PROCEEDINGS OF SCIENCE

Top quark mass measurements at the LHC: standard methods

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Top quarks are produced abundantly at the Large Hadron Collider at CERN, and a variety of measurements of top quark properties have been gathered in the recent years from the two collaborations ATLAS and CMS. In this review, the most recent results on the measurement of the top quark mass by the two collaborations, using the most standard techniques, are reported. The data refer to pp collisions at $\sqrt{s} = 7$ (8) TeV with up to 5 (20) fb^{-1} of integrated luminosity. The top quark mass has been measured with a relative uncertainty smaller than 0.3%, making the top quark the most accurately measured quark.

8th International Workshop on Top Quark Physics
14-18 September, 2015
Ischia, Italy

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[†] The measurements described here are presented on behalf of the ATLAS and CMS collaborations.

PoS(TOP2015)034

1. Introduction

At hadron colliders top quarks are produced predominantly in pairs via strong interaction. At LHC this production becomes quite copious: more than 5 million $t\bar{t}$ pairs have been produced during pp collisions at $\sqrt{s} = 7$ and 8 TeV (the so–called Run 1), yielding a $t\bar{t} \to W^+bW^-\bar{b}$ final state distinguished by the W's decay into *dilepton*, *lepton+jets*, and *all-jets* final states.

The top quark mass, M_t, is an important free parameter of the Standard Model (SM) which can be measured directly from the observation of its decay products. The quantity M_t requires however a theoretical interpretation, see [1].

Precise measurements of M_t, the W mass, M_W, and the Higgs boson mass, M_H, are used to assess the self-consistency within the SM of global electroweak fits [2]. On the other hand, top quarks might play a peculiar role in models for new physics [3, 4, 5]. Finally, M_t and M_H are related to the vacuum stability [6] of the SM. In fact the value $M_H \approx 125$ GeV [7], measured by ATLAS and CMS, is associated to a near-criticality of the SM vacuum, see [8].

2. Measuring the Top Quark Mass at the LHC

The $t\bar{t}$ events collected by ATLAS and CMS have common physics signatures: high-p_T isolated leptons (e or μ); high-p_T jets, some of which can be associated to the hadronization of b quark (i.e. b-jets); missing transverse energy, $E_T^{\rm miss}$, corresponding to the transverse momentum imbalance associated to neutrinos. These physics objects are used to reconstruct the $pp \to t\bar{t} \to WbW\bar{b}$ final state, with inherent ambiguities and permutations for their mapping to the leptons/quarks of the final state. In addition, there is an uncertainty in the knowledge of the absolute value of jet energies, i.e. the so-called jet energy scale (JES), and the sharing of the $E_T^{\rm miss}$ between multiple neutrinos.

Methods for measuring the top quark mass. Having reconstructed fully or partially the final state, there are several methods for the measurement of the top quark mass, and the most common ("standard") are: the *template* method; the *ideogram* method; and the *analytical matrix-weighting* technique. These methods are described briefly below, while alternative methods are discussed in [9].

The template method is based on distributions of variables sensitive to M_t. The typical choice is the reconstructed top quark mass $m_t^{\rm rec}$ associated to the $WbWb$ ($W \to jjb$ or $W \to \ell\nu$) hypothesis which yields the smallest χ^2, while the W boson mass, M_W, is constrained to its measured value. Normalized distributions (templates) are then derived for Monte Carlo (MC) simulated events, assuming different values of M_t, and parametrized as a function of M_t. A likelihood is then computed based on these functions, and maximized to derive the best value for M_t. A simultaneous *in-situ* calibration of the JES can be performed by including M_W templates which depend explicitly on JES shifts from the nominal value. It is also possible to add specific constraints on the JES of the b-jets.

The ideogram method is a modification of the template method which accounts for the M_t resolution on an event-by-event basis. Starting from the kinematical reconstruction of the $WbWb$ final state, the method then computes an event likelihood as a function of M_t, convoluting Breit-

Wigner (or similar) distributions with experimental resolutions. Multiple combinations for the jet-to-quark matching are considered with weights depending on the goodness of the fit.

In the dilepton channel the $t\bar{t}$ system is under-constrained unless one assumes a given top quark mass and infers the neutrino momenta from the $E_T^{\rm miss}$ value. This is performed in the analytical matrix-weighting technique (AMWT) scanning the M_t values in small increments, sharing the momentum imbalance among the two neutrinos. This carries along multiple solutions per event, each one with a given weight. The mass value which has the largest sum of these weights becomes the top quark mass estimator, called the AMWT-mass.

Systematic uncertainties. Large samples of $t\bar{t}$ events have been collected at the LHC so, in general, the statistical uncertainties are small and the measurements are instead dominated by systematic uncertainties.

There are several sources of systematic uncertainty which need to be accounted for. The most relevant uncertainties are related to: the imperfect knowledge of the JES for generic jets or for b-flavored jets (bJES); the modeling of the $t\bar{t}$ signal, as evaluated by using different MC generators, hadronization models, color-reconnection schemes, varying the amount of underlying events and of initial/final state radiation (ISR/FSR), or choosing different parton distribution functions (PDF); uncertainties related to the background modeling or the lepton energy/momentum determination; specific features of the method applied, and the size of the MC samples used. A successful treatment of these uncertainties is based on a thourough classification/discussion of each contribution, common bewteen ATLAS and CMS collaborations. For more on this see [10].

3. Latest measurements by ATLAS and CMS

We discuss now the most recent measurements of the top quark mass performed at the LHC by the ATLAS and CMS collaborations, with up to 25.0 fb^{-1} of integrated luminosity collected for pp collisions at $\sqrt{s} = 7$ and 8 TeV.

Lepton+jets channel. The lepton+jets channel provides the most accurate measurements at LHC, both for ATLAS and CMS.

For this channel ATLAS recurs to a 3-dimensional template method, applying the *in-situ* calibration both of the JES and of the bJES. For the latter a quantity $R_{bq}^{\rm reco}$ is introduced, derived from the ratio of the p_T of untagged and tagged jets, which is sensitive to shifts in the bJES. The M_t value measured with 4.6 fb^{-1} at 7 TeV amounts [11] to $172.33 \pm 0.75({\rm stat+JES+bJES}) \pm 1.02({\rm syst})$ GeV, with a total uncertainty of 1.27 GeV (0.73%). The systematic uncertainty is dominated by contributions due to the b-jet tagging efficiency (0.50 GeV), the residual JES (0.58 GeV) uncertainty, and ISR/FSR effects (0.32 GeV). Observed and expected distributions for $m_t^{\rm rec}$ are shown in Fig. 1 (left).

CMS uses for this channel the ideogram method with *in-situ* JES calibration. Adding a Gaussian constraint of the JES to what measured with dijet or Z/γ+jet events ("hybrid fit") results in a reduction in the total uncertainty. The value of M_t measured at 8 TeV with 19.7 fb^{-1} amounts [12] to $172.35 \pm 0.16({\rm stat+JES}) \pm 0.48({\rm syst})$ GeV, with a total uncertainty of 0.51 GeV (0.29%). The systematic uncertainty is dominated by contributions due to the bJES (0.32 GeV), assumptions on the generator (0.12 GeV) and modeling of the underlying event (0.11 GeV). The agreement between data and simulations is shown in Fig. 1 (right). CMS studies also differential distributions finding good agreement with the expectations based on current theoretical models.

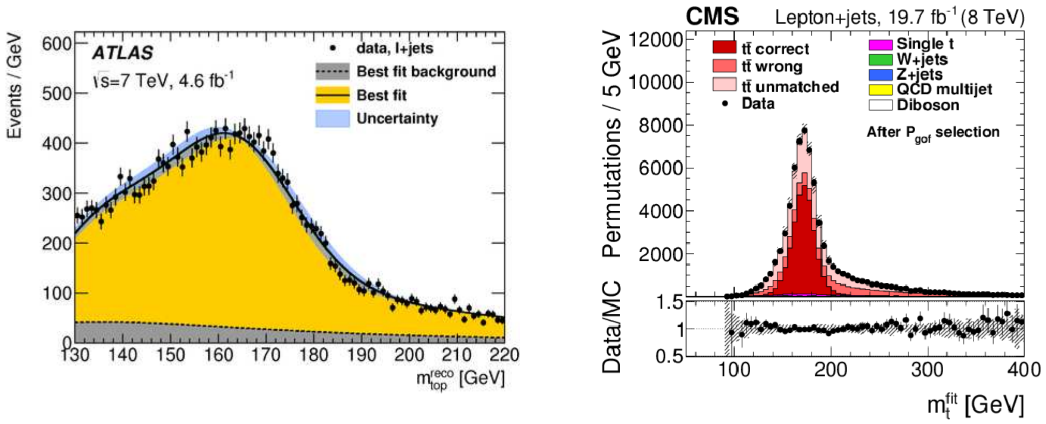

Figure 1: Reconstructed top quark mass and best fit for the lepton+jet channel. Left: ATLAS (4.6 fb^{-1} at 7 TeV). Right: CMS (19.7 fb^{-1} at 8 TeV).

All-jets channel. ATLAS applies a template method using as reference distribution the ratio $R_{3/2}$ between the invariant masses reconstructed from the jet triplets and doublets associated to top quark and W decays. The M_t value which provides the best agreement is [13] $175.1 \pm 1.4(\text{stat}) \pm 1.2(\text{syst})$ GeV (7 TeV, 4.6 fb^{-1}), with a total uncertainty of 1.8 GeV. The systematic uncertainty is dominated by contributions from the bJES (0.62 GeV) and the JES (0.51 GeV), and from the modeling of the hadronization (0.50 GeV). Distributions of $R_{3/2}$ are shown in Fig. 2 (left).

With the ideogram method, and with hybrid *in-situ* JES calibration, CMS measures [12] $M_t = 172.32 \pm 0.25(\text{stat}) \pm 0.59(\text{syst})$ GeV (8 TeV, 18.2 fb^{-1}), with a total uncertainty of 0.64 GeV. The systematic uncertainty is dominated by contributions from the bJES (0.29 GeV) and the JES (0.26 GeV) uncertainties, and from the modeling of the background (0.20 GeV). The observed and expected distributions for m_t^{rec} are shown in Fig. 2 (right).

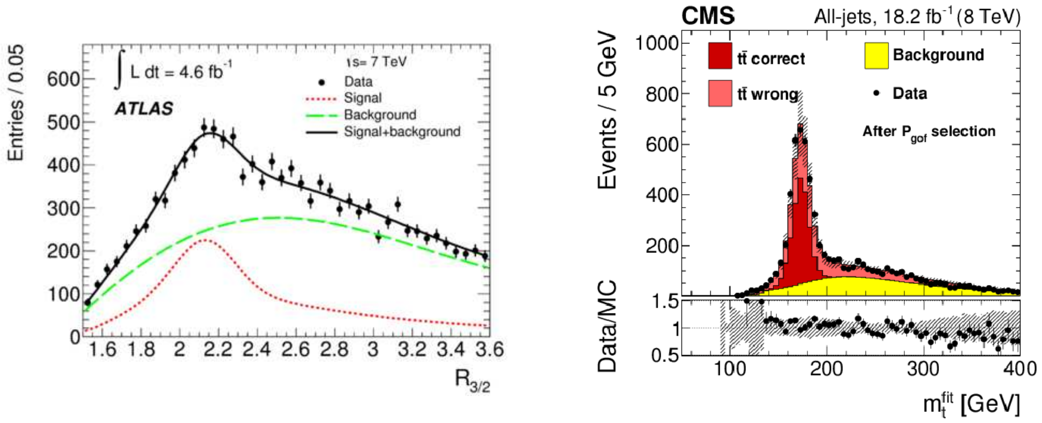

Figure 2: All-jets event. Left: Distribution of $R_{3/2}$ for ATLAS (4.6 fb^{-1} at 7 TeV). Right: Distribution of the reconstructed top quark mass for CMS (18.2 fb^{-1} at 8 TeV).

Dilepton channel. ATLAS measures M_t in the dilepton channel by employing templates based on the $m_{\ell b}$ variable, which is the invariant mass of the charged lepton + tagged jet system. The value measured [11] is $M_t = 173.79 \pm 0.54(\text{stat}) \pm 1.30(\text{syst})$ GeV (7 TeV, 4.6 fb^{-1}), with a total uncertainty of 1.41 GeV. The major contributions to the systematic uncertainty come from the JES (0.75 GeV) and the bJES (0.68 GeV) uncertainties, and the hadronization modeling (0.53 GeV).

In the case of CMS, the missing neutrinos are handled with the AMWT which gives [12] $M_t = 172.82 \pm 0.19(\text{stat}) \pm 1.22(\text{syst})$ GeV (8 TeV, 19.7 fb^{-1}). The major contributions to the systematic uncertainty come from uncertainties on the renormalization/factorization scales (0.75 GeV), the modeling of the *b*-quark fragmentation (0.69 GeV), and the bJES (0.34 GeV).

Combined mass measurements. CMS released in time for this conference a combination of all Run 1 top quark mass measurements. Such a combination is performed with the BLUE method [14, 15], with a careful definition and evaluation of the correlations between the various systematic uncertainties. The resulting value [12] is $M_t^{\text{CMS}} = 172.44 \pm 0.13(\text{stat}) \pm 0.47(\text{syst})$ GeV, with a total uncertainty of 0.49 GeV corresponding to 0.28% of the mass itself.

For the time being, ATLAS combines measurements in the dilepton and lepton+jets channels into a value [11] $M_t^{\text{ATLAS}} = 172.99 \pm 0.48(\text{stat}) \pm 0.78(\text{syst})$ GeV.

4. Summary

Since the discovery of the top quark, the measurement of its mass has been pursued in a variety of channels and with different techniques. The level of precision reached is impressive, smaller than 0.3%, thanks to 20 years of continuous accumulation of data and improvements in the methodology. An even better precision is expected from ongoing and future measurements at the LHC. New measurements at increasing precision will help to explore fundamental issues like cosmological models for inflation, vacuum stability of the SM, and physics beyond the SM.
To achieve these goals it will be important to reduce the systematic uncertainties, mainly those related to signal modeling, by improving the tuning of the parameters in the MC generators and their agreement with the data.

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