Leptoquark production in ultrahigh-energy neutrino interactions revisited

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Abstract

The prospects for producing leptoquarks (LQs) in ultrahigh-energy (UHE) neutrino nucleon collisions are re-examined in the light of recent interpretations of HERA data in terms of leptoquark production. We update predictions for cross-sections for the production of first- and second-generation leptoquarks in UHE $\nu-N$ and $\bar{\nu}-N$ collisions including (i) recent experimental limits on masses and couplings from the LEP and TEVATRON colliders as well as rare processes, (ii) modern parton distributions, and (iii) radiative corrections to single leptoquark production. If the HERA events are due to an $SU(2)$ doublet leptoquark which couples mainly to $e^\pm q$ states, we argue that there are likely other LQ states which couple to neutrinos which are close in mass, due to constraints from precision electroweak measurements.
The recent observation by two groups at HERA \[1\] of an excess of events in deep inelastic neutral-current scattering at large $Q^2$ in the $e^+p$ channel has spawned a large number of papers which attempt to interpret the deviation from the standard model prediction in terms of new particles. While many interpretations have been put forth, the possibility that leptoquarks (LQs) of mass roughly $200 \text{GeV}$ are responsible has received the most attention. (For recent reviews of these general ideas, with references to many of the original papers, see Refs. \[2\], \[3\], \[4\], and \[5\].)

While the production of leptoquarks in $eq$ collisions are HERA depends on the unknown LQ-q-e coupling, pair production of leptoquarks in $e^+e^-$ collisions at the $Z^0$ pole at LEP and in hadron collisions, which rely solely on the LQ electroweak and strong couplings (which are restricted in form), have now set stringent mass limits. LEP experiments \[6\] have excluded leptoquarks with masses below $\sim 45 \text{GeV}$, independent of their couplings to leptons and quarks, while recent analyses of TEVATRON collider data have yielded limits on first-generation scalar leptoquarks of $M(LQ_1) > 210 \text{GeV}$ \[7\] (assuming a branching ratio to $eq$ final states of $\beta = 1.0$) and $M(LQ_1) \geq 147 \text{GeV} (71 \text{GeV})$ \[8\] for $\beta = 0.5 (0.0)$ where the $\beta = 0.0$ limit is important as it provides a constraint on LQs which couple exclusively to $\nu q$ final states. These limits include the results of NLO QCD calculations of LQ pair-production cross-sections \[9\] and are even more stringent for vector leptoquarks (which have a larger strong-interaction cross-section at leading order) where one finds $M(LQ_1) > 298 \text{GeV} (270 \text{GeV})$ for $\beta = 1.0 (0.5)$.

Kunszt and Stirling \[10\] have argued that these mass limits are likely sufficient to already exclude vector leptoquarks from consideration as candidates for the HERA
events, while constraints from atomic parity violation force one to consider only iso-
doublet leptoquarks in the standard $SU_C(3) \times SU_2(L) \times U(1)$ invariant coupling classification scheme $[10]$. The two iso-doublet leptoquarks which we will then consider can be written in the form $[5]$

\[
S_2 = \begin{pmatrix} S_2^{(5/3)} \\ S_2^{(2/3)} \end{pmatrix} \quad \tilde{S}_2 = \begin{pmatrix} \tilde{S}_2^{(2/3)} \\ \tilde{S}_2^{(-1/3)} \end{pmatrix}
\]

(1)

with couplings

\[
S_2^{(5/3)} : \quad g_{2L}(e^+u), \quad g_{2R}(e^+u)
\]
\[
S_2^{(2/3)} : \quad g_{2L}(\bar{\nu}_e u), \quad -g_{2R}(e^+d)
\]
\[
\tilde{S}_2^{(2/3)} : \quad \tilde{g}_{2L}(e^+d)
\]
\[
\tilde{S}_2^{(-1/3)} : \quad \tilde{g}_{2L}(\bar{\nu}_e d)
\]

(2)

In addition, because of the stringent limits from the leptonic decays of charged pions and kaons, one assumes that only one chiral coupling is present, namely that $g_{2L} << g_{2R}$ or $g_{2L} >> g_{2R}$. Assuming that there is only one leptoquark accessible in the HERA energy range, we are left with three candidates for LQs which couple to $e^+q$ states and various corresponding possibilities for LQs which interact with neutrinos. If the leptoquark interpretation is correct and the state observed at HERA is $S_2^{(5/3)} \leftrightarrow e^+u$ (therefore with $g_{2L} >> g_{2R}$) or $\tilde{S}_2^{(2/3)} \leftrightarrow e^+d$ (with only $\tilde{g}_{2L}$), then there will be an iso-doublet partner which will couple to neutrinos, namely $S_2^{(2/3)} \leftrightarrow \bar{\nu}_e u$ (also with $g_{2L} >> g_{2R}$) or $\tilde{S}_2^{(-1/3)} \leftrightarrow \bar{\nu}_e d$ (with only $\tilde{g}_{2L}$). Only in the case where the state nominally seen at HERA is $S_2^{(5/3),(2/3)} \leftrightarrow (e^+u), (e^+d)$ (with $g_{2R} >> g_{2L}$) will there be no state which couples directly to $\nu_e - q$.

In the first two cases above, the iso-doublet partners of the particles discussed in the context of HERA could be produced in ultra-high energy $E_\nu > M(LQ)^2/2m_N$ neutrino-nucleon collisions and this topic was discussed some time ago by one of the authors $[11]$. In this note, we update the discussion of Ref. $[11]$ to discuss the prospects
for producing first-generation leptoquarks in $\nu_e, \bar{\nu}_e - N$ collisions, motivated by the new HERA interpretations. We extend the discussion of Ref. [11] as well to include (i) modern parton distributions which include new information on the low-$x$ parton content of the proton as obtained from more recent fits including HERA data, (ii) the next-to-leading order single leptoquark production cross-section formulae in Ref. [4], (iii) recent TEVATRON collider limits on LQ masses, and, most importantly, (iv) the limits on mass splittings between the iso-doublet leptoquark states which couple to $eq$ and $\nu q$ states which arise from precision electroweak measurements.

We will consider two scenarios in which a LQ coupled to neutrinos might be produced in a way which is consistent with existing collider mass bounds, limits from rare processes [12], and precision electroweak measurements. Let us first assume that the HERA events are due to a $\sim 200 GeV \tilde{S}_2^{52/3}$ with a required coupling [4] of $\tilde{g}_{2L}^2 = 0.002$ or $\tilde{g}_{2L} \approx 0.045$. The iso-doublet partner of this particle, to leading order, should be degenerate with it, but mass splittings are possible provided they are consistent with limits from precision electroweak measurements such as the $\rho$ parameter. In this case, for example, we have an almost degenerate scalar doublet which would give a contribution [13], [14] to the $\rho$ parameter of

$$\Delta \rho = \frac{1}{2} \left[ \frac{3G_F}{8\sqrt{2}\pi^2} \Delta m^2 \right]$$

where

$$\Delta m^2 = m_1^2 + m_2^2 - \frac{2m_1^2m_2^2}{m_1^2 - m_2^2} \log \left( \frac{m_1^2}{m_2^2} \right)$$

(This contribution is one-half that of a chiral quark doublet or that from both chiral ($L$ and $R$) components of a squark doublet [13].) To be conservative, if we assume
that three such LQ splittings (one per generation) are allowed, using fits discussed in
the most recent Review of Particle Properties [15], we find the bounds

\[ \Delta m^2 \leq (62 \text{GeV})^2, (80 \text{GeV})^2, (100 \text{GeV})^2 \]

corresponding to a mass of a standard model Higgs boson of \( M_H = 80 \text{GeV} \), 300 GeV, and 1000 GeV respectively. Using the middle value of \( M_H \), we find that this implies that
the component of \( \tilde{S} \) which couples to neutrinos could only be as light as \( M(\tilde{S}_2^{(-1/3)}) \approx 130 \text{GeV} \). This limit is already more stringent than that set by direct searches for \( \nu \nu jj \) final states [8] due to a LQ which couples exclusively to \( \nu q \) states. (During the
completion of this project, we became aware of Ref. [16] which uses more electroweak
data and the parameters \( S \) and \( T \) and derives slightly more stringent limits on such
splittings than this. On the other hand, it has been pointed out [17] that mixings
between various LQ states could significantly weaken such bounds, even giving rise to
negative contributions to \( \Delta \rho \).)

Thus, for this scenario, we use the parameters

Scenario I: \[ M(LQ) = 130 \text{GeV} \quad \tilde{g}_{2L} = 0.045 \]

We note that if the HERA events are due to the process \( e^+u \rightarrow S_2^{(5/3)} \rightarrow e^+u \) with \( g_{2L} \neq 0 \) (and hence \( g_{2R} \approx 0.0 \)), a similar scenario would be possible. However, in
that case the required coupling [4] of the \( S_2^{(5/3)} \) is much smaller (because it couples
to a valence \( u \)-quark) so that one would use \( g_{2L} \approx \sqrt{0.00049} \approx 0.022 \) with resulting
cross-sections in \( \nu - N \) interactions which would be 4 times smaller.

A second scenario assumes that the LQ which couples to neutrinos is \textbf{not} the iso-
doublet partner of the one putatively seen at HERA, but rather of one which has a
mass just outside of the HERA range (say, \( M(LQ) \geq 250 \text{GeV} \)). In this case, the \( \rho \)-parameter splitting limits imply that the neutrino-coupled LQ could be only as light as \( M(LQ) \approx 180 \text{GeV} \), but the limits on the common coupling, either \( g_{2L} \) or \( \tilde{g}_{2L} \), are now only constrained by rare processes. From the compilation of Davidson et al. \[12\], we find that this coupling could be as large as \( g_{2L}, \tilde{g}_{2L} \approx 0.11 \). Thus, in this scenario we use

\[
\text{Scenario II: } M(LQ) = 180 \text{GeV} \quad \tilde{g}_{2L} = 0.11 \tag{6}
\]

We then use the standard, narrow-width approximation for the resonant production of such LQ states in both \( \nu_e - N \) and \( \bar{\nu}_e - N \) collisions, namely

\[
\sigma_{\nu N} = \frac{\pi g^2}{4M^2} [xq(x, Q^2)] \tag{7}
\]

where \( q(x, Q^2) \) is the relevant parton distribution, evaluated at \( x = M^2/s \) and using \( Q^2 = M^2 \). We also include the recent calculations of the next-to-leading order (NLO) contributions to LQ production in \( lq \) interactions in Ref. \[4\]. We use the parton distributions of Ref. \[18\], both of which give very similar results: they are extended to smaller values of \( x \), beyond their fitted range, using the methods discussed in Ref. \[19\]. We plot the resulting cross-sections for \( \nu_e - N \) scattering (assuming an isoscalar nucleon target with equal numbers of \( u \) and \( d \)-quarks) in Fig. 1 for both Scenarios I and II and the same quantities in Fig. 2, but for \( \bar{\nu}_e - N \) scattering. For comparison on each plot, we reproduce the recent calculations by Gandhi et al. \[19\] for the standard model charged current (CC) and neutral current (NC) neutrino and antineutrino cross-sections at ultra-high energies.

Just as the more recent calculations of Gandhi et al. find a larger \( \nu - N \) and \( \bar{\nu} - N \) cross-section due to the increased size of the low-\( x \) parton distributions, our
LQ production calculations are now consistently larger than those originally found in Ref. [1]. However, the effect of the NLO correction terms are dominated here by a negative $\pi^2$ term multiplying the $\delta(1-z)$ term in the virtual corrections which leads to a 10 – 15% decrease in the overall cross-section, compared to leading order. (This is in comparison to the result near threshold where a different term [4] produces a small enhancement in the single LQ production cross-section.)

We note that the hint of a resonant structure is only apparent in the $\nu_e$ cross-section (where the $\nu_e$ interacts with valence $u$ or $d$ quarks) with the LQ contribution equal to the standard model neutral-current cross-section (at roughly $E_\nu \approx 10^5 \text{GeV}$) only in the most optimistic scenario. The other problem is that future UHE neutrino telescopes [20] (such as AMANDA, BAIKAL, and NESTOR) are being designed to detect muon signatures from $\nu_\mu N \rightarrow \mu X$ interactions and not necessarily to detect electrons or purely neutral current events.

Motivated by this experimental constraint, we also examine the prospects for the production of purely second-generation leptoquarks in neutrino interactions via the processes, $\nu_\mu q \rightarrow LQ_2 \rightarrow \nu_\mu q, \mu q'$. Limits on purely second-generation scalar leptoquark masses from hadron collider data are only slightly less stringent than those for the first generation case with limits $M(LQ_2) > 167 \text{GeV}$ [8] and $M(LQ_2) > 195 \text{GeV}$ [7] having been quoted, both for $\beta = 1.0$. The same limits on splittings of neutrino-coupled LQ will then imply that the lightest second-generation LQ which could interact via $\nu_\mu s \rightarrow LQ_2 \rightarrow \nu_\mu s$ would be roughly $M(LQ) \approx 130 \text{GeV}$. If we consider only purely second-generation leptoquarks, then the very stringent limits on admixtures of chiral couplings from charged pion and kaon decays are avoided. Processes such as $D_s = (c \bar{s}) \rightarrow \mu^+ \nu_\mu$ can be used (as in Ref. [12]) to derive limits which are of the form
$g_{L,R} \leq M(LQ_2)/380 \text{GeV}$ on the purely second-generation scalar leptoquark mass and couplings. (Compare the similar limits in Ref. [12] on the $(11)(22)$ generation changing couplings derivable from limits on $D \rightarrow \mu \tau$.) Such LQs also contribute to low-energy muon neutrino and antineutrino neutral-current scattering and we find that the ratio

$$\frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X)_{LQ}}{\sigma(\nu_\mu N \rightarrow \nu_\mu X)_{SM}} \approx 0.7 \left( \frac{g_{2L,2R}/M(LQ_2)}{g/M_W} \right)^4$$

(8)

for the ratio of the LQ-induced contribution to the standard electroweak expression. If we insist that this contribution be no more than 1/2% of the standard model result, we find the slightly more restrictive bound $g_{R,L} > M(LQ_2)/430 \text{GeV}$.

We show examples of the resulting possible contributions to muon-neutrino charged-current and neutral-current scattering in Fig. 3 where we assume three scenarios: (i) purely NC scattering due to a LQ with $M(LQ_2) = 200 \text{GeV}$ with $g_{2L,2R} = 0.3$, (ii) CC scattering due to a LQ which couples with equal strength to both $\nu_\mu q$ and $\mu q'$ with $M(LQ_2) = 200 \text{GeV}$ and $g_{2L,2R} = 0.5$ and (iii) the same scenario as (ii) but with a smaller coupling, namely $g_{2L,2R} = 0.1$. We see once again that even the most optimistic scenarios are just at the limit of having an observable effect on UHE neutrino interactions. We have calculated the LQ-induced cross-sections for a large number of masses and find that the scaling law

$$\frac{\sigma(\nu_\mu N \rightarrow \mu X)_{LQ}}{\sigma(\nu_\mu N \rightarrow \mu X)_{SM}} \approx 1.8 g^2 \left( \frac{200 \text{GeV}}{M(LQ_2)} \right)^{2.5}$$

(9)

is a good representation over a wide range of masses for incident neutrino energies which satisfy $E_\nu >> M^2(LQ_2)/2m_N$, i.e. far above threshold. Using the low-energy constraint on $g$ and $M(LQ)$ mentioned above for the second-generation case, we then find the approximate bound

$$\frac{\sigma(\nu_\mu N \rightarrow \mu X)_{LQ}}{\sigma(\nu_\mu N \rightarrow \mu X)_{SM}} \leq 0.4 \left( \frac{200 \text{GeV}}{M(LQ_2)} \right)^{0.5}$$

(10)
Thus, even more stringent constraints on LQ masses from collider experiments will likely push any LQ-mediated effects in ultrahigh-energy neutrino interactions beyond an observable limit.

In conclusion, recent limits of leptoquark masses from hadron collider experiments, supplemented by theoretical constraints on mass splittings from precision electroweak measurements provide very strong lower bounds on the masses of leptoquarks which couple only to neutrino-quark final states, better than the direct limits \([8]\). Even more stringent limits are likely from the upgraded TEVATRON with higher energies and vastly increased statistics as well as from future LHC experiments where limits \([21]\) of the order of \(M(LQ) = 750\, GeV\, (1000\, GeV)\) for \(\beta = 0.5\, (\beta = 1.0)\) will likely be possible. Such increased mass limits, coupled with even relatively weak low-energy constraints on couplings can be combined, as in Eqn. (11), to very tightly constrain any new contribution to ultrahigh-energy neutrino interactions from leptoquark production.

**Acknowledgments**

We thank C. Quigg for inspiring our renewed interest in this topic and T. Rizzo for communications about precision electroweak limits and leptoquarks. One of us (M.A.D) acknowledges the support of Penn State University through a Research Development Grant (RDG).
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Figure Captions

Fig. 1. The cross-section (in $mb$) for standard model charged current (CC) (solid curve) and neutral current (NC) (dashed curve) $\nu_e - N$ scattering for isoscalar nucleons versus incident neutrino energy, $E_\nu$. The other solid (dashed) curves correspond to the contribution of first-generation leptoquarks described by Scenario I (SI, in Eqn. (5), solid curve) and Scenario II (SII, in Eqn. (6), dashed curve).

Fig. 2. Same as for Fig. 1 except for antineutrino-induced processes, $\bar{\nu}_e - N$.

Fig. 3. The cross-section (in $mb$) for standard model charged current $\nu_\mu N \rightarrow \mu^- X$ (solid curve) and $\bar{\nu}_\mu N \rightarrow \mu^+ X$ (dashed curve) interactions versus incident neutrino energy, $E_\nu$. Also shown are the contributions from purely second-generation leptoquarks. The various cases considered are (i) purely NC interactions via $\nu_\mu s \rightarrow LQ_2 \rightarrow \nu_\mu s$ with $M(LQ_2) = 130 GeV$ and $g_{2L,2R} = 0.3$, (ii) charged current interactions via $\nu_\mu s \rightarrow LQ_2 \rightarrow \mu^- c$ with $M(LQ_2) = 200 GeV$ and $g_{2L,2R} = 0.5$ and (iii) the same as (ii) but with the smaller couplings $g_{2L,2R} = 0.1$. 
The graph shows the cross-section $\sigma$ (in mbarn) as a function of $E_\nu$ (in GeV) for different processes: SM $\bar{\nu}_e$-N CC and SM $\bar{\nu}_e$-N NC. The cross-sections are plotted on a log-log scale.
$\sigma$ (mbarn)

$E_\nu$ (GeV)

- $\text{SM } \nu_\mu$ -N CC
- $\text{SM } \bar{\nu}_\mu$ -N CC

(i)

(ii)

(iii)