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A Search for Boosted Top Quarks by CDF II

CDF II Collaboration

Abstract

We present the 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 fb^{-1} of 1.96 TeV proton-antiproton collisions at the Fermilab Tevatron. We observe 57 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 46 ± 8.5 (stat.) ± 13.8 (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 $p_T > 400$ GeV/c of 38 fb at 95% confidence level (C.L.). We place an upper limit on the production of a pair of massive objects with masses near the top quark mass with at least one resulting jet with $p_T > 400$ GeV/c of 20 fb at 95% 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 fb^{-1} of Run I data. The DZero collaboration has recently published a new measurement using 1 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 $p_T > 400$ 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 $p_T > 400$ 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 [17]. Using a 5.95 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 $p_T > 400$ 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 $p_T > 400$ GeV/c.

This analysis is unique in several ways. Because we are looking for boosted top quarks with Lorentz γ 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 results of this search after optimizing the search by studying several different jet finding algorithms implemented in the Fastjet package [18]. The results presented here were found using the standard Midpoint algorithm.

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 7.58×10^7 events for 5.95 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 $|z_{vtx}| < 60$ 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 this momentum range, the typical jet energy correction is 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 $\not\!\!E_T$ requirement of $S_{MET} < 10$, where S_{MET} is the standard $\not\!\!E_T$ significance

$$S_{MET} \equiv \frac{\not\!\!E_T}{\sqrt{\sum E_T}}, \tag{1}$$

where the sum in the denominator is over all the towers in the calorimeter. This $\not\!\!E_T$ significance requirement is adjusted subsequently in the analysis.

There are 4230 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^2 [19]. 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 5.58×10^{-4}.

We also calculate this cross section by using a PYTHIA 6.216 calculation to predict the fraction of high p_T top quarks produced and then scale this to the measured cross section. Using a 4.75×10^6 event $t\bar{t}$ MC sample, we observe 4041 events with at least one top quark with $p_T > 400$ GeV/c, or a fractional rate of 8.51×10^{-4}. We normalize this to the CDF average value of the measured total cross section of 7.50 ± 0.48 pb [20], 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 1027 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 1.15 ± 0.14 fb, where the uncertainty includes the statistical uncertainty of the MC sample (almost neglible) and the uncertainty on the top quark cross section (which dominates). We note that this is approximately 600 times smaller than the observed rate of such jets in the data. As there are 866 events that are responsible for these jets, there are 161 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 ~ 0.9 fb.

3.2 QCD Jet Production

We use a PYTHIA 6.216 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 4.89×10^6 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 [17], 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 4230 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 $\not{E}_T$. 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 130 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.

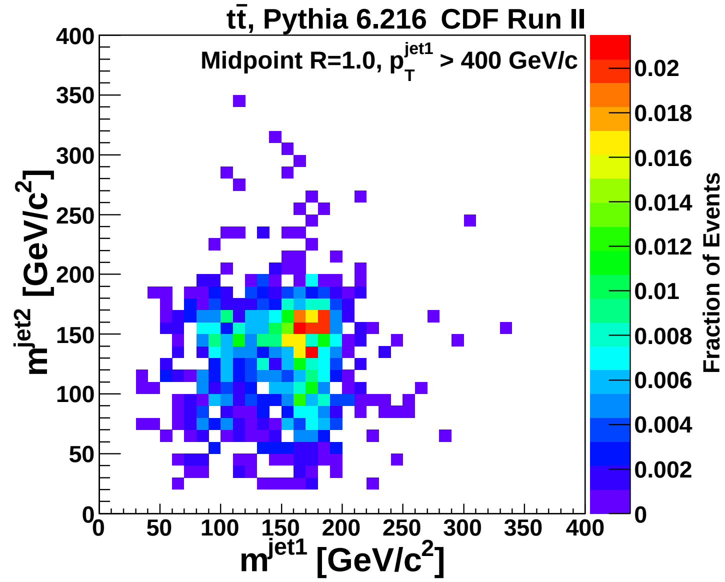

Figure 1: The m^{jet2} versus m^{jet1} distribution for $t\bar{t}$ MC events with at least one jet with $p_T > 400$ GeV/c^2 and $|\eta| < 0.7$ using $R = 1.0$ Midpoint cones. All events are required to have $S_{MET} < 4$.

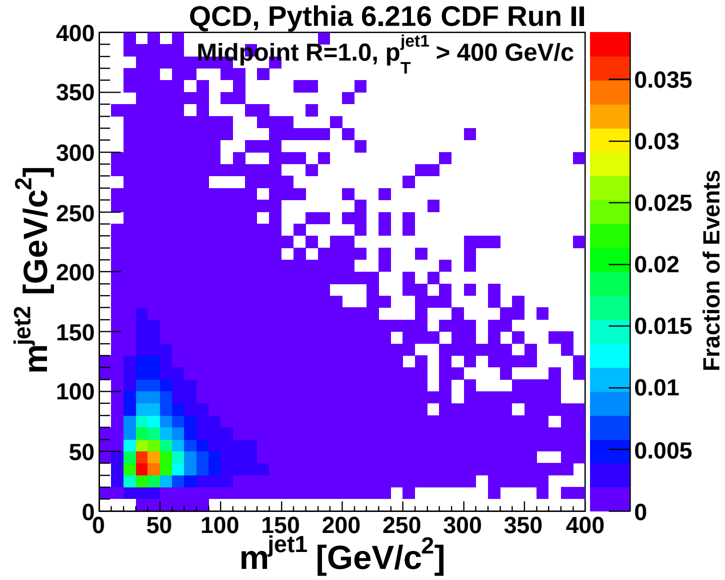

Figure 2: The m^{jet2} versus m^{jet1} distribution for QCD MC events with at least one jet with $p_T > 400$ GeV/c^2 and $|\eta| < 0.7$ using $R = 1.0$ Midpoint cones. All events are required to have $S_{MET} < 4$.

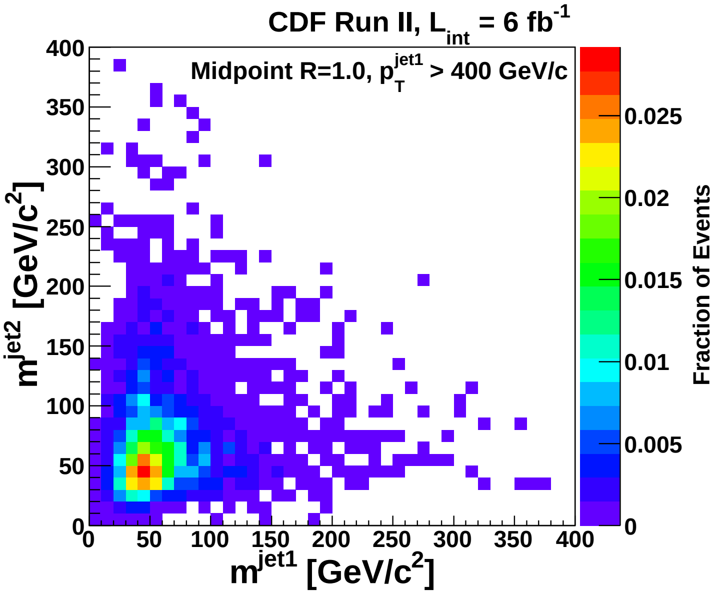

Figure 3: The m^{jet2} versus m^{jet1} distribution for all data events with at least one jet with $p_T > 400$ GeV/c^2 and $|\eta| < 0.7$ using $R = 1.0$ Midpoint cones. The MI corrections have been performed and all events are required to have $S_{MET} < 4$.

Recent studies [11, 12] have shown that the mass distributions of the leading and second-leading jet are slightly correlated. This correlation can be expressed using the variable

$$R_{mass} = \frac{N_B N_C}{N_A N_D}, \tag{2}$$

where N_X is the number of observed events in region X, as defined below. 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 30-50 GeV/c^2) relative to events in the top mass window of 130 to 210 GeV/c^2 to estimate the QCD background in the signal region where both jet masses are between 130 and 210 GeV/c^2.

We find that there are 370 events with both jets in the mass region 30 to 50 GeV/c^2 (region A). We also find 47 events with $m^{jet1} \in (130, 210)$ and $m^{jet2} \in (30, 50)$ (region B). We find twice that number of events – 102 – in the region $m^{jet2} \in (130, 210)$ and $m^{jet1} \in (30, 50)$ (region C). The difference in region B and C arise from having the p_T cut on the leading jet. We use $R_{mass} = 0.89 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})$. This number was derived from events generated using a POWHEG MC calculation [13, 14, 15, 16] with the CTEQ6M PDF set and hadronization by the PYTHIA 6.4.24 Monte Carlo program. The systematic uncertainty is the difference between the POWHEG result and the lowest value in [11] using a MC calculation employing jet-parton matching to reduce double-counting of large-angle parton radiation. With these data, we estimate the number of QCD background events in the signal region (region D) to be 14.6 ± 2.76 (stat.). We observe 31 events in the signal region. This calculation is summarized in Tab. 1.

Applying the same selection to our $t\bar{t}$ MC sample, we find 452 events in the signal region out of the 4041 $t\bar{t}$ MC events that have a top quark with $p_T > 400$ GeV/c. If we use the sensitivity of the MC sample

Region	m^{jet1} (GeV/c^2)	m^{jet2} (GeV/c^2)	Data (Events)	$t\bar{t}$ MC (Events)
A	$(30,50)$	$(30,50)$	370	0.00
B	$(130,210)$	$(30,50)$	47	0.08
C	$(30,50)$	$(130,210)$	102	0.01
D (signal)	$(130,210)$	$(130,210)$	31	3.03
Predicted QCD in D			14.6 ± 2.76	

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.

of 888 fb^{-1}, we would expect to see

$$N_{t\bar{t}} = \left(\frac{452}{888}\right)(5.95) = 3.0 \text{ events} \tag{3}$$

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 $\not{E}_T$. 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 $m^{jet1} \in (130,210)$ GeV/c^2 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 ttbar 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 $\not{E}_T$, we use the observation that these two variables are uncorrelated for QCD background events and perform a data-driven background calculation similar to that performed for the all-hadronic channel candidates. We define region A to be $m^{jet1} \in (30,50)$ and $S_{MET} \in (2,3)$, region B as $m^{jet1} \in (130,210)$ and $S_{MET} \in (2,3)$, region C to be $m^{jet1} \in (30,50)$ and $S_{MET} \in (4,10)$ and region D to be the signal region. We find that there are 256 events in region A, 42 events in region B and 191 events in region C. With these event counts, we predict 31.3 ± 8.1 (stat.) events in region D (the signal region).

Applying the same selection to our $t\bar{t}$ MC sample, we find 283 events in the signal region out of the 4041 $t\bar{t}$ MC events that have a top quark with $p_T > 400$ GeV/c. If we use the the sensitivity of the MC sample of 631 fb^{-1}, we would expect to see

$$N_{t\bar{t}} = \left(\frac{283}{888}\right)(5.95) = 1.9 \text{ events} \tag{4}$$

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

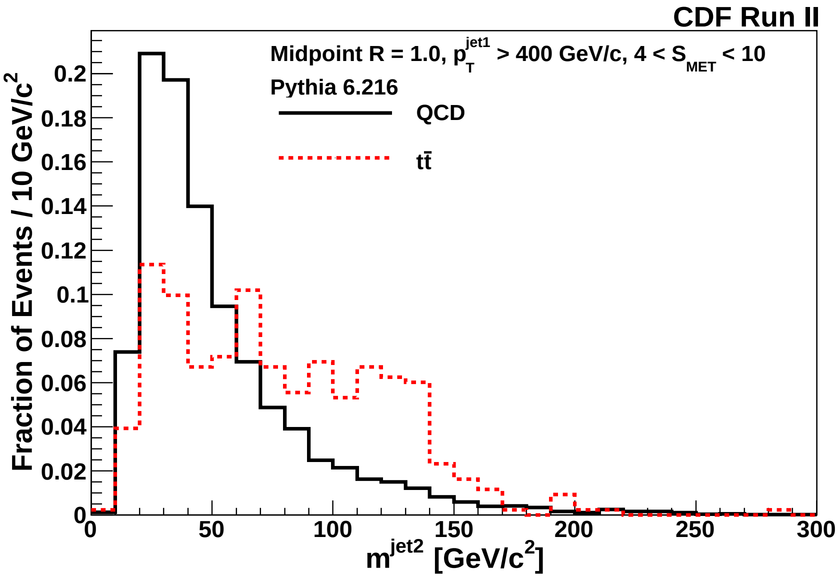

Figure 4: The m^{jet2} distribution for $t\bar{t}$ and QCD MC events when we require that the event have a leading jet with $p_T > 400$ GeV/c^2 and $|\eta| < 0.7$ using $R = 1.0$ Midpoint cones and $S_{MET} \in (4,10)$.

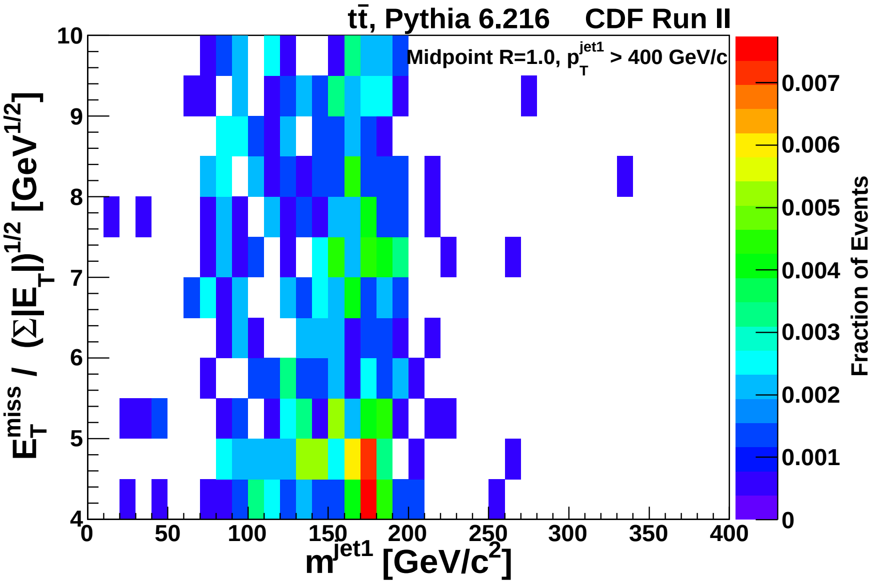

Figure 5: The S_{MET} versus m^{jet1} distribution for $t\bar{t}$ MC events with at least one jet with $p_T > 400$ GeV/c^2 and $|\eta| < 0.7$ using $R = 1.0$ Midpoint cones, where we have required $S_{MET} \in (4,10)$.

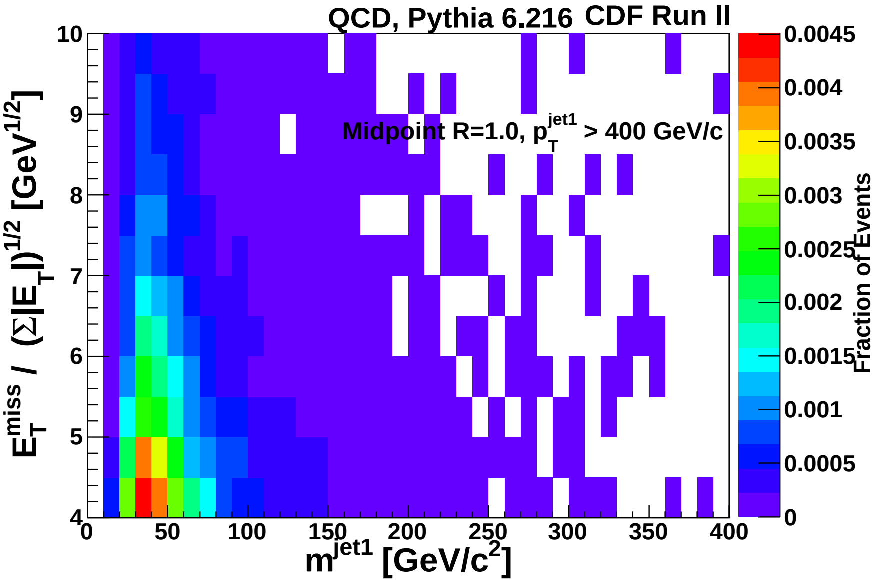

Figure 6: The S_{MET} versus m^{jet1} distribution for QCD MC events with at least one jet with $p_T > 400$ GeV/c^2 and $|\eta| < 0.7$ using $R = 1.0$ Midpoint cones, where we have required $S_{MET} \in (4, 10)$.

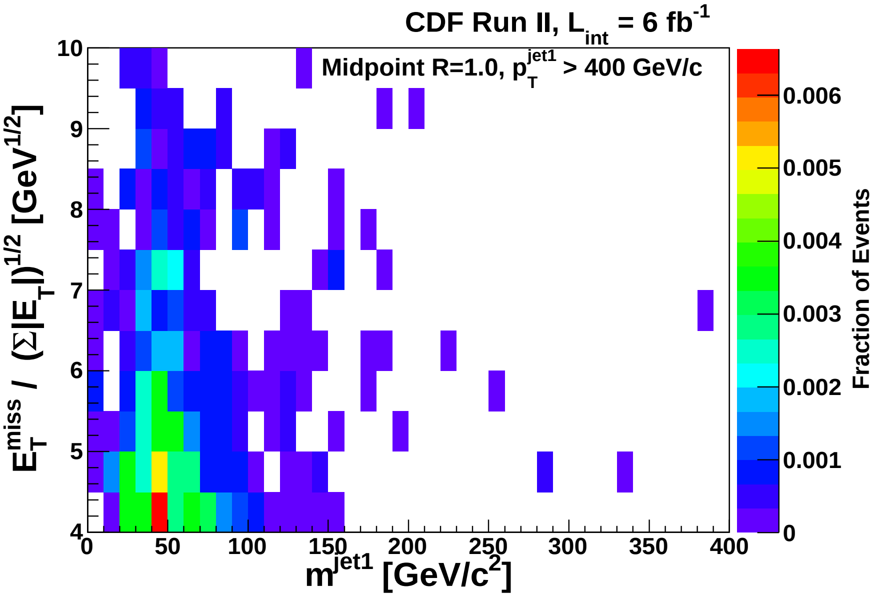

Figure 7: The S_{MET} versus m^{jet1} distribution for all data events with at least one jet with $p_T > 400$ GeV/c^2 and $|\eta| < 0.7$ using $R = 1.0$ Midpoint cones, where we have required $S_{MET} \in (4, 10)$.

We observe 26 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.

Region	m^{jet1} (GeV/c^2)	S_{MET} ($\sqrt{GeV/c^2}$)	Data (Events)	MC (Events)
A	$(30,50)$	$(2,3)$	256	0.01
B	$(130,210)$	$(2,3)$	42	1.07
C	$(30,50)$	$(4,10)$	191	0.03
D (signal)	$(130,210)$	$(4,10)$	26	1.90
Predicted QCD in D			31.3 ± 8.1	

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.

If we combine the results of the two channels, we find 57 candidate events with an expected background from QCD jets of 46 ± 8.5 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 46 ± 8.5 (stat.) ± 13.8 (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 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 ± 10.2 GeV/c^2 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 ± 10.2 GeV/c^2 and observing how the QCD background estimate changes. This results in a systematic uncertainty of ±30% on the combined background rate of 44 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 ±24.5%, using the p_T distribution from the NNLO calculation.

We incorporate a systematic uncertainty on the integrated luminosity of ±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 ±0.3%.

We assign a systematic uncertainty of 0.03 on R_{mass} derived from the difference between the POWHEG calculation and previous calculations [11].

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 ±44.2%.

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 [21].

The resulting upper limit, taking into account the $t\bar{t}$ detection efficiency of 0.182 and the integrated luminosity of 5.95 fb^{-1}, is 38 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 4.9 events. Our Bayesian calculation yields an upper limit of 33 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.

It is interesting to set a limit on the fully hadronic channel, as this creates a selection that is sensitive to pair production of two massive objects near the mass of the top quark. An example of such a scenario would be a light baryon number violating neutralino or gluino particle in the context of supersymmetry (see *e.g.* [22, 23]) and in some cases within theories of colored resonances [24]. We have 31 events with two massive jets with $m^{jet} \in (130, 210)$ GeV/c^2, with a background estimate of 14.6 ± 2.76 (stat.) ± 4.4 (syst.) events. As we are interested in beyond-SM contributions to this final state, we now include in the background estimate the expected $t\bar{t}$ contribution of 3.0 ± 0.8 events. If we use the acceptance for top quark pair production in this channel (0.112) but then take out the top quark hadronic branching fraction of $4/9 = 0.44$, employ the systematic uncertainties described earlier and use the mclimits calculation, we set an upper limit of 20 fb at 95% C.L.

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 – 57 candidate events with an estimated background of 46 ± 8.5 (stat.) $\pm$ 13.8 (syst.) events – identified in either a configuration with two high p_T jets each with mass between 130 and 210 GeV/c^2 or where we observe a massive jet recoiling against a second jet with significant missing transverse energy.

We expect approximately 5 signal events from Standard Model top quark production where at least one of the top quarks has $p_T > 400$ 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 $p_T > 400$ GeV/c of 38 fb at 95% C.L.. We use these data to also search for pair production of a massive object with masses comparable to that of the top quark with at least one of the objects having $p_T > 400$ GeV/c. We set an upper limit on the pair production of 20 fb at 95% C.L..

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