ATLAS measurements of the properties of jets for boosted particle searches

The ATLAS Collaboration

Abstract

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I. INTRODUCTION

The high center-of-mass energy at the Large Hadron Collider (LHC) combined with the coverage and granularity of the ATLAS calorimeter provide an excellent environment to study hadronic jets. Measurements of dijet cross sections [1, 2], jet shapes [3, 4], jet substructure [5] and angular correlations [6, 7] have already been published using the data taken by the ATLAS and CMS Collaborations in 2010.

Massive, hadronically decaying particles produced with a significant boost (such as top quarks, Higgs bosons, or new particles) will tend to have collimated decays, such that their decay products are contained within a single jet. The substructure of jets resulting from such decays is expected to result in deviations in the observables measured here for light-quarks and gluons, thus providing discriminating power in heavy particle searches.

The observable jet properties presented here are mass, width, eccentricity, planar flow and angularity. All of these have been shown to be useful in Monte Carlo studies in the search for high transverse momentum ($p_T$) jets. This additional energy deposition can be characterized by the number of reconstructed primary vertices ($N_{PV}$) [15, 16], with events having a single good vertex ($N_{PV} = 1$) being considered free from the effects of pileup. The 2010 ATLAS data set provides a unique opportunity to study these effects; a significant fraction of the 2010 data set comprises $N_{PV} = 1$ events, making this data set ideal for evaluating the effects of pileup on jet substructure measurements. This data set has an average $N_{PV} \simeq 2.2$.

II. THE ATLAS DETECTOR

The ATLAS detector [17] at the LHC was designed to study a wide range of physics. It covers almost the entire solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. Tracks and vertices are reconstructed with the inner detector, which consists of a silicon pixel detector, a silicon strip detector and a transition radiation tracker, all immersed in a 2 T axial magnetic field provided by a superconducting solenoid.

The ATLAS reference system is a Cartesian right-handed co-ordinate system, with the nominal collision point at the origin. The anti-clockwise beam direction defines the positive $z$-axis, while the positive $x$-axis is defined as pointing from the collision point to the center of the LHC ring and the positive $y$-axis upwards. The azimuthal angle $\phi$ is measured around the beam axis, and the polar angle $\theta$ is the angle measured with respect to the $z$-axis. The pseudorapidity is given by $\eta = -\ln \tan(\theta/2)$. Transverse momentum is defined relative to the beam axis.

For the measurements presented here, the high-granularity calorimeter systems are of particular importance. The ATLAS calorimeter system provides fine-grained measurements of shower energy depositions over a large range in $\eta$.

Electromagnetic calorimetry in the range $|\eta| < 4.9$ is
provided by liquid-argon (LAr) sampling calorimeters. This calorimeter system enables measurements of the shower energy in up to four depth segments. For the jets measured here, the transverse granularity ranges from 0.003 × 0.10 to 0.10 × 0.10 in ∆η × ∆φ, depending on depth segment and pseudorapidity.

Hadronic calorimetry in the range |η| < 1.7 is provided by a steel/scintillator-tile sampling calorimeter. This system enables measurements of the shower energy deposition in three depth segments at a transverse granularity of typically 0.1 × 0.1. In the end-caps (|η| > 1.5), LAr technology is used for the hadronic calorimeters that match the outer η-limits of the end-cap electromagnetic calorimeters. This system enables four measurements in depth of the shower energy deposition at a transverse granularity of either 0.1 × 0.1 (1.5 < |η| < 2.5) or 0.2 × 0.2 (2.5 < |η| < 3.2).

III. MONTE CARLO SIMULATION

The QCD predictions for the hadronic final state in inelastic pp collisions are based on several Monte Carlo generators.

The Pythia 6.423 generator [18] with the ATLAS Minimum Bias Tune 1 (AMBT1) [19] parameter set is used as the primary generator for comparisons with the data and for extracting corrections to the data for detector effects. The AMBT1 tune uses the MRST LO* [20] parton distribution function (PDF) set with leading-order (LO) perturbative QCD matrix elements for 2→2 processes and a leading-logarithmic, pT-ordered parton shower followed by fragmentation into final-state particles using the Lund string model [21]. In addition to charged particle measurements from ATLAS minimum bias data [22, 23], the AMBT1 tune uses data from LEP, SPS, and the Tevatron.

An additional Pythia tune, Perugia2010 [24, 25], is used for comparison with AMBT1. The Perugia2010 tune also uses data from LEP, SPS, and the Tevatron and additionally improves the description of jet shape measurements in LEP data. The CTEQ5L [26] PDF set is used. This tune of Pythia is used in the calculation of the systematic uncertainties on the measurements and for comparison with the data, along with the HERWIG++ 2.4.2 generator with its default settings [27].

The more recent HERWIG++ 2.5.1 generator is included for comparison with the final measurements at particle level, as are the AUET2B tune [28] of Pythia 6.423, the PowHEG generator interfaced to this same Pythia tune, and the Pythia 8.153 generator [30] with tune 4C [26, 28]. The main difference between HERWIG++ versions 2.4.2 and 2.5.1 is the inclusion of color-reconnections in the latter. The PowHEG generator, which implements next-to-leading-order (NLO) calculations within a shower Monte Carlo context [41, 42], uses the CTEQ6M [26] PDF set.

Generated events are passed through the ATLAS detector simulation program [35], which is based on Geant4 [36]. The quark–gluon string model with an additional precompound [37] is used for the fragmentation of nuclei, and the Bertini cascade model [38] is used to describe the interactions of hadrons with the nuclear medium.

Monte Carlo events are reconstructed and analyzed using the same event selection and simulated trigger as for the data. The size and position of the collision beam spot and the detailed description of detector conditions during the data-taking runs are included in the simulation.

IV. EVENT SELECTION

Events containing pileup can be identified by the presence of more than one primary vertex in the event, herein referred to as N_{PV} > 1. Events recorded in the 2010 ATLAS data set contain an average N_{PV} ≃ 2.2 and include a significant fraction of N_{PV} = 1 events (≃ 28%); these may be used for testing the pileup correction methods.

After applying data-quality requirements, the data sample corresponds to a total integrated luminosity of 35.0 ± 1.1 pb−1 [39, 40].

A. Trigger selection

Events must pass the ATLAS first-level trigger requiring a jet (built from calorimeter towers with a granularity of 0.1 × 0.1 in ∆η × ∆φ) with transverse energy $E_T \geq 95$ GeV. The selection efficiency of this trigger has been found to be close to 100% for events satisfying the offline selection criteria implemented here, with a negligible dependence on jet mass [5].

B. Primary vertex selection

All events are required to have at least one good primary vertex. This is defined as a vertex with at least five tracks with $p_T > 150$ MeV and both transverse and longitudinal impact parameters consistent with the LHC beamspot [13, 14]. The analysis presented here makes use of the full 2010 data set. The requirement of $N_{PV} = 1$ is applied only where derivation of pileup corrections is not possible.

C. High pT jet selection

Jets are reconstructed from locally calibrated topological clusters [41] using the anti-kT algorithm [42] with distance parameters of $R = 0.6$ and 1.0. Jets satisfying $p_T > 300$ GeV and $|\eta| < 2$ are selected for analysis. Any event containing an $R = 0.6$ jet with $p_T > 30$ GeV that fails to satisfy the criteria [43] designed to safeguard
against jets caused by transient detector effects and beam backgrounds is excluded from this analysis.

In simulated data, jets are reconstructed from locally calibrated topological clusters to derive corrections for pileup and determine the systematic uncertainties and detector correction factors. The corrected data distributions are then compared to Monte Carlo predictions at particle level; in this case jets are reconstructed from stable particles as opposed to clusters. Particles are deemed to be stable for the purpose of jet reconstruction if their mean lifetimes are longer than 10 ps. Neutrinos and muons are excluded, just as they are for the Monte Carlo-based jet energy scale calibration that is applied to the data. This exclusion has a negligible effect on the final measurements.

The total numbers of jets in data satisfying the selection criteria detailed here are \( \sim 122,000 \) jets and \( \sim 87,000 \) jets; however, only the highest \( p_T \) jet in each event is selected for this analysis. The total numbers selected for analysis are \( \sim 83,000 \) jets and \( \sim 62,000 \) jets.

V. SUBSTRUCTURE OBSERVABLES AND THEIR CORRELATIONS

A. Jet mass

The jet mass \( M \) is calculated from the energies and momenta of its constituents (particles or clusters) as follows:

\[
M^2 = \left( \sum_i E_i \right)^2 - \left( \sum_i \vec{p}_i \right)^2,
\]

where \( E_i \) and \( \vec{p}_i \) are the energy and three-momentum of the \( i \)th constituent. The sum is over all jet constituents in this and all subsequent summations. At both particle level and detector level, the jet constituents themselves are allowed to have mass.

B. Jet width

The jet width \( W \) is defined as:

\[
W = \frac{\sum_i \Delta R^i p_T^i}{\sum_i p_T^i},
\]

where \( \Delta R^i = \sqrt{(\Delta \phi_i)^2 + (\Delta \eta_i)^2} \) is the radial distance between the jet axis and the \( i \)th jet constituent and \( p_T^i \) is the constituent \( p_T \) with respect to the beam axis.

C. Eccentricity

The jet eccentricity \( E \) is calculated using a principal component analysis (PCA) [12]. The PCA method provides the vector which best describes the energy-weighted geometrical distribution of the jet constituents in the \((\eta, \phi)\) plane. The eccentricity is used to characterize the deviation of the jet profile from a perfect circle in this plane, and is defined as

\[
E = 1 - \frac{v_{\text{min}}}{v_{\text{max}}},
\]

where \( v_{\text{max}} \) (\( v_{\text{min}} \)) is the maximum (minimum) value of variance of the jet constituents’ positions with respect to the principal vector. The calculation consists of the following steps:

1. For each jet the energy-weighted centers in \( \eta \) and \( \phi \) are calculated as:

\[
\vec{\phi}_{\text{jet}} = \frac{\sum_i \Delta \phi_i E_i}{\sum_i E_i}, \quad \vec{\eta}_{\text{jet}} = \frac{\sum_i \Delta \eta_i E_i}{\sum_i E_i},
\]

where the energy and position in the \((\eta, \phi)\) space that passes through the energy-weighted center of the face of the jet and results in a minimum in the variance of the constituents’ positions. The angle \( \theta \) of this vector with respect to the jet center \((\vec{\eta}_{\text{jet}}, \vec{\phi}_{\text{jet}})\) is given by:

\[
\tan 2\theta = \frac{2 \times \sum_i E_i \Delta \phi_i \Delta \eta_i}{\sum_i E_i (\Delta \phi_i^2 - \Delta \eta_i^2)}
\]

and the angle of the orthogonal vector \( x_2 \) is \( \theta - \frac{\pi}{2} \).

2. The PCA is performed to determine the vector \( \vec{x}_1 \) in \((\eta, \phi)\) space that passes through the energy-weighted center of the face of the jet and results in a minimum in the variance of the constituents’ positions.

3. The energy-weighted variances \( v_1 \) and \( v_2 \) with respect to \( x_1 \) and \( x_2 \) are calculated as:

\[
v_1 = \frac{1}{N} \sum_i E_i \left( \cos \theta \Delta \eta_i - \sin \theta \Delta \phi_i \right)^2,
\]

\[
v_2 = \frac{1}{N} \sum_i E_i \left( \sin \theta \Delta \eta_i + \cos \theta \Delta \phi_i \right)^2,
\]

where \( N \) is the number of constituents.

4. Finally, the largest value of the variance is assigned to \( v_{\text{max}} \) and the smallest to \( v_{\text{min}} \). The jet eccentricity ranges from zero for perfectly circular jets to one for jets that appear pencil-like in the \((\eta, \phi)\) plane.
Eccentricity is measured for jets in the mass range $M > 100$ GeV; this is the mass region of interest for the search for a Higgs boson or other massive, hadronically decaying particles predicted in various extensions to the Standard Model.

D. Planar flow

A variable complementary to the eccentricity is planar flow $P$ [10] [11] [12]. The planar flow measures the degree to which the jet’s energy is evenly spread over the plane across the face of the jet (high planar flow) versus spread linearly across the face of the jet (small planar flow).

To calculate planar flow, one first constructs a two-dimensional matrix $I_E^{kl}$:

$$ I_E^{kl} = \frac{1}{M} \sum_i \frac{1}{E_i} p_i^k p_i^l. \quad (7) $$

Here, $M$ is the jet mass, $E_i$ is the energy of the $i^{th}$ constituent of the jet and $p_i^k$ and $p_i^l$ are the $k$ and $l$ components of its transverse momentum calculated with respect to the jet axis. The planar flow is:

$$ P = 4 \times \frac{\det(I_E)^2}{\text{Tr}(I_E)^2}. \quad (8) $$

Vanishing or low planar flow corresponds to a linear energy deposition, as in the case of a two-pronged decay, while completely isotropic energy distributions are characterized by unit planar flow [10]. Jets with many-body kinematics are expected to have a planar flow distribution that peaks towards unity. In general, QCD jets have a rising $P$ distribution that peaks at $P = 1$; the hadronization process has contributions from many soft gluons and is largely isotropic. However, jets with high $p_T$ and high mass are well-described by a single hard gluon emission. Consequently, these jets have a planar flow distribution that peaks at a low value [13]. The planar flow distributions are measured in the context of boosted, massive particle searches by applying a mass cut, $130 < M < 210$ GeV, consistent with the window in which one would expect to observe a boosted top quark decay collimated within a single jet. The contribution from top quark decays in this subset of the data is negligible — here we measure the properties of light-quark and gluon jets that constitute a substantial fraction of the background in boosted top quark measurements.

E. Angularity

Angularities ($\tau_a$) are a family of observables that are sensitive to the degree of symmetry in the energy flow inside a jet. The general formula for angularity [10] is given by:

$$ \tau_a = \frac{1}{M} \sum_i E_i \sin^a \theta_i [1 - \cos \theta_i]^{1-a}, \quad (9) $$

Here $a$ is a parameter that can be chosen to emphasize radiation near the edges ($a < 0$) or core ($a > 0$) of the jet, $M$ is the jet mass, $E_i$ is the energy of the $i^{th}$ jet constituent and $\theta_i$ is its angle with respect to the jet axis. In the limit of small-angle radiation ($\theta_i \ll 1$), $\tau_a$ is approximated by:

$$ \tau_a \approx \frac{2^{(a-1)}}{M} \sum_i E_i \theta_i^{(2-a)}. \quad (10) $$

Angularities are infrared-safe for $a \leq 2$ [13]. In the analysis presented here, Eq. 9 with a value of $a = -2$ is used. The $\tau_{-2}$ observable can be used as a discriminator for distinguishing QCD jets from boosted particle decays by virtue of the broader tail expected in the QCD distribution [10]. At a given high mass, the angularity of jets with two-body kinematics should peak around a minimum value $\tau_a^{\text{peak}} \approx \left( \frac{M}{2p_T} \right)^{1-a}$, which corresponds to the two hard constituents being in a symmetric $p_T$ configuration around the jet axis. An estimate for the maximum of the distribution can also be calculated in the limit of small angle radiation, $\tau_a^{\text{max}} \approx \left( \frac{M}{2p_T} \right)^{1-a}$, which corresponds to a hard constituent close to the jet axis and a soft constituent on the jet edge.

The measurement of $\tau_{-2}$ is aimed primarily at testing QCD, which makes predictions for the shape of the $\tau_{-2}$ distribution in jets where the small angle approximation is valid. For this reason, this measurement is made only for anti-$k_t$ jets with $R = 0.6$.

Here, $\tau_{-2}$ is measured for jets in the mass range $100 < M < 130$ GeV. This mass region is chosen to have minimal contributions from hadronically decaying $W$ or $Z$ bosons or boosted top quarks (PYTHIA predictions estimate a relative fraction below 0.2%).

F. Correlations between the observables

The levels of correlation between the variables presented here provide information that is valuable in deciding which variables may potentially be used together in a search for boosted particles. Here the correlation factors between pairs of variables are calculated as the covariance divided by the product of their standard deviations:

$$ \rho = \frac{\text{cov}(x, y)}{\sigma_x \sigma_y}. \quad (11) $$

Summaries of the correlations between all of the ob-
observables studied here are shown in Fig. 1 for \( R = 1.0 \) jets in Pythia at particle level. The coefficients are shown both with and without a jet mass cut of \( M > 100 \) GeV. Jets subjected to a mass cut are also restricted to \( |\eta| < 0.7 \). This additional restriction on \( \eta \) is applied wherever a mass cut is made on the observables presented here; this has a negligible effect on the shapes of the distributions while allowing direct comparisons with other measurements of the same quantities.

The strongest correlations observed are those between jet mass and width (85%) and between planar flow and eccentricity (–80%). The correlation between mass and width reduces considerably when jets are required to be in the kinematic region \( M > 100 \) GeV. This trend is followed by almost all observables. The planar flow and eccentricity, however, are even more strongly anti-correlated in high mass jets (–90%). The correlation between mass and \( p_T \) is weak (12–16%). Angularity is largely uncorrelated with all of the other observables.

VI. CORRECTIONS FOR PILEUP AND DETECTOR EFFECTS

The contribution from pileup is measured using the complementary cone method first introduced by the CDF experiment \[13, 46\]. A complementary cone is drawn at a right-angle in azimuth to the jet (\( \phi_{\text{comp}} = \phi_{\text{jet}} \pm \frac{\pi}{2} \), \( \eta_{\text{comp}} = \eta_{\text{jet}} \)) and the energy deposits in this cone are added into the jet such that the effect on each of the jet properties can be quantified. The shift in each observable after this addition is attributed to pileup and the underlying event (UE), the latter being the diffuse radiation present in all events and partially coherent with the hard scatter. The effects of these two sources are separated by comparing events with \( N_{\text{PV}} = 1 \) (UE only) to those with \( N_{\text{PV}} > 1 \) (UE and pileup): the difference between the average shift for single-vertex and multiple-vertex events is attributed to the contribution from pileup only.

The presence of additional energy in events with \( N_{\text{PV}} > 1 \) affects the substructure observables in different ways: the effect of pileup on the shape of the \( \tau_{-2} \) distribution is negligible (below 1%) in this data set, and so no corrections are applied. The other observables under study have their distributions noticeably distorted by the presence of pileup. The \( p_T \)-dependent corrections for this effect are applied to the mass, width and eccentricity distributions, whilst the planar flow distribution of high mass jets is measured only in events with \( N_{\text{PV}} = 1 \). There are a small number of jets (\( \sim 100 \) anti-\( k_t \), \( R = 0.6 \)) jets) in the high mass range (\( M > 130 \) GeV), making it too difficult to derive robust pileup corrections for planar flow (which is limited to this mass range in this analysis) in this data set.

A. Pileup corrections for \( R = 0.6 \) jets

The mass shift due to the UE and pileup in \( N_{\text{PV}} = 1 \) and \( N_{\text{PV}} > 1 \) events is shown in Fig. 2 for \( R = 0.6 \) jets in the range \( 300 < p_T < 400 \) GeV. The shift follows the expected behavior, given by:

\[
\Delta M = p_{0M} + \frac{p_{1M}}{M},
\]

where \( p_{\text{0M}} \) and their associated uncertainties are determined from the data. \( \Delta M \) is the increase in the jet mass.
due to the addition of the energy deposits in the complementary cone to the jet. Corrections to the jet mass are limited to the region $M > 30$ GeV, as the $\frac{\Delta M}{M}$ parameterization uses a leading-order approximation and is only valid for $\Delta M \ll M$. This has a negligible effect on the final measurements in the range $M > 20$ GeV, as illustrated for $R = 1.0$ jets in Fig. 3; low mass, high $p_T$ jets tend to have a small contribution from pileup.

The corresponding parameterizations for the shifts in width $\Delta W$ and eccentricity $\Delta E$ are:

$$\Delta W = p_{0W} + p_{1W} W,$$

$$\Delta E = p_{0E} + p_{1E} E + p_{2E} E^2. \quad (13)$$

The pileup corrections for width and eccentricity are applied to jets across the full mass range.

B. Pileup corrections for $R = 1.0$ jets

The complementary cone technique cannot be applied directly to $R = 1.0$ jets due to the high probability of overlap between the complementary cone and the jet; scaling factors are therefore applied to the corrections measured for $R = 0.6$ jets. The expected (observed) behaviors for the scaling of the shifts in mass and width are:

$$\Delta M : p_{1M} \sim R^4 \left( R^{3.5} \right), \quad (14)$$

$$\Delta W : p_{0W} \sim R^3 \left( R^{2.5} \right), \quad p_{1W} \sim R^2 \left( R^1 \right). \quad (15)$$

Here, the scaling of the shift in width is different for the two coefficients in the parameterization; this is not the case for the scaling of mass or eccentricity.

There is no phenomenological prediction for the scaling of $\Delta E$ with pileup, therefore the nominal value of the scaling of the shift in this variable is measured in data by comparing anti-$k_t$ jets reconstructed with $R = 0.4$ with those reconstructed with $R = 0.6$. The $R$-dependence is then validated with a comparison between $R = 1.0$ jets in $N_{PV} > 1$ and $N_{PV} = 1$ events. The measurements find the scaling of the parameterization to be a function of mass:

$$\Delta E(M < 40 \text{ GeV}) : p_{1E} \sim R^2,$$

$$\Delta E(M \geq 40 \text{ GeV}) : p_{1E} \sim R^3. \quad (16)$$

The scaling behavior of the shifts in mass and width are also measured in data (given in brackets in Eq. 14 and Eq. 15), and the discrepancies between observation and prediction are considered systematic uncertainties in this procedure.

The performance of the pileup correction procedure in the case of mass, width and eccentricity is shown in Fig. 3. The observable most sensitive to pileup is the jet mass; the mean $R = 1.0$ jet mass is shifted upwards by $\sim 7$ GeV in events with $N_{PV} > 1$, and there is a significant change in the shape of the mass distribution. In the case of jet width and eccentricity, the effect of pileup is a small ($\sim 5\%$) shift towards wider, less eccentric jets. This supports the expected behavior: width is less sensitive to pileup than mass, making it a promising alternative to mass as a criterion for selecting jets of interest in boosted particle searches in the high pileup conditions of later LHC operations. For all observables the discrepancies between the pileup-corrected distributions and those for events with $N_{PV} = 1$ are small, and agreement is obtained within the systematic uncertainties on the corrections.

C. Corrections for detector effects

After correcting the distributions for pileup, each distribution is corrected to particle level, using bin-by-bin corrections for detector effects. The bin migrations due to detector effects are determined and controlled by increasing the bin sizes until all bins have a purity and efficiency above $50\%$ according to Monte Carlo predictions, where purity and efficiency are defined as:

$$p_i = \frac{A_i^{\text{part+det}}}{A_i^{\text{det}}}, \quad e_i = \frac{A_i^{\text{part+det}}}{A_i^{\text{part}}}. \quad (17)$$

Here $A_i^{\text{part+det}}$ is the number of detector-level jets (reconstructed from locally calibrated clusters) in bin $i$ that have a particle-level jet (reconstructed from stable Monte Carlo particles), matched within $\Delta R < 0.2$ and falling in the same bin. $A_i^{\text{part}}$ is the total number of particle-level
jets in bin $i$ and $A^\text{det}_i$ is the total number of detector-level jets in bin $i$.

The particle-level value for an observable in bin $i$ is found by multiplying its measured value by the relevant correction factor $C_i$:

$$C_i = \frac{A^\text{part}_i}{A^\text{det}_i}.$$  \hspace{1cm} (18)

The size of the corrections varies quite significantly between observables and between bins, being around 20% for mass, (5–10% around the peak, 20% elsewhere) and width (30% in the peak for $R = 0.6$ jets, 1–5% elsewhere). The corrections for eccentricity are below 10% in the peak, increasing to 40% in the most sparsely populated bin. The detector corrections for angularity and planar flow are smaller, generally around 0–5%.

\section{VII. SYSTEMATIC UNCERTAINTIES}

The experimental systematic uncertainties can be divided into three categories: how well-modeled the observables are in Monte Carlo simulations (Sec. VIIA), the modeling of the detector material and cluster reconstruction (Sec. VIIB) and the pileup corrections (Sec. VII C). These are evaluated by determining the difference in the factors obtained after the application of systematic variations to the samples used in the correction for detector effects. The dominant sources of uncertainty, described in detail below, arise from varying the cluster energy scale (CES) and from the differences found when the calculation of detector corrections is done using the \textsc{Herwig++} Monte Carlo sample in place of \textsc{Pythia AMBT1}. These dominant effects are shown in Fig. 4 for $R = 0.6$ jets and Fig. 5 for $R = 1.0$ jets.

\subsection*{A. Uncertainties on the Monte Carlo model}

The distributions are corrected to particle level using the correction factors $C_i$ determined with a specific Monte Carlo generator, inclusive of parton shower, hadronization and UE model, which in this case is \textsc{Pythia} with the AMBT1 tune. To determine the uncertainty introduced on the final measurement by choosing this particular model to calculate the detector correction factors, the differences in these $C_i$ are found when the \textsc{Pythia AMBT1} tune is replaced with the \textsc{Perugia 2010} tune, and with \textsc{Herwig++} (2.4.2).

A primary source of the uncertainty on the mass measurements is due to the observed differences in the detector correction factors between \textsc{Herwig++} and \textsc{Pythia}, with uncertainties ranging between 10–20% as shown in Fig. 4 and Fig. 5.

\subsection*{B. Uncertainties on the detector material description and cluster reconstruction}

Performance studies \cite{48} have shown that there is excellent agreement between the measured positions of clusters and tracks in data, indicating no systematic misalignment between the calorimeter and inner detector. The Monte Carlo modeling of the position of clusters with respect to tracks is also good, indicating that the detector simulation models the calorimeter position resolution
adequately; however, there remains a small discrepancy between data and Monte Carlo in the mean and RMS of the track-cluster separation. This source of uncertainty is taken into account by (Gaussian) smearing the positions of simulated clusters in $\eta$ and $\phi$ by 5 mrad. This smearing is done independently in $\eta$ and $\phi$, and the impact on the measurement of the correction factors for each observable, bin-by-bin, is quantified by taking the difference, $\Delta C_i$, between the correction factors obtained before and after the position smearing. Smearing the positions in $\eta$ and $\phi$ results in small $\Delta C_i$ for mass and shapes alike, introducing uncertainties that do not exceed 5% in any bin.

The variation on the CES follows the procedure used by previous studies \(^3\) according to:

$$p_{\text{clus,new}} = p_{\text{clus}} \times \left(1 \pm 0.05 \times \left(1 + \frac{1.5}{p_T/\text{GeV}}\right)\right) \quad (19)$$

where $p_{\text{clus}}$ is each component of the cluster’s four-momentum and $p_T$ is the cluster $p_T$ in GeV. The CES is varied up and down independently for each momentum component of each cluster, and the correction factors are recalculated in each case as before. The CES is a large source of systematic uncertainty in the measurement of mass (of order 20% across the mass range) and width (of order 10% beyond the first two bins). The effects...
of varying the CES are in general smaller for the eccentricity, planar flow and angularity measurements, all of which are made on high mass jets only. The effects of varying the CES on all observables are shown with the label $E_{clus}$ in Fig. 4 for $R = 0.6$ jets and Fig. 5 for $R = 1.0$ jets.

The uncertainty introduced as a result of losing energy due to dead material in the detector is taken into account by discarding a fraction of low energy ($E < 2.5$ GeV) clusters, following the technique and utilizing the observations of a previous study of the single hadron response at $\sqrt{s} = 900$ GeV [49]. Clusters are not included in jet reconstruction if they satisfy:

$$r \leq \mathcal{P}(E_0) \times e^{-2E},$$  \hspace{1cm} (20)$$

where $r$ is a random number $r \in (0,1)$, $\mathcal{P}(E_0)$ is the measured uncertainty (28%) on the probability that a particle does not leave a cluster in the calorimeter, and $E$ is the cluster energy in GeV. The impact on the measurement of each observable is quantified by comparing the correction factors before and after this dropping of low energy clusters. The impact of this variation is small, resulting in a contribution to the systematic uncertainty less than a few percent in all measurements.
C. Uncertainties on the pileup corrections

There is a statistical uncertainty on the fit $f(x, p_T, M)$ describing the pileup correction $\Delta x$ for observable $x$ in $R = 0.6$ jets. Dedicated studies have shown that the parameterizations of the pileup corrections in data and in Pythia AMBT1 Monte Carlo with simulated pileup agree, within the statistical uncertainties, for jets across the $p_T$ range considered. The statistical uncertainties on these fits are accounted for by implementing $+1\sigma$ and $-1\sigma$ variations independently, as shown for mass in Fig. 2. The correction factors are recalculated, and in each case the difference is taken as a contribution to the systematic uncertainty on the measurement. This is a small contribution to the overall systematic uncertainty on the measurements, contributing at most a few percent in bins that are statistically limited, and is a negligible ($< 1\%)$ effect elsewhere.

For $R = 1.0$ jets, the correction factors are scaled using the phenomenological predictions described in Sec. VII B. These scaling factors are also calculated in data and in Pythia AMBT1 Monte Carlo with simulated pileup; good agreement is observed, indicating that the effect of pileup on jets is well-modeled. In the case of mass and width, where there is a phenomenological prediction for the scaling, this prediction is used for the determination of the nominal scaling factors and the variation is taken from the scaling factors found in data. In the case of eccentricity there is no phenomenological prediction for the scaling of the pileup corrections with $R$, so the behavior observed in data is used. The $R$-scaling of the pileup corrections for eccentricity is dependent on jet mass, so the variations found in data across the mass range are taken as the systematic variations.

The uncertainties introduced by the pileup corrections contribute a small amount (in general 1–2%) to the total systematic uncertainties on the mass, width and eccentricity.

The sources of systematic uncertainty described above are added in quadrature with the statistical uncertainty in each bin and symmetrized where appropriate (the contributions from the cluster energy scale and parameterization of the pileup corrections are determined separately for upward and downward fluctuations, and so are not symmetrized).

VIII. RESULTS

The distributions of jet characteristics presented in this section are corrected for detector effects and are compared to Monte Carlo predictions at the particle level. In the case of mass and $\tau_3$, comparison is also made between data and the eikonal approximation $^{[4]}$ of NLO QCD. The results shown here are available in HepData $^{[50, 51]}$ and the analysis and data are available as a RIVET $^{[52, 53]}$ routine.

A. Jet mass

The jet mass distributions are shown in Fig. 6 for jets satisfying $p_T > 300\text{ GeV}$ and $|\eta| < 2$, corrected to the particle level, and the corresponding numerical values are given in Table IV and Table V. The mass distribution for $R = 0.6$ anti-$k_t$ jets has a broad peak beginning at around 20 GeV, while the corresponding distribution for $R = 1.0$ jets peaks at around 60 GeV and has a tail that falls away quickly, with the highest mass jet being above 200 GeV.

In the case of $R = 1.0$ jets, the data are compared to the calculations for jet masses derived at NLO QCD in the eikonal approximation:

$$J \simeq \frac{\alpha_S}{\pi M} \log \left( \frac{1}{z} \tan \left( \frac{R}{2} \sqrt{4 - z^2} \right) \right),$$

where $J$ is the value of the jet mass distribution at $M$, $\alpha_S$ is the strong coupling constant, $z = M/p_T$, $c$ represents the flavor of the parton which initiated the jet and $C_c = \frac{3}{4}$ (3) for quarks (gluons). The strong coupling constant is calculated using the Pythia prediction of the average jet $p_T \simeq 365\text{ GeV}$ and has the value of $\alpha_S = 0.0994$. Theoretical uncertainties for such predictions are sizable (more than 30%) $^{[4]}$ in the region above the mass peak. The lower mass region $M \lesssim 90\text{ GeV}$ is strongly affected by non-perturbative physics and as such cannot be predicted by such calculations. The size and shape of the high-mass tail is in rough agreement with the analytical eikonal approximation for NLO QCD for jet masses above 90 GeV, with most of the data points lying between the predictions for quark-initiated and gluon-initiated jets. QCD LO predictions predict that the majority of the jets in this sample should arise from gluons. Also included in Fig. 6 are a number of Pythia, Herwig++, and PowHeg predictions for the jet mass distributions. Unlike the analytical calculation discussed above, the Monte Carlo predictions are meaningful down to the low mass region due to the inclusion of soft radiation and hadronization. The Pythia calculation describes the data well. The Herwig++ 2.4.2 prediction indicates a significant shift to a higher jet mass that is inconsistent with the data and the other Monte Carlo predictions, while the more recent Herwig++ 2.5.1 generator is in much better agreement with the data. PowHeg+Pythia is in good agreement with data within systematic uncertainties across the whole mass range.

B. Width

The jet width distributions are shown in Fig. 7 for anti-$k_t$ jets reconstructed with distance parameters of $R = 0.6$ and 1.0, and the corresponding numerical values are given in Table III and Table IV. There is significant variation between the different Monte Carlo predictions in the first bin, beyond which there is good agreement between the
distribution measured in data and all the predictions.

C. Eccentricity

The eccentricity distributions for high mass \( M > 100 \text{ GeV} \) anti-\( k_t \) jets reconstructed with distance parameters of \( R = 0.6 \) and \( R = 1.0 \) are shown in Fig. 8 and the corresponding numerical values are given in Table VI and Table VII. The Monte Carlo predictions generally describe the data, while some small discrepancies can be observed between the various predictions and between predictions and data.

D. Planar flow

The planar flow distributions are shown only for events known to be uncontaminated by pileup, corresponding to events with \( N_{\text{PV}} = 1 \). These distributions are shown in Fig. 9 for jets reconstructed with the anti-\( k_t \) algorithm with \( R = 1.0 \) for the mass range \( 130 < M < 210 \text{ GeV} \), and the corresponding numerical values are given in Table VIII. The \( \text{HERWIG++} \) 2.4.2 generator predicts jets with a more planar, isotropic energy distribution than is observed in data, while version 2.5.1 provides a very accurate description of the planar flow. The various \( \text{PYTHIA} \) and \( \text{POWHEG} \) Monte Carlo predictions also describe the data well, within uncertainties.

E. Angularity

The \( \tau_{-2} \) distribution for anti-\( k_t \) \( R = 0.6 \) jets in the mass region \( 100 < M < 130 \text{ GeV} \) is presented in Fig. 10 and the corresponding numerical values are given in Table VIII. The QCD predictions for the peak position and the maximum value of \( \tau_{-2} \) \([13]\), calculated using the averages \( \langle M \rangle = 111 \text{ GeV} \) and \( \langle p_T \rangle = 434 \text{ GeV} \) of the jets in this kinematic region, are also shown on the distributions. Good agreement is observed between the data and the Monte Carlo simulation for the shape of the \( \tau_{-2} \) distribution.

The comparison between data and the analytic QCD prediction is limited by the intrinsic resolution of the data distribution; however, there is good agreement between theory and data within these limitations. The position of the peak of the distribution, \( \tau_{-2, \text{peak}} \), indicates that the majority of jets in this data set can be described by a two-body substructure in a symmetric \( p_T \) configuration with respect to the jet axis. No jets are observed above the small-angle kinematic limit, \( \tau_{-2, \text{peak}} \).
FIG. 7. The jet width distributions for leading \( p_T \), anti-\( k_T \), \( R = 0.6 \) (top) and \( R = 1.0 \) (bottom) jets in the full 2010 data set, corrected for pileup and corrected to particle level.

FIG. 8. The jet eccentricity distributions for high mass (\( M > 100 \) GeV), leading \( p_T \), anti-\( k_T \), \( R = 0.6 \) (top) and \( R = 1.0 \) (bottom) jets in the full 2010 data set, corrected for pileup and corrected to particle level.
FIG. 9. The jet planar flow distributions for high mass (130 < M < 210 GeV), leading \( p_T \), anti-\( k_t \) \( R = 1.0 \) jets in \( N_{PV} = 1 \) events, corrected to particle level.

FIG. 10. The angularity \( \tau_{-2} \) distributions for leading \( p_T \), anti-\( k_t \) \( R = 0.6 \) jets in the mass range 100 < M < 130 GeV, in the full 2010 data set, corrected to particle level. The peak and maximum positions predicted by the small angle approximation of Eq. [10] are indicated.

<table>
<thead>
<tr>
<th>Bin [GeV]</th>
<th>( \frac{1}{N} \frac{dN}{dM} ) ± stat. ± sys. (×10^{-4})/( \tau_{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 – 40</td>
<td>212 ± 2 ± 34</td>
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<tr>
<td>40 – 60</td>
<td>152 ± 1 ± 16</td>
</tr>
<tr>
<td>60 – 80</td>
<td>65 ± 1 ± 10.11</td>
</tr>
<tr>
<td>80 – 110</td>
<td>24 ± 1 ± 4</td>
</tr>
<tr>
<td>110 – 140</td>
<td>5.0 ± 0.2 ± 0.8</td>
</tr>
</tbody>
</table>

TABLE I. Measured values of the anti-\( k_t \) \( R = 0.6 \) jet mass distribution given with their statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>Bin [GeV]</th>
<th>( \frac{1}{N} \frac{dN}{dM} ) ± stat. ± sys. (×10^{-4})/( \tau_{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 – 55</td>
<td>69 ± 1 ± 23.4</td>
</tr>
<tr>
<td>55 – 90</td>
<td>122 ± 1 ± 17</td>
</tr>
<tr>
<td>90 – 125</td>
<td>56 ± 1 ± 13</td>
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<tr>
<td>125 – 160</td>
<td>22.6 ± 0.4 ± 3.3</td>
</tr>
<tr>
<td>160 – 200</td>
<td>9.0 ± 0.2 ± 2.3</td>
</tr>
<tr>
<td>200 – 240</td>
<td>4.3 ± 0.2 ± 2.1</td>
</tr>
</tbody>
</table>

TABLE II. Measured values of the anti-\( k_t \) \( R = 1.0 \) jet mass distribution given with their statistical and systematic uncertainties.

IX. CONCLUSIONS

The properties of high \( p_T \) (> 300 GeV) jets reconstructed with the anti-\( k_t \) jet algorithm have been studied in \( pp \) collisions at a center-of-mass energy of 7 TeV. There is good agreement between data and Pythia for all observables, and the PowHe+Pythia prediction describes the mass distribution well for jets with \( M > 20 \) GeV. Herwig++ 2.4.2 predicts jets with a slightly more isotropic energy flow and higher mass than observed in data, while Herwig++ 2.5.1 predictions are in good agreement with the data. The angularity measurement of high mass jets agrees with the small-angle QCD approximations.
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; DNRF, 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, GVA, DIP and Benoziyo Center, Israel; INFN, Italy; MEET and JSPS, Japan; CNRST, Morocco: FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRESCE and FCT, Portugal; MERYS (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.

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### X. ACKNOWLEDGEMENTS

#### TABLE III. Measured values of the anti-\(k_t\) \(R = 0.6\) jet width distribution given with their statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>Bin</th>
<th>(\frac{1}{N} \frac{dN}{d\eta} \pm \text{stat.} \pm \text{sys.} \times 10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.025</td>
<td>61.1 ± 1.2 ± 8.2</td>
</tr>
<tr>
<td>0.025 – 0.05</td>
<td>106 ± 1 ± 12</td>
</tr>
<tr>
<td>0.05 – 0.1</td>
<td>55.3 ± 0.4 ± 10</td>
</tr>
<tr>
<td>0.1 – 0.15</td>
<td>26.4 ± 0.3 ± 3</td>
</tr>
<tr>
<td>0.15 – 0.2</td>
<td>14.0 ± 0.3 ± 2</td>
</tr>
<tr>
<td>0.2 – 0.25</td>
<td>7.7 ± 0.2 ± 1.3</td>
</tr>
<tr>
<td>0.25 – 0.3</td>
<td>4.0 ± 0.2 ± 0.9</td>
</tr>
</tbody>
</table>

#### TABLE IV. Measured values of the anti-\(k_t\) \(R = 1.0\) jet width distribution given with their statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>Bin</th>
<th>(\frac{1}{N} \frac{dN}{d\eta} \pm \text{stat.} \pm \text{sys.} \times 10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.025</td>
<td>12.1 ± 0.5 ± 4.8</td>
</tr>
<tr>
<td>0.025 – 0.05</td>
<td>55.3 ± 0.8 ± 15.0</td>
</tr>
<tr>
<td>0.05 – 0.1</td>
<td>50.8 ± 0.4 ± 8.2</td>
</tr>
<tr>
<td>0.1 – 0.15</td>
<td>33.6 ± 0.3 ± 4.9</td>
</tr>
<tr>
<td>0.15 – 0.2</td>
<td>21.8 ± 0.3 ± 3.3</td>
</tr>
<tr>
<td>0.2 – 0.25</td>
<td>15.1 ± 0.2 ± 2.1</td>
</tr>
<tr>
<td>0.25 – 0.3</td>
<td>10.4 ± 0.2 ± 2.4</td>
</tr>
<tr>
<td>0.3 – 0.35</td>
<td>7.3 ± 0.2 ± 2.2</td>
</tr>
<tr>
<td>0.35 – 0.4</td>
<td>5.9 ± 0.2 ± 1.6</td>
</tr>
</tbody>
</table>

#### TABLE V. Measured values of the eccentricity distribution for anti-\(k_t\) \(R = 0.6\) jets with \(M > 100\) GeV, given with their statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>Bin</th>
<th>(\frac{1}{N} \frac{dN}{d\eta} \pm \text{stat.} \pm \text{sys.} \times 10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.2</td>
<td>0.2 ± 0.1 ± 0.2</td>
</tr>
<tr>
<td>0.2 – 0.4</td>
<td>1.1 ± 0.3 ± 0.6</td>
</tr>
<tr>
<td>0.4 – 0.6</td>
<td>5.1 ± 0.7 ± 1.3</td>
</tr>
<tr>
<td>0.6 – 0.8</td>
<td>11.0 ± 0.9 ± 1.4</td>
</tr>
<tr>
<td>0.8 – 1.0</td>
<td>32.9 ± 1.7 ± 2.4</td>
</tr>
</tbody>
</table>

#### TABLE VI. Measured values of the eccentricity distribution for anti-\(k_t\) \(R = 1.0\) jets with \(M > 100\) GeV, given with their statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>Bin</th>
<th>(\frac{1}{N} \frac{dN}{d\eta} \pm \text{stat.} \pm \text{sys.} \times 10^{-4})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.2</td>
<td>0.8 ± 0.1 ± 0.3</td>
</tr>
<tr>
<td>0.2 – 0.4</td>
<td>4.2 ± 0.2 ± 0.9</td>
</tr>
<tr>
<td>0.4 – 0.6</td>
<td>9.8 ± 0.3 ± 1.2</td>
</tr>
<tr>
<td>0.6 – 0.8</td>
<td>17.2 ± 0.4 ± 2.2</td>
</tr>
<tr>
<td>0.8 – 1.0</td>
<td>18.6 ± 0.4 ± 2.8</td>
</tr>
</tbody>
</table>

TABLE VII. Measured values of the planar flow distribution for anti-$k_T$ $R = 1.0$ jets in $N_{\text{jet}}=1$ events with $130 < M < 210$ GeV, given with their statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>Bin</th>
<th>$\frac{1}{N} \frac{dN}{dR}$ ± stat. ± sys. (×10$^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.2</td>
<td>5.1 ± 0.7 ± 1.4</td>
</tr>
<tr>
<td>0.2 – 0.4</td>
<td>13.6 ± 0.9 ± 2.7 ± 3.0</td>
</tr>
<tr>
<td>0.4 – 0.6</td>
<td>13.8 ± 0.9 ± 2.9 ± 2.7</td>
</tr>
<tr>
<td>0.6 – 0.8</td>
<td>9.5 ± 0.8 ± 1.2 ± 0.9 ± 0.9</td>
</tr>
<tr>
<td>0.8 – 1.0</td>
<td>8.1 ± 0.7 ± 1.5 ± 1.7</td>
</tr>
</tbody>
</table>

TABLE VIII. Measured values of the angularity $\tau_2$ distribution for anti-$k_T$ $R = 0.6$ jets with $100 < M < 130$ GeV, given with their statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>Bin</th>
<th>$\frac{1}{N} \frac{dN}{d\tau_2}$ ± stat. ± sys.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 0.002</td>
<td>75 ± 10 ± 38</td>
</tr>
<tr>
<td>0.002 – 0.004</td>
<td>223 ± 15 ± 27 ± 28</td>
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<tr>
<td>0.004 – 0.006</td>
<td>158 ± 13 ± 33 ± 33</td>
</tr>
<tr>
<td>0.006 – 0.008</td>
<td>40 ± 6 ± 33</td>
</tr>
<tr>
<td>0.008 – 0.010</td>
<td>9 ± 5 ± 26</td>
</tr>
</tbody>
</table>

[19] ATLAS Collaboration, “Charged-particle multiplicities in pp interactions at sqrt(s) = 0.9 and 7 TeV in a diffractive limited phase-space measured with the ATLAS detector at the LHC and new Pythia 6 tune,” ATL-CONF-2010-031 (2010).
[51] HEPPDATA: ATLAS measurements of the properties of jets for boosted particle searches,
http://hepdata.cedar.ac.uk/view/red4992.


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<th>Page</th>
<th>Content</th>
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<tr>
<td>11</td>
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<td>12</td>
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<td>(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 Física, Universidade de Sao Paulo, Sao Paulo, Brazil</td>
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<td>(a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile</td>
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<td>Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3,</td>
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Aubiere Cedex, France
34 Nevis Laboratory, Columbia University, Irvington NY, United States of America
35 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
36 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
37 ACH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas TX, United States of America
40 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham NC, United States of America
45 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46 Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 32700 Wiener Neustadt, Austria
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 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, 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, UPAN and Université Paris-Diderot and CNRS/IN2P3, Paris, France
79 Fysiska institutionen, Lunds universitet, Lund, Sweden
80 Departamento de Física Teorica C-15, Universidad Autonoma 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
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

158 Department of Physics, University of Toronto, Toronto ON, Canada

159 (a)TRIUMF, Vancouver BC; (b)Department of Physics and Astronomy, York University, Toronto ON, Canada

160 Institute of Pure and Applied Sciences, University of Tsukuba,1-1-1 Tennodai,Tsukuba, Ibaraki 305-8571, Japan

161 Science and Technology Center, Tufts University, Medford MA, United States of America

162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

164 (a)INFN Gruppo Collegato di Udine; (b)ICTP, Trieste; (c)Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

165 Department of Physics, University of Illinois, Urbana IL, United States of America

166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

168 Department of Physics, University of British Columbia, Vancouver BC, Canada

169 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

170 Department of Physics, University of Warwick, Coventry, United Kingdom

171 Waseda University, Tokyo, Japan

172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

173 Department of Physics, University of Wisconsin, Madison WI, United States of America

174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

175 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

176 Department of Physics, Yale University, New Haven CT, United States of America

177 Yerevan Physics Institute, Yerevan, Armenia

178 Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

179 Also at Laboratorio de Instrumentacao e Física Experimental de Partículas - LIP, Lisboa, Portugal

180 Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal

181 Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

182 Also at TRIUMF, Vancouver BC, Canada

183 Also at Department of Physics, California State University, Fresno CA, United States of America

184 Also at Novosibirsk State University, Novosibirsk, Russia

185 Also at Fermilab, Batavia IL, United States of America
Also at Department of Physics, University of Coimbra, Coimbra, Portugal
Also at Department of Physics, UASLP, San Luis Potosí, Mexico
Also at Università di Napoli Parthenope, Napoli, Italy
Also at Institute of Particle Physics (IPP), Canada
Also at Department of Physics, Middle East Technical University, Ankara, Turkey
Also at Louisiana Tech University, Ruston LA, United States of America
Also at Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Also at Department of Physics and Astronomy, University College London, London, United Kingdom
Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
Also at Department of Physics, University of Cape Town, Cape Town, South Africa
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
Also at Manhattan College, New York NY, United States of America
Also at School of Physics, Shandong University, Shandong, China
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy
Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France
Also at Section de Physique, Université de Genève, Geneva, Switzerland
Also at Departamento de Física, Universidade de Minho, Braga, Portugal
Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
Also at California Institute of Technology, Pasadena CA, United States of America
Also at Institute of Physics, Jagiellonian University, Krakow, Poland
Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Also at Nevis Laboratory, Columbia University, Irvington NY, United States of America
Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Also at Department of Physics, Oxford University, Oxford, United Kingdom
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
* Deceased