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Top quark mass measurements in ATLAS

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An overview of the measurements of the top quark mass in proton-proton collisions with the ATLAS detector at the Large Hadron Collider is presented. Different top quark pair decay signatures are studied, with analyses based on the template method on events in the dilepton, lepton+jets and all-hadronic final states. All those measurements use data samples collected in 2011 at a centre-of-mass energy of $\sqrt{s} = 7$ TeV, corresponding to integrated luminosities of up to 4.7 fb^{-1}. The most precise measurement is obtained in the lepton+jets channel using a three-dimensional template technique which determines the top quark mass together with a global jet energy scale factor, and a relative b-jet to light jet energy scale factor.

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1. Introduction

The top quark is the heaviest of all known quarks and its mass, m_{top}, is an important parameter of the Standard Model (SM) of particle physics. The latest combination of the measurements of m_{top} performed at the LHC based on integrated luminosities of up to 4.9 fb^{-1} resulted in m_{top} = 173.29 $\pm$ 0.23 (stat) $\pm$ 0.92 (syst) GeV [1]. Thanks to its large mass and its Yukawa coupling close to unity, the top quark plays an important role in the electroweak (EW) sector of the SM. Quantum loops involving the top quark give large contributions to the tree level expectation for the Higgs boson mass, making the hierarchy problem closely related to the size of the top quark mass. Precise determinations of m_{top} together with the W and Higgs masses, combined with precise EW measurements, can thus provide a stringent test of the internal consistency of the SM [2].

The measurements of the ATLAS Collaboration presented in this paper are based on data from LHC proton-proton collisions, collected at a centre-of-mass energy of $\sqrt{s} = 7$ TeV with the ATLAS detector [3] during the year 2011 and corresponding to integrated luminosities of up to 4.7 fb^{-1}. Under those conditions, the top quark is mainly produced in pairs through gluon-fusion processes with a cross-section of 177^{+10}_{-11} pb, calculated at next-to-next-to-leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic soft gluon terms, assuming a top quark mass of 172.5 GeV (see [14] and references therein). Since the CKM element V_{tb} is close to unity and m_{top} is large, the top quark decays almost exclusively to a W boson and a b quark. The top pair production experimental signatures can be thus classified with respect to the decay modes of the W boson. In 4% of all the $t\bar{t}$ decays both W bosons decay into an electron or muon and a neutrino, resulting in the so called dilepton channel; in 30% of the decays only one W boson decays into an electron or muon and a neutrino while the other into a pair of quarks, resulting in the lepton+jets channel; in 46% of the cases both W bosons decay into quarks, resulting in the so called all-hadronic channel. The remaining top pair decays involve the presence of at least one tau lepton in the final state. Those signatures are not targeted directly by any of the analyses presented in the following, where the event selection is based only on the reconstruction of electrons, muons and jets, but they nevertheless give small contributions to the dilepton, lepton+jets and all-hadronic channels through the leptonic and hadronic decays of tau leptons.

The latest results obtained by the ATLAS Collaboration in each of the three channels discussed above are based on the template method. In this method, simulated distributions are constructed for a chosen quantity sensitive to the physics parameter under study (*i.e.* m_{top}), using a number of discrete values of that parameter. These templates are fitted to functions that interpolate between different input values of the physics parameter, fixing all other parameters of the functions. A likelihood fit to the observed data distribution is then used to obtain the value of the physics parameter that best describes the data. In this procedure, the experimental distributions are constructed such that they are unbiased estimators of the physics parameter used as input in the signal Monte Carlo samples. Consequently, the top quark mass determined this way from data corresponds to the mass definition used in the Monte Carlo generator. The uncertainty in the relation between the Monte Carlo generator mass and the pole mass can lead to a difference between this two mass definitions of the order of 1 GeV [4].

2. Signal simulation samples

Monte Carlo (MC) simulated events are used to model the $t\bar{t}$ signal, the single top production events and most of the background contributions. In the dilepton and lepton+jets analyses the production of $t\bar{t}$ events is simulated using the next-to-leading order (NLO) MC program POWHEG-hvq [5] with the NLO parton density function set CT10 [6]. Parton showering, hadronisation and underlying event are modelled using the PYTHIA [7] program with the PERUGIA 2011C tune [8]. Single top quark production in the s and Wt-channels is also generated with POWHEG-hvq and PYTHIA using the same configuration, while single top quark production in the t-channel is simulated using the ACERMC generator [9] interfaced to PYTHIA. For the all-hadronic analysis, $t\bar{t}$ signal events are generated using the program MC@NLO [10] with the NLO parton density function set CTEQ6.6 [6] interfaced to HERWIG [11]. For the template parameterization, the $t\bar{t}$ samples are generated with different input values for $m_{\rm top}$ ranging from 160 GeV to 190 GeV, depending on the analysis. Multiple soft proton-proton interactions are added to all simulated samples. The events are re-weighted such that the distribution of the number of interactions per bunch crossing in the simulated samples matches that in the data. The samples are then processed through the simulation of the detector and the reconstruction software used for ATLAS data.

3. Object reconstruction

The event selection in the different $t\bar{t}$ decay channels is based on the following reconstructed objects in the detector: electrons, muons, jets and missing transverse momentum ($E_{\rm T}^{\rm miss}$).

Electron candidates are defined as energy deposits in the electromagnetic calorimeter with an associated reconstructed track. They are required to have transverse energy $E_{\rm T} > 25$ GeV and pseudorapidity $|\eta| < 2.47$, excluding the transition region between the barrel and end-cap calorimeter, *i.e.* $1.37 < |\eta| < 1.52$. Muon candidates are reconstructed from track segments in different layers of the muon chambers that are then combined starting from the outermost layer and matched with tracks in the inner detector. The final candidates are refitted using the complete track information and are required to satisfy $p_{\rm T} > 20$ GeV and $|\eta| < 2.5$. Electron and muon candidates are also required to be isolated both at calorimeter and tracking level, to reduce backgrounds from hadrons mimicking lepton signatures and from heavy flavour decays inside jets.

Jets are reconstructed using the anti-$k_{\rm t}$ algorithm [12] with a radius parameter $R = 0.4$, starting from energy clusters of adjacent calorimeter cells. They are then calibrated first by correcting the jet energy using the scale established for electromagnetic objects (EM scale), then performing a further correction to the hadronic energy scale using energy and η dependent calibration factors obtained from simulation, and finally applying a residual in-situ calibration derived from both data and MC simulation [13]. Jets originating from the hadronisation of b-quarks are "tagged" using a neural network based algorithm relying on topological properties such as the vertex decay length significance. The chosen working point of this algorithm corresponds to a b-tagging efficiency of 70% for jets originating from b-quarks in simulated $t\bar{t}$ events and a light quark jet rejection factor of about 130. The calibrations used for the results presented in this paper were developed from data recorded in 2010 and 2011 and have a generic uncertainty for the energy scale of an inclusive jet sample (JES) and a specific b-jet energy scale (bJES) uncertainty. The typical JES uncertainties

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for the spectrum of $t\bar{t}$ jets vary between about 1% and 3% depending on jet p_{T} and η, while the additional *b*JES uncertainty ranges from about 1% to 2.5%. The measurements in the dilepton and lepton+jets channels profit from a more recent JES calibration that became available at the end of 2011. Thanks to the improved detector understanding, with those calibrations both the average JES and *b*JES uncertainties are about 40% lower for the jets used in those analyses.

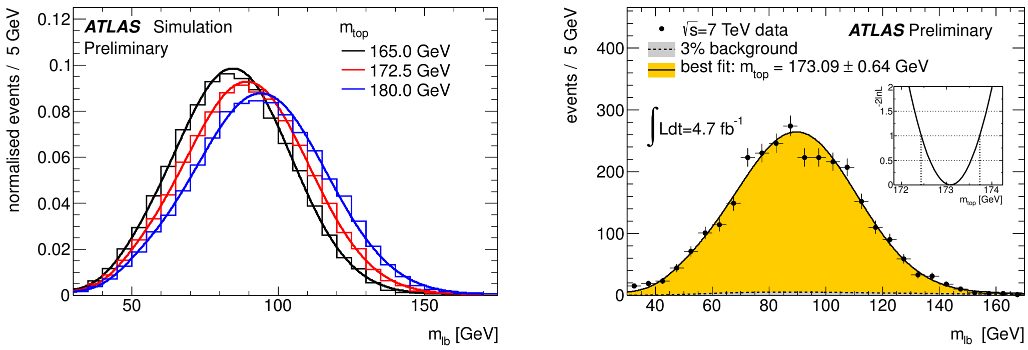
The reconstruction of $E_{\mathrm{T}}^{\mathrm{miss}}$ is based upon the vector sum of calorimeter energy deposits projected onto the transverse plane, calibrated at the EM scale and corrected according to the energy scale of the associated physics object. Contributions to the $E_{\mathrm{T}}^{\mathrm{miss}}$ from muons are also taken into account by using their momentum measured in the tracking and muon spectrometer systems.

4. The dilepton channel

The $t\bar{t}$ events in the dileptonic final state are characterised by the presence of two high p_{T} isolated leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$ arising from the two neutrinos coming from the leptonic W boson decays, and two b-jets. This decay signature is identified by requiring the presence of two opposite-sign reconstructed electrons or muons in events collected with a single lepton trigger. For the same flavour channels $E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV is required and values of the invariant mass of the lepton-lepton system compatible with the Z boson mass are vetoed to reduce the Z+jets background, while for the $e\mu$ channel $H_T > 130$ GeV is required, where H_T is the scalar sum of the p_{T} of the two selected leptons and the jets. The event is also required to have at least two b-tagged jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$. To reject jets coming from additional pp interactions each jet is also required to have $|\mathrm{JVF}| > 0.75$, where JVF is the fraction of the sum of the p_{T} of tracks associated with the jet that is from the p_{T} of tracks compatible with the primary vertex.

The QCD multi-jet background with misidentified and non-prompt leptons (collectively referred to as "fake leptons"), is estimated using a data-driven technique, based on the determination of the probability for a reconstructed lepton to be a fake in a background enhanced control region. Physics background processes with two charged leptons from W or Z decay in the final state are dominated by single top quark production in the Wt-channel. Additional contributions come from Drell-Yan processes and diboson production with additional jets and are estimated directly from MC simulation. Thanks to the strict event selection requirements, the overall background contribution in this channel is lower than 3%.

The top quark mass is determined using the $m_{\ell b}$ estimator, defined as the average invariant mass of the two charged lepton plus b-tagged jet sytems in each event. There are two possible assignments of the two b-tagged jets to the two charged leptons, each leading to two values for the corresponding pair of invariant masses. For the calculation of $m_{\ell b}$, the assignment providing the lowest average mass is chosen. Signal and background templates for $m_{\ell b}$ are constructed as a function of the top quark mass used in the MC generation, with the single top contribution treated as a mass-dependent background. Fig. 1 (a) shows the sensitivity of the $m_{\ell b}$ observable to the input value of the top quark mass and the corresponding signal template fits for three input m_{top} values. These functions are then used in an unbinned likelihood fit to identify the signal plus background template combination that best describes the data. The linearity of the fit with m_{top} is checked using pseudo-experiments. The result of the fit is displayed in Fig. 1 (b), where the distribution of $m_{\ell b}$ in data is shown together with the corresponding fitted probability density functions for signal plus



(a) (b)

Figure 1: Dependence of the $m_{\ell b}$ distribution on $m_{\rm top}$ for $t\bar{t}$ Monte Carlo events in the dilepton channel generated with different input top quark masses (a), together with the signal probability density functions obtained from the template fit functions. Fitted $m_{\ell b}$ distribution in dilepton data (b). The fitted probability density functions for the signal plus background and for the background contribution alone are also shown, together with the likelihood profile as a function of the fitted top quark mass [14].

background and for the background contribution alone. Using pseudo-experiments to determine the impact of the various sources of systematic uncertainty on the measurement, the analysis of 4.7 fb^{-1} of 2011 $\sqrt{s} = 7$ TeV ATLAS data yields $m_{\rm top} = 173.09 \pm 0.64$ (stat) $\pm$ 1.50 (syst) GeV. As expected from an analysis without in-situ calibration of the jet energy scale, the systematic uncertainty on $m_{\rm top}$ is dominated by the imperfect knowledge of the jet energy calibration, the JES uncertainty (0.89 GeV) and the *b*JES uncertainty (0.71 GeV) [14].

5. The lepton+jets channel

Events compatible with the $t\bar{t}$ lepton+jets topology are selected by requiring the presence of one reconstructed electron or muon in data collected with a single lepton trigger, together with four or more jets with $p_{\rm T} > 25$ GeV, $|\eta| < 2.5$ and $|{\rm JVF}| > 0.75$, with at least one of those jets being *b*-tagged. Depending on the lepton flavour, different requirements on $E_{\rm T}^{\rm miss}$ and $m_{\rm T}^{\rm W}$, the transverse W boson mass, are applied to reject backgrounds. The main background contributions in this channel include the production of W bosons in association with jets and QCD multi-jet events. These processes are estimated directly from collision data, both in terms of rates and shapes. Additional background contributions from Z+jets and diboson production are determined from dedicated simulated samples.

The events are reconstructed using a kinematic likelihood fitter that chooses the object topology that best matches the $t\bar{t}$ lepton+jets channel hypothesis, by mapping reconstructed quantities to the response of partons from the top quark and W boson decays using transfer functions determined from simulation. For each event, the reconstructed top quark mass $m_{\rm top}^{\rm reco}$ is calculated through the maximisation of this kinematic likelihood, that is also used to choose the assignment of jets to partons. The final result is extracted by using a three-dimensional unbinned likelihood fit, in which the sensitivity of the measurement to the determination of the JES and *b*JES is reduced by performing a simultaneous fit of $m_{\rm top}$, a global jet energy scale factor (JSF) and a global relative *b*-jet to light jet energy scale factor (bJSF). Templates for different input $m_{\rm top}$, JSF and bJSF are derived from simulation, including single top production as a mass-dependent contribution to the signal templates, for three observables: $m_{\rm top}^{\rm reco}$, the invariant mass of the hadronically decaying W boson $m_{\rm W}^{\rm reco}$, and $R_{\rm lb}^{\rm reco}$, defined as the ratio of the average $p_{\rm T}$ of the b-tagged jets assigned to the top decays to the average $p_{\rm T}$ of the light jets assigned to the W boson decay. For events with one b-tagged jet, $R_{\rm lb}^{\rm reco}$ is defined as the ratio of the $p_{\rm T}$ of this b-tagged jet to the average $p_{\rm T}$ of the jets assigned to the W decay. These three observables are mainly sensitive to the value of $m_{\rm top}$, JSF and bJSF respectively. A three-dimensional unbinned likelihood fit to the three observables in 4.7 fb^{-1} of 2011 $\sqrt{s} = 7$ TeV ATLAS data yields the result of $m_{\rm top} = 172.31 \pm 0.75$ (stat) $\pm$ 1.35 (syst) GeV [15], where the statistical error includes the additional components due to the simultaneous fit of the JSF and bJSF, that scale with the luminosity of the sample. Thanks to the introduction of the third dimension in the fit, the systematic uncertainty on $m_{\rm top}$ due to the residual relative b-jet to light jet energy scale is almost negligible (0.08 GeV). The dominant systematic uncertainties for this measurement are due to the residual η and $p_{\rm T}$ dependent components of the JES uncertainty (0.79 GeV), that cannot be fully constrained using a global JSF, and to the modelling of b-tagging (0.81 GeV). Both these sources of uncertainty show a pronounced dependence on the $p_{\rm T}$ spectrum of the jets, that largely affects the shape of the predicted distribution for $R_{\rm lb}^{\rm reco}$, causing a significant systematic effect in the fit. However, the gain with respect to a two-dimensional analysis determining only $m_{\rm top}$ and JSF is still substantial, with a reduction of the total uncertainty on $m_{\rm top}$ from 2.05 GeV to 1.55 GeV, given that many other simulation-related uncertainties are lowered thanks to addition of the third dimension to the fit, as discussed in detail in Ref. [15].

6. The all-hadronic channel

The candidate top pair production events in this channel are selected from data collected with a multi-jet trigger by requiring the presence of at least five jets with $p_{\rm T} > 55$ GeV and a sixth jet with $p_{\rm T} > 30$ GeV, with exactly two of those jets being b-tagged. Events with two close-by jets in $\Delta R < 0.6$, with well reconstructed electrons or muons or with significant $E_{\rm T}^{\rm miss}$ are rejected. The top quark candidates are identified as those three-jet combinations which minimize a χ^2 measuring the compatibility of the jets with a particular assignment to the $t\bar{t}$ decay products. To determine the very large and dominant QCD multi-jet background, an "event mixing" technique is used. This background contribution is modelled directly from data using signal-like events with exactly five jets, to which jets with transverse momentum lower than that of the fifth highest transverse momentum jet from events with six or more jets have been added. The top quark mass is measured with a one-dimensional binned likelihood fit of the templates obtained from signal MC as a function of $m_{\rm top}$ and those for multi-jet background obtained through event mixing to the reconstructed three-jet invariant mass distribution in data, leaving the background fraction as a free parameter in the fit. The result of the fit on 2.04 fb^{-1} of 2011 $\sqrt{s} = 7$ TeV ATLAS data is $m_{\rm top} = 174.9 \pm 2.1$ (stat) $\pm$ 3.8 (syst) GeV. This analysis does not yet take advantage of the latest ATLAS improvements in MC modelling, JES and bJES determination achieved in late 2011, such that the dominant systematic uncertainties for this measurement are related to the JES (2.1 GeV), the bJES (1.4 GeV), the modelling of the initial and final state radiation (1.7 GeV) and of the background (1.9 GeV) [16].

7. Summary

The latest direct top quark mass measurements performed using data collected with the ATLAS detector at the LHC have been presented. The most precise measurement is obtained in the lepton+jets channel using a three-dimensional template technique which determines the top quark mass together with a global jet energy scale factor and a relative b-jet to light jet energy scale factor, reaching a total uncertainty on $m_{\rm top}$ of 1.55 GeV, less than 1% relative to the measured top quark mass. A similar precision is reached using the template method with the $m_{\ell b}$ variable in the dilepton channel, obtaining a total uncertainty on $m_{\rm top}$ of 1.63 GeV.

In the future, by analysing the larger 2012 data sample, the statistical component due to the JSF and *b*JSF determination in the lepton+jets analysis will naturally decrease, opening the possibility for an even more precise determination of $m_{\rm top}$ at ATLAS.

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