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## **Kinematic Top Analyses at CDF**

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# KINEMATIC TOP ANALYSES AT CDF

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## **Abstract**

We present an update of the top quark analysis using kinematic techniques in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV with the Collider Detector at Fermilab (CDF). We reported before on a study which used  $19.3 \text{ pb}^{-1}$  of data from the 1992-93 collider run, but now we use a larger data sample of  $67 \text{ pb}^{-1}$ . First, we analyse the total transverse energy of the hard collision in  $W + \geq 3$  jet events, showing the likely presence of a  $t\bar{t}$  component in the event sample. Next, we compare in more detail the kinematic structure of  $W + \geq 3$  jet events with expectations for top pair production and with background processes, predominantly direct  $W +$  jet production. We again find  $W + \geq 3$  jet events which cannot be explained in terms of background, but show kinematic features as expected from top. These events also show evidence for beauty quarks. The findings confirm the observation of top events made earlier in the data of the 1992-93 collider run.

# 1. Introduction

At the  $p\bar{p}$  collider, the top quark is predominantly produced in  $t\bar{t}$  pairs, which in turn decay to W's and beauty quarks. In this paper we study events where one of the W's decays leptonically and the other one hadronically ("single lepton events"):  $p\bar{p} \rightarrow t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow l^\pm\nu bjj\bar{b}$ ; two light quarks from the second W and two beauty quarks can create hadronic jets. There may also be jets from associated gluon radiation. At CDF both a counting experiment<sup>1)</sup> and a kinematic study referred to as "event structure analysis"<sup>2),3)</sup> were performed with the data from run 1A (19.3 pb<sup>-1</sup>). The evidence of top events produced in these analyses was confirmed by an improved version of the counting experiment<sup>4)</sup>, using the data collected in two running periods (run 1A in 1992-93 and run 1B, still in progress) for a total integrated luminosity of about 67.3 pb<sup>-1</sup>. The D0 Collaboration has also observed the production of top quark pairs with an analysis based in part on kinematic information<sup>5)</sup>.

In Section 2 of this paper we report on a study of the total transverse energy of  $W+\geq 3$  jet events<sup>6)</sup>, which leads to evidence for a  $t\bar{t}$  component in the data. In Section 3 we report the updated results of the event structure analysis using the full 1A+1B data sample<sup>7)</sup>.

The expected  $W$  + jets background is computed with the Vecbos Monte Carlo, which uses the lowest order  $W+n$  parton matrix elements,  $n=1,4$ <sup>8)</sup>. The parton fragmentation process is simulated with a Herwig type shower module<sup>9)</sup>. The lowest order matrix elements are sensitive to the choice of the mass scale in the strong coupling constant  $\alpha_s$ . We assume  $q^2 = M_W^2$ , that means  $\alpha_s = \text{constant}$ , as a conservative choice which results in rather hard jet transverse energy ( $E_T$ ) spectra. Top events are simulated by the Herwig program.

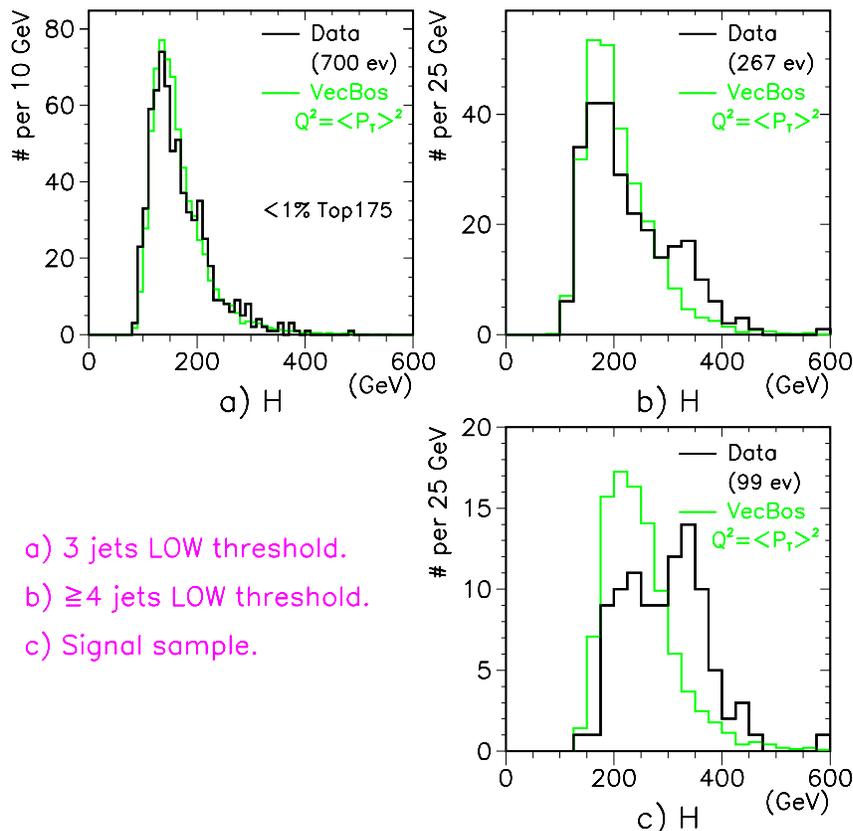
## 2. H Analysis

W events are selected by requiring an isolated, high transverse momentum lepton and missing transverse energy ( $\cancel{E}_T$ ).

Three W+jet samples are defined: (a) an exclusive W+3 jet sample consisting of events with precisely three jets with  $E_T > 8$  GeV, (b) a 'low threshold' sample of events with at least four jets with  $E_T > 8$  GeV, (c) a 'high threshold' sample - a subsample of (b) - requiring in addition that the three leading jets have  $E_T > 15$  GeV<sup>1</sup>. Sample (a) is used as a background enriched sample since Monte Carlo calculations predict that it should contain a fraction of not more than 1% top events ( $M_{top} = 175$  GeV), due to the bias against a fourth jet. The low and high threshold samples, (b) and (c), should be increasingly enriched with top events. We define H as the scalar sum of the transverse energies of the lepton, neutrino and jets<sup>6)</sup>. A similar variable has been used by the D0

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<sup>1</sup>Jets are ordered in  $E_T(\text{jet})$  with  $E_{T1} > E_{T2} > E_{T3}$ .



- a) 3 jets LOW threshold.
- b)  $\geq 4$  jets LOW threshold.
- c) Signal sample.

Figure 1: H distribution for data (solid line) and Vecbos events (dotted). Vecbos is normalised to the data. (a) Exclusive W+3 jet sample with  $E_T > 8$  GeV; (b) W+ $\geq 4$  jet sample with  $E_T > 8$  GeV; (c) W+ $\geq 4$  jet sample with  $E_{T1}, E_{T2}, E_{T3} > 15$  GeV,  $E_{T4} > 8$  GeV.

Collaboration<sup>5</sup>).

The jet  $E_T$  and the  $\cancel{E}_T$  are corrected by a rapidity and energy dependent factor, which accounts for calorimeter non-linearity and reduced response at detector boundaries<sup>10</sup>). Jets are reconstructed with a cone of  $R = 0.4$ <sup>2</sup>. In figure 1 we compare the data distributions in H to the expectation from direct QCD W+jets production, as calculated by the Vecbos Monte Carlo program. In the W+3 jet (a) sample we find a good agreement between QCD prediction and data. In sample (b) we find an excess of data events at large H; this excess becomes more pronounced in sample (c). CDF is able to detect b-quarks with two algorithms. One algorithm identifies charged tracks originating from a secondary vertex, separated in space from the primary one ("SVX tag"). The other algorithm identifies electrons or muons in jets (soft lepton tag, or "SLT"). The 'double peak' structure of the H distribution for sample (c), as well as the presence of b-tagged events at high values of H in this sample gives evidence for the presence of top events in

<sup>2</sup>  $R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ , where  $\Delta\phi$  is the cone half-width in azimuth and  $\Delta\eta$  is the cone half-width in pseudorapidity.

the sample. A more detailed discussion can be found in<sup>11)</sup>.

### 3. Event Structure Analysis

To select (leptonic)  $W$  candidate events, we require  $\cancel{E}_T > 25$  GeV, and we cut on the transverse mass<sup>3</sup>  $M_T > 40$  GeV/ $c^2$ . The events need to contain at least three jets with  $E_T > 20$  GeV and  $|\eta| < 2.0$ <sup>4</sup>. The three leading jets are required to be separated from each other by  $\Delta R \geq 0.7$ . This  $W + \geq 3$  jet event sample contains 158 events.

We then select a top enriched sample (“signal sample”) of  $W + \geq 3$  jet events by requiring the three jets with highest  $E_T$  to have  $|\cos\theta^*| < 0.7$ , where  $\theta^*$  is the jet polar angle in the rest system of the event. The system is defined as the sum of the charged lepton, the  $\cancel{E}_T$  and the jets with  $E_T > 15$  GeV. The remaining events in which at least one of the jets has  $|\cos\theta^*| > 0.7$  form a complementary background enriched sample (“control sample”). The cuts  $|\cos\theta^*| < 0.7$  and  $\Delta R \geq 0.7$  for the signal sample are meant to suppress initial or final state gluon jet radiation and therefore to improve the signal/background ratio<sup>12)</sup>.

For a quantitative comparison of data and Vecbos we calculate a “relative likelihood” for each event, as a measure of whether the event is more “top-like” or more “QCD-like”. The relative likelihood is defined in terms of the Monte Carlo predicted jet  $E_T$  distributions  $d\sigma/dE_T$  of the second and third highest  $E_T$  jets, for  $t\bar{t}$  ( $M_{top}=170$  GeV) and direct  $W + \text{jets}$  production. The cross sections are normalised to 1.

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

In figure 2(a),(b) we show the signal sample  $\ln(L)$  distributions for Monte Carlo events and data events, respectively. There are 25 events at  $\ln(L) < 0$  and 22 events at  $\ln(L) > 0$ . The QCD Monte Carlo predicts that not more than  $22 \pm 5\%$  of QCD  $W + \text{jet}$  events will be at  $\ln(L) > 0$ .

We have evaluated other backgrounds, such as non- $W$  and  $WW$  events. We have found that these background events have softer jet  $E_T$  distributions for the second and third highest  $E_T$  jet than the Vecbos prediction for direct QCD  $W + \text{jets}$  production<sup>2),3)</sup>. Conservatively, we take the QCD background shape as predicted by Vecbos to represent the shape of all background. Taking the various uncertainties into account, we obtain a probability of  $< 0.26\%$  that the 47 events would be distributed with at least 22 events at  $\ln(L) > 0$ . The control sample contains 111 data events. From Monte Carlo studies, this sample is expected to contain about the same number of top events as the signal sample. There are 79 events at  $\ln(L) < 0$  and 32 at  $\ln(L) > 0$ . Due to the larger signal/background ratio in the control sample, the systematic errors on the expected QCD rate are about as

<sup>3</sup>The transverse mass is defined as  $M_T = [2E_T \cancel{E}_T (1 - \cos\Delta\Phi)]^{1/2}$ , where  $\Delta\Phi$  is the difference in azimuthal angle between the missing energy direction and the direction of the lepton.

<sup>4</sup> $\eta = -\ln \tan(\theta/2)$ , and  $\theta$  is the polar angle with respect to the beam.

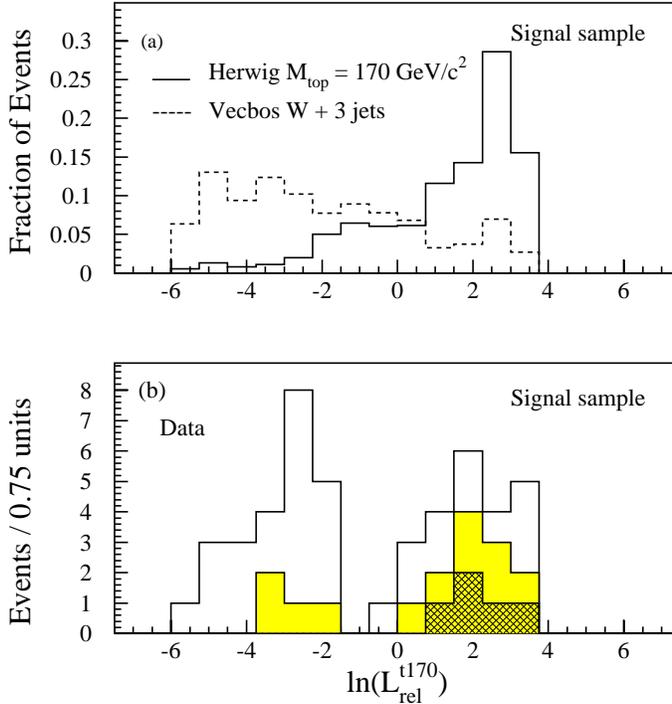


Figure 2: (a) Vecbos QCD and Herwig ( $M_{top} = 170 \text{ GeV}/c^2$ ) top Monte Carlo predicted distributions for the  $W + \geq 3$  jet signal sample. Both distributions are normalized to one;  $Q^2 = M_W^2$  is used in the Vecbos calculation; (b) Data; The shaded area indicates the  $b$ -tagged events from SVX and SLT; The darker area indicates events with more than one SVX or SLT tag.

large as the expected top component, such that the data of this sample are compatible with either containing or not containing a top signal.

In figure 2(b), the shaded areas indicate the  $b$ -tagged events. The darker areas indicate events with more than one SVX or SLT tag. We observe that a large number of events in the signal enriched event sample are  $b$ -tagged. We find a total of 13 SVX tags (in 8 events) compared to  $2.80 \pm 0.35$  SVX tags expected from background alone. All 13 tags of SVX type are associated with events with  $\ln(L) > 0$ , namely in the region where we expect most top events. At  $\ln(L) > 0$  we expect only  $1.37 \pm 0.17$  SVX tags from background, compared to an observation of 8 events. The probability that this observation be due to a statistical fluctuation of background tags is  $< 1.2 \times 10^{-4}$ . The SLT  $b$ -tag algorithm gives consistent information, but has a much larger background.

## 4. Conclusions

The excess of  $W$ +jets events at large total transverse energy,  $H$ , fits well the top hy-

pothesis. The same is true for the event structure analysis that makes use of several different kinematic parameters. The kinematically top-like events show a large content of beauty quark candidates, in agreement with expectations from top.

In conclusion, we have observed that a new physics process contributes to the final state with  $W+\geq 3$  jets. In the context of the Standard Model this process can only be top. With the top quark found, one should now proceed to a more detailed study of its properties, investigating as many parameters in the events as possible.

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