Measurement of charged-particle event shape variables in inclusive $\sqrt{s} = 7$ TeV proton–proton interactions with the ATLAS detector

The ATLAS Collaboration

Abstract

The measurement of charged-particle event shape variables is presented in inclusive inelastic $pp$ collisions at a center-of-mass energy of 7 TeV using the ATLAS detector at the LHC. The observables studied are the transverse thrust, thrust minor and transverse sphericity, each defined using the final-state charged particles' momentum components perpendicular to the beam direction. Events with at least six charged particles are selected by a minimum-bias trigger. In addition to the differential distributions, the evolution of each event shape variable as a function of the leading charged particle transverse momentum, charged particle multiplicity and summed transverse momentum is presented. Predictions from several Monte Carlo models show significant deviations from data.
I. INTRODUCTION

Event shape variables describe the structure of hadronic events and the properties of their energy flow. In this analysis, three event shape observables [1, 2] are measured: the transverse thrust, thrust minor and the transverse sphericity, each built from the momenta of charged particles using tracking information from proton-proton collisions at \( \sqrt{s} = 7 \) TeV collected with the ATLAS detector [3]. Event shape observables are among the simplest experimentally measured quantities and, depending on the events being considered, may have sensitivity to both the perturbative and non-perturbative aspects of quantum chromodynamics (QCD).

Event shapes in hadronic collisions were investigated first at the ISR [4] and at the SPS [5, 6] at CERN to examine the emergence of jets, and later at Tevatron [7] to study the dependence of the event shape observables on the transverse energy of the leading jet and on contributions from the underlying event. At the Large Hadron Collider (LHC), event shape observables were recently studied in inclusive interactions [8] and multi-jet events [9, 10]. In e+e− and ep deep-inelastic scattering experiments, the study of the energy flow in hadronic final states has allowed tests of the predictions of perturbative QCD, and the extraction of a precise value for the strong coupling constant \( \alpha_s \) [11–17].

The study of event shape observables in inclusive inelastic collisions plays an important role in understanding soft-QCD processes at LHC center-of-mass energies [18], where “soft” refers to interactions with low momentum transfer between the scattering particles. Soft interactions cannot be reliably calculated from theory and are thus generally described by phenomenological models, usually implemented in Monte Carlo (MC) event generators. These models contain many parameters whose values are a priori unknown and thus need to be constrained by measurements. Inclusive and semi-inclusive observables sensitive to soft-QCD processes have been measured at the LHC by the ATLAS [19–21], CMS [22, 23] and ALICE [24, 25] collaborations. The measurements presented in this paper can further constrain the event generator models, which encapsulate our understanding of these soft processes.

In this analysis, the event shape observables are constructed from six or more primary charged particles in the pseudorapidity range \( |\eta| < 2.5 \) and with transverse momentum \( p_T > 0.5 \) GeV [26]. Primary charged particles are defined as those with a mean proper lifetime \( \tau > 30 \) ps, produced either directly in the pp interaction or from the subsequent decay of particles with a shorter lifetime. The particle level refers to particles as they emerge from the proton–proton interaction. The detector level corresponds to tracks as measured after interaction with the detector material, and includes the detector response. The results are corrected for detector effects, using simulation, to obtain distributions of the event shape variables defined at particle level which can be directly compared to MC models.

This paper is organized as follows: Section II defines the event shape variables; the detector is described in Section III; Section IV discusses the MC models used in this analysis; Section V and VI respectively describe the event selections and background contributions. The correction of the data back to particle level, and estimation of the systematic uncertainties are described in Section VII and VIII; the results are discussed in Section IX and finally the conclusions are presented in Section X.

II. EVENT SHAPE OBSERVABLES

In particle collisions, event shape observables describe the geometric properties of the energy flow in the final state. A single event shape variable can distinguish in a continuous way between configurations in which all the particles are flowing (forward and backward) along a single axis and configurations where the energy is distributed uniformly over the 4\( \pi \) solid angle. If defined as a ratio of measured quantities, the corresponding systematic uncertainties may be small.

In hadron collisions, where the center-of-mass frame of the interaction is usually boosted along the beam axis, event shape observables are often defined in terms of the
transverse momenta, which are Lorentz-invariant under such boosts. Different formulations of event shape observables are possible; the most intuitive is to calculate the event shape from all particles in an event. These are denoted by directly global event shapes [1, 2]. In hadron collider experiments, it is not usually possible to detect all particles in an event due to the finite detector acceptance, limited at small scattering angles by the presence of the beam pipe. Event shapes which include only particles from a restricted phase space in pseudorapidity \( \eta \), are called central event shapes: in this analysis charged particles within the range \( |\eta| < 2.5 \) are used. These central event shapes are nevertheless sensitive to non-perturbative effects at low momentum transfer and provide useful information about the event structure for development of models of proton–proton collisions. The thrust is one of the most widely used event shape variables. The transverse thrust for a given event is defined as:

\[
T_\perp = \max_\hat{n} \sum_i \frac{|\vec{p}_{T,i} \cdot \hat{n}|}{\sum_i |\vec{p}_{T,i}|}
\]  

where the sum is performed over the transverse momenta \( \vec{p}_{T,i} \) of all charged particles in the event. The thrust axis \( \hat{n}_T \) is the unit vector \( \hat{n} \) that maximizes the ratio in Eq. (1). The transverse thrust ranges from \( T_\perp = 1 \) for a perfectly balanced, pencil-like, dijet topology to \( T_\perp = 1 - T_\perp \) for a circularly symmetric distribution of particles in the transverse plane, where \( \psi \) is the azimuthal angle between the thrust axis and each respective particle. It is convenient to define the complement of \( T_\perp \), \( \tau_\perp = 1 - T_\perp \), to match the behavior of many event shape variables, which vanish in a balanced dijet topology.

The thrust axis \( \hat{n}_T \) and the beam axis \( \hat{z} \) define the event plane. The transverse thrust minor measures the out-of-event-plane energy flow:

\[
T_M = \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_m|}{\sum_i |\vec{p}_{T,i}|}, \quad \hat{n}_m = \hat{n}_T \times \hat{z}.
\]

The transverse thrust minor is 0 for a pencil-like event in azimuth and \( 2/\pi \) for an isotropic event.

Another widely used event shape variable is the sphericity, \( S \), which describes the event energy flow based on the momentum tensor,

\[
S^{\alpha \beta} = \frac{\sum_i p_{T,i}^\alpha p_{T,i}^\beta}{\sum_i |\vec{p}_{T,i}|^2},
\]

where the Greek indices represent the \( x, y \), and \( z \) components of the momentum of the particle \( i \). The sphericity of the event is defined in terms of the two smallest eigenvalues of this tensor, \( \lambda_2 \) and \( \lambda_3 \):

\[
S = \frac{3}{2}(\lambda_2 + \lambda_3).
\]

The sphericity has values between 0 and 1, where a balanced dijet event corresponds to \( S = 0 \) and an isotropic event to \( S = 1 \). Sphericity is essentially a measure of the summed \( p_T^2 \) with respect to the event axis [27, 28], where the event axis is defined as the line passing through the interaction point and oriented along the eigenvector associated with the largest eigenvalue, \( \lambda_1 \). Similarly to transverse thrust, the transverse sphericity, \( S_\perp \), is defined in terms of the transverse components only:

\[
S_{xy} = \sum_i \frac{1}{|\vec{p}_{T,i}|^2} \left[ p_{x,i}^2 p_{y,i}^2 - (p_{x,i} p_{y,i})^2 \right]
\]

and

\[
S_\perp = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}},
\]

where \( \lambda_2^{xy} < \lambda_1^{xy} \) are the two eigenvalues of \( S_{xy} \).

The following distributions are measured:

- Normalized distributions: \( \frac{1}{N_{ev}} dN_{ev} / d\tau_{ch} \), \( \frac{1}{N_{ev}} dN_{ev} / dT_M^{ch} \), \( \frac{1}{N_{ev}} dN_{ev} / dS^{ch} \);
- Average values: \( \langle \tau_{ch} \rangle \), \( \langle T_M^{ch} \rangle \) and \( \langle S^{ch} \rangle \) as functions of \( N_{ch} \) and \( \sum p_T \);

where \( N_{ev} \) is the number of events with six or more charged particles within the selected kinematic range; \( N_{ch} \) is the number of charged particles in an event; \( \sum p_T \) is the scalar sum of the transverse momenta of the charged particles in the event. The event shape observables \( \tau_{ch} \), \( T_M^{ch} \) and \( S^{ch} \) are defined as above, with the superscript indicating that they are constructed from charged particles.

The three normalized differential distributions are studied separately for:

- \( 0.5 \text{ GeV} < p_T^{\text{lead}} \leq 2.5 \text{ GeV} \)
- \( 2.5 \text{ GeV} < p_T^{\text{lead}} \leq 5.0 \text{ GeV} \)
- \( 5.0 \text{ GeV} < p_T^{\text{lead}} \leq 7.5 \text{ GeV} \)
- \( 7.5 \text{ GeV} < p_T^{\text{lead}} \leq 10.0 \text{ GeV} \)
- \( p_T^{\text{lead}} > 10 \text{ GeV} \)

where \( p_T^{\text{lead}} \) is the transverse momentum of the highest \( p_T \) (leading) charged particle.

### III. THE ATLAS DETECTOR

The ATLAS detector [3] covers almost the full solid angle around the collision point with layers of tracking...
Monte Carlo (MC) event samples are used to compute the detector acceptance and reconstruction efficiency, determine background contributions, correct the measurements for detector effects, and to calculate systematic uncertainties. Finally, different phenomenological models implemented in the MC generators are compared to the data corrected to the particle level.

The **Pythia** 6 [30], **Pythia** 8 [31] and **Herwig** ++ [32, 33] event generators were used to produce the simulated event samples for the analysis. These generators implement leading-logarithm parton shower models matched to leading-order matrix element calculations with different hadronization models and orderings for the parton shower. The Pythia 6 and Pythia 8 generators use a hadronization model based upon fragmentation of color strings and a $p_T$-ordered or virtuality-ordered shower, whereas the Herwig ++ generator implements a cluster hadronization scheme with parton showering ordered by emission angle. The Pythia 8 generator uses a multi-parton interaction (MPI) model interleaved with both initial-state and final-state (ISR and FSR) radiation, and all three processes compete against each other for emission phase space in the resulting evolution. The Herwig ++ UE7-2 tune employs color reconnection. Different settings of model parameters, tuned to reproduce the existing experimental data were used for the MC generators. Table I shows the different MC models used in this paper.

The reference model for this analysis is chosen to be Pythia6 AMBT1. Samples generated with this tune were passed through the ATLAS detector and trigger simulations [44] based on GEANT4 [45] and then reconstructed and analyzed using the same procedure and software that are used for the data. Reconstructed MC events are then used to correct the data for detector effects. The sample generated with an older version of **Herwig** ++, 2.5.0 with no additional tuning, was also passed through the full detector simulation and the analysis chain for systematic studies of unfolding corrections.

## V. Event and Track Selection

The data used for the analysis presented here were collected in April 2010 with a minimal prescale factor for the minimum-bias trigger. The only further requirement for selecting the data sample is that the MBTS trigger and all inner detector subsystems were at nominal operating conditions. In each event the reconstructed vertices are ordered by the $\sum p_T^2$ over the tracks assigned to each vertex, and the vertex with the highest $\sum p_T^2$ is taken as the primary interaction vertex of the event. To reduce the contribution from beam-related backgrounds and decays of long-lived particles, and to minimize the systematic uncertainties, events are rejected if they contain any other vertex reconstructed with four or more tracks.

If there is only one vertex in the event, or if any additional vertex in the event has three or fewer tracks, all tracks from the event that pass the track selection (described below) are retained. After this selection, the fraction of events with more than one proton–proton interaction in the same bunch crossing (referred to as pile-up) is found to be approximately 0.1% and this residual contribution is therefore neglected. The average number of pp interactions per bunch crossing during this data-taking period was less than 0.15, indicating a negligible pile-up contribution. The MC samples used have no pile-up contribution.

Events are required to contain at least six tracks that fulfill the following criteria:

- $p_T > 0.5$ GeV;
- $|\eta| < 2.5$;
- a minimum of one pixel and six SCT hits;
- a hit in the innermost pixel layer, if the corresponding pixel module was active;
- transverse and longitudinal impact parameters with respect to the primary vertex, $|d_0| < 1.5$ mm and $|z_0| \sin \theta < 1.5$ mm;
- a track-fit probability $\chi^2 > 0.01$ for tracks with $p_T > 10$ GeV in order to remove mis-measured tracks.

Tracks with $p_T > 0.5$ GeV are less prone than lower-$p_T$ tracks to inefficiencies and systematic uncertainties resulting from interactions with the material inside the tracking volume.
TABLE I. Details of the MC models used. It is emphasized that the tunes use data from different experiments to constrain different processes, but for brevity only the data which had the most weight in each specific tune are shown. Here “LHC” indicates data taken at $\sqrt{s} = 7$ TeV, although $\sqrt{s} = 900$ GeV data were also included in ATLAS tunes, with much smaller weight. Some tunes are focused on describing the minimum-bias (MB) distributions better, while the rest are tuned to describe the underlying event (UE) distributions, as indicated. Authors indicates a tune performed by the MC developers.

<table>
<thead>
<tr>
<th>Generator</th>
<th>Version</th>
<th>Tune</th>
<th>PDF</th>
<th>Focus</th>
<th>Data From</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA6</td>
<td>6.425</td>
<td>AMBT1 [34]</td>
<td>MRST LO** [35]</td>
<td>MB</td>
<td>Early LHC ATLAS</td>
</tr>
<tr>
<td>PYTHIA6</td>
<td>6.421</td>
<td>DW [38]</td>
<td>CTEQ5L [39]</td>
<td>UE</td>
<td>Tevatron CDF</td>
</tr>
<tr>
<td>PYTHIA6</td>
<td>6.425</td>
<td>Z1 [40]</td>
<td>CTEQ5L</td>
<td>UE</td>
<td>LHC CMS</td>
</tr>
<tr>
<td>HERWIG ++</td>
<td>2.5.1</td>
<td>UE7-2 [43]</td>
<td>MRST LO**</td>
<td>UE</td>
<td>LHC Authors</td>
</tr>
<tr>
<td>HERWIG ++</td>
<td>2.5.0</td>
<td>Default</td>
<td>MRST LO**</td>
<td>UE</td>
<td>LHC Authors</td>
</tr>
</tbody>
</table>

After event selection, the analysis is based on approximately 17 million events containing approximately 300 million tracks. For the PYTHIA6 generator and for the PYTHIA8 generator, which has a harder diffractive model than the former, the contribution to the event shape observables from diffractive events is negligible when requiring six or more tracks in the event.

The $p_T$ distributions of all tracks and of the leading track in the selected event are shown in Fig. 1. The fraction of events in each $p_T^{\text{lead}}$ bin is shown in Table II.

![Graph](image)

**FIG. 1.** The distribution of the transverse momentum of all tracks and of the leading transverse momentum track in data at detector level. The uncertainties shown are statistical. Where not visible, the statistical error is smaller than the marker size.

VI. BACKGROUND CONTRIBUTIONS

A. Backgrounds

Backgrounds comprise beam-induced events, due to beam-gas and beam-material interactions, as well as non-beam backgrounds from cosmic-ray interactions and detector noise. The contribution of these background events remaining after the event selection is estimated using the number of pixel hits not associated with reconstructed tracks. This multiplicity includes unassigned hits from low-$p_T$ looping tracks, but is dominated at higher multiplicities by hits from charged particles produced in inelastic interactions of protons with the residual gas inside the beam pipe. The vertex requirement removes most of the beam background events and the residual contribution is below 0.1%. As the level of background is very low, no explicit background subtraction is performed.

B. Secondary track fraction

The primary charged particle multiplicities are measured from selected tracks after correcting for the fractions of secondary and poorly reconstructed tracks in the sample. The potential background from fake tracks is found from MC studies to be less than 0.01% [19].
Non-primary tracks arise predominantly from hadronic interactions, photon conversions to positron–electron pairs in the detector material and decays of long-lived particles. For $p_T > 0.5$ GeV the contribution from photon conversions is small. The systematic uncertainty from secondary decays is included in the uncertainties associated with the tracking performance.

VII. CORRECTION TO PARTICLE LEVEL

To facilitate comparison with theoretical predictions and other measurements, the event shape distributions for charged particles are presented at particle level, after correction for trigger and event selection efficiencies, as well as detector resolution effects. A two-step correction procedure is used: first, corrections for event selection efficiency are applied, followed by an additional bin-by-bin correction to account for tracking inefficiencies, possible bin migrations and any remaining detector effects.

A. Event-level correction

Trigger and vertexing efficiencies are taken from a previous analysis using the same data sample [19]. The efficiency of the MBTS trigger is determined from data using a control trigger and found to be fully efficient for the analysis requirement of at least six tracks. The vertex reconstruction efficiency is also measured in data by taking the ratio of the number of triggered events with a reconstructed vertex to the total number of triggered events. This ratio is also found to be very close to unity. The total correction applied to account for events lost due to the trigger and vertex requirements is less than 1% and it varies very weakly with the number of tracks associated with the primary vertex.

B. Bin-by-bin correction

The event shape observables presented here are sensitive to changes in the configuration of the selected tracks. Applying average track efficiencies to individual tracks on a track-by-track basis and reweighting tracks distorts the event shape distribution. A more robust approach is to apply bin-by-bin corrections to find the event shape distribution at particle level. Such a bin-by-bin correction is applied to all distributions after applying the event-level efficiency corrections described above. The correction factors $C_{\text{bin}}$ are evaluated separately in each bin for each event shape observable, where $V_{\text{Gen}}^\text{bin}$ and $V_{\text{Reco, eff corr}}^\text{bin}$ represent the generator-level MC value of the bin content and the reconstructed MC value after applying the event-level efficiency corrections for each bin, respectively. The corrected value of the bin content for an observable is found by multiplying the measured bin content by the corresponding correction factor. The bin sizes are chosen to be consistent with the resolution of the correction procedure.

The correction factors are calculated using the two different models implemented in PYTHIA 6 AMBT1 and HERWIG ++. This correction accounts for bin-by-bin migrations and tracking inefficiencies. For each distribution, the unfolding factor is typically within ±10% of unity for most of the range. It is very close to unity for the average values, except at the highest $\sum p_T$. The difference from unity becomes more pronounced at the statistically limited edges of the distributions. The correction factors for the inclusive distributions of the three event shape observables are shown in the bottom panels of Fig. 2 for the two MC event generators mentioned above. Although the two MC generators have different distributions, the bin-by-bin correction factors are similar.

VIII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties on the measured distributions are assessed with the following sources of uncertainty included:

Tracking: The largest of the systematic uncertainties for the tracking inefficiency [19] is found to be due to the material description in the inner detector. This is determined to produce a relative uncertainty of 2% in the efficiency in the barrel region, rising to $\sim 7\%$ for $2.3 < |\eta| < 2.5$. The contribution of the propagated uncertainty is found to be less than 1% of the content in each bin of the shape distributions.

Bin-by-bin correction model dependence: The remaining contributions to the overall systematic uncertainty result from the specific correction method used in this analysis. The bin-by-bin corrections in general depend on the number of charged particles and their $p_T$ distributions, so there is some dependence on the event generators. In order to estimate this uncertainty, it is necessary to compare different plausible event generators, which deviate significantly from each other, but still give predictions close to the data. The corrected results using the two very different PYTHIA 6 AMBT1 and HERWIG ++ models are compared. As these two generators use very different soft-QCD models the difference is assigned as a systematic uncertainty. The generated and reconstructed distributions are shown in Fig. 2 for the two MC event generators and compared with the detector-level data.

Statistical uncertainty of bin-by-bin correction: In addition to the model-dependent uncertainty in the bin-by-bin correction, there is also a statistical
The distributions shown in Figs. 3–5 indicate a prevalence of spherical events in the lower $p_T^{\text{lead}}$ ranges. A slight shift toward less spherical events and a broadening of the distributions is observed for events starting with $p_T^{\text{lead}} > 7.5$ GeV in Fig. 3(d) for $\tau_T^1$ and in Fig. 4(d) for $T_M^2$. For both variables, a transition to less spherical events is seen for $p_T^{\text{lead}} > 10$ GeV in Fig. 3(e) and in Fig. 4(e). The distribution of transverse sphericity is more sensitive to the increase of $p_T^{\text{lead}}$, and shows a marked shift toward less spherical events starting at $p_T^{\text{lead}} > 5.0$ GeV in Fig. 5(e). The average value of the distributions, the RMS width and the skewness of the distributions are given in Table IV, which supports this uncertainty due to the finite size of the MC sample. The statistical fluctuations of the PYTHIA6 AMBT1 correction factor are found to be negligible for most of each distribution, increasing to a few percent in the tails of the distributions. This is also added to the overall systematic uncertainty estimate.

The systematic uncertainty due to the small number of residual multiple proton–proton interactions is estimated to be negligible.

All the above mentioned systematic uncertainties are added in quadrature. Table III lists representative values for the various contributions to the systematic uncertainty in the content of each bin for all the event shape observables away from the edges of the distributions.

**TABLE III. Summary of systematic uncertainties in %.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger and vertex efficiency</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>0.1–0.5</td>
</tr>
<tr>
<td>Correction model difference</td>
<td>1–5</td>
</tr>
<tr>
<td>PYTHIA correction stat. uncertainty</td>
<td>0.1–2</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>1–5</td>
</tr>
</tbody>
</table>

**IX. RESULTS AND DISCUSSION**

The distributions of the complement of the transverse thrust, thrust minor and transverse sphericity are presented in Figs. 3–5, in different $p_T^{\text{lead}}$ ranges. The behavior of the average values of the shape variables as functions of the charged particle multiplicity, $N_{\text{ch}}$, and transverse momentum scalar sum, $\sum p_T$, is presented in Fig. 6. Predictions from the PYTHIA6 AMBT2B, PYTHIA 6 DW, PYTHIA 6 Z1, PYTHIA 8 A2 and HERWIG ++ UE7-2 models are also shown. AMBT2B is chosen instead of AMBT1, which was used to correct the data back to the particle level because it shows a slight improvement in reproducing the distributions of charged particle transverse momentum and multiplicity [36].

The distributions shown in Figs. 3–5 indicate a prevalence of spherical events in the lower $p_T^{\text{lead}}$ ranges. A slight shift toward less spherical events and a broadening of the distributions is observed for events starting with $p_T^{\text{lead}} > 7.5$ GeV in Fig. 3(d) for $\tau_T^1$ and in Fig. 4(d) for $T_M^2$. For both variables, a transition to less spherical events is seen for $p_T^{\text{lead}} > 10$ GeV in Fig. 3(e) and in Fig. 4(e). The distribution of transverse sphericity is more sensitive to the increase of $p_T^{\text{lead}}$, and shows a marked shift toward less spherical events starting at $p_T^{\text{lead}} > 5.0$ GeV in Fig. 5(e). The average value of the distributions, the RMS width and the skewness of the distributions are given in Table IV, which supports this
observation. Mean values of the complement of transverse thrust and the transverse thrust minor are observed to initially rise with increasing $p_T^{\text{lead}}$, with their maximum value in the range $2.5 < p_T^{\text{lead}} < 5$ GeV, before decreasing. A similar trend is observed by the ALICE Collaboration, which has measured the transverse sphericity distribution selecting charged particles with $|\eta| < 0.8$, in inelastic 7 TeV $pp$ collisions [8].

Overall, the *pythia*6 tune Z1, tuned to the underlying event distributions at the LHC, agrees the best with most of the distributions. The *pythia*6 DW tune predictions are consistently furthest from the data, as seen in the $T^x$ and $T^\perp$ distributions. This is not unexpected as DW is tuned to reproduce the Tevatron data and does not agree with the charged particle multiplicity and $p_T$ distributions in LHC data [19]. However it performs similarly to other models/tunes for the $S^{ch}$ distribution in intermediate to high $p_T^{\text{lead}}$ values, as is seen in Fig. 5(c)–Fig. 5(e). The AMBT2B tune, which is based on minimum-bias LHC data, shows better agreement for the lowest $p_T^{\text{lead}}$ distributions than for the intermediate $p_T^{\text{lead}}$ distributions, as is seen in Fig. 3(a) and in Fig. 4(a). Compared to the *pythia*6 AMBT2B tune, the predictions of the *pythia*8 A2 and HERWIG ++ UE7-2 tunes show better agreement with the data in the intermediate to high $p_T^{\text{lead}}$ ranges. The UE7-2 tune, based like Z1 on LHC underlying event data, is expected to perform better in events characterized by a hard scatter, resulting in higher $p_T^{\text{lead}}$ values. However, the minimum-bias A2 tune shows a similar or slightly better level of agreement with data for the high $p_T^{\text{lead}}$ distributions, possibly indicating that the improved MPI modeling compared to *pythia*6 tunes does play a role. All models tend to better reproduce the data selected with the higher $p_T^{\text{lead}}$ ranges.

The mean values of event shape observables as functions of $N_{ch}$ and $\sum p_T$ are shown in Fig. 6. They are seen to increase with $N_{ch}$, but the increase is less marked at values of $N_{ch}$ above about 30. For low values of $N_{ch}$, the mean values of the event shape variables correspond to less spherical events, while the average values for large multiplicity is largely consistent with the positions of the maxima of the corresponding distributions for the lowest $p_T^{\text{lead}}$ range. A similar trend is seen for distributions as a function of $\sum p_T$; however, for $\sum p_T$ over 100 GeV, the mean starts to decrease again, indicating the events are more dijet-like. In general, the MC models predict fewer high-sphericity events than are seen in the data. With the exception of *pythia*6 DW, the MC models seem to predict the behavior with multiplicity reasonably well in Fig. 6. However, the MC predictions are seen to differ in shape at very high $\sum p_T$, where the decrease of mean values happens in the MC predictions before the data. The behavior of mean transverse sphericity as a function of multiplicity measured by the ALICE Collaboration [8] exhibits a similar behavior to that observed here, with the data lying at values higher than predicted by the MC models.

X. CONCLUSIONS

The event shape observables, transverse thrust, transverse thrust minor, and transverse sphericity, have been measured in inelastic proton–proton collisions at $\sqrt{s} = 7$ TeV requiring at least six charged particles per event selected by a minimum-bias trigger. The distributions and mean values have been compared to predictions of different MC models tuned to inclusive particle distributions and underlying event data. The dependence of the event shapes on the number of charged particles, on the sum of charged particle $p_T$ and on the leading charged particle $p_T$ has been studied.

The distributions of all three event shape variables show an evolution toward less spherical events as $p_T^{\text{lead}}$ increases, but the effect is smaller for transverse thrust and thrust minor compared to transverse sphericity. The dependence of the event shape mean values as functions of $N_{ch}$ and $\sum p_T$ is similar, due the correlation between the two variables [19]. For each variable, the evolution toward a more spherical event shape with increasing multiplicity is rapid initially and slows at higher multiplicities. All tested MC generators underestimate the fraction of events of spherical character and none reproduces accurately the event shape distributions. The MC tunes based on the properties of the underlying event show in general better agreement with the data than those based on the inclusive distributions measured in minimum-bias events. The *pythia*6 MC generator with the Z1 tune provides the most accurate description of the observed distributions presented in this analysis, but the level of agreement is still not satisfactory over the whole range of the data. These measurements provide information complementary to inclusive particle distributions and thus they are useful for improving the MC description of inelastic proton–proton collisions at the LHC.
FIG. 3. Normalized distributions of the complement of transverse thrust using at least six charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ for different requirements on the transverse momentum of the leading charged particle, $p_T^{\text{lead}}$. The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty. Where not visible, the statistical error is smaller than the marker size.
FIG. 4. Normalized distributions of transverse thrust minor using at least six charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ for different requirements on the transverse momentum of the leading charged particle, $p_{T,\text{lead}}$. The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty. Where not visible, the statistical error is smaller than the marker size.
FIG. 5. Normalized distributions of transverse sphericity using at least six charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ for different requirements on the transverse momentum of the leading charged particle, $p_T^{\text{lead}}$. The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty. Where not visible, the statistical error is smaller than the marker size.
FIG. 6. Mean values of the complement of transverse thrust, transverse thrust minor and transverse sphericity (top to bottom) using at least six charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ versus charged particle multiplicity of the event (left) and versus charged particle transverse momentum scalar sum of the event (right). The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty. Where not visible, the statistical error is smaller than the marker size.
TABLE IV. Mean, RMS and skewness for each event shape distribution is shown, in different intervals of $p_T^{lead}$. Combined statistical and systematic uncertainty is shown, where the systematic uncertainty is obtained from the difference of unfolded results using PYTHIA 6 and HERWIG++ MC predictions.

<table>
<thead>
<tr>
<th>$p_T^{lead}$ range</th>
<th>Mean</th>
<th>RMS</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 GeV $&lt; p_T^{lead} \leq$ 2.5 GeV</td>
<td>0.227 ± 0.002</td>
<td>0.064 ± 0.008</td>
<td>−0.54 ± 0.03</td>
</tr>
<tr>
<td>2.5 GeV $&lt; p_T^{lead} \leq$ 5.0 GeV</td>
<td>0.240 ± 0.006</td>
<td>0.062 ± 0.001</td>
<td>−0.68 ± 0.04</td>
</tr>
<tr>
<td>5.0 GeV $&lt; p_T^{lead} \leq$ 7.5 GeV</td>
<td>0.227 ± 0.007</td>
<td>0.065 ± 0.003</td>
<td>−0.55 ± 0.04</td>
</tr>
<tr>
<td>7.5 GeV $&lt; p_T^{lead} \leq$ 10 GeV</td>
<td>0.210 ± 0.010</td>
<td>0.068 ± 0.005</td>
<td>−0.36 ± 0.09</td>
</tr>
<tr>
<td>$p_T^{lead} &gt;$ 10 GeV</td>
<td>0.215 ± 0.011</td>
<td>0.070 ± 0.006</td>
<td>−0.11 ± 0.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$p_T^{lead}$ range</th>
<th>Mean</th>
<th>RMS</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 GeV $&lt; p_T^{lead} \leq$ 2.5 GeV</td>
<td>0.508 ± 0.002</td>
<td>0.090 ± 0.010</td>
<td>−0.70 ± 0.05</td>
</tr>
<tr>
<td>2.5 GeV $&lt; p_T^{lead} \leq$ 5.0 GeV</td>
<td>0.514 ± 0.005</td>
<td>0.087 ± 0.012</td>
<td>−0.89 ± 0.05</td>
</tr>
<tr>
<td>5.0 GeV $&lt; p_T^{lead} \leq$ 7.5 GeV</td>
<td>0.490 ± 0.006</td>
<td>0.099 ± 0.010</td>
<td>−0.76 ± 0.05</td>
</tr>
<tr>
<td>7.5 GeV $&lt; p_T^{lead} \leq$ 10 GeV</td>
<td>0.459 ± 0.007</td>
<td>0.107 ± 0.009</td>
<td>−0.54 ± 0.08</td>
</tr>
<tr>
<td>$p_T^{lead} &gt;$ 10 GeV</td>
<td>0.415 ± 0.010</td>
<td>0.117 ± 0.011</td>
<td>−0.28 ± 0.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$p_T^{lead}$ range</th>
<th>Mean</th>
<th>RMS</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 GeV $&lt; p_T^{lead} \leq$ 2.5 GeV</td>
<td>0.618 ± 0.005</td>
<td>0.190 ± 0.006</td>
<td>−0.35 ± 0.05</td>
</tr>
<tr>
<td>2.5 GeV $&lt; p_T^{lead} \leq$ 5.0 GeV</td>
<td>0.579 ± 0.013</td>
<td>0.204 ± 0.003</td>
<td>−0.28 ± 0.12</td>
</tr>
<tr>
<td>5.0 GeV $&lt; p_T^{lead} \leq$ 7.5 GeV</td>
<td>0.449 ± 0.019</td>
<td>0.206 ± 0.002</td>
<td>0.16 ± 0.24</td>
</tr>
<tr>
<td>7.5 GeV $&lt; p_T^{lead} \leq$ 10 GeV</td>
<td>0.337 ± 0.017</td>
<td>0.183 ± 0.004</td>
<td>0.57 ± 0.09</td>
</tr>
<tr>
<td>$p_T^{lead} &gt;$ 10 GeV</td>
<td>0.230 ± 0.024</td>
<td>0.157 ± 0.007</td>
<td>1.06 ± 0.04</td>
</tr>
</tbody>
</table>

XI. ACKNOWLEDGEMENTS

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNR F, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), CIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.


[hep-ph].


[26] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as η = −ln tan(θ/2).


High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

Department of Physics, University of Arizona, Tucson AZ, United States of America

Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America

Physics Department, University of Athens, Athens, Greece

Physics Department, National Technical University of Athens, Zografou, Greece

Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain

(a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

Department for Physics and Technology, University of Bergen, Bergen, Norway

Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

Department of Physics, Humboldt University, Berlin, Germany

Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

(a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dugos University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Department of Physics, Istanbul Technical University, Istanbul, Turkey

(a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy

Physikalisches Institut, University of Bonn, Bonn, Germany

Department of Physics, Boston University, Boston MA, United States of America

Department of Physics, Brandeis University, Waltham MA, United States of America

(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

(a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania

Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

Department of Physics, Carleton University, Ottawa ON, Canada

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong, China

Laboratoire de Physique Corpusculaire, Clermont Université et Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France

Nevis Laboratory, Columbia University, Irvington NY, United States of America

Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

(a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland

Physics Department, Southern Methodist University, Dallas TX, United States of America

Physics Department, University of Texas at Dallas, Richardson TX, United States of America

DESY, Hamburg and Zeuthen, Germany

Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany

Department of Physics, Duke University, Durham NC, United States of America

SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

INFN Laboratori Nazionali di Frascati, Frascati, Italy

(a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy

E. Andronikashvili Institute of Physics, Tbilisi, Georgia

Supranational Institute of Physics, Tbilisi, Georgia

Dipartimento di Fisica and Dipartimento di Fisica, Pontificia Universidad Católica de Chile, Santiago

II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

II Physikalisches Institut, Georg-August-Universität,
Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 Department of Physics, Indiana University, Bloomington IN, United States of America
61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
62 University of Iowa, Iowa City IA, United States of America
63 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
66 Graduate School of Science, Kobe University, Kobe, Japan
67 Faculty of Science, Kyoto University, Kyoto, Japan
68 Kyoto University of Education, Kyoto, Japan
69 Department of Physics, Kyushu University, Fukuoka, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Física Teorica C-15, Universidad Autónoma de Madrid, Madrid, Spain
81 Institut für Physik, Universität Mainz, Mainz, Germany
82 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
83 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
84 Department of Physics, University of Massachusetts, Amherst MA, United States of America
85 Department of Physics, McGill University, Montreal QC, Canada
86 School of Physics, University of Melbourne, Victoria, Australia
87 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
88 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
89 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
90 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
91 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
92 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
93 Group of Particle Physics, University of Montreal, Montreal QC, Canada
94 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
95 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
96 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
97 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
98 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
100 Nagasaki Institute of Applied Science, Nagasaki, Japan
101 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
102 (a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
103 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
104 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
106 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
107 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
108 Department of Physics, New York University, New York, USA
Oxford, United Kingdom
* ak Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
* al Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
* am Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
* Deceased
Measurement of charged-particle event shape variables in inclusive $\sqrt{s} = 7$ TeV proton–proton interactions with the ATLAS detector

The ATLAS Collaboration

Abstract

The measurement of charged-particle event shape variables is presented in inclusive inelastic $pp$ collisions at a center-of-mass energy of 7 TeV using the ATLAS detector at the LHC. The observables studied are the transverse thrust, thrust minor and transverse sphericity, each defined using the final-state charged particles' momentum components perpendicular to the beam direction. Events with at least six charged particles are selected by a minimum-bias trigger. In addition to the differential distributions, the evolution of each event shape variable as a function of the leading charged particle transverse momentum, charged particle multiplicity and summed transverse momentum is presented. Predictions from several Monte Carlo models show significant deviations from data.
Measurement of charged-particle event shape variables in inclusive $\sqrt{s} = 7$ TeV proton–proton interactions with the ATLAS detector

The ATLAS Collaboration

The measurement of charged-particle event shape variables is presented in inclusive inelastic $pp$ collisions at a center-of-mass energy of 7 TeV using the ATLAS detector at the LHC. The observables studied are the transverse thrust, thrust minor and transverse sphericity, each defined using the final-state charged particles’ momentum components perpendicular to the beam direction. Events with at least six charged particles are selected by a minimum-bias trigger. In addition to the differential distributions, the evolution of each event shape variable as a function of the leading charged particle transverse momentum, charged particle multiplicity and summed transverse momentum is presented. Predictions from several Monte Carlo models show significant deviations from data.

PACS numbers: 12.38.-t, 13.75.-n

I. INTRODUCTION

Event shape variables describe the structure of hadronic events and the properties of their energy flow. In this analysis, three event shape observables [1, 2] are measured: the transverse thrust, the thrust minor and the transverse sphericity, each built from the momenta of charged particles using tracking information from proton-proton collisions at $\sqrt{s} = 7$ TeV collected with the ATLAS detector [3]. Event shape observables are among the simplest experimentally measured quantities and, depending on the events being considered, may have sensitivity to both the perturbative and non-perturbative aspects of quantum chromodynamics (QCD).

Event shapes in hadronic collisions were investigated first at the ISR [4] and at the SppS [5, 6] at CERN to examine the emergence of jets, and later at Tevatron [7] to study the dependence of the event shape observables on the transverse energy of the leading jet and on contributions from the underlying event. At the Large Hadron Collider (LHC), event shape observables were recently studied in inclusive interactions [8] and multi-jet events [9, 10]. In $e^+ e^-$ and $ep$ deep-inelastic scattering experiments, the study of the energy flow in hadronic final states has allowed tests of the predictions of perturbative QCD, and the extraction of a precise value for the strong coupling constant $\alpha_s$ [11–17].

The study of event shape observables in inclusive inelastic collisions plays an important role in understanding soft-QCD processes at LHC center-of-mass energies [18], where “soft” refers to interactions with low momentum transfer between the scattering particles. Soft interactions cannot be reliably calculated from theory and are thus generally described by phenomenological models, usually implemented in Monte Carlo (MC) event generators. These models contain many parameters whose values are a priori unknown and thus need to be constrained by measurements. Inclusive and semi-inclusive observables sensitive to soft-QCD processes have been measured at the LHC by the ATLAS [19–21], CMS [22, 23] and ALICE [24, 25] collaborations. The measurements presented in this paper can further constrain the event generator models, which encapsulate our understanding of these soft processes.

In this analysis, the event shape observables are constructed from six or more primary charged particles in the pseudorapidity range $|\eta| < 2.5$ and with transverse momentum $p_T > 0.5$ GeV [26]. Primary charged particles are defined as those with a mean proper lifetime $\tau > 30$ ps, produced either directly in the $pp$ interaction or from the subsequent decay of particles with a shorter lifetime. The particle level refers to particles as they emerge from the proton–proton interaction. The detector level corresponds to tracks as measured after interaction with the detector material, and includes the detector response. The results are corrected for detector effects, using simulation, to obtain distributions of the event shape variables defined at particle level which can be directly compared to MC models.

This paper is organized as follows: Section II defines the event shape variables; the detector is described in Section III; Section IV discusses the MC models used in this analysis; Section V and VI respectively describe the event selections and background contributions. The correction of the data back to particle level, and estimation of the systematic uncertainties are described in Section VII and VIII; the results are discussed in Section IX and finally the conclusions are presented in Section X.

II. EVENT SHAPE OBSERVABLES

In particle collisions, event shape observables describe the geometric properties of the energy flow in the final state. A single event shape variable can distinguish in a continuous way between configurations in which all the particles are flowing (forward and backward) along a single axis and configurations where the energy is distributed uniformly over the $4\pi$ solid angle. If defined as a ratio of measured quantities, the corresponding systematic uncertainties may be small.

In hadron collisions, where the center-of-mass frame of the interaction is usually boosted along the beam axis, event shape observables are often defined in terms of the
transverse momenta, which are Lorentz-invariant under such boosts. Different formulations of event shape observables are possible; the most intuitive is to calculate the event shape from all particles in an event. These are denoted by directly global event shapes [1, 2]. In hadron collider experiments, it is not usually possible to detect all particles in an event due to the finite detector acceptance, limited at small scattering angles by the presence of the beam pipe. Event shapes which include only particles from a restricted phase space in pseudorapidity $\eta$, are called central event shapes: in this analysis charged particles within the range $|\eta| < 2.5$ are used. These central event shapes are nevertheless sensitive to non-perturbative effects at low momentum transfer and provide useful information about the event structure for development of models of proton–proton collisions. The thrust is one of the most widely used event shape variables. The transverse thrust for a given event is defined as:

$$T_\perp = \max_n \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}|}{\sum_i |\vec{p}_{T,i}|}$$  \hspace{1cm} (1)$$

where the sum is performed over the transverse momenta $\vec{p}_{T,i}$ of all charged particles in the event. The thrust axis $\hat{n}_T$ is the unit vector $\hat{n}$ that maximizes the ratio in Eq. (1). The transverse thrust ranges from $T_\perp = 1$ for a perfectly balanced, pencil-like, dijet topology to $T_\perp = 0$ for a circularly symmetric distribution of particles in the transverse plane, where $\psi$ is the azimuthal angle between the thrust axis and each respective particle. It is convenient to define the complement of $T_\perp$, $\tau_\perp = 1 - T_\perp$, to match the behavior of many event shape variables, which vanish in a balanced dijet topology.

The thrust axis $\hat{n}_T$ and the beam axis $\hat{z}$ define the event plane. The transverse thrust minor plane flow:

$$T_M = \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_m|}{\sum_i |\vec{p}_{T,i}|}, \quad \hat{n}_m = \hat{n}_T \times \hat{z}.$$  

The transverse thrust minor is 0 for a pencil-like event in azimuth and $2/\pi$ for an isotropic event.

Another widely used event shape variable is the sphericity, $S$, which describes the event energy flow based on the momentum tensor,

$$S^{\alpha \beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2},$$

where the Greek indices represent the $x$, $y$, and $z$ components of the momentum of the particle $i$. The sphericity of the event is defined in terms of the two smallest eigenvalues of this tensor, $\lambda_2$ and $\lambda_3$:

$$S = \frac{3}{2}(\lambda_2 + \lambda_3).$$

The sphericity has values between 0 and 1, where a balanced dijet event corresponds to $S = 0$ and an isotropic event to $S = 1$. Sphericity is essentially a measure of the summed $p_T^2$ with respect to the event axis [27, 28], where the event axis is defined as the line passing through the interaction point and oriented along the eigenaxis associated with the largest eigenvalue, $\lambda_1$. Similarly to transverse thrust, the transverse sphericity, $S_\perp$, is defined in terms of the transverse components only:

$$S^{xy}_\perp = \frac{1}{N_{ch}} \sum_{i \leq 5} \left( \frac{p_{T,i}^2}{|\vec{p}_{T,i}|^2} \cdot p_x i, p_y i \right)$$

and

$$S_\perp = \frac{2\lambda^{xy}_1}{\lambda^{xy}_1 + \lambda^{xy}_2},$$

where $\lambda^{xy}_1 < \lambda^{xy}_1$ are the two eigenvalues of $S^{xy}$.

The following distributions are measured:

- Normalized distributions: $(1/N_{ev})dN_{ev}/dT_M^{ch}$, $(1/N_{ev})dN_{ev}/d\tau^{ch}_M$, $(1/N_{ev})dN_{ev}/dS^{ch}$;
- Average values: $(\tau^{ch}_M)$, $(T^{ch}_M)$ and $(S^{ch})$ as functions of $N_{ch}$ and $\sum p_T$;

where $N_{ev}$ is the number of events with six or more charged particles within the selected kinematic range; $N_{ch}$ is the number of charged particles in an event; $\sum p_T$ is the scalar sum of the transverse momenta of the charged particles in the event. The event shape observables $\tau^{ch}_M$, $T^{ch}_M$ and $S^{ch}_\perp$ are defined as above, with the superscript indicating that they are constructed from charged particles. The three normalized differential distributions are studied separately for:

- $0.5 \text{ GeV} < p_T^{\text{lead}} \leq 2.5 \text{ GeV}$
- $2.5 \text{ GeV} < p_T^{\text{lead}} \leq 5.0 \text{ GeV}$
- $5.0 \text{ GeV} < p_T^{\text{lead}} \leq 7.5 \text{ GeV}$
- $7.5 \text{ GeV} < p_T^{\text{lead}} \leq 10.0 \text{ GeV}$
- $p_T^{\text{lead}} > 10 \text{ GeV}$

where $p_T^{\text{lead}}$ is the transverse momentum of the highest $p_T$ (leading) charged particle.

III. THE ATLAS DETECTOR

The ATLAS detector [3] covers almost the full solid angle around the collision point with layers of tracking
detectors, calorimeters and muon chambers. The components that are relevant for this analysis are the tracking detectors. The inner tracking detector has full coverage in azimuthal angle $\phi$ and covers the pseudorapidity range $|\eta| < 2.5$. It consists of a silicon pixel detector (pixel), a semiconductor tracker (SCT) and for $|\eta| < 2.0$, a straw-tube transition radiation tracker (TRT). These detectors, immersed in a 2 T axial magnetic field, are located at a radial distance from the beam line of 50.5–150 mm, 299–560 mm and 563–1066 mm, respectively. They provide position resolutions typically of 10 $\mu$m, 17 $\mu$m and 130 $\mu$m for the $r$–$\phi$ coordinate, and of 115 $\mu$m and 580 $\mu$m for the $z$ coordinate in the case of the pixel and SCT detectors.

The measurements presented here use events triggered by the minimum-bias trigger scintillator (MBTS) system [29]. The MBTS detectors are mounted at each end of the tracking detector at $z = \pm 3.56$ m and are segmented into eight sectors in azimuth and two concentric rings in pseudorapidity (2.09 < $|\eta|$ < 2.82 and 2.82 < $|\eta|$ < 3.84). The MBTS trigger was configured to require at least one hit above threshold from either side of the detector in coincidence with a fast beam-pickup device ensuring that the event is compatible with a bunch crossing.

IV. MONTE CARLO MODELS

Monte Carlo (MC) event samples are used to compute the detector acceptance and reconstruction efficiency, determine background contributions, correct the measurements for detector effects, and to calculate systematic uncertainties. Finally, different phenomenological models implemented in the MC generators are compared to the data corrected to the particle level.

The pythia 6 [30], pythia 8 [31] and Herwig ++ [32, 33] event generators were used to produce the simulated event samples for the analysis. These generators implement leading-logarithm parton shower models matched to leading-order matrix element calculations with different hadronization models and orderings for the parton shower. The pythia 6 and pythia 8 generators use a hadronization model based upon fragmentation of color strings and a $p_T$-ordered or virtuality-ordered shower, whereas the Herwig ++ generator implements a cluster hadronization scheme with parton showering ordered by emission angle. The pythia 8 generator uses a multi-parton interaction (MPI) model interleaved with both initial-state and final-state (ISR and FSR) radiation, and all three processes compete against each other for emission phase space in the resulting evolution. The Herwig ++ UE7-2 tune employs color reconnection. Different settings of model parameters, tuned to reproduce the existing experimental data were used for the MC generators. Table I shows the different MC models used in this paper.

The reference model for this analysis is chosen to be pythia6 AMBT1. Samples generated with this tune were passed through the ATLAS detector and trigger simulations [44] based on GEANT4 [45] and then reconstructed and analyzed using the same procedure and software that are used for the data. Reconstructed MC events are then used to correct the data for detector effects. The sample generated with an older version of Herwig ++, 2.5.0 with no additional tuning, was also passed through the full detector simulation and the analysis chain for systematic studies of unfolding corrections.

V. EVENT AND TRACK SELECTION

The data used for the analysis presented here were collected in April 2010 with a minimal prescale factor for the minimum-bias trigger. The only further requirement for selecting the data sample is that the MBTS trigger and all inner detector subsystems were at nominal operating conditions. In each event the reconstructed vertices are ordered by the $\sum p_T^2$ over the tracks assigned to each vertex, and the vertex with the highest $\sum p_T^2$ is taken as the primary interaction vertex of the event. To reduce the contribution from beam-related backgrounds and decays of long-lived particles, and to minimize the systematic uncertainties, events are rejected if they contain any other vertex reconstructed with four or more tracks.

If there is only one vertex in the event, or if any additional vertex in the event has three or fewer tracks, all tracks from the event that pass the track selection (described below) are retained. After this selection, the fraction of events with more than one proton–proton interaction in the same bunch crossing (referred to as pile-up) is found to be approximately 0.1% and this residual contribution is therefore neglected. The average number of $pp$ interactions per bunch crossing during this data-taking period was less than 0.15, indicating a negligible pile-up contribution. The MC samples used have no pile-up contribution.

Events are required to contain at least six tracks that fulfill the following criteria:

- $p_T > 0.5$ GeV;
- $|\eta| < 2.5$;
- a minimum of one pixel and six SCT hits;
- a hit in the innermost pixel layer, if the corresponding pixel module was active;
- transverse and longitudinal impact parameters with respect to the primary vertex, $|d_0| < 1.5$ mm and $|z_0|\sin\theta < 1.5$ mm;
- a track-fit probability $\chi^2 > 0.01$ for tracks with $p_T > 10$ GeV in order to remove mis-measured tracks.

Tracks with $p_T > 0.5$ GeV are less prone than lower-$p_T$ tracks to inefficiencies and systematic uncertainties resulting from interactions with the material inside the tracking volume.
TABLE I. Details of the MC models used. It is emphasized that the tunes use data from different experiments to constrain different processes, but for brevity only the data which had the most weight in each specific tune are shown. Here “LHC” indicates data taken at $\sqrt{s} = 7$ TeV, although $\sqrt{s} = 900$ GeV data were also included in ATLAS tunes, with much smaller weight. Some tunes are focused on describing the minimum-bias (MB) distributions better, while the rest are tuned to describe the underlying event (UE) distributions, as indicated. Authors indicates a tune performed by the MC developers.

<table>
<thead>
<tr>
<th>Generator</th>
<th>Version</th>
<th>Tune</th>
<th>PDF</th>
<th>Focus</th>
<th>Data</th>
<th>From</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA 6</td>
<td>6.425</td>
<td>AMBT1 [34]</td>
<td>MRST LO** [35]</td>
<td>MB</td>
<td>Early LHC</td>
<td>ATLAS</td>
</tr>
<tr>
<td>PYTHIA 6</td>
<td>6.421</td>
<td>DW [38]</td>
<td>CTEQ5L [39]</td>
<td>UE</td>
<td>Tevatron</td>
<td>CDF</td>
</tr>
<tr>
<td>PYTHIA 8</td>
<td>8.157</td>
<td>Z1 [40]</td>
<td>CTEQ5L</td>
<td>UE</td>
<td>LHC</td>
<td>CMS</td>
</tr>
<tr>
<td>HERWIG ++</td>
<td>2.5.1</td>
<td>UE7-2 [43]</td>
<td>MRST LO**</td>
<td>UE</td>
<td>LHC</td>
<td>Authors</td>
</tr>
<tr>
<td>HERWIG ++</td>
<td>2.5.0</td>
<td>Default</td>
<td>MRST LO**</td>
<td>UE</td>
<td>LHC</td>
<td>Authors</td>
</tr>
</tbody>
</table>

After event selection, the analysis is based on approximately 17 million events containing approximately 300 million tracks. For the PYTHIA 6 generator and for the PYTHIA 8 generator, which has a harder diffractive model than the former, the contribution to the event shape observables from diffractive events is negligible when requiring six or more tracks in the event.

The $p_T$ distributions of all tracks and of the leading track in the selected event are shown in Fig. 1. The fraction of events in each $p_T^{\text{lead}}$ bin is shown in Table II.

![FIG. 1. The distribution of the transverse momentum of all tracks and of the leading transverse momentum track in data at detector level. The uncertainties shown are statistical. Where not visible, the statistical error is smaller than the marker size.](image_url)

VI. BACKGROUND CONTRIBUTIONS

A. Backgrounds

Backgrounds comprise beam-induced events, due to beam-gas and beam-material interactions, as well as non-beam backgrounds from cosmic-ray interactions and detector noise. The contribution of these background events remaining after the event selection is estimated using the number of pixel hits not associated with reconstructed tracks. This multiplicity includes unassigned hits from low-$p_T$ looping tracks, but is dominated at higher multiplicities by hits from charged particles produced in inelastic interactions of protons with the residual gas inside the beam pipe. The vertex requirement removes most of the beam background events and the residual contribution is below 0.1%. As the level of background is very low, no explicit background subtraction is performed.

B. Secondary track fraction

The primary charged particle multiplicities are measured from selected tracks after correcting for the fractions of secondary and poorly reconstructed tracks in the sample. The potential background from fake tracks is found from MC studies to be less than 0.01% [19].

TABLE II. Percentage of events in each $p_T^{\text{lead}}$ bin

<table>
<thead>
<tr>
<th>$p_T^{\text{lead}}$ bin [GeV]</th>
<th>Percentage of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5–2.5</td>
<td>68.45</td>
</tr>
<tr>
<td>2.5–5.0</td>
<td>28.20</td>
</tr>
<tr>
<td>5.0–7.5</td>
<td>2.65</td>
</tr>
<tr>
<td>7.5–10.0</td>
<td>0.47</td>
</tr>
<tr>
<td>&gt; 10.0</td>
<td>0.23</td>
</tr>
</tbody>
</table>
Non-primary tracks arise predominantly from hadronic interactions, photon conversions to positron-electron pairs in the detector material and decays of long-lived particles. For $p_T > 0.5$ GeV the contribution from photon conversions is small. The systematic uncertainty from secondary decays is included in the uncertainties associated with the tracking performance.

VII. CORRECTION TO PARTICLE LEVEL

To facilitate comparison with theoretical predictions and other measurements, the event shape distributions for charged particles are presented at particle level, after correction for trigger and event selection efficiencies, as well as detector resolution effects. A two-step correction procedure is used: first, corrections for event selection efficiency are applied, followed by an additional bin-by-bin correction to account for tracking inefficiencies, possible bin migrations and any remaining detector effects.

A. Event-level correction

Trigger and vertexing efficiencies are taken from a previous analysis using the same data sample [19]. The efficiency of the MBTS trigger is determined from data using a control trigger and found to be fully efficient for the analysis requirement of at least six tracks. The vertex reconstruction efficiency is also measured in data by taking the ratio of the number of triggered events with a reconstructed vertex to the total number of triggered events. This ratio is also found to be very close to unity. The total correction applied to account for events lost due to the trigger and vertex requirements is less than 1% and it varies very weakly with the number of tracks associated with the primary vertex.

B. Bin-by-bin correction

The event shape observables presented here are sensitive to changes in the configuration of the selected tracks. Applying average track efficiencies to individual tracks on a track-by-track basis and reweighting tracks distorts the event shape distribution. A more robust approach is to apply bin-by-bin corrections to find the event shape distribution at particle level. Such a bin-by-bin correction is applied to all distributions after applying the event-level efficiency corrections described above.

The correction factors $C_{\text{bin}}$ are evaluated separately in each bin for each event shape observable,

$$C_{\text{bin}} = \frac{V_{\text{bin}}^{\text{Gen}}}{V_{\text{bin}}^{\text{Reco, eff corr}}}$$

where $V_{\text{bin}}^{\text{Gen}}$ and $V_{\text{bin}}^{\text{Reco, eff corr}}$ represent the generator-level MC value of the bin content and the reconstructed MC value after applying the event-level efficiency corrections for each bin, respectively. The corrected value of the bin content for an observable is found by multiplying the measured bin content by the corresponding correction factor. The bin sizes are chosen to be consistent with the resolution of the correction procedure.

The correction factors are calculated using the two different models implemented in PYTHIA 6 AMBT1 and HERWIG ++. This correction accounts for bin-by-bin migrations and tracking inefficiencies. For each distribution, the unfolding factor is typically within ±10% of unity for most of the range. It is very close to unity for the average values, except at the highest $\sum p_T$. The difference from unity becomes more pronounced at the statistically limited edges of the distributions. The correction factors for the inclusive distributions of the three event shape observables are shown in the bottom panels of Fig. 2 for the two MC event generators mentioned above. Although the two MC generators have different distributions, the bin-by-bin correction factors are similar.

VIII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties on the measured distributions are assessed with the following sources of uncertainty included:

Tracking: The largest of the systematic uncertainties for the tracking inefficiency [19] is found to be due to the material description in the inner detector. This is determined to produce a relative uncertainty of 2% in the efficiency in the barrel region, rising to ~7% for $2.3 < |\eta| < 2.5$. The contribution of the propagated uncertainty is found to be less than 1% of the content in each bin of the shape distributions.

Bin-by-bin correction model dependence: The remaining contributions to the overall systematic uncertainty result from the specific correction method used in this analysis. The bin-by-bin corrections in general depend on the number of charged particles and their $p_T$ distributions, so there is some dependence on the event generators. In order to estimate this uncertainty, it is necessary to compare different plausible event generators, which deviate significantly from each other, but still give predictions close to the data. The corrected results using the two very different PYTHIA 6 AMBT1 and HERWIG ++ models are compared. As these two generators use very different soft-QCD models the difference is assigned as a systematic uncertainty. The generated and reconstructed distributions are shown in Fig. 2 for the two MC event generators and compared with the detector-level data.

Statistical uncertainty of bin-by-bin correction:

In addition to the model-dependent uncertainty in the bin-by-bin correction, there is also a statistical
FIG. 2. The generated and reconstructed MC distributions of the complement of transverse thrust, the thrust minor and the transverse sphericity are shown in the top part of each plot for the lowest $p_T^{\text{lead}}$ range. The correction factors are shown in the lower parts for PYTHIA 6 AMBT1 and the HERWIG ++ default tune. The data are shown with only the efficiency corrections and statistical uncertainties. Where not visible, the statistical error is smaller than the marker size.

uncertainty due to the finite size of the MC sample. The statistical fluctuations of the PYTHIA6 AMBT1 correction factor are found to be negligible for most of each distribution, increasing to a few percent in the tails of the distributions. This is also added to the overall systematic uncertainty estimate.

The systematic uncertainty due to the small number of residual multiple proton–proton interactions is estimated to be negligible.

All the above mentioned systematic uncertainties are added in quadrature. Table III lists representative values for the various contributions to the systematic uncertainty in the content of each bin for all the event shape observables away from the edges of the distributions.

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger and vertex efficiency</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>0.1–0.5</td>
</tr>
<tr>
<td>Correction model difference</td>
<td>1–5</td>
</tr>
<tr>
<td>PYTHIA correction stat. uncertainty</td>
<td>0.1–2</td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td><strong>1–5</strong></td>
</tr>
</tbody>
</table>

IX. RESULTS AND DISCUSSION

The distributions of the complement of the transverse thrust, thrust minor and transverse sphericity are presented in Figs. 3–5, in different $p_T^{\text{lead}}$ ranges. The behavior of the average values of the shape variables as functions of the charged particle multiplicity, $N_{\text{ch}}$, and transverse momentum scalar sum, $\sum p_T$, is presented in Fig. 6. Predictions from the PYTHIA6 AMBT2B, PYTHIA 6 DW, PYTHIA 6 Z1, PYTHIA 8 A2 and HERWIG ++ UE7-2 models are also shown. AMBT2B is chosen instead of AMBT1, which was used to correct the data back to the particle level because it shows a slight improvement in reproducing the distributions of charged particle transverse momentum and multiplicity [36].

The distributions shown in Figs. 3–5 indicate a prevalence of spherical events in the lower $p_T^{\text{lead}}$ ranges. A slight shift toward less spherical events and a broadening of the distributions is observed for events starting with $p_T^{\text{lead}} > 7.5$ GeV in Fig. 3(d) for $T_M^{\perp}$ and in Fig. 4(d) for $T_M^{\perp}$. For both variables, a transition to less spherical events is seen for $p_T^{\text{lead}} > 10$ GeV in Fig. 3(e) and in Fig. 4(e). The distribution of transverse sphericity is more sensitive to the increase of $p_T^{\text{lead}}$, and shows a marked shift toward less spherical events starting at $p_T^{\text{lead}} > 5.0$ GeV in Fig. 5(e). The average value of the distributions, the RMS width and the skewness of the distributions are given in Table IV, which supports this
observation. Mean values of the complement of transverse thrust and the transverse thrust minor are observed to initially rise with increasing $p_T^{\text{lead}}$, with their maximum value in the range $2.5 < p_T^{\text{lead}} < 5$ GeV, before decreasing. A similar trend is observed by the ALICE Collaboration, which has measured the transverse sphericity distribution selecting charged particles with $|\eta| < 0.8$, in inelastic 7 TeV $pp$ collisions [8].

Overall, the PYTHIA 6 tune Z1, tuned to the underlying event distributions at the LHC, agrees the best with most of the distributions. The PYTHIA 6 DW tune predictions are consistently furthest from the data, as seen in the $r_T^\perp$, and $T_M$ distributions. This is not unexpected as DW is tuned to reproduce the Tevatron data and does not agree with the charged particle multiplicity and $p_T$ distributions in LHC data [19]. However it performs similarly to other models/tunes for the $S_{ch}^\perp$ distribution in intermediate to high $p_T^{\text{lead}}$ values, as is seen in Fig. 5(c)–Fig. 5(e). The AMBT2B tune, which is based on minimum-bias LHC data, shows better agreement for the lowest $p_T^{\text{lead}}$ distributions than for the intermediate $p_T^{\text{lead}}$ distributions, as is seen in Fig. 3(a) and in Fig. 4(a). Compared to the PYTHIA 6 AMBT2B tune, the predictions of the PYTHIA 8 A2 and HERWIG ++ UE7-2 tunes show better agreement with the data in the intermediate to high $p_T^{\text{lead}}$ ranges. The UE7-2 tune, based like Z1 on LHC underlying event data, is expected to perform better in events characterized by a hard scatter, resulting in higher $p_T^{\text{lead}}$ values. However, the minimum-bias A2 tune shows a similar or slightly better level of agreement with data for the high $p_T^{\text{lead}}$ distributions, possibly indicating that the improved MPI modeling compared to PYTHIA 6 tunes does play a role. All models tend to better reproduce the data selected with the higher $p_T^{\text{lead}}$ ranges.

The mean values of event shape observables as functions of $N_{ch}$ and $\sum p_T$ are shown in Fig. 6. They are seen to increase with $N_{ch}$, but the increase is less marked at values of $N_{ch}$ above about 30. For low values of $N_{ch}$, the mean values of the event shape variables correspond to less spherical events, while the average values for large multiplicity is largely consistent with the positions of the maxima of the corresponding distributions for the lowest $p_T^{\text{lead}}$ range. A similar trend is seen for distributions as a function of $\sum p_T$; however, for $\sum p_T$ over 100 GeV, the mean starts to decrease again, indicating the events are more dijet-like. In general, the MC models predict fewer high-sphericity events than are seen in the data. With the exception of PYTHIA 6 DW, the MC models seem to predict the behavior with multiplicity reasonably well in Fig. 6. However, the MC predictions are seen to differ in shape at very high $\sum p_T$, where the decrease of mean values happens in the MC predictions before the data.

The behavior of mean transverse sphericity as a function of multiplicity measured by the ALICE Collaboration [8] exhibits a similar behavior to that observed here, with the data lying at values higher than predicted by the MC models.

X. CONCLUSIONS

The event shape observables, transverse thrust, transverse thrust minor, and transverse sphericity, have been measured in inelastic proton–proton collisions at $\sqrt{s} = 7$ TeV requiring at least six charged particles per event selected by a minimum-bias trigger. The distributions and mean values have been compared to predictions of different MC models tuned to inclusive particle distributions and underlying event data. The dependence of the event shapes on the number of charged particles, on the sum of charged particle $p_T$ and on the leading charged particle $p_T$ has been studied.

The distributions of all three event shape variables show an evolution toward less spherical events as $p_T^{\text{lead}}$ increases, but the effect is smaller for transverse thrust and thrust minor compared to transverse sphericity. The dependence of the event shape mean values as functions of $N_{ch}$ and $\sum p_T$ is similar, due to the correlation between the two variables [19]. For each variable, the evolution toward a more spherical event shape with increasing multiplicity is rapid initially and slows at higher multiplicities. All tested MC generators underestimate the fraction of events of spherical character and none reproduces accurately the event shape distributions. The MC tunes based on the properties of the underlying event show in general better agreement with the data than those based on the inclusive distributions measured in minimum-bias events. The PYTHIA 6 MC generator with the Z1 tune provides the most accurate description of the observed distributions presented in this analysis, but the level of agreement is still not satisfactory over the whole range of the data. These measurements provide information complementary to inclusive particle distributions and thus they are useful for improving the MC description of inelastic proton–proton collisions at the LHC.
FIG. 3. Normalized distributions of the complement of transverse thrust using at least six charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ for different requirements on the transverse momentum of the leading charged particle, $p_T^{lead}$. The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty. Where not visible, the statistical error is smaller than the marker size.
FIG. 4. Normalized distributions of transverse thrust minor using at least six charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ for different requirements on the transverse momentum of the leading charged particle, $p_T^{\text{lead}}$. The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty. Where not visible, the statistical error is smaller than the marker size.
FIG. 5. Normalized distributions of transverse sphericity using at least six charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ for different requirements on the transverse momentum of the leading charged particle, $p_T^{\text{lead}}$. The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty. Where not visible, the statistical error is smaller than the marker size.
FIG. 6. Mean values of the complement of transverse thrust, transverse thrust minor and transverse sphericity (top to bottom) using at least six charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ versus charged particle multiplicity of the event (left) and versus charged particle transverse momentum scalar sum of the event (right). The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty. Where not visible, the statistical error is smaller than the marker size.
TABLE IV. Mean, RMS and skewness for each event shape distribution is shown, in different intervals of $p_T^{\text{lead}}$. Combined statistical and systematic uncertainty is shown, where the systematic uncertainty is obtained from the difference of unfolded results using Pythia 6 and Herwig++ MC predictions.

<table>
<thead>
<tr>
<th>$p_T^{\text{lead}}$ range</th>
<th>Mean</th>
<th>RMS</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 GeV &lt; $p_T^{\text{lead}}$ ≤ 2.5 GeV</td>
<td>0.227 ± 0.002</td>
<td>0.064 ± 0.008</td>
<td>–0.54 ± 0.03</td>
</tr>
<tr>
<td>2.5 GeV &lt; $p_T^{\text{lead}}$ ≤ 5.0 GeV</td>
<td>0.240 ± 0.006</td>
<td>0.062 ± 0.001</td>
<td>–0.68 ± 0.04</td>
</tr>
<tr>
<td>5.0 GeV &lt; $p_T^{\text{lead}}$ ≤ 7.5 GeV</td>
<td>0.227 ± 0.007</td>
<td>0.065 ± 0.003</td>
<td>–0.55 ± 0.04</td>
</tr>
<tr>
<td>7.5 GeV &lt; $p_T^{\text{lead}}$ ≤ 10 GeV</td>
<td>0.210 ± 0.010</td>
<td>0.068 ± 0.005</td>
<td>–0.36 ± 0.09</td>
</tr>
<tr>
<td>$p_T^{\text{lead}}$ &gt; 10 GeV</td>
<td>0.185 ± 0.011</td>
<td>0.070 ± 0.006</td>
<td>–0.11 ± 0.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$p_T^{\text{lead}}$ range</th>
<th>Mean</th>
<th>RMS</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 GeV &lt; $p_T^{\text{lead}}$ ≤ 2.5 GeV</td>
<td>0.508 ± 0.002</td>
<td>0.090 ± 0.010</td>
<td>–0.70 ± 0.05</td>
</tr>
<tr>
<td>2.5 GeV &lt; $p_T^{\text{lead}}$ ≤ 5.0 GeV</td>
<td>0.514 ± 0.005</td>
<td>0.087 ± 0.012</td>
<td>–0.89 ± 0.05</td>
</tr>
<tr>
<td>5.0 GeV &lt; $p_T^{\text{lead}}$ ≤ 7.5 GeV</td>
<td>0.490 ± 0.006</td>
<td>0.099 ± 0.010</td>
<td>–0.76 ± 0.05</td>
</tr>
<tr>
<td>7.5 GeV &lt; $p_T^{\text{lead}}$ ≤ 10 GeV</td>
<td>0.459 ± 0.007</td>
<td>0.107 ± 0.009</td>
<td>–0.54 ± 0.08</td>
</tr>
<tr>
<td>$p_T^{\text{lead}}$ &gt; 10 GeV</td>
<td>0.415 ± 0.010</td>
<td>0.117 ± 0.011</td>
<td>–0.28 ± 0.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$p_T^{\text{lead}}$ range</th>
<th>Mean</th>
<th>RMS</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 GeV &lt; $p_T^{\text{lead}}$ ≤ 2.5 GeV</td>
<td>0.618 ± 0.005</td>
<td>0.190 ± 0.006</td>
<td>–0.35 ± 0.05</td>
</tr>
<tr>
<td>2.5 GeV &lt; $p_T^{\text{lead}}$ ≤ 5.0 GeV</td>
<td>0.579 ± 0.013</td>
<td>0.204 ± 0.003</td>
<td>–0.28 ± 0.12</td>
</tr>
<tr>
<td>5.0 GeV &lt; $p_T^{\text{lead}}$ ≤ 7.5 GeV</td>
<td>0.449 ± 0.019</td>
<td>0.206 ± 0.002</td>
<td>0.16 ± 0.24</td>
</tr>
<tr>
<td>7.5 GeV &lt; $p_T^{\text{lead}}$ ≤ 10 GeV</td>
<td>0.337 ± 0.017</td>
<td>0.183 ± 0.004</td>
<td>0.57 ± 0.09</td>
</tr>
<tr>
<td>$p_T^{\text{lead}}$ &gt; 10 GeV</td>
<td>0.230 ± 0.024</td>
<td>0.157 ± 0.007</td>
<td>1.06 ± 0.04</td>
</tr>
</tbody>
</table>

XI. ACKNOWLEDGEMENTS

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and Fapesp, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DLR, DMSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; INFN, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MZVT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.


ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as η = − ln tan(θ/2).


http://cdsweb.cern.ch/record/1363300.


The ATLAS Collaboration

<table>
<thead>
<tr>
<th>Institution</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Energy Physics Division, Argonne National Laboratory, Argonne IL</td>
<td>United States of America</td>
</tr>
<tr>
<td>Department of Physics, University of Arizona, Tucson AZ</td>
<td>United States of America</td>
</tr>
<tr>
<td>Department of Physics, The University of Texas at Arlington, Arlington TX</td>
<td>United States of America</td>
</tr>
<tr>
<td>Physics Department, University of Athens, Athens, Greece</td>
<td></td>
</tr>
<tr>
<td>Physics Department, National Technical University of Athens, Zografou,</td>
<td>Greece</td>
</tr>
<tr>
<td>Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan</td>
<td></td>
</tr>
<tr>
<td>Institut de Física d’Altes Energies and Departament de Física de la</td>
<td>Barcelona and ICREA, Barcelona, Spain</td>
</tr>
<tr>
<td>Universitat Autònoma de Barcelona and</td>
<td></td>
</tr>
<tr>
<td>(a) Institute of Physics, University of Belgrade, Belgrade;</td>
<td></td>
</tr>
<tr>
<td>(b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade,</td>
<td>Serbia</td>
</tr>
<tr>
<td>Department for Physics and Technology, University of Bergen, Bergen,</td>
<td>Norway</td>
</tr>
<tr>
<td>Physics Division, Lawrence Berkeley National Laboratory and University</td>
<td>California, Berkeley, CA, United States of America</td>
</tr>
<tr>
<td>Department of Physics, Humboldt University, Berlin, Germany</td>
<td></td>
</tr>
<tr>
<td>Albert Einstein Center for Fundamental Physics and Laboratory for High</td>
<td>Bern, Switzerland</td>
</tr>
<tr>
<td>Energy Physics, University of Bern, Bern, Switzerland</td>
<td></td>
</tr>
<tr>
<td>School of Physics and Astronomy, University of Birmingham, Birmingham,</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>(a) Department of Physics, Bogazici University, Istanbul;</td>
<td></td>
</tr>
<tr>
<td>(b) Division of Physics, Dogus University, Istanbul;</td>
<td></td>
</tr>
<tr>
<td>(c) Department of Physics Engineering, Gaziantep University, Gaziantep;</td>
<td></td>
</tr>
<tr>
<td>(d) Department of Physics, Istanbul Technical University, Istanbul,</td>
<td>Turkey</td>
</tr>
<tr>
<td>INFN Sezione di Bologna;</td>
<td></td>
</tr>
<tr>
<td>Dipartimento di Fisica, Università di Bologna, Bologna, Italy</td>
<td></td>
</tr>
<tr>
<td>Physikalisches Institut, University of Bonn, Bonn, Germany</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, Boston University, Boston MA, United States of</td>
<td>America</td>
</tr>
<tr>
<td>Department of Physics, Brandeis University, Waltham MA, United States of</td>
<td>America</td>
</tr>
<tr>
<td>(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;</td>
<td></td>
</tr>
<tr>
<td>(b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal</td>
<td></td>
</tr>
<tr>
<td>University of Sao Joao del Rei (UFSJ), Sao Joao del Rei;</td>
<td></td>
</tr>
<tr>
<td>Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil</td>
<td></td>
</tr>
<tr>
<td>Physics Department, Brookhaven National Laboratory, Upton NY, United</td>
<td>State of America</td>
</tr>
<tr>
<td>(a) National Institute of Physics and Nuclear Engineering, Bucharest;</td>
<td></td>
</tr>
<tr>
<td>(b) University Politehnica Bucharest, Bucharest; (c) West University in</td>
<td></td>
</tr>
<tr>
<td>Timisoara, Romania</td>
<td></td>
</tr>
<tr>
<td>Departamento de Física, Universidad de Buenos Aires, Buenos Aires,</td>
<td>Argentina</td>
</tr>
<tr>
<td>Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, Carleton University, Ottawa ON, Canada</td>
<td></td>
</tr>
<tr>
<td>CERN, Geneva, Switzerland</td>
<td></td>
</tr>
<tr>
<td>Enrico Fermi Institute, University of Chicago, Chicago IL, United States</td>
<td></td>
</tr>
<tr>
<td>(a) Departamento de Física, Pontificia Universidad Católica de Chile,</td>
<td>Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa</td>
</tr>
<tr>
<td>(a) (b) Institute of High Energy Physics, Chinese Academy of Sciences,</td>
<td>China; (b) Department of Modern Physics, University of Science and</td>
</tr>
<tr>
<td>(c) Department of Physics, Nanjing University, Jiangsu; (d) School of</td>
<td>Technology of China, Anhui;</td>
</tr>
<tr>
<td>(c) Physics, Shandong University, Shandong, China</td>
<td></td>
</tr>
<tr>
<td>Laboratoire de Physique Corpusculaire, Clermont Université et</td>
<td></td>
</tr>
<tr>
<td>Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France</td>
<td></td>
</tr>
<tr>
<td>Nevis Laboratory, Columbia University, Irvington NY, United States of</td>
<td>America</td>
</tr>
<tr>
<td>Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark</td>
<td></td>
</tr>
<tr>
<td>(a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica,</td>
<td></td>
</tr>
<tr>
<td>Università della Calabria, Arcavata di Rende, Italy</td>
<td></td>
</tr>
<tr>
<td>AGH University of Science and Technology, Faculty of Physics and Applied</td>
<td>Krakow, Poland</td>
</tr>
<tr>
<td>(a) The Henryk Niewodniczanski Institute of Nuclear Physics, Polish</td>
<td></td>
</tr>
<tr>
<td>Physics, Krakow, Poland</td>
<td></td>
</tr>
<tr>
<td>Physics Department, Southern Methodist University, Dallas TX, United</td>
<td>States of America</td>
</tr>
<tr>
<td>DESY, Hamburg and Zeuthen, Germany</td>
<td></td>
</tr>
<tr>
<td>Institut für Experimentelle Physik IV, Technische Universität Dortmund,</td>
<td>Germany</td>
</tr>
<tr>
<td>Institut für Kern- und Teilchenphysik, Technical University Dresden,</td>
<td></td>
</tr>
<tr>
<td>Section de Physique, Université de Genève, Geneva, Switzerland</td>
<td></td>
</tr>
<tr>
<td>(a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di</td>
<td></td>
</tr>
<tr>
<td>Genova, Genova, Italy</td>
<td></td>
</tr>
<tr>
<td>SUPA - School of Physics and Astronomy, University of Edinburgh,</td>
<td></td>
</tr>
<tr>
<td>INFN Laboratori Nazionali di Frascati, Frascati, Italy</td>
<td></td>
</tr>
<tr>
<td>Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg,</td>
<td>Germany</td>
</tr>
<tr>
<td>Section de Physique, Université de Genève, Geneva, Switzerland</td>
<td></td>
</tr>
<tr>
<td>(a) E. Andronikashvili Institute of Physics, Tbilisi State University,</td>
<td></td>
</tr>
<tr>
<td>High Energy Physics Institute, Tbilisi State University, Tbilisi; (b)</td>
<td></td>
</tr>
<tr>
<td>II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen,</td>
<td>Germany</td>
</tr>
<tr>
<td>SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow,</td>
<td></td>
</tr>
<tr>
<td>(a) II Physikalisches Institut, Georg-August-Universität,</td>
<td></td>
</tr>
</tbody>
</table>
Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
58 (a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 Department of Physics, Indiana University, Bloomington IN, United States of America
61 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
62 University of Iowa, Iowa City IA, United States of America
63 Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
64 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
65 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
66 Graduate School of Science, Kobe University, Kobe, Japan
67 Faculty of Science, Kyoto University, Kyoto, Japan
68 Kyoto University of Education, Kyoto, Japan
69 Department of Physics, Kyushu University, Fukuoka, Japan
70 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
71 Physics Department, Lancaster University, Lancaster, United Kingdom
72 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
73 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
74 Department of Physics, Józef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
75 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
76 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
77 Department of Physics and Astronomy, University College London, London, United Kingdom
78 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
81 Institut für Physik, Universität Mainz, Mainz, Germany
82 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
83 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
84 Department of Physics, University of Massachusetts, Amherst MA, United States of America
85 Department of Physics, McGill University, Montreal QC, Canada
86 School of Physics, University of Melbourne, Victoria, Australia
87 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
88 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
89 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
90 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
91 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
92 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
93 Group of Particle Physics, University of Montreal, Montreal QC, Canada
94 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
95 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
96 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
97 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
98 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
99 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
100 Nagasaki Institute of Applied Science, Nagasaki, Japan
101 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
102 (a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
103 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
104 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
105 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
106 Department of Physics, Northern Illinois University, DeKalb IL, United States of America
107 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
108 Department of Physics, New York University, New
York NY, United States of America
109 Ohio State University, Columbus OH, United States of America
110 Faculty of Science, Okayama University, Okayama, Japan
111 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
112 Department of Physics, Oklahoma State University, Stillwater OK, United States of America
113 Palacky University, RCPTM, Olomouc, Czech Republic
114 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
115 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
116 Graduate School of Science, Osaka University, Osaka, Japan
117 Department of Physics, University of Oslo, Oslo, Norway
118 Department of Physics, Oxford University, Oxford, United Kingdom
119 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
120 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
121 Petersburg Nuclear Physics Institute, Gatchina, Russia
122 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
123 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
124 (a) Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; (b) Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
125 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
126 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
127 Czech Technical University in Prague, Praha, Czech Republic
128 State Research Center Institute for High Energy Physics, Protvino, Russia
129 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
130 Physics Department, University of Regina, Regina SK, Canada
131 Ritsumeikan University, Kusatsu, Shiga, Japan
132 (a) INFN Sezione di Roma I; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
133 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
134 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
135 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l‘Energie des Sciences Techniques Nucléaires, Rabat; (c) Faculté des Sciences Semalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
138 Department of Physics, University of Washington, Seattle WA, United States of America
139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
140 Department of Physics, Shinshu University, Nagano, Japan
141 Fachbereich Physik, Universität Siegen, Siegen, Germany
142 Department of Physics, Simon Fraser University, Burnaby BC, Canada
143 SLAC National Accelerator Laboratory, Stanford CA, United States of America
144 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
145 (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
150 School of Physics, University of Sydney, Sydney, Australia
151 Institute of Physics, Academia Sinica, Taipei, Taiwan
152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
<table>
<thead>
<tr>
<th>Institution</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Department of Physics, University of Toronto, Canada</td>
<td>Canada</td>
</tr>
<tr>
<td>TRIUMF, Vancouver BC; Department of Physics and Astronomy, York University</td>
<td>Canada</td>
</tr>
<tr>
<td>Toronto ON, Canada</td>
<td></td>
</tr>
<tr>
<td>Institute of Pure and Applied Sciences, University of Tsukuba</td>
<td>Japan</td>
</tr>
<tr>
<td>1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan</td>
<td></td>
</tr>
<tr>
<td>Science and Technology Center, Tufts University, Medford MA</td>
<td>United States</td>
</tr>
<tr>
<td>Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia</td>
<td>Colombia</td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University of California Irvine</td>
<td>United States</td>
</tr>
<tr>
<td>Irvine, Irvine CA, United States of America</td>
<td></td>
</tr>
<tr>
<td>INFN Gruppo Collegato di Udine; ICTP, Trieste; Dipartimento di Chimica,</td>
<td>Italy</td>
</tr>
<tr>
<td>Fisica e Ambiente, Università di Udine, Udine, Italy</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, University of Illinois, Urbana</td>
<td>United States</td>
</tr>
<tr>
<td>Columbia, Vancouver BC, Canada</td>
<td></td>
</tr>
<tr>
<td>Department of Physics and Astronomy, University of Victoria</td>
<td>United States</td>
</tr>
<tr>
<td>Victoria BC, Canada</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, University of Warwick, Coventry, United Kingdom</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>Waseda University, Tokyo, Japan</td>
<td></td>
</tr>
<tr>
<td>Department of Particle Physics, The Weizmann Institute of Science, Rehovot</td>
<td>Israel</td>
</tr>
<tr>
<td>Department of Physics, University of Wisconsin, Madison WI</td>
<td>United States</td>
</tr>
<tr>
<td>Julius-Maximilians-Universität, Würzburg, Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany</td>
<td></td>
</tr>
<tr>
<td>Department of Physics, Yale University, New Haven CT, United States of</td>
<td>United States</td>
</tr>
<tr>
<td>America</td>
<td></td>
</tr>
<tr>
<td>Yerevan Physics Institute, Yerevan, Armenia</td>
<td>Armenia</td>
</tr>
<tr>
<td>Université Paris-Sud and CNRS/IN2P3, Orsay, France</td>
<td>France</td>
</tr>
<tr>
<td>CEA Saclay (Commissariat à l’Energie Atomique), Gif-sur-Yvette, France</td>
<td></td>
</tr>
<tr>
<td>Experimental de Particulas - LIP, Lisbon, Portugal</td>
<td>Portugal</td>
</tr>
<tr>
<td>Also at Laboratory de Instrumentacao e Fisica</td>
<td></td>
</tr>
<tr>
<td>CNRS/IN2P3, Villeurbanne Cedex, France</td>
<td></td>
</tr>
<tr>
<td>Also at Faculdade de Ciencias and CNFNL, Universidade de Lisboa, Lisbon</td>
<td>Portugal</td>
</tr>
<tr>
<td>Also at Particle Physics Department, Rutherford Appleton Laboratory,</td>
<td></td>
</tr>
<tr>
<td>Didcot, United Kingdom</td>
<td></td>
</tr>
<tr>
<td>Also at TRIUMF, Vancouver BC, Canada</td>
<td></td>
</tr>
<tr>
<td>Also at Department of Physics, California State University, Fresno CA</td>
<td>United States</td>
</tr>
<tr>
<td>United States of America</td>
<td></td>
</tr>
<tr>
<td>Also at Novosibirsk State University, Novosibirsk, Russia</td>
<td>Russia</td>
</tr>
<tr>
<td>Also at Fermilab, Batavia IL, United States of America</td>
<td></td>
</tr>
<tr>
<td>Also at Department of Physics, University of Coimbra, Coimbra, Portugal</td>
<td>Portugal</td>
</tr>
<tr>
<td>Also at Department of Physics, UASLP, San Luis Potosi, Mexico</td>
<td></td>
</tr>
<tr>
<td>Also at Università di Napoli Parthenope, Napoli, Italy</td>
<td>Italy</td>
</tr>
<tr>
<td>Also at Institute of Particle Physics (IPP), Canada</td>
<td>Canada</td>
</tr>
<tr>
<td>Also at Department of Physics, Middle East Technical University, Ankara,</td>
<td>Turkey</td>
</tr>
<tr>
<td>Turkey</td>
<td></td>
</tr>
<tr>
<td>Also at Louisiana Tech University, Ruston LA, United States of America</td>
<td></td>
</tr>
<tr>
<td>Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia,</td>
<td>Portugal</td>
</tr>
<tr>
<td>Universidade Nova de Lisboa, Caparica, Portugal</td>
<td></td>
</tr>
<tr>
<td>Also at Department of Physics and Astronomy, University College London,</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>London, London, United Kingdom</td>
<td></td>
</tr>
<tr>
<td>Also at Group of Particle Physics, University of Montreal, Montreal QC,</td>
<td>Canada</td>
</tr>
<tr>
<td>Also at Department of Physics, University of Cape Town, Cape Town, South</td>
<td>United States</td>
</tr>
<tr>
<td>Also at Institute of Physics, Azerbijan Academy of Sciences, Baku,</td>
<td>Armenia</td>
</tr>
<tr>
<td>Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg,</td>
<td>Germany</td>
</tr>
<tr>
<td>Also at Manhattan College, New York NY, United States of America</td>
<td>United States</td>
</tr>
<tr>
<td>Also at School of Physics, Shandong University, Shandong, China</td>
<td>China</td>
</tr>
<tr>
<td>Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France</td>
<td>France</td>
</tr>
<tr>
<td>Also at School of Physics and Engineering, Sun Yat-sen University,</td>
<td>China</td>
</tr>
<tr>
<td>Guangzhou, China</td>
<td></td>
</tr>
<tr>
<td>Also at Academia Sinica Grid Computing, Institute of Physics, Academia</td>
<td>Taiwan</td>
</tr>
<tr>
<td>Sinica, Taipei, Taiwan</td>
<td></td>
</tr>
<tr>
<td>Also at Dipartimento di Fisica, Universitá La Sapienza, Roma, Italy</td>
<td></td>
</tr>
<tr>
<td>Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de</td>
<td>France</td>
</tr>
<tr>
<td>l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France</td>
<td></td>
</tr>
<tr>
<td>Also at Section de Physique, Université de Genève, Geneva, Switzerland</td>
<td></td>
</tr>
<tr>
<td>Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal</td>
<td></td>
</tr>
<tr>
<td>Also at Department of Physics and Astronomy, University of South</td>
<td>United States</td>
</tr>
<tr>
<td>Carolina, Columbia SC, United States of America</td>
<td></td>
</tr>
<tr>
<td>Also at Institute for Particle and Nuclear Physics, Wigner Research</td>
<td>Hungary</td>
</tr>
<tr>
<td>Centre for Physics, Budapest, Hungary</td>
<td></td>
</tr>
<tr>
<td>Also at California Institute of Technology, Pasadena CA, United States</td>
<td></td>
</tr>
<tr>
<td>Also at Institute of Physics, Jagiellonian University, Krakow, Poland</td>
<td></td>
</tr>
<tr>
<td>Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France</td>
<td></td>
</tr>
<tr>
<td>Also at Nevis Laboratory, Columbia University, Irvington NY, United</td>
<td>United States</td>
</tr>
<tr>
<td>States of America</td>
<td></td>
</tr>
<tr>
<td>Also at Department of Physics and Astronomy, University of Sheffield,</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>Sheffield, United Kingdom</td>
<td></td>
</tr>
<tr>
<td>Also at Department of Physics, Oxford University,</td>
<td></td>
</tr>
</tbody>
</table>
Oxford, United Kingdom

\textsuperscript{ak} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

\textsuperscript{al} Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

\textsuperscript{am} Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa

* Deceased