Search for New Particles Decaying to Dijets in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We have used 19 pb^{-1} of data collected with the Collider Detector at Fermilab to search for new particles decaying to dijets. We exclude at 95% confidence level models containing the following new particles: axigluons with mass between 200 and 870 GeV/c^2, excited quarks with mass between 80 and 570 GeV/c^2, and color octet technirhos with mass between 320 and 480 GeV/c^2.

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Within the framework of perturbative QCD two-jet events are expected to arise in proton-antiproton collisions from hard parton-parton scattering. The outgoing scattered partons manifest themselves as hadronic jets. The predicted two-jet mass spectrum falls rapidly with increasing two-jet mass. Many extensions of the standard model predict the existence of new massive objects that couple to quarks and gluons, and result in resonant structures in the two-jet mass spectrum. In this Letter we report a search for narrow resonances in the two-jet mass spectrum measured in proton-antiproton collisions at a center of mass energy $\sqrt{s} = 1.8$ TeV.

In addition to this general search, we specifically search for the following six resonance phenomena. First, in a model where the symmetry group SU(3) of QCD is replaced by the chiral symmetry $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$, there are axial vector particles called axigluons A [1]. The axigluon is produced and decays in the quark-antiquark channel ($A \rightarrow q\bar{q}$); here we have assumed they decay only to the quarks in the standard model. Second, if quarks are composite particles then excited states q^* are expected [2]; we search for mass degenerate excited quarks in the quark-gluon channel ($q^* \rightarrow qg$). Third, models of walking technicolor [3], which seek to explain electroweak symmetry breaking via the dynamics of a new interaction among techniquarks, predict the presence of color octet technirhos ρ_T. We consider such a model in which the ρ_T are mass degenerate and decay to dijets only ($\rho_T \rightarrow g \rightarrow q\bar{q}$ or gg); in this model the technipion is too massive to be a decay product of the ρ_T. Fourth and fifth models which propose new gauge symmetries often predict new gauge bosons [4] which decay to quarks ($W', Z' \rightarrow q\bar{q}$). Here we assume standard model couplings and when calculating the cross section include a K factor [5] to account for higher order terms. Finally, superstring theory suggests that E_6 may be the grand unified strong and electroweak gauge group; E_6 models predict the presence of scalar diquarks D and D^c [6] which decay to quarks ($D \to \bar{u}\bar{d}$ and $D^c \to ud$). We assume electromagnetic strength couplings and mass degenerate diquarks.

A detailed description of the Collider Detector at Fermilab (CDF) can be found elsewhere [7]. We use a coordinate system with z along the proton beam, transverse coordinate perpendicular to the beam, azimuthal angle ϕ, polar angle θ, and pseudorapidity $\eta = -\ln\tan(\theta/2)$. Jets are reconstructed as localized energy depositions in the CDF calorimeters which are constructed in a tower geometry. The jet energy E and momentum $\vec{P}$ are defined as the scalar and vector sums, respectively, of calorimeter tower energies inside a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$ centered on the jet direction. E and $\vec{P}$ are corrected for calorimeter nonlinearities, energy lost in uninstrumented regions and outside the clustering cone, and energy gained from the underlying event. The jet energy corrections increase the jet energies on average by roughly 27% (15%) for 50 GeV (500 GeV) jets. Full details of jet reconstruction and jet energy corrections at CDF can be found elsewhere [8].

We define the dijet sysetm as the two jets with the highest transverse momentum in the event (leading jets) and define the dijet mass $m = \sqrt{(E_1 + E_2)^2 - (\vec{P}_1 + \vec{P}_2)^2}$. The dijet mass resolution is approximately 10%. Our data sample was obtained in the 1992–93 running period using four single jet triggers with thresholds on the uncorrected cluster transverse energies of 20, 50, 70, and 100 GeV. After jet energy corrections these trigger samples were used to measure the dijet mass spectrum above 150, 241, 265, and 353 GeV/c^2, respectively. At these mass thresholds the trigger efficiencies for the four triggers were 1.0, 0.99, 0.87, and 0.89, and the four data samples corresponded to integrated luminosities of 0.038, 0.66, 3.2, and 19.1 pb^{-1} after prescaling. Off-line we required that both jets have pseudorapidity $|\eta| < 2$ and a scattering angle in the dijet center of mass frame $|\cos\theta^*| = |\tanh[(\eta_1 - \eta_2)/2]| < 2/3$. The $\cos\theta^*$ cut provides uniform acceptance as a function of mass and reduces the QCD background which peaks at $|\cos\theta^*| = 1$. To maintain the projective nature of the calorimeter towers, the z position of the event vertex was required to be within 60 cm of the center of the detector; this cut was 94% efficient. Backgrounds from cosmic-ray interactions were rejected if the energy deposited in the central hadronic calorimeters occurred at times other than the $p\bar{p}$ crossing. Remaining backgrounds from cosmic rays, beam halo, and detector noise produced events with unusually large or unbalanced energy depositions and were removed by requiring $\not{E}_T/\sqrt{\sum E_T} < 6$ and $\sum E_T < 2$ TeV, where $\not{E}_T$ is the missing transverse energy [9] and $\sum E_T$ is the total transverse energy in the event.

In Fig. 1 we present the inclusive dijet mass distribution for $p\bar{p} \to 2$ leading jets $+X$, where X can be anything, including additional jets. The dijet mass distribution has been corrected for trigger and z vertex inefficiencies. We plot the differential cross section versus the mean dijet mass in bins equal to the dijet mass resolution (rms $\sim$ 10%). The data are compared to a QCD prediction [10] which includes a simulation of the CDF detector. The QCD prediction uses CTEQ2L parton distributions [11] and a renormalization scale $\mu = P_T$, and is normalized to the data. We also fit the data with the parametrization $d\sigma/dm = A(1 - m/\sqrt{s})^N/m^P$ with parameters A, N, and P. This parametrization gives a good description of both the observed distribution ($\chi^2/N_{\mathrm{DF}} = 0.96$) and the QCD prediction ($\chi^2/N_{\mathrm{DF}} = 0.75$). The fit to the observed distribution gave $A = (6.4 \pm 0.1) \times 10^{15}$ pb/(GeV/c^2), $N = 5.512 \pm 0.002$, and $P = 6.69 \pm 0.09$, where the quoted errors are statistical only. Figure 1 shows the background fit on a logarithmic scale, and Fig. 2 shows the fractional difference between the data and background fit on a linear scale. The fit shows no significant evidence for any new particle. Upward fluctuations appearing in the data near 250, 550, and 850 GeV/c^2 have statistical significance 2.3, 1.3, and 1.8 standard deviations when interpreted as "signals" for new particles at these masses. However, this minimal significance is reduced by roughly a factor of 2 after incorporating systematic uncertainties (discussed later).

To set limits on dijet resonances it is sufficient to determine the mass resolution for only one new particle type assuming each new particle's natural half-width ($\Gamma/2$) is small compared to the dijet mass resolution. This is the case for these models of axigluons ($\Gamma/2M \approx 0.05$), excited quarks ($\Gamma/2M \approx 0.02$), color octet technirhos ($\Gamma/2M \approx 0.01$), new gauge bosons ($\Gamma/2M \approx 0.01$), and

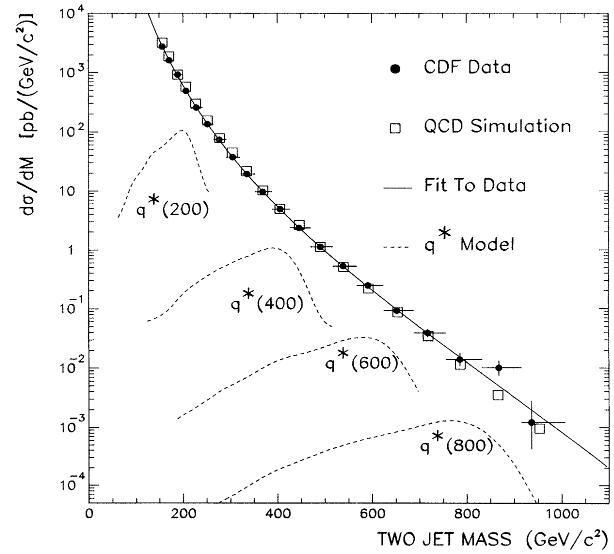

FIG. 1. The dijet mass distribution (circles) compared to a QCD simulation (boxes) and fit to a smooth parametrization (solid curve). Also shown are simulations of excited quark signals in the CDF detector (dashed curves). In the data and simulations we require that both jets have pseudorapidity $|\eta| < 2.0$ and the dijet satisfies $|\cos\theta^*| < 2/3$.

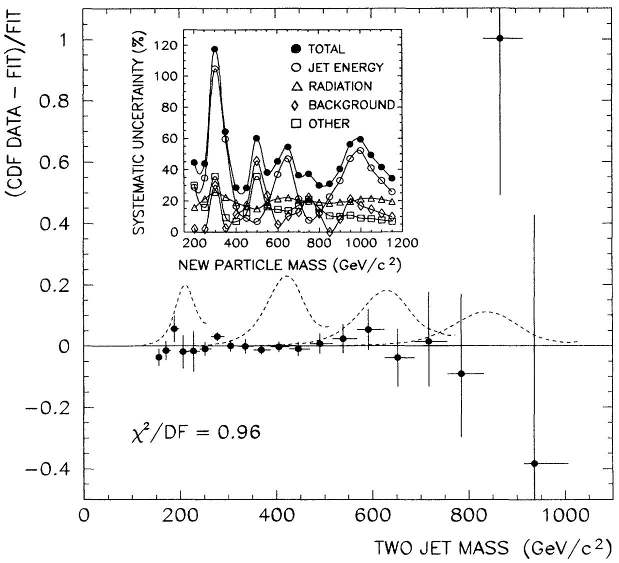

FIG. 2. The fractional difference between the dijet mass distribution (points) and a smooth background fit (solid line) is compared to simulations of excited quark signals in the CDF detector (dashed curves). The inset shows the systematic uncertainty for a new particle signal (see text).

E_6 diquarks ($\Gamma/2M \approx 0.004$ for D and 0.001 for D^c). In Figs. 1 and 2 we show the predicted mass resolution for excited quarks (q^*) using the PYTHIA Monte Carlo program [10] and a CDF detector simulation. The mass resolution has a Gaussian core (rms/$M \sim 0.1$) from jet energy resolution and a long tail toward low mass from QCD radiation. We have used the q^* mass resonance curves in Figs. 1 and 2 to model the shape of all new particles decaying to dijets. As in our previous search for excited quarks [12], we perform a binned maximum likelihood fit of the data to both the background parametrization and the signal hypothesis. The method gave a Poisson likelihood as a function of the signal cross section. This was done independently at 20 different values of new particle mass from 200 to 1150 GeV/c^2, resulting in 20 statistical likelihood distributions.

Systematic uncertainties on the cross section for observing a new particle in the CDF detector are shown in Fig. 2. Each systematic uncertainty on the fitted signal cross section was determined by varying the source of uncertainty by $\pm 1\sigma$ and refitting. In decreasing order of importance the sources of uncertainty are the 5% jet energy scale uncertainty, QCD radiation's effect on the mass resonance line shape, the background parametrization, trigger efficiency, jet energy resolution, jet energy scale of CDF calorimeters relative to the central calorimeter, luminosity, and efficiency. For example, at 300 GeV/c^2 reducing the jet energy by 5% centers the resonance on an upward fluctuation, and increases the fitted signal by over 100%. The total systematic uncertainty was found by adding the above sources in quadrature. We convoluted each of the 20 likelihood distributions with the corresponding total Gaussian systematic uncertainty, and found the 95% confidence level (C.L.) upper limit shown in Fig. 3.

In Fig. 3 and Table I we compare our measured upper limit on the cross section times branching ratio for a new particle decaying to dijets to the theoretical predictions. The predictions are lowest order with one-loop strong coupling $\alpha_s(m^2)$ and CTEQ2L parton distributions [11]. Branching fractions to top quarks are included but do not add to the dijet mass resonance cross section. New particle decay angular distributions are included, and we required $|\eta| < 2$ and $|\cos\theta^*| < 2/3$. We exclude at 95% CL new particles in mass regions for which the theory curve lies above our upper limit. For axigluons [1] we exclude the region $200 < M_A < 870$ GeV/c^2, significantly extending the previous CDF exclusions of $120 < M_A < 210$ GeV/c^2 [13] and $240 < M_A < 640$ GeV/c^2 [14] and the UA1 exclusion of $110 < M_A < 310$ GeV/c^2 [15]. For the first time we exclude a model of technicolor [3] with color octet technirhos in the mass range $320 < M_{\rho_T} < 480$ GeV/c^2. From Fig. 3 we exclude excited quarks in the mass range $200 < M^* < 560$ GeV/c^2 at 95% C.L. This limit from dijets can be improved by combining it with published limits in the γ + jet and the W + jet channel [12] (by multiplying the likelihood distributions). Combining all three channels excludes excited quarks in the mass interval $80 < M^* < 570$ GeV/c^2 for standard model couplings. The excluded regions in the coupling [2] vs mass plane are shown in Fig. 4 compared to previous excluded regions. The cross section for new gauge bosons and E_6 diquarks is too small to be excluded by our data.

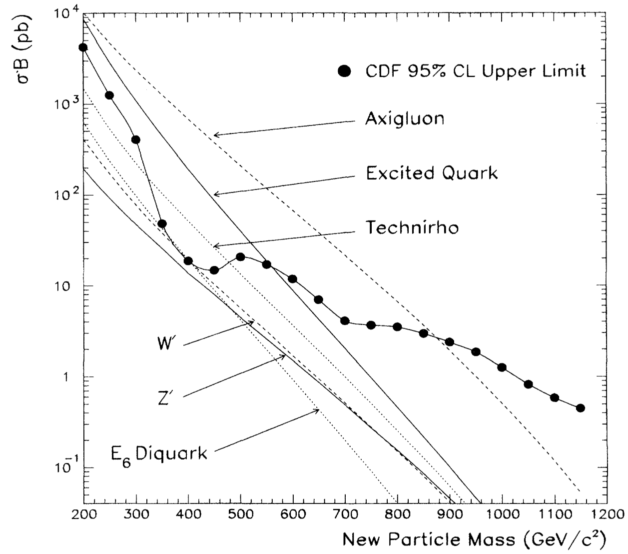

FIG. 3. The upper limit on the cross section times branching ratio for new particles decaying to dijets (points) is compared to theoretical predictions for axigluons [1], excited quarks [2], color octet technirhos [3], new gauge bosons W' and Z' [4,5], and E_6 diquarks [6]. The limit and theory curves require that both jets have pseudorapidity $|\eta| < 2.0$ and the dijet satisfies $|\cos\theta^*| < 2/3$.

TABLE I. As a function of new particle mass we list our 95% C.L. upper limit on cross section times branching ratio and the theoretical prediction for axigluons (A), excited quarks ($q*$), color octet technirhos (ρ_T), new gauge bosons (W' and Z'), and E_6 diquarks ($D + D^c$). The limit and predictions require that both jets have pseudorapidity $|\eta| < 2.0$ and the dijet satisfies $|\cos\theta^*| < 2/3$.

	95% C.L.	Theoretical cross section × branching ratio					
Mass (GeV/c^2)	σB limit (pb)	A (pb)	q^* (pb)	ρ_T (pb)	W' (pb)	Z' (pb)	$D + D^c$ (pb)
200	4.2×10^3	1.0×10^4	8.6×10^3	1.5×10^3	4.1×10^2	1.9×10^2	6.3×10^2
250	1.3×10^3	4.7×10^3	2.9×10^3	5.3×10^2	1.7×10^2	9.2×10^1	2.4×10^2
300	4.0×10^2	2.4×10^3	1.1×10^3	2.2×10^2	7.8×10^1	4.7×10^1	9.8×10^1
350	4.8×10^1	1.3×10^3	4.5×10^2	1.0×10^2	3.8×10^1	2.6×10^1	4.3×10^1
400	1.9×10^1	6.8×10^2	1.9×10^2	5.2×10^1	1.9×10^1	1.4×10^1	1.9×10^1
450	1.5×10^1	3.8×10^2	8.7×10^1	2.7×10^1	1.0×10^1	8.0	8.9
500	2.1×10^1	2.1×10^2	4.0×10^1	1.4×10^1	5.6	4.4	4.2
550	1.7×10^1	1.2×10^2	1.9×10^1	7.3	3.2	2.6	2.0
600	1.2×10^1	6.8×10^1	8.9	3.8	1.7	1.5	9.2×10^{-1}
650	7.0	3.8×10^1	4.2	2.0	9.4×10^{-1}	8.6×10^{-1}	4.3×10^{-1}
700	4.1	2.2×10^1	2.0	1.1	5.1×10^{-1}	4.9×10^{-1}	2.0×10^{-1}
750	3.7	1.2×10^1	9.7×10^{-1}	5.5×10^{-1}	2.8×10^{-1}	2.7×10^{-1}	9.0×10^{-2}
800	3.5	6.7	4.6×10^{-1}	2.8×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	4.0×10^{-2}
850	2.9	3.6	2.2×10^{-1}	1.4×10^{-1}	7.9×10^{-2}	8.5×10^{-2}	1.7×10^{-2}
900	2.4	1.9	1.0×10^{-1}	6.9×10^{-2}	4.1×10^{-2}	4.6×10^{-2}	7.3×10^{-3}
950	1.9	1.0	4.6×10^{-2}	3.3×10^{-2}	2.1×10^{-2}	2.4×10^{-2}	3.0×10^{-3}
1000	1.2	5.1×10^{-1}	2.1×10^{-2}	1.6×10^{-2}	—	—	—
1050	8.1×10^{-1}	2.4×10^{-1}	9.4×10^{-3}	—	—	—	—
1100	5.8×10^{-1}	1.2×10^{-1}	4.2×10^{-3}	—	—	—	—
1150	4.5×10^{-1}	5.2×10^{-2}	1.8×10^{-3}	—	—	—	—

In conclusion, the measured dijet mass spectrum is a smoothly falling distribution within statistics. We see no significant evidence for new particle production and set limits on axigluons, excited quarks, and color octet technirhos.

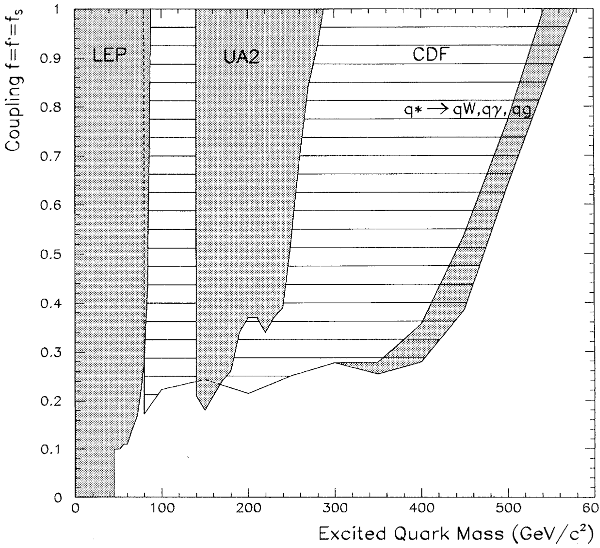

FIG. 4. The region of the coupling vs mass plane excluded by previous CDF measurements [12] in the $q^* \to q\gamma$ and $q^* \to qW$ channels (hatched region) is extended by combining them with this search in the $q^* \to qg$ channel (shaded and hatched region). The CDF excluded regions are compared to the regions excluded by LEP and UA2 (shaded regions) [16].

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