Measurements of neutral current processes off the Z-peak are sensitive probes of new interactions, which may be induced by the exchange of new particles such as leptoquarks or extra Z's. This talk reviews the phenomenology of extra interactions in four-fermion processes and updates a global fit to contact terms in the neutral current sector.

1 Introduction

Ever since the discovery of weak neutral currents (NC) at Gargamelle 25 years ago, their study has been a proving ground for the Standard Model (SM). During this period, the precision with which the SM has been confirmed has been improved dramatically, now reaching the 0.1% level in Z-pole precision experiments. Despite these successes of the SM, NC processes remain an excellent tool to search for, and perhaps discover, signals for new interactions and, hence, physics beyond the SM. The observation, two years ago at HERA, of an apparent excess of events in deep inelastic scattering at high $Q^2$ is a case in point, even though the excess has not been confirmed by subsequent observations. This possible signal for new physics has triggered much research, which has led to a better understanding of the experimental constraints on new interactions in the NC sector. This talk tries to summarize these constraints in a model independent way.

Precision experiments on NC interactions can largely be understood as four-fermion scattering, and among these $\ell\ell qq$ amplitudes are particularly important. In Section 2 we start out by describing these four fermion NC amplitudes in the SM, and discuss the general form of deviations due to new interactions. Two such deviations, from very different sources, are discussed in some detail: extra Z bosons are considered in Section 3. Section 4 deals

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with leptoquarks, whose low energy effects can also be described as effective neutral current interactions.

While experiments at the high energy frontier (HERA for leptoquark searches, the Tevatron for extra $Z$s) can search for direct resonances of these new particles, most other experiments can be analyzed in a more model-independent way, via effective four-fermion contact terms. We discuss the general form of such contact terms in Section 5. The main part of this talk deals with present experimental constraints on new NC interactions which can be described in the contact term approximation. Section 6 gives a summary of the available data on lepton-quark four-fermion interactions, away from the $Z$-peak. These data are then used in Section 7 to perform a global fit of $eeqq$ contact terms. This fit is an update of the one performed in 1997 and includes new HERA, LEP2, Tevatron, and neutrino scattering data. Final conclusions are drawn in Section 8.

2 Neutral Current Exchange within the SM

Neutral current four fermion interactions in the Standard Model are due to photon and $Z$-exchange. For definiteness, let us consider electron-quark interactions, as in $e^+e^- \rightarrow q\bar{q}$ annihilation, deep-inelastic scattering (DIS) experiments, or atomic parity violation (APV). Generalization to four lepton processes or neutrino-nucleon scattering will be straightforward.

It is convenient to first discuss the amplitudes for the scattering process $e_\alpha q_\beta \rightarrow e_\alpha q_\beta$, where $\alpha, \beta = L, R$ denote the chirality of the individual fermions. The restriction to equal initial and final state chiralities for the electron and quark, respectively, anticipates chirality conservation in gauge boson interactions. The scattering amplitude can be decomposed into a reduced amplitude, which contains the full dynamical information on NC interactions, and wavefunction factors, which separate out all angular and spin correlation information in terms of the external Dirac spinors $\psi_i = u(p_i, \sigma_i), v(p_i, \sigma_i)$.

\[
M(e_\alpha q_\beta \rightarrow e_\alpha q_\beta) = \overline{\psi}_e \gamma^\mu P_\alpha \psi e \overline{\psi}_q \gamma^\mu P_\beta \psi q \, M_{\alpha\beta}^{eq}.
\]

Within the SM, the reduced amplitudes, $M_{\alpha\beta}^{eq}$, $\alpha, \beta = L, R$, are given by

\[
M_{\alpha\beta}^{eq}(q^2)_{SM} = \frac{e^2 Q_e Q_q}{q^2} + \frac{g_Z^2 (T_{f_\alpha}^3 - s_w^2 Q_e) (T_{f_\beta}^3 - s_w^2 Q_q)}{q^2 - m_Z^2},
\]

where $Q_f$ and $T_{f_\alpha}^3$ are the charge and third component of weak isospin, respectively, of the external fermion $f_\alpha$, and the coupling constant factors can be written in terms of the weak mixing angle as $g_Z = e/(\sin \theta_w \cos \theta_w), s_w = \sin \theta_w$. 2
A major advantage of the decomposition of Eq. (1) is that the dynamics of crossing related processes is given by the same reduced amplitudes, at the appropriate value of the momentum transfer $q$. For example,

$$q^2 = \hat{s} = (E_{c.m.})^2$$  
for $e^+e^- \rightarrow q\bar{q}$, 

$$q^2 = \hat{t} = -Q^2 = -s_{xy}$$  
for $e^\pm p \rightarrow ejX$, \hspace{1cm} (3) 

$$q^2 = \hat{s} = sx_1x_2$$  
for $p\bar{p} \rightarrow e^+e^-X$.

For $s$-channel processes in the vicinity of the $Z$-pole, one needs to replace the $Z$-propagator by its Breit-Wigner form,

$$q^2 - m_Z^2 \rightarrow \hat{s} - m_Z^2 + i \hat{s} \frac{\Gamma_Z}{m_Z}.$$ \hspace{1cm} (4)

Any new physics contributions to NC processes can be parameterized by adding an additional term to the reduced amplitude,

$$M_{\alpha\beta}^{eq}(q^2) = M_{\alpha\beta}^{eq}(q^2)_{SM} + \eta_{eq}^{\alpha\beta}(q^2).$$ \hspace{1cm} (5)

For a large class of new interactions (examples will be given later) the new physics contributions $\eta_{eq}^{\alpha\beta}$ vary slowly with $q^2$, effectively being constant at energies accessible to present experiments. In this case the $\eta_{eq}^{ij}$ correspond to constant four-fermion contact interactions (see Section 5), and Eq. (5) relates the sensitivity to new physics of all experiments probing a given combination of external quarks and leptons, such as $ep \rightarrow eX$, $p\bar{p} \rightarrow e^+e^-X$, $e^+e^- \rightarrow$ hadrons and atomic physics parity violation experiments.

For a comparison with precision data, electroweak radiative corrections must be included in the reduced amplitudes discussed above. This is largely achieved by replacing the coupling constants of the reduced amplitude (2) by running couplings

$$e^2 \rightarrow \tilde{e}^2(q^2),$$  
$$\sin^2\theta_w \rightarrow \tilde{s}^2(q^2)$$  
$$g_Z^2 \rightarrow \tilde{g}_Z^2(q^2),$$ \hspace{1cm} (6)

and by adding typically small, process specific vertex and box corrections.

The photon and $Z$ couplings which define the SM amplitudes need to be extracted from data, which may contain the effects of both SM and new interactions. A priori, this mingling of SM and new physics effects presents a problem. In practice, however, the two decouple. The parameters which define the SM may be taken as the fine-structure constant in the Thomson
limit, \( \alpha_{\text{QED}} = \frac{\bar{e}^2(0)}{4\pi} = 1/137.036 \), the \( Z \)-mass and the value of \( \bar{s}^2(m_Z^2) \) as determined on the \( Z \)-pole, the top-quark mass as determined at the Tevatron and the Higgs mass obtained from fits to \( Z \) data and the measured \( W \)-mass. All these parameters are essentially unaffected by the \( \eta_{\alpha\beta}^{I/I'} \) in Eq. (5). At \( q^2 \to 0 \), photon exchange completely dominates the NC amplitudes and the measured fine-structure constant is not affected by the new interactions which are due to the exchange of heavy quanta. Precision experiments on the \( Z \)-pole have put very stringent limits on possible \( Z-Z' \) mixing effects, and we can safely ignore them in a phenomenological analysis of \( Z' \) effects on other NC observables. This leaves deviations \( \eta_{\alpha\beta}^{I/I'} \) from the SM which are essentially constant and real in the vicinity of the \( Z \)-pole and, hence, do not interfere with the purely imaginary \( Z \)-contribution on top of the \( Z \)-resonance. A corollary to this statement is the fact that \( Z \)-data are quite insensitive to additional NC contact interactions and the constraints on the latter, to be derived in Section 5, are stringent enough to exclude significant effects on the \( Z \)-pole data. Thus, we can use the fine-structure constant and \( Z \)-pole data to define the SM and then study other NC data to probe for possible evidence of new interactions. Because electroweak fits are completely dominated by the high precision \( Z \)-data for our purposes it does not matter whether one determines the SM parameters from a global fit or from the \( Z \) data alone.

3 Models with extra \( Z \) bosons

Many models of physics beyond the SM involve extensions of the \( SU(3) \times SU(2)_L \times U(1) \) gauge symmetry, be it grand unified theories, horizontal symmetries, or extra \( W' \) and/or \( Z' \) gauge bosons. For our analysis of new interactions in the NC sector it is sufficient to consider models with extra \( U(1) \) symmetries, i.e. extensions

\[
SU(3) \times SU(2)_L \times U(1)_1 \times U(1)_2 \to SU(3) \times SU(2)_L \times U(1)_Y,
\]

where the two extra \( U(1) \) factors are spontaneously broken to the hypercharge symmetry of the SM, leaving behind a massive gauge boson \( Z_E \), in addition to the still massless hypercharge and \( W^3 \) gauge fields of the SM. As mentioned before, LEP1 and SLC precision data imply that mixing of the \( Z_E \) with the SM gauge fields is negligible. Let us call \( g_E \) the gauge coupling of this extra \( Z \) boson, and denote the \( Z_E \) couplings to a fermion \( f \) of chirality \( \alpha = L,R \) by \( g_{\alpha}^{Z_E f} \). The exchange of this extra \( Z \) boson will alter the reduced amplitudes of Eq. (3) to

\[
M_{\alpha\beta}^{eq}(q^2) = M_{\alpha\beta}^{eq}(q^2)_{\text{SM}} + \frac{g_E^2}{q^2 - m_{Z_E}^2} g_{\alpha}^{Z_E f} g_{\beta}^{Z_E f}
\]

(8)
Table 1: Charges of the electroweak fermion multiplets under the $U(1)$ factors contained in $E_6$, as given in Eq. (10). Note that an extra $Z_\psi$ couples purely axially to both quarks and leptons.

|         | $Y\sqrt{24}Q_\chi$ | $\sqrt{72/5}Q_\psi$ |
|---------|---------------------|----------------------|
| $(\nu,e)_L$ | $-\frac{1}{2}$     | 3                    |
| $\nu_R$  | 0                   | 5                    |
| $e_R$    | -1                  | 1                    |
| $(u,d)_L$ | $\frac{1}{2}$       | -1                   |
| $u_R$    | $-\frac{3}{2}$     | 1                    |
| $d_R$    | $-3$                | -1                   |

For experiments which operate at $|q^2| << m_{Z_E}^2$, the $Z_E$ propagator may be approximated by a constant, and the overall effect of $Z'$ exchange is an approximately constant addition to the SM reduced amplitude, given by

$$\eta_{\alpha\beta}^{eq} = -\frac{g_{E_6}^2}{m_{Z_E}^2} g_{Z_E}^{Z_E\alpha\beta} g_{Z_E}^{Z_E\alpha\beta} \left(1 + \frac{q^2}{m_{Z_E}^2} + \cdots \right).$$

(9)

The non-observation of an extra $Z$ resonance in Tevatron Drell-Yan data suggests that a $Z_E$, if it exists, must be sufficiently heavy to make the contact term approximation of Eq. (9) valid for all but the highest energy experiments, probing momentum transfers in excess of $|q^2| \approx 10^5$ GeV$^2$.

The chiral charges $g_{Z_E \alpha\beta} = Q_E$ of the various quark and lepton multiplets are model dependent. As an example, let us consider a popular class of $Z'$ models, namely extra $U(1)$ symmetries which allow to embed the known fermions into 27 dimensional representations of $E_6$. $E_6$ models have been studied as candidates for grand unified theories and also as a “low-energy” manifestation of strings.

Extra $U(1)$ factors can arise in two steps of the $E_6$ breaking chain

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi,$$

(10)

with two extra $Z$ bosons, $Z_\psi$ and $Z_\chi$, respectively. The $U(1)$ charges $Q_\chi$ and $Q_\psi$ are fixed by the embedding of the known fermion representations into the 27 of $E_6$, and are given in Table [1]. In these models, in the absence of mixing with the SM $Z$-boson, the lightest extra $Z$ boson is a linear combination of the $Z_\psi$ and $Z_\chi$ fields and consequently the chiral charges $g_{Z_E \alpha\beta} = Q_E$ of (9) can be written as

$$Q_E = Q_\chi \cos \beta_E + Q_\psi \sin \beta_E,$$

(11)

with the mixing angle $\beta_E$ a free parameter in phenomenological studies, and the $Q_\chi$ and $Q_\psi$ charges given in Table [1].
The most direct observation of a $Z'$ is possible at the Tevatron, as a resonance in Drell-Yan $\ell^+\ell^-$ production. The non-observation of such a resonance in the 110 fb$^{-1}$ of run I data has allowed the CDF Collaboration to place a lower bound\(^1\) of approximately

$$m_{Z_E} > 600 \text{ GeV} \quad \text{at 95\% CL.}$$

Precise bounds depend somewhat on the value of the mixing angle $\beta_E$, and range between 565 and 620 GeV for a discrete set of models considered by CDF. In addition these mass bounds assume a $U(1)$ gauge coupling of strength similar to the SM hypercharge coupling, $g_E = g_Y = e/\cos \theta_w$.

For all other present experiments, a $Z_E$ mass in excess of 600 GeV is extremely heavy, and fully justifies the contact term approximation of Eq. (9). A global analysis, using data from a large set of NC experiments, has recently been performed by Cho et al.\(^2\) Results are shown in Fig. 1 assuming $g_E = g_Y$. A more general analysis, allowing an arbitrary $g_E$ coupling and kinetic mixing of the SM $Z$ and the $Z_E$, has been performed in Ref. [21], demonstrating that $Z$-pole data severely limit any mixing effects, while other low energy data provide the most stringent constraints in the absence of mixing.

Fig. 1 shows that the low energy constraints are somewhat weaker than
the Tevatron bounds from the direct search. One must keep in mind, however, that the Tevatron sensitivity quickly disappears for \( Z_E \) masses closer to the absolute kinematic limit set by the machine energy of 1.8 TeV. The low energy bounds, on the other hand, are on the combination \( g_E^2/m_Z^2 \), which appears in Eq. (3), and thus also rule out TeV scale \( Z_E \)’s with large gauge couplings. Even though such strongly interacting \( U(1) \) gauge bosons are not expected in the context of GUT models, the different sensitivity of low energy and direct search experiments to mass and couplings of a \( Z_E \) demonstrate their complementarity.

4 Leptoquark models

It is fairly obvious that an extra neutral gauge boson \( Z_E \) will lead to new NC interactions. However, very different types of new particles can have similar effects at low energies. One prominent example is the exchange of leptoquarks, scalar or spin-1 bosons whose emission transforms quarks into leptons and vice versa. We will only consider scalar leptoquarks in the following. The reason is that within the framework of renormalizable field theories, elementary vector leptoquarks can only appear as gauge bosons. Since they must carry both color and electroweak charges they will be the gauge bosons of a grand unified symmetry and consequently are much too heavy to be relevant for measurable effects in NC experiments. Composite models might produce TeV scale vector leptoquarks as bound states, but since we want to consider calculable models only, we disregard this possibility here.

As a first example, motivated by the excitement about a possible \( eq \) resonance in \( ep \) collisions at HERA, consider a leptoquark \( \phi \) which could give such a resonance via

\[
\phi^+ d \to \phi \to e^+ d. \tag{13}
\]

The only renormalizable interactions giving this process are the Yukawa interactions

\[
\mathcal{L}_{LQ} = \lambda \overline{d_L} e_R \phi \quad \text{with} \quad Y(\phi) = Y(d_L) - Y(e_R) = \frac{1}{6} - (-1) = \frac{7}{6}, \tag{14}
\]

or

\[
\mathcal{L}_{LQ} = \lambda \overline{d_R} e_L \phi \quad \text{with} \quad Y(\phi) = Y(d_R) - Y(e_L) = -\frac{1}{3} - \left(-\frac{1}{2}\right) = \frac{1}{6}. \tag{15}
\]

Clearly, only one of these terms can be realized since the hypercharge assignments, \( Y(\phi) \), of the leptoquark are different in the two cases. In addition, \( SU(2)_L \) invariance requires that this leptoquark be a member of an \( SU(2)_L \) doublet, since the fermion fields have combined weak isospin 1/2.
In the first case, for a $Y(\phi) = 7/6$ leptoquark coupling to $d_L e_R$, the leptoquark contributes to $e_R^+ d_L \rightarrow e_R^+ d_L$ scattering, and the corresponding amplitude is given by

$$M = -\lambda^2 \frac{1}{q^2 - m_\phi^2} e_R d_L = \frac{1}{2} \frac{\lambda^2}{\hat{s} - m_\phi^2} e_R \gamma^\mu \gamma^5 e_R d_L \gamma^\mu d_L,$$  

(16)

where, in the second step, a Fierz rearrangement has been performed. Obviously, $s$-channel leptoquark exchange leads to the same spin structure as $t$-channel NC exchange, and for momentum transfers well below the leptoquark mass the leptoquark contributions leads to an approximately constant addition

$$\eta_{ed} = -\frac{1}{2} \frac{\lambda^2}{m_\phi^2} \left( 1 + \hat{s} + \cdots \right)$$  

(17)

to the reduced amplitude of Eq. 9. As a result, leptoquark effects can be analyzed in a search for new interactions in the NC sector.

This equivalence of leptoquark and NC exchange in low energy experiments is not limited to the specific model of Eq. 14. Another example is provided by R-parity violating SUSY models, where an up-type squark, preferentially a scharm or stop, acts like a leptoquark. These models are obtained by adding a lepton-number violating but baryon number conserving term

$$W_R = \lambda_{ij} L_i Q_j D_k^c$$  

(18)

to the superpotential of the MSSM. Here $L$, $Q$ and $D$ denote the superfields describing lepton and quark doublets and the righthanded down-quark field, respectively, and $i, j, k$ are generation indices. This addition to the superpotential leads to Yukawa couplings of squarks and sleptons,

$$\mathcal{L}_R = \lambda_{ij} \left( \bar{e}_i^c d_R^c u_L^c + \bar{u}_L^c d_R^c e_i^c + \bar{d}_R^c \gamma^\mu \gamma^5 d_L + \bar{u}_L^c \gamma^\mu \gamma^5 u_i^c 
- \bar{d}_R^c \gamma^\mu \gamma^5 d_L - \bar{d}_L^c \gamma^\mu \gamma^5 d_R + \n + \text{h.c.} \right).$$  

(19)

For $\lambda_{ij} \neq 0$, the $\bar{u}_L^c$ and $\bar{d}_R^c$ terms lead to $ed$ and $\nu d$ scattering via squark exchange. At energies well below the squark masses these interactions can again effectively be described by a four-fermion contact interaction,

$$\mathcal{L}_{ed} = \frac{(\lambda_{ij})^2}{m_{\bar{u}_L^c}^2} \bar{e}_i^c d_R^c d_L e_L + \frac{(\lambda_{ij})^2}{m_{\bar{d}_R^c}^2} \bar{\nu}_L d_R^c d_L \nu_L$$

$$= \left( \frac{(\lambda_{ij})^2}{2m_{\bar{u}_L^c}^2} e_L \gamma^\mu e_L - \frac{(\lambda_{ij})^2}{2m_{\bar{d}_R^c}^2} \nu_L \gamma^\mu \nu_L \right) \bar{d}_R^c \gamma_\mu d_L.$$

(20)
A Fierz rearrangement has again cast the interaction into NC form. Another interesting feature emerges here. For equal squark masses, \( m_{\tilde{u}_j^L} = m_{\tilde{d}_j^L} \), the resulting contact interaction is \( SU(2)_L \) symmetric,

\[
\eta_{LR}^{ed} = -\frac{(\lambda'_{1ij})^2}{2m^2_{\tilde{u}_j^L}} = -\frac{(\lambda'_{1ij})^2}{2m^2_{\tilde{d}_j^L}} = \eta_{LR}^{ed}.
\]  

This relation is expected to be satisfied for squarks of the first two generations, but may be violated substantially for stop and sbottom squark exchange.

5 Model independent description

In the previous two Sections we have seen how very different new physics contributions can give rise to very similar changes in NC amplitudes, provided the mass of the exchanged new particle is well above the typical momentum transfer which is accessible experimentally. Under this assumption a universal description in terms of NC four-fermion contact terms is possible. Let us consider the case of electron-quark contact interactions in detail. The generalization to other flavors will be straightforward.

The most general \( eeqq \) current-current contact interaction can be parameterized as

\[
\mathcal{L}_{NC} = \sum_q \left[ \eta_{LL}^{eq} (\bar{e}_L \gamma_\mu e_L) (\bar{q}_L \gamma^\mu q_L) + \eta_{RR}^{eq} (\bar{e}_R \gamma_\mu e_R) (\bar{q}_R \gamma^\mu q_R) \\
+ \eta_{LR}^{eq} (\bar{e}_L \gamma_\mu e_L) (\bar{q}_R \gamma^\mu q_R) + \eta_{RL}^{eq} (\bar{e}_R \gamma_\mu e_R) (\bar{q}_L \gamma^\mu q_L) \right].
\]  

The coefficients \( \eta_{\alpha\beta}^{eq} \) exactly correspond to the extra contributions to reduced amplitudes in Eq. (5). Conventionally they are expressed as \( \eta_{\alpha\beta}^{eq} = \epsilon 4\pi/\Lambda_{eq}^2 \), where \( \epsilon = \pm 1 \) allows for either constructive or destructive interference with the SM \( \gamma \) and \( Z \) exchange amplitudes and \( \Lambda_{eq} \) is the effective mass scale of the contact interaction.

Even though contact interactions were originally introduced in the context of composite models, the discussion of the previous Sections shows that they are the tools of choice in a much wider context. How general, however, is this parameterization of low-energy effects in \( eeqq \) interactions? Using symmetry arguments we can show that it is general enough for all practical purposes. From the success of the SM in describing electroweak precision data we are confident that \( SU(2)_L \times U(1) \) gauge invariance is indeed a (spontaneously broken) symmetry of nature. This implies that the contact term Lagrangian must be \( SU(2)_L \times U(1) \) symmetric, with possible violations only arising from mass
splittings of the heavy quanta in the same $SU(2)$ multiplet (see discussion at
the end of Section 4). Symmetry restrictions on the dimension-six effective La-
grangian have been analyzed in detail. Considering first generation fermions
only, i.e. limiting the fermion content to the fields $L = (\nu_L, e_L), Q = (u_L, d_L),
e_R, u_R, and d_R$, the most general $SU(2)_L \times U(1)$ gauge invariant contact term
Lagrangian of energy dimension six can be written as
\[ \mathcal{L}_{SU(2)} = \eta_1 \overline{L} \gamma^{\mu} L \overline{Q} \gamma_{\mu} Q + \eta_2 \overline{L} \gamma^{\mu} T^a \overline{L} \gamma_{\mu} T^a Q + \eta_3 \overline{L} \gamma^{\mu} L \overline{u}_R \gamma_{\mu} u_R \\
+ \eta_4 \overline{L} \gamma^{\mu} L \overline{d}_R \gamma_{\mu} d_R + \eta_5 \overline{e}_R \gamma^{\mu} e_R \overline{\nu}_L \gamma_{\mu} Q + \eta_6 \overline{e}_R \gamma^{\mu} e_R \overline{u}_R \gamma_{\mu} u_R \\
+ \eta_7 \overline{e}_R \gamma^{\mu} e_R \overline{d}_R \gamma_{\mu} d_R \\
+ \left( \eta_8 \overline{e}_R \overline{d}_R Q + \eta_9 \overline{e}_R \overline{Q} u_R + \eta_{10} \overline{e}_R \sigma^{\mu\nu} e_R \overline{Q} \sigma_{\mu\nu} u_R + \text{h.c.} \right). \] (23)

All but the last three are of current-current type and can directly be related
to the parameters appearing in Eq. (22). The $\eta_8$ and $\eta_9$ terms can be written
as
\[ \mathcal{L}_{8,9} = \eta_8 \left( \overline{\nu} L e_R \overline{d}_R u_L + \overline{\nu} L e_R \overline{Q} d_L \right) + \eta_9 \left( \overline{\nu} L e_R \overline{d}_R u_R - \overline{\nu} L e_R \overline{u}_R u_R \right) + \text{h.c.}. \] (24)

Both terms induce helicity-non-suppressed $\pi^- \rightarrow e^\nu_R \nu_L$ decay and are severely
constrained by data. The same is true for the tensor term $\eta_{10}$, which
contributes to $\pi^- \rightarrow e^\nu_R \nu_L$ via a photon loop. Baring cancellations between
the three terms, the experimental constraints on the scalar and tensor coefficients
$\eta_i = \pm 4\pi/\Lambda_i^2$ can be expressed as
\[ \Lambda_8, \Lambda_9 \gtrsim 500 \text{ TeV}, \\
\Lambda_{10} \gtrsim 90 \text{ TeV}. \] (25)

Both bounds are so stringent that no visible signal can be expected in any of
the NC experiments to be discussed below, and we can safely ignore the scalar
and tensor terms in the following.

Let us turn back to the current-current type contact terms in the La-
grangian of Eq. (23). The seven free parameters directly correspond to the
eight different $e e u u$ and $e e d d$ coefficients $\eta_{\alpha\beta}^q$ in Eq. (22). Thus, $SU(2)$ pro-
vides only one constraint among $e e q q$ contact terms, namely
\[ \eta_{\alpha L}^q = \eta_5 = \eta_{\alpha L}^d. \] (26)

The main benefit of the $SU(2)$ symmetry is to relate electron and neutrino
couplings:
\[ \eta_{\nu L}^{\nu L} = \eta_1 + \frac{1}{4} \eta_2 = \eta_{\nu L}^{e d}, \]

10
\[ \eta_{LL}^{ud} = \eta_1 - \frac{1}{4} \eta_2 = \eta_{LL}^{eu}, \]
\[ \eta_{LR}^{ud} = \eta_3 = \eta_{LR}^{EU}, \]
\[ \eta_{LR}^{ed} = \eta_4 = \eta_{LR}^{ed}. \]  

As is evident from Eq. (27), \( SU(2) \) does not relate the \( \eta_{LL}^{eq} \) for different quark flavors. The difference \( \eta_{LL}^{ed} - \eta_{LL}^{eu} = \eta_2/2 \) measures the exchange of isospin triplet quanta between left-handed leptons and quarks, as indicated by the presence of the \( SU(2) \) generators \( T^a = \sigma^a/2 \) in the \( \eta_2 \) term. This term also provides an \( e\nu ud \) contact term in CC processes. Such contributions, however, are severely limited by lepton-hadron universality of weak charged currents within the experimental verification of unitarity of the CKM matrix. The experimental values

\[ |V_{ud}^{\text{exp}}| = 0.9740 \pm 0.0010, \quad |V_{us}^{\text{exp}}| = 0.2196 \pm 0.0023, \quad |V_{ub}^{\text{exp}}| = 0.0032 \pm 0.0008, \]

lead to the constraint

\[ (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) \left( 1 - \frac{\eta_2}{4\sqrt{2}G_F} \right)^2 = 0.9969 \pm 0.0022, \]

when flavor universality of the contact interaction is assumed. As a result \( \eta_2 \) must be small, though not necessarily negligible,

\[ \eta_2 = (0.102 \pm 0.073) \text{ TeV}^{-2}. \]

When considering constraints from neutrino scattering experiments in the next Section, we will want to invoke \( SU(2) \) symmetry and \( e\mu \) universality in order to restrict the number of free parameters. In addition to using the relations of Eqs. (26) and (27), we will also impose the CC constraint on \( \eta_2 \) when neutrino data are included in the fits.

In the discussion above we have considered first generation quarks and leptons only, because the “HERA anomaly” raises particular interest in such couplings. In principle, all \( \eta \)’s carry four independent generation indices and may give rise to other flavor conserving and flavor changing transitions. The non-observation of intergenerational transitions like \( K \rightarrow \mu e \) puts severe experimental constraints on flavor changing couplings. We therefore take a phenomenological approach and restrict our discussion to first generation contact terms. Only where required by particular data (e.g. when including \( \nu_e N \) scattering) will we assume universality of contact terms between electrons and muons.
6 Overview of Neutral Current Data

Many different experiments have been performed to test the NC sector of the SM. In the following we are interested in a model independent analysis of possible new interactions, in terms of effectively constant four fermion contact terms. As explained before, these contact terms hardly influence the $Z$-pole data, which can therefore be used to extract the parameters which define the SM, like $m_Z$, $\sin^2 \theta_W$, or the best fit value for the Higgs mass. In practice, a global fit of all experiments to the SM parameters gives results very similar to a fit of $Z$-pole data only, and therefore we use the “best fit” results as given in 1998 by the Particle Data Group to define the SM, against which we compare off $Z$-pole data in our search for new NC interactions.

The search for new interactions in the leptonic sector, via $e e \ell \ell$ contact terms, is discussed elsewhere in these proceedings. Thus, we concentrate our attention to $eeqq$ contact terms. This analysis is an update of the one performed a year ago and we follow the basic procedure developed there. Relevant constraints arise from a variety of experiments:

1. atomic parity violation (APV)
2. polarized lepton nucleon scattering
3. DIS at HERA
4. Drell-Yan production of lepton pairs at the Tevatron
5. $e^+e^- \rightarrow \text{hadrons}$ at LEP2 and
6. $\nu_\mu$–nucleon scattering.

For the first five data sets we can perform a completely model-independent analysis, in terms of the eight parameters $\eta_{eu}^{\alpha \beta}$ and $\eta_{ed}^{\alpha \beta}$. In order to include neutrino-nucleon scattering data, we must assume $e-\mu$ universality and $SU(2)$ symmetry of the contact terms, as given by Eq. (27). We now discuss these various data sets in turn. Additional details can be found in Refs. [6,14].

6.1 Atomic Parity Violation

Parity violation in the SM is due to weak gauge boson exchange, with vector-axial-vector (VA) and axial-vector-vector (AV) terms contributing. Atomic physics parity violation experiments measure the weak charge $Q_W$ of heavy atoms, which is given by

$$Q_W = -2 \left[ C_{1u}(2Z + N) + C_{1d}(Z + 2N) \right],$$

(31)
where \( Z \) and \( N \) are the number of protons and neutrons respectively in the nucleus of the atom. Here the \( C_{1q} \) are the coefficients describing \( A_e V_q \) couplings in a contact term description of standard model \( eeqq \) NC couplings. The new physics contact terms of Eq. (22) lead to a shift of these couplings,

\[
\Delta C_{1q} = \frac{1}{2\sqrt{2}G_F} (\eta_{RL}^e + \eta_{RR}^e - \eta_{LL}^e - \eta_{LR}^e) . \tag{32}
\]

Recently a very precise measurement was made of the parity violating transition between the 6S and 7S states of \( ^{133}\text{Cs} \) with the use of a spin-polarized atomic beam. Accounting for a slight improvement in the atomic theory calculation, the resulting \( Q_W \) is given as

\[
Q_W^{\text{exp}} = -72.41 \pm 0.25 \pm 0.80 , \tag{33}
\]

where the first uncertainty is experimental and the second is theoretical. This needs to be compared with the value for Cs predicted by the SM, including radiative corrections,

\[
Q_W^{\text{SM}} = -73.10 \pm 0.04 . \tag{34}
\]

This theoretical value agrees with the measurement within errors, leading to the constraint

\[
\Delta C_{1u} + 1.122\Delta C_{1d} = -0.0018 \pm 0.0022 . \tag{35}
\]

Some chirality combinations of \( LL, RR, LR, RL \) give zero contributions to \( \Delta C_{1q} \) and thus satisfy the experimental \( Q_W \) constraint trivially. Such possibilities include (i) \( LL = RR = LR = RL \) (\( VV \)), (ii) \( LL = RR = LR = RL \) (\( AA \)), (iii) \( LL = RR = LR = RL \) (an SU(12) symmetry), (iv) \( LR = RL, LL = RR = 0 \) (a minimal choice used in fitting the HERA data).
Table 2: The measured and expected number of events as a function of $Q^2_{\text{min}}$ at HERA.

| $Q^2_{\text{min}}$ (GeV$^2$) | $N_{\text{obs}}$ | $N_{\text{exp}}$ | $Q^2_{\text{min}}$ (GeV$^2$) | $N_{\text{obs}}$ | $N_{\text{exp}}$ |
|-----------------------------|------------------|------------------|-----------------------------|------------------|------------------|
| 2500                        | 1817             | 1792±93          | 2500                        | 1297             | 1276±98          |
| 5000                        | 440              | 396±24           | 5000                        | 322              | 336±29.6         |
| 10000                       | 66               | 60±4             | 10000                       | 51               | 55.0±6.42        |
| 15000                       | 20               | 17±2             | 15000                       | 22               | 14.8±2.13        |
| 35000                       | 2                | 0.29±0.02        | 20000                       | 10               | 4.39±0.73        |
|                             |                  |                  | 25000                       | 6                | 1.58±0.29        |

The most precise data on polarized lepton-nucleon scattering come from three experiments. Comparing with the SM expectations, the results of these experiments can be summarized as follows:

1. The SLAC $e^-$-D scattering experiment\[14\],\[16\] gives

$$\Delta(2C_{1u} - C_{1d}) = -0.22 \pm 0.26, \quad \Delta(2C_{2u} - C_{2d}) = 0.77 \pm 1.23, \quad \rho_{\text{corr}} = -0.975, \quad (38)$$

where $\rho_{\text{corr}}$ is the correlation. The Mainz $e$-Be scattering experiment\[36\] yields the constraint

$$\Delta C_{1u} - 0.24\Delta C_{1d} + 0.80\Delta C_{2u} - 0.74\Delta C_{2d} = -0.024 \pm 0.070. \quad (39)$$

Finally, the Bates $e$-C scattering experiment\[37\] implies

$$\Delta C_{1u} + \Delta C_{1d} = -0.015 \pm 0.033. \quad (40)$$

6.3 $e^+p$ scattering at HERA

In early 1997, the H1\[3\] and ZEUS\[4\] experiments at DESY reported an excess of DIS events at large $Q^2$. The possibility of a significant deviation from the SM has triggered much of the recent research on new interactions in the NC sector. Since the original publications, the amount of data collected by the two HERA groups has roughly been doubled. Our analysis is based on the HERA data as presented at the 1998 spring and summer conferences\[5\] which correspond to a combined integrated luminosity of over 80 pb$^{-1}$. The input to our fit is listed in Table 2,\[5\] together with the SM expectation and its theoretical error.

Neutral current deep inelastic scattering occurs via the subprocess $eq \rightarrow eq$. In terms of the reduced amplitudes $M^{eq}_{\alpha\beta}(\hat{t})$ ($\alpha, \beta = L, R$) of Eq. (5), the spin-
and color-averaged amplitude-squared for $e^+q \rightarrow e^+q$ is given by

$$\sum |M(e^+q \rightarrow e^+q)|^2 =$$

$$\left(|M_{LL}^q(\hat{t})|^2 + |M_{RR}^q(\hat{t})|^2\right) \hat{u}^2 + \left(|M_{LR}^q(\hat{t})|^2 + |M_{RL}^q(\hat{t})|^2\right) \hat{s}^2,$$

(41)

where $\hat{s} = sx$ is bounded by the HERA center of mass energy, $s \simeq (300\text{GeV})^2$, $\hat{t} = -Q^2$, and $\hat{u} = -\hat{s} + Q^2$. Because additional contact terms are most important at large $Q^2$, which favors small $|\hat{u}|$, $e^+q$ scattering at HERA is most sensitive to $\eta_{RL}$ and $\eta_{LR}$ contact terms. $\eta_{LL}$ and $\eta_{RR}$ contributions are enhanced by the $\hat{s}^2$ factor in $e^+\bar{q}$ collisions, but here the smaller antiquark distributions at large $x$ lead to a loss in sensitivity. Similarly, because $u(x,Q^2) > d(x,Q^2)$, and because the SM couplings of the up-quark are larger in DIS than those of the down-quark, leading to larger interference contributions of the $\eta_u$, the HERA experiments are most sensitive to deviations in the $M_{RL}^u$ and $M_{LR}^u$ reduced amplitudes.

6.4 Drell-Yan Cross Section at the Tevatron

The production of Drell-Yan lepton pairs at the Tevatron, via the subprocess $q\bar{q} \rightarrow e^+e^-$, probes $eeqq$ contact terms at the highest accessible energies. The double differential cross section, versus the lepton pair invariant mass, $\sqrt{s}$, and rapidity, $y$, is given by

$$\frac{d^2\sigma}{d\hat{s}dy} = K \frac{\hat{s}}{144\pi s} \sum_q q(x_1)\bar{q}(x_2) \sum_{\alpha,\beta=L,R} |M_{\alpha\beta}^q(\hat{s})|^2,$$

(42)

where $q(x_1)$ and $\bar{q}(x_2)$ are parton distributions evaluated at $Q^2 = \hat{s}$, $x_{1,2} = e^{\pm y} \sqrt{\hat{s}/s}$, and the reduced amplitudes $M_{\alpha\beta}^q(\hat{s})$ are given by Eqs. (2,5). $K$ is the QCD $K$-factor for Drell-Yan production.

Since our previous analysis, CDF has published the observed number of events in bins of invariant mass of the lepton pair, as given in Table 3. We use these data for our fit, together with the SM expectation provided by CDF. The SM expectation is normalized to the number of events seen at the $Z$ peak, which effectively fixes the $K$-factor. Since the data are consistent with $e^\mu$ universality, we use both the electron and muon data. The Tevatron data extend out to very large lepton invariant masses, where they exclude large deviations in any of the squared reduced amplitudes. This eliminates the possibility of large cancellations between different flavor and helicity combinations of the $\eta_u$, and is crucial for reducing the correlations in the global fit.
Table 3: The electron and muon samples of Drell-Yan production in CDF together with the SM expectation.

| $M_{\ell\ell}$ | $N_{\text{obs}}$ | $N_{\text{exp}}$ | $N_{\text{obs}}$ | $N_{\text{exp}}$ |
|---------------|-----------------|-----------------|-----------------|-----------------|
| 50–150        | 2581            | 2581            | 2533            | 2533            |
| 150–200       | 8               | 10.8            | 9               | 9.7             |
| 200–250       | 5               | 3.5             | 4               | 3.2             |
| 250–300       | 2               | 1.4             | 2               | 1.3             |
| 300–400       | 1               | 0.97            | 1               | 0.94            |
| 400–500       | 1               | 0.25            | 0               | 0.27            |
| 500–600       | 0               | 0.069           | 0               | 0.087           |

6.5 $e^+e^- \rightarrow q\bar{q}$ at LEP2

The same reduced amplitudes as in Drell-Yan production, however with somewhat different weighting, are measured in $e^+e^- \rightarrow$ hadrons. At leading order in the electroweak interactions, the total hadronic cross section for $e^+e^- \rightarrow q\bar{q}$, summed over all flavors $q = u, d, s, c, b$, is given by

$$\sigma_{\text{had}} = K \sum_{q} \frac{s}{16\pi} \left[ |M_{LL}^{qq}(s)|^2 + |M_{RR}^{qq}(s)|^2 + |M_{LR}^{qq}(s)|^2 + |M_{RL}^{qq}(s)|^2 \right],$$

(43)

where $K = 1 + \frac{\alpha_s}{\pi} + 1.409(\alpha_s/\pi)^2 - 12.77(\alpha_s/\pi)^3$ is the QCD $K$ factor.42

Since charge or flavor identification of light quark jets is problematic, we only consider the LEP2 results on the total hadronic cross section in our analysis, summed over five quark flavors. Contact interactions are included in $e^+e^- \rightarrow u\bar{u}$ and $e^+e^- \rightarrow d\bar{d}$ amplitudes only.

The LEP collaborations have presented measurements of the total hadronic cross section at center of mass energies between $\sqrt{s} = 130$ and 189 GeV.7 The data used for our global fit are summarized in Table 4.

6.6 Neutrino-Nucleon DIS Experiments

Deep inelastic scattering experiments with neutrino and anti-neutrino beams have provided important tests for the SM since the early 80s.43,44 Assuming $e-\mu$ universality and SU(2)$_L$ invariance, we can use $\nu_N$ DIS data to constrain the lepton-quark contact interactions of Eq. (23).

While older measurements are available (see e.g. the discussion in Ref. [2]), the most precise data come from recent CCFR and NuTeV measurements.
Table 4: Total hadronic cross sections $\sigma_{\text{had}}$ measured by the LEP collaborations and SM expectations.

| $\sqrt{s}$ (GeV) | $\sigma_{\text{had}}$ | $\sigma_{\text{SM}}$ |
|------------------|----------------------|---------------------|
|                  |                      |                     |
| ALEPH            |                      |                     |
| 130              | $79.9 \pm 4.1$       | $77.16$             |
| 136              | $64.5 \pm 3.8$       | $62.52$             |
| 183              | $23.6 \pm 0.73$      | $23.05$             |
| DELPHI           |                      |                     |
| 130.2            | $82.2 \pm 5.2$       | $83.1$              |
| 136.2            | $65.9 \pm 4.7$       | $67.0$              |
| 161.3            | $40.2 \pm 2.1$       | $34.8$              |
| 172.1            | $30.6 \pm 2.0$       | $28.9$              |
| L3               |                      |                     |
| 130.3            | $81.8 \pm 6.4$       | $78$                |
| 136.3            | $70.5 \pm 6.2$       | $63$                |
| 140.2            | $67 \pm 47$          | $56$                |
| 161.3            | $37.3 \pm 2.2$       | $34.9$              |
| 170.3            | $39.5 \pm 7.5$       | $29.8$              |
| 172.3            | $28.2 \pm 2.2$       | $28.9$              |
| OPAL             |                      |                     |
| 130.25           | $64.3 \pm 5.1$       | $77.6$              |
| 136.22           | $63.8 \pm 5.2$       | $62.9$              |
| 161.34           | $35.5 \pm 2.2$       | $33.7$              |
| 172.12           | $27.0 \pm 1.9$       | $27.6$              |
| 183              | $23.7 \pm 0.81$      | $24.3$              |
| 189              | $21.8 \pm 0.89$      | $22.3$              |

The CCFR collaboration has obtained a model-independent constraint on the effective $\nu \nu qq$ couplings from a measurement of the NC to CC cross section ratio:

$$\kappa = 1.6981 \left( g_{\nu L}^q \right)^2 + 1.8813 \left( g_{\nu R}^q \right)^2 + 1.0697 \left( g_{\nu R}^d \right)^2 + 1.2261 \left( g_{\nu R}^d \right)^2 = 0.5820 \pm 0.0041,$$

which should be compared to the SM prediction $\kappa = \kappa_{\text{SM}} = 0.5830 \pm 0.0005$. Here $g_{\nu L}^q, g_{\nu R}^q$ (called $\epsilon_L(q), \epsilon_R(q)$ in Ref. [32]) are the coefficients in the neutrino-quark effective Lagrangian describing their NC interactions.

A second combination of these couplings appears in the Paschos-Wolfenstein parameter and has recently been measured by the NuTeV collaboration.
Table 5: The best estimate of the $\eta_{\nu\beta}^{\alpha\beta}$ parameters when various data sets are added successively. In the last column, when the $\nu N$ data and the CC universality constraint of Eq. (30) are included, the $\eta_{\nu\beta}^{\alpha\beta}$ are given in terms of $\eta_{L,R}^{\alpha\beta}$ by the SU(2) relations of Eq. (27) and we assume $\eta_{L,R}^{\alpha\beta} = \eta_{RL}^{\alpha\beta}$.

|       | HERA only | +APV+eN | +DY | +LEP | +$\nu N$ |
|-------|-----------|---------|-----|------|----------|
| $\eta_{LL}^{u}$ | 2.04$\pm$5.26 | 2.24$\pm$3.63 | 0.22$\pm$0.57 | -0.08$\pm$0.35 | 0.02$\pm$0.22 |
| $\eta_{LR}^{u}$ | -4.30$\pm$3.78 | -2.77$\pm$1.70 | 0.60$\pm$0.66 | 0.77$\pm$0.62 | 0.41$\pm$0.28 |
| $\eta_{RL}^{u}$ | -1.74$\pm$2.60 | -3.53$\pm$0.90 | 0.00$\pm$0.72 | 0.00$\pm$0.74 | 0.49$\pm$0.39 |
| $\eta_{RR}^{u}$ | 2.62$\pm$5.35 | 2.23$\pm$3.41 | 0.04$\pm$0.62 | -0.14$\pm$0.53 | -0.25$\pm$0.33 |
| $\eta_{LL}^{d}$ | -1.72$\pm$6.76 | -2.23$\pm$4.54 | 0.25$\pm$1.71 | 0.04$\pm$0.80 | 0.07$\pm$0.24 |
| $\eta_{LR}^{d}$ | -0.01$\pm$4.85 | -0.95$\pm$3.47 | 1.65$\pm$2.79 | 0.04$\pm$3.47 | 0.50$\pm$0.61 |
| $\eta_{RL}^{d}$ | -1.87$\pm$4.37 | -0.95$\pm$3.23 | 1.98$\pm$2.74 | 0.36$\pm$1.44 | $\eta_{RL}^{u}$ |
| $\eta_{RR}^{d}$ | -2.26$\pm$7.24 | -1.60$\pm$4.85 | 0.55$\pm$1.73 | 0.40$\pm$0.91 | 0.20$\pm$0.64 |

|       | HERA | APV+eN | DY | LEP | $\nu N$ |
|-------|------|--------|----|-----|--------|
| Total $\chi^2$ | 7.57 | 7.86 | 12.10 | 12.80 | 13.06 |
| SM $\chi^2$ | 17.27 | 19.79 | 24.08 | 45.91 | 49.22 |
| SM d.o.f. | 11 | 16 | 28 | 47 | 50 |

They find

$$0.8587 \left(g_L^u\right)^2 + 0.8828 \left(g_L^d\right)^2 - 1.1657 \left(g_R^u\right)^2 - 1.2288 \left(g_R^d\right)^2 = 0.2277 \pm 0.0022,$$

(45)

compared to a SM value of 0.2302 $\pm$ 0.0003.

The presence of new interactions in the NC sector, as parameterized by Eq. (23), leads to shifts in the $g_{L,R}^{u,d}$ given by

$$\Delta g_L^u = -\frac{1}{2\sqrt{2}G_F}\eta_{LL}^{u}, \quad \Delta g_R^u = -\frac{1}{2\sqrt{2}G_F}\eta_{RL}^{u}, \quad \Delta g_L^d = -\frac{1}{2\sqrt{2}G_F}\eta_{LL}^{d}, \quad \Delta g_R^d = -\frac{1}{2\sqrt{2}G_F}\eta_{RL}^{d},$$

(46)
as compared to the SM expectations given in Ref. [32]. The $\eta_{\nu\beta}^{\alpha\beta}$ are related to the corresponding $eeqq$ contact terms by Eq. (27). When using these SU(2) relations to constrain physics beyond the SM, we also impose the concomitant CC constraint of Eq. (30).
Table 6: The best estimate on $\eta^{eq}_{\alpha\beta}$ and the 95% CL limits on the compositeness scale $\Lambda^{eq}_{\alpha\beta}$, where $\eta^{eq}_{\alpha\beta} = 4\pi\epsilon/(\Lambda^{eq}_{\alpha\beta}\epsilon)^2$. When one of the $\eta$’s is considered the others are set to zero. SU(2) relations are assumed and $\nu N$ data are included.

| Chirality ($q$) | $\eta$ (TeV$^{-2}$) | $\chi^2_{\text{min}}$ | 95% CL Limits |
|----------------|---------------------|---------------------|--------------|
| LL($u$)        | $-0.036 \pm 0.029$  | 47.61               | 18.4 12.1    |
| LR($u$)        | $0.094 \pm 0.067$   | 47.26               | 7.8 12.2     |
| RL($u$)        | $-0.028 \pm 0.035$  | 48.56               | 15.5 11.9    |
| RR($u$)        | $-0.079 \pm 0.070$  | 47.93               | 11.5 8.0     |
| LL($d$)        | $0.057 \pm 0.029$   | 45.51               | 10.9 19.8    |
| LR($d$)        | $0.041 \pm 0.064$   | 48.81               | 9.0 11.1     |
| RR($d$)        | $-0.046 \pm 0.065$  | 48.71               | 11.2 8.8     |

7 Discussion

Table 6 summarizes the results of our new global fit, at various steps of including additional data. In the first four columns the eight phenomenological parameters $\eta^{eq}_{\alpha\beta}$ are treated as free. $e\mu$ universality is assumed when considering Tevatron Drell-Yan data. Only in the last column, when adding constraints from $\nu N$ scattering, do we assume the SU(2) relations of Eqs. (26,27), and, thus, this column represents a seven parameter fit. Note that here the CC constraint of Eq. (23) is also included in the fit.

The $\chi^2$ per degree of freedom ($\chi^2_{\text{cont.}}$/d.o.f.=0.931) of the contact interactions is very close to that of the SM ($\chi^2_{\text{SM}}$/d.o.f.=0.984) for the last column in Table 6, and both are excellent fits. Thus, no signal for new interactions in the NC sector is found in the present data. As is apparent from the jump in $\chi^2$ for the HERA data alone, from 7.86 to 12.1 when going from column 2 to 3, there is some clash between the still persistent excess of high $Q^2$ events at HERA with the Tevatron Drell-Yan data. However, one should note that this is mainly due to the pre-1997 HERA data. The effect would be minimal if 1997 data only had been considered.

The errors listed for the fit parameters in Table 6 are fairly large and caused by strong correlations between the $\eta^{eq}_{\alpha\beta}$. The correlations hide the stringency of constraints, in particular from the APV and $\nu N$ scattering experiments. Table 6 gives a complementary view by fitting the data with a single nonzero $\eta^{eq}_{\alpha\beta} = 4\pi\epsilon/(\Lambda^{eq}_{\alpha\beta}\epsilon)^2$ at a time. Also included are the 95% CL limits on the corresponding $\Lambda_{\pm}$. Note that the $\pm$ definition is from the sign of the terms in the Lagrangian. So, whether the “+” sign will interfere constructively or
Table 7: The best estimate on $\eta^{eq}$ for the minimal setting, $VV$, $AA$, and SU(12), and the corresponding 95% CL limits on the compositeness scale $\Lambda$, where $\eta = 4\pi \epsilon / (\Lambda^2)$. Apart from the $\eta$-combination specified, all the others are set to zero. Here we do not use SU(2) relations and, hence, do not include the $\nu N$ data.

| Chirality ($q$) | $\eta$ (TeV$^{-2}$) | $\chi^2_{\text{min}}$ | 95% CL Limits |
|----------------|---------------------|----------------------|----------------|
| $\eta^{eu}_{LR} = \eta^{eu}_{RL}$ | $0.42^{+0.23}_{-0.25}$ | 43.31 | $4.0$ $6.6$ |
| $\eta^{ed}_{LR} = \eta^{ed}_{RL}$ | $-0.67^{+0.47}_{-0.32}$ | 44.34 | $2.7$ $3.3$ |
| $\eta^{eu}_{VV}$ | $-0.0092^{+0.078}_{-0.076}$ | 45.90 | $9.1$ $9.1$ |
| $\eta^{ed}_{VV}$ | $0.11^{+0.16}_{-0.19}$ | 45.53 | $5.8$ $5.0$ |
| $\eta^{eu}_{AA}$ | $-0.17^{+0.11}_{-0.099}$ | 43.45 | $9.0$ $6.2$ |
| $\eta^{ed}_{AA}$ | $0.11^{+0.12}_{-0.14}$ | 45.24 | $6.3$ $7.3$ |
| $\eta^{eu}_{LL} = -\eta^{eu}_{RR}$ | $-0.28^{+0.18}_{-0.16}$ | 43.70 | $6.3$ $4.8$ |
| $\eta^{ed}_{LL} = -\eta^{ed}_{RR}$ | $0.33^{+0.20}_{-0.20}$ | 43.41 | $4.5$ $5.5$ |
| $\eta^{ed}_{LL} = -\eta^{ed}_{RL}$ | $0.19^{+0.22}_{-0.25}$ | 45.29 | $4.8$ $4.9$ |
| $\eta^{ed}_{RL} = -\eta^{ed}_{RR}$ | $-0.23^{+0.28}_{-0.24}$ | 45.20 | $3.8$ $4.5$ |

Destructively with the SM amplitude depends on the sign of the SM amplitude. We find that parity violating new interactions, which contain $A_e V_q$ current-current couplings, must have an intrinsic scale $\Lambda > 10$ TeV.

For new interactions in the NC sector which do not affect APV observables, the constraints can be considerably weaker. This is demonstrated in Tables 7 and 8 where several APV blind combinations of $\eta^{eq}$ are considered. Note that in this comparison we cannot impose $SU(2) \times U(1)$ symmetry without relating $eeuu$ and $eedd$ couplings. Hence the fits of Table 8 which consider couplings to either up- or down-quarks, do not include $\nu N$ scattering data. While $VV$ and $AA$ interactions still require scales $\Lambda$ in excess of 5 to 9 TeV, some fairly large contact terms are allowed for special combinations, the largest being $\eta^{ed}_{LR} = \eta^{ed}_{RL}$, for which scales as small as 3 TeV are still allowed.

Much of the recent interest in new interactions in the NC sector has been motivated by the apparent excess of high $Q^2$ events in the pre-1997 HERA data. Comparing the results of a HERA only fit with the results of the global fit in Table 8 it may appear that the severe constraints by other experiments, at LEP2 or the Tevatron for example, exclude the observation of signals for new interactions at a machine like HERA. Is this conclusion justified?
Table 8: Same as the last Table but with a further condition: $\eta^{eu} = \eta^{ed}$. Here $q = u = d$ and SU(2) constraints and the $\nu N$ data are included.

| Chirality (q) | $\eta$ (TeV$^{-2}$) | $\chi^2_{\text{min}}$ | 95% CL Limits |
|---------------|---------------------|---------------------|----------------|
| $\eta^{eq}_{LR} = \eta^{eq}_{RL}$ | $0.40^{+0.19}_{-0.22}$ | 46.15 | $4.3$ | $6.0$ |
| $\eta^{eq}_{VV}$ | $0.0092^{+0.12}_{-0.11}$ | 49.21 | $6.9$ | $8.1$ |
| $\eta^{eq}_{AA}$ | $-0.29^{+0.13}_{-0.12}$ | 44.77 | $8.3$ | $5.2$ |
| $\eta^{eq}_{LL} = -\eta^{eq}_{LR}$ | $-0.33^{+0.17}_{-0.16}$ | 45.65 | $7.6$ | $4.7$ |
| $\eta^{eq}_{RL} = -\eta^{eq}_{RR}$ | $0.50^{+0.20}_{-0.25}$ | 46.25 | $4.0$ | $4.0$ |

The most straightforward signature for new interactions at HERA is an enhancement in the differential DIS cross section, $d\sigma^{NC}/dQ^2$. In Fig. 2 the present measurements are compared with the SM expectation. Also included in this plot is the ratio of non-standard over SM cross sections expected for the best fit result, in the last column of Table 5 (solid line), and the analogous cross section ratio for the case with the smallest $\chi^2$ in Table 7, $\eta_{LR}^{eu} = \eta_{RL}^{eu} = 0.42$ TeV$^{-2}$ (dashed line). The best fits clearly favor an interpretation of the excess high $Q^2$ events as a statistical fluctuation. However, it is also obvious that sizable and significant signals for new NC interactions remain possible with higher statistics at HERA.

8 Conclusions

After 25 years of neutral current experiments, the Standard Model has been confirmed to amazing precision. Nevertheless, ongoing and future experiments may well discover new physics in NC processes. There are many possible sources of such new interactions. History might repeat and the exchange of an extra Z boson could lead to new neutral quark and lepton currents. However, also other phenomena, which are not a priori of current-current type, may give rise to effective neutral current interactions, leptoquark exchange being one example.

More general new interactions between quarks and leptons are possible, but our knowledge of chirality conservation in $eeqq$ interactions and the apparent $SU(2)_L \times U(1)$ symmetry of nature relegates such more general scalar and tensor interactions to very high scales. This makes it quite possible that new quanta in the 1 to 10 TeV range will first be observed indirectly, as new neutral current interactions.
Figure 2: Ratio of the neutral current cross section $d\sigma^{NC}/dQ^2$ to the SM expectation. Shown are H1 data (squares) and ZEUS data (circles). Errors are statistical only. Superimposed are the expectations for two contact term choices: the best global fit result in the last column of Table 5 (solid line), and the choice $\eta_{eL} = \eta_{eR} = 0.42$ TeV$^{-2}$ (dashed line) (see Table 7).

The range of competitive experiments in this field is truly remarkable, ranging from atomic physics parity violation measurements, over DIS experiments, to $e^+e^-$ annihilation at LEP, and Drell-Yan pair production at the Tevatron. None of these experiments dominates the field. APV and $\nu_{e}N$ scattering experiments have similar sensitivities to parity violating observables, and the sensitivity of LEP and the Tevatron, while slightly lower for specific couplings, is needed to exclude cancellations of different couplings in the other experiments. Only future experiments can tell whether nature has such new interactions in store for us or whether the SM is a perfect model for NC data at the much higher energies yet to be explored.

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