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Highlights on top quark properties, mass and cross-section measurements with the ATLAS detector

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The top-quark mass is one of the key fundamental parameters of the Standard Model that must be determined experimentally. Its value has an important effect on many precision measurements and tests of the Standard Model. The Tevatron and LHC experiments have developed an extensive program to determine the top quark mass using a variety of methods. In this contribution, the top quark mass measurements by the ATLAS experiment are reviewed. These include measurements in two broad categories, the direct measurements, where the mass is determined from a comparison with Monte Carlo templates, and determinations that compare differential cross-section measurements to first-principle calculations. In addition, new results on top-quark properties are shown. This includes the first observation of quantum entanglement in top-quark pair events and a test of lepton-flavour universality in emu final states.

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1. Introduction

The top quark (t) is the most massive particle in the Standard Model (SM) and is produced abundantly in proton-proton (pp) collisions at the LHC [1]. Due to its coupling to all gauge bosons and the Higgs boson, top quark production provides a valuable opportunity to test the SM, constrain quantum chromodynamics (QCD) parameters, and explore BSM physics. At a luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ and 13 TeV, approximately eight $t\bar{t}$ pairs are produced per second. Each top quark decays into a bottom (b) quark and a W boson with nearly 100% probability. The final state of a $t\bar{t}$ event is classified based on the W boson decays: about 9% of events result in two charged leptons, while 45% produce a single charged lepton plus jets.

In this contribution, a comprehensive overview of the top quark mass measurements performed by the ATLAS experiment [2] is presented. These measurements are generally divided into two main categories. The first category includes direct measurements, where the top quark mass is extracted by comparing the experimental data to MC simulations or templates that model the reconstructed mass distributions. The second category involves determinations based on the comparison of differential cross-section measurements with theoretical predictions derived from first-principles calculations, such as those based on QCD. These methods provide complementary insights into the precise value of the top quark mass, as well as its relation to fundamental SM parameters.

In addition to mass measurements, several new results related to top quark properties are discussed. Among these, the first observation of quantum entanglement in top-quark pair ($t\bar{t}$) events is particularly notable, shedding light on fundamental aspects of quantum mechanics within the context of high-energy physics. Furthermore, a test of lepton-flavour universality in events with final states involving an electron-muon ($e\mu$) pair is also presented. These findings offer valuable contributions to our understanding of the SM, as well as potential deviations that could signal new physics beyond the Standard Model.

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2. Results

Top-quark mass using dileptonic invariant mass

In this analysis [2], the top-quark mass was measured using the dileptonic channel in ATLAS, where templates for the m_{lb} distribution were generated as a function of m_{top}. The events were reconstructed using a Deep Neural Network (DNN), and a likelihood fit was performed to obtain the best estimate for m_{top} (see the DNN output distribution in left plot of Figure 1). The result obtained was $m_t = 172.21 \pm 0.20$, (stat) ± 0.67, (syst) ± 0.39, (recoil), GeV. The leading systematic uncertainties included jet energy scale (JES), recoil scheme, matrix element (ME) matching, and color reconnection effects. In the right plot of Figure 1 is showed the m_{lb}^{High} distribution in data compared to the predicted distribution.

Top-quark mass using a leptonic invariant mass

In this study, the top-quark mass has been measured using a leptonic invariant mass method, based on data from the semileptonic decay channel with an integrated luminosity of (36.1fb^{-1}). The invariant mass $m_{\ell\mu}$ is reconstructed from a lepton (either e or μ) from the W boson decay, along with a soft muon originating from a b-quark decay. A likelihood fit was employed to extract the best estimate for the top-quark mass m_{top}.

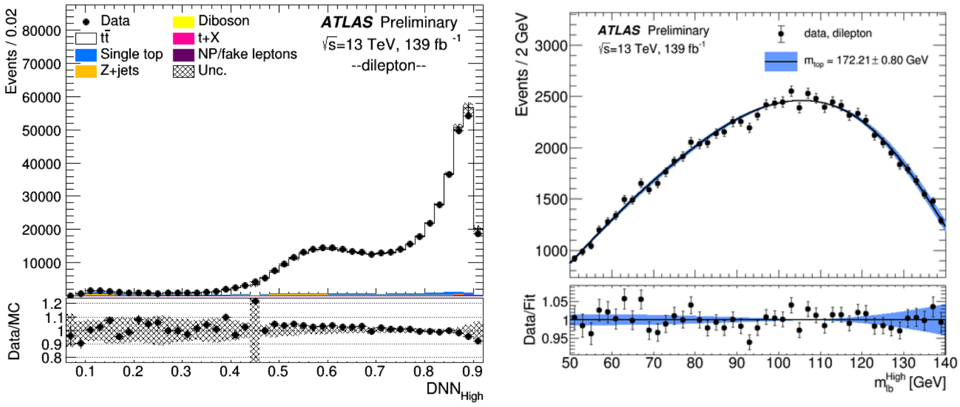
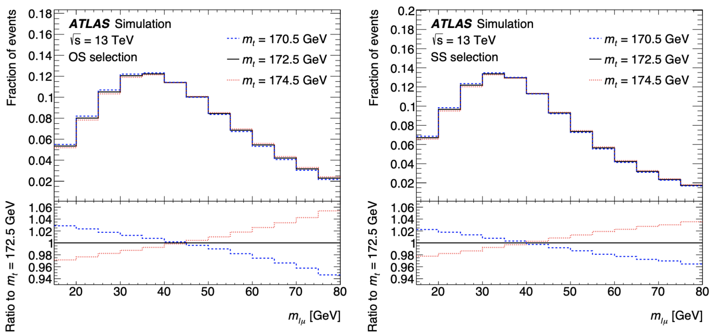


Figure 1: The distribution of the $\mathrm{DNN_{High}}$ for events passing the preselection (left plot) and the m_{lb}^{High} distribution in data compared to the predicted distribution (right plot). Taken from Reference [2].

This method offers advantages over standard direct reconstruction approaches, such as reduced sensitivity to the Jet Energy Scale (JES) and Jet Energy Resolution (JER), and less dependence on top-quark production modeling. The final result obtained is $m_{\mathrm{top}} = 174.41 \pm 0.39\,(\mathrm{stat}) \pm 0.66\,(\mathrm{syst}) \pm 0.25\,(\mathrm{recoil})$ GeV. In Figure 2 is showed the distribution to different input top-quark masses from simulated events, separately for the OS (left plot) and SS samples (right plot).



(a) (b)

Figure 2: Sensitivity of the $m_{l\mu}$ distribution to different input top-quark masses from simulated events, separately for the OS and SS samples. Taken from Reference [10].

Top-quark mass combination ATLAS/CMS run 1

The combination of 15 top-quark mass measurements from the ATLAS and CMS experiments at the LHC, conducted at $\sqrt{s} = 7$ and 8 TeV in various final state channels, was performed using the Best Linear Unbiased Estimator (BLUE) method. In this analysis [4], correlations between measurements had to be calculated or estimated in order to obtain the final covariance matrix. The combined result for the top-quark mass was found to be $m_t = 172.52 \pm 0.14$, (stat)± 0.30, (syst), GeV, achieving a total precision of approximately 0.2%. This combination led to a 31% improvement in the total uncertainty compared to the most precise individual measurement. In Figure 3 is showed the comparison of the individual m_t measurements and the result of the m_t combination.

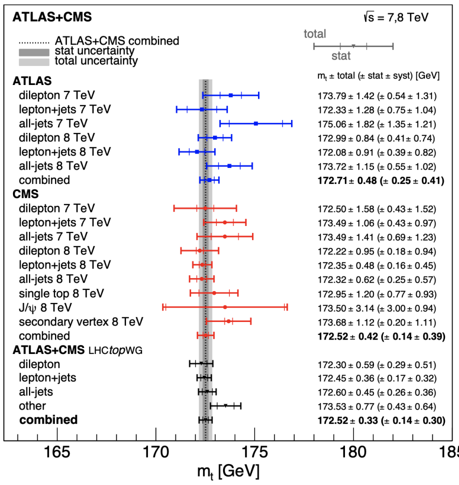


Figure 3: Comparison of the individual m_t measurements and the result of the m_t combination. Taken from Reference [4].

Single top t-channel total cross-section

This analysis [6] focuses on the precise measurement of the inclusive t-channel top and anti-top cross-sections, along with their ratio $R_t = \frac{\sigma_t}{\sigma_{\bar{t}}}$, utilizing the full Run 2 dataset of 140 fb^{-1}. This precision measurement targets the largest single top production channel, improving upon previous results which used a much smaller dataset.

A neural network has been employed to efficiently distinguish the t-channel single top-quark signal from background processes, with $t\bar{t}$ production being the largest component. In the Figure 4 is showed the agreement between data and predictions of the D_{nn} distribution in SR plus, demonstrating good consistency between the observed and expected results.

The total cross-sections for tq and $\bar{t}q$ production are measured to be

$$\sigma(tq) = 137 \begin{array}{c} +\,8 \\ -\,8 \end{array} \text{ and } \sigma(\bar{t}q) = 84 \begin{array}{c} +\,6 \\ -\,5 \end{array} .$$

The fits to the observed data for the $\sigma(tq + \bar{t}q)$ cross-section and R_t give the following results:

$$\sigma(tq + \bar{t}q) = 221 \begin{array}{c} +\,13 \\ -\,13 \end{array} \text{ and } R_t = 1.636 \begin{array}{c} +\,0.036 \\ -\,0.034 \end{array} .$$

In addition to testing parton distribution functions (PDFs), particularly through R_t, the analysis enables the extraction of $|V_{tb}|$ and sets constraints on other CKM matrix elements. The result obtained is

$$f_{lv}|V_{tb}| = 1.015 \pm 0.031$$

improving the precision by 30% compared with combination ATLAS and CMS Run I measurement [7].

$t\bar{t}$ cross-section and $t\bar{t}/Z$ cross-section ratio using LHC Run 3

In this analysis [8], measurements of the inclusive $t\bar{t}$ cross-section and the ratio of $t\bar{t}/Z$ cross-sections using LHC Run 3 data are presented. The dilepton channel is selected due to its smaller

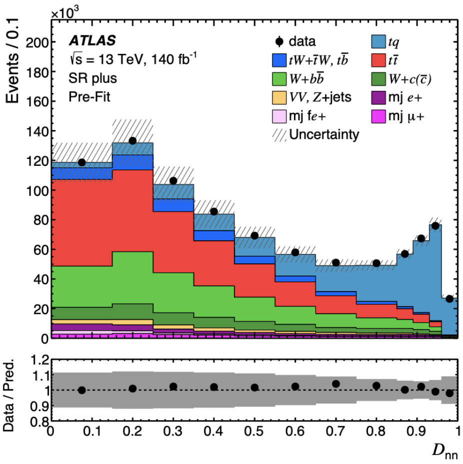


Figure 4: Distribution of the D_{nn} in SR plus. The observed distribution (dots) is compared with the expected distributions (histograms) from simulated events. In these distributions, the signal contribution is shown stacked on top of contributions from all considered background processes. All uncertainties considered in the analysis are included in the hatched uncertainty band. The lower panel shows the ratio of data and the prediction; in this panel, the uncertainty is displayed as a grey band.Taken from Reference [6].

background and reduced dependence on jet uncertainties. Additionally, the $t\bar{t}/Z$ ratio is measured to reduce uncertainties related to leptons and increase sensitivity to gluon and quark parton distribution functions (PDFs).

A profile likelihood fit was applied to events with one or two b-tagged jets (N_1 and N_2), and the results were compared to theoretical predictions. The measured ratio $\sigma_{t\bar{t}}/\sigma_Z$ was determined to be 1.145 ± 0.003 (stat) ± 0.021 (syst) ± 0.002 (lumi), in agreement with the Standard Model prediction of 1.245 ± 0.076. The cross-sections were found to be $\sigma_{t\bar{t}}$ = 850 ± 3 (stat) ± 18 (syst) pb and σ_Z = 743.6 ± 0.2 (stat) ± 10.7 (syst) pb. Experimental uncertainties, ranging from 2% to 3%, were observed to be smaller than those of the theoretical predictions, underscoring the precision of the measurements.

Differential cross section and large-R jet substructure measurement

In this study [9], measurements of the differential cross-section and large-R jet substructure of top-quark decays in the boosted regime were performed, using both the lepton+jets and all-hadronic final states. The substructure was analyzed through various observables, including N-subjettiness ratios, energy-correlation functions, ECF variables, and splitting functions, with unfolding carried out using an iterative Bayesian approach.

Poor agreement between the data and Monte Carlo (MC) generators was observed, particularly for the variable τ_{32}. In Figure 5, the single differential cross-sections, plotted against large-R jet τ_{32}, indicate that the predictions from the PWG+H7 and PWG+PY8 FSR down generators best matched the data in the lepton+jets channel. In the double-differential results, as shown in Figure 6, the correlation between τ_{32} and m_{top} revealed poor agreement in the central m_{top} region, whereas the variable D_2 demonstrated better consistency with the unfolded data. Predictions for D_2, correlated with both m_{top} and p_T^{top}, were generally in better agreement with the data compared to those for τ_{32}.

Quantum entanglement in events with top-quark pairs

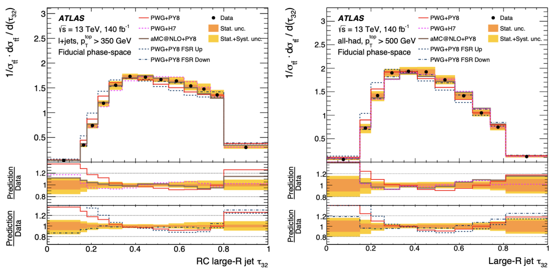


Figure 5: Particle-level normalized differential cross-sections as a function of τ_{32} for the data and several NLOME+PS MC. The unfolded results shown here are in the l+jets (left plot)and all-hadronic (right plot) channels. Taken from Reference [9].

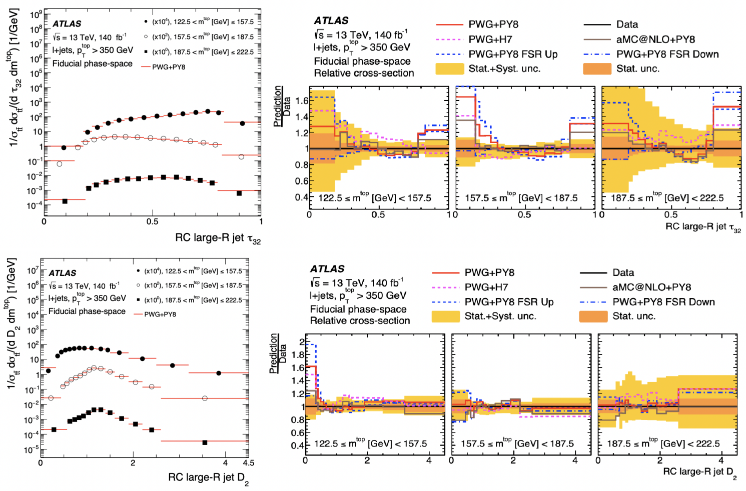


Figure 6: Particle-level normalized differential cross-sections as a function of τ_{32} and jet mass (top plots), and of D_2 and jet mass (bottom plots) for the data and several NLOME+PS MC. The unfolded results shown here are in the l+jets channel. Taken from Reference [6].

In this analysis [10], quantum entanglement in events with top-quark pairs has been studied, based on the principle that the quantum state of each particle cannot be described independently of the other. The properties of the top quark allow the testing of quantum entanglement, specifically using the dilepton channel, as leptons carry 100% of the spin information from their parent top quarks (see left plot of Figure 7). The condition for entanglement is defined by $\mathrm{tr}[C] + 1 < 0$, where C is the spin correlation matrix. If $D = \mathrm{tr}[C]/3$, the condition for entanglement becomes $D = -3\langle\cos\phi\rangle \rightarrow D < -1/3$.

To maximize sensitivity, the kinematic region $m_{t\bar{t}} < 380\,\mathrm{GeV}$ was selected, and the measured D-value was obtained from a calibration curve. The measurement was conducted at the particle level to minimize uncertainties from parton showers (see right plot of Figure 7). The final result is: $D = -0.537 \pm 0.002\,(\mathrm{stat}) \pm 0.019\,(\mathrm{syst}) \quad \text{for} \quad m_{t\bar{t}} < 380\,\mathrm{GeV}$.

This represents the first observation of quantum entanglement in top-quark events.

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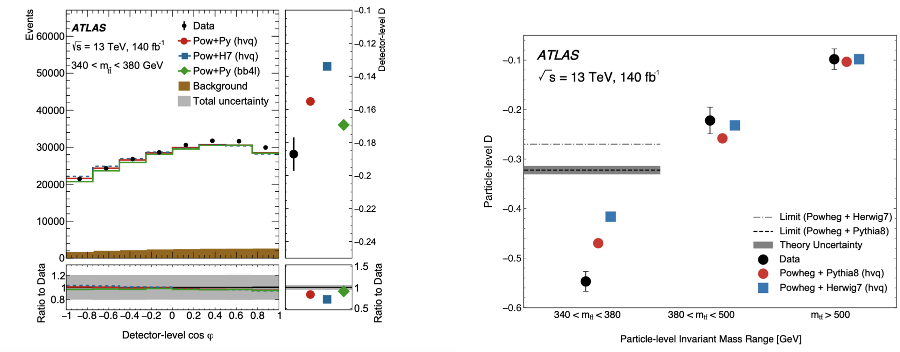

Figure 7: Sensitivity of the $m_{l\mu}$ distribution to different input top-quark masses from simulated events, separately for the OS and SS samples. Taken from Reference [10].

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