Has the substructure of quarks been found by the Collider Detector at Fermilab?

Keiichi Akama
Department of Physics, Saitama Medical College, Kawakado, Moroyama, Saitama 350-04, Japan

Hidezumi Terazawa
Institute for Nuclear Study, University of Tokyo, Midori-cho, Tanashi, Tokyo 188, Japan

(Received 1 August 1996)

The significant excess recently found by the Collider Detector at Fermilab (CDF) Collaboration in the inclusive jet cross section for jet transverse energies $E_T \geqslant 200$ GeV over current QCD predictions can be explained either by possible production of excited bosons (excited gluons, weak bosons, Higgs scalars, etc.) or excited quarks. The masses of the excited boson and the excited quark are estimated to be around 1600 and 500 GeV, respectively. [S0556-2821(97)50305-5]

PACS number(s): 12.60.Rc, 12.60.Cn, 13.85.Ni, 13.87.Ce

The Collider Detector at Fermilab (CDF) Collaboration at the Tevatron collider [1] has reported their data on the inclusive jet cross section for jet transverse energies E_T from 15 to 440 GeV, in the pseudorapidity region $0.1 \leqslant |\eta| \leqslant 0.7$, with a significant excess over current predictions based on perturbative QCD calculations for $E_T \geqslant 200$ GeV, which may indicate the presence of quark substructure at the compositeness energy scale Λ_C of the order of 1.6 TeV. It can be taken as an exciting and already intriguing historical discovery of the substructure of quarks (and leptons), which has been long predicted, or as the first evidence for the composite models of quarks (and leptons), which has been long proposed since the middle of the 1970s [2–4]. Note that such a relatively low energy scale for Λ_C of the order of 1 TeV has recently been anticipated rather theoretically [5] or by precise comparison between currently available experimental data and calculations in the composite models of quarks (and leptons) [6]. However, the CDF experimental observation may certainly be taken as a more direct evidence for the substructure of quarks. Note that the other experimental group at the Fermilab Tevatron collider, D0 Collaboration [7], has not confirmed the excess. Also note that Huston *et al.* [8] have investigated whether it can be explained by a modified gluon distribution, concluding rather affirmatively, while Glover *et al.* [9] have made a similar investigation and concluded negatively. A possible explanation due to the even higher order QCD corrections has also been tried in Ref. [10]. The purpose of this Rapid Communication is to explain the observed excess either by possible production of excited bosons (excited gluons, weak bosons, Higgs scalars, etc.) or by that of excited quarks and to estimate the masses of the excited boson and the excited quark to be around 1600 GeV and 500 GeV, respectively.

An important motivation for composite models of quarks and leptons is to explain the repetition of generation structure in the quark and lepton spectrum. The repetition of isodoublets of quarks and leptons suggests the possible existence of an isodoublet of subquarks, w_i $(i=1,2)$, while the repetition of color quartets of quarks and leptons does that of a color quartet of subquarks, C_α $(\alpha=0,1,2,3)$ [2]. Then, the quarks (q) and leptons (l) are taken as composites of subquarks including w_i and C_α. In this picture, the weak bosons ($W^\pm$ and Z), the gluons (G^a, $a=1,2,\ldots,8$), 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 these models, we expect that there may appear not only exotic states and excited states of the fundamental fermions but also those of the fundamental bosons [11]. Their expected properties and various effects have been studied extensively in Ref. [12]. In what follows, we shall discuss the results of our investigation on the leading-order effects of such excited quarks and bosons to the inclusive jet production cross section for $p\overline{p}$ scattering of $p\overline{p}\rightarrow$ jet + anything.

Let us first consider excited bosons or bosonic composites in more detail. Let us denote the vector and color-octet, vector and color-singlet, scalar and color-octet, and scalar and color-singlet bosonic composites by V^a_μ, V_μ, S^a, and S, respectively. Then, the dimensionless couplings between these bosonic composites and quarks are given by the interaction Lagrangian

$$L_{\rm int}=\tfrac{1}{2}[g_{V8}\overline{q\lambda}_a V^a_\mu\gamma^\mu(\eta_{L8}\gamma_L+\eta_{R8}\gamma_R)q+g_{S8}\overline{q\lambda}_a S^a q + g_{V1}\overline{q\lambda}_0 V^a_\mu\gamma^\mu(\eta_{L1}\gamma_L+\eta_{R1}\gamma_R)q+g_{S1}\overline{q\lambda}_0 S q] \qquad (1)$$

where $\gamma_L=(1-\gamma_5)/2$, $\gamma_R=(1+\gamma_5)/2$, g_{V8}, g_{S8}, g_{V1}, g_{S1} are coupling constants, λ_a $(a=1,2,\ldots,8)$ are the Gell-Mann matrices for color SU(3), λ_0 is the $\sqrt{2/3}$ times 3×3 unit matrix, and (η_{L8},η_{R8}) or $(\eta_{L1},\eta_{R1})=$ (1,1), (1,−1), (1,0), and (0,1) for the vector, axial vector, left-handed, and right-handed couplings, respectively. V^a_μ and V_μ are Hermitian fields while S^a and S are in general complex. These interactions respect the chiral symmetry of quarks. Note that the dimensionless coupling between gluons, G^a, and V^a must have a form of $G^{a\mu\nu}(D_\mu V^a_\nu - D_\nu V^a_\mu)$ and, therefore, has no physical effect since it can be absorbed into the kinetic term of $(G^a_{\mu\nu})^2$ after diagonalizing of G^a and V^a. Also note that there exist no dimensionless couplings of G^a and V, G^a and S^a, or G^a and S. Therefore, these bosonic composites contribute to $p\overline{p}$ scatterings only through $q\overline{q}\rightarrow q\overline{q}$ scatterings and their crossed channels.

Let (s,t,u) and z be the Mandelstam variables for the elementary process of $q\overline{q}\rightarrow q\overline{q}$ scattering and $\cos\theta$ with the scattering angle θ in the center-of-mass system. Then, the differential cross section for the scattering is given by

 © 1997 The American Physical Society

$$\frac{d\sigma}{dz}=\frac{1}{36}\frac{1}{32\pi s}[A_L(s,t,u)+A_R(s,t,u)+2B(s,t,u)+2B(t,s,u)] \tag{2}$$

where

$$A_x(s,t,u)=4u^2\{2|V_8^{xx}(s)|^2+2|V_8^{xx}(t)|^2+9|V_1^{xx}(s)|^2+9|V_1^{xx}(t)|^2+2\mathrm{Re}[-\tfrac{2}{3}V_8^{xx}(s)^*V_8^{xx}(t)+4V_8^{xx}(s)^*V_1^{xx}(t)$$
$$+4V_1^{xx}(s)^*V_8^{xx}(t)+3V_1^{xx}(s)^*V_1^{xx}(t)]\}\quad (x=L,R), \tag{3}$$

$$B(s,t,u)=t^2\{4[2|V_8^{LR}(s)|^2+9|V_1^{LR}(s)|^2]+[2|S_8(t)|^2+9|S_1(t)|^2]-4\mathrm{Re}[-\tfrac{2}{3}V_8^{LR}(s)^*S_8(t)+4V_8^{LR}(s)^*S_1(t)$$
$$+4V_1^{LR}(s)^*S_8(t)+3V_1^{LR}(s)^*S_1(t)]\} \tag{4}$$

with the propagators

$$V_1^{xy}(s)=\begin{cases}\dfrac{e^2}{s}+\dfrac{g_{Zx}g_{Zy}}{s-M_Z^2+iM_Z\Gamma_Z}+\dfrac{g_{V1}^2\eta_{x1}\eta_{y1}}{s-M_{V1}^2+iM_{V1}\Gamma_{V1}} & (x,y=L,R)\\ \dfrac{g_Wg_W'}{s-M_W^2+iM_W\Gamma_W}, & (x,y=L)\end{cases} \tag{5}$$

$$V_8^{xy}(s)=\frac{g^2}{s}+\frac{g_{V8}^2\eta_{x8}\eta_{y8}}{s-M_{V8}^2+iM_{V8}\Gamma_{V8}},\quad (x,y=L,R) \tag{6}$$

$$S_1(s)=\frac{g_{S1}^2}{s-M_{S1}^2+iM_{S1}\Gamma_{S1}}, \tag{7}$$

$$S_8(s)=\frac{g_{S8}^2}{s-M_{S8}^2+iM_{S8}\Gamma_{S8}}. \tag{8}$$

Here, e is the electromagnetic coupling constant, g is the QCD coupling constant, g_{ZL} and g_{ZR} are the left- and right-handed coupling constants of Z boson, g_W is the weak gauge coupling constant times the relevant Cabibbo-Kobayashi-Mashawa matrix element, M_X is the mass of particle X and Γ_X is the decay width (which is neglected if it is in the t or u channel). If the decay of the excited boson is dominated by the two body decay due to the interactions given in Eq. (1), its decay width is given by

$$\Gamma_{V8}=\Gamma_{V1}=\frac{M_V}{48\pi}\sum g_V^2\sqrt{1-4m^2/M_V^2}\left[\left(1-\frac{m^2}{M_V^2}\right)(\eta_L^2+\eta_R^2)+\frac{6m^2}{M_V^2}\eta_L\eta_R\right], \tag{9}$$

$$\Gamma_{S8}=\Gamma_{S1}=\frac{M_S}{48\pi}\sum g_S^2\sqrt{1-4m^2/M_S^2}\left(1-\frac{2m^2}{M_S^2}\right), \tag{10}$$

where Σ denotes the summation over flavors of final quarks and m's are the final quark masses, all of which but the top quark mass can be practically neglected.

Let us next consider excited quarks (of spin 1/2 for simplicity), which are denoted by Q's. Then, the interaction of Q with quarks (q) and gluons (G_μ^a) is given by

$$L_{\mathrm{int}}=-\frac{g_Q}{4M_Q}(\overline{Q}\lambda^a\sigma^{\mu\nu}G_{\mu\nu}^a q_L+\overline{Q'}\lambda^a\sigma^{\mu\nu}G_{\mu\nu}^a q_R+\mathrm{H.c.}), \tag{11}$$

where g_Q is a coupling constant and M_Q is the excited quark mass. Note that an excited quark (Q) coupling with q_L and another excited quark (Q') coupling with q_R must be different from one another if the chiral symmetry of quarks is preserved. If this is the case, the differential cross section for the scattering of $q\overline{q}\to GG$ is given by

$$\frac{d\sigma}{dz}=\frac{1}{27\pi s}\left[g^4(t^2+u^2)\left(\frac{1}{tu}-\frac{9}{4s^2}\right)+\frac{g^2}{4}\mathrm{Re}[tP(t)+uP(u)]+ut[|P(t)|^2+|P(u)|^2]\right], \tag{12}$$

and those for the crossed channels are obtained by exchanging (s,t,u) appropriately and by rewriting the statistical factors due to the different spins and colors of initial (and final) quarks (or gluons), where

$$P(s)=\frac{g_Q^2}{M_Q^2}\cdot\frac{s}{s-M_Q^2+iM_Q\Gamma_Q}. \tag{13}$$

If the propagator is in the s channel, Γ_Q is the decay width of Q, while it is neglected otherwise. If the decay of Q is dominated by the interactions given in Eq. (11), the decay width is given by

$$\Gamma_Q=\frac{g_Q^2}{6\pi}M_Q\left(1-\frac{m^2}{M_Q^2}\right), \tag{14}$$

where m is the final quark mass, any one of which except the top quark mass can be practically neglected. Note that if an

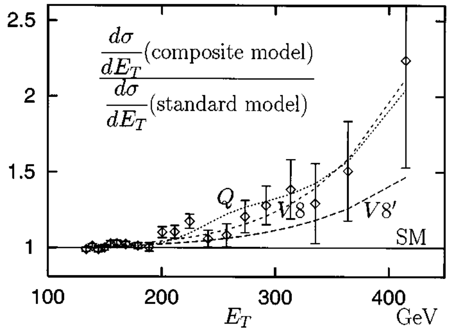

FIG. 1. The predictions of the composite models with excited states for the single jet E_T inclusive distribution divided by those of the standard model. The label SM indicates the prediction of the standard model, $V8$ ($V8'$) indicates that with a vector octet excited boson with $M_{V8}=1600$ GeV (2000 GeV) and $\alpha_{V8}=g_{V8}^2/4\pi=1$, and Q indicates that with the excited quark with $M_Q=500$ GeV, $\alpha_Q=g_Q^2/4\pi=0.2$, and $r=3$, where r is the ratio of the decay width to the partial width of the decay to the two-jet mode. The points with error bars (statistical) represent the difference between the CDF cross section measurement in Ref. [1] and NLO standard model QCD using MRSD0′ PDFs.

excited quark (Q) coupling with q_L and another excited quark (Q') coupling with q_R are not discriminated against one another, which leads to breaking of the chiral symmetry of quarks, the above differential cross section (12) would need an additional term,

$$\frac{1}{27\pi s}ut\left[|P(t)|^2+|P(u)|^2-\frac{1}{4}\mathrm{Re}[P(t)^*P(u)]\right] \quad (15)$$

with the decay width twice as much as that in Eq. (14).

Now we evaluate the single jet p_T inclusive distribution, dijet invariant mass distribution, and dijet angular distribution in the $p\bar{p}$ scattering in the CDF energy region. For the elementary processes, we take $2\to 2$ processes of quarks, antiquarks, and gluons. Also, we assume that either one of u, d, s, c, b quarks or gluons in the final states is to be observed as a jet. Although the authors of Ref. [1] have found the excess at high p_T in comparison of their data with the next-to-leading order calculations, we have restricted ourselves to the leading order contribution from composite models. Since higher order corrections are supposed to contribute almost equally both in the standard model calculations and in the composite model ones, the ratio of the composite model calculation to the standard model one may not be so much affected by higher order corrections and may be meaningful enough even if both of the calculations are only in the leading order. As for the parton distribution functions (PDFs) we use those of Glück-Reya-Vogt in Ref. [13] since we expect that the ratio may not so much depend on PDFs. The CDF Collaboration has compared various different PDFs including Martin-Roberts-Stirling set (MRSD0′) PDFs [14], which best fits the data for $E_T<200$ GeV, and found that the differences due to the different PDFs are of the order of 10%. Therefore, we must admit that errors due to the ambiguities in PDFs are of order 10% in our predictions. We have calculated the jet inclusive cross sections from $2\to 2$ processes and the PDFs in the standard way [15].

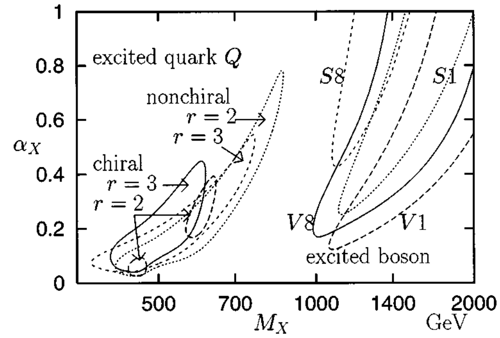

FIG. 2. The allowed regions (95% confidence level) of the mass M_X and coupling constant $\alpha_X(\equiv g_X^2/4\pi)$ of various types of excited states X. The labels $V8$, $V1$, $S8$, and $S1$ indicate vector-octet, vector-singlet, scalar-octet, and scalar-singlet excited bosons, respectively.

In Fig. 1, the predictions of the composite models with excited states for the single jet E_T inclusive distribution divided by those of the standard model are compared with the corresponding CDF experimental result for the difference between the measured cross section and next leading order (NLO) QCD with MRSD0′ shown in Ref. [1]. We have taken the same average over the pseudorapidity range of $0.1\leqslant|\eta|\leqslant 0.7$ as the CDF experiment [1]. Based on such comparison, we have performed detailed chi-square analyses, and determined the allowed regions (95% confidence level) of the mass M_X and coupling constant $\alpha_X(\equiv g_X^2/4\pi)$ of various types of excited states X (See Fig. 2). It indicates that the excited bosons with $\alpha_X>0.1$ and $M_X>1000$ GeV are allowed. The excess of the E_T distribution is well fitted by the tail of the high mass resonance of the excited boson. On the other hand, there is no allowed region for a single excited quark, as far as we assume the two-jet decay mode dominates the decay. This is because the width (14) is too narrow to fit the rather gentle slope of the observed data in Fig. 1. This is consistent with the exclusion of the excited quarks with the masses smaller than 570 GeV made previously by the CDF Collaboration [16]. The width, however, can be broadened due to (i) other decay modes such as multijet or semijet processes, (ii) coexistence of several resonances, or (iii) limited resolution for the jet energy and momentum

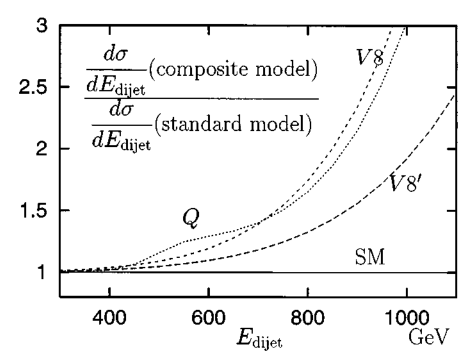

FIG. 3. The predictions with the typical excited state for the dijet invariant mass ($=E_{\rm dijet}$) distribution divided by those of the standard model. The labels SM, $V8$, $V8'$, and Q are the same as those in Fig. 1.

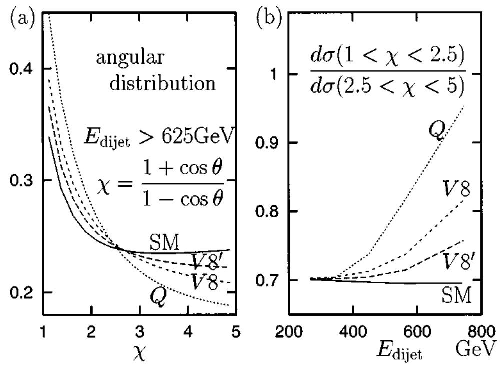

FIG. 4. (a) The predicted dijet angular distribution as a function of χ normalized by the average over the region of $1 \leqslant \chi \leqslant 5$. (b) The ratio of the number of the expected events for $\chi < 2.5$ to that for $\chi > 2.5$ as a function of the dijet invariant mass $E_{\rm dijet}$. The labels SM, $V8$, $V8'$, and Q are the same as those in Fig. 1.

measurement. Let r be the ratio of the total decay width to the partial width (14) of the decay to the two-jet mode. In Fig. 2, we also show the allowed region for the M_X and α_X of the excited quarks for the cases of $r=2$ and 3. It is restricted in the low-mass region 400 GeV$<M_X<$900 GeV and $0.03<\alpha_X<0.8$.

To get more precise information, it may be extremely useful to investigate the dijet invariant mass and angular distributions. Figure 3 shows the predictions with the typical excited states for the dijet invariant mass ($E_{\rm dijet}$) distribution divided by those of the standard model. It predicts a significant excess in the high dijet mass region. Figure 4(a) shows the predicted dijet angular distribution as a function of $\chi \equiv (1+\cos\theta)/(1-\cos\theta)$ (normalized by the average over the region of $1 \leqslant \chi \leqslant 5$). The model with excited states predicts relative excess in low χ (i.e., large θ) region, since the peak at $\theta=0$ due to exchange of light quarks and massless gluons is absent in the additional contributions from the excited state. To see it more clearly, we show in Fig. 4(b) the ratio of the number of the expected events for $\chi<2.5$ to that for $\chi>2.5$ as a function of the dijet invariant mass $E_{\rm dijet}$.

To sum up, we have shown in this Rapid Communication that the significant excess found by the CDF Collaboration can be explained either by possible production of excited bosons whose masses are around 1600 GeV or by that of excited quarks whose masses are around 500 GeV. Note that our parameters for the substructure, M_X $(X=Q,V,S)$, are not directly related to the parameters, Λ_C, in the contact term of Eichten-Lane-Peskin [17] although Λ_C and M_X/g_X must be the same order of magnitude. The copious production of such excited particles can be expected in the future e^+e^- Next Linear Collider (NLC) experiments and $p\bar{p}$ CERN Large Hadron Collider (LHC) experiments. In conclusion, we must mention that although we have assumed the excited quarks of spin 1/2 for simplicity, one can also assume those of spin 3/2, which has very recently been emphasized by Bander [18]. After submitting the original form of this Rapid Communication, the CDF Collaboration [19] have reported their measurement of jet angular distributions in events with two jets in the final state and the agreement with the next-to-leading order predictions of QCD in all dijet invariant mass regions, excluding the contact interaction scale (Λ_C) of Eichten *et al.* of the order of 1.6 GeV. A simple comparison between their data and our predictions indicates that excited quarks whose masses are around 500 GeV are excluded while excited bosons whose masses are around 2 TeV are perfectly allowed for the explanation.

The authors would like to thank Professor Kunitaka Kondo for giving them the valuable information on the CDF experiment and for sending them the manuscripts before publication. One of the authors (H.T.) also wishes to thank Professor Stanley J. Brodsky and all the other staff members, especially Professors James D. Bjorken and Michael Peskin, of Theoretical Physics Group at Stanford Linear Accelerator Center, Stanford University not only for their useful discussions on the substructure of quarks but also for their warm hospitality extended to him during his visit when this work was completed. The other author (K.A.) also wishes to thank Professor Yuichi Chikashige and Professor Tadashi Kon for useful discussions and communications.

[1] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **77**, 438 (1996).
[2] J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); H. Terazawa, Y. Chikashige, and K. Akama, *ibid.* **15**, 480 (1977); H. Terazawa, *ibid.* **22**, 184 (1980).
[3] For a review, see, for example, H. Terazawa, in *Proceedings of the XXII International Conference on High Energy Physics*, Leipzig, 1984, edited by A. Meyer and E. Wieczorek (Akademie der Wissenschaften der DDR, Zeuthen, 1984), Vol. I, p. 63.
[4] For a recent review, see, for example, H. Terazawa, in *Proceedings of the Fourth International Conference on Squeezed States and Uncertainty Relations*, Taiyuan, Shanxi, China, 1995, edited by D. Han *et al.*, NASA Conference Publication 3322 (NASA Goddard Space Flight Center, Greenbelt, Maryland, 1996), p. 179.
[5] See, for examples, H. Terazawa, Prog. Theor. Phys. **79**, 734 (1988); Phys. Rev. Lett. **65**, 823 (1990); Mod. Phys. Lett. A **6**, 1825 (1991); K. Akama, H. Terazawa, and M. Yasuè, Phys. Rev. Lett. **68**, 1826 (1992).
[6] See, for example, K. Akama and H. Terazawa, Phys. Lett. B **321**, 145 (1994); Mod. Phys. Lett. A **9**, 3423 (1994); H. Terazawa, *ibid.* **11,** 2463 (1996).
[7] See, for example, D0 Collaboration, S. Abachi *et al.*, Report No. FERMILAB-Conf-96/280-E (unpublished).
[8] J. Huston *et al.*, Phys. Rev. Lett. **77**, 444 (1996); H. L. Lai *et al.*, Phys. Rev. D **55**, 1280 (1997).
[9] E. W. N. Glober *et al.*, Phys. Lett. B **381**, 353 (1996).
[10] S. Catani *et al.*, Nucl. Phys. **B478**, 273 (1996)
[11] Terazawa [2].
[12] K. Akama and T. Hattori, Phys. Rev. D **40**, 3688 (1989); K.

Akama, T. Hattori, and M. Yasuè, *ibid.* **42**, 789 (1990); **43**, 1702 (1991); S. Ishida and M. Sekiguchi, Prog. Theor. Phys. **86**, 491 (1991); K. Akama and T. Hattori, Int. J. Mod. Phys. A **9**, 3503 (1994).

[13] M. Glück, E. Reya, and A. Vogt, Z. Phys. C **67**, 433 (1995).

[14] A. D. Martin, R. G. Roberts, and W. J. Stirling, Phys. Lett. B **306**, 145 (1993).

[15] For a review, see E. J. Eichten, I. Hinchliffe, K. D. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984).

[16] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **74**, 3538 (1995).

[17] E. Eichten, K. Lane, and M. Peskin, Phys. Rev. Lett. **50**, 811 (1983).

[18] M. Bander, Phys. Rev. Lett. **77**, 601 (1996).

[19] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **77**, 5336 (1996).