PROCEEDINGS OF SCIENCE

Jet substructure and boosted jet measurements at CMS

Deniz Sunar Cerci[a,1,*]

[a] *Adiyaman University,*
Faculty of Arts and Sciences, Department of Physics, 02040 Adiyaman, Turkey

E-mail: deniz.sunar.cerci@cern.ch

Results on measurements involving jet substructure and boosted jets are presented. The data have been recorded by the CMS Collaboration in proton-proton collisions at the LHC at a center-of-mass energy of 13 TeV. The measured cross sections are compared to various theoretical predictions, including new calculations using analytical resummation. Furthermore, multiple jet substructure observables measured in $t\bar{t}$ events are presented.

40th International Conference on High Energy Physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

[1]For the CMS Collaboration
*Speaker

https://pos.sissa.it/

PoS(ICHEP2020)507

1. Introduction

Jets, abundantly produced at the LHC, are collimated sprays of hadrons usually associated with an elementary particle production carrying colour charge, i.e. quarks and gluons. The strong force which is described by quantum chromodynamics (QCD) governs the evolution of jets. Experimentally jets are clustered from the final state particles using the jet reconstruction algorithms. The anti-k_T algorithm is commonly used by the CMS [1] experiment where the signals from all subdetectors are first combined in a particle flow (PF) algorithm, reconstructing electrons, photons, and muons as well as charged and neutral hadrons [2].

In recent years, a vibrant research field has emerged on identifying the internal structure of jets. At high energy collisions electroweak scale resonances such as W/Z/H bosons and the top quark are produced beyond threshold, i.e. their energy or transverse momentum can significantly exceed their mass. Hence, strategies developed at earlier colliders where the electroweak scale particles produced with small velocities, should be reconsidered. Since electroweak resonances dominantly decay into quarks, the decay products can become collimated in the laboratory frame. The investigation of the internal structure of jets i.e, jet substructure aims to eliminate contributions from soft emission.

Jet-grooming techniques [3–5] can be used to separate the soft parts of the jets from the hard part. The effects of pileup, which is not correlated with the hard part of the jet can be reduced by using such techniques. The “mass drop” (MD) procedure [6] has been modified into such a theoretically controlled jet-grooming algorithm [7]. Its generalization, the “soft drop” (SD) algorithm [8], removes soft parts of a jet, resulting in a dramatically reduced Sudakov peak in the jet mass distribution. Understanding the behavior of the jet mass and the grooming techniques from first principles is important to further develop boosted object identification algorithms.

2. Jet mass in dijet events

CMS has measured the differential jet cross section as a function of the jet mass in bins of jet transverse momentum from dijet events, with and without a jet grooming algorithm [9]. Comparison of the production cross section with respect to the ungroomed (m_u) and groomed (m_g) jet mass provides insight into both the soft and hard physics. The data are compared to PYTHIA8, POWHEG+PYTHIA8, and HERWIG++ predictions including new calculations using analytical resummation. The events having at least two jets, without an explicit third jet veto, are selected. The asymmetry between the leading and subleading jet transverse momenta, defined as p_{T1} and p_{T2} respectively, is required by $(p_{T1} - p_{T2})/(p_{T1} + p_{T2} < 0.3)$. The difference in azimuthal angles is required to satisfy $\Delta(\phi_1 - \phi_2) > \pi/2$. Jets are clustered using the anti-k_T algorithm [10] with a distance parameter of $R = 0.8$ which is chosen to coincide with the majority of CMS beyond the standard model (BSM) searches using jet substructure techniques. The soft drop algorithm procedure is applied to groom the jets. Figure 1 shows the normalized cross sections for ungroomed and groomed jets as a function of the jet mass for all p_T bins. Overall, an agreement is observed between the theoretical predictions and the measured cross sections within the uncertainties for masses from 10 to 30% of the jet transverse momentum.

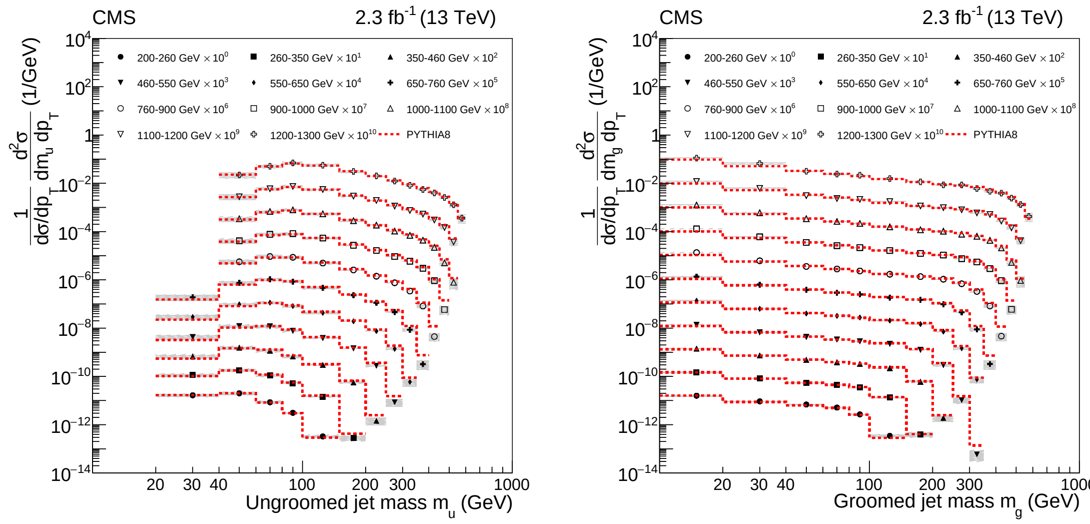

Figure 1: Normalized cross section for ungroomed (left) and groomed (right) jets for all p_T bins [9].

3. Jet substructure observables in $t\bar{t}$ events

An analysis of the jet substructure observables in resolved $t\bar{t}$ lepton + jets events from pp collisions at $\sqrt{s}$ = 13 TeV has been performed by the CMS Collaboration [11]. Multiple jet substructure observables such as generalized angularities, eccentricity, groomed momentum fraction, N-subjettiness ratios, and energy correlation functions are measured for jets identified as bottom, light-quark, and gluon jets, as well as for inclusive jets (no flavor information). The results are compared to theoretical predictions from POWHEG interfaced with the parton shower generators PYTHIA 8, HERWIG 7, and DIRE 2. After applying SD algorithm to remove the soft radiation, the groomed momentum fraction is expressed as $z_g = p_T(j_2)/p_T(j_0)$ where j_2 and j_0 are the last declustering iteration and the softer subjet, respectively. The unfolded z_g distribution for the first time is shown in Figure 2 (left). An agreement between the data and the prediction of HERWIG7 using the angular-ordered shower is observed. The distribution of angle between groomed subjets, ΔR_g, is shown for charged particles in Figure 2 (right) . This observable is related to jet width and the groomed jet area and shows a strong dependency on the amount of final state radiation (FSR). The present data provide useful tests for tuning and improving final-state parton showers as well as quantum chromodynamics analytical calculations including higher-order fixed and logarithmic corrections, for infrared- and/or collinear-safe observables.

4. Jet mass in $t\bar{t}$ events

CMS has been investigating the running of the top quark mass m_t for the first time [12]. In the modified minimal subtraction ($\overline{MS}$) renormalization scheme, the top quark mass and the strong coupling constant α_s depend on the renormalization scale μ which is described by the renormalization group equations (RGEs) as following:

$$\mu^2 \frac{\mathrm{d}m(\mu)}{\mathrm{d}\mu^2} = -\gamma(\alpha_s(\mu))m(\mu) \tag{1}$$

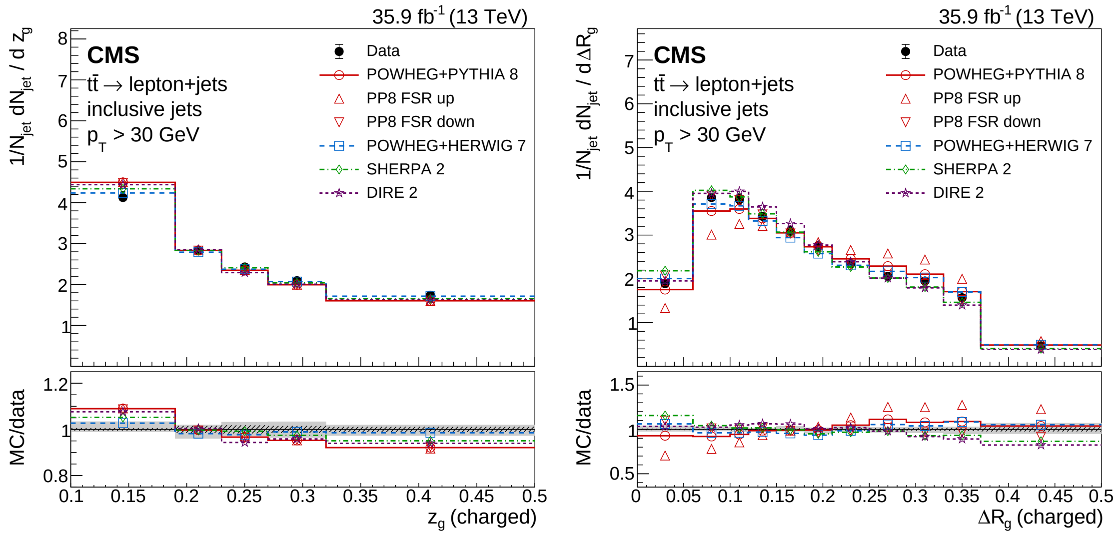

Figure 2: Distributions of the groomed momentum fraction z_g (left) and the angle between the groomed subjets R_g (right) for inclusive jets reconstructed with charged particles [11].

Here, $-\gamma(\alpha_s(\mu))$ and $m(\mu)$ represent the quark mass anomalous dimension and the quark mass evaluated at the scale μ, respectively. In order to extract the running of m_t, a comparison of next-to-leading order (NLO) theoretical predictions to a measurement of the differential top quark-antiquark ($t\bar{t}$) production cross section as a function of $m_{t\bar{t}}$ is performed. In order to minimize the correlation between the extracted ratios ($m_t(\mu_k)/m_t(\mu_2)$), the running is determined with respect to a reference scale μ_{ref} which is chosen to be $\mu_2 = 476$ GeV. The extracted running together with the RGE prediction at one-loop precision is shown in Figure 3 (left). Good agreement with the one-loop RGE prediction is observed within 1.1 standard deviations, and the no-running hypothesis is excluded at above 95% confidence level. Figure 3 (right) shows a comparison between the the extracted ratios $m_t(\mu_k)/m_t(\mu_2)$ to the value of $m_t^{incl}(\mu_k)/m_t(\mu_2)$. The running of m_t is probed up to a scale of the order of 1 TeV.

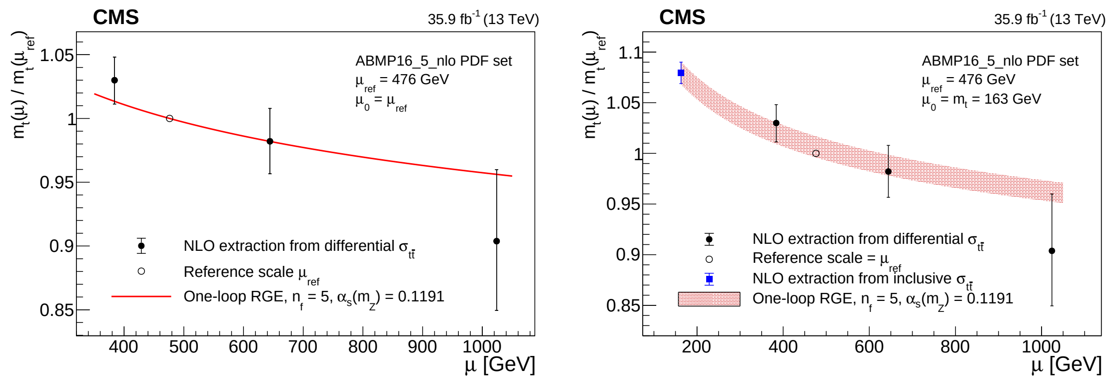

Figure 3: Extracted running of m_t compared to the RGE prediction at one-loop precision (left) and the comparison to the value of $m_t^{incl}(\mu_k)/m_t(\mu_2)$ (right) [12].

5. Differential $t\bar{t}$ cross section

A measurement of the differential $t\bar{t}$ production cross section in the boosted regime in the all-jet and lepton+jets final states is performed by the CMS Collaboration [13]. The measurement is based on pp collisions at $\sqrt{s}$ = 13 TeV corresponding to a total integrated luminosity of 35.9 fb^{-1}. Events consisting of either one or both top quarks decaying to jets and where the decay products cannot be resolved but are instead clustered in a single large-radius (R) jet with p_T > 400 GeV are used. The absolute (left) and normalized (right) differential cross sections unfolded to the parton-level as a function of $m_{t\bar{t}}$ are shown in Figure 4. The absolute cross section is significantly overestimated by all the models. However, the normalized differential cross sections are consistently well described.

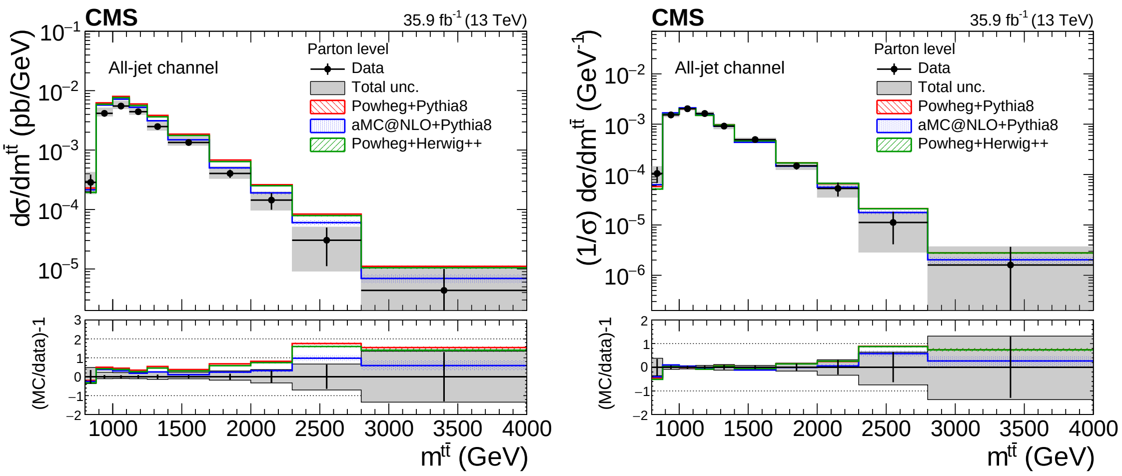

Figure 4: Differential cross section unfolded to the parton level, absolute (left) and normalized (right), as a function of $m_{t\bar{t}}$ in the all-jet channel [13].

6. Summary

CMS has recently published several studies on various jet substructure observables in order to characterize the jet evolution. As measurements probe larger energy scales, jet substructure algorithms and boosted objects are increasingly relied upon. Comparison of the normalized groomed and ungroomed cross sections has shown that the grooming algorithm considerably decreases the jet mass and reduce the sensitivity of the observable to details of the physics modeling and pileup effects. The present measurements provide useful tests for improved quantum chromodynamics analytical calculations as well as tuning and improving final-state parton showers.

References

[1] CMS Collaboration, *The CMS experiment at the CERN LHC*, *JINST* **3** (2008) S08004.

[2] CMS Collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, *JINST* **12** (2017) P10003.

[3] A. Abdesselam et al., *Boosted objects: A probe of beyond the standard model physics*, *Eur. Phys. J.* **C 71** (2011) 1661.

[4] A. Altheimer et al., *Boosted objects and jet substructure at the LHC*, *Eur. Phys. J.* **C 74** (2014) 2792.

[5] D. Adams et al., *Towards an understanding of the correlations in jet substructure*, *Eur. Phys. J.* **C 75** (2015) 409.

[6] DJ.M. Butterworth, A.R. Davison, M. Rubin and G.P. Salam, *Jet substructure as a new Higgs search channel at the LHC*, *Phys. Rev. Lett.* **100** (2008) 242001.

[7] M. Dasgupta, A. Fregoso, S. Marzani and G.P. Salam, *Towards an understanding of jet substructure*, *JHEP* **09** (2013) 029.

[8] A.J. Larkoski, S. Marzani, G. Soyez and J. Thaler, *Soft drop*, *JHEP* **05** (2014) 146.

[9] CMS Collaboration, *Measurements of the differential jet cross section as a function of the jet mass in dijet events from proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, *JHEP* **11** (2018) 113.

[10] M. Cacciari, G.P. Salam and G. Soyez, *The anti-*k_t *jet clustering algorithm*, *JHEP* **04** (2008) 063.

[11] CMS Collaboration, *Measurement of jet substructure observables in* $t\bar{t}$ *events from proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, *Phys. Rev. D* **98** (2018) 092014

[12] CMS Collaboration, *Running of the top quark mass from proton-proton collisions at* $\sqrt{s} =$ 13 *TeV*, *Phys.Lett.B* **803** (2020) 135263

[13] CMS Collaboration, *Measurement of differential* $t\bar{t}$ *production cross sections for high-*p_T *top quarks in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, Submitted to Phys. Rev. D `arXiv:2008.07860 [hep-ex]`