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Kinematical Evidence for Top Pairs at the Tevatron

Hans Grassmann,
The CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Duke University

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We present a top search analysis of W+jet events which combines a study of the kinematic features of the events with a search for bottom quarks.

Introduction

Presently each top analysis starts from a sample of leptonically decaying W's because of the increased background in the purely hadronic decay channel. There are two major differences between W's from top decays and W's from QCD W+jet production. First, within the Standard Model, each top event will always contain a second W and two bottom quarks. An excess of additional W's and b-quarks in the W event sample gives evidence for top pairs. This so called 'counting experiment' is discussed in the talk by G.Unal at this conference and in[1]. The second difference between top and QCD W+jet events is in their kinematical distributions. Once top candidates are identified based on their kinematics features, one will verify that they contain bottom quarks. This line of analysis is called 'event structure' analysis and is the subject of this paper. A more complete discussion can be found in [2].

Data Sample and Cuts

We use 19.3 pb^{-1} of electron and muon data from the 1992/93 Tevatron run with $p\bar{p}$ collisions at 1.8 TeV. We require leptonic W events with at least three jets with $E_T > 20$ GeV. More jets are allowed for but not required. The jets are corrected for various detector effects and for radiation out of the jet reconstruction cone in order to improve the jet energy resolution and to bring the jet E_T as close as possible to P_T(parton) [3]. The missing energy is also corrected in order to help supress non-W events. These energy corrections are mostly responsible for the difference between the data sample of this analysis and the one described in [1] (the overlap is about 50%). Events with an additional isolated high pt charged track are rejected as dilepton candidates [4]. A detailed description of the cuts and procedures can be found in [2]. Top events were simulated with Isajet [5], QCD W+jet events with Vecbos [6] which uses the lowest order matrix element for W+n parton production, n=1 to 4. The absence of higher order contributions results in some dependence of the jet $E_T$spectra on the choice of q^2 in α_s. Vecbos provides inclusive predictions. This means that one can use the W+3 parton matrix element to predict the E_T spectra of the three leading jets in W+$\geq$3 jet data events. In order to start from an event sample which is as similar as possible to the one described in[1] we require that all jets have |rapidity| < 2.

Top and QCD Predictions

The kinematical properties of QCD events have been subject of many careful studies at UA2 and CDF, giving us confidence that the theoretical and experimental uncertainties are understood [3], [7], [8]. Additional studies of the CDF W+$\geq$2 jet sample were done, applying the same event reconstruction procedures as for the W+$\geq$3 jet analysis. In the W+$\geq$2 sample, the top contribution is expected to be small. Good agreement between Vecbos W+2 jet prediction and data is found, as shown in figure 1.
Top events will create high E_T jets with little correlation to the initial state. QCD events will tend to emit the jets close to the beams, and the jet E_T spectrum will be softer. We deter-

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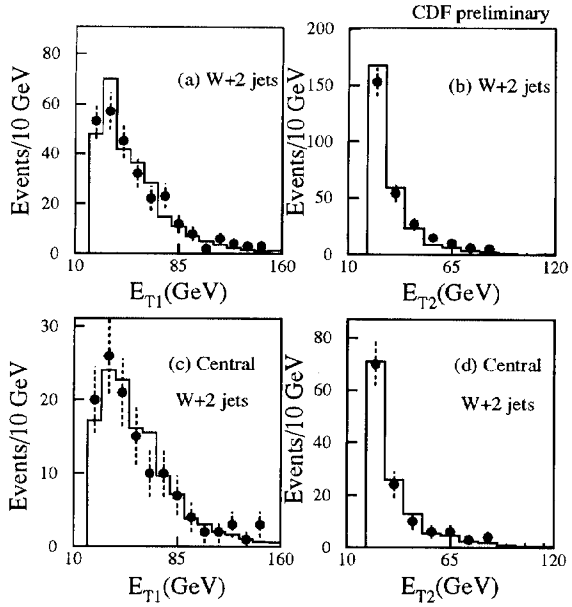

Figure 1: *E_T distribution of the two leading jets in W+≥2 jet data events, compared to the prediction of the Vecbos W+2 jet Monte Carlo. Vecbos is normalised to the data. (a),(b) : a cut at |rapidity| < 2 is applied to both jets. (c),(d) : an additional cut $|cos\theta^*|$<0.7 is applied to both jets.*

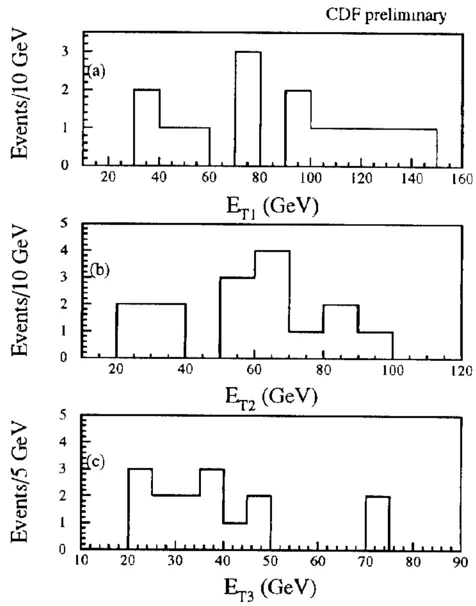

Figure 2: *E_T distribution of the three leading jets in the 15 events of the signal enriched sample. There is one overflow in the first plot.*

mine the angle θ^* between jet and beam direction in the rest frame of the W+jet system, ignoring the ν longitudinal momentum. We select a *top enriched sample* by requiring for the three leading jets $|cos\theta^*|< 0.7$. All events which do not pass this requirement are the so called background enriched, or *control sample.* Various top Monte Carlos agree in predicting that there will be about equal numbers of top events in the signal and in the control sample. Vecbos predicts that about 1/4 of QCD W events will enter the signal sample.
The basic concept of the event structure analysis was described in [9].

Kinematical Analysis

The signal enriched sample contains 15 events, the background enriched sample 31 events. The E_T distribution of the three leading jets in the signal sample is shown in figures 2, 3 for data and for Monte Carlo events. We order the jets in E_T, $E_T(\text{jet}i) > E_T(\text{jet}(i+1))$. To improve the signal to background separation power, we define a 'relative likelihood' (rL) for top versus QCD as

$$rL = aL^{top}/aL^{QCD}. \qquad (1)$$

with aL being the so called 'absolute likelihood'

$$aL = (d\sigma/dE_{T2}) \times (d\sigma/dE_{T3}) \qquad (2)$$

for the top and QCD processes. We normalise the E_T distributions to 1. It has been verified that the data events of the control sample are distributed in aL as a sample of QCD events should, with a possible minor contribution from top. On the other hand, the aL distribution of the signal sample does not agree with the Vecbos prediction. The deviation from this prediction is as expected for a component from a top with M^{top} of about 150 to 170 GeV. We mostly want to base our discussion on the relative likelihood. The relative likelihood gives us the possibility to compare each individual event to both the expectation from QCD and from top in terms of a single number. Furthermore, it provides us with a natural way of combining kinematic and b-tag information. A disadvantage of rL might be seen in its dependence on the assumed M_{top}. Our main concern for the following discussion is

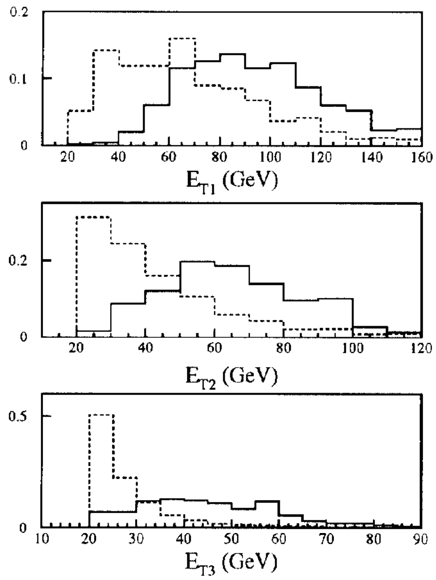

Figure 3: *E_T distribution of the three leading jets in Vecbos W+3 jet (dotted line) and in Isajet top events (solid line), M^{top} = 170 GeV. The cuts of the signal sample were applied.*

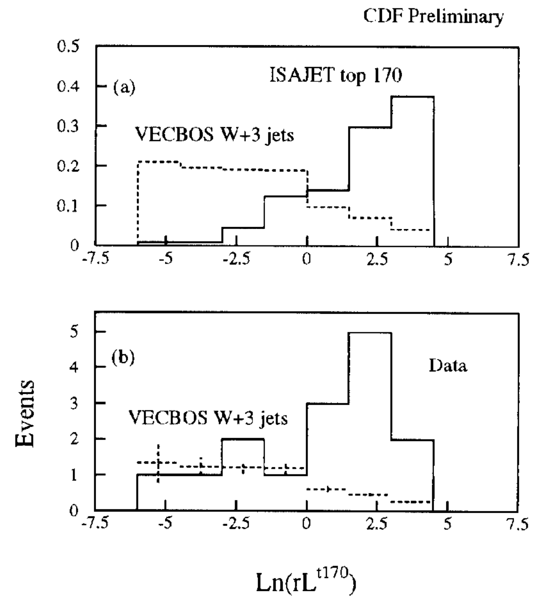

Figure 4: *(a) $ln(rL^{t170})$ distributions for Vecbos and Isajet Monte Carlo events normalized to 1. (b) data events. In (b) Vecbos is shown again, normalized to the data events at $ln(rL) < 0$.*

whether there is any reasonable value M^{top} for which the data can be described as a mixture of QCD W and top events, but cannot be described in terms of QCD alone. In figure 4(a) we show how Vecbos W+3 jet events and Isajet top events are distributed in $\ln(rL^{t170})$ when the cuts of the signal sample are applied (rL^{t170} indicates that we used M^{top}=170 GeV for the top template). One observes that the two distributions are separated well enough to make a top signal visible, provided signal/background is not much smaller than 1. Had we based our analysis on the Monte Carlo predictions for the absolute numbers of events, we would have not been sensitive to a top signal unless signal/background was considerably larger than 2, since the Vecbos cross sections are uncertain by as much as a factor of two because of the lack of higher order contributions. Figure 4(b) shows how the data events of the signal enriched sample are distributed in $\ln(rL^{t170})$. The data are not distributed as would be expected from a pure QCD W+jet sample. An excess of events for $\ln(rL) > 0$ is clearly seen. For the Vecbos events in figure 4 we used $q^2{=}{<}p_T{>}^2$ in α_s. Slightly harder E_T spectra are predicted when one uses $q^2{=}M_W^2$. We normalise Vecbos to the 5 data events at $\ln(rL) < 0$ to calculate the number of events expected at $\ln(rL) > 0$. We find that for $q^2{=}{<}p_T{>}^2$ ($q^2{=}M_W^2$) there are $79^{+2.3}_{-2.7}$% ($72^{+3.1}_{-3.7}$%) of the Vecbos events at $\ln(rL) < 0$. Normalizing to the 5 data events at $\ln(rL) < 0$ results in an expectation of $1.34^{+0.75}_{-0.53}$ ($1.92^{+1.10}_{-0.77}$) events at $\ln(rL) > 0$. We observe 10 events in this region. The probability that this be due to a statistical fluctuation is in both cases much less than 1%. There are minor non-top contributions to our data sample which are not included in the Vecbos prediction. We expect about 1 event from WW production in our signal sample, less than 1 event from non-W background ('fake' leptons or leptons from b or c quarks), about 0.1 events from WZ production. We found that these backgrounds do not have a larger probability than Vecbos events to show up at $\ln(rL) > 0$. Including them does not increase the non-top expectation there. The effect of a possible energy scale uncertainty in the calorimeter is studied using the Vecbos events. When we scale their jets up or down by 10%, we find that the number of events expected at $\ln(rL) > 0$ changes by less than 10%.

We did additional studies using several independent Monte Carlo samples where we modified the way the parton fragmentation is simulated. As a conservative result we conclude that the probability for observing 10 or more events at ln(rL) > 0 is less than 2%. The control sample shows little deviation from QCD predictions, but still leaves room for several top events.

Search for b-quarks

If the excess of events at ln(rL) > 0 in the signal sample is indeed due to top production , then we should be able to find an increased content of bottom quarks. We used two different methods to detect bottom quark candidates, the JETVTX secondary vertex finding algorithm and soft leptons in jets, the SLT algorithm (see[1] for more details). The JETVTX algorithm has a chance of about 22% to find a tag in a top event, and about 15% of top events will show a SLT tag. The probability to find a tag in a non-top event is much less [O(1%) per jet], although it depends on the properties of the jet under consideration. In 6 of the 15 events of the signal sample we find 4 JETVTX bottom candidates, as shown in table 1 (and 4 SLT, with 2 overlaps). All but one are found at ln(rL) > 0. In order to assess the probability of a background fluctuation, the expected JETVTX b-tag background was computed accurately. It is due to measurement errors as well as to real longlived particles and is monitored by studying events with generic jets, without a W. This expected background rate is calculated for the signal sample events based on the observed properties of the jet activity in the events and amounts to 0.6 events. Additional minor contributions come from processes which are typical for W events like W+c production, adding another 0.1 to 0.2 events. Overall, the expected background in the signal sample is less than 1 event while 4 JETVTX tags are observed. The probability for this to be due to a background fluctuation is small. The background expectation in the control sample is higher, and the observed tags are only 2. There is no excess of b-tags over the expectation for generic jets in the control sample.

ln(rL)	JETVTX	SLT	4th jet	lept.
3.3	♠		*	*el*
3.3	♠		*	*el*
2.9			*	μ
2.7	♠	♠	*	μ
1.8				μ
1.3			*	*el*
1.0		♠	*	μ
-2.7	♠	♠		μ
-3.9				*el*
-4.6				*el*
2.4		♠	*	*el*
2.2			*	*el*
1.2				μ
-1.2				*el*
-2.7				*el*

Table 1: *JETVTX and SLT bottom-tags and the values for* $ln(rL^{t170})$ *for the 15 events of the signal sample. The upper section shows the 10 events which have at least one jet which is SVX-taggable (within the geometrical acceptance of the SVX). The asteriscs in the third column indicates that there is a 4th jet in the event with* $E_T > 15$ *GeV.*

Consistency Checks

For a heavy top, one should be able to improve signal/background by requiring a fourth jet. We find 7 events with E_T(jet4) > 15 GeV. Their ln(rL) distribution is shown in figure 5, together with the Vecbos prediction, based on the W+4 parton matrix element. Vecbos is normalised to the 5 events at ln(rL) < 0 before the cut on jet4, in the same way as the W+3 parton Vecbos events were normalised (compare with figure 4). The resulting normalisation factor is kept when we require a fourth jet. The result is shown as a dotted line in figure 5(a). In the 7 events of figure 5(a), we find three JETVTX tags. The tagged events are at ln(rL)> 0, as shown in figure 5(b). The expected background from generic jets is also shown (shaded area).
Another check was made by trying to kinematically reconstruct the subsample of events with precisely 4 jets, according to the top hypothesis. The procedure described in[1] was used, but without making use of the b-tag information. It

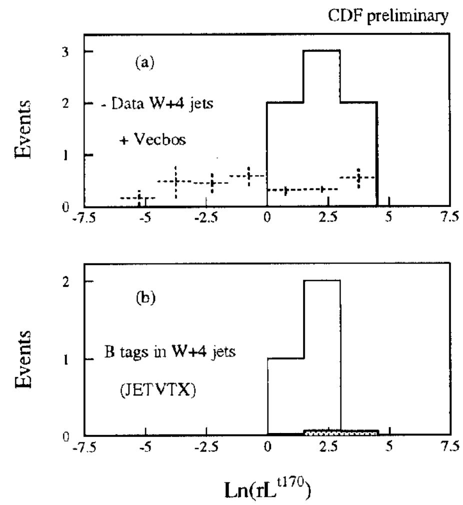

Figure 5: *(a) $ln(rL^{t170})$ distribution for data and Vecbos W+4 jet events. Vecbos was normalised to the data at $ln(rL) < 0$ before requiring a fourth jet. (b) the three events with a JETVTX b-tag and the background expectation from generic jets.*

was possible to reconstruct the events, and all values obtained for M^{top} were in the range of 161 to 172 GeV/c^2, compatible with the findings in [1].

Conclusions

We defined a sample of 15 W+$\geq$3 jet events which should be enriched in top events because the jets are required to be central. More events have high E_T jets than QCD predicts for W+jet production. Taking systematic errors and various backgrounds into account we find a probability of not more than 2% for a statistical fluctuation to be responsible for the disagreement between data and QCD prediction. Studies in different data samples indicated that the QCD predictions are reliable. Either the QCD predictions are incorrect only in the kinematical region of interest, or there is a component of 'top like' events present in the data. Further information is obtained from a search for bottom quark candidates in the sample. Four bottom candidates are found using the JETVTX secondary-vertex algorithm, while less than one event would be expected from the various background sources. The QCD W+jet calculations which have been used for the kinematical studies do not enter the background calculation for the bottom quark search. Therefore the result of the kinematical study and of the independent b-quark search confirm and strengthen each other. Additional consistency checks are made by investigating the subsample of events with a fourth jet. The 7 four jet events observed are all in the kinematical region where top is expected, and show a further enhanced rate of b-tags. We also succeed to reconstruct W+4 jet events following the top hypothesis.
We conclude that the most natural interpretation of these results is that our event sample contains a contribution from top.

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