Top Quark Mass Measurements at CDF

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Recent measurements of the mass of the top quark (t) are presented using $162\,\text{pb}^{-1}$ of data of $p\overline{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$ collected by the CDF detector at the Tevatron collider during Run II. The analyses focus on the semi-leptonic decay mode $t\bar{t} \rightarrow (bl\nu)(\bar{b}q\bar{q})$ with one or two identified bottom quarks (b). The Template Method (TM) reconstructs the invariant mass of the top quark in each event. The Multivariate Template Method (MTM) enhances this approach by adding information on the event topology. The Dynamical Likelihood Method (DLM) discriminates between possible mass values using top quark decay observables and attempts to use the maximum amount of information on top quarks provided by the Standard Model. All three methods produce similar results. The Dynamical Likelihood Method yields a top quark mass of $177.8^{+4.5}_{-5.0}\,(\text{stat}) \pm 6.2\,(\text{sys})\,\text{GeV}/c^2$.

1. INTRODUCTION

The first experimental observation of the top quark (t) by the CDF and DØ collaborations at the Tevatron about ten years ago [1] represented an impressive confirmation of the Standard Model (SM) and marked the beginning of a successful top quark physics program at the Tevatron. Properties of the top quark were first investigated using $110\,\text{pb}^{-1}$ of data at $\sqrt{s} = 1.8\,\text{TeV}$ collected in the Run I period between 1992 and 1996. The top quark mass, m_t, was measured in all decay topologies (*e.g.* [2,3]) arising from $p\overline{p} \rightarrow t\bar{t}X$ final states. After a recent reanalysis of DØ Run I data [4], the collaborations updated the combined Run I value to $m_t = 178.0 \pm 4.3\,\text{GeV}/c^2$ [5].

The precise knowledge of m_t is of great interest for particle physics. It is a fundamental parameter of the SM, but more importantly, the extremely high mass gives the top quark particular relevance in the calculation of other SM parameters. Electroweak corrections to the W propagator introduce a quadratic dependence on the W boson mass m_W and a logarithmic dependence on the mass of the long-hypothesized but still unobserved Higgs boson, m_H. With the current precision level of 2.5% for m_t and < 0.1% for m_W, the most likely value for m_H obtained from global SM fits is $m_H = 114^{+69}_{-45}\,\text{GeV}/c^2$, and the upper 95% CL limit is $260\,\text{GeV}/c^2$ [5]. A more accurate determination of m_t would provide the opportunity for stringent consistency tests of the SM.

The precision measurement of the top quark mass is therefore a very active topic in the current physics program of CDF in Run II. The upgraded Tevatron complex started in 2001, producing $p\overline{p}$ collisions at $\sqrt{s}=1.96\,\text{TeV}$ with steadily increasing instantaneous luminosities up to a record of $\sim 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$ (as of the time of this report). The higher collision energy led to an increase of the SM production $t\bar{t}$ cross-section of 35% [6]. The CDF detector [7] underwent substantial improvements in the geometrical acceptance of the tracking and calorimeter systems as well as of the silicon vertex detector which is crucial for the identification of B-hadrons from t decays.

All $t\bar{t}$ decay modes are being investigated intensively. Here we report on three recent CDF measurements of m_t in the lepton plus jets channel using $162\,\text{pb}^{-1}$ data collected between March 2002 and September 2003.

2. EVENT SELECTION

According to the Standard Model, top quarks at the Tevatron are mainly produced in pairs through quark-anti-quark annihilation (85%) or gluon-gluon fusion (15%), followed by a prompt decay $t \rightarrow Wb$ with a branching ratio BR$\sim$ 100%. The subsequent W decays define the event signature. In the decay mode studied here, one W decays into two quarks, and the other W decays into

an electron (e) or a muon (μ) and the corresponding neutrino (ν). This channel has a manageable signal to background ratio $S/B \sim \mathcal{O}(1)$ and a satisfactory $BR \sim \frac{8}{27}$ that is viewed as a good compromise between all available decay modes.[1]

The final state has a spherical topology due to $t\bar{t}$ production near threshold and is characterized by four jets, one charged lepton with high transverse energy ($E_{\rm T}$), and a sizable amount of missing transverse energy ($\not{E}_T$) due to the undetectable ν. Top quark candidate events are selected by requiring exactly one isolated e or μ with $E_{\rm T} > 20\,{\rm GeV}$ and $\not{E}_T > 20\,{\rm GeV}$. Furthermore, at least three jets with $E_{\rm T} > 15\,{\rm GeV}$ and one jet with $E_{\rm T} > 8\,{\rm GeV}$ have to be present. The DLM analysis (explained below) requires exactly four jets with $E_{\rm T} > 15\,{\rm GeV}$. The jets must lie in the pseudo-rapidity region $|\eta| < 2$ so that they are well measured by the detector. Finally, one or two displaced secondary vertices (originating from the decay of long-lived B-hadrons) are identified by the silicon vertex detector ("b-tags"). This requirement improves the sample purity by a factor of 3-4 compared to the non-b-tagged case.

Dominant background sources are $Wb\bar{b}$ and $Wc\bar{c}$ final states, non-W QCD processes and events where one jet is misidentified as a b-jet. Minor sources of background are WW/WZ, Wc and single top quark ($t\bar{b}$) events.

3. TOP MASS MEASUREMENTS

3.1. Template Method (TM)

This method closely follows the traditional mass measurement strategy in Run I. To get the momenta of the daughter particles of the assumed initial $t\bar{t}$ configuration, the raw jet energies are corrected for detector effects and artifacts due to the limited jet cone size, as well as for hadronization and for various non-$t\bar{t}$ contributions of the same event. One part of the corrections are directly derived from the data, another part is derived using a Herwig $t\bar{t}$ Monte Carlo [8] and a simulation of the CDF detector. The analysis treats the four leading $E_{\rm T}$ jets as quark jets from the $t\bar{t}$ system. The event reconstruction is complicated

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[1] The *dilepton mode* (with e or μ) has $S/B \sim 10$, $BR \sim \frac{4}{81}$, the *all-hadronic* mode has $S/B < \frac{1}{10}$, $BR \sim \frac{4}{9}$.
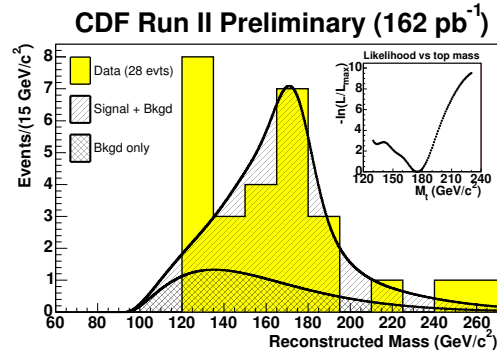

Figure 1. Reconstructed top quark mass data compared with the combined signal plus background fit.

by the combinatorial problem of correctly assigning these jets to the four initial partons, yielding six (two) solutions ("permutations") for the single (double) b-tag case. The number of solutions double because of the twofold ambiguity of the longitudinal component of the ν momentum.

For each configuration, an invariant top quark mass is reconstructed by minimizing a χ^2 expression calculated using the transverse momenta of the jets, the charged lepton, and the missing energy. The χ^2 takes into account the detector resolution as well as the decay widths of the t and the W, and also incorporates various kinematic constraints (e.g. $m_t = m_{\bar{t}}$, $M_{W^+} = M_{W^-}$). The solution with the smallest χ^2 value is taken as the "reconstructed top mass" of the candidate event. This quantity is used to build templates for signal Monte Carlo samples with varying generated m_t but also for various background samples. The signal templates are parametrized by continuous functions of m_t. The templates serve as probability densities to be compared with the data in order to derive a top quark mass probability for each event. The most likely value for m_t is extracted using an unbinned likelihood fit that maximizes the joint probability density (= product of all event-by-event probability densities) for the whole sample of reconstructed masses. It also includes a background fraction constraint.
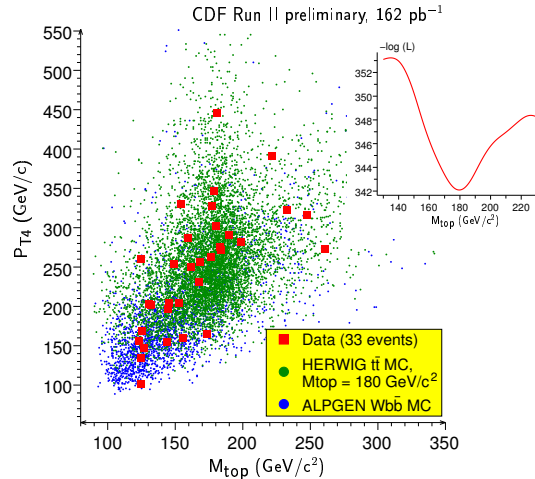
With a sample of 28 candidate events (Fig. 1) and 6.8 ± 1.2 expected background events [9] the method yields $m_t = 174.9^{+7.1}_{-7.7}(\text{stat}) \pm 6.5(\text{sys})\,{\rm GeV}/c^2$. The systematic error is dominated by uncertainties of the jet energy scale ($\pm 6.3\,{\rm GeV}/c^2$) which mainly arises from the cal-
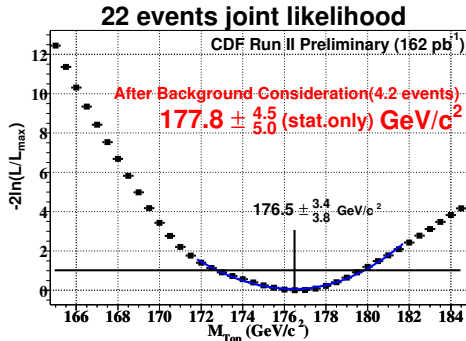
22 events joint likelihood

Figure 3. DLM joint negative log likelihood.

the four jet configuration using transfer functions $w(\mathbf{x}, \mathbf{y}; m_t)$ (TF). These are Bayesian probabilities that a $t\bar{t}$ parton configuration $\mathbf{x}$ with a given m_t was generated when $\mathbf{y}$ was reconstructed. The TFs are functions of $(E_T^{\text{parton}} - E_T^{\text{jet}})/E_T^{\text{parton}}$ and parametrized in jet E_T and η bins. They are calculated for W or b jets separately using a Herwig $t\bar{t}$ MC for a fixed top quark mass. DLM performs some of the jet corrections like TM and MTM (*e.g.* relative calorimeter response, calorimeter to particle correction), while it handles the transition from partons to particles via TFs.

The likelihood function $L^{(i)}$ sums up *all* permutations and neutrino solutions. The most likely top quark mass is obtained by maximizing $\Pi_i L^{(i)}(m_t)$. The joint negative log likelihood curve extracted from a sample of 22 selected events is shown in Fig. 3. It should be noted that the likelihood considers only the signal but not the background matrix elements. The background contribution is hence minimized by requiring exactly four jets. Residual background effects, but also the top quark mass dependence of the TFs, are taken into account by applying an MC based correction ("mapping" function) to the maximum likelihood mass. Using 4.2 ± 0.2 expected background events, this method yields $m_t = 177.8^{+4.5}_{-5.0}(\text{stat}) \pm 6.2(\text{sys}) \, \text{GeV}/c^2$.

4. SUMMARY AND OUTLOOK

Three recent CDF measurements of the top quark mass have been performed in the $t\bar{t}$ lepton plus jets channel using $162 \, \text{pb}^{-1}$ of Tevatron Run II data. The results are $m_t = 174.9^{+7.1}_{-7.7}(\text{stat}) \pm 6.5(\text{sys}) \, \text{GeV}/c^2$ (TM), $m_t =$

$179.6^{+6.4}_{-6.3}(\text{stat}) \pm 6.8(\text{sys}) \, \text{GeV}/c^2$ (MTM), and $m_t = 177.8^{+4.5}_{-5.0}(\text{stat}) \pm 6.2(\text{sys}) \, \text{GeV}/c^2$ (DLM).[2] The systematic error is dominated by jet energy uncertainties. MTM allows for optimal trading of statistical and systematic errors and will be more powerful at higher accumulated luminosity. The DLM result has a considerably less statistical uncertainty than the other methods and is competitive with the best CDF Run I measurement [2].

Tevatron is performing well and is expected to provide $400 \, \text{pb}^{-1}$ by the end of 2004, $1 \, \text{fb}^{-1}$ by the end of 2005, and 4.4-$8.5 \, \text{fb}^{-1}$ by the end of Run II, thus leading to a significant improvement of the statistical error. A priority is the reduction of the jet energy systematics. The stated CDF goal for the total error is $3 \, \text{GeV}/c^2$. Substantial progress is expected soon, *e.g.* due to recent developments in the calorimeter simulation. Furthermore there is a big potential to refine the analyses. Through these measurements, CDF has established techniques that will provide a precise determination of the top quark mass in the future.

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[2] The results are consistent with an updated CDF measurement in the dilepton channel reported after this conference: $m_t = 176.5^{+17.2}_{-16.0}(\text{stat}) \pm 6.9(\text{sys}) \, \text{GeV}/c^2$.