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Kinematics of Top Decays from CDF

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We present a study of the kinematics of W + $\geq$ 3 jet events produced in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. We describe several techniques used to compare the observed events with expectations both from direct W + jets production and from production and decay of heavy top quark pairs. We also study the kinematic features of the events used to measure the top mass. Finally we show the results obtained looking for top candidates in the channel with 6 jets in the final state.

1 Introduction

At the Tevatron top quarks are expected to be produced primarily through the process $p\bar{p} \rightarrow t\bar{t}$. In the Standard Model (SM) framework each top quark decays into a real W and a b quark. The $t\bar{t} \rightarrow W^+bW^-\bar{b}$ events can be identified by means of different combinations of energetic leptons and jets.

The CDF data was collected in two running periods (run 1A and run 1B). Both a counting experiment [1] and a kinematic study [2] ("*event structure*") were performed with the data from run 1A (19.3 pb^{-1}). The first evidence of top events reported in these analyses was confirmed by an improved version of the counting experiment, using a bigger data sample (67 pb^{-1}) [3].

We present several analyses which exploited the kinematic features of the top decay in the channel where one of the W's decays leptonically and the other one hadronically ("*single lepton channel*") [4, 5]. We report also the preliminary results from an analysis which searches for a top signal in the channel where both W's decay hadronically ("*hadronic channel*").

For all these studies, the $t\bar{t}$ simulation is done with HERWIG, a parton shower Monte Carlo using leading order QCD for the hard process. The W + jets background is computed with VECBOS, a parton level Monte Carlo which uses the lowest order matrix elements. The parton fragmentation process is simulated with a HERWIG type shower module [1]. A detailed description of the CDF detector can be found elesewhere [6].

2 H analysis

We use the $W+ \geq 4$ jet subsample and study the total transverse energy H, which is defined as the scalar sum of the lepton transverse energy (E_T), the missing transverse energy ($\not{E}_T$) and the E_T of each jet [4]. The H variable is

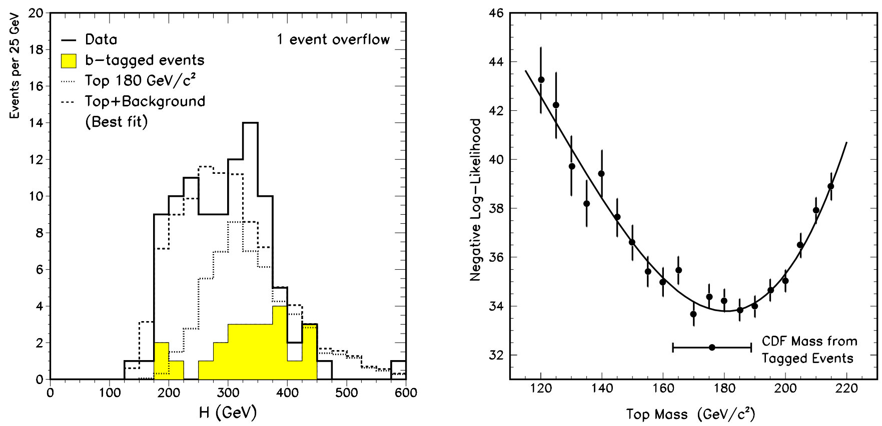

Figure 1: Left (L): H distributions. Solid is data, dashed is best fit, and dotted is the top component of best fit. The shaded area indicates b–tagged events. Right (R): Negative log–likelihood for the fit of the data to VECBOS plus $t\bar{t}$ vs top mass.

expected to discriminate between $t\bar{t}$ and W + multijet events, because the W and b quark resulting from the top quark decay have higher transverse momenta than radiated gluons in background processes. The results are based on 67 pb^{-1} of data. W events are selected by requiring an isolated high E_T lepton and high $\not{E}_T$ [4]. We then require events to have 3 jets with the observed calorimeter $E_T \geq 15$ GeV and $|\eta_{jet}| \leq 2.0$ [a], and at least one additional jet with $E_T \geq 8$ GeV and $|\eta_{jet}| \leq 2.4$. When calculating H, jet energies and $\not{E}_T$ are corrected by a rapidity and energy dependent factor, which accounts for calorimeter non–linearity and reduced response at detector boundaries [7].

There are 99 events in the signal sample. The H distribution for these events is shown in Fig. 1(L). Also shown is the best fit to the data of a mixture of $t\bar{t}$ and VECBOS events ($q^2 = < P_T >^2$). CDF is able to identify b quarks with two algorithms. The first one looks for b decay secondary vertices, which are displaced from the primary vertex ("*SVX tag*") [1]. The other one looks for electrons or muons from semileptonic b decays inside jets ("*Soft Lepton Tag*") [1]. The shaded area in Fig. 1(L) indicates the 23 tagged events. The structure of the H distribution as well as the clustering of b–tagged events at large H give evidence that the excess above the background results from $t\bar{t}$ production.

Figure 1(R) shows the negative log–likelihood for the two component fit as a function of the top mass. The best fit is given by $M_{top} = 180 \pm 12(stat.)\ ^{+19}_{-15}$

[a] $\eta = -\ln \mathrm{tg}(\theta/2)$, and θ is the polar angle with respect to the beam.

(*syst.*) GeV/c^2. Changing the q^2 value ($q^2 = M_W^2$) we find $M_{top} = 184 \pm 15 ^{+19}_{-15}$ GeV/c^2. The masses are consistent, within the errors, with the published result of $M_{top} = 176$ GeV/c^2 [3]. The two estimates are correlated since the 19 events used to reconstruct the mass [3] are a subset of the 99 used here.

3 Event Structure Analysis

This analysis searches for top in the $W + \geq 3$ jet subsample. The results presented here are based on 67 pb^{-1} of data [5]. We apply tight cuts to select leptonic W candidates. We further require $\not{E}_T > 25$ GeV and the transverse mass $M_T > 40$ GeV/c^2 [b]. The events need to contain at least three jets with $E_T > 20$ GeV and $|\eta_{jet}| < 2.0$. The three leading jets are required to be separated from each other by $\Delta R \geq 0.7$, where ΔR is the distance in the η, ϕ plane. Jet energies and missing energy are already corrected before event selection [2]. The sample contains 158 events.

Jets from $t\bar{t}$ decay are expected to be emitted at larger angles (θ) than those from directly produced W's with associated jets [8]. Therefore we select a top enriched sample ("*signal sample*") by requiring all the three highest E_T jets to have $|cos\theta^*(jet)| < 0.7$, where θ^* is the jet polar angle in the rest frame of the lepton, the missing E_T and all the jets with $E_T > 15$ GeV. Events in which at least one of the jets fails the $|cos\theta^*(jet)|$ cut form a background enriched sample ("*control sample*"). There are 47 events in the signal sample and 111 events in the control sample.

We use the E_T of the second and third highest E_T jets to calculate a "relative likelihood" (L) for each event, as a measure of whether the event is more "top–like" or more "QCD background–like". L is defined as [2]:

$$L = \left[\left(\frac{1}{\sigma} \frac{d\sigma}{dE_{T2}} \right) \times \left(\frac{1}{\sigma} \frac{d\sigma}{dE_{T3}} \right) \right]^{t\bar{t}} / \left[\left(\frac{1}{\sigma} \frac{d\sigma}{dE_{T2}} \right) \times \left(\frac{1}{\sigma} \frac{d\sigma}{dE_{T3}} \right) \right]^{QCD} \quad (1)$$

The cross sections σ are normalized to 1. When $L > 1$ (i.e. $\ln(L) > 0$) the event is more top–like than QCD–like, and viceversa. L does not depend on absolute rate predictions but rather depends on differences in the predicted shapes of the jet E_T distributions.

In Fig. 2(L) we show the signal sample $\ln(L)$ distribution for Monte Carlo events (a) and data events (b), respectively. There are 25 data events at $\ln(L) < 0$ and 22 at $\ln(L) > 0$. The background Monte Carlo predicts that

[b] The transverse mass of the lepton and missing energy is defined as $M_T = [2E_T \not{E}_T(1-\cos\Delta\Phi)]^{1/2}$, where $\Delta\Phi$ is the difference in azimuthal angle between the missing energy direction and the direction of the charged lepton.

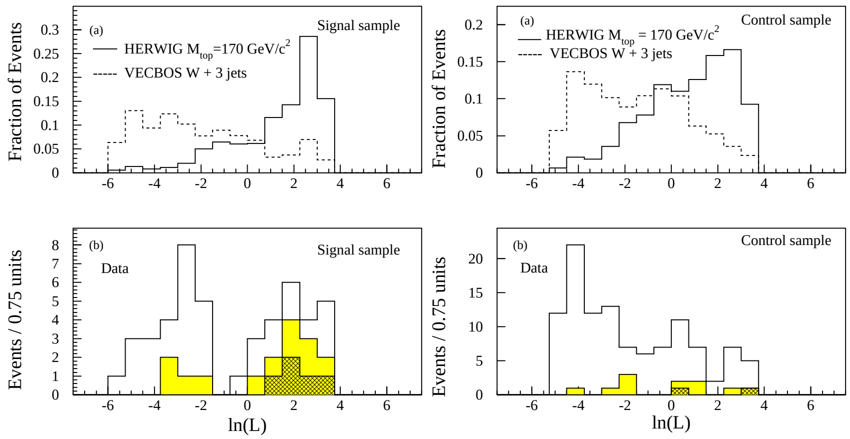

Figure 2: Left (L): Signal Sample. Right (R): Control Sample. The top plots (a) show Monte Carlo expectations and the bottom plots (b) the data (b–tags are shaded).

22 $\pm$ 5% of direct $W+$ jet events will be at $\ln(L) > 0$. We have evaluated other backgrounds, such as non–W and WW events. These backgrounds are expected to have softer jet E_T distributions than the VECBOS prediction for $W+$jets production. As a result, these events are expected primarily at $\ln(L) < 0$. Conservatively, we take the QCD background shape to represent the shape of all backgrounds.

If we make the assumption that all events at $\ln(L) < 0$ are background and normalize the expected background distribution to the events with $\ln(L) < 0$, we expect 7.2 $\pm$ 2.1 events at $\ln(L) > 0$ compared to the 22 observed. If we assume that the signal sample is all background, then we obtain a maximum probability of $< 0.26\%$ (including systematic errors) that the 47 events of the signal sample are distributed with at least 22 events at $\ln(L) > 0$.

In Fig. 2(R) we show the control sample $\ln(L)$ distribution for Monte Carlo events (a) and data events (b), respectively. There are 79 data events at $\ln(L) < 0$ and 32 at $\ln(L) > 0$.

In Figs. 2 (b) the shaded area indicates the SVX and SLT b–tagged events. The darker area indicates events with more than one SVX or SLT tag. A large number of events in the signal enriched sample are b–tagged. There are 13 SVX tags in 8 events. These events are all at $\ln(L) > 0$, the region where we expect most top events and only 1.37 $\pm$ 0.17 SVX tags from background. The probability for this observation to be due to a statistical fluctuation of the background is $< 1.2 \times 10^{-4}$. In the control sample we observe 5 SVX tags compared to a background expectation of 4.10 ± 0.44. The SLT b–tag algorithm gives consistent information, but has a much larger background.

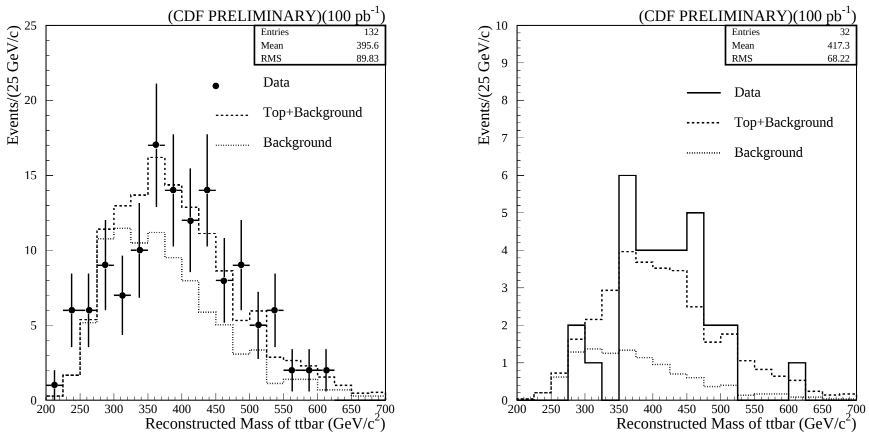

Figure 3: The $t\bar{t}$ mass. Left (L): before requiring a b–tag. Right (R): after requiring a b–tag.

4 Kinematics requiring a Mass Fit

After establishing the existence of the top quark, other properties of the $t\bar{t}$ system need to be investigated. The mass fit constraints improve the resolution of kinematic quantities. However the situation is complicated because of gluon radiation and combinatorics. The $t\bar{t}$ invariant mass distribution is sensitive to non SM top production mechanism. It could reveal the existence of high mass resonances. The analysis is based on 100 pb^{-1} of data and it is still preliminary. There are 132 $W + \geq 4$ jet events before requiring a b–tag which have a good mass fit, and 32 after b–tagging. In Fig. 3(L) we show the $t\bar{t}$ invariant mass before tagging. In Fig. 3(R) the same distribution is shown for the b–tagged events. These plots are consistent with Monte Carlo predictions within the statistical accuracy of the data. Other quantities as the P_T of the $t\bar{t}$ system, the P_T of the top, the $\Delta\phi$ of the t and the $\bar{t}$ and the rapidity of the leptonic top, hadronic top, and $t\bar{t}$ system have been studied. They all show reasonable agreement with Monte Carlo predictions.

5 Hadronic Channel

The $t\bar{t}$ decay channel in which both W's decay hadronically has the highest branching ratio (44%). In principle the two top quarks could be reconstructed because there are no neutrinos in the event. However, the signal/background ratio (s/b) at trigger level is very small because the QCD multijet background has a much higher rate than the top production. We improve s/b with the combined use of kinematic selection, b–tagging and application of a mass fit. With the single b–tagging approach reported here we have reached a significant evidence of a top quark component in the data. The analysis is based on 85 pb^{-1} of data collected with a multijet trigger.

The final state has a 6–jet topology and it is characterized by the production of central jets with high transverse energy. We select events requiring at least 6 jets with $E_T \geq 15$ GeV and $|\eta_{jet}| \leq 2.0$. We further apply cuts on other global calorimetric variables (like the sum of all jets transverse energy $\sum E_T$, $\sum E_T/\sqrt{\hat{s}}$, aplanarity etc.) at the values which maximize $s/\sqrt{b}$.

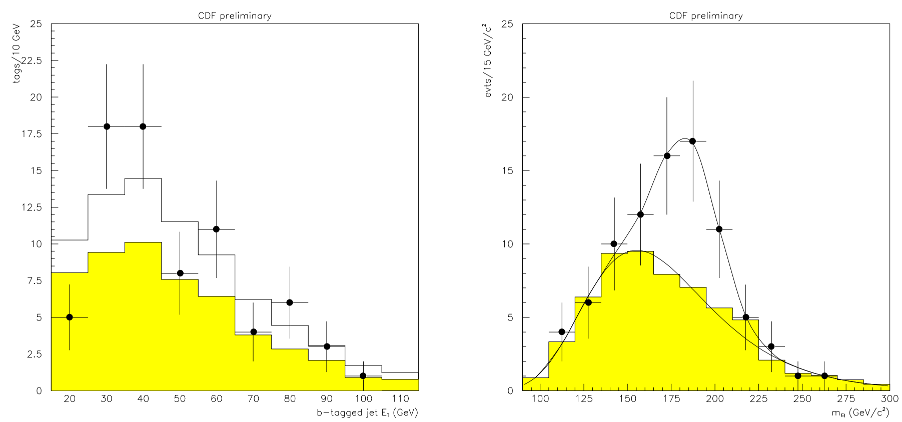

Figure 4: Left (L): E_T spectrum for b–tagged jets. Right (R): fitted top mass of the b–tagged events; the background function used in the fit is shown.

If we look for SVX tags, they can come, besides from $t\bar{t}$ events, from real heavy flavor production and from tracking mismeasurements. The tagging rate, defined as the number of tagged jets divided by the number of *taggable* jets [1] has been parametrized as a function of jet E_T, the number of SVX tracks in the jet and η_{jet}. It has been calculated using a sample of events collected with a multijet trigger. Fig. 4(L) shows the comparison between the E_T spectra of the tagged jets and of the estimated background.

Table 1 summarizes the comparison between the observed number of tagged events (jets) N_{obs} and the expected one N_{exp} calculated using the estimated tagging rate. There is an excess of 23.7 tags. The corresponding production cross section has been estimated to be 9.7 ± 3.3 pb (the error is statistical).

Table 1: Preliminary results from the top search in the hadronic channel.

Selection	N_{obs}	N_{exp}	$N_{obs} - N_{exp}$
≥ 6 jets	446 (473)	403 (431.5)	43 (41.5)
kinematic selection	62 (69)	42.9 (45.3)	19.1 (23.7)

A looser kinematic selection is applied in order to reconstruct the mass. We use a 2–vertices fit (i.e. we do not constraint the W's). Fig. 4(R) shows the fitted top mass distribution for the b–tagged events. The shaded histogram indicates the background. The upper curve is the sum of a Landau distribution used to describe the background and a Gaussian distribution describing the $t\bar{t}$ signal. The obtained mass value is consistent with the value found in the W + jets channel [3].

6 Conclusion

We observe an excess of W + multijet events with large total transverse energy H which can be explained assuming a top quark component in the data. The same is true for the event structure analysis, based on the assumption that top events have high E_T jets produced at large angles relative to the beam. In both cases we observe a large beauty quark content in those events kinematically more consistent with top.

For the first time we evidentiate the presence of $t\bar{t}$ production in the hadronic channel. Constraining the selected events to the $t\bar{t} \rightarrow jjbjj\bar{b}$ hypothesis we observe a mass signal over a background of equal size.

The study of top production properties is still in progress. Up to now we find no evidence for substantial deviation from SM predictions.

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