DØ note 5257-Conf

Measurement of the $\mathrm{t\bar{t}}$ Production Cross Section in $\mathrm{p\bar{p}}$ Collisions at $\sqrt{s} = 1.96$ TeV Using Soft Muon b-tagged Lepton+Jets Events

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A measurement of the $t\bar{t}$ cross-section at $\sqrt{s} =$ 1.96 TeV is presented. The analysis has been performed in the $e + jets$ and $\mu + jets$ channels, using 425 pb^{-1} of D0 Run II data. Soft Muon Tagging method is used to enhance top signal with respect to backgrounds. For a top quark mass of 175 GeV, the measured cross-section is :

$$\sigma_{p\overline{p}\rightarrow t\bar{t}+X} = 7.3\ ^{+2.0}_{-1.8}\,(\mathrm{stat+syst})\ \pm 0.4\,(\mathrm{lumi})\ \mathrm{pb}.$$

D0 Preliminary Result for 2006 DPF Conference

I. INTRODUCTION

After the top quark discovery at Run I of the Fermilab Tevatron collider, Run II data are extensively analyzed to measure top properties and in particular the top pair production cross section . Theoretical calculations performed within the standard model have been refined and predict the production cross section with an uncertainty of less than 15% : $\sigma_{p\overline{p}\to t\overline{t}+X} = 6.7\ ^{+0.7}_{-0.9}$ pb at $m_{top} = 175$ GeV [1]. Measurement of the $t\bar{t}$ cross section is a good test of QCD and any deviation from the theoretical rate would signal the presence of new physics either in the production mechanism or in the top quark decay.

Within the standard model, $p\bar{p}$ collisions at a center of mass energy of 1.96 TeV, produce top quark pairs through $q\bar{q}$ annihilation (85%) and gluon fusion (15%). Almost 100% of the top quarks then decay to a W boson and a b quark. This note describes the top pair cross section measurement in the lepton and jets decay channel (denoted $l + jets$) where one of the W boson decays to a lepton and a neutrino and the other hadronically. Cases where the lepton is a muon or an electron is considered in this analysis. Events with a tau lepton decaying into a muon or an electron are also included.

The main physics background to the lepton and jets channel consists of W boson production associated with jets ($W + jets$). To disentangle $W + jets$ from top events, the presence of two b jets in the top pair decays is used. b jets are identified through the presence of soft muons from the semi-leptonic decays of b hadrons (soft muon tagger). 425 pb^{-1} of D0 data have been used to measure the cross section. This analysis is complementary to the other D0 analyses in this channel, which use either the specific topology of top events or another b-tagging method based on separated secondary vertices from b-hadrons decay.

II. D0 DETECTOR

The Run II D0 detector is a standard collider detector with a central tracking system, a liquid-argon/uranium calorimeter and a muon spectrometer.

The central tracking system includes a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located in a 2 T superconducting solenoid magnet. The SMT is designed to provide efficient tracking and vertexing capability at pseudorapidities up to $|\eta| < 2.5$. The system has a six-barrel longitudinal structure, each with a set of four layers arranged axially around the beam-pipe, and interspersed with 16 radial disks. The CFT has eight coaxial barrels, each supporting two doublets of overlapping scintillating fibers of 0.835 mm diameter, one doublet being parallel to the collision axis, and the other alternating by $\pm 3°$ relative to the axis [2].

The calorimeter is divided into a central section (CC) providing coverage out to $|\eta| \approx 1$, and two end calorimeters (EC) extending coverage to $|\eta| \approx 4$ all housed in separate cryostats. Scintillators placed between the CC and EC provide sampling of showers at $1.1 < |\eta| < 1.4$ [3].

The muon system, covering pseudorapidities up to $|\eta| < 2$, resides beyond the calorimetry, and consists of three layers of tracking detectors and scintillating trigger counters. Moving radially outward, the first layer is placed before the 1.8 T toroid magnets, and the two following layers are located after the magnets [4].

III. EVENT SELECTION

Data used in this analysis have been recorded by the D0 detector between August 2002 and August 2004. The sample is divided into an electron and muon sample after a trigger selection of events with at least an electron or muon with $p_T > 15$ GeV/c and a jet with $E_T > 20$ GeV. The integrated luminosity of these samples has been measured to be 422 ± 26 and 426 ± 26 pb^{-1} respectively.

Top-pair events decaying in the lepton and jets channel are characterized by two b jets, one high p_T and isolated lepton, an undetected neutrino from one of the W boson decay, and two jets from the other W decay. Additional jets could also be present due to initial or final state radiation. Data are further selected requiring an isolated electron with $p_T > 20$ GeV/c in the central calorimeter ($|\eta| < 1.1$), or an isolated muon with $p_T > 20$ GeV/c and $|\eta| < 2.0$. An electron is considered as isolated if $\frac{E(0.4)-E(0.2)}{E(0.2)} < 0.15$, where $E(R)$ is the energy contained in a cone of radius R in the $\eta - \phi$ plane ($R = \sqrt{\eta^2 + \phi^2}$). A muon is considered as isolated if its angular distance R to the nearest jet in the event is greater than 0.5. More details on the lepton identification as well as trigger requirements are reported in [5] and [6]. In both channels, we require $\not{E}_T$ to exceed 20 GeV and not be collinear with the lepton direction in the transverse plane in order to reject multi-jet events. Jets are reconstructed using a cone algorithm with radius $\Delta R = 0.5$ [7]. Events are classified as a function of their jet multiplicity. To be taken into account, the leading jet should have a p_T greater than 40 GeV/c and the other jets should have $p_T > 20$ GeV/c. To ensure statistical independence from the $t\bar{t}$ cross section measurement in the dilepton channel, events with a second high p_T lepton candidate are vetoed.

Signal events are mostly concentrated in the third and fourth jet multiplicity bins, which are subsequently used to extract the cross section. The first and the second bins, dominated by $W + jets$ and multi-jet QCD events, are used to check that backgrounds are evaluated well.

The $t\bar{t}$ selection efficiency in the two last jet multiplicity bins has been measured to be 21% and 22% in the muon and electron channel, respectively.

IV. SOFT MUON TAGGING

The presence of two b quarks in top pair events allows them to be distinguished from the production of W bosons in association with jets. To identify heavy flavor jets we take advantage of the frequent semi-leptonic decays of b and charm hadrons. Considering that we have two b quarks per $t\bar{t}$ event, that on average a c quark is produced in 1/3 W hadronic decays, and finally taking into account the following branching fractions [8]:

- $Br(b \to \mu) = 11.0\%$
- $Br(b \to c \to \mu) = 8.0\%$
- $Br(c \to \mu) = 8.7\%$,

approximately 40% of $t\bar{t}$ events should contain a soft muon in a jet.

A jet is considered as b-tagged with Soft Muon Tagging if there is, in a cone of radius $R = 0.5$ in the $\eta - \phi$ plane ($R = \sqrt{\eta^2 + \phi^2}$), a muon with $p_T > 4$ GeV/c matched to a central track. An event is qualified as b-tagged if at least one of its jets (passing the identification jet criteria) is b-tagged with Soft Muon Tagging.

After the selection described in the previous section, Soft Muon Tagging is applied to the data samples. The tagging efficiency of $t\bar{t}$ events, measured on simulated samples and corrected for data to MC differences, is approximately 16% in the third and fourth jet multiplicity bins.

The probability to tag light-jets is directly measured on the MC background samples used in this analysis. It is corrected for data to MC differences measured on di-jet samples after removal of their heavy flavor content. The probability to tag a light-jet is around 0.2% in average.

V. BACKGROUNDS EVALUATION

To determine the cross section, remaining background levels after selection and tagging have to be evaluated.

Small backgrounds such as dibosons or single top events are evaluated using simulation, making sure that the Monte Carlo reproduces the data well. All simulated events including signal events are generated using Alpgen 1.3 [9] with CTEQ5L parton distribution functions [10] interfaced with PYTHIA 6.2 [11] to simulate the fragmentation, the underlying event and unstable particle decays. Decays of heavy flavor bound states and of τ leptons are modeled using EVTGEN [12] and TAUOLA [13] respectively.

The three main remaining backgrounds after selection and tagging are $Z + jets$, multi-jet QCD and $W + jets$ events. Their evaluation is described below.

$Z + $jets background : Such events are selected when one lepton from Z boson decay is lost outside the detector acceptance leading to the presence of missing transverse energy. Moreover, in the case where the Z boson decays to a muon pair, there is also the possibility that a muon is superimposed on a jet, leading to its mistagging as a b jet. The $Z + jets$ background is evaluated using kinematic information from simulation after having rescaled the cross section to the one observed in data, comparing the dimuon invariant mass (at a loose selection level for the second muon) between data and simulation.

QCD multi-jet background : Some QCD multi-jet events remain in the sample because one of their jets is misidentified as a lepton (fake lepton). The fraction of such events in each jet multiplicity bin is estimated using the so-called Matrix Method [14], which relies on the fact that events containing a fake lepton have smaller probability to pass tight lepton quality requirements than events with a real electron or muon. Table I summarizes the number of events observed in data and estimated number of QCD multi-jet and W-like events. At this stage $t\bar{t}$ events are considered as a part of the W-like event subset. To evaluate the multi-jet background, the matrix method is applied after the tagging step.

TABLE I: Number of data events at selection and b-tagging level and output of the matrix method in the $e+jets$ and $\mu+jets$ channels, predicting the fraction of events with true and fake leptons, as a function of the jet multiplicity.

Sample	$e+jets$				$\mu+jets$			
	1 jet	2 jets	3 jets	$\geq$ 4 jets	1 jet	2 jets	3 jets	$\geq$ 4 jets
Selection level								
N_{data}	6153	2217	466	119	6827	2267	439	100
$N_{true\ lepton}$	5805.6±83.2	1975.8±50.0	394.9±23.0	99.8±11.6	6607.0±84.9	2155.1±49.9	405.5±22.1	91.4±10.7
$N_{fake\ lepton}$	347.4±17.7	241.2±11.0	71.1±4.7	19.2±2.3	220.0±10.2	111.9±8.2	33.5±4.2	8.6±1.9
Tagging level								
N_{data}	59	38	17	17	64	45	21	7
$N_{true\ lepton}$	55.5±8.0	35.1±6.5	14.5±4.4	17.1±4.3	60.8±8.2	43.8±7.0	20.0±4.8	4.9±2.9
$N_{fake\ lepton}$	3.5±1.1	2.9±0.9	2.5±0.8	<0.01	3.2±0.9	1.2±0.8	1.0±0.7	2.1±0.8

W + jets background : The number of selected $W+jets$ event is deduced from the output of the matrix method at selection level. To obtain the number of tagged events, the tagging probability is evaluated using the simulation. We rely on Monte Carlo to predict the flavor composition of the jets produced in association with a W boson. In most cases, the jets accompanying the W boson originate from light (u, d, s) quarks and gluons ($W+light\ jets$). Depending on the jet multiplicity, between 2% and 14% of $W+jets$ events contain heavy flavor jets resulting from gluon splitting into $b\bar{b}$ or $c\bar{c}$ ($Wb\bar{b}$ or $Wc\bar{c}$, respectively), while in about 5% of events, a single c quark is present in the final state as a result of the W boson radiated from an s quark from the proton's or antiproton's sea (Wc). The number of tagged events is derived from the number of W-like events observed in the data before tagging, multiplied by the fraction of a certain flavor component and the probability to tag such a combination of jets derived from Monte Carlo calibrated to reproduce data.

VI. TOP PAIR CROSS SECTION: EXTRACTION PROCEDURE AND RESULTS

The cross section is calculated by performing a maximum likelihood fit to the observed number of events N^{obs}. The analysis is split into four different channels: $\mu+jets$ or $e+jets$ with 3 or $\geq$4 jets. If the index i refers to a channel (μ+3 jets, μ+4 jets, e+3 jets, e+4 jets), then an estimator of the true number of event N^{true} and of the $t\bar{t}$ cross section $\sigma_{t\bar{t}}$ is obtained maximizing the following likelihood $\mathcal{L}$

$$\mathcal{L} = \prod_i \mathcal{P}(N_i^{\rm obs}, N_i^{\rm true}(\sigma_{t\bar{t}})); \qquad (1)$$

$\mathcal{P}(N^{\rm obs}, N^{\rm true})$ is the Poisson probability to observe $N^{\rm obs}$ events when the reality is $N^{\rm true}$. The number of events in each channel is the sum of the number of background events ($W+jets$, $Z+jets$, QCD, single top and diboson processes) and the number of $t\bar{t} \to l+jets$ events which is a function of the $t\bar{t}$ cross section. Selected $t\bar{t}$ events from the dilepton channel are included and considered as signal assuming the same cross section as the $l+jets$ channel.

At each step in the maximization, the multi-jet background event count in the four tagged samples, and the corresponding samples before tagging, is constrained within errors to the output of the Matrix Method.

In addition, we include in the likelihood a Gaussian term for each of the systematic uncertainties considered, following the procedure described in Ref. [15]. In this approach, each source of systematic uncertainty is allowed to vary within its Gaussian distribution and thus to affect the central value of the cross section during the maximization procedure. This yields a combined statistical and systematic uncertainty on $\sigma_{t\bar{t}}$.

The following cross sections are obtained in the muon and electron channels separately:

$$e + jets \;:\; \sigma_{p\bar{p}\to t\bar{t}+X} \;=\; 8.7\,^{+2.5}_{-2.2}\,(\text{stat}+\text{syst})\;\pm 0.5\,(\text{lumi})\;\text{pb},$$
$$\mu + jets \;:\; \sigma_{p\bar{p}\to t\bar{t}+X} \;=\; 4.2\,^{+2.9}_{-2.6}\,(\text{stat}+\text{syst})\;\pm 0.3\,(\text{lumi})\;\text{pb}. \quad (2)$$

The measured cross section using all channels is:

$$\sigma_{p\bar{p}\to t\bar{t}+X} \;=\; 7.3\,^{+2.0}_{-1.8}\,(\text{stat}+\text{syst})\;\pm 0.4\,(\text{lumi})\;\text{pb}.$$

It is in good agreement with other D0 measurements [16] and the standard model prediction [1].

Table II summarizes the sample composition after tagging of $l + jets$ events. The $t\bar{t}$ contribution is calculated using the measured $t\bar{t}$ production cross section. It may be noticed that, contrary to the lifetime tagging analysis, $W + light\ jets$ and $Z + jets$ backgrounds are not negligible.

Figures 1 and 2 show the observed and predicted number of tags for each jet multiplicity, for the electron and muon channels separately and for both combined.

Kinematic distributions for selected and tagged data events are compared to the sum of predicted backgrounds and $t\bar{t}$ signal in Appendix A. An overall good agreement is shown for both channels.

TABLE II: Number of selected data events and evaluated background events in both $e + jets$ and $\mu + jets$ channels combined as a function of the jet multiplicity. The number of $t\bar{t}$ events is obtained using the measured cross section. Only statistical uncertainties are quoted.

Sample	1 jet	2 jets	3 jets	$\geq$ 4 jets
$W + light$	62.0±9.8	17.2±6.1	5.5±1.3	0.63±0.29
Wc	23.3±2.3	10.3±1.7	1.49±0.33	0.23±0.06
$Wc\bar{c}$	6.30±0.7	8.3±1.0	1.1±0.2	0.46±0.13
$Wb\bar{b}$	9.7±0.5	11.7 ±0.7	3.1±0.3	0.45±0.08
W+jets	101.3±10.1	47.4±6.4	11.2±1.4	1.77±0.33
QCD	6.7±1.4	4.10±1.22	3.50±1.07	2.01±0.85
tb	0.53±0.02	2.18±0.05	0.28±0.02	0.02±0.01
tqb	0.91±0.06	2.21±0.09	0.92±0.06	0.13±0.02
diboson	1.83±0.25	3.05±0.30	0.32±0.10	< 0.01
$Z \to \tau^+\tau^- + jets$	0.78±0.52	0.22±0.15	0.26±0.15	< 0.01
$Z \to \mu^+\mu^- + jets$	11.5±1.1	9.6±0.6	2.84±0.45	1.10±0.28
background	123.4±10.2	68.8±6.6	19.3±1.8	4.0±1.0
$t\bar{t} \to l + jets$	0.49±0.05	6.6±0.2	20.4±0.4	16.6±0.3
$t\bar{t} \to ll$	1.18±0.04	6.0±0.1	2.16±0.06	0.31±0.02
total	125.1±10.2	81.4±6.6	41.9±1.8	22.0±1.0
data	123	83	38	24

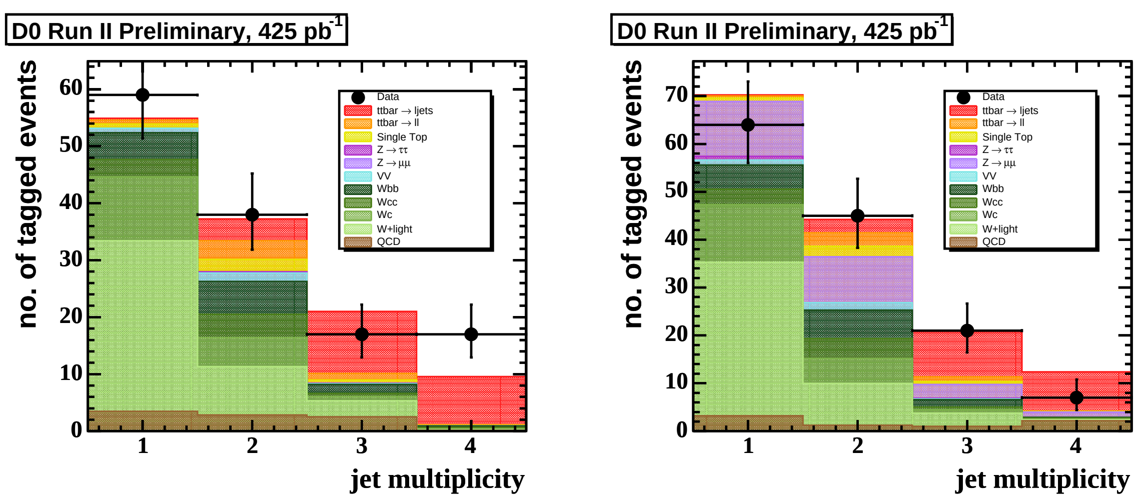

FIG. 1: Predicted background composition as a function of jet multiplicity, in the electron channel (left) and muon channel (right). The $t\bar{t}$ signal prediction is shown assuming the measured cross section (both channels combined).

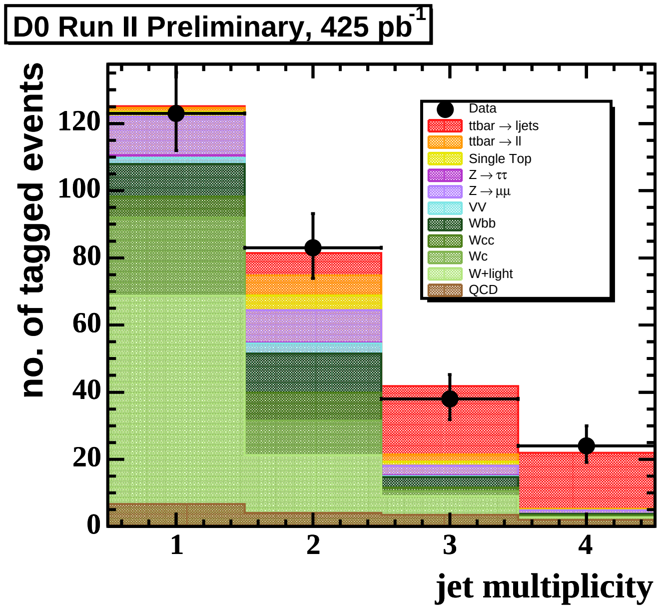

FIG. 2: Predicted background composition as a function of jet multiplicity for both channel combined. The $t\bar{t}$ signal prediction is shown assuming the measured cross section.

VII. SYSTEMATIC UNCERTAINTIES

The contribution due to each individual source of systematic uncertainty can be estimated by redoing the fit after fixing all but the corresponding Gaussian term and unfolding the statistical uncertainty from the resulting total uncertainty. The statistical uncertainty of $^{+1.7}_{-1.6}$ pb is obtained from the fit where all Gaussian terms are fixed.

The light-jet tagging efficiency evaluation is the main source of systematic uncertainty in this analysis. It is measured on di-jet data after removal of the heavy flavor contamination. This uncertainty comprises uncertainties about the heavy flavor fraction and tagging efficiency of this sample, as well as the tagging difference between data and MC. The second main systematic originate from the event statistic used by the matrix method. Moreover a 6.1% error is assigned to the luminosity measurement.

Contributions of the main sources of systematic uncertainties to the total error on the cross section are summarized in Table III.

VIII. CONCLUSIONS

The $t\bar{t}$ cross section measurement in the lepton+jets final state has been measured using data from Run II of the Fermilab Tevatron collider recorded by the upgraded D0 detector. Data analyzed corresponds to an integrated luminosity of 425 pb^{-1}. A $t\bar{t}$ sample has been selected using a Soft Muon Tagging algorithm to identify b jets and disentangle top events from W boson associated to jets production. The measured cross section

$$\sigma_{p\bar{p}\to t\bar{t}+X} = 7.3\ ^{+2.0}_{-1.8}\,(\mathrm{stat}+\mathrm{syst})\ \pm 0.4\,(\mathrm{lumi})\ \mathrm{pb},$$

is in good agreement with the standard model prediction and other D0 measurements.

IX. ACKNOWLEDGMENTS

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TABLE III: Systematic uncertainties in the $e + jets$ and $\mu + jets$ channels combined.

Source	σ_{+}(pb)	σ_{-}(pb)
Muon preselections	+0.18	−0.13
Electron preselections	+0.19	−0.13
EM triggers	+0.00	−0.03
Muon triggers	+0.12	−0.09
Jet triggers	+0.00	−0.04
Jet energy scale	+0.19	−0.12
Jet energy resolution	+0.02	−0.02
Jet ID	+0.14	-0.12
$Z + jets$ normalization	+0.06	−0.07
Heavy flavor tagging	+0.24	−0.17
Fake tagging rate	+0.84	−0.78
Matrix method	+0.33	−0.35
Monte Carlo statistics	+0.25	−0.27
W fractions	+0.13	−0.19
Total systematics (quad sum of the above)	+1.04	-0.98

(Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); PPARC (United Kingdom); MSMT (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); Research Corporation; Alexander von Humboldt Foundation; and the Marie Curie Program.

APPENDIX A: KINEMATIC DISTRIBUTIONS

A comparison of data and the sum of predicted backgrounds and $t\bar{t}$ signal after selection and tagging is illustrated here. Figures 3 and 4 show, in the electron and muon channels respectively, the following kinematic distributions:

- transverse impulsion of the isolated lepton (electron or muon),
- transverse energy of the leading jet,
- transverse W boson mass,
- sum of the jet transverse energies: H_T.

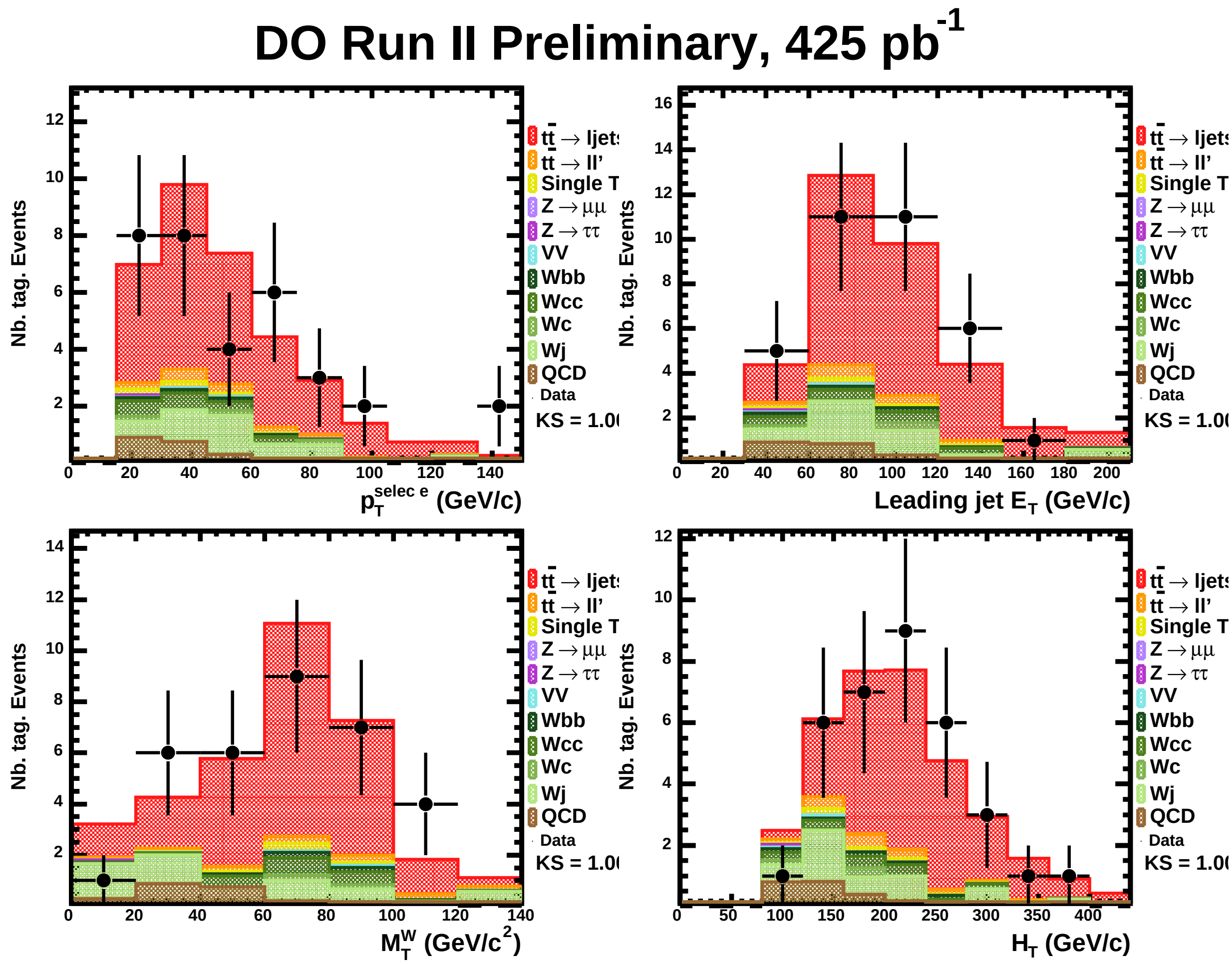

FIG. 3: Data compared to the sum of the predicted backgrounds and $t\bar{t}$ signal for events with more than three jets in the electron channel. The $t\bar{t}$ signal prediction is obtained using the measured cross section.

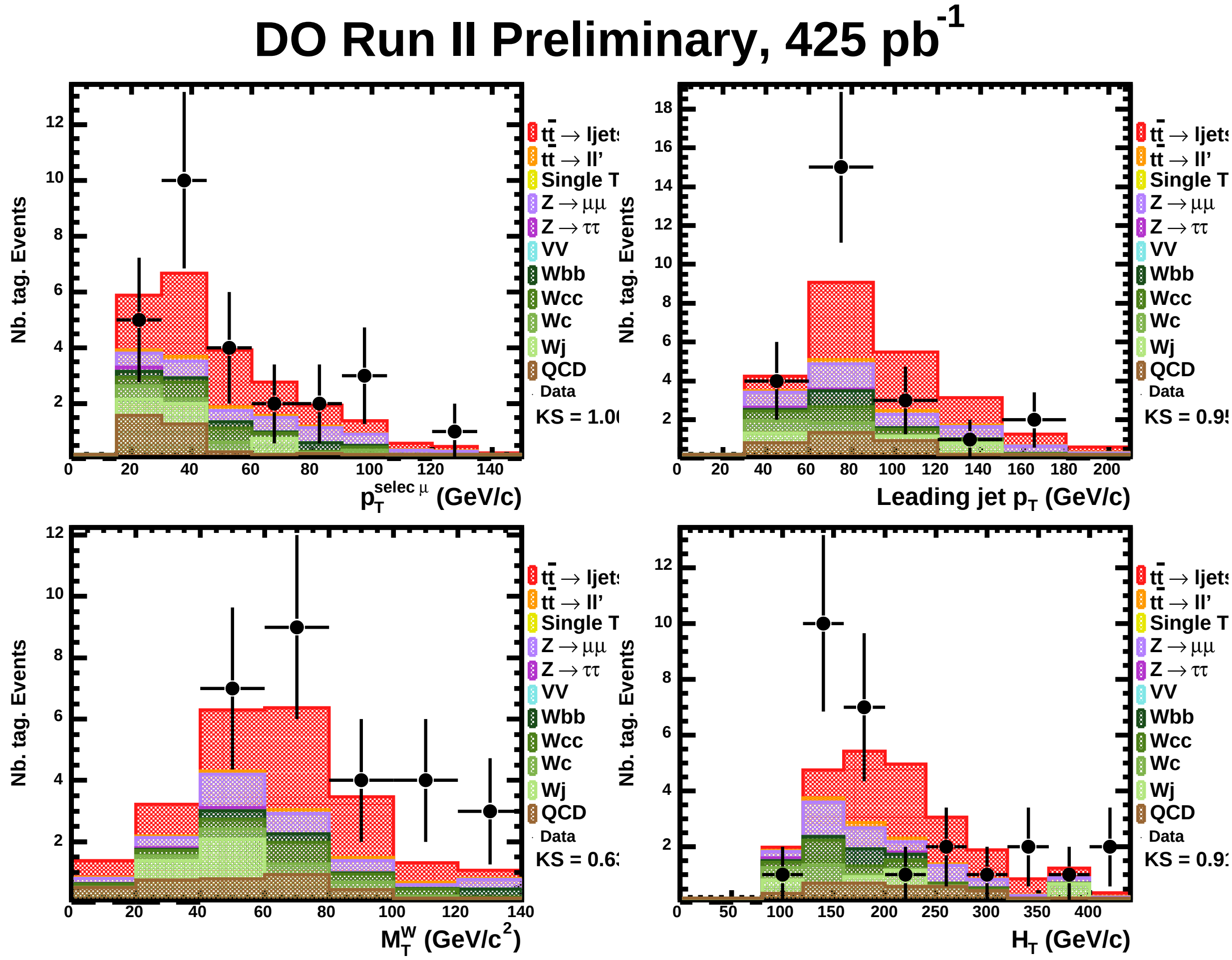

FIG. 4: Data compared to the sum of the predicted backgrounds and $t\bar{t}$ signal for events with more than three jets in the muon channel. The $t\bar{t}$ signal prediction is obtained using the measured cross section.

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