CDF note 7637

Updated Top Quark Mass Measurement in the Lepton+Jets Channel Using the Jet Probability Algorithm

The CDF Collaboration
URL http://www-cdf.fnal.gov
(Dated: May 6, 2005)

We report a measurement of the mass of the top quark in $t\bar{t}$ pair production events decaying into the lepton+jets channel. The events belong to a sample of 318 pb^{-1} of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV collected by the CDF II detector. The identification of b-quark jets in the analysis of $t\bar{t}$ events not only suppresses the background but also improves the reconstruction of signal events. In particular, the reconstruction of candidate events with two b tags is especially reliable. This analysis aims to enhance the sensitivity of the measurement of the mass of the top quark by using two different b-tagging algorithms, thereby increasing the number of double-tag candidate events. After passing our kinematical selection criteria, events are classified into five independent categories according to the number of b-tagged jets they contain. We found a total of 138 $t\bar{t}$ candidates, and measured the top mass to be $173.0\ ^{+2.9}_{-2.8}(\mathrm{stat})\ \pm 3.3(\mathrm{syst})\ \mathrm{GeV}/c^2$.

I. INTRODUCTION

The top quark was discovered by the CDF and DØ collaborations in 1995 during the Tevatron Run I [1]. It still remains one of the least well-studied elementary particles discovered so far. In particular, the measurement of the mass of the top quark is a valuable input to precision electroweak analyses, where the validity of the Standard Model can be checked extensively. This measurement also constrains the mass of the Higgs boson, the last particle to be discovered in the Standard Model.

A measurement of the top quark mass in the lepton + jets channel has already been reported for the so-called Template Method [2], yielding 173.2 $^{+2.9}_{-2.8}$(stat) $\pm$ 3.4(syst) GeV/c^2. This result is based on 318 pb^{-1} of data. The template analysis classifies candidate events passing the kinematical cuts into 0, 1 and 2-tag samples according to the number of b-tagged jets they contain. This strategy improves the measurement sensitivity because b-tagging of jets provides an important clue for the correct reconstruction of $t\bar{t}$ events and also helps to suppress the background. The 1-tag sample is further subdivided into two classes (1tagL and 1tagT) according to the E_T of the jets in the events. An attempt to improve the sensitivity of the Template Method was performed by calibrating the jet energy scale event by event (JES Method) [3], resulting in a measured top quark mass of 173.5 $^{+3.7}_{-3.6}$(stat) $\pm$ 1.7(syst) GeV/c^2.

The analysis described in this report is another attempt to improve the measurement of the top quark mass. It is an update of Ref. [4], where we measured the mass of the top quark to be 177.2 $^{+4.9}_{-4.7}$ (stat) $\pm$ 6.6(syst) GeV/c^2 using 162 pb^{-1} of collision data. As mentioned below, b-tagging plays an important role in the analysis of $t\bar{t}$ events, and a sample of events having two b-tagged jets (double tagged events) is especially sensitive to the mass of the top quark. Both the Template and JES analyses mentioned above used the SECVTX b-tagging algorithm. Another b-tagging algorithm, called Jet Probability, has a looser tagging condition than SECVTX, resulting in a higher efficiency for heavy flavor jets. Our analysis uses Jet Probability in addition to SECVTX in order to further enhance the double tagging efficiency. We subdivide our candidate event sample into five categories, labeled 0tag, 1tagL, 1tagT, 2tag(S+S) and 2tag(S+J). We tuned the Jet Probability tagger to optimize the sensitivity of the top quark mass measurement. Using 318 pb^{-1} of data, we found 40, 21, 43, 16 and 18 candidate events in each of the above subsamples, respectively. The mass of the top quark was measured to be 173.0 $^{+2.9}_{-2.8}$(stat) $\pm$ 3.3(syst) GeV/c^2.

II. EVENT SELECTION

Our signal process is $t\bar{t}$ pair creation followed by $t\bar{t}$ decay into the lepton + jets channel :

$$p\bar{p} \to t\bar{t} + X \to (Wb)(Wb) + X \to (\ell\nu b)(q\bar{q}'b) + X$$

Our event selection is designed to identify all the final particles in the $t\bar{t}$ decay chain. We require exactly one lepton (either e or μ) with transverse momentum $P_T > 20$ GeV/c and pseudo-rapidity $|\eta| < 1.0$. In order to ensure that there is a neutrino in the event, we require a missing E_T ($\not\!\!E_T$) of magnitude greater than 20 GeV. Final state quarks are detected as jets, which we reconstruct with the JETCLU algorithm [5], with a cone size of 0.4. We require four or more jets within $|\eta| < 2.0$ and with :

- $E_T > 15$ GeV for the first three jets, and
- $E_T > 8$ GeV for the fourth jet,

in tagged events (events with b-tagged jets). In 0-tag events we apply a tighter cut on jets in order to reduce the background:

- $E_T > 21$ GeV for the first four jets.

When more than four jets are found, we simply assume that the leading four jets in order of E_T correspond to the four partons in the $t\bar{t}$ decay. When counting b-tagged jets, we only consider the tagging information of the leading four jets.

Since there are two b quarks in the $t\bar{t}$ final state, identifying jets originating from b quarks helps to correctly reconstruct the event. We adopt two b-tagging algorithms: SECVTX and Jet Probability. The SECVTX algorithm reconstructs the secondary vertex of a B meson decay by fitting the tracks found in the jet with the constraint that they originate from one point, and tags the jet according to the displacement between the primary and secondary vertexes. On the other hand, the Jet Probability algorithm compares the transverse displacement of a track with respect to the primary vertex with measured resolution functions, and calculates the resulting probability that the track originated from the primary vertex. By combining these probabilities for all the tracks in a jet, the algorithm determines how likely the jet is to have originated from the primary vertex. Both algorithms rely on the high precision tracking obtained with the silicon detector of CDF. The SECVTX efficiency is estimated from a sample of events containing two jets with $E_T > 15$ GeV and $|\eta| < 1.5$, one of which is associated with an electron or muon with $E_T > 8$ GeV. A similar sample is used for estimating the efficiency of Jet Probability, except that only events with an electron are used. For both algorithms, the jet without a lepton is required to be tagged by the b-tagging algorithm to ensure that the event is consistent with pair production of heavy flavor quarks. The jet associated with a lepton is then assumed to have originated from the semi-leptonic decay of a B hadron and is used to estimate the b-tagging efficiency. The average efficiencies of these b-taggers for heavy flavor jets with $E_T > 15$ GeV are estimated to be 28% for SECVTX and 33% for Jet Probability. Due to the finite tracking resolution of our detector, b-tags of light-flavor jets are also possible. Efficiencies for light flavor jets (mistag rates) are estimated by looking at jets with secondary vertexes reconstructed on the opposite side of the primary vertex with respect to the jet direction. All jets with $|\eta| < 2.4$ and $E_T > 10$ GeV (8 GeV in the case of Jet Probability) found in a data sample containing events with at least one jet with $E_T > 20$ GeV are used to estimate the mistag rate. The latter is found to be 0.34% for SECVTX and 4.1% for Jet Probability. Since SECVTX is better at rejecting light flavor jets than Jet Probability, we conservatively require at least one SECVTX tagged jet in the event selection of tagged samples. We use Jet Probability to enhance the double tagging capability of our analysis by allowing it to tag the second b jet in an event. To benefit from the low background contamination of events with high E_T jets, we further subdivide the 1-tag category into two subcategories according to jet E_T. Thus, our subsamples are defined as follows:

2tag (S+S):	3 jets with $E_T > 15$ GeV + 1 jet with $E_T > 8$ GeV, 2 SECVTX tagged jets among the leading four;
2tag (S+J):	3 jets with $E_T > 15$ GeV + 1 jet with $E_T > 8$ GeV, 1 SECVTX tagged jet + 1 Jet Probability tagged jet among the leading four;
1tagT:	4 jets with $E_T > 15$ GeV, 1 SECVTX tagged jet among the leading four;
1tagL:	3 jets with $E_T > 15$ GeV + 4$^{\text{th}}$ leading jet with $8 < E_T < 15$ GeV, 1 SECVTX tagged jet among the leading four;
0tag:	4 jets with $E_T > 21$ GeV, 0 SECVTX tagged jets among the leading four.

III. EVENT RECONSTRUCTION

For each candidate $t\bar{t}$ event, there are 12 possible ways to assign the four leading jets to the four partons in $t\bar{t}$ decay. Furthermore, there are two neutrino p_z solutions when the masses of the two W bosons are constrained, although these two solutions mostly converge to the same result in our fit. For each of these 24 combinations we calculate the "reconstructed top quark mass" M_t by minimizing the following χ^2:

$$\chi^2 = \sum_{i=\ell,4jets} \frac{\left(p_T^{i,fit} - p_T^{i,measured}\right)}{\sigma_i^2} + \sum_{j=x,y} \frac{\left(U_T^{j,fit} - U_T^{j,measured}\right)}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{jjb} - M_t)^2}{\Gamma_t^2} + \frac{(M_{\ell\nu b} - M_t)^2}{\Gamma_t^2} \tag{1}$$

In the first term, σ_ℓ and σ_{jet} are the lepton and four leading jet p_T resolutions. In the second term, $U_T^{x,y}$ and $\sigma_{x,y}$ are the components of the unclustered energy measured in the calorimeter, and their errors. Each of $M_{\ell\nu}$, M_{jj}, M_{jjb} and $M_{\ell\nu b}$ refers to the invariant mass of the sum of the four-vectors denoted in the subscript. For example, M_{jj} is the invariant mass of the W daughter jets. The quantities M_W and M_t are the pole masses of the W boson and top quark, and Γ_W and Γ_t are the total widths of the W boson and top quark. We set $M_W = 80.41$ GeV/c^2 and $\Gamma_W = 2.06$ GeV as taken from the measured world average, and $\Gamma_t = 1.5$ GeV is from a theoretical calculation. The free parameters in the fit are $p_T^{i,fit}$, $U_T^{j,fit}$ and M_T. This fit enables the momenta of lepton, jets and neutrino to float around their measured values, while constraining the reconstructed W masses. We also require that the t and $\bar{t}$ have the same mass, as seen in the last two terms. We then consider M_t to be the reconstructed mass in each event, after the χ^2 is minimized. Among the 24 reconstructed top masses, we reject those for which the jet-parton assignment is inconsistent with the b-tagging configuration. With this condition, the number of allowed combinations is 24 for 0-tag, 12 for 1-tag and 4 for 2-tag events. As a result, the probability of selecting the wrong combination is much smaller for 2-tag events than for the others. We choose M_t with the smallest χ^2 as the reconstructed top mass in each event. Events with large χ^2 are rejected as likely to be background events. The χ^2 cut has been optimized for the best sensitivity to the mass of the top quark, and we cut events with $\chi^2 > 9$.

IV. TOP MASS TEMPLATES

In our measurement of the top quark mass, we fit the distribution of the reconstructed top mass extracted from data events to a sum of signal and background distributions derived from Monte Carlo samples. We call these distributions obtained with Monte Carlo samples "templates". The signal and background shapes must be described as a function of the true top mass to perform the top mass measurement.

A. Signal Templates

The signal shape is parametrized by the following function :

$$f_s(M_t|m_t) \;=\; p_8\; f_1\left(M_t, \{p_1, p_2, p_3\}\right) \;+\; p_9\; f_2\left(M_t, \{p_4, p_5\}\right) \;+\; (1 - p_8 - p_9)\; f_2\left(M_t, \{p_6, p_7\}\right), \tag{2}$$

with:

$$f_1\left(M_t, \{p_1, p_2, p_3\}\right) \;=\; \frac{{p_3}^{1+p_2}}{\Gamma(1+p_2)}(M_t - p_1)^{p_2} e^{-p_3(M_t - p_1)}, \tag{3}$$

$$f_2\left(M_t, \{p_4, p_5\}\right) \;=\; \frac{1}{\sqrt{2\pi} p_5} e^{-\frac{1}{2}\left(\frac{M_t - p_4}{p_5}\right)^2}, \tag{4}$$

where M_t refers to the event-by-event reconstructed top mass and m_t to the true top mass. The nine parameters p_i are linear functions of the true top mass:

$$p_i = \alpha_i + \alpha_{i+9} \times \left(m_t - \left(175\ \mathrm{GeV}/c^2\right)\right), \qquad i = 1, 2, ..., 9. \tag{5}$$

Thus we describe the mass distribution of the signal events with eighteen α's plus the true top mass m_t. The values of the α's are determined by fitting 32 signal templates simultaneously. These signal templates are generated with HERWIG [6] with different top mass inputs. Some of the signal templates for the 2tag (S+J) sample are shown along with the fit result in Fig.1. The signal shapes of other samples are parametrized in the same fashion.

B. Background Templates

The background in the tagged samples consists mainly of W+heavy flavor, mistags (W+light flavor), non-W (QCD events containing no W boson), single top, and WW and WZ dibosons. For estimating the number of background events passing our event selection, we used ALPGEN [7] to model W+heavy flavor and mistags, and PYTHIA [8] to model single top, WW, and WZ. The non-W background is considered to be mainly due to events where a QCD jet is misidentified as a lepton. This effect is modeled using a high-p_T lepton data sample, where we assume that the spectrum of the lepton isolation variable does not depend on the $\not\!\!E_T$. The number of events with a poorly isolated lepton or small $\not\!\!E_T$ is then extrapolated into the signal region to estimate the non-W background. Table I summarizes our background estimates in each tagged sample. The background template is constructed by adding the histograms

Mass Template Source	2tag (S+J)	2tag (S+S)	1tagT	1tagL
W+heavy flavor	0.52 ± 0.26	0.37 ± 0.14	2.56 ± 0.85	4.24 ± 1.24
mistag	0.38 ± 0.19	0.18 ± 0.04	2.29 ± 0.32	3.00 ± 0.41
non-W (QCD)	0.15 ± 0.08	0.14 ± 0.04	1.68 ± 0.39	1.53 ± 0.42
single top	0.08 ± 0.04	0.003 ± 0.007	0.29 ± 0.07	0.34 ± 0.07
WW/WZ	0.05 ± 0.03	0.02 ± 0.004	0.31 ± 0.07	0.44 ± 0.09
Total	1.18 ± 0.59	0.71 ± 0.18	7.11 ± 1.24	9.55 ± 1.71

TABLE I: Summary of background estimates.

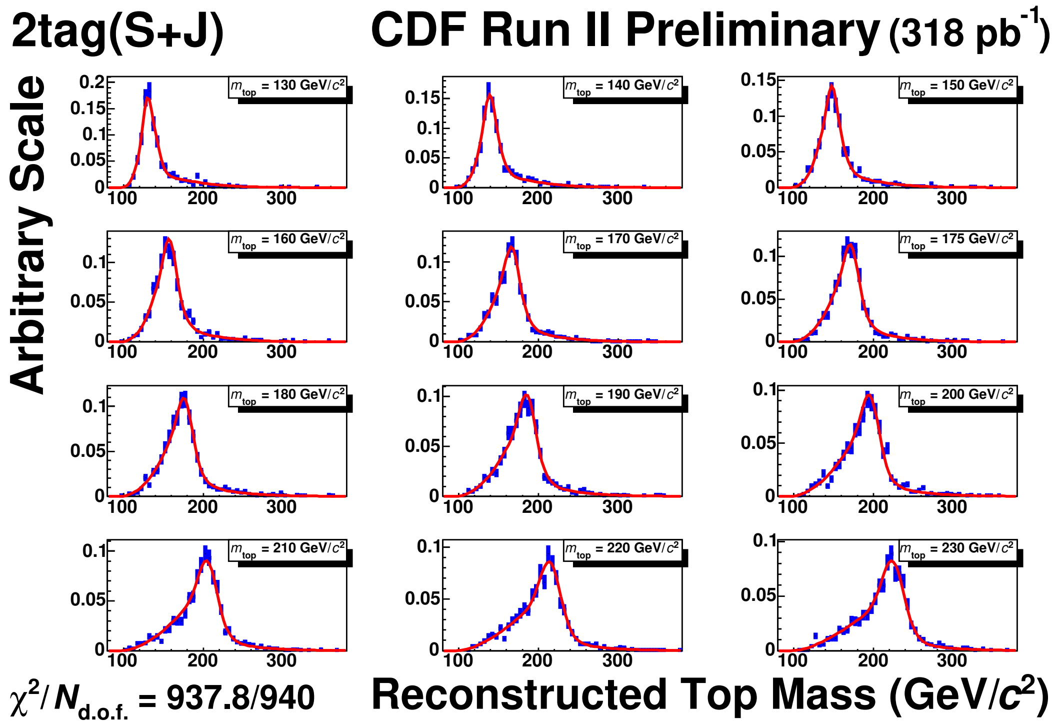

FIG. 1: Signal templates for the 2tag (S+J) sample for input masses from 130 up to 230 GeV/c^2, along with the parametrized signal shape functions.

of the individual background processes, each weighted by its contribution to the total background. This template is described with the function :

$$f_b(M_t) = f_1(M_t, \{\beta_1, \beta_2, \beta_3\}) \tag{6}$$

where the β_i are fit parameters. Fig. 2 shows the fit result for the 2tag (S+J) sample.

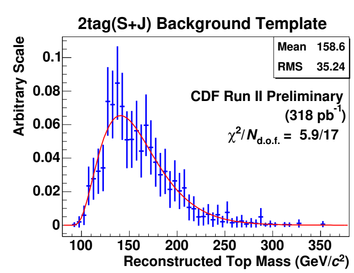

FIG. 2: Background template and the fit result for 2tag (S+J) sample.

The background of the 0tag sample is modeled as a W+jets process. Its estimated normalization is not used in our top mass measurement.

V. DETERMINATION OF THE TOP QUARK MASS

We measure the top quark mass by fitting the reconstructed top mass distribution in the data sample to a sum of templates for $t\bar{t}$ signal and background using an unbinned likelihood method. The likelihood L for each tagged sample is the product of two likelihoods:

$$L = L_{shape} \times L_{bkg}, \tag{7}$$

where L_{shape}, L_{bkg} describe the likelihoods for the top mass distribution and for the number of background events:

$$L_{shape} = \frac{e^{-(N_s+N_b)}(N_s+N_b)^N}{N!} \prod_{i=1}^{N} \frac{N_s f_s(M_t^i|m_t,\vec{\alpha}) + N_b f_b(M_t^i|\vec{\beta})}{N_s+N_b}, \quad (8)$$

$$L_{bkg} = \exp\left(-\frac{1}{2}\left[\frac{N_b - N_b^{pred.}}{\sigma^2_{N_b^{pred.}}}\right]^2\right). \quad (9)$$

Here, M_t^i is the reconstructed top mass of event i in the data sample. In this fit, m_t, N_s and N_b are free parameters describing the true top mass, and the numbers of signal and background events, respectively; N is the total number of events in the sample, and $\vec{\alpha}$ and $\vec{\beta}$ are the parameters of the functions describing the signal and background template shapes. The quantities $N_b^{pred.}$ and $\sigma_{N_b^{pred.}}$ refer to the estimated number of background events and its error, as listed in Table I. In the 0tag sample we do not constrain the number of background events, so that:

$$L^{0tag} = L^{0tag}_{shape}.$$

Since our subsamples are statistically independent of each other, it is straightforward to combine their likelihood functions:

$$L^{combine} = L^{0tag} \times L^{1tagL} \times L^{1tagT} \times L^{2tag(S+S)} \times L^{2tag(S+J)} \quad (10)$$

The true top quark mass is a free parameter that is common to the five likelihood components.

VI. OPTIMIZATION OF THE JET PROBABILITY TAGGER

The small background contamination and reliable signal reconstruction of double-tag events motivate the main feature of this analysis, which is to enhance the double-tagging efficiency by introducing Jet Probability as a secondary b-tagger. The adjustable nature of the Jet Probability tagging requirement allows us to optimize the analysis by balancing the signal tagging rate against the mistag rate. With this goal in mind, we performed a study where we repeatedly fit Monte Carlo generated samples to the templates, and plotted the resulting average statistical uncertainty on the top mass as a function of the Jet Probability cut value. As shown in Fig. 3, the optimal cut value is 0.05, and this is what we use in our final measurement.

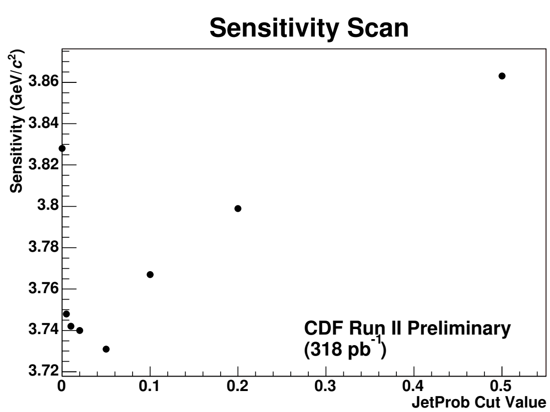

FIG. 3: Expected statistical sensitivity of the top quark mass measurement as a function of the cut on Jet Probability.

VII. SANITY CHECK

In order to evaluate a possible bias in our measurement method, we repeatedly performed the likelihood fit to samples generated with Monte Carlo, with the top mass input to Monte Carlo varying between 140 and 205 GeV/c^2.

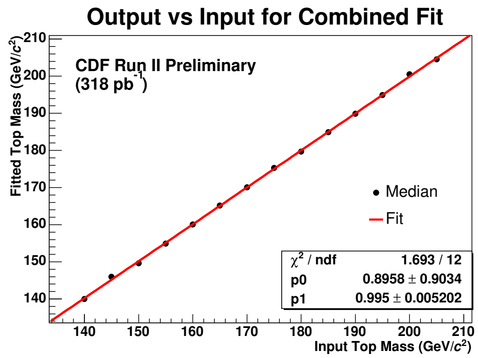

FIG. 4: Top mass returned by the likelihood fit as a function of input top mass. The solid line shows output=input.

Fig. 4 shows the top mass returned by the likelihood fit as a function of input top mass. One can see that the output is consistent with the input.

Another concern is whether the statistical error calculated in our likelihood fit is reasonable. We calculate the pull for each likelihood fit:

$$\text{pull} = \frac{m_{top}^{output} - m_{top}^{input}}{\sigma_m} \tag{11}$$

where m_{top}^{input} is the input top mass, and m_{top}^{output} and σ_m are the measured top mass and its error as returned by the likelihood fit. If the error is estimated correctly, the width of the pull distribution must be consistent with 1. The width of the pull distribution is plotted against the input top mass in Fig. 5. We find that the width is somewhat

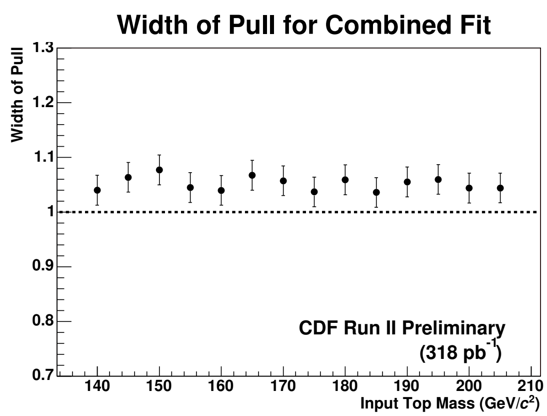

FIG. 5: Width of the pull as a function of the input top mass. The line shows pull width = 1.

larger than 1, implying that the statistical uncertainty is underestimated. We correct for this by scaling the statistical uncertainty in such a way that measured 1-σ intervals will cover the true top mass 68% of the time if the experiment is repeated. The scale factor is found to be 1.037.

VIII. RESULTS

We analyzed 318 pb^{-1} of data collected with the CDF detector from March 2002 through August 2004 and found 138 events passing our event selection. The number of candidate events in each sample is listed in Table II, along with the corresponding expected number of events. The number of signal events is based on a $t\bar{t}$ production cross section of 8.0 pb, as recently measured by CDF [9].

	2tag (S+J)	2tag (S+S)	1tagT	1tagL	0tag
$t\bar{t}$(8.0 pb)	11.3	18.4	33.7	14.6	25.4
Background	1.18 ± 0.59	0.71 ± 0.18	7.11 ± 1.24	9.55 ± 1.71	–
Total expected	12.5	19.1	40.8	24.1	–
Observed	18	16	43	21	40

TABLE II: Number of candidate events in each subsample. The expected numbers of signal and background events are shown for reference.

Using these candidate events, we performed the likelihood fit. Fig. 6 shows the reconstructed top mass in the data along with the results of the fit. Fig. 7 shows the likelihood as a function of top mass. From this curve, we obtain :

$$m_{top} = 173.0 \, ^{+2.8}_{-2.7} \text{ GeV}/c^2 \tag{12}$$

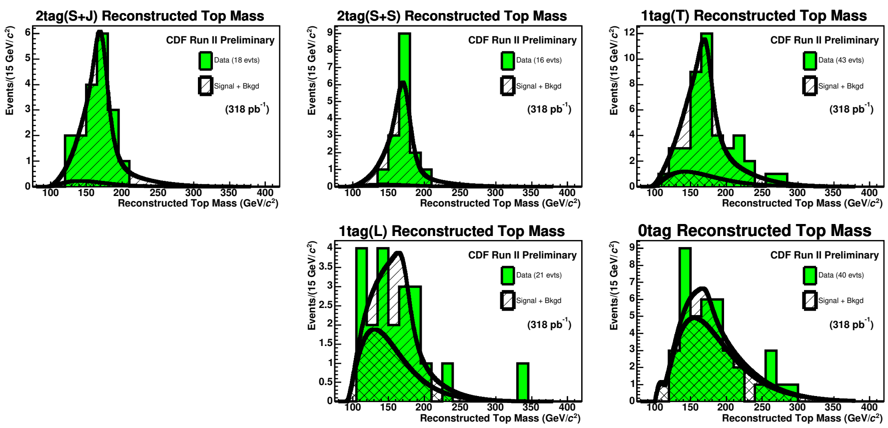

FIG. 6: Results of likelihood fit to data. The histograms are distributions of the reconstructed top mass in data. The lines show the best fit and the background component returned by the likelihood fit.

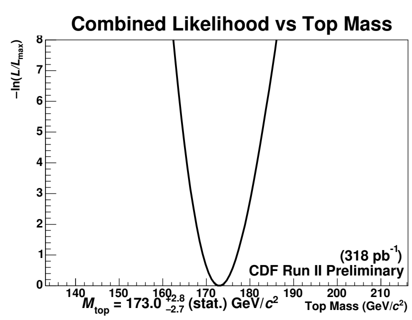

FIG. 7: Results of likelihood fit to data. Likelihood as a function of the mass of the top quark.

Fig. 8 shows a comparison of the statistical uncertainty obtained in our data fit to the distribution obtained in a Monte Carlo study assuming $m_{top} = 172.5$ GeV/c^2. One can see that the error obtained in the data fit is consistent with expectation.

As mentioned in Section VII, we apply a scale factor of 1.037 to correct the statistical uncertainty and obtain:

$$m_{top} = 173.0 \, ^{+2.9}_{-2.8} \text{ GeV}/c^2 \tag{13}$$

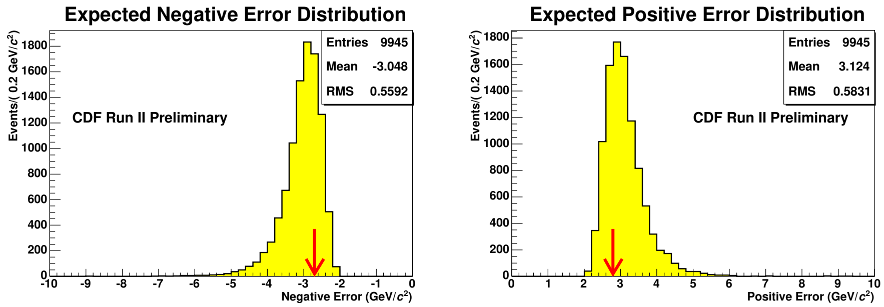

FIG. 8: The distribution of statistical uncertainties obtained in a Monte Carlo study assuming 172.5 GeV/c^2 as input top mass. The red arrows indicate the error obtained in our fit to data. The left plot is for negative and the right is for positive error.

IX. SYSTEMATIC UNCERTAINTY

Systematic uncertainties arise from our limited understanding of physics processes and detector response. For each source of systematic uncertainty we consider a typical alternative model, such as a $\pm 1\sigma$ change in the value of the relevant parameter. We then generate an ensemble of Monte Carlo pseudo-experiments to evaluate the corresponding change in the expected value of the measured top mass, and assign this change as systematic uncertainty.

We consider systematic uncertainties from the following sources :

- ISR: Initial state radiation uncertainty is estimated by varying the parton shower parameters in the PYTHIA $t\bar{t}$ Monte Carlo generator. The appropriate amount of parameter variation was determined by a study of CDF high-mass Drell-Yan data.
- FSR: Final state radiation uncertainty is also estimated by varying the parton shower parameters in PYTHIA. In this case, the appropriate amount of parameter variation was determined from a study of the $W \to q\bar{q}'$ process at LEP.
- Jet Energy Scale: This is the dominant source of systematic uncertainty in our measurement. We changed jet energies by $\pm 1\sigma$ in the calculation of the reconstructed top mass, and assigned half the difference in the resulting top mass measurements as systematic uncertainty. The exact value of 1σ of jet energy is determined from calorimeter calibration with data and Monte Carlo simulations.
- Monte Carlo Generator: Our primary signal Monte Carlo generator is HERWIG. We replaced it by PYTHIA to estimate the uncertainty due to generator modeling.
- b-jet modeling: Separately from Monte Carlo generator uncertainty, we considered the uncertainty due to heavy quark fragmentation, color flow effects, and semileptonic decay rates.
- Background Shape: This includes uncertainties in the relative contributions of different types of background, as well as the Q^2 dependence of each background process.
- b-tagging: Here we consider the uncertainty on the b-tagging efficiency, including the effect of a possible jet E_T dependence of the efficiency and the correlation between SECVTX and Jet Probability.
- Monte Carlo statistics: The finite statistics of the Monte Carlo samples can systematically bias the measurement. To quantify this effect, we generated ensembles of Monte Carlo pseudo-experiments in which the data events were drawn from templates that were fluctuated from one ensemble to the next. Each ensemble yielded an expected top mass measurement, and the width of the distribution of these expected measurements was assigned as systematic uncertainty.

Table III lists the systematic uncertainties from each source. The total systematic uncertainty is found to be 3.3 GeV/c^2.

Source	Uncertainty (GeV/c^2)
Initial State Radiation	0.3
Final State Radiation	0.6
Jet Energy Scale	3.0
Parton Distribution Functions	0.4
Generator Model	0.2
b-jet modeling	0.6
Background Shape	0.7
b-tagging	0.3
Monte Carlo statistics	0.4
Total	3.3

TABLE III: Summary of systematic uncertainties.

X. CONCLUSION

The top quark mass is measured in the lepton + jets decay channel of $t\bar{t}$ events. We analyzed 318 pb^{-1} of data collected by the CDF detector from March 2002 through August 2004, and found a total of 138 events passing our event selection. Using these candidate $t\bar{t}$ events we obtained a measured top mass of

$$m_{top} = 173.0\ ^{+2.9}_{-2.8}\ (\text{stat})\ \pm 3.3\ (\text{syst})\ \text{GeV}/c^2. \tag{14}$$

Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium fuer Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comision Interministerial de Ciencia y Tecnologia, Spain; and in part by the European Community's Human Potential Programme under contract HPRN-CT-20002, Probe for New Physics.

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