nu} B^{\mu\nu}$$

$$O_7^{(VS)} = \phi^\dagger W_{\mu\nu} \phi\, B^{\mu\nu}$$

$$O_8^{(VS)} = \phi^\dagger W_{\mu\nu} \phi\, \tilde{B}^{\mu\nu}$$

$$O_9^{(VS)} = i\, (D_\mu\phi)^\dagger W^{\mu\nu} (D_\nu\phi)$$

$$O_{10}^{(VS)} = i\, (D_\mu\phi)^\dagger (D_\nu\phi) B^{\mu\nu}$$

$$O_{11}^{(VS)} = (\phi^\dagger\phi)\, [(D_\mu\phi)^\dagger (D^\mu\phi)]$$

$$O_{12}^{(VS)} = (\phi^\dagger D_\mu\phi)\, [(D_\mu\phi)^\dagger \phi]$$

$$O_{13}^{(VS)} = (D^2\phi)^\dagger (D^2\phi)$$

FERMILAB-PUB-84/74-T

VI.) Fermions and Scalars

$$O_1^{(FS)} = (\phi^\dagger\phi)(\bar{L}\phi E) + h.c.$$

$$O_2^{(FS)} = (\phi^\dagger\phi)(\bar{Q}\phi D) + h.c.$$

$$O_3^{(FS)} = (\phi^\dagger\phi)(\bar{Q}\tilde{\phi} U) + h.c.$$

$$O_4^{(FS)} = \partial_\mu(\phi^\dagger\phi)(\bar{L}\gamma^\mu L)$$

$$O_5^{(FS)} = \partial_\mu(\phi^\dagger\phi)(\bar{E}\gamma^\mu E)$$

$$O_6^{(FS)} = \partial_\mu(\phi^\dagger\phi)(\bar{Q}\gamma^\mu Q)$$

$$O_7^{(FS)} = \partial_\mu(\phi^\dagger\phi)(\bar{U}\gamma^\mu U)$$

$$O_8^{(FS)} = \partial_\mu(\phi^\dagger\phi)(\bar{D}\gamma^\mu D)$$

VII.) Vectors, Fermions and Scalars

$$O_1^{(VFS)} = i(\phi^\dagger\phi)(\bar{L}\gamma^\mu \overleftrightarrow{D}_\mu L)$$

$$O_2^{(VFS)} = i(\phi^\dagger\phi)(\bar{E}\gamma^\mu \overleftrightarrow{D}_\mu E)$$

$$O_3^{(VFS)} = i(\phi^\dagger\phi)(\bar{Q}\gamma^\mu \overleftrightarrow{D}_\mu Q)$$

$$O_4^{(VFS)} = i(\phi^\dagger\phi)(\bar{U}\gamma^\mu \overleftrightarrow{D}_\mu U)$$

$$O_5^{(VFS)} = i(\phi^\dagger\phi)(\bar{D}\gamma^\mu \overleftrightarrow{D}_\mu D)$$

$$O_6^{(VFS)} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{L}\gamma^\mu L)$$

$$O_7^{(VFS)} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{E}\gamma^\mu E)$$

$$O_8^{(VFS)} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q)$$

$$O_9^{(VFS)} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{U}\gamma^\mu U)$$

$$O_{10}^{(VFS)} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{D}\gamma^\mu D)$$

$$O_{11}^{(VFS)} = \bar{Q}\sigma_{\mu\nu} G^{\mu\nu}\tilde{\phi} U + h.c.$$

$$O_{12}^{(VFS)} = \bar{Q}\sigma_{\mu\nu} G^{\mu\nu}\phi D + h.c.$$

$$O_{13}^{(VFS)} = \bar{L}\sigma_{\mu\nu} W^{\mu\nu}\phi E + h.c.$$

$$O_{14}^{(VFS)} = \bar{Q}\sigma_{\mu\nu} W^{\mu\nu}\tilde{\phi} U + h.c.$$

$$O_{15}^{(VFS)} = \bar{Q}\sigma_{\mu\nu}W^{\mu\nu}\phi D + h.c.$$

$$O_{16}^{(VFS)} = \bar{L}\sigma_{\mu\nu}B^{\mu\nu}\phi E + h.c.$$

$$O_{17}^{(VFS)} = \bar{Q}\sigma_{\mu\nu}B^{\mu\nu}\tilde{\phi} U + h.c.$$

$$O_{18}^{(VFS)} = \bar{Q}\sigma_{\mu\nu}B^{\mu\nu}\phi D + h.c.$$

$$O_{19}^{(VFS)} = (\overline{D_\mu L})\phi D^\mu E + h.c.$$

$$O_{20}^{(VFS)} = (\overline{D_\mu Q})\tilde{\phi} D^\mu U + h.c.$$

$$O_{21}^{(VFS)} = (\overline{D_\mu Q})\phi D^\mu D + h.c.$$

$$O_{22}^{(VFS)} = \bar{L}(D_\mu \phi) D^\mu E + h.c.$$

$$O_{23}^{(VFS)} = \bar{Q}(D_\mu \tilde{\phi}) D^\mu U + h.c.$$

$$O_{24}^{(VFS)} = \bar{Q}(D_\mu \phi) D^\mu D + h.c.$$

$$O_{25}^{(VFS)} = (\overline{D_\mu L})(D^\mu \phi) E + h.c.$$

$$O_{26}^{(VFS)} = (\overline{D_\mu Q})(D^\mu \tilde{\phi}) U + h.c.$$

$$O_{27}^{(VFS)} = (\overline{D_\mu Q})(D^\mu \phi) D + h.c.$$

The low energy effects of the new interaction are described by the effective Lagrangian

$$\mathcal{L}_{eff} = \sum_{T=V}^{VFS} \sum_{i} \frac{1}{\Lambda^2} C_i^{(T)} O_i^{(T)} , \qquad (2)$$

where $C_i^{(T)}$ are C-number coefficients and Λ characterizes the new interaction scale. Notice that we have not imposed CP invariance and have included both CP even and CP odd operators. In particular, operators with a field strength and the analogous operators with the correpsonding dual have opposite CP parities. They can, in principle, induce CP violating effects and their corresponding coefficients (divided by Λ^2) will be constrained by empirical data on CP violation in the K^0-$\bar{K}^0$ system. It is, however, out of the scope of this note to perform such an analysis.

Of particular interest are operators involving only vectors and/or scalars. One of the most immediate consequences of these operators is the deviation of the W and Z masses from the standard model prediction. The operators $O_i^{(V)}$, $i = 8,10,11,13$, and $O_j^{(VS)}$, $j=3,5,7,11,12$, contribute to the W and Z masses through the quadratic terms in the effective Lagrangian (2). [SU(2)×U(1) breaking is accounted for by allowing the neutral component of ϕ to develop a vacuum expectation value $v/\sqrt{2}$]. This quadratic Lagrangian is given by

$$\mathcal{L}^{(W,Z)}_{quadratic} = W^+_\mu \Big\{ \Big[(2C_8^{(V)} + C_{10}^{(V)}) \frac{\partial^2}{\Lambda^2} - C_3^{(VS)} \frac{v^2}{\Lambda^2} \Big] (\partial^2 g^{\mu\nu} - \partial^\mu \partial^\nu)$$
$$+ \frac{1}{2} C_{11}^{(VS)} \frac{v^2}{\Lambda^2} M^2_{W(Std.)} g^{\mu\nu} - C_{13}^{(VS)} \frac{M^2_{W(Std.)}}{\Lambda^2} \partial^\mu \partial^\nu \Big\} W^-_\nu$$
$$+ \frac{1}{2} Z_\mu \Big\{ \Big[\Big[(2C_8^{(V)} + C_{10}^{(V)}) \cos^2\theta_W + (4C_{11}^{(V)} + 2C_{13}^{(V)}) \sin^2\theta_W \Big] \frac{\partial^2}{\Lambda^2}$$
$$- (C_3^{(VS)} \cos^2\theta_W + 2C_5^{(VS)} \sin^2\theta_W + C_7^{(VS)} \sin\theta_W \cos\theta_W) \frac{v^2}{\Lambda^2} \Big]$$
$$\cdot (\partial^2 g^{\mu\nu} - \partial^\mu \partial^\nu)$$
$$+ \frac{1}{2} (C_{11}^{(VS)} + C_{12}^{(VS)}) \frac{v^2}{\Lambda^2} M^2_{Z(Std.)} g^{\mu\nu} \tag{3}$$
$$- C_{13}^{(VS)} \frac{M^2_{Z(Std.)}}{\Lambda^2} \partial^\mu \partial^\nu \Big\} Z_\nu .$$

From (3) the W and Z masses are found to be

$$M_W^2 = M^2_{W(Std.)} \Big\{ 1 + \frac{M^2_{W(Std.)}}{\Lambda^2} \Big[2C_8^{(V)} + C_{10}^{(V)} + \frac{\sin^2\theta_W}{\pi\alpha} (C_3^{(VS)} + \frac{1}{2} C_{11}^{(VS)}) \Big] \Big\} \tag{4}$$

$$M_Z^2 = M^2_{Z(Std.)} \Big\{ 1 + \frac{M^2_{W(Std.)}}{\Lambda^2} \Big[2C_8^{(V)} + C_{10}^{(V)} + \tan^2\theta_W (4C_{11}^{(V)} + 2C_{13}^{(V)})$$
$$+ \frac{\sin^2\theta_W}{\pi\alpha} (C_3^{(VS)} \cos^2\theta_W + 2C_5^{(VS)} \sin^2\theta_W \tag{5}$$
$$+ C_7^{(VS)} \sin\theta_W \cos\theta_W + \frac{1}{2} C_{11}^{(VS)} + \frac{1}{2} C_{12}^{(VS)}) \Big] \Big\} ,$$

where $M_{W(std.)}$ and $M_{Z(std.)}$ are the standard model predictions of the W and Z masses, including radiative corrections, θ_W is defined by

$$M^2_{W(std.)}/M^2_{Z(std.)} \cos^2\theta_W = 1$$

and α is the fine structure constant.

To get an order of magnitude estimate of Λ, one can use the constraint from the ρ parameter, defined to be

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \quad . \qquad (6)$$

The experimental observation that ρ differs from the standard model value of 1 by no more than 2% implies, assuming all the coefficients to be of order unity, that $\Lambda \gtrsim 20\ M_{W(std.)} \sim 2$ TeV. This translates into a 1.5% (2.5%) deviation of M_W (M_Z) from its standard model value. This can be tested in future precise measurements of the W and Z masses, particularly in the Z factory.

Another interesting possibility arising from the operators containing only vectors and scalars concerns phenomena involving the Higgs particle. The operators $O_i^{(VS)}$, i=3,4,..., 10 , all contain a Z-Higgs-photon vertex. If the Higgs particle is lighter than the Z, these operators can enhance the decay $Z \to H\gamma$, thereby increasing the Z width. The signature of this decay depends on the dominant decay modes of the Higgs. In the standard model, it prefers to decay to the heaviest possible fermion pair. Thus, depending on the Higgs mass, one might see a single photon with a heavy lepton pair, such as $\tau^+\tau^-$, or a single photon with jets. It should be pointed out that the operators

$O_i^{(VS)}$, i=3,4,...,8 , also contain a H-γ-γ vertex, with a strength comparable to (or in some case stronger than) the Z-H-γ vertex. Hence, if the decay $Z \to H\gamma$ is enhanced by these operators to an observable level, so is the decay $H \to \gamma\gamma$. This would give a very distinctive signature, with only photons in the final state. Finally, the operators $O_1^{(VS)}$ and $O_2^{(VS)}$ could enhance the decay of Higgs to two gluons. All of these should be searched for in collider experiments.

An interesting alternative is that the Higgs is heavier than the Z. It was pointed out recently that a Higgs with a mass around 150 GeV together with an enhancement of its coupling to two gluons can account for some of the observed nonstandard events.[7]

The other operators of immediate interest are those which can contribute to the radiative decays of the weak gauge bosons: $Z \to l^+l^-\gamma$, $Z \to \nu\bar{\nu}\gamma$, and $W \to l\nu\gamma$. Some of the operators $(O_{13}^{(VF)}$ and $O_{14}^{(VF)})$ only contribute to $Z \to l^+l^-\gamma$, some $(O_{24}^{(VF)}$ and $O_{13}^{(VFS)})$ only contribute to $W \to l\nu\gamma$, some $(O_{19}^{(VFS)}$, $O_{22}^{(VFS)}$, and $O_{25}^{(VFS)})$ contribute to both $Z \to l^+l^-\gamma$ and $W \to l\nu\gamma$, and yet some $(O_7^{(VF)}$, $O_8^{(VF)}$, $O_{11}^{(VF)}$ and $O_{12}^{(VF)})$ contribute to all three types of processes. Thus, depending on the associated coefficients of these operators, any of such processes can be enhanced. For example, the decay $Z \to l^+l^-\gamma$ could be enhanced if the coefficients $C_{13}^{(VF)}$ and $C_{14}^{(VF)}$ assumed appropriate values.

In conclusion, we have listed all $SU(3) \times SU(2) \times U(1)$ invariant and baryon and lepton number conserving dimension six operators in the hope that they could be used in future phenomenological studies of deviations from the standard model due to a new interaction characterized by a scale Λ. A crude lower bound of 2 TeV on Λ is derived. Operators relevant to nonstandard events are pointed out. Interesting processes to search for include $Z \to H\gamma$, $H \to \gamma\gamma$ and $H \to gg$.

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