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Top Quark Mass and Properties at DØ

An optimized Method to extract Top Quark Properties

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Abstract. DØ has developed an optimized method to extract information on top quark properties. An Extended–Maximum–Likelihood method is used, where the event probabilities are obtained by convoluting the differential cross section with the resolution and acceptance of the detector. This method is used to remeasure the top quark mass in the lepton + jets $t\bar{t}$ sample collected by the DØ experiment during Run 1 of the Fermilab Tevatron. A new preliminary measurement of the top quark mass of $M_t = 180.1 \pm 3.6(\text{stat}) \pm 4.0(\text{sys})\,\text{GeV}$ is obtained, corresponding to a significant reduction in uncertainty on M_t. The method used can also be applied to other properties of the top quark, such as the polarization of the W's in top decays.

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1 Introduction

The discovery of the top quark is one of the major confirmations of the Standard Model of particle physics [1,2]. Together with the mass of the W boson, its mass serves as an input to fits to electroweak precision data and gives an indication for the value of the hypothesized Higgs boson [3,4]. M_W is known to a precision of $< 0.1\,\%$, while the uncertainty on M_t is at the $3\,\%$ level [3]. To improve the measurement of M_t, it is important to develop methods and techniques to extract the mass of the top quark in the most precise way.
At the current time, apart from its mass and pair production cross section, only few properties of the top quark are known. These include its charge, spin, properties of the decay products, and top-antitop spin correlations. In view of the current Run 2 of the Tevatron accelerator, it is also important to consider techniques to measure additional top quark properties.

2 Optimized Method

This paper describes an optimized method to extract top quark properties in the lepton+jets final state. The technique is similar to that suggested for dilepton decay channels [5], and was used in the previous mass analyses of dilepton events [6]. The method is an event based likelihood and has the advantage that it not only considers all permutations of jet-parton assignments and neutrino solutions, but also takes into account all reconstructable kinematic information of each event, instead of comparing distributions of selected variables to expected distributions derived from Monte Carlo simulations [7]. This method is described in detail in [8].

2.1 General Principle

Given N observed events, an unknown quantity α of the observed physics process e.g. M_t, can be deduced by maximizing the likelihood

$$L(\alpha; x_1 \ldots x_N) = e^{-N \int P_m(\alpha;x)dx} \prod_{i=1}^{N} P_m(\alpha; x_i) \qquad (1)$$

where x is the set of objects (leptons, jets) reconstructed in the event and P_m is the probability of measuring that event. This probability has to be related to the probability to produce an event with these kinematic quantities. This can be done by a multiplicative factor $A(x)$ which describes the acceptance (geometrical, trigger efficiency, event selection,...), which is independent of α. In addition, effects of smearing, such as energy and angular resolutions, merging and splitting of jets, etc. , have to be taken into account by convoluting the differential cross section with a transfer function $W(y, x)$:

$$P_m(\alpha; x) = \frac{A(x)}{\sigma} \int d^n\sigma(y; \alpha) dq_1 dq_2 f(q_1) f(q_2) W(x, y) \qquad (2)$$

$W(y, x)$, which is normalized to unity in x, is the probability to reconstruct a set of objects x when y was produced,

$d^n(y, \alpha)$ is the partonic differential cross-section, $f(q)$ are the parton distribution functions and σ is the total cross section. In addition the integral in equation 2 sums over all possible parton states leading to the observed objects in the detector. In this way reconstruction ambiguities are taken into account. In case of $t\bar{t}$ events in the lepton+jets channel these consist of the 12 ways to assign the jets to partons and 2 possible neutrino solutions.
Contributions of background events are taken into account by adding the probabilities:

$$P_m(\alpha; x_i) = c_1 P_{m,\mathrm{t\bar{t}}}(\alpha; x_i) + c_2 P_{m,bkg.}(x_i) \qquad (3)$$

The likelihood function is then maximized with respect to the parameters c_i at each value of α seperately.

2.2 Application to the Measurement of the top quark Mass.

The method described above is used to remeasure M_t from $t\bar{t}$ data accumulated by the DØ experiment in Run 1 of the Tevatron. The integrated luminosity corresponds to $125\,pb^{-1}$, using the same dataset as in [7]. Information concerning the DØ detector and the previous analysis can be found in [7,9].
Offline selections require one isolated lepton with $E_T > 20\,\mathrm{GeV}$ and $|\eta_\mu| < 1.7$ for muons, $|\eta_e| < 2.0$ for electrons, at least four jets with $E_T > 15\,\mathrm{GeV}$ and in $|\eta| < 2.0$, imbalance in transverse momentum ($E_T^{miss} > 20\,\mathrm{GeV}$). Selections on W decay products ($|E_T^{lep}| + |E_T^{miss}| > 60\,\mathrm{GeV}$, $|\eta_W| < 2.0$) and several less important criteria [7] are applied. The resulting event sample consists of 91 events. The leading order matrix element calculation for $t\bar{t}$ production and for background the VECBOS [10] $W + 4$ jets matrix element calculation, is used to calculate the differential cross-sections in equation 2. The multijet background was found to be adequately described by the $W+4$ jets matrix element calculation as well and is expected to be small compared to real $W+4$ jet events [7]. This procedure requires the restriction of the sample to events with exactly four jets, which reduces the data sample to 71 events.
To calculate the integrals in equation 2, the measured angles of all objects (jets and charged lepton) are assumed to reflect the angles of the partons in the final state. For electrons the energy is assumed to be well measured and the muon energy is smeared according to the known resolution. The remaining transfer function relating the energies of jets and partons is determined using a large MC sample of $t\bar{t}$ events (generated with top masses between 140 and 200 GeV and processed through the DØ detector-simulation). It is parametrized using a set of ten parameters, which are different for b quarks and lighter quarks. The signal- and background probabilities are then calculated from equation 2, using the techniques described in [8] and the CTEQ4M parton distribution functions.
Studies on samples of HERWIG [11] MC events used in [7] show that the method introduces a systematic shift in the extracted M_t that depends on the sample purity. This shift can reach about 2 GeV when the background contribution approaches 80%. To minimize this effect a selection based on the probability for an event to be background from W+jets, as given by the VECBOS differential cross section without absolute normailzation, is used. Figure 1a) shows a comparison between the probability for a background interpretation for a large sample of MC events (histograms) and for the 71 $t\bar{t}$ candidates (data points with error bars). Events to the left of the vertical line are retained ($P_{bkg} < 10^{-11}$). This value is obtained from MC studies and, for a top mass of 175 GeV, it retains 71% of the signal while rejecting 70% of the background. 22 events are left for the final analysis, expected to be 12 signal and 10 background events.
The use of the discriminant $P_{t\bar{t}}/(P_{t\bar{t}} + P_{W+4jets})$ to separate signal and background as applied in [7] is not suited here, as its value depends directly on M_t. Figure 1b) shows a comparison of this discriminant between data (points with error bars) and MC (histograms) calculated with the signal probability for the most likely M_t.
Figure 2 shows the $-\ln L(\alpha)$ and the probability density as a function of M_t. From a gaussian fit to this curve a top quark mass of (180.1 ± 3.6) GeV is obtained, including a 0.5 GeV upward bias correction based on the results of MC ensemble tests. Figure 3 shows the extracted top mass versus the chosen cutoff in P_{bkg}. Changing the cutoff by more than an order of magnitude changes the number of events used in the analysis by more than a factor of two, but does not have significant impact on the extracted M_t.
Systematic uncertainties are evaluated in similar ways to [7] and are summarized in table 1. The main contribution arises from the calibration of the jet energy scale, which was estimated from γ+jet events [7]. To estimate this effect, all jet energies were rescaled according to the upper and lower uncertainty of the calibration. Half of the difference in the total change in M_t was taken as the systematic error due to the uncertaitnty in the jet energy scale.
Adding all systematic errors in quadrature, the following result is obtained:

$$M_t = 180.1 \pm 3.6(\mathrm{stat}) \pm 4.0(\mathrm{sys})\,\mathrm{GeV}\ (\mathrm{prelim.}) \qquad (4)$$

Table 1. Overview of systematic uncertainties.

Systematic uncertainty	Value
Model for $\mathrm{t\bar{t}}$	1.5 GeV
Model for background (W + jets)	1.0 GeV
Noise and multiple interactions	1.3 GeV
Jet energy scale	3.3 GeV
Parton distribution function	0.2 GeV
Acceptance correction	0.5 GeV

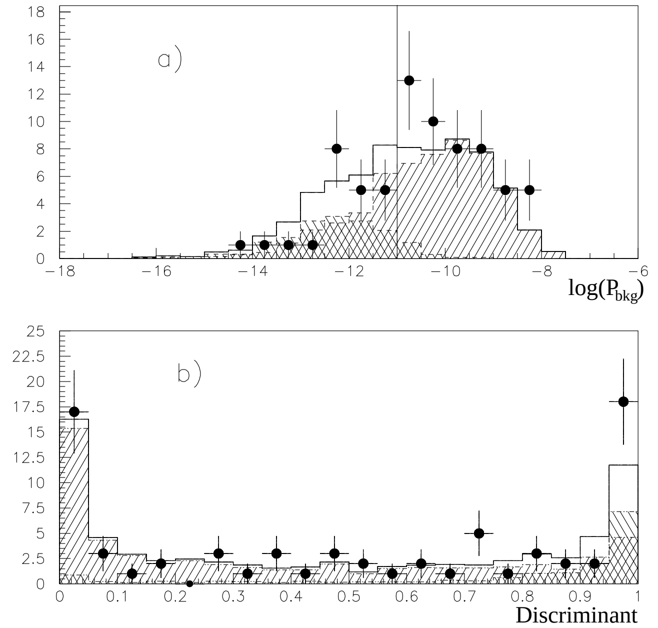

Fig. 1. a) Distribution of the probability of events to be background, and b) discriminant $P_{t\bar{t}}/(P_{t\bar{t}}+P_{W+4jets})$, calculated for the 71 $t\bar{t}$ candidates (data points). The data is compared to the expected results from MC-simulated signal (left-hatched histogram) and background (right-hatched histograms). The open histogram is the sum of signal and background expectations.

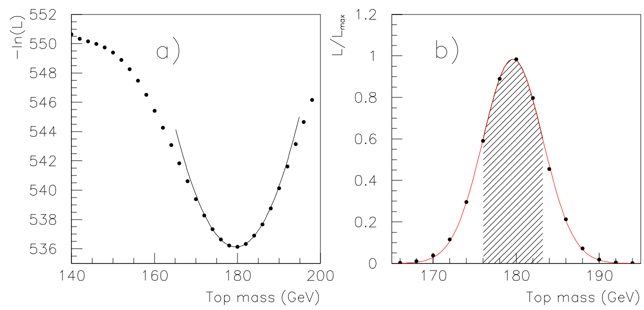

Fig. 2. a) Negative of the logarithm of the likelihood and b) the Likelihood (normalized to the maximum value) as function of the mass of the top quark. The hatched area correspond to the 68.27 % probability interval.

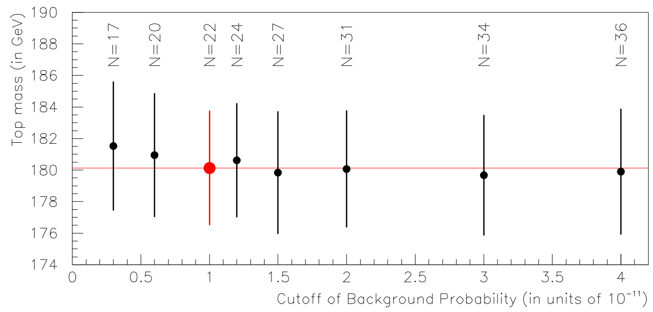

Fig. 3. Extracted $M_t$as a function of the cutoff in background probablity. The number of remaining events is shown above each point. The point with the larger dot is the value used in this analysis.

3 Outlook

The described method is not limited to the measurement of the top quark mass, but can be used to extract any unknown parameter that influences the event kinematics. Among these is e.g. the helicity of the W boson from top decays, where the Standard Model predicts the ratio of longitudinal to the left-handed component as well as the right-handed component to be zero [12].
In Run 2 of the Tevatron, which is currently underway, much larger data samples than in Run 1 are being collected, allowing for the first time detailed studies of the properties of the top quark. It is expected to measure the top quark mass to a precision of about 3 GeV.

4 Summary

An optimized method to extract top quark properties in the lepton+jets channel is presented. In this method each event enters with its individual probability to be produced. The method is used to extract a new preliminary result for the top quark mass in the lepton+jets channel, giving a significant improvement in statistical uncertainty over the previous measurement [7] that is equivalent to a factor of 2.4 more data. The analysis is also less sensitive to the uncertainties of the jet energy scale calibration. Adding statistical and and systematic uncertainties in quadrature, the obtained value of the top quark mass is

$$M_t = 180.1 \pm 5.4\,\mathrm{GeV}\ \text{(preliminary)}. \qquad (5)$$

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