

# Preliminary Results of a Search for Boosted Top Quarks by CDF II

CDF II Collaboration

## Abstract

We present the preliminary results of a search for boosted top quarks in a sample of high transverse momentum jets observed in the CDF II detector. The data were selected from a sample of  $5.95 \text{ fb}^{-1}$  of 1.96 TeV proton-antiproton collisions at the Fermilab Tevatron. We observe 103 candidate events in a sample where we require two massive jets or one massive jet with significant missing transverse energy, with an estimated background of  $76 \pm 10$  (stat.) $^{+26}_{-20}$  (syst.) events. We use these data to set an upper limit on the Standard Model  $t\bar{t}$  events with at least one top quark produced with  $p_T > 400 \text{ GeV}/c$  of 54 fb at 95% confidence level (C.L.)

## 1 Introduction

High transverse momentum ( $p_T$ ) massive QCD jets are interesting to study from various aspects (see *e.g.* [1, 2, 3] for recent reviews). From the experimental perspective, the substructure of these objects have not been extensively studied at the Tevatron and the studies that have been performed [4, 5] have been limited in both the  $p_T$  and mass of the jets. Theoretically, the observation of massive collimated jets provides an important test of perturbative QCD, an opportunity to tune the various Monte Carlo (MC) event generators and gives insight into the parton showering mechanism.

We also note that there have been relatively few studies at the Tevatron that explore the production of very highly boosted top quarks. The first top quark  $p_T$  measurement was by CDF [6] using  $0.1 \text{ fb}^{-1}$  of Run I data. The DZero collaboration has recently published a new measurement using  $1 \text{ fb}^{-1}$  of Run II data [7]. In both cases, the statistics of these measurements have been limited by the integrated luminosity, the branching fractions of the top quark pairs into final state and/or identification efficiencies for the  $t\bar{t}$  final states. Furthermore, no data is available for top quarks with  $p_T > 400 \text{ GeV}/c$ . Theoretical predictions for the differential top quark production cross section as a function of  $p_T$  now exist up to approximately next-to-next-to-leading order (NNLO) [10] so that a measurement or upper limit on the top quark production cross section for  $p_T > 400 \text{ GeV}/c$  will add in a unique way to our understanding of top quark production.

The first detailed study of massive jets produced in 1.96 TeV proton-antiproton collisions at the Tevatron Collider and recorded by the CDF II detector was recently completed [11]. Using a  $5.95 \text{ fb}^{-1}$  sample of data collected with a trigger that required the presence of at least one jet cluster with transverse energy ( $E_T$ ) greater than 100 GeV, this study measured the mass distribution of jets with  $p_T > 400 \text{ GeV}/c$ , as well as several variables developed to measure jet substructure. We have taken this data sample and extended the analysis to directly search for and set limits on the production of top quarks with  $p_T > 400 \text{ GeV}/c$ .

This analysis is unique in several ways. Because we are looking for boosted top quarks with Lorentz  $\gamma$  factors in excess of 3, the decay products of the top quark are expected to collimate into a single massive jet. Given our understanding of the jet mass from the earlier study, we have developed techniques to separate the signal from the primary backgrounds to this search, which come from the production of massive QCD jets. Finally, we have developed a data-driven technique to measure these backgrounds.

We present here the preliminary results of this search.

## 2 Data Sample

Our data sample consists of events collected with a trigger that required at least one jet cluster with transverse energy  $E_T > 100$  GeV. The entire inclusive jet sample consisted of  $7.58 \times 10^7$  events for  $5.95 \text{ fb}^{-1}$ . This corresponds to an effective triggered cross section of 12.7 nb. We required each event to meet a standard “good run” requirement for high-quality data and that it have a well-reconstructed primary vertex within  $|z_{\text{vtx}}| < 60$  cm of the nominal beam-beam crossing point.

Jet clusters were constructed with the Midpoint algorithm with a cone size of  $R = 1.0$  [8]. The calorimeter towers associated with a given jet were then recombined into a single four-vector using the “E-scheme”, which treats each tower as a massless four-vector and performs a four-vector sum to calculate the four-vector of the jet. The jet four-vector was then corrected using the standard CDF jet energy corrections [9]. Our earlier studies showed that multiple interactions (MI) in the event shift the jet mass upward. Using a data-driven technique, we correct the jet mass for this effect and use this corrected mass in the analysis described below. Each event was required to have at least one jet cluster with  $p_T > 400$  GeV/c in the pseudoradipity intervals  $|\eta| < 0.7$ . For these momentum, the typical jet energy correction is a factor of 1.12, with an uncertainty of 3%. The  $p_T > 400$  GeV/c requirement is made after these jet corrections have been applied.

Finally, we require each event to satisfy a loose  $\cancel{E}_T$  requirement of  $S_{\text{MET}} < 15$ , where  $S_{\text{MET}}$  is the standard  $\cancel{E}_T$  significance

$$S_{\text{MET}} \equiv \frac{\cancel{E}_T}{\sqrt{\sum E_T}}, \quad (1)$$

where the sum in the denominator is over all the towers in the calorimeter. This  $\cancel{E}_T$  significance requirement is adjusted subsequently in the analysis.

There are 5233 events satisfying these requirements.

## 3 Expected Sources of Events

### 3.1 NNLO Prediction for High $p_T$ Top Quark Production

Top quark production is dominantly a pair-production process ( $t\bar{t}$ ) with the transverse momentum of the top quark being approximately half the mass of the quark, but with a long tail to higher transverse momentum. It is this tail that contributes to any analysis looking at boosted objects.

A recent approximately NNLO calculation of the  $t\bar{t}$  differential cross section [10] has been updated with the MSTW 2008 parton distribution functions and a top quark mass of  $m_{top} = 173$  GeV/c<sup>2</sup> [12]. The calculation itself includes next-to-leading-order (NLO) corrections to the leading-order diagrams along with next-to-next-to-leading-order (NNLO) soft-gluon corrections. No rapidity cut was placed on this cross section though the author believe this would have a negligible effect on the overall rate. The scale used is  $\mu^2 = p_T^2 + M_{top}^2$ . This updated NNLO calculation for the  $p_T$  distribution yields a total cross section of

8.15 pb and a cross section for  $p_T > 400$  GeV/c of  $4.55^{+0.50}_{-0.41}$  fb. Said another way, the fraction of top quarks produced with  $p_T > 400$  GeV/c is  $5.58 \times 10^{-4}$ .

We also calculate this cross section by using a PYTHIA 6.1.4 calculation to predict the fraction of high  $p_T$  top quarks produced and then scale this to the measured cross section. Using a  $4.75 \times 10^6$  event  $t\bar{t}$  MC sample, we observe 4041 events with at least one top quark with  $p_T > 400$  GeV/c. This yields a fractional rate of  $8.51 \times 10^{-4}$ . We normalize this to the CDF average value of the measured total cross section of  $7.50 \pm 0.48$  pb [13], which yields a cross section for top quarks with  $p_T > 400$  GeV/c of 6.38 fb, or about 40% higher than the NNLO prediction.

The PYTHIA sample is passed through a full simulation of the CDF II detector and is used to calculate acceptances, efficiencies and signal yields. In our calculations of expected  $t\bar{t}$  contributions, we will employ the NNLO cross section of  $4.55^{+0.50}_{-0.41}$  fb for top quarks produced with  $p_T > 400$  GeV/c. With this cross section, the PYTHIA MC sample for this  $p_T$  range has a sensitivity of 888 fb $^{-1}$ .

We make the same requirements on the top quark MC sample. We observe 1608 jets with the leading jet  $p_T > 400$  GeV/c and  $|\eta| < 0.7$  in this MC sample, which corresponds to an observed cross section for jets meeting these requirements of  $1.8 \pm 0.2$  fb, where the uncertainty includes the statistical uncertainty of the MC sample (almost negligible) and the uncertainty on the top quark cross section (which dominates). We note that this is approximately 500 times smaller than the observed rate of such jets in the data. As there are 1390 events that are responsible for these jets, there are 218 events in this sample with two jets with  $p_T > 400$  GeV/c. This corresponds to an expected  $t\bar{t}$  event rate in our data sample of  $\sim 1.6$  fb.

### 3.2 QCD Jet Production

We use a PYTHIA 6.1.4 calculation of light quark and gluon production to create a large sample of the primary background process to boosted top quark production, namely high transverse momentum quark and gluon jets, requiring the parton transverse momentum to be greater than 300 GeV/c and employing the CTEQ5L parton distribution functions. The total number of generated events is  $4.89 \times 10^6$  with a calculated total cross section of 6.157 pb. Hence, this sample corresponds to an integrated luminosity of 795 fb $^{-1}$ , giving us a high-statistics sample to compare with data.

In a separate analysis [11], we have shown that the characteristics of this PYTHIA sample agree with the observed data in terms of kinematic distributions and jet properties for jets with  $p_T > 400$  GeV/c and  $|\eta| \in (0.1, 0.7)$ .

## 4 Selection of an Enriched Top Quark Sample

### 4.1 Employing Both $m^{jet1}$ and $m^{jet2}$

We start with the 5233 events with a high  $p_T$  leading jet requirement of jet  $p_T > 400$  and  $|\eta| < 0.7$ .

A simple strategy to detect the presence of  $t\bar{t}$  production when one is searching for fully-hadronic  $t\bar{t}$  decays is to require two massive jets with no evidence of large  $\cancel{E}_T$ . We show in Fig. 1 the distribution of the mass of the second-leading jet ( $m^{jet2}$ ) vs the mass of the leading jet ( $m^{jet1}$ ) for  $t\bar{t}$  MC events where we have required the events to satisfy our event selection and have in addition required  $S_{MET} < 4$ . We define a signal region for the all-hadronic channel by requiring that both jet candidates have a jet mass between 140 and 210 GeV/c $^2$ . We show in Fig. 2 the same distribution for the QCD MC sample, showing that the top quark signal and the QCD background are well-separated, but with some overlap. Finally, we show in Fig. 3 the same mass plot for the data sample.

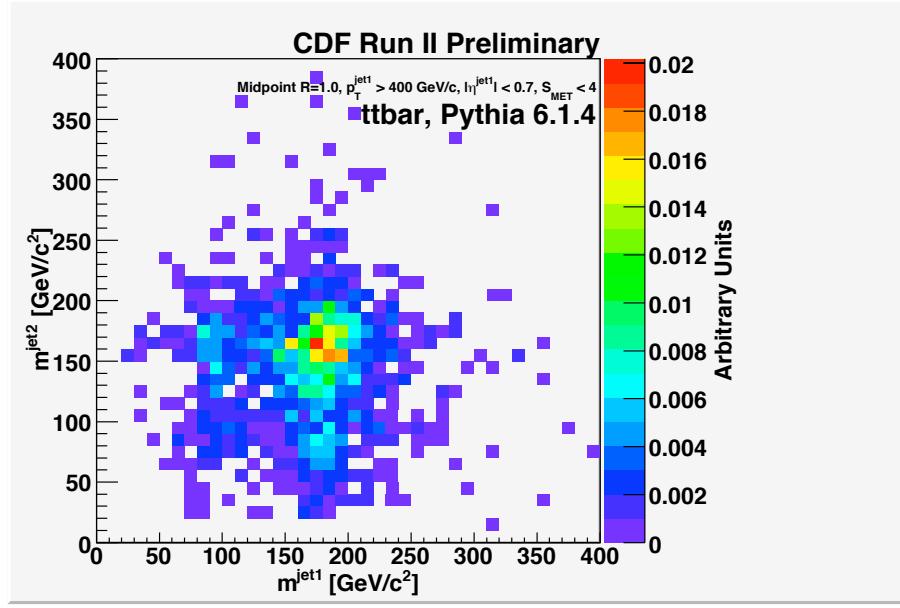


Figure 1: The  $m^{jet2}$  versus  $m^{jet1}$  distribution for  $t\bar{t}$  MC events with at least one jet with  $p_T > 400 \text{ GeV}/c^2$  and  $|\eta| < 0.7$  using  $R = 1.0$  Midpoint cones. All events are required to have  $S_{MET} < 4$ .

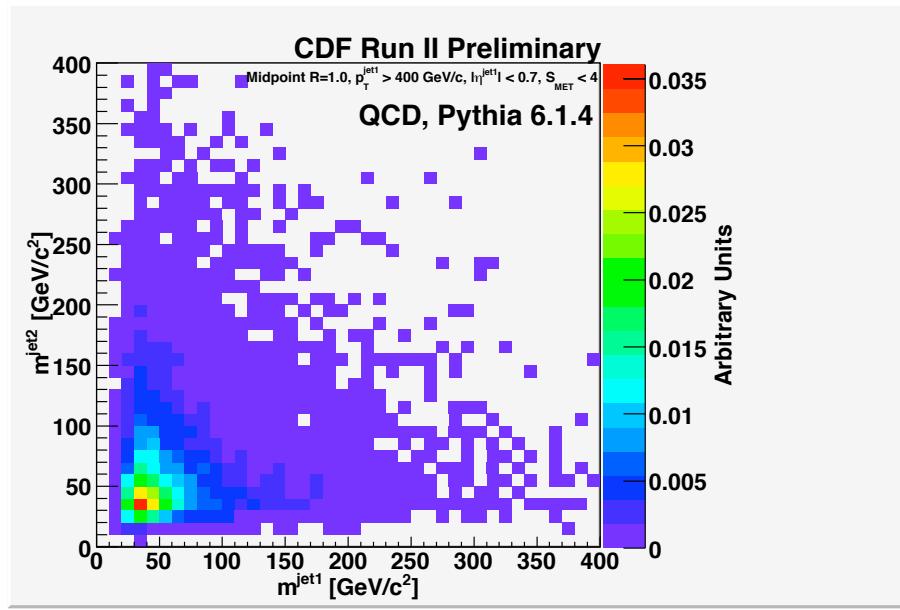


Figure 2: The  $m^{jet2}$  versus  $m^{jet1}$  distribution for QCD MC events with at least one jet with  $p_T > 400 \text{ GeV}/c^2$  and  $|\eta| < 0.7$  using  $R = 1.0$  Midpoint cones. All events are required to have  $S_{MET} < 4$ .

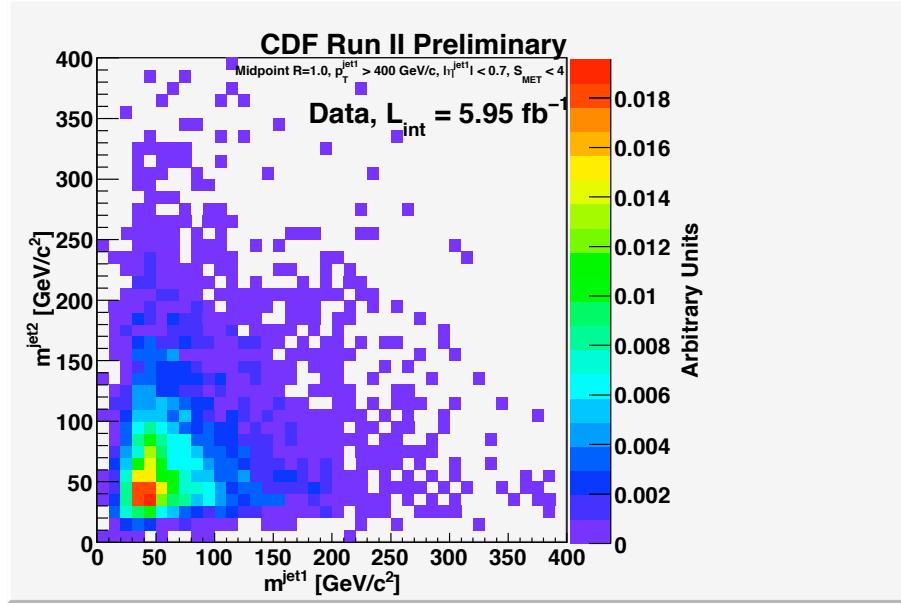


Figure 3: The  $m^{jet2}$  versus  $m^{jet1}$  distribution for all events with at least one jet with  $p_T > 400 \text{ GeV}/c^2$  and  $|\eta| < 0.7$  using  $R = 1.0$  Midpoint cones. The MI corrections have been performed and all events are required to have  $S_{MET} < 4$ .

Our previous studies [11] have shown that the mass distributions of the leading and second-leading jet are largely uncorrelated variables for QCD jet production. This allows us to estimate the background coming from QCD jet production in the top quark signal region by using the observed distribution in either  $m^{jet1}$  or  $m^{jet2}$  of events in the low jet mass peak (defined here to be  $30\text{--}50 \text{ GeV}/c^2$ ) relative to events in the top mass window of  $140\text{--}210 \text{ GeV}/c^2$  to estimate the QCD background in the signal region where both jet masses are between  $140$  and  $210 \text{ GeV}/c^2$ .

We find that there are 320 events with both jets in the mass region  $30\text{--}50 \text{ GeV}/c^2$  (region A). We also find 89 events with  $m^{jet1} \in (140, 210)$  and  $m^{jet2} \in (30, 50)$  (region B). We find an equivalent number of events – 113 – in the region  $m^{jet2} \in (140, 210)$  and  $m^{jet1} \in (30, 50)$  (region C). With these data, we estimate the number of QCD background events in the signal region (region D) to be  $31.4 \pm 4.8$  (stat.). We observe 61 events in the signal region. This calculation is summarized in Tab. 1.

| Region             | $m^{jet1}$<br>( $\text{GeV}/c^2$ ) | $m^{jet2}$<br>( $\text{GeV}/c^2$ ) | Data<br>(Events) | $t\bar{t}$ MC<br>(Events) |
|--------------------|------------------------------------|------------------------------------|------------------|---------------------------|
| A                  | (30, 50)                           | (30, 50)                           | 320              | 0.00                      |
| B                  | (140, 210)                         | (30, 50)                           | 89               | 0.13                      |
| C                  | (30, 50)                           | (140, 210)                         | 113              | 0.05                      |
| D (signal)         | (140, 210)                         | (140, 210)                         | 61               | 3.45                      |
| Predicted QCD in D |                                    |                                    | $31.4 \pm 4.8$   |                           |

Table 1: The observed number of events in the three control regions used to predict the background rate in the signal region (Region D). The  $t\bar{t}$  MC event rates in each region are also shown.

Applying the same selection to our  $t\bar{t}$  MC sample, we find 515 events in the signal region out of the

1390  $t\bar{t}$  MC events that have a leading jet with  $p_T > 400$  GeV/c. If we use the sensitivity of the MC sample of 888  $\text{fb}^{-1}$ , we would expect to see

$$N_{t\bar{t}} = \left( \frac{515}{888} \right) (5.95) = 3.4 \text{ events} \quad (2)$$

in the signal region.

## 4.2 Employing $m^{jet1}$ and Missing $E_T$ Significance

In order to observe  $t\bar{t}$  events where one top quark has decayed semileptonically (a “lepton+jets” final state), we turn to the sample of high  $p_T$  jet events where a recoil jet has not been identified as a potential top quark candidate through its mass but where the event has substantial  $\cancel{E}_T$ . The top quark MC sample predicts that the requirement of  $4 < S_{MET} < 10$  is effective in identifying those top quark decays where the recoil jet does not contain all the decay products of the top quark, as shown in Fig. 4 where we plot the jet mass distribution of the second-leading jets in  $t\bar{t}$  MC events. We also show the PYTHIA QCD background distribution for these events, illustrating that the second-leading jet mass is no longer an effective discriminant between signal and background. We therefore define our “lepton+jets” signal event sample as those with a leading jet with high  $m^{jet1}$  and  $S_{MET}$ , forming a signal region defined by  $m^{jet1} \in (140, 210)$  GeV/c $^2$  and  $S_{MET} \in (4, 10)$ .

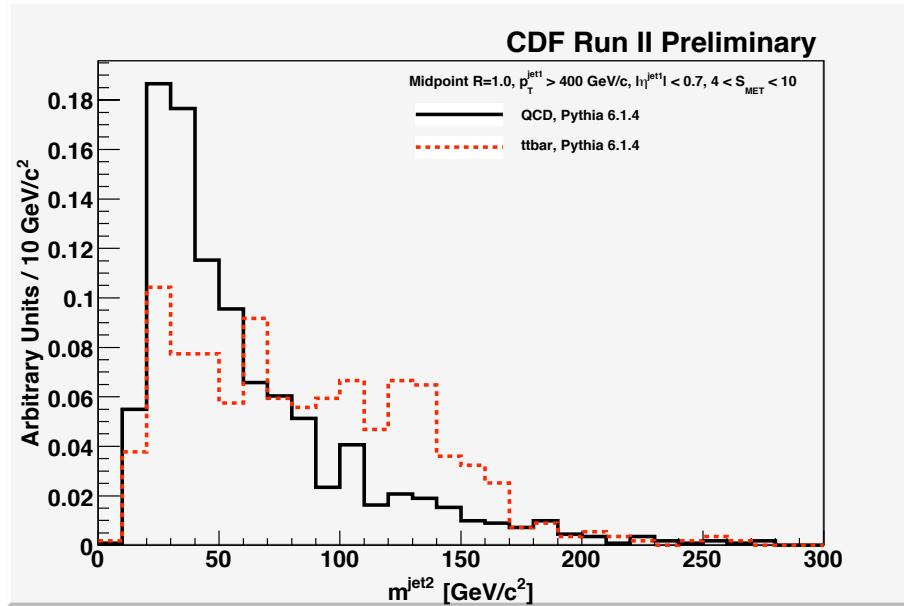


Figure 4: The  $m^{jet2}$  distribution for  $t\bar{t}$  and QCD MC events when we require that the event have a leading jet with  $p_T > 400$  GeV/c $^2$  and  $|\eta| < 0.7$  using  $R = 1.0$  Midpoint cones and  $S_{MET} \in (4, 10)$ .

We show in Figs. 5, 6 and 7 the distributions of  $S_{MET}$  vs  $m^{jet1}$  for the events where we have required a leading jet with  $p_T > 400$  GeV/c and  $|\eta| < 0.7$ , requiring in addition that the event have  $4 < S_{MET} < 10$  for the  $t\bar{t}$  MC sample, QCD MC sample and the data sample, respectively. This illustrates the effectiveness of the  $S_{MET}$  requirement to separate the signal from the background for this sample.

To estimate the remaining QCD background in the signal region defined by a requiring a leading massive jet and significant  $\cancel{E}_T$ , we use the observation that these two variables are uncorrelated for QCD background

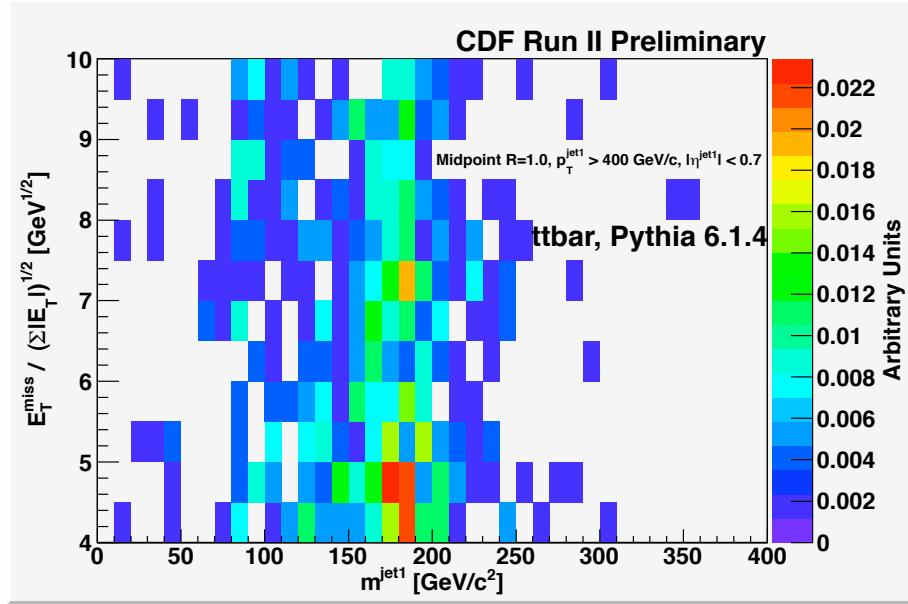


Figure 5: The  $S_{MET}$  versus  $m^{jet1}$  distribution for  $t\bar{t}$  MC events with at least one jet with  $p_T > 400$  GeV/ $c^2$  and  $|\eta| < 0.7$  using  $R = 1.0$  Midpoint cones, where we have required  $S_{MET} \in (4, 10)$ .

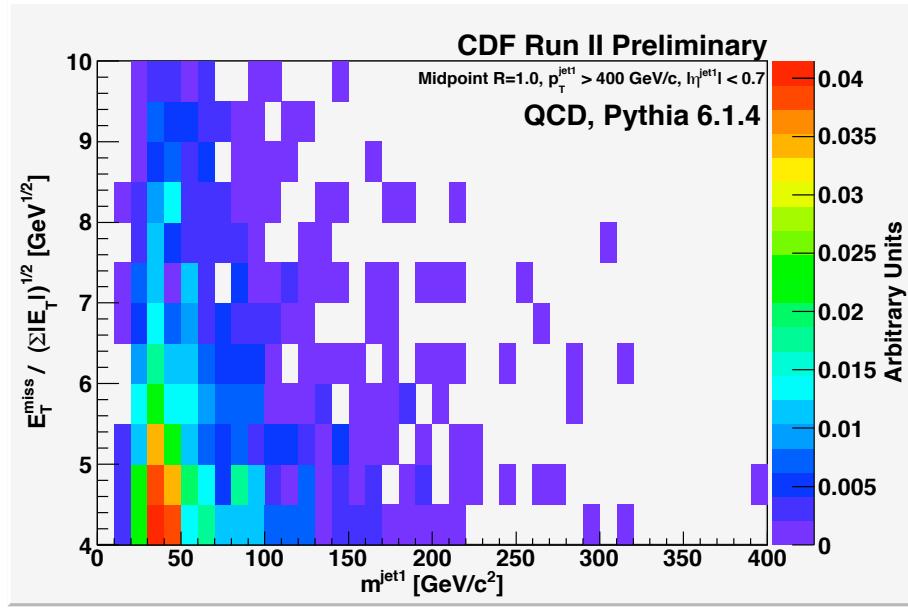


Figure 6: The  $S_{MET}$  versus  $m^{jet1}$  distribution for QCD MC events with at least one jet with  $p_T > 400$  GeV/ $c^2$  and  $|\eta| < 0.7$  using  $R = 1.0$  Midpoint cones, where we have required  $S_{MET} \in (4, 10)$ .

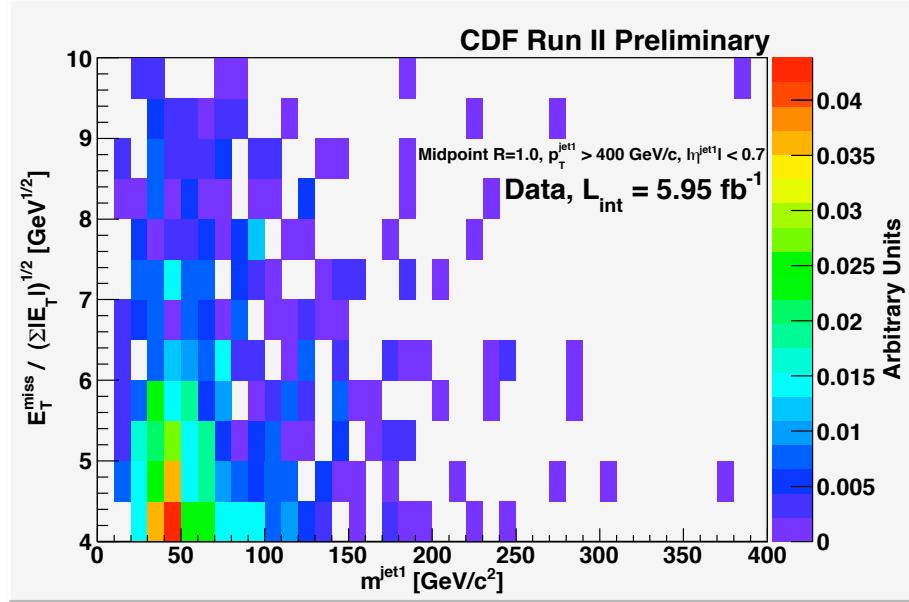


Figure 7: The  $S_{MET}$  versus  $m_{jet1}^2$  distribution for all events with at least one jet with  $p_T > 400$  GeV/c and  $|\eta| < 0.7$  using  $R = 1.0$  Midpoint cones, where we have required  $S_{MET} \in (4, 10)$ .

events and perform a data-driven background calculation similar to that performed for the all-hadronic channel candidates. We define region A to be  $m_{jet1}^2 \in (30, 50)$  and  $S_{MET} \in (2, 3)$ , region B as  $m_{jet1}^2 \in (140, 210)$  and  $S_{MET} \in (2, 3)$ , region C to be  $m_{jet1}^2 \in (30, 50)$  and  $S_{MET} \in (4, 10)$  and region D to be the signal region. We find that there are 269 events in region A, 65 events in region B and 186 events in region C. With these event counts, we predict  $44.9 \pm 7.0$  (stat.) events in region D (the signal region).

Applying the same selection to our  $t\bar{t}$  MC sample, we find 343 events in the signal region out of the 1390  $t\bar{t}$  MC events that have a leading jet with  $p_T > 400$  GeV/c. If we use the the sensitivity of the MC sample of  $631 \text{ fb}^{-1}$ , we would expect to see

$$N_{t\bar{t}} = \left( \frac{343}{888} \right) (5.95) = 2.3 \text{ events} \quad (3)$$

from  $t\bar{t}$  production in the signal region.

We observe 42 events in this signal region, consist with the background estimate and also consistent with the number of expected background and signal events. This calculation is summarized in Tab. 2.

If we combine the results of the two channels, we find 103 candidate events with an expected background from QCD jets of  $76.4 \pm 10.5$  events (the uncertainty is only statistical). The systematic uncertainty on the background rate is dominated by the uncertainty on the jet mass scale (see the next subsection), and results in a background estimate of  $76 \pm 10$  (stat.) $^{+26}_{-20}$  (syst.) events. The statistical significance of the observed excess of events in the background region is modest, so we cannot use these data to claim observation of boosted top. However, we can set useful upper limits on the boosted top cross section.

### 4.3 Systematic Uncertainties

The largest source of systematic uncertainty in this measurement arises from the uncertainty on the jet mass scale. The other sources of uncertainty are the uncertainty in the top quark acceptance due to the uncertainty

| Region             | $m^{jet1}$<br>(GeV/c <sup>2</sup> ) | $S_{MET}$<br>( $\sqrt{GeV/c^2}$ ) | Data<br>(Events) | MC<br>(Events) |
|--------------------|-------------------------------------|-----------------------------------|------------------|----------------|
| A                  | (30, 50)                            | (2, 3)                            | 269              | 0.01           |
| B                  | (140, 210)                          | (2, 3)                            | 65               | 1.26           |
| C                  | (30, 50)                            | (4, 10)                           | 186              | 0.05           |
| D (signal)         | (140, 210)                          | (4, 10)                           | 42               | 2.30           |
| Predicted QCD in D |                                     |                                   | $44.9 \pm 9.3$   |                |

Table 2: The observed number of events in the three control regions used to predict the background rate in the signal region (Region D) for high  $S_{MET}$  and high  $m^{jet1}$ . The  $t\bar{t}$  MC event rates are also shown normalized to the sensitivity of the data sample.

in the jet energy scale, the uncertainty in the integrated luminosity in the sample, and the uncertainty on the  $t\bar{t}$  acceptance due to the top mass uncertainty. The other key assumption in the background calculation, namely the lack of correlation between  $m^{jet1}$ ,  $m^{jet2}$  and  $S_{MET}$ , has been checked and introduces a negligible uncertainty.

Our earlier studies have set a systematic uncertainty on the jet mass measurement of  $\pm 11$  GeV/c<sup>2</sup> for high mass jets, largely coming from studies of the relative calorimeter energy response inside a massive jet. We estimate the effect of this uncertainty on the jet mass scale by shifting the upper mass window by  $\pm 11$  GeV/c<sup>2</sup> and observing how the QCD background estimate changes. This results in systematic uncertainties of  $-24\%$  and  $+35\%$  on the combined background rate of 76 events.

The jet energy scale uncertainty results in a systematic uncertainty on the top quark acceptance, which we determine by shifting the jet  $p_T$  scale by 3% (the efficiency is sensitive to the jet energy scale simply because, for example, an underestimate in the jet energy scale would reduce the observed rate of  $t\bar{t}$  events and vice-versa). The resulting change in the top quark acceptance is  $\pm 24.5\%$ , using the  $p_T$  distribution from the NNLO calculation.

We incorporate a systematic uncertainty on the integrated luminosity of  $\pm 6\%$ , the current uncertainty for CDF II luminosity measurements. We also find that the  $t\bar{t}$  acceptance uncertainty due to possible variations in the top quark mass is  $\pm 0.3\%$ .

We assume these are all independent sources of uncertainty and add them in quadrature. Together, these result in overall systematic uncertainties on the total cross section limit of  $-37\%$  and  $+45\%$ .

#### 4.4 Limits on $t\bar{t}$ Production

Given that we expect comparable signal-to-noise and acceptance in the all-hadronic and lepton+jets channels, we combine the total number of candidate events and total background rate and use these to set an upper limit on  $t\bar{t}$  production for top quarks with  $p_T > 400$  GeV/c. We calculate the 95% C.L. limit, folding in the systematic uncertainties, using a Bayesian approach employing a flat prior on the cross section and treating the sources of systematic uncertainty as nuisance parameters [14].

The resulting upper limit, taking into account the  $t\bar{t}$  detection efficiency of 0.212 and the integrated luminosity of  $5.95 \text{ fb}^{-1}$ , is 54 fb at 95% C.L. on standard model  $t\bar{t}$  production for top quark  $p_T > 400$  GeV/c. This is approximately an order of magnitude higher than the estimated Standard Model rate, and is limited by the QCD background rates. It is, however, the most stringent limit on boosted top quark production to date.

Finally, we calculate the “expected limit” by using the background estimated from the data-driven technique and assuming an observation of  $t\bar{t}$  events at the expected level of 5.75 events. Our Bayesian calculation

yields an upper limit of 39 fb at 95% C.L., which is lower than the observed limit since we see an excess of events above the expected signal plus background in the data.

## 5 Conclusion

We present the first search for boosted top quark production using data gathered with an inclusive jet trigger. We find a modest excess of events – 103 candidate events with an estimated background of  $76^{+29}_{-21}$  events – identified in either a configuration with two high  $p_T$  jets each with mass between 140 and 210  $\text{GeV}/c^2$  or where we observe a massive jet recoiling against a second jet with significant missing transverse energy.

We expect approximately 6 signal events from Standard Model top quark production where at least one of the top quarks has  $p_T > 400 \text{ GeV}/c$ . The data do not have sufficient significance to support a claim for observation of such boosted top quark production. However, we set a 95% C.L. upper limit on the rate of top quark production for top quarks with  $p_T > 400 \text{ GeV}/c$  of 54 fb at 95% C.L.

## Acknowledgements

We acknowledge the contributions of numerous theorists for insights and calculations. Special thanks go to Ilmo Sung and George Sterman, for their elucidation of the “soft function” that determines the behaviour of QCD jets at low jet masses, and to Nikolaos Kidonakis for performing an updated calculation of the top quark  $p_T$  distribution at NNLO and providing us with an estimate of the uncertainties in the cross section for top quarks with  $p_T > 400 \text{ GeV}/c$ .

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 World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

This work was supported in part by a grant from the Shrum Foundation. One of us (P. Sinervo) gratefully acknowledges the Rosi and Max Varon Visiting Professorship of the Weizmann Institute of Science for supporting the early stages of this study. G. Perez, E. Duchovni and R. Alon were supported by the Weizmann Institute of Science and one of them (G.Perez) is supported by the Isreal Science Foundation (grant #1087/09), Marie Curie, IRG fellowship and the Peter & Patricia Gruber Award.

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