

Constraints on Electron-quark Contact Interactions

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Abstract

In this talk, I summarize a global analysis on electron-quark contact interactions using the updated NC DIS data at HERA, Drell-yan production at the Tevatron, total hadronic cross sections at LEP, atomic parity violation measurement, low energy e -nucleon scattering data, and the ν -nucleon scattering data. The global data do not show any evidence for contact interactions. Thus, we obtain limits of 8–15 TeV on the compositeness scale, which are significantly better than those published by each individual experiment.

I. INTRODUCTION

Four-fermion contact interaction is not something new, but was proposed decades ago by Fermi to account for the nuclear beta decay. The interaction is represented by

$$\mathcal{L} \sim G_F \left(\bar{e} \gamma^\mu (1 - \gamma^5) \nu \right) \left(\bar{u} \gamma_\mu (1 - \gamma^5) d \right) \quad (1)$$

where G_F is the fermi constant with dimension $(\text{mass})^{-2}$. This interaction is not renormalizable because amplitudes grow indefinitely with the energy scale if G_F is kept constant. It was only until 60's that the electroweak theory was proposed. The four-fermion contact interaction was then replaced by exchange of weak gauge bosons and G_F replaced by the W boson propagator: $G_F \rightarrow 1/(p^2 - m_W^2)$. The weak gauge bosons were only discovered later when the energy scale reached the hundred GeV level. In the above history we learn a couple of lessons: (i) the existence of four-fermion contact interactions is a signal of new physics beyond the existing standard theory; (ii) the exact nature of new physics is unknown at the low energy scale. Only when the energy scale is high enough can the nature of new physics be probed.

The purpose of this analysis [1] is to examine the data from current accelerator experiments to see if there is any sign of contact interactions. If so it is a signal of new physics; if not we put limits on the compositeness scale Λ . Four-fermion contact interactions have been searched in recent high energy experiments: (i) the $qqqq$ contact interaction studied at

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the Tevatron by CDF [2]; (ii) $eeqq$ interactions at LEP [3], HERA [4], Drell-yan production at the Tevatron [5,6], and low energy e -Nucleon scattering experiments [7]. We concentrate on $eeqq$ contact interactions. In particular, the neutral current (NC) deep-inelastic scattering (DIS) data collected by H1 [8] and ZEUS [9] at HERA between 1994–96 showed a significant excess in cross section in the high- Q^2 region, which aroused an enormous amount of phenomenological activities. One of the explanations is the $eeqq$ contact interaction at the scale of 3 TeV. However, the data collected in 1997 alone agreed very well with the SM and, therefore, the logical explanation for the excess in 1996 was statistical fluctuation. The overall result of the combined 94-97 data is as follows [10]: (i) data by ZEUS agreed with the SM expectation up to $Q^2 \sim 30000 \text{ GeV}^2$ while there are 2 events at $Q^2 > 35000 \text{ GeV}^2$, where only 0.29 ± 0.02 is expected; (ii) data by H1 only showed a slight deviation above the SM for $Q^2 > 15000 \text{ GeV}^2$ and the excess events in the mass window of 200 GeV are now much less significant. Although the outcome is somewhat discouraging for searching for new physics, we can, however, use the data to constrain new physics. The objective here is to constrain the $eeqq$ contact interactions using the global data, which include: (i) NC DIS data at HERA [10], (ii) Drell-yan production at the Tevatron [5], (iii) total hadronic cross sections at LEP and the left-right asymmetry at SLD [3], (iv) atomic physics parity violation measurement [11] on ^{133}Cs , (v) low energy e -N scattering experiments [7], and (vi) low energy ν -N scattering experiment by CCFR [12]. We shall obtain fits of parameters of $eeqq$ contact interactions and finally the limits on the compositeness scale Λ .

In this write-up, we shall summarize the analysis in Ref. [1]. The results presented here, however, use the more updated data since Ref. [1].

II. PARAMETERIZATION

The conventional effective Lagrangian of $eeqq$ contact interactions has the form

$$L_{NC} = \sum_q \left[\eta_{LL} (\bar{e}_L \gamma_\mu e_L) (\bar{q}_L \gamma^\mu q_L) + \eta_{RR} (\bar{e}_R \gamma_\mu e_R) (\bar{q}_R \gamma^\mu q_R) \right. \\ \left. + \eta_{LR} (\bar{e}_L \gamma_\mu e_L) (\bar{q}_R \gamma^\mu q_R) + \eta_{RL} (\bar{e}_R \gamma_\mu e_R) (\bar{q}_L \gamma^\mu q_L) \right], \quad (2)$$

where eight independent coefficients $\eta_{\alpha\beta}^{eu}$ and $\eta_{\alpha\beta}^{ed}$ have dimension $(\text{TeV})^{-2}$ and are conventionally expressed as $\eta_{\alpha\beta}^{eq} = \epsilon g^2 / \Lambda_{eq}^2$, with a fixed $g^2 = 4\pi$. The sign factor $\epsilon = \pm 1$ allows for either constructive or destructive interference with the SM γ and Z exchange amplitudes and Λ_{eq} represents the mass scale of the exchanged new particles, with coupling strength $g^2/4\pi = 1$. A coupling of this order is expected in substructure models and therefore Λ_{eq} is sometimes called the ‘‘compositeness scale’’.

Left-handed electrons and quarks belong to SU(2) doublets $L = (\nu_L, e_L)$ and $Q = (u_L, d_L)$ and thus from SU(2) symmetry one expects relations between contact terms involving left-handed u or d quarks; similarly, contact terms for left-handed electrons and neutrinos should be related. We start with the most general $SU(2) \times U(1)$ invariant contact term Lagrangian,

$$\mathcal{L}_{SU(2)} = \eta_1 (\bar{L} \gamma^\mu L) (\bar{Q} \gamma_\mu Q) + \eta_2 (\bar{L} \gamma^\mu T^a L) (\bar{Q} \gamma_\mu T^a Q) \\ + \eta_3 (\bar{L} \gamma^\mu L) (\bar{u}_R \gamma_\mu u_R) + \eta_4 (\bar{L} \gamma^\mu L) (\bar{d}_R \gamma_\mu d_R)$$

$$\begin{aligned}
& +\eta_5(\bar{e}_R\gamma^\mu e_R)(\bar{Q}\gamma_\mu Q) + \eta_6(\bar{e}_R\gamma^\mu e_R)(\bar{u}_R\gamma_\mu u_R) \\
& +\eta_7(\bar{e}_R\gamma^\mu e_R)(\bar{d}_R\gamma_\mu d_R).
\end{aligned} \tag{3}$$

By expanding the η_5 term we have

$$\eta_{RL}^{eu} = \eta_5 = \eta_{RL}^{ed}. \tag{4}$$

In addition, the four neutrino and the lepton couplings are related by SU(2),

$$\eta_{LL}^{\nu u} = \eta_{LL}^{ed}, \eta_{LL}^{\nu d} = \eta_{LL}^{eu}, \eta_{LR}^{\nu u} = \eta_{LR}^{eu}, \eta_{LR}^{\nu d} = \eta_{LR}^{ed}. \tag{5}$$

In our analysis, the relations of Eqs. (4) and (5) are only used when neutrino scattering data are included in the analysis. Even though we expect that $SU(2) \times U(1)$ will be a symmetry of the renormalizable interactions which ultimately manifest themselves as the contact terms of Eq. (2), electroweak symmetry breaking may break the degeneracy of SU(2) multiplets of new, heavy quanta whose exchanges give rise to (2). This would result in a violation of the relations of Eqs. (4) and (5). One example is the exchange of the stop \tilde{t}_1, \tilde{t}_2 , and the sbottom \tilde{b}_L, \tilde{b}_R in R -parity violating SUSY models. The large top-quark mass may lead to substantial splitting of the masses of these squarks which could easily lead to violations by up to a factor of two of SU(2) relations such as $\eta_{LR}^{\nu d} = \eta_{LR}^{ed}$.

Because of severe experimental constraints on intergenerational transitions like $K \rightarrow \mu e$ we restrict our discussion to first generation contact terms. Only where required by particular data (e.g. the muon sample of Drell-yan production at the Tevatron) will we assume universality of contact terms between e and μ .

III. GLOBAL DATA

The global data used in this analysis have been described in Ref. [1]. Here we only list those that have been updated since then.

A. HERA data

The 1997 data alone by H1 and ZEUS agreed very well with the SM expectation, though the combined 1994–1997 data still showed an excess of cross section at high Q^2 . The significance of excess is far less severe now. We use the Q^2 distribution presented in the 1998 spring conferences [10]. Note that using Q^2 distribution will not reduce appreciably the sensitivity to contact interactions than using the x - y distribution, because x distribution is not sensitive to contact interactions (unlike the narrow-width leptoquark model) but y is somewhat sensitive to it. The updated data are tabulated in Table I.

TABLES

TABLE I. The measured number of events as a function of Q_{\min}^2 at HERA.

ZEUS ($\mathcal{L} = 46.60 \text{ pb}^{-1}$)			H1 ($\mathcal{L} = 37.04 \text{ pb}^{-1}$)		
Q_{\min}^2 (GeV ²)	N_{obs}	N_{exp}	Q_{\min}^2 (GeV ²)	N_{obs}	N_{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

B. Drell-yan Production

Since our previous analysis, in which we used the plotted data on a CDF graph, CDF [5] has published the observed number of events in bins of invariant mass of the lepton pair. The data are given in Table II. In this CDF paper, they obtained limits on the compositeness scale using only the CDF data, in the order of a few TeV ¹. At the end, we shall obtain limits significantly better than these limits.

TABLE II. The electron and muon samples of Drell-yan production in each mass bin by CDF.

$M_{\ell\ell}$	e^+e^-		$\mu^+\mu^-$	
	N_{obs}	N_{exp}	N_{obs}	N_{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

¹ D0 Collaboration [6] has also recently published a paper on “Search for Quark-lepton Compositeness using the Drell-Yan process at D0”.

C. LEP

The LEP collaborations have published new measurements of total hadronic cross sections at $\sqrt{s} = 130, 172,$ and 183 GeV. The data that we used are shown in Table III.

TABLE III. Total hadronic cross sections σ_{had} measured by the LEP collaborations.

\sqrt{s} (GeV)	σ_{had}	σ_{SM}
ALEPH		
130	79.5 ± 4.14	77.16
136	64.5 ± 3.85	62.52
183	23.6 ± 0.73	23.05
DELPHI		
130.2	82.2 ± 5.2	83.1
136.2	65.9 ± 4.7	67.0
161.3	40.2 ± 2.1	34.8
172.1	30.6 ± 2.0	28.9
L3		
130.3	81.8 ± 6.4	78
136.3	70.5 ± 6.2	63
140.2	67 ± 47	56
161.3	37.3 ± 2.2	34.9
170.3	39.5 ± 7.5	29.8
172.3	28.2 ± 2.2	28.9
OPAL		
130.25	64.3 ± 5.1	77.6
136.22	63.8 ± 5.2	62.9
161.34	35.5 ± 2.2	33.7
172.12	27.0 ± 1.9	27.6

IV. FITS AND LIMITS

TABLE IV. The best estimate of the $\eta_{\alpha\beta}^{eq}$ parameters when various data sets are added successively. In the last column when the ν -N data are included the $\eta_{L\beta}^{\nu q}$ are given in terms of $\eta_{L\beta}^{eq}$ by Eq. (5) and we assume $\eta_{RL}^{eu} = \eta_{RL}^{ed}$ in the last column.

	HERA only	HERA+APV +eN	HERA+APV +eN+DY	HERA+APV +eN+DY+LEP	HERA+DY+APV +eN+LEP+ ν N
η_{LL}^{eu}	$2.04^{+3.97}_{-5.26}$	$2.25^{+2.29}_{-3.63}$	$0.22^{+0.67}_{-0.57}$	$0.049^{+0.63}_{-0.43}$	$-0.046^{+0.62}_{-0.38}$
η_{LR}^{eu}	$-4.30^{+4.30}_{-0.78}$	$-2.77^{+3.20}_{-1.70}$	$0.60^{+0.51}_{-0.66}$	$0.76^{+0.38}_{-0.63}$	$0.76^{+0.35}_{-0.68}$
η_{RL}^{eu}	$-1.75^{+3.75}_{-2.59}$	$-3.53^{+2.91}_{-0.90}$	$-0.004^{+0.72}_{-0.72}$	$0.042^{+0.73}_{-0.75}$	$0.13^{+0.73}_{-0.77}$
η_{RR}^{eu}	$2.62^{+4.28}_{-5.36}$	$2.23^{+1.77}_{-3.41}$	$0.040^{+0.66}_{-0.62}$	$-0.051^{+0.68}_{-0.57}$	$-0.091^{+0.71}_{-0.56}$
η_{LL}^{ed}	$-1.71^{+7.87}_{-6.77}$	$-2.22^{+5.62}_{-4.55}$	$0.25^{+1.64}_{-1.72}$	$0.39^{+0.76}_{-0.92}$	$0.11^{+0.82}_{-0.53}$
η_{LR}^{ed}	$-0.011^{+4.85}_{-4.48}$	$-0.95^{+3.76}_{-3.47}$	$1.65^{+1.39}_{-2.79}$	$0.79^{+1.33}_{-2.08}$	$0.36^{+1.16}_{-1.82}$
η_{RL}^{ed}	$-1.86^{+4.86}_{-4.38}$	$-0.95^{+3.87}_{-3.23}$	$1.97^{+1.30}_{-2.74}$	$1.11^{+1.27}_{-2.02}$	$= \eta_{RL}^{eu}$
η_{RR}^{ed}	$-2.28^{+7.87}_{-7.22}$	$-1.61^{+5.59}_{-4.85}$	$0.55^{+1.60}_{-1.73}$	$0.73^{+0.85}_{-1.03}$	$0.86^{+0.60}_{-1.16}$
HERA	7.57	7.86	12.10	12.34	12.73
APV		0.00	0.00	0.001	0.001
eN		0.46	0.47	0.46	0.51
DY			4.40	4.38	4.39
LEP				23.57	23.49
ν N					0.00
Total χ^2	7.57	8.32	16.97	40.75	41.12
SM χ^2	17.27	20.27	24.55	51.20	51.21
SM d.o.f.	11	16	28	47	48

The fits of contact parameters are obtained by minimizing the χ^2 of the data sets. In order to see how each data set affects the fit, we obtain the fit with each data set added one at a time. The fits with various combinations of data sets are shown in Table IV. Two important observations are offered as follows. (i) When the Drell-yan data are added to “HERA+APV+eN”, the fitted parameters change dramatically and so are the χ^2 's of each data set. This can be understood as follows. The HERA data actually favor non-zero contact parameters (especially the last entries of ZEUS and H1 data): see Fig. 1(a). However, this fit of contact parameters very much contradicts the Drell-yan data: see Fig. 1(b). Therefore, when DY data are taken into account, the fit changes drastically. The curves of the fit with all data sets are also shown in Fig. 1. (ii) The goodness of the fits is indicated by the χ^2 per degree of freedom (d.o.f.). The $\chi^2/\text{d.o.f.}$ ($\chi_{\text{cont.}}^2/\text{d.o.f.}=1.003$) of contact interactions is very close to that of the SM ($\chi_{\text{SM}}^2/\text{d.o.f.}=1.067$) for the last column in Table IV. For the second last column in Table IV, $\chi_{\text{cont.}}^2/\text{d.o.f.}= 1.045$ and $\chi_{\text{SM}}^2/\text{d.o.f.}= 1.089$.

FIGURES

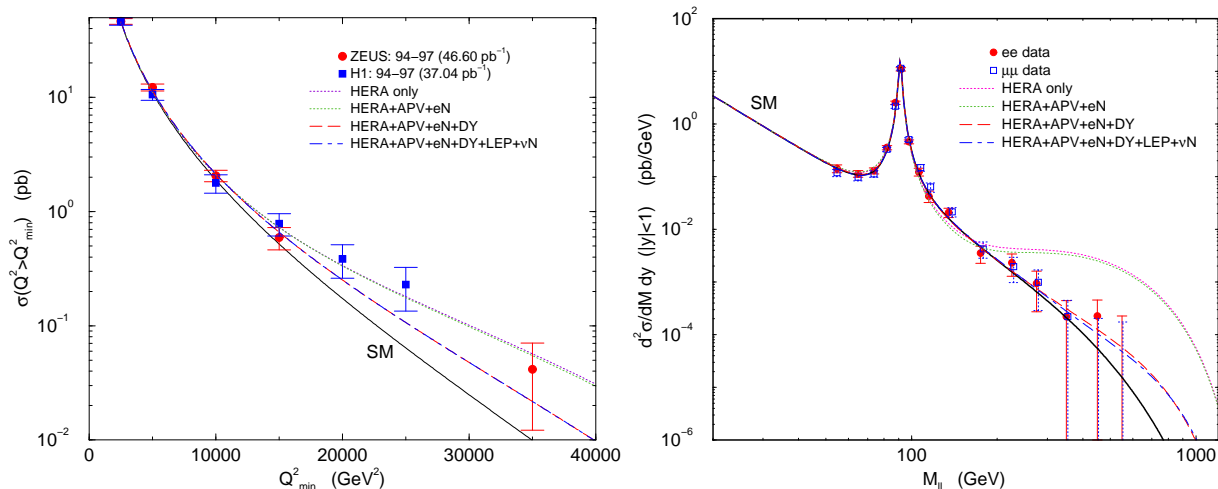


FIG. 1. (a) The cumulated cross section $\sigma(Q^2 > Q_{\min}^2)$ at HERA as a function of Q_{\min}^2 . The 94–97 H1 and ZEUS data, and curves of fits to various data sets are shown, (b) the differential cross section $d^2\sigma/dM dy$ for Drell-yan production at the Tevatron.

In view of these, we conclude that the global data do not show any sign of contact interactions. Thus, we can derive 95% CL limits on the compositeness scale, below which the contact interaction is ruled out. The limits on Λ_{\pm} are listed in Table V–VII. In Table V, for each chirality coupling considered the others are put to zero. The limits on Λ obtained range from 8–15 TeV, which improve significantly from each individual experiment [3–6]. We also calculate the limits on the compositeness scale when some symmetries on contact terms are considered, as shown in Tables VI and VII. VV stands for vector-vector: $\eta_{LL} = \eta_{LR} = \eta_{RL} = \eta_{RR} = \eta_{VV}$, while AA stands for axial-vector-axial-vector: $\eta_{LL} = -\eta_{LR} = -\eta_{RL} = \eta_{RR} = \eta_{AA}$. These limits, in general, are not as strong as those in the previous table because the additional symmetry automatically satisfies the parity violation experiments: APV and e -N.

TABLE V. The best estimate on $\eta_{\alpha\beta}^{eq}$ and the 95% CL limits on the compositeness scale $\Lambda_{\alpha\beta}^{eq}$, where $\eta_{\alpha\beta}^{eq} = 4\pi\epsilon/(\Lambda_{\alpha\beta\epsilon}^{eq})^2$. When one of the η 's is considered the others are set to zero. $SU(2)$ relations are assumed and νN data are included.

Chirality (q)	η (TeV^{-2})	95% CL Limits	
		Λ_+ (TeV)	Λ_- (TeV)
LL(u)	0.026 ± 0.056	9.9	11.6
LR(u)	0.11 ± 0.079	7.3	11.1
RL(u)	-0.043 ± 0.038	15.5	10.8
RR(u)	-0.12 ± 0.078	11.5	7.0
LL(d)	0.072 ± 0.060	8.5	12.5
LR(d)	0.079 ± 0.072	7.8	11.2
RR(d)	-0.064 ± 0.072	10.9	8.1

TABLE VI. The best estimate on η^{eq} for the minimal setting, VV , AA , and $SU(12)$, and the corresponding 95% CL limits on the compositeness scale Λ , where $\eta = 4\pi\epsilon/(\Lambda_\epsilon)^2$. When one of the η 's is considered the others are set to zero. Here we do not use $SU(2)$ relations nor do we include the νN data.

Chirality (q)	η (TeV $^{-2}$)	95% CL Limits	
		Λ_+ (TeV)	Λ_- (TeV)
$\eta_{LR}^{eu} = \eta_{RL}^{eu}$	$0.41^{+0.23}_{-0.27}$	4.0	6.1
$\eta_{LR}^{ed} = \eta_{RL}^{ed}$	$-1.19^{+0.37}_{-0.30}$	2.3	2.8
η_{VV}^{eu}	$-0.064^{+0.090}_{-0.089}$	9.3	7.6
η_{VV}^{ed}	$0.38^{+0.18}_{-0.21}$	4.4	4.9
η_{AA}^{eu}	$-0.30^{+0.12}_{-0.11}$	9.4	5.1
η_{AA}^{ed}	$0.31^{+0.15}_{-0.16}$	4.8	7.5
$\eta_{LL}^{eu} = -\eta_{LR}^{eu}$	$-0.47^{+0.19}_{-0.18}$	6.5	4.1
$\eta_{RL}^{eu} = -\eta_{RR}^{eu}$	$0.54^{+0.19}_{-0.21}$	3.9	5.8
$\eta_{LL}^{ed} = -\eta_{LR}^{ed}$	$0.54^{+0.24}_{-0.27}$	3.7	4.8
$\eta_{RL}^{ed} = -\eta_{RR}^{ed}$	$-0.62^{+0.30}_{-0.26}$	3.6	3.5

TABLE VII. Same as the last Table but with a further condition: $\eta^{eu} = \eta^{ed}$. Here $q = u = d$.

Chirality (q)	η (TeV $^{-2}$)	95% CL Limits	
		Λ_+ (TeV)	Λ_- (TeV)
$\eta_{LR}^{eq} = \eta_{RL}^{eq}$	$0.46^{+0.25}_{-0.33}$	3.9	5.5
η_{VV}^{eq}	$-0.026^{+0.15}_{-0.13}$	5.3	6.9
η_{AA}^{eq}	$-0.40^{+0.17}_{-0.15}$	4.3	4.5
$\eta_{LL}^{eq} = -\eta_{LR}^{eq}$	$-0.61^{+0.25}_{-0.21}$	3.4	3.7
$\eta_{RL}^{eq} = -\eta_{RR}^{eq}$	$0.65^{+0.21}_{-0.25}$	3.6	3.3

In conclusion, the global data have been examined and do not support the existence of $eeqq$ contact interactions with the compositeness scale upto 8–15 TeV. Although the 1994–97 the NC DIS data at HERA favor a slightly non-zero contact interaction, the other data, especially the Drell-yan data at the Tevatron and the atomic parity violation measurement, severely constrain it. Finally, the limits on the compositeness scale obtained in this analysis are significantly better than the results published by each individual experiment. We urge others to use the limits of Λ obtained in this analysis. The above analysis can also be applied in a straight-forward fashion to other new physics such as Z' and leptoquark models.

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