Search for Quark Compositeness, Axigluons, and Heavy Particles Using the Dijet Invariant Mass Spectrum Observed in $p\bar{p}$ Collisions

F. Abe,[13] M. Albrow,[7] H. Akimoto,[30] D. Amidei,[16] C. Anway-Wiese,[4] G. Apollinari,[26] H. Areti,[7] P. Auchincloss,[25] F. Azfar,[21] P. Azzi,[20] N. Bacchetta,[18] W. Badgett,[16] M. W. Bailey,[24] J. Bao,[33] P. de Barbaro,[25] A. Barbaro-Galtieri,[14] V. E. Barnes,[24] B. A. Barnett,[12] G. Bauer,[15] T. Baumann,[9] F. Bedeschi,[23] S. Behrends,[2] S. Belforte,[23] G. Bellettini,[23] J. Bellinger,[32] D. Benjamin,[31] J. Benlloch,[15] D. Benton,[21] A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[26] K. Biery,[11] M. Binkley,[7] F. Bird,[28] D. Bisello,[20] R. E. Blair,[1] C. Blocker,[28] A. Bodek,[25] V. Bolognesi,[23] D. Bortoletto,[24] C. Boswell,[12] T. Boulos,[14] G. Brandenburg,[9] C. Bromberg,[17] E. Buckley-Geer,[7] H. S. Budd,[25] K. Burkett,[16] G. Busetto,[20] A. Byon-Wagner,[7] K. L. Byrum,[1] C. Campagnari,[7] M. Campbell,[16] A. Caner,[7] W. Carithers,[14] D. Carlsmith,[32] A. Castro,[20] Y. Cen,[21] F. Cervelli,[23] J. Chapman,[16] G. Chiarelli,[8] T. Chikamatsu,[30] S. Cihangir,[7] A. G. Clark,[23] M. Cobal,[23] M. Contreras,[5] J. Conway,[27] J. Cooper,[7] M. Cordelli,[8] D. P. Coupal,[28] D. Crane,[7] J. D. Cunningham,[2] T. Daniels,[15] M. Deninno,[3] F. DeJongh,[7] S. Dell'Agnello,[23] M. Dell'Orso,[23] L. Demortier,[26] B. Denby,[7] P. F. Derwent,[16] T. Devlin,[27] M. Dickson,[25] J. P. Done,[29] R. B. Drucker,[14] A. Dunn,[16] K. Einsweiler,[14] J. E. Elias,[7] E. Engels, Jr.,[22] R. Ely,[14] S. Eno,[5] D. Errede,[10] S. Errede,[10] A. Etchegoyen,[7,*] Q. Fan,[25] B. Farhat,[15] I. Fiori,[3] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[9] M. Frautschi,[18] J. Freeman,[7] J. Freidman,[15] H. Frisch,[5] A. Fry,[28] T. A. Fuess,[28] Y. Fukui,[13] S. Funaki,[30] A. F. Garfinkel,[24] S. Geer,[7] D. W. Gerdes,[16] P. Giannetti,[23] N. Giokaris,[26] P. Giromini,[8] L. Gladney,[21] D. Glenzinski,[12] M. Gold,[18] J. Gonzalez,[21] A. T. Goshaw,[6] K. Goulianos,[26] H. Grassmann,[28] A. Grewal,[21] G. Grieco,[23] L. Groer,[27] C. Grosso-Pilcher,[5] C. Haber,[14] S. R. Hahn,[7] R. Hamilton,[9] R. Handler,[32] R. M. Hans,[33] K. Hara,[30] B. Harral,[21] R. M. Harris,[7] S. A. Hauger,[6] J. Hauser,[4] C. Hawk,[27] J. Heinrich,[21] D. Hennessy,[6] R. Hipple,[17] R. Hollebeek,[21] A. Hölscher,[11] S. Hong,[16] G. Houk,[21] P. Hu,[22] J. Huston,[17] B. T. Huffman,[22] R. Hughes,[25] P. Hurst,[9] J. Huth,[7] J. Hylen,[7] M. Incagli,[23] J. Incandela,[7] H. Iso,[30] H. Jensen,[7] C. P. Jessop,[9] U. Joshi,[7] R. W. Kadel,[14] T. Kamon,[29] T. Kaneko,[30] D. A. Kardelis,[10] H. Kasha,[33] Y. Kato,[19] L. Keeble,[29] R. Kennedy,[27] R. Kephart,[7] P. Kesten,[14] R. M. Keup,[10] H. Keutelian,[7] F. Keyvan,[4] D. H. Kim,[7] H. Kim,[11] S. B. Kim,[16] S. H. Kim,[30] Y. K. Kim,[14] L. Kirsch,[2] P. Koehn,[25] K. Kondo,[30] J. Konigsberg,[9] S. Kopp,[5] K. Kordas,[11] W. Koska,[7] E. Kovacs,[7,*] M. Krasberg,[16] S. E. Kuhlmann,[1] E. Kuns,[27] A. T. Laasanen,[24] S. Lammel,[4] J. I. Lamoureux,[32] T. LeCompte,[10] S. Leone,[23] J. D. Lewis,[7] P. Limon,[7] M. Lindgren,[4] T. M. Liss,[10] N. Lockyer,[21] O. Long,[21] M. Loreti,[20] E. H. Low,[21] J. Lu,[29] D. Lucchesi,[23] C. B. Luchini,[10] P. Lukens,[7] P. Maas,[32] K. Maeshima,[7] A. Maghakian,[26] P. Maksimovic,[15] M. Mangano,[23] J. Mansour,[17] M. Mariotti,[23] J. P. Marriner,[7] A. Martin,[10] J. A. J. Matthews,[18] R. Mattingly,[2] P. McIntyre,[29] P. Melese,[26] A. Menzione,[23] E. Meschi,[23] S. Mikamo,[13] M. Miller,[5] R. Miller,[17] T. Mimashi,[30] S. Miscetti,[8] M. Mishina,[13] H. Mitsushio,[30] S. Miyashita,[30] Y. Morita,[13] S. Moulding,[26] J. Mueller,[27] A. Mukherjee,[7] T. Muller,[4] L. F. Nakae,[28] I. Nakano,[30] C. Nelson,[7] D. Neuberger,[4] C. Newman-Holmes,[7] L. Nodulman,[1] S. Ogawa,[30] K. E. Ohl,[33] R. Oishi,[30] T. Okusawa,[19] R. Paoletti,[23] V. Papadimitriou,[7] S. Park,[7] J. Patrick,[7] G. Pauletta,[23] L. Pescara,[20] M. D. Peters,[14] T. J. Phillips,[6] G. Piacentino,[3] M. Pillai,[25] R. Plunkett,[7] L. Pondrom,[32] J. Proudfoot,[1] N. Produit,[14] F. Ptohos,[9] G. Punzi,[23] K. Ragan,[11] F. Rimondi,[3] L. Ristori,[23] M. Roach-Bellino,[31] W. J. Robertson,[6] T. Rodrigo,[7] J. Romano,[5] L. Rosenson,[15] W. K. Sakumoto,[25] D. Saltzberg,[5] A. Sansoni,[8] V. Scarpine,[29] A. Schindler,[14] P. Schlabach,[9] E. E. Schmidt,[7] M. P. Schmidt,[33] O. Schneider,[14] G. Sciacca,[23] A. Scribano,[23] S. Segler,[7] S. Seidel,[18] Y. Seiya,[30] G. Sganos,[11] M. Shapiro,[14] N. M. Shaw,[24] Q. Shen,[24] P. F. Shepard,[22] M. Shimojima,[30] M. Shochet,[5] J. Siegrist,[28] A. Sill,[7,*] P. Singh,[22] P. Sinervo,[11] J. Skarha,[12] K. Sliwa,[31] D. A. Smith,[23] F. D. Snider,[12] L. Song,[7] T. Song,[16] J. Spalding,[7] P. Sphicas,[15] A. Spies,[12] L. Stanco,[20] J. Steele,[32] S. Stefanini,[23] K. Strahl,[11] G. Sullivan,[5] K. Sumorok,[15] R. L. Swartz, Jr.,[10] T. Takahashi,[19] K. Takikawa,[30] F. Tartarelli,[23] Y. Teramoto,[19] S. Tether,[15] D. Theriot,[7] J. Thomas,[28] R. Thun,[16] M. Timko,[31] P. Tipton,[25] A. Titov,[26] S. Tkaczyk,[7] A. Tollestrup,[7] J. Tonnison,[24] J. Tseng,[12] M. Turcotte,[28] N. Turini,[3] F. Ukegawa,[21] G. Unal,[21] N. Uemura,[30] S. Vejcik III,[16] R. Vidal,[7] M. Vondracek,[10] R. G. Wagner,[1] R. L. Wagner,[7] N. Wainer,[7] R. C. Walker,[25] J. Wang,[5] Q. Wang,[26] A. Warburton,[11] G. Watts,[25] T. Watts,[27] R. Webb,[29] C. Wendt,[32] H. Wenzel,[7,*] W. C. Wester III,[14] T. Westhusing,[10] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[21] H. H. Williams,[21] B. L. Winer,[25] J. Wolinski,[29] D. Y. Wu,[16] X. Wu,[23] J. Wyss,[20] A. Yagil,[7] W. Yao,[14] K. Yasuoka,[30] Y. Ye,[11] G. P. Yeh,[7] M. Yin,[6] J. Yoh,[7] T.

0031-9007/93/71(16)/2542(5)$06.00

© 1993 The American Physical Society

Yoshida,[19] D. Yovanovitch,[7] I. Yu,[33] J. C. Yun,[7] A. Zanetti,[23] F. Zetti,[23] L. Zhang,[32] S. Zhang,[15]
W. Zhang,[21] and S. Zucchelli[3]

(CDF Collaboration)

[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*Brandeis University, Waltham, Massachusetts 02254*
[3]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40126 Bologna, Italy*
[4]*University of California at Los Angeles, Los Angeles, California 90024*
[5]*University of Chicago, Chicago, Illinois 60637*
[6]*Duke University, Durham, North Carolina 27708*
[7]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[8]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[9]*Harvard University, Cambridge, Massachusetts 02138*
[10]*University of Illinois, Urbana, Illinois 61801*
[11]*Institute of Particle Physics, McGill University, Montreal H3A 2T8*
and University of Toronto, Toronto M5S 1A7, Canada
[12]*The Johns Hopkins University, Baltimore, Maryland 21218*
[13]*National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan*
[14]*Lawrence Berkeley Laboratory, Berkeley, California 94720*
[15]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[16]*University of Michigan, Ann Arbor, Michigan 48109*
[17]*Michigan State University, East Lansing, Michigan 48824*
[18]*University of New Mexico, Albuquerque, New Mexico 87131*
[19]*Osaka City University, Osaka 588, Japan*
[20]*Università di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*
[21]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[22]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[23]*Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[24]*Purdue University, West Lafayette, Indiana 47907*
[25]*University of Rochester, Rochester, New York 14627*
[26]*Rockefeller University, New York, New York 10021*
[27]*Rutgers University, Piscataway, New Jersey 08854*
[28]*Superconducting Super Collider Laboratory, Dallas, Texas 75237*
[29]*Texas A&M University, College Station, Texas 77843*
[30]*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[31]*Tufts University, Medford, Massachusetts 02155*
[32]*University of Wisconsin, Madison, Wisconsin 53706*
[33]*Yale University, New Haven, Connecticut 06511*

(Received 18 June 1993)

The dijet invariant mass distribution has been measured in the region between 140 and 1000 GeV/c^2, in 1.8 TeV $p\bar{p}$ collisions. Data collected with the Collider Detector at Fermilab show agreement with QCD calculations. A limit on quark compositeness of $\Lambda_c > 1.3$ TeV is obtained. Axigluons with masses between 240 and 640 GeV/c^2 are excluded at 95% C.L. if we assume ten open decay channels. Model-independent limits on the production of heavy particles decaying into two jets are also presented.

PACS numbers: 13.85.Rm, 12.38.Qk, 13.85.Ni, 13.87.Ce

We present limits on new physics from fits to the measured dijet invariant mass spectrum in proton-antiproton collisions at a center of mass energy $\sqrt{s} = 1.8$ TeV. The data are based on an integrated luminosity of 4.2 pb^{-1} recorded by the Collider Detector at Fermilab (CDF) [1] during the 1988-1989 run at the Fermilab Tevatron Collider. Previous studies reported by UA1 [2] and UA2 [3] at $\sqrt{s} = 630$ GeV and by CDF [4] at $\sqrt{s} = 1.8$ TeV showed agreement with leading order (LO) QCD calculations. Higher statistics CDF data allow for more precise tests of QCD and of some theoretical hypotheses beyond the standard model. In particular, the dijet mass spectrum is sensitive to quark compositeness [5] and to the existence of new particles that decay into two jets, such as axigluons [6]. We report in this article a summary of a study of the dijet mass spectrum. Further details can be found in Ref. [7].

The data are based on information from the CDF central calorimeter ($|\eta| \leq 1.1$) [8], composed of projective towers of scintillator-absorber sandwich construction, segmented in $\Delta\eta \times \Delta\phi = 0.1 \times 15°$. Jets were reconstructed using a fixed-cone clustering algorithm [9] with cone radius $R=\sqrt{\Delta\eta^2+\Delta\phi^2}$, where $\eta=-\ln[\tan(\theta/2)]$ is the pseudorapidity, ϕ is the azimuth (in radians), and θ is the polar angle with respect to the proton beam direction. The jet energy is defined as the scalar sum of the energies of all calorimeter towers associated with the cluster. The jet momentum is calculated by assuming that the energy in each tower of the cluster is released by a massless particle hitting the center of that tower. Results presented in this paper are based upon a cone radius $R=1$. Cross section predictions including coherent sums of QCD matrix elements and either compositeness or axigluon contributions are presently available only to LO. The choice of a large cone reduces the sensitivity of the measured dijet mass spectrum to higher order effects such as gluon radiation.

Three single-jet on-line triggers were employed requiring at least one cluster of transverse energy $E_T=E\sin\theta$ greater than thresholds of 20, 40, or 60 GeV. The measured energy and momentum of each jet were corrected, on average, for detector effects. The average correction is 22% for the dijet mass $M_{jj}=140$ GeV/c^2 and 17% for $M_{jj}>600$ GeV/c^2. These corrections are based on a Monte Carlo study with a full detector simulation. The true jet energy and momentum are defined as the total energy and momentum of all the particles emerging from the primary vertex within a cone of fixed radius R around the cluster centroid. No corrections are applied to account for energy lost out of the clustering cone or to account for the soft component of the $p\bar{p}$ interaction (underlying event). Since these corrections are model dependent they have not been applied to the measurement, but they are taken into account when smearing the LO theoretical predictions.

Events are selected requiring (a) the event vertex along the beam line to be within 60 cm of the center of the detector and (b) the axes of the two leading jets (i.e., those with the highest transverse energies) to be in the pseudorapidity range $|\eta|<0.7$. This ensures that the jet core is well contained in the central calorimeter.

We define $M_{jj}^{\text{obs}}=\sqrt{(E_1+E_2)^2-(p_1+p_2)^2}$ as the measured mass of the system composed of the two leading jets. Any remaining jets, produced largely by radiation from the initial and final states of the hard parton process, are not taken into account in the computation of M_{jj}^{obs}. The data from the three different on-line triggers were combined. The observed differential cross section $d\sigma/dM_{jj}^{\text{obs}}$, integrated over the pseudorapidity interval $|\eta|<0.7$ and averaged over the mass bins, is shown in Fig. 1. The vertical error bars on the data points represent the statistical errors and the M_{jj}^{obs}-dependent part of the systematic uncertainties combined in quadrature.

The major sources of systematic uncertainty on the differential cross section measurement are determination of the integrated luminosity, calorimeter calibration, and our model of parton fragmentation into jets. The uncertainty in the integrated luminosity is 7% [10]. Fragmentation was studied by comparing different versions of the shower Monte Carlo HERWIG [11] fragmentation scheme. The uncertainty in the calorimeter response to hadrons arises from several sources, the biggest effect coming from low energy particles [7]. The sum in quadrature of all the contributions ranges from 33% at $M_{jj}^{\text{obs}}=140$ GeV/c^2 to 60% at 1000 GeV/c^2. Theoretical uncertainties in the LO QCD predictions arise from parton shower products falling outside of the clustering cone, the underlying event, and the presence of additional jets from higher order processes. The sum in quadrature of these theoretical uncertainties is 14% for $M_{jj}^{\text{obs}}>500$ GeV/c^2 and 36% at $M_{jj}^{\text{obs}}=140$ GeV/c^2.

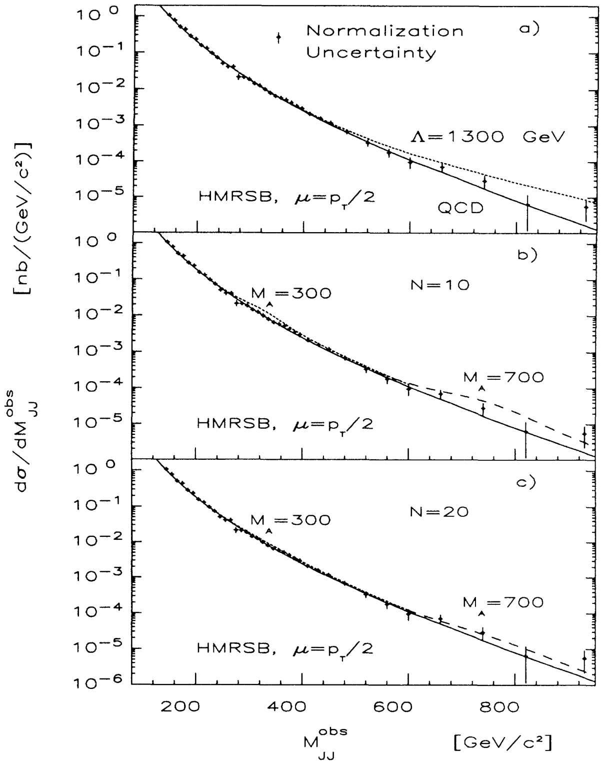

FIG. 1. Observed dijet mass spectrum (cone size $R=1$), integrated over the pseudorapidity interval $|\eta|<0.7$. The error bars on the data are statistical and M_{jj}-dependent systematic uncertainties combined in quadrature. An overall normalization uncertainty is shown in (a). All the theoretical curves (structure function HMRS-B, renormalization scale $\mu=p_T/2$) are smeared and normalized to the data. The lines in (a) are the LO QCD prediction with (dotted line) and without (solid line) the contact term representing quark substructure at the scale $\Lambda_c=1.3$ TeV. The M_{jj}^{obs} spectrum is compared to that expected from axigluons of different masses for $N=10$ (b) and $N=20$ (c), N being the number of open decay channels. The 300 GeV/c^2 axigluon (dotted line) is excluded by the data, while the 700 GeV/c^2 axigluon (dashed line) is not excluded, both at 95% C.L. The QCD prediction (solid line) is also shown.

The M_{jj}^{obs} spectrum differs from the true spectrum because of the finite M_{jj} resolution, which smears the distribution. We define the smearing function, $g(t,M_{jj})$, as the probability density function of making a measurement error $t=M_{jj}^{\text{obs}}-M_{jj}$, thereby observing a mass M_{jj}^{obs} for a given true mass M_{jj}. The function $g(t,M_{jj})$ and its uncertainties are determined with the Monte Carlo program HERWIG and the full detector simulation [7]. Theoretical models ae checked by folding the predicted cross sections with appropriate smearing functions before comparing them to the observed M_{jj}^{obs} spectrum.

New phenomena such as quark compositeness, or new particles decaying to two jets, or axigluons, would all produce in a particular dijet mass region a different number of events from that expected by QCD. We place 95% confidence level (C.L.) limits on the number of events that can be associated with these phenomena given our observed rate and QCD background predictions. In all cases, we convolute the predicted rate with both Poisson statistical fluctuations and non-Gaussian resolution functions with their correlated bin-to-bin uncertainties. For each theoretical spectrum the statistical test is optimized for sensitivity in the specific signal region.

We place limits on quark compositeness by including in the theoretical prediction an effective contact term in the QCD Lagrangian [5] characterized by an energy scale Λ_c. If quarks are composite structures, an excess of events at high masses should be observed. The 95% C.L. limit is inferred by comparing the number of events observed by CDF in the region $M_{jj}^{\text{obs}}>580$ GeV/c^2 with the number of events expected by QCD. The QCD prediction is smeared and normalized to the data in the region $160<M_{jj}^{\text{obs}}<300$ GeV/c^2. The statistical test has been performed with recent sets of structure functions (HMRS [12] and MT [13]) and the renormalization scales $\mu=2p_T,p_T,p_T/2$. The results are shown in Table I. The most conservative limit on Λ_c is 1.3 TeV, set by HMRS-B, $\mu=p_T/2$. Previous limits obtained with the same data are $\Lambda_c>1.4$ TeV from the inclusive jet cross section [14], and $\Lambda_c>1.0$ TeV from the dijet angular distribution [15]. The LO QCD predictions with and without the contact term representing quark substructure at the scale $\Lambda_c=1.3$ TeV (HMRS-B, $\mu=p_T/2$) are compared to the data in Fig. 1(a).

In order to set model-independent limits on the production of particles that decay into two jets, we parametrize a resonance as a Breit-Wigner line shape $f(M_{jj})=S\Gamma/2\pi[(M_{jj}-M_0)^2+(\Gamma/2)^2]$, where M_0 and Γ are the central value and the width of the resonance and S is the cross section (in pb) for the decay products within our acceptance ($|\eta|<0.7$). The resonance width is assumed to be proportional to the mass: $\Gamma=kM_0$, with $k=0.02$, 0.1, 0.2. The following simplifications have been applied: (a) the resonance is incoherently added to the QCD background, (b) the Breit-Wigner function, which in principle describes only the parton cross section, is not folded with the structure functions, and (c) no spin effect is taken into account. The Breit-Wigner resonance is folded with a smearing function $g'(t,M_{jj})$. The smearing function g' for resonances differs from the one used for QCD [7]. It not only takes into account detector effects, but also includes radiation from the scattered partons, which influences both the average measured mass and the mass resolution. These radiation effects have been studied with the shower Monte Carlo program HERWIG [11], whose capability to reproduce "multijet" events has been checked with the data [16]. Since phase space effects are not negligible for decays into the massive top quark and the smearing function depends strongly on the unknown top mass, we set limits on resonant cross sections times the branching ratio into light quarks (u,d,s,c,b). We obtain the limit on S, as a function of M_0 and Γ, by comparing the number of events observed by CDF in a window around the mass of the resonance with the number of events expected by QCD (MT-B2, $\mu=p_T/2$) in the same M_{jj}^{obs} region. The limits on the observable cross section times the branching ratio into light quarks for different resonance masses and widths are listed in Table II. CDF data exclude the region above the listed cross sections at the 95% C.L.

TABLE I. Compositeness limits at 95% C.L. for recent structure functions and different renormalization scales.

		Λ (GeV)	
μ/p_T	0.5	1	2
HMRS-B	1300	1330	1360
HMRS-E	1480	1500	1520
MT-E1	1390	1440	1490
MT-B2	1490	1540	1580
MT-B1	1360	1410	1460
MT-S1	1340	1400	1460

TABLE II. 95% C.L. Limits on observable cross sections (pb) times the resonance branching ratio into light quarks as a function of the resonance mass M_0 (GeV/c^2) and width Γ (GeV/c^2).

M_0	$\Gamma=0.02M_0$	$\Gamma=0.1M_0$	$\Gamma=0.2M_0$
200	2603	3073	3628
250	779	960	1408
300	79	241	214
350	106	214	192
400	44	60	48
450	36	41	19
500	9	7	13
550	3	4	11
600	7	10	13
650	10	13	13
700	9	9	11
750	6	6	7
800	4	5	5
850	5	4	5
900	2	5	7

Recently proposed chiral-color models [6] predict the

TABLE III. Axigluon masses (GeV/c^2) excluded by CDF data using the two structure functions HMRS-B and MT-B2; N is the number of open decay channels.

	$N=10$	$N=20$
MT-B2	$240 \leq M_a \leq 730$	$260 \leq M_a \leq 280$;$420 \leq M_a \leq 580$
HMRS-B	$220 \leq M_a \leq 640$	$240 \leq M_a \leq 330$;$450 \leq M_a \leq 550$

existence of a massive octet of vector bosons, the axigluons. The dominant decay mode of the axigluon is into a pair of quarks and its width can be parametrized as $\Gamma_a = N\alpha_s M_a/6$, where N is the number of open decay channels and M_a is the axigluon mass. Limits on axigluon masses have been previously reported by UA1 [2,17] and CDF [4]. The same method described for resonances parametrized with a Breit-Wigner line shape has been applied. However, in this case, the axigluon amplitudes are coherently summed to QCD and convoluted with the structure functions. The acceptance for the decay products of the axigluons and the branching ratio into top are also taken into account. The statistical test has been performed with the two structure functions HMRS-B and MT-B2 and the renormalization scale $\mu = p_T/2$. Table III shows the results. With a luminosity of 4.2 pb^{-1}, axigluons of masses $240 \leq M_a \leq 640$ GeV/c^2 are excluded for $N=10$, while for $N=20$ we exclude the windows $260 \leq M_a \leq 280$ GeV/c^2 and $450 \leq M_a \leq 550$ GeV/c^2. As examples, Fig. 1 shows QCD and axigluons (HMRS-B, $\mu = p_T/2$) of different masses for $N=10$ (b) and $N=20$ (c). In both cases the lower axigluon mass is excluded, while the higher mass cannot be excluded at 95% C.L. The range of excluded masses breaks in two windows for $N=20$ because a small excess of events is observed in the data between 350 and 400 GeV/c^2. However QCD alone is consistent with the measurement in that region.

We thank the Fermilab Accelerator Division, the Computer Division, and the CDF technical staff for their dedicated effort that made this experiment possible. This work was supported by the Department of Energy, the National Science Foundation, the Natural Sciences and Engineering Research Council of Canada, the Italian Istituto Nazionale di Fisica Nucleare, the Ministry of Science, Culture and Education of Japan, and the A.P. Sloan Foundation.

---

*Visitor.

[1] CDF Collaboration, F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988).

[2] UA1 Collaboration, C. Albajar *et al.*, Phys. Lett. B **209**, 127 (1988).

[3] UA2 Collaboration, J. Alitti *et al.*, Z. Phys. C **49**, 17 (1991).

[4] F. Abe *et al.*, Phys. Rev. D **41**, 1722 (1990).

[5] E. Eichten *et al.*, Rev. Mod. Phys. **56**, 579 (1984).

[6] P. Frampton and S. Glashow, Phys. Lett. B **190**, 157 (1987).

[7] F. Abe *et al.*, Phys. Rev. D **48**, 998 (1993).

[8] L. Balka *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **267**, 272 (1988); S. Bertolucci *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **267**, 301 (1988).

[9] F. Abe *et al.*, Phys. Rev. D **45**, 1448 (1992).

[10] F. Abe *et al.*, Phys. Rev. D **44**, 29 (1991).

[11] G. Marchesini and B. Webber, Nucl. Phys. **B310**, 461 (1988).

[12] P. Harriman, A. D. Martin, W. J. Stirling, and R. G. Roberts, Phys. Rev. D **42**, 798 (1990).

[13] J. Morfin and W. Tung, Z. Phys. C **52**, 13 (1991).

[14] F. Abe *et al.*, Phys. Rev. Lett. **68**, 1104 (1992).

[15] F. Abe *et al.*, Phys. Rev. Lett. **69**, 2896 (1992).

[16] F. Abe *et al.*, Phys. Rev. D **45**, 2249 (1992); Emilio Meschi, Laurea thesis, University of Pisa, 1991.

[17] J. Bagger, C. Schmidt, and S. King, Phys. Rev. D **37**, 1188 (1988).