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STUDIES OF $t\bar{t}$ PRODUCTION IN THE LEPTON+JETS AND ALL-HADRONIC CHANNELS

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FOR THE CDF COLLABORATION

The CDF collaboration has studied the process $t\bar{t} \to WbW\bar{b}$, where $WbW\bar{b}$ decays into the lepton+jets or all-hadronic channel. In the lepton+jets channel, distributions of various kinematical quantities are found to agree well with Monte Carlo predictions based on the Standard Model. Kinematical techniques to select $t\bar{t}$ candidate events are being refined. In the all-hadronic channel, considerable progress has been made in identifying a top signal, and in measuring the corresponding top mass.

1 Introduction

The discovery of the top quark at the Tevatron resulted from a search for the process $t\bar{t} \to WbW\bar{b}$, where $WbW\bar{b}$ decays into the dilepton or lepton+jets channel [1,2]. The CDF evidence for $t\bar{t}$ production relied mainly on tagging of b-quark decays inside jets, and did not depend on accurate Monte Carlo modelling of $t\bar{t}$ and background kinematics. Since the discovery, the CDF data sample has increased by about 50%, enabling more detailed studies of $t\bar{t}$ kinematics in the lepton+jets channel and offering preliminary evidence for all-hadronic $t\bar{t}$ production.

We present several kinematical analyses of the lepton+jets channel in section 2. The first analysis compares kinematic distributions of b-tagged events with Monte Carlo calculations. Although still statistically limited, this comparison shows good agreement with Standard Model production of $t\bar{t}$. The next two analyses rely on Monte Carlo models to prepare samples of $t\bar{t}$ events without the help of b-tagging. This is achieved by using a relative likelihood variable in section 2.2, and a global transverse energy sum in section 2.3.

The last part of this paper presents the progress made by CDF in identifying a top signal in the all-hadronic channel. The actual evidence for top in this channel is discussed in section 3.1, and the corresponding top mass measurement in section 3.2.

2 Lepton+Jets studies

2.1 Kinematic Distributions

This analysis starts with the same selection of b-tagged $W+\geq 4$-jet events which are fit to the $t\bar{t}$ hypothesis for the top mass measurement [1]. As a byproduct of this fit, one obtains the four-momenta of the t and $\bar{t}$ quarks, from which quantities such as the top quark transverse momentum, pseudo-rapidity and azimuth can be computed and compared with Monte Carlo calculations based on the Standard Model. The distributions shown here were made with 100 pb^{-1} of data and are still preliminary. They should not be interpreted as differential cross sections, since event selection and reconstruction biases have not been removed. The top quark transverse momentum distribution is plotted in Fig. 1. There is reasonable

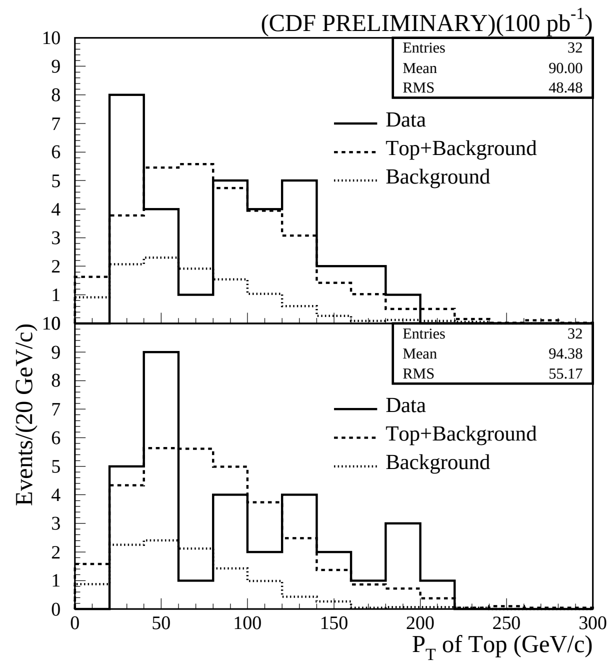

Figure 1: Reconstructed top quark transverse momentum for the 32 b-tagged $W+\geq 4$-jet events. In the $t\bar{t}$ hypothesis, each of these events contains a semileptonically decaying top quark (top plot), and a hadronically decaying top quark (bottom plot).

agreement between data and Monte Carlo, and also between the leptonic and hadronic sides of the events.

The $t\bar{t}$ invariant mass distribution is sensitive to non-Standard Model top quark production mechanisms, as it could reveal the existence of high-mass resonances. This distribution is shown in Fig. 2. To produce this plot, each event was reconstructed to fit the $t\bar{t}$ hypothesis with the additional constraint that the t and $\bar{t}$ masses equal the measured value of 176 GeV/c^2. This constraint improves the resolution of $M_{t\bar{t}}$ by almost a factor of two.

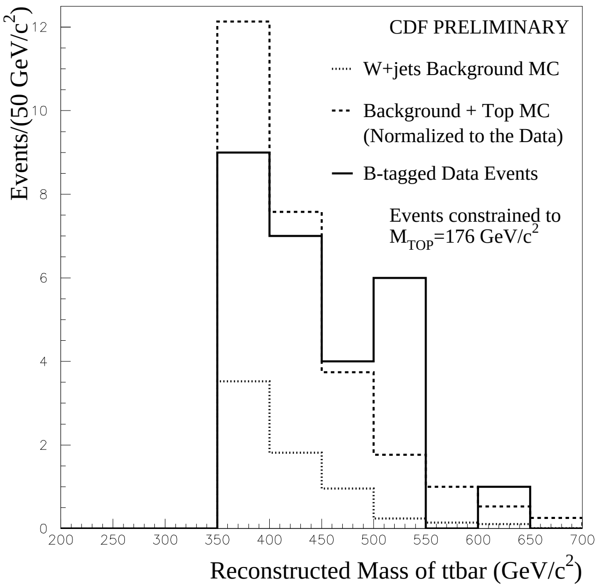

Figure 2: Reconstructed $t\bar{t}$ invariant mass for tagged $W+\geq$ 4-jet events (100 pb^{-1}).

CDF has looked at several other kinematic distributions describing the $t\bar{t}$ system. So far, no significant deviation from minimal Standard Model expectations has been observed.

2.2 Relative Likelihood Analysis

Jets originating from the decay of a heavy top quark are expected to have higher transverse energies than gluons radiated in background processes such as direct W production. This feature is used to identify $t\bar{t}$ events without the help of b-tagging [3]. The analysis starts from a sample of inclusive W events, and requires at least three jets with $E_T > 20$ GeV, $|\eta| < 2$, and mutual separation $\Delta R \geq 0.7$, where ΔR is the distance in (η, ϕ) space. Further background rejection is obtained by requiring all three highest E_T jets to have $|\cos\theta^\star| < 0.7$, where $\theta^\star$ is the jet polar angle in the rest system of the lepton, $\not\!\!E_T$, and all jets with $E_T > 15$ GeV. This selection defines the signal sample. A variable L is then introduced, which measures the relative likelihood for an event to be "top-like" rather than "QCD background-like". This likelihood is defined in terms of the Monte Carlo predicted jet E_T distributions $d\sigma/dE_T$ for $t\bar{t}$ for a given top mass, and for QCD W+jet production:

$$L \stackrel{\text{def}}{=} \frac{\left(\frac{1}{\sigma^{t\bar{t}}}\frac{d\sigma^{t\bar{t}}}{dE_{T2}}\right)\left(\frac{1}{\sigma^{t\bar{t}}}\frac{d\sigma^{t\bar{t}}}{dE_{T3}}\right)}{\left(\frac{1}{\sigma^{\rm QCD}}\frac{d\sigma^{\rm QCD}}{dE_{T2}}\right)\left(\frac{1}{\sigma^{\rm QCD}}\frac{d\sigma^{\rm QCD}}{dE_{T3}}\right)} \qquad (1)$$

where E_{T2} and E_{T3} are the transverse energies of the second and third highest E_T jets respectively. An event with $\ln(L) > 0$ is more top-like than QCD-like, and vice-versa. The distribution in $\ln(L)$ of the signal sample is shown in Fig. 3, along with Monte Carlo predictions for $t\bar{t}$ and W+jet production. The shaded areas indicate events with one or more b-tagged jets. Almost all tagged events have $\ln(L) > 0$, thereby supporting the interpretation of L given above.

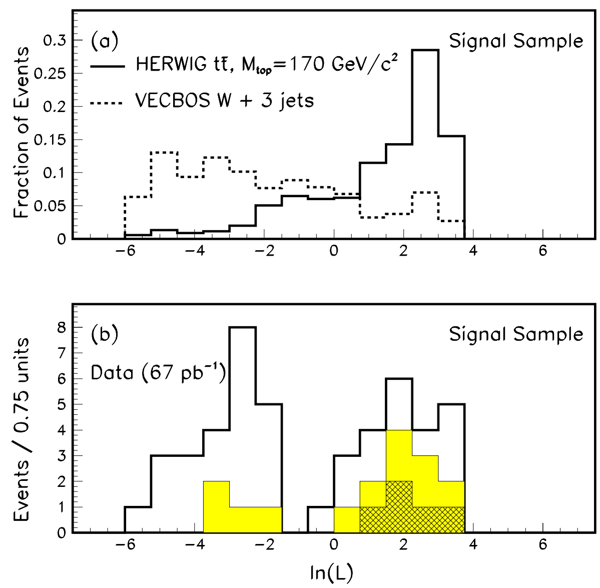

Figure 3: Distribution in $\ln(L)$ of signal sample events for (a) Monte Carlo, and (b) data. The shaded subhistogram is for b-tagged events. Darker shading is for events with multiple b-tags.

2.3 $\mathcal{H}$ Analysis

Due to the large top quark mass, $t\bar{t}$ events are produced with large $\sqrt{\hat{s}}$ compared to background processes. A variable which is strongly correlated with $\sqrt{\hat{s}}$ is the scalar sum $\mathcal{H}$ of the lepton transverse momentum, the missing transverse energy $\not\!\!E_T$, and the transverse energies of all jets with $E_T \geq 8$ GeV and $|\eta| \leq 2.4$ [4]. Fig. 4 shows the $\mathcal{H}$ distribution for events with a W candidate, three jets with $E_T \geq 15$ GeV and $|\eta| \leq 2.0$, and at least one more jet with $E_T \geq 8$ GeV and $|\eta| \leq 2.4$. It can be seen that $\mathcal{H}$ provides good separation between background and $t\bar{t}$. Also, as expected, the b-tagged events cluster at high $\mathcal{H}$, around the $t\bar{t}$ component of the distribution. We performed two-component binned maximum-likelihood fits of the $\mathcal{H}$ distribution of this data sample, to a sum of

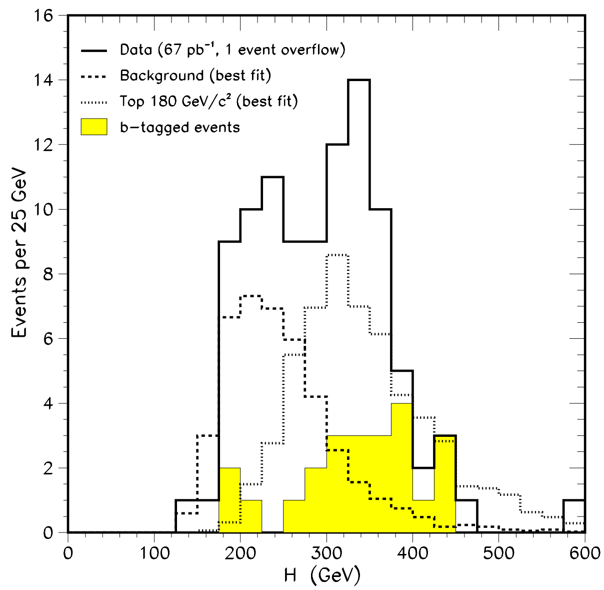

Figure 4: $\mathcal{H}$ distribution of CDF data (solid line), background $W+ \geq$ 4-jet Monte Carlo (dashed line), and $t\bar{t}$ Monte Carlo for $M_{top} = 180$ GeV (dotted line). The shaded subhistogram shows the b-tagged data events.

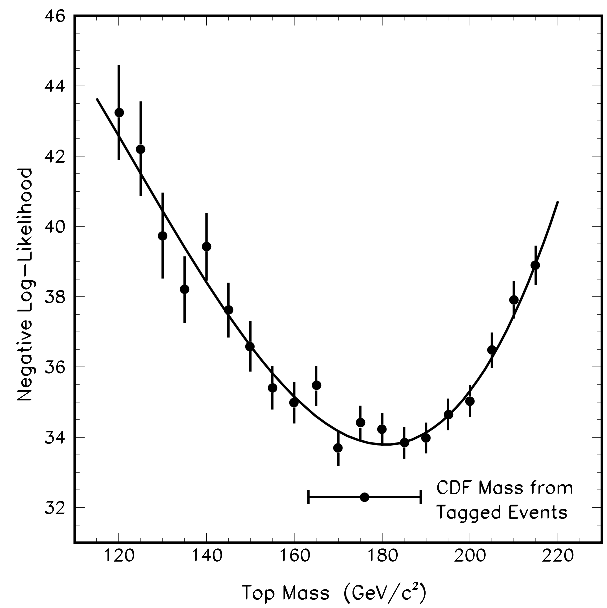

Figure 5: Least-squares fit of a cubic polynomial to the negative log-likelihood values from the two-component fits versus the top quark mass. The error bars reflect the statistical uncertainties of the fit due to finite Monte Carlo event samples. Also shown is the CDF mass result and error of Reference 1.

Monte Carlo distributions for background and $t\bar{t}$, for several values of the top mass. The negative logarithms of the resulting maximum-likelihood values are plotted as a function of top mass in Fig 5, and fitted to a smooth curve. The minimum of this curve provides an estimate of the top mass: $180 \pm 12(\text{stat})^{+19}_{-15}(\text{syst})$ GeV/c^2. This estimate is based on the full $W+ \geq$ 4-jet sample (99 events in 67 pb^{-1}), before any b-tag requirement. It agrees very well with the measurement obtained from a full reconstruction of the subsample of 19 b-tagged events ($176 \pm 8 \pm 10$ GeV/c^2) [1].

3 All-Hadronic Studies

One way to overcome the huge QCD multijet background to all-hadronic $t\bar{t}$ production is to select events by applying tight kinematical cuts and requiring at least one b-tag in the SVX. Section 3.1 describes how this strategy helps in isolating a top quark signal and section 3.2 outlines the top mass measurement.

The search for top in the all-hadronic mode is currently based on a data sample of 81 pb^{-1}.

3.1 Counting Analysis

For the purpose of establishing a clear $t\bar{t}$ signal, the kinematical selection has been optimized over a wide range of top masses (160–200 GeV/c^2). Events must satisfy the following requirements:

- $N_{\text{jet}} \geq 6$,
  where N_{jet} is the number of jets with $E_T > 15$ GeV, $|\eta| < 2$ and mutual (η,ϕ) separation $\Delta R \geq 0.5$.

- $\sum E_T \geq 130 + 15 \times N_{\text{jet}}$,
  where $\sum E_T$, expressed in GeV, is the transverse energy sum over all N_{jet} jets.

- $\sum E_T/\sqrt{\hat{s}} \geq 0.75$,
  where $\hat{s} = x_1\, x_2\, s$ and $x_{1,2} = \left(\sum E \pm \sum p_z\right)/\sqrt{s}$.

- $A \geq -0.003 \times \sum_3^N E_T + 0.45$,
  where A is the aplanarity calculated in the center of mass system of the N_{jet} jets.

The efficiency of this selection, including all top quark decay modes, is $7.4 \pm 0.2(\text{stat})$ % for $M_{top} = 175$ GeV/c^2.

Each event is then required to contain at least one SVX b-tag. Monte Carlo studies indicate that the E_T spectrum of tagged jets is harder in $t\bar{t}$ events than in other multijet events. Therefore, the E_T cut on the b-tagged jet is raised from 15 to 25 GeV.

The results of this analysis are shown in table 1. The background prediction is calculated by applying to the kinematically selected sample a tagging rate parameterization extracted from generic jets. After correcting this prediction for the presence of $t\bar{t}$ events in the sample, the remaining excess of tagged events agrees with the amount of $t\bar{t}$ production expected from the $t\bar{t}$ cross section measured in the lepton+jets channel.

Table 1: Preliminary results from a search for $t\bar{t}$ in the all-hadronic channel in a data sample of 81 pb^{-1}. For each selection, the table gives numbers of b-tagged events, and between parentheses, numbers of b-tagged jets.

Selection	$N_{observed}$	$N_{background}$	Excess
$N_{jet} \geq 6$	446 (473)	403 (431.5)	43 (41.5)
all cuts	62 (69)	42.9 (45.3)	19.1 (23.7)

The probability for a background fluctuation to reproduce the observed excess of tags is estimated to be 3.3×10^{-3}, corresponding to a significance level of 2.9 standard deviations for a Gaussian distribution. This probability is obtained after raising the background prediction by 10% to take into account systematic uncertainties. The calculation uses tagged jets rather than tagged events, in order to take into consideration the additional weight of double tags.

3.2 Top Mass Reconstruction

Events with six jets can be individually reconstructed to fit the all-hadronic $t\bar{t}$ hypothesis. Momentum conservation is required at the two top quark decay vertices, and the masses of the t and $\bar{t}$ are constrained to be equal. Only the six leading jets are taken into account when reconstructing the t and $\bar{t}$ momenta.

Some of the event selection cuts described in section 3.1 bias the mass reconstruction and must therefore be loosened. In particular, the $\sum E_T$ cut is replaced by the requirement that $\sum E_T \geq 150$ GeV, and the cut on the transverse energy of the b-tagged jet is lowered from 25 to 15 GeV. All the other cuts have been checked to introduce no bias on the reconstruction of a high mass top and are kept unchanged. The efficiency of this looser mass analysis selection, including all top quark decay modes, is 8.6 ± 0.4(stat) % for $M_{top} = 175$ GeV/c^2.

The shape of the background mass spectrum is obtained from events which pass all the mass analysis kinematical cuts and which have no b-tagged jet. This sample is expected to have a signal to background ratio of about 1/20. The signal sample consists of all events passing the kinematical cuts and with at least one b-tag. The shape of the signal sample mass distribution is fit to the sum of a Landau function describing the background, and a Gaussian function for the $t\bar{t}$ component. As can be seen from Fig. 6, the fit is excellent and agrees with the top mass measurement extracted from the lepton+jets channel. Several checks have been made to ensure that the observed mass peak is not due to b-tagging biases.

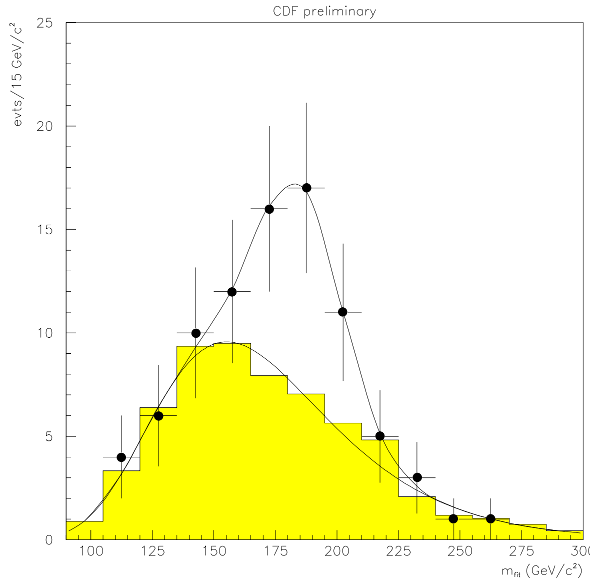

Figure 6: Fitted top mass distribution in all-hadronic channel. Dots mark the b-tagged data events; the shaded histogram is the background normalized to the outcome of the fit. The lower curve is a Landau distribution describing the background. The upper curve is the sum of this Landau distribution and a Gaussian distribution describing the $t\bar{t}$ signal.

4 Conclusion

Studies of $t\bar{t}$ production in the lepton+jets channel are still limited by statistics, but so far no significant deviation from Standard Model expectations is observed. Evidence for all-hadronic $t\bar{t}$ production is beginning to emerge: using a combination of tight kinematical cuts and b-tagging, a 2.9σ signal is observed in a partial data sample of 81 pb^{-1}. The corresponding top mass measurement agrees with the lepton+jets result.

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