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TOP QUARK MASS AND KINEMATICS

Emanuela Barberis
Northeastern University, Boston, MA 02115 USA

Abstract

A summary of the results on the measurement of the Top Quark mass and the study of the kinematics of the $t\bar{t}$ system at the Tevatron collider is presented here. Results from both the CDF and DØ collaborations are reported.

1 Introduction

In proton anti-proton collisions at Tevatron energies, $\sqrt{s} = 1.96$ TeV, Top quarks are primarily produced in pairs ($t\bar{t}$) via strong interactions. According to the Standard Model (SM), the Top quark decays to a W boson and a b-quark with a branching ratio close to 100%. Final states of $t\bar{t}$ production are classified according to the decay modes of the W boson. A "dilepton" final state corresponds to both W bosons from the Top and anti-Top quarks decaying leptonically. A "lepton+jets" final state corresponds to one W boson decaying leptonically and the second one decaying hadronically. When both W bosons decay hadronically, we have a "all jets" final state. Only measurements performed in the dilepton and lepton+jets channels are reported here: measurements of the Top quark mass, studies of anomalous kinematics, and searches for resonances decaying in a $t\bar{t}$ pair.

Results from the two Tevatron collider experiments, CDF and DØ are reported. They correspond to a Run 2 integrated luminosity ranging from 160 pb^{-1} to 750 pb^{-1}. For Run 2, both CDF 1) and DØ 2) have undergone extensive upgrades resulting in precise tracking and vertexing volumes embedded in a solenoidal magnetic field: new silicon vertex detectors, and new outer tracking chambers. All other detector systems have also been upgraded, including the calorimeters , the preshowers detectors, the muon detection systems, and the data acquisition and trigger systems. Both experiments are running with high data taking efficiency, $\geq 85\%$.

2 Measurement of the Top Quark Mass

The mass of the Top quark is a fundamental parameter of the Standard Model and it affects the prediction of other Standard Model observables through radiative correction (it can be related, together with the mass of the W boson, to the mass of the yet undiscovered Higgs boson). Moreover the mass of the Top quark is roughly one half the vacuum expectation value of the Higgs field, thus suggesting that the Top quark might play a special role in the mechanism of Electroweak Symmetry Breaking, and therefore lead to signatures of new physics beyond the Standard Model.

The goal of Run 2 for the measurement of the Top quark mass is to achieve a precision measurement. We project that, with 2 fb^{-1} of integrated luminosity, a 1.5 GeV uncertainty on the mass of the Top quark will be achievable. This translates in a relative indirect uncertainty on the mass of the Higgs boson of 30%.

2.1 Ingredients to the Measurement of the Top Quark Mass

Several steps need to be taken in order to reach a precision measurement of the Top quark mass. The key ingredients are the combined maximization of the statistical significance by means of sophisticated mass extraction techniques, and the minimization of the systematic uncertainties, the dominant ones being the uncertainty associated with the calibration of the jet energies, and the uncertainty related to the Monte Carlo modeling of the signal and background sources.

The mass extraction techniques can be divided into two broad categories, with many variants. Techniques based on template methods rely on the determination of, typically, one mass per event from a kinematic fit to the $t\bar{t}$ hypothesis, and then compare the data to Monte Carlo templates. Techniques based on dynamical methods determine event by event weights according to the quality of agreement of the data with the Standard Model Top and background differential cross-sections. The event by event weight, or probability, is usually of the form: $\mathrm{P(x;m}_{top})=\frac{1}{\sigma}\int d^n\sigma(y;m_{top})dq_1dq_2f(q_1)f(q_2)W(x|y)$, where $d^n\sigma$ indicates the differential cross section (usually at Leading Order), $f(q_1)f(q_2)$ are the Parton Distribution Functions (PDF's), and $W(x|y)$ is the transfer functions which performs the mapping from the parton level variables y to the reconstructed level variables x.

In order to have a better handle on the systematic uncertainties, it has been found that in lepton + jets events, the uncertainty associated with the determination of the jet energy scale (JES) can be reduced using the in-situ calibration of the hadronic W mass in Top quark decays. In this case, a simultaneous determination (a 2-dimensional fit) of the Top quark mass and of the JES is obtained from templates of the reconstructed Top quark and the W boson mass.

The identification of $b-$jets through $b-$tagging techniques can also be used to reduce physics as well as combinatorial backgrounds.

At last, many systematic uncertainties are expected to decrease with larger data samples.

2.2 Determination of the Top Quark Mass in the lepton+jets channel

Results on the determination of the Top quark mass in the lepton+jets channel are reported here, for both Tevatron experiments, starting with the measurements based on Template techniques.

CDF applies the Template Method to an integrated luminosity data set of 680 pb^{-1} 3). In this measurement the reconstructed Top mass (m_{top}) and the dijet invariant mass (m_{jj}) from data are compared to templates of various true Top mass (M_{top}) and Δ_{JES} (jet energy calibration shift) using an unbinned likelihood fit. The measurement therefore uses the in-situ m_W

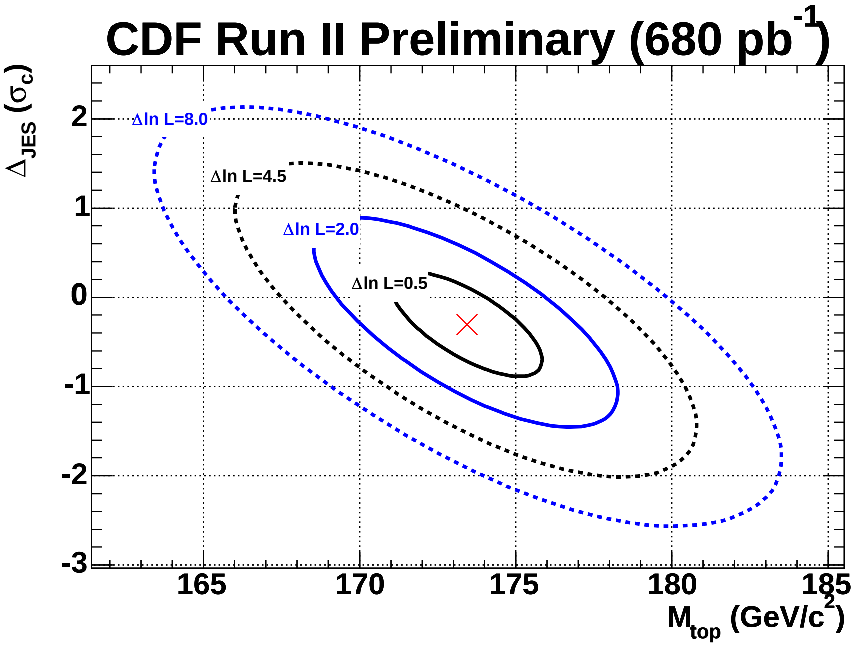

Figure 1: *Combined likelihood Δ_{JES} versus M_{top} in the CDF Template Method measurement of the Top quark mass in the lepton+jets channel (680 pb^{-1}).*

constraint to calibrate the jet energy scale. The event selection is typical of a lepton+jets analysis. In this case, it consists of one electron or one muon with $p_T > 20$ GeV, large missing transverse energy from the neutrino, $E_T^{miss} > 20$ GeV, and requirements on the jet transverse energies and multiplicities. Four exclusive samples with different jet p_T selections and $b-$tagging requirements are chosen (0 tags, 1 loose tag, 1 tight tag, and 2 tags). The four samples, for a total of 360 candidates, have different signal to background ratios and different sensitivities to M_{top}. Fig.1 shows the combined likelihood of Δ_{JES} and M_{top} for all four samples. The m_{jj} in-situ calibration leads to a 40% improvement over the external jet energy scale uncertainty of 3 GeV. This method results in the single most precise measurement of the top quark mass: $M_{top} = 173.4 \pm 2.5(stat. + \Delta_{JES}) \pm 1.3$ GeV/c^2, or $M_{top} = 173.4 \pm 2.8$ GeV/c^2.

The DØ collaboration also performed a Template method analysis, on a 230 pb^{-1} data set. Two measurements are performed, one which requires one or more jets to be $b-$tagged, in addition to the standard selection, and a second one which performs a topological selection based on the output of a discriminant built from kinematical variables uncorrelated to m_{top}. The topological and $b-$tagged analyses yield a result of $M_{top} = 169.9 \pm 5.8(stat.)^{+7.8}_{-7.1}(sys.)$ GeV/c^2 and $M_{top} = 170.6 \pm 4.2(stat.) \pm 6.0(sys.)$ GeV/c^2, respectively.

An additional method used by the DØ collaboration is the Ideogram method, which uses the same kinematic fitting and discriminant as the Template analysis, but an event by event likelihood. Each event gives a distribution of masses. An earlier measurement was performed using this method, on a 160 pb^{-1} data sample, yielding a value for the Top quark mass of $M_{top} = 177.5 \pm 5.8(stat.) \pm 7.1(sys.)$ GeV/c^2.

Uncorrelated to all other measurements, is the measurement of the Top quark mass using the Decay Length method, performed by CDF on a 695 pb^{-1} data set. This measurement is uncorrelated because it relies on tracking, and has therefore no dependency on the jet energy scale determination and uncertainty. The method is based on the observation that the boost of the $b-$quarks in Top decay is correlated to m_{top}. By using an observable related to the boost, such as the measurement of the $b-$lifetime, or the secondary vertex decay length, it possible to infer m_{top}. The event selection requires one less jets than most of the other lepton+jets analyses, i.e. at least 3 jets with $E_T > 15$ GeV are required, of which at least one $b-$tagged. The mass of the Top quark is measured to be: $M_{top} = 183.9^{+15.7}_{-13.9}(stat.) \pm 5.6(sys.)$ GeV/c^2.

Dynamical methods of extracting the Top quark mass have been used extensively by both experiments since DØ pioneered this method with the reanalysis of the Run 1 data (4). The main dynamical method applied by both CDF and DØ to Run 2 data, also called Matrix Element (ME) method, uses the in-situ constraint to the W boson mass to calibrate the jet energy scale in the lepton+jets channel.

The ME method makes maximal use of information in each event by calculating an event by event probability to be signal or background, based on the respective matrix elements of the processes. All events are combined in a likelihood, and the likelihood is maximized as a function of m_{top} and jet energy scale. The ME method uses events with exactly four jets. The CDF measurement incorporates the use of $b-$tagging, the DØ measurement described here does not.

The DØ ME measurement was performed on a 320 pb^{-1} data set. The likelihood fit yields simultaneously the value of m_{top}, the relative value of the JES, and the fraction of signal in the sample. Additional cross-checks on the reconstructed W mass are also performed. The extracted value of the Top quark mass is: $M_{top} = 169.5 \pm 4.4(stat. + JES)^{+1.7}_{-1.6}(sys.)$ GeV/c^2.

The CDF ME measurement is similar in method, and was performed using a 680 pb^{-1} data set. The event selection requires one or more jets to be $b-$tagged. The result, which is very close in precision to the CDF template measurement, is $M_{top} = 174.1 \pm 2.5(stat. + JES) \pm 1.3(sys.)$ GeV/c^2.

An earlier CDF result obtained with a dynamical method, denoted as Dynamical Likelihood Method [3] (DLM), made use of a likelihood based on an event by event probability of being signal only. A shift on m_{top} was applied, based on the estimate of the variation of m_{top} with background fraction. The DLM measurement, performed on 318 pb^{-1}, yielded $M_{top} = 173.2^{+2.6}_{-2.4}(stat.) \pm 3.2(sys.)$ GeV/c^2.

2.3 Determination of the Top Quark Mass in the dilepton+jets channel

Both template and dynamical methods have been applied to the determination of the Top quark mass in the dilepton channel. The template method results will be discussed first, for both CDF and DØ , and then the CDF ME method will be described.

Due to the presence of two neutrinos in the event, a kinematic fit of a dilepton event to the $t\bar{t}$ hypothesis is under-constrained. The template methods assume values for certain variables in order to extract a solution, and assign weights to the different solutions. Different schemes of the weights exist, and the choice of the weight characterizes the measurement.

The DØ Matrix Weighting method, applied to a data set of 370 pb^{-1}, scans over Top quark masses and assigns a weight to the solution, based on the matrix element predictions for the lepton p_T's. A binned maximum likelihood fit of the data to signal and background templates is then performed. The event selection, typical of the dilepton channel, requires a pair of high p_T electrons, muons, or an electron and muon, at least two jets, and topological cuts to remove backgrounds from QCD and Z production. An untagged and a $b-$tagged analysis are performed, with the $b-$tagged one corresponding to the highest purity sample of all Top quark mass analyses (signal over background ratio of 48). Fig.2 shows the likelihood curve for the $b-$tagged analysis. The results are $M_{top} = 165.0 \pm 13.5(stat.) \pm 3.8(sys.)$ GeV/c^2 for the untagged analysis and $M_{top} = 176.6 \pm 11.2(stat.) \pm 3.8(sys.)$ GeV/c^2 for the $b-$tagged one.

A weighting scheme adopted by both experiments is the Neutrino Weighting method, which scans over Top masses and the η's of the two neutrinos in the event and assigns a weight (as a function of m_{top}) to the solution, based on the agreement of the neutrino p_T's and the observed E_T^{miss}. A maximum likelihood fit of the data to signal and background templates is then performed.

DØ has applied this method to the same data set as the Matrix Weighting method, i.e. 370 pb^{-1}, with a similar event selection, and an untagged analysis. The result is $M_{top} = 175.6 \pm 10.7(stat.) \pm 6.0(sys.)$ GeV/c^2. A Neutrino Weighting analysis performed by CDF, on 358.6 pb^{-1} [5], yields a value of $M_{top} = 170.7^{+6.9}_{-6.5}(stat.) \pm 4.6(sys.)$ GeV/c^2. The main difference in the CDF analysis is that the selection does not require two isolated high p_T leptons (e

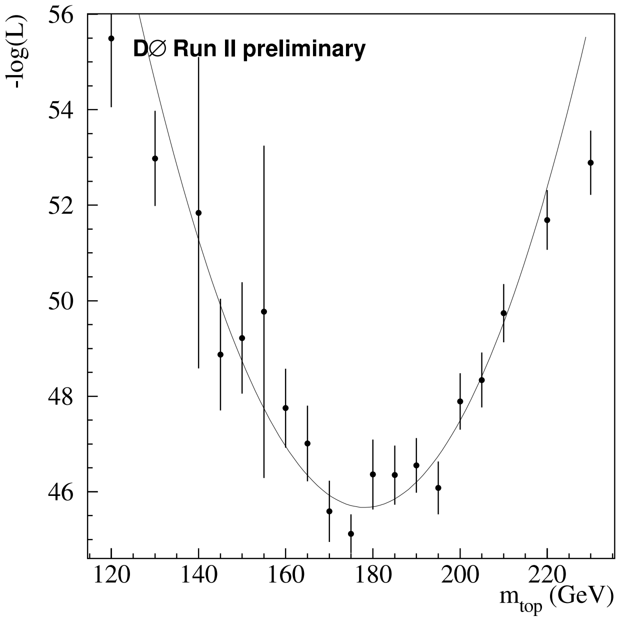

Figure 2: *Likelihood as a function of m_{top} for the DØ Matrix Weighting measurement of the Top quark mass in the dilepton channel (370 pb^{-1}). At least one jet is required to be $b-$tagged.*

or μ), but one lepton and one isolated high p_T track.

Two additional Template methods with different schemes have been used by CDF: one which weights on the neutrinos azimuthal angles 5), and another which integrates over the value of the $t\bar{t}$ P_z 5). They were applied on 340 pb^{-1} of data and result into a determination of the mass of the Top quark of $M_{top} = 169.7^{+8.9}_{-9.0}(stat.) \pm 4.0(sys.)$ GeV/c^2 and $M_{top} = 169.5^{+7.7}_{-7.2}(stat.) \pm 4.0(sys.)$ GeV/c^2, respectively.

At last, CDF has applied the Matrix Element method, a dynamical method, to the determination of the Top quark mass in the dilepton final state. The measurement 5) is performed on the largest data set, i.e. 750 pb^{-1} and uses a per-event probability for the mass as a weighted sum of the differential cross section for LO $t\bar{t}$ production and of the differential cross sections for background processes. A posterior probability density (Fig. 3) is formed as the product of a flat prior and the joint event likelihood. The

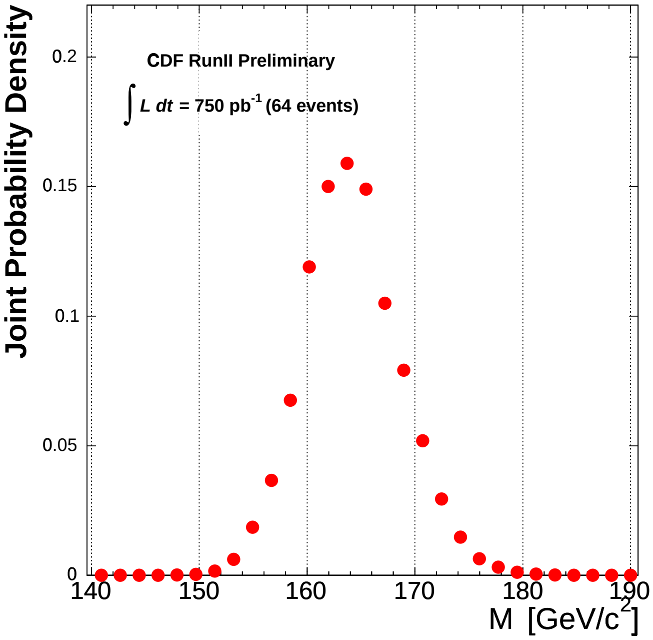

Figure 3: *The joint probability density for the CDF ME measurement of the Top quark mass in the dilepton channel (750 pb*$^{-1}$*).*

mean and σ of the posterior probability correspond to the value of the Top quark mass and its uncertainty. The extracted value of the Top quark mass is $M_{top} = 164.5 \pm 4.5(stat.) \pm 3.1(sys.)$ GeV/c^2, the most precise dilepton measurement.

2.4 Top Quark Mass average

With Run 2, the Tevatron experiments are aiming at a precision measurement of the mass of the Top quark. Some of the results shown in here already exceed the Run 1 world average. A combined CDF result, $M_{top} = 172.0 \pm 2.7$ GeV/c^2, which includes Run 1 measurements, the Run 2 ME dilepton measurement and the Run 2 Template lepton+jets measurement, already exceeds the 2005 Run 1 and Run 2 world average 6). A new world average result was made public recently, including all of the measurements described above 7). The impact on the indirect constraints on the Standard Model Higgs boson mass is such that the uncertainty on the Higgs is now dominated by the uncertainty on the

W boson mass.

3 Searches for new Physics

Searches for new physics in the production and decay of the Top quarks have been carried out with the larger statistics of Run 2. Two analyses on the kinematics of $t\bar{t}$ production are presented here.

3.1 Anomalous $t\bar{t}$ kinematics

Using an early (193 pb^{-1}) dilepton sample, CDF estimated $^{8)}$ the consistency of the observed kinematics of the $t\bar{t}$ system with the prediction of the Standard Model. In Run 1, CDF observed several events at high E_T^{miss} and lepton p_T, and this type of analysis is effectively a model independent search for new physics. The Run 2 comparison, which uses four kinematics variables, suggests that the data is consistent with the Standard Model with a probability of $1-4.5\%$ (this value mainly due to a small excess of events at low lepton p_T).

3.2 $t\bar{t}$ mass spectrum

Both CDF and DØ have performed a search for new particles decaying in $t\bar{t}$, leading to a resonance in the $t\bar{t}$ mass spectrum. Both experiments use the lepton+jets ($\geq$ 4 jets) final state sample (370 pb^{-1} and 682 pb^{-1} for DØ and CDF, respectively), in addition DØ requires at least one jet to be tagged as a $b-$jet. The $t\bar{t}$ invariant mass is reconstructed with a kinematic fitting to the $t\bar{t}$ production hypothesis, and model independent limits on $\sigma \times Br(X \rightarrow t\bar{t})$ are extracted (Fig.4 and Fig.5). A limit on a narrow leptophobic Z' (with a total width $\Gamma_{Z'} = 1.2\% M_{Z'}$) is also placed at 95% confidence level: $M_{Z'} > 680$ GeV for DØ , and $M_{Z'} > 725$ GeV for CDF.

4 Conclusions

Results on the determination of the Top quark mass and studies of kinematics of the $t\bar{t}$ system were presented for Tevatron Run 2 data sets up to 750 pb^{-1}, with single mass measurements already exceeding the precision of past world averages.

The excellent performance of the Tevatron and of the CDF and DØ detectors are the key to precision measurements in Top quark physics and to the search for new physics coupled to the Top quark.

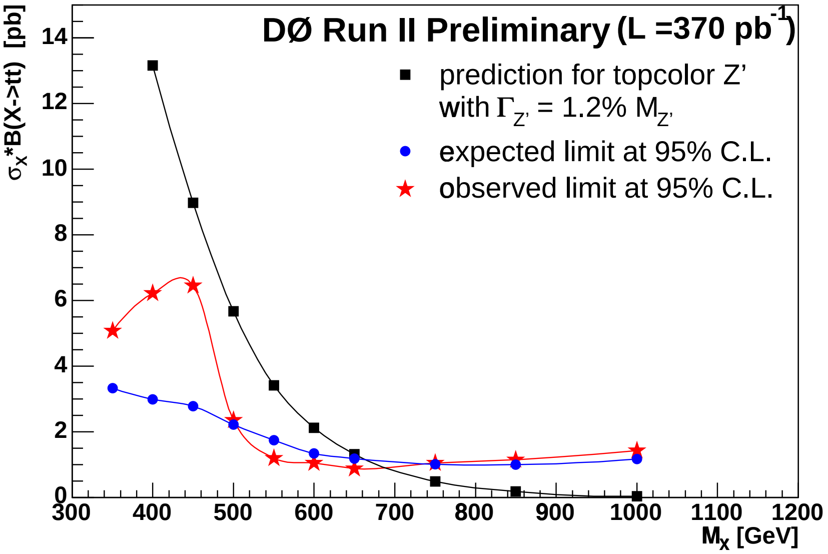

Figure 4: *Limits on* $\sigma \times BR(X \to t\bar{t})$ *as a function of* M_X*. DØ measurement in the lepton+jets channel (370* pb^{-1}*).*

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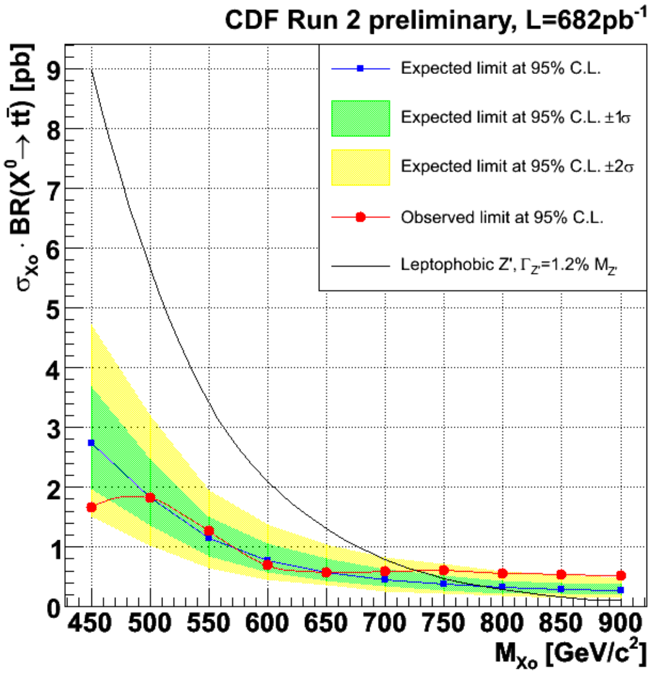

Figure 5: *Limits on* $\sigma \times Br(X \to t\bar{t})$ *as a function of* M_X*. CDF measurement in the lepton+jets channel (682* pb^{-1}*).*

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