Measurement of the $t\bar{t}$ Production Cross Section in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV Using Missing E_T + jets Events with Secondary Vertex b Tagging

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(Received 22 March 2006; published 23 May 2006)

We present a measurement of the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV which uses events with an inclusive signature of significant missing transverse energy and jets. This is the first measurement which makes no explicit lepton identification requirements, so that sensitivity to $W \to \tau\nu$ decays is maintained. Heavy flavor jets from top quark decay are identified with a secondary vertex tagging algorithm. From 311 pb^{-1} of data collected by the Collider Detector at Fermilab, we measure a production cross section of $5.8 \pm 1.2(\text{stat})^{+0.9}_{-0.7}(\text{syst})$ pb for a top quark mass of 178 GeV$/c^2$, in agreement with previous determinations and standard model predictions.

DOI: 10.1103/PhysRevLett.96.202002 PACS numbers: 14.65.Ha, 13.85.Ni

At the Tevatron $p\bar{p}$ collider, top quarks are produced mainly in pairs through quark-antiquark annihilation and gluon-gluon fusion processes. In the standard model (SM), the calculated cross section for pair production is $6.1^{+0.6}_{-0.8}$ pb [1] for a top mass of 178 GeV$/c^2$ [2] and varies linearly with a slope of -0.2 pb$/(\text{GeV}/c^2)$ with the top quark mass in the range $170\ \text{GeV}/c^2 < m_t < 190\ \text{GeV}/c^2$. Because the Cabibbo-Kobayashi-Maskawa matrix element V_{tb} is close to unity and m_t is large, the SM top quark decays to a W boson and a b quark almost

100% of the time. The final state of top quark pair production thus includes two W bosons and two b-quark jets. When only one W decays leptonically, the $t\bar{t}$ event typically contains a charged lepton, missing transverse energy from the undetected neutrino, and four high transverse energy jets, two of which originate from b quarks [3]. Previous cross section analyses [4–6] select this distinct $t\bar{t}$ signature by requiring well-identified leptons (e, μ) with high transverse momentum. In this Letter, we describe a $t\bar{t}$ production cross section measurement which is sensitive to leptonic W decays regardless of the lepton type and has a sizable acceptance to τ decays of the W boson. The direct identification of τ from $W \to \tau\nu$ decays suffers from a very low efficiency; thus, our measurement, using data collected by a multijet trigger, selects top decays by inclusively requiring a high-p_T neutrino signature rather than charged lepton identification. Events with well-identified high-p_T electrons or muons are explicitly vetoed in order to avoid statistical overlap and provide complementary results with respect to lepton-based measurements.

Results reported in this Letter are obtained from 311 pb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the Collider Detector at Fermilab (CDF II). The CDF II detector consists of a magnetic spectrometer surrounded by calorimeter systems and muon chambers and has been described in detail elsewhere [7]. The beam luminosity is determined, with an uncertainty of 6% [8], using gas Cherenkov counters which measure the average number of inelastic $p\bar{p}$ collisions per bunch crossing.

The data sample used in this analysis is collected by a multijet trigger, which requires four or more $E_T \geq 15$ GeV clusters of contiguous calorimeter towers and a total transverse energy clustered in the calorimeter of $\sum E_T \geq$ 125 GeV. The initial data sample consists of 4.2×10^6 events. The understanding of signal acceptances and efficiencies relies on a detailed simulation of the production processes and the detector response. Inclusively decaying $t\bar{t}$ events, assuming a top quark mass of 178 GeV$/c^2$, are simulated using PYTHIA v6.2 [9] and HERWIG v6.5 [10] generators in conjunction with the CTEQ5L [11] parton distribution functions, QQV9.1 [12] for the modeling of b and c hadron decays, and a full simulation of the CDF II detector. Jets are identified as groups of calorimeter tower energy deposits which fall within a cone of radius $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \leq 0.4$. Jet energies, after the absolute energy scale setting, are corrected for calorimeter nonlinearity, losses in the gap between towers, and multiple interactions [13].

The $t\bar{t}$ signature used in the present study ($\not{E}_T$ + jets) consists of large missing transverse energy $\vec{\not{E}}_T$, associated with the neutrino from the leptonic decay of a W boson, and jets. Since the $\not{E}_T$ resolution $\sigma(\not{E}_T)$ is observed to degrade as a function of the total transverse energy of the event, in the form $\sigma(\not{E}_T) \propto \sqrt{\sum E_T}$ [14], the missing E_T significance, defined by $\not{E}_T^{\mathrm{sig}} = |\vec{\not{E}}_T|/\sqrt{\sum E_T}$, is used for event selection. Besides the requirement of large $\not{E}_T^{\mathrm{sig}}$, further background rejection can be achieved by exploiting $\vec{\not{E}}_T$-related geometrical properties. The neutrino direction for $t\bar{t} \to \not{E}_T$ + jets events is, in general, uncorrelated with the jet directions in the transverse plane. On the contrary, background events for which the $\vec{\not{E}}_T$ is mainly due to jet energy mismeasurement or to b-quark semileptonic decays are more likely to have $\vec{\not{E}}_T$ aligned with a jet direction. The minimum $\Delta\phi$ difference between the $\vec{\not{E}}_T$ and any jet in the event, $\min\Delta\phi(\not{E}_T, \mathrm{jets})$, is used as an analysis cut. Events containing identified high-p_T electrons or muons, as defined in Ref. [5], are removed, in order to increase the relative contribution of $W \to \tau\nu$ decays and to provide a statistically independent sample with respect to other lepton+jets cross section analyses.

To reject events with only light quark or gluon jets, we require at least one jet to be identified as originating from a b quark. The presence of b jets ("tags") is established by the identification of secondary decay vertices using the SECVTX algorithm [5]. An optimization procedure, aimed at minimizing the relative statistical uncertainty on the cross section measurement, sets $N_{\mathrm{jet}}(E_T \geq 15\,\mathrm{GeV}; |\eta| \leq 2.0) \geq 4$, $\not{E}_T^{\mathrm{sig}} \geq 4.0$ GeV$^{1/2}$ and $\min\Delta\phi(\not{E}_T, \mathrm{jets}) \geq 0.4$ rad as the best kinematical selection cuts. After these requirements, the data sample is reduced to 597 events with an expected pretag signal to background ratio $S/B \sim 1/5$.

Background events with b tags arise from QCD heavy flavor production, electroweak production of W bosons associated with heavy flavor jets, and from false identification by the SECVTX algorithm. The overall number of background b tags is estimated from the multijet sample by applying a parametrization of the per-jet tagging probability. The tagging probability is calculated using $\sim$879 000 multijet data events with exactly three jets having $E_T \geq$ 15 GeV and $|\eta| \leq 2.0$. It is parametrized on a per-jet basis as a function of the jet E_T, track multiplicity, and the projection of the $\vec{\not{E}}_T$ along the jet direction, defined by $\not{E}_T^{\mathrm{prj}} = \vec{\not{E}}_T \cos\Delta\phi(\not{E}_T, \mathrm{jet})$. The $t\bar{t}$ contamination in this control sample is negligible. The jet b-tagging rate, calculated as the ratio of the number of b-tagged jets to the number of jets with at least two good tracks with hits in the silicon detector, is shown in Fig. 1. The $\not{E}_T^{\mathrm{prj}}$ parametrization accounts for background b tags from $b\bar{b}$ production processes, whose b-tag rate is enhanced at high positive values of the $\not{E}_T^{\mathrm{prj}}$ due to the correlation of $\vec{\not{E}}_T$ and b-jet direction in the case of a semileptonic b-quark decay. The extrapolation of the 3-jet b-tag rate to higher jet multiplicity events is checked by comparing the predicted and observed b-tag rates as a function of the number of jets in the multijet sample without the kinematical selection on $\not{E}_T^{\mathrm{sig}}$ and $\min\Delta\phi(\not{E}_T, \mathrm{jets})$, as shown in Fig. 2(a). The capability of the parametrization to track possible sample composition changes introduced by the kinematical

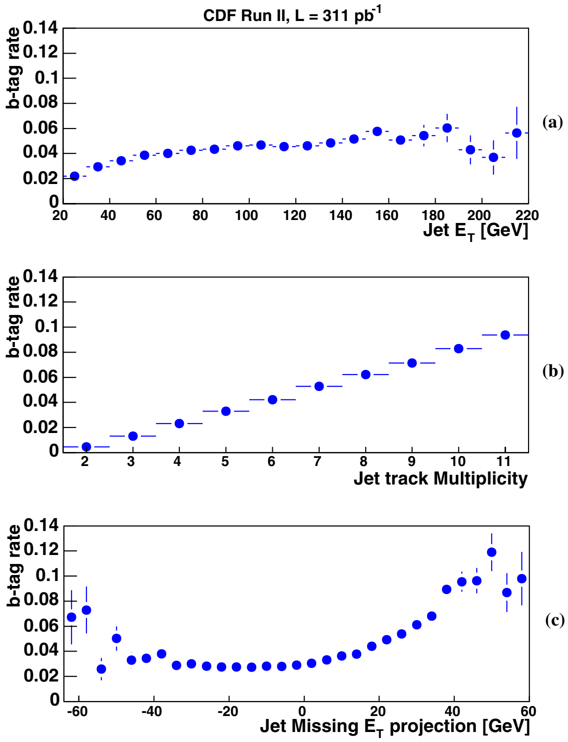

FIG. 1 (color online). Tagging rate probability parametrization in the multijet sample as a function of (a) jet E_T, (b) track multiplicity, and (c) missing E_T projection.

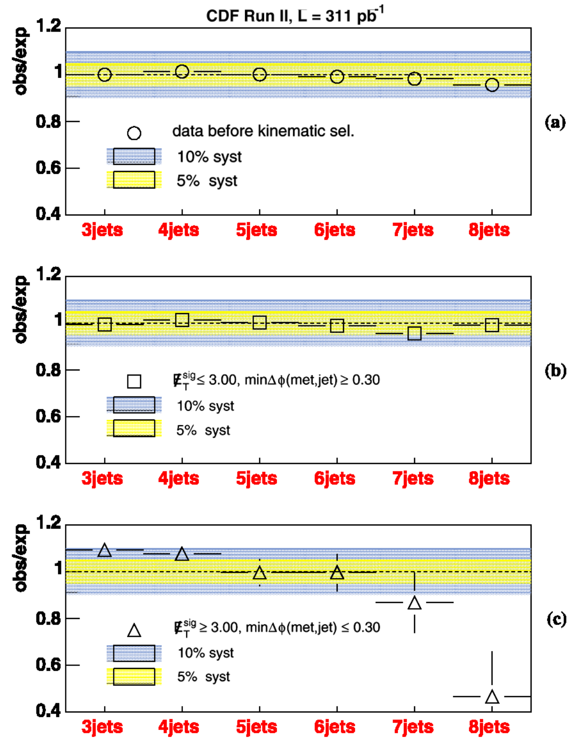

FIG. 2 (color online). Ratio of observed to expected b tags as a function of the number of jets in the data before the optimized kinematical selection on $\not{E}_T^{\rm sig}$ and min$\Delta\phi(\not{E}_T, \text{jets})$ (a) and in control samples: $\not{E}_T^{\rm sig} \leq 3.0$ GeV$^{1/2}$, min$\Delta\phi(\not{E}_T, \text{jets}) \geq 0.3$ rad (b) and $\not{E}_T^{\rm sig} \geq 3.0$ GeV$^{1/2}$, min$\Delta\phi(\not{E}_T, \text{jets}) \leq 0.3$ rad (c).

selection is established by constructing the ratio of observed over expected b tags in two separate control samples of multijet data, depleted of signal contaminations, as shown in Figs. 2(b) and 2(c), respectively. The first control sample is defined by $\not{E}_T^{\rm sig} \leq 3.0$ GeV$^{1/2}$, min$\Delta\phi(\not{E}_T, \text{jets}) \geq 0.3$ rad; the second as $\not{E}_T^{\rm sig} \geq 3.0$ GeV$^{1/2}$, min$\Delta\phi(\not{E}_T, \text{jets}) \leq 0.3$ rad. The b-tag rate parametrization is found to predict the non-$t\bar{t}$ background to within 10% in the $4 \leq N_{\rm jet} \leq 6$ region where 96.4% of the $t\bar{t}$ signal is expected. This value is thus adopted as the systematic uncertainty on the background prediction. Additional checks, using low jet multiplicity events from leptonic W data samples, show agreement between observed and predicted b tags to within the quoted uncertainty.

The sample selected with the optimized kinematical requirements described above and the requirement of at least one b-tagged jet consists of 106 events, containing a total of 127 b-tagged jets. The number of b-tagged jets yielded by background processes in that sample is expected to be $N_{\rm exp} = 67.4 \pm 2.7 \pm 6.7$. The first uncertainty contribution is due to the limited number of events in the 3-jet sample used for the tagging rate parametrization, while the second contribution is the 10% systematic uncertainty on the b-tag rate parameterization discussed above (Fig. 2). The 597 pretag data events are expected to contain a non-negligible $t\bar{t}$ component, due to the S/B enhancement provided by the kinematical selection, which yields a background overestimate. The $N_{\rm exp}$ value is corrected, to $N'_{\rm exp} = 57.4 \pm 8.1$, to account for this effect. Table I summarizes the number of b-tagged jets expected from Monte Carlo simulation for each $t\bar{t}$ decay mode satisfying the kinematical and ≥ 1 b-tag requirements, as well as the predicted and observed b tags in the selected data sample as a function of the jet multiplicity of the events. In Table I, the numbers of b tags from events with only three jets are provided as a cross-check of the background. The excess in the number of b tags, for $N_{\rm jet} \geq 4$, is ascribed to top pair production. Final states with $W \to \tau\nu$ decays account for $\sim$44% of the signal acceptance.

In order to further establish the $t\bar{t}$ signal in the selected data, we perform binned likelihood fits to kinematical distributions. The stability of the fitting technique is checked using simulations with known signal fractions. We fit $\not{E}_T$ and $\Delta\phi(\not{E}_T, \text{tagged jet})$ data distributions to the sum of a $t\bar{t}$ and a background template. The former is obtained from Monte Carlo $t\bar{t}$ inclusive events; the latter is derived from the tagging rate parametrization applied to the data. Results for the $\Delta\phi(\not{E}_T, \text{tagged jet})$ fit are dis-

TABLE I. Number of b-tagged jets expected from Monte Carlo $t\bar{t}$ production using $\sigma(t\bar{t}) = 6.1$ pb ($m_t = 178$ GeV$/c^2$), predicted by the tagging rate parametrization, and observed in the selected sample, as a function of the jet multiplicity. The total uncertainty on the number of predicted background b tags is the sum in quadrature of the statistical uncertainty and of a 10% systematic uncertainty. The number of background b tags corrected for the $t\bar{t}$ contamination in the pretagging data sample is also provided for the signal region. Uncertainties on signal contributions are statistical only.

Number of jets	3	4	5	≥ 6
$t\bar{t} \to ll'(l, l' = e/\mu)$	0.15 ± 0.02	0.75 ± 0.04	0.30 ± 0.02	0.10 ± 0.02
$t\bar{t} \to \tau l$ ($l = e/\mu/\tau$)	0.22 ± 0.02	1.80 ± 0.05	0.79 ± 0.04	0.26 ± 0.02
$t\bar{t} \to e$ + jets	0.68 ± 0.04	6.61 ± 0.11	8.70 ± 0.13	4.25 ± 0.09
$t\bar{t} \to \mu$ + jets	1.07 ± 0.04	11.92 ± 0.15	6.56 ± 0.11	2.47 ± 0.07
$t\bar{t} \to \tau$ + jets	1.00 ± 0.04	10.98 ± 0.14	11.71 ± 0.15	5.53 ± 0.10
$t\bar{t} \to$ jets	0.01 ± 0.01	0.09 ± 0.01	0.14 ± 0.02	0.22 ± 0.02
$t\bar{t} \to X$	3.13 ± 0.08	32.15 ± 0.24	28.14 ± 0.23	12.83 ± 0.15
Background b-tagged jets	32.68 ± 3.46	37.53 ± 4.14	21.44 ± 2.76	8.47 ± 1.40
Corrected background b-tagged jets	$\cdots$	33.14 ± 4.01	17.58 ± 2.85	6.71 ± 2.78
Observed b-tagged jets	31	53	55	19

played in Fig. 3. The fitted $t\bar{t}$ components in the selected data [$68 \pm 12\%$ and $44 \pm 12\%$ for the $\not\!\!E_T$ and $\Delta\phi(\not\!\!E_T$, tagged jet) fits, respectively] are in agreement with the overall prediction calculated from b-tag counting, before any correction to account for the $t\bar{t}$ contamination in the pretagging data sample ($47 \pm 5\%$ determined comparing the number of expected and observed b tags, for $N_{\rm jet} \geq 4$, in Table I).

The efficiency of the trigger, the kinematical selection, and the b-tagging algorithm are evaluated using inclusive $t\bar{t}$ Monte Carlo events. The combined efficiency of the trigger and kinematical selection amounts to $\epsilon_{\rm kin} = 4.88\% \pm 0.43\%$ for a top mass of $m_t = 178$ GeV$/c^2$, where the dominant uncertainty is determined by the comparison of the results from the PYTHIA and HERWIG generators. Other sources of systematic uncertainty are evaluated by varying Monte Carlo generation settings with respect to the default values and by applying systematic variations of the jet energy correction factors; the trigger acceptance uncertainty is determined by comparing trigger turn-on curves between Monte Carlo and data events (Table II). The average number of b tags per Monte Carlo $t\bar{t}$ event is found to be $\epsilon_{\rm tag}^{\rm ave} = 0.789 \pm 0.046$, and it is corrected according to the Monte Carlo SECVTX efficiency scale factor of 0.909 ± 0.060 to reproduce the data b-tagging efficiency [5].

The cross section is calculated with a Poisson likelihood function in which the maximum likelihood solution for $\sigma(t\bar{t})$ is given by: $\sigma(t\bar{t}) = (N_{\rm obs} - N'_{\rm exp})/(\epsilon_{\rm kin} \cdot \epsilon_{\rm tag}^{\rm ave} \cdot \mathcal{L}_{\rm int})$, where $N_{\rm obs}$ and $N'_{\rm exp}$ are the number of b-tagged jets observed and expected from background events by the tagging rate parametrization in the selected data, and $\mathcal{L}_{\rm int}$ is the integrated luminosity of the multijet data sample. The input parameters $\mathcal{L}_{\rm int}$, $\epsilon_{\rm kin}$, $\epsilon_{\rm tag}^{\rm ave}$, and $N'_{\rm exp}$ are subject to Gaussian constraints. With these input values, we measure a top pair production cross section of $5.8 \pm 1.2({\rm stat})^{+0.9}_{-0.7}({\rm syst})$ pb. Additional samples of inclu-

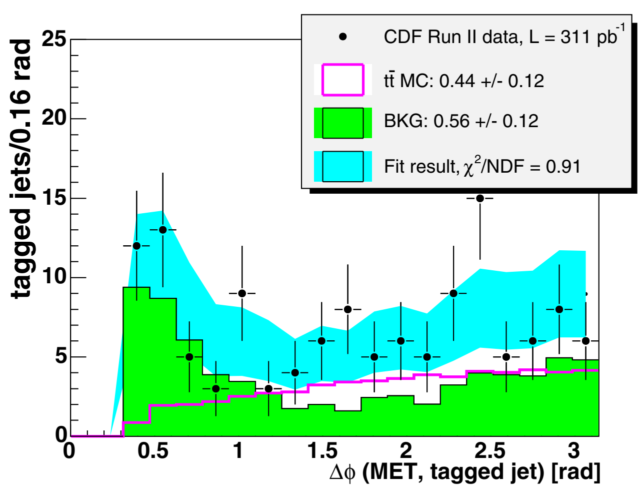

FIG. 3 (color online). $\Delta\phi(\not\!\!E_T$, tagged jet) distribution for data after kinematical selection and with at least one b-tagged jet. The data are fit to the sum of $t\bar{t}$ signal and background templates as described in the text.

TABLE II. Relevant sources of systematic uncertainty.

Source	Relative error
$\epsilon_{\rm kin}$ systematics	
Generator dependence	8.2%
Trigger acceptance	2.0%
Gluon radiation	2.0%
Parton distribution functions	1.6%
Jet energy scale	1.5%
Others	
Background prediction method	10.0%
Luminosity measurement	6.0%
$\epsilon_{\rm tag}^{\rm ave}$ (SECVTX scale factor)	5.8%

sive $t\bar{t}$ Monte Carlo events generated with different m_t values in the range $[130, 230]$ GeV$/c^2$ are used to compute the cross section measurement dependence on m_t. The cross section measurement changes by ± 0.05 pb for each ∓ 1 GeV$/c^2$ change in the top quark mass from the initial value of 178 GeV$/c^2$. For instance, we measure $\sigma(t\bar{t}) = 6.0 \pm 1.2(\text{stat})^{+0.9}_{-0.7}(\text{syst})$ pb assuming a top quark mass of 175 GeV$/c^2$. The change is due to the varying signal selection efficiency with top quark mass.

In conclusion we report the first measurement of the top pair production cross section of $\sigma(t\bar{t}) = 5.8^{+1.5}_{-1.4}$ pb using an inclusive selection of $\not{E}_T$ + jets $t\bar{t}$ decays. The result is complementary to other cross section analyses [4–6], maintains high sensitivity with respect to $W \to \tau\nu$ $t\bar{t}$ decays, and is in good agreement with SM calculations [1] and previous measurements.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, United Kingdom; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; in part by the European Community's Human Potential Programme under Contract No. HPRN-CT-2002-00292; and by the Academy of Finland.

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[3] The CDF II coordinate system uses θ and ϕ as the polar and azimuthal angles, respectively, defined with respect to the proton beam axis direction, z. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$. The transverse momentum of a particle is $p_T = p\sin(\theta)$, and the transverse energy is defined as $E_T = E\sin(\theta)$. The missing transverse energy $\vec{\not{E}}_T$ is defined by $\vec{\not{E}}_T = -\sum_i E_T^i \hat{\mathbf{n}}_\mathbf{i}$, where the index i runs over all calorimeter towers with $|\eta| < 3.6$, and $\hat{\mathbf{n}}_\mathbf{i}$ is a unit vector perpendicular to the beam axis and pointing at the ith calorimeter tower.

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