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Dependence of the $t\bar{t}$ production cross section on the transverse momentum of the top quark

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We present a measurement of the differential cross section for $t\bar{t}$ events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV as a function of the transverse momentum (p_T) of the top quark. The selected events contain a high-p_T lepton (ℓ), four or more jets, and a large imbalance in p_T, and correspond to 1 fb^{-1} of integrated luminosity recorded with the D0 detector. Each event must have at least one candidate for a b jet. Objects in the event are associated through a constrained kinematic fit to the $t\bar{t} \to WbW\bar{b} \to \ell\nu b\, q\bar{q}'\bar{b}$ process. Results from next-to-leading-order perturbative QCD calculations agree with the measured differential cross section. Comparisons are also provided to predictions from Monte Carlo event generators using QCD calculations at different levels of precision.

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The transverse momentum (p_T) of top quarks in $t\bar{t}$ events provides a unique window on heavy-quark production at large momentum scales. In the standard model (SM), the lifetime of the top quark is far shorter than the characteristic hadron-formation time of quantum chromodynamics (QCD), which provides access to the properties and kinematics of a "free" quark, such as mass, charge, spin, and p_T, that are almost unaffected by bound-state formation or final-state interactions [8]. Measurements of differential cross sections in the $t\bar{t}$ system test perturbative QCD (pQCD) for heavy-quark production, and can constrain potential physics beyond the

SM [9].

In this Letter, we present a new high-statistics measurement of the inclusive differential cross section for $p\bar{p} \to t\bar{t} + X$ production at $\sqrt{s} = 1.96$ TeV as a function of the p_T of the top quark. The data were acquired with the D0 detector at the Fermilab Tevatron Collider and correspond to an integrated luminosity of ≈ 1 fb^{-1}. This measurement was performed in the ℓ+jets decay channel of $t\bar{t} \to WbW\bar{b} \to \ell\nu + b\bar{b} + \geq 2$ jets, where ℓ represents an e or μ from the decay of the W boson or from $W \to \tau \to \ell$. The analysis uses similar data samples, event selection, and corrections as used in the inclusive $t\bar{t} \to \ell$+jets cross-section measurements detailed in Ref. [10]. The dependence of the cross section on the p_T of the top quark was examined previously using $\approx 100\,\text{pb}^{-1}$ of Tevatron Run I data at $\sqrt{s} = 1.8$ TeV [11], where no deviations from the SM were reported.

The D0 detector [12] is equipped with a 2 T solenoidal magnet surrounding silicon-microstrip and scintillating-fiber trackers. These are followed by electromagnetic (EM) and hadronic uranium/liquid argon calorimeters, and a muon spectrometer consisting of 1.8 T iron toroidal magnets and wire chambers and scintillation counters. Electrons are identified as track-matched energy clusters in the EM calorimeter. Muons are identified by matching tracks in the inner tracking detector with those in the muon spectrometer. Jets are reconstructed from calorimeter energies using the Run II iterative seed-based midpoint cone algorithm with a radius of 0.5 [13]. Jets are identified as originating from a b quark using an artificial neural network (b NN) which combines several tracking variables [14]. Large missing transverse energy, $\not\!\!E_T$ (the negative of the vector sum of transverse energies of calorimeter cells, corrected for reconstructed muons) signifies the presence of an energetic neutrino. Events are selected using a three-level trigger system, which has access to tracking, calorimeter, and muon information, and assures that only events with the desired topology or with objects above certain energy thresholds are kept for further analysis.

Events accepted by lepton+jets triggers are subject to additional selection criteria including exactly one isolated lepton with $p_T > 20$ GeV/c and ≥ 4 jets with $p_T > 20$ GeV/c and $|\eta| < 2.5$ [15]; at least one jet must have $p_T > 40$ GeV/c. At least one jet is also required to be tagged by the b NN algorithm. Additionally, we require $\not\!\!E_T > 20$ GeV (25 GeV) for the e+jets (μ+jets) channel and electrons (muons) with $|\eta| < 1.1$ (2.0).

Our measurement uses the ALPGEN [16] event generator, with PYTHIA [17] for parton showering, hadronization, and modeling of the underlying event, to simulate the inclusive $t\bar{t}$ signal. A PYTHIA sample serves as a cross check. Backgrounds are modeled with ALPGEN+PYTHIA for W+jets and Z+jets production, PYTHIA for diboson (WW, WZ, and ZZ) production, and COMPHEP [18] for single top-quark production. The detector response is simulated using GEANT [19]. The simulated $t\bar{t}$ signal is normalized to the cross section measured in the same final state using the same event selections (including the b-tagging requirement) and data as Ref. [10], namely to $8.46^{+1.09}_{-0.97}$ pb at a top-quark mass $m_t = 170$ GeV/c^2 (in good agreement with the value extracted in this study). The diboson and single top-quark backgrounds are normalized to their SM predictions, Z+jets to the prediction from next-to-leading-order (NLO) pQCD, and W+jets such that the predicted number of events matches the data before applying b tagging. The small multijet background, where a jet mimics an isolated lepton, is estimated from the data [10].

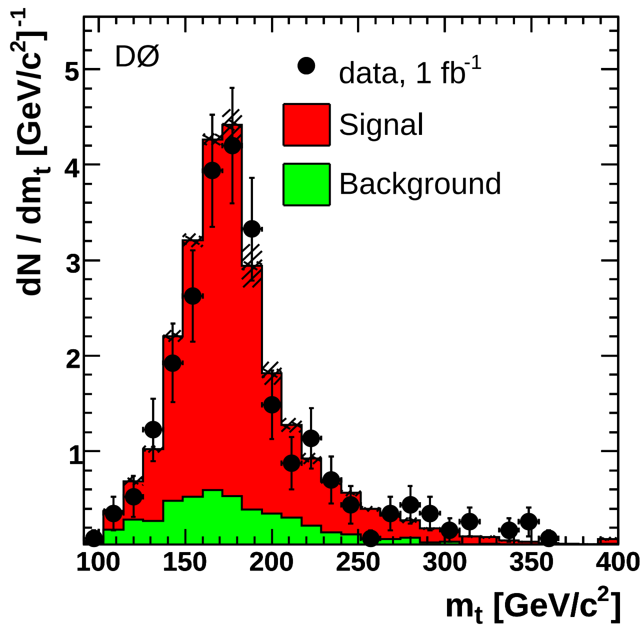

FIG. 1: The reconstructed top-quark mass compared with expectation. Hashed areas represent statistical and jet energy calibration uncertainties on the prediction.

The selection yields 145 and 141 events in the e+jets and μ+jets decay channels, respectively. The measured $t\bar{t}$ signal fraction is 0.79, indicating that this sample is suitable for detailed studies of $t\bar{t}$ production. A constrained kinematic fit to the $t\bar{t}$ final state, which takes account of the unreconstructed neutrino and finite experimental resolution, is used to associate leptons and jets with individual top quarks [20, 21]. The fit assumes equal masses for the two reconstructed top quarks and the two reconstructed W boson masses are constrained to 80.4 GeV/c^2. All possible permutations of objects needed to produce the $t\bar{t}$ system are considered, and the solution of fitted leptonic and hadronic top-quark four-momenta with the smallest χ^2 (the goodness of the fit) is selected for further analysis. The reconstructed top-quark mass (m_t) from the best fit in data, simulated $t\bar{t}$ signal, and background is shown in Fig. 1. There is good agreement between the

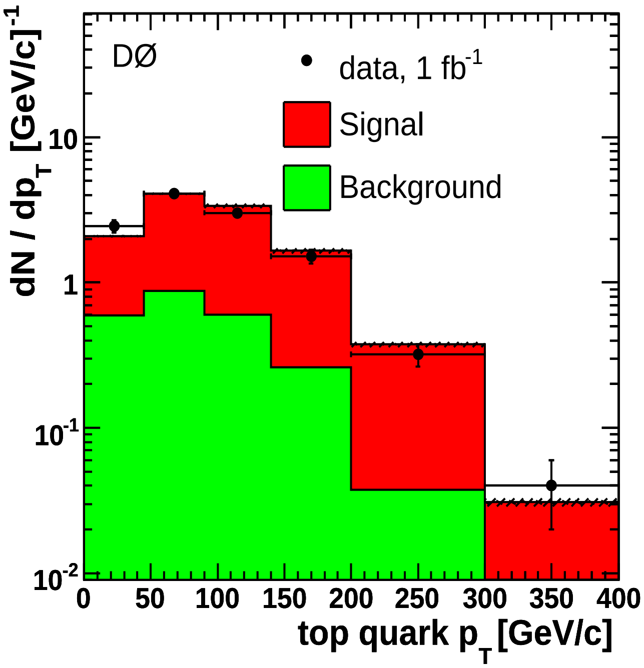

FIG. 2: The p_T spectrum of top quarks (two entries per event) compared with expectation. Hashed areas represent statistical and jet energy calibration uncertainties on the prediction.

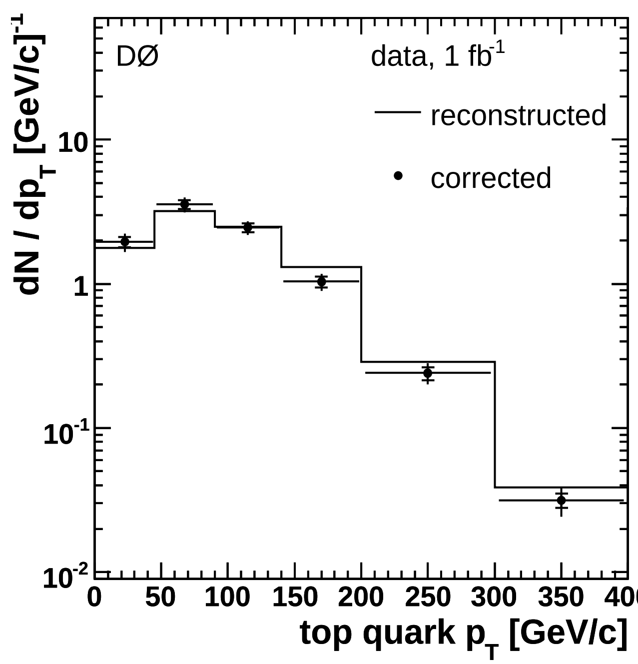

FIG. 3: Comparison between the background-subtracted reconstructed top-quark p_T spectrum and the one corrected for the effects of finite experimental resolution (two entries per event). Inner and outer error bars represent the statistical and total (statistical and systematic added in quadrature) uncertainties, respectively.

data and the sum of signal and background expectations in terms of the shape, resolution, and mean of the distribution in m_t (χ^2/NDF = 1.28). The p_T spectrum of the top quark (for leptonic and hadronic entries) in data, together with predicted signal and background, is shown in Fig. 2 for the best solution but now refitted with a top-quark mass fixed to 170 GeV/c^2 (the value used in the inclusive cross section paper [10]) to improve resolution. To obtain a background-subtracted data spectrum, the signal purity is fitted using signal and background contributions as a function of p_T, and applied as a smooth multiplicative factor to the data. The result is the background-corrected distribution shown as a solid line in Fig. 3.

The reconstructed p_T spectrum is subsequently corrected for effects of finite experimental resolution, based on a regularized unfolding method [22, 23] using a migration matrix between the reconstructed and parton p_T derived from simulation. Figure 3 compares the reconstructed (solid line) and corrected (points) results as a function of the p_T of the top quark. The correlation between reconstructed and corrected p_T is $> 80\%$, and about 40% of the events migrate to different bins for the chosen bin widths (Table I). The dependence of the unfolding on the parton spectrum shape in the migration matrix is tested by reweighting the distribution with arbitrary functions. Shape variations of $\approx 20\%$ induce $2-6\%$ changes in the differential cross section. A correction for acceptance from the dependence of the spectrum on kinematic restrictions of reconstructed quantities is applied to the unfolded distributions.

The measured differential cross section as a function of the p_T of the top quark (using for each event the two measurements obtained from the leptonic and hadronic top quark decays), dσ/dp_T, is shown in Fig. 4 and tabulated in Table II together with the NLO pQCD prediction [24, 25]. The statistical uncertainties are estimated by performing 1000 pseudo-experiments where, in each experiment, the background-corrected spectrum is allowed

TABLE I: The migration matrix between the reconstructed (rows) and parton (columns) p_T derived from ALPGEN $t\bar{t}$ events passed through full detector simulation. The matrix indicates the fraction of events migrated from a given parton bin to the reconstructed bins. The binning used for correlating reconstructed and parton levels of p_T are given at the left and top, respectively. Results in bold print are for diagonal terms.

p_T (GeV/c)	0–45	45–90	90–140	140–200	200–300	300–400
0–45	**0.530**	0.162	0.062	0.020	0.003	0.000
45–90	0.344	**0.578**	0.227	0.072	0.021	0.000
90–140	0.103	0.228	**0.560**	0.223	0.055	0.031
140–200	0.019	0.029	0.145	**0.581**	0.232	0.071
200–300	0.002	0.002	0.006	0.103	**0.650**	0.363
300–400	0.000	0.000	0.000	0.001	0.038	**0.535**

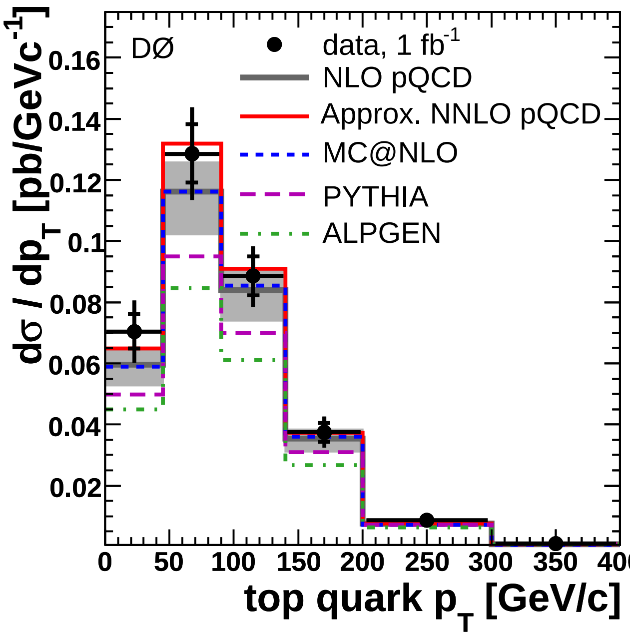

FIG. 4: Inclusive $d\sigma/dp_T$ for $t\bar{t}$ production (two entries per event) in data (points) compared with expectations from NLO pQCD (solid lines), from an approximate NNLO pQCD calculation, and for several event generators (dashed and dot-dashed lines). The gray band represents the uncertainty on the pQCD scale. Inner and outer error bars represent the statistical and total (statistical and systematic added in quadrature) uncertainties, respectively.

TABLE II: Inclusive differential cross section $d\sigma/dp_T$ for $t\bar{t}$ production at $\sqrt{s} = 1.96$ TeV and $m_t = 170$ GeV/c^2. There are two entries per event, with the total normalized to the $t\bar{t}$ production cross section. In addition to total systematic uncertainties on the shape in p_T in each bin, there is a p_T-independent systematic uncertainty of 9.6% that is not included in the table.

p_T (GeV/c)	$\langle p_T \rangle$ (GeV/c)	Cross Section (fb/GeV)	Stat. Unc. (fb/GeV)	Shape Sys. Unc. (fb/GeV)	NLO pQCD (fb/GeV)
0−45	29	70	11	5	59.6
45−90	68	130	20	10	116
90−140	113	89	13	6	83.8
140−200	165	37	6	3	35.6
200−300	233	8.7	1.7	0.7	7.72
300−400	329	1.1	0.3	0.1	0.814
$\sigma_{t\bar{t}}$ (pb)		8.31	1.28		7.54

TABLE III: The χ^2/NDF and χ^2 probability for comparisons between the measured data and predictions using correlated (uncorrelated) uncertainties for the absolute (shape) comparison.

Prediction	Absolute χ^2/NDF	Absolute prob.	Shape χ^2/NDF	Shape prob.
NLO pQCD	0.695	0.653	0.315	0.904
Approx. NNLO pQCD	0.521	0.793	0.497	0.779
MC@NLO	1.22	0.295	0.777	0.566
PYTHIA	2.61	0.0157	0.352	0.881
ALPGEN	5.04	3.54×10^{-5}	0.204	0.961

to vary according to Poisson statistics and is then unfolded using the regularized migration matrix (Table I). Systematic uncertainties include jet energy calibration in data and in simulation (1.5 − 5.0%), jet reconstruction efficiency (0.7 − 3.5%), and jet energy resolution (≈ 0.5%). The residual dependence of the unfolded result on the generated spectrum is 2 − 6%. The uncertainty on the integrated luminosity is 6.1%. The rest of the uncertainties follow those of Ref. [10], and total 5.9%. Quoted systematic uncertainties combine the uncertainty in normalization (independent of p_T) with the shape-dependent systematics. The total correlated systematic uncertainty is 9.6% (including the uncertainty on luminosity) and the total systematic uncertainty on the cross section, integrating over p_T, is 10.7%.

Results from a NLO pQCD [24, 25] calculation are overlaid on the measured differential cross section in Fig. 4. Also shown are results from an approximate next-to-NLO (NNLO) pQCD calculation [26] and from the MC@NLO [27], ALPGEN, and PYTHIA event generators. A comparison of the ratio of $d\sigma/dp_T$ relative to NLO pQCD is shown in Fig. 5. The NLO pQCD calculations agree with the measured cross section, however, results from ALPGEN (PYTHIA) have a normalization shift of about 45% (30%) with respect to data. A shape comparison of the ratio of $(1/\sigma)\ d\sigma/dp_T$ relative to NLO pQCD is shown in Fig. 6. All of the calculations reproduce the observed shape. The χ^2 and corresponding χ^2 probabilities [28] for the comparisons in Figs. 5 and 6 of predictions to data are given in Table III.

In conclusion, we have presented a 1 fb^{-1} measurement of the differential cross section of the top-quark p_T for $t\bar{t}$ production in the ℓ+jets channel using $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. Results from NLO and NNLO pQCD calculations and from the MC@NLO event generator agree with the normalization and shape of the measured cross section. Results from ALPGEN+PYTHIA and PYTHIA describe the shape of the data distribution, but not its normalization.

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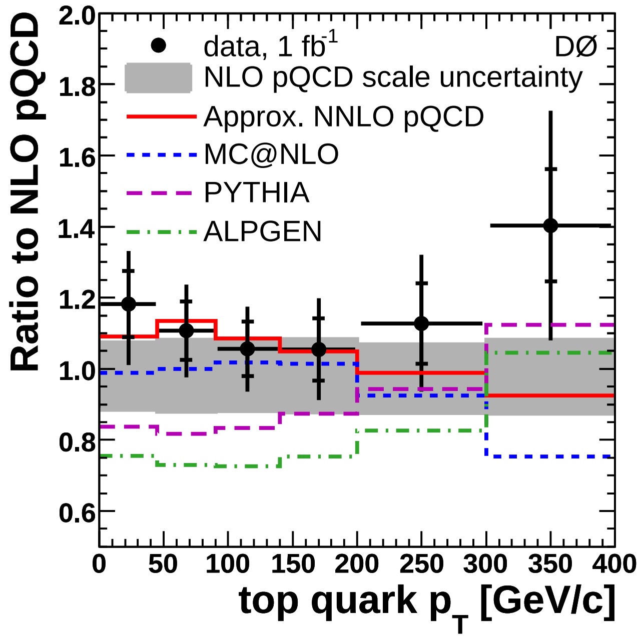

FIG. 5: Ratio of $d\sigma/dp_T$ for top quarks in $t\bar{t}$ production (two entries per event) to the expectation from NLO pQCD. The uncertainty in the scale of pQCD is displayed as the gray band. Also shown are ratios relative to NLO pQCD for an approximate NNLO pQCD calculation and of predictions for several event generators. Inner and outer error bars represent statistical and total (statistical and systematic added in quadrature) uncertainties, respectively.

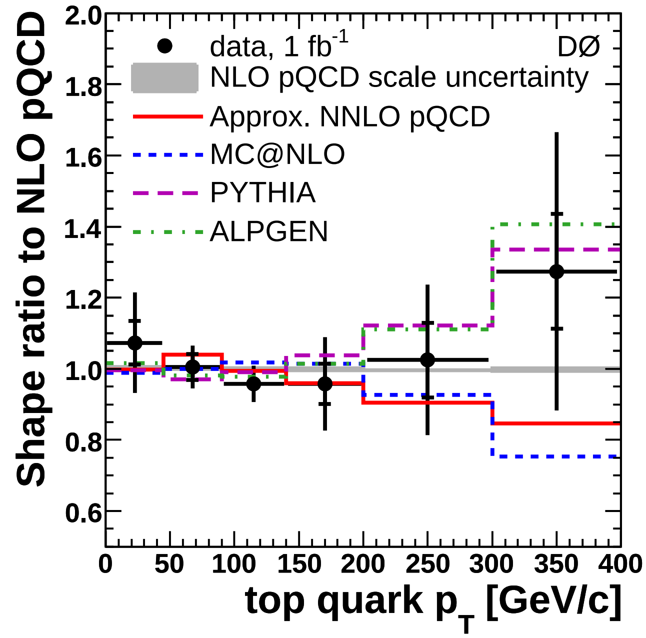

FIG. 6: Ratio of $(1/\sigma)\, d\sigma/dp_T$ for top quarks in $t\bar{t}$ production (two entries per event) to the expectation from NLO pQCD. The uncertainty in the scale of pQCD is displayed as the gray band. Also shown are ratios relative to NLO pQCD for an approximate NNLO pQCD calculation and of predictions for several event generators. Inner and outer error bars represent statistical and total (statistical and systematic added in quadrature) uncertainties, respectively.

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