PROCEEDINGS OF SCIENCE

Top quark mass measurements at DØ experiment

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We present the measurement of the top quark mass at D0 using ℓ+jets and dilepton events from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, corresponding to an integrated luminosity of 9.7 fb^{-1} at the Fermilab Tevatron Collider. Likelihood technique is used in both of the analyses, with the ℓ+jets measurement featuring a Matrix-Element method and the dilepton measurement featuring a template method. Both analyses receive significant improvements to the statistical uncertainty on top of the increase in data size.

XXIII International Workshop on Deep-Inelastic Scattering
27 April - May 1 2015
Dallas, Texas

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PoS(DIS2015)173

1. Introduction

As a fundamental parameter of the Standard Model (SM), the mass of the top quark, m_t, became one of the main topics in the top sector at Tevatron Collider after its discovery in 1995 at Fermilab [1, 2] and recently at CERN Large Hadron Collider (LHC). The top quark mass is related to the mass of the W boson (M_W) and the mass of the Higgs boson (M_H) through radiative corrections, which can be utilized for self-consistency check of the SM [3]. Besides, a precise measurement of m_t provides a test on the stability/meta-stability of our universe within the SM context [4, 5, 6]. Also, the top-to-Higgs Yukawa coupling, $Y_t = \sqrt{2}m_t/v$, where v is the vacuum expectation value of the Higgs field, is close to unity, which implies that the top quark may play a special role in electroweak symmetry breaking.

The current world-average of m_t is m_t = 173.34 $\pm$ 0.76 GeV [7], which corresponds to a precision of 0.5%. The uncertainty of this value is now dominated by systematic uncertainties, with the jet energy scale (JES) and the modeling of $t\bar{t}$ events in Monte Carlo (MC) simulations being the main sources. Here, we present the current measurement of m_t by analyzing the full set of $p\bar{p}$ data at $\sqrt{s} = 1.96$ TeV that collected by the D0 detector in Run II operation of the Fermilab Tevatron Collider, corresponding to an integrated luminosity of 9.7 fb^{-1}. The measurement of m_t is performed in two channels at D0: one in the ℓ+jets channel and one in the dilepton channel. The analysis in the ℓ+jets channel [8] utilizes $t\bar{t}$ events with two b jets, one lepton and a corresponding neutrino, and two light quark jets in the final states. The dilepton channel [9] features one extra lepton and one extra neutrino instead of two light quarks, resulting in the dilepton event system to be under-constrained. Due to the presence of two light quarks from the decay of a W boson in the ℓ+jets channel, by constraining the invariant mass of the two light quarks to M_W, we derive a more precise determination of a global JES factor that reduces that JES uncertainty significantly in the ℓ+jets channel. We also perform studies to demonstrate that this JES factor can also be adopted in the dilepton channel [10].

2. ℓ+jets channel

The measurement of m_t in the ℓ+jets channel is performed with a likelihood technique, using the kinematic information of final state objects and probability densities (PD) defined by the Matrix-Elements (ME) [11] of $t\bar{t}$ and background processes contributing to the observed events. In the ME calculation, a tranfer function (TF) is constructed to describe the difference between the measured quantites and the partonic variables in the final states that caused by finite detector resolution and parton hadronization. In TF, the global in-situ JES factor k_{JES} is introduced to correct the energy of reconstructed jet to that in the particle level. The W boson mass M_W = 80.4 GeV [12] is used as a constraint for the in-situ JES calibration by integrating over W boson masses from a Breit-Wigner distribution. The signal and background probability densities, P_{sig} and P_{bg}, are calculated through a convolution of the differential partonic cross-section using the leading order (LO) ME. All 24 possible jet-parton assignments are weighted based on their agreement with the b-tagging information and summed together. A likelihood function is constructed by multiplying the per-event probability densities from all selected events, where the signal fraction f is derived by maximizing the likelihood for each tried value of m_t and k_{JES}. The value and statistical uncertainty of the top quark mass estimate and k_{JES} are obtained by projecting the likelihood on to the k_{JES} and m_t axes, and taking each of their mean and standard deviation. The measured top quark mass and k_{JES} are $m_t = 174.98 \pm 0.58$ GeV and $k_{JES} = 1.025 \pm 0.005$ [8], where the total statistical uncertainty on m_t includes the statistical contribution from k_{JES}. The two-dimensional likelihood distribution in (m_t, k_{JES}) is shown in Fig. 1 (a). Fig. 1 (b) compares the measured total statistical uncertainty on m_t with the distribution of this quantity from the pseudo-experiments (PEs) at $m_t^{MC} = 172.5$ GeV and $k_{JES} = 1$. Comparisons of SM predictions to data for $m_t = 175 GeV$ and $k_{JES} = 1.025$ are shown in Fig. 2 for the invariant mass of the jet pair matched to one of the W bosons and the invariant mass of the $t\bar{t}$ system.

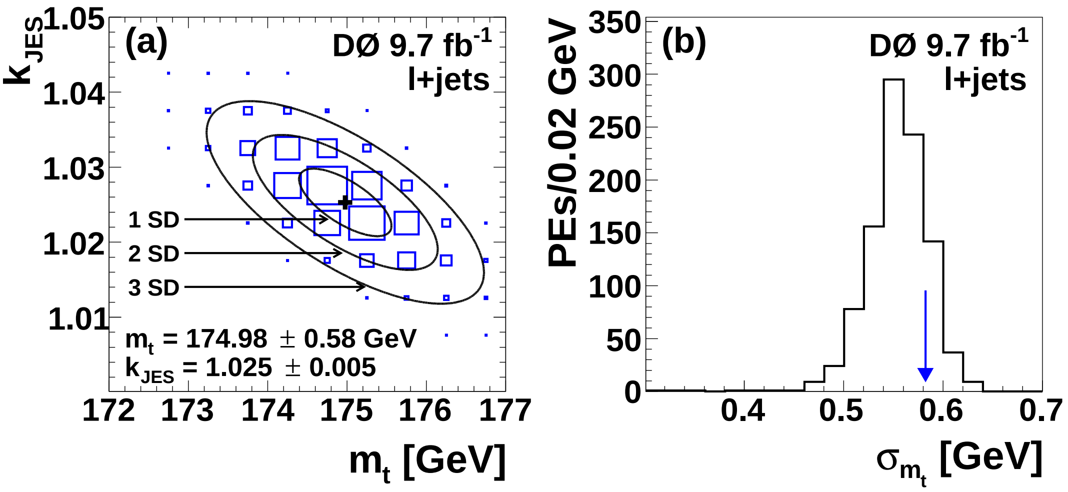

Figure 1: (a) Two-dimensional likelihood for data. Fitted contours of equal probability are overlaid as solid lines. The maximum is marked with a cross. Note that the bin boundaries do not necessarily correspond to the grid points on which likelihood is calculated. (b) Expected uncertainty distributions for m_t with the measured uncertainty indicated by the arrow.

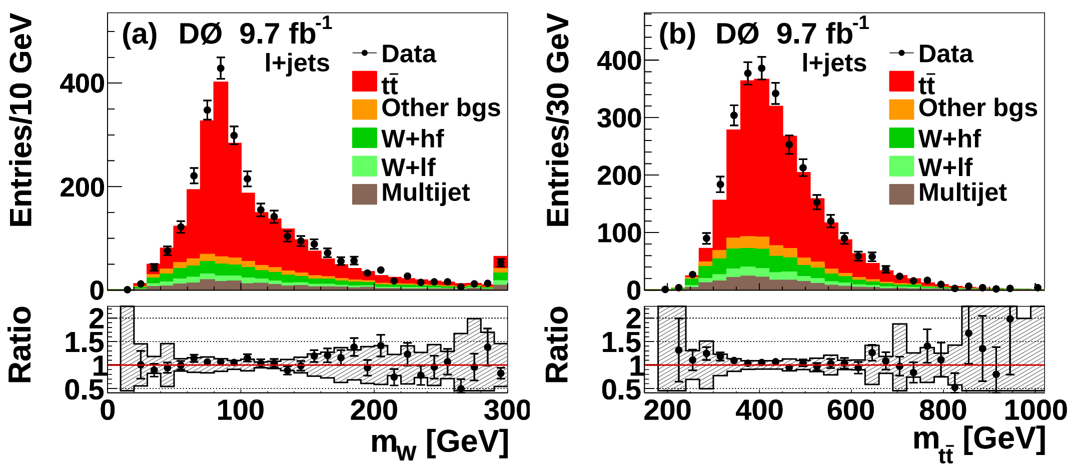

Figure 2: (a) Invariant mass of the jet pair matched to one of the W bosons. (b) Invariant mass of the $t\bar{t}$ system. In the ratio of data to SM prediction, the total systematic uncertainty is shown as a shaded band.

This analysis receives improvements in the calculation of the signal ME, which is accelerated by about two orders of magnitude in order to be able to process the extended simulated MC samples and extended systematic samples. The estimation of systematic uncertainties is also refined through an updated detector calibration, in particular improvements to the b-quark JES corrections [13], and using recent improvements in modeling the $t\bar{t}$ signal events. The final result of this analysis is $m_t = 174.98 \pm 0.58(\text{stat} + \text{JES}) \pm 0.49(\text{syst})$ GeV, or $m_t = 174.98 \pm 0.76$ GeV [8], which is currently the most precise measurement in the ℓ+jets channel.

3. Dilepton channel

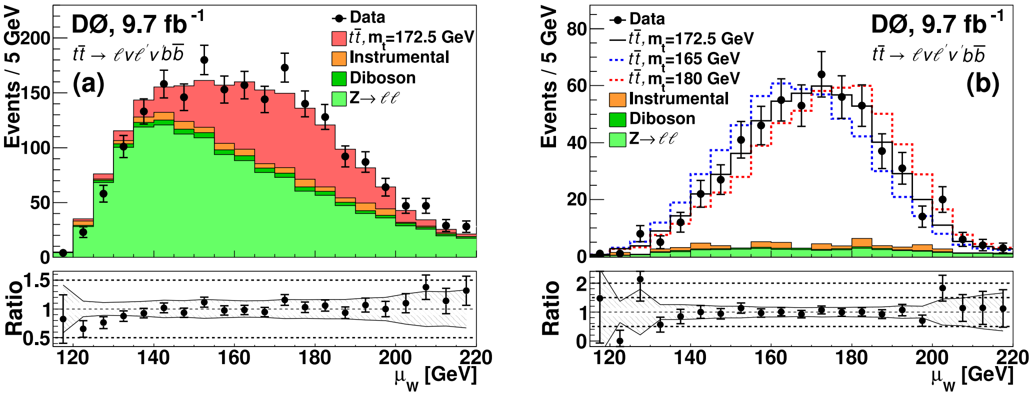

Figure 3: The distribution in the mass estimator, μ_w, for the combination of the ee, $e\mu$, and $\mu\mu$ channels for (a) the preselected sample and (b) the final event sample. The MC events are normalized separately to the number of observed events in data in each channel. The ratios show the total number of observed events divided by the number of expected events in a given bin of μ_w for $m_t^{\text{MC}} = 172.5$ GeV. The band of systematic uncertainty is shown as the shaded area in the ratio plots, which includes contributions from the dominant sources: jet energy scale, lepton identification, lepton momentum scale, luminosity, b quark modeling, initial and final state radiation, color reconnection, as well as hadronization and higher-order QCD effects for $t\bar{t}$ events.

The dilepton channel also employs a likelihood technique to extract the top quark mass [10, 14]. Since there are two neutrinos in the final states, the dilepton system is one constraint short to kinematically reconstruct. This is solved by scanning a wide range of hypothesized m_t and all possible η's for the two neutrinos, and deriving the neutrino momenta, which is compared with the observed missing transver momentum ($\not{E}_T$). A weight is calculated based on the consistency of calculated $\not{E}_T$ and observed $\not{E}_T$. By integrating the weight over all the possible neutrino η's for each of the hypothesized m_t, a weight vs m_t distribution is derived. The mean and root-mean-square (RMS) of the distribution are extracted to characterize each individual event. The distributions of the mean (μ_ω) in a preselected sample, omitting requirements on b-tagging and topological cuts, are shown in Fig. 3 (a). The $t\bar{t}$ component is evident in the preselected data. The mass dependence of the μ_ω distribution is given in Fig. 3 (b) for three m_t^{MC} mass points with all selections applied. Templates are built using the mean μ_ω and the RMS σ_ω for the signal samples and background samples. We construct a likelihood function using these templates, expected signal and background event fractions by multiplying contributions from all data events. A parabolic fit is performed on the negative log of the likelihood to extract the top quark mass and the statistical uncertainty estimates.

Finally we perform ensemble testing by running pseudo-experiments, and calibrate fitted m_t and its statistical uncertainty.

This analysis receives improvements in statistical and systematic uncertainties from various aspects. For statistical uncertainty, we optimize the parameter which represents the difference between calculated $\not{E}_T$ and measured $\not{E}_T$ in weight calculation, through a flat fit to include all possible sources. The optimization on the hypothesized mass range for weight calculation is done independently for low mass end and high mass end. Event selections are also optimized separately in each individual channel, including H_T (scalar sum of jet p_T's and leading lepton p_T), $\not{E}_T$, $\not{E}_T$ significance, and b-tagging. The binning of templates are adjusted with respect to the inceased statistics of signal and background samples. Finally, we determine the number of pseudo-experiments (PEs) in ensemble testing by looking for the turning point where the fluctuation of $m_t\acute{s}$ from systematic samples become almost independent of the number of PEs. An overall 20% improvement to the statistical uncertainty, which is on top of the increased luminosity, is obtained by integrating all the optimizations together. For the systematic uncertainty, especially for JES effects, we improved the JES uncertainty by a factor of about 4 times, comparing to standard D0 JES corrections, through carrying over in-situ JES factor from the ℓ+jets channel [8]. The validity of this adoption is studied by comparing the b jets in the ℓ+jets channel and the b jets in the dilepton channel, which are brought to the same footing by single particle response correction in JES calibration [13]. The final result in the dilepton channel is found to be: $m_t = 173.32 \pm 1.36(\text{stat}) \pm 0.85(\text{syst})$ GeV, or $m_t = 173.32 \pm 1.60$ GeV [9], which is currently the Tevatron best in the dilepton channel.

4. Conclusions

We have performed measurements of the top quark mass using the matrix element technique in the ℓ+jets channel of $t\bar{t}$ events, and the template method in the dilepton final states. For the 9.7 fb^{-1} of D0 Run II integrated luminosity that collected using D0 detector at the Fermilab Tevatron Collider, we measure the top quark mass to be $m_t = 174.98 \pm 0.58(\text{stat} + \text{JES}) \pm 0.49(\text{syst})$ GeV in the ℓ+jets channel, and $m_t = 173.32 \pm 1.36(\text{stat}) \pm 0.85(\text{syst})$ GeV in the dilepton channel. These results are consistent with the current Tevatron and world combinations of the top quark mass [7]. With an uncertainty of 0.43%, the ℓ+jets measurement constitutes the most precise single measurement of the top quark mass. Both of the analyses have their total systematic uncertainty being the smallest among any other single measurement in the corresponding channel.

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