Search for Excited Quarks in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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If quarks are composite particles then excited states are expected. We have searched in $p\bar{p}$ collisions for excited quarks (q^*) which decay to common quarks by emitting a W boson ($q^* \rightarrow qW$) or a photon ($q^* \rightarrow q\gamma$). The simplest model of excited quarks has been excluded for mass $M^* < 540$ GeV/c^2 at 95% confidence level.

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Models in which quarks are composite particles usually predict that quarks can be excited from the ground state (e.g., u or d) to some excited state (u^* or d^*). In the simplest model [1] excited quarks can be produced in $p\bar{p}$ collisions via quark-gluon fusion, and decay to a common quark by emitting any gauge boson [2]. The effective Lagrangian for transitions between excited quarks (q^*) of mass M^* and common quarks (q) is constrained by gauge invariance to be [1]

$$\mathcal{L} = \frac{1}{2M^*}\bar{q}_R^*\sigma^{\mu\nu}\left[g_s f_s \frac{\lambda_a}{2} G^a_{\mu\nu} + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}\right] \times q_L + \text{H.c.}, \quad (1)$$

where G^a, W, and B are the field-strength tensors for the SU(3), SU(2), and U(1) gauge fields; λ_a, τ, and Y are the corresponding gauge structure constants; and g_s, g, and g' are the gauge coupling constants. Finally f_s, f, and f' are unknown couplings determined by the composite dynamics, and are all assumed to be equal to 1 unless otherwise stated. Here we search for excited quarks decaying to either a quark and a W boson or a quark and a photon.

A description of the Collider Detector at Fermilab (CDF) may be found elsewhere [3]. We use a coordinate system with z along the proton beam, azimuthal angle ϕ, polar angle θ, and pseudorapidity $\eta = -\ln\tan(\theta/2)$. This search used data from both the 1988-89 and 1992-93 running periods. During the 1988-89 (1992-93) run we accumulated photon triggers of total integrated luminosity 3.3 pb^{-1} (21.3 pb^{-1}), and electron and muon triggers of total integrated luminosity 4.05 pb^{-1} and 3.54 pb^{-1} (21.3 pb^{-1}). To reject jet backgrounds, software triggers required that at least 89% of the transverse energy of photon or electron candidates be in the electromagnetic compartment of the calorimeter. To maintain the projective nature of the calorimeter towers, we required the event z vertex be within 60 cm of the center of the detector.

For the $q^* \to q\gamma$ search, a photon candidate is an isolated neutral cluster of electromagnetic energy. The isolation requirement was that the extra transverse energy inside a cone of radius $R=\sqrt{(\Delta\eta)^2+(\Delta\phi)^2}=0.7$ surrounding the photon was less than 4 GeV. Charge neutrality was determined by selecting only events with no tracks pointing at the cluster, or at most one track with $P_T < 1$ GeV/c. The transverse profile of the cluster and nearby energy depositions were required to be compatible with a photon shower in order to reduce the background from decays of π^0 and η mesons. To reject photons from cosmic ray muon bremsstrahlung, we required the missing transverse energy [4] in the detector to be less than 80% of the photon transverse energy. The efficiency of all cuts, including fiducial cuts, for photons in the measured pseudorapidity interval $|\eta| < 0.9$ varied from 57% at low q^* mass to 47% at high mass. The total acceptance for $q^* \to q\gamma$ varied from 34% at low mass to 27% at high mass.

For the $q^* \to qW$ search, we selected W bosons which decay leptonically into electrons or muons with high lepton transverse momentum ($P_T > 20$ GeV/c) and event missing transverse energy [4] ($\not{E}_T > 20$ GeV). The electron (muon) was required to have $|\eta| < 0.95$ ($|\eta| < 0.6$) and be separated from any nearby jets by a distance $R > 0.9$ ($R > 0.25$) in η-ϕ space. Cuts defining an electron and muon were the same as previously published [4,5]. For both lepton varieties, cosmic ray events were reduced by rejecting events with out-of-time energy deposition, and cuts on the presence of a second lepton were included to reject Z boson events. The efficiency of all cuts, including fiducial cuts, for electrons (muons) in the measured pseudorapidity interval varied from 32% (34%) at low q^* mass to 49% (43%) at high mass. The total acceptance for $q^* \to qW$ for W decays to an electron (muon) varied with mass from 16% (11%) to 34% (21%).

Events with high P_T photon candidates or W bosons typically contain a recoiling jet of hadrons. The jet energy was defined as the total energy inside a cone of radius $R=0.7$ corrected for calorimeter response. The quark from the hypothetical q^* decay was assumed to correspond to the leading jet: the highest transverse energy jet in the event. For the $q^* \to qW$ search the jet was required to have greater than 15 GeV transverse energy; at lower energies jet measurement is difficult.

For the $q^* \to q\gamma$ search, we improved our mass resolution by avoiding the use of the jet energy and assumed that the jet and photon balanced in P_T, as they must for the lowest order process $qg \to q^* \to q\gamma$. The photon +jet mass is given by $M=(2P_{T\gamma}/c)\cosh\eta^*$ where $\eta^* =(\eta_\gamma - \eta_{\rm jet})/2$ and we required $P_{T\gamma} > 30$ GeV/c. For the $q^* \to qW$ search, the z component of the neutrino momentum $P_{z\nu}$ in the decay $W \to l\nu$ was constrained to give an $l\nu$ mass equal to the W boson mass. Events that could not be constrained to the W mass were constrained to the transverse mass of the W in the event (25% of the events). The constraint resulted in two solutions for both $P_{z\nu}$ and the $W+$ jet mass. We picked the smaller mass solution in order to present a conservative mass distribution. The experimental mass resolution for the $q^* \to q\gamma (q^* \to qW)$ search was roughly 5% (13% rms, compared to the predicted half width of the q^* resonance, $\Gamma/2=2\%$ [1].

Excited quark decays are isotropic, producing an angular distribution that is flat in $\cos\theta^*$, while the t-channel dominated QCD background is strongly peaked at $|\cos\theta^*|=1$. Here θ^* is the angle between the jet and the proton beam in the center of momentum frame of the collision products. To reduce QCD backgrounds and control the acceptance as a function of mass we required $|\cos\theta^*| < \frac{2}{3}$ ($|\cos\theta^*| < 0.9$) in the $q^* \to q\gamma$ ($q^* \to qW$) search. To further reduce background in the $q^* \to qW$ mode, we required the rapidity boost along the z axis from the laboratory to the center of momentum frame to satisfy $|Y_{\rm boost}| < 1.5$, and required the difference in azimuthal angle between the neutrino and the jet to satisfy $|\Delta\phi_{\nu j}| > 0.4$ rad.

In Figs. 1 and 2 we present differential cross sections as a function of mass in bins equal to the mass resolution. In Fig. 1 the photon candidate+leading jet mass spectrum is compared with an estimate of the QCD background, obtained by multiplying a next-to-leading order prediction of prompt photon production [6] by our independent measurement of the ratio of photon candidates to true photons [7]. The data and QCD background prediction are in good agreement, and there is no compelling evidence for an excited quark signal as illustrated in Fig. 1 for a few different values of the q^* mass. In Fig. 2 the

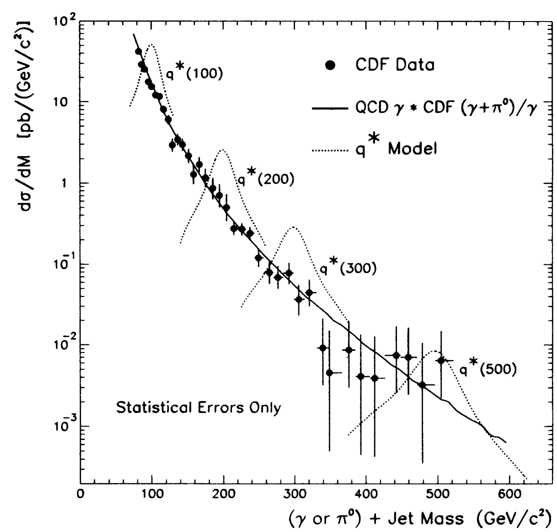

FIG. 1. The photon candidate+leading jet invariant mass distribution (points) compared to an estimate of the QCD background (solid curve) and excited quark signal at four different q^* mass values (dotted curves). Corrected for acceptance and efficiency except for the cuts $|\eta_\gamma| < 0.9$ and $|\cos\theta^*| < \frac{2}{3}$.

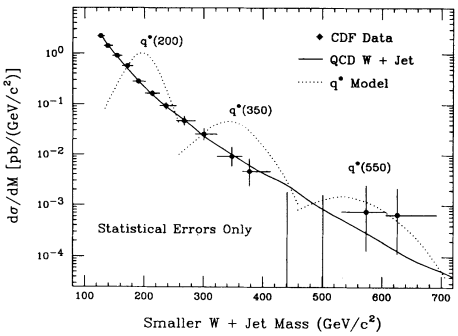

FIG. 2. The distribution of the smaller of the two solutions for the W+leading jet invariant mass (points) compared to a Monte Carlo simulation of the QCD background (solid curve) and excited quark signal at three different q^* mass values (dotted curves). Not corrected for acceptance and detector efficiency.

distribution of the smaller of the two solutions for the W boson+leading jet mass is compared with the predictions of a Monte Carlo simulation and detector simulation for both the QCD background [8,9] and examples of an excited quark signal [9]. Again, the measured mass distribution is in good agreement with the QCD background prediction, and there is no evidence for an excited quark signal. There are two bins within the distribution which have no events; for these we show only the Poisson 1σ error bar rising from 0 to 1.84 event. Only Poisson statistical uncertainties are shown in Figs. 1 and 2; systematic uncertainties are only used when setting limits. Figure 1 has been corrected for acceptance and efficiency to allow future comparisons with theory, while Fig. 2 has not been fully corrected since theoretical predictions of the W+jet mass require a modeling of the significant effects of the detector resolution.

To set a limit on the cross section for excited quark production as a function of excited quark mass, we assumed that the measured mass spectrum came from the sum of an excited quark signal and a QCD background. The predicted signal at mass M from an excited quark of mass M^* was calculated from the theory [1,10] and then smeared with our detector resolution. For the photon channel this was done both analytically and with a Monte Carlo simulation [11] and detector simulation; both methods included the effect of gluon radiation on our mass definition and gave the same result. Resolution smeared peaks for a few excited quark masses are shown in Figs. 1 and 2. The predicted QCD background came from a smooth parametrization [12] for the photon channel and a QCD Monte Carlo simulation [8] and detector simulation for the W channel. In each channel separately, we let the normalization of the signal float by multiplying it by a normalization parameter α, and added in the background to obtain the predicted number of events μ_i in each mass bin (these bins had a fixed width of 5 GeV/c^2 for the photon analysis and 25 GeV/c^2 for the W analysis). The background normalization was also allowed to float except that it was effectively constrained so that signal plus background equal the number of events in the data. For each possible value of M^* we formed the Poisson likelihood for observing the measured events n_i when μ_i are predicted: $L=\prod(\mu_i^{n_i}e^{-\mu_i})/(n_i!)$. For the $q^*\to q\gamma$ search, the background normalization and shape parameters [12] were allowed to float to values that maximized L for the maximum likelihood value of α only. Correlations among the background parameters and α were small; including them in the likelihood produces a negligible change in the final results. For the $q^*\to qW$ search, the shape of the background was determined by Monte Carlo simulation [9], and the normalization of the background was constrained at each value of α to require the total predicted events equal the observed events. For both searches, the Poisson likelihood was convoluted with Gaussian systematic uncertainties in the parameter α, arising from uncertainties in detector response, acceptance, and luminosity; other sources of systematic uncertainty were negligible. Systematic uncertainties reduced the upper excluded mass value (discussed later) by only 2, 6, and 15 GeV/c^2 for the γ, W, and combined channels, respectively. We found the 95% confidence level (C.L.) limit in the parameter α, $\alpha_{\rm limit}$, by solving

$$\left[\int_0^{\alpha_{\rm limit}} L(\alpha)d\alpha\right] \Big/ \left[\int_0^{\infty} L(\alpha)d\alpha\right] = 0.95\,.$$

Multiplying the total expected cross section for an excited quark of mass M^* by $\alpha_{\rm limit}$ gives the 95% C.L. upper limit on the cross section for excited quark production.

TABLE I. The 95% C.L. upper limits on the cross section times branching ratio for $q^*\to q\gamma$ (with $|\eta_\gamma|<0.9$ and $|\cos\theta^*|<\frac{2}{3}$) in column 2, for $q^*\to qW$ in column 3, the combined limit on the total q^* production cross section in column 4, and the predicted [1,10] value of the total q^* cross section in column 5.

	95% C.L. upper limits			Theory
M^* (GeV/c^2)	$\sigma(q^*\to q\gamma)$ (pb)	$\sigma(q^*\to qW)$ (pb)	$\sigma(q^*)$ (pb)	$\sigma(q^*)$ (pb)
80	79.6	···	2.26×10^4	7.55×10^5
100	63.4	···	1.56×10^4	3.16×10^5
150	32.9	206	3.38×10^3	5.72×10^4
200	4.55	87.2	6.93×10^2	1.51×10^4
250	2.80	36.4	3.07×10^2	4.90×10^3
300	1.69	16.3	1.39×10^2	1.81×10^3
350	0.66	9.46	56.1	7.24×10^2
400	0.68	5.35	39.3	3.08×10^2
450	1.04	3.32	39.8	1.36×10^2
500	0.93	3.41	36.9	62.2
550	0.62	3.93	31.0	28.8
600	0.44	4.00	25.4	13.5
650	0.35	3.94	21.9	6.37

In Table I we list the 95% C.L. upper limits and the predicted total q^* cross section. The limits on cross section times branching ratio can be used to set limits on phenomena other than excited quarks provided the width

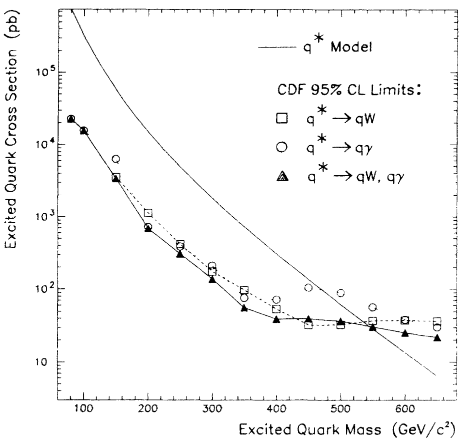

FIG. 3. The 95% C.L. upper limit on the cross section vs mass from the W channel (squares), the photon channel (circles), and the two channels combined (triangles) is compared to the theoretical prediction (solid curve).

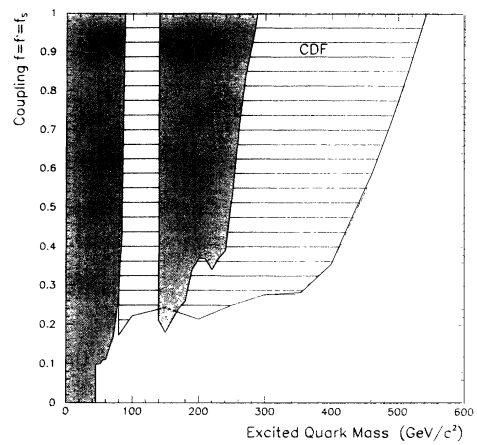

FIG. 4. The region of the coupling vs mass plane excluded at 95% C.L. by the CDF measurement (hatched region) is compared to the regions excluded by LEP [13] at 95% C.L. in the $q^* \to q\gamma, qg$ channels (shaded region) and the region excluded by UA2 [14] at 90% C.L. in the $q^* \to qg$ channel (shaded region).

of the predicted signal is significantly less than our mass resolution. In Fig. 3 we show the 95% C.L. upper limit on the total excited quark production cross section vs excited quark mass for the W channel, the photon channel, and the two channels combined (from multiplying the likelihood distributions). These limits use the predicted branching ratios [1,2,10]. Comparing our 95% C.L. upper limits to the theoretical prediction we exclude excited quarks in the following mass ranges: $80 < M^* < 460$ GeV/c^2 from $q^* \to q\gamma$, $150 < M^* < 530$ GeV/c^2 from $q^* \to qW$, and $80 < M^* < 540$ GeV/c^2 from both channels combined. These exclusions assume the coupling $f = f_s = f' \geq 1$. Since the mass limit is sensitive to the choice of coupling, in Fig. 4 we show the regions excluded at 95% C.L. in the coupling vs mass plane for the combined channel. Figure 4 shows that the CDF excluded range extends those from previously reported searches at LEP [13] and UA2 [14], excluding the simplest model of excited quarks for mass $M^* < 540$ GeV/c^2 at 95% C.L.

We have searched for excited quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The photon+jet and W+jet mass spectra are in good agreement with QCD background calculations and there is no compelling evidence for a q^* mass resonance. We exclude the simplest model of excited quarks [1] for mass $80 < M^* < 540$ GeV/c^2 at 95% C.L.

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*Visitor.

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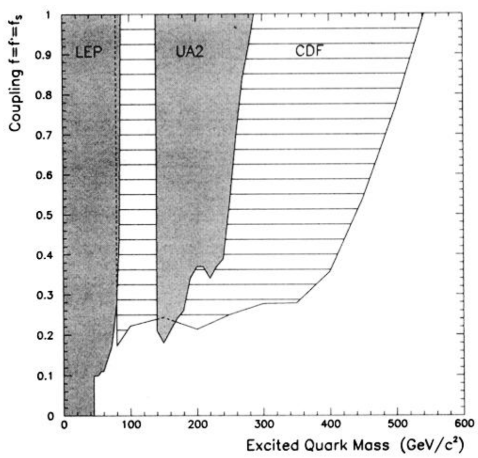

FIG. 4. The region of the coupling vs mass plane excluded at 95% C.L. by the CDF measurement (hatched region) is compared to the regions excluded by LEP [13] at 95% C.L. in the $q^* \rightarrow q\gamma, qg$ channels (shaded region) and the region excluded by UA2 [14] at 90% C.L. in the $q^* \rightarrow qg$ channel (shaded region).