TOP MASS MEASUREMENT AT THE TEVATRON

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Results on the measurement of the top quark mass from the two Tevatron collider experiments, CDF and DØ are presented here. We start with an introduction to top quark physics and the techniques used by both experiments to achieve a precise measurement of the top quark mass. The most recent and/or most precise measurements performed by the two experiments in different final state channels are then described. The measurements are performed on datasets corresponding to integrated luminosities up to 1 fb^{-1}. We conclude by presenting the latest world average value for the mass of the top quark: $M_{top} = 170.9 \pm 1.1(stat.) \pm 1.5(sys.)$.

1 Top Quark Physics and the Top Quark Mass

In proton anti-proton collisions at Tevatron energies, $\sqrt{s} = 1.96$ TeV, top quarks are primarily produced in pairs (a top and an anti-top quark) via strong interactions. We measure the top quark mass in this production mode. Approximately 85% of the production cross-section at Leading Order (LO) is initiated by qq' annihilation, while the remainder originates from gluon-gluon fusion. In 2006, the DØ experiment found evidence for the second Standard Model (SM) mode of production, i.e. the electroweak production of single top quarks [1]. In the SM, a top quark decays $\sim 100\%$ of the time into a W boson and a b-quark. The final state decays of the W boson(s) are used to classify the final state signatures of top quark pair production. If 0, 1, or 2 W bosons decay into a charged lepton and a neutrino, the pair production final states are classified as: all-hadronic, lepton+jets, and dilepton. The branching ratio for a particular final state decreases in this same order.

A precise measurement of the top quark mass is very important for several reasons. First of all, the mass of the top quark is a fundamental parameter of the SM. In addition, the mass of the top quark affects other SM observables via radiative corrections, e.g. the mass of the top quark together with the mass of the W boson can be related to the mass of the yet undiscovered Higgs

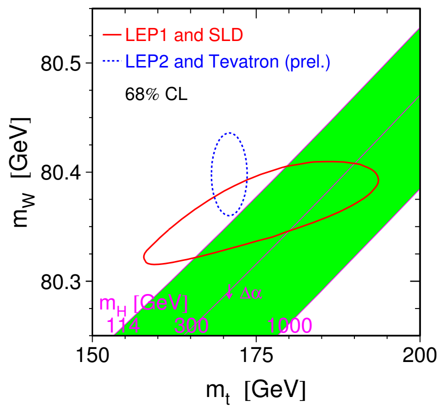

Figure 1: 68% CL contours in the m_{top}, m_W plane from global fits to the electroweak data.

boson, thus setting indirect constraints on its value. Figure 1 shows the latest 68% CL contours from a global fit to the electroweak data. The fit yields [2] a prediction for the Higgs boson mass of 76^{+33}_{-24} GeV/c^2 and, taking into account the LEP-2 direct limits, a 95% CL one-sided upper limit of 182 GeV/c^2.

The mass of the top quark is also measured to be very large compared to the mass of the other quarks, and of the same order as 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 SM. The Tevatron experiments are aiming at a precise measurement of the top quark mass. The prediction for the total uncertainty on such a measurement is $\sim$1.5(1.0) GeV for an integrated luminosity of 2(8) fb^{-1}.

2 Mass Measuring Techniques

The techniques used by the Tevatron collaborations to extract a measurement of the top quark mass fall into two main categories: template and dynamical methods. The template methods typically extract one value of the top quark mass per event from a kinematic fit to the $t\bar{t}$ hypothesis, then compare the data to a combination of background Monte Carlo templates and signal Monte Carlo templates generated for different top quark mass input values. The dynamical methods weight each event according to the quality of agreement with Standard Model top and background differential cross-sections. The event-by-event weight, or probability, integrates the matrix element for the signal or background processes (LO calculations are used), the parton distributions functions, and the transfer functions. The transfer functions map parton-level variables to reconstructed objects variables. Many variations exist that combine template and dynamical techniques.

As for all other top quark physics measurements, the determination of the mass poses several challenges. Given the complexity of the final state, top quark physics exercises the understanding of all detector components. Top quark production is a rare process, with significant backgrounds. Experimentally, jets are measured, not quarks (with hadronization, radiation, detector effects to be taken into account when trying to calibrate jets and relate jet energies to parton energies). Also, experiments can only infer the presence of a neutrino from the measurement of missing transverse energy. Systematic uncertainties reflect these challenges, and with the increased statistics brought by Run 2 of the Tevatron, the main measurements in top physics are starting to see comparable statistical and systematic uncertainties. With larger and larger data sets becoming available, the key to a precise measurement of the top quark mass is the control of systematic effects. There are several handles on systematic uncertainties that have been used by the Tevatron collaborations. The uncertainty associated with the determination of the jet energy scale (JES) is predominant in nearly all of the top quark mass measurements. The JES systematic uncertainty can be reduced, in lepton+jets and all-hadronic final states, with the in-situ calibration of the hadronic W mass in top decays. Identification of $b-$jets with $b-$tagging can be used to reduce backgrounds as well as combinatorial effects, at the cost of a decrease in statistical power. Most systematic uncertainties are also expected to decrease with the increased statistics of control samples.

3 Results

Within the scope of this contribution it would be impossible to carefully characterize all of the measurement of the top quark mass performed by CDF and DØ since the beginning of Run 2, therefore only the most recent and/or the most precise results in the lepton+jets, dilepton, and all-hadronic final states are reviewed. Most of the results shown here use a data set corresponding to an integrated luminosity of 1 fb^{-1}.

3.1 Top quark mass measurement in the lepton+jets channel

At leading order, the lepton+jets channel final state signature consists of one high p_T lepton (electron and muon results are considered here), significant E_T^{miss} from the W decay's neutrino, and four jets, two of which originate from $b-$quarks (0, 1, 2 $b-$tags can be required). This channel has good statistics and manageable backgrounds, from W+jets and QCD multijet processes. An in-situ calibration of light quark jets can be performed using the hadronically decaying W mass.

Both Tevatron experiments use a dynamical method in the determination of the most precise value of the top quark mass in this channel. The so-called Matrix Element (ME) method was pioneered by DØ with a re-analysis of the Run 1 data [3]. It makes maximal use of the information in each event by calculating, for each event, a probability of being signal or background based on the matrix elements for the respective processes. All event probabilities are combined in a likelihood which is maximized as a function of three parameters: top quark mass, relative JES, and top signal fraction, f_{top}. The ME measurement requires exactly four jets in the final state.

A new ME measurement by DØ was shown at this conference in the lepton+jets channel [4]. The simultaneous fit to the top quark mass, relative JES, and top fraction yields a value for the top quark mass of $M_{top} = 170.5 \pm 2.4(stat. + JES) \pm 1.2(sys.)$ GeV/c^2 with an integrated luminosity of 0.9 fb^{-1}. This measurement requires at least one jet to be $b-$tagged and it is in good agreement with the result of a similar, but untagged, analysis where the extracted top quark mass is $M_{top} = 170.5 \pm 2.5(stat. + JES) \pm 1.4(sys.)$ GeV/c^2. Note that, since the hadronically decaying W's in the decay of top events are used to constraint the JES, the JES error depends on the available statistics and it is incorporated in the statistical error. Figure 2 shows the 2-dimensional likelihood contours as a function of the top quark mass and relative JES for this measurement.

CDF extracts [5] a value for the top quark mass, with a similar integrated luminosity and with the same method (ME): $M_{top} = 170.9 \pm 2.2(stat. + JES) \pm 1.4(sys.)$ GeV/c^2.

An additional method used by the DØ collaboration is the Ideogram method, which uses the same kinematic fitting and discriminant as basic template analyses, but an event by event likelihood where each event gives a distribution of masses. This method has the advantage of being less CPU intensive than the ME method. A result was recently published with this method [6], based on a 0.4 fb^{-1} data sample, yielding a value for the top quark mass of $M_{top} = 173.7 \pm 4.4(stat. + JES)^{+2.1}_{-2.0}(sys.)$ GeV/c^2.

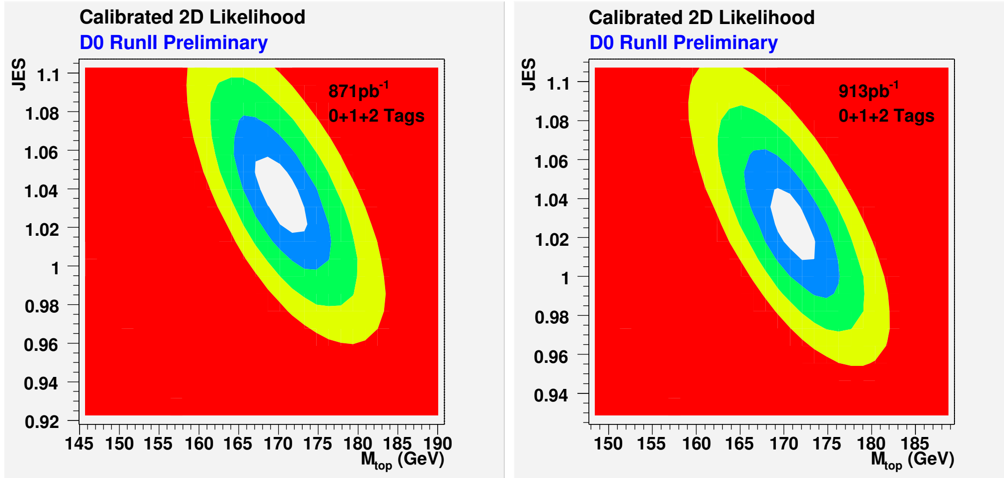

Figure 2: Measurement of the top quark mass at DØ, in the lepton+jets channel with the ME method: 68% CL contours in the m_{top}, relative JES plane for the μ+jets channel (left) and the e+jets channel (right) separately.

3.2 Top quark mass measurement in the dilepton channel

The event signature typical of the dilepton channel at LO consists of a pair of high p_T charged leptons (ee, $\mu\mu$, or eμ are considered here), two jets originating from $b-$quarks ($b-$tagging can be incorporated) and significant E_T^{miss}. The backgrounds are low (primarily from diboson and W,Z+jets production), even without requiring one jet or more to be $b-$tagged. The challenge of this channel is the presence of two neutrinos.

Both template and dynamical methods have been applied to the determination of the top quark mass in the dilepton channel.

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.

DØ uses two weighting schemes: the matrix weighting and the neutrino weighting (the latter one has been used by CDF as well). The matrix weighting method scans over top quark masses and assigns a weight to the solution, based on the matrix element predictions for the lepton p_T's. The neutrino weighting method, scans over several values for the top quark mass 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 for all methods in order to extract the top quark mass value and its statistical uncertainty. Since there is no constraint on the JES from a hadronically decaying W, the JES error is part of the systematic uncertainty.

DØ performed a new measurement [7] with the neutrino weighting method and an integrated luminosity of 1 fb^{-1}, yielding a result for the top quark mass of: $M_{top} = 172.5 \pm 5.8(stat.) \pm 5.5(sys.)$ GeV/c^2. An earlier result [8] with the matrix weighting method on the eμ+jets final state alone yields a consistent result of: $M_{top} = 177.7 \pm 8.8(stat.)^{+3.7}_{-4.5}(sys.)$ GeV/c^2.

The Matrix Element method is applied to the determination of the top quark mass in the dilepton final state by CDF. The measurement [9] is performed on 1 fb^{-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 (Figure 3) is formed as the product of a flat prior and the joint event likelihood. The mean and σ of the posterior probability correspond to the value of the top quark mass and its uncertainty.

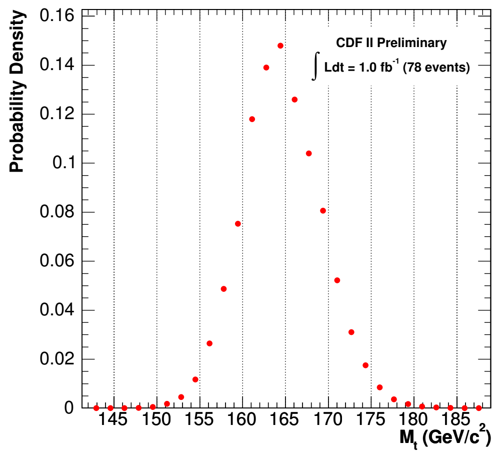

Figure 3: The joint probability density for the CDF ME measurement of the Top quark mass in the dilepton channel (1030 pb^{-1}).

The extracted value of the top quark mass is $M_{top} = 164.5 \pm 3.9(stat.) \pm 3.9(sys.)$ GeV/c^2, the most precise dilepton measurement. This is in good agreement with a similar measurement which requires at least one jet to be tagged as a $b-$jet: $M_{top} = 167.3 \pm 4.6(stat.) \pm 3.8(sys.)$ GeV/c^2. The major contributor to the systematic uncertainty in all of the dilepton measurements is the JES uncertainty.

3.3 Top quark mass measurement in the all-hadronic channel

The all-hadronic channel has the highest branching ratio and a final state signature, at LO, of six jets, two of which originate from $b-$quarks. Since the QCD multi-jet background in this channel is rather large, at least one jet is required to be $b-$tagged. Selection criteria based on the specific topology of the signal events are also applied to further reduce the background. This channel contains two hadronically decaying W's in the decay of top and anti-top quarks, thus allowing a similar in-situ calibration of the jet energy scale to the lepton+jets channel.

CDF performed a measurement of the top quark mass in this channel using a Matrix Element assisted template method [10]. This analysis uses 2-dimensional (in the top quark mass and JES) signal templates derived from ME calculations and background templates modeled on data. Figure 4 shows the extracted top quark mass distribution for single $b-$tagged and for double $b-$tagged events. Based on a 0.9 fb^{-1} data sample, the top quark mass is measured to be: $M_{top} = 171.1 \pm 3.7(stat. + JES) \pm 2.1(sys.)$ GeV/c^2.

Although this channel is the most challenging one, it must be noted that the precision of the measurement is competitive with the precision of the measurements in the other channels.

3.4 The top quark mass world average

The measurements of the top quark mass from different channels and the two Tevatron experiments are combined [11]. The resulting world average for the top quark mass is: $M_{top} = 170.9 \pm 1.1(stat.) \pm 1.5(sys.)$. The total uncertainty is 1.8 GeV, the relative uncertainty is 1.1%. The precision of the measurement gives confidence that a $\sim$1 GeV total uncertainty can be achieved with the full integrated luminosity of Run 2 of the Tevatron. The impact of the new Spring 2007 top quark mass world average on the indirect Higgs boson mass constraints was discussed in Section 1.

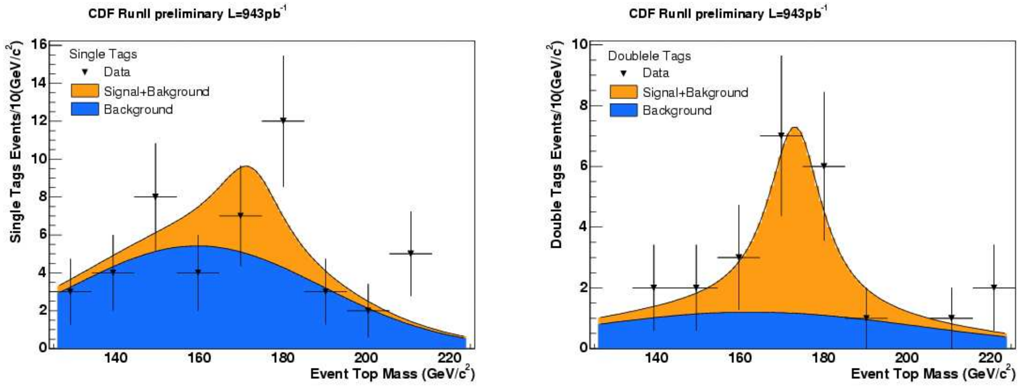

Figure 4: Results of the unbinned likelihood fit for the top quark mass in the all-hadronic channel at CDF, requiring one $b-$tag (left) or two $b-$tags (right) in the event.

4 Conclusions and outlook

Results on the measurement of the top quark mass at the Tevatron were presented for datasets corresponding to integrated luminosities up to 1 fb^{-1}. All of the 1 fb^{-1} measurements are currently converging and analyses of the 2 fb^{-1} dataset have started. Measurements now extend to final states which were once considered challenging, such as the all-hadronic mode, with results competitive in precision with other channels. The current relative uncertainty on the combined value of the top quark mass from the Tevatron is 1.1%. The Tevatron collaborations are aiming at a combined $\sim$1 GeV total uncertainty ($<$ 1% in relative uncertainty) by the end of Run 2 of the Tevatron. At this level of precision, a discussion about theoretical uncertainties in how to interpret this measurement will be needed. The current excellent performance of the Tevatron and of the CDF and DØ detectors are the key to precise measurements in top physics.

Acknowledgments

I would like to thank the organizers of the Rencontres de Moriond, and my CDF and DØ collaborators. Many thanks in particular to Lisa Shabalina, Robin Erbacher, Kirsten Tollefson, Ulrich Heintz and Michele Weber for their help in the preparation of this talk and proceedings. I acknowledge the support of the National Science Foundation grant PHY-0447987 and of the European Union Marie Curie Programme.

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