CDF note 9518

Measurement of the Mass of the Top Quark Using Partially Reconstructed Invariant Mass in Soft Muon b-tagged events.

The CDF Collaboration
URL http://www-cdf.fnal.gov
(Dated: September 12, 2008)

We present a measurement of the mass of the top quark, using the distribution of invariant mass between the lepton from the W decay and the muon from the semileptonic b-decay in candidate $t\bar{t} \to \ell^{\pm}\nu b\bar{b}jj$ events. Using a sample of ~ 2 fb^{-1} of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV, we fit the invariant mass distribution to template histograms derived from the modeling of the background and MC simulation of $t\bar{t}$ events and measure the top quark mass value of $181.3 \pm 12.4(\text{stat}) \pm 3.5(\text{syst})$ GeV$/c^2$.

Preliminary Results for Summer 2008 Conferences

Contact email: *lucio@fnal.gov*

I. INTRODUCTION

Measurements of the top quark mass with minimal dependence on the jet energy scale have previously been performed using the W lepton p_T and the b-decay length line-shapes [1]. These techniques aim at minimizing the dependence of the measurement on the jet energy precision calibration, and are of particular interest for large statistics sample of top quarks. In this context, we present the first measurement that uses as an observable the invariant mass between the lepton from the W decay and the muon from the semileptonic b-decay in candidate $t\bar{t} \rightarrow \ell^{\pm}\nu b\bar{b}jj$ events. Since this variable combines information from both the b and the W kinematics, the observable is naturally more sensitive to the top mass than the W lepton p_T only, although it is limited to a smaller sample due to the semileptonic decay branching ratio. The technique is similar to the one proposed in the context of the Large Hadron Collider experiments that would use the invariant mass of the W lepton and the $J/\Psi \rightarrow \mu\mu$ from B decays, but is not subject to the low branching fraction of J/Ψ production from B hadrons. It also does not require displaced vertex tracking in order to select the $t\bar{t}$ sample. The sensitivity to the top mass is reduced due to mis-pairing and background, both resulting in an increased statistical uncertainty.

II. DATA SAMPLE & EVENT SELECTION

We identify top quark events by the standard model decay $t \rightarrow Wb$, providing a final state from $t\bar{t}$ production that includes two W bosons and two bottom quarks. We select events where one of the W bosons decays to an isolated electron (muon) carrying large transverse energy, E_T (momentum, p_T) with respect to the beam line, plus a neutrino. We refer to these high-p_T electrons or muons as "primary leptons"(PL). The neutrino escapes the detector causing an imbalance of total transverse energy, referred to as "missing E_T"($\not\!\!E_T$) [2]. The other W boson in the event decays hadronically to a pair of quarks. The two quarks from the W boson, and the two b quarks from the top decays, hadronize and are observed as jets of charged and neutral particles. We take advantage of the semileptonic decay of B-hadrons to muons "soft-lepton tagging, or SLTμ"to identify final-state jets that result from hadronization of the bottom quarks expected in the top decay.

The CDF II detector is described in detail elsewhere [3]. The components relevant to this analysis include the silicon vertex detector, the central outer tracker (COT), the central electromagnetic and hadronic calorimeters, the central muon detectors and the luminosity counters. The data sample, produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV during Run II of the Fermilab Tevatron, was collected between March 2002 and May 2007. This analysis is based on an integrated luminosity of 2034 ± 120 pb^{-1}. Monte Carlo (MC) simulations of $t\bar{t}$ events are performed using `PYTHIA` (`v6.216` [4]) and `HERWIG` (`v6.510` [5]). The generators are used with the `CTEQ5L` [6] parton distribution functions (PDF). Modeling of b and c hadron decay is provided by `EvtGen` (`v9.1` [7]). Modeling of $W+$ jets production is performed using `ALPGEN` (`v2.1` [8]), coupled with `PYTHIA v6.326` for the shower evolution and `EvtGen` for the heavy flavor (HF) hadron decays. Single-top production is modeled with `MADEVENT` [9] with `PYTHIA` for the showering. Events are selected with an inclusive lepton trigger requiring an electron (muon) with $E_T > 18$ GeV ($p_T > 18$ GeV/c). Further selection requires that candidate PLs are isolated ($I < 0.1$ [10]) and have E_T (p_T) greater than 20 GeV with $|\eta| < 1.1$. The event must also have $\not\!\!E_T > 30$ GeV. Jets are identified using a cone algorithm [11] with a cone opening of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ and are constrained to originate from the $p\bar{p}$ collision vertex.

Muons inside jets are identified by matching the tracks of the jet, as measured in the COT, with track segments ("stubs") in the muon detectors. The distance between the extrapolated track and the muon chamber track segment depends upon muon multiple scattering and, at high p_T, intrinsic resolution of the drift chambers. A single quantity (L), with the distribution centered around zero and normalized by its expected width, is constructed using a parametrization of the matching resolutions directly measured from $J/\psi \rightarrow \mu^+\mu^-$, $Z \rightarrow \mu^+\mu^-$ and $W \rightarrow \mu\nu$ data [12]. Candidate tracks are identified as muons if $|L| < 3.5$, where the efficiency for identifying a muon plateaus at about 85%. Such a muon with $p_T > 3$ GeV/c and within $\Delta R < 0.6$ of a jet axis is an SLTμ. The probability of misidentifying a hadron as an SLTμ, denoted as the "mistag probability", is measured using a sample of pions, kaons and protons from D^* and Λ^0 decays. An SLTμ mistag probability look-up table is constructed as a function of the track p_T, η. The number of false tags predicted with the look-up table agrees to within 5% of the observation, in HF-suppressed jets of QCD multijets and $\gamma+$jet events [13]. To reduce background from di-muon resonances and double-semileptonic B hadron decays we remove events in which the muon PL and SLTμ are oppositely charged and have an invariant mass consistent with a Z, Υ or, irrespectively of the PL flavor, less than 5 GeV/c^2. Remaining cuts are as in [13]. The jet energies are corrected to account for variations of the detector response in η and time, calorimeter gain instability, non linearity of calorimeter energy response, multiple $p\bar{p}$ interactions in an event and for energy loss in un-instrumented regions, but are not corrected back to the parton energy. Finally, the $W+$jet dataset is partitioned according to the number of jets with $E_T > 20$ GeV and $|\eta| < 2.0$ in the event. The $t\bar{t}$ candidate sample consists of W candidate events with 3 or more jets, of which at least one contains an SLTμ. To reduce background from QCD production of W plus bosons with multiple jets, we require the total transverse energy [14] $H_T > 200$ GeV.

III. BACKGROUNDS

The composition of the $t\bar{t}$ candidate sample used in this analysis has been studied extensively in [13], where we have measured the production cross section for $p\bar{p} \to t\bar{t}$ at $\sqrt{s}$=1.96 TeV to be $8.7 \pm 1.1^{+0.9}_{-0.8} \pm 0.6$ pb. Table I summarizes the sample composition. The dominant source of background is due to W+jets events. Events without W bosons that enter the signal sample are typically QCD jet events where one jet has faked a high-p_T lepton, mismeasured energies produce apparent $\not{E}_T$ and an additional jet contains an SLTμ. A fraction of these events are from $b\bar{b}$ and $c\bar{c}$, where the primary lepton results from a semileptonic decay on one of the fragmenting heavy quark and the SLTμ from a semileptonic decay on the other.

CDF II Preliminary (2 fb^{-1})

Taggable Events	3707
W+light flavor	53.84±2.71
Wbb+Wcc+Wc	14.41±3.82
QCD multi-jet	7.05±1.52
$WW+WZ+ZZ$	1.88±0.30
$Z \to \tau\tau$	0.65±0.27
Drell-Yan	0.82±0.48
Single top	8.13±0.68
Total Background	86.8±5.6
Tagged Events	248
$t\bar{t}$ (measured)	161.2±5.6 (syst)

TABLE I: Composition of the $t\bar{t}$ candidates sample as determined in [13].

We compute the invariant mass between the primary lepton and the SLTμ of the $t\bar{t}$ candidate sample. No attempt is made to choose the correct pairing from the decay chain of the two top-quarks. The line-shape of the invariant mass between the W lepton and the SLTμ is given by the contribution of $t\bar{t}$ and background events. The invariant mass distribution of W+jets events is modelled with MC simulation, while for the non-W background we use events from the data themselves in the kinematic-region of I >0.15, $\not{E}_T$ >30 GeV, topologically close to the signal region. Single top events and the remaining backgrounds are also modelled with MC simulation. We check the background model in W+1,2 jet SLTμ-tagged events, and find the predicted distribution of invariant mass in agreement with the data to within the statistical uncertainty (Figure 1(a)).

IV. MEASUREMENT METHOD

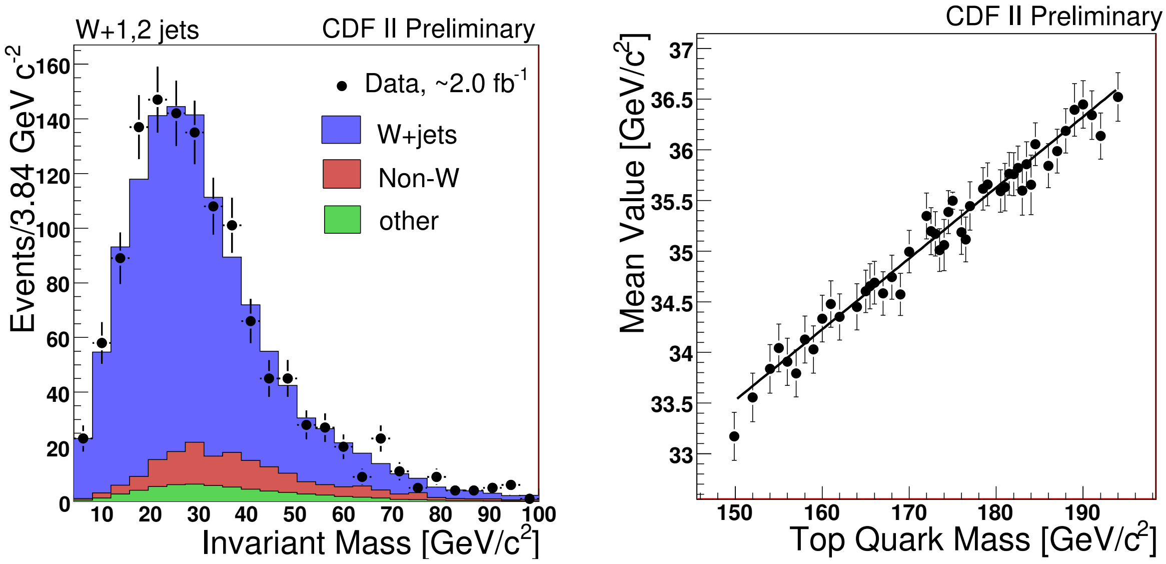
We perform a binned-likelihood fit of the invariant mass distribution from data, in the range 4–100 GeV/c^2, to a set of templates constructed using MC simulation of $t\bar{t}$ events. The $t\bar{t}$ samples are generated with different top quark mass values in the range 150–195 GeV/c^2, incrementing by steps of 0.5 GeV/c^2. The complete invariant mass distributions are determined by adding the expected signal and background histograms. Figure 1(b) shows the mean value of the distributions versus the input top quark mass. The likelihood is defined as:

$$-lnL(m_t) = -\sum_{i=1}^{\text{nbin}} n_i^{\text{data}} \ln \frac{n_i^{\text{MC}}(m_t)}{n_{\text{tot}}^{\text{MC}}} \equiv -\sum_{i=1}^{\text{nbin}} n_i^{\text{data}}\ ln[p_i(m_t)], \tag{1}$$

where $n_{\text{tot}}^{\text{MC}} = n_{\text{tot}}^{\text{data}}$, therefore $p_i(m_t)$ is the probability of the i-th bin and $\sum_i p_i = 1$. The background normalization is fixed and is varied in the evaluation of the systematic uncertainty. The measured top quark mass mass is calculated at the minimum of the likelihood function, and its uncertainty is determined from the values corresponding to 1/2 units above the minimum.

V. SYSTEMATIC UNCERTAINTIES

The sources of systematic uncertainty considered that affect the measured value of the top quark mass are summarized in Tab. II. The limited size of the MC samples at different input top quark mass determines an uncertainty of



(a) (b)

FIG. 1: (a): The distributions of predicted and observed invariant mass in the sample of W+1,2 jet SLTμ-tagged events. (b): The correlation between the mean value of the Monte Carlo generated signal+background invariant mass histograms and the input top quark mass.

± 0.3 GeV/c^2. Several components enter the uncertainty on the modeling of the background: the uncertainty on the W plus heavy and light flavor relative normalizations yields an uncertainty of $\Delta m_t = \pm 0.8$ GeV/c^2. The uncertainty on the shape of the W+jets histogram is evaluated by varying the distribution, to within the statistical accuracy associated with the comparison in the W+1,2 jets sample between the data and the background model, and yields an uncertainty of ± 1.4 GeV/c^2. The normalization of the non-W background contributes $\Delta m_t = \pm 0.1$ GeV/c^2 and the shape of the non-W distribution accounts for $\Delta m_t = \pm 0.3$ GeV/c^2, as determined by replacing the anti-isolated sample with data selected with $I < 0.1$ and $\not{E}_T$ <15 GeV. For the remaining backgrounds the uncertainty on the measured top mass is negligible. Finally, an additional uncertainty is due to the uncertainty on the overall background normalization, and accounts for a shift on m_t of ± 0.8 GeV/c^2. Monte Carlo modeling of the signal invariant mass distributions includes effects of PDFs, initial-state radiation (ISR), final-state radiation (FSR), and jet energy scale. The uncertainty due to the MC modeling of $t\bar{t}$ production and decay is determined by comparing the standard MC with a simulation using `HERWIG` and gives $\Delta m_t = \pm 2.1$ GeV/c^2. The PDF uncertainty is evaluated by varying the PDF according to the 20 CTEQ eigenvectors [15] added in quadrature with the difference between the CTEQ5L PDF used for the standard MC with that obtained using MRST in the default configuration and with two alternate choices for α_s. The three contributions in quadrature yield an uncertainty on the measured mass of ± 1.0 GeV/c^2 from PDF. The uncertainty due to the limited knowledge of ISR is constrained by studies of radiation in Drell-Yan events in the data. We vary both ISR and FSR in the $t\bar{t}$ Monte Carlo within the allowed range and add the deviations in quadrature. The systematic uncertainty due to this effect is ± 1.3 GeV/c^2. The calibration of the jet energies enters the measurement through the event selection. The uncertainty due to the jet energy scale is measured by shifting the energies of the jets in $t\bar{t}$ MC by $\pm 1\sigma$ of the jet energy scale [16] and results in $\Delta m_t = \pm 0.3$ GeV/c^2. The uncertainty of $\pm 1\%$ on the difference between data and MC of the W lepton energy and momentum scales determines an uncertainty of ± 0.9 GeV/c^2 on m_t. The differences in the data versus MC for the SLTμ p_T spectrum depends on the b-quark fragmentation modeling and the momentum calibration. Comparisons of the muon p_T spectra in $B \to \mu^- D^0 X$ [17] and $b\bar{b}$ [18] indicate an uncertainty of $\sim$0.8%, corresponding to $\Delta m_t = \pm 0.9$ GeV/c^2. An additional contribution is due to the uncertainty on the SLTμ tagging efficiency and yields a shift of the top mass of ± 0.2 GeV/c^2. Finally, an additional source of systematic uncertainty is due to the modeling of pile-up events from multiple $p\bar{p}$ interactions and is estimated to affect the measured mass by $\leq \pm 0.5$ GeV/c^2, as determined by comparing in the MC events with a large number of z-vertices. Overall, the systematic uncertainties are largely limited by the statistics of the data or the MC samples.

CDF II Preliminary (2 fb^{-1})	
Source	Δm_t [GeV/c^2]
Linearity	± 0.3
Background modeling	± 1.8
Lepton energy/momentum scale	± 0.9
SLTμ momentum	± 0.9
MC modeling	± 2.1
JES	± 0.3
PDFs	± 1.0
ISR/FSR	± 1.3
Pileup	± 0.5
Total	± 3.5

TABLE II: Summary of systematic uncertainties

VI. RESULTS

From 240 $t\bar{t}$ candidate events with invariant mass of the SLTμ and primary lepton in the window considered, the likelihood fit returns the best value of the top quark mass:

$$m_{\rm top} = 181.3 \pm 12.4({\rm stat}) \pm 3.5({\rm syst})\ {\rm GeV}/c^2, \tag{2}$$

Figure 2 shows the invariant mass distribution, the best fit, and the likelihood profile.

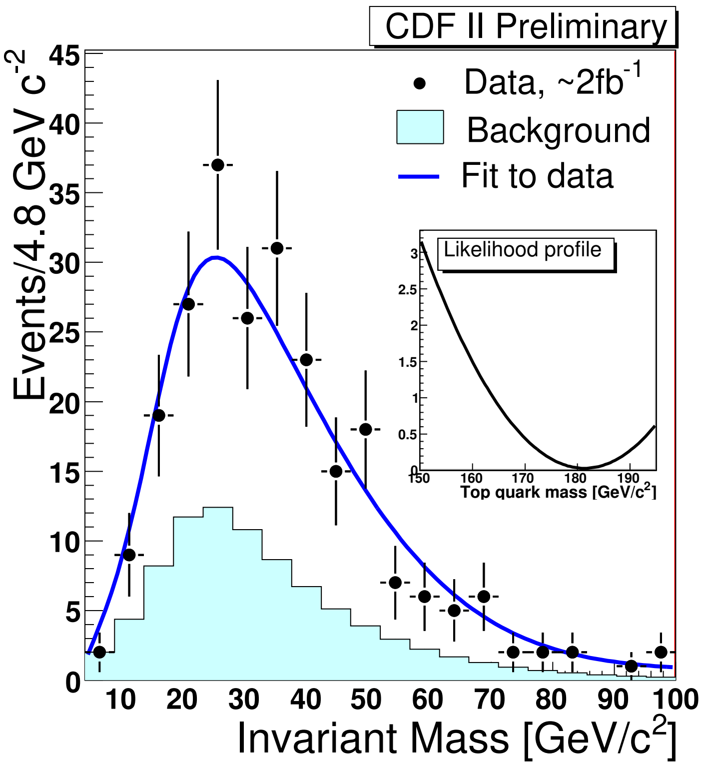


FIG. 2: The invariant mass distribution of the data, the best fit and the likelihood profile.

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.

[1] A. Abulencia *et al* (CDF Collaboration), Phys. Rev. D **75**, 071102(R) (2007).
[2] We use a (z, ϕ, θ) coordinate system where the z-axis is in the direction of the proton beam, and ϕ and θ are the azimuthal and polar angles respectively. The pseudo-rapidity is $\eta \equiv -\ln(\tan\frac{\theta}{2})$. Transverse energy and momentum are $E_T \equiv E\sin\theta$ and $p_T \equiv p\sin\theta$ respectively, where E and p are energy and momentum. The missing transverse energy is $\not{E}_T \equiv |-\sum_i E_T^i \hat{n}_i|$, where E_T^i is the magnitude of the transverse energy contained in each calorimeter tower i in the region $|\eta| < 3.6$, and $\hat{n}_i$ is the direction unit vector of the tower in the plane transverse to the beam direction.
[3] F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res. A **271**, 387 (1988); D. Amidei *et al.*, Nucl. Instum. Methods Phys. Res. A **350**, 73 (1994); F. Abe *et al.*, Phys. Rev. D **52**, 4784 (1995); P. Azzi *et al.*, Nucl. Instrum. Methods Phys. Res. A **360**, 137 (1995); The CDFII Detector Technical Design Report, Fermilab-Pub-96/390-E; D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).
[4] T. Sjostrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).
[5] G. Corcella *et al.*, J. High Energy Phys. **01**, 010 (2001).
[6] H. L. Lai *et al.*, Eur. Phys. J. C **12**, 375 (2000).
[7] D. Lange, Nucl. Instrum. Methods Phys. Res. A **462**, 152 (2001).
[8] M. L. Mangano *et al.*, J. High Energy Phys. **07**, 001 (2003).
[9] F. Maltoni and T. Stelzer, J. High Energy Phys. **02**, 27 (2003).
[10] The isolation (I) is defined as the calorimeter transverse energy in a cone of opening $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the lepton (not including the lepton energy itself) divided by the lepton E_T or p_T.
[11] A. Bhatti *et al.*, Nucl. Instrum. Methods Phys. Res. A **566**, 375 (2006).
[12] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **72**, 032002 (2005).
[13] The CDF Collaboration, Conference note 9304 (2008), in preparation for publication on Physical Review D.
[14] H_T is defined as the scalar sum of the electron (muon) E_T (p_T), $\not{E}_T$ and jet E_T for jets with $E_T > 8$ GeV and $|\eta| < 2.4$.
[15] H. L. Lai *et al.*, Eur. Phys. J. C **12**, 375 (2000).
[16] A. Bhatti et al., Nucl. Instrum. Methods Phys. Res. **566**, 375 (2006).
[17] The CDF Collaboration, *Measurement of the b hadron Production Cross Section Using Decays to* $\mu^- D^0 X$ *Final States in* $p\bar{p}$ *Collisions at* $\sqrt{s} = 1.96\,TeV$ (2008), note 8890(2008) and J.A. Kraus, Ph.D. thesis, University of Illinois (2006).
[18] T. Aaltonen *et al* (CDF Collaboration), Phys. Rev. D **77**, 072004 (2008).