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Study of hadronic event-shape variables in multijet final states in pp collisions at 7 TeV

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Abstract

Event-shape variables, which are sensitive to perturbative and nonperturbative aspects of quantum chromodynamic (QCD) interactions, are studied in multijet events recorded in proton-proton collisions at $\sqrt{s} = 7$ TeV. Events are selected with at least one jet with transverse momentum $p_T > 110$ GeV and pseudorapidity $|\eta| > 2.4$, in a data sample corresponding to integrated luminosities of up to 5 fb^{-1} . The distributions of five event-shape variables in various leading jet p_T ranges are compared to predictions from different QCD Monte Carlo event generators.

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1 Introduction

Event shapes measure geometrical properties of the energy flow in hadronic final states from a variety of interactions. These variables are collinear and infrared safe and thus are robust against measurements of soft or close-by particles. However they are sensitive to the details of the features of QCD radiation.

Measurements of event-shape variables in hadron-hadron collisions are complicated because a large fraction of the final-state activity is emitted at very forward pseudorapidities not covered by the detectors, and also because the elementary (parton-parton) kinematics cannot be determined precisely. These difficulties have led to the redefinition of event-shape variables in the transverse plane. A large set of event-shape variables in proton-proton (pp) collisions, which are sensitive to different aspects of the rich dynamics of the strong interaction from soft (hadronization) to hard (multijet radiation) scales has been proposed [1, 2].

This study is done using a data set corresponding to an integrated luminosity of $5fb^{-1}$ in pp collisions at $\sqrt{s} = 7$ TeV collected by CMS [3] detector in the year 2011. Overall this analysis [4] is sensitive to features of the event generators that were not probed in the previous CMS result.

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2 Event-shape variables

Five event-shape variables [1, 2] are analysed in this paper: the transverse thrust $\tau_\perp$, the total jet broadening B_{tot} , the total jet mass ρ_{tot} , the total transverse jet mass ρ_{tot}^T and the third-jet resolution parameter Y_{23} . In the formulae below, $p_{T,i}$, η_i , and ϕ_i represent the transverse momentum, pseudorapidity, and azimuthal angle of the i th jet, and $\hat{n}_T$ is the unit vector that maximizes the sum of the projections of $\vec{p}_{T,i}$. Based on the direction of $\hat{n}_T$, the transverse region is separated into an upper side $\mathcal{C}_U$, consisting of all jets with $\vec{p}_{T,i} \cdot \hat{n}_T > 0$, and a lower side $\mathcal{C}_L$, with $\vec{p}_{T,i} \cdot \hat{n}_T < 0$.

Transverse Thrust: The event thrust observable in the transverse plane is defined as

$$\tau_\perp \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i p_{T,i}} \quad (1)$$

In the limit of a perfectly balanced two-jet event, $\tau_\perp$ is zero, while in isotropic multijet events it amounts to $(1 - 2/\pi)$.

Jet Broadenings: The pseudorapidities and the azimuthal angles of the axes for the upper and lower event regions are defined by

$$\eta_X \equiv \frac{\sum_{i \in \mathcal{C}_X} p_{T,i} \eta_i}{\sum_{i \in \mathcal{C}_X} p_{T,i}}, \quad (2)$$

$$\phi_X \equiv \frac{\sum_{i \in \mathcal{C}_X} p_{T,i} \phi_i}{\sum_{i \in \mathcal{C}_X} p_{T,i}}, \quad (3)$$

where X refers to upper (U) or lower (L) side. From these, the jet broadening variable in each region is defined as

$$B_X \equiv \frac{1}{2P_T} \sum_{i \in \mathcal{C}_X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}, \quad (4)$$

where P_T is the scalar sum of the transverse momenta of all the jets. The total jet broadening is then defined as

$$B_{tot} \equiv B_U + B_L. \quad (5)$$

Jet Masses: The normalized squared invariant mass of the jets in the upper and lower regions of the event is defined by

$$\rho_X \equiv \frac{M_X^2}{P^2} \quad (6)$$

where M_X is the invariant mass of the constituents of the jets in the region X , and P is the scalar sum of the momenta of all constituents in both sides.

The jet mass variable is defined as the sum of the masses in the upper and lower regions,

Trigger $p_{T,th}(GeV)$	Range of $p_{T,1}$ (GeV)	Luminosity	Number of events	Fraction of events (%)			
				$N_{jet} = 2$	$N_{jet} = 3$	$N_{jet} = 4$	$N_{jet} > 4$
60	110 – 170	0.403 pb^{-1}	96833	57.9	32.6	7.8	1.7
110	170 – 250	7.15 pb^{-1}	228854	43.0	37.7	14.6	4.7
190	250 – 320	153 pb^{-1}	601554	34.8	37.8	19.1	8.3
240	320 – 390	520 pb^{-1}	497827	31	37	21.2	10.9
300	> 390	5.0 fb^{-1}	2234304	28.4	35.6	22.5	13.5

Table 1 Characteristics of the data samples selected for this analysis, in categories of leading jet transverse momentum $p_{T,1}$: effective integrated luminosity, selected number of events, and relative abundances of the number of selected jets (N_{jet}) with $p_{T,jet} > 30$ GeV and $|\eta_{jet}| < 2.4$ is shown.

$$\rho_{tot} \equiv \rho_U + \rho_L, \quad (7)$$

The corresponding jet mass in the transverse plane, ρ_{tot}^T , is also similarly calculated in transverse plane.

Third-jet resolution parameter: The third-jet resolution parameter is defined as

$$Y_{23} \equiv \frac{\min(p_{T,3}^2, [\min(p_{T,i}, p_{T,j})^2 \times (\Delta R_{ij})^2 / R^2])}{P_{12}^2} \quad (8)$$

where i, j run over all three jets, $(\Delta R_{ij})^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$, and $p_{T,3}$ is the transverse momentum of the third jet in the event. If there are more than three jets in the event, they are iteratively merged using the k_T algorithm [5] with a distance parameter $R = 0.6$. To compute P_{12} , three jets are merged into two using the procedure described above and P_{12} is then defined as the scalar sum of the transverse momenta of the two remaining jets.

3 Event selection and Monte Carlo samples

This analysis is restricted to jets in the acceptance region $|\eta| < 2.4$ and considers several different p_T ranges (table 1) for the leading jet. The events used are collected with single-jet triggers, where the p_T of at least one jet is above a certain threshold, $p_{T,th}$, while the p_T threshold (> 30 GeV) for the other jets. Spurious jets, which are due to noise in the calorimeters or other non-collision backgrounds, are eliminated using jet quality criteria.

Four Monte Carlo (MC) generators, Pythia6.426 [7] (TUNE D6T, TUNE PERU-GIAP0, TUNE Z2), Pythia8.153 [8] (TUNE 4C), Herwig++2.5.3 [9] (TUNE 23), and Madgraph 5.1.5.7 [10] are chosen to generate multijet events. Particles are fed to Geant4 [11] for full CMS detector simulation. The simulated events are then reconstructed in the same way as real data.

4 Unfolding and systematic uncertainties

In order to correct the measured distributions for bin migrations due to detector effects, a response matrix is constructed with simulated events. The D’Agostini method [12] is employed to unfold the experimental data, using the response matrix obtained from Pythia 6-tuneZ2, Pythia 8, and MadGraph samples. Although the results are consistent for the generators, small differences ($< 3\%$) are observed, which are taken as a systematic uncertainty. Another source of systematic uncertainty in the unfolding procedure is the choice of the algorithm. A regularized unfolding method based on singular value decomposition (SVD) of the response matrix [13] is also used as a consistency check.

Other sources of systematic uncertainty include the finite jet energy and angular resolutions and the jet energy scale [6].

5 Results

The distributions of the logarithms of the five event-shape variables analysed ($\tau_{\perp}$, B_{tot} , jet mass (both ρ_{tot} and ρ_{tot}^T), and Y_{23}) are shown in figure 1 for the leading jet p_T range 320 – 390 GeV. All distributions are unfolded, normalized to unitary; they are compared to the predictions from the six generator models. The error bars around the data points indicate the statistical uncertainties and the shaded bands represent the sum in quadrature of statistical and systematic uncertainties. The corresponding ratios between the model predictions and the data are shown in the lower plots. The distributions are plotted in a logarithmic horizontal axis scale so that the details at small values of the event-shape variables are also visible.

Overall, the models tend to reproduce the transverse thrust $\tau_{\perp}$, total transverse jet mass ρ_{tot}^T , and third-jet resolution parameter Y_{23} distributions better than the total jet mass ρ_{tot} and jet broadening B_{tot} ones. The model that consistently reproduces all the distributions within the uncertainties is the MadGraph matrix-element calculator combined with pythia 6-tuneZ2 for the PS and UE.

6 Summary

Event shape variables that are defined in the transverse plane exhibit better agreement between data/MC than the those which are sensitive to longitudinal energy flow. The modelling of colour connection between the soft scatters and beam remnants, and initial and final state radiations are the major sources of differences between the various QCD event generators. The study of infra-red and collinear safe event shape provides detailed information in further improving the modelling of parton radiation and hadronization in event generators for high energy hadronic collisions.

Fig. 1 Comparison between the data and different Monte Carlo models for transverse thrust, total jet broadening, total jet mass, total transverse jet mass and third-jet resolution parameter spectra.

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