Measurement of Dijet Angular Distributions at \( \sqrt{s} = 1.96 \) TeV and Searches for Quark Compositeness and Extra Spatial Dimensions


(The D0 Collaboration)

1 Universidad de Buenos Aires, Buenos Aires, Argentina
2 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4 Universidade Federal do ABC, Santo André, Brazil
5 Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
6 University of Alberta, Edmonton, Alberta, Canada; Simon Fraser University, Burnaby, British Columbia, Canada; York University, Toronto, Ontario, Canada and McGill University, Montreal, Quebec, Canada
7 University of Science and Technology of China, Hefei, People’s Republic of China
8 Universidad de los Andes, Bogotá, Colombia
9 Center for Particle Physics, Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
10 Czech Technical University in Prague, Prague, Czech Republic
11 Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
12 Universidad San Francisco de Quito, Quito, Ecuador
13 LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
14 LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
15 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
16 LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France
17 LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France
18 CEA, Ifre, SPP, Saclay, France
19 IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
20 IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
21 III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
22 Physikalisches Institut, Universität Bonn, Bonn, Germany
23 Physikalisches Institut, Universität Freiburg, Freiburg, Germany
24 II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
25 Institut für Physik, Universität Mainz, Mainz, Germany
26 Ludwig-Maximilians-Universität München, München, Germany
27 Fachbereich Physik, Universität Wuppertal, Wuppertal, Germany
28 Panjab University, Chandigarh, India
29 Delhi University, Delhi, India
30 Tata Institute of Fundamental Research, Mumbai, India
31 University College Dublin, Dublin, Ireland
32 Korea Detector Laboratory, Korea University, Seoul, Korea
33 SungKyunkwan University, Suwon, Korea
34 CINVESTAV, Mexico City, Mexico
35 CAR, Irfu, SPP, Saclay, France
We present the first measurement of dijet angular distributions in $pp$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron Collider. The measurement is based on a dataset corresponding to an integrated luminosity of 0.7 fb$^{-1}$ collected with the D0 detector. Dijet angular distributions have been measured over a range of dijet masses, from 0.25 TeV to above 1.1 TeV. The data are in good agreement with the predictions of perturbative QCD and are used to constrain new physics models including quark compositeness, large extra dimensions, and TeV$^{-1}$ scale extra dimensions. For all models considered, we set the most stringent direct limits to date.

PACS numbers: 12.60.Rc, 11.25.Wx, 12.38.Qk, 13.87.Ce

At large momentum transfers, dijet production has the largest cross section of all processes at a hadron collider and therefore directly probes the highest energy regime. It can be used to test the standard model (SM) at previously unexplored small distance scales and to search for signals predicted by new physics models. The angular
distribution of dijets with respect to the hadron beam
direction is directly sensitive to the dynamics of the un-
derlying reaction. While in quantum chromodynamics
(QCD) this distribution shows small but noticeable de-
viations from Rutherford scattering, an excess at large
angles from the beam axis would be a sign of new physics
processes not included in the SM, such as substructure
of quarks (“quark compositeness”) [1, 2, 3], or the existence
of additional compactified spatial dimensions (“extra di-

mensions”) [4, 5, 6, 7, 8]. Earlier measurements of dijet
angular distributions and related observables in pp colli-
sions at $\sqrt{s} = 1.8$ TeV were used to set limits on quark
compositeness [9, 10].

In this Letter we present the first measurement of
dijet angular distributions in pp collisions at a center-
of-mass energy of $\sqrt{s} = 1.96$ TeV. The data sample,
collected with the D0 detector during 2004–2005 in
Run II of the Fermilab Tevatron Collider, corresponds
to an integrated luminosity of 0.7 fb$^{-1}$. In the exper-
iment and in theory calculations, jets are defined by the
Run II midpoint cone jet algorithm [11] with a cone ra-
adius of $R = (\Delta y)^2 + (\Delta \phi)^2 = 0.7$ in rapidity $y$
and azimuthal angle $\phi$. Rapidity is related to the po-
lar scattering angle $\theta$ with respect to the beam axis by
$y = 0.5 \ln [(1 + \beta \cos \theta)/(1 - \beta \cos \theta)]$ with
$\beta = |p_T|/E$. We measure distributions in the dijet variable $X_{\text{dijet}} = \exp[(y_1 - y_2)]$ in ten regions of dijet invariant mass $M_{jj}$
where $y_1$ and $y_2$ are the rapidities of the two jets with
highest transverse momentum $p_T$ with respect to the
beam axis in an event. For massless $2 \rightarrow 2$ scattering,
the variable $X_{\text{dijet}}$ is related to the polar scattering
angle $\theta^*$ in the partonic center-of-mass frame by
$X_{\text{dijet}} = (1 + \cos \theta^*)/(1 - \cos \theta^*)$. The choice of this
variable is motivated by the fact that Rutherford scat-
tering is independent of $X_{\text{dijet}}$. The phase space of this
analysis is defined by $M_{jj} > 0.25$ TeV, $X_{\text{dijet}} < 16$, and
$y_{\text{boost}} = 0.5 |y_1 + y_2| < 1$. Together, the $X_{\text{dijet}}$ and $y_{\text{boost}}$
requirements restrict the jet phase space to $|y_{\text{jet}}| < 2.4$
where jets are well-reconstructed in the D0 detector and
the energy calibration is known to high precision. To
minimize sensitivity to correlated experimental and the-
etrical uncertainties, the $X_{\text{dijet}}$ distributions in the dif-
ferent $M_{jj}$ ranges are normalized by their respective inte-
grals. Based on the measurement, we set limits on quark
compositeness [1, 2, 3], large spatial extra dimensions
according to the model proposed by Arkani-Hamed, Di-
mopoulos and Dvali (ADD LED) [4, 5], and TeV$^{-1}$ scale
extra dimensions (TeV$^{-1}$ ED) [6, 7, 8].

A detailed description of the D0 detector can be found
in Ref. [12]. The event selection, jet reconstruction, jet
energy and momentum correction in this measurement
follow closely those used in our recent measurement of
the inclusive jet cross section [13]. The primary tool for
jet detection is the finely segmented uranium-liquid ar-
gon calorimeter that has almost complete solid angular
coverage $1.7^\circ \lesssim \theta \lesssim 178.3^\circ$ [12]. Events are triggered by
the jet with highest $p_T$, referred to as $p_T^{\text{max}}$. In each $M_{jj}$
region, events are taken from a single trigger which is cho-

sen such that the smallest $p_T^{\text{max}}$ in the $M_{jj}$ region is above
the threshold that ensures 100% efficiency. The $M_{jj}$
regions utilize triggers with different prescales, resulting
in integrated luminosities of $0.10\text{ pb}^{-1}$ ($M_{jj} < 0.4$ TeV),
$1.54\text{ pb}^{-1}$ ($0.4 < M_{jj} < 0.5$ TeV), $17\text{ pb}^{-1}$ ($0.5 < M_{jj} <
0.6$ TeV), $73\text{ pb}^{-1}$ ($0.6 < M_{jj} < 0.8$ TeV), $0.5\text{ fb}^{-1}$ ($0.8 <
M_{jj} < 1.0$ TeV), and $0.7\text{ fb}^{-1}$ ($M_{jj} > 1.0$ TeV).

The position of the pp interaction is reconstructed
using a tracking system consisting of silicon microstrip
detectors and scintillating fibers, located inside a 2 T
solenoidal magnet [12], and is required to be within 50 cm
of the detector center along the beam direction. The
jet four-momenta are corrected for the response of the
calorimeter, the net energy flow through the jet cone,
energy from event pile-up and multiple pp interactions,
and for systematic shifts in $|y|$ due to detector effects [13].
Cosmic ray backgrounds are suppressed by requirements
on the missing transverse momentum in an event [13].
Requirements on characteristics of shower shape are used
to suppress the remaining background due to electrons,
photons, and detector noise that mimic jets. The effi-
cency for these requirements is above 97.5%, and the
fraction of background events is below 0.1% in all $M_{jj}$
regions.

The $X_{\text{dijet}}$ distributions are corrected for instrument-
effects using events generated with PYTHIA v6.419 [14]
using tune QW [15] and MSTW2008LO parton distribu-
tion functions (PDFs) [16]. The generated particle-level
events are subjected to a fast simulation of the D0 de-
tector response, based on parametrizations of resolu-
tion effects in $p_T$, the polar and azimuthal angles of jets, jet
reconstruction efficiencies, and misidentification of the
event vertex. These parametrizations have been deter-

mined either from data or from a detailed simulation of
the D0 detector using GEANT [17]. The generated events
are reweighted according to the $M_{jj}$ distribution in data.
To minimize migrations between $M_{jj}$ regions due to reso-
lution effects, we use the simulation to obtain a rescaling
function in $M_{jj}$ that optimizes the correlation between
the reconstructed and true values. The bin sizes in the
$X_{\text{dijet}}$ distributions are chosen to be much larger than the
$X_{\text{dijet}}$ resolution. The bin purity after $M_{jj}$ rescaling, de-

fined as the fraction of all reconstructed events that were
generated in the same bin, is between 42% and 68%. We
then use the simulation to determine $X_{\text{dijet}}$ bin correction
factors for the differential cross sections in the different
$M_{jj}$ regions. These also include corrections for the en-
ergies of unreconstructed muons and neutrinos inside the
jets. The total correction factors for the differential cross
sections are typically between 0.9 and 1.0, and always in
the range 0.7 to 1.1. The corrected differential cross sec-
tions within each $M_{jj}$ range are subsequently normalized
to their integrals, providing the corrected, final results
for $1/\sigma_{\text{dijet}} \cdot d\sigma/dX_{\text{dijet}}$ at the “particle level” as defined.
In order to take into account correlations between systematic uncertainties, the experimental systematic uncertainties are separated into independent sources, for which each of the effects are fully correlated between all data points. In total we have identified 76 independent sources, of which 48 are related to the jet energy calibration and 15 to the jet $p_T$ resolution uncertainty. These are the dominant sources of uncertainty. Smaller contributions are from the jet $\theta$ resolution and from the systematic shifts in $\eta$. All other sources are negligible.

All sources and their effects are documented in Ref. [19]. For $M_{jj} < 1$ TeV ($M_{jj} > 1$ TeV) systematic uncertainties are 1%-5% (3%-11%); they are in all cases less than the statistical uncertainties.

The results are available in Ref. [19] and displayed in Fig. 1. The normalized $\chi^2_{dijet}$ distributions are presented in ten $M_{jj}$ regions, starting from $M_{jj} > 0.25$ TeV, and including one region for $M_{jj} > 1.1$ TeV. The data are compared to predictions from a perturbative QCD calculation at next-to-leading order (NLO) with non-perturbative corrections applied. The non-perturbative corrections are determined using PYTHIA. They are defined as the product of the corrections due to hadronization and to the underlying event. The NLO results are computed using FASTNLO [20] based on nlojet++ [21, 22]. All theory calculations use MSTW2008NLO PDFs [16] and the corresponding value of $\alpha_s(M_Z) = 0.120$. The PDF uncertainties are provided by the twenty MSTW2008NLO 90% C.L. eigenvectors. Renormalization and factorization scales $\mu_r$ are varied simultaneously around the central value of $\mu_r = \langle p_T \rangle$ in the range $0.5 \mu_r \leq \mu \leq 2 \mu_r$, where $\langle p_T \rangle$ is the average dijet $p_T$. The quadratic sum of scale and PDF uncertainties is displayed as a band around the central SM value in Fig. 1. The scale (PDF) uncertainties are always below 5% (2%) so the band is nearly a line. The theory, including the perturbative results and the non-perturbative corrections, is in good agreement with the data over the whole $M_{jj}$ range with a $\chi^2$ (defined later) of 127.2 for 120 data points in ten normalized distributions. Based on the agreement of the $\chi^2_{dijet}$ measurement with the SM, we proceed to set limits on quark compositeness, ADD LED, and TeV$^{-1}$ ED models.

Hypothetically, quarks could be made of other particles, as assumed in the quark compositeness model in Ref. [1, 2, 3]. We investigate the model in which all quarks are considered to be composite. The parameters in this model are the energy scale $\lambda$ and the sign of the interference term $\eta$ between the standard model and the new physics terms. The ADD LED model [4, 5] assumes that extra spatial dimensions exist in which gravity is allowed to propagate. Jet cross sections receive additional contributions from virtual exchange of Kaluza-Klein excitations of the graviton. There are two different formalisms (GRW [23] and HLZ [24]). The model parameter is the effective Planck scale, $M_S$, and the HLZ formalism also includes the subleading dependence on the number of extra dimensions. The TeV$^{-1}$ ED model [6, 7, 8] assumes that extra dimensions exist at the TeV$^{-1}$ scale. SM production cross sections are modified due to virtual Kaluza-Klein excitations of the SM gauge bosons. In this model, gluons can travel through the extra dimensions, which changes the dijet cross section. The parameter in this model is the compactification scale, $M_C$.

The new physics contributions have only been calculated to leading order (LO), while the QCD predictions are known to NLO. In this analysis, to obtain the best estimate for new physics processes, we multiply the new physics LO calculations bin-by-bin by the SM $k$-factors ($k = \sigma_{NLO}/\sigma_{LO}$). The $k$-factors are in the range 1.25–1.5, increasing with $M_{jj}$ and decreasing with $\chi^2_{dijet}$. Their effects on single bins of the normalized $\chi^2_{dijet}$ distributions within the different $M_{jj}$ regions is below 12%. The new physics cross sections are computed using the matrix elements from Refs. [2, 3, 5, 8]. The theoretical variations (scale variations and PDF uncertainties) are consistently propagated into both the SM and the new physics contributions. Predictions for the different mod-
els are compared to the \( \chi_{\text{dijet}} \) data and to the SM results in Fig. 1. It is observed that all models predict increased contributions as \( \chi_{\text{dijet}} \rightarrow 1 \) towards large \( M_j \). The \( M_j \) evolution of the excess towards small \( \chi_{\text{dijet}} \) is observed to be different for different models.

We define the \( \chi^2 \) between data and theory using the Hessian approach [25] which introduces nuisance parameters for all correlated sources of experimental and theoretical uncertainty. The \( \chi^2 \) is then minimized with respect to all nuisance parameters, and is therefore only a function of the new physics model parameter(s). In most cases \( \chi^2 \) has the minimum for a new physics mass scale of infinity, corresponding to the SM value. Only for the quark compositeness model with positive interference and for the TeV\(^{-1} \) ED model \( \chi^2 \) has small minima at \( \Lambda = 9.88 \text{ TeV} \) with \( \Delta \chi^2 = 0.01 \) and \( M_C = 2.96 \text{ TeV} \) with \( \Delta \chi^2 = 0.28 \) below the SM value, respectively.

The \( \chi^2 \) is then transformed into a likelihood which is used in a Bayesian procedure [10] to obtain 95\% C.L. limits on the new physics mass scales \( \Lambda \), \( M_C \), and \( M_S \) in the different models. The prior is chosen to be flat in the new physics mass scale raised to the power in which it appears in the Lagrangian or, alternatively, raised to the power in which it enters the model cross section. While the former has been used in many previous analyses, the latter is statistically preferred for being unbiased in the cross section. Alternatively, we have applied a procedure which defines the 95\% C.L. limit as the mass scale at which \( \chi^2 - \chi^2_{\text{min}} = 3.84 \) [26]. This procedure has the advantage of being independent of an assumed prior. The observed limits and the expectation values are listed in Table I. All observed limits are within one standard deviation of the expected limits.

The limit on \( M_C \) obtained in this analysis, while inferior to indirect limits from electroweak precision measurements (Ref. [8] and references therein), is complementary and is the result of the first direct search for TeV\(^{-1} \) extra dimensions at a particle collider. The limits on \( M_S \) in the different formalisms of the ADD LED model are on average slightly higher as compared to recent D0 results from the combination of 1 fb\(^{-1} \) of dielectron and diphoton data in Ref. [27], which were so far the most restrictive limits on ADD LED. Our limits on quark compositeness improve previous results from related dijet observables [9, 10] and are the most stringent limits to date.

In summary, we have presented the first measurement of dijet angular distributions in Run II of the Fermilab Tevatron Collider. This is the first measurement of angular distributions of a hard partonic scattering process at energies above 1 TeV in collider-based high energy physics. The normalized \( \chi_{\text{dijet}} \) distributions are well-described by theory calculations in next-to-leading order in the strong coupling constant and are used to set limits on quark compositeness, ADD large extra dimensions, and TeV\(^{-1} \) extra dimensions models. For the TeV\(^{-1} \) extra dimensions model this is the first direct search at a collider. For all models considered, this analysis sets the most stringent direct limits to date.

We thank the teams at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACYT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); and the Alexander von Humboldt Foundation (Germany).

---

Table I: Expected and observed 95\% C.L. limits in units of TeV on various new physics (NP) models for different Bayesian priors, and for the \( \Delta \chi^2 = 3.84 \) criterion.

<table>
<thead>
<tr>
<th>Model (parameter)</th>
<th>Prior flat in NP Lagrangian</th>
<th>Prior flat in NP ( x )-section</th>
<th>( \Delta \chi^2 = 3.84 ) criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quark compositeness ( \Lambda )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \eta = +1 )</td>
<td>2.91</td>
<td>3.06</td>
<td>2.76</td>
</tr>
<tr>
<td>( \eta = -1 )</td>
<td>2.97</td>
<td>3.06</td>
<td>2.75</td>
</tr>
<tr>
<td>TeV(^{-1} ) ED ( M_C )</td>
<td>1.73</td>
<td>1.67</td>
<td>1.60</td>
</tr>
<tr>
<td>ADD LED ( M_S )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRW</td>
<td>1.53</td>
<td>1.67</td>
<td>1.47</td>
</tr>
<tr>
<td>HLZ ( n = 3 )</td>
<td>1.81</td>
<td>1.98</td>
<td>1.75</td>
</tr>
<tr>
<td>HLZ ( n = 4 )</td>
<td>1.53</td>
<td>1.67</td>
<td>1.47</td>
</tr>
<tr>
<td>HLZ ( n = 5 )</td>
<td>1.38</td>
<td>1.51</td>
<td>1.33</td>
</tr>
<tr>
<td>HLZ ( n = 6 )</td>
<td>1.28</td>
<td>1.40</td>
<td>1.24</td>
</tr>
<tr>
<td>HLZ ( n = 7 )</td>
<td>1.21</td>
<td>1.33</td>
<td>1.17</td>
</tr>
</tbody>
</table>

\[ [a] \text{ Visitor from Augustana College, Sioux Falls, SD, USA.} \]
Visitor from Rutgers University, Piscataway, NJ, USA.
Visitor from The University of Liverpool, Liverpool, UK.
Visitor from Centro de Investigacion en Computacion - IPN, Mexico City, Mexico.
Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacan, Mexico.
Visitor from Helsinki Institute of Physics, Helsinki, Finland.
Visitor from Universität Bern, Bern, Switzerland.
Visitor from Universität Zürich, Zürich, Switzerland.
Deceased.

B. Abbott et al. (D0 Collaboration), Phys. Rev. D 64, 032003 (2001).
See EPAPS Document No. E-PRLTA0-103-025947 for the measurement results and uncertainty correlations. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html
V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 102, 051601 (2009).