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Measurement of the $t\bar{t}$ Production Cross Section in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV using Lepton plus Jets Events

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We present the measurement of the top quark pair production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using 318 pb^{-1} of data collected by the CDF detector at the Fermilab Tevatron. We measure the cross section in events with one high transverse momentum electron or muon, large missing transverse energy and three or more jets, where at least one bottom quarks from the top quark decay is identified via a secondary vertex tagging algorithm. The measured $t\bar{t}$ cross section is $8.7^{+0.9}_{-0.9}(\text{stat})^{+1.2}_{-0.9}(\text{syst})$ pb, assuming a top quark mass of 178 GeV. The cross section measurement in the subsample in which both b-quark jets are identified gives $10.1^{+1.6}_{-1.4}(\text{stat})^{+2.1}_{-1.4}(\text{syst})$ pb. We present one additional measurement of the $t\bar{t}$ cross section in the same dataset but without the b-tagging requirement. Top quark events are distinguished from the primary background of W boson production with associated jets using an artifical neural network method with a variety of kinematic quantities. This measurement uses a larger dataset albeit with a smaller $t\bar{t}$ fraction. The $t\bar{t}$ cross section without b-tagging is measured to be $6.0 \pm 0.8(\text{stat}) \pm 1.0(\text{syst})$ pb.

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The top quark, discovered at the Fermilab Tevatron in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV [1], completes the third fermion generation in the Standard Model (SM). In Run II, top quarks are pair-produced in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV through $q\overline{q}$ annihilation ($\sim 85\%$) or gluon fusion ($\sim 15\%$). The determination of the top pair production cross section ($\sigma_{t\bar{t}}$) is a test of quantum chromodynamics (QCD) and large deviations from SM predictions would be an indication of new physics. The $\sigma_{t\bar{t}}$ theoretical predictions have an uncertainty of approximately 15% [2]. This level of precision has been achieved experimentally for the first time with the measurements presented here.

We report on several measurements of the top quark pair production cross section in the lepton + jets decay channel using the Collider Detector at Fermilab (CDF) with 318 pb^{-1} of data collected between March 2002 and August 2004. In the lepton + jets channel, one W boson decays to an electron or a muon and a neutrino, while the other decays hadronically. The final state includes a charged lepton with high transverse momentum (p_T), large missing transverse energy ($\not\!\!E_T$) from the undetected neutrino, two light-quark jets from the hadronic W, and two b-quark jets.

The CDF detector is a general-purpose particle detector located at one of the two interaction points at the Tevatron Collider. Its detailed description can be found elsewhere[3]. The data were collected with an inclusive high-p_T lepton trigger that requires an electron (muon) with $E_T > 18$ GeV ($p_T > 18$ GeV/c). Inclusive lepton + jets samples are selected by requiring exactly one lepton that satisfies tight lepton identification criteria, and $\not\!\!E_T > 20$ GeV. Electron events are selected by requiring one isolated electron with transverse energy $E_T > 20$ GeV in the central electromagnetic calorimeter. Muon events are required to have one isolated muon with transverse momentum $p_T >$ 20 GeV$/c$ in the central region. To extract the $t\bar{t}$ signal from this inclusive sample, we require at least three jets with $|\eta| < 2$ and corrected transverse energy [6] greater than 15 GeV, clustered with a cone-based algorithm with a cone size $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$.

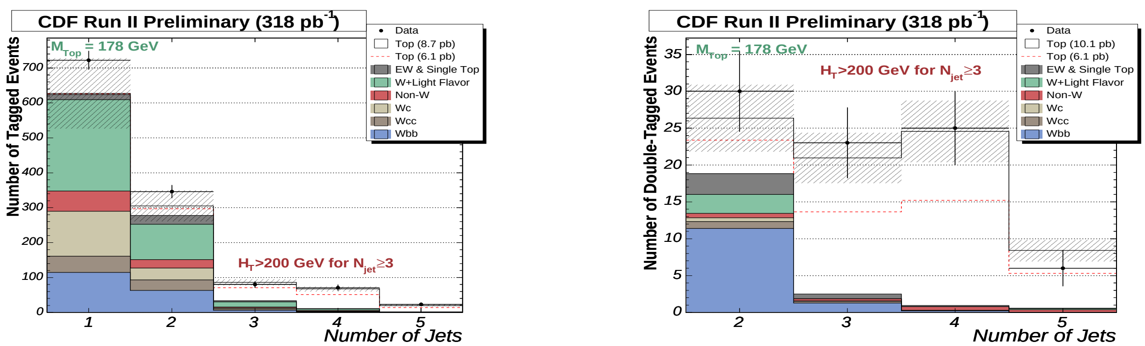
The major source of background in the lepton + jets sample is the production of W bosons in association with multiple jets. Smaller contributions come from generic QCD production in which the W signature is faked (non-W) and lower-rate electroweak processes such as single top production, diboson production (WW, WZ, ZZ) associated with jets, and $Z \to \tau\tau$.

On average, events from $t\bar{t}$ production have larger total transverse energy than background events; therefore, for events with at least three jets, we require the scalar sum of all transverse energy in the event (H_T) to be larger than 200 GeV. In order to reduce backgrounds from non-W events, we require the transverse mass of the lepton and the missing energy to be consistent with W boson production, $M_T^W > 20$ GeV.

Identification of at least one b-quark jet (b-tagging) allows for a significant increase in the signal-to-background ratio. When both b-quark jets are identified, $t\bar{t}$ events can be fully reconstructed; the only remaining ambiguities are the longitudinal component of the neutrino momentum and the $b-W$ pairing. We perform the measurement with a new, high-efficiency version of the secondary vertex b-tagging algorithm (SecVtx) [4]. The result is cross-checked with the high-purity version of the SecVtx algorithm and with an artificial neural network (ANN) measurement that does not require b-tagging. In data, the b-tagging efficiency per $t\bar{t}$ event with ≥ 1 (≥ 2) b-tags is $(69 \pm 5)\%$ ($(23 \pm 3)\%$).

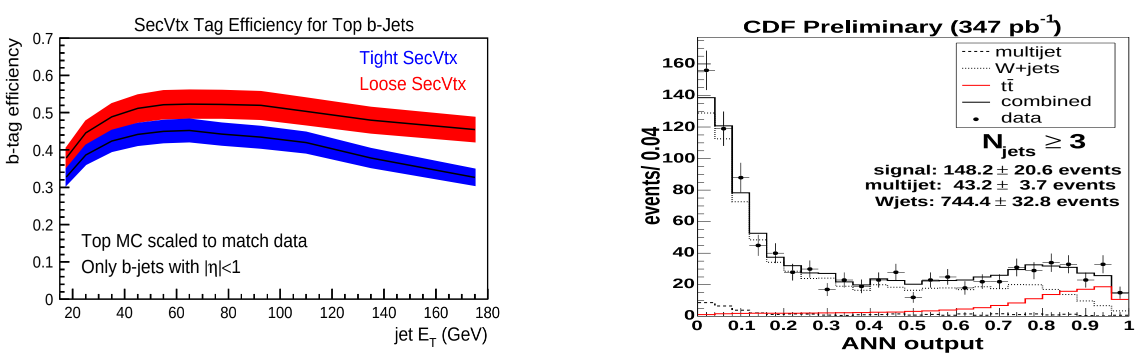
The total corrected background in the signal region with at least one b-tag (two b-tags) is 46 ± 9 (4.1 ± 2.5) events. We observe 174 events with at least one b-tag and 54 events with at least two b-tagged jets. The double b-tagged sample has been increased by a factor of seven since our last $\sigma_{t\bar{t}}$ publication [4], benefiting from a factor of 2.1 increase in the $t\bar{t}$ double-tagging efficiency. We interpret the excess of events over the expected background as $t\bar{t}$ signal. Figure 1 shows the sample composition as a function of the number of jets in the event.

Assuming a top quark mass of 178 GeV/c^2, we measure $\sigma_{t\bar{t}} = 8.7^{+0.9}_{-0.9}(\text{stat})^{+1.2}_{-0.9}(\text{syst})$ pb, where the systematic uncertainty includes a 6% contribution from the integrated luminosity estimate. The $\sigma_{t\bar{t}}$ measurement with double b-tagged events is $10.1^{+1.6}_{-1.4}(\text{stat})^{+2.1}_{-1.4}(\text{syst})$ pb. The acceptance and efficiency both have a small dependence on the top quark mass; the cross section measurement changes by ± 0.08 pb for each ∓ 1 GeV/c^2 change in the assumed top mass from the initial value of 178 GeV/c^2, in the range of 160 – 190 GeV/c^2.



(a) (b)

Figure 1: Top cross section measurement with high-efficiency b-tagging. Data event yields compared to expectations from $t\bar{t}$ and backgrounds as a function of the number of jets in the event. (a) Measurement with at least one b-tag; (b) Measurement with at least two b-tags.



(a) (b)

Figure 2: (a) Efficiency of the high-efficiency (loose) and high-purity (tight) secondary vertex algorithms for b-jets in $t\bar{t}$ events, as a function of the jet E_T. (b) Top cross section measurement without b-tagging requirement. Neural network output for events with at least three jets. The data is compared with the expectations from background and the $t\bar{t}$ signal.

The measurement with the high-purity b-tagging follows the same analysis procedure and it is used to cross check these results. Figure 2(a) shows the efficiency of the two b-tagging algorithms for b-jets in $t\bar{t}$ events, as a function of the jet E_T. We observe 138 (33) events with at least one (two) b-tags in the signal region, compared to a background of 25 ± 5 (3 ± 2) events. This gives $\sigma_{t\bar{t}} = 8.7^{+0.9}_{-0.9}(\text{stat})^{+1.2}_{-0.9}(\text{syst})$ pb and $8.7^{+1.8}_{-1.6}(\text{stat})^{+1.9}_{-1.3}(\text{syst})$ pb for single- and double-tagged events, both in good agreement with the cross section results from the high-efficiency b-tagger.

The measurement without b-tagging uses a similar lepton+jets event selection, with the following two exceptions: first, there is no requirement on the H_T; second, we do not use the M_T^W requirement to reduce the non-W background. Instead, if the $\not\!\!E_T$ is below 30 GeV, we require that the angle between the $\not\!\!E_T$ and the highest E_T jet in the transverse plane, $\Delta\phi$, be greater than 0.5 and less than 2.5 radians. This analysis uses an ANN technique [5] to discriminate between top pair production and background processes. The ANN uses kinematic and topological variables independent of b-jet identification. This kinematic method allows to check the assumptions in the b-tag method and test the modeling of signal and background processes with higher statistics.

The observed ANN output distribution and fit result for $W+\geq 3$ jet events is shown in Figure 2(b). From the 936 events in the $W+\geq 3$ jet data sample, we found that 148.2 ± 20.6 are $t\bar{t}$ events. This results in $\sigma_{t\bar{t}} = 6.0 \pm 0.8(\text{stat}) \pm 1.0(\text{syst})$ pb, assuming a top mass of 178 GeV/c^2. The measured cross section depends on the assumed top mass because both the $t\bar{t}$ acceptance and the shape of the $t\bar{t}$ neural network template change as the top mass changes. For a top mass of 175 GeV/c^2, we get a measured cross section of $6.3 \pm 0.8(\text{stat}) \pm 1.0(\text{syst})$ pb.

We have made several measurements of the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} =$ 1.96 TeV using lepton + jets events. The most precise measurement, $8.7^{+0.9}_{-0.9}(\text{stat})^{+1.2}_{-0.9}(\text{syst})$ pb, obtained when we require at least one b-tagging, has a relative uncertainty similar to the theoretical prediction. The $\sigma_{t\bar{t}}$ measurement with the two b-jets identified is $10.1^{+1.6}_{-1.4}(\text{stat})^{+2.1}_{-1.4}(\text{syst})$ pb; while the measurement without the b-tagging requirement is $6.0 \pm 0.8(\text{stat}) \pm 1.0(\text{syst})$ pb. These cross section measurements are in good agreement among each other and with SM theoretical expectations.

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