UTHEP-97-0103
April, 1997

e^+ (Anti)Quark Scattering in the Presence of the Anomalous HERA Positron-Jet Event Phenomenon

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Abstract

We discuss the leptoquark interpretation of the anomalous HERA positron-jet events in the context of the YFS exponentiated Monte Carlo event generator treatment of the attendant multiple photon radiative effects for both the would-be signal and the SM background, wherein finite-p_T photon effects are properly taken into account and wherein infrared singularities are cancelled to all orders in α. We show that the H1 and ZEUS data are consistent with such an interpretation for a leptoquark coupling $\lesssim 0.3 g_W$, mass $\sim$ 200 GeV, and width $\lesssim$ 2GeV. Possible future tests are proposed.

To be submitted to Phys. Rev. Lett.

UTHEP-97-0103
April, 1997

† Work supported in part by the US DoE contract DE-FG05-91ER40627 and DE-AC03-76SF00515, Polish Government grants KBN 2P03B17210, the European Union under contract No. ERB-CIPD-CT94-0016, and Polish-French Collaboration within IN2P3.

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Recently, the H1 and ZEUS Collaborations have reported [1, 2] an anomalous amount of high Q^2 , high x_{Bj} events in the deep inelastic e^+p scattering at HERA. In this paper, we investigate in detail the interplay between the rigorous treatment of the attendant multiple photon radiative effects, which we treat by the YFS [3] exponentiated Monte Carlo technique introduced in Ref. [4] and applied to deep-inelastic lepton-nucleon scattering in Refs. [5, 6], see also Ref. [7], in the event generator LESKO-YFS, and the HERA phenomenon if it is interpreted as the exchange of a spin 1 or 0 object in the s-channel in the reduced $e^{+}\overset{(-)}{q}$ parton level process at HERA. For, to our knowledge so far, only structure function based, zero-p_T, treatments of the higher order QED radiative effects have been applied to the HERA data [1, 2] so that our work will actually serve two purposes: (1), it will show that the proper treatment of the higher order finite-p_T photon effects in the multiple photon radiation cannot account for the phenomenon; and that, (2), when a resonance of the appropriate coupling and mass is introduced, the H1 and ZEUS data, in the presence of the realistic $n(\gamma)$ radiation do indeed agree with the theoretical expectations. Of course, other possible interpretations of the data are also possible and we refer the reader to Refs. [8, 9, 10] for further discussion of such approaches to the HERA phenomenon.

For definiteness, we shall call this object a 'leptoquark', since according to Ref. [11], it has a mass $\sim$ 200 GeV and a width $\lesssim$ 2.2 GeV. We stress as it has been already done in Ref. [12] that as long as the couplings of this object, which may be composite or elementary, are sufficiently chiral and diagonal in flavor and zero on diquark fields, it is not in contradiction with any known physical requirement. In Ref. [13], we have discussed the constraints implied by recent LEP2 data [14] on this interpretation of the HERA data due to crossing it into the $e^+e^- \rightarrow hadrons$ channel, as well as the constraints derived in Refs. [15, 16]. See also Refs. [9, 17, 10] for related and similar analyses of the crossed reaction and see Refs. [8, 18, 10] for a discussion of contraints on this interpretation implied by recent TEVATRON data. The net result of these discussions is that the leptoquark interpretation is still viable if the coupling strength to fermions is small enough, $\lesssim 0.3 g_W$, where g_W is the EW coupling constant. Thus, we proceed entirely phenomenologically and try to answer the very definite question as to whether the HERA data are consistent with a 'leptoquark' explanation if we treat the attendant higher order radiative effects via the YFS exponentiated Monte Carlo methods of two of us (S.J. and B.F.L.W.) as they are realized in the event generator LESKO-YFS [5, 6], for both the signal and the background.

More specifically, we first record the differential cross section for $e^{+}\overset{(}{\bar{q}}\overset{)}{} \to e^{+}\overset{(}{\bar{q}}\overset{)}{}$ in the presence of the HERA leptoquark for two models of leptoquark charges. We have, for the outgoing e^+ elemental solid angle $d\Omega_{e^+}$ in the CM system,

$$\frac{d\sigma}{d\Omega_{e^+}} = \frac{1}{64\pi^2 \hat{s}} |\bar{\mathcal{M}}|^2, \tag{1}$$

where the spin averaged squared matrix element, for the leptoquark (X) charges $(Q, Q-1)$ with $Q = 5/3$ coupling to left(right)-handed quarks {model (1)(model (2))} and with $Q = 4/3$ coupling to left(right)-handed quarks {model (3)(model (4))}, is

$$\begin{aligned} |\bar{\mathcal{M}}|^2_{\{Q,Q-1\}_H} = & \\ & \left| \frac{(-\frac{1}{2}\delta_{S,0}\delta_{Q,\frac{4}{3}} + \delta_{S,1}\delta_{Q,\frac{5}{3}}) g_X^2 (1-h(H))}{4 D_X(\hat{s})} + \sum_{\rho=A,Z} \frac{G_\rho^2 (v_\rho(q)+a_\rho(q))(v_\rho(e)+a_\rho(e))}{D_\rho(\hat{t})} \right|^2 \hat{u}_Q^2 \\ & + \left| \frac{(-\frac{1}{2}\delta_{S,0}\delta_{Q,\frac{4}{3}} + \delta_{S,1}\delta_{Q,\frac{5}{3}}) g_X^2 (1+h(H))}{4 D_X(\hat{s})} + \sum_{\rho=A,Z} \frac{G_\rho^2 (v_\rho(q)-a_\rho(q))(v_\rho(e)-a_\rho(e))}{D_\rho(\hat{t})} \right|^2 \hat{u}_Q^2 \\ & + \left| \frac{(\frac{1}{2}\delta_{S,0}\delta_{Q,\frac{5}{3}} - \delta_{S,1}\delta_{Q,\frac{4}{3}}) g_X^2 (1+h(H))}{4 D_X(\hat{s})} + \sum_{\rho=A,Z} \frac{G_\rho^2 (v_\rho(q)-a_\rho(q))(v_\rho(e)+a_\rho(e))}{D_\rho(\hat{t})} \right|^2 \hat{s}_Q^2 \\ & + \left| \frac{(\frac{1}{2}\delta_{S,0}\delta_{Q,\frac{5}{3}} - \delta_{S,1}\delta_{Q,\frac{4}{3}}) g_X^2 (1-h(H))}{4 D_X(\hat{s})} + \sum_{\rho=A,Z} \frac{G_\rho^2 (v_\rho(q)+a_\rho(q))(v_\rho(e)-a_\rho(e))}{D_\rho(\hat{t})} \right|^2 \hat{s}_Q^2, \end{aligned} \tag{2}$$

where $h(H) = -1(+1)$ for the left $(H \equiv L)$-, right $(H \equiv R)$-handed cases respectively, S is the spin of X, δ_{ab} is the Kronecker delta function, $\hat{u}_Q = \delta_{Q,\frac{5}{3}}\hat{u} + \delta_{Q,\frac{4}{3}}\hat{s}$, $\hat{s}_Q = \delta_{Q,\frac{5}{3}}\hat{s} + \delta_{Q,\frac{4}{3}}\hat{u}$ and where we have defined the following kinematical and dynamical variables: $D_X(\hat{s}) = \hat{s} - M_X^2 + i\Gamma_X\hat{s}/M_X$, $M_X = 200\ GeV$, $\Gamma_X \lesssim 2\ GeV$, $D_Z(\hat{t}) = \hat{t} - M_Z^2$, $D_A(\hat{t}) = \hat{t}$, $v_Z(f) = \frac{1}{2}I_3 - Q_f \sin^2\theta_W$, $a_Z(f) = \frac{1}{2}I_3$, $v_A(f) = Q_f$, $a_A(f) = 0$, $G_Z = e/(\sin\theta_W \cos\theta_W)$, $G_A = e$, $g_X = (e/\sin\theta_W)(1+\delta)$, $\hat{s} = (p_1 + q_1)^2$, $\hat{t} = (p_1 - p_2)^2$, $\hat{u} = (p_1 - q_2)^2$, where $\{p_1, q_1\}$ are the incoming $\{e^+, {}^{(}\bar{q}^{)}\}$ 4-momenta respectively and $\{p_2, q_2\}$ are the outgoing $\{e^+, {}^{(}\bar{q}^{)}\}$ 4-momenta respectively. Here, δ is unknown and is to be varied to see what the data will allow. (According to Refs. [13, 17], from the crossed reaction constraints we hope to find that $-1.5 \lesssim \delta \lesssim -0.5$ for spin 1.) I_3 is the usual weak isospin 3-component for fermion f and Q_f is its electric charge in units of the positron charge e. We have thus complied with the constraint from Refs. [12, 15, 16] that only quarks of a specific chirality should couple to any particular leptoquark.

The formulae presented above we have implemented into the LESKO-YFS Monte Carlo program [5, 6]. We have performed the technical tests of the matrix elements as implemented in LESKO-YFS and compared them with analytical results on several approximated forms of the above matrix elements, e.g. for $Z+\gamma$ or only Z exchange excluded. Agreement of 4-5 digits was always found. Later, QED corrections were extended (to our X-exchange, i.e. non t-channel Z, γ interaction) according to the prescription explained in Ref. [19] for the similar type of modification of the Monte Carlo KORALZ [20] in Ref. [13].

We stress that the leptoquark-quark-lepton vertices which we have assumed in (2), corresponding to the $U_1, \tilde{U}_1, \tilde{V}_2, V_2$, and U_3 spin 1 and $R_2, \tilde{R}_2, S_1, \tilde{S}_1$ and S_3 spin 0 examples in Ref. [12]), are intended to be generic and not exhaustive: it is straightforward to include more general coupling scenarios into our LESKO-YFS calculational framework, should this become necessary. We point-out further that we may identify our states in models

$(1),\cdots,(4)$ for spin 1,0 respectively with the corresponding charge and mass eigenstates formed from the states S_L, T, $\tilde{S}_R$, S_R, D_L, D_R and $\tilde{D}$ in the notation of Refs. [15, 16]; for, at scales ~ 200 GeV, we expect the $SU_{2L}\times U_1$ EW symmetry to be broken with leptoquark states of the same charge and color mixed into the respective mass eigenstates and it is these mass eigenstates that we have used in (1). In other words, from the HERA data we we may have that $\bar{e}q$ resonates into the leptoquark X, $q=u,d$, models (1) and (2) with t-channel X exchange in $e^+e^-\to\bar{q}q$ and $F=0$ in the language of Refs. [12, 15, 16], or that $\bar{e}\bar{q}$ resonates into the leptoquark X, $q=u,d$, models (3) and (4) with u-channel X exchange in $e^+e^-\to\bar{q}q$ and $F=-2$ in the language of Refs. [12, 15, 16], where F is the fermion number of X. For definiteness, we have assumed strong isospin symmetry for simplicity; it is trivial to relax this last assumption, should more data render this necessary. For completeness, we then note that the interaction Lagrangian densities which we used to arrive at the results (2) are, for $S=1$, $\mathcal{L}^{\{5/3,2/3\}}_{int,1,H}=-(g_X/\sqrt{2})\left(X^{(-5/3)\alpha}_\mu\bar{e}_H\gamma^\mu u^\alpha_H+X^{(-2/3)\alpha}_\mu\bar{e}_H\gamma^\mu d^\alpha_H+h.c.\right)$, and $\mathcal{L}^{\{4/3,1/3\}}_{int,1,H}=-\frac{g_X}{\sqrt{2}}\left(X^{(-4/3)\alpha}_\mu\bar{d}^\alpha_H\gamma^\mu e^c_{H'}+X^{(-1/3)\alpha}_\mu\bar{u}^\alpha_H\gamma^\mu e^c_{H'}+h.c.\right)$, where here $H=L,R$, $H'=L$ when $H=R$ and $H'=R$ when $H=L$, and we have defined $\psi_{L(R)}=P_{L(R)}\psi$ as well as $\psi^c=C\bar{\psi}^T$ for all ψ when T denotes transposition. The the chiral projections are here $P_L=(1-\gamma^5)/2$,$P_R=(1+\gamma^5)/2$ and C is the charge conjugation matrix in an appropriate representation. Thus, $\mathcal{L}^{\{5/3,2/3\}}_{int,1,L}$ describes the interactions used to derive the result (2) for $Q=5/3$, $S=1$, $H=L,\ldots$, and so on. For $S=0$, the analogous formulas follow from the corresponding replacements vector $X\times$ Dirac vector current $\Leftrightarrow$ scalar $X\times$ Dirac scalar current. Finally, to facilitate contact with Refs. [15, 16], we note that, if we make the simplest possible assumption about the leptoquark weak isospin mixing matrix, that is that our spin 1 states are composed of only those states in Refs. [15, 16], then we may identify $\{T^{(-5/3)},(T^{(-2/3)}-S_L^{-(2/3)})/\sqrt{2}\}\Leftrightarrow\{X^{(-5/3)},X^{(-2/3)}\}$ in model (1), $\{\tilde{S}^{(-5/3)},S_R^{(-2/3)}\}\Leftrightarrow\{X^{(-5/3)},X^{(-2/3)}\}$ in model (2), $\{D_L^{(-4/3)},D_L^{(-1/3)}\}\Leftrightarrow$

$\{X^{(-4/3)}, X^{(-1/3)}\}$ in model (3), and $\{D_R^{(-4/3)}, \tilde{D}^{(-1/3)}\} \Leftrightarrow \{X^{(-4/3)}, X^{(-1/3)}\}$ in model (4), with the attendant coupling constant relations $2g = g_X$, $\sqrt{2}g = g_X$, $\sqrt{2}g = g_X$, and $\sqrt{2}g = g_X$, respectively where g is the coupling constant in Refs. [15, 16] (an analogous transformation holds for the spin 0 case).

In the Fig. 1, we exhibit the comparison of the expectations of the models (1)-(2) in comparison to the SM expectations for several observables available in the HERA data at low Q^2 ($2500 < Q^2 < 15000$ GeV^2) for a value of δ in the range allowed [13] by the LEP2 data. Models (3) and (4) are simply too close to the SM expectation in this regime to describe the data for any value of δ of order 1 in magnitude so that we do not bother to indicate these latter predictions explicitly in the comparisons with the data. Values of δ several orders of magnitude in size larger than 1 are already excluded by the lack of observation of pronounced anomalies in the HERA e^- data for models (3) and (4) [8]. Shown are the M_e and y_e distributions in Fig. 1(a) and 1(b), respectively, for $2500 < Q_e^2 < 15000$ GeV^2 and in Fig. 1(c) the y_e distribution for 100 GeV $< M_e <$ 180 GeV in the HERA kinematics in the hard scattering CM system for which we have the definitions $s = (p_p + p_1)^2$, $Q_e^2 = -\hat{t}$, $x_e = Q_e^2/(2(p_1 - p_2)p_p)$, $y_e = Q_e^2/(sx_e)$, so that $M_e = \sqrt{sx_e}$ is the invariant mass of the outgoing positron-jet system– the subscript e means that the observable is computed from variables on the $\bar{\mathrm{e}}$ line [1, 2]. Here, p_p is the incoming proton 4-momentum. Our $\bar{\mathrm{e}}$ kinematics is defined so that all photons within a cone of half-angle 5^o is included in the definition of the outgoing $\bar{\mathrm{e}}$ four-vector, to give a more realistic simulation of the definition of the outgoing $\bar{\mathrm{e}}$ in the HERA detectors. We also impose a cut on the initial state photon radiation by requiring that a fraction of the $\bar{\mathrm{e}}$ energy lost to this radiation is ≤ 0.1. We see that for g_X such that $\delta \cong -0.7$ for example the $S = 0$ models are well within the experimental errors at HERA [1, 2] of the SM expectations. By comparison, the $S = 1$ models are disfavored at low y_e.

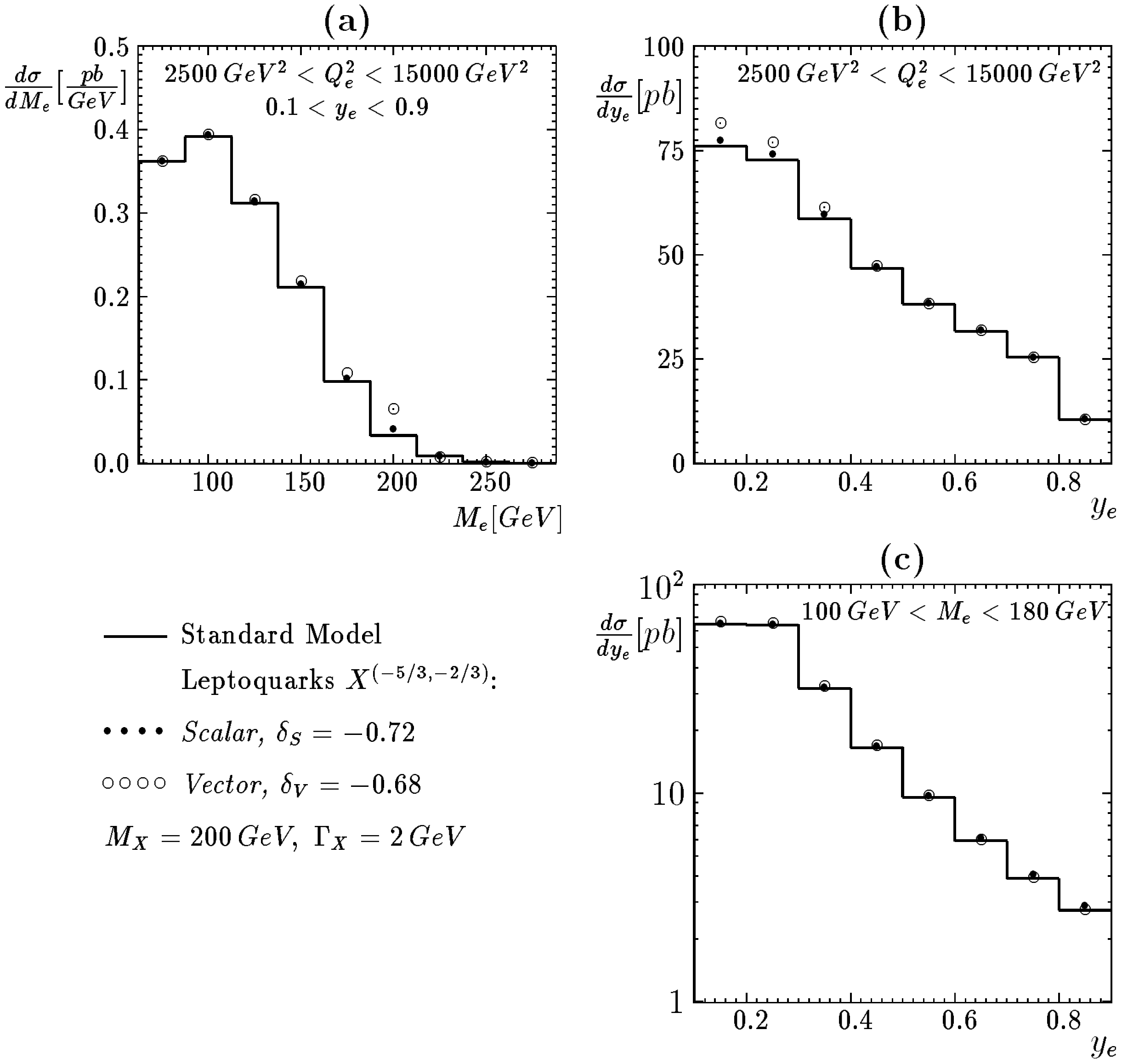

Figure 1: Distributions of M_e and y_e obtained from LESKO-YFS for the Standard Model process (solid histograms) and in the presence of the scalar (full circles) and vector (open circles) leptoquarks $X^{(-5/3,-2/3)}$ in models (1) and (2) – both models give identical distributions. All the results were obtained for the MRSA [21] parametrization of the proton structure functions.

We then show in Figs. 2 and 3 the comparison of the H1 and ZEUS data, respectively, with the models for the observables Q_e^2, y_e and M_e for H1, and the observables x_{DA} and Q_{DA} (see Refs. [1, 2] for their definition) for ZEUS, where for H1 we show data for Q_e^2 with $0.1 < y_e < 0.9$, for y_e with $M_e > 180$ GeV, for M_e with $Q_e^2 > 15000$ GeV^2, $0.1 < y_e < 0.9$,

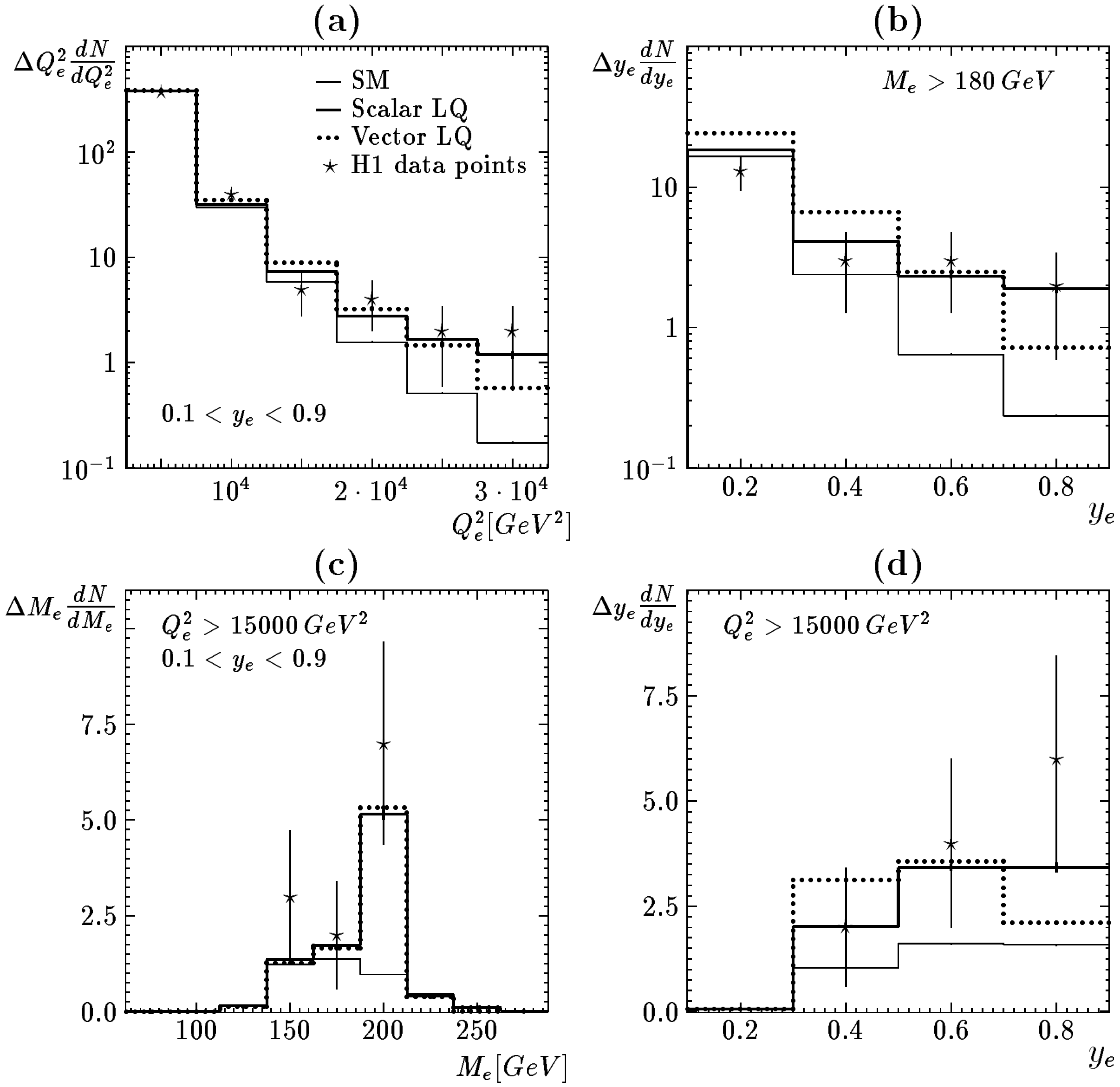

Figure 2: Distributions of Q_e^2, y_e and M_e obtained from LESKO-YFS for the Standard Model process (thin-line histograms) and in the presence of the scalar (thick-line histograms) and vector (dotted histograms) leptoquarks in models (1) and (2) with $M_X = 200\,GeV$, $\Gamma_X = 2\,GeV$, $\delta_S = -0.72$, $\delta_V = -0.68$ (see the text for details) compared with the recent H1 high Q^2 events ($\star$ symbols) as given in Ref. [1]. $\Delta v\,(v = Q_e^2, y_e, M_e)$ denotes bin size for respective histograms.

and for y_e with $Q_e^2 > 15000$ GeV^2 and for ZEUS we show data for x_{DA} with $y_{DA} > 0.25$, $Q_{DA}^2 > 5000$ GeV^2, and for Q_{DA}^2 in the regions of the anomalous numbers of events. The respective experimental acceptances [1, 2] are included in the above results. In all

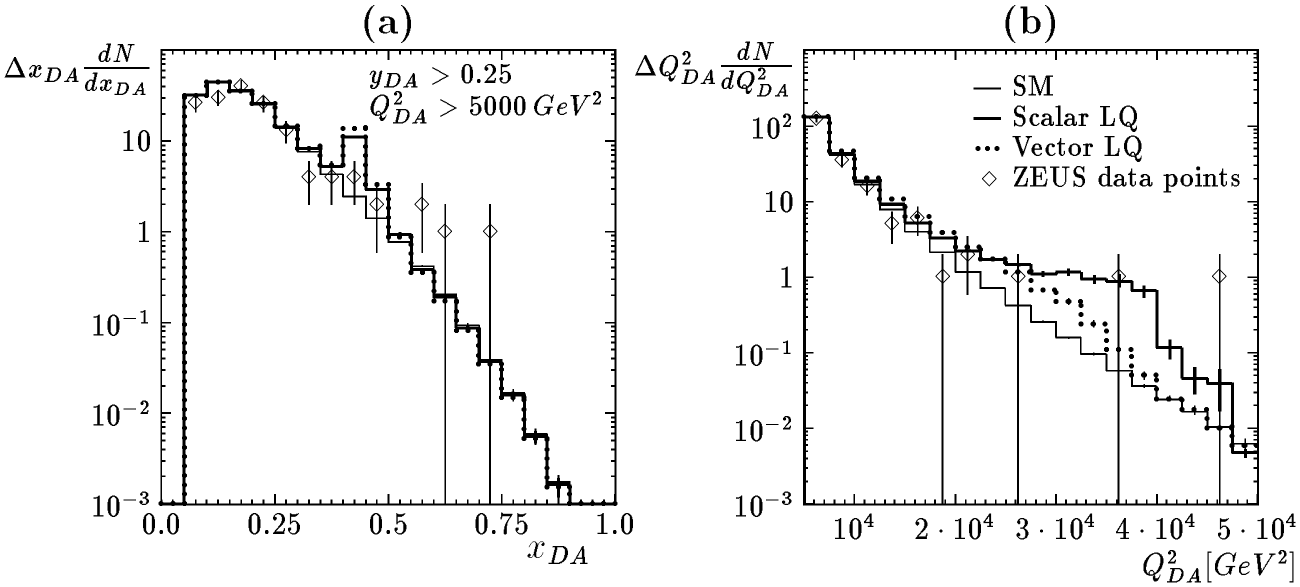

Figure 3: Distributions of x_{DA} and Q^2_{DA} obtained from LESKO-YFS for the Standard Model process (thin-line histograms) and in the presence of the same scalar (thick-line histograms) and vector (dotted histograms) leptoquarks as in Fig. 2 compared with the recent ZEUS high Q^2 events ($\diamond$ symbols) as given in Ref. [2]. $\Delta v\,(v = x_{DA}, Q^2_{DA})$ denotes bin size for respective histograms.

six distributions, we see that, for $\delta \cong -0.7$, there is reasonable agreement between the data and the theoretical prediction for models (1) and (2) for $S = 0$ whereas for $S = 1$ the comparison with the data in Figs. 2a,b,d and 3a,b is less favorable but still tolerable (within 3σ). Thus, we must await more data for a detailed check of the models (1) and (2).

In our plots we have used the upper limit [1] value $\Gamma_X = 2\,\mathrm{GeV}$; if we use the theoretical lower limit $\Gamma_X = g_X^2 M_X/32\pi(48\pi)$ for $S = 0(1)$ the required value of δ in Figs. 2, 3 changes to ~ -0.95 but our qualitative conclusions do not change. We have also checked that varying our structure functions between those in Ref. [22] and those in Refs. [21] does not affect our results in any significant way at the level of precision of the HERA data. What we can do is to emphasize that, if models (1) and (2) are indeed correct, we do not expect similar anomalies in the e^- data because that would involve scattering from the sea and this would be strongly suppressed. Further, we do not have to have charged current events: to get them, we need to add more terms to the interactions in the $\mathcal{L}^{\{Q,Q-1\}}_{int,S,H}$ given above but in our general phenomenological framework, this is neither mandated nor forbidden. We also comment on the expectations at FNAL. What they are in general depends on the assumed BR to the initial state channel at HERA for the final state decay as well as on the detailed coupling scenario between gluons and X: as emphasized in Ref. [8], a BR near unity with only two higher multipoles in the gluon-X coupling scenario may already be disfavored by the D0+CDF [23, 24, 25] limits if this combination can be done without unforseen systematics although as Ref. [18] has stressed the situation depends in detail on cuts, BR's, etc. and the implied signal may be small enough that it is missed and hence the matter is still unsettled; but, in our general phenomenological approach, we have no reason to expect a BR near unity or a naive coupling between leptoquarks and gluons: an infinite series of multipoles is in principle allowed in our effective low energy Lagrangian for X and gluons, with the truly underlying renormalizable theory awaiting yet higher energy probes to reveal itself. Thus, we can only encourage the FNAL experiments to continue their search for the observation of X as well.

In summary, we have investigated the comparison with HERA data of the expectations on the leptoquark interpretation of the anomalous positron-jet phenomenon at DESY. We used the LESKO-YFS [5, 6] Monte Carlo event generator so that higher radiative corrections to the Born level leptoquark signal are calculated with the YFS exponentiated $\mathcal{O}(\alpha)$ LL $\bar{\beta}_{0,1}$ residuals, for both initial and final state radiation with finite-p_T effects in this radiation properly realized, in the framework of Ref. [26, 27]. We find that, in agreement with the analysis in Ref. [13], a leptoquark coupling of $\lesssim 0.3 g_W$ in our models (1) and (2), positron-quark resonances, where spin 0 is preferred over spin 1, is in general agreement with the HERA data distributions at both high and low Q^2 for $\Gamma_X \lesssim 2$GeV and that our models (3) and (4), positron-anti-quark resonances, like the SM itself, even in the presence of the rigorous higher order initial and final state radiation with finite-p_T photon effects, cannot account for the data for any reasonable value of the respective leptoquark coupling parameter. We look forward with excitement to more precise data.

Acknowledgements

Two of us (S.J. and B.F.L.W.) acknowledge the kind hospitality of Prof. G. Veneziano and the CERN TH Division and the support of Prof. D. Schlatter and the ALEPH Collaboration while this work was done. We thank Dr. S.-M. Kim for assistance with the implementation of the MRSA structure functions.

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