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Technicolor leptoquarks and the excess of NC and CC events with high- Q^2 at HERA

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Abstract

In this paper we pursue a consistent leptoquark interpretation for HERA anomalies in the framework of Technicolor. We find that: (a) one $F=0$ scalar Technicolor leptoquark P'_3 with a mass of 200 GeV can provide the required contributions to account for the excess of both neutral and charged current events with high- Q^2 at HERA; (b) the current data still allow the coexistence of P'_3 with $m(P'_3) = 200\text{GeV}$ and P_3^0 with $m(P_3^0) = 225\text{GeV}$, they could contribute effectively to e^+p collision process and may be responsible for the apparent splitting of average mass of H1 and ZEUS NC events with high- Q^2 .

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1. Introduction

In this February, the two HERA collaborations H1 [1] and ZEUS [2] reported the excess of neutral current (NC) events with high- Q^2 ($Q^2 > 15000 GeV^2$) compared with the Standard Model (SM) expectations, based on their 1994-96 e^+p data. This observation has triggered extensive investigations about the possible new mechanisms beyond the SM responsible for this excess [3]. Among many possible solutions, the most favored one is the resonant production of new bosonic particle with a mass of about $200 GeV$, namely the *Leptoquark* (LQ) [4, 5] predicted by Technicolor (TC) and other new physics theories [5] or the *Squarks* (\tilde{t} and/or \tilde{c}) in the Minimal Supersymmetric Standard Model (MSSM) with R_p violating interactions [6, 7]. But the newest experimental results seem to disfavor the leptoquark interpretation based on the popular leptoquark scenario [8].

Firstly, the CDF [9] and D0 [10] collaborations reported their new lower mass bounds on scalar leptoquarks (and R_p violating \tilde{q} 's) very recently, based on their negative searches for the pair production of first generation scalar leptoquarks using the full RUN I data set and the new NLO theoretical cross section [11]. Assuming $\beta = Br(S \rightarrow eq) = 1$, the CDF and D0 limit is $M_S \geq 213 GeV$ [9] and $M_S \geq 225 GeV$ [10] respectively, and the combined limit is $M_S \geq 240 GeV$ [12]. The corresponding lower mass bounds on vector leptoquarks as well as squarks are in general significantly higher than that for scalar leptoquarks because the corresponding production cross sections for these particles are much more larger than that for scalar leptoquarks.

Secondly, H1 and ZEUS Collaborations [13, 14] reported more high- Q^2 neutral current and charge current (CC) events at the 1997 Lepton-Photon conference according to their new data obtained through June 1997. With a combined luminosity of $57.2 Pb^{-1}$ the former reported excess of high- Q^2 NC events is supported by the new data, and a clear tendency for the CC data to be above the SM deep inelastic scattering (DIS) expectations at large Q^2 was found by H1 and ZEUS collaborations [13, 14]. For $Q^2 > 10^4 GeV^2$, they observed 28 CC events where 17.7 ± 4.3 are expected. We now have to explain the excess for both NC and CC events simultaneously.

Moreover, the invariant mass distributions of the high- Q^2 NC events of H1 and ZEUS are rather different. For the 1994-96 e^+p data, the 7 H1 events appear clustered around $M \approx 200 GeV$, while the 5 ZEUS events clustered at $M \approx 220 GeV$. Recent

studies [15, 13] showed that this splitting can not be accounted for either by initial state radiation (ISR) or by detector effects, and it is unlikely that excesses observed by H1 and ZEUS could be caused by the production and decay of a single narrow resonance [13].

Although a scalar leptoquark with a mass of about 200 GeV is still allowed by the Tevatron data if it can decay to other channels, but the $F=0$ scalar leptoquarks \mathcal{R} and $\tilde{\mathcal{R}}$ in the Buchmuller, R ukle and Wyler (BRW) leptoquark scenario [8] could not decay to both e^+d and $\bar{\nu}u$ channels and therefore can not contribute to both NC and CC processes at HERA simultaneously. In order to provide a consistent interpretation for HERA anomalies, one has to study something new beyond the classic BRW leptoquark scenario [16, 17, 18].

In this paper, we will consider: (a) mixed states of color-triplet pseudo-Goldstone bosons, (b) more than one TC leptoquarks contribute effectively, in the framework of Technicolor [19, 20]. We will calculate the contributions to both NC and CC $e^\pm p$ collision processes at HERA from the $F=0$ scalar Technicolor (TC) leptoquark P'_3 and P_3^0 , the mixed states of color-triplet pseudo-Goldstone bosons $P_{U\bar{N}}$ and $P_{D\bar{E}}$. We find that: (a) one P'_3 with mass of 200 GeV can provide the required extra contributions to account for the HERA anomalies. For $Q_{min}^2 = 15000 GeV^2$, we have $\sigma_{LQ}^{NC} = 0.216 pb$ and $\sigma_{LQ}^{CC} = 0.306 pb$ assuming $m(P'_3) = 200 GeV$, $F_{2L} = 0.02$ and $\beta_{NC} = 0.7$; (b) the current data still allow the coexistence of a P'_3 with $m(P'_3) = 200 GeV$ and a P_3^0 with $m(P_3^0) = 225 GeV$, they could contribute the required extra cross sections to both NC and CC processes and may be responsible for the apparent splitting of average mass of H1 and ZEUS NC events with very high Q^2 . We also estimated the possible contributions from other heavier $F=0$ scalar TC leptoquarks.

This paper is organized as follows. in Sec.2 we briefly review the masses and the couplings of TC leptoquarks and the relevant experimental constraints. In Sec.3 we calculate the contributions to the $e^\pm p$ collision processes from the $F=0$ scalar TC leptoquarks and present the numerical results. Section 4 contains the conclusion and discussions.

2. Technicolor leptoquarks, masses and couplings

As is well known, the color triplet pseudo-Goldstone bosons (i.e. the leptoquarks in TC models) appeared in almost all non-minimal TC models which include one generation or more technifermions, such as the one generation TC model [19], one-family $SU(2)_{TC}$ model [21] and the Postmodern TC model [21], etc. For definiteness, we calculate the possible contributions to $e^\pm p$ scattering process from F=0 scalar TC leptoquarks as described in the often-discussed Farhi-Susskind one generation technicolor model (OGTM) and follow the nomenclature defined in ref.[20]. Although this model is not rich enough to describe the real world ¹, it does provide a typical description for the production and decays of such leptoquarks which would have to be present in any realistic TC models. For our studies in this paper, what we care most are the masses of TC leptoquarks and their effective Yukawa couplings to lepton-quark pairs, as well as the mixing patterns.

Under the gauge group $SU(N)_{TC} \otimes SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, the technifermions transform as [20]

$$\begin{aligned}
 Q_L &= \begin{pmatrix} U_L \\ D_L \end{pmatrix} \sim (N, 3, 2, 1/3), \\
 U_R &\sim (N, 3, 1, 4/3), \quad D_R \sim (N, 3, 1, -2/3), \\
 L_L &= \begin{pmatrix} N_L \\ E_L \end{pmatrix} \sim (N, 1, 2, -1), \\
 E_R &\sim (N, 1, 1, -2), \quad N_R \sim (N, 1, 1, 0),
 \end{aligned} \tag{1}$$

where the techniquarks and technileptons have the same charges as those ordinary quarks and leptons. When the technifermion condensate $\langle \bar{T}T \rangle \neq 0$ is formed, the global flavor chiral symmetry $SU(8)_L \otimes SU(8)_R$ is broken down to $SU(8)_{L+R}$. Consequently, 63 pseudo-Goldstone bosons(PGB's) would be produced. Corresponding to each of these 1S_0 pseudoscalars is a hyperfine partner 3S_1 technirho. Among all these PGB's and technirhos, the color-triplet $Q\bar{L}$ and $\bar{Q}L$ bound states are what we are most interested in for HERA experiments. Since only those F=0 TC leptoquarks may have a sizable contribution to the e^+p collision process at HERA we will not consider other PGB's and technirhos in this paper.

¹for the S parameter problem and the current status of Technicolor theory, see a recent review [22].

In Table 1 we classify the TC leptoquarks according to their $SU(3)_c$ and $SU(2)_v$ quantum numbers. Among all color-triplets the technirhos ρ_3 are the usual $F = 0$ vector leptoquarks, and they form one isotriplet $(\rho_3^1, \rho_3^0, \rho_3^{-1})$ and isosinglet ρ_3' . These vector leptoquarks may acquire large masses from the strong QCD interactions, and are expected to be very heavy, say $m_\rho \approx 800\text{GeV}$ [20]. These heavy technirhos therefore will decouple from the HERA $e^\pm p$ collision process. Although the color-triplet technirhos may be relatively light in some new TC models, the stringent Tevatron limits clearly ruled out the vector leptoquark interpretation for HERA high- Q^2 anomaly. We thus will not consider these vector TC leptoquarks anymore.

As shown in Table 1, the 24 color-triplet PGB's form one isotriplet (P_3^1, P_3^0, P_3^{-1}) and isosinglet P_3' and their antiparticles. They are the usual $F = 0$ scalar leptoquarks. The P_3^0 and P_3' are the mixed states of the charge $2/3$ pseudo-Goldstone bosons $P_{U\bar{N}}$ and $P_{D\bar{E}}$ [23, 20]. At HERA, P_3^1 , P_3^0 and P_3' could be produced directly by resonant production of $e^\pm p \rightarrow LQ$ if they have low masses $m_{LQ} < \sqrt{s}$ [24]. The P_3^{-1} is irrelevant to HERA experiments because it could not be produced by $e^\pm p$ collision process at HERA, and the Tevatron lower mass bounds on M_S also do not apply to P_3^{-1} since it decays uniquely to $\bar{\nu}d$ final state.

According to previous studies [25, 26], the scalar leptoquarks $P_3^{1,0,-1}$ and P_3' receive masses from QCD, ETC and electroweak interactions, $m(P_3) \sim 160\text{GeV}$ with a mass splitting of about 10 GeV. But we also know that the TC leptoquark masses could be increased greatly in Walking TC theories since the condensate enhancement [27] also enhances the masses of TC leptoquarks. We also expect additional uncertainties for Multiscale Technicolor Model [28] and other TC models where the TC dynamics is quite different from the QCD.

The gauge interactions of technicolor leptoquarks with the standard model gauge bosons occur dynamically through technifermion loops. Their coupling to gauge bosons ($\gamma, Z^0, W^\pm, gluon$) can be evaluated reliably by using well-known techniques of current algebra or effective lagrangian methods. Consequently, the parameter free pair production cross sections of leptoquarks at $\bar{p}p$ colliders have been calculated at leading and next-to-leading order [11]. It is this merit that makes it possible for D0 and CDF collaborations to obtain their lower mass bounds on leptoquarks based on their negative searches at Tevatron.

The coupling of a TC leptoquark to lepton-quark pairs occurs when the tech-

Table 1: Technicolor leptoquarks in the Farhi-Susskind one generation TC model, as given in Table II of ref.[18] . The $SU(3)_c$ index α runs over 1,2,3.

States	Technifermion wave function	$SU(3)_c$	(I, I_3)	Charge
P_3^1, ρ_3^1	$ U_\alpha \bar{E} \rangle$	3	(1,1)	5/3
P_3^0, ρ_3^0	$(1/\sqrt{2}) U_\alpha \bar{N} - D_\alpha \bar{E} \rangle$	3	(1,0)	2/3
P_3^{-1}, ρ_3^{-1}	$ D_\alpha \bar{N} \rangle$	3	(1,-1)	-1/3
P_3', ρ_3'	$(1/\sqrt{2}) U_\alpha \bar{N} + D_\alpha \bar{E} \rangle$	3	(0,0)	2/3

nifermion constituents of the leptoquark exchange an ETC gauge boson and turn into an ordinary quark and lepton. the "Yukawa" coupling of leptoquarks is therefore model-dependent and currently not known with confidence. Following ref.[23], we rewrite the effective Yukawa couplings of F=0 scalar TC leptoquarks to lepton-quark pairs before mixing as the form of

$$\begin{aligned} \mathcal{L} = & \lambda_{1L} P_{U\bar{N}} \bar{\nu}_L u_R + P_{D\bar{E}} [\lambda_{2L} \bar{e}_L d_R - \lambda_{2R} \bar{e}_R d_L] \\ & + P_{U\bar{E}} [\lambda_{3L} \bar{e}_L u_R - \lambda_{3R} \bar{e}_R u_L] + \lambda_{4L} P_{D\bar{N}} \bar{\nu}_L d_R + h.c. \end{aligned} \quad (2)$$

where the e, ν, d , and u are vectors (e, μ, τ) , $(\nu_e, \nu_\mu, \nu_\tau)$, (d, s, b) and (u, c, t) respectively, and the effective Yukawa couplings λ_i in eq.[2] generally depend on the Technicolor and Extended Technicolor dynamics and therefore could vary over a large range. If we assume, according the general sense, that the Yukawa coupling is something like $\lambda \approx (m_q + m_l)/F_\pi$ (the F_π is the Goldstone boson decay constant and $F_\pi = 123 GeV$ in the QCD-like OGTM), the couplings will be very small for light $(u, d) - e^\pm$ pairs. Although the low energy constraints could be avoided automatically by such kinds of couplings [29], but numerical estimation shows that the relevant couplings (i.e. λ_{e+u} , λ_{e+d} and $\lambda_{\bar{\nu}u}$) are too small to provide an adequate contribution to the e^+p collision process at HERA. For $\lambda_{e+u} = \lambda_{e+d} = \lambda_{\bar{\nu}u} \approx m_u/F_\pi \approx 10^{-4}$, for example, the neutral current cross-section from P_3' is smaller than 1 fb assuming $m(P_3') = 200 GeV$ and $\beta = 0.7$.

On the other hand, in the popular BRW leptoquark scenario [8], the interactions of leptoquarks with quark-lepton pairs were described by an "effective" Lagrangian [8] involving scalar and vector leptoquarks with general $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant

Yukawa couplings $\lambda_{L,R}^{i,j}$, constrained by low-energy experiments. The $F = 0$ scalar TC leptoquarks in Table 1 are indeed the same kinds of leptoquarks as the R and \tilde{R} leptoquarks in ref.[8] and couple to quark-lepton pairs in the similar way. It is therefore reasonable for us to assume that the Yukawa couplings of TC leptoquarks are also the dimensionless parameters to be determined by experiments. They are constrained by low energy experiments in the same way as that for ordinary leptoquarks:

- (a). baryon- and lepton number conserving;
- (b). no generation mixing, a given leptoquark couple only to one generation of fermions and only via λ_L or only via λ_R ;
- (c). $(\lambda/\sqrt{4\pi\alpha}) < 0.17(M_{LQ}/200GeV)^2$ [30].

As for the explicit mixing patterns of P'_3 and P_3^0 , we assume that

$$\begin{pmatrix} P'_3 \\ P_3^0 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} P_{U\bar{N}} \\ P_{D\bar{E}} \end{pmatrix} \quad (3)$$

After mixing, the effective Yukawa couplings of the P'_3 and P_3^0 to lepton-quark pairs are

$$\begin{aligned} \mathcal{L} = & P'_3 [\lambda_{2L} \sin \theta \bar{e}_L d_R - \lambda_{2R} \sin \theta \bar{e}_R d_L + \lambda_{1L} \cos \theta \bar{\nu}_L u_R] \\ & + P_3^0 [\lambda_{2L} \cos \theta \bar{e}_L d_R - \lambda_{2R} \cos \theta \bar{e}_R d_L - \lambda_{1L} \sin \theta \bar{\nu}_L u_R] + h.c. \end{aligned} \quad (4)$$

where the $\lambda_{1L,R}$ and $\lambda_{2L,R}$ are the effective Yukawa couplings before mixing as given in eq.[2]. For P'_3 and P_3^0 , the branching ratios to the e^+d final state are

$$BR(P'_3 \rightarrow e^+d) = \frac{(\lambda_{2L}^2 + \lambda_{2R}^2) \sin^2 \theta}{(\lambda_{2L}^2 + \lambda_{2R}^2) \sin^2 \theta + \lambda_{1L}^2 \cos^2 \theta}, \quad (5)$$

$$BR(P_3^0 \rightarrow e^+d) = \frac{(\lambda_{2L}^2 + \lambda_{2R}^2) \cos^2 \theta}{(\lambda_{2L}^2 + \lambda_{2R}^2) \cos^2 \theta + \lambda_{1L}^2 \sin^2 \theta}. \quad (6)$$

The size of the branching ratios depend on the values of λ_1 , λ_2 and θ . For the sake of simplicity, we assume that $\theta = \pi/4$ and $\lambda_R = 0$ ².

In Table 2 we list the Yukawa couplings of all $F=0$ scalar TC leptoquarks to first generation lepton-quark pairs, and the couplings of R and \tilde{R} [8] to lepton-quark pairs are also included as a comparison.

²If $\lambda_R \neq 0$ and $\lambda_L = 0$ the P'_3 and P_3^0 could not contribute to CC process as being shown in section 3, we therefore assume implicitly that $\lambda_L \neq 0$ and $\lambda_R = 0$ in the following calculations.

Table 2: The Yukawa couplings of the F=0 scalar Technicolor leptoquarks to first generation quark-lepton pairs. The subscripts L, R of the coupling refer to the lepton chirality. The couplings \mathcal{R} and $\tilde{\mathcal{R}}$ to lepton-quark pairs are listed as a comparison.

Channel	P'_3	P_3^1	P_3^0	P_3^{-1}	\mathcal{R}	$\tilde{\mathcal{R}}$
$e_{L,R}^- \bar{d}$	$\lambda_{2L}, -\lambda_{2R}$	-	$\lambda_{2L}, -\lambda_{2R}$	-	$-h_{2R}$	\tilde{h}_{2L}
$e_{L,R}^- \bar{u}$	-	$\lambda_{3L}, -\lambda_{3R}$	-	-	$h_{2L,R}$	-
$\nu_L \bar{u}$	λ_{1L}	-	$-\lambda_{1L}$	-	h_{2L}	-
$\nu_L \bar{d}$	-	-	-	λ_{4L}	-	\tilde{h}_{2L}

The TC leptoquarks P'_3, P_3^0 and P_3^1 would contribute to NC and/or CC processes in the similar way if they were not heavy, but they could not be light simultaneously because of the stringent Tevatron mass bounds [9, 10, 12]. In order to compare with the HERA data quantitatively, we consider the following three typical cases in detail:

- Case-1 . Assuming $m(P_3^1) = 225\text{GeV}$, $m(P'_3) = m(P_3^0) = 280 \sim 300\text{GeV}$, i.e., only the charge 5/3 TC leptoquark P_3^1 contribute effectively; If we apply the combined Tevatron limit, $m(P_3^1) = 240\text{GeV}$ is still allowed [12];
- Case-2 . Assuming $m(P'_3) = 200\text{GeV}$, $m(P_3^1) = m(P_3^0) = 280 \sim 300\text{GeV}$, i.e., only the lighter mixed state P'_3 contribute effectively; For this case, $\beta_{NC} \leq 0.7(0.5)$ is allowed by CDF and D0 (combined) limit [9, 10, 12];
- Case-3 . Both P'_3 and P_3^0 contribute effectively. If we assume that $m(P'_3) = 200\text{GeV}$, $m(P_3^0) = 225\text{GeV}$ and $m(P_3^1) = 280 \sim 300\text{GeV}$, the value of branching ratios $\beta_1 = Br(P'_3 \rightarrow e^+ d)$ and $\beta_2 = Br(P_3^0 \rightarrow e^+ d)$ will be constrained strongly by the Tevatron upper limits on the pair production cross section of scalar leptoquarks. For $\beta_1 = 0.6$, $\beta_2 \leq 0.5$ is allowed by D0 95%*C.L.* upper limit of $\sigma \leq 0.078\text{pb}$. For $\beta_1 = 0.4$, $\beta_2 \leq 0.4$ is allowed by combined Tevatron upper limit of $\sigma \leq 0.04\text{pb}$.

3. Contributions from TC leptoquarks

In this section we will calculate the contributions to the $e^\pm p$ collision process from those F=0 scalar TC leptoquarks. In numerical calculations, we use the LEPTO 6.5

[31] program and the MRS96 parton distribution functions [32] with the inclusion of high order QED and QCD corrections. For all relevant masses, decay widths or coupling constants such as M_Z , M_W , α , G_F , etc., we use the default values as given in PYTHIA 5.724/JETSET 7.410 [33].

The TC leptoquarks (P_3^1, P_3^0, P_3') can be produced directly in e^+p deep inelastic scattering from a u or d valence quark in proton as illustrated in Figs.(1a,1c,1e), if their masses are smaller than the e^+p center of mass energy \sqrt{s} [34]. The leptoquarks will also contribute indirectly by u-channel exchange as shown in Figs.(1b, 1d, 1f). The TC leptoquarks can also be produced through “gluon fusion” in which the incoming positron annihilates with the quark from the virtual $q\bar{q}$ pair of a gluon. We will not consider the case of “gluon fusion” since the corresponding production rate is unobservably small at HERA [34, 35]. we at first present the relevant formulae being used in the numerical calculations.

3.1 Electroweak and new physics cross sections

At HERA $e^\pm p$ collider, the reaction $e^\pm + p \rightarrow l^\pm + X$ is expected to occur through the subprocess

$$e^\pm + q_1 \rightarrow l^\pm + q_2 \quad (7)$$

where the q_1 is an initial state quark in the proton, q_2 is the final state quark. In the framework of the SM, $l^\pm = e^\pm, \nu$ or $\bar{\nu}$ for NC and CC processes respectively. In new physics models beyond the SM, the l^\pm could be all three generation leptons [36]. But we here consider only the first generation fermions.

In leading order, the differential NC cross-section for an incoming polarized electron beam colliding with unpolarized proton beam is given by [31]

$$\frac{d^2 \sigma_{NC}(e_{L,R}^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[(1 + (1-y)^2) F_2^{L,R}(x, Q^2) + (1 - (1-y)^2) x F_3^{L,R}(x, Q^2) \right] \quad (8)$$

where the structure functions $F_{2,3}^{L,R}$ are the form of

$$F_2^{L,R}(x, Q^2) = \sum_q x \left[q(x, Q^2) + \bar{q}(x, Q^2) \right] A_q^{L,R}, \quad (9)$$

$$x F_3^{L,R}(x, Q^2) = \sum_q x \left[q(x, Q^2) - \bar{q}(x, Q^2) \right] B_q^{L,R}, \quad (10)$$

with the coefficient functions

$$A_q^{L,R}(Q^2) = e_q^2 - 2e_q(v_e \pm a_e)v_q P_Z + (v_e \pm a_e)^2(v_q^2 + a_q^2)P_Z^2, \quad (11)$$

$$B_q^{L,R}(Q^2) = \mp 2e_q(v_e \pm a_e)a_q P_Z \pm 2(v_e \pm a_e)^2 v_q a_q P_Z^2 \quad (12)$$

where e_q is the electric charge of quarks ($e_e = -1$), $v_f = (I_{3f} - 2e_f \sin^2 \theta_W) / \sin 2\theta_W$ and $a_f = I_{3f} / \sin 2\theta_W$ are the vector and axial vector electroweak couplings, and $P_Z = Q^2 / (Q^2 + M_Z^2)$. For incoming $e_{L,R}^\pm$ beams, the corresponding cross sections are obtained from the above formulae by the replacements

$$F_2^{L,R} \longrightarrow F_2^{R,L}, \quad xF_3^{L,R} \longrightarrow -xF_3^{R,L}. \quad (13)$$

For the charged current e^-p (e^+p) collision process, only the polarized e_L^- (e_R^+) beam contribute. If we consider only four massless quark flavours (u, d, s, c) and use the unitarity relation of CKM matrix, the differential cross section for incoming e_L^- and e_R^+ beams colliding with unpolarized proton are given respectively by [31]

$$\frac{d^2\sigma_{CC}(e_L^-p)}{dx dQ^2} \approx \frac{G_F^2}{\pi} \left(1 + \frac{Q^2}{M_W^2}\right)^{-2} \left[(u+c) + (1-y)^2(\bar{d} + \bar{s})\right] \quad (14)$$

$$\frac{d^2\sigma_{CC}(e_R^+p)}{dx dQ^2} \approx \frac{G_F^2}{\pi} \left(1 + \frac{Q^2}{M_W^2}\right)^{-2} \left[(\bar{u} + \bar{c}) + (1-y)^2(d+s)\right] \quad (15)$$

The explicit formulae for the leptoquark contributions to both NC and CC $e^\pm p$ collision processes are rather simple. If we neglect all interference terms such as that between the SM amplitudes and leptoquark amplitudes. These interference terms are in general very small in the high- Q^2 region. In the mass region ($m_{LQ} < \sqrt{s} = 300 \text{ GeV}$) considered here, the s-channel will dominate.

For a $F=0$ scalar TC leptoquark, the neutral current leptoquark differential cross sections for an incoming polarized e^\pm beam colliding with an unpolarized proton are

$$\frac{d^2\sigma_{NC}(e_L^-p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \frac{F_L^i(F_L^f + F_R^f)}{4} \left[\frac{\hat{t}^2 x \bar{q}(x, Q^2)}{[\hat{s} - m_{LQ}^2]^2 + m_{LQ}^2 \Gamma_{LQ}^2} + \frac{\hat{u}^2 y^2 x q(x, Q^2)}{[\hat{u} - m_{LQ}^2]^2} \right] \quad (16)$$

$$\frac{d^2\sigma_{NC}(e_R^+p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \frac{F_L^i(F_L^f + F_R^f)}{4} \left[\frac{\hat{t}^2 x q(x, Q^2)}{[\hat{s} - m_{LQ}^2]^2 + m_{LQ}^2 \Gamma_{LQ}^2} + \frac{\hat{u}^2 y^2 x \bar{q}(x, Q^2)}{[\hat{u} - m_{LQ}^2]^2} \right] \quad (17)$$

where the \hat{s} , \hat{t} and \hat{u} are the Mandelstam variables, defined as $\hat{s} = sx$, $\hat{t} = -Q^2 = -sxy$ and $\hat{u} = -\hat{s} + Q^2 = -xy(1-y)$. And the $F_{L,R}$ are the redefined couplings and the superscripts i and f refer to the couplings at the production and the decaying vertices,

$$F_{L,R} = \lambda_{L,R}^2 / (4\pi\alpha) \quad (18)$$

with electroweak coupling $F_{EW} = 1$. We neglected the interference terms between the SM amplitudes and leptoquark amplitudes, since such interference terms are very small, say less than 1 fb, for $Q^2 > 10000 \text{ GeV}^2$. The cross sections for incoming e_R^- and e_L^+ beams are obtained by exchanging the L and R in eq.[16] and eq.[17], respectively. The low energy constraints on effective Yukawa couplings can be rewritten as

$$F_L \leq 0.03 \left(\frac{m_{LQ}}{200 \text{ GeV}} \right)^4 \quad (19)$$

and we had assumed that $F_R \equiv 0$.

For charged current process $e^\pm p \rightarrow \bar{\nu}(\nu)X$, the $F=0$ scalar leptoquark interactions do not interfere with the standard model DIS, and the leptoquark differential cross section for an incoming polarized e^\pm beam colliding with an unpolarized proton are [37]

$$\frac{d^2\sigma_{CC}(e_L^- p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \frac{F_L^i F_L^f}{4} \left[\frac{\hat{t}^2 x \bar{d}(x, Q^2)}{[\hat{s} - m_{LQ}^2]^2 + m_{LQ}^2 \Gamma_{LQ}^2} + \frac{\hat{u}^2 y^2 x u(x, Q^2)}{[\hat{u} - m_{LQ}^2]^2} \right] \quad (20)$$

$$\frac{d^2\sigma_{CC}(e_R^- p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \frac{F_R^i F_R^f}{4} \left[\frac{\hat{t}^2 x \bar{d}(x, Q^2)}{[\hat{s} - m_{LQ}^2]^2 + m_{LQ}^2 \Gamma_{LQ}^2} + \frac{\hat{u}^2 y^2 x u(x, Q^2)}{[\hat{u} - m_{LQ}^2]^2} \right] \quad (21)$$

$$\frac{d^2\sigma_{CC}(e_L^+ p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \frac{F_L^i F_R^f}{4} \left[\frac{\hat{t}^2 x d(x, Q^2)}{[\hat{s} - m_{LQ}^2]^2 + m_{LQ}^2 \Gamma_{LQ}^2} + \frac{\hat{u}^2 y^2 x \bar{u}(x, Q^2)}{[\hat{u} - m_{LQ}^2]^2} \right] \quad (22)$$

$$\frac{d^2\sigma_{CC}(e_R^+ p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \frac{F_L^i F_L^f}{4} \left[\frac{\hat{t}^2 x d(x, Q^2)}{[\hat{s} - m_{LQ}^2]^2 + m_{LQ}^2 \Gamma_{LQ}^2} + \frac{\hat{u}^2 y^2 x \bar{u}(x, Q^2)}{[\hat{u} - m_{LQ}^2]^2} \right] \quad (23)$$

It may be seen that there could be no TC leptoquark contribution to CC processes if $F_L = 0$, while only the incoming e_L^- (e_R^+) beam contributes to the CC $e^- p$ ($e^+ p$) collision process if $F_L \neq 0$ and $F_R = 0$.

3.2 Case-1, NC contribution from P_3^1

As shown in Fig.1a, the charge 5/3 TC leptoquark P_3^1 can be produced by e^+u fusion and will decay uniquely back to e^+u lepton-quark pair. It can not contribute to the CC cross section, but could provide a rather large contribution to NC process if it was light.

As discussed in Section 2, $m(P_3^1) = 225$ (240) GeV is allowed by D0 (combined Tevatron) limit when other TC leptoquarks are heavy and effectively decouple.

Table 3 shows the integrated NC cross sections from the P_3^1 , assuming $F_{3L} = \lambda_{3L}^2/(4\pi\alpha) = (0.005, 0.01, 0.02)$, $F_R = 0$ and $m(P_3^1) = 200 - 300$ GeV, respectively.

For $m(P_3^1) = 225\text{GeV}$ and a left-handed chiral coupling of 0.008, the P_3^1 itself can provide the required extra NC cross section, say $\Delta\sigma_{NC} \approx 0.2\text{pb}$ for $Q_{min}^2 = 15000\text{GeV}^2$, to explain the HERA NC anomaly. This result is consistent with that of previous similar studies [4]. For $m(P_3^1) = 240\text{GeV}$, the required extra contributions can still be achieved for $F_{3L} = 0.02$. For more heavier P_3^1 , its contribution decreases rapidly and can be neglected for $m(P_3^1) \geq 280\text{GeV}$. But the key problem for P_3^1 is that it could not contribute to CC process. A relatively light P_3^1 therefore will be excluded if the excess of CC events with high- Q^2 is finally confirmed by HERA data.

Table 3: The neutral current cross sections from TC leptoquark P_3^1 with $Q_{min}^2 = 15000, 25000\text{GeV}^2$, assuming $F_{3L} = (0.005, 0.01, 0.02)$, $F_R = 0$ and $m(P_3^1) = 200 - 300$ GeV, respectively. All cross sections in pb

Mass (GEV)	$Q_{min}^2 = 15000\text{GeV}^2$			$Q_{min}^2 = 25000\text{GeV}^2$		
	$F_{3L} = 0.005$	0.01	0.02	$F_{3L} = 0.005$	0.01	0.02
200	0.324	0.651	1.297	0.192	0.384	0.767
220	0.145	0.293	0.582	0.100	0.201	0.401
240	0.047	0.096	0.189	0.035	0.071	0.142
260	0.009	0.019	0.035	0.007	0.014	0.028
280	0.0005	0.002	0.004	0.0003	0.001	0.002
300	10^{-6}	0.0007	10^{-5}	0	0.0002	0.0002

3.3 Case-2, the NC and CC contributions from single P_3'

For the assumed mass spectrum of Case-2, only P_3' , the lighter mixed state, contribute to both NC and CC e^+p collision processes effectively. For $m(P_3') = 200\text{GeV}$, $\beta_{NC} \leq 0.7$ (0.5) is allowed by D0 (combined) limit. As for the Yukawa coupling F_{1L} , we have

$$F_{1L} = F_{2L}(1 - \beta_{NC})/\beta_{NC} \quad (24)$$

Assuming $F_{2L} = \lambda_{2L}^2/(4\pi\alpha) = 0.02$ and $\beta_{NC} = (0.7, 0.6, 0.5)$, we have $F_{1L} = 0.009, 0.013$ and 0.02 respectively.

Table 4 shows the contributions to NC cross sections from P_3' , assuming $F_{2L} = 0.02$ and $\beta_{NC} = 0.7, 0.6$ and 0.5 respectively. As a comparison, we also list the preliminary

1994-97 combined ZEUS and H1 NC cross sections with different Q_{min}^2 cuts[13], and the corresponding standard model predictions for NC cross sections.

Table 4: The integrated NC cross sections from TC leptoquark P'_3 , assuming $m(P'_3) = 200GeV$, $F_{2L} = 0.02$. The σ_{NC}^a , σ_{NC}^b and σ_{NC}^c corresponding to $\beta_{NC} = 0.7, 0.6$ and 0.5 respectively. The second and third columns show the combined H1 and ZEUS NC data with Q_{min}^2 cuts. All cross sections in pb .

Q_{min}^2 (GeV^2)	H1 + ZEUS			P'_3 Contributions		
	N_{obs}	σ_{obs}	σ_{sm}	σ_{NC}^a	σ_{NC}^b	σ_{NC}^c
2500	724 ^(a)	$43.3^{+4.6}_{-3.9}$	45.7	0.337	0.289	0.241
5000	193 + 326 ^(b)	10.7 ± 0.7	10.6	0.311	0.267	0.222
10000	31 + 50 ^(b)	$1.70^{+0.23}_{-0.20}$	1.79	0.263	0.226	0.188
15000	18+ 18 ^(b)	$0.71^{+0.14}_{-0.12}$	0.49	0.217	0.186	0.155
20000	7 + 7 ^(b)	$0.30^{+0.092}_{-0.076}$	0.161	0.172	0.147	0.123
25000	4 + 3 ^(b)	$0.16^{+0.069}_{-0.053}$	0.059	0.128	0.110	0.091
30000	2+ 2 ^(b)	$0.098^{+0.059}_{-0.042}$	0.023	0.085	0.073	0.060
35000	2 ^(c)	$0.060^{+0.059}_{-0.037}$	0.0091	0.042	0.036	0.030
40000	1 ^(c)	$0.032^{+0.044}_{-0.023}$	0.0036	0.00004 ^(d)	0.00004 ^(d)	0.00004 ^(d)

(a). ZEUS 1994-97 e^+p NC data, $\mathcal{L} = 33.5pb^{-1}$;

(b). Combined H1 and ZEUS 1994-97 e^+p NC data, $\mathcal{L} = 57.2pb^{-1}$;

(c). H1 1994-97 e^+p NC data, $\mathcal{L} = 23.7pb^{-1}$;

(d). For $m(P'_3) = 215GeV$ and $\beta_{NC} = 0.7, 0.6$ and 0.5 , the σ_{NC} is 0.020, 0.017 and 0.014 respectively.

As shown in Table 5, the F=0 scalar TC leptoquark P'_3 with $m(P'_3) = 200GeV$ can indeed provide the required extra contributions to the CC process. For $Q_{min}^2 = 10000GeV^2$, for example, $\sigma_{CC}^{a,b,c} = (0.381, 0.509, 0.636) pb$, assuming $F_{2L} = 0.02$, $F_R = 0$ and $\beta_{CC} = 0.3, 0.4$ and 0.5 respectively. The SM predictions and the preliminary CC results from 1994-97 H1 and ZEUS e^+p data [13] are also included in Table 5 as a comparison.

At HERA, the initial and final state particles in leptoquark-mediated interactions are identical to those in NC and CC DIS. Events due to leptoquark-mediated interactions

are therefore expected to be identical to those from DIS processes. Like the DIS CC events, The TC leptoquark CC events will be experimentally very clean and can be selected with similar high efficiency. In order to estimate roughly how much extra CC contributions are required from the new physics sources, based on the current H1 and ZEUS data, we define $\Delta\sigma_{CC}$ the required extra CC cross section, as

$$\Delta\sigma_{CC} = \frac{N_{obs} - N_{exp}}{N_{exp}}\sigma_{SM} \pm \frac{\delta N_{exp}}{N_{exp}}\sigma_{SM} \quad (25)$$

where the N_{obs} and N_{exp} are the numbers of observed and expected CC events by H1 and/or ZEUS collaboration respectively, and the σ_{SM} is the SM CC cross section.

Table 5: The integrated CC cross sections from TC leptoquark P'_3 with different Q_{min}^2 cuts, assuming $m(P'_3) = 200GeV$, $F_{2L} = 0.02$. The σ_{CC}^a , σ_{CC}^b and σ_{CC}^c corresponding to $\beta_{CC} = 0.3, 0.4$ and 0.5 respectively. The ZEUS and H1 preliminary 1994-97 e^+p CC data included. All cross sections in pb .

Q_{min}^2 (GeV^2)	H1 + ZEUS			P'_3 Contributions		
	N_{obs}	N_{expect}	σ_{sm}	σ_{CC}^a	σ_{CC}^b	σ_{CC}^c
1000	455 (a)	419 ± 36	16.47	0.391	0.521	0.651
2500	61 (b)	56.3 ± 9.4	7.32	0.389	0.519	0.649
5000	43 (b)	34.7 ± 6.9	2.54	0.381	0.509	0.636
10000	13 + 15 (c)	17.7 ± 4.3	0.493	0.351	0.468	0.584
15000	6 + 5 (c)	4.9 ± 1.7	0.127	0.306	0.408	0.510
20000	4 + 1(c)	1.7 ± 0.7	0.037	0.253	0.338	0.442
30000	1 (a)	$0.034^{+0.038}_{-0.018}$	0.004	0.133	0.177	0.221

- (a). ZEUS 1994-97 e^+p CC data, $\mathcal{L} = 33.5pb^{-1}$;
- (b). H1 1994-97 e^+p CC data, $\mathcal{L} = 23.7pb^{-1}$;
- (c). Combined H1 and ZEUS 1994-97 e^+p CC data, $\mathcal{L} = 57.2pb^{-1}$.

Table 6 shows the $\Delta\sigma_{CC}$ from the preliminary 1994-97 H1 and ZEUS e^+p data. As a simple estimation, we neglected the difference between the Q_h^2 and Q_{JB}^2 used by H1 and ZEUS respectively. The data show clearly a need for positive extra contribution $\Delta\sigma_{CC}$, especially for CC events with very high- Q^2 . For $Q_{min}^2 = 10000, 25000GeV^2$, the deviation is $+2.4\sigma$ and $+4.7\sigma$ respectively. For $Q_{min}^2 = 30000GeV^2$, ZEUS observed

1 event while the SM expectation is only $0.034_{-0.018}^{+0.038}$. Inclusion of the TC leptoquark contribution can achieve a very good agreement between the data and the theoretical expectations.

For e^-p collision process, the $F=0$ scalar TC leptoquarks ($\overline{P}_3^1, \overline{P}_3^0, \overline{P}_3'$) could be produced directly by the s-channel e^-u and/or e^-d "fusion". But the relevant cross sections are strongly suppressed by the smallness of the parton density of sea quarks in a proton. Assuming $m(P_3') = 200 GeV$, $F_{2L} = 0.02$, $F_{2R} = 0$, $\beta_{NC} = 0.7$ and $\beta_{CC} = 0.3$, the NC cross section due to P_3' is only about $0.01 pb$ (less than 1% of the corresponding SM contribution) for $Q_{min}^2 = 15000 GeV^2$, while the CC cross section is only $0.02 pb$ (less than 0.6% of the corresponding SM cross section) for $Q_{min}^2 = 10000 GeV^2$. The contributions to e^-p collision process from $F=0$ scalar TC leptoquarks are indeed very small and can be neglected safely.

Table 6: The required extra CC cross section $\Delta\sigma_{CC}$, and the P_3' contributions with different Q_{min}^2 cuts, assuming $m(P_3') = 200 GeV$, $F_{2L} = 0.02$. The $\sigma_{CC}^{a,b,c}$ corresponding to $Br(P_3' \rightarrow \bar{\nu}u) = 0.3, 0.4$ and 0.5 respectively. The ZEUS and H1 preliminary 1994-97 e^+p CC data included. All cross sections in pb .

Q_{min}^2 (GeV^2)	H1 + ZEUS		δ	σ_{sm}	$\Delta\sigma_{CC}$	P_3' Contributions		
	N_{obs}	N_{expect}				σ_{CC}^a	σ_{CC}^b	σ_{CC}^c
1000	455	419 ± 36	$+1\sigma$	16.47	1.4 ± 1.4	0.391	0.521	0.651
2500	61	56.3 ± 9.4	$+0.5\sigma$	7.32	0.61 ± 1.22	0.389	0.519	0.649
5000	43	34.7 ± 6.9	$+1.2\sigma$	2.54	0.61 ± 0.51	0.381	0.509	0.636
10000	28	17.7 ± 4.3	$+2.4\sigma$	0.493	0.287 ± 0.12	0.351	0.468	0.584
15000	11	4.9 ± 1.7	$+3.6\sigma$	0.127	0.158 ± 0.04	0.306	0.408	0.510
20000	5	1.7 ± 0.7	$+4.7\sigma$	0.037	0.072 ± 0.015	0.253	0.338	0.442
30000	1	$0.034_{-0.018}^{+0.038}$	$+25\sigma$	0.004	$0.114_{-0.002}^{+0.004}$	0.133	0.177	0.221

From Tables (4, 5, 6) three observations are in order. First, even one single scalar TC leptoquark P_3' can account for both excesses of NC and CC events with very high Q^2 at HERA simultaneously, while all relevant parameters are still within the region allowed by experiments. For the neutral current process, the total cross section, σ_{SM} plus σ_{NC} , reproduce the observed NC cross sections within the $1 - \sigma$ experimental error

for the whole range of $Q^2 = 2500 - 40000 GeV^2$. The same is true for the charged current process. For $Br(P'_3 \rightarrow \bar{\nu}u) \geq 0.3$ a single P'_3 with $m(P'_3) = 200 - 220 GeV$ can provide an adequate extra cross section to explain the excess of CC events with very high- Q^2 . Secondly, the relative strength of NC and CC contributions from P'_3 depends on the ratio of the corresponding branching ratio to e^+d and $\bar{\nu}u$. The “best” choice is apparently $Br(P'_3 \rightarrow e^+d) \approx 0.7$. For $Br(P'_3 \rightarrow e^+d) = 0.5$, the NC contribution seems to be a little inadequate while the CC contribution seems a bit larger than that required. Finally, the effective Yukawa coupling of TC leptoquark to quark-lepton pairs must be left-handed, i.e., $F_L \neq 0$ and $F_R = 0$. Otherwise, there will be no any charged current contribution from the $F=0$ scalar TC leptoquarks.

3.4 Case-3, contributions from both P'_3 and P_3^0

As discussed in ref.[15], the HERA anomaly is complicated by the fact that the invariant mass distributions of the event samples of the H1 and ZEUS collaborations are quite different. For the 1994-96 e^+p data, the 7 H1 NC events clustered at $M \approx 200 GeV$ with the average mass of $M_e^{avg} = 200 \pm 2.6 GeV$ and $M_\omega^{avg} = 199 \pm 2.5 GeV$, while the 5 ZEUS NC events clustered at $M \approx 220 GeV$ with the average mass of $M_{DA}^{avg} = 226 \pm 9 GeV$ and $M_\omega^{avg} = 216 \pm 7 GeV$. Bassler and Bernardi claimed that the H1 and ZEUS samples are concentrated at significantly different mass values and this splitting cannot be accounted for either by ISR or by detector effects. B.Straub also reaches a similar conclusion [13]: It is unlikely that both excesses observed by H1 and ZEUS could be caused by a single narrow resonance! A natural and reasonable solution is that: there are two $F=0$ scalar TC leptoquarks with a moderate mass splitting of about 25 GeV, and they both contribute to e^+p collision processes effectively. That is the motivation for us to consider the Case-3 in detail.

As given in Table 2, the TC leptoquark P'_3 and P_3^0 have the same coupling λ_{2L} to e^+d pair, while their couplings to $\bar{\nu}d$ are same in size but with opposite sign. Consequently, the interference terms will be constructive to NC cross section but destructive to CC cross section. For all possible interference terms, only the one between two s-channel amplitudes, $2\mathcal{R}e(M_1^S M_2^{S*})$, may be important. The differential cross sections from this interference term are

$$\frac{d^2\sigma_{NC}(e^-p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \frac{F_{2L}F_{1L}}{4} \left[2t^2 D_{12} x \bar{d}(x, Q^2) \right] \quad (26)$$

$$\frac{d^2\sigma_{NC}(e_R^+p)}{dx dQ^2} = \frac{2\pi\alpha^2 F_{2L}F_{1L}}{xQ^4} \frac{1}{4} [2\tilde{t}^2 D_{12} x d(x, Q^2)] \quad (27)$$

$$\frac{d^2\sigma_{CC}(e_L^-p)}{dx dQ^2} = \frac{2\pi\alpha^2 F_{2L}F_{1L}}{xQ^4} \frac{1}{4} [-2\tilde{t}^2 D_{12} x \bar{d}(x, Q^2)] \quad (28)$$

$$\frac{d^2\sigma_{CC}(e_R^+p)}{dx dQ^2} = \frac{2\pi\alpha^2 F_{2L}F_{1L}}{xQ^4} \frac{1}{4} [-2\tilde{t}^2 D_{12} x d(x, Q^2)] \quad (29)$$

with

$$D_{12} = \frac{(\hat{s} - m_1^2)(\hat{s} - m_2^2) + m_1 m_2 \Gamma_1 \Gamma_2}{[(\hat{s} - m_1^2)^2 + m_1^2 \Gamma_1^2][(\hat{s} - m_2^2)^2 + m_2^2 \Gamma_2^2]} \quad (30)$$

where m_1 (m_2) is the mass of P_3' (P_3^0), and the Γ_1 (Γ_2) is the corresponding decay width. The numerical calculation shows that the cross section due to the above interference term is very small for $\Delta m = 25 GeV$, say $\sim 1 pb$ for both NC and CC processes.

As for the couplings, we have $F_{1L} = 0.013, 0.02$ and 0.03 for $F_{2L} = 0.02$ and $\beta = 0.6, 0.5$, and 0.4 respectively. More specifically, we will consider the following three sets of branching ratios:

$$\text{Set-A: } Br(P_3' \rightarrow e^+d) = 0.6, Br(P_3^0 \rightarrow e^+d) = 0.5;$$

$$\text{Set-B: } Br(P_3' \rightarrow e^+d) = 0.5, Br(P_3^0 \rightarrow e^+d) = 0.5;$$

$$\text{Set-C: } Br(P_3' \rightarrow e^+d) = 0.4, Br(P_3^0 \rightarrow e^+d) = 0.4.$$

All three sets of branching ratios are allowed by CDF and D0 limit [9, 10] respectively. However, if we consider the combined Tevatron limit[12], the Set-A and Set-B are excluded, but the Set-C is still allowed. For completeness, we present the numerical results corresponding to all three sets of branching ratios in Table 7 and Table 8.

Table 7 shows the total contributions to NC cross sections from both the lighter mixed state P_3' and the heavier mixed state P_3^0 , assuming $m(P_3') = 200 GeV$, $m(P_3^0) = 225 GeV$, $F_{2L} = 0.02$ and $F_R = 0$. The P_3' and P_3^0 can provide the required contribution to NC cross sections. For $Q_{min}^2 = 15000 GeV^2$, for example, $\sigma_{NC}^A = 0.216 pb$ and $\sigma_{NC}^C = 0.157 pb$.

If we change the Case-3 mass spectrum to $m(P_3') = 205 GeV$ and $m(P_3^0) = 230 GeV$, the TC leptoquark contribution to NC cross section will generally decrease by about 25%, but still large enough to account for the excess of NC events with high- Q^2 .

Table 8 shows the total leptoquark contribution to CC cross section from both P_3' and P_3^0 , assuming the Case-3 parameters. The TC leptoquark P_3' and P_3^0 can provide the

Table 7: The total integrated NC cross sections from TC leptoquarks P'_3 and P_3^0 for different Q^2 cuts. The cross sections $\sigma_{NC}^{A,B,C}$ corresponding to the three sets of branching ratios respectively. The preliminary 1994-97 ZEUS and H1 e^+p NC data are included. All cross sections in pb .

Q^2_{min} (GeV^2)	H1 + ZEUS			P'_3 and P_3^0 Contributions		
	N_{obs}	σ_{obs}	σ_{sm}	σ_{NC}^A	σ_{NC}^B	σ_{NC}^C
2500	724 (a)	$43.3^{+4.6}_{-3.9}$	45.7	0.322	0.277	0.240
5000	193 + 326 (b)	10.7 ± 0.7	10.6	0.311	0.267	0.222
10000	31 + 50 (b)	$1.70^{+0.23}_{-0.20}$	1.79	0.274	0.237	0.189
15000	18 + 18 (b)	$0.71^{+0.14}_{-0.12}$	0.49	0.216	0.197	0.157
20000	7 + 7 (b)	$0.30^{+0.092}_{-0.076}$	0.161	0.183	0.158	0.126
25000	4 + 3 (b)	$0.16^{+0.069}_{-0.053}$	0.059	0.140	0.121	0.097
30000	2 + 2 (b)	$0.098^{+0.059}_{-0.042}$	0.023	0.096	0.084	0.067
35000	2(c)	$0.060^{+0.059}_{-0.037}$	0.0091	0.054	0.047	0.038
40000	1(c)	$0.032^{+0.044}_{-0.023}$	0.0036	0.012	0.012	0.010

(a). ZEUS 1994-97 e^+p NC data, $\mathcal{L} = 33.5pb^{-1}$;

(b). Combined H1 and ZEUS 1994-97 e^+p NC data, $\mathcal{L} = 57.2pb^{-1}$;

(c). H1 1994-97 e^+p NC data, $\mathcal{L} = 23.7pb^{-1}$.

required contributions to account for both excesses of NC and CC events with very high Q^2 simultaneously. For $Q_{min}^2 = 15000 GeV^2$, for instance, we have $\sigma_{NC}^A = 0.216 pb$ and $\sigma_{CC}^A = 0.553 pb$ respectively. The lighter P_3' again dominates the total CC contribution, about 75% of σ_{CC} comes from the lighter P_3' . While the size of σ_{NC}^A is just what we want to get, the CC contribution σ_{CC}^A seems to be a bit large when compared with the corresponding $\Delta\sigma_{CC}$ as shown in Table 8. The difference becomes more apparent for other two sets of branching ratios.

Fig.2 and Fig.3 show the NC and CC cross sections from different sources as a function of Q^2 cut, assuming $m(P_3') = 200 GeV$, $m(P_3^0) = 225 GeV$, $F_{2L} = 0.02$, $F_R = 0$ and Set-B branching ratios. The σ_{SM} represents the SM contribution, while the σ_1 and σ_2 shows the contribution from P_3' and P_3^0 respectively. For NC cross section, the σ_{tot} now is in very good agreement with the combined 1994-97 H1 and ZEUS NC data. For both NC and CC process, the lighter P_3' dominates: about 70% of the total leptoquark cross section is due to the lighter P_3' for $Q_{min}^2 < 35000 GeV^2$.

For e^-p collision process, the contributions from both P_3' and P_3^0 are negligibly small when compared with that to e^+p process because of the strong suppression by the smallness of parton density of sea quarks in a proton.

Table 8: The total leptoquark contributions to CC cross sections with different Q_{min}^2 cuts, assuming the Case-3 parameters. The CC cross sections $\sigma_{CC}^{A,B,C}$ corresponding to three sets of branching ratios respectively. The ZEUS and H1 preliminary 1994-97 e^+p CC data included. All cross sections in pb .

Q_{min}^2 (GeV^2)	H1 + ZEUS		σ_{SM}	$\Delta\sigma_{CC}$	P_3' and P_3^0 Contributions		
	N_{obs}	N_{expect}			σ_{CC}^A	σ_{CC}^B	σ_{CC}^C
1000	455	419 ± 36	16.47	1.4 ± 1.4	0.694	0.824	0.989
2500	61	56.3 ± 9.4	7.32	0.61 ± 1.2	0.692	0.821	0.986
5000	43	34.7 ± 6.9	2.54	0.61 ± 0.51	0.679	0.806	0.967
10000	28	17.7 ± 4.3	0.493	0.287 ± 0.12	0.628	0.744	0.893
15000	11	4.9 ± 1.7	0.127	0.158 ± 0.04	0.553	0.655	0.787
20000	5	1.7 ± 0.7	0.037	0.072 ± 0.015	0.466	0.550	0.660
30000	1	$0.034^{+0.038}_{-0.018}$	0.004	$0.114^{+0.004}_{-0.002}$	0.266	0.310	0.372

4. Conclusion and discussions

In this paper we try to pursue a consistent TC leptoquark interpretation for both excesses of NC and CC events with very high Q^2 observed by H1 and ZEUS collaborations.

In the framework of Technicolor, the $F=0$ scalar leptoquark P'_3 and P_3^0 are produced naturally by mixing of charge $2/3$ color-triplet pseudo-Goldstone bosons $P_{U\bar{N}}$ and $P_{D\bar{E}}$, and therefore they can contribute to both NC and CC processes simultaneously through their decays to e^+d and $\bar{\nu}u$ final states.

The size of the TC leptoquark contributions strongly depends on the mass spectrum of leptoquarks and the value of effective Yukawa couplings. If the Yukawa couplings of TC leptoquarks to first generation lepton-quark pairs was proportional to light fermion mass, say $\lambda \approx (m_u + m_e)/F_\pi$, the corresponding TC leptoquark contribution to NC and CC processes would be too small to account for the observed excesses at HERA.

If we assume, following the general BRW leptoquark scenario [8], that the effective Yukawa couplings of TC leptoquarks to light lepton-quark pairs are also the dimensionless parameters being constrained by the known experiments, the TC leptoquarks with mixing can indeed provide the required extra contributions to both NC and CC e^+p processes. For e^-p collision process, on the contrary, the contributions from $F=0$ scalar TC leptoquarks are indeed very small and can be neglected safely.

The charge $5/3$ TC leptoquark P_3^1 can provide an adequate contribution to NC process, but it could not contribute to CC process at HERA.

The charge $2/3$ TC leptoquarks P'_3 and P_3^0 can contribute to both NC and CC processes simultaneously. But they could not be light at the same time because of the stringent limits from Tevatron experiments. Using the parameters allowed by all known experiments, one single $F=0$ scalar TC leptoquark P'_3 with $m(P'_3) = 200\text{GeV}$ can provide the required contributions to account for the observed excesses of both NC and CC events with very high Q^2 simultaneously, as shown in Tables (4,5,6). For $Q_{min}^2 = 15000\text{GeV}^2$, we have $\sigma_{NC}^a = 0.217\text{pb}$ and $\sigma_{CC}^a = 0.306\text{pb}$, while about 0.2pb extra NC and CC contributions are required to explain the observed NC and CC excess respectively.

Inspired by the apparent splitting of the average mass for H1 and ZEUS NC events, we suppose that: there may exist two scalar TC leptoquarks P'_3 and P_3^0 , they are relatively light with the masses of $m(P'_3) = 200\text{GeV}$ and $m(P_3^0) = 225\text{GeV}$. Using the

parameters allowed by current experimental constraints, we found that P_3' and P_3^0 can provide the required contributions to NC and CC e^+p processes simultaneously. For $Q_{min}^2 = 15000 GeV^2$, we have $\sigma_{NC}^A = 0.216 pb$ and $\sigma_{CC}^A = 0.553 pb$. The size of σ_{NC}^A is just what we need, but the CC cross sections $\sigma_{CC}^{A,B,C}$ seem to be larger than that required. For $m(P_3') = 205 GeV$ and $m(P_3^0) = 230 GeV$, the total NC and CC contributions will in general decrease by about 25%.

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Figure Captions

Fig.1: The Feynman diagrams for the production and decay of F=0 scalar TC leptoquarks through s-channel and u-channel.

Fig.2: The neutral current cross sections from the SM (γ, Z) gauge bosons and the F=0 scalar TC leptoquarks P_3' and P_3^0 for $Q^2 > Q_{min}^2$, assuming the Case-3 parameters. The σ_1 and σ_2 shows the contribution from the P_3' and P_3^0 , respectively. $\sigma_{tot} = \sigma_{SM} + \sigma_1 + \sigma_2$ is the total NC cross section.

Fig.3: The charged current cross sections from the SM W gauge boson and the F=0 scalar TC leptoquarks P_3' and P_3^0 for $Q^2 > Q_{min}^2$, assuming the Case-3 parameters. The σ_1 and σ_2 shows the contribution from the P_3' and P_3^0 , respectively. The σ_{tot} is the total CC cross section.

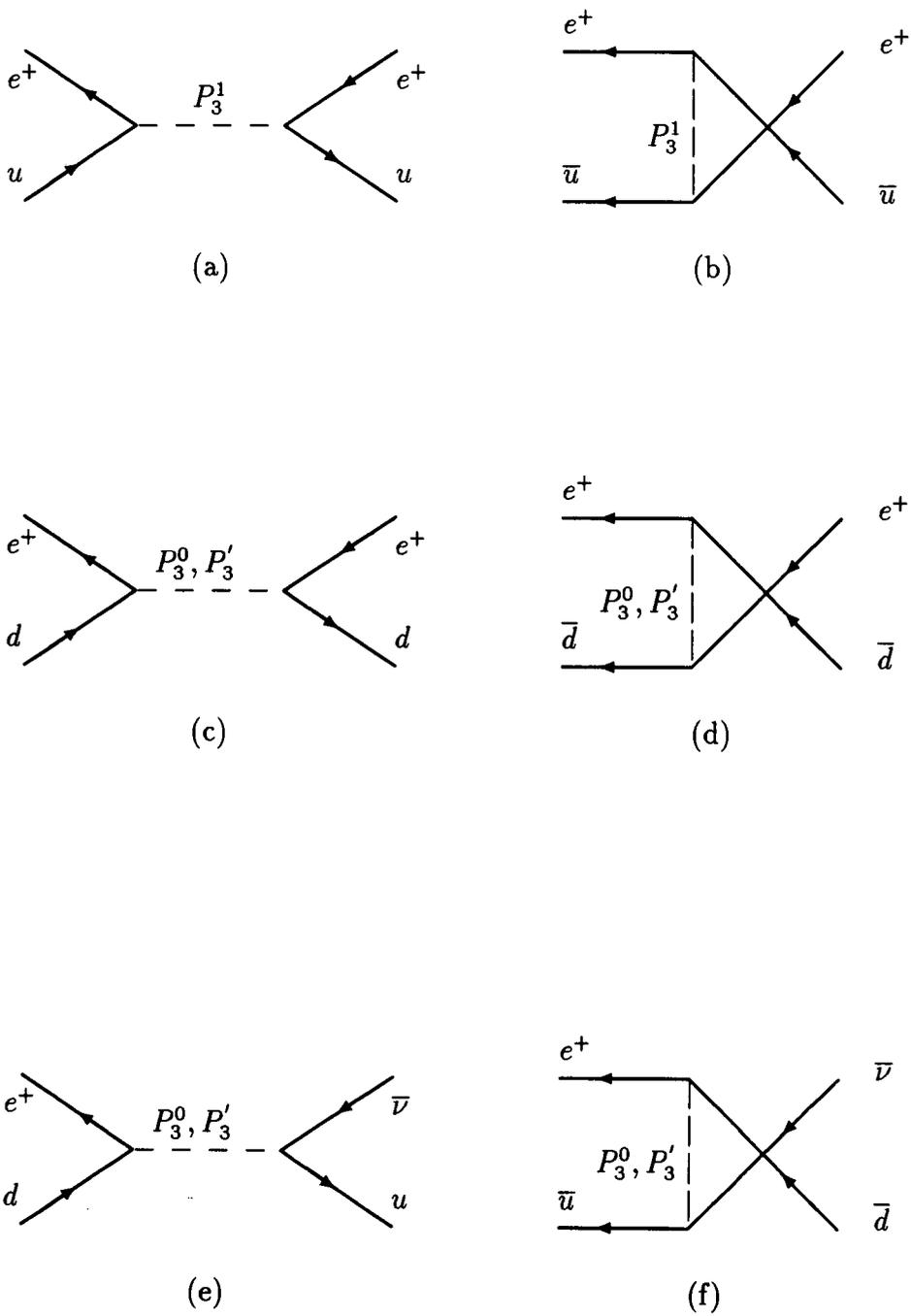


Fig.1

Neutral Current Cross Sections

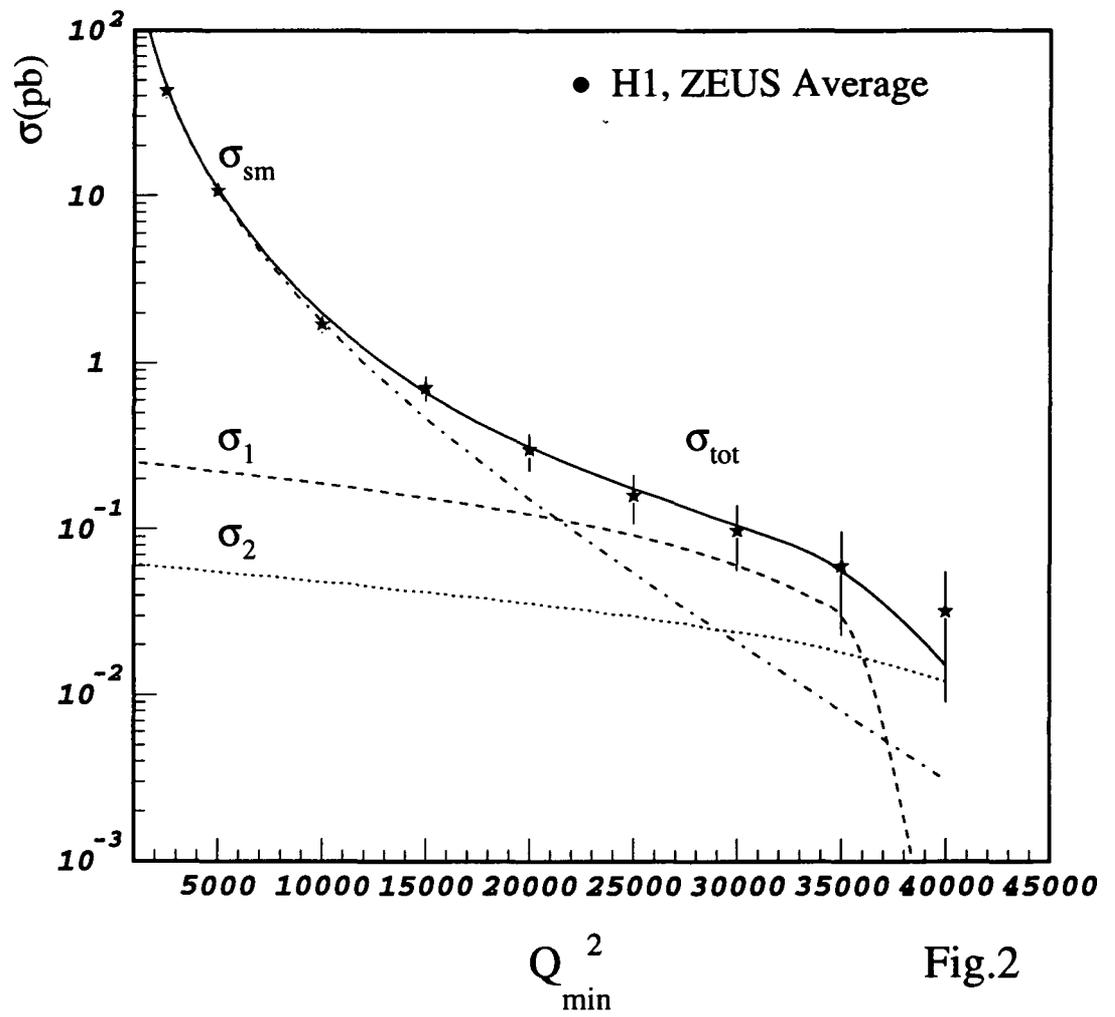


Fig.2

Charged Current Cross Sections

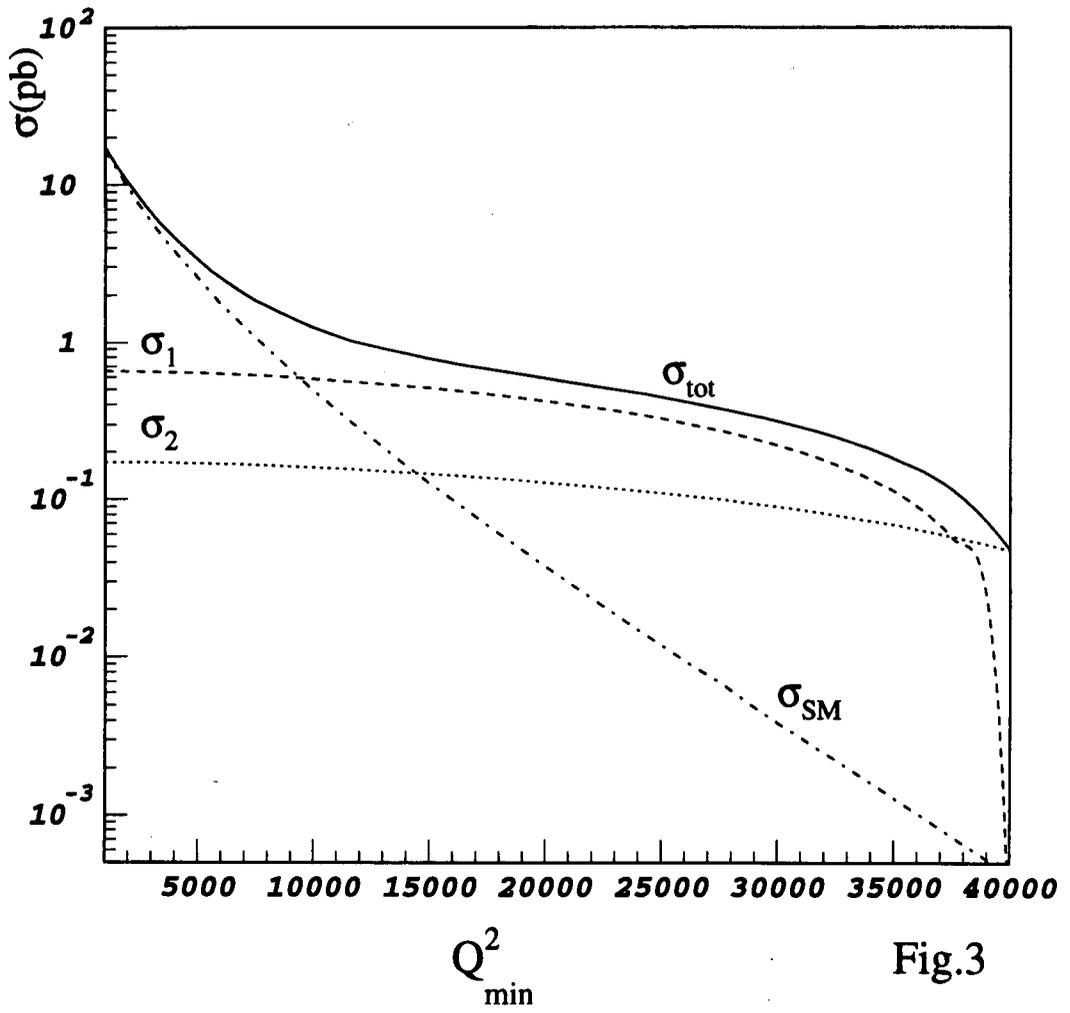


Fig.3