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Has the Substructure of Quarks and Leptons Been Found also by the H1 and ZEUS Detectors at HERA?

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The significant excess of events recently found by the H1 and ZEUS Collaborations at HERA in the deep-inelastic e^+p scattering for high momentum-transfers squared $Q^2 > 15000\text{GeV}^2$ over the expectation of the standard model can be explained by either one of the following possible consequences of the substructure of quarks and leptons: 1) production of leptoquarks (Φ), 2) exchange of an excited Z boson (Z'), 3) intrinsic form factors of quarks (or leptons), 4) intrinsic anomalous magnetic moments of quarks, 5) production of excited quarks (q^*), and 6) that of excited positrons (e^{*+}). The masses of these new particles are estimated to be $m_\Phi \cong 280 - 440\text{GeV}$, $m_{Z'} \cong 200 - 250\text{GeV}$, $m_{q^*} \cong 120 - 140\text{GeV}$, and $m_{e^*} \cong 300 - 370\text{GeV}$, although the possibilities 2) and 5) are excluded by the currently available experimental constraints.

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Very recently, the H1 [1] and ZEUS [2] Collaborations at HERA have reported their data on the deep-inelastic e^+p scattering with a significant excess of events over the expectation of the standard model of electroweak and strong interactions for high momentum-transfers squared $Q^2 > 15000\text{GeV}^2$, which may indicate a sign for new physics beyond the standard model. There have already appeared many phenomenological analyses [3] 1 in which various interpretations of the excess are presented. They are either by productions of leptoquarks, "leptogluons", and squarks, or by contact interactions of quarks and leptons. In our previous Rapid Communication [4], we have tried to explain the significant excess earlier found by the CDF Collaboration [5] in the inclusive jet cross section for jet transverse energies $E_T \geq 200\text{GeV}$ over current QCD predictions either by possible production of excited bosons (excited gluons, weak bosons, Higgs scalars, etc.) or excited quarks and have concluded that excited quarks whose masses are around 500GeV are excluded while excited bosons whose masses are around 2 TeV are allowed for the explanation. The purpose of this Rapid Communication is to report our similar trial for explaining the new excess found by the H1 and ZEUS Collaborations by either one of the following possible consequences of the substructure of quarks and leptons [6–8]: 1) production of leptoquarks (Φ), 2) exchange of an excited Z boson (Z'), 3) intrinsic form factors of quarks (or leptons), 4) intrinsic anomalous magnetic moments of quarks, 5) production of excited quarks (q^*), and 6) that of excited positrons (e^{*+}).

The minimal composite model of quarks and leptons [6–8] consists of an isodoublet of subquarks, $w_i (i = 1, 2)$ with the charge of $\pm 1/2$, and a color quartet of subquarks, $C_\alpha (\alpha = 0, 1, 2, 3)$ with the charge of $-1/2$ (for $\alpha = 0$) and $+1/6$ (for $\alpha = 1, 2, 3$). The quarks (q) and leptons (l) are taken as composites of subquarks consisting of w_i and C_α while the weak bosons ($W^\pm$ and Z), the gluons (G^a, $a = 1, 2, ..., 8$), the Higgs scalars (ϕ^+, ϕ^0) [and even the photon (γ)] can also be taken as composites of a subquark and an antisubquark such as w_i and $\overline{w_j}$ or C_α and $\overline{C_\beta}$. In this model, we expect that there may appear not only exotic states and excited states of the fundamental bosons such as the leptoquarks ($\Phi^{\pm 2/3}$) consisting of $\overline{C_0}(C_0)$ and $C_\alpha(\overline{C_\alpha})(\alpha = 1, 2, 3)$ and the excited Z boson (Z') consisting of $w_i(C_\alpha)$ and $\overline{w_i}(\overline{C_\alpha})$, but also excited states of the fundamental fermions such as the excited quarks (q^*) consisting of w_i and $C_\alpha (\alpha = 1, 2, 3)$ and the excited leptons (l^*) consisting of w_i and C_0 [9,10]. Also, we expect that quarks (and leptons) may have intrinsic form factors [11] and intrinsic anomalous magnetic moments [12] due to the substructure. Note that the existence of leptoquark gauge bosons has been predicted in the grand unified gauge theories of strong and electroweak interactions [13] but with extremely large masses of the grand unification energy scale ($> 10^{15}\text{GeV}$). Also note that the existence of additional extra Z bosons (Z_R, etc.) has been predicted in many extensions of the standard model [14] with fairly large masses ($> 500\text{GeV}$). Here, however, we concentrate on the possibility of relatively low energy scale of the order of 1 TeV for compositeness, which has recently been anticipated rather theoretically [15] or by precise comparison between currently available experimental data and calculations in the composite models of quarks and leptons [16,17]. In what follows, we shall check the above mentioned possibilities 1)–6) one by one.

Let us first define some kinematical variables for the deep inelastic scattering of $e^+ + p \to e^+ +$ anything. Let P, k, and k' be the momenta of the initial proton, the initial positron, and the final positron, respectively. Then, the

Mandelstam variables are defined as $s=(P+k)^2$ and $t=(k-k')^2(\equiv -Q^2)$, and the scaling variables as $x=|t|/2P\cdot q$ and $y=P\cdot q/P\cdot k$ for $q=k-k'$, which have an approximate relation of $sxy\cong|t|$ for $s\gg m_p^2$ where m_p is the proton mass. In the parton model, the differential cross section for e^+p scattering is given by

$$d\sigma=\sum_a f_a(x)dxd\widehat{\sigma}_a, \tag{1}$$

where $f_a(x)$ is the distribution function for the parton a and $d\widehat{\sigma}_a$ is the differential cross section for the subprocess of $e^+a\to e^+a$. As for the parton distribution functions (PDFs), we use those of Glück-Reya-Vogt [18]. We expect that the ratio of our composite model calculation to the standard model one may not so much depend on PDFs. For definiteness, the differential cross section for the subprocess $e^+a\to e^+a$ is given by

$$d\widehat{\sigma}_a/dt=16\pi\left[(1-y)^2(|P_{LL}|^2+|P_{RR}|^2)+(|P_{LR}|^2+|P_{RL}|^2)\right], \tag{2}$$

with

$$P_{XY}=\frac{-e^2Q_a}{t}+\frac{g_X^e\,g_Y^a}{t-m_Z^2}\quad(X,Y=L,R), \tag{3}$$

where e is the electromagnetic coupling constant ($e^2=4\pi\alpha$), Q_a is the charge of a, g_X^ψ is the coupling constant of Z to the fermion ψ ($\psi=e$ or q) with the chirality X ($X=L$ or R), and m_Z is the Z boson mass.

The first possibility is the production of leptoquarks. Since the leptoquark $\Phi^{+2/3}$ consisting of $\overline{C_0}$ and $C_\alpha(\alpha=1,2,3)$ can be produced by annihilation of e^+ (consisting of $\overline{w_2}$ and $\overline{C_0}$) and d [consisting of w_2 and $C_\alpha(\alpha=1,2,3)$] but neither by annihilation of e^+ and u or by collision of e^- (consisting of w_2 and C_0) and any quarks [consisting of $w_i(i=1,2)$ and C_α], we expect the possible excess due to the production of Φ in e^+p scatterings but not in e^-p scatterings. Let us assume the scalar leptoquark $\Phi_i(i=1,2,3)$ for simplicity. Then, the effective interaction Lagrangian is given by

$$L_\Phi=f_\Phi\bar{l}\Phi_i^\dagger d_i+\text{H.c.}, \tag{4}$$

where f_Φ is the coupling constant. The differential cross section for inelastic e^+p scatterings including the effect of Φ production can be calculated by using Eqs. (1) and (2) with the following terms added to P_{LR} and P_{RL}:

$$\Delta P_{LR}=\Delta P_{RL}=\frac{f_\Phi^2}{4(\widehat{s}-m_\Phi^2+im_\Phi\Gamma_\Phi)}, \tag{5}$$

where $\widehat{s}(=xs)$ is the invariant mass squared of e^+d channel, m_Φ is the Φ mass, and Γ_Φ is the decay width. If Φ decays predominantly into two-body channels of $\Phi\to l\overline{q}$, the decay width is approximated as

$$\Gamma_\Phi\cong\frac{f_\Phi^2m_\Phi}{8\pi}\left[5+\theta(m_\Phi^2-m_t^2)\left(1-\frac{m_t^2}{m_\Phi^2}\right)^{1/2}\right], \tag{6}$$

where m_t is the top-quark mass. The H1 and ZEUS experiments [1,2] altogether have observed 10 events for $|t|\geq 20000\text{GeV}^2$ while they have expected 4.08 events in the standard model. We estimate the expected number of events in the model to be $n_{th}=n_{SM}\sigma/\sigma_0$ where n_{SM} is the expected number of events in the standard model given in Refs. [1,2], and σ and σ_0 are the integrated cross sections with and without the composite-model effects, respectively. The upper (lower) bound of m_Φ at the confidence level p is given by the value for which the Poisson probability to find as many as or more (less) than the actually ovserved number of events becomes $(1-p)/2$. Therefore, we can obtain the bounds on the Φ mass as $291\text{GeV}\leq m_\Phi\leq 444\text{GeV}$ at 95% C.L. for $f_\Phi=g$ (the gauge coupling constant of $SU(2)_L$ in the standard model). On the other hand, by knowing that 313 events are observed in the whole region of $|t|\geq 5000\text{GeV}^2$, where 313 events are expected in the standard model, we can obtain the lower bound on m_Φ as $m_\Phi\geq 271\text{GeV}$ at 95% C.L. for $f_\Phi=g$. In Fig. 1, the ratio (r) of the differential cross section for inelastic e^+p scattering including the effect of Φ production for $m_\Phi=271\text{GeV}$ and $f_\Phi=g$ to that in the standard model is compared with the corresponding H1 experimental result [1].

The second possibility is the exchange of an extra Z boson (Z'). For simplicity, let us assume that Z' behaves as $\overline{w_L}\gamma_\mu w_L$ or a singlet of $SU(2)_L$. Then, the effective interaction Lagrangian is given by

$$L_{Z'}=f_{Z'}\sum_\psi\overline{\psi_L}\gamma^\mu Z'_\mu\psi_L, \tag{7}$$

where $f_{Z'}$ is the coupling constant and the summation is over all quarks and leptons, *i.e.* $\psi = q_i (i = 1, 2, 3)$ and l. The differential cross section for inelastic e^+p scattering including the effect of Z' exchange can be calculated by using Eqs. (1) and (2) with the following term added to P_{LL}:

$$\Delta P_{LL} = \frac{f_{Z'}^2}{t - m_{Z'}^2}, \tag{8}$$

where $m_{Z'}$ is the Z' mass. For having 10 events for $|t| \geq 20000\text{GeV}^2$, the H1 and ZEUS results [1,2] indicate $m_{Z'} \leq 248\text{GeV}$ for $f_{Z'} = g$ (95% C.L.) while for having 313 events for $|t| \geq 5000\text{GeV}^2$, they suggest $m_{Z'} \geq 199\text{GeV}$ for $f_{Z'} = g$ (95% C.L.). In Fig. 1, the ratio r of the differential cross section for inelastic e^+p scattering including the effect of Z' exchange for $f_{Z'} = g$ and $m_{Z'} = 199\text{GeV}$ to that in the standard model is compared with the H1 result [1].

The third possibility is the effect of intrinsic form factors of quarks (or leptons). For simplicity, let us assume that both the γ_μ vertex of the photon and quarks (or leptons) and that of the Z boson and quarks (or leptons) be modified into $\gamma_\mu F(t)$ and that the form factor $F(t)$ is approximately parametrized as

$$F(t) \cong 1 + |t|/\Lambda_F^2 \quad \text{for} \quad |t| \ll \Lambda_F^2, \tag{9}$$

where Λ_F is the mass scale parameter. Then, the differential cross section for inelastic e^+p scattering including the effect of quark (or lepton) intrinsic form factors can be calculated by using Eqs. (1) and (2) simply multiplied by the factor of $|F(t)|^2$. For having 10 events for $|t| \geq 20000\text{GeV}^2$, the H1 and ZEUS results [1,2] indicate $\Lambda_F \leq 546\text{GeV}$ (95% C.L.) while for having 313 events for $|t| \geq 5000\text{GeV}^2$, they suggest $\Lambda_F \geq 365\text{GeV}$ (95% C.L.). In Fig. 1, the ratio r including the form factor effect for $\Lambda_F = 365\text{GeV}$ is compared with the H1 result [1].

The fourth possibility is the effect of intrinsic anomalous magnetic moments of quarks. Since the effect of intrinsic anomalous magnetic moments of leptons due to the possible substructure of leptons, if any, is not only extremely small but also hard to be discriminated against radiative corrections to the cross sections, we simply ignore it. For simplicity, we assume the universality for the intrinsic anomalous magnetic moments of quarks, which is parametrized by the effective interaction Lagrangian of

$$L_A = \sum_q \frac{eQ_q}{4\Lambda_A} \overline{q_i} \sigma_{\mu\nu} F^{\mu\nu} q_i, \tag{10}$$

where Q_q is the quark charge and Λ_A is the mass scale parameter. The differential cross section for inelastic e^+p scattering including the effect of quark intrinsic anomalous magnetic moments can be calculated by using Eqs. (1) and (2) with the following term added to $d\widehat{\sigma}_a/dt$:

$$\Delta \left(\frac{d\widehat{\sigma}_a}{dt} \right) = \frac{\pi \alpha Q_q^2 (1 - y)}{\Lambda_A^2 |t|}. \tag{11}$$

For having 10 events for $|t| \geq 20000\text{GeV}^2$, the H1 and ZEUS results [1,2] indicate $\Lambda_A \leq 171\text{GeV}$ (95% C.L.) while for having 313 events for $|t| > 5000\text{GeV}$, they suggest $\Lambda_A \geq 119\text{GeV}$ (95% C.L.). In Fig. 1, the ratio r including the effect for $\Lambda_A = 119\text{GeV}$ is compared with the H1 result [1].

The fifth possibility is the production of excited quarks through the subprocess of $e^+q \to e^+q^*$. For simplicity, we assume the universality for all quarks. The effective interaction Lagrangian is then given by

$$L_{q^*} = \sum_q \frac{eQ_q \lambda_{q^*}}{2m_{q^*}} \overline{q_i^*} \sigma^{\mu\nu} F_{\mu\nu} q_i + \text{H.c.}, \tag{12}$$

where m_{q^*} is the excited quark mass and λ_{q^*} is a constant parameter. Let us define the parton momentum fraction ξ by $\xi = x(|t| + m_{q^*}^2)/|t|$. Then, the differential cross section for inelastic e^+p scattering including the effect of q^* productions can be calculated by using Eq. (1) with the following term added to $d\sigma$:

$$\Delta(d\sigma) = f_a(\xi) d\xi \frac{d\widehat{\sigma}_a}{dt}, \tag{13}$$

where

$$\frac{d\widehat{\sigma}_a}{dt} = \frac{4\pi\alpha^2 \lambda_{q^*}^2}{m_{q^*}^2 |t|} \left[1 - y + \frac{y^2 m_{q^*}^2}{2(|t| + m_{q^*}^2)} \right]. \tag{14}$$

For having 10 events for $|t| \geq 20000\text{GeV}^2$, the H1 and ZEUS results [1,2] indicate $m_{q^*} \leq 136\text{GeV}$ for $\lambda_{q^*} = 1$ (95% C.L.) while having 313 events for $|t| \geq 5000\text{GeV}^2$, they suggest $m_{q^*} \geq 116\text{GeV}$ for $\lambda_{q^*} = 1$ (95% C.L.). In Fig. 1, the ratio r including the effect of q^* production for $\lambda_{q^*} = 1$ and for $m_{q^*} = 116\text{GeV}$ is compared with the H1 result [1].

The sixth possibility is the production of excited positrons. For simplicity, let us assume that excited positrons be produced electromagnetically via the effective interaction whose Lagrangian is given by [19]

$$L_{e^*} = \frac{-e\lambda_{e^*}}{2m_{e^*}}\overline{e^*}\sigma_{\mu\nu}F^{\mu\nu}e + \text{H.c.}, \tag{15}$$

where m_{e^*} is the excited electron mass and λ_{e^*} is a constant parameter, and that they decay predominantly into an electron and a composite boson (X) via the effective interaction whose Lagrangian is given by [20]

$$L_X = f_{e^*}\overline{e^*}Xe + \text{H.c.}, \tag{16}$$

where f_{e^*} is the coupling constant. The decay width of e^* can be calculated to be

$$\Gamma_X = \frac{f_{e^*}^2 m_{e^*}}{16\pi}\left(1 - \frac{m_X^2}{m_{e^*}^2}\right)^2, \tag{17}$$

where m_X is the X mass. The differential cross section for the process of $e^+p \to e^{*+}p \to e^+Xp$ can be calculated in the equivalent-photon approximation [21] as

$$\frac{d\sigma}{dt} \cong \frac{4\pi\alpha^2\lambda_{e^*}^2}{m_{e^*}^2(m_{e^*}^2 - m_X^2)}\left[1 - \frac{m_{e^*}^2}{s} + \frac{1}{2}\left(\frac{m_{e^*}^2}{s}\right)^2\right]\ln\left[\frac{s(s-m_{e^*}^2)^2}{m_p^2 m_{e^*}^4}\right]. \tag{18}$$

Let us define the invariant mass squared of e^{*+} channel $\tilde{s}$ by $\tilde{s} = (|t| + m_X^2)/y$. Then, the double differential cross section, which will be needed in later discussions, can also be approximated as

$$\frac{d\sigma}{dxdt} \cong \frac{m_{e^*}^3\Gamma_{e^*}}{\pi x[(\tilde{s} - m_{e^*}^2)^2 + m_{e^*}^2\Gamma_{e^*}^2]}\frac{d\sigma}{dt}, \tag{19}$$

where the terms vanishing at $\tilde{s} = m_{e^*}^2$ are neglected. For having 10 events for $|t| \geq 20000\text{GeV}^2$, the H1 and ZEUS results [1,2] indicate $m_{e^*} \leq 373\text{GeV}$ for $\lambda_{e^*} = 1$ and $m_X = 100\text{GeV}$ (95% C.L.) while for having 313 events for $|t| \geq 5000\text{GeV}^2$, they suggest $m_{e^*} \geq 304\text{GeV}$ for $\lambda_{e^*} = 1$ and $m_X = 100\text{GeV}$ (95% C.L.). In Fig. 1, the ratio r including the effect of e^{*+} productions for $\lambda_{e^*} = 1$, $m_{e^*} = 304\text{GeV}$, and $m_X = 100\text{GeV}$ is compared with the H1 result [1].

To sum up, we have shown that the significant excess found by the H1 and ZEUS Collaborations can be explained by either one of the following possible consequences of the substructure of quarks and leptons: 1) production of leptoquarks whose masses are around 300GeV, 2) exchange of an excited Z boson whose masses are around 200GeV, 3) intrinsic form factors of quarks (or leptons) whose mass scales are around 500GeV, 4) intrinsic anomalous magnetic moments of quarks whose mass scales are around 150GeV, 5) production of excited quarks whose masses are around 130GeV, and 6) that of excited positrons whose mass is around 350 GeV. Among these possibilities, the possibilities 2) and 5) contradict with the currently available experimental bound of $m_{Z'} > 505\text{GeV}$ and $m_{q^*} > 570\text{GeV}$ (95% C.L.) (unless q^* decays predominantly into channels other than qW, $q\gamma$, and qg) [22] but the others may not be excluded by any existing experimental constraints. In order to distinguish between these possibilities, it may be extremely useful to investigate not only the t-distribution of events but also the others such as the x- and y-distributions. In Fig. 2, we illustrate our predictions for the y-distributions of the relevant ratio r with the minimum x cut of $x \geq 0.36$ for various possibilities. The Figure shows that the different possibilities may be well distinguished in the y-distribution if a better statistics becomes available in the coming H1 and ZEUS experiments.

In conclusion, in our two analyses of the CDF and HERA anomalies, we have found that possible production of excited bosons (excited gluons, weak bosons, Higgs scalars, etc.) whose masses are around 2TeV may be responsible for the CDF anomaly while that of either leptoquarks whose masses are around 300GeV or excited positrons whose masses are around 350GeV may be responsible for the HERA anomaly, and that these two anomalies can be explained by different "sectors" of the same model, the composite model of not only quarks and leptons, but also gauge bosons and Higgs scalars [6–8].

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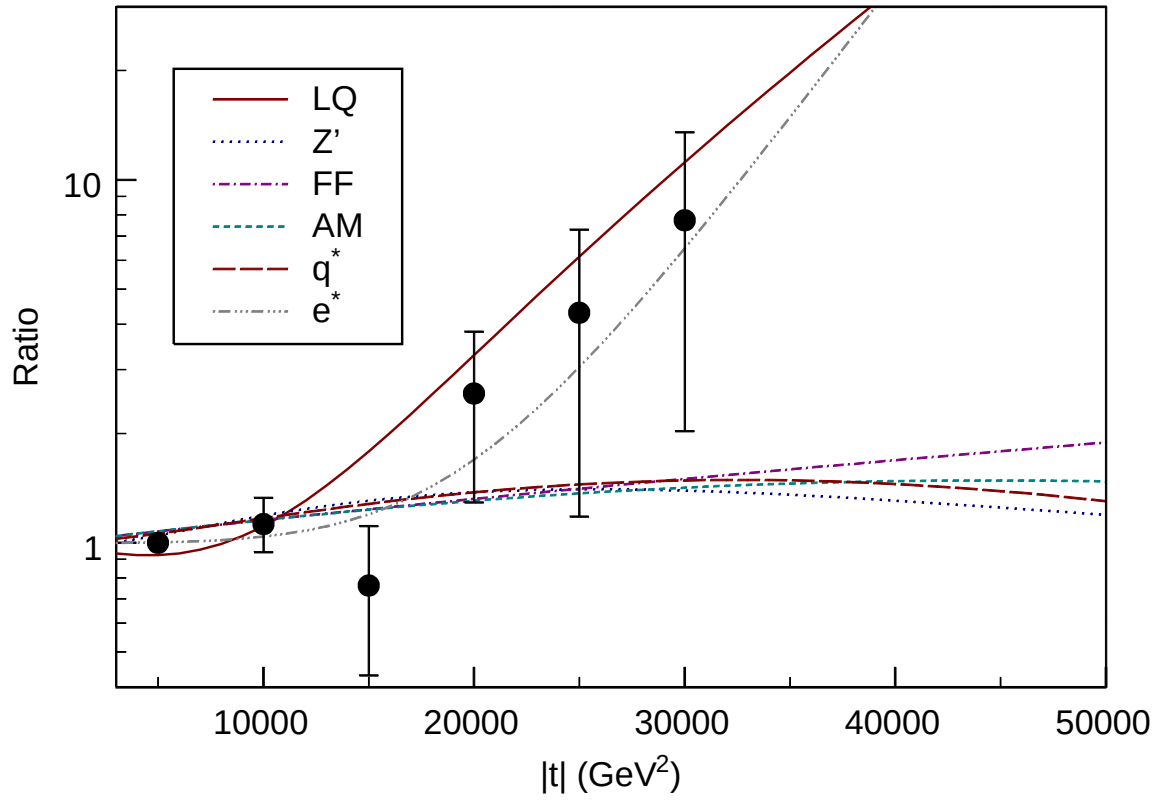

FIG. 1. The predictions of the ratio of the differential cross section $d\sigma/dt$ for inelastic e^+p scattering including one of the following effects to that in the standard model: the effects of 1) leptoquarks (LQ), 2) an excited Z boson (Z'), 3) intrinsic form factors of quarks(FF), 4) intrinsic anomalous magnetic moments of quarks (AM), 5) excited quarks (q^*), and 6) an excited positron (e^*). The mass scale parameters are fixed at the 95%C.L. lower bound extracted by using the number of events observed in the whole region of $|t| \geq 5000\text{GeV}^2$. The points with an error bar are the corresponding H1 experimental results reported in Ref. [1].

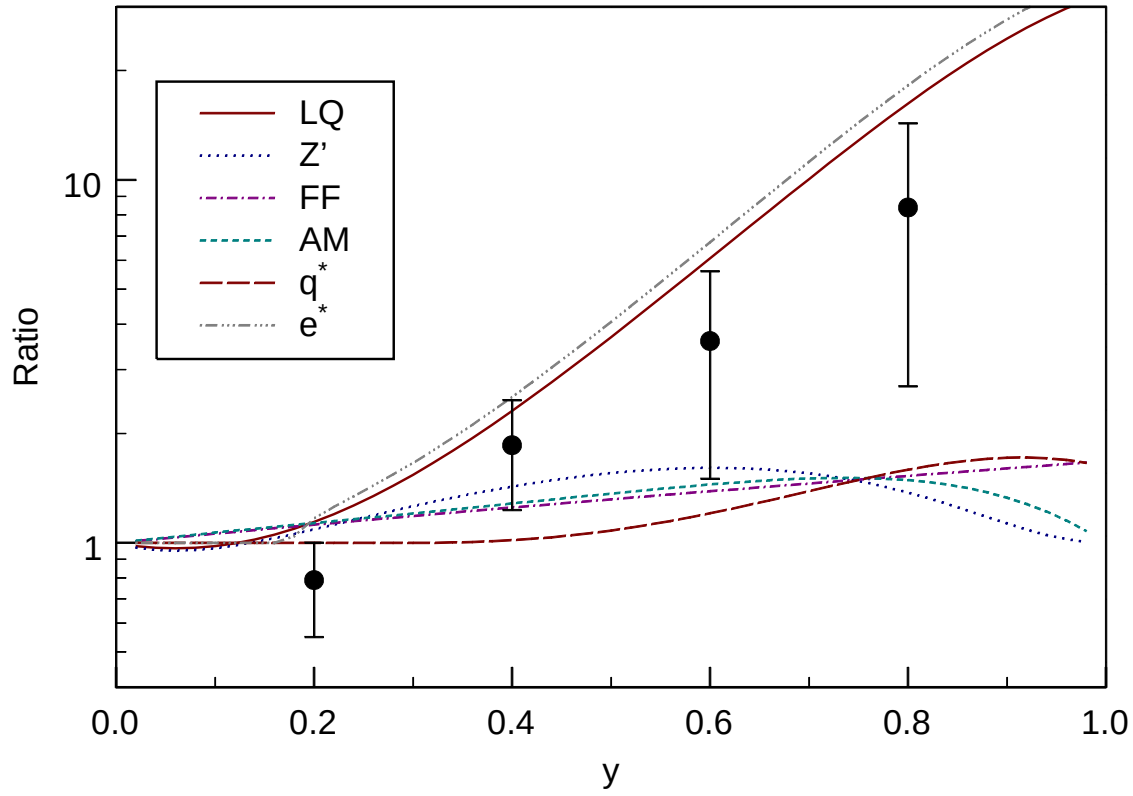

FIG. 2. The predictions of the ratio of the differential cross section $d\sigma/dy$ (with the minimum x cut of $x \geq 0.36$) for inelastic e^+p scattering including one of the following effects to that in the standard model: the effects of 1) leptoquarks (LQ), 2) an excited Z boson (Z'), 3) intrinsic form factors of quarks(FF), 4) intrinsic anomalous magnetic moments of quarks (AM), 5) excited quarks (q^*), and 6) an excited positron (e^*). The mass scale parameters are fixed at the 95%C.L. lower bound extracted by using the number of events observed in the whole region of $|t| \geq 5000\text{GeV}^2$. The points with an error bar are the corresponding H1 experimental results reported in Ref. [1].