PROCEEDINGS OF SCIENCE

Measurement of the jet mass distribution of boosted top quarks and the top quark mass with CMS

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Alexander M. Paasch* **on behalf of the CMS Collaboration**

Institut für Experimentalphysik, Universität Hamburg,
Luruper Chaussee 149, Hamburg, Germany

E-mail: alexander.paasch@uni-hamburg.de

We present a measurement of the jet mass distribution in fully hadronic decays of boosted top quarks with full Run 2 data. The measurement is performed in the lepton+jets channel of top quark pair production. The top quark decay products of the all-hadronic decay cascade are reconstructed with a single large-radius jet with transverse momentum greater than 400 GeV. The top quark mass is extracted from the normalised differential top quark pair production cross section at the particle level. The uncertainties arising from the calibration of the jet mass scale and modelling of the final state radiation in simulation are improved by dedicated studies of the jet substructure. These studies lead to a significant increase in precision in the top quark mass with respect to an earlier measurement, now reaching a precision below 1 GeV.

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*Speaker

1. Introduction

The top quark stands out as the most massive elementary particle discovered so far. It takes a prominent role in the standard model (SM), because of its large mass and a Yukawa coupling close to unity. Precise measurements of top quark properties, such as its mass, enable precision tests of the SM, unravel the stability characteristics of our universe, and allow for searches of small deviations from the SM from new physics effects.

Highly energetic top quarks result in very collimated decays because of the large Lorentz boost, and therefore can be reconstructed in one single jet. In the context of hadronic top quark decays, the jet mass m_{jet} is sensitive to m_{top}. Here, m_{jet} represents the invariant mass of the sum of all jet constituents. Furthermore, the differential $\text{t}\bar{\text{t}}$ production cross section as a function of m_{jet} can be determined from analytic calculations from first principles [1]. By unfolding the jet mass distribution to the particle level, data can be compared to these calculations allowing the measurement of a well-defined top quark mass. Notably, these calculations are restricted to jets with a transverse momentum $p_{\text{T}}^{\text{jet}}$ exceeding 750 GeV, a phase space currently beyond the reach of experiments at the LHC.

Previous analyses by the CMS Collaboration at $\sqrt{s} = 8$ TeV [2] and $\sqrt{s} = 13$ TeV [3] aimed for the reconstruction of boosted top quark decays with $p_{\text{T}}^{\text{jet}} > 400$ GeV. Although analytic calculations have not yet been applicable to this phase space, the top quark mass has been measured with event generators, reaching a precision of $\Delta m_{\text{top}} = 2.5$ GeV. The precision is limited by two significant uncertainties; the calibration of the jet mass scale (JMS) and the modeling of the final state radiation (FSR). This article introduces a methodology to calibrate the JMS utilizing the hadronic W boson decay. In addition, the uncertainty in the modelling of the FSR is reduced by measurements of angular correlations in the substructure of jets. Furthermore, the analyzed data is extended to the full dataset recorded by the CMS experiment in Run 2 of the LHC, with an integrated luminosity of 138 fb^{-1}. Details of this study are published in Ref. [4] and a detailed description of the CMS detector can be found in Ref. [5].

2. Event reconstruction and selection of boosted top quark decays

The analysis presented in this article focuses on the ℓ+jets channel of $\text{t}\bar{\text{t}}$ events. The lepton ℓ is either an electron or moun. Jets in the event are clustered with the exclusive XCone jet algorithm [6]. This jet clustering algorithm returns a fixed number of jets, and is therefore particularly well-suited for reconstructing processes with a predetermined number of jets in the final state. For the purpose of reconstructing boosted top quark decays, a two-step clustering sequence is used. First, two large-R jets with $R = 1.2$ are found to cluster the full $\text{t}\bar{\text{t}}$ event. Subsequently, the particles from each jet are clustered with three smaller jets with $R = 0.4$, also referred to as subjets. The mass of the final jet is set to be the invariant mass of the sum of the three subjets, thereby minimizing the effects of uncorrelated soft radiation and pile-up. The jet with the greater angular distance ΔR to the lepton is associated with to the hadronic top quark decay and denoted as XCone jet. The other jet is then referred to as second XCone jet. In order to select boosted top quark events, the XCone jet must have a transverse momentum of $p_{\text{T}}^{\text{jet}} > 400$ GeV. The four-momentum of the subjets are corrected with the centrally provided jet energy corrections (JEC) [7]. Given that the corrections

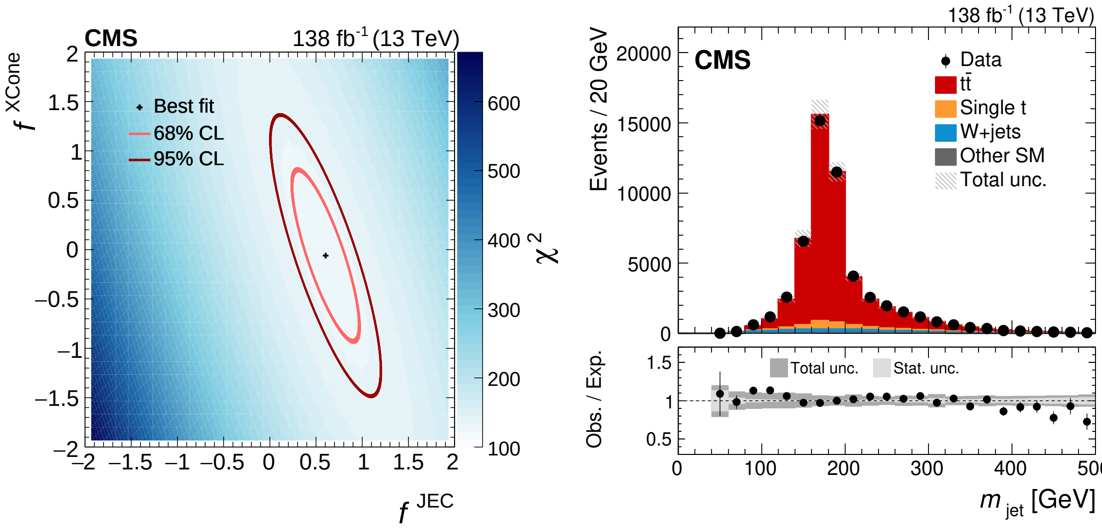

Figure 1: Left: χ^2 function for jet correction factors fitted to data. Displayed are the minimum value (black marker), the 68% (light red line) and 95% (dark red line) confidence intervals. Right: Jet mass distribution after full event selection and dedicated calibration of the jet mass scale. Published in Ref. [4].

are determined based on measurements with jets clustered with anti-k_T clustering algorithm, further corrections are calculated and applied to the subjets. These additional corrections account for the differences between those two jet algorithms.

3. Calibration of the jet mass scale

The JMS is determined using the hadronic W boson decay in the XCone jet. One subjet is identified to originate from the b quark using b tagging information, and the invariant mass of the two light-flavor jets yields the W boson mass. The JMS in simulations is determined by fitting data to the variations of the JEC and the additional XCone corrections, minimizing the χ^2. Here, two factors, f^{JEC} and f^{Xcone}, are introduced, which adjust the central corrections.

The measurement is conducted in two p_T^W bins and the two bins of the ratio $r_{p_T} = p_T^{s1}/p_T^W$, where s_1 is the p_T leading subjet. The measurement in four regions reduces the correlation of both jet corrections. The fit only focuses on the peak position of the distribution to exclude the contribution of wrong assigned subjets during the reconstruction of the W boson. The χ^2 function, displayed on the left in Figure 1, yields the best-fit values $f^{\mathrm{JEC}} = 0.60 \pm 0.24$ and $f^{\mathrm{XCone}} = -0.06 \pm 0.57$ with respect to the jet correction variations. Moving forward, the JES only impacts the three-momentum of the jets, while the JMS exclusively influences the jet mass. The XCone jet mass, after applying the JMS, is displayed in Figure 1 (right), exhibiting a close peak to the top quark mass and a good agreement between data and simulation is found.

4. Modeling of the final state radiation

The modeling of the FSR is the largest model uncertainty from the previous analysis. The renormalization scale μ in the simulation of FSR affects the amount of radiation in jets through the

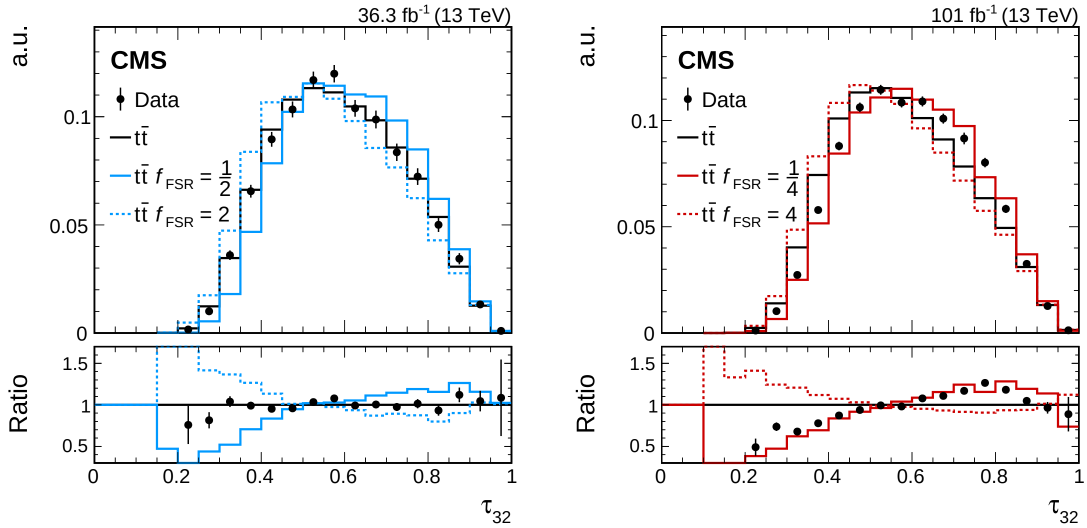

Figure 2: N-subjettiness ratio $\tau_{32} = \tau_3/\tau_2$ for boosted hadronically decaying top quarks for 2016 (left) and 2017+2018 (right). Published in Ref. [4].

value of the strong coupling $\alpha_S(\mu^2)$. To regulate the strength of α_S and consequently control the amount of FSR, the energy scale is varied by a factor f_{FSR}. We measure the N-subjettiness ratio $\tau_{32} = \tau_3/\tau_2$ to determine the value of f_{FSR} that describes the data best. The ratio τ_{32} is used to distinguish three-prong decays from decays with two or less prongs, and shows high sensitivity to additional radiation in jets. Figure 2 illustrates the dependency of τ_{32} on the parameter f_{FSR} for 2016 (left plot) and the combined data from 2017 and 2018 (right plot). These distributions are measured with jets reconstructing boosted hadronic top quark decays. The year 2016 is studied separately because of different settings used in the simulation of $t\bar{t}$ events, most notably a different value of the effective strong coupling. The factor f_{FSR}, which describes data best is obtained by minimizing the χ^2. For 2016 the factor $f_{FSR} = 0.97 \pm 0.07$ corresponds to a similar central value as the initial setting. In contrast, the combination of 2017 and 2018, $f_{FSR} = 0.33 \pm 0.02$, indicates the need to shift the energy scales to lower values to describe data, as evident in Figure 2 (right).

5. Results

The data are corrected for detector effects and migrations using a regularized unfolding technique as implemented in the TUnfold framework [8]. In addition to the primary phase space region, five side band regions are introduced by loosening the requirements on the XCone jet, the subjets, the lepton and the b tagging score. The final measurement combines data from all years and both the electron and muon channels. The top quark mass is extracted from the normalized differential cross section, shown in Figure 3, by fitting various m_{top} hypotheses to data. The top quark mass is measured to be $m_{top} = 173.06 \pm 0.84$ GeV. The dedicated calibrations for the JMS lead to an uncertainty of $\Delta m_{top}(\text{JMS+JES}) = 0.46$ GeV, which is significantly smaller compared to the previous analysis with $\Delta m_{top}(\text{JES}) = 1.5$ GeV. The same improvement is observed for the modeling of the FSR, which has been reduced from $\Delta m_{top}(\text{FSR}) = 1.2$ GeV to 0.02 GeV, becoming a negligible source of uncertainty.

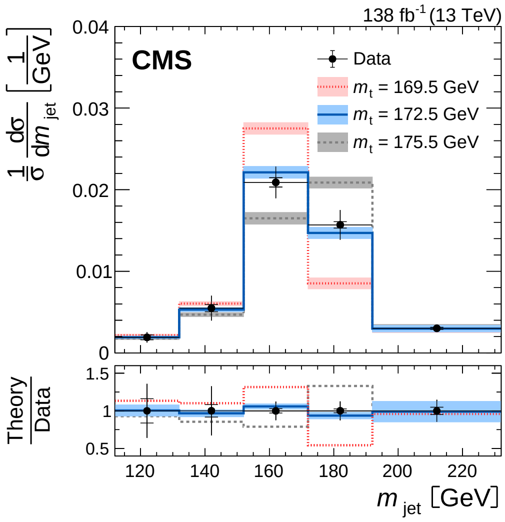

Figure 3: Normalized differential cross section as a function of m_{jet}. The data are compared to predictions from simulations using different values of m_{top}. Published in Ref. [4].

6. Summary

We presented a measurement of the jet mass distribution in hadronic decays of boosted top quarks, resulting in a precise determination of the top quark mass, $m_{\mathrm{top}} = 173.06 \pm 0.84\,\mathrm{GeV}$. Through dedicated studies, the primary experimental and model uncertainties from a prior analysis are mitigated; namely the calibration of the JMS and the modeling of the FSR. Performing a dedicated measurement of the JMS independently from the JES increased the precision to $\Delta m_{\mathrm{top}}(\mathrm{JMS{+}JES}) = 0.46\,\mathrm{GeV}$. Likewise, the uncertainty from the modeling of the FSR was significantly reduced and became a subleading uncertainty in the extraction of m_{top}.

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PoS(EPS-HEP2023)327

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