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Event shape variables measured using multijet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract: The study of global event shape variables can provide sensitive tests of predictions for multijet production in proton-proton collisions. This paper presents a study of several event shape variables calculated using jet four momenta in proton-proton collisions at a centre-of-mass energy of 13 TeV and uses data recorded with the CMS detector at the LHC corresponding to an integrated luminosity of 2.2 fb^{-1}. After correcting for detector effects, the resulting distributions are compared with several theoretical predictions. The agreement generally improves as the energy, represented by the average transverse momentum of the two leading jets, increases.

Keywords: Hadron-Hadron scattering (experiments), Jet physics, Jets

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Contents

1 Introduction

The production of quarks and gluons in hadron collisions and the process of hadron formation are subject to in-depth theoretical and experimental studies. The experiments at the CERN LHC have studied production of hadronic jets by measuring differential cross-sections, ratios of numbers of jets, angular distributions, etc., to deepen the understanding of quantum chromodynamics (QCD). While the production of quarks and gluons with large transverse momentum (p_{T}) is well described by calculations based on perturbative QCD, the hadronization process probes energy scales where perturbative calculations are not applicable. Instead, phenomenological models inspired by QCD are used to predict the experimental results.

Event shape variables (ESVs) are sensitive to the flow of energy in hadronic final states. These variables are safe from collinear and infrared divergences and have reduced experimental uncertainties [1]. Some distributions of ESVs are sensitive to the details of the hadronization process [2–4], so they can be used to tune parameters of Monte Carlo (MC) event generators, determine the strong coupling α_S [5–7], and to search for new physics phenomena [8–10].

Various ESVs have been studied in electron-positron collisions at the CERN LEP collider to determine α_S [11–15]. ESVs have also been studied in electron-proton collisions at the DESY HERA collider [16] and in proton-antiproton collisions at the FNAL Tevatron collider [17], where they were compared with next-to-leading-order (NLO) calculations and with various tunes of the PYTHIA6 event generator [18]. At the CERN LHC collider studies by the ALICE, ATLAS, and CMS Collaborations have exploited proton-proton collisions at centre-of-mass energies of $\sqrt{s} = 0.9$, 2.76, and 7 TeV to evaluate ESVs [19–26].

This paper reports a measurement of ESVs by the CMS Collaboration using hadronic jets in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ corresponding to an integrated luminosity ($\mathcal{L}_{\text{int}}$) of $2.2\,\text{fb}^{-1}$. The following variables are studied: the complement of transverse thrust, total jet broadening, total jet mass, and total transverse jet mass. The theoretical uncertainties in the predictions of these ESVs can be reduced by careful choice of the quantity used to classify the energy scale of the events. Following ref. [4], we use $H_{\text{T},2} = (p_{\text{T,jet1}} + p_{\text{T,jet2}})/2$, where $p_{\text{T,jet1}}$ and $p_{\text{T,jet2}}$ refer to the transverse momenta of the highest and second highest p_{T} jets.The measured distributions are corrected for detector effects and compared with the predictions of QCD models implemented in the PYTHIA8 [27], MADGRAPH5_aMC@NLO+PYTHIA8 [28], and HERWIG++ [29] event generators.

The paper is organized as follows. The ESVs are discussed in section 2. After briefly describing the elements of the CMS detector in section 3, the jet reconstruction relevant to this analysis is described in section 4. The data sample and event selection criteria are described in section 5. Sections 6 and 7 present the unfolding technique and the systematic uncertainties, respectively. Section 8 contains comparisons between CMS data and theoretical predictions, and the results are summarized in section 9.

2 Event shape variables

The four ESVs studied in this analysis are defined using the four-momenta of hadronic jets.

The complement of transverse thrust: the complement of thrust is defined as:

$$\tau_\perp \equiv 1 - T_\perp, \tag{2.1}$$

where the thrust in the transverse plane is:

$$T_\perp \equiv \max_{\hat{n}_\text{T}} \frac{\sum_i |\vec{p}_{\text{T},i} \cdot \hat{n}_\text{T}|}{\sum_i p_{\text{T},i}}. \tag{2.2}$$

Here, $\vec{p}_{\text{T},i}$ is the component of momentum of the i^{th} jet perpendicular to the beam direction and thrust direction $\hat{n}_\text{T}$ is the unit vector that maximizes the projection and defines the transverse thrust axis. The $\tau_\perp$ is zero for a perfectly balanced two-jet event and is $1 - 2/\pi$ for an isotropic multijet event.

Total jet broadening: for each event, the transverse thrust axis is used to divide the event into upper (U) and lower (L) regions. The jets in U satisfy $\vec{p}_{\text{T},i}.\hat{n}_\text{T} > 0$ and those in L have $\vec{p}_{\text{T},i}.\hat{n}_\text{T} < 0$. For these two regions, the p_T-weighted pseudorapidities and azimuthal angles are

$$\eta_X \equiv \frac{\sum_{i\in X} p_{\text{T},i}\eta_i}{\sum_{i\in X} p_{\text{T},i}}, \phi_X \equiv \frac{\sum_{i\in X} p_{\text{T},i}\phi_i}{\sum_{i\in X} p_{\text{T},i}}, \tag{2.3}$$

where X refers to the U or L regions. The jet broadening variable in each region is defined as

$$B_X \equiv \frac{1}{2\,P_T} \sum_{i \in X} p_{\mathrm{T},i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}, \tag{2.4}$$

where P_{T} is the scalar p_{T} sum of all the jets in the event. The total jet broadening is then defined as

$$B_{\mathrm{Tot}} \equiv B_{\mathrm{U}} + B_{\mathrm{L}}. \tag{2.5}$$

Total jet mass: the normalized squared invariant mass of the jets in the U and L regions of the event is defined by

$$\rho_X \equiv \frac{M_X^2}{P^2}, \tag{2.6}$$

where M_{X} is the invariant mass of the jets in the region X, and P is the scalar sum of the momenta of all central jets. The total jet mass is defined as the sum of the masses in the U and L regions,

$$\rho_{\mathrm{Tot}} \equiv \rho_{\mathrm{U}} + \rho_{\mathrm{L}}. \tag{2.7}$$

Total transverse jet mass: the quantity corresponding to ρ_{Tot} in the transverse plane, the total transverse jet mass ($\rho^{\mathrm{T}}_{\mathrm{Tot}}$), is similarly calculated using $\vec{p}_{\mathrm{T},i}$ of jets.

These four ESVs probe different aspects of QCD [2] and are designed to have higher values for multijet, spherical events and lower values for back-to-back dijet events. While $\tau_\perp$ is sensitive to the hard-scattering process, the jet masses and jet broadening depend more on the nonperturbative aspects of QCD, responsible for hadronisation process.

3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. The solenoid volume holds a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Steel and quartz-fibre Cherenkov hadron forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors to the region $3.0 < |\eta| < 5.2$. Muons are measured in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in η and 0.087 radians in azimuthal angle (ϕ). For $|\eta| < 1.48$, the HCAL cells map onto 5×5 ECAL crystals arrays in the η-ϕ plane to form calorimeter towers projecting radially outwards from close to the nominal interaction point. At larger values of η, the size in η of the towers increases and the matching ECAL arrays contain fewer crystals. CMS uses a two stage online trigger to select events for offline analysis. In the first stage, a hardware-based level-1 (L1) trigger uses information from calorimeter and muon subsystems and selects event at a rate of about 100 kHz. In the second stage, a software-based high-level trigger (HLT), running on computer farms, uses full event information and reduces the event rate to about 1 KHz before data storage. A more detailed description of the CMS detector can be found in ref. [30].

4 Jet reconstruction

The particle-flow (PF) event algorithm [31] reconstructs photons, electrons, charged and neutral hadrons, and muons with an optimised combination of information from the various elements of the CMS detector. The energy of a photon is directly obtained from the ECAL measurement. The energy of an electron is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The momentum of a muon is obtained from the curvature of the corresponding track. The energy of a charged hadron is determined from a combination of its momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of a neutral hadron is obtained from the corresponding energy deposits in ECAL and HCAL.

Jets are reconstructed from photons, electrons, charged and neutral hadrons, and muons using the anti-k_{T} clustering algorithm [32, 33] with a distance parameter $\mathrm{R} = 0.4$. Measurement of jet energy is affected by contamination from additional pp interactions in the same bunch crossing (pileup), as well as by the nonuniform and nonlinear response of the CMS calorimeters. The technique of charged-hadron subtraction [31] is used to reduce the contribution of particles that originate from pileup interactions to the jet energy measurement. The jet four-momentum is corrected for the difference observed in simulation between jets built from reconstructed particles and generator-level particles. The jet mass and direction are kept constant for the corrections, which are functions of the η and p_{T} of the jet, as well as the energy density and jet area quantities defined in ref. [34]. The latter are used to correct the energy offset introduced by the pileup interactions. The energy of the jets is further corrected using dijet, Z+jet, and γ+jet events, where the p_{T}-balance of the event is exploited. The jet energy resolution typically amounts to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV.

5 Data set and event selection

5.1 Collision data

This analysis uses pp collision data collected in 2015 at $\sqrt{s} = 13\,\mathrm{TeV}$, corresponding to $\mathcal{L}_{\mathrm{int}} = 2.2\,\mathrm{fb}^{-1}$. Events are selected at L1 and HLT that have jet p_{T} or $H_{\mathrm{T},2}$ thresholds, respectively, as shown in table 1. The turn-on point for each trigger, offline $H_{\mathrm{T},2}$ at which the trigger is 99% efficient, is used to define the $H_{\mathrm{T},2}$ ranges for events.

Collision and simulated events are required to have at least three jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ within the coverage of the tracker $|\eta| < 2.4$. For each event, three jets are used for the calculation of the ESVs. The jets with the highest and the second-highest p_{T} are selected. From the remaining jets, the one with the highest recoil term is selected as the third jet. The recoil term for jet k is

$$\mathcal{R}_{\perp,\mathrm{k}} = \frac{|\vec{p}_{\mathrm{T,jet1}} + \vec{p}_{\mathrm{T,jet2}} + \vec{p}_{\mathrm{T,jetk}}|}{|\vec{p}_{\mathrm{T,jet1}}| + |\vec{p}_{\mathrm{T,jet2}}| + |\vec{p}_{\mathrm{T,jetk}}|}.$$

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L1 threshold for $p_{\mathrm{T,jet}}$ (GeV)	HLT threshold for $H_{\mathrm{T},2}$ (GeV)	$H_{\mathrm{T},2}$ range (GeV)	Number of events
ZeroBias	60	73–93	222 184
52	80	93–165	36 452
92	140	165–225	81 932
128	200	225–298	363 294
128 or 176	260	298–365	134 320
128 or 176	320	365–452	354 140
128 or 176	400	452–557	443 361
128 or 176	500	>557	295 578

Table 1. L1 trigger thresholds, HLT thresholds, $H_{\mathrm{T},2}$ range and number of events used in the analysis.

The data sample is divided into eight $H_{\mathrm{T},2}$ ranges such that the uncertainty due to the trigger inefficiency is negligible. The ranges (in GeV) are: 73–93, 93–165, 165–225, 225–298, 298–365, 365–452, 452–557 and >557, as shown in table 1, with the number of events in each range.

5.2 Simulated events

Events are simulated using PYTHIA v8.212, MADGRAPH5_aMC@NLO V5 2.2.2+PYTHIA8, and HERWIG++ v2.7.1. The NNPDF3.0 [35] parton distribution function (PDF) set is used. The PYTHIA8 and HERWIG++ event generators use leading order 2→2 matrix element (ME) calculations and parton shower (PS) for generation of multijet topologies. The PYTHIA8 event generator uses a p_{T}-ordered PS, and the underlying event description is based on the multiple parton interaction (MPI) model. Events are generated with two PYTHIA8 tunes: CUETP8M1 [36] and Monash [37]. Minimum bias data collected by the CMS experiment were used to derive the PYTHIA8 CUETP8M1 tune, which is based on the Monash tune. The MADGRAPH5_aMC@NLO generator uses ME calculations to generate hard-scattering events with two to four partons and PYTHIA8 CUETP8M1 for subsequent fragmentation and hadronization. The MLM [38] matching procedure is used to avoid double counting of jets between the ME calculation and the PS description. The HERWIG++ generator uses an angular-ordered PS. For simulated events, particle-level jets are obtained by applying the anti-k_{T} clustering algorithm to all generated stable particles, excluding neutrinos, with $R = 0.4$.

The simulation events are passed through a complete and detailed reconstruction in the CMS detector using the same reconstruction as the collision events.

6 Unfolding of distributions

A reconstructed collision event differs from the true event because of finite resolution of the detector, detector acceptances, and uncertainties and efficiencies of measurement. Hence, the detector-level distributions obtained from data are unfolded to estimate the underlying particle-level distributions, which can be compared with predictions from theoretical models as well as with results obtained by other experiments.

Simulated events passing through the complete detector simulation, event reconstruction, and selection chain are used to construct the response matrix for an ESV, which relates its particle-level distribution with that at detector level. The response matrix incorporates all the experimental effects and is subsequently used as input for the unfolding of the observed distribution in data. Some events that satisfy the selection criteria at the particle level might not at the detector level, leading to an inefficiency. The reverse may also happen, leading to misidentification. Further, an event may migrate from one $H_{\mathrm{T},2}$ range to another. The corresponding efficiency and misidentification rates are also incorporated in the unfolding process, and they contribute to the related uncertainty of the unfolding process.

To investigate possible bias due to the choice of an MC generator to construct the response matrices, we generate event samples from three different generators: PYTHIA8 CUETP8M1, MADGRAPH5_aMC@NLO, and HERWIG++. Each detector level distribution is unfolded using these three response matrices and the corresponding particle-level distributions are compared. No evidence for significant bias is observed.

Two different methods, which are implemented in RooUnfold [39], are used for unfolding the observed distributions: D'Agostini iteration with early stopping [40], and Singular Value Decomposition (SVD) [41]. The difference between the unfolded distributions produced with these two methods is much smaller than 1%. Our unfolding is done using the D'Agostini iteration and PYTHIA8 CUETP8M1 is used for constructing the response matrix. The SVD method is used as a cross-check.

7 Systematic uncertainties

There are multiple sources of uncertainties in the unfolding process, and the contributions from each individual source are added in quadrature to obtain the total uncertainty. Figure 1 shows the total uncertainty and the contributions from various sources as a function of each ESV for the specific range $225 < H_{\mathrm{T},2} < 298\,\mathrm{GeV}$.

- *Jet energy scale (JES):* CMS considers 26 different sources of uncertainties in the JES [42]. To estimate the effect of each source, the four-momentum of each jet is scaled up and down by the corresponding uncertainty, the ESV is calculated, and the response matrix obtained with the nominal JES is used to unfold the distributions obtained with the nominal, scaled up, and scaled down JES values. For each bin of the unfolded distribution, the larger of the differences between the nominal, and the varied ones is taken as the systematic uncertainty. The systematic uncertainties due to different sources are then added in quadrature. For most bins in the distribution of an ESV, the uncertainty is 4–6%. However, it reaches about 12% for the highest and lowest bins of ρ_{Tot}, lowest bins of $\rho^{\mathrm{T}}_{\mathrm{Tot}}$, and about 8% for the highest bins of B_{Tot}. Typically JES is the largest source of systematic uncertainty in the ESVs.

- *Jet energy resolution (JER):* the JER is obtained from the ratio of p_{T} of the two jets in dijet events as a function of p_{T} and η [42]. It has been observed that the JER is worse in data compared to simulation. Hence, extra smearing is applied to the simulated events, and different response matrices are constructed. The detector-level distribution of an ESV is unfolded with the different response matrices incorporating the uncertainty due to JER. The estimated uncertainties in the ESVs are of the order of 1%.

- *Unfolding:* the detector-level distribution of an ESV obtained from simulated events of PYTHIA8 CUETP8M1 is unfolded with two response matrices derived from MADGRAPH5_aMC@NLO and HERWIG++, and compared with the corresponding particle-level distribution in the same sample. Similar exercises are carried out for the MADGRAPH5_aMC@NLO sample using PYTHIA8 CUETP8M1 and HERWIG++ response matrices, and for the HERWIG++ sample using PYTHIA8 CUETP8M1 and MADGRAPH5_aMC@NLO response matrices. Out of these six differences for each bin, the largest is taken as the systematic uncertainty. In the closure tests of the individual response matrices, if, for a particular bin, the difference in the unfolded and generated values is larger than the uncertainty already assigned, the larger one is taken as the uncertainty due to the unfolding for that bin. The bias inherent in the D'Agostini method is estimated by using different generators. The difference in the unfolded results is included as an unfolding uncertainty. The uncertainty due to unfolding is of the order of 2%, except for a few lowest, and highest bins where it dominates the total uncertainty.

- *Parton distribution function:* the uncertainty due to the PDFs in the particle-level distribution of an ESV is estimated using the 100 sets of NNPDF3.0 replicas. The standard deviation of the 100 values thus obtained for a bin is taken as the uncertainty due to PDFs for that bin. For most bins, the uncertainty due to the PDFs is less than 1%, but increases for higher values of the variables. For B_{Tot} the uncertainty due to the PDFs increases very rapidly (>20%) and dominates for the last few bins.

The contribution of other sources of systematic uncertainty, i.e., pileup, and trigger efficiency are negligible.

8 Results

The modelling of initial-state radiation (ISR), final-state radiation (FSR) of gluons, and MPI in PYTHIA8 CUETP8M1 is tested by studying each aspect individually, via the comparison of simulated ESV distributions with data, as shown in figure 2. This study shows that the effect of disabling ISR results in a very large shift of the ESVs to lower values, i.e., reducing the spherical nature of the multijet events. The effect of disabling the FSR is small compared to the ISR, and the effect of MPI is even smaller.

The unfolded distributions for the ESVs obtained from data are compared with the particle-level predictions of various MC generators, as shown in figures 3–10 for various $H_{\mathrm{T},2}$ ranges. Comparisons are made to the central predictions of the event generators only. Each figure presents the variables $\tau_{\perp}$ (upper left), B_{Tot} (upper right), ρ_{Tot} (lower left), and $\rho^{\mathrm{T}}_{\mathrm{Tot}}$ (lower right) for a range of $H_{\mathrm{T},2}$. The ratios of individual MC predictions to that of data are shown in the lower panel of each plot.

The MPI parameters in the PYTHIA8 Monash and CUETP8M1 tunes are very similar. The predictions of these two tunes agree well for the four ESVs studied. In general, the

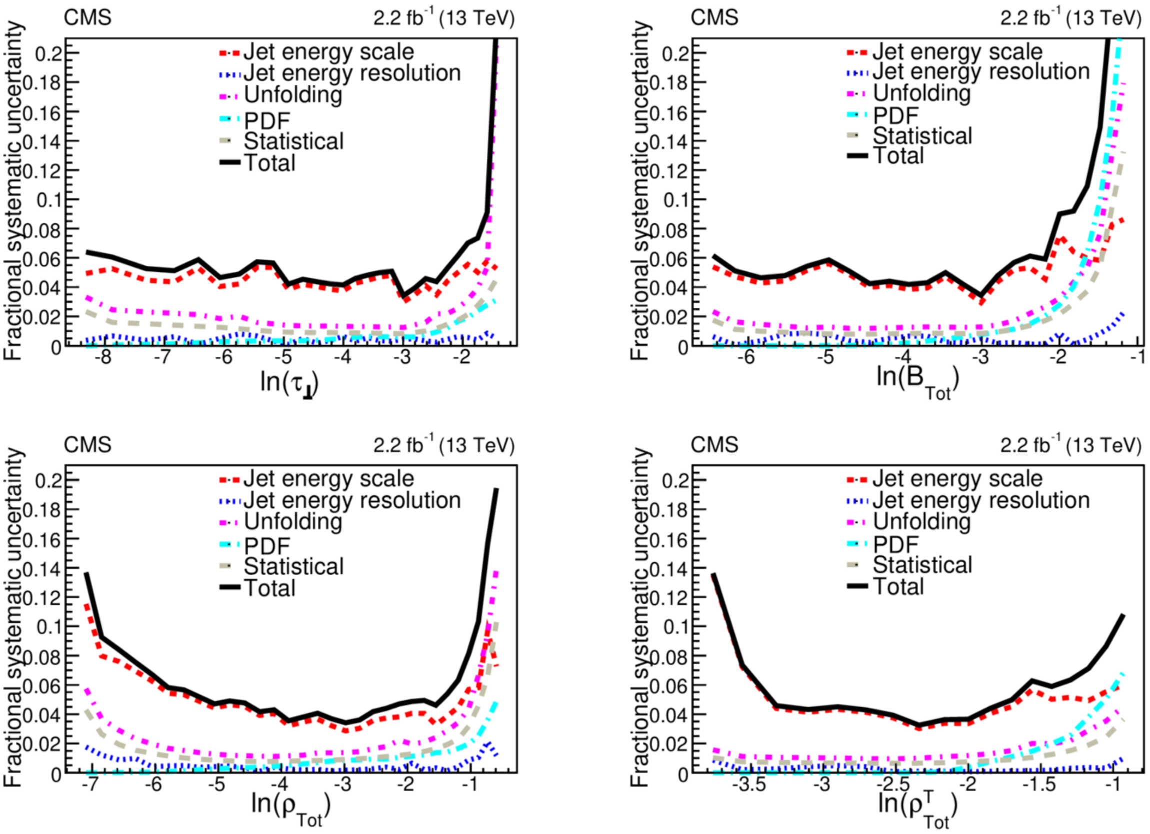

Figure 1. Total uncertainty (black line) for the four event shape variables: the complement of transverse thrust ($\tau_\perp$) (upper left), total jet broadening (B_Tot) (upper right), total jet mass (ρ_Tot) (lower left) and total transverse jet mass (ρ^T_Tot) (lower right) evaluated with jets for $225 < H_{\text{T},2} < 298\,\text{GeV}$. The contributions from different sources are also shown in each plot: JES (red dashed line), JER (blue dotted line), unfolding (pink dash-dotted line), PDF (light-blue dash-dotted line) and statistics (grey dashed line).

agreement between them improves with increasing $H_{\text{T},2}$. Both tunes show good agreement with data for the $\tau_\perp$ and ρ^T_Tot variables, except for the two lowest ranges of $H_{\text{T},2}$, and both overestimate the multijet contribution to ρ_Tot and B_Tot. We note that $\tau_\perp$ and ρ^T_Tot variables are evaluated in the transverse plane, whereas B_Tot and ρ_Tot are evaluated using both longitudinal and transverse components of the jets. This indicates that the treatment of the energy flow in the transverse plane is modelled well in the Monash and CUETP8M1 tunes of PYTHIA8, whereas the energy flow out of the transverse plane is not.

The HERWIG++ generator shows good agreement with data for all four ESVs studied, and it is better than the CUETP8M1 and Monash tunes of PYTHIA8 in predicting ρ_Tot and B_Tot. This implies its better treatment of energy flow out of the transverse plane. Although both PYTHIA8 and HERWIG++ use a PS approach to generate multijet events and hadronization, the former uses string fragmentation and a p_T-ordered shower, whereas the latter uses cluster fragmentation and angular-ordered shower.

The MADGRAPH5_aMC@NLO generator shows good agreement with data for $\tau_\perp$ and ρ^T_Tot and its agreement with data for ρ_Tot and B_Tot is much better compared to the CUETP8M1 and Monash tunes of PYTHIA8. The ME approach for generating multi-

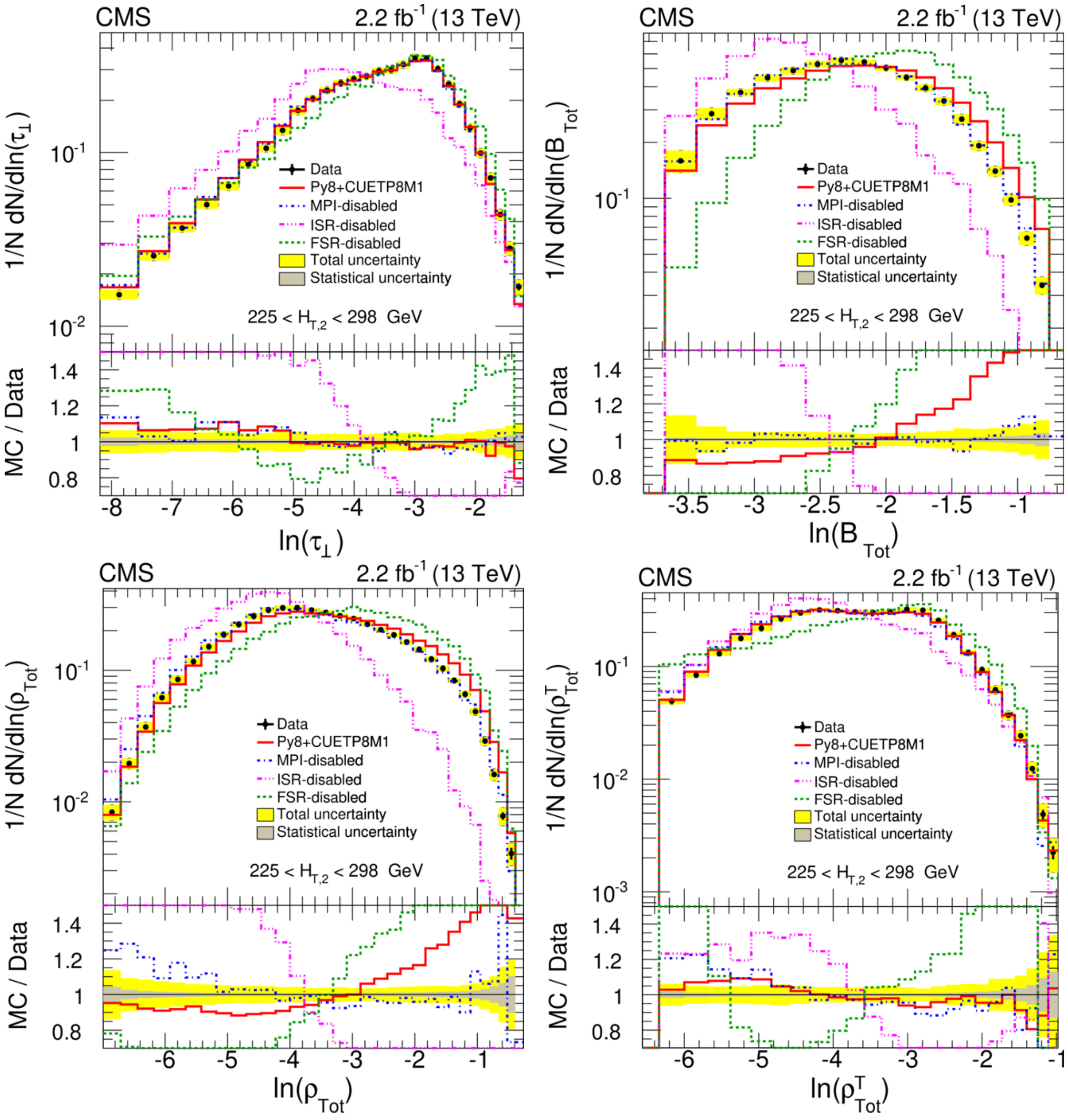

Figure 2. The effects of MPI, ISR, and FSR in PYTHIA8 CUETP8M1 on $\tau_\perp$ (upper left), $B_{\rm Tot}$ (upper right), $\rho_{\rm Tot}$ (lower left) and $\rho^{\rm T}_{\rm Tot}$ (lower right) for a typical range $225 < H_{\rm T,2} < 298$ GeV. The ratio plots for simulation (MC) with respect to data are shown in the lower panel of each plot. The inner gray band represents the statistical uncertainty and the yellow band represents the total uncertainty (systematic + statistical) in each plot.

parton hard scattering processes models the transverse as well as longitudinal flows of energy better than PYTHIA8.

The following features emerge from the comparison plots of the four ESVs. Agreement between data and benchmark event generators improves with $H_{\rm T,2}$. Figure 11 shows the evolution of the mean value of each ESV with $H_{\rm T,2}$ and confirms the above observations. With higher $H_{\rm T,2}$, the initial partons are more boosted, and hence the event tends to be

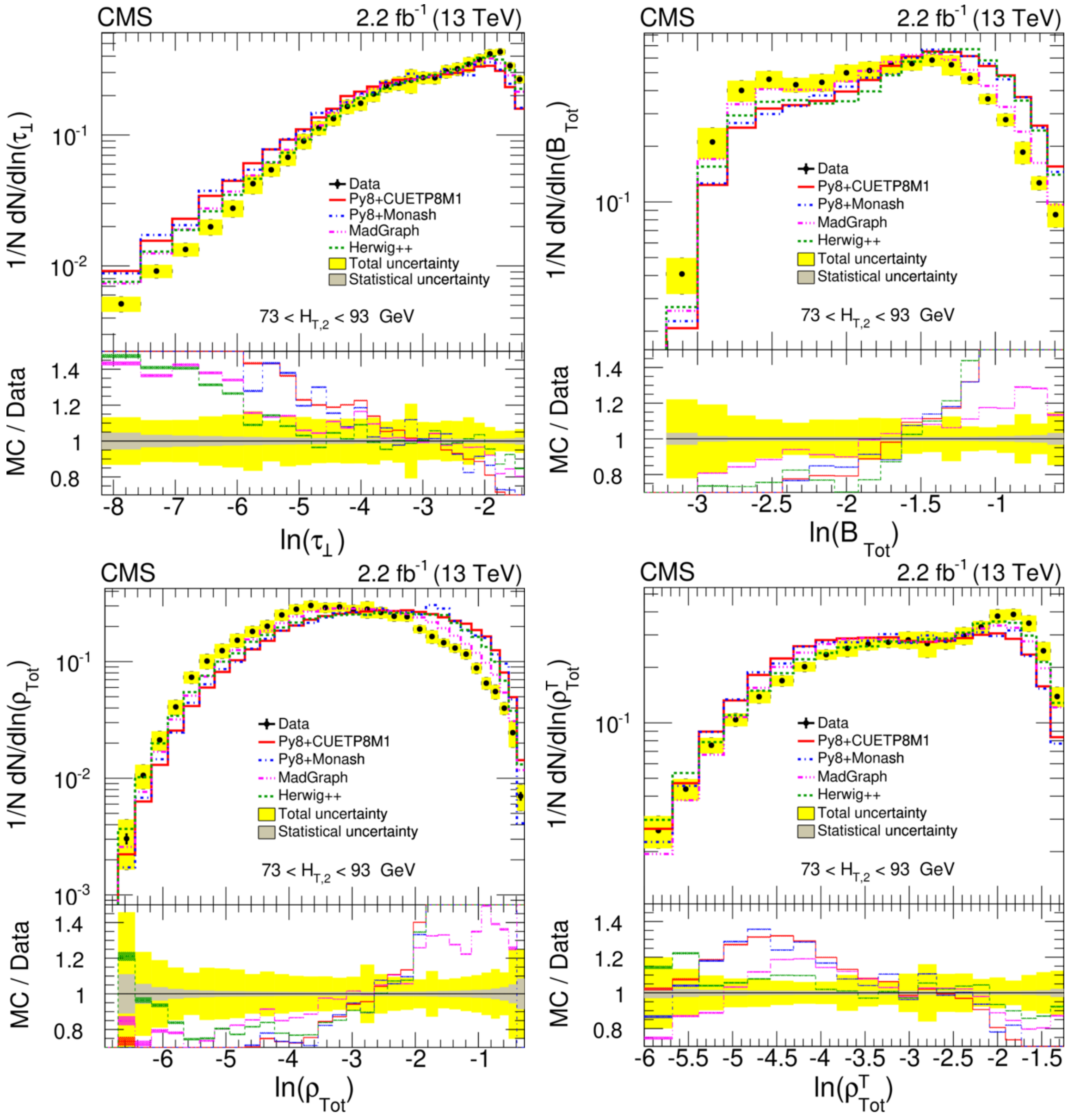

Figure 3. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust ($\tau_\perp$) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho^{\mathrm{T}}_{\mathrm{Tot}}$) (lower right) for $73 < H_{\mathrm{T},2} < 93\,\mathrm{GeV}$. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

less spherical. Also, α_S decreases with $H_{\mathrm{T},2}$, resulting in less emission of hard gluons, which further spoils the multijet, spherical nature of the event. Thus, the mean value of each ESV decreases with increasing $H_{\mathrm{T},2}$.

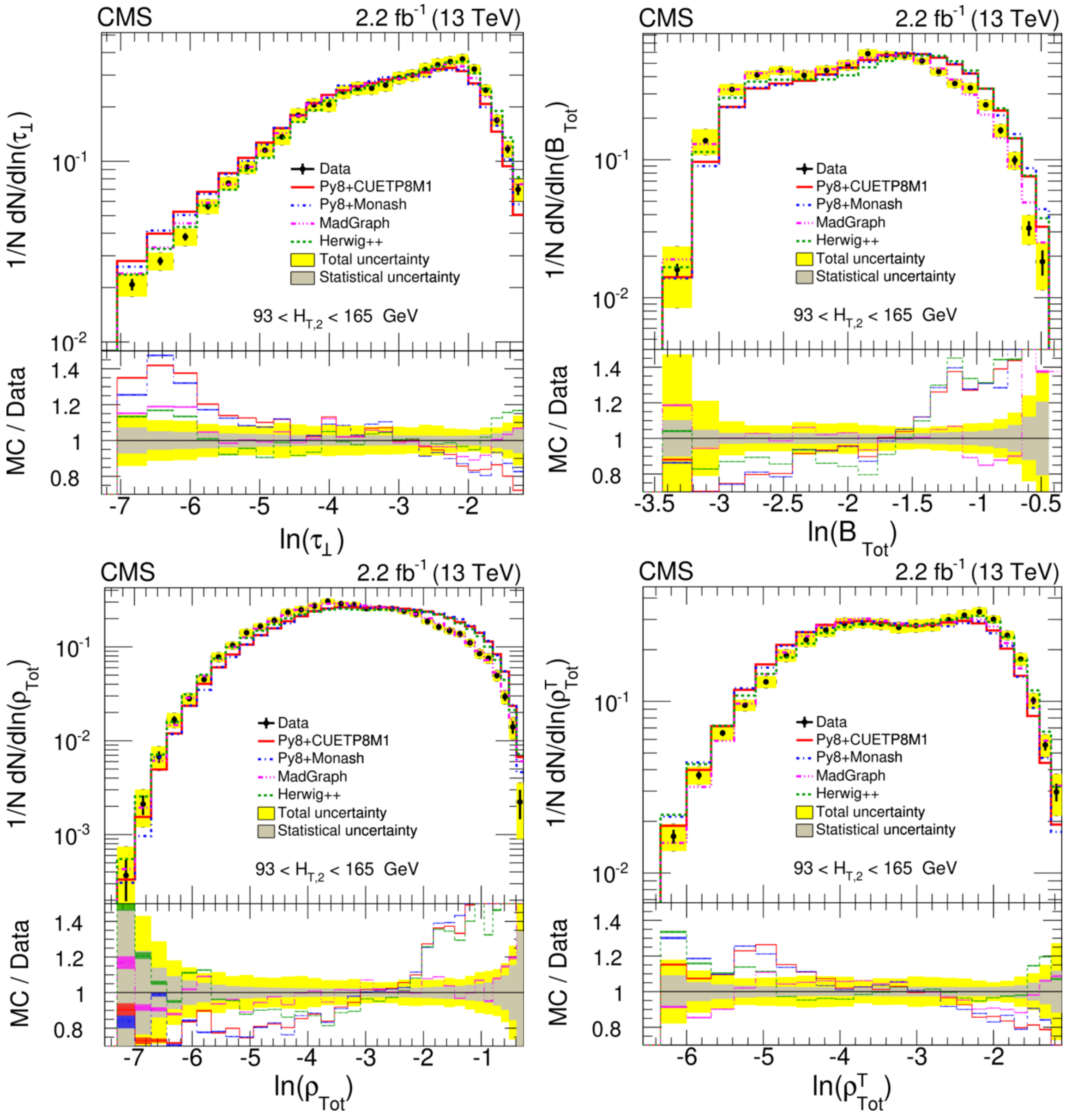

Figure 4. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust ($\tau_\perp$) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho^{\mathrm{T}}_{\mathrm{Tot}}$) (lower right) for $93 < H_{\mathrm{T},2} < 165\,\mathrm{GeV}$. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

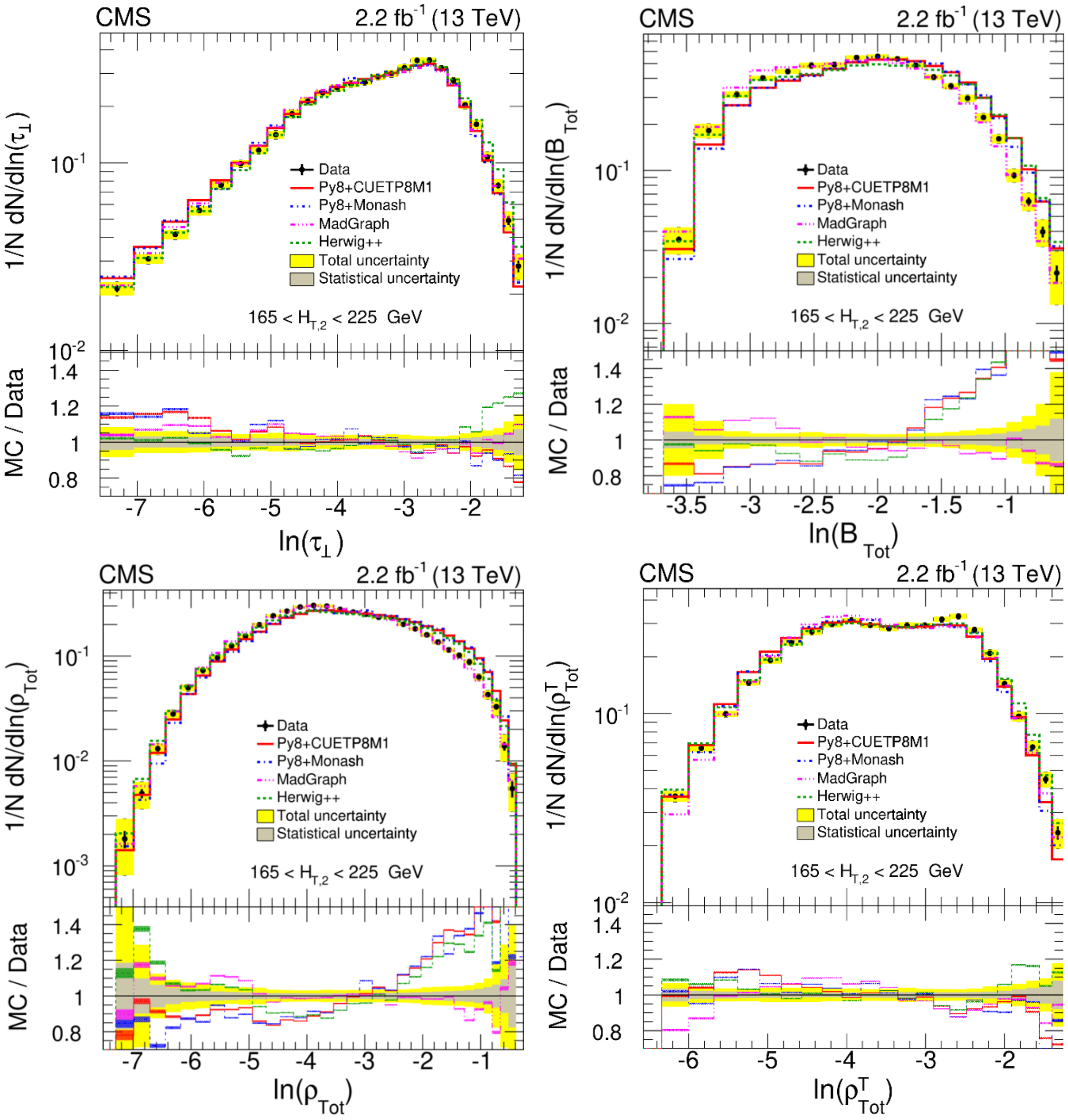

Figure 5. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust ($\tau_\perp$) (upper left), total jet broadening ($B_{\rm Tot}$) (upper right), total jet mass ($\rho_{\rm Tot}$) (lower left) and total transverse jet mass ($\rho^{\rm T}_{\rm Tot}$) (lower right) for $165 < H_{\rm T,2} < 225\,\rm GeV$. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

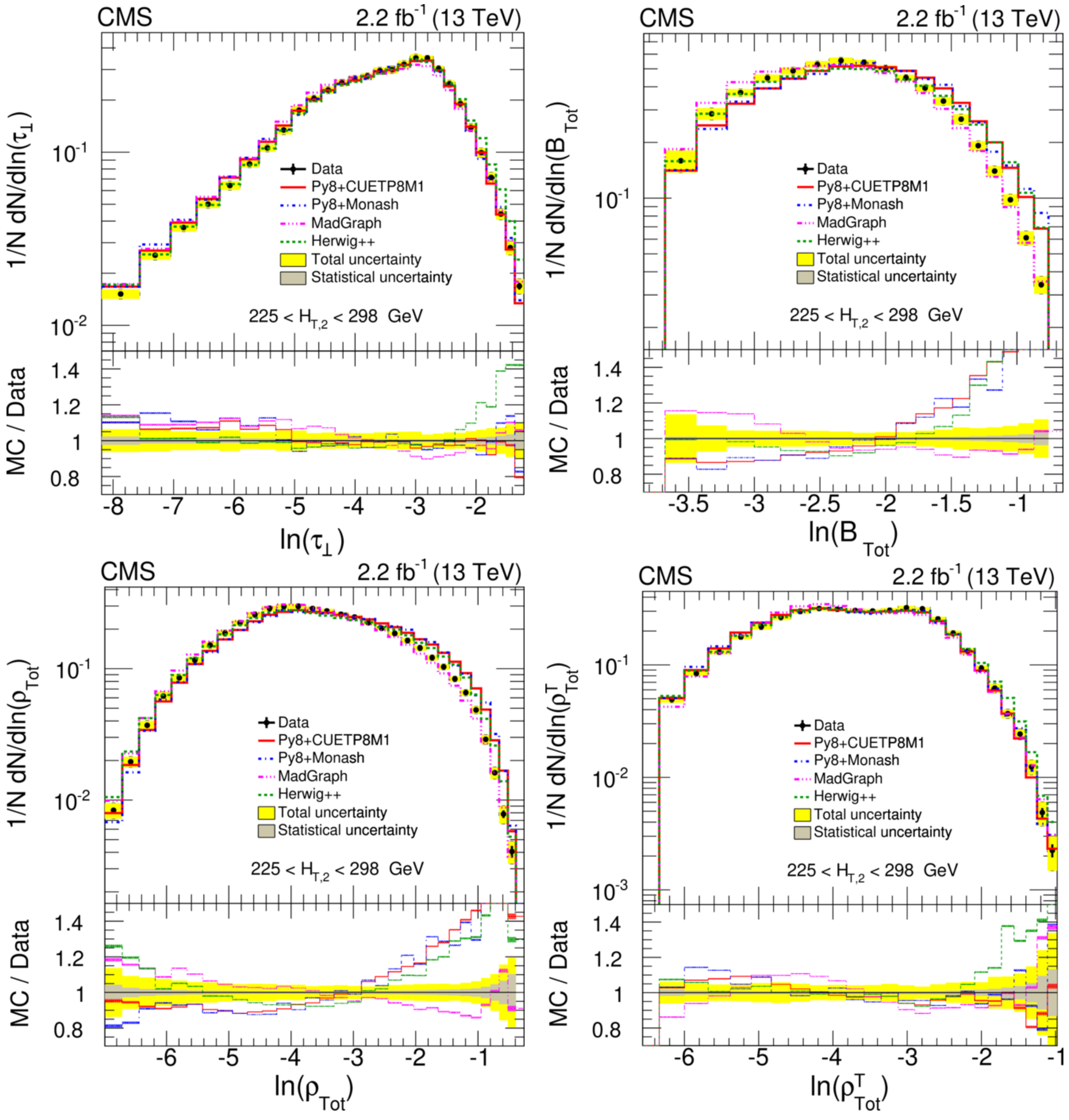

Figure 6. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust ($\tau_\perp$) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho^{\mathrm{T}}_{\mathrm{Tot}}$) (lower right) for $225 < H_{\mathrm{T},2} < 298\,\mathrm{GeV}$. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

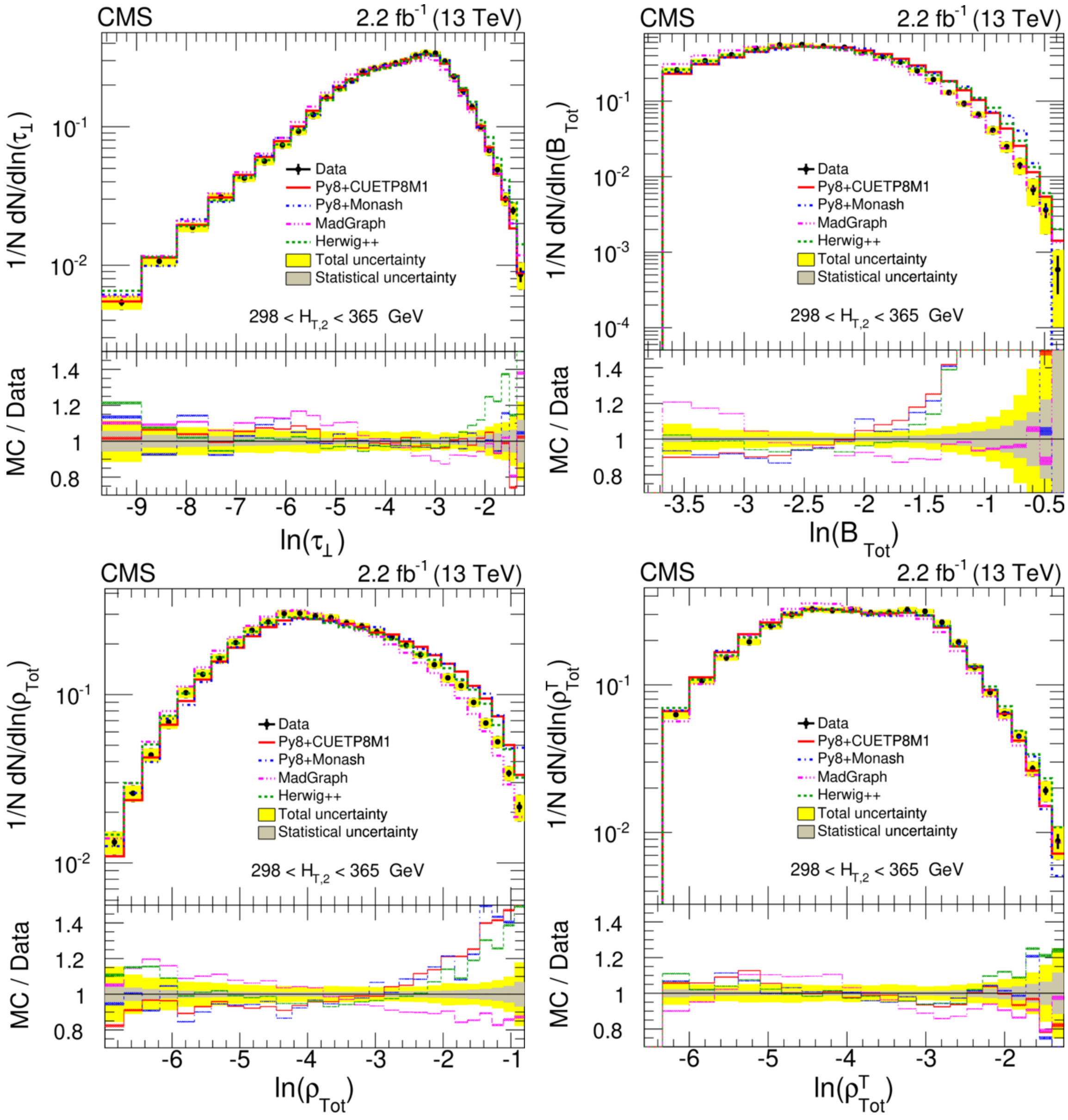

Figure 7. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust ($\tau_\perp$) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho^{\mathrm{T}}_{\mathrm{Tot}}$) (lower right) for $298 < H_{\mathrm{T},2} < 365\,\mathrm{GeV}$. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

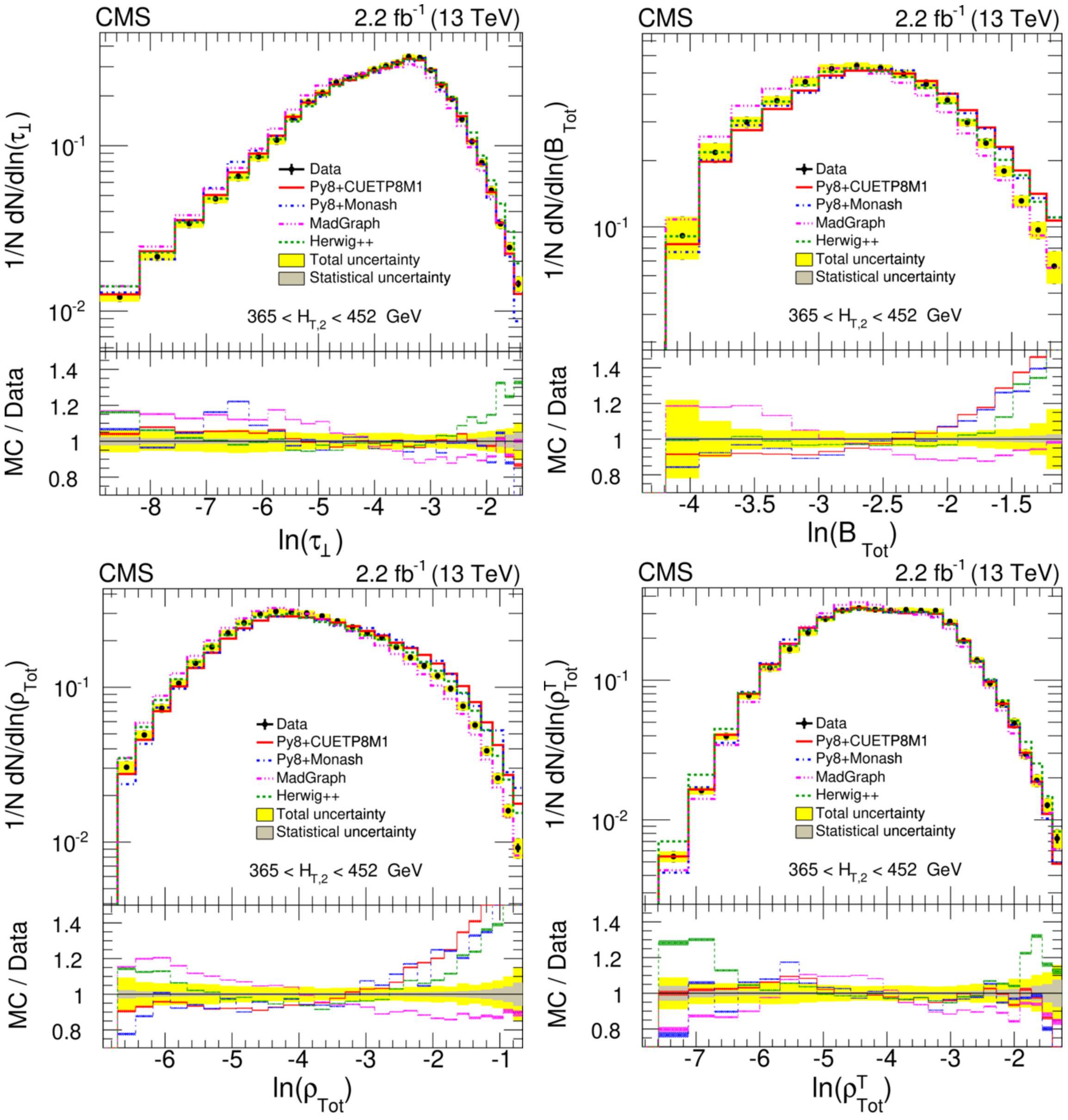

Figure 8. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust ($\tau_\perp$) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho^{\mathrm{T}}_{\mathrm{Tot}}$) (lower right) for $365 < H_{\mathrm{T},2} < 452\,\mathrm{GeV}$. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

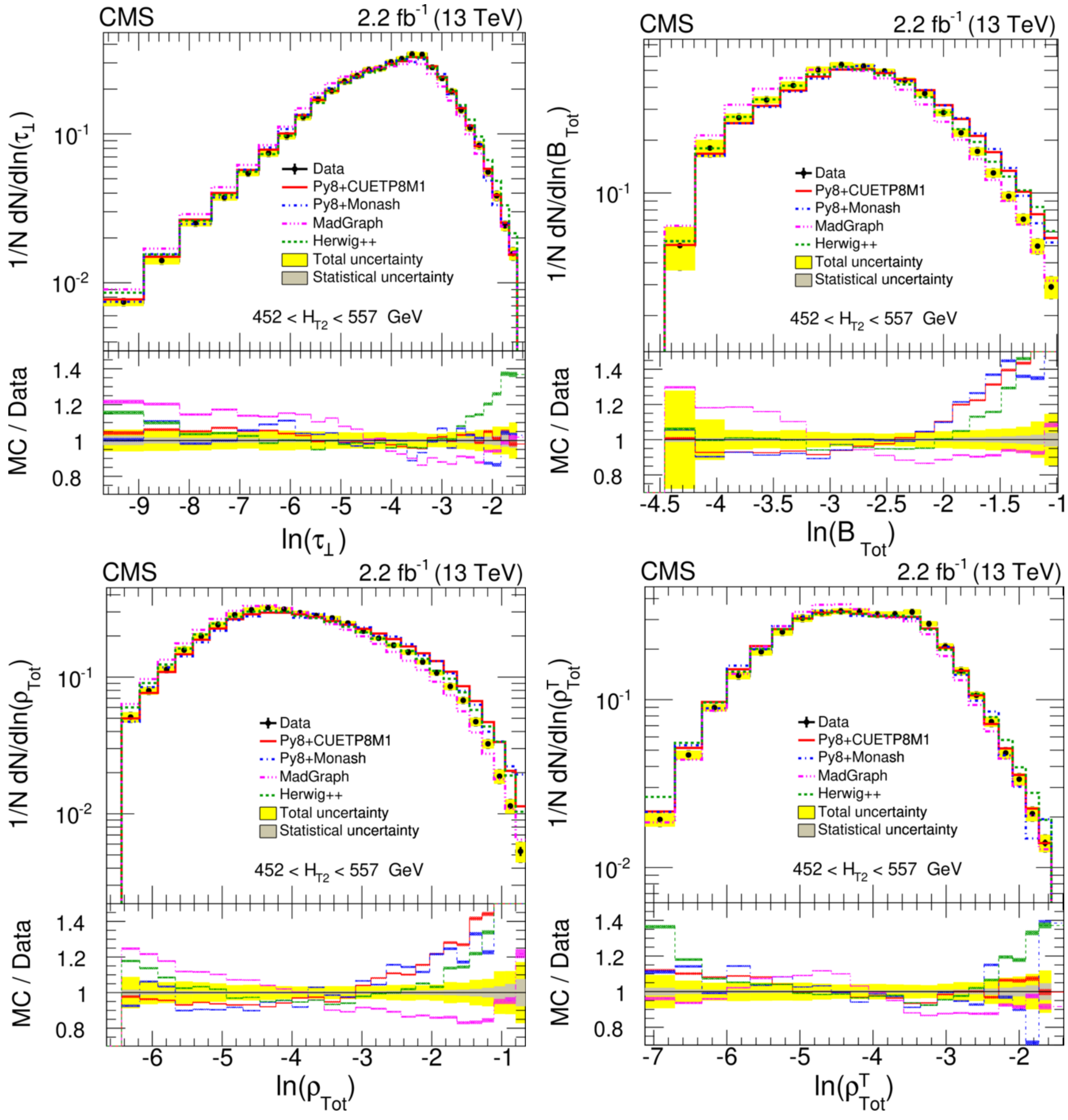

Figure 9. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust ($\tau_\perp$) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho^{\mathrm{T}}_{\mathrm{Tot}}$) (lower right) for $452 < H_{\mathrm{T},2} < 557\,\mathrm{GeV}$. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

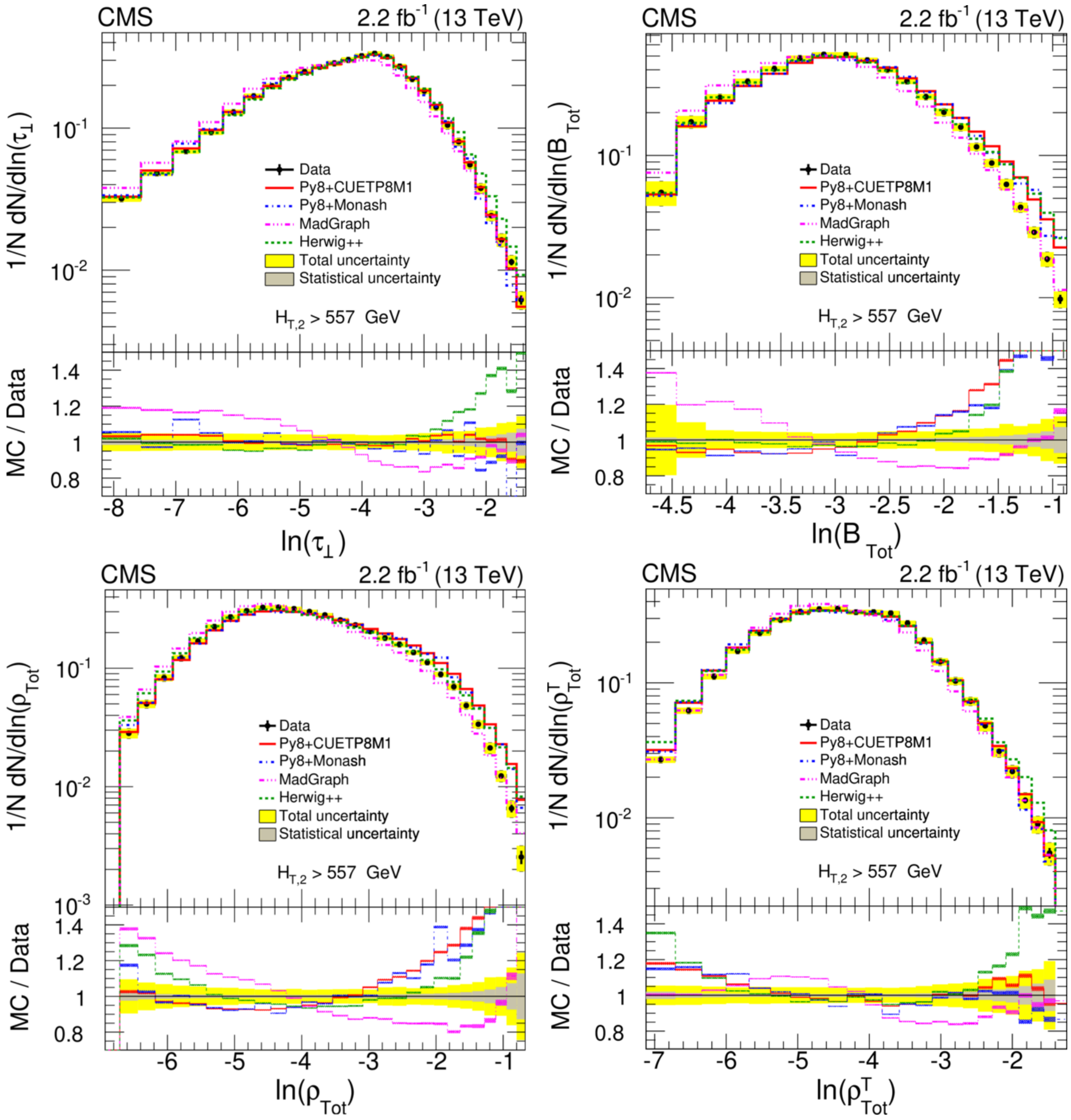

Figure 10. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust ($\tau_\perp$) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) transverse jet mass ($\rho^{\mathrm{T}}_{\mathrm{Tot}}$) (lower left) and total transverse jet mass ($\rho^{\mathrm{T}}_{\mathrm{Tot}}$) (lower right) for $H_{\mathrm{T},2} > 557\,\mathrm{GeV}$. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

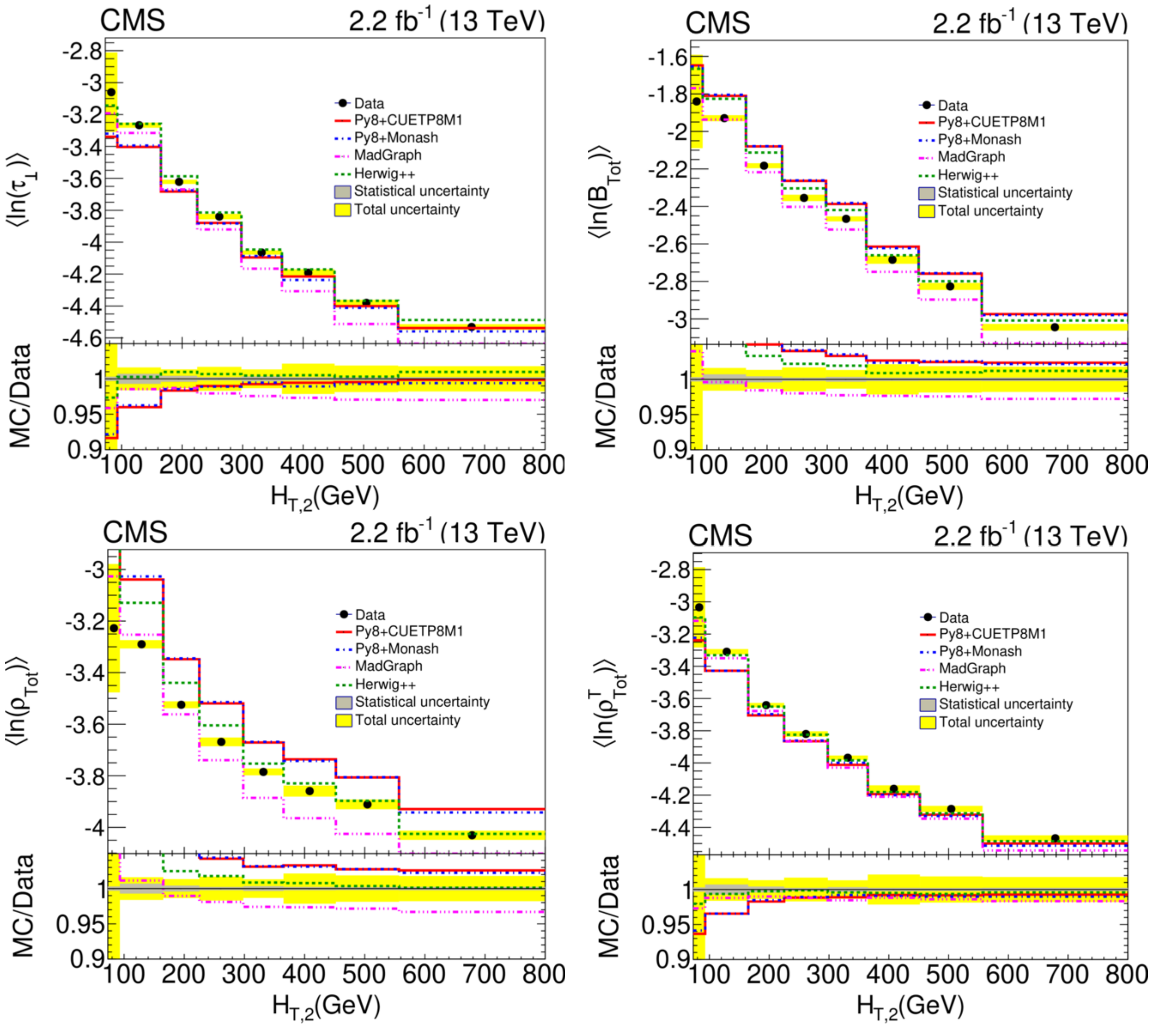

Figure 11. The evolution of the mean of $\tau_{\perp}$ (upper left), B_{Tot} (upper right), ρ_{Tot} (lower left) and $\rho^{\mathrm{T}}_{\mathrm{Tot}}$ (lower right) and with increasing $H_{\mathrm{T},2}$. The ratio plots with respect to data are presented in the bottom panel to compare predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line). The yellow band represents the total uncertainty (systematic and statistical components added in quadrature).

9 Summary

This paper presents the first measurement at $\sqrt{s} = 13\,\text{TeV}$ of four event shape variables: complement of transverse thrust ($\tau_{\perp}$), total jet broadening (B_{Tot}), total jet mass (ρ_{Tot}), and total transverse jet mass ($\rho^{\text{T}}_{\text{Tot}}$) using proton-proton collision data. It also covers a wider range of energy than the analysis at $\sqrt{s} = 7\,\text{TeV}$ [19, 22]. Data are compared with theoretical predictions from event generators PYTHIA8, HERWIG++, and MADGRAPH5_aMC@NLO+PYTHIA8. The PYTHIA8 generator describes the flow of energy in the transverse plane well as seen in the $\tau_{\perp}$ and $\rho^{\text{T}}_{\text{Tot}}$ distributions. HERWIG++ and MADGRAPH5_aMC@NLO show good agreement with the data for all the four event shape variables and are better than PYTHIA8 in predicting ρ_{Tot} and B_{Tot}. A study of the effects of initial state radiation, final state radiation, and multiple parton interactions in PYTHIA8 is also presented.

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39: Also at California Institute of Technology, Pasadena, U.S.A.
40: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
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43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
49: Also at Adiyaman University, Adiyaman, Turkey
50: Also at Istanbul Aydin University, Istanbul, Turkey
51: Also at Mersin University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Gaziosmanpasa University, Tokat, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
59: Also at Istanbul Bilgi University, Istanbul, Turkey
60: Also at Hacettepe University, Ankara, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Monash University, Faculty of Science, Clayton, Australia
64: Also at Bethel University, St. Paul, U.S.A.
65: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
66: Also at Utah Valley University, Orem, U.S.A.
67: Also at Purdue University, West Lafayette, U.S.A.
68: Also at Beykent University, Istanbul, Turkey
69: Also at Bingol University, Bingol, Turkey
70: Also at Sinop University, Sinop, Turkey
71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
72: Also at Texas A&M University at Qatar, Doha, Qatar
73: Also at Kyungpook National University, Daegu, Korea

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