Bounds on Contact Interactions from LEP1 Data

and the High–$Q^2$ HERA Events

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Abstract

A contact four–fermion interaction between light quarks and electrons has been evoked as a possible explanation for the excess of events observed by HERA at high–$Q^2$. We explore the 1–loop effects of such interaction in $\Gamma(Z^0 \rightarrow e^+e^-)$ measured at LEP and impose strong bounds on the lower limit of the effective scale. Our results are able to discard some of the contact interactions as possible explanation for the HERA events.
Recently the H1 [1] and ZEUS [2] experiments at HERA have reported the observation of an excess of events, compared with the Standard Model prediction, in the reaction \( e^+p \rightarrow e^+X \) at very high–\( Q^2 \). The H1 Collaboration observed events seem to be concentrated at an invariant mass of \( \sim 200 \text{ GeV} \), what could suggest the presence of a \( s \)–channel resonant state. The ZEUS Collaboration data, however, are more spread in invariant mass. The probability of a statistical fluctuation seems to be quite small (less than \( 6 \times 10^{-3} \), for the H1 data). Nevertheless, up to this moment, it is not possible to establish the resonant or continuum aspect of the events.

It seems very hard to find an explanation for these events in the scope of the Standard Model, e.g. modifying the partonic distribution functions, or including new QCD corrections. Among the possible new physics explanations for these events, there is the \( s \)–channel production of leptoquarks or squarks of a R–parity violating supersymmetric model [3,4]. Besides this scenario, we can think of a non–resonant interpretation of the HERA data, which involves an effective four–fermion interaction \( eeqq \), where \( q = u, d \) quarks [4].

A convenient parametrization of the four–fermion contact interaction is [5],

\[
\mathcal{L}_{eeqq} = g^2 \sum_{i,j=L,R} \sum_{q=u,d} \eta_{i,j} \left( \frac{1}{\Lambda_{ij}^{qq}} \right)^2 \left( \bar{e}_i \gamma^\mu e_i \right) \left( \bar{q}_j \gamma_\mu q_j \right), \tag{1}
\]

where \( i, j \) refer to the different fermion helicities, and \( \eta_{i,j} = \pm 1 \) enables us to consider constructive and destructive interference with standard contribution to the processes. Such effective interaction can be generated at low energy by the exchange of a heavy particle in the \( t \)–channel between the quark and the electron lines. This appears naturally in models where quarks and leptons are composite particles through the exchange of some common constituent or of the binding particles. In the same fashion, interaction (1) can be used to describe the low energy limit of the exchange of a new heavy neutral particle, like the \( Z' \) gauge boson.

In general, bounds on the scale \( \Lambda_{ij}^{qq} \) are obtained assuming \( g^2/4\pi = 1 \) for the new strong interaction coupling. Lagrangian (1) has been used in Ref. [4,6] to fit the integrated \( Q^2 \) distributions of the HERA data, taking into account bounds on the scale \( \Lambda_{ij}^{qq} \) from CDF
Collaboration \cite{7} at Tevatron collider, as well as those from LEP \cite{8}, including the new ones obtained by the OPAL Collaboration at $\sqrt{s} = 170, 172$ GeV \cite{9}. Altarelli \textit{et al.} best fits were obtained for the $RL$ or $LR$ polarizations with the minimum allowed value for the scale $\Lambda_{ij}^{qq}$.

In this letter, we analyze the one–loop effect of the interaction (1) in the leptonic width of $Z^0$, and we employ the most recent LEP data \cite{10} on $\Gamma(Z^0 \to e^+e^-)$ to establish strong bounds on the scale $\Lambda_{ij}^{qq}$. We evaluate the relevant Feynman diagram (see Fig. 1) in dimensional regularization neglecting the external (electron) and internal (light quark) fermion masses. We retain only the leading non-analytical contributions from the loop diagram by making the identification

$$\frac{2}{4-d} \to \log \frac{\Lambda^2}{\mu^2}, \quad (2)$$

where $d = 4 - 2\epsilon$ is the space–time dimension, $\Lambda$ is the energy scale which characterizes the appearance of new physics, and $\mu$ is the scale involved in the process, which we choose $\mu = M_Z$ and we drop finite terms.

In this way, we obtain a quite compact result for the light quark loop contribution of the four–fermion interaction to $\Gamma(Z^0 \to e^+e^-) \equiv \Gamma_{ee}$,

$$\Delta\Gamma_{ee} = -\eta_{ij} \frac{\alpha}{6\pi s_W c_W} G_i^e G_j^q \frac{M_Z^3}{(\Lambda_{ij}^{qq})^2} \log \left(\frac{(\Lambda_{ij}^{qq})^2}{M_Z^2}\right), \quad (3)$$

where $s_W(c_W) = \sin \theta_W(\cos \theta_W)$ and $G_R^f = -Q^f s_W^2, G_L^f = T_3^f - Q^f s_W^2$, with $T_3^f$, and $Q^f$ being the third component of the weak isospin and electric charge of the fermion, respectively.

The most recent LEP experimental result \cite{10} can be compared with the Standard Model predictions for the leptonic width, $\Gamma_{ll} = 83.91 \pm 0.11$ TeV, in order to establish bounds on the scale $\Lambda_{ij}^{qq}$ through Eq. (3). The Standard Model result depends on the top quark and Higgs boson masses and we have generated using ZFITTER \cite{11} the results for $\Gamma_{ll}$ with the top quark mass in the range $m_{top} = 175 \pm 6$ GeV and for the Higgs boson mass $M_H = 60, 300, \text{and } 1000$ GeV (see Table I).

Our limits on the scale $\Lambda_{ij}^{qq}$ are summarized in Table I. We present the 95\% CL lower limit on the scale $\Lambda_{ij}^{qq}$ for different values of $m_{top}$ and $M_H$. Some comments are in order. As
can be seen from Table I, the experimental result coincides precisely with the SM prediction for $m_{\text{top}} = 175$ GeV and $M_H = 300$ GeV. The SM expectation is lower (higher) than the measured value for lighter (heavier) top quark and heavier (lighter) Higgs boson. In consequence, those interactions which yield a positive increase in the leptonic width are more severely constrained for larger $m_{\text{top}}$ and smaller $M_H$. The opposite holds for interactions which tend to decrease the leptonic width. In particular, contact interactions which decrease the leptonic $Z$ width are ruled out for a heavy Higgs boson and a light top quark for any value of the scale.

Table II shows that, taking for instance $m_{\text{top}} = 175$ GeV, and $M_H = 300$ GeV, our limits for $\Lambda_{\text{LL}}^{\pm q}, \Lambda_{\text{RL}}^{\pm q}$ ($q = u, d$), $\Lambda_{\text{LR}}^{\pm u}$, and $\Lambda_{\text{RR}}^{\pm u}$ are always stronger than those obtained recently by the OPAL Collaboration [8]. In particular for $\Lambda_{\text{RL}}^{\pm d}$ our limits are stronger than OPAL bounds for any value of $M_H$ and $m_{\text{top}}$. This result strongly disfavours the contact four–fermion interaction term $\Lambda_{\text{RL}}^{\pm d}$ as a possible solution for the HERA data puzzle. Moreover, other configurations suggested in Ref. [4,6], such as $\Lambda_{\text{LR}}^{-d} = 1.7$ TeV, $\Lambda_{LR}^{+u} = 2.5$ TeV, $\Lambda_{RL}^{+d} = 2.5$ TeV, or the combination $\Lambda_{LR}^{+u} = \Lambda_{RL}^{+d} = 3$ TeV are not allowed for large values of $M_H$ with a light top quark.

In conclusion, we have shown that the one–loop contribution to leptonic $Z^0$ width coming from contact effective interactions involving electrons and light quarks can lead to a strong bound on the compositeness scale $\Lambda_{ij}^{\pm q}$. These bounds are in general more stringent than the ones obtained from the tree–level contribution to the total cross section $e^+ e^- \rightarrow q\bar{q}$ directly measure at LEP [8,9].

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FIG. 1. Feynman diagram leading to the correction of $\Gamma_{ll}$. 
TABLES

TABLE I. Standard Model prediction for $\Gamma_{ll}$, in MeV, for different values of $m_{\text{top}}$ and $M_H$.

| $m_{\text{top}}$ | 169  | 175  | 181  |
|------------------|------|------|------|
| 1000             |      |      |      |
| $M_H$ 300        | 83.72| 83.77| 83.82|
| 60               | 83.96| 84.02| 84.08|

TABLE II. 95% CL limits on the effective contact interaction scale $\Lambda_{ij}^{\eta}$ in TeV. In the entries marked as “—” no value of $\Lambda_{ij}^{\eta}$ is allowed.

|               | $\bar{e}e\bar{u}u$ | $\bar{e}e\bar{d}d$ |
|---------------|---------------------|---------------------|
|               | $\eta = -1$         | $\eta = +1$         | $\eta = -1$         | $\eta = +1$ |
| $m_{\text{top}}$ | 169 175 181         | 169 175 181         | 169 175 181         | 169 175 181 |
| $LL$ $M_H$ 300 | 1000               | 1000               | 1000               | 1000         |
| 1000          | — 5.8 3.6           | 1.6 1.7 1.9        | 1.8 1.9 2.2        | — 6.5 4.1    |
| 2.9 2.4 2.1   | 2.1 2.4 2.9         | 2.4 2.7 3.3        | 3.3 2.7 2.4        |
| 2.1 1.8 1.6   | 2.9 4.2 12          | 3.3 4.7 14         | 2.4 2.1 1.8        |
| 1000 1.0 1.1 1.2 | — 3.6 2.3          | — 2.4 1.5         | 0.6 0.7 0.8        |
| 1.3 1.5 1.8   | 1.8 1.5 1.3         | 1.2 1.0 0.8        | 0.8 1.0 1.2        |
| 1.8 2.6 7.9   | 1.3 1.1 1.0         | 0.8 0.7 0.6        | 1.2 1.7 5.3        |
| $LR$ $M_H$ 300 | 1000               | 1000               | 1000               | 1000         |
| 1.4 1.6 1.8   | 1.8 5.3 3.3         | — 6.0 3.8          | 1.6 1.8 2.0        |
| 1.9 2.2 2.7   | 2.7 2.2 1.9         | 3.0 2.5 2.2        | 2.2 2.5 3.0        |
| 2.7 3.9 11    | 1.9 1.7 1.5         | 2.2 1.9 1.7        | 3.0 4.3 13         |
| $RL$ $M_H$ 300 | 1000               | 1000               | 1000               | 1000         |
| 3.4 2.1 0.9   | 0.9 1.0 1.1         | 0.6 0.6 0.7        | — 2.2 1.4          |
| 1.7 1.4 1.2   | 1.2 1.4 1.7         | 0.8 0.9 1.1        | 1.1 0.9 0.8        |
| 1.2 1.0 0.9   | 1.7 2.4 7.3         | 1.1 1.6 4.9        | 0.8 0.7 0.6        |
| $RR$ $M_H$ 300 | 1000               | 1000               | 1000               | 1000         |
| 1.7 1.4 1.2   | 1.2 1.4 1.7         | 0.8 0.9 1.1        | 1.1 0.9 0.8        |
| 1.2 1.0 0.9   | 1.7 2.4 7.3         | 1.1 1.6 4.9        | 0.8 0.7 0.6        |