PROCEEDINGS OF SCIENCE

Measurements of the top-quark mass using the ATLAS detector at the LHC

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The top-quark mass is a fundamental parameter of the Standard Model and its determination is of great relevance per-se and for new physics scenarios. The demand for further improvements in the precision and accuracy with which the top-quark mass is determined brings new challenges and makes clear the importance of combining single measurements and the need for an accurate top-quark mass definition. The recent results from the ATLAS collaboration presented in this talk address such challenges by measuring the top-quark mass in an unusual final state identified by the presence of a low-energy muon from $t\bar{t}$ semileptonic decay, as well as measuring the top-quark mass with alternative theoretical definitions.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

PoS(ICHEP2022)882

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[*] Speaker

1. Introduction

The top-quark, with a pole mass around 172 GeV, is the heaviest particle in the Standard Model (SM) and its detailed study is of high relevance in testing high energy particle physics theories [1, 2]. 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 proton-proton collisions. Since the beginning of its operations in 2011, the LHC produced roughly 10^9 top-quarks. About 95% of those were produced from 2015 to 2018, when the LHC was colliding protons at a centre of mass energy of 13 TeV. With such a massive amount of top-quarks, high precision studies on the top-quark mass (m_t) become relevant and possible. In the following, the latest results produced by the ATLAS collaboration [3] are presented.

2. Top-quark mass definitions and measurements

The top-quark mass is a fundamental parameter of the SM and, given the nature of quarks, is not an observable quantity. Hence its value has to be inferred from a comparison between theoretical predictions and measured quantities. Theoretical predictions can come from a fixed order calculation or from a simulation performed via a Monte Carlo (MC) event generator. In the former case, for next-to-leading-order (NLO) QCD accuracy, the top-quark mass is typically defined with an uncertainty smaller than few hundreds MeV [4]. On the other hand, the value of the m_t parameter in the MC simulations does not have a direct interpretation with respect to the parameters of the SM Lagrangian.

Measurements relying on data-to-MC comparisons are typically assigned an extra uncertainty of $\sim$ 0.5 GeV to cover potential mis-interpretations [2] and efforts to quantify this value more precisely have been made [5]. With experimental uncertainties starting to affect the measured m_t value at the same level of precision of the theoretical uncertainties, it is important to cover a wide range of experimental final states and techniques to further improve the understanding of the top-quark and its mass.

3. Top-quark mass measurement with soft-μ tagger

The experimental uncertainty on the top-quark mass in single analyses is driven by the precision with which single physical objects (jets, muons, electrons) are reconstructed in the detector and in how well the processes considered are modelled [6]. Apart from improving the objects reconstruction and calibration and the modelling of the top-quark production modes, which is an always ongoing effort, another way to reduce the experimental uncertainties is to combine the single measurements, as done in a recent m_t ATLAS combination [6]. To fully profit from the combination, it is ideal if the various single measurements which contribute to it are affected by orthogonal or anti-correlated systematic uncertainties. This can be achieved by looking at different final states.

The analysis of Ref. [7] goes in that direction by studying $t\bar{t}$ final states where the b-quarks produced in the top-quark decay hadronize into B-hadrons, which subsequently decay semileptonically producing a low-energy muon (soft-μ). The shape of the invariant mass distribution between the soft-μ and the lepton from W-boson decay is shown to be greatly sensitive to the top-quark mass value and hence ideal to measure m_t. Two categories were defined, where the soft-μ and the lepton have either same or opposite electric charge, and were used for the m_t extraction.

A dedicated soft-μ tagger (SMT) was developed to select the interesting events and reduce the backgrounds from π- and K-hadrons in-flight decays. In order to enhance the tagger performances, the efficiency of the SMT was calibrated using events where J/ψ were produced, while the SMT mis-identification was calibrated in events where a W-boson and extra-jets were produced.

The top-quark mass was extracted from a profile likelihood fit where data was compared to MC predictions. The distributions of the observables in data and MC are showed in Figure 1. Using 36.8 fb^{-1} of data collected by ATLAS at a center-of-mass energy of pp collisions of 13 TeV, the analysis measured

$$m_t = 174.48 \pm 0.40\ (\text{stat})\ \pm 0.67\ (\text{syst})\ \text{GeV}$$

resulting in the single m_t measurement with the highest experimental precision.

The main systematic effects affecting the m_t extraction are found to be the uncertainty on the branching ratios of the B-hadrons to soft-μ, the modelling of the b-quark fragmentation function in the $t\bar{t}$ simulation and the background normalisation from the mis-tagged soft-μ.

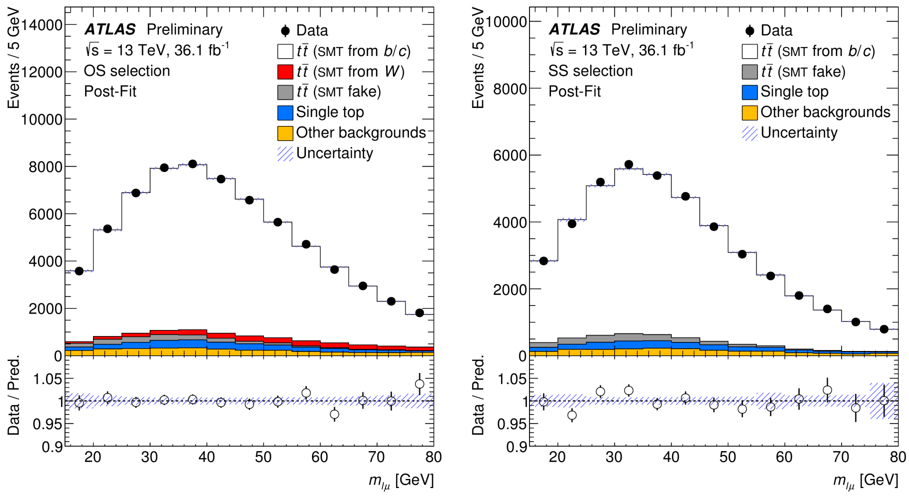

Figure 1: The observables used in the top-quark measurement by the analysis employing a soft-muon tagger, in the opposite-charge (left) and same-charge (right) categories [7].

4. Top-quark mass measurement in $t\bar{t} + 1$ jet events

Another way to improve the knowledge on the top-quark mass is to consider observables sensitive to the m_t value, for which high precision fixed order calculations exist. This helps to have a better control over the theoretical interpretation of m_t.

In this regard ATLAS measured the top-quark mass in $t\bar{t} + 1$jet final states using the observable

$$\mathcal{R} = \frac{1}{\sigma_{t\bar{t}+1\text{ jet}}} \cdot \frac{\mathrm{d}\sigma_{t\bar{t}+1\text{ jet}}}{\mathrm{d}\rho_s} ,$$

where $\sigma_{t\bar{t}+1\text{ jet}}$ is the $t\bar{t} + 1$ jet cross section and ρ_s is a variable proportional to the inverse invariant mass of the $t\bar{t} + 1$ jet system [8].

The full $t\bar{t}+1$ jet system was reconstructed at detector level selecting events with $t\bar{t}$ semileptonic decays and the additional presence of a jet with transverse momentum $p_T > 50$ GeV.

The measured observable was then corrected using iterative unfolding procedure to bring it to the phase spaces where theoretical calculations exist and hence make the comparison to them as well defined as possible. The observable $\mathcal{R}$ is shown in Figure 2, corrected for detector effects to *particle-level*, and corrected for detector, hadronization and top-quark decays effects to *parton-level*.

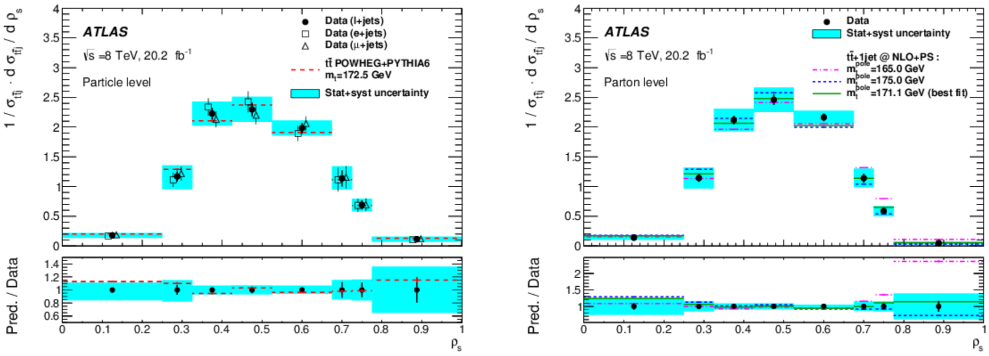

Figure 2: The observables used in the top-quark measurement in $t\bar{t} + 1$ jet events, unfolded to parton level (left) and parton level (right) [8].

Theoretical calculations at NLO QCD accuracy for $\mathcal{R}$, in the pole mass and modified minimal subtraction ($\overline{\text{MS}}$) renormalization schemes were compared to the measured distribution unfolded to the parton-level. The analysis used 20.8 fb^{-1} of data produced by 8 TeV pp collisions and collected by ATLAS to extract values of m_t through a template fit, obtaining:

$$m_t^{\text{pole}} = 171.1 \pm 0.4\ (\text{stat})\ \pm 0.9\ (\text{syst})\ \pm {}^{+0.7}_{-0.3}\ (\text{theo})\ \text{GeV}$$

for the top-quark pole mass and

$$m_t^{\overline{\text{MS}}} = 162.9 \pm 0.5\ (\text{stat})\ \pm 1.0\ (\text{syst})\ \pm {}^{+2.1}_{-1.2}\ (\text{theo})\ \text{GeV}$$

for the top-quark running mass at its scale in the $\overline{\text{MS}}$ scheme.

The values of m_t^{pole} and $m_t^{\overline{\text{MS}}}$ are found to be compatible, given the known relation between the m_t parameters in the two renormalization schemes. The leading experimental systematic uncertainties come from the $t\bar{t}$ modelling, the jet energy scale and the limited statistics of the data analyzed. The leading theoretical uncertainties are due to the variations of the renormalisation and factorisation scales in the theoretical predictions of $\mathcal{R}$. Theoretical uncertainties are larger in the case of the $\overline{\text{MS}}$ renormalization scheme, since for that scheme the region of the observable with high sensitivity to m_t is highly affected by the scale variations.

5. Differences of top-quark mass definitions for boosted top-quarks

Recently an ATLAS MC-based study [9] attempted to relate the m_t parameter as implemented in a MC event generator (m_t^{MC}) to a mass parameter defined in a next-to-leading-logarithm (NLL) theoretical calculation in a low-scale short-distance mass scheme (m_t^{MSR}, scale dependent) [5].

The observable used for the comparison is the mass of a large-radius (large-R) jets originated by hadronic top-quark decays, with $p_T^{\text{jet}} \in [0.75, 2]$ TeV, as shown in Figure 3. For the jet definition the XCone algorithm [10] was used for the jet clustering and the Soft-Drop algorithm [11] for the grooming.

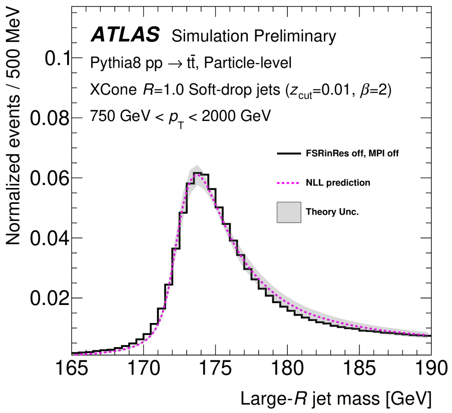

Figure 3: The mass distribution of large-R jets originated by top-quark hadronic decay, as used in Ref. [9]. The NLL theoretical prediction is shown together with the prediction from a Powheg+Pythia8 MC simulation.

The NLL theoretical prediction for the jet mass shape is mostly affected by three parameters: Ω, which accounts for QCD-leading order hadronization contributions, x_2 which accounts for radiation corrections poorly correlated to m_t, and m_t^{MSR}.

A detailed study on the impact of the underlying event and multiple particle interactions on the MC prediction was carried out, as such non-perturbative effects are not taken into account in the NLL calculation. Different MC tunings and modelings of color-reconnection were also considered in the comparison. Uncertainties from the NLL theoretical prediction were estimated by varying the values of multiple dynamic scales. A fit of a Powheg+Pythia8 MC simulation to a 3-dimensional template function of $[m_t^{\text{MSR}}(1\text{ GeV}), \Omega, x_2]$ variables, where 1 GeV is the scale chosen for the short-distance mass definition, gave:

$$m_t^{\text{MSR}}(1\text{ GeV}) = m_t^{\text{PowhegPythia8}} - 80^{+350}_{-400}\text{ MeV}$$

and using a known relation to the pole mass scheme

$$m_t^{\text{pole}} = m_t^{\text{PowhegPythia8}} - 350^{+300}_{-360}\text{ MeV}$$

The phase space considered, with the tight cut on a high value of $p_{\text{T}}^{\text{jet}}$, makes it challenging using this technique to perform an actual m_t measurement of high precision, but efforts are ongoing to make it possible in the near future.

6. Conclusions

In the last years the ATLAS collaboration released various results on m_t. In this talk three recent results were presented. Firstly, it was introduced an analysis measuring the top-quark mass in final states where a low-energy muon from B-hadron decay was produced. Such analysis resulted in a measured $m_t = 174.48$ GeV with an experimental uncertainty of 0.5%. Secondly, the most precise ATLAS top-quark pole mass analysis was presented. The analysis measured $t\bar{t}+1$ jet events to obtain $m_t^{\text{pole}} = 171.1$ GeV, with a total uncertainty of 0.8%. Lastly, a study based on ATLAS MC simulation and very boosted top-quarks was shown, which was able to relate the m_t parameter in the MC simulation to a theoretically more precisely defined top-quark mass definition, with a ≈ 350 MeV precision. More studies are ongoing within the ATLAS collaboration and the near future seems to be an interesting time for improving the current knowledge on the top-quark mass.

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