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Top quark mass measurement at the Large Hadron Collider

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Summary. — Measurements of the top quark mass in proton-proton collisions at the LHC at $\sqrt{s} = 7\,\text{TeV}$ are presented from data collected by the CMS and ATLAS experiments. The $t\bar{t}$ samples are reconstructed in the lepton+jet final state, where events are required to have exactly one isolated electron or muon and at least four jets, and in the dilepton final state, with two leptons, at least two jets, and missing transverse energy. The different methods used for the top quark measurement are described. The indirect top quark mass determination from the cross section and the measurement of the top-antitop quark mass difference are also presented.

PACS 14.65.Ha – Top quarks.
PACS 12.15.Ff – Quark and lepton masses and mixing.
PACS 14.80.Bn – Standard-model Higgs bosons.

1. – Introduction

The top quark is an important piece of the standard model (SM), and a precise measurement of its mass is one fundamental input to the global electroweak fits which provide constraints on the properties of the yet unobserved Higgs boson. The mass of the top quark (m_{top}) has been measured precisely by the Tevatron experiments, and the current world average is $173.3 \pm 0.6(\text{stat.}) \pm 0.9(\text{syst.})\,\text{GeV}/c^2$ [1]. At the Large Hadron Collider (LHC), top quarks are produced mainly in pairs through the hard processes $gg \to t\bar{t}$ (90%) and $q\bar{q} \to t\bar{t}$ (10%). Within the SM, the top quark decays almost exclusively to a W boson and a b-quark. Depending on the decay mode of the W bosons, the $t\bar{t}$ events can be classified into three channels: the lepton+jet channel ($BR \approx 30\%$, considering only electrons and muons), the dilepton channel ($BR \approx 5\%$) and the fully hadronic channel ($BR \approx 44\%$). First direct measurements of m_{top} in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ have been performed at the LHC with the data collected in 2010, in the dilepton and lepton+jet channels.

2. – Mass reconstruction and results

The dilepton channel provides the purest sample of top quark events, as it has the largest signal-to-background ratio. However, the decays of $t\bar{t}$ pairs contain at least two neutrinos in the final state, and only the sum of their transverse momenta p_{T} can be measured, leading to a kinematically under-constrained system. Therefore, one additional variable must be used in order to fully constrain the system, chosen either from simulation or from data.

The first measurement of m_{top} at the LHC has been performed in the dilepton channel, using a data sample of $36\,\mathrm{pb}^{-1}$ [2]. Events are selected by requiring two leptons, at least two jets, and missing transverse energy. The mass is reconstructed from the kinematic characteristics of the events with two numerical methods, a full kinematic analysis (KINb) and an analytical matrix weighting technique (AMWT), which have been improved over those used at the Tevatron. For each method, a set of templates are constructed from simulated samples and a likelihood fit is performed to derive the top quark mass. The combination of the results yields a measurement of $m_{\mathrm{top}} = 175.5 \pm 4.6(\mathrm{stat.}) \pm 4.6(\mathrm{syst.})\,\mathrm{GeV}/c^2$. In the KINb method, the kinematic equations describing the $t\bar{t}$ system are solved many times per event for each lepton-jet combination. Each time, the jet p_T, the $\not\!\!E_T$ direction, and the longitudinal momentum of the $t\bar{t}$ system $p_z^{t\bar{t}}$ are varied independently according to their resolutions to scan the kinematic phase space compatible with the $t\bar{t}$ system. The jet p_{T} and $\not\!\!E_T$-direction resolutions are obtained from the data; the $p_z^{t\bar{t}}$ description, which is minimally dependent on m_{top}, is taken from simulation. Solutions with the lowest invariant mass of the $t\bar{t}$ system are accepted if the mass difference between the two top quark masses, is less than $3\,\mathrm{GeV}/c^2$. The combination with the largest number of solutions is chosen, and the mass value is estimated by a Gaussian fit in a $50\,\mathrm{GeV}/c^2$ window around the most probable value. Events with no solutions do not contribute to the m_{top} measurement. The lepton-jet pair is correctly assigned in 75% of the cases. In the analytical matrix weighting technique (AMWT), the kinematic equations describing the $t\bar{t}$ system are also solved many times per event. For this measurement, an analytical method is used. In each event, there are two possible lepton-jet pairings with four solutions for each pairing. Because the system is under-constrained, solutions are obtained for all values of m_{top} in the range 100 to $300\,\mathrm{GeV}/c^2$ in $1\,\mathrm{GeV}/c^2$ steps. In order to determine a preferred value of m_{top}, a weight is assigned to each solution, based on the matrix element expectation for the reconstructed lepton p_{T}.

The lepton+jet channel is generally considered the most precise channel to measure m_{top} as it provides an unconstrained system. Two measurements of m_{top} were performed in this channel by the CMS and ATLAS collaborations, using the Ideogram and the Template methods, respectively. The first method uses a simplified version of the Ideogram technique that was used by the D0 experiment at the Tevatron [3]. In the ideogram method, a constrained kinematic fit is used to reconstruct the complete kinematics of the event under the hypothesis that it is a $t\bar{t}$ event decaying into a lepton+jets final state. A likelihood is calculated for each event in the data sample from the output of the kinematic fit. The likelihood calculation takes into account all the possible assignments of jets to quarks in the $t\bar{t}$ lepton+jet event hypothesis, and considers the possibility that the event is a $t\bar{t}$ event or a background event. A joint likelihood fit over all events in the data sample is then used to extract the value of m_{top}. The main difference with the D0 implementation is that no in-situ fit of the jet energy scale (JES) is performed. Events are selected by requiring one electron or muon, missing transverse energy and at least four jets, with a final signal-to-background ratio of $S/B = 378/324 \approx 1.2$; b-tagging information is not used for the selection of events but it is used in the event likelihood calculation to improve the extraction of m_{top} from the events. The results in the electron+jets and muon+jets channels are statistically consistent, and the combined likelihood of the two channels yields $m_{\text{top}} = 173.1 \pm 2.1(\text{stat.}) \pm 2.4(\text{JES}) \pm 1.4(\text{other syst.})\,\text{GeV}/c^2$. A combination of this measurement with the previous CMS results in the dilepton channel [2] is performed using the Best Linear Unbiased Estimate (BLUE) method [4], and it yields $m_{\text{top}} = 173.4 \pm 1.9(\text{stat.}) \pm 2.7(\text{syst.})\,\text{GeV}/c^2$ [5].

The top quark mass is also measured in the lepton+jet channel using the template method with a data sample of about $0.70\,\text{fb}^{-1}$. The 2-dimensional template analysis determines m_{top} together with a global jet energy scale factor (JSF) between data and simulation. In the 2-dimension template analysis, both m_{top} and JSF are simultaneously determined from the distributions of the reconstructed invariant masses of the top quark $m_{\text{top}}^{\text{reco}}$ and the W boson m_W^{reco}. Events are selected by requiring one electron or muon, missing transverse energy, and at least four jets (of which at least one b-tagged). For the selected events, each light jet pair with a reconstructed mass in the range 50–100 GeV/c^2 is combined with every b-tagged jet. From this list, the jet triplet with the maximum p_T defines the top quark candidate. The hadronic W boson decay candidate is chosen from the two untagged jets whose measured invariant mass is constrained to m_W using the natural width $\Gamma_W = 2.2\,\text{GeV}$. Two observables m_W^{reco} and $m_{\text{top}}^{\text{reco}}$ are then constructed. Templates are constructed as a function of an input m_{top} in the range [160–190] GeV/c^2, and input values for the JSF in the range [0.9–1.1]. The signal templates for the $m_{\text{top}}^{\text{reco}}$ distribution are fitted by the sum of a Gaussian and a Landau function whereas the m_W^{reco} distributions are fitted by the sum of two Gaussian functions. The dependence of the parameters of the fitted Gaussian or Landau functions are parameterized as a function of m_{top} and the JSF to produce probability density functions for the signal and the background. For any set of observed ($m_{\text{top}}^{\text{reco}}$, m_W^{reco}), a likelihood can be maximized with respect to m_{top}, JSF and the fraction of background, which is left free in the fit. The electron and muon channels yield consistent results. Combining both electron and muon channels of the 2011 data together with the results from the 2010 data, the ATLAS measurement has a total uncertainty of 2.8 GeV, $m_{\text{top}} = 175.9 \pm 0.9(\text{stat.}) \pm 2.7(\text{syst.})\,\text{GeV}/c^2$ [6].

3. – Top quark mass determination from the cross section

Direct measurements of m_{top} at hadron colliders rely on the reconstruction of the kinematic observables which are sensitive to m_{top}. These direct measurements depend on the details of the kinematics, reconstruction, and calibration. Alternatively, m_{top} can be derived indirectly from the cross section measurement. Both ATLAS and CMS collaborations extract m_{top} from the $t\bar{t}$ cross section measurements in the lepton+jet [7] and dilepton [8] channels, for samples of $35\,\text{pb}^{-1}$ and $1.14\,\text{fb}^{-1}$, respectively. At higher order QCD predictions, the top quark mass depends on the renormalization scheme and its value can differ considerably for, *e.g.*, pole mass or $\overline{\text{MS}}$ mass definitions. The value of m_{top} is extracted by comparing the measured inclusive $t\bar{t}$ production cross section, $\sigma_{t\bar{t}}$, to fully inclusive calculations at high-order QCD that involve an unambiguous definition of m_{top}. This extraction provides an important test of the mass scheme as applied in simulation and gives complementary information, with different sensitivity to theoretical and experimental uncertainties than the direct measurements which rely on the kinematic details of the mass reconstruction. The results are in very good agreement with similar measurements at the Tevatron [9] and provide for the first time the determination of the top quark pole and $\overline{\mathrm{MS}}$ mass at the LHC. This extraction also tests the top quark internal consistency of perturbative QCD calculations for $\sigma_{t\bar{t}}(m_{\mathrm{top}}^{\mathrm{pole}})$, calculated in a well-defined top renormalization scheme.

4. – Top quark mass difference of top and antitop quarks

The individual symmetries are known to be violated in the weak interactions, but their combination, the CPT symmetry, is not expected to be violated. A direct measurement of a mass difference between particle and anti-particle would indicate a violation of CPT symmetry. Quarks carry color charge and cannot be observed directly as they hadronize to colorless particles before decaying. One exception is the top quark, as it decays before hadronization due to its short lifetime of the order of 10^{-24} s. The top quark is therefore the only quark which can be used in this way to test CPT symmetry since the other quarks have a much longer lifetime. The mass difference between the top quark and the antitop quark Δm_{top} has been measured before at the Tevatron and no significant deviation from zero was found. A measurement of Δm_{top} is performed using events with a muon and at least four jets in the final state with data collected in 2011 and corresponding to an integrated luminosity of $1.09\,\mathrm{fb}^{-1}$. The measured value of $\Delta m_{\mathrm{top}} = -1.2 \pm 1.2(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})\,\mathrm{GeV}/c^2$ [10] is consistent with the SM. In the measurement, most of the systematic uncertainties cancel out when the difference is computed. The measurement at the LHC is dominated by the statistical uncertainty, unlike at the Tevatron where the dominant uncertainty is systematical.

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