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Top Quark Mass Measurements at the Tevatron

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Abstract. We present two new measurements of the top-quark mass. Using the same methodology applied in Run I, the CDF experiment uses 72 pb^{-1} of Run II data to measure $M_{top} = 171.2 \pm 13.4_{stat} \pm 9.9_{syst}$ GeV/c^2. On the other hand, the DØ experiment, using 125 pb^{-1} from Run I, and appling a new method that extracts information from data through a direct calculation of a probability for each event, obtains $M_{top} = 180.1 \pm 3.6_{stat} \pm 4.0_{syst}$ GeV/c^2.

INTRODUCTION

In proton-antiproton collisions at Tevatron energies, top quarks are produced primarily in pairs, either via $q\bar{q}$ or gg fusion. At the Tevatron, the main contribution to the $t\bar{t}$ yield is from $q\bar{q}$ annihilation. This is purely the result of the fact that the parton distribution functions (PDFs) favor this channel at Run I $\sqrt{s}$=1.8 TeV and Run II $\sqrt{s}$=1.96 TeV. In fact, about 90% of the top quarks are produced through the quark interaction.

The top quark is detected indirectly via its decay products. It decays via the weak interaction, and according to the Standard Model is almost always expected to decay to a b quark and a W boson. This is followed by the W decaying into two quarks or a lepton and a neutrino. The final state of the $t\bar{t}$ system has different topological classifications that depend on the decay of the W. The results presented here use the lepton+jets channel, and corresponds to one W decaying leptonically (into a electron or a muon), while the other W decays hadronically. This channel has a branching fraction of about 30%.

Although its value is not predicted, M_{top} is a fundamental parameter in the Standard Model. The best value of the top quark mass found from combining all channels at the Tevatron is [1],

$$M_{top} = 174.3 \pm 5.1 \ \mathrm{GeV/c^2} \tag{1}$$

The top quark mass, along with the mass of the W boson, provides through radiative corrections the best indication for the value of the mass of the Higgs boson [2]. The measurement of M_W will improve significantly in the future, with an uncertainty of 27 GeV/c^2 being a realistic goal for Run II of the Tevatron. To be able to make maximum use of this precision measurement to constrain the mass of the Higgs, the top mass should be measured with an uncertainty of less than 3 GeV/c^2. This will yield a prediction for the Higgs mass with an uncertainty of 40%. It is therefore important to develop techniques for extracting the mass of the top quark that will optimize the use of the Run II data.

CDF RUN II TOP-QUARK MASS MEASUREMENT

This is the first measurement of the top-quark mass using data from Run II of the Tevatron. The luminosity in this analysis corresponds to 72 pb^{-1}. The selection criteria applied and the method used to extract the top quark mass are the same as in the previous analysis of Run I data [3]. The selection criteria consist of requiring one isolated high-p_T electron or muon, $\not{E}_T$ >20 GeV, E_T^{jets} >15 GeV and $|\eta^{jets}|$ <2, which reduces the sample to 33 candidates.

A constrainted fitting technique is employed to reconstruct the mass of the top quark, requiring $M_{l\nu} = M_W$, $M_{jj} = M_W$;$M_{top} = M_{\bar{top}}$. The inability to identify uniquely the four jets in the lepton+jets channel results in 12 posibilities to reconstruct the event. Since the longitudinal momentum of the neutrino is not known, every combination can have two possible solutions for the neutrino p_z. After the constrained fit, the combination with lowest χ^2 is chosen as a measure of the top mass. These reconstructed top masses are compared to parameterized templates of top and background Monte Carlos. The top mass is extracted using a maximum likelihood method comparing the data and template distributions. The top mass obtained (see Figure 1) is :

$$M_{top}(preliminary) = 171.2 \pm 13.4_{stat} \pm 9.9_{syst} \text{ GeV/c}^2 \tag{2}$$

The systematic error is dominated by the uncertainty on the jet energy. CDF aims to reduce this error to ≈2 GeV/c^2.

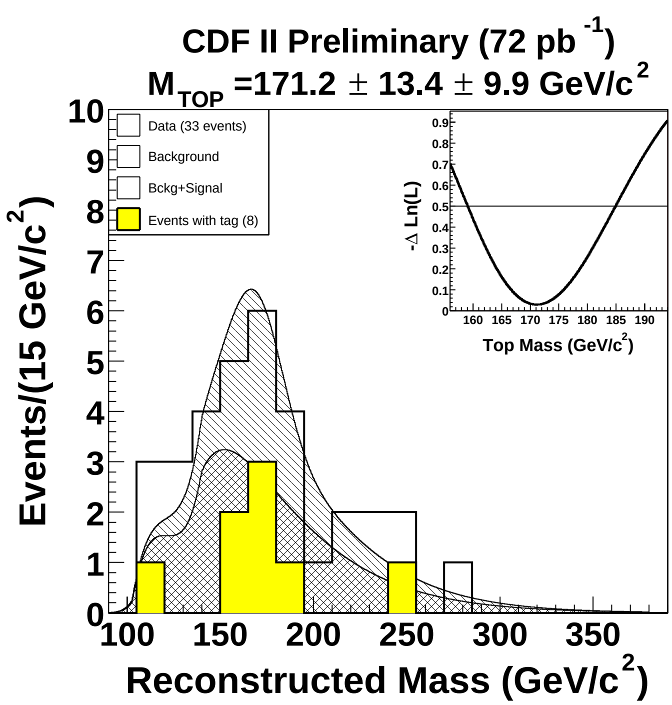

FIGURE 1. Mass of the top quark using lepton+jets events from Run II data. The white histogram consists of 33 events. The filled histogram is a subsample where at least one of the jets has been b-tagged. (This information is not used in reconstructing the top mass).

NEW DØ RUN I TOP-QUARK MASS MEASUREMENT

This is a preliminary measurement of the mass of the top quark using a method that compares each individual event with the differential cross section for $t\bar{t}$ production and decay. This method is similar to that suggested for $t\bar{t}$ dilepton decay channels, and used in previous mass analyses of dilepton events [4, 5]. The luminosity used in this analysis corresponds to 125 pb^{-1}, and the data was accumulated by the DØ experiment during Run I of the Tevatron. This analysis is based on the same sample that was used to extract the mass of the top quark in the previous publication [6]. A set of selections was introduced to improve acceptance for lepton+jets from $t\bar{t}$ relative to background. The standard requirements were: $E_T^{lepton} > 20$ GeV, $|\eta_e| < 2$, $|\eta_\mu| < 1.7$, $E_T^{jets} > 15$ GeV, $|\eta_{jets}| < 2$, $\not{E}_T > 20$ GeV, $|E_T^{lepton}| + |\not{E}_T| > 60$ GeV, and $|\eta_{lepton+\not{E}_T}| < 2$. A total of 91 events remained after these selections.

The $t\bar{t}$ production probability is calculated as:

$$P_{t\bar{t}} = \frac{1}{12\sigma_{t\bar{t}}} \int d\rho_1 dm_1^2 dM_1^2 dm_2^2 dM_2^2 \sum_{\text{perm.},\nu} |\mathscr{M}_{t\bar{t}}|^2 \frac{f(q_1)\,f(q_2)}{|q_1||q_2|} \Phi_6 W_{jet}(E_y, E_x) \tag{3}$$

where $|\mathscr{M}_{t\bar{t}}|^2$ is the leading-order matrix element, $f(q_1)$ and $f(q_2)$ are the CTEQ4M parton distribution functions for the incident quarks, Φ_6 is the phase-space factor for the 6-object final state, and the sum is over all 12 permutations of the jets (the permutation of the jets from W decay was performed by symmetrizing the matrix element), and all possible longitudinal momenta of the neutrino solutions. The integration variables used in the calculation are the top masses ($m_{1,2}$), the W masses ($M_{1,2}$), and the energy of one of the jets (ρ_1). Observed electron momenta are assumed to correspond to those of produced electrons. The angles of the jets are also assumed to reflect the angles of the partons on the final state, and we ignore any transverse momentum for the incident partons. $W_{jet}(E_y, E_x)$ corresponds to a transfer function that parameterizes the mapping between parton-level energies E_y and energies measured in the detector E_x. A large Monte Carlo sample of $t\bar{t}$ events (generated with masses between $140-200$ GeV in HERWIG [7], and processed through the DØ detector-simulation package) is used to determine $W_{jet}(E_y, E_x)$. For a final state with a muon, W_{jet} is expanded to include the known muon momentum resolution, and an integration over muon momentum is added to Eq. 3. Effects such as geometrical acceptance, trigger efficiencies, event selection, etc, are taken into account through a multiplicative function $A(x)$ that is independent of M_{top}. This function relates the production probability $P(x; M_{top})$ to the measured probability $P_m(x; M_{top})$: $P_m(x; M_{top}) = A(x)P(x; M_{top})$. All processes that can contribute to the observed final state must be included in the probability. Therefore the final probability is written as $c_1 P(x; M_{top}) + c_2 P_b(x)$. The VECBOS [8] W+jets matrix element is used to calculate the background probability, which is integrated over the four jet energies and the W-boson mass, and later summed over the 24 jet permutations and neutrino solutions.

Since the method involves a comparison of the data with a leading-order matrix element for the production and decay process, the sample is restricted to only four jets events, thereby reducing the sample to 71 events. In order to increase the purity

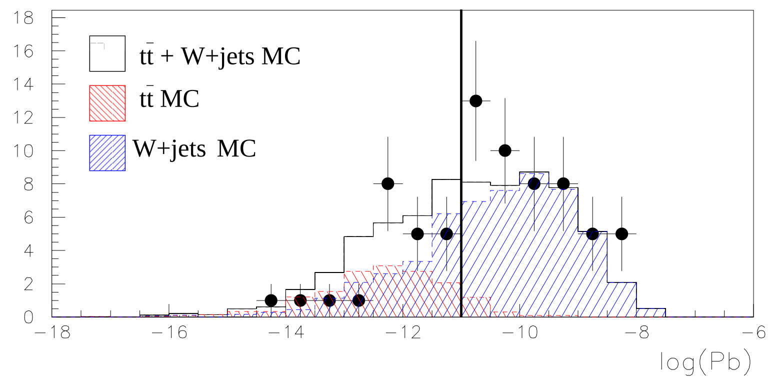

FIGURE 2. Distribution for probability of events being background. The data (dots) is compared with the results expected from MC-simulated samples (solid histogram). Only events which have $P_b < 10^{-11}$ are used in this analysis.

of tne signal, a selection in the background probability, $P_b < 1.10^{-11}$, is applied. This selection is required to minimize a bias introduced by the presence of background, and its imposition leaves a sample of only 22 events. Figure 2 shows a comparison between the probability for a background interpretation of events calculated for a sample of Monte Carlo events (solid histogram) and for the 71 $t\bar{t}$ candidates (data points). The left-hatched (right-hatched) histogram shows the contribution from $t\bar{t}$ (W+4 jets) MC events. The probabilities are inserted into a likelihood function for N observed events, which compares the Standard-Model prediction with the data. The best estimate of M_{top} is obtained by maximizing this likelihood function. Figure 3a) shows the value of -ln$L$ as a function of M_{top} for the 22 events that pass all the selection criteria, 12 of which are signal and 10 background. ($-lnL$ was minimized with respect to the parameters c_1 and c_2 at each mass point.) Figure 3b) shows the likelihood normalized to its maximum value. The Gaussian fit in the figure yields M_{top}=179.6 GeV/c^2, and an uncertainty δM_{top}=3.6 GeV/c^2. Monte Carlo studies show that there is a shift to 0.5 GeV/c^2 in the extracted mass. Applying this shift the new result yields:

$$M_{top}(preliminary) = 180.1 \pm 3.6(\text{stat}) \pm 4.0(\text{syst})\ \text{GeV/c}^2 \quad (4)$$

The main systematic uncertainties are due to the jet-energy scale (3.6 GeV/c^2), model for $t\bar{t}$ (1.5 GeV/c^2), model for background (1.0 GeV/c^2), noise and multiple interactions (1.3 GeV/c^2), parton distribution functions (0.2 GeV/c^2), and acceptance corrections (0.5 GeV/c^2).

CONCLUSIONS

Measuring the top quark mass with an uncertainty of less than 3 GeV/c^2 is important to restrict the mass of the Higgs boson. With the new data and improved techniques, this appears to be a realistic goal. CDF has made the first attempt to measure the top mass using Run II data. Meanwhile, DØ developed a method to maximize the use of

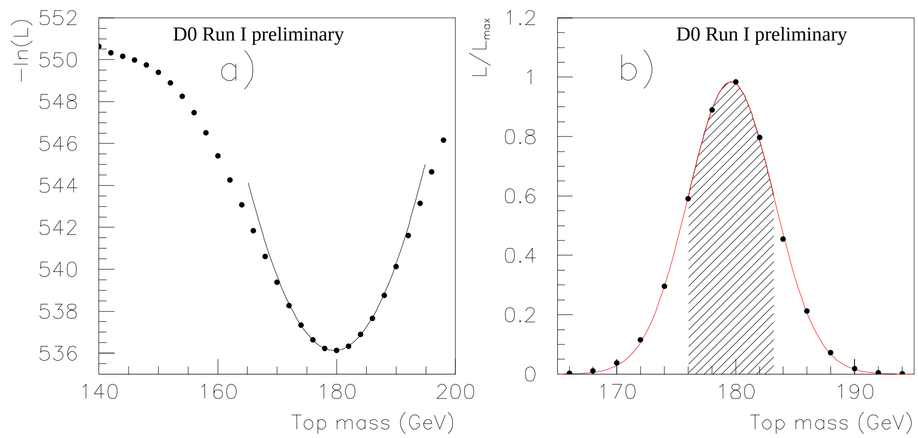

FIGURE 3. a) Negative of the log of the likelihood as a function of the mass of the top quark for the 22 $t\bar{t}$ candidates in our final sample. b) Likelihood normalized to the maximum value. The curves are Gaussian fits to the likelihood plot b). The hatched area corresponds to the 68.27% probability interval.

information in each event to reduce the uncertainty on the top mass. Applying this method to Run I data, yields a result with an error comparable to all previous DØ and CDF measurements of the mass of the top quark combined.

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