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# Top Quark Mass Measurement using the Dynamical Likelihood Method in the lepton plus jets channel at CDF RunII

The CDF Collaboration
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We report a measurement of the top quark mass obtained by DLM (Dynamical Likelihood Method) in the lepton+jets channel. The likelihood is defined as the differential cross section as a function of $M_{top}$ per unit phase space volume of the final partons, multiplied by the transfer function from jets to parton quantities. The method takes into account all possible jet combinations in an event and the likelihood is multiplied event by event to derive the top quark mass by the maximum likelihood method. Using 63 $t\bar{t}$ candidates in the data with 9.2 events expected from background, which corresponds to an integrated luminosity of 318 $pb^{-1}$ accumulated by the CDF Run II detector, we measure the top quark mass to be 173.2 $^{+2.6}_{-2.4}$(stat.)$\pm$ 3.2(syst.) GeV/$c^2$, or 173.2 $^{+4.1}_{-4.0}$ GeV/$c^2$.

## I. INTRODUCTION

The mass of the top quark is an important ingredient in particle physics. Its precise measurement not only provides a constraint on the mass of Higgs boson but also serves for setting basic parameters in beyond-the-standard models. We present a measurement of the top quark mass with the Dynamical Likelihood Method (DLM). The data are obtained with the Collider Detector at Fermilab (CDF II) operated during Run II of the Tevatron, which has a center-of-mass energy of 1.96 TeV. The integrated luminosity of the data sample, collected from 2001 through 2004, is 318 $pb^{-1}$.

Within the standard model, the top quark decays approximately 100% of the time into $Wb$. The $W$ can then decay to a quark-antiquark or lepton-neutrino pair. The measurement presented here uses events with $t\bar{t}$ decaying into the "lepton+jets" channel: $t\bar{t} \to W^+bW^-\bar{b} \to (l^+\nu b)(q\bar{q}'\bar{b})$. This channel is characterized by a single high $P_T$ lepton (electron or muon) and missing transverse energy from a $W \to l\nu$ decay, plus four jets from a hadronically decaying $W$ boson and two b quarks from the top decays. Jets formed by the fragmentation of $b$ quarks can be identified ("$b$-tagged") by reconstructing secondary vertices from $b$ hadron decays with the silicon vertex detector(SECVTX tagging).

To be used for the mass measurement, each event is required to contain a single isolated electron or muon with $E_T(P_T) > 20$ GeV(GeV/c) in the central region of the detector ($\mid \eta \mid < 1$) and missing transverse energy, $\mid \not{E}_T \mid > 20$ GeV, indicating the presence of a neutrino. In the present analysis, exactly four jets with $E_T \geq 15$ GeV and $\mid \eta \mid < 2.0$ are required in each event. This selection criterion minimizes the contamination by initial and final state radiation. We also require that at least one of the four jets is tagged by the secondary vertex (SECVTX) algorithm as a $b$ jet. All jets in this analysis are formed as clusters of calorimeter towers within cones of fixed radius $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$. The above selection yields 63 events from CDF RunII data accumulated until August 2004. The method we use in this paper is a version of DLM[1−4]. We assume the standard model and use the differential cross section per unit phase space as the likelihood of the parton kinematics inferred from observed quantities.

### A. Definition of the likelihood

*Differential cross section* The parton process in a $p\bar{p}$ collision can generally be written as,

$$a/p + b/\bar{p} \to \cdots \to C, \qquad C \equiv \sum_{i=1}^{n} c_i. \tag{1}$$

where $a$ and $b$ are the initial partons, a quark, anti-quark or gluon, in the proton and anti-proton, respectively, and $c_1, c_2, ...c_n$ are final state partons. States of partons are after initial- and before final-state radiation. In the case of the $t\bar{t}$ lepton+jets channel, the initial parton set $(a, b)$ is $(q, \bar{q})$, $(\bar{q}, q)$ or $(g, g)$, and the final partons are $l^+, \nu, q, b, \bar{q}', \bar{b}$ or their anti-particles, where $l = e$ or $\mu$ and $q$, $\bar{q}'$ are quarks from the $W$. Throughout this paper, a particle symbol $p$ represents its 4-momentum, and $\boldsymbol{p}$ its 3-momentum. The final partons are assumed to have their pole masses so that the 3-momenta define their states unambiguously.

The hadronic cross-section for the $t\bar{t}$ production is given by

$$d\sigma = dz_a dz_b d^2\boldsymbol{p}_T f^*_{a/p}(z_a) f^*_{b/\bar{p}}(z_b) f_T(p_T) d\hat{\sigma}(a + b \to C; M_{top}), \tag{2}$$

where $M_{top}$ is the mass of the top quark, and $d\hat{\sigma}$ is the parton level cross section,

$$d\hat{\sigma}(a + b \to C; M_{top}) = \frac{(2\pi)^4 \delta^4(a + b - C)}{4\sqrt{(a \cdot b)^2 - m_a^2 m_b^2}} |\mathcal{M}(a + b \to C; M_{top})|^2 d\Phi_n^{(f)}(a + b; C). \tag{3}$$

Variables $z_a$ and $z_b$ are the energy fractions of $a$ and $b$ in hadrons $p$ and $\bar{p}$ respectively, and $\boldsymbol{p}_T$ is the total momentum of the initial and final systems in the plane transverse to the beam axis. Functions $f^*_{a/p}(z_a)$ and $f^*_{b/\bar{p}}(z_b)$ denote the effective Parton Distribution Functions(PDF's), while $f_T(\boldsymbol{p}_T)$ is the probability function for the total transverse momentum of the system acquired by initial state radiation. In Eq.(3), $\mathcal{M}$ is the matrix element of process (1), and $d\Phi_n^{(f)}$ is the Lorentz invariant phase space factor,

$$d\Phi_n^{(f)} \equiv \prod_{i=1}^{n} \frac{d^3\boldsymbol{c}_i}{(2\pi)^3 2E_i}. \tag{4}$$

The basic postulate in this paper is that final partons in a single event occupy an $n$-dimensional unit phase space in the neighborhood of $\boldsymbol{c}(c_1, \cdots, c_n)$. The total probability for this final state to occur is obtained by integrating Eq. (2) with initial state variables, $z_a$, $z_b$ and $\boldsymbol{p}_T$, as

$$\frac{d\sigma}{d\Phi_n^{(f)}} = I(a, b) \, |\mathcal{M}(a + b \to C; M_{top})|^2 \,, \tag{5}$$

where

$$I(a, b) = \frac{(2\pi)^4}{4\sqrt{(a \cdot b)^2 - m_a^2 m_b^2}} f^*_{a/p}(z_a) f^*_{b/\bar{p}}(z_b) f_T(p_T) \tag{6}$$

is the integration factor for the initial state. Because of the $\delta$-function in Eq. (3), the initial parton momenta $a$ and $b$ are uniquely defined by that of $C$.

When the parton kinematics are given, we define the likelihood as

$$L_1(M_{top}|\boldsymbol{c}) = l_0 \frac{d\sigma}{d\Phi_n^{(f)}}, \tag{7}$$

where $l_0$ stands for the integrated luminosity required to generate the event. But since the beam state is unknown, we set it to a constant, according to Bayes' postulate, " Equidistribution of Ignorance".

<u>*Resonances*</u> When process (1) includes resonance $r$, i.e. the internal line of a Feynman graph, as

$$a/p + b/\bar{p} \to r + c_{j+1} + \cdots + c_n \tag{8}$$

$$r \to c_1 + \cdots + c_j, \tag{9}$$

the matrix element factorizes is factorized as

$$|\mathcal{M}(a + b \to C; M_{top})|^2 = |\mathcal{M}_{prod}|^2 \mathcal{P}(s_r) |\mathcal{M}_{dec}|^2, \tag{10}$$

where $\mathcal{M}_{prod}$ and $\mathcal{M}_{dec}$ are matrix elements for process (8) and (9) respectively, and $\mathcal{P}(s_r)$ is the propagator factor of the resonance,

$$\mathcal{P} = \frac{1}{(s_r - M_r^2)^2 + M_r^2 \Gamma_r^2}. \tag{11}$$

In Eq.(11), $s_r$ is the virtual mass squared of $r$, which satisfies

$$s_r = (\sum_{i=1}^{j} c_i)^2. \tag{12}$$

In $t\bar{t}$ production, the $t$, $\bar{t}$, $W^+$ and $W^-$ are resonances. In the leptonic decay channel of the $W$, the $z$ component of neutrino momentum $\nu_z$ is not observed. We infer $s_W$ according to the posterior probability density for $s_W$, which is

$$\Pi(s_W) = \mathcal{P}(s_W) \Big/ \int_0^\infty \mathcal{P}(s_W) ds_W, \tag{13}$$

and $\nu_z$ is determined by solving Eq. (12). $s_r$ of other resonances in $l + jets$ process are determined by Eq. (12) from the momenta of the daughters.

<u>*Transfer functions for observables*</u> Final partons are not directly observed; they undergo parton-shower/hadronization and are observed by detectors with finite resolution. In analysis, quarks and gluons are reconstructed as jets. To describe the correlation between the final parton state and observed quantities (observables), we introduce the transfer function (TF) denoted by $w(\boldsymbol{y}|\boldsymbol{x}||M_{top})$, which represents a $M_{top}$ dependent probability density function for $\boldsymbol{y}$ when $\boldsymbol{x}$ is given. Symbol $\boldsymbol{y}$ is a set of observables and $\boldsymbol{x}$ is a parton variable set that corresponds to $\boldsymbol{y}$. In the present analysis of the $l + jets$ process, we use TF for jets only. We assume $w(\boldsymbol{y}|\boldsymbol{x}||M_{top})$ can be factorized into the individual observable components,

$$w(\boldsymbol{y}|\boldsymbol{x}||M_{top}) = \prod_i w(y_i|x_i||M_{top}). \tag{14}$$

Abbreviating variable index $i$, TF for a variable set $(x,y)$, $w(y|x||M_{top})$, is obtained from the $(x,y)$ distribution in the $t\bar{t}$ Monte Carlo events by removing the cross section factor. We use separate TFs for $b$ jets and jets from the W decay.

The parton kinematics reconstruction is made by the use of the posterior TF,

$$w(\boldsymbol{x}|\boldsymbol{y}||M_{top}) = w(\boldsymbol{y}|\boldsymbol{x}||M_{top}) \Big/ \int w(\boldsymbol{y}|\boldsymbol{x}||M_{top}) d\boldsymbol{x}. \tag{15}$$

To save statistics of the Monte Carlo sample and get TF with precision, we make mass averaged TFs by integrating 21 samples with different input top mass values in the range of 130-230 GeV.

*Single path reconstruction and its likelihood* A set of parton kinematics is reconstructed in the following steps:

(1) Jets are assigned to quarks. Each set of assignments is called a "topology", and is sorted by topology number $I_t$ ($I_t = 1, \cdots, N_t$).

(2) A set of 3-momenta of observable partons $\boldsymbol{b}, \bar{\boldsymbol{b}}, \boldsymbol{q}, \bar{\boldsymbol{q}}'$ is generated from the TFs.

(3) The transverse components of the neutrino momentum $(\nu_x, \nu_y)$ are identified with the measured value of MET. One infers $s_W$ according to $\Pi(s_W)$ with a fixed value of $M_W$, then the z-component of the neutrino momentum is obtained by solving Eq.(12). The two solutions$(\nu_{z1}, \nu_{z2})$ are sorted by integer $I_s$ ($I_s = 1, 2$).

(4) For a set of variables thus reconstructed, we scan the value of $M_{top}$ in its search region.

Steps from (1) through (4) constitutes a unit of the reconstruction procedure, which we call a "path". Each path is specified by integers $(I_t, I_s, k)$, where $k$ ($k = 1, \cdots, K$) is the path number, representing a set of $(s_W, \boldsymbol{x})$. When observable set $\boldsymbol{y}^{(i)}$ is given for the $i$-th event, the single path likelihood for the $k$-th path is defined by

$$\boldsymbol{L}_1^{(i)}(M_{top}; I_t, I_s, k|\boldsymbol{y}^{(i)}) = l_0 \frac{d\sigma}{d\Phi}(I_t, I_s, k; M_{top}) \tag{16}$$

where subscript 1 stands for a single path. Note that the likelihood for a path is a function of $M_{top}$.

*Single event likelihood* The likelihood of the $i$-th event is defined by the average (or the expectation value) of the single path likelihood over all reconstructed paths,

$$\boldsymbol{L}^{(i)}(M_{top}) \ = \ \frac{1}{2KN_t} \sum_{I_t=1}^{N_t} \sum_{k=1}^{K} \sum_{I_s=1}^{2} \boldsymbol{L}_1^{(i)}(M_{top}; I_t, I_s, k|\boldsymbol{y}^{(i)}). \tag{17}$$

By this definition, the event likelihood for the true values of $I_t$ and $I_s$ is always included in $\boldsymbol{L}^{(i)}(M_{top})$, if the event is signal. The scanning of $k$, i.e. kinematical reconstruction, is to be done until the value of the event likelihood converges.

*Joint likelihood for multiple events and maximum likelihood estimate of $M_{top}$* The event likelihoods given by Eq. (17) for individual events are mutually independent probability functions for $M_{top}$. Thus to obtain the top quark mass from a total of $N_{ev}$ events, we multiply the event likelihood functions, and take -2ln(likelihood) of the product,

$$\boldsymbol{\Lambda}(M_{top}) = -2ln \left( \prod_{i=1}^{N_{ev}} \boldsymbol{L}^{(i)}(M_{top}) \right). \tag{18}$$

The mass of top quark is determined from the maximum likelihood estimator of $M_{top}$,

$$\hat{M}_{top} = M_{top} \ at \ minimum \ of \ \boldsymbol{\Lambda}(M_{top}). \tag{19}$$

### B. Matrix Element Calculation in the *l+jets* channel

In this channel, the reconstruction path from observed $\boldsymbol{y}$ to parton momenta $\boldsymbol{c}(\boldsymbol{c}_1, \cdots, \boldsymbol{c}_n)$ are specified by the assignment of the 4 jets to quarks$(b, \bar{b}, q, \bar{q})$, the value of $\boldsymbol{x}$, and the two solutions for the neutrino longitudinal momentum$(\nu_z)$. Since we require at least one b-tagged jet, we consider 12 or 4 combinations for the reconstruction depending on whether 1 or 2 jets are b-tagged. The parton distribution functions $f_{a/p}(z_1)$ and $f_{b/\bar{p}}(z_2)$ are obtained from PYTHIA using the leading order PDF, CTEQ5L. Other PDF sets are used as a systematic uncertainty. The transverse distribution function $f_T(p_T)$ is obtained by running the PYTHIA generator.

The spin averaged matrix element squared $|\mathcal{M}|^2$ is factorized into 3 parts: (1) $t\bar{t}$ production($|\mathcal{M}_{t\bar{t}}|^2$), (2) the propagators of the top and anti-top($|\mathcal{P}_{tl}|^2$ and $|\mathcal{P}_{th}|^2$), and (3) the top decay matrices $|\mathcal{D}_{tl}|^2$ and $|\mathcal{D}_{th}|^2$, where $tl$ and $th$ indicate leptonic and hadronic decay channels of top respectively. Namely,

$$|\mathcal{M}|^2 = |\mathcal{M}_{t\bar{t}}|^2 |\mathcal{P}_{tl}|^2 |\mathcal{P}_{th}|^2 |\mathcal{D}_{tl}|^2 |\mathcal{D}_{th}|^2 . \tag{20}$$

The production matrix element for the $q\bar{q}$ process is

$$|\mathcal{M}_{t\bar{t}}(q\bar{q} \to t\bar{t})|^2 = \frac{g_s^4}{9}(2 - \beta^2 \sin^2\theta^*), \tag{21}$$

where $\theta^*$ is the angle between the top quark and the incident quark in the proton in the $t\bar{t}$ center of mass system, $\beta$ is the velocity of the top and $g_s$ is the strong coupling constant.

For the $gg$ process, the matrix element can be expressed as

$$|\mathcal{M}_{t\bar{t}}(gg \to t\bar{t})|^2 = g_s^4\left(\frac{1}{6\tau_1\tau_2} - \frac{3}{8}\right)\left(\tau_1^2 + \tau_2^2 + \rho - \frac{\rho^2}{4\tau_1\tau_2}\right), \tag{22}$$

where

$$\tau_1 = \frac{2(q \cdot t)}{\hat{s}}, \tau_1 = \frac{2(\bar{q} \cdot t)}{\hat{s}}, \rho = \frac{4M^2}{\hat{s}}. \tag{23}$$

In these equations, the $t\bar{t}$ spin correlations for both the $q\bar{q}$ and $gg$ processes are averaged out, since correlations do not affect the mass measurement. Likewise, whether the $t\bar{t}$ is produced via $q\bar{q}$ or $gg$ has no effect on the mass measurement, hence the likelihoods for the two processes are summed up in the event likelihood with the appropriate PDF weight.

The decay matrix elements for the leptonic and hadronic channels are expressed as

$$|\mathcal{D}_{tl}|^2 = \frac{g_w^4}{4}\frac{(t \cdot l)(b \cdot \nu)}{(S_{l\nu} - M_W^2)^2 + M_W^2\Gamma_W^2}, \tag{24}$$

$$|\mathcal{D}_{th}|^2 = \frac{g_w^4}{4}\frac{1}{2}\sum_{i\leftrightarrow j}^{2}\frac{(\bar{t} \cdot j_i)(\bar{b} \cdot j_j)}{(S_{2j} - M_W^2)^2 + M_W^2\Gamma_W^2}, \tag{25}$$

where $S_{l\nu}$ and $S_{2j}$ represent the invariant masses squared of the lepton+neutrino and the 2jets from the W respectively. As for the mass and the decay width of W, we assume the world average values, $M_W = 80.4$ GeV/c$^2$ and $\Gamma_W = 2.1$ GeV/c$^2$. Since the z-component of the neutrino momentum is not measured, $S_{l\nu}$ is inferred with $\Pi(s_W)$. The generated value of $S_{l\nu}$ gives the z-component of the neutrino momentum via Eq. (12). In Eq.(25), we make both possible assignments of the 2 jets to $q$ and $\bar{q}'$ from the W, and the likelihoods corresponding to the two possibilities are averaged.

| Source | Expected Number of events in W+4jets |
|---|---|
| Mistag | 2.27 ± 0.45 |
| $Wb\bar{b}$ | 1.70 ± 0.79 |
| $Wc\bar{c}$ | 0.81 ± 0.40 |
| Wc | 0.51 ± 0.23 |
| WW/WZ/ZZ | 0.39 ± 0.08 |
| single top | 0.41 ± 0.09 |
| QCD(nonW) | 3.07 ± 1.06 |
| Background Total | 9.2 ± 1.8 |
| Observed events | 63 |

TABLE I: The numbers of expected events for individual background sources.

## II. TOP QUARK MASS RECONSTRUCTION

### A. Estimated number of background events in the data

The expected numbers of background events in our sample are summarized in Table I. We evaluate the total number of background events to be 9.2 ± 1.8 which is 14.5 % of the number of observed events (63).

### B. The mapping function to extract the top mass

The mass-dependent correction factor, which we call the mapping function, is obtained with 1000 sets of pseudo-experiments. There are two sources that cause a non-unit-slope between the input top mass and the reconstructed top mass. One is the top mass dependence of the transfer function, and the other is the effect of background. We integrate the two effects into a single mapping function. Figure 1 shows the reconstructed top mass as a function of its input mass with different background fractions. The background fraction is varied from 0% to 50%, where the relative fraction of each background source is Poisson fluctuated using the mean numbers given in Table I and the total number of events is 63. As one can see in the figure, even with 0% background the reconstructed top mass does not have unit slope. This is due to a small top mass dependence of the transfer function as well as to the effect of gluon radiation and the contamination of other decay modes. In addition, we assume all events are $t\bar{t}$ candidates. If background events are included in the data sample, the likelihood peak is pulled to lower mass by these background events, since we multiply the event likelihoods. The reconstructed top mass is shifted lower as the background fraction increases. Our estimated background fraction of 14.5 % is used to extract the top mass.

### C. Sanity check: mass pull distribution after using the mapping functions

Each set of 63 events in a pseudo-experiment consists of on average 53.8 signal events and 9.2 background events, with both Poisson fluctuated. After applying mapping functions for a 14.5% background fraction to each pseudo-experiment, we obtain a slope of 1.0 between the input and reconstructed masses as illustrated in Figure 2(a)(sanity check). The width of the pull distribution as a function of input top mass is shown in Figure 2(b). We conclude that the top mass is reconstructed without bias over a wide range of input masses by applying the mapping function.

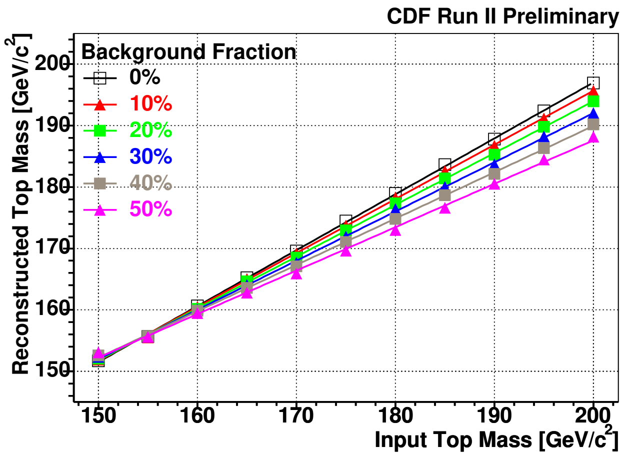
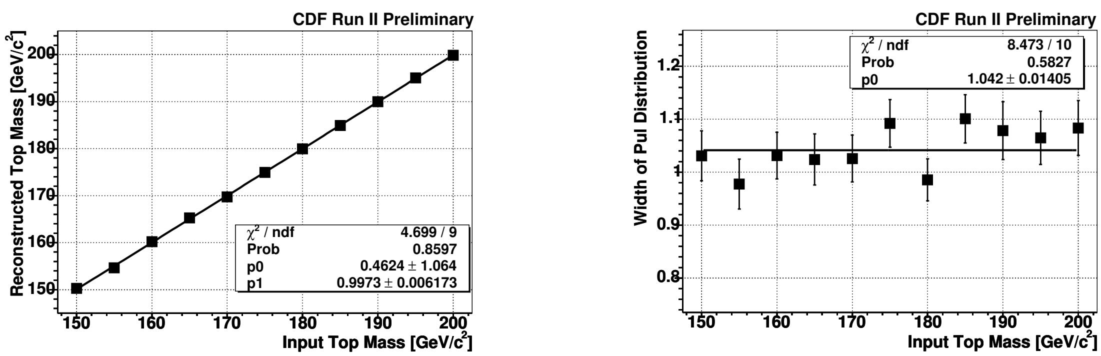



FIG. 1: The reconstructed mass as a function of input mass with the background fraction from 0% to 50%.




(a) Sanity check

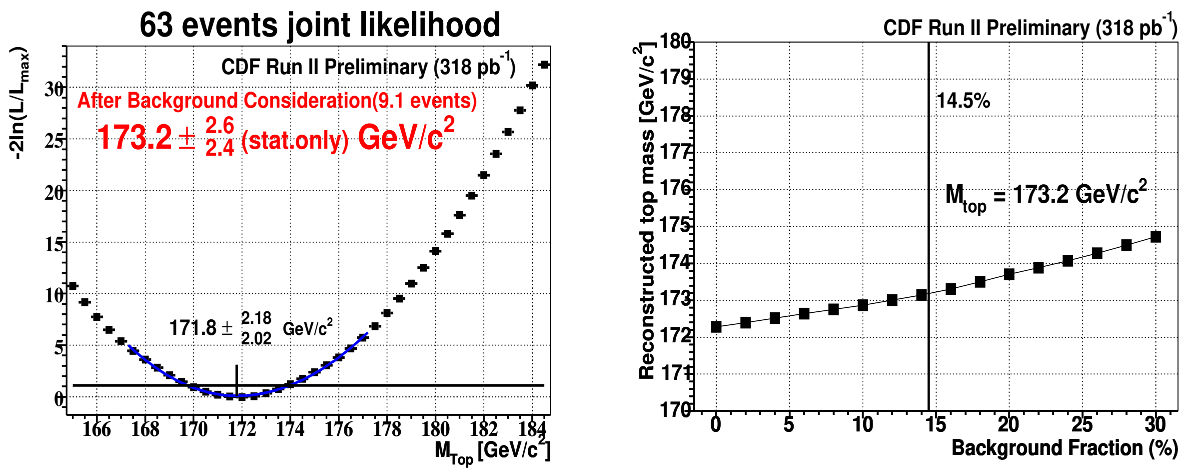
(b) Width of pull distribution

FIG. 2: Sanity check after applying the mapping functions with a background of 14.5%. (a)The slope of the linear fit between the reconstructed top mass and its input mass is consistent with 1.0. (b) The width of the mass pull distribution is 1.04 which is used to correct for the statistical uncertainty.

## III. EXTRACTING THE TOP QUARK MASS

We have 63 $t\bar{t}$ candidate events passing our event selection criteria. The joint likelihood of these events is fitted with a second order polynomial as shown in Figure 3(a). From the fit, we obtain $M_{top} = 171.8^{+2.18}_{-2.02}$ $(stat.only)$ GeV/c$^2$, assuming there is no background. We apply the mapping function to remove the mass-pulling effect of the background. Figure 3(b) shows the extracted top mass as a function of the background fraction. The top mass changes by less than 2.0 GeV/c$^2$ in the background fraction range of [0%-20%].

For the final result, we use the estimated 14.5% background fraction, which gives $M_{top} = 173.2^{+2.6}_{-2.4}$ $(stat.only)$ GeV/c$^2$. Note that the statistical uncertainty must be scaled by two factors, one is due to the slope of the mapping function as a function of top mass and the other is 1.04 from the pull width.




(a) The joint likelihood from data

(b) Background shift effect

FIG. 3: (a): The joint negative log likelihood distribution of the 63 events gives $M_{top} = 171.8^{+2.18}_{-2.02}$ GeV/c$^2$. (b): Extracted top mass using the mapping function as a function of the background fraction.

### A. The Statistical Uncertainty and Systematic Uncertainty

Figure 4 shows the expected negative and positive statistical uncertainties obtained from $t\bar{t}$ Monte Carlo ($M_{top} = 175$ GeV/c$^2$). The black arrows indicate the statistical errors in the data. A probability of having smaller uncertainty than that from data is estimated to be 18%.

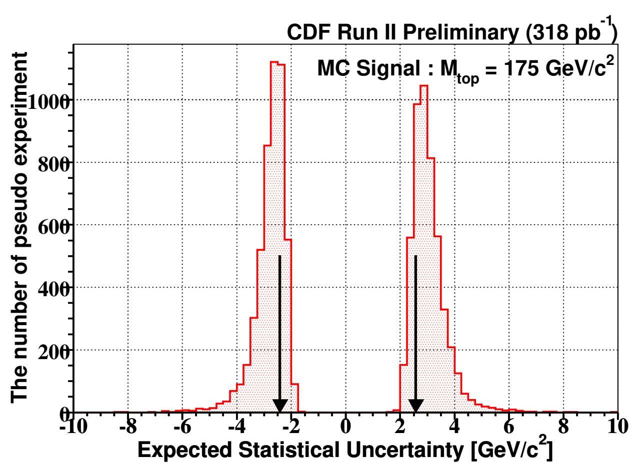



FIG. 4: The expected statistical errors from 63-event pseudo-experiments. The black arrows indicate those in the data.

The systematic uncertainties are summarized in Table II. The largest one comes from the uncertainty in the jet energy measurement, which includes calorimeter non-uniformity and absolute energy scale corrections. The uncertainty in the amount of a quark's energy that is deposited outside the jet cone is also taken into account. Initial and final state radiation uncertainties are estimated using PYTHIA samples for which the range of QCD parameters comes from studying Drell-Yan data. For the parton distribution functions, we added in quadrature uncertainties from two sources: the differences from the 20 pairs of CTEQ6M uncertainty eigenvectors($\pm\sigma$) and

MRST using two different $\alpha_s$ values. The sum in quadrature of all the systematic uncertainties is 3.2 GeV/c$^2$.

| Source | $\Delta$ M$_{top}$ GeV/c$^2$ |
|---|---|
| Jet Energy Corrections | 3.0 |
| Transfer Function | 0.2 |
| ISR | 0.4 |
| FSR | 0.5 |
| PDFs | 0.5 |
| Generator | 0.3 |
| Background fraction | 0.4 |
| Background modeling | 0.4 |
| $b$ jet energy modeling | 0.6 |
| $b$ tagging | 0.2 |
| Total | 3.2 |

TABLE II: The summary of systematic uncertainties

## IV. CROSS CHECKS

### A. Event by event comparison

We compare data and Monte Carlo for (1) the absolute likelihood and (2) the maximum likelihood mass. The signal likelihood for the $i$-th event is defined as

$$\boldsymbol{L}^i_{event} = \int L^i(M)dM. \tag{26}$$

where the integration is over the search region [155-195] GeV/c$^2$. We compare the log of the event likelihoods in the data and Monte Carlo samples in Figure 5(a). The expectation values for the simulation sample are normalized to the numbers in the data (53.8 events for signal, and combined background of 9.2 events).

Another check uses the event-by-event maximum likelihood mass. We use the maximum likelihood mass in each event which is shown in Figure 5(b).

## V. CONCLUSION

Using the dynamical likelihood method, we have measured the top quark mass to be $173.2^{+2.6}_{-2.4} \pm 3.2$ GeV/c$^2$, or $173.2^{+4.1}_{-4.0}$, from 63 events corresponding to an integrated luminosity of 318 $pb^{-1}$ accumulated by the CDF in Run II. This precision is better than the Run I world average.

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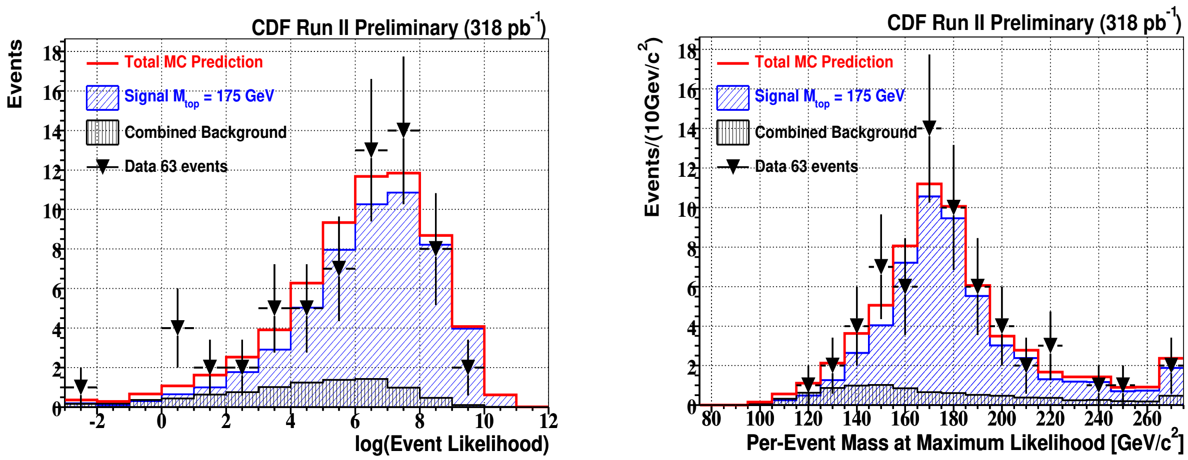


(a) Event likelihood distribution (b) Maximum mass distribution

FIG. 5: (a) Log of the integrated event likelihood distribution. The number of signal and background events is normalized to the number of observed events (63 events). Shaded blue is signal events and black is background, The red line corresponds to the combined Monte Carlo expectation. The triangles are the 63 data events. (b) The maximum likelihood mass distributions in data and Monte Carlo. The signal Monte Carlo sample is for $M_{top}$=175. The first(last) bin includes under(over)flow.

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