Top-quark mass results at the LHC

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Abstract. The mass of the top quark has been measured by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) in pp collisions at $\sqrt{s} = 7$ TeV. Both experiments use large samples of 2011 data in all decay channels of top-quark pairs to obtain very precise results. An overview of the recent measurements is given in this report.

1. Introduction

The top-quark mass, $m_t$, is an important parameter of the standard model of particle physics and has been measured with great precision by the CDF and D0 collaborations at the Fermilab Tevatron [1]. At the CERN LHC both multi-purpose experiments, ATLAS [2] and CMS [3], study the production and properties of top quarks. Besides being significant by themselves, these measurements also constitute benchmarks for detector performance.

A new challenge for the reconstruction of top-quark events at the LHC is due to the large amount of high-energetic QCD radiation at $\sqrt{s} = 7$ TeV. This complicates the correct assignment of reconstructed jets to the quarks from the decay $t\bar{t} \rightarrow bW^+\bar{b}W^-$ where the subsequent decays of the W bosons result in either two charged leptons and the corresponding neutrinos (“dilepton channel”), one charged lepton, the corresponding neutrino and two light flavor jets (“lepton+jets”) or four light-flavor jets (“all-hadronic”). The higher top-quark production cross-section and instantaneous luminosity compared to the Tevatron results in nearly 1 million top-quark pairs produced at each experiment in 2011, where an integrated luminosity of up to 5 fb$^{-1}$ was recorded. Efficient trigger systems and algorithms for identifying b-jets allow the selection of top-quarks in unprecedented quantity. The uncertainties on the jet energy corrections reach a level of 1% [4, 5], giving an excellent opportunity for studying top-quarks with high precision.

2. Direct measurements using lepton+jets final states

Due to its large branching ratio and decent background contamination, the lepton+jets channel is considered to be the “golden channel” for direct top-quark mass measurements, where electrons and muons are considered as well-identifiable leptons. The background from W+jets production can be controlled using b-tagging and the constrained kinematics allow for a complete reconstruction of the event.
2.1. ATLAS: Measurements using template methods \[6\]

In the event selection exactly one isolated muon/electron with transverse momentum \(p_T\) above 20/25 GeV within \(|\eta| < 2.5\) and at least four jets with \(p_T > 25\) GeV, \(|\eta| < 2.5\) are required, where at least one jet has to be b-tagged. A significant amount of missing transverse energy \(E_T^{miss} < 20/35\) GeV, \(E_T^{miss} + m_{W,lep} > 60\) GeV and an untagged jet pair with 50 GeV < \(m_{jj}\) < 110 GeV as a W boson candidate are required. The top-quark candidate is then formed by choosing the jbj triplet with maximum \(p_T\) and constraining \(m_{jj}\) to the W boson mass. In total, 11 781 events are selected in 1 fb\(^{-1}\) data with an estimated purity of 72% \(t\bar{t}\) events.

Two different approaches are used for extracting the top-quark mass from the selected sample. In the 2D template method, templates for \(m_{\text{top}}^{\text{reco}}\) as a function of an assumed global jet energy scale factor (JSF) and for \(m_{\text{top}}^{\text{reco}}\) as a function of the input top-quark mass and JSF are constructed. An unbinned likelihood fit is performed to extract the top-quark mass, JSF and the number of background events simultaneously as shown in Fig. 1 and yields a result of \(m_t = 174.5 \pm 0.6 \, \text{(stat)} \pm 2.3 \, \text{(syst)}\) GeV. The systematic uncertainty is dominated by the uncertainty on the amount of additional radiation (ISR/FSR) and the b-jet energy scale.

The alternative approach uses improved event reconstruction through a likelihood fit, selecting a subset of 2875 events in 1 fb\(^{-1}\) data. 1D templates are created for \(R_{32} \equiv m_{\text{top}}^{\text{reco}}/m_{W}^{\text{reco}}\) as a function of \(m_t\) in an attempt to minimize the impact of the jet energy scale uncertainty. A binned likelihood fit is employed to extract \(m_t = 174.4 \pm 0.9 \, \text{(stat)} \pm 2.5 \, \text{(syst)}\) GeV, where the systematic uncertainty is dominated by radiation and the jet energy scale.

2.2. CMS: Measurement using the ideogram method \[7\]

At CMS exactly one isolated lepton with \(p_T > 30\) GeV, \(|\eta| < 2.1\), at least four jets with \(p_T > 30\) GeV, \(|\eta| < 2.4\), and exactly two b-tags are required. For the event reconstruction b-tagged jets are assigned to b-quarks and untagged jets to light quarks. A constrained kinematic fit checks the compatibility of each possible permutation with the \(t\bar{t}\) hypothesis, i.e. \(m_W = 80.4\) GeV, \(m_t = m_{\bar{t}}\). The permutations are weighted by their goodness-of-fit probability \(P_{\text{gof}}(\chi^2) = \exp(-\frac{1}{2}\chi^2)\) and are required to fulfill \(P_{\text{gof}}(\chi^2) > 0.2\). The selected sample contains 5194 events in 5 fb\(^{-1}\) data, with an estimated purity of 96% \(t\bar{t}\) events and 44% correct permutations (Fig. 2).
3.1. ATLAS: Measurement using the \( m_{T2} \) method \([9]\)

Events with exactly one isolated muon and one isolated electron with opposite charge and \( p_{T, e/\mu} > 20/25 \text{ GeV} \), \(|\eta| < 2.5\) are selected. At least two b-tagged jets
Under the $t\bar{t}$ hypothesis, $m_{T2}$ represents the lower bound of the parent particle mass:

$$m_{T2} = \min_{\vec{p}_T^{(1)}, \vec{p}_T^{(2)}} \left\{ \max \left[ m_T(m_{\text{invis}}, \vec{p}_T^{(1)}), m_T(m_{\text{invis}}, \vec{p}_T^{(2)}) \right] \right\}.$$ 

Requiring $m_{T2} < 220$ GeV and taking the permutation with smallest $m_{T2}$, 731 events are selected in $4.7$ fb$^{-1}$ data, with a purity of 95% $t\bar{t}$ (Fig. 3a). As $m_{T2}$ is proportional to the simulated input mass, the mean value $m_{T2}$ serves as an estimator for $m_t$. The calibration is cross-checked using simulated same-flavor events and the measurements yields $m_t = 175.2 \pm 1.6$ (stat)$^{+3.1}_{-2.8}$ (syst) GeV, where the JES, b-JES and color reconnection are the leading systematic uncertainties.

3.2. CMS: Measurement using the AMWT method [10]

Two isolated, oppositely charged leptons (e or $\mu$, $p_T > 20$ GeV, $|\eta| < 2.4$, $m_{\ell\ell} > 20$ GeV) and at least two jets ($p_T > 30$ GeV, $|\eta| < 2.4$, 1 b-tag) are required. Same-flavor events have to fulfill additionally $E_{T\text{miss}} > 40$ GeV and $m_{\ell\ell} < 76$ GeV and $m_{\ell\ell} > 106$ GeV. In 5 fb$^{-1}$ data 11 627 events are selected, with an estimated purity of 89% $t\bar{t}$ signal events (Fig. 3b).

For the analytical reconstruction of the unknown neutrino momenta, a scan of top mass hypotheses in the range $100 – 300$ GeV is performed and up to $2 \times 4$ solutions per event and top mass hypothesis are retrieved. Each solution is assigned a weight based on the LO matrix element. For each event the calculation is repeated 1000 times with the jets smeared within detector resolutions and the $m_{\text{top}}$ hypothesis with the highest averaged weight is taken as $m_{\text{AMWT}}$. A likelihood fit of the $m_{\text{AMWT}}$ distribution is performed and yields a result of $172.5 \pm 0.4$ (stat)$\pm 1.5$ (syst) GeV, where the JES is the largest contribution to the systematic uncertainty.

3.3. CMS: Measurement using the endpoint method [11]

A new method fits the endpoints of $m_{T2,\perp} = m^{\min}_{\ell\ell}$ (using only momentum components transverse to $p_T^{\ell}$), and of $m^{\max}_{\ell\ell}$ directly in data to retrieve a result with minimal dependence.
on simulation and thus complementary systematic uncertainties. Two leptons and two b-tagged jets are required so that 8678 events are selected in 5 fb⁻¹ of data (Fig. 3b). The result \( m_t = 173.9 \pm 0.9 \) (stat) \( ^{+1.2}_{-1.8} \) (syst) GeV is limited by the JES uncertainty.

4. Direct measurements using all-hadronic final states

All-hadronic final states are produced with the highest branching ratio and their kinematics are fully constrained. Measurements are challenging due to a large fraction of multijet background.

4.1. ATLAS: Measurement using the template method \[12\]

Events are selected with at least five jets \( (p_T > 55 \text{ GeV}) \) and a sixth jet \( (p_T > 30 \text{ GeV}) \), where two b-tagged jets with \( p_T > 55 \text{ GeV} \), \( |\eta| < 2.5 \) have a separation in \( \eta - \phi \) space of at least \( \Delta R_{bb} > 1.2 \), and \( E_T^\text{miss}/\sqrt{H_T} < 3 \). The permutation that minimizes a \( \chi^2 \) based on kinematic constraints \( (m_W = 80.4 \text{ GeV}, m_t = m_{\bar{t}}) \) and fulfills \( 50 < m_{ij} < 110 \text{ GeV}, \chi^2 < 8 \) is chosen. The light-jet energies are rescaled with \( m_W/m_{ij} \) and the two values of \( m_{jjb} \) are taken as mass estimator from each event (Fig. 4a). The background is modeled using an event mixing technique, where jets from \( \geq 6 \)-jet events are added to events with exactly 5 jets. The template fit to the \( m_{jjb} \) distribution yields \( m_t = 174.9 \pm 2.1 \) (stat) \( \pm 3.8 \) (syst) GeV and the total uncertainty is dominated by statistics, background modeling, ISR/FSR, and JES.

4.2. CMS: Measurement using the ideogram method \[13\]

The preselection requires events with at least four jets with \( p_T > 60 \text{ GeV} \), \( |\eta| < 2.4 \), at least five jets with \( p_T > 50 \text{ GeV} \), at least six jets with \( p_T > 40 \text{ GeV} \) and at least two jets with b-tag and \( p_T > 30 \text{ GeV} \). A kinematic fit with the constraints \( m_W = 80.4 \text{ GeV} \) and \( m_t = m_{\bar{t}} \) is performed and the permutation with minimum \( \chi^2 \) and \( P_{\text{fit}} > 9\% \), \( \Delta R_{bb} > 1.5 \) is chosen. In 3.5 fb⁻¹ of data 2418 events are selected with a composition of 51% \( t\bar{t} \) and 49% multijet (Fig. 4b).

For modeling the multijet background new events are constructed from the preselected sample (minor \( t\bar{t} \) contribution of 17\%), where each jet is taken from a random event in the order of the jet \( p_T \) ranking. Only events containing at least two b-tagged jets are used.

The signal contribution contains 28% correct \( t\bar{t} \) permutations. Templates are created for each permutation case and the ideogram method is employed to extract the top-quark
Table 1: Results of the top-quark mass extraction from the top pair production cross-section. The results are given for different cross-section calculations and mass schemes.

| Approx. NNLO × MSTW08NNLO | ATLAS [14] | CMS [15] |
|---------------------------|------------|---------|
|                           | $m_{t}^{pole}$ / GeV | $m_{t}^{pole}$ / GeV | $m_{t}^{MS}$ / GeV |
| Langenfeld et al. [16]    | 166.4$^{+7.8}_{-7.2}$ | 170.3$^{+7.4}_{-7.6}$ | 163.1$^{+6.8}_{-6.1}$ |
| Kidonakis [17]            | 166.2$^{+7.8}_{-7.4}$ | 170.0$^{+7.6}_{-7.1}$ | - |
| Ahrens et al. [18]        | 162.9$^{+8.0}_{-7.6}$ | 167.6$^{+7.6}_{-7.1}$ | 159.8$^{+7.3}_{-6.7}$ |

mass result of $m_{t} = 173.49 \pm 0.69$ (stat) $\pm 1.25$ (syst) GeV. The result is robust against radiation uncertainties and the leading uncertainty stems from the JES.

5. Extraction from the top pair production cross-section

The extraction of the top-quark mass from the production cross-section exhibits the usage of a well-defined mass definition and different systematic uncertainties. Cross-section measurements in all final states can be used as input.

The ATLAS measurement [14] is based on the $t\bar{t}$ cross-section measured in the lepton+jets channel with 35 pb$^{-1}$, while the CMS measurement [15] uses the $t\bar{t}$ cross-section measured in the dilepton channel with 1.1 fb$^{-1}$. The measured and predicted cross-sections are parametrized in dependency of $m_{t}$ and the top-quark mass is extracted using a joint-likelihood approach. The evaluated uncertainties are: Experimental, PDF, scale variation and $\alpha_{S}(M_Z)$ (CMS). The results are summarized in Table 1.

6. Summary

Measurements of the top-quark mass at the LHC have reached a great precision, profiting from formidable detector performance and large samples of $t\bar{t}$ events that can be selected with low background contamination. In the future an even larger integrated luminosity will allow for tighter constraints on systematic uncertainties and will enable new measurement methods with reduced or complementary uncertainties.

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