Precision Top Quark Mass From a Simultaneous Fit in Lepton + Jets and Dilepton Channels Using $2\ \mathrm{fb}^{-1}$ of data collected by the CDFII detector

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We present a preliminary measurement of the top quark mass employing the template method with data sample collected by the CDF Run II detector corresponding to integrated luminosity of $2\ \mathrm{fb}^{-1}$. Lepton + Jets and Dilepton final states are selected. For each event in the Lepton + Jets channel we apply kinematic constraints on the pair of top quarks and their decay products to determine a reconstructed top quark mass. We simultaneously determine the invariant mass of the decaying W boson to calibrate the energy response of the detector. The events in the Dilepton sample are reconstructed using the Neutrino Weighting Algorithm. To improve the precision, for each Dilepton event we calculate H_T - the linear sum of missing transverse energy and transverse momenta of jets and leptons. The reconstructed top quark mass and W boson invariant mass distributions from the Lepton + Jets channel and reconstructed top quark mass and H_T distributions from the Dilepton channel are fit to Monte Carlo derived templates in a likelihood fit to extract the top quark mass and an *in-situ* measurement of the jet energy scale. We measure $\mathrm{M}_{\mathrm{top}} = 171.9 \pm 2.0\ \mathrm{GeV}/c^2$.

1 Introduction

Since it's discovery [1,2] at the Tevatron the top quark has been one of the most studied fundamental particles. It is more than an order of magnitude heavier than the next heaviest Standard Model fermion. This points to it's crucial role in a puzzle of the origin of mass. The top quark and the Higgs boson contribute in the loop corrections to the W boson mass, therefore knowing precisely the top quark mass and the W boson mass allows to constrain indirectly the Higgs boson mass [3]. Once the Higgs boson is discovered the knowledge of it's mass together with measurements of the top quark mass and the W boson mass will provide a sensitive test of the Standard Model [4]. Current measurements of the top quark mass and the W boson mass may be giving us hints on the nature of physics beyond the Standard Model [5]. In this letter we present a preliminary top quark mass measurement using the Lepton + Jets and Dilepton decay channels simultaneously. This approach is applied for the first time in a top quark mass measurement. More details on this analysis can be found in [6].

2 Top Quark Production and Decay

Top quarks are produced at the Tevatron mainly in quark-antiquark anihilation events where a gluon is produced, splitting into a $t\bar{t}$ pair. Each of the top quarks then decays into a W boson and a b quark with essentially 100% branching fraction. The W bosons can decay into a quark pair or a charged lepton-neutrino pair, giving rise to classification of the $t\bar{t}$ decays into three classes. Thus we have an All-hadronic decay channel with six jets in the final state, a Lepton + Jets decay channel where we find four jets, one lepton and missing transverse energy and a Dilepton decay channel characterized by two leptons, two jets and missing transverse energy. Due to difficulty of reconstructing τ leptons we restrict the meaning of lepton to an electron or a muon.

3 Combination Strategy

Measurements in all decay topologies are valuable as statistically independent cross-checks and are all needed to obtain best precision possible. Traditionally a dedicated analysis is performed in each channel and the results are combined using an averaging technique [7]. In any such combination one must assume the values of correlations in systematic effects between the measurements in different channels. A form of the likelihood shape is also required as an input and is usually assumed to be Gaussian. In this letter we present a preliminary top quark mass measurement using two decay channels simultaneously. The analysis presented here allows us not to make any assumptions mentioned above, yielding a more robust measurement.

4 The Jet Energy Scale

In the top quark mass measurements a major source of uncertainty is the modelling of the jet callibration or the jet energy scale (JES). Multiple effects contribute to the uncertainty on the jets [8]. A major uncertainty arises from modelling of nonlinearities of the calorimeter and energy loss in uninstrumented regions (absolute energy scale). Flow of particles outside of the jet cone (out of cone energy scale) gives large uncertainty especially for low energy jets. Another large systematic uncertainty arises from detector nonuniformity as a function of the pseudorapidity (relative energy scale). Interactions of the spectator partons (underlying event energy scale) and additional soft $p\bar{p}$ interactions in the same bunch crossing are sources of small systematics. We measure the offset from a nominal calibration in units of the total systematic uncertainty on the calibration σ_c. In Lepton + Jets channel presence of a hadronically decaying W boson allows us to callibrate *in-situ* the value of the shift Δ_{JES} from the nominal JES. Since the measurement is performed in two channels simultaneously this callibration will be applied uniformly to the two decay channels used.

5 Event Selection

5.1 Lepton + Jets Channel

To select the Lepton + Jets sample we require at least four jets with high transverse energies. At least one of the jets has to be identified as a b quark jet based on a presence of a secondary vertex or a “b-tag”. We separate the Lepton + Jets sample into 1-tag and 2-tag subsamples. In the 1-tag sample we require that there are exactly four jets with transverse energies greater than 20 GeV when corrected to the paritcle level. In the 2-tag samples we relax the energy for the fourth most energetic jet to have $E_T > 12$ GeV. We also allow additional jets in the event. We require a central electron or a muon with E_T or $p_T > 20$ GeV. The missing transverse energy must be greater than 20 GeV.

The background estimate for the Lepton + Jets samples is obtained form combination data - Monte Carlo technique. The major backgrounds arise from production of W boson in association with heavy flavour jets and light flavor jets where the light flavour jet is tagged (so called “mistag”) and from QCD events where one of the jets is misidentified as a lepton. We expect in the 1-tag sample 42.7 ± 12.5 and in the 2-tag 4.2 ± 1.9 background events.

5.2 Dilepton Channel

We require at least two jets with $E_T > 15$ GeV. Two leptons of opposite charge must be present with transverse energies of at least 20 GeV. If the leptons are of the same flavor we impose the requirement that their invariant mass lies at least 15 GeV$/c^2$ from the Z boson mass. Additionally we require that $H_T > 200$ GeV, $\not{E}_T > 25$ GeV where H_T is a linear sum of $\not{E}_T$ and transverse energies of jets and leptons. Topological cuts designed to remove events where $\not{E}_T$ arises due to instrumentational effects or τ production are applied. The Dilepton sample is divided into two subsets: a 0-tag sample and a 1-tag sample.

The background contributions to the Dilepton channel include events where a lepton is produced in association with jets and one of the jets is reconstructed as a lepton ("Fakes"), Drell-Yan production and diboson production. The Fakes background is estimated from data while other backgrounds are estimated using data-Monte Carlo and Monte Carlo only techniques. In the non-tagged sample we expect 31.1 ± 5.6 and in the tagged sample 2.4 ± 0.6 background events

5.3 Event Reconstruction

In each event we form a reconstructed top quark mass, a variable which is highly sensitive to the true top quark mass. In the Lepton + Jets channel we use a χ^2 fit where the magnitudes of lepton and jet momenta and the transverse components of unclustered energy are allowed to float within their resolution around the observed values. We impose a constraint that the invariant masses of the neutrino-lepton system and the light quark system are close to the measured W boson mass. The invariant mass of the leptonically decaying top quark daughters is constrained to be within the theoretical top quark width from the invariant mass of the hadronically decaying top quark daughters. The constraint is impsed through fit parameter taken to be the reconstructed top quark mass. The χ^2 minimization is performed for all jet-to-quark assignmets consistent with b-tagging combination and the combination with lowest minimum χ^2 is used. To form a reconstructed top quark mass in the Dilepton channel events we use the Neutrino Weighting Algorithm. We scan a range of top quark masses. At each point in the scan we integrate over the pseudorapidities of the two neutrinos and sum over the two possible jet-to-quark assignments. Knowing the top quark mass, neutrino pseudorapidities and masses of all particles in the decay cascade we solve for the neutrino transverse momenta. The integrand is formed by a Gaussian weight that compares the measured $\not{E}_T$ value to the solution obtained for the neutrino transverse momenta. The top quark mass in the scan that yields the highest weight is taken as the reconstructed top quark mass in this event. Additionally in each Dilepton event we calculate the H_T. In the Lepton + Jets channel we reconstruct also the invariant mass of the hadronically decaying W boson. As mentioned above this variable captures the shifts in JES.

5.4 Mass Fitting

We employ a template approach in this analysis. We generate $t\bar{t}$ Monte Carlo samples with a range of top quark mass and JES shifts. We also construct background models using data and Monte Carlo samples. We form probability density functions (pdf) for the observables mentioned above and compare them to the distributions of the observables obtained from data in an extended likelihood fit, to obtain a measurement of the top quark mass $\mathrm{M}_{\mathrm{top}}$ and the jet energy scale shift Δ_{JES}. The probability density functions are constructed using the Kernel Density Estimation (KDE) techniques [9,10,11]. In this approach the probability for an event to have certain values of the observables is calculated as a sum of values of kernel functions from all events in a given Monte Carlo sample. This technique treats intrinsically the correlations between observables. KDE gives the value of signal pdf at distinct values of $\mathrm{M}_{\mathrm{top}}$ and Δ_{JES} where Monte Carlo samples were generated. To obtain a pdf that varies smoothly as a function of those two parameters we use Local Polynomial Smoothing (LPS) [12]. LPS performs a fit to a parabolic function using the KDE estimates from Monte Carlo templates with the $\mathrm{M}_{\mathrm{top}}$, Δ_{JES} parameters lying close to the point where the estimate is desired. The value of the parabola at that point is interpreted as the pdf.

Using the distributions of observables in data, the negative log-likelihood is minimized for the top quark mass of 171.9 ± 1.7 (stat.+JES) GeV/c^2. Fitted Δ_{JES} value is consistent with nominal calibration of 0 σ_c.

6 Systematics

The largest systematic (0.6 GeV/c^2), b quark jet energy scale arises due to differences in modelling b and light flavour jets. As described in section 4 many effects contribute to uncertainty on JES. Modelling the offset from the nominal calibration as just one number Δ_{JES} gives source to the residual JES uncertainty of 0.5 GeV. Another large systematic (0.5 GeV/c^2 is due to the modelling of the initial and final state radiation. Additional systematics include generator differences (0.2 GeV/c^2), background shape (0.1 GeV/c^2), Monte Carlo sample statistics (0.1 GeV/c^2), lepton energy scale (0.1 GeV/c^2) and multiple $p\bar{p}$ interactions (0.1 GeV/c^2). Total systematic uncertainty is 1.0 GeV/c^2.

7 Conclusions

We performed the first top quark mass measurement simultaneously in two decay channels treating the correlations in the systematic effects intrinsically. No assumptions on the form of the likelihood needed to be made and the JES calibration was applied uniformly to both channels. The result obtained is:

$$\mathrm{M}_{\mathrm{top}} = 171.9 \pm 1.7\ (\mathrm{stat.} + \mathrm{JES}) \pm 1.0\ (\text{other syst.})\ \mathrm{GeV}/c^2 = 171.9\ \pm\ 2.0\ \mathrm{GeV}/c^2$$

References

1. F. Abe et al. *Phys. Rev. Lett.*, 74:2626–2631, 1995.
2. S. Abachi et al. *Phys. Rev. Lett.*, 74:2632–2637, 1995.
3. L3 OPAL The LEP Collaborations ALEPH, DELPHI and the LEP Electroweak Working Group. arXiv:hep-ex/07120929. Updated for 2008 winter conferences, 03/19/2008 , http://www.cern.ch/LEPEWWG.
4. M Beneke et al. Top quark physics. arXiv:hep-ph/0003033v1.
5. D. Stockinger A.M. Weber G. Weiglein S. Heinemeyer, W. Hollik. arXiv:hep-ph/0604147.
6. CDF9206 CDF Collaboration. http : //www − cdf.fnal.gov/physics/new/top/confNotes/cdf9206_thepublictopmass_2.pdf.
7. The Tevatron Electroweak Working Group for the CDF and DØ Collaborations. arXiv:hep-ex/0803.1683v1.
8. A. Bhatti et al. *Nucl. Instrum. Meth.*, A566:375–412, 2006.
9. David W. Scott. *Multivariate Density Estimation: Theory, Practice and Visualization.* Wiley-Interscience, 1992.
10. B. W. Silverman. *Density Estimation for Statistics and Data Analysis.* Chapman and Hall, 1986.
11. Kyle Cranmer. *Computer Physical Communcations*, 136(3):198–207, 2001.
12. Clive Loader. *Local Regression and Likelihood.* Springer, 1999.