Top Quark Mass Measurements

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The top quark mass is a fundamental parameter of the Standard Model (SM). The precision measurement of its mass combined with W boson mass measurement can constrain the mass range of the SM Higgs boson, which is the only unobserved SM particle. In this letter we present updated results of selected analyses using data up to 4.8 fb^{-1} of $p\bar{p}$ collisions at Tevatron Fermilab obtained by the CDF and D0 detector.

1 Introduction

The top quark, observed by both the CDF and D0 experiments in 1995 [1,2], is by far the heaviest known elementary particle and its mass is almost 40 times heavier than its isospin partner, the bottom (b) quark [3]. Due to the heavy mass, the top quark plays an important role in electroweak radiative corrections. Therefore, top quark mass (M_{top}) measurements are important tests of the Standard Model (SM) and provide constraints on the Higgs boson mass. For these reasons, the CDF and D0 collaborations have measured M_{top} in all possible ways, and with continuous improvement.

2 Top quark production and decay

Top quarks at the Tevatron are predominantly produced in pairs, and decay almost always to a W boson and a b quark in the SM. The topology of $t\bar{t}$ events depends on the different decay of the two W bosons. In the dilepton channel, each W boson decay to charged lepton (electron and muon) and neutrino. Events in this channel thus contain two leptons, two b-quark jets, and two undetected neutrino. Because of the presence of two leptons, this channel has the lowest background. However the dilepton channel has the smallest branching fraction. In the all-jets channel, each W boson decays to two jets so that this channel contains two b quark jets and four light quark jets. This channel has the largest branching fraction but also the largest background from QCD multijet production. The lepton+jets channel has one W boson decaying leptonically and the other hadronically so that we have one charged lepton, two b-quark jets, two light quark jets, and one undetected neutrino. Because of the relatively large branching fraction with manageable background levels, we made the most precise M_{top} measurements using events in the lepton+jets decay topology.

To improvement the M_{top} measurement, CDF and D0 collaborations identify b quarks using the properties of the longer lifetime of metastable B hadrons [4,5]. Therefore jets arising from b quarks have secondary vertices that are displayed from the primary collision vertex. b-tagging significantly improve not only background fraction but also the combinatorics of jet-to-parton assignments, improving $\mathrm{M_{top}}$ resolution.

In the lepton+jets and all-jets channels, we have at least one W boson decaying hadronically (W decaying to two jets). Therefore we use the reconstructed dijet mass from W boson decay to constrain, *in situ*, the largest systematic in M_{top} measurements, the jet energy scale (JES), which is the calibration between jets energies and parton level energies, because of the narrow decay width and well known mass of the W boson.

3 Top quark mass measurement

For the M_{top} measurements, two primary techniques have been established. The template method (TM) uses the distributions of variables (templates) which are strongly correlated with the top quark mass and JES. In the building of a probability, only a few variables (usually less than two) are used, for instance reconstructed top quark mass and dijet mass in the lepton+jets channel. The Matrix Element Method (ME) uses event's probability to be a combinates signals and background. ME exploit all the information in the event by using a leading order matrix element calculation convoluted with parton distribution function and transfer functions (TFs) making connection between detector response and parton level particle. Because we can use all the information in principle, ME usually provide better precision of $\mathrm{M_{top}}$ than TM. Both techniques employ a likelihood to compare data to the modeling of signals and background to extract M_{top}.

D0 has a ME measurement in the lepton+jets channel using 3.6 fb^{-1}. D0 employed neural network (NN) based b-tagging [5] to improve signal to background ratio and also reduce jets to partons assignments. The TF factorizes into contributions from the individual top pair decay products. One can assume that the angles are well measured while their energy and momentum resolutions are determined from MC simulations. D0 estimates TF for four different η regions and for b jets, light jets, and leptons. A W+jets ME is used to estimate background probabilities. *In situ* JES calibration is performed using dijet mass from hadronically decaying W bosons. D0 measure $\mathrm{M_{top}} = 173.7 \pm 1.8$ GeV/c^2 [6].

CDF also has a ME based measurement in the lepton+jets channel using 4.8 fb^{-1}. This analysis integrates over more than 19 variables using a quasi-MC integration technique to account imperfect assumptions about perfectly measured angles and intermediate particle masses. TF is parameterized as a function of η and p_T separately for b-jets and light jets. This analysis also makes a cut using a NN to reject not only background contribution but also poorly modeled signal events where the objects in the detector do not match the assumed partons at the matrix element level. In this measurement, we increase muon acceptance by using missing energy plus two jets trigger which give almost 30% more candidate events with a similar signal to background ratio. With *in situ* JES calibration, we measure $\mathrm{M_{top}} = 172.8 \pm 1.3$ GeV/c^2 [7]. This measurement is the most precise top quark mass measurement in the world to date.

CDF has another lepton+jets channel measurement using TM. We uses exactly the same data as the ME analysis, including missing energy plus two jets trigger to increase muon acceptance. In this measurement, three variables are used to estimate probabilities of events. The first two variables are the reconstructed top quark mass from the kinematic fitter and dijet mass from hadronically decaying W boson used to make the $\mathrm{M_{top}}$ measurement with *in situ* JES calibration in the same channel [8]. In addition, a 3^{rd} variable is introduced: the 2^{nd} best reconstructed top quark mass by choosing 2^{nd} jets to parton assignment based on the kinematic fit. To take into account correlation between the variables and build probabilities without parameterization, kernel density estimation (KDE) [8,9] was employed. This revisit in a measured $\mathrm{M_{top}} = 172.0 \pm 1.5$ GeV/c^2 [10]. This measurement use a technique complementary to the ME based measurement and gives a consistent result.

CDF has a dilepton channel measurement using TM. Two variables sensitive to M_{top} are used by taking into account the correlations using KDE. One variable is the reconstructed top quark mass using the neutrino weighting algorithm (NWA) [11,12] in the underconstrained system from two neutrinos. The unknown pseudorapidities of the two neutrinos are integrated over. The solutions for a given top quark mass are weighted by using measured missing transverse energy. The other variable is m_{T2} [13,14] which is a measure of transverse mass in two missing particles final states. It provides a measured M_{top} in the dilepton channel [15] and is the first use of this technique. The simultaneous measurement with the two variables gives $M_{top} = 170.6 \pm 3.8$ GeV/c^2 [10].

Because two TM measurements share the same machinery, a simultaneous measurement can be made using the lepton+jets and dilepton channels [8]. The correlation of systematic uncertainties is intrinsically taken into account. The combined measurement both lepton+jets and dilepton channels using 4.8 fb^{-1} data gives $M_{top} = 171.9 \pm 1.5$ GeV/c^2 [10].

D0 makes a dilepton channel measurement using a rather different idea with 1 fb^{-1} of data. The basic idea is to use the measured $t\bar{t}$ production cross section as a function of top quark mass and compare with predictions from theoretical calculations. In general, the different theoretical prediction gives different results but all the measurements are consistent with results from the direct measurement [16].

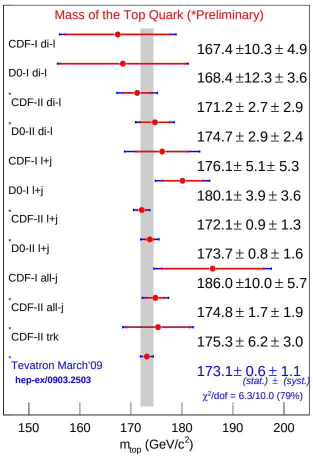

Figure 1: World average top quark mass and comparison with individual measurements from CDF and D0 experiments.

The measurements from different channels and different experiments can be combined using the best linear unbiased estimation technique, as shown in Fig. 1. In such combinations correlations among uncertainties for different results are properly taken into account. As a world average, we have $M_{top} = 173.1 \pm 1.3$ GeV/c^2 [17] with a good agreement between different channels and methods. However, this combination does not reflect recent updates. Especially CDF ME measurement in the lepton+jets channel has approximately same precision with this world average due to improvements of machinery, using more data, and increasing muon acceptance etc. The combination reflecting all the updated measurements will give much better precision of M_{top} .

3.1 Top and anti-top quark mass difference measurement

The precision determination of M_{top} allows us to measure the mass difference between top quark and anti-top quark to a few GeV. In the CPT theorem, which is fundamental to any local Lorentz-invariant quantum field theory, the quark mass should be same as its anti-quark partner. Despite the fact that no violations have ever been observed in the meson and baryon sectors, it is important to test CPT violation in all sectors such as quarks and high mass particles. D0 collaboration has a first direct measurement of top quark and anti-top quark mass difference (δM_{top}) in the lepton+jets channel using the ME technique. In the ME calculation, one assumes SM-like $t\bar{t}$ production and decay, where identical particle and antiparticle masses are assumed for b quarks and W bosons but not for top quarks. Using 1 fb^{-1} of $p\bar{p}$ collisions data, they measure $\delta M_{top} = 3.8 \pm 3.7$ GeV/c^2 [18].

4 Conclusion

The CDF and D0 collaborations have performed a robust set of analyses using many techniques and improvements to have better understand the important fundamental parameter of the SM. As a result, CDF ME measurement gives $M_{top} = 172.8 \pm 1.3$ GeV/c^2 which has consistent result and similar uncertainty with a year ago world average, $M_{top} = 173.1 \pm 1.3$ GeV/c^2 . The new world average considering the most recent updated analyses will be available soon to give much better precision of M_{top} . By end of Run II, we expect 8∼12 fb^{-1} of data delivered by the Tevatron which could be almost a double the data sample used in this letter for both CDF and D0. An ultimate precision of about 1 GeV/c^2 or below on the mass of the top quark is expected to be reached.

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