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D0 Top Analyses: Recent Results on the Properties of the Sixth Quark

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DØ TOP ANALYSES: RECENT RESULTS ON THE PROPERTIES OF THE SIXTH QUARK

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The DØ collaboration updates measurements of the Standard Model top quark in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV at the Fermilab Tevatron, with a new data sample of approximately twice the integrated luminosity used for the discovery measurements (~100 pb^{-1}). We observe 37 $t\bar{t}$ candidate events from seven decay modes with an expected background of 13.4 ± 3.0 events. We present a preliminary new top mass measurement of 170 ±15 (stat.) ±10 (syst.) GeV/c^2 using the single-lepton + jets decay modes. For the central value of our measured mass we calculate the production cross section to be 5.2 ± 1.8 pb. DØ is also analyzing additional decay modes and we report preliminary results from two new channels.

I. INTRODUCTION

Almost a year ago to the date of this conference, the discovery of the top quark was annouced at Fermilab by DØ [1] and CDF [2]. Since the discovery announcement, DØ has acquired more than a factor of two in delivered luminosity, for a total of roughly 100 pb^{-1}. Along with the increase in our data sample we have made advances in understanding the detector. Applicable to the following analyses are improved particle identification and a re-calibration of jet energy corrections, the latter leading to better resolution and reduced systematic error on the measurement of the top mass.

The analyses presented here represent a change in emphasis from searching for top to a measurement of its properties. Hence the selection requirements are designed differently for the cross section measurement to that for the extraction of the top mass. The selection for the cross section analysis is optimize on Monte Carlo to minimize the relative error, whereas the event selection for the mass measurement balances good signal acceptance with minimizing mass bias from the selection criteria. Mostly those aspects of the DØ top analyses that have changed or improved since the discovery will be presented here. Details of the full analysis can be found elsewhere [3].

We assume for our analyses that the top quark is pair-produced and decays 100% of the time into a W boson and a b quark. The cross section measurement is based on signal of $t\bar{t}$ decay through seven distinct channels depending on how the two W bosons decay, and on whether or not a soft muon from a b or c quark semileptonic decay is observed. The dilepton channels are those in which both W bosons decay leptonically ($e\mu+$jets, $ee+$jets, and $\mu\mu+$ jets). The single-lepton channels occur when just one W boson decays leptonically ($e+$ jets and $\mu+$ jets). The single-lepton channels are subdivided into b-tagged and untagged channels according to whether or not a muon is observed consistent with $b \rightarrow \mu + X$. The muon-tagged channels are denoted $e+\text{jets}/\mu$ and $\mu+\text{jets}/\mu$.

We have also investigated searching for the signal of $t\bar{t}$ decay in more of the available decay modes. Two channels in which we present preliminary results are the $e\nu+$ jets channel, characterized by events with very large $\not{E}_T$, and the *all-jets* mode defined by a six jet final state. These channels give confirmation of the $t\bar{t}$ event yield we expect from our previous measurements and will in the future contribute further acceptance to our cross section measurement.

II. PARTICLE DETECTION

Muons are detected and their momentum determined using an iron toroid spectrometer located outside of a uranium-liquid argon calorimeter and a non-magnetic central tracking system inside the calorimeter. Two distinct types of muons are defined. High-P_T muons, which are predominantly from gauge boson decay, are required to be isolated from jet axes by distance $\Delta\mathcal{R} > 0.5$ in η-ϕ space (η = pseudorapidity = $\tanh^{-1}(\cos\theta)$; θ, ϕ = polar, azimuthal angle), and to have transverse momentum $P_T > 15$ GeV/c. Tag muons, which are primarily from b, c or π/K decay, are required to be within distance $\Delta\mathcal{R} < 0.5$ of any jet axis. The minimum P_T for soft muons is 4 GeV/c.The muon identification has been refined by the use of the finely segmented calorimeter to further discriminate combinatoric and cosmic ray backgrounds in the forward regions, while increasing muon efficiency overall by 20%.

The electron identification algorithm has also been improved. Electrons are clusters of electromagnetic energy, characterized by a number of variables that describe shower

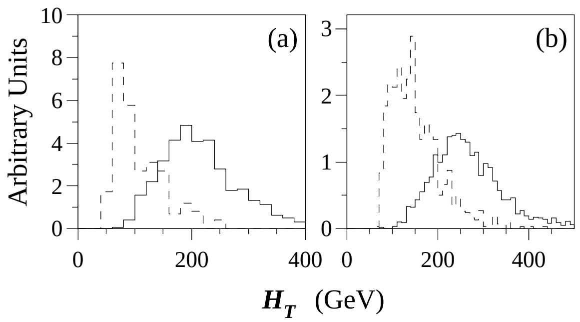

FIG. 1. Shape of H_T distributions expected for the principal backgrounds (dashed line) and 180 GeV/c^2 top quarks (solid line) for (a) $e\mu+$jets and (b) untagged single-lepton + jets.

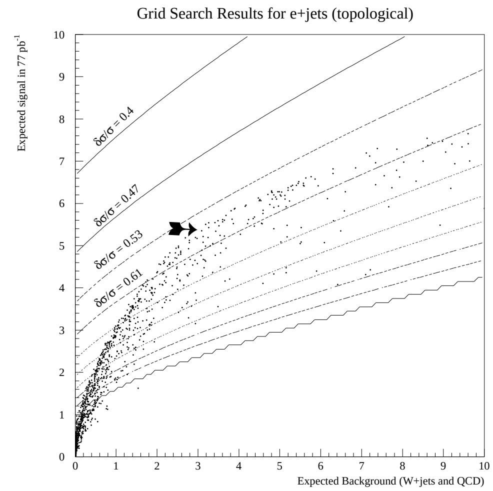

FIG. 2. Monte Carlo e + jets expected signal event yield *vs.* expected background event yield for various values of $\mathcal{A}$ and H_T. Lines are contours of constant relative error on cross section. Arrow denotes point where cuts are chosen, H_T = 180 GeV/c^2 and $\mathcal{A}$ = 0.065.

shape and the associated charged track. We select clusters based on the ratio of the joint likelihood of these variables for electrons and background. Using the joint likelihood rather than selection cuts on the individual variables reduces the multijet background by a factor of 2. The efficiency for finding electrons was measured from $Z \to ee$ data. Electrons are required to have $|\eta| < 2.5$ and transverse energy $E_T > 15$ GeV.

Jets are reconstructed using a cone algorithm of radius $\mathcal{R} = 0.5$.

The presence of neutrinos in the final state is inferred from missing transverse energy ($\not\!\!E_T$). The calorimeter-only $\not\!\!E_T$ ($\not\!\!E_T^{\rm cal}$) is determined from energy deposition in the calorimeter. Correcting $\not\!\!E_T^{\rm cal}$ for the measured p_T of detected muons yields the total $\not\!\!E_T$.

The reader is referred to reference [4] for a full description of the DØ detector and data collection systems.

III. THE COUNTING EXPERIMENT

The signature for the dilepton channels is defined as two isolated leptons, two or more jets, and large $\not\!\!E_T$. The signature for the single-lepton channels is defined as one isolated lepton, large $\not\!\!E_T$, and three or more jets (with muon tag) or four or more jets (without tag). A summary of the kinematic cuts can be found in Table I.

Additional special cuts are used in the ee + jets, $\mu\mu$ + jets and μ + jets/μ channels to remove background from Z + jets. To remove $Z \to ee$ background in ee + jets, we require that $|m_{ee} - m_Z| > 12$ GeV/c^2, or $\not\!\!E_T^{\rm cal} > 40$ GeV. To remove background from $Z \to \mu\mu$, the event as a whole is required to be inconsistent with Z + jets based on a global kinematic fit (Prob($\chi^2_{Z fit}$)). H_T is defined as the scalar sum of the jet E_T in the event and is a powerful discriminator between background and top quark production. The definition of H_T for the dilepton channels is slightly modified and includes the electron E_T in the sum. Figure 1 shows a comparison of the shapes of the H_T distributions expected from background and 180 GeV/c^2 top quarks in the channels (a) $e\mu$ + jets and (b) untagged single-lepton + jets.

The lepton + jets channels, having larger

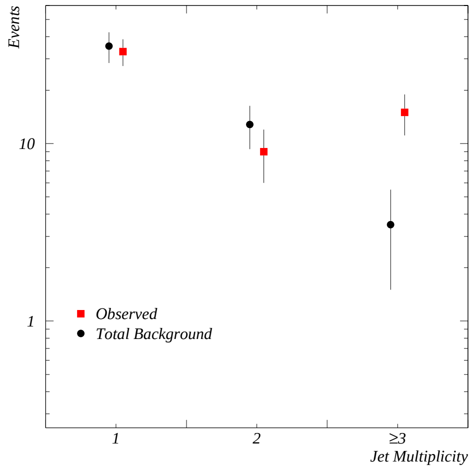

FIG. 3. Jet multiplicity of b tagged lepton + jets events before Aplanarity and H_T cuts. The E_T threshold on the jets is 15 GeV. Square markers are the data, circles markers are expected background.

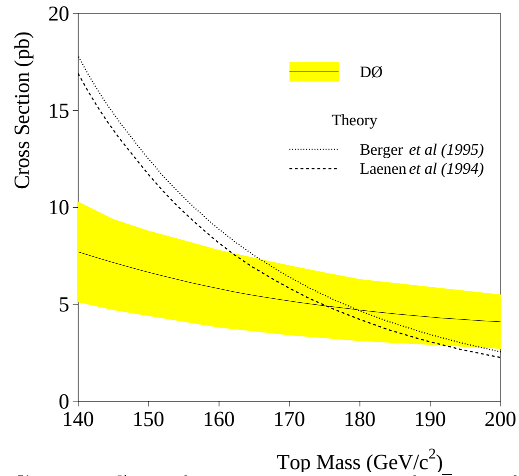

FIG. 4. DØ preliminary measured $t\bar{t}$ production cross section (solid line with one standard deviation error band) as a function of assumed top quark mass. Also shown are two theoretical calculations (dashed line [6] and dotted line [7]).

event yield, give the greatest contribution in determining the cross section. In the updated analysis we modify the cuts on Aplanarity, $\mathcal{A}$, and H_T, and incorporate a new cut on the sum leptonic E_T, E_T^{ℓ}, defined as the vector sum of the E_T of the electron(or muon) and $\not{E}_T$. The requirements on H_T and Aplanarity were chosen such that the error on the cross section measurement is minimized. The cuts were optimized based on studies of Monte Carlo event sets of signal and background using a grid search technique. Figure 2 shows expected signal event yields *vs.* expected background event yields where each point on the plot represents a separate experiment with different choices for cuts on $\mathcal{A}$ and H_T. Overlayed on the same plot are contours of constant relative error on cross section. Note that the choice for smallest relative error on the cross section does not necessarily correspond to the largest possible signal over background.

For the untagged single-lepton channels, the principle backgrounds are from W + jets, Z + jets, and multijet production with a jet misidentified as a lepton. The W + jets background is estimated using jet-scaling. In this method, we extrapolate the W + jets cross section from one and two jets, to four or more jets assuming an exponential dependence on the number of jets, as predicted by QCD [8], and as observed experimentally.

For the tagged single-lepton channels the observed jet multiplicity spectrum of untagged single lepton background events is convoluted with the measured tagging rate per jet to determine the total background. The tagging rate is observed to be a function of the number of jets in the event and the E_T of the jets and is the same within error for both multijet and W + jets events. As a cross check, tagging-rate predictions were made for dijet, multijet, and gamma+jet samples and found to agree with the data. Figure 3 shows the number of observed and estimated background events per number of 15 GeV jets exclusive. A clear excess is seen for events with three or more jets.

The acceptance for $t\bar{t}$ events is calculated

TABLE I. Minimum kinematic requirements for the standard event selection (energy in GeV).

Channel	High-p_T Leptons $E_T(e)$	High-p_T Leptons $p_T(\mu)$	Jets $N_{\rm jet}$	Jets $E_T({\rm jet})$	Missing E_T $\not\!\!E_T^{\rm cal}$	Missing E_T $\not\!\!E_T$	Muon Tag $p_T(\mu)$	Topological H_T	Topological $\mathcal{A}$	Topological specific
$e\mu$ + jets	15	15	2	20	20	10	-	120	-	-
ee + jets	20		2	20	25	-	-	120	-	$\|M_{ee} - M_{Z^0}\|$ >12 GeV/c^2
$\mu\mu$ + jets		15	2	20	-	-	-	100	-	Prob($\chi^2_{Z fit}$)< 1%
$e\nu$ + jets*	20		2	30	50	50	-	-	-	$M_T(e, \not\!\!E_T)$ >115 GeV/c^2
e + jets	20		4	15	25	-	-	180	0.065	E_T^ℓ >60 GeV
μ + jets		20	4	15	20	20	-	180	0.065	E_T^ℓ >60 GeV
e + jets/μ	20		3	20	20	-	4	110	0.04	-
μ + jets/μ		20	3	20	20	20	4	110	0.04	Prob($\chi^2_{Z fit}$)< 1%

* Not yet included in cross section measurement.

using the ISAJET event generator [5] and a detector simulation based on the GEANT program [9]. Differences in the acceptance found using the HERWIG event generator [10] are included in the systematic error.

From seven channels, we observe 37 events with an expected background of 13.4$\pm$ 3.0 events (see Table II). Our measured cross section as a function of the top quark mass hypothesis is shown in Figure 4. Assuming a top quark mass of 160 GeV/c^2 (200 GeV/c^2) the production cross section is 5.8$\pm$ 2.0 pb (4.1 $\pm$ 1.4) pb respectively. Note that due to the factor of two increase in our data statistics combined with improvements in the analyses, our measured cross section is now quite flat as a function of top quark mass. The error in the cross section includes an overall 5.4% uncertainty in the luminosity. A top production cross-section was calculated for the dilepton, tagged, and untagged single-lepton channels independently. All agree well within errors.

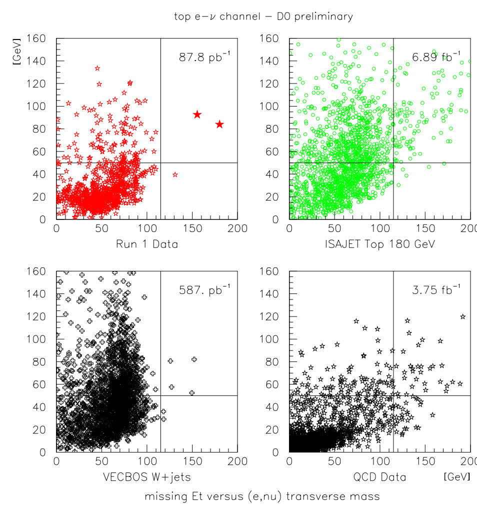

FIG. 5. $\not\!\!E_T$ *vs.* $M_T(e, \not\!\!E_T)$ for data, Monte Carlo signal and $W \rightarrow e\nu$+jets background, and QCD multijet background. Two data events fall into the signal region.

IV. TWO NEW DECAY CHANNELS

The event topology of the $e\nu$ + jets mode arises when one W decays to $e\nu$ in such a way that the e takes most of the momentum from the W's decay and p_T, while the second W decays to e, μ, or τ where this time the

TABLE II. Expected number of top quark events, $\langle N \rangle$, in the seven channels, based on the central theoretical $t\bar{t}$ production cross section of Ref. [6], for a top mass of 180 GeV/c^2. Also given are expected background, integrated luminosity, and the number of observed events in each channel.

channel	$e\mu +$ jets	$ee +$ jets	$\mu\mu +$ jets	$e +$ jets	$\mu +$ jets	$e +$ jets/μ	$\mu +$ jets/μ	ALL
$\langle N \rangle (M_{top}$ =180 GeV/$c^2)$	1.7 ± 0.3	0.9 ± 0.1	0.5 ± 0.1	6.5 ± 1.4	6.4 ± 1.5	2.4 ± 0.4	2.8 ± 0.9	21.2 ± 3.8
Background	0.4 ± 0.1	0.7 ± 0.2	0.5 ± 0.3	3.8 ± 1.4	5.4 ± 2.0	1.4 ± 0.4	1.1 ± 0.2	13.4 ± 3.0
$\int \mathcal{L}dt$ (pb^{-1})	90 ± 5	106 ± 6	87 ± 5	106 ± 6	96 ± 5	91 ± 5	96 ± 5	
Data	3	1	1	10	11	5	6	37

corresponding neutrino(s) receive most of the momentum from the W's decay and p_T, resulting in the signature of large $\not\!\!E_T$. The $e\nu$ channel opens the acceptance to top decays including contributions from τ's and regions of phase space from our other dilepton and single e + 4jets analyses cuts where acceptance is low.

The dominant background processes for this channel are $W \to e\nu +$ jets and QCD production of three jet events where one jet is misidentified as an electron along with a coincident fluctuation in $\not\!\!E_T$ measurement. The most effective reduction of the $W \to e\nu +$jets background comes from placing a cut on the transverse mass of the W at 115 GeV. The QCD production of three jet events is controlled by the cut on the signal's signature of $\not\!\!E_T > 50$ GeV. The effectiveness of these cuts (summarized in Table I) are illustrated in Figure 5, comparing $\not\!\!E_T$ *vs.* $M_T(e, \not\!\!E_T)$ for data, Monte Carlo signal and $W \to e\nu +$ jets background, and QCD multijet background. A preliminary expected event yield of 1.4 ± 0.05 for background, and 1.1 ± 0.1 for $M_{top} = 180$ GeV/c^2 is calculated for the $e\nu$ +jets mode. Two events are observed passing all cuts.

The signature for the $t\bar{t}$ event in the all-jets channel is six or more high E_T jets with no significant $\not\!\!E_T$. Although this channel has the largest branching fraction (36/81), a very large background exists from QCD multijet production. DØ uses a combination of topological selection and $b \to \mu$ tagging to reduce this background. For a full description of the variables and techniques used the reader is referred to reference [11]. After applying strict topological cuts and requiring a single $b \to \mu$ tag, 15 events survive in the data with an expected background of 11 ± 2.3 events, and with a double $b \to \mu$ tag there are 2 events with an expected background of 1.4 ± 0.4 events. These determine preliminary cross sections of 4.4 ± 4.9 pb and 3.9 ± 9.8 pb for the single and double tags respectively. These results are statistically limited but in good agreement with our other cross section results, and provide confirmation of the expected excess we expect from $t\bar{t}$ production.

V. MASS ANALYSIS

The mass of the top quark, extracted from our single-lepton + four-jet event sample, proceeds in the same manner as previously published [1]. The major aspects of using a 2-constraint kinematic fit to the hypothesis $t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu q\bar{q}b\bar{b}$, assignment of the four highest E_T jets to partons made using a combinatoric algorithm, and the use of a maximum likelihood fit to the above assignments to get M_{top} remain essentially unchanged in method.

The mass analysis now uses selection criteria different from that used for the counting experiment. The new selection uses four kinematic variables chosen for good discrimination between top and background with-

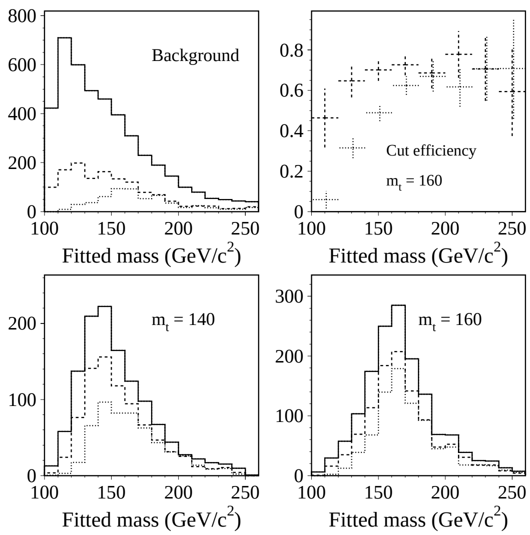

FIG. 6. Fitted top mass distributions of Monte Carlo, comparing parent distributions (solid), counting experiment cuts (dotted) and the log likelihood cuts (dashed) for: background, and signal for M_{top} =140 and 160 GeV/c^2. The top right plot compares the efficiency of selection of the counting experiment to that of the log likelihoods as a function of M_{top} for signal events generated at 160 GeV/c^2.

out large apparent bias on fitted top mass. Polynomial functions of the variables of $\not{E}_T$, Aplanarity, $h \equiv E_T^W/H_T^{jets+W}$, and $\langle\eta^2\rangle \equiv (\Sigma_{jets,W} E_T \eta^2/H_T^{jets+W})^{1/2}$ are incorporated into two log likelihood functions, where each polynomial is weighted in order to minimize the correlation of the likelihood function with the apparent top mass from the combination of signal and background expected. The first log likelihood is that the event is top rather than W + jets and the second is that the event is top rather than QCD multi-jet background. Figure 6 shows as a function of fit top mass the distributions of events from the parent sample, the counting experiment selection and the selection for the mass determination described.

These criteria are applied to an aforementioned parent sample obtained by requiring one high P_T electron or muon and four or more jets with E_T > 15 GeV (90 events). After requiring the cut on the log likelihood discriminator 30 data events remain for mass extraction.

The new preliminary DØ top quark mass extracted from the likelihood curve is 170 $\pm$ 15 (stat.)$\pm$10 (sys.) GeV/c^2 with the background constrained to our best estimate of 17.4 $\pm$ 2.2 events (see Figure 7). If the background is allowed to float in the fit the central value is unchanged and the background is found to be 15.7 $\pm$ 6.9 events. The statistical error is obtained though ensemble tests of Monte Carlo signal (HERWIG) and background (VECBOS and multijet data) events in a 0.42/0.58 ratio in accordance with our best estimate of signal over background. The signal and background is varied within constraints, and the width of the ensemble distribution is taken as the statistical error.

The systematic error on the mass determination is still dominated by the jet energy scale uncertainty. Using our new larger Z + jets data sample we estimate the jet scale uncertainty to be 4% + 1GeV/c^2 per jet for a 7 GeV/c^2 error on M_{top}. We assign a 6 GeV/c^2 uncertainty for resolution functions derived from HERWIG *vs.* ISAJET. Other contributions to the systematic uncertainty are from the likelihood fitting technique (3 GeV/c^2), background estimation (3 GeV/c^2) and Monte Carlo statistics (1 GeV/c^2).

VI. CONCLUSIONS

We have updated our measurements of the top quark in seven channels in a data sample from an integrated luminosity of roughly 100 pb^{-1}. With improved understanding of particle identification, selection cut efficiency, and jet energy scale, DØ measures the top quark mass to be 170 $\pm$ 15 (stat.)$\pm$10 (sys.) GeV/c^2 from the lepton+jet final state events. Using the acceptance calculated at our central top quark

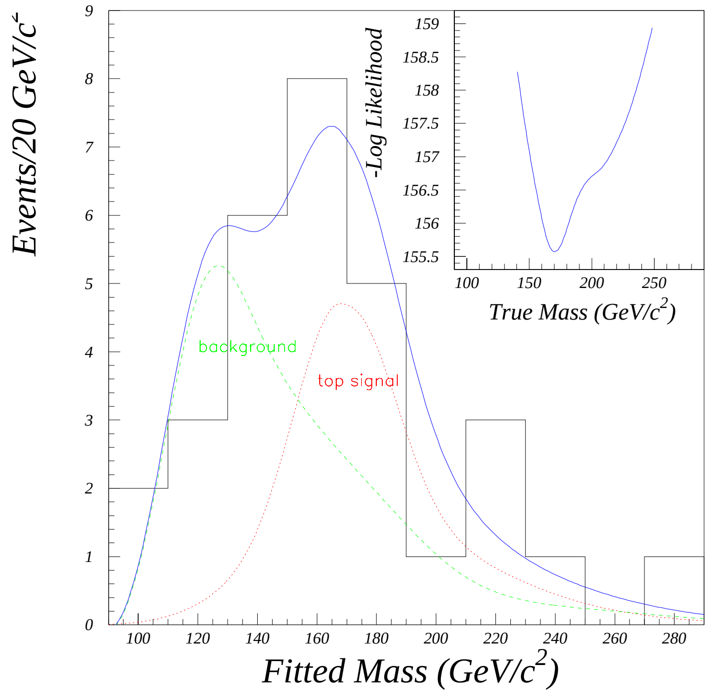

FIG. 7. DØ Preliminary fitted mass and mass likelihood distributions. Histogram is data, solid line is best fit, dashed line is background component, and dotted line is signal component.

mass, we measure the top quark pair production cross section to be $\sigma_{t\bar{t}} = 5.2 \pm 1.8$ pb. Preliminary results from analysis of two new decay modes, $e\nu+$ jets and all-jets, confirm the excess from top production expected in these channels.

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