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Alternative methods for top quark mass measurements at the CMS

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Abstract. The top quark mass is a fundamental parameter of the standard model and together with the W boson mass and the Higgs boson mass it provides a strong self-consistency check of the electroweak theory. Recently several new measurements of the top quark mass using alternative observables and reconstruction methods are performed by the CMS collaborations at the CERN LHC. Alternative methods can give a insight by providing different systematic sensitivities while standard ones are currently limited by jet energy uncertainties. We introduce various results from new methods including the one using a charmed meson, which are found to be consistent with what is obtained in standard measurements.

1 Introduction

The top quark is the heaviest elementary particle observed so far, and thus is expected to have the highest of the Yukawa couplings with the Higgs boson. Thus, its mass, m_t, is an important input to global fits of electroweak parameters along with measurements of the W boson and Higgs boson masses, and gives significant cross-check of the consistency of the electroweak theory. In addition, by comparing precision electroweak measurements and theoretical predictions, an exact measurement of m_t can place strong constraints on contributions from physics beyond the standard model (SM). The top quark mass has been measured with ever-increasing precision, using a full kinematic reconstruction of the $t\bar{t}$ final states since it was discovered at the Tevatron [1, 2]. Most precise measurements reconstruct top quarks decayed in hadronic jets and calibrate the energy of hadronic jets in situ, using constraints from the reconstructed W boson mass [3–5]. Currently, the world's best measurement of the top quark mass at 7 and 8 TeV by the CMS experiment [6] is value of 172.44 ± 0.48 GeV, reaching a precision of 0.28% [7] and is in good agreement with the 2014 world average combined from four experiments (ATLAS, CDF, CMS, and D0) [8]. Experimental uncertainties stem from the calibration of reconstructed jet energies and their resolution are one of the biggest limits of the most precise top quark mass measurements. The other important uncertainties are concerning the modeling of the bottom quark fragmentation and hadronization. Alternative measurements can give us a hand to improve the precision of the top quark mass measurement and give a insight by providing different systematic sensitivities. In this note, alternative measurements of the top quark mass performed at CMS without using jets or by extracting it from the theoretically calculable observables or by using single-top event topologies are described.

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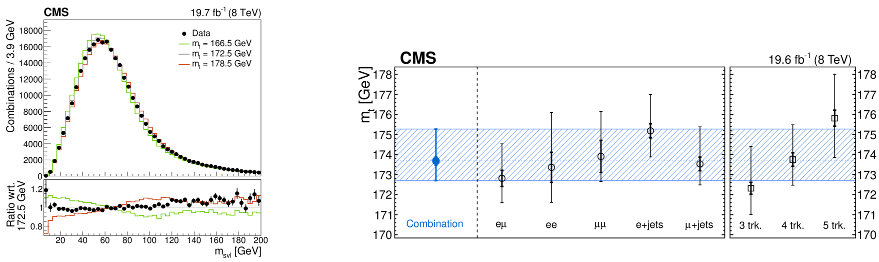

Figure 1. Lepton-SV invariant mass distribution for a combination of all five channels, compared to simulated distributions at three different generated top quark mass values (left) and results of the m_t measurement in the individual channels and their combination (right).

2 Measurements without jets

2.1 Using secondary vertices and leptons

The mass of the top quark is estimated by measuring the invariant mass of a charged lepton from the W boson decay and the tracks used in the reconstruction of a secondary vertex (SV) resulting from the b hadrons. This secondary vertex-lepton invariant mass system (m_{svl}) is highly sensitive to the top quark mass and lessens experimental uncertainties from the calibration of jets, but brings about uncertainties in the modeling of top quark decays and b hadronization. In the recent results of extracting the top mass by using m_{svl} [9], m_t is obtained as 173.68 ± 0.2(stat) $^{+1.58}_{-0.97}$(syst) GeV. Figure 1 shows the observed m_{svl} distribution for a combination of all five channels($e\mu$, ee, $\mu\mu$, $e + jets$ and $\mu + jets$), compared to simulated distributions at three different generated top quark mass values (left) and results of the m_t measurement in the individual channels and their combination (right). The leading source of systematic uncertainty is the modeling of b-quark fragmentation in the simulation. Experimental systematic uncertainty and the overall modeling of hadronization do not impact on the analysis strongly, hence it can be complementary to the standard methods.

2.2 Using charm mesons and leptons

The idea on estimation of the top quark mass using J/ψ was suggested in [10] and implemented by the CMS collaboration using LHC 8 TeV data for the first time [11]. Correlation with the invariant mass of J/ψ from the B hadron decays and an isolated lepton from the W boson decay and top mass is used to extract the top quark mass. The measured top quark mass is 173.5 GeV ± 3.0 GeV (stat.) ± 0.9 GeV (syst.) GeV. As the top quark mass is reconstructed by using only leptons, several systematic uncertainties related to QCD, jet reconstruction and b-tagging techniques, are considerably reduced, while the b quark fragmentation modeling is to be dominant. With the statistics available in the Run I dataset this is one of the few top mass measurements which is not yet dominated by systematics. As such it is one of the more promising methods to follow up in Run II of the LHC.

2.3 Using lepton kinematics

Another alternative approach [12] is to use observables that rely only on the kinematics of lepton originating from the decay of the top quark. Amongst several kinematic observables, $p_t(l^+l^-)$ is found to be the most sensitive to m_t and the more robust against the uncertainties in the modelling of the dynamics of top production. m_t obtained by the CMS is 171.7 ± 1.1 (stat.) ± 0.5 (exp.) $^{+2.5}_{-3.1}$ (th.) $^{+0.8}_{-0.0}$ (p_t(t)) GeV [13]. The dominant theoretical uncertainties are caused from the modeling of the top quark p_T and the choice of QCD scales of leading order signal MC, hence it could be significantly reduced in the next MC generation at NLO at 13 TeV. Furthermore, with the LHC larger datasets and a better calibration of the momentum of the leptons, we expect lower uncertainties.

3 Measurements using theoretically calculable observables

3.1 Inclusive production cross section

The top quark pole mass can be inferred by comparing the measured cross section to a precise theoretical prediction of the dependence of the inclusive $t\bar{t}$ cross-section on m_t. At center-of-mass energy of 7 or 8 TeV, precision of the top mass measured by CMS at NNLO with NNLL resummation reached below 2 GeV [14]. Recently, CMS extracted the top pole mass m_t = 172.3 $^{+2.7}_{-2.3}$ GeV at 13 TeV [15]. Figure 2 (left) shows the measured production cross section as a function of the assumed top-quark mass, compared with the mass-dependent prediction at NNLO+NNLL, for 7 and 8 TeV in LHC run I. The top quark mass is extracted by maximizing the product of the likelihoods corresponding to the measured cross-section at those energies and uncertainties are assigned to the cross-section to account for the LHC luminosity uncertainties.

3.2 $t\bar{t}$ + jet invariant mass

A method using the normalized differential cross section as a function of the invariant mass of the $t\bar{t}$ system and the leading extra jet which is not coming from top quark decay is proposed in [16] and experimentally tested by the CMS experiments [17]. The measured differential cross section is compared to the predicted cross sections for each bin of the ρ_s (=$2m_0/m(t\bar{t}, jet)$) distribution using different top quark masses and the most probable top quark mass is extracted. The precision is mostly limited by the systematic uncertainties arising from modeling sources and the theoretical uncertainties from POWHEG $t\bar{t}$+jet simulation.

4 Measurements in alternative topologies

While most measurements of the top quark mass to date are obtained from $t\bar{t}$ events, measuring the top quark mass in single-top quark production has performed because of sufficient statistics of those events and systematic uncertainties partially uncorrelated from those considered in $t\bar{t}$ production. In this analysis, top quark candidates are reconstructed from the muon, missing transverse energy, and b-jet and constraint is that the muon and the neutrino come from W boson decay. The measured value is m_t = 172.60 ± 0.77 (stat.) $^{+0.97}_{-0.93}$ (syst) GeV [18] and shows very good agreement with the current world average, based on measurements with $t\bar{t}$ events. The potential differences in sensitivity to the hard scattering and the modeling of underlying events and color reconnection are so far not observed and the measurements is limited by jet energy scale related uncertainties.

5 Summary and prospects

Figure 2 (right) [19] summarizes the most recent top mass measurements performed by the CMS Collaboration employing alternative methods. The precision of the standard measurements have approached ≈500 MeV, remains still unchallenged by the precision of the alternative methods explored

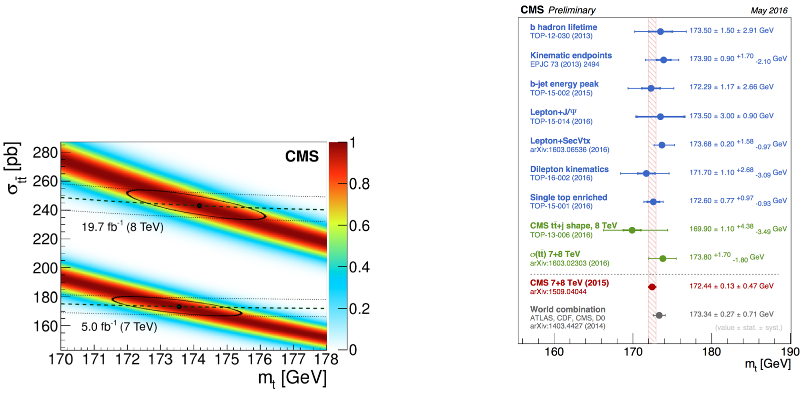

Figure 2. Predicted dependence of the $t\bar{t}$ production cross section on the top quark pole mass at NNLO+NNLL for 7 and 8 TeV (left) and recent alternative top-quark mass measurements from the CMS collaboration compared to the combination of standard measurements from CMS and to the 2014 world average (right).

so far. Nevertheless, alternative mass measurements can provide insights in the modeling of top quark events and bottom quark hadronization and produce important cross checks by using different mass definitions. With the expected higher integrated luminosity and $t\bar{t}$ cross sections at the Run II of the LHC, many of these methods will be more important and might play a crucial role in improving the overall precision on the top quark mass.

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