



**Fermi National Accelerator Laboratory**

**FERMILAB-Pub-93/151-E**  
**CDF**

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

F. Abe et al  
The CDF Collaboration

*Fermi National Accelerator Laboratory  
P.O. Box 500, Batavia, Illinois 60510*

June 1993

Submitted to *Physical Review Letters*

## **Disclaimer**

*This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.*

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

F. Abe,<sup>(13)</sup> M. Albrow,<sup>(7)</sup> H. Akimoto,<sup>(30)</sup> D. Amidei,<sup>(16)</sup> S. R. Amendolia,<sup>(23)</sup>  
C. Anway-Wiese,<sup>(4)</sup> G. Apollinari,<sup>(26)</sup> H. Areti,<sup>(7)</sup> P. Auchincloss,<sup>(25)</sup> F. Azfar,<sup>(21)</sup>  
P. Azzi,<sup>(20)</sup> N. Bacchetta,<sup>(18)</sup> W. Badgett,<sup>(16)</sup> M. W. Bailey,<sup>(24)</sup> J. Bao,<sup>(33)</sup> P. de  
Barbaro,<sup>(25)</sup> A. Barbaro-Galtieri,<sup>(14)</sup> V. E. Barnes,<sup>(24)</sup> B. A. Barnett,<sup>(12)</sup> G. Bauer,<sup>(15)</sup>  
T. Baumann,<sup>(9)</sup> F. Bedeschi,<sup>(23)</sup> S. Behrends,<sup>(2)</sup> S. Belforte,<sup>(23)</sup> G. Bellettini,<sup>(23)</sup>  
J. Bellinger,<sup>(32)</sup> D. Benjamin,<sup>(31)</sup> J. Benlloch,<sup>(15)</sup> D. Benton,<sup>(21)</sup> A. Beretvas,<sup>(7)</sup>  
J. P. Berge,<sup>(7)</sup> S. Bertolucci,<sup>(8)</sup> A. Bhatti,<sup>(26)</sup> K. Biery,<sup>(11)</sup> M. Binkley,<sup>(7)</sup> F.  
Bird,<sup>(28)</sup> D. Bisello,<sup>(20)</sup> R. E. Blair,<sup>(1)</sup> C. Blocker,<sup>(28)</sup> A. Bodek,<sup>(25)</sup> V. Bolognesi,<sup>(23)</sup>  
D. Bortoletto,<sup>(24)</sup> C. Boswell,<sup>(12)</sup> T. Boulos,<sup>(14)</sup> G. Brandenburg,<sup>(9)</sup> C. Bromberg,<sup>(17)</sup>  
E. Buckley-Geer,<sup>(7)</sup> H. S. Budd,<sup>(25)</sup> K. Burkett,<sup>(16)</sup> G. Busetto,<sup>(20)</sup> A. Byon-Wagner,<sup>(7)</sup>  
K. L. Byrum,<sup>(1)</sup> C. Campagnari,<sup>(7)</sup> M. Campbell,<sup>(16)</sup> A. Caner,<sup>(7)</sup> W. Carithers,<sup>(14)</sup>  
D. Carlsmith,<sup>(32)</sup> A. Castro,<sup>(20)</sup> Y. Cen,<sup>(21)</sup> F. Cervelli,<sup>(23)</sup> J. Chapman,<sup>(16)</sup>  
G. Chiarelli,<sup>(8)</sup> T. Chikamatsu,<sup>(30)</sup> S. Cihangir,<sup>(7)</sup> A. G. Clark,<sup>(23)</sup> M. Cobal,<sup>(23)</sup>  
M. Contreras,<sup>(5)</sup> J. Conway,<sup>(27)</sup> J. Cooper,<sup>(7)</sup> M. Cordelli,<sup>(8)</sup> D. P. Coupal,<sup>(28)</sup>  
D. Crane,<sup>(7)</sup> J. D. Cunningham,<sup>(2)</sup> T. Daniels,<sup>(15)</sup> M. Deninno,<sup>(3)</sup> F. DeJongh,<sup>(7)</sup>  
S. Dell'Agnello,<sup>(23)</sup> M. Dell'Orso,<sup>(23)</sup> L. Demortier,<sup>(26)</sup> B. Denby,<sup>(7)</sup> P. F. Derwent,<sup>(16)</sup>  
T. Devlin,<sup>(27)</sup> M. Dickson,<sup>(25)</sup> J. P. Done,<sup>(29)</sup> R. B. Drucker,<sup>(14)</sup> A. Dunn,<sup>(16)</sup>  
K. Einsweiler,<sup>(14)</sup> J. E. Elias,<sup>(7)</sup> E. Engels, Jr.,<sup>(22)</sup> R. Ely,<sup>(14)</sup> S. Eno,<sup>(5)</sup> D. Errede,<sup>(10)</sup>  
S. Errede,<sup>(10)</sup> A. Etchegoyen,<sup>(7a)</sup> Q. Fan,<sup>(25)</sup> B. Farhat,<sup>(15)</sup> I. Fiori,<sup>(3)</sup> B. Flaughner,<sup>(7)</sup>

Submitted to Physical Review Letters June 17, 1993.

G. W. Foster,<sup>(7)</sup> M. Franklin,<sup>(9)</sup> M. Frautschi,<sup>(18)</sup> J. Freeman,<sup>(7)</sup> J. Friedman,<sup>(15)</sup>  
 H. Frisch,<sup>(5)</sup> A. Fry,<sup>(28)</sup> T. A. Fuess,<sup>(28)</sup> Y. Fukui,<sup>(13)</sup> S. Funaki,<sup>(30)</sup> A. F. Garfinkel,<sup>(24)</sup>  
 S. Geer,<sup>(7)</sup> D. W. Gerdes,<sup>(16)</sup> P. Giannetti,<sup>(23)</sup> N. Giokaris,<sup>(26)</sup> P. Giromini,<sup>(8)</sup>  
 L. Gladney,<sup>(21)</sup> D. Glenzinski,<sup>(12)</sup> M. Gold,<sup>(18)</sup> J. Gonzalez,<sup>(21)</sup> A. T. Goshaw,<sup>(6)</sup>  
 K. Goulianos,<sup>(26)</sup> H. Grassmann,<sup>(28)</sup> A. Grewal,<sup>(21)</sup> G. Grieco,<sup>(23)</sup> L. Groer,<sup>(27)</sup>  
 C. Grosso-Pilcher,<sup>(5)</sup> C. Haber,<sup>(14)</sup> S. R. Hahn,<sup>(7)</sup> R. Hamilton,<sup>(9)</sup> R. Handler,<sup>(32)</sup>  
 R. M. Hans,<sup>(33)</sup> K. Hara,<sup>(30)</sup> B. Harral,<sup>(21)</sup> R. M. Harris,<sup>(7)</sup> S. A. Hauger,<sup>(6)</sup> J. Hauser,<sup>(4)</sup>  
 C. Hawk,<sup>(27)</sup> J. Heinrich,<sup>(21)</sup> D. Hennessy,<sup>(6)</sup> R. Hipple,<sup>(17)</sup> R. Hollebeek,<sup>(21)</sup>  
 A. Hölscher,<sup>(11)</sup> S. Hong,<sup>(16)</sup> G. Houk,<sup>(21)</sup> P. Hu,<sup>(22)</sup> J. Huston,<sup>(17)</sup> B. T. Huffman,<sup>(22)</sup>  
 R. Hughes,<sup>(25)</sup> P. Hurst,<sup>(9)</sup> J. Huth,<sup>(7)</sup> J. Hylen,<sup>(7)</sup> M. Incagli,<sup>(23)</sup> J. Incandela,<sup>(7)</sup>  
 H. Iso,<sup>(30)</sup> H. Jensen,<sup>(7)</sup> C. P. Jessop,<sup>(9)</sup> U. Joshi,<sup>(7)</sup> R. W. Kadel,<sup>(14)</sup> T. Kamon,<sup>(29)</sup>  
 T. Kaneko,<sup>(30)</sup> D. A. Kardelis,<sup>(10)</sup> H. Kasha,<sup>(33)</sup> Y. Kato,<sup>(19)</sup> L. Keeble,<sup>(29)</sup>  
 R. Kennedy,<sup>(27)</sup> R. Kephart,<sup>(7)</sup> P. Kesten,<sup>(14)</sup> R. M. Keup,<sup>(10)</sup> H. Keutelian,<sup>(7)</sup>  
 F. Keyvan,<sup>(4)</sup> D. H. Kim,<sup>(7)</sup> H. Kim,<sup>(11)</sup> S. B. Kim,<sup>(16)</sup> S. H. Kim,<sup>(30)</sup> Y. K. Kim,<sup>(14)</sup>  
 L. Kirsch,<sup>(2)</sup> P. Koehn,<sup>(25)</sup> K. Kondo,<sup>(30)</sup> J. Konigsberg,<sup>(9)</sup> S. Kopp,<sup>(5)</sup> K. Kordas,<sup>(11)</sup>  
 W. Koska,<sup>(7)</sup> E. Kovacs,<sup>(7a)</sup> M. Krasberg,<sup>(16)</sup> S. E. Kuhlmann,<sup>(1)</sup> E. Kuns,<sup>(27)</sup>  
 A. T. Laasanen,<sup>(24)</sup> S. Lammel,<sup>(4)</sup> J. I. Lamoureux,<sup>(32)</sup> T. LeCompte,<sup>(10)</sup> S. Leone,<sup>(23)</sup>  
 J. D. Lewis,<sup>(7)</sup> P. Limon,<sup>(7)</sup> M. Lindgren,<sup>(4)</sup> T. M. Liss,<sup>(10)</sup> N. Lockyer,<sup>(21)</sup>  
 O. Long,<sup>(21)</sup> M. Loreti,<sup>(20)</sup> E. H. Low,<sup>(21)</sup> J. Lu,<sup>(29)</sup> D. Lucchesi,<sup>(23)</sup> C. B. Luchini,<sup>(10)</sup>  
 P. Lukens,<sup>(7)</sup> P. Maas,<sup>(32)</sup> K. Maeshima,<sup>(7)</sup> A. Maghakian,<sup>(26)</sup> P. Maksimovic,<sup>(15)</sup>  
 M. Mangano,<sup>(23)</sup> J. Mansour,<sup>(17)</sup> M. Mariotti,<sup>(23)</sup> J. P. Marriner,<sup>(7)</sup> A. Martin,<sup>(10)</sup>  
 J. A. J. Matthews,<sup>(18)</sup> R. Mattingly,<sup>(2)</sup> P. McIntyre,<sup>(29)</sup> P. Melese,<sup>(26)</sup> A. Menzione,<sup>(23)</sup>  
 E. Meschi,<sup>(23)</sup> S. Mikamo,<sup>(13)</sup> M. Miller,<sup>(5)</sup> R. Miller,<sup>(17)</sup> T. Mimashi,<sup>(30)</sup> S. Miscetti,<sup>(8)</sup>  
 M. Mishina,<sup>(13)</sup> H. Mitsushio,<sup>(30)</sup> S. Miyashita,<sup>(30)</sup> Y. Morita,<sup>(13)</sup> S. Moulding,<sup>(26)</sup>

J. Mueller,<sup>(27)</sup> A. Mukherjee,<sup>(7)</sup> T. Muller,<sup>(4)</sup> L. F. Nakae,<sup>(28)</sup> I. Nakano,<sup>(30)</sup>  
C. Nelson,<sup>(7)</sup> D. Neuberger,<sup>(4)</sup> C. Newman-Holmes,<sup>(7)</sup> L. Nodulman,<sup>(1)</sup> S. Ogawa,<sup>(30)</sup>  
K. E. Ohl,<sup>(33)</sup> R. Oishi,<sup>(30)</sup> T. Okusawa,<sup>(19)</sup> R. Paoletti,<sup>(23)</sup> V. Papadimitriou,<sup>(7)</sup>  
S. Park,<sup>(7)</sup> J. Patrick,<sup>(7)</sup> G. Pauletta,<sup>(23)</sup> L. Pescara,<sup>(20)</sup> M. D. Peters,<sup>(14)</sup>  
T. J. Phillips,<sup>(6)</sup> G. Piacentino,<sup>(3)</sup> M. Pillai,<sup>(25)</sup> R. Plunkett,<sup>(7)</sup> L. Pondrom,<sup>(32)</sup>  
J. Proudfoot,<sup>(1)</sup> N. Produit,<sup>(14)</sup> F. Ptohos,<sup>(9)</sup> G. Punzi,<sup>(23)</sup> K. Ragan,<sup>(11)</sup> F. Rimondi,<sup>(3)</sup>  
L. Ristori,<sup>(23)</sup> M. Roach-Bellino,<sup>(31)</sup> W. J. Robertson,<sup>(6)</sup> T. Rodrigo,<sup>(7)</sup> J. Romano,<sup>(5)</sup>  
L. Rosenson,<sup>(15)</sup> W. K. Sakumoto,<sup>(25)</sup> D. Saltzberg,<sup>(5)</sup> A. Sansoni,<sup>(8)</sup> V. Scarpine,<sup>(29)</sup>  
A. Schindler,<sup>(14)</sup> P. Schlabach,<sup>(9)</sup> E. E. Schmidt,<sup>(7)</sup> M. P. Schmidt,<sup>(33)</sup> O. Schneider,<sup>(14)</sup>  
G. Sciacca,<sup>(23)</sup> A. Scribano,<sup>(23)</sup> S. Segler,<sup>(7)</sup> S. Seidel,<sup>(18)</sup> Y. Seiya,<sup>(30)</sup> G. Sganos,<sup>(11)</sup>  
M. Shapiro,<sup>(14)</sup> N. M. Shaw,<sup>(24)</sup> Q. Shen,<sup>(24)</sup> P. F. Shepard,<sup>(22)</sup> M. Shimojima,<sup>(30)</sup>  
M. Shochet,<sup>(5)</sup> J. Siegrist,<sup>(28)</sup> A. Sill,<sup>(7a)</sup> P. Singh,<sup>(22)</sup> P. Sinervo,<sup>(11)</sup> J. Skarha,<sup>(12)</sup>  
K. Sliwa,<sup>(31)</sup> D. A. Smith,<sup>(23)</sup> F. D. Snider,<sup>(12)</sup> L. Song,<sup>(7)</sup> T. Song,<sup>(16)</sup> J. Spalding,<sup>(7)</sup>  
P. Sphicas,<sup>(15)</sup> A. Spies,<sup>(12)</sup> L. Stanco,<sup>(20)</sup> J. Steele,<sup>(32)</sup> A. Stefanini,<sup>(23)</sup> K. Strahl,<sup>(11)</sup>  
G. Sullivan,<sup>(5)</sup> K. Sumorok,<sup>(15)</sup> R. L. Swartz, Jr.,<sup>(10)</sup> T. Takahashi,<sup>(19)</sup> K. Takikawa,<sup>(30)</sup>  
F. Tartarelli,<sup>(23)</sup> Y. Teramoto,<sup>(19)</sup> S. Tether,<sup>(15)</sup> D. Theriot,<sup>(7)</sup> J. Thomas,<sup>(28)</sup>  
R. Thun,<sup>(16)</sup> M. Timko,<sup>(31)</sup> P. Tipton,<sup>(25)</sup> A. Titov,<sup>(26)</sup> S. Tkaczyk,<sup>(7)</sup> A. Tollestrup,<sup>(7)</sup>  
J. Tonnison,<sup>(24)</sup> J. Tseng,<sup>(12)</sup> M. Turcotte,<sup>(28)</sup> N. Turini,<sup>(3)</sup> F. Ukegawa,<sup>(21)</sup> G. Unal,<sup>(21)</sup>  
N. Uemura,<sup>(30)</sup> S. Vejcik, III,<sup>(16)</sup> R. Vidal,<sup>(7)</sup> M. Vondracek,<sup>(10)</sup> R. G. Wagner,<sup>(1)</sup>  
R. L. Wagner,<sup>(7)</sup> N. Wainer,<sup>(7)</sup> R. C. Walker,<sup>(25)</sup> J. Wang,<sup>(5)</sup> Q. Wang,<sup>(26)</sup>  
A. Warburton,<sup>(11)</sup> G. Watts,<sup>(25)</sup> T. Watts,<sup>(27)</sup> R. Webb,<sup>(29)</sup> C. Wendt,<sup>(32)</sup> H. Wenzel,<sup>(7a)</sup>  
W. C. Wester, III,<sup>(14)</sup> T. Westhusing,<sup>(10)</sup> A. B. Wicklund,<sup>(1)</sup> E. Wicklund,<sup>(7)</sup>  
R. Wilkinson,<sup>(21)</sup> H. H. Williams,<sup>(21)</sup> B. L. Winer,<sup>(25)</sup> J. Wolinski,<sup>(29)</sup> D. Y. Wu,<sup>(16)</sup>  
X. Wu,<sup>(23)</sup> J. Wyss,<sup>(20)</sup> A. Yagil,<sup>(7)</sup> W. Yao,<sup>(14)</sup> K. Yasuoka,<sup>(30)</sup> Y. Ye,<sup>(11)</sup> G. P. Yeh,<sup>(7)</sup>

M. Yin,<sup>(6)</sup> J. Yoh,<sup>(7)</sup> T. Yoshida,<sup>(19)</sup> D. Yovanovitch,<sup>(7)</sup> I. Yu,<sup>(33)</sup> J. C. Yun,<sup>(7)</sup>  
A. Zanetti,<sup>(23)</sup> F. Zetti,<sup>(23)</sup> L. Zhang,<sup>(32)</sup> S. Zhang,<sup>(15)</sup> W. Zhang,<sup>(21)</sup> S. Zucchelli,<sup>(3)</sup>

## The 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) *Universita 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*

## Abstract

The dijet invariant mass distribution has been measured in the region between 140 and 1000 GeV/c<sup>2</sup>, in 1.8 TeV  $p\bar{p}$  collisions. Data collected with the Collider Detector at Fermilab (CDF) show agreement with QCD calculations. A limit on quark compositeness of  $\Lambda_c > 1.3$  TeV is obtained. Axiguons with masses between 240 and 640 GeV/c<sup>2</sup> are excluded at 95% CL if we assume 10 open decay channels. Model-independent limits on the production of heavy particles decaying into two jets are also presented.

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

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<sup>-1</sup> recorded by CDF [1] during the 1988-1989 run at the Fermilab Tevatron Collider. Previous studies reported by UA1 [2] and UA2 [3] at  $\sqrt{s} = 540$  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 [6] and to the existence of new particles that decay into two jets, such as axiguons [7]. We report in this article a summary of a study of the dijet mass spectrum. Further details can be found in Reference [5].

The data are based on information from the CDF central calorimeter ( $|\eta| \leq 1.1$ ) [9], composed of projective towers of scintillator-absorber sandwich construction, segmented in  $\Delta\eta \times \Delta\phi = 0.1 \times 15^\circ$ . Jets were reconstructed using a fixed-cone clustering



algorithm [8] with cone radius  $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ , where  $\eta = -\ln[\tan(\theta/2)]$  is the pseudorapidity,  $\phi$  is the azimuth (in radians) and  $\theta$  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 online 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  $M_{jj} = 140 \text{ GeV}/c^2$  and 17% for  $M_{jj} > 600 \text{ GeV}/c^2$ . 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 jets are well contained in the central calorimeter.

We define  $M_{jj}^{obs} = \sqrt{(E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2}$  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 online triggers were combined. The observed differential cross section  $d\sigma/dM_{jj}^{obs}$ , 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 [5]. The sum in quadrature of all the contributions ranges from 33% at  $M_{jj}^{obs} = 140 \text{ GeV}/c^2$  to 60% at  $1000 \text{ GeV}/c^2$ . 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  $M_{jj}^{obs} > 500 \text{ GeV}/c^2$  and is 36% at  $M_{jj}^{obs} = 140 \text{ GeV}/c^2$ .

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  $t = M_{jj}^{obs} - M_{jj}$ , thereby observing a mass  $M_{jj}^{obs}$  for a given true mass  $M_{jj}$ . The procedure to determine an analytic approximation of  $g(t, M_{jj})$  is fully described in [5]. Theoretical models are 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, all would produce in a particular dijet mass region a different number of events from what expected by QCD. We place 95% confidence level (CL) 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 [6] characterised by an energy scale  $\Lambda_c$ . If quarks are composite structures, an excess of events at high masses should be observed. The 95% CL limit is inferred by comparing the number of events observed by CDF in the region  $M_{jj}^{obs} > 580 \text{ GeV}/c^2$  with the number of events expected by QCD. The QCD prediction is smeared and normalized to the data in the region  $160 < M_{jj}^{obs} < 300 \text{ GeV}/c^2$ . The statistical test has been performed with recent sets of structure functions (HMRS[12], MT[13]) and the renormalization scales  $\mu = 2p_T$ ,  $\mu = p_T$  and  $\mu = p_T/2$ . The results are shown in Table 1. The most conservative limit on  $\Lambda_c$  is 1.3 TeV, set by HMRS-B,  $\mu = p_T/2$ . Previous limits obtained with the same data are  $\Lambda_c > 1.4 \text{ TeV}$  from the inclusive jet cross [14], and  $\Lambda_c > 1.0 \text{ TeV}$  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. 1a.

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 lineshape  $f(M_{jj}) = \frac{S\Gamma}{2\pi[(M_{jj}-M_0)^2+(\frac{\Gamma}{2})^2]}$  where  $M_0$  and  $\Gamma$  are the central value and the width of the resonance and  $S$  is the cross section (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, 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 [5]. 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 included in the smearing function have been studied with the shower Monte Carlo HERWIG [11], whose capability to reproduce the characteristics of “multi jet” 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 95% CL limit on  $S$ , as a function of  $M_0$  and  $\Gamma$ , 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 2. CDF data exclude the region above the listed cross sections at the 95% CL.

Recently proposed chiral-color models [7] predict the 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 [17, 2] and CDF [4]. The same method described for resonances parametrized with a Breit-Wigner lineshape 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 3 shows the results. With a luminosity of  $4.2 \text{ pb}^{-1}$ , axigluons of masses  $240 \leq M_a \leq 640 \text{ GeV}/c^2$  are excluded for N=10, while for N=20 we exclude the windows  $260 \leq M_a \leq 280 \text{ GeV}/c^2$  and  $450 \leq M_a \leq 550 \text{ GeV}/c^2$ . 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% CL. 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  $\text{GeV}/c^2$ . 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.

## References

- [1] F. Abe *et al.* (CDF Collaboration), Nucl. Instr. Meth. A 271, 387 (1988).
- [2] C. Albajar *et al.* (UA1 Collaboration), Phys. Lett. B 209, 127 (1988).
- [3] J. Alitti *et al.* (UA2 Collaboration), Z. Phys. C 49, 17 (1991).
- [4] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D 41, 1722 (1990).
- [5] F. Abe *et al.*, Fermilab Report No. Fermilab-Pub-93/017-E (Submitted to Phys. Rev. D).
- [6] E. Eichten *et al.*, Rev. Mod. Phys. 56, 579 (1984).
- [7] P. Frampton and S. Glashow, Phys. Lett. B 190, 157 (1987).
- [8] F. Abe *et al.*, Phys. Rev. D 45, 1448 (1992).
- [9] L. Balka *et al.*, Nucl. Instr. Meth. A 267, 272 (1988); S. Bertolucci *et al.*, Nucl. Instr. Meth. A 267, 301 (1988).
- [10] F. Abe *et al.*, Phys. Rev. D 44, 29 (1991).
- [11] G. Marchesini and B. Webber, Nucl. Phys. B 310, 461 (1988).
- [12] P. Harriman *et al.*, 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).



	$\Lambda(\text{GeV})$		
$\mu/p_T$	0.5	1	2
<b>HMRS-B</b>	1300	1330	1360
<b>HMRSE</b>	1480	1500	1520
<b>MT E1</b>	1390	1440	1490
<b>MT B2</b>	1490	1540	1580
<b>MT B1</b>	1360	1410	1460
<b>MT S1</b>	1340	1400	1460

Table 1: Compositeness limits at 95% CL for recent structure functions and different renormalization scales.

$M_0$	$\Gamma = 0.02M_0$	$\Gamma = 0.1M_0$	$\Gamma = 0.2M_0$
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

Table 2: 95% CL 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  $\Gamma$  (GeV/ $c^2$ ).

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

Table 3: Axigluon masses ( $\text{GeV}/c^2$ ) excluded by CDF data using the two structure functions HMRS-B and MT set B2;  $N$  is the number of open decay channels

## Figure Captions.

Figure 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  $300 \text{ GeV}/c^2$  axigluon (dotted line) is excluded by the data, while the  $700 \text{ GeV}/c^2$  axigluon (dashed line) is not excluded, both at 95% CL. The QCD prediction (solid line) is also shown.

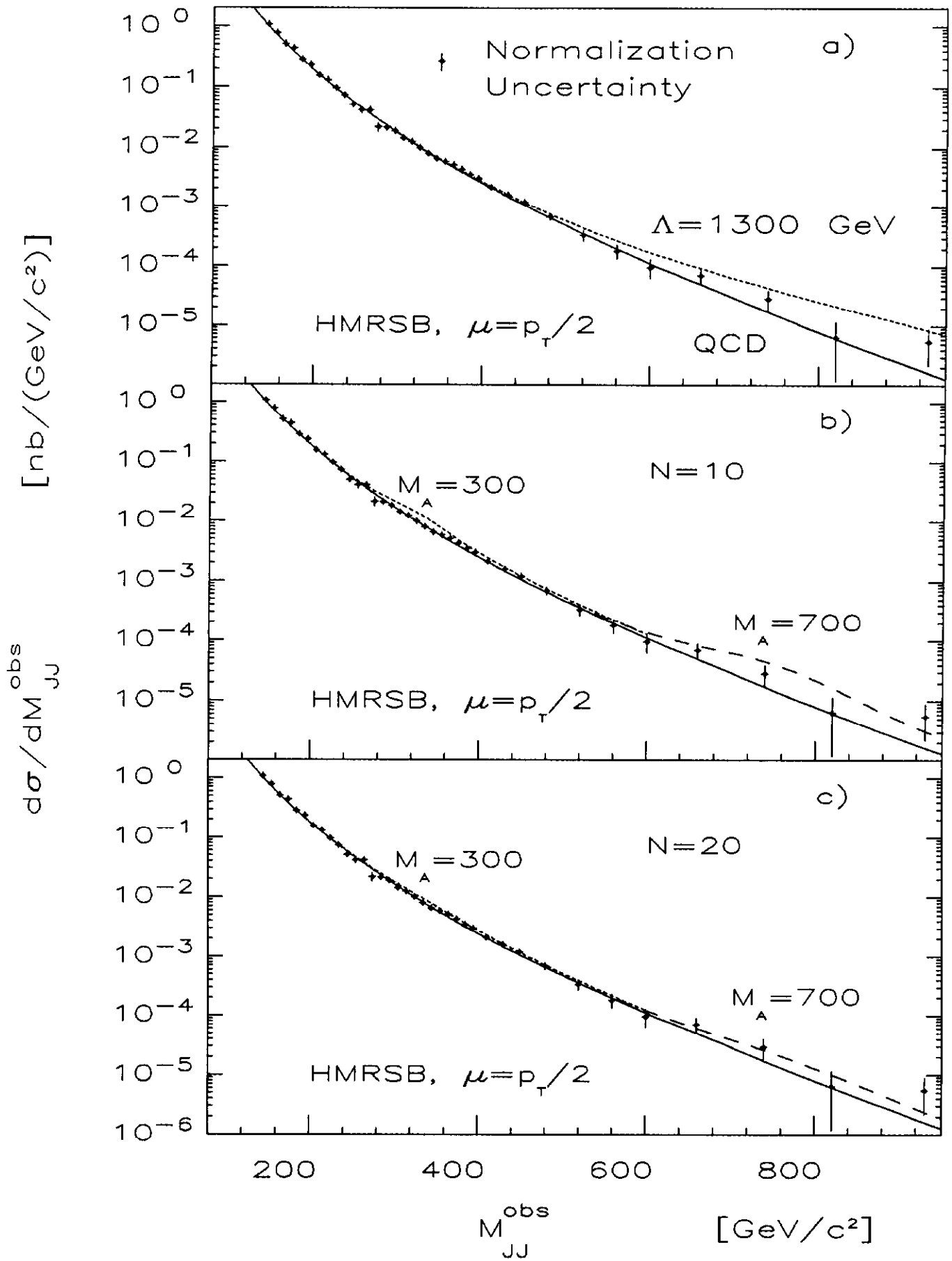


FIG. 1