FERMILAB-CONF-10-588-E

PROCEEDINGS OF SCIENCE

Precision measurements of the top quark mass and width with the DØ detector

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Since the discovery of the top quark in 1995 at the Fermliab Tevatron Collider, top quark properties have been measured with ever higher precision. In this article, recent measurements of the top quark mass and its width using up to 3.6 fb^{-1} of DØ data are summarized. Different techniques and final states have been examined and no deviations within these measurements have been observed. In addition to the direct measurements, a measurement of the top quark mass from its production cross section and a measurement of the top-antitop quark mass difference are discussed.

35th International Conference of High Energy Physics - ICHEP2010,
July 22-28, 2010
Paris France

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1. Introduction

With a mass of 173.3 $\pm$ 1.1 GeV [1], the top quark is the heaviest of all known fundamental particles. Due to the high mass, its Yukawa coupling is close to unity suggesting that it may play a special role in electroweak symmetry breaking[2]. Precise measurements of both, the W boson and the top quark mass, constrain the mass of the yet unobserved Higgs boson and allow to restrict certain extensions of the Standard Model[3]. At the Tevatron collider with a center-of-mass energy of 1.96 TeV, 85% of the top quark pairs are produced in quark-antiquark annihilation; 15% originate from gluon fusion. Top quarks are predicted to decay almost exclusively to a W boson and a bottom quark. According to the number of hadronic W decays, top events are classified into all-jets, lepton+jets and dilepton events. The lepton+jets channel is characterized by four jets, one isolated, energetic charged lepton and missing transverse energy. With 30%, the branching fraction of the lepton+jets channel is about seven times larger than the one of the dilepton channel whereas the signal to background ratio is about three times smaller. The main background in this final state comes from $W+$jets events. Instrumental background arises from events in which a jet is misidentified as an electron and events with heavy hadrons that decay into leptons which pass the isolation requirements. The topology of the dilepton channel is described by two jets, two isolated, energetic charged leptons and significant missing transverse energy from the undetected neutrinos. The main background are $Z+$jets and diboson events ($WW/WZ/ZZ+$jets) as well as instrumental background as characterized above. At the DØ experiment, different techniques are used to measure the top quark mass. They are summarized in the following sections together with the first measurement of the top anti-top quark mass difference and the first precise determination of the top quark width.

2. Top quark mass measurement using the Neutrino Weighting method

The Neutrino Weighting method [4] is a template based approach. For each event, the neutrino momenta are calculated assuming a certain top mass and different neutrino pseudorapidities. A weight w is assigned according to the agreement of the calculated sum of the neutrino momenta $\sum_{i=1}^{2} p_x^{\nu_i}$, $\sum_{i=1}^{2} p_y^{\nu_i}$, and the measured missing transverse momentum, given by

$$w = \exp\left(\frac{-(\not{E}_x - \sum_{i=1}^{2} p_x^{\nu_i})^2}{2\sigma_{\not{E}_x}^2}\right)\exp\left(\frac{-(\not{E}_y - \sum_{i=1}^{2} p_y^{\nu_i})^2}{2\sigma_{\not{E}_y}^2}\right), \tag{2.1}$$

where $\sigma_{\not{E}_x}, \sigma_{\not{E}_y}$ denote the resolution of the missing energy measurement. Next, signal probability distributions as a function of the top quark mass, the mean and the RMS of the weight distributions are derived using Monte Carlo simulated signal events of different top quark masses. To reduce the bias from background, background probability distributions are determined accordingly using simulated background events. Finally, the top quark mass is extracted from a likelihood fit.

The analyzed data set corresponds to an integrated luminosity of up to 1.0 fb^{-1} of dilepton top pair candidate events yielding

$$m_{\text{top}} = 176.2 \pm 4.8(\text{stat}) \pm 2.1(\text{syst})\ \text{GeV}.$$

The main systematic uncertainties on this measurement come from the energy scale of the jets, the modeling of the simulated signal events and the fragmentation of the jets from b quarks.

3. Top quark mass measurement using the Matrix Element method

The Matrix Element method yields the most precise approach to measure the top quark mass.

For each final state $y = (p_1, \ldots, p_6)$ of 6 partons with four-momenta $p_i, i = 1, \ldots, 6$, the probability to originate from the signal process assuming a certain top mass m_{top} is given by

$$P_{\text{sgn}}(x; m_{\text{top}}) = \frac{1}{\sigma_{\text{obs}}(m_{\text{top}})} \int \mathrm{d}\varepsilon_1 \, \mathrm{d}\varepsilon_2 \; f_{\text{PDF}}(\varepsilon_1) \; f_{\text{PDF}}(\varepsilon_2) \; \frac{(2\pi)^4 \, |M(y)|^2}{\varepsilon_1 \varepsilon_2 s} \, \mathrm{d}\Phi_6 \; W(x,y) \; , \quad (3.1)$$

where ε_1, ε_2 denote the energy fraction of the incoming quarks from the protons and antiprotons, f_{PDF} the parton distribution function, s, the center-of-mass energy squared, $M(y)$, the leading-order matrix element [5] and $\mathrm{d}\Phi_6$, an element of the 6-body phase space. The finite detector resolution is taken into account using a transfer function $W(x,y)$ that describes the probability of a partonic final state y to be measured as $x = (\tilde{p}_1, \ldots, \tilde{p}_n)$ in the detector. The signal probability is normalized with the observable cross section σ_{obs}.

In a similar way, for each event the probability to arise from background is calculated. Taking the huge amount of computing time into account, only the leading source of background is considered, i.e. $Z+$jets probabilities in the dilepton case, $W+$jets probabilities for lepton+jets. Finally, both probabilities are combined to an event probability using the signal fraction f_{top}

$$P_{\text{evt}}(x; m_{\text{top}}) = f_{\text{top}} \cdot P_{\text{sgn}}(x; m_{\text{top}}) + (1 - f_{\text{top}}) \cdot P_{\text{bkg}}(x) \, . \quad (3.2)$$

The top quark mass is extracted from a likelihood fit of the product of the event-by-event probabilities. To calibrate the method and correct for any bias, Monte Carlo simulated events are used to perform ensemble tests.

3.1 Dilepton channel

The analyzed data set corresponds to an integrated luminosity of up to 3.6 fb^{-1} of electron+muon events[6]. The top quark mass is measured to be

$$m_{\text{top}} = 174.8 \pm 3.3(\text{stat}) \pm 2.6(\text{syst}) \text{ GeV}.$$

The dominant sources of systematic uncertainties are jet uncertainties, such as their energy scale and resolution. With a statistical uncertainty of 3.3 GeV, this measurement has the smallest uncertainty of all top mass measurements performed in the dilepton channel at the DØ experiment.

3.2 Lepton+Jets channel

As stated above, the largest systematic uncertainty on the top quark mass arises from the jet energy scale[7]. Since one of the W boson decays hadronically in the lepton+jets channel, the well known W mass can be used to constrain the jet energies. An additional scale factor is introduced in Eq. (3.1) and both, the top quark mass and the jet energy scale are measured simultaneously.

In the lepton+jets channel, an integrated luminosity of 3.6 fb^{-1} is used and the top quark mass in this sample is measured to be

$$m_{\text{top}} = 173.7 \pm 0.8(\text{stat} + \text{JES}) \pm 1.6(\text{syst}) \text{ GeV}.$$

The systematic uncertainty is dominated by the uncertainty on the difference between the nominal inclusive response and the response of jets from b quarks in the calorimeter.

4. Top quark mass from production cross section

Two different schemes are commonly used to define the top quark mass: the $\overline{\text{MS}}$ and the pole mass definition. Direct top quark mass measurements are based on leading-order Monte Carlo generators where the top quark is described by a Breit-Wigner resonance and the measured mass corresponds only approximately to a pole mass. Since the top quark pair production cross section depends on the top quark mass, a measurement with a well-defined and renormalization-scheme independent mass definition can be realized comparing the results from cross section measurements to fully inclusive calculations in higher-order QCD[8]. Here, the pole mass definition is applied and the extracted value can be unambiguously interpreted. Comparing the combined measured cross sections from the lepton+jets, dilepton and lepton+tau channel to the NLO+NNLL calculations from S. Moch *et al.* [9] yields a top quark mass of

$$m_{\text{top}} = 169.1^{+5.9}_{-5.2}(\text{stat} + \text{syst})\ \text{GeV}.$$

This result is in good agreement with the direct measurements.

5. Top-antitop quark mass difference

In the Standard Model, particles and antiparticles are assumed to have same mass. Any observed deviation would indicate CPT violation. Replacing the top quark mass and the JES parameter in the lepton+jets Matrix Element with a free parameter for the top and antitop quark mass, the difference between both of the them can be evaluated[10]. This first measurement of the mass difference between a bare quark and antiquark was performed in the lepton+jets channel using 1 fb^{-1} of data. With a difference of

$$m_{\text{top}} - m_{\bar{\text{top}}} = 3.8 \pm 3.7(\text{stat} + \text{syst})\ \text{GeV}$$

the measurement is consistent with the Standard Model expectation. As this result is still dominated by the statistical uncertainty, future measurements will help to achieve even better precision and a stronger test of the Standard Model.

6. Top quark width

While the top quark mass is very precisely know, the top quark width isn't. A template based measurement has been performed at the CDF experiment but could only set an upper limit of 7.6 GeV at 95%C.L.[11]. Comparing this to the next-to-leading order Standard Model expectation of 1.3 GeV at a top quark mass of 170 GeV, the experimental precision is quite poor. To achieve a more precise estimation, it has to be assumed that the coupling in the t-channel single top quark production and the top quark decay are identical, i.e. $\sigma(t-\text{channel}) \propto \Gamma(W \to tb)$. Combining the measurement of the branching fraction $BR(t \to Wb) = 0.96\ ^{+0.093}_{-0.084}$ [12] and the single top production cross section of $\sigma(t-\text{channel}) = 3.14 + 0.94 - 0.80$ pb [13] the total width of the top quark can be extracted via

$$\Gamma_{top} = \frac{\sigma(t-\text{channel})\Gamma(W \to tb)_{\text{SM}}}{BR(t \to Wb)\sigma(t-\text{channel})_{\text{SM}}}. \tag{6.1}$$

Using a staitical Bayesian approach, the top quark width has been measured to be

$$\Gamma_{top} = 2.05 + 0.57 - 0.52(\text{stat} + \text{syst})\ \text{GeV}.$$

Apart from a very good precision of the top quark width, this measurement also offers a window to study new physics. As an example it allows to set a limit on 4th generation b' quark assuming unitarity of the 4x4 CKM matrix, $m_{b'} > m_{top} - m_W$ and a flat prior for $|V_{tb'}|$ between 0 and 1 an upper limit of 0.63 at the 95%C.L. [14].

7. Conclusion

The top quark mass has been measured at the DØ experiment in different final states using different techniques. In the dilepton channel, the largest systematic uncertainty arises from the jet energy scale. This has been addressed in the lepton+jets channel with a simultaneous measurement of the top quark mass and the jet energy scale which is well constrained by the mass of the hadronically decaying W boson. Combining all measurements with the Best Linear Unbiased Estimate, the top quark mass is determined at the DØ experiment [15] to be m_{top} = 174.2 $\pm$ 1.7 (stat+syst) GeV The top quark mass has also been extracted from cross section measurements comparing them to fully inclusive calculations in higher-order QCD. Both measurements, direct and indirect, are in good agreement. For the first time, the difference of the top and antitop quark mass has been measured at the DØ experiment. With $m_{\text{top}} - m_{\bar{\text{top}}}$ = 3.8 $\pm$ 3.7 (stat+syst) GeV, no deviation within uncertainties has been observed. Assuming that the coupling in t-channel single top quark production and top quark decay are identical, the top quark width could be determined for the first time with excellent precision. The measured value of 2.0$\pm$ 0.6 is in very good with the next-to-leading order expectation of 1.3 GeV for an assumed top quark mass of 170 GeV.

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