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

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ABSTRACT: Measurements of the differential jet cross section are presented as a function of the jet mass in dijet events, in bins of jet transverse momentum, with and without a jet grooming algorithm. 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 and correspond to an integrated luminosity of $2.3\,\text{fb}^{-1}$. The absolute cross sections show slightly different jet transverse momentum spectra in data and Monte Carlo event generators for the settings used. Removing this transverse momentum dependence, the normalized cross section for ungroomed jets is consistent with the prediction from Monte Carlo event generators for masses below 30% of the transverse momentum. The normalized cross section for groomed jets is measured with higher precision than the ungroomed cross section. Semi-analytical calculations of the jet mass beyond leading logarithmic accuracy are compared to data, as well as predictions at leading order and next-to-leading order, which include parton showering and hadronization. Overall, in the normalized cross section, the theoretical predictions agree with the measured cross sections within the uncertainties for masses from 10 to 30% of the jet transverse momentum.

KEYWORDS: Hadron-Hadron scattering (experiments), Jet physics

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Contents

1 Introduction

The understanding of the evolution of jets in quantum chromodynamics (QCD) is important to the understanding of physics at hadron colliders. Jets are involved in nearly every final state in proton-proton (pp) collisions. In the past, most predictions of jet properties did not focus on the jet mass m, defined as the mass of the sum of the four-momenta of the constituents inside the jet. However, the jet mass is the simplest observable that is nonzero only beyond leading order (LO) in perturbation theory for dijet production. Thus, it is more sensitive to the internal structure and evolution of jets than the jet transverse momentum p_{T}. The evolution of jets is theoretically described by parton showering as reviewed in refs. [1, 2]. Experimental measurements of the jet mass provide an important test of these theoretical concepts.

Jet mass has been used extensively to investigate signals of physics beyond the standard model (BSM) that are reviewed in refs. [3–5]. In particular, the jet mass generated by QCD radiation is typically lower than that generated by heavy hadronically decaying standard model (SM) particles that have 2- and 3-prong decays, such as top quarks, W bosons, Z bosons, or Higgs (H) bosons. This observation can be exploited to identify BSM particles that decay into highly Lorentz-boosted SM particles (boosted objects).

The jet mass generated by QCD arises from the radiation of gluons from the higher-energy (hard) portion of the jet. The probability that a gluon is radiated increases as its energy or angle of emission decreases (soft or collinear radiation, respectively). Hence, the probability of having $m = 0$ vanishes since many soft and/or collinear gluons will be radiated. Above $m/p_{\mathrm{T}} \approx 0.1$, there is an overall decrease in the jet mass spectrum as the dominant contributions come from gluon emissions with high energy or at large angles. The distribution terminates around $m/p_{\mathrm{T}} \approx 0.3$ for jets with $R = 0.8$ (where R is the distance parameter of the algorithm). At that point, the jets become wide enough to start

splitting into two separate jets (the splitting threshold). The appearance of a large peak at low mass is described in ref. [6] as a "Sudakov peak". The jet mass is sensitive to soft QCD effects and to additional pp interactions in the same bunch crossing (pileup) [7]. There is further sensitivity in hadron colliders to correlations among soft gluon emissions from underlying event interactions, and wide-angle emissions among different jets. While the impacts on global event-wide observables (such as the event thrust) have been understood for some time [8–11], the impact on nonglobal jet observables, such as mass, are difficult to calculate. The technical difficulty arises from the treatment of nonglobal logarithms (NGLs) in the perturbative next-to-leading logarithmic (NLL) order calculations of the jet mass that arise from radiation that exits the jet re-radiating soft gluons back into the jet. It is currently unknown how to fully account for these NGLs in the perturbative integrals.

The hard part of the jet can be separated from the soft parts using jet-grooming techniques [3–5]. These techniques also reduce the effects of pileup, which is not correlated with the hard part of the jet. The earliest grooming techniques were unable to completely remove the soft parts of a jet systematically. More recently, major improvements have been made to separate the hard and soft parts of the jet without contamination from NGLs [6, 8, 12–15]. The "mass drop" (MD) procedure [16] has been modified into such a theoretically controlled jet-grooming algorithm [6]. Its generalization, the "soft drop" (SD) algorithm [12], has similar properties. By applying the SD algorithm, soft parts of a jet are removed, resulting in a dramatically reduced Sudakov peak in the jet mass distribution. This also systematically removes the effects that cause NGLs in the calculation, allowing for direct comparisons of the semi-analytical NLL resummation calculations (in particular, from the authors of refs. [17] and [18]) to Monte Carlo (MC) simulated predictions and data. We therefore apply the SD procedure to groom the jets in this paper. A similar analysis has been published by the ATLAS Collaboration in ref. [19]. Understanding the behavior of the jet mass and the grooming techniques from first principles is important to further develop boosted object identification algorithms, to gain confidence in the tools should they uncover BSM physics, and to check that parton showering algorithms are correct.

In this paper, we present a measurement of the differential jet production cross section as a function of the jet mass in bins of p_{T} from dijet events, before and after the jets are groomed with the SD procedure (for our choice of parameters the SD and MD procedures are identical). Comparing the production cross section with respect to the groomed (m_{g}) and ungroomed (m_{u}) jet mass separately allows us to gain insight into both the hard and soft physics.

This analysis is similar to that of ref. [7], except we correct both the jet p_{T} and m for detector effects, and the SD algorithm is used. We present the double-differential production cross section of dijet events with respect to the jet p_{T} and jet mass m (where $m = m_{\mathrm{u}}$ or m_{g}):

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}m}\ (\mathrm{pb/GeV}^2). \tag{1.1}$$

In addition, we define a normalized distribution:

$$\frac{1}{\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}}\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}m}\ (1/\mathrm{GeV}). \tag{1.2}$$

In both cases, the two jets in the dijet system are included in the distributions. We have used only the $2.3\,\mathrm{fb}^{-1}$ dataset instead of all the available luminosity, because we present the ungroomed cross section, which is systematically limited by the pileup uncertainty in higher luminosity data samples.

2   Theoretical predictions

There are five theoretical calculations used in this study: three MC event generator predictions, and two predictions using analytic resummation merged with fixed order MC simulations.

The three MC event generators used in this study are PYTHIA8, HERWIG++, and POWHEG. Version 8.212 of PYTHIA8 [20] is used with underlying event tune CUETP8M1 [21] and NNPDF 3.0 parton distribution functions (PDFs) NNPDF30_lo_as_0130 [22]. The PDF4LHC15_NLO_100 meta-PDF set is used for uncertainty estimation, along with the PYTHIA8 generator. We use the LHAPDF [23] software package for this purpose, following the recommendations of ref. [24]. The HERWIG++ version 2.7.0 generator [25] is used with tune CUETHS1 [21]. The HERWIG++ simulation sample is used for systematic uncertainty estimation and for generator-level comparisons, as it has a physics model that is different from PYTHIA8 in various aspects like parton showering, hadronisation, multiple-parton interactions, and the set of model parameters tuned to data. Finally, the POWHEG 2.0 [26–29] generator interfaced with PYTHIA8 is used as a next-to-leading order (NLO) perturbative dijet event generator, supplemented with parton showering and multiparton interactions. The same underlying event tune CUETP8M1 [21] is used.

Two semi-analytical resummation-based calculations merged with fixed-order MC simulation are also used. The authors of ref. [17] have provided a prediction of the groomed jet mass distribution for dijet events at LO using MADGRAPH v2.4.2 [30] and NNPDF 3.0 LO PDFs [22], resummed at NLL accuracy using soft collinear effective theory. Nonperturbative effects are included as an uncertainty in their prediction. The authors of ref. [18] have provided a prediction of the groomed jet mass distribution for dijet events at NLO using NLOJET++ [31] and CT14NLO PDFs [32] with NLL resummation using perturbative QCD. They include an estimate of the nonperturbative effects directly, using PYTHIA8.

The semi-analytical predictions are expected to be accurate for intermediate masses $0.1 < m/p_{\mathrm{T}} < 0.3$, since at low mass nonperturbative effects are large. Moreover, at high mass the resummed predictions are matched to fixed-order predictions at LO and NLO, which cannot account for more than one or two additional gluons, respectively, as would occur within genuine jets. For a single gluon emission, there is a kinematic upper limit at $m = p_{\mathrm{T}} R/2$ (where $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is the distance parameter for the jet clustering), from the relativistic kinematics of a $1 \to 2$ decay. However, in the all-orders limit, the approximate kinematic limit is closer to $m = p_{\mathrm{T}} R/\sqrt{2}$. Consider a particle of energy E and mass m decaying to two massless particles, each with an energy $E/2$ and separated by an angle θ. The mass must satisfy $m^2 < E^2 (1 - \cos\theta)/2$. In the small-angle limit, this would be $m^2 < E^2\theta^2/4$, or $m < E\theta/2$. With more particles, the stochastic nature of the shower increases this cutoff point. Thus, a single emission $(1 \to 2)$ decay will have a

lower approximate kinematic limit than an all-orders $(1 \rightarrow \text{many})$ decay. Reference [18] calculates these thresholds to be $m/E \approx 0.28$ at LO and $m/E \approx 0.45$ at NLO.

3 Experimental setup

The central feature of the CMS detector [33] is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each split in the barrel and two endcap sections. In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in pseudorapidity (η) and 0.087 radians in azimuth (ϕ). In the η-ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map onto 5×5 ECAL crystal arrays to form calorimeter towers projecting radially outwards from close to the nominal interaction point. At larger values of $|\eta|$, the size of the towers increases and the matching ECAL arrays contain fewer crystals. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Electron momenta are estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. In this analysis, the jet rapidity (y) is used in the computation of jet quantities. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [33].

Events of interest are selected using a two-tiered trigger system [34]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz with a latency of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

The event reconstruction is based on the CMS particle-flow (PF) algorithm [35], which includes information from all subdetectors, including charged-particle tracks from the tracking system, energy deposits in the ECAL and HCAL, and tracks reconstructed in the muon chambers. Particles in an event are reconstructed and identified as electrons, muons, photons, charged hadrons, or neutral hadrons. Charged hadrons associated with pileup vertices are removed from consideration. This method is referred to as "charged-hadron subtraction" (CHS) [36]. In our dataset, the average number of pileup interactions per beam crossing is 14.

Jets are clustered using the anti-k_{T} algorithm [37] with the FASTJET 3.0 software package [38], with a distance parameter of $R = 0.8$ (AK8 jets). This distance parameter is chosen to coincide with the majority of CMS BSM searches using jet substructure techniques. To reconstruct the groomed jets, the constituents of the AK8 jets are reclustered using the Cambridge-Aachen algorithm [39, 40] with the same characteristic radius (CA8) to retain substructure information. The hierarchical sequence of clustering is then reversed ("declustering"). The jet grooming algorithm used is the SD algorithm [12]. For each

declustering step, the "soft-drop condition" is applied:

$$\frac{\min(p_{\mathrm{T},i}, p_{\mathrm{T},j})}{(p_{\mathrm{T},i} + p_{\mathrm{T},j})} > z_{\mathrm{cut}} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}, \tag{3.1}$$

where $p_{\mathrm{T},i}$ and $p_{\mathrm{T},j}$ are the transverse momenta of the ith and jth particle at each declustering step, ΔR_{ij} is the distance between them, z_{cut} corresponds to the threshold to separate the "soft" and "hard" parts of the jet, and β is an angularity exponent. If any declustering step does not satisfy the soft-drop condition, the softer constituent is removed from consideration by the jet algorithm. We choose $\beta = 0$, $z_{\mathrm{cut}} = 0.1$ and hence R_0 is no longer a relevant parameter. For this choice of parameters, the SD algorithm is identical to the variant of the MD algorithm described in ref. [6]. The choice of $\beta = 0$ was made for simplicity to agree with most other CMS analyses, whereas other values of β will be addressed in future work. The measurement is not very sensitive to the value of z_{cut}, and is chosen to be consistent with ref. [6] and other CMS analyses.

For the reconstructed jets, all PF candidates that survive the CHS procedure are included. The same reconstruction criteria are also used to create generator-level jets using generated stable particles (mean path length $c\tau > 1\,\mathrm{cm}$, no minimum p_{T} requirement), removing neutrinos. Simulated pileup particles are not included in the generator-level jets. The ungroomed jet mass is taken as the mass of the four-momentum sum of the constituents of the AK8 jet without grooming applied. The groomed jet mass is taken as the mass of the four-momentum sum of the constituents of the AK8 jet with the SD algorithm applied. For this measurement, the p_{T} of the ungroomed AK8 jet is used for both the groomed and ungroomed jet cross sections, since it has been shown that the groomed jet p_{T} is not collinear-safe for the SD algorithm chosen [18].

Since only charged hadrons arising from pileup interactions are removed with the CHS procedure, corrections based on the jet area [41] are applied to the jet energies to remove the energy contribution of neutral hadrons from pileup. The area-based residual subtraction is not applied to the jet mass because it is observed [42] that this overcorrects the mass of hadronically decaying W bosons in a $t\bar{t}$ control sample. Further jet energy scale (JES) corrections are applied as functions of η and p_{T}, derived from simulation. Data-to-simulation correction factors are also applied, using the methodology of ref. [42]. These corrections are also applied to the jet mass by scaling the mass by the same factor used for the p_{T} in the four-momentum of the jet.

To account for the poorer jet energy resolution (JER) in the data with respect to MC simulation, the reconstructed simulated jets are smeared compared to generator-level jets by the amounts listed in ref. [42]. The typical values of the JER are around 5–8%. After these corrections, the JES and JER in MC simulation agree with those in data for both groomed and ungroomed jets.

The jet mass can also have different scales and resolutions in experimental data and in MC simulation. In the MC simulation, the jet mass scale (JMS) and jet mass resolution (JMR) are respectively determined by comparing the means and widths of distributions of the jet mass at the reconstructed and generator levels ($m_{\mathrm{reco}}/m_{\mathrm{gen}}$). The JMSs in MC simulation for groomed and ungroomed jets with our selection are shown in figure 1 as a
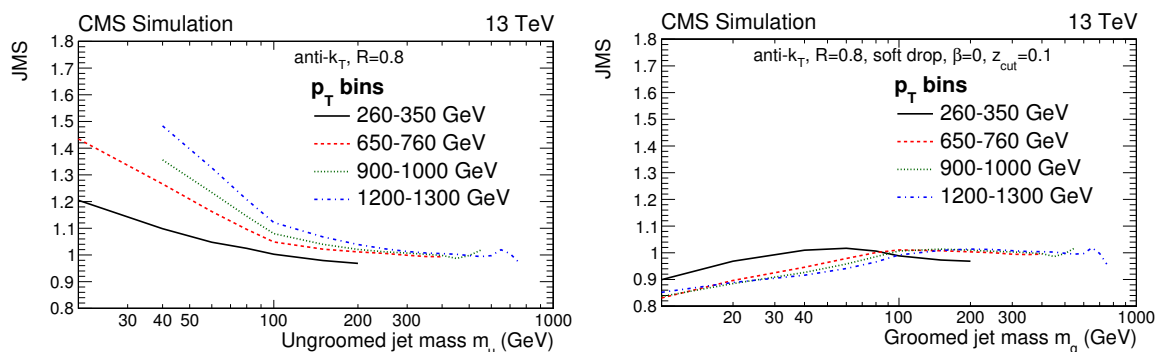
Figure 1. JMS in simulation (mean of a fit to $m_{\mathrm{reco}}/m_{\mathrm{gen}}$) for ungroomed (left) and groomed (right) jets in different generated p_{T} bins, as a function of the generated mass, with our selection. The correction to match the data is 0.98 ± 0.01. Uncertainties are not shown, for clarity, although statistical fluctuations at high masses near the splitting threshold for each p_{T} bin are not negligible.

function of the jet mass for various p_{T} bins, and similar distributions are shown for the JMR in figure 2. In these figures, finite-size effects of the jet can be observed at the highest masses in the lowest p_{T} bin. The JMS and JMR are accounted for directly in a detector response parameterization along with corrections to the MC simulation as to match data. The latter are derived using the approach outlined in ref. [43], except we use the SD algorithm to groom the jets, which is based on a fit of the jet mass from hadronically decaying W bosons in $t\bar{t}$ events where one W boson decays hadronically and the other decays leptonically (the "lepton plus jets" channel). The ratio of the fitted means in data and in MC simulation is the correction to the JMS, and the ratio of the fitted widths is the correction to the JMR. This estimate assumes that detector-related uncertainties will be the same for jets from W boson decays and jets initiated by quarks and gluons. The remaining differences are effects from the physics model, and are thus accounted for with our physics model uncertainty. The JMR and JMS corrections in the 2015 run of the LHC ("Run 2") are measured to be 1.07 ± 0.12 and 0.98 ± 0.01, respectively, using the methods of ref. [43]. In the 2010-2012 run of the LHC ("Run 1"), they were observed to be 1.11 ± 0.09 and 1.017 ± 0.006, respectively [44]. In addition to smearing the entire four-vector (including the p_{T} and the mass) of the jet by the JER, we also correct the jet mass distribution in the MC simulation to match the data in the W reference sample.

The data used in this analysis are from pp collisions collected in 2015 with 50 ns bunch spacing, as in ref. [45], as well as with 25 ns bunch spacing. The integrated luminosities of the 25 and 50 ns samples correspond to approximately 2.3 and 0.07 fb^{-1}, respectively. The data were collected with single-jet triggers of varying p_{T} thresholds as in the inclusive jet analysis from ref. [45]. As in that paper, the ensemble of events is constructed such that any given trigger only contributes to a specific p_{T} region, where it is fully efficient. However, since we are using a different R-parameter for the jet clustering algorithm (we use $R = 0.8$ as opposed to $R = 0.4$ and 0.7), our thresholds, shown in table 1, are slightly different than those from the inclusive jet analysis [45]. The same p_{T} thresholds are used for both 50 and 25 ns data. In the collisions with 50 ns bunch spacing, the trigger prescales were
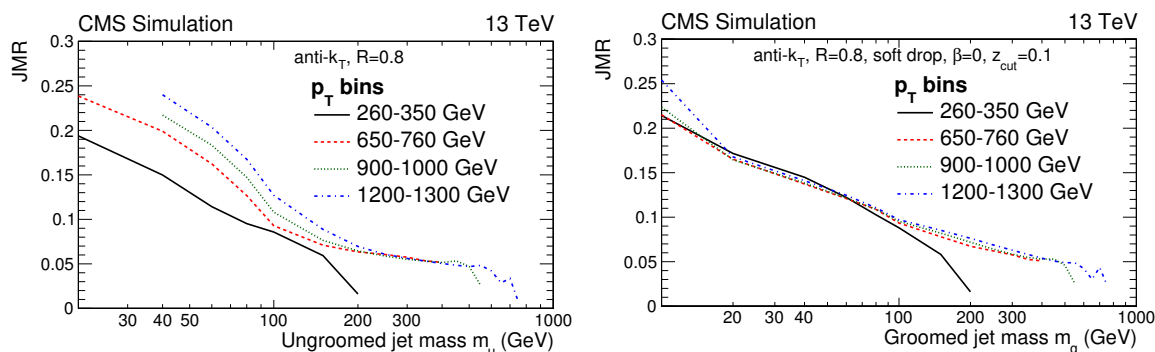
Figure 2. JMR in simulation (width of a fit to $m_{\mathrm{reco}}/m_{\mathrm{gen}}$) for ungroomed (left) and groomed (right) jets in different generated p_{T} bins, as a function of the generated mass, with our selection. The correction to match the data is 1.07 ± 0.12. Uncertainties are not shown, for clarity, although statistical fluctuations at high masses near the splitting threshold for each p_{T} bin are not negligible.

Trigger p_{T} threshold (GeV)	p_{T} range (GeV)
80	200–260
140	260–350
200	350–460
260	460–550
320	550–650
400	650–760
450	>760

Table 1. List of trigger thresholds used for each high-level trigger path. The ungroomed jet p_{T} ranges are shown in the second column. Events are selected such that exactly one fully efficient trigger is used for each p_{T} bin.

lower, and thus this dataset increases the number of events collected for $p_{\mathrm{T}} < 460\,\mathrm{GeV}$ by 10% compared to the 25 ns run alone, where the prescales are considerably higher. There are 43.9 million events in the 25 ns sample and 4.4 million events in the 50 ns sample.

4 Analysis strategy

The measurement of the dijet cross section is corrected for detector effects using an unfolding technique. The detector response is parameterized as a four-dimensional response matrix representing the migrations from reconstructed m and p_{T} to generated m and p_{T}. This response matrix is used to correct the measured distribution, and the resulting unfolded distribution is compared to various theoretical models.

The events are required to have at least two jets, without an explicit third jet veto, which allows for an easier comparison to semi-analytical calculations. To ensure a high-purity dijet-like sample, we require that the asymmetry between the leading and subleading jet transverse momenta, defined as $p_{\mathrm{T}1}$ and $p_{\mathrm{T}2}$ respectively, satisfies $(p_{\mathrm{T}1} - p_{\mathrm{T}2})/(p_{\mathrm{T}1} +$

$p_{\mathrm{T}2}) < 0.3$ and the difference in azimuthal angles satisfies $\Delta(\phi_1 - \phi_2) > \pi/2$. In addition to ensuring a dijet topology, these criteria reduce the number of jets from detector noise. Both jets in the dijet system are included in the measurement.

All reconstructed AK8 jets are required to have $p_{\mathrm{T}} > 200\,\mathrm{GeV}$ and rapidity $|y| < 2.4$, and jet identification requirements that remove detector noise outlined in ref. [46]. After the identification and topological requirements, the number of jets from detector noise in this sample is negligible. Generator-level AK8 jets are required to have $|y| < 2.4$ and a very low p_{T} selection ($>50\,\mathrm{GeV}$) to ensure an accurate estimate of the migration of events between p_{T} bins, but the measurement is presented only for $p_{\mathrm{T}} > 200\,\mathrm{GeV}$ at the generator level. The p_{T} asymmetry and $\Delta\phi$ selections are also applied at the generator level, but the p_{T} asymmetry is a slowly varying function of p_{T}, so this does not strongly affect the p_{T} migration.

The bins in ungroomed jet p_{T} are chosen so that each bin is populated by exactly one trigger, with binning as shown in table 1 (i.e., the trigger with a threshold of $80\,\mathrm{GeV}$ will be used to populate the 200-260 GeV bin, etc). Above the threshold of the lowest unprescaled trigger at $p_{\mathrm{T}} = 760\,\mathrm{GeV}$, more uniform p_{T} binning is used. The lower bin boundaries are 200, 260, 350, 460, 550, 650, 760, 900, 1000, 1100, 1200, >1300 GeV. The choice of jet mass bins is a trade-off among the approximate detector resolution of $\sim 10\,\mathrm{GeV}$ [42], the purity (the fraction of events in a reconstructed bin that are generated in the same bin), and the stability (the fraction of events in a generated bin that are reconstructed in the same bin). The lower bin boundaries are 10, 20, 40, 60, 80, 100 GeV and then increase by 50 GeV beyond 100 GeV. The same binning is used for both the reconstructed and generated jet mass. There are, however, kinematic regions that have insufficient accuracy for the jet mass measurement. This inaccuracy can arise from the finite spatial resolution of the detector or from excessive pileup contamination. These regions in p_{T} and m are removed by requiring that the uncertainty in a Gaussian fit to the distribution of $m_{\mathrm{reco}}/m_{\mathrm{gen}}$ in MC simulation is less than 50% for that region. We do not consider the measurements below those thresholds. For ungroomed jets, the dominant effect is pileup contamination, and we do not consider jet masses below $20\,\mathrm{GeV}$ when $p_{\mathrm{T}} < 760\,\mathrm{GeV}$, or below $40\,\mathrm{GeV}$ when $p_{\mathrm{T}} > 760\,\mathrm{GeV}$. For groomed jets, the dominant effect is the finite spatial resolution of the detector, and we do not consider jet masses below $10\,\mathrm{GeV}$ for all p_{T} bins.

The unfolding procedure of D'Agostini with early stopping is applied [47–49]. The detector response is from MC simulation, and parameterized in bins of ungroomed jet p_{T} and ungroomed jet mass for the ungroomed case, and in bins of ungroomed jet p_{T} and groomed jet mass for the groomed case. The central value of the response matrix is constructed using PYTHIA8. The uncertainty in the response matrix is estimated by varying the systematic uncertainties described below, rederiving the matrix for each case, and applying the modified response matrix to the reconstructed data, taking the difference in the unfolded distribution as the resultant uncertainty.

The number of iterations in the early stopping procedure has been optimized as follows. The response matrix is used to unfold the PYTHIA8 MC simulation varying the number of iterations in the regularization. A simple matrix multiplication is then used to refold the unfolded MC simulation. The resulting refolded distribution is compared to the original

reconstructed distribution and a χ^2 probability is calculated. The optimal number of iterations is determined as the lowest number such that the χ^2 probability exceeded 99%. We found $n = 3$ to be optimal. Varying the number of iterations did not lead to a significant change in the results.

The uncertainties in the unfolded result due to statistical uncertainties in the MC simulation are nontrivial to estimate in the unfolding procedure because the events have different weights, so the statistical uncertainty is not correctly estimated by simply adding the uncertainties from weighted events in quadrature. Instead of standard methods, we employ a "jackknife resampling" technique (a linear bootstrapping method) [50, 51], where we create 10 samples, each with 90% of the MC events (such that each event is excluded from exactly one resampling), and unfold the spectrum. The root-mean-square of this ensemble of distributions, multiplied by $\sqrt{10/9}$ to account for using 90% of the events per iteration, is taken as the statistical uncertainty in the MC simulation.

There are both theoretical and experimental systematic uncertainties that affect this measurement, along with uncertainties from the unfolding procedure. The uncertainties are estimated by creating response matrices with the systematic effect applied, and unfolding the reconstructed data to account for systematic migrations. Unless otherwise specified, the difference between the systematically varied output and the nominal output is taken to be the systematic uncertainty for that source. The uncertainties from different sources are then added together in quadrature.

The experimental uncertainties that affect the measurement are the JES, JER, JMS, JMR, pileup, and luminosity. The theoretical uncertainties include uncertainties in the physics model and PDFs.

The JES uncertainty is evaluated by varying the jet energy and mass up and down by the appropriate uncertainties for all of the JES uncertainty sources as described in ref. [42]. The JER uncertainty is evaluated by smearing the jet energy and mass by an additional factor as described in ref. [42]. The central value is determined by correcting the MC simulation to match the JER from data, and the uncertainties are evaluated by correcting the MC simulation by the JER systematic variations. This is also propagated to the jet mass because these effects are correlated for jets reconstructed from PF candidates. The uncertainty due to the finite resolution of the jet angle is found to be negligible compared to other uncertainties.

As mentioned in section 3, the JMR in simulation is corrected by 1.07 ± 0.12 to match the measured difference between data and MC simulation for the mass of W boson jets in lepton+jets $t\bar{t}$ events [52]. The JMS in MC simulation approaches unity for larger jet p_{T} and masses. Deviations from unity are included directly in the response matrix, as described in section 3.

The pileup uncertainty is estimated by reweighting the pileup distribution of the MC simulation up and down, assuming a change of the minimum bias cross section by 2.7% [53]. For the absolute cross section, the luminosity uncertainty of 2.7% is also taken as an additional systematic uncertainty.

The PDF uncertainty is taken from the PDF4LHC15_NLO_100 meta-PDF set using the PYTHIA8 generator. The physics model uncertainty is evaluated by comparing a response
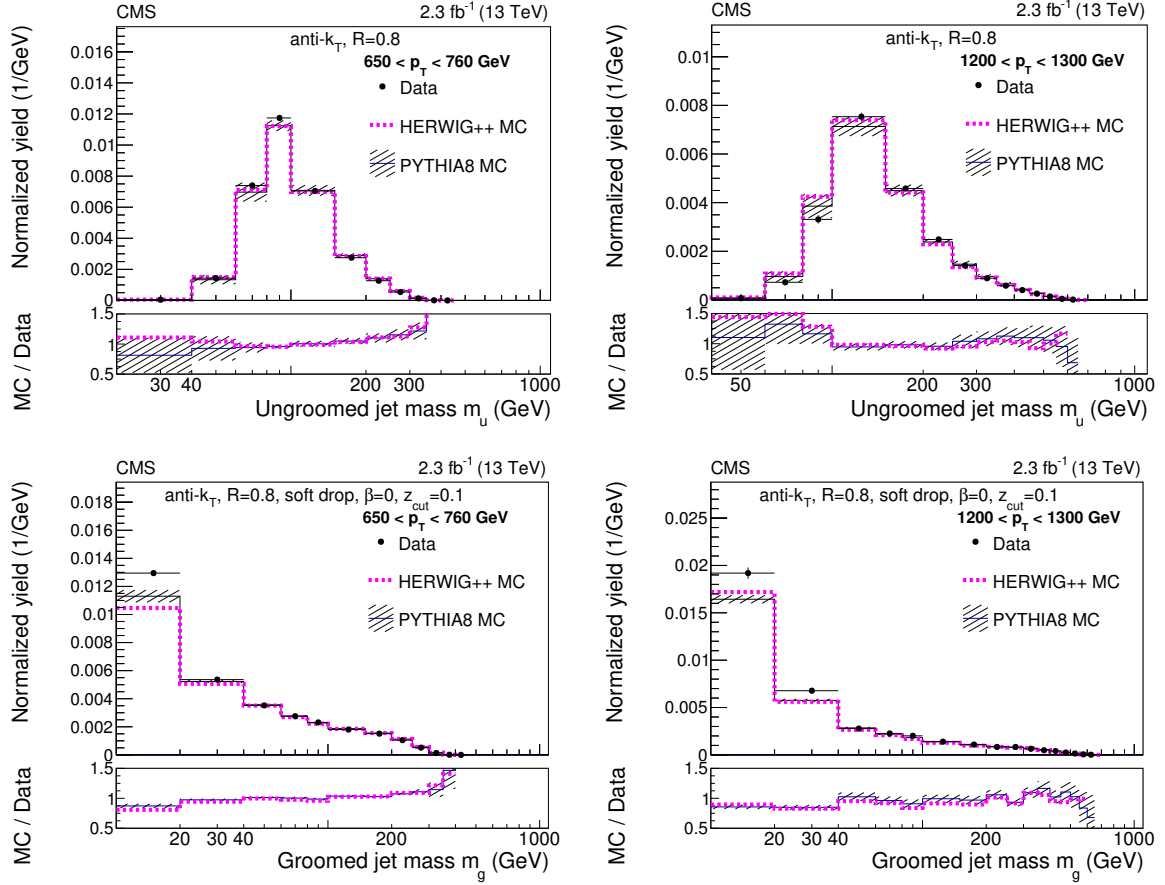
Figure 3. Comparison of data to MC simulation for ungroomed jets (top) and groomed jets (bottom) for two p_{T} bins at the detector level. The data and their statistical uncertainties are shown by the black points with the error bars. The PYTHIA8 results before the unfolding are shown in the shaded histograms, including experimental and theoretical systematic uncertainties. The HERWIG++ results before unfolding are shown without uncertainties as a dashed magenta histogram.

matrix derived from PYTHIA8 to a response matrix derived from HERWIG++. The difference between the two results for the two cases is taken as the systematic uncertainty.

The jet mass distributions in data before unfolding are compared to PYTHIA8 and HERWIG++ MC simulations in figure 3. The uncertainties before the unfolding are evaluated by varying the MC simulation up and down by each systematic effect described in the previous paragraphs, and using the sum of the differences to the nominal case in quadrature as the uncertainty band. The MC simulation distributions include the theoretical systematic uncertainties, the experimental systematic uncertainties, and the statistical uncertainties of the MC samples. The data distributions include only the statistical uncertainties. These data distributions are unfolded to obtain the cross section measurements.

Figure 4 shows the uncertainties in the absolute cross section for all of the various sources listed above, while figure 5 shows the same uncertainties in the normalized cross section. The jet energy uncertainties in the normalized cross sections are smaller than
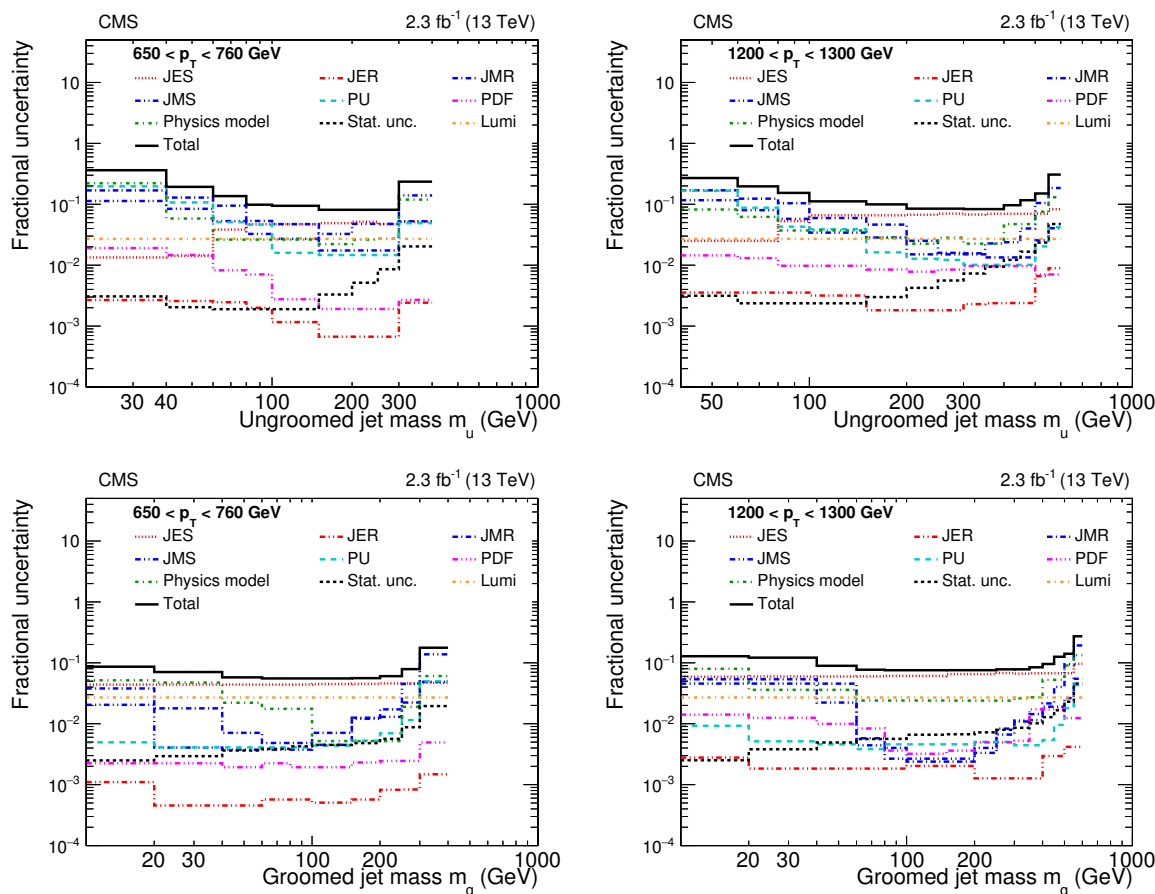
Figure 4. Systematic uncertainties in the absolute cross section after unfolding for two p_T bins before grooming (top) and after grooming (bottom). The red dotted lines show the JES uncertainties. The red dash-dot-dotted lines show the JER uncertainties. The blue dash-dotted lines show the JMR uncertainties. The blue dash-dot-dotted lines show the JMS uncertainties. The cyan dashed lines show the PU uncertainties. The orange dash-dotted lines show the luminosity uncertainties. The magenta dash-dot-dot-dotted lines show the PDF uncertainties. The green dash-dotted lines show the physics model uncertainties. The black short-dashed lines show the statistical uncertainties.

in the absolute cross sections because the distributions are normalized per p_T bin. The uncertainties at low jet mass are dominated by the physics model, JMS, JMR, and pileup uncertainties for the ungroomed jets. However, the grooming procedure dramatically reduces the physics model uncertainties by removing the soft components that are difficult to model, as well as the pileup uncertainty, since pileup mimics soft radiation. At higher jet mass, the jets are at the threshold of splitting into two, so the uncertainties increase because of p_T bin migration. In addition, the phase space is severely restricted in this regime, so the statistical uncertainty also grows.
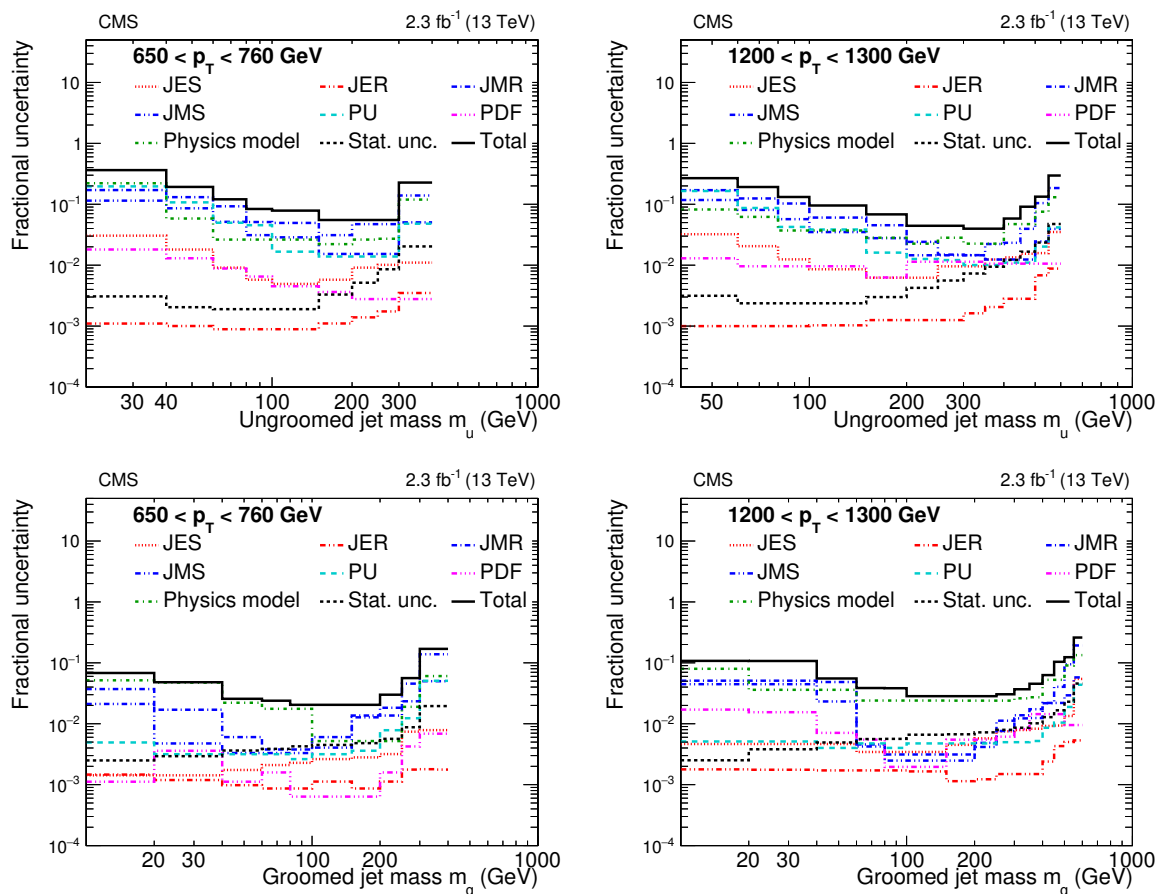
Figure 5. Systematic uncertainties in the normalized cross section after unfolding for two p_T bins before grooming (top) and after grooming (bottom). The red dotted lines show the JES uncertainties. The red dash-dot-dotted lines show the JER uncertainties. The blue dash-dotted lines show the JMR uncertainties. The blue dash-dot-dotted lines show the JMS uncertainties. The cyan dashed lines show the PU uncertainties. The orange dash-dotted lines show the luminosity uncertainties. The magenta dash-dot-dot-dotted lines show the PDF uncertainties. The green dash-dotted lines show the physics model uncertainties. The black short-dashed lines show the statistical uncertainties.

5 Results

The absolute cross sections as a function of the jet mass are shown for two p_T bins in figure 6. The cross sections are compared to PYTHIA8, POWHEG + PYTHIA8, and HERWIG++ predictions, which are scaled to match the number of events in the data.

The normalized cross sections as a function of the jet mass are shown for two p_T bins in figure 7. All p_T bins of the normalized cross section are shown in figures 8 and 9. The lowest masses in the measurement are difficult to measure experimentally, as described in section 4. As mentioned there, the mass measurements are presented for ungroomed jets for $m > 20\,\mathrm{GeV}$ when $p_T < 760\,\mathrm{GeV}$, and $m > 40\,\mathrm{GeV}$ for jets with $p_T > 760\,\mathrm{GeV}$. Results for groomed jets are presented for $m > 10\,\mathrm{GeV}$ for all p_T. The normalized results for the
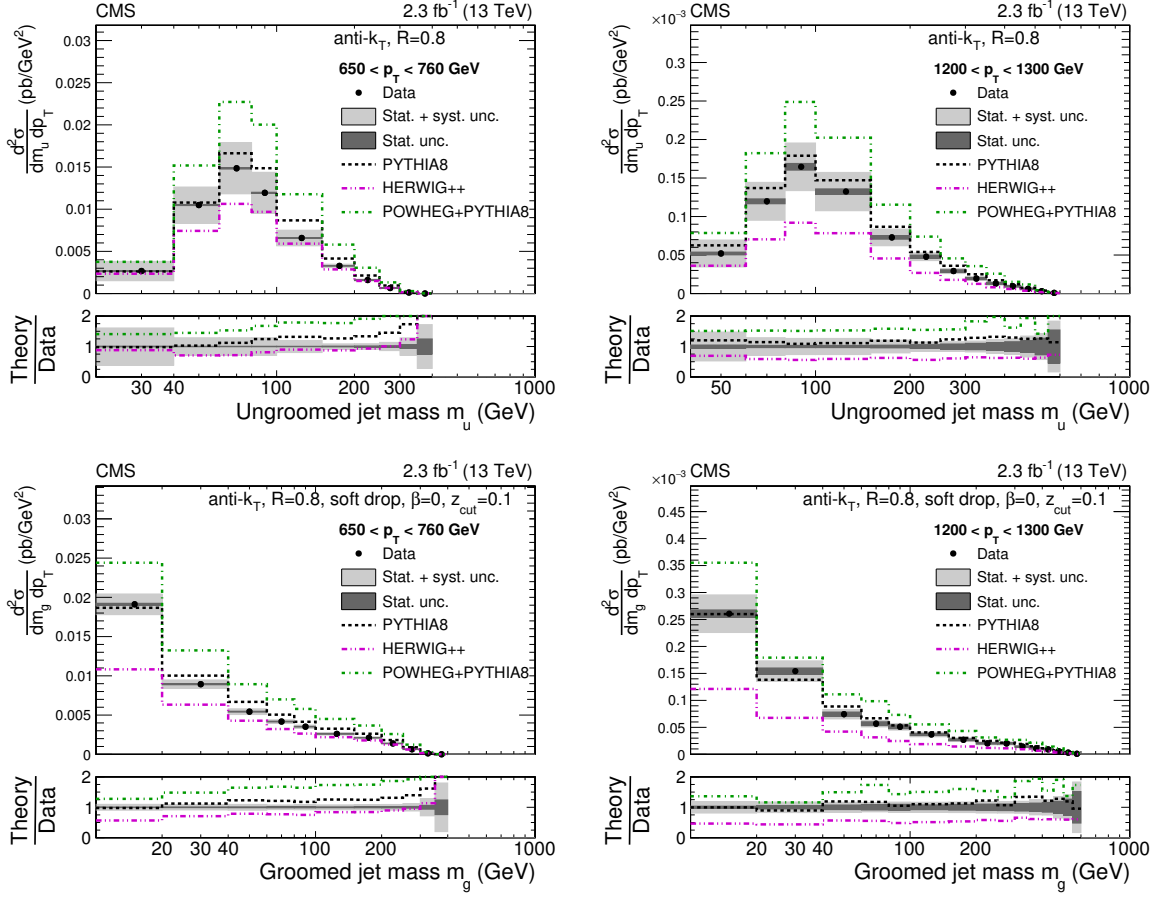
Figure 6. Absolute cross section for ungroomed (top) and groomed (bottom) jets for two p_T bins. The data are shown by the black points, with dark grey bands for the statistical uncertainty (Stat. unc.) and with light grey bands for the total uncertainty (Stat. + sys. unc., added in quadrature). The predictions from PYTHIA8, HERWIG++, and POWHEG + PYTHIA are shown with dashed black, dash-dot-dotted magenta, and dash-dotted green histograms, respectively, with no uncertainties shown. The MC simulations are normalized to the data over the entire p_T range.

groomed jets are also compared to the calculation of the jet mass from refs. [17] and [18]. The normalized results are scaled to unity for each individual jet p_T bin for the unfolded data, for the PYTHIA8, HERWIG++, POWHEG + PYTHIA8 predictions, and for the results from the calculation from the authors of ref. [18]. The calculation from ref. [17], on the other hand, is normalized to match the data at 50 GeV, since the calculation does not consider nonperturbative corrections that are important below that value. As a reminder, the prediction from ref. [17] includes nonperturbative effects as an uncertainty, while the prediction from ref. [18] directly includes nonperturbative effects in the prediction, and has smaller systematic uncertainties in low-mass regions where nonperturbative effects are important.

Comparing the normalized ungroomed and groomed cross sections (figure 7), our results show that the grooming algorithm considerably lowers the jet mass and suppresses the Sudakov peak, as expected. The precision of the measurement improves, since the grooming algorithm removes the parts of the jet arising from soft radiation and the pileup
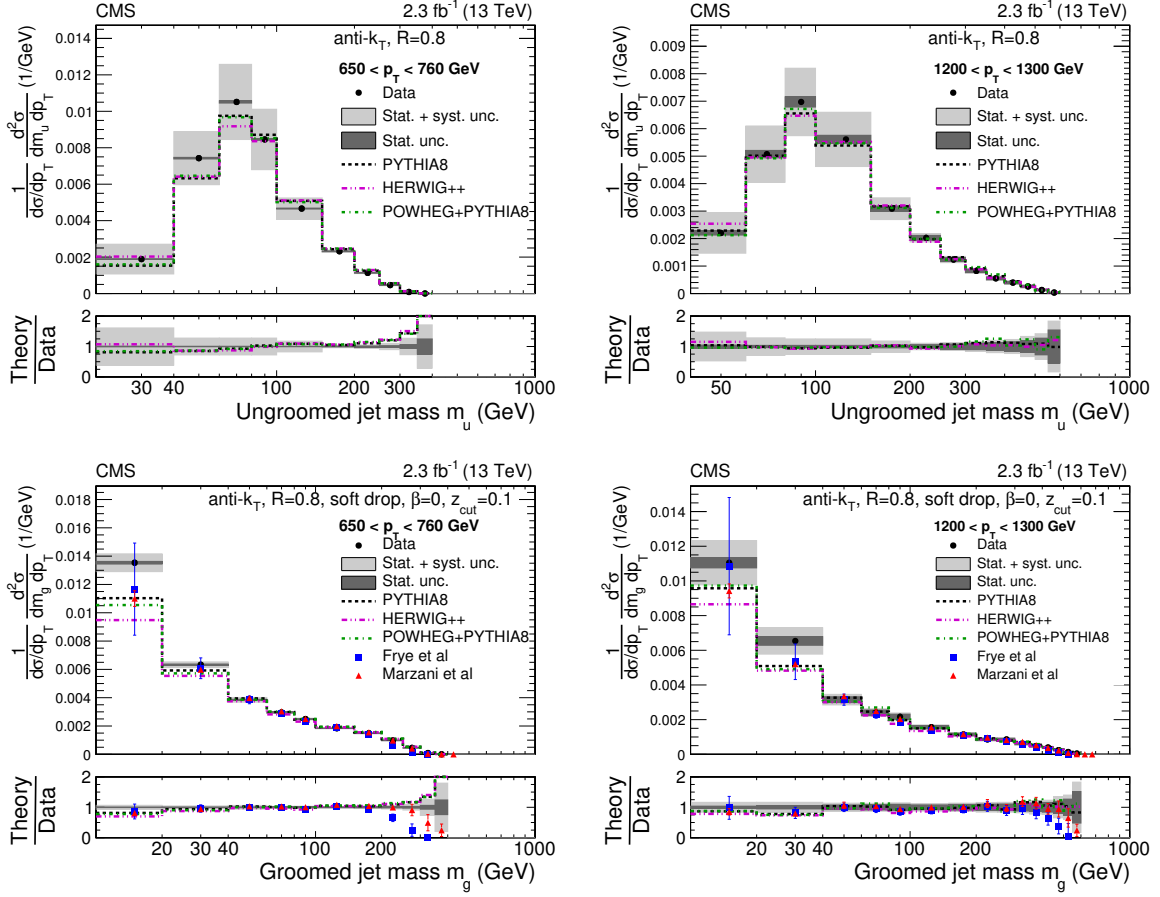
Figure 7. Normalized cross section for the ungroomed (top) and groomed (bottom) jets for two p_T bins. The predictions from PYTHIA8, HERWIG++, and POWHEG + PYTHIA are shown with dashed black, dash-dot-dotted magenta, and dash-dotted green histograms, respectively, with no uncertainties shown. The predictions from ref. [17] (Frye et al.) are shown with blue squares. The uncertainties include scale variations and an estimate of nonperturbative effects. The predictions from ref. [18] (Marzani et al.) are shown with red triangles. The uncertainties include only effects from scale variations, since nonperturbative corrections have been considered directly in the calculation. Both predictions diverge from the data at high mass due to fixed-order matching.

contribution. Figure 5 shows the reduced effect of the uncertainties from the physics model and pileup, decreasing the overall uncertainty from ∼8–12% at $m = 100\,\text{GeV}$ for ungroomed jets to ∼2–5% for groomed jets at the same mass. The absolute cross sections (figure 6) have larger uncertainties than the normalized cross sections because of jet energy uncertainties (JES and JER), as shown in figure 4.

The LO theory predictions with a MC-based physics model are from PYTHIA8 and HERWIG++, and they predict the ungroomed jet mass measurement within uncertainties, although the experimental uncertainties are large. Above the splitting threshold ($m/p_T >$ 0.3), the prediction is slightly larger than the data. After grooming, the experimental precision improves, so some deviations from the data can be observed at very low jet masses. Some disagreements are observed between PYTHIA8 and HERWIG++. The PYTHIA8
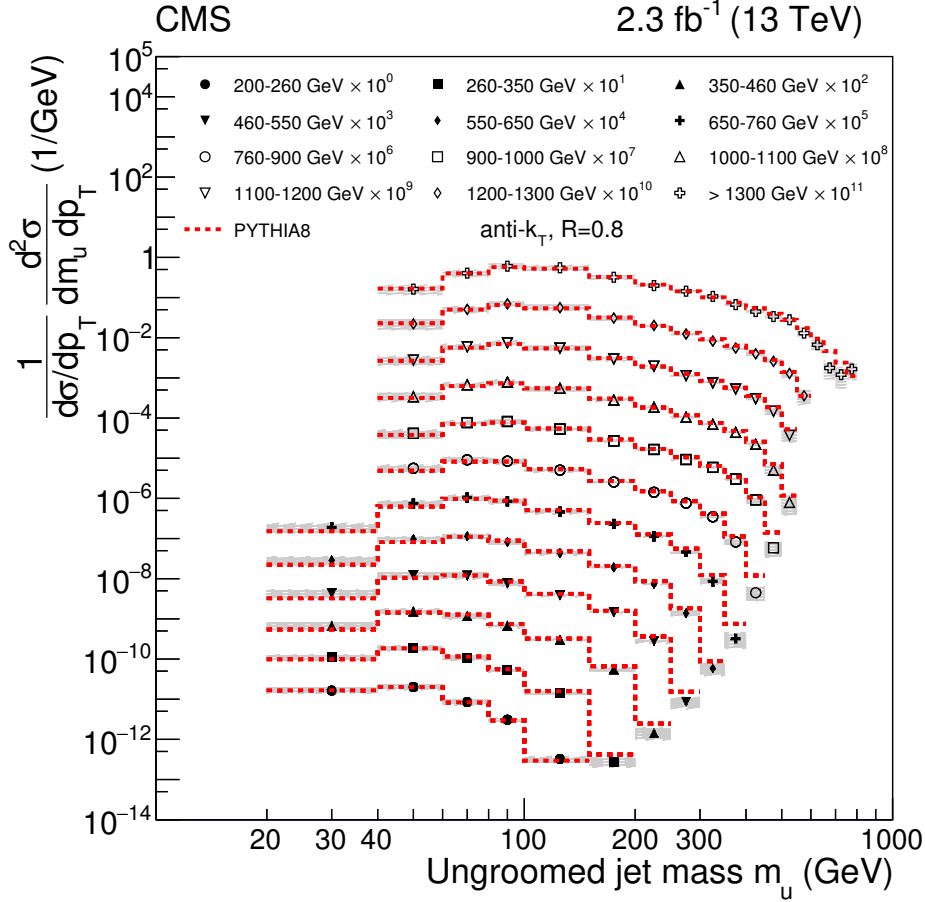
Figure 8. Normalized cross section for ungroomed jets for all p_T bins. Bins with statistical uncertainty larger than 60% are not shown. The data are shown with markers for each p_T bin, scaled by a factor for better visibility. The total uncertainties (statistical added to systematic in quadrature) are shown with grey bands. The predictions from PYTHIA8 are shown as a dashed red line.

generator tends to predict the data better, although for $m/p_T < 0.1$, the agreement is worse than in the range $0.1 < m/p_T < 0.3$. The same disagreement above the splitting threshold is observed as in the ungroomed case. The NLO theory prediction with a MC-based physics model is from POWHEG + PYTHIA8, and is observed to have largely the same behavior as PYTHIA8 alone, so the largest effects are coming from the physics model.

The LO and NLO theory predictions with analytic resummation (refs. [17] and [18], respectively) agree overall with the data, with some slight disagreements at very low masses. For $m/p_T > 0.3$, the fixed-order matrix element merging is insufficient to capture the true dynamics due to kinematic effects, as described in section 2, so the predictions diverge from the data. They agree with the predictions using MC-based physics models, although some disagreement is observed at very low masses. The resummed predictions are slightly closer to the PYTHIA8 prediction than to the HERWIG++ one.
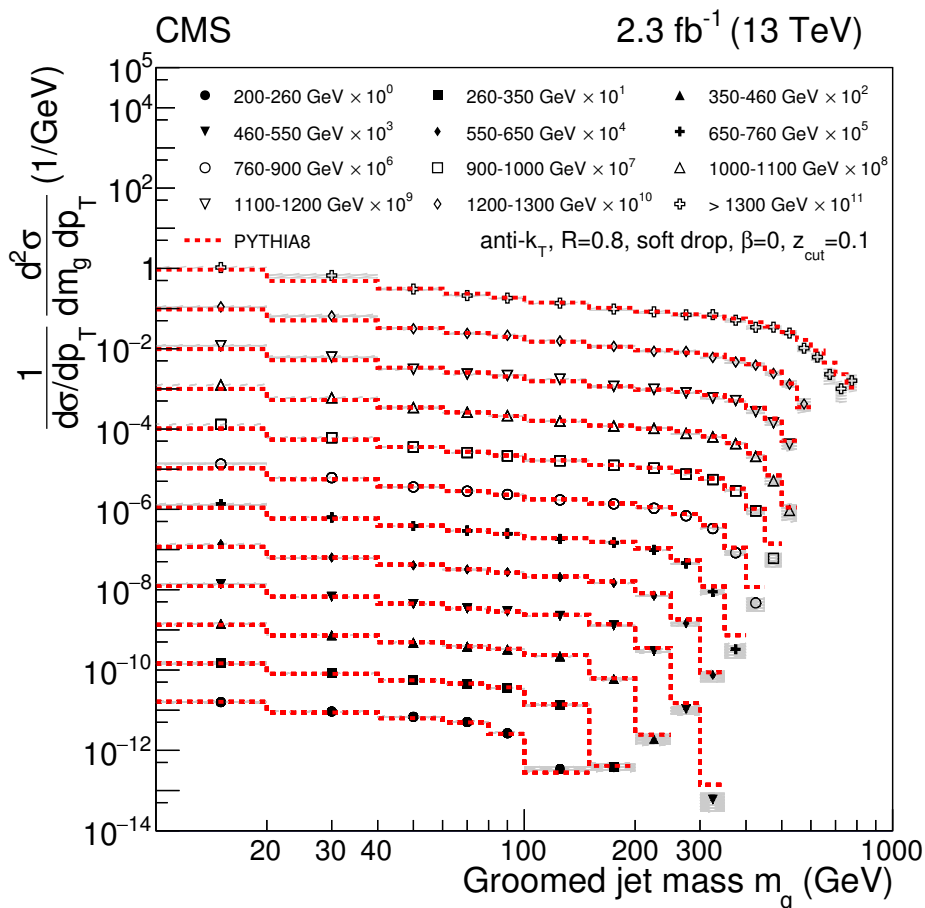
Figure 9. Normalized cross section for groomed jets for all p_T bins. Bins with statistical uncertainty larger than 60% are not shown. The data are shown with markers for each p_T bin, scaled by a factor for better visibility. The total uncertainties (statistical added to systematic in quadrature) are shown with grey bands. The predictions from PYTHIA8 are shown as a dashed red line.

6   Summary

The double-differential production cross section has been presented for dijet events in bins of ungroomed jet p_T as a function of the jet mass, with and without a jet grooming algorithm applied. The grooming algorithm is observed to decrease the jet mass overall, and reduce the sensitivity of the observable to details of the physics modeling and pileup effects. The data are compared to various theoretical predictions, including new calculations using analytical resummation. Overall, in the normalized cross section, the theoretical predictions agree with the measured cross sections within the uncertainties for masses from 10 to 30% of the jet transverse momentum.

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