MEASURING THE TOP-QUARK POLE MASS USING $t\bar{t}+1$ JET EVENTS*

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(Received February 12, 2018)

The top quark is the heaviest particle discovered so far. Its mass, m_t, is a fundamental parameter of the Standard Model (SM) and its values is an input of many theoretical calculations. Since top quarks are not free-particles, m_t is not an observable and has to be inferred from other distributions. With the Large Hadron Collider (LHC) entering the precision era, an accurate measurement of the top-quark mass which takes into account all sources of error is important in consistency tests of the SM and in constraining new physics (NP) scenarios through precise electroweak fits. The $pp \to t\bar{t}+1$ jet process is interesting since the extra-jet radiation depends on the value of m_t. A study of the normalized differential cross section as a function of the invariant mass of the $t\bar{t}+1$ jet system is presented, which aims to reduce the total uncertainty on the extraction of m_t.

DOI:10.5506/APhysPolBSupp.11.267

1. Introduction

After the discovery of a particle looking like the Higgs boson [1,2] at the LHC [3], it seems like the last missing particle predicted by the SM has been found. In addition, no direct evidence for new physics (NP) has been found by the ATLAS [4] and CMS [5] experiments so far. Nevertheless, the SM is not expected to be the ultimate theory, since it cannot explain phenomena such as dark matter and neutrino masses. Hence mainly two scenarios are possible. Either deviations from the SM predictions are so small they have not been detected yet, or energies probed at the LHC are not sufficiently

* Presented at the Final HiggsTools Meeting, Durham, UK, September 11–15, 2017.

high to access the NP regime. To be able to spot such deviations, more precise measurements alongside with improved theoretical calculations with high accuracy are needed.

The top quark was discovered at the Tevatron [6, 7] and its mass value is not predicted by the SM. It is thus important to measure it with high precision and accuracy, since the value of m_t is important in consistency checks of the SM [8] and in NP scenarios [9], as well as playing an important role in the stability of the electroweak (EW) vacuum [10]. Being the quark which has the strongest coupling to the Higgs boson, the top quark also arouses speculations on playing a special role in the breaking of the electroweak symmetry (EWSB) [11, 12].

Since quarks are not free particles due to confinement, m_t is not an observable. Hence, it is only possible to infer its value from fits to distributions which are sensitive to it, such as cross sections. In order to have a theoretical well-defined definition of the top-quark mass, dynamical expressions have to be used, the most popular ones being the pole mass and the modified minimal subtraction ($\overline{\mathrm{MS}}$) scheme definitions. The two renormalization schemes are connected between each other and a well-known relation exists between the top-quark mass in the pole mass scheme, m_t^{pole}, and the value of the top-quark running mass in $\overline{\mathrm{MS}}$ at its scale, $m_t(m_t)$ [13].

The top quark is the only quark which decays before hadronization. Hence, one can also define a kinematic mass, m_t^{MC}, as the invariant mass of the decay products of the top quark. There is no known empirical connection between m_t^{MC} and the top-quark mass parameter in the SM Lagrangian. The difference between m_t^{MC} and m_t has been estimated to be of the order of $\lesssim 1$ GeV [14]. With measurements of m_t reaching the GeV precision, it becomes important to measure theoretically well-defined quantities and keep all the sources of uncertainty under control. In the next sections, a strategy which could improve the measurement of m_t^{pole} is explained. Thanks to a recent calculation [15], a similar strategy also allows to extract the value of $m_t(m_t)$.

These proceedings are structured as follows. In Section 2, the observable from which m_t^{pole} is extracted is presented and in Section 3 its properties are studied. Implications on repeating the measurement in different phase spaces are studied in Section 4. Evaluation of $m_t(m_t)$ is presented in Section 5, while conclusions are given in Section 6.

2. Using $t\bar{t} + 1$ jet events to measure m_t

Being a parameter of the SM Lagrangian, the top-quark mass can only be extracted from observables which can be measured in experiments. This can be done by comparing the measured observable to predictions computed in a theoretical framework. When asking for a high precision measurement, typically at least a next-to-leading order (NLO) calculation is needed, so that fixing a renormalization scheme removes ambiguities in the definition of the renormalised Lagrangian parameters. This also applies to m_t, and is therefore important when a high precision measurement is performed. NLO QCD corrections have been computed for $t\bar{t}+1$ jet production [16, 17]. The $pp \to t\bar{t}+1$ jet process has also been implemented in Monte Carlo generators [18, 19] and its matching to parton shower programs [18, 20] is also available.

In the case of $t\bar{t}+1$ jet production, in [21] a new observable was presented, which showed a promising sensitivity to $m_t^{\rm pole}$

$$\mathcal{R}\left(m_t^{\rm pole}, \rho_{\rm s}\right) = \frac{1}{\sigma_{t\bar{t}+1\ \rm jet}} \frac{{\rm d}\sigma_{t\bar{t}+1\ \rm jet}}{{\rm d}\rho_{\rm s}}\left(m_t^{\rm pole}, \rho_{\rm s}\right), \tag{1}$$

where $\rho_{\rm s} = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\ \rm jet}}}$, with $\sqrt{s_{t\bar{t}+1\ \rm jet}}$ the invariant mass of the $t\bar{t}+1$ jet system and m_0 a constant of the order of the top-quark mass (fixed to $m_0 = 170$ GeV in the following). The extra-jet in the equation was required to have $p_{\rm T}^{\rm extra-jet} > 50$ GeV and $|\eta^{\rm extra-jet}| < 2.5$, in order to have an observable free of infrared divergences [21]. The shape of $\mathcal{R}$ is presented in Fig. 1. Such observable shares a number of nice features. Firstly, it can be computed at NLO in QCD, which fixes the renormalization scheme. Also, NLO QCD corrections were found to be small ($\sim 15\%$), which allows to keep theoretical uncertainties well under control. Being the differential cross section with respect to the invariant mass of the $t\bar{t}+1$ jet system, the sensitivity to $m_t^{\rm pole}$ was found to be much higher of the inclusive $t\bar{t}+1$ jet cross section [21]. The extra-jet radiation strongly depends on the value of the mass of the top quark, making the observable defined in $t\bar{t}+1$ jet topologies, more sensitive than the equivalent defined for $t\bar{t}$ topologies [21], as it is shown in Fig. 1.

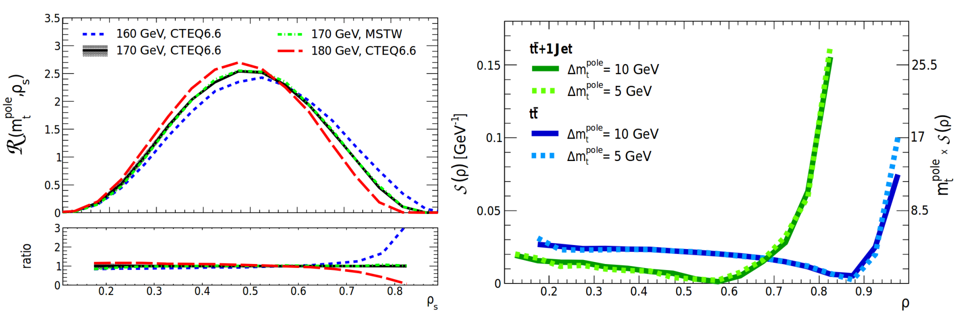

Fig. 1. (Colour on-line) The $\mathcal{R}$ observable for $t\bar{t}+1$ jet events calculated for different m_t values (left), and its sensitivity (right) compared to $t\bar{t}$ events (darker/blue line). Figures from [21].

From the experimental side, $t\bar{t}+1$ jet events are $\sim$ 30% of top-pair production at the LHC, which means that the data sample is large enough to allow for a measurement with statistical precision comparable with the $t\bar{t}$ analyses. Additionally, being $\mathcal{R}$ a normalised quantity, many sources of systematic uncertainties, such as PDF uncertainties, get reduced in the ratio.

The measurement was performed by the ATLAS and CMS collaborations [22, 23] using data collected from 7 TeV pp collisions. The result presented in [22] was the most precise determination of $m_t^{\rm pole}$ at that time, with a total error of ~ 2 GeV. The $\mathcal{R}$ observable has been recently also calculated in the $\overline{\rm MS}$ scheme [15], resulting in the most precise measurement of $m_t(m_t)$, with a precision comparable to the $m_t^{\rm pole}$ measurement.

With the new data at a centre-of-mass energy of $\sqrt{s}=8$ TeV and $\sqrt{s}=13$ TeV, a higher precision on $m_t^{\rm pole}$ can be achieved. In the following, we present a study of the properties of the $\mathcal{R}$ observable, which could help in measuring $m_t^{\rm pole}$ with a smaller total uncertainty.

3. Analysis optimisation at higher luminosity

3.1. Binning

Due to the finite amount of $t\bar{t}+1$ jet events which pass the event selection cuts, the LHC experiments need to choose a binning when measuring the $\mathcal{R}$ distribution. In [22, 23], a wide binning was chosen due to the lack of statistics, in particular in the high sensitivity region $\rho_{\rm s} \gtrsim 0.65$.

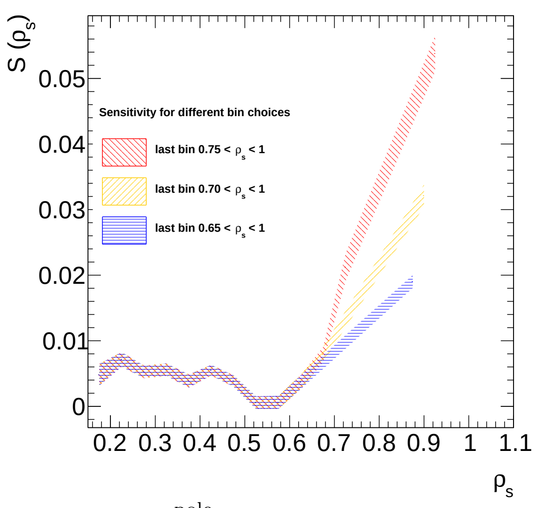

Fig. 2. Plots of $\mathcal{R}$ sensitivity to $m_t^{\rm pole}$ (left) and of ratio of sensitivity over statistical error (right). In both cases, having a finer binning in the high sensitivity region increases the precision on $m_t^{\rm pole}$ measurement.

With an increasing amount of data collected during the $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV LHC runs, it becomes possible to chose a finer one. This increases the sensitivity of the observable to m_t, as it is shown in Fig. 2.

If systematic errors grow slowly than the observable sensitivity as a function of ρ_s and the number of bins, the total experimental error can be reduced.

It is of course not possible to make the binning arbitrary small. From one side, the procedure is limited by the given amount of data which is collected by the experiments, since bins with $\rho_s \gtrsim 0.65$ need to be enough populated. From a theoretical side, one has to be careful to avoid regions which could be affected by theoretical uncertainties, such as the threshold region, where $\rho_s \gtrsim 0.9$.

4. Unfolding, particle and parton levels

4.1. $\mathcal{R}$ at parton and particle levels

The observable presented in Section 2 is defined in a phase space where top quarks are stable particles. Such phase space is usually called *parton level*. Because of its short lifetime of $\sim 5 \times 10^{-25}$ s, top quark decays before hadronization occur. In 99.8% of the cases, its decay products are a b quark and a W boson. The latter then decays either into a quark pair (hadronic decay), or into a neutrino and lepton (leptonic decay). The typical lifetime of the particles which interact with the detector at the LHC is $\sim 3 \times 10^{-11}$ s. The phase space formed by these particles, just before their interaction with the detector, is usually referred to as the *particle level*. At this level, only part of the information of the original top quark is available, namely the one which is accessible through its decay products.

Algorithms exist which aim to reconstruct the top-quark four momentum from its decay products. The reconstructed top candidates in this case are often called *pseudo-tops*. It is important to notice that pseudo-tops and stable top quarks are different objects. This fact has important effects on the definition of the $\mathcal{R}$ observable. One can define an $\mathcal{R}$-like observable at particle level using pseudo-tops, which has a different shape and properties than the parton level one. In particular, it can have a different shape and sensitivity, as it is shown in Fig. 3.

4.2. Unfolding

When extracting m_t using a certain observable and its theoretical prediction, it is important to make the comparison between observables which share the same definition. For instance, extracting m_t using parton level $\mathcal{R}$ predictions from an $\mathcal{R}$-like observable at particle level, would result in a

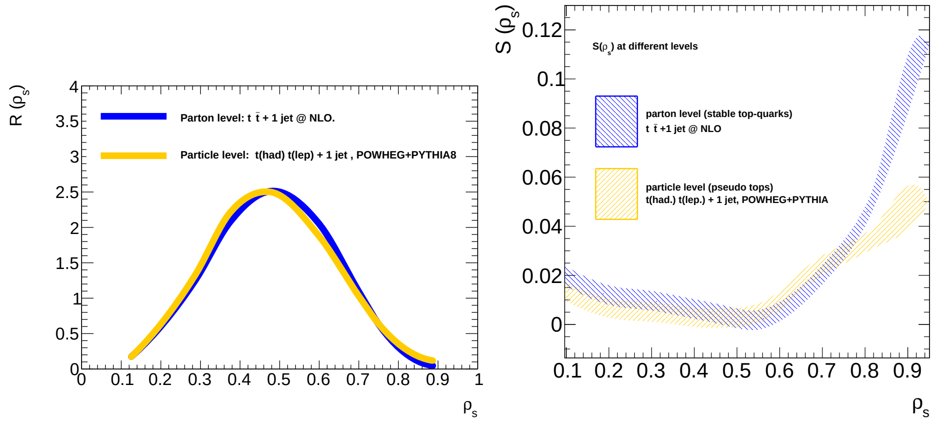

Fig. 3. $\mathcal{R}$ at parton and particle level (left) and corresponding sensitivity (right). The parton level $\mathcal{R}$ has been computed with the fixed order $t\bar{t}+1$ jet NLO QCD calculation. The particle level one has been obtained with a Powheg+Pythia8 simulation, where the top-quark pair was decaying semileptonically. Pseudo-top quarks have been defined following the algorithm presented in [22].

wrong estimation of the value of m_t and its error. In order to do so, the LHC experiments need to correct the events they select at detector level at least by the detector response. This process is usually called unfolding.

When unfolding to particle level, collected data is only corrected taking into account the modelling of the interaction of long living particles with the detector. The only assumptions which enter in the measurement are then given by the knowledge of the detector response. A particle level measurement, performed in a well-defined (*i.e.* fiducial) phase space, minimises the dependence of the measurement on the underlying theoretical model. It also allows to compare different theories to data without worrying too much if the theoretical assumptions on the measurement are compatible with the ones from another theory.

Unfolding to parton level instead, requires correcting data for detector, hadronization and top-quark decay effects. Hence, assumptions have to be made on the theoretical model used in the correction procedure. This typically results in larger errors on observables unfolded to parton level, since more modelling errors have to be taken into account.

5. The top-quark mass in the $\overline{\mathrm{MS}}$ scheme

Observables at NLO can be computed in different renormalization schemes. In the previous sections, we focused on the extraction of the top-quark mass using the $\mathcal{R}$ observable in the pole mass scheme.

A recent calculation [15] computed the same observable in the $\overline{\text{MS}}$ scheme, opening the possibility to extract the running mass of the top quark at its scale, $m_t(m_t)$. One can hence extract the top-quark running mass directly from data corrected to parton level using $\mathcal{R}(m_t(m_t), \rho_{\text{s}})$. This was done in [15] using the data information from [22], as it is shown in Fig. 4, and resulted in the most precise $m_t(m_t)$ measurement to date. Using different renormalization schemes could end up in different theoretical errors. The pole mass scheme, for instance, offers a better description of the physics near the threshold of $t\bar{t}+1$ jet production. The $\overline{\text{MS}}$ scheme instead is better in describing long-distance effects. $\mathcal{R}$ has its more sensitive region to m_t for values approaching the threshold, as it is shown in Fig. 1. If one had a fine binning near the threshold region, extracting m_t using the $\overline{\text{MS}}$ scheme could result in a larger theoretical uncertainties than if using the pole mas scheme. In order to obtain a more precise measurement of the top-quark mass, it is hence important to study the observable in both renormalization schemes.

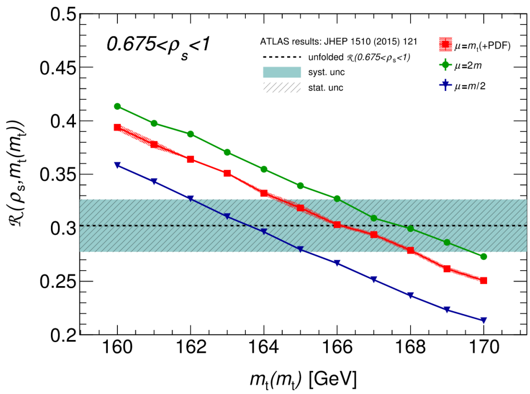

Fig. 4. $\mathcal{R}(m_t(m_t))$ in the interval $0.675 < \rho_{\text{s}} < 1$, compared to ATLAS data from [22] corrected to parton level. Scale variations as well as variations due to the choice of PDF distributions is also shown. Figure taken from [15].

6. Conclusions

The top-quark mass is a fundamental parameter of the SM Lagrangian, and its accurate determination is of great importance for the incoming high precision LHC era [8]. It also plays a role in constraining NP models [9]. Since the top quark is not a free particle, its mass can only be extracted in a well-defined way by observables which are sensitive to its value. One successful observable which has been used recently [22,23] is the normalised $t\bar{t}+1$ jet cross-section differential in the invariant mass of the $t\bar{t}+1$ jet system, $\mathcal{R}(\rho_{\text{s}})$. A strategy to optimise top-quark mass measurements at the

LHC using such observable has been presented. Many theoretical and experimental aspects have to be taken into account in such a measurement. In particular, the same definition of the observable has to be used when comparing data to theory. $\mathcal{R}$ has been studied at parton and particle levels and it has been highlighted how a different definition can affect its properties: using pseudo-tops instead of on-shell top quarks drastically reduced $\mathcal{R}$ sensitivity to the top-quark mass. Finally, the choice of the renormalization scheme could also affect the theoretical error on m_t. The choice of pole mass or $\overline{\text{MS}}$ schemes could be visible if a thin binning is chosen for $\mathcal{R}$ near the threshold. All these aspects have to be taken into account in the future, aiming for a high precision measurement of m_t^{pole} and $m_t(m_t)$, aiming to reach the 1 GeV precision.

We thank R. Pittau, J. Fuster Verdu and M. Vos for supervising and for the useful discussions and support. We acknowledge the Research Executive Agency (REA) of the European Union for funding this work through the Grant Agreement PITN-GA-2012-316704 (“HiggsTools”).

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