PROCEEDINGS OF SCIENCE

Direct top-quark decay width measurement at $\sqrt{s} = 13$ TeV with the ATLAS experiment

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The excellent performance of the LHC accelerator allows precise measurements of the top quark properties. A direct measurement of the top-quark decay width is presented using the full Run 2 dataset collected by the ATLAS detector at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 139 fb^{-1}. The measurement uses a profile likelihood technique with multiple templates to minimise the impact of the systematic uncertainties. The measured width is $\Gamma_t = 1.9 \pm 0.5$ GeV, in agreement with the Standard Model prediction.

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1. Introduction

Discovered in 1995 by the CDF [1] and D0 [2] experiments, the top quark is the heaviest known elementary particle. More than 20 years after its discovery, top quarks are produced abundantly at the Large Hadron Collider (LHC), which allows for precise measurements of its properties. Decay width, which is trivially related to the mean life time of the top quark, is one of the fundamental properties of the top quark. Due to its large mass of about 172.5 GeV [3, 4], the life-time of the top quark is very short, and the top quark decays before it forms a bound state. This makes the top quark unique amongst quarks. In the Standard Model (SM), the top-quark decay width, Γ_t, strongly depends on the top-quark mass, m_t, as $\Gamma_t \sim m_t^3$. The most precise theoretical predictions at next-to-next-to-leading order (NNLO) yield $\Gamma_t = 1.322$ GeV for a top-quark mass of 172.5 GeV [5]. Thus, a precise measurement of Γ_t could be used to test the SM predictions.

At the LHC, the top quarks are produced predominantly in pairs. In the SM, the top quark decays almost exclusively into a W boson and a b quark. Based on the subsequent decays of the W boson, three decay channels of the $t\bar{t}$ pair exist. This proceeding focuses only on the dileptonic channels of the $t\bar{t}$ decay. Only electrons, muons, and taus decaying leptonically are considered.

2. Event selection

The measurement [6] of the top-quark decay width uses data recorded by the ATLAS detector [7] in proton-proton collisions at $\sqrt{s} = 13$ TeV in the years 2015–2018, corresponding to an integrated luminosity of 139 fb^{-1}. Only events passing a single-electron or single-muon trigger are selected. Events are required to have exactly two reconstructed leptons of opposite charge with $p_{\mathrm{T}} > 25$ GeV for the 2015 data taking period and $p_{\mathrm{T}} > 27$ GeV for data taken from 2016–2018 to match the trigger thresholds. The events are split into three orthogonal regions based on the flavour of the charged leptons: ee (two electrons), $e\mu$ (one electron and one muon) and $\mu\mu$ (two muons). Only leptons passing quality and isolation criteria are considered.

Additionally, events are required to have at least two jets identified to originate from a b-hadron decay. Jets containing b-hadrons are identified using a multivariate algorithm [8] combining information from the impact parameter, secondary vertices and a multi-vertex reconstruction algorithm. Jets are reconstructed using the anti-k_t algorithm [9] with a radius $R = 0.4$. The working point of the b-tagger is chosen to have an efficiency of 60% to tag a b-jet. Hadronic resonances are suppressed by requiring the invariant mass of the lepton system, $m_{\ell\ell}$, to be larger than 15 GeV. Events with the same flavour of leptons are further required to have the magnitude of the missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV and to have $m_{\ell\ell}$ outside of 80 GeV $< m_{\ell\ell} <$ 100 GeV to suppress the Z+jets background.

The background events that mimic the signal consist of single-top-quark processes, Z+jets processes, diboson processes ($WW/WZ/ZZ$), and associated production of the $t\bar{t}$ pair with the W, Z, or Higgs bosons. Furthermore, processes with less than two prompt leptons contribute to the event selection via mis-identification of jets or photons as electrons or semi-leptonic decays of heavy-flavour hadrons. This source of background events is denoted as "fake leptons". After the selection, the backgrounds constitute less than 5% of all events.

3. Event reconstruction and template creation

The variable sensitive to the decay width is the invariant mass of the lepton and the corresponding b-jet, $m_{\ell b}$. The $m_{\ell b}$ distribution is sensitive to the decay width only if the charged lepton and the b-jet originate from the same top quark. Thus, pairing of the lepton and the b-jet is a crucial step of the measurement. The pair of the charged lepton and the b-jet with the smallest angular distance between the lepton and the b-jet is considered to be the correct one. In $t\bar{t}$ Monte Carlo (MC) simulation, both jet-lepton pairs are correctly identified in 63% of all selected $t\bar{t}$ events. Since the $m_{\ell b}$ distribution is sensitive to NLO effects in the decay vertex of the top quark for $m_{\ell b} > 150$ GeV [10], the fit to extract Γ_t is restricted to $m_{\ell b} < 150$ GeV.

To measure the top-quark decay width, templates corresponding to different underlying Γ_t are created for the $m_{\ell b}$ distribution using a reweighting technique. The nominal signal $t\bar{t}$ MC sample is generated using the POWHEG-BOX v2 [11, 12, 13], based on NLO QCD calculations. The matrix-element (ME) calculation uses the NNPDF3.0NLO PDF set [14] with a top-quark mass of 172.5 GeV. For the simulation of parton shower, fragmentation and the underlying event, the ME generator is interfaced with PYTHIA 8. The A14 [15] tune together with the NNPDF2.3LO PDF set is applied for the PYTHIA 8 showering.

The top-quark mass distribution follows a Breit-Wigner (BW) curve with the width Γ_t. In the reweighting, the MC simulation of the nominal $t\bar{t}$ sample generated with a decay width of $\Gamma_t = 1.32$ GeV is modified such that the reweighted samples follow the BW distribution with alternative widths.

The reweighting method is validated by comparing two dedicated samples, generated with POWHEG interfaced to PYTHIA 8, with the width set to 0.7 and 3.0 GeV, respectively. Good agreement in the shapes between the reweighted and the simulated distributions is observed, but a difference in the normalisation is seen. Therefore, the $t\bar{t}$ rate is left to float freely in the fit to data.

Figure 1 illustrates various top-quark decay widths in the $e\mu$ channel for the $m_{\ell b}$ distribution.

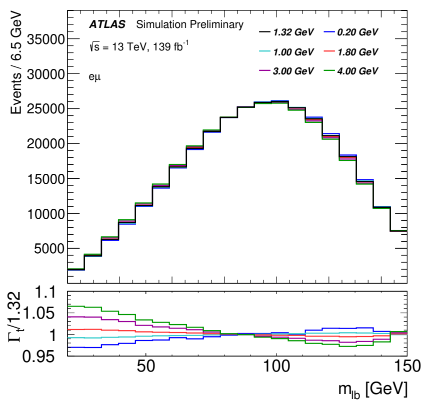

Figure 1: The $m_{\ell b}$ distribution in the $e\mu$ channel for various top-quark decay widths [6]. The bottom part of the plot shows the ratio of events for alternative top-quark decay widths with respect to the SM expected value $\Gamma_t = 1.32$ GeV in each bin. Only events with $m_{\ell b} < 150$ GeV are considered. The first bin contains underflow events.

4. Profile-likelihood template fit

The standard implementation of the profile-likelihood techniques allows only three templates representing a nominal distribution and up and down systematic variation. However, the analysis requires an incorporation of multiple templates representing underlying decay widths. Thus, a modification of the standard techniques is required. The chosen approach transforms the shape fitting into a normalisation fitting by interpolating between the width templates using a piece-wise linear interpolation. The normalisation of the i-th width template is additionally weighted with w_i that depends on Γ_t. Thus, by fitting the normalisation of the individual templates, the decay width can be extracted.

Templates representing widths from 0.2 to 4.0 GeV are created for the $m_{\ell b}$ distribution in the $e\mu$ $t\bar{t}$ channel. The invariant mass of the $b\bar{b}$ system, $m_{b\bar{b}}$, from the combined same-flavour events is used as a control variable in the fit, due to its sensitivity to jet-related systematic uncertainties and no sensitivity to the decay width.

To validate the fitting procedure, a linearity response using Poisson-varied pseudo-data without systematic uncertainties and fit with the full set of systematic uncertainties is used. In both cases a linear response is observed, with a non-closure below 0.01 GeV.

5. Results

A simultaneous fit of the $m_{\ell b}$ and $m_{b\bar{b}}$ distributions to the observed data yields the following result:

$$\Gamma_t = 1.94^{+0.52}_{-0.49}\ \text{GeV}.$$

Repeating the fit without including the systematic uncertainties results in $\Gamma_t = 1.90 \pm 0.21$ GeV.

Figure 2 shows pre- and post-fit distributions used in the fit. A significant reduction in the uncertainty band is observed in the post-fit distributions. The likelihood curve is displayed in Figure 3. Dominant systematic uncertainties originate from jet reconstruction, signal modelling and MC statistics.

The top-quark mass is not considered as a source of systematic uncertainties in the fit. The impact of the top-quark mass is estimated by repeating the fit with different underlying m_t assumptions as summarised in Table 1.

	$m_t = 172$ **GeV**		$m_t = 172.5$ **GeV**		$m_t = 173$ **GeV**	
	Mean [GeV]	**Unc. [GeV]**	**Mean [GeV]**	**Unc. [GeV]**	**Mean [GeV]**	**Unc. [GeV]**
Measured	2.01	$^{+0.53}_{-0.50}$	1.94	$^{+0.52}_{-0.49}$	1.90	$^{+0.52}_{-0.48}$
Theory	1.306	$< 1\%$	1.322	$< 1\%$	1.333	$< 1\%$

Table 1: Fitted values of Γ_t and their uncertainties under different top-quark mass hypotheses [6]. The theoretical values are extracted from the leading order values that are corrected following Ref. [5].

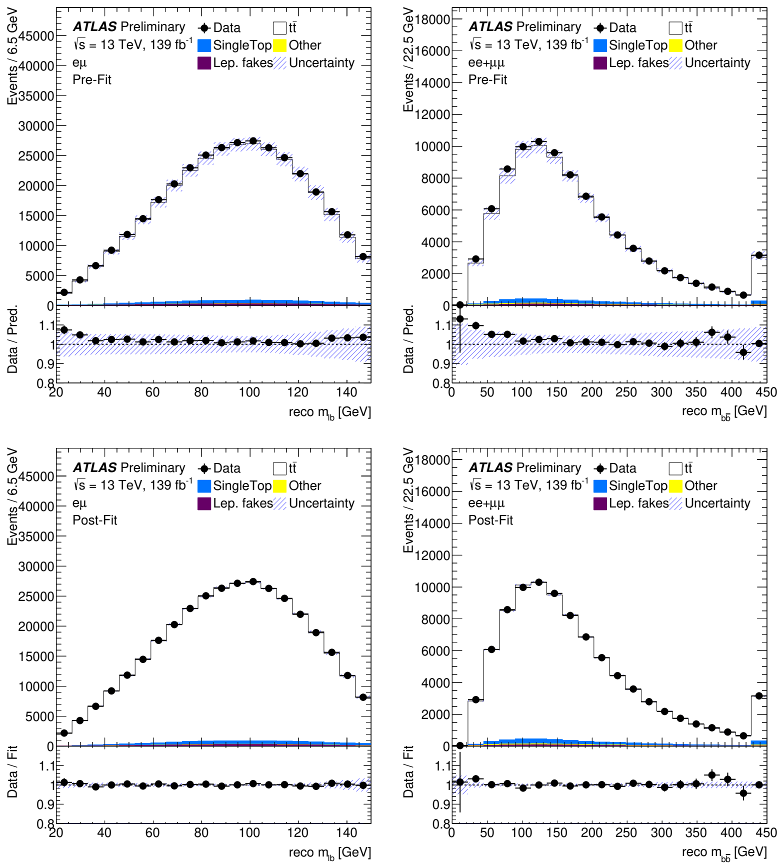

Figure 2: Pre-fit (top) and post-fit (bottom) plots for $m_{\ell b}$ (left) and $m_{b\bar{b}}$ (right) distributions used in the fit for Γ_t [6]. The post-fit uncertainties are calculated using the correlation matrix obtained from the fit. In the pre-fit plots, the SM prediction of $\Gamma_t = 1.32$ GeV is assumed.

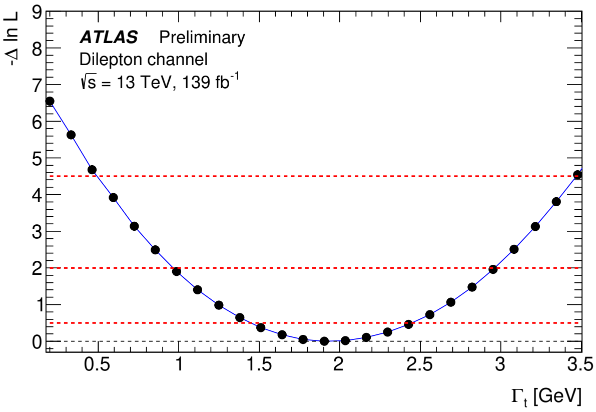

Figure 3: The likelihood curve for the top-quark decay width obtained from the fit to data [6]. The black points represent the individual likelihood values shifted by a constant such that the minimum is at zero. Dotted red lines represent the values at 1, 2 and 3 standard deviations from the best fit value.

6. Conclusion

A direct measurement of the top-quark decay width has been performed using LHC proton-proton collision data recorded by the ATLAS detector in years 2015–2018 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV with a corresponding luminosity of 139 fb^{-1}. The measured top-quark decay width is $\Gamma_t = 1.9 \pm 0.5$ GeV for a top-quark mass of $m_t = 172.5$ GeV, in agreement with the Standard Model prediction.

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