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OVERVIEW ON RECENT TOP-QUARK MEASUREMENTS AT THE LHC

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Abstract

The top-quark was the last quark to be discovered, in 1995, and since then its production and decay mechanisms as well as its properties have been studied. In the latest years in particular, the Large Hadron Collider (LHC) produced a huge quantity of top-quarks, which allowed experiments to measure the behaviour of top-quarks with a precision never seen before. In these proceedings a selection of the latest results on top-quark physics produced by the LHC experiments is presented.

1 Introduction

The top-quark is the heaviest particle in the Standard Model (SM) and its detailed study is of paramount importance for testing high energy particle physics theories. The Large Hadron Collider (LHC) is the best machine available at the moment to study top-quarks, since such particles are produced in abundance in high energy pp collisions. Since the beginning of its operations in 2011, the LHC produced roughly 10^9 top-quarks, 95% of which produced from 2015 to 2018 when the LHC was colliding protons at a centre of mass energy of 13 TeV. This massive amount of top-quarks allowed LHC experiments such as ATLAS and CMS to study with a never seen before accuracy the properties of the top-quark and its behaviour in various regions of its phase space. In the following the latest top-quark results are presented, from recent measurements of cross sections to determinations of top-quark properties.

2 Top-quark cross sections

Top-quarks at the LHC are mostly produced in $t\bar{t}$ pairs, with a predicted cross section of roughly 820 pb^{-1} in 13 TeV pp collisions, for top-quarks with a mass of 172.5 GeV. It corresponds to an increase in cross section of roughly four times in comparison to the 8 TeV predictions.

2.1 Inclusive cross sections

Inclusive cross sections are usually measured by experiments in a particular final state and then extrapolated to the full phase space considering the chosen final state probability..

A recent analysis [1] measured for the first time the $t\bar{t}$ inclusive cross section in a final state where one τ lepton decaying to hadrons (τ_h) is present. Such a channel is difficult to measure given the fact that the τ lepton does not leave a signal in detectors as clean as the one left by electrons and muons. The analysis measured $\sigma_{t\bar{t}} = 781 \pm 66$ pb^{-1}, in agreement with the theoretical predictions and previous measurements. Its uncertainty was dominated by systematic uncertainties, in particular related to the τ_h reconstruction. Measuring the $t\bar{t}$ cross section in such final state also proved that lepton flavour universality is preserved and that partial widths ratio are in agreement with the expectations.

Top-quark production modes which have a much smaller cross section have also been measured: two recent analyses measured the $t\bar{t}b\bar{b}$ inclusive cross section, which is important to constraint experimentally, given it is a large and irreducible background in $t\bar{t}H(b\bar{b})$ measurements. Final states with at least one lepton [2] (semileptonic $t\bar{t}$ decay) and fully hadronic [3] final states were considered. The measured cross section in all the different final states were found to be slightly larger than the SM theoretical predictions at Next-to-Leading-Order (NLO) plus Parton Shower (PS) in Quantum-Chromo-Dynamic (QCD) , but consistent within two standard deviations.

Other processes still are too elusive to be measured. That is the case for the $pp \to t\bar{t}t\bar{t}$ production, which is predicted by the SM to have a NLO cross section $\sigma_{t\bar{t}t\bar{t}} \sim 12$ fb^{-1}. Such cross section is very challenging to measure experimentally given the complexity of its final state. Three different recent analyses [4, 5, 6] looked for four top-quarks production in final states with one or more leptons, but did not find any evidence for it. The most stringent limits to date on $t\bar{t}t\bar{t}$ production were set and constraints on anomalous four-top-quark coupling deriving from potential new physics effects were given.

2.2 Differential cross sections

The large amount of statistics also benefits top-quark differential cross sections measurements.

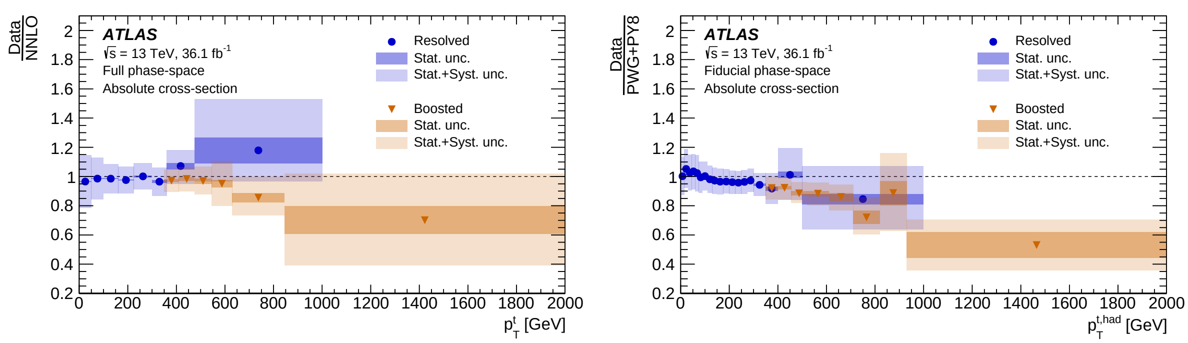

Figure 1: *Comparison between theoretical predictions and measured data of the hadronic top-quark p_T distribution. Data is measured in the resolved and boosted regime and then corrected to parton level (left) and particle level (right), where it is compared to theoretical calculations at NNLO QCD and NLO+PS respectively.*

A recent measurement of the kinematic distributions of semileptonic $t\bar{t}$ events [7] was published. A number of differential distributions were measured and then corrected for detector effects only (particle level), and also for hadronisation and top-quark decay effects (parton level). Two different kinematic regimes were studied and found to give compatible results in their overlap region: the resolved channel, where the decay products of the hadronic decaying top-quark are contained inside three separated jets, and the boosted channel, where the top-quark hadronic decays are contained within a single jet of large radius. The large statistics used to perform the measurement allowed also the extraction of two dimensional differential distributions. It was found that the theoretical predictions slightly overestimate the measured data in the high energy tails of various distributions, such as the hadronic top-quark transverse momentum (p_T^{had}) shown in fig.1. The tension is more evident at particle level, where the uncertainties on the measurement are around 10-15% and the comparison to the theory is done with MC simulations at NLO+PS. At parton level the systematic uncertainties were larger since data had to be corrected for more effects, and the total uncertainty ranges from 10% to 30%. Such uncertainty fully covers the tension between NNLO predictions and the measured corrected data.

Another recent measurement [8] focused on measuring the leptonic distributions in $t\bar{t}$ events with two leptons (dileptonic $t\bar{t}$ decay) with different flavours and opposite electromagnetic charges in their final state . Such channel has a very clean experimental signature and allow to extract differential distributions at particle level with percent-level precision. The measured distributions were found to agree well, within uncertainties, with the available NNLO theoretical predictions which also included Next-to-Leading-Logarithm (NNLL) accuracy . On the other hand a slight mismodelling was found for MC simulations, which could not reproduce the data spectra of the lepton p_T above ~ 130 GeV and of the dilepton invariant mass below 50 GeV.

3 Properties

A number of interesting quantities related to the top-quark have been measured at the LHC. New recent measurements reduce the uncertainties on previous results, taking advantage of up to $\sim 140\mathrm{fb}^{-1}$ of collected data and the development of new techniques and approaches.

3.1 Asymmetries

Top-quarks in $t\bar{t}$ event produced in pp collisions are predicted in the SM to behave slightly asymmetrically: while t quarks are produced more along the the beam axis, the $\bar{t}$ are more perpendicular to it. To test such fact the number N of $t\bar{t}$ events where the top-quarks are produced with higher/lower absolute rapidity y than the anti-top-quarks is considered. A measurement of the so-called *charge asymmetry*

$$A_C = \frac{N_{|y_t|>|y_{\bar{t}}|} - N_{|y_t|<|y_{\bar{t}}|}}{N_{|y_t|->|y_{\bar{t}}|} + N_{|y_t|<|y_{\bar{t}}|}} \qquad (1)$$

was recently performed [9] in semileptonic $t\bar{t}$ events, in both resolved and boosted topologies. A 4σ evidence for A_C was found, compatible to the SM expectations, but not significant enough to claim the discovery of such effect. The distribution of A_C as a function of the invariant mass of the $t\bar{t}$ system ($m_{t\bar{t}}$) was also measured and corrected to parton level, where it was found to agree to MC simulations and an advanced SM theoretical prediction which includes NNLO QCD and NLO electro-weak (EW) effects.

Another effect predicted to happen in $t\bar{t}$ production is that the spins of the top-quark and anti-top-quark are correlated. Such prediction can be tested by experiments since the top-quark lifetime is shorter than the hadronisation and spin decorrelation time scales, hence allowing the top-quark spin information to pass to its decay products. Two recent measurements [10, 11] evaluated spin correlations in dileptonic $t\bar{t}$ events using very different approaches.

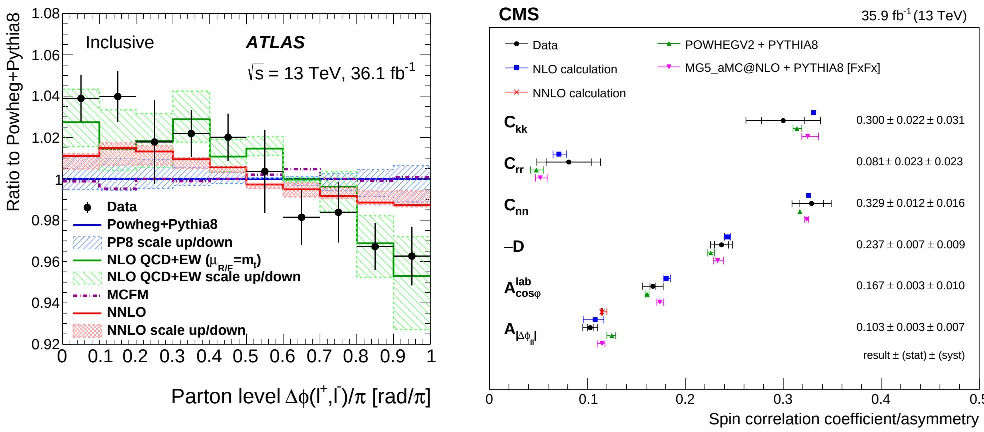

Figure 2: *Summary of recent results on spin correlation measurements. On the left, differences in the distribution of the angular distance $\Delta(\phi)$ between two leptons from $t\bar{t}$ decay. Data is corrected to parton level where it is compared to different available theoretical calculations. On the right, measurements of various coefficients responsible for spin correlations in $t\bar{t}$ production.*

Spin correlations affect the angular distances $\Delta\eta$ and $\Delta\phi$ between the two leptons and one method [10] measured such distributions. The $\Delta\phi$ distribution, corrected to parton level, was found to be in slight tension with NLO and NNLO QCD predictions, but in good agreement with NLO QCD+EW calculations as can be seen in fig. 2. This result showed that EW correction in certain region of the phase space can be very important and cannot be neglected.

In an alternative approach all the 15 coefficients which can be used to parametrise the spin dependent part of the $t\bar{t}$ production were constrained through the measurement of 15 different observables [11]. In this case a good agreement was found between the values of the coefficients as extracted from data and the NLO QCD predictions from the SM, as shown in fig. 2.

3.2 Width and mass

One of the most peculiar properties of the top-quark is its short lifetime, which is due to its very high mass, m_t and strictly connected to the value of its decay width Γ_t. The SM predicts at NNLO QCD a value $\Gamma_t^{\mathrm{SM}} = 1.322$ GeV for a top-quark with a mass of 172.5 GeV, with a small 6% theoretical uncertainty.

In a recent article [12] the top-quark decay width was measured in $t\bar{t}$ dileptonic events. The analysis employed the invariant mass of the lepton and b+jet system, which was found to be quite sensitive to changes of the top-quark width. A fit at detector level of MC predictions to data yielded $\Gamma_t = 1.94 \pm 0.50$ GeV, where systematics uncertainties where included in the fit and constrained through a simultaneous fit to the $b\bar{b}$ system invariant mass.

The top-quark mass is, contrary to Γ_t, a free parameter of the SM and its direct determination is therefore of great importance. Top-quark mass measurements have a long tradition and experimental uncertainties are usually very well under control. In fact, the evaluation of the theoretical uncertainties associated to m_t determinations started to play a key role, since such uncertainties are becoming the dominant ones with values estimated to be around 0.5-1 GeV. In this direction, the extraction of m_t may benefit from using fixed order calculations beyond the LO. Such calculations are computed in a well defined renormalisation scheme and allow for precise definition of the parameters of the Lagrangian, including the top-quark mass. This makes possible the determination of quantities such as the pole mass (m_t^{pole}) and the running mass ($m_t(\mu)$) with a theoretical uncertainty estimated with a few hundreds MeV precision.

One analysis [13] exploiting this direction studied $t\bar{t}+1$ jet events produced in pp collisions at 8 TeV, with exactly one lepton in their final state. The cross section as a function of the invariant mass of the $t\bar{t}+1$ was measured and corrected to the parton level, as shown in fig.3. A fit to NLO QCD calculations estimated the best value of the top-quark pole mass to be $m_t^{\text{pole}} = 171.1 \pm 1.1$ GeV, where the reported uncertainty includes statistical and systematic experimental uncertainties as well as theoretical uncertainties covering the choice of parton distribution functions (PDFs), the choice of the value of α_s and the impact of missing higher orders not included in the theoretical calculation. Even though only the 8 TeV dataset was used in this measurement, its precision was found to be competitive with other mass measurements at 13 TeV, due to the high sensitivity of the chosen observable on the top-quark mass.

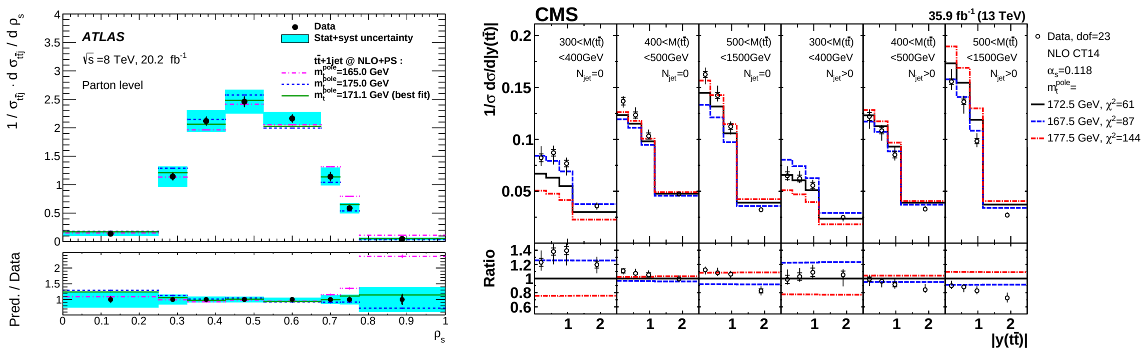

Figure 3: *Observables used in recent m_t^{pole} measurements. On the left, the normalised differential cross section of $t\bar{t}$+1 jet as a function of $\rho_s = 340\ GeV/m_{t\bar{t}+1\ jet}$. On the right the triple differential cross section of $t\bar{t}$ events as a function of the number of extra jets (N_{jet}) and invariant mass ($M_{(t\bar{t})}$) and absolute pseudo-rapidity ($|y_{(t\bar{t})}|$) of the $t\bar{t}$ system. Both observables are present at parton level and compared to NLO QCD predictions.*

A second analysis [14] used $t\bar{t}$ events at 13 TeV, with two opposite sign leptons in the final state, and measured the triple differential cross section as function of number of jets and invariant mass and rapidity of the $t\bar{t}$ system. A fit to NLO QCD theoretical predictions at parton level was developed which simultaneously extracted the best values of $m_t^{\text{pole}}, \alpha_s$ and constrained the PDF choice. It resulted in a top-quark pole mass value of $m_t^{\text{pole}} = 170.5$ GeV with a total experimental and theoretical uncertainty of ± 0.8 GeV. In this case the theoretical uncertainty only covered the impact of perturbative terms not included in the calculation, given that the α_s and PDF dependencies were constrained by the fit.

Both these recent m_t measurements were found to prefer a central value for the top-quark mass which is slightly lower than other previous mass measurements which extracted top-quark mass from a direct comparison of data to MC simulations. More tension exists if comparing these new results to recent global EW fits [15], which predict $m_t^{\text{pole}} \sim 176.5 \pm 2$ GeV. On the other hand, good agreement is found with the m_t determination from a NNLO QCD global fit [16].

Finally, two new measurements strictly related to the top-quark mass were published for the first time. One analysis [17] measured directly the Yukawa coupling of the top-quark (Y_t), proportional to m_t in the SM. The measurement took advantage of the fact that EW corrections to $t\bar{t}$ production depends on Y_t. Using a profile likelihood fit, the analysis found $Y_t \sim 1.1 \pm 0.4$ where the large uncertainty comes from the limited sensitivity of the method. Another study [18] looked for the running of the top-quark mass parameter, as defined in the modified minimal subtraction ($\overline{MS}$) scheme. To do so $\overline{m}_t(\mu)$ was extracted in four different $m_{t\bar{t}}$ intervals, which were setting the scale of the process, i.e. $\mu = m_{t\bar{t}}$. Comparing data corrected to parton level to NLO QCD calculations produced in the $\overline{MS}$ scheme, a slight evidence of the running of $\overline{m}_t(\mu)$ was found.

4 Summary and conclusions

Top-quark physics is an important part of the scientific program of the LHC experiments. The successful operation of the LHC allowed experiments to collect an unprecedented amount of data which allowed to deepen the knowledge of top-quark behaviour. Recent analyses provided results for inclusive and differential cross sections, as well as top-quark properties, setting a new standard of precision for top-quark measurements. Overall good agreement was found between the measured data and the available theoretical predictions. Few tensions and non significant disagreements were also found between data and theory, which motivate an even deeper study of the top-quark physics and a further improvements in top-quark modelling.

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