Measurement of the $p \bar{p} \rightarrow t \bar{t}$ production cross section at $\sqrt{s} = 1.96$ TeV in the fully hadronic decay channel

V.M. Abazov,35 B. Abbott,75 M. Abolins,65 B.S. Acharya,28 M. Adams,51 T. Adams,49 E. Aguilo,5 S.H. Ahn,40 M. Ahsan,59 G.D. Alexeev,45 G. Alkhazov,39 A. Alton,64* G. Alversen,63 G.A. Alves,2 M. Anastassio,55 L.S. Ancu,34 T. Andeen,53 S. Anderson,45 B. Andrieu,16 M.S. Anzelm,53 Y. Arnoud,33 M. Arov,52 A. Askew,49 B. Åsman,40 A.C.S. Assis Jesus,3 O. Atramentov,49 C. Autermann,20 C. Avila,7 C. Ay,23 F. Badaud,12 A. Baden,61 L. Bagby,52 B. Baldwin,50 D.V. Bandurin,59 P. Banerjee,28 S. Banerjee,28 E. Barberis,63 P. Bargassa,80 P. Baringer,58 C. Barnes,43 J. Barreto,2 J.F. Bartlett,50 U. Bassler,16 D. Bauer,43 S. Beale,5 A. Bean,58 M. Begalli,3 M. Begel,71 C. Belanger-Champagne,49 L. Bellantoni,50 A. Bellavance,67 J.A. Benitez,65 S.B. Beri,26 G. Bernardi,16 R. Bernhard,22 L. Bernzton,14 I. Bertram,42 M. Besançon,17 R. Beuselinck,43 V.A. Bezzubov,38 P.C. Bhat,50 V. Bhatnagar,26 M. Bender,24 C. Biscarot,19 I. Blackler,43 G. Blazey,52 F. Blekan,43 S. Blessing,49

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(DO Collaboration)

1 Universidad de Buenos Aires, Buenos Aires, Argentina
2 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3 Universidade do Estado de Rio de Janeiro, Rio de Janeiro, Brazil
4 Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
5 University of Alberta, Edmonton, Alberta, Canada, Simon Fraser University, Burnaby, British Columbia, Canada, York University, Toronto, Ontario, Canada, and McGill University, Montreal, Quebec, Canada
6 University of Science and Technology of China, Hefei, People’s Republic of China
7 Universidad de los Andes, Bogotá, Colombia
8 Center for Particle Physics, Charles University, Prague, Czech Republic
9 Czech Technical University, Prague, Czech Republic
10 Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
11 Universidad San Francisco de Quito, Quito, Ecuador
12 Laboratoire de Physique Corpusculaire, IN2P3-CNRS, Université Blaise Pascal, Clermont-Ferrand, France
13 Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS, Université de Grenoble I, Grenoble, France
14 CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France
15 Laboratoire de l’Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud, Orsay, France
16 LPNHE, IN2P3-CNRS, Universités Paris VI and VII, Paris, France
17 DAPNIA/Service de Physique des Particules, CEA, Saclay, France
18 IPHC, IN2P3-CNRS, Université Louis Pasteur, Strasbourg, France, and Université de Haute Alsace, Mulhouse, France
19 Institut de Physique Nucléaire de Lyon, IN2P3-CNRS, Université Claude Bernard, Villeurbanne, France
20 III. Physikalisches Institut A, RWTH Aachen, Aachen, Germany
21 Physikalisches Institut, Universität Bonn, Bonn, Germany
22 Physikalisches Institut, Universität Freiburg, Freiburg, Germany
23 Institut für Physik, Universität Mainz, Mainz, Germany
24 Ludwig-Maximilians-Universität München, München, Germany
25 Fachbereich Physik, Universität Wuppertal, Wuppertal, Germany
26 Punjab University, Chandigarh, India
27 Delhi University, Delhi, India
28 Tata Institute of Fundamental Research, Mumbai, India
29 University College Dublin, Dublin, Ireland
30 Korea Detector Laboratory, Korea University, Seoul, Korea
A measurement of the top quark pair production cross section in proton anti-proton collisions at an interaction energy of $\sqrt{s} = 1.96$ TeV is presented. This analysis uses 405 pb\(^{-1}\) of data collected with the DØ detector at the Fermilab Tevatron Collider. Fully hadronic $t\bar{t}$ decays with final states of six or more jets are separated from the multijet background using secondary vertex tagging and a neural network. The $t\bar{t}$ cross section is measured as $\sigma_{t\bar{t}} = 4.5^{+1.7}_{-1.4}(\text{stat})^{+1.2}_{-1.1}(\text{syst}) \pm 0.3(\text{lumi})$ pb for a top quark mass of $m_t = 175$ GeV/c\(^2\).
The standard model (SM) predicts that the top quark decays primarily into a $W$ boson and a $b$ quark. The measurement presented here tests the prediction of the SM in the dominant decay mode of the $t\bar{t}$ system: when both $W$ bosons decay to quarks, the so-called fully hadronic decay channel. This topology occurs in 46% of $t\bar{t}$ events. The theoretical signature for fully hadronic $t\bar{t}$ events is six or more jets originating from the hadronization of the six quarks. Of the six jets, two originate from $b$ quark decays. Fully hadronic $t\bar{t}$ events are difficult to identify at hadron colliders because the background rate is many orders of magnitude larger than that of the $t\bar{t}$ signal.

We report a measurement of the production cross-section of top quark pairs, $\sigma_{t\bar{t}}$, using data collected with DØ in the fully hadronic channel, that exploits the long lifetime of the $b$ hadrons in identifying $b$ jets. To increase the sensitivity for $t\bar{t}$ events, we used a neural network to distinguish signal from the overwhelming background of multijet production through Quantum Chromodynamic processes (QCD).

The DØ detector [1] has a central tracking system consisting of a silicon micro strip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively. Rapidity $y$ and pseudorapidity $\eta$ are defined as functions of the polar angle $\theta$ and parameter $\beta$ as $y(\theta, \beta) = \frac{1}{2} \ln[(1 + \beta \cos \theta)/(1 - \beta \cos \theta)]$ and $\eta(\theta) = y(\theta, 1)$, where $\beta$ is the ratio of the particle’s momentum to its energy. The liquid-argon and uranium calorimeter has a central section (CC) covering pseudorapidities $|\eta|$ up to $\approx 1.1$ and two end calorimeters (EC) that extend coverage to $|\eta| \approx 4.2$, with all three housed in separate cryostats. Each calorimeter cryostat contains a multilayer electromagnetic calorimeter, a finely segmented hadronic calorimeter and a third hadronic calorimeter that is more coarsely segmented, providing both segmentation in depth and in projective towers of size $0.1 \times 0.1$ in $\eta$-$\phi$ space, where $\phi$ is the azimuthal angle in radians. An outer muon system, covering $|\eta| < 2$, consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T iron toroids, followed by two similar layers after the toroids. The luminosity is measured using plastic scintillator arrays placed in front of the EC cryostats.

The data set was collected between 2002 and 2004, and corresponds to an integrated luminosity $\mathcal{L} = 405 \pm 25 \text{ pb}^{-1}$ [2]. To isolate events with six jets, we used a dedicated multijet trigger. The requirements on the trigger, particularly on jet and trigger tower energy thresholds, were tightened during the collection of the data set to manage the increasing instantaneous luminosities delivered by the Fermilab Tevatron Collider. The change in trigger requirements had little effect on the efficiency for signal, while removing an increasing number of background events [3]. The trigger was tuned for the fully hadronic $t\bar{t}$ channel and was optimized to remain as efficient possible while using limited bandwidth. The collection rate after all trigger levels was fixed to a few Hz, which was completely dominated by QCD multijet events as the hadronic $t\bar{t}$ event production rate is expected to be a few events per day. We required three or four trigger towers above an energy threshold of 5 GeV at the first trigger level, three reconstructed jets with transverse energies ($E_T$) above 8 GeV at the second trigger level, combined with a requirement on the sum of the transverse momenta ($p_T$) of the jets, and four or five reconstructed jets at transverse energy thresholds between 10 and 30 GeV at the highest trigger level [1].

We simulated $t\bar{t}$ production using ALPGEN 1.3 to generate the parton-level processes, and PYTHIA 6.2 to model hadronization [4, 5]. We used a top quark invariant mass of $m_t = 175 \text{ GeV}/c^2$. The decay of hadrons carrying bottom quarks was modeled using EVTGEN [6]. The simulated $t\bar{t}$ events were processed with the full GEANT-based DØ detector simulation, after which the Monte Carlo (MC) events were passed through the same reconstruction program as was used for data. The small differences between the MC model and the data were corrected by matching the properties of the reconstructed objects. The residual differences were very small and were corrected using factors derived from detailed comparisons between the MC model and the data for well understood SM processes such as the jets in $Z$ boson and QCD dijet production.

In the offline analysis, jets were defined with an iterative cone algorithm [7]. Before the jet algorithm was applied, calorimeter noise was suppressed by removing isolated cells whose measured energy was lower than four standard deviations above cell pedestal. In the case that a cell above this threshold was found to be adjacent to one with an energy less than four standard deviations above pedestal, the latter was retained if its signal exceeded 2.5 standard deviations above pedestal. Cells that were reconstructed with negative energies were always removed.

The elements for cone jet reconstruction consisted of projective towers of calorimeter cells. First, seeds were defined using a preclustering algorithm, using calorimeter towers above an energy threshold of 0.5 GeV. The cone jet reconstruction, an iterative clustering process where the jet axis was required to match the axis of a projective cone, was then run using all preclusters above 1.0 GeV as seeds. As jets from $t\bar{t}$ production are relatively narrow due to relatively high jet $p_T$, the jets were defined using a cone with radius $R_{\text{cone}} = 0.5$, where $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. The resulting jets (proto-jets) took into account all energy deposits contained in the jet cone. If two proto-jets were within $1 < \Delta R/R_{\text{cone}} < 2$, an additional midpoint clustering was applied, where the combination of the two proto-jets was used as a seed for a possible additional proto-jet. At this stage, the proto-jets that share transverse momentum were examined with a splitting and merging algorithm, after which each calorimeter tower was assigned to one proto-jet at most. The proto-jets were merged if the shared $p_T$ ex-
ceeded 50% of the $p_T$ of the proto-jet with the lowest transverse momentum and the towers were added to the most energetic proto-jet while the other candidate was rejected. If the proto-jets shared less than half of their $p_T$, the shared towers were assigned to the proto-jet which was closest in $\Delta R$ space. The collection of stable proto-jets remaining was then referred to as the reconstructed jets in the event. The minimal $p_T$ of a reconstructed jet was required to be 8 GeV/c before any energy corrections were applied.

We removed jets caused by electromagnetic particles and jets resulting from noise in hadronic sections of the calorimeter by requiring that the fraction of the jet energy deposited in the calorimeter ($EMF$) was 0.05 < $EMF$ < 0.95 and the fraction of energy in the coarse hadronic calorimeter was less than 0.4. Jets formed from clusters of calorimeter cells known to be affected by noise were also rejected. The remaining noise contribution was removed by requiring that the jet also fired the first level trigger.

To correct the calorimeter jet energies back to the level of particle jets, a jet energy scale (JES) correction $C^{JES}$ was applied. The same procedure has to be applied to Monte Carlo jets to ensure an identical calorimeter response in data and simulation. The particle level or true jet energy $E^{true}$ was obtained from the measured jet energy $E^m$ and the detector pseudorapidity, measured from the center of the detector ($\eta_{det}$), using the relation

$$E^{true} = \frac{E^m - E_0(\eta_{det},L)}{R(\eta_{det}, E^m) S(\eta_{det}, E^m)} = C^{JES}(E^m, \eta_{det}, L).E^m.$$  

In data and MC the total correction was applied to the measured energy $E^m$ as a multiplicative factor $C^{JES}$. $E_0(\eta_{det},L)$ was the offset energy created by electronics noise and noise signal caused by the uranium in the calorimeter, pile-up energy from previous collisions and the additional energy from the underlying physics event. The dependence on the luminosity $L$ was caused by the fact that the number of additional interactions was dependent on the instantaneous luminosity, while the dependence on $y$ was caused by variations in the calorimeter occupancy as a function of the jet rapidity. $R(\eta_{det}, E^m)$ parameterized the energy response of the calorimeter, while $S(\eta_{det}, E^m)$ represents the fraction of the true partonic jet energy that was deposited inside the jet cone. This out-of-cone showering correction depended on the energy of the jet and its location in the calorimeter.

The JES was measured directly using $p_T$ conservation in photon + jet events. The method was identical for data and simulation and used transverse momentum balancing between the jet and the photon. As the energy scale of the photon was directly and precisely measured (the electromagnetic calorimeter response was derived from measurements of resonances in the $e^+e^-$ spectrum like the $Z$ boson), the true jet energy could be derived from the difference between the photon and jet energy. $E_0$, $R$ and $S$ were fit as a function of jet rapidity and measured energy, which lead to uncertainties coming from the fit (statistical) and the method (systematic). The total correction $C^{JES}$ was approximately 1.4 for data jets in the energy range expected for jets associated with top quark events. The uncertainties on $C^{JES}$, which were dominated by the systematic uncertainty of the out-of-cone showering correction $S(\eta_{det}, E^m)$, were a few percent and were dependent on the jet energy and rapidity.

The jet energy resolution was measured in photon + jet data for low jet energies and dijet data for higher jet energy values. Fits to the transverse energy asymmetry $|p_T(1) - p_T(2)|/(p_T(1) + p_T(2))$ between the transverse momenta of the back-to-back jets and/or photon ($p_T(1)$ and $p_T(2)$) were then used to obtain the jet energy resolution as a function of jet rapidity and transverse energy. The uncertainties on the jet energy resolution were dominated by limited statistics in the samples used.

In this analysis, we considered a data set consisting of events with four or more reconstructed jets, in which the scalar sum of the uncorrected transverse momenta $H_T^{uncorr}$ of all the jets in the event was greater than 90 GeV/c. The final analysis sample was a subset of this sample, where at least six jets with corrected transverse momentum greater than 15 GeV/c and $|y| < 2.5$ were required. Events with isolated high transverse momentum electron or muon candidates were vetoed to ensure that the all-hadronic and leptonic $tt$ samples were disjunct. In addition, we rejected events where two distinct $p\bar{p}$ interactions with separate primary vertices were observed and the jets in the event were not assigned to only one of the two primary vertices. The primary vertex requirement did not affect minimum bias interactions or $tt$ events. Table 1 lists the efficiencies after the first set of selection cuts, commonly referred to as preselection, which includes the requirements on the primary vertex, the number of reconstructed jets and the presence of isolated leptons, and the efficiency after preselection and after preselection and the trigger. Besides selecting all hadronic $tt$ events, the analysis was also expected to accept a small contribution from the semi-leptonic (lepton+jets) $tt$ decay channel. The combined efficiency included the fully hadronic and semi-leptonic $W$-boson branching fractions of 0.4619±0.0048 and 0.4349±0.0027 respectively [10].

We used a secondary vertex tagging algorithm (SVT) to identify $b$-quark jets. The algorithm was the same as used in previously published DØ $tt$ production cross-section measurements [8, 9]. Secondary vertex candidates were reconstructed from two or more tracks in the jet, removing vertices consistent with originating from long-lived light hadrons as for example $K^{0}_{S}$ and $\Lambda$. Two configurations of the secondary vertex algorithm were used; these were labeled “loose” and “tight” respectively. If a reconstructed secondary vertex in the jet had a transverse decay length $L_{xy}$ significance ($L_{xy}/\sigma_{L_{xy}} > 5$) (7), the jet was tagged as a loose (tight) $b$-quark jet. The loose SVT was chosen to efficiently identify $b$-quark jets, while the tight SVT was configured to accept only very few light quark jets while sacrificing a small reduction in the effi-
preselection 0.2706 ± 0.0016 0.0311 ± 0.0008 0.1385 ± 0.0011
trigger 0.2527 ± 0.0015 0.0268 ± 0.0007 0.1284 ± 0.0010

FIG. 1: The $H_T$ distribution for single-tag events (a) and
double-tag events (b). Shown are the data (points), the back-
ground (solid line) and the expected $t\bar{t}$ distribution (filled his-
togram) multiplied by 140 (60) for the single (double)-tag
analysis.

(4) $\langle \eta^2 \rangle$: The $p_T$-weighted mean square of the $y$ of
the jets in an event (Fig. 4), see also Ref. [11].
(5) $\mathcal{M}$: The mass-$\chi^2$ variable, which was defined as
$\mathcal{M} = (M_{W_1} - M_W)^2/\sigma_{M_W}^2 + (M_{W_2} - M_W)^2/\sigma_{M_W}^2 + (m_t - m_{\ell})^2/\sigma_{m_t}^2$, where the parameters $M_W$, $\sigma_{M_W}$ and $\sigma_{m_t}$
were the invariant mass and mass resolution from the jet

FIG. 2: The $E_T^{56}$ distribution for single-tag events (a) and
double-tag events (b). Shown are the data (points), the back-
ground (solid line) and the expected $t\bar{t}$ distribution (filled his-
togram) multiplied by 140 (60) for the single (double)-tag
analysis.

FIG. 3: The $A$ distribution for single-tag events (a) and
double-tag events (b). Shown are the data (points), the back-
ground (solid line) and the expected $t\bar{t}$ distribution (filled his-
togram) multiplied by 140 (60) for the single (double)-tag
analysis.

FIG. 4: The $\langle \eta^2 \rangle$ distribution for single-tag events (a) and
double-tag events (b). Shown are the data (points), the back-
ground (solid line) and the expected $t\bar{t}$ distribution (filled his-
togram) multiplied by 140 (60) for the single (double)-tag
analysis.
FIG. 5: The $\mathcal{M}$ distribution for single-tag events (a) and double-tag events (b). Shown are the data (points), the background (solid line) and the expected $t\bar{t}$ distribution (filled histogram) multiplied by 140 (60) for the single (double)-tag analysis.

FIG. 6: The $M_{34}^{\text{min}}$ distribution for single-tag events (a) and double-tag events (b). Shown are the data (points), the background (solid line) and the expected $t\bar{t}$ distribution (filled histogram) multiplied by 140 (60) for the single (double)-tag analysis.

due to increased heavy flavor content in the double-tag sample, both samples showed a clear discrimination between signal and background.

The overwhelming background also made it possible to use the entire (tagged and untagged) sample to estimate the background. For the loose and tight SVT, we derived a tag rate function ($\text{trf}$ — the probability for any individual jet to have a secondary vertex tag) from the data with $N_{\text{tags}} \leq 1$. $\text{trf}$ was parameterized in terms of the $p_T$, $\phi$ and $y$ of the jet and the coordinate along the beam axis ($z$) of the primary vertex of the event, $z_{\text{PV}}$, in four different $H_T$ bins. To predict the number of tagged jets in the event, it was necessary to correct for a possible correlation between tagged jets. In the single-tag analysis the correlation factor was negligible, unlike in the double-tag analysis, where the presence of $b\bar{b}$+jets events in the sample enhanced the correlation correction. We corrected for correlations caused by $b\bar{b}$ background by applying a correlation factor $C_{ij}$, that was parameterized as a function of the cone distance between the tagged jets, $\Delta R$. Figure 8 shows the number of double-tagged events versus $\Delta R$ as observed in data, and the distribution as modeled by the $\text{trf}$ with and without including $C_{ij}$. We considered significantly different functional forms for the parameterization of $C_{ij}$ and found that the choice of parameterization had little effect on the shape of the modeled background distribution.

The probabilities $p_i$ were used to assign a weight, the probability that the event could have a given number of
FIG. 8: The performance of the TRF prediction on double-tag events (points), without including the correlation factor $C_{ij}$ (dashed histogram), and including $C_{ij}$ for two different functional parameterizations (solid histograms).

tags, to every tagged and untagged event in the sample. To ensure the TRF prediction was accurate in the region of phase space outside the “background” peak of the neural network, we used the region $-0.7 < NN < 0.5$ to determine a normalization. In this region of phase space, the $tt$ content was negligible. A possible dependence on $tt$ content was studied by the addition and/or subtraction of simulated $tt$ events, as was the variation of the interval used for the normalization. Outside the background peak, the TRF predictions were corrected by:

$$SF_i = 1.000 \pm 0.009$$

for the single-tag analysis, and

$$SF_2 = 0.969 \pm 0.014$$

for the double-tag analysis. The errors on the normalization were taken into account as a systematic uncertainty on the number of background events.

Both the single-tag and the double-tag analysis were expected to be dominated by background, even at large values of $NN$. Figures [9] and [10] show the distribution for data (points), the Monte Carlo simulation prediction for $\sigma_{tt} = 0.5$ pb (filled histogram), the background prediction (line histogram) and the signal+background distribution (dashed histogram) [9, 10].

The optimal cut for the single (double)-tag analysis was $NN \geq 0.81$ ($0.78$) shown by a vertical line in Figs. [9] and [10]. Table [II] gives the observed numbers of events ($N_{obs}$), the background prediction ($N_{bg}$) and the efficiency for signal ($\varepsilon_{tt}$) that can be used to calculate the $tt$ production cross section via:

$$\sigma_{tt} = \frac{N_{obs} - N_{bg}}{\varepsilon_{tt}^T (1 - \varepsilon_{TRF}^T)},$$

where $i$ was “$= 1$” for the single-tag analysis and “$\geq 2$” for the double-tag analysis. The number of background events is predicted using the TRF method. It was likely that at values of $NN$ close to unity a certain fraction of the sample used to predict the background actually consists of tagged or untagged $tt$ events, resulting in an increased background prediction. The expected $tt$ contamination of the background sample was corrected by a factor $\varepsilon_{TRF}^T$. In the higher value bins of $NN$, the contribution from untagged $tt$ events was significant. $\varepsilon_{TRF}^T$ was estimated by applying the TRF on $tt$ MC, and comparing the predicted tagging probability for signal to what was expected from background. The size of the Monte Carlo sample dominates the uncertainty on $\varepsilon_{TRF}^T$.

Table [II] lists the systematic uncertainties on the estimate of the number of background events, the selection efficiency and the background contamination. The first was uncorrelated between the two analyses, while the latter two were correlated as they were derived from the same Monte Carlo samples. For the single-tag analysis, the systematic uncertainty
TABLE II: Overview of observed events, background predictions and efficiencies.

| symbol | value |
|--------|-------|
| observed events | $N^{ob}_{\bar{t}t}$ | 495 |
| background events | $N^{bg}_{\bar{t}t}$ | 464.3 ± 4.6(syst) |
| $t\bar{t}$ efficiency | $\varepsilon_T^{2}$ | 0.0242±0.0049(syst) |
| $t\bar{t}$ contamination | $\varepsilon_{TF}^{2}$ | 0.245±0.031(syst) |

The NN output variable for $t\bar{t}$ production cross section in $pp$ interactions at $\sqrt{s}=1.96$ TeV in the fully hadronic decay channel. We used lifetime $b$-tagging and an artificial neural network to distinguish $t\bar{t}$ from background. Our measurement yields a value consistent with SM predictions and previous measurements.

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value assumed for the optimization.