Transverse momentum and process dependent azimuthal anisotropies in $\sqrt{s_{NN}} = 8.16$ TeV p+Pb collisions with the ATLAS detector

The ATLAS Collaboration

DOI
10.1140/epjc/s10052-020-7624-4

Publication date
2020

Document Version
Final published version

Published in
European Physical Journal C

License
CC BY

Citation for published version (APA):
The ATLAS Collaboration (2020). Transverse momentum and process dependent azimuthal anisotropies in $\sqrt{s_{NN}} = 8.16$ TeV p+Pb collisions with the ATLAS detector. European Physical Journal C, 80(1), [73]. https://doi.org/10.1140/epjc/s10052-020-7624-4
Transverse momentum and process dependent azimuthal anisotropies in $\sqrt{s_{\text{NN}}} = 8.16$ TeV $p+$Pb collisions with the ATLAS detector

ATLAS Collaboration

CERN, 1211 Geneva 23, Switzerland

Received: 31 October 2019 / Accepted: 7 January 2020 / Published online: 30 January 2020

© CERN for the benefit of the ATLAS collaboration 2020

Abstract

The azimuthal anisotropy of charged particles produced in $\sqrt{s_{\text{NN}}} = 8.16$ TeV $p+$Pb collisions is measured with the ATLAS detector at the LHC. The data correspond to an integrated luminosity of 165 nb$^{-1}$ that was collected in 2016. Azimuthal anisotropy coefficients, elliptic $v_2$ and triangular $v_3$, extracted using two-particle correlations with a non-flow template fit procedure, are presented as a function of particle transverse momentum ($p_T$) between 0.5 and 50 GeV. The $v_2$ results are also reported as a function of centrality in three different particle $p_T$ intervals. The results are reported from minimum-bias events and jet-triggered events, where two jet $p_T$ thresholds are used. The anisotropies for particles with $p_T$ less than about 2 GeV are consistent with hydrodynamic flow expectations, while the significant non-zero anisotropies for $p_T$ in the range 9–50 GeV are not explained within current theoretical frameworks. In the $p_T$ range 2–9 GeV, the anisotropies are larger in minimum-bias than in jet-triggered events. Possible origins of these effects, such as the changing admixture of particles from hard scattering and the underlying event, are discussed.

1 Introduction

The collisions of heavy nuclei at relativistic speeds generate hot and dense droplets of matter composed of deconfined quarks and gluons known as the quark–gluon plasma (QGP) [1,2]. Studies of the QGP at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have yielded a wealth of surprising results that reveal a complex set of QGP-related phenomena. Bulk hadron production, occurring mainly at low transverse momentum ($p_T \lesssim 3$ GeV), exhibits significant azimuthal anisotropies that are well described in terms of nearly inviscid hydrodynamic flow of the QGP [1]. The final hadron momentum anisotropies arise from inhomogeneities in the initial spatial distribution of the QGP translated to momentum space via strong differential pressure gradients. These anisotropies are characterised in terms of a Fourier decomposition:

$$Y(\phi) = G \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n)) \right],$$

where $v_n$ are the anisotropy coefficients, $\Psi_n$ is the $n$th-order orientation of the anisotropy, and the normalization, $G$, is set by the integral of the distribution. In particular, $v_2$ and $v_3$ are referred to as the elliptic and triangular coefficients, respectively.

In addition, the production of high transverse momentum hadrons ($p_T \gtrsim 10$ GeV) is highly suppressed relative to the yields expected from nuclear thickness scaling of proton–proton collision yields [3]. This suppression is understood to result from high momentum transfer parton–parton interactions followed by the outgoing partons losing energy via radiative and collisional processes in the QGP – processes referred to as jet quenching [4–6]. These high-$p_T$ hadrons and associated jets are also observed to have a non-zero azimuthal anisotropy [7–9], despite being well outside the nominal domain where the anisotropies are interpreted in terms of hydrodynamic flow. Instead, these anisotropies are understood to also arise from inhomogeneities in the initial spatial distribution of the QGP, but in this case, where the jet quenching effect is stronger for partons traversing longer paths through the QGP and weaker for partons traversing shorter paths [10]. In this way, low- and high-$p_T$ hadrons have a common orientation of their azimuthal anisotropy in a given event, because both are correlated with the orientation of the initial geometry of the colliding nucleons. It is notable that, for more than a decade, an outstanding and challenging theoretical puzzle has been how to quantitatively describe both high-$p_T$ hadron suppression and azimuthal anisotropy in Pb+Pb collisions [11]. There are a number of proposed explanations for resolving this puzzle in heavy-ion collisions – see Refs. [12–17] for examples.

*e-mail: atlas.publications@cern.ch*
Measurements in smaller collision systems, pp and p+Pb collisions at the LHC [18–23] and p+Au, d+Au, and 3He+Au at RHIC [24], indicate significant azimuthal anisotropies for low-\( p_T \) hadrons with patterns quite similar to those observed in the larger heavy-ion collision systems. For a recent review see Ref. [25]. These observations have raised the question of whether smaller and shorter-lived droplets of QGP are formed in these smaller collision systems. Indeed, models employing nearly inviscid hydrodynamics for the QGP provide a quantitative description of this large body of data at low \( p_T \) [26].

In contrast, measurements aimed at observing signatures of jet quenching in small collision systems have found no such effect. Measurements of hadron and jet \( p_T \) spectra at high \( p_T \) indicate production yields consistent with those in pp collisions scaled up by the expected nuclear thickness in p+Pb [27–29] and d+Au collisions [30], and that the \( p_T \)-balance between dijets or hadron–jet pairs is unmodified in p+Pb collisions within uncertainties [31, 32]. The ATLAS experiment has also published results for the hadron azimuthal anisotropy up to \( p_T \approx 12 \) GeV that hint at a non-zero anisotropy extending into the region beyond the usual hydrodynamic interpretation and into the regime of jet quenching [33]. However, it is unlikely that there can be differential jet quenching as a function of orientation relative to the QGP geometry if there is no jet quenching in p+Pb collisions as observed in the spectra. Thus, there are two related outstanding puzzles, one being the lack of jet quenching observed in the spectra, if indeed small droplets of QGP are formed, and the other being what mechanism can lead to high-\( p_T \) hadron anisotropies other than differential jet quenching.

This paper presents a measurement of the azimuthal anisotropy of unidentified hadrons as a function of \( p_T \) and centrality in \( \sqrt{s_{NN}} = 8.16 \) TeV p+Pb collisions with the ATLAS detector. The measurement is made using two-particle correlations, measured separately for minimum-bias triggered (MBT) events and events requiring a jet with \( p_T \) greater than either 75 GeV or 100 GeV. There are contributions to the azimuthal correlations from particle decays, jets, dijets, and global momentum conservation, which have traditionally been referred to as ‘non-flow’ [34]. Using this nomenclature, a standard template fitting procedure is applied to subtract non-flow contributions [19, 20]. To decrease the residual influence of the non-flow correlation in the jet events, a novel procedure is used to restrict the acceptance of particles according to the location of jets in the event. Assuming that the two-particle anisotropy coefficients are the products of the corresponding single-particle coefficients (factorisation), the elliptic and triangular anisotropy coefficients, \( v_2 \) and \( v_3 \), are reported as a function of \( p_T \). Additionally, \( v_2 \) results are presented as a function of centrality in three different \( p_T \) ranges. Finally, the fractional contribution to the correlation functions from jet particles is determined as a function of \( p_T \).

### 2 ATLAS detector

The ATLAS experiment [35] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and nearly 4\( \pi \) coverage. This analysis relies on the inner detector, the calorimeter, and the data acquisition and trigger system.

The inner detector (ID) comprises three major subsystems: the pixel detector and the silicon microstrip tracker, which extend up to |\( \eta \)| = 2.5, and the transition radiation tracker, which extends to |\( \eta \)| = 2.0. The inner detector covers the full azimuth and is immersed in a 2 T axial magnetic field. The pixel detector consists of four cylindrical layers in the barrel region and three discs in each endcap region. A new innermost layer, the insertable B-layer [36, 37], has been operating as a part of the pixel detector since 2015. The silicon microstrip tracker comprises four cylindrical layers (nine discs) of silicon strip detectors in the barrel (endcap) region. The minimum-bias trigger scintillator detects charged particles over 2.07 < |\( \eta \)| < 3.86 using two hodoscopes of 12 counters positioned at |\( z \)| = 3.6 m.

The calorimeter is a large-acceptance, longitudinally segmented sampling detector covering |\( \eta \)| < 4.9 with electromagnetic (EM) and hadronic sections. The EM calorimeter is a lead/liquid-argon sampling calorimeter with an accordion-shaped geometry. It is divided into a barrel region, covering |\( \eta \)| < 1.475, and two endcap regions, covering 1.375 < |\( \eta \)| < 3.2. The hadronic calorimeter surrounds the EM calorimeter. It consists of a steel/scintillator-tile sampling calorimeter covering |\( \eta \)| < 1.7 and a liquid-argon calorimeter with copper absorber covering 1.5 < |\( \eta \)| < 3.2. The forward calorimeter (FCal) is a liquid-argon sampling calorimeter located on either side of the interaction point. It covers 3.1 < |\( \eta \)| < 4.9 and each half is composed of one EM and two hadronic sections, with copper and tungsten serving as the absorber material, respectively. The FCal is used to characterise the centrality of p+Pb collisions as described below.

In this analysis, a two-level trigger system was used to select events, with a first-level (L1) trigger implemented in hardware followed by a software-based high-level trig-

---

\(^{1}\) 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 (\( r, \phi \)) are used in the transverse plane, \( \phi \) being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \). Transverse momentum and transverse energy are defined as \( p_T = p \sin \theta \) and \( E_T = E \sin \theta \), respectively. Angular distance \( \Delta R \) is defined as \( \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \).
ger (HLT) which reconstructs the event in a manner similar to the final offline reconstruction. Events used for the measurements presented in this paper were selected using several triggers. MBT events were selected by a trigger that requires a signal in at least one minimum-bias trigger scintillator counter at L1 [38] followed by the requirement of at least one reconstructed track at the HLT stage. Events with a high-$p_T$ jet were acquired using a high-level jet trigger covering the central region ($|\eta| < 3.2$). These events were first required to have energy deposits at L1 that are compatible with the presence of a jet and then to pass various thresholds for the jet transverse energy at the HLT stage.

3 Data and event selection

During $p+$Pb data-taking in 2016, the LHC was configured with a beam composed of protons with an energy of 6.5 TeV and a beam of lead ions with an energy per nucleon of 2.51 TeV. This resulted in a collision system with proton–nucleon centre-of-mass energy $\sqrt{s_{\text{NN}}} = 8.16$ TeV and a rapidity shift of the centre of mass by $+0.465$ units in the proton-going direction relative to the laboratory frame. The data were taken over two running periods with different configurations of the LHC beam directions. In the first period of data-taking, comprising a total integrated luminosity of 57 nb$^{-1}$, the lead ions circulated counterclockwise in beam 1, while the protons circulated clockwise in beam 2. For the second period of data-taking, which comprised 108 nb$^{-1}$, the beam species were interchanged. The analysed data were provided by the minimum-bias trigger described above, which was prescaled and sampled 0.079 nb$^{-1}$ of luminosity. In addition, data were selected by the high-level jet triggers with transverse energy thresholds of 75 GeV and 100 GeV, which sampled 26 nb$^{-1}$ and the full 165 nb$^{-1}$ of $p+$Pb luminosity, respectively.

Events selected by the triggers described above were reconstructed offline following procedures that were optimised for the Run-2 detector configuration [39]. Events are required to have at least one reconstructed vertex. To reduce the contribution from events with multiple in-time $p+$Pb interactions, events with more than one vertex are used only if the additional vertices have fewer than seven associated reconstructed tracks with $p_T > 0.4$ GeV. That is, events are only allowed to have one vertex with seven or more associated tracks. Two classes of jet events were defined by requiring an offline jet with $p_T > 75$ GeV or $p_T > 100$ GeV respectively, and were drawn from the jet-triggered event samples with the analogous online thresholds. The trigger efficiency, given this offline selection, was greater than 97% for both jet samples.

Events were further characterised by the sum of the transverse energy in the FCal module in the direction of the Pb beam, $\Sigma E_{\text{T}}^\text{Pb}$. The event centrality is defined as the $\Sigma E_{\text{T}}^\text{Pb}$ percentile of the events in minimum-bias collisions, after accounting for the inefficiency introduced by the trigger and event selection criteria, and was determined in a way similar to previous analyses of Run-1 $p+$Pb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [27,40]. Events within the 0–90% centrality range were used in this analysis, with low (high) values corresponding to high-$\Sigma E_{\text{T}}^\text{Pb}$ (low-$\Sigma E_{\text{T}}^\text{Pb}$) events with large (small) overall particle multiplicity. Since the acceptance of the FCal is separate from that of the ID, this centrality definition has the benefit of reducing event-selection-induced biases in the measured quantities [41].

4 Track and jet reconstruction

The reconstruction, selection, and calibration of charged-particle tracks and calorimetric jets, and their performance as determined using Monte Carlo (MC) simulations, are described below.

Charged-particle tracks and collision vertices are reconstructed in the ID using the algorithms described in Ref. [39]. Inner detector tracks with $p_T > 0.4$ GeV and $|\eta| < 2.5$ were required to satisfy a set of quality criteria similar to those described in Ref. [19]. The total number of reconstructed ID tracks satisfying these selection criteria in a given event is called the multiplicity or $N_{\text{rec}}$. The reconstruction and selection efficiency for primary [42] charged hadrons to meet these criteria was determined using a sample of 3 million minimum-bias $p+$Pb events simulated by the HIJING generator [43]. Events were generated with both beam configurations. The ATLAS detector response to the generated events was determined through a full GEANT4 simulation [44,45], and the simulated events were reconstructed in the same way as the data. Over the measured kinematic range, the efficiency varies from approximately 50% for the lowest-$p_T$ hadrons at large pseudorapidity, to greater than 90% for hadrons with $p_T > 3$ GeV at mid-rapidity.

Jets are reconstructed using energy deposits in the calorimeter system, $|\eta| < 4.9$, in a range partially overlapping with both the ID and the FCal used to determine centrality. The reconstruction closely follows the procedure used in other measurements for Pb+Pb and $pp$ collisions [46,47]. Jets are measured by applying the anti-$k_t$ algorithm [48,49] with radius parameter $R = 0.4$ to energy deposits in the calorimeter. No jets with $p_T < 15$ GeV are considered. An iterative procedure is used to obtain an event-by-event estimate of the $n$-dependent underlying-event energy density, while excluding jets from that estimate. The jet kinematics are corrected for this background and for the detector response using an $n$- and $p_T$-dependent calibration derived from fully simulated and reconstructed PYTHIA 8 [50] hard-scattering events configured with the NNPDF23LO parton distribution func-
tion set [51] and the A14 set of tuned parameters [52] to model non-perturbative effects. An additional, small correction, based on in situ studies of jets recoiling against photons, Z bosons, and jets in other regions of the calorimeter, is applied [53,54]. Simulation studies show that for jets with $p_T > 75$ GeV, the average reconstructed jet $p_T$ is within 1% of the generator level jet $p_T$ and has a relative $p_T$ resolution below 10% after the calibration procedure.

5 Analysis procedure

This analysis is based on previous ATLAS two-particle correlation studies [19,20]. To construct the two-particle correlation functions, the selected inner-detector tracks with $p_T > 0.4$ GeV are divided into two sets, referred to as A- and B-particles in this paper, although they are sometimes referred to as trigger and associated particles in the literature. To reduce the contribution of non-flow correlations from decays and jets, two restrictions are placed on A–B particle pairs drawn from the two sets. First, as was done in previous analyses [19,20], the particles are required to be separated in pseudorapidity with $|\Delta\eta^{AB}| = |\eta^B - \eta^A| > 2$. This requirement removes the short-range decay and jet fragmentation structure, while emphasising global, early-time correlations. Due to the enhanced contribution from jet correlations in the jet-triggered events, an additional constraint was developed for this analysis. Namely, B-particles are required to be separated in pseudorapidity by one unit from all reconstructed jets with $p_T^{jet} > 15$ GeV, i.e. $|\Delta\eta^B| = |\eta^B - \eta^{jet}| > 1$. This latter requirement is only applied to the jet-triggered events, and in this way, the jets act as a source of high-$p_T$ A-particles but contribute few B-particles.

The correlation functions, $S(\Delta\phi)$, are defined as the yields of particle pairs passing the above event and pair selection, binned in $\Delta\phi = \phi^A - \phi^B$, and normalised by the total number of A-particles. Corrections for the imperfect trigger and tracking efficiencies are applied as weights to the entries of the correlation functions. A mixed-event correction, $M(\Delta\phi)$, is generated by correlating A-particles from one event with B-particles from a different event with a vertex $z$-position differing by less than 10 mm and a number of reconstructed charged particles ($N^{rec}_{ch}$) differing by less than 10 for $N^{rec}_{ch} < 100$ and less than 20 for $N^{rec}_{ch} > 100$. Thus, the mixed events contain only trivial detector acceptance effects and no physical correlations. To reduce the statistical uncertainty introduced by the correction, each event is mixed with five others meeting the above vertex $z$ and $N^{rec}_{ch}$ conditions. The corrected correlation is, then, $Y(\Delta\phi) = S(\Delta\phi)/M(\Delta\phi)$, where $M(\Delta\phi)$ is normalised such that the ratio preserves the overall integral of $S(\Delta\phi)$. Jet events are mixed with other jet events, and the $|\Delta\eta^B|$ condition is applied with respect to the jets in the A-particle event only. Thus, the B-particle acceptance is consistent between the same- and mixed-event correlations.

To extract the anisotropy coefficients while accounting for residual non-flow, the ATLAS template fitting procedure, as used for previous results [19,20], is applied to $Y(\Delta\phi)$. In this procedure, $Y(\Delta\phi)$ is found for two different selections of event activity quantified by centrality: a central selection, $Y^{cent}(\Delta\phi)$, and a peripheral selection, $Y^{peri}(\Delta\phi)$. In this analysis, the peripheral selection corresponds to the 60–90% centrality interval. Assuming that the shape of the non-flow correlation is independent of centrality, $Y^{cent}(\Delta\phi)$ is expressed as

$$Y^{cent}(\Delta\phi) = F Y^{peri}(\Delta\phi) + G \left[ 1 + 2 \sum_{n=2}^{4} v_{n,n} \cos(n \Delta\phi) \right],$$

where $F$ and each $v_{n,n}$ are parameters of a global $\chi^2$ fit, and $G$ is fixed by the requirement that the integral of the fit model is that of $Y^{cent}$. The parameter $F$ allows for a linear scaling of the non-flow between the two centrality classes. The fit includes the fourth harmonic, $v_{4,4}$, but it is not presented in the results because it is statistically insignificant. The fit $\chi^2$ function incorporates the statistical uncertainties from both $Y^{cent}$ and the peripheral template, $Y^{peri}$, although the examples shown in Figs. 1 and 2 do not show the uncertainties of $Y^{peri}$ for readability. The statistical uncertainties of the extracted $v_{n,n}$ parameters are returned from the MINUIT $\chi^2$ minimiser [55], accounting for correlations between parameters.

Figure 1 shows an example of two template fits using jet-triggered events with jet $p_T > 100$ GeV. The left plot shows the fit for correlations made without the B-particle jet rejection condition, and the right plot shows the same correlation, but with the condition $|\Delta\eta^{AB}| > 1$ applied. In this figure, $Y^{ridge}_{N}$ represents the $N^{th}$-order harmonic component of the fit. The left plot has a dominant non-flow contribution, and a distortion in the resulting subtracted distribution is observed near $\Delta\phi \approx \pi$. Removing much of the jet correlation in this way reduces the overall sensitivity to the template method assumption that the shape of the non-flow contribution is the same for the central and peripheral selections. However, violation of this assumption will introduce distortions that could potentially bias the harmonic coefficients. This is explicitly tested by varying the centrality selection of the peripheral template, as discussed further in Sect. 6. Two additional examples of template fits from the jet-triggered events with jet $p_T > 100$ GeV and with the B-particle jet rejection are plotted in Fig. 2. These show the behaviour of the template fits for high A-particle $p_T$.

If the particle momentum correlations originate from a global field, as is the case for collective expansion, the $v_{n,n}$ will factorise such that $v_{n,n}(p_T^A, p_T^B) = v_n(p_T^A) \cdot v_n(p_T^B)$. 
Fig. 1 Template fitting output for events with jet $p_T > 100$ GeV. Both require $3.5 < p_T^1 < 4.0$ GeV and are made with 60–90% peripheral selection and 0–5% central selection. The left plot is made with no selection on the B-particles and the right plot is made requiring the B-particles to have $|\Delta y| > 1$ relative to all jets with $p_T > 15$ GeV in the event. The upper panels, the open circles show the scaled and shifted peripheral template with uncertainties omitted, the closed circles show the central data, and the red line shows the fit (template and harmonic functions). The blue dashed line shows the second-order harmonic component, $Y_2^{\text{ridge}}$, and the orange dotted line shows the third-order harmonic component, $Y_3^{\text{ridge}}$ (the $n = 2$ and $n = 3$ contributions to the sum in Eq. 1, respectively). The lower panels show the difference between the central data and the peripheral template along with the second and third harmonic functions. The resulting $v_{2,2}$, $v_{3,3}$, and global fit $\chi^2$/NDF values are reported in the legends. In these fits, NDF= 35 and harmonic functions). By assuming this relation and making specific $p_T$ selections on A- and B-particles, the single-particle $v_n(p_T^A)$ can be obtained from

$$v_n(p_T^A) = v_{n,n}(p_T^A, p_T^B)/v_{n,n}(p_T^A, p_T^B),$$

where $v_{n,n}(p_T^A, p_T^B)$ is determined with A- and B-particles having $p_T$ in range $p_T^A$ and $p_T^B$, respectively, and $v_{n,n}(p_T^A, p_T^B)$ is determined with A- and B-particles both having $p_T$ in range $p_T^B$. In this analysis, this range is nominally $p_T^B > 0.4$ GeV, although the dependence of the extracted anisotropy on this choice is explored in Sect. 7.

The relative yield of particle pairs entering the correlation functions is estimated assuming a simple, two-component model of particle production. Particles are assumed to be produced either by hard scattering (HS) processes, such as jet production, or by soft underlying event (UE) processes. With this assumption, the correlation functions are constructed from pairs pulled from a mixture of the two sources. Particle pairs can be formed in the following four A–B combinations: UE–UE, UE–HS, HS–UE, and HS–HS. The event-by-event yields of the UE and HS processes are estimated by classifying the charged particles according to their azimuthal orientation relative to the leading jet or, in the case of MBT events that contain no jets with $p_T > 15$ GeV and $|\eta| < 4.9$, relative to the leading hadron. The following regions are defined relative to this leading vector:

- towards: $|\phi_B - \phi_{\text{jet}}| < \frac{\pi}{4}$ or $|\phi_B - \phi_{\text{jet}}| > \frac{3\pi}{4}$
- transverse: $\frac{\pi}{4} < |\phi_B - \phi_{\text{jet}}| < \frac{3\pi}{4}$

Then, assuming that HS particles are completely contained in the towards region and the UE particles are distributed uniformly in azimuth, the following relations are inferred:

$$N_{\text{UE}} = 2N_{\text{trans}},$$

$$N_{\text{HS}} = N_{\text{toward}} - N_{\text{trans}},$$

where $N_{\text{UE}}$ and $N_{\text{HS}}$ are the single-particle yields from UE and HS processes, respectively, and $N_{\text{trans}}$ and $N_{\text{toward}}$ are the particle yields in the transverse and toward regions, respectively. The quantities $N_{\text{UE}}$ and $N_{\text{HS}}$ are statistically determined from the event averaged $N_{\text{trans}}$ and $N_{\text{toward}}$ and are, thus, insensitive to event-by-event fluctuations. However, it is not possible to classify individual particles. It should be noted that the assumptions used in this derivation are likely not perfect; for example, the UE is not uniformly distributed in $\phi$, event by event, due to the presence of azimuthal anisotropy. The leading object may be more likely to be oriented with the
Fig. 2  Template fitting output for events with jet $p_T > 100$ GeV with 60–90% peripheral selection and 0–5% central selection. The left plot is made with $11 < p_T^A < 16$ GeV and the right plot with $16 < p_T^A < 100$ GeV. In the upper panels, the open circles show the scaled and shifted peripheral template with uncertainties omitted, the closed circles show the central data, and the red line shows the fit (template and harmonic functions). The blue dashed line shows the second-order harmonic component, $Y_2^{\text{ridge}}$, and the orange dotted line shows the third-order harmonic component, $Y_3^{\text{ridge}}$ (the $n = 2$ and $n = 3$ contributions to the sum in Eq. 1, respectively). The lower panels show the difference between the central data and the peripheral template along with the second and third harmonic functions. The resulting $v_2$, $v_3$, and global fit $\chi^2$/NDF values are reported in the legends. In these fits, NDF = 35.

6 Systematic uncertainties

The systematic uncertainties fall into two categories: those associated with both the MBT and jet events and those associated with only the jet events. The uncertainties are determined by assessing the difference between the nominal value of $v_2$ or $v_3$ and the value after a given variation. Unless otherwise stated, the uncertainties are defined as asymmetric one-standard-deviation errors. The final uncertainty is the quadrature sum of the uncertainty from each individual source. The relative downward and upward systematic uncertainties from different sources and all sources combined are shown for $v_2$ in Table 1 and for $v_3$ in Table 2. The rest of this section focuses primarily on the systematic uncertainties of $v_2$. While the absolute uncertainties in $v_2$ and $v_3$ are of similar magnitude, this represents larger relative uncertainties in the $v_3$ values since they are generally smaller than the $v_2$ values at any given $p_T$.

For both the MBT and jet events, the sensitivity to the trigger and tracking efficiency corrections was assessed by removing each. This variation (‘Track/trig Eff.’ in Table 1) yields a 0–2% (2–4%) difference for MBT (jet) events, depending on track $p_T$, and is subdominant. In the construction of the correlation functions, the uncertainty in the mixed-event correction was again found by removing it from the analysis. This variation results in an uncertainty that vanishes at low $p_T$ but grows to 20% (10%) at high $p_T$ for MBT (jet) events, but remains subdominant to statistical uncertainties over the whole $p_T$ range. Regarding the template fitting procedure, the centrality range for the peripheral reference anisotropy, in which case the UE yield would be underestimated and the HS yield overestimated. However, the analysis proceeds with the assumptions as given and includes no additional uncertainty for this potential effect.

The $\Delta \eta^{\text{AB}}$ and $\Delta \eta^{\text{IB}}$ rejections produce a geometric correlation between the yields of A- and B-particles and, thus, the number of pairs is not the simple product of the two individual yields. Accounting for the dependencies, the total yield of particle pairs can be expressed in the following way

$$Y_{X-Z} = \int_{-2.5}^{2.5} dN_A^X(\eta^A) \left[ \int_{2}^{5} d^2N_B^{\Delta \eta^{\text{AB}}}(\eta^A, |\Delta \eta^{\text{AB}}|) d|\Delta \eta^{\text{AB}}| \right] d\eta^A,$$

(2)

where $X-Z$ could be any pairwise combination of UE and HS. In the case of jet events, the $\Delta \eta^{\text{IB}}$ condition is enforced when filling the $\eta^A$ and $\Delta \eta^{\text{AB}}$ distributions so it’s effects are taken into account.

The systematic uncertainties fall into two categories: those associated with both the MBT and jet events and those associated with only the jet events. The uncertainties are determined by assessing the difference between the nominal value of $v_2$ or $v_3$ and the value after a given variation. Unless otherwise stated, the uncertainties are defined as asymmetric one-standard-deviation errors. The final uncertainty is the quadrature sum of the uncertainty from each individual source. The relative downward and upward systematic uncertainties from different sources and all sources combined are shown for $v_2$ in Table 1 and for $v_3$ in Table 2. The rest of this section focuses primarily on the systematic uncertainties of $v_2$. While the absolute uncertainties in $v_2$ and $v_3$ are of similar magnitude, this represents larger relative uncertainties in the $v_3$ values since they are generally smaller than the $v_2$ values at any given $p_T$.

For both the MBT and jet events, the sensitivity to the trigger and tracking efficiency corrections was assessed by removing each. This variation (‘Track/trig Eff.’ in Table 1) yields a 0–2% (2–4%) difference for MBT (jet) events, depending on track $p_T$, and is subdominant. In the construction of the correlation functions, the uncertainty in the mixed-event correction was again found by removing it from the analysis. This variation results in an uncertainty that vanishes at low $p_T$ but grows to 20% (10%) at high $p_T$ for MBT (jet) events, but remains subdominant to statistical uncertainties over the whole $p_T$ range. Regarding the template fitting procedure, the centrality range for the peripheral reference
Table 1 Systematic uncertainty summary for anisotropy coefficients $v_2$. The values are approximate, as they represent the average variation in each $p_T$ range, and are reported relative to $v_2$. Negative and positive values indicate downward and upward uncertainties respectively. Commas separate the downward and upward uncertainty where applicable.

<table>
<thead>
<tr>
<th>Source</th>
<th>$p_T &lt; 2$ GeV</th>
<th>$p_T = 2$–10 GeV</th>
<th>$p_T &gt; 10$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MBT</td>
<td>Jet</td>
<td>MBT</td>
</tr>
<tr>
<td>Track/trig Eff.</td>
<td>&lt; +1%</td>
<td>+2%</td>
<td>&lt; +1%</td>
</tr>
<tr>
<td>Mixed event</td>
<td>&lt; +1%</td>
<td>&lt; +1%</td>
<td>−4%</td>
</tr>
<tr>
<td>Peri. reference</td>
<td>−1, +2%</td>
<td>−2, +2%</td>
<td>−2, +10%</td>
</tr>
<tr>
<td>Trig jet $p_T$</td>
<td>−</td>
<td>&lt; +1%</td>
<td>−</td>
</tr>
<tr>
<td>Reject jet $p_T$</td>
<td>−</td>
<td>−2, +2%</td>
<td>−</td>
</tr>
<tr>
<td>Reject jet mult.</td>
<td>−</td>
<td>&lt; +1%</td>
<td>−</td>
</tr>
<tr>
<td>Disabled HEC sector</td>
<td>−</td>
<td>&lt; +1%</td>
<td>−</td>
</tr>
<tr>
<td>Jet-UE bias</td>
<td>−</td>
<td>−5%</td>
<td>−</td>
</tr>
<tr>
<td>Total</td>
<td>−1, +2%</td>
<td>−5, +4%</td>
<td>−5, +10%</td>
</tr>
</tbody>
</table>

Table 2 Systematic uncertainty summary for anisotropy coefficients $v_3$. The values are approximate, as they represent the average variation in each $p_T$ range, and are reported relative to $v_3$. Negative and positive values indicate downward and upward uncertainties respectively. Commas separate the downward and upward uncertainty where applicable.

<table>
<thead>
<tr>
<th>Source</th>
<th>$p_T &lt; 2$ GeV</th>
<th>$p_T = 2$–10 GeV</th>
<th>$p_T &gt; 10$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MBT</td>
<td>Jet</td>
<td>MBT</td>
</tr>
<tr>
<td>Track/trig Eff.</td>
<td>+1%</td>
<td>+4%</td>
<td>&lt; +6%</td>
</tr>
<tr>
<td>Mixed event</td>
<td>&lt; +1%</td>
<td>−4%</td>
<td>−20%</td>
</tr>
<tr>
<td>Peri. reference</td>
<td>−2, +2%</td>
<td>−7, +10%</td>
<td>−8, +8%</td>
</tr>
<tr>
<td>Trig jet $p_T$</td>
<td>−</td>
<td>&lt; +1%</td>
<td>−</td>
</tr>
<tr>
<td>Reject jet $p_T$</td>
<td>−</td>
<td>−2, +2%</td>
<td>−</td>
</tr>
<tr>
<td>Reject jet mult.</td>
<td>−</td>
<td>&lt; +1%</td>
<td>−</td>
</tr>
<tr>
<td>Disabled HEC sector</td>
<td>−</td>
<td>−2%</td>
<td>−</td>
</tr>
<tr>
<td>Total</td>
<td>−2, +2%</td>
<td>−10, +10%</td>
<td>−20, +10%</td>
</tr>
</tbody>
</table>

Fig. 3 Distribution of $v_2$ (left) and $v_3$ (right) plotted as a function of the $A$-particle $p_T$. Values from MBT events are plotted as black squares, and those from events with jet $p_T > 75$ GeV and events with jet $p_T > 100$ GeV are plotted as blue circles and orange diamonds respectively. Statistical uncertainties are shown as narrow vertical lines on each point, and systematic uncertainties are presented as coloured boxes behind the points.
Fig. 4 Measured $v_2$ values plotted as a function of the A-particle $p_T$ for MBT events (top), events with jet $p_T > 75$ GeV (bottom left), and events with jet $p_T > 100$ GeV (bottom right). The nominal values (closed black circles) are overlaid with points generated by making different B-particle $p_T$ selections: $0.4 < p_T^B < 1$ GeV (blue open circles), $1 < p_T^B < 2$ GeV (open violet squares), and $2 < p_T^B < 3$ GeV (open red triangles). The points with different B-particle $p_T$ selections are offset slightly from the nominal horizontal-axis positions to make the uncertainties visible. For clarity, systematic uncertainties are omitted from the three sets of restricted B-particle $p_T$ ranges; they are, however, consistent with those from the inclusive results and are highly correlated between the selections.

Selection was varied from the nominal 60–90% to 50–70% and 70–90%. This variation (‘Peri. reference’) results in an uncertainty of about 2% at low $p_T$ and increasing to about 10% or 18% in the mid $p_T$ range between 2 and 10 GeV depending on the event trigger. This last uncertainty is dominant in this category for most of the $p_T$ range probed in the measurement. At high $p_T$, the sensitivity of the measurements in MBT events to the mixed event correction and reference selection is significantly higher than in jet events; this is particularly noticeable for the $v_2$ values, where the relative uncertainties in the MBT events for $p_T > 10$ GeV are 5–10 times larger than in the jet-triggered events.

The following set of uncertainties is associated with jet events only. To assess the sensitivity to the uncertainty in the jet energy scale and the impact of imperfect trigger efficiency, the jet $p_T$ thresholds used to select events were varied from 75 GeV and 100 GeV to 80 GeV and 105 GeV, respectively. This variation (‘Trig jet $p_T$’) results in a symmetric uncertainty that is smaller than 1% at low particle $p_T$ and that increases to about 10% with increasing $p_T$. It is subdominant to other sources in this category. The jets used in the B-particle jet rejection were varied to include only jets with $p_T$ greater than 20 GeV instead of the nominal 15 GeV (‘Reject jet $p_T$’). The 2% and 10% differences at low and high $p_T$ are incorporated as a symmetric uncertainty that is subdominant to other sources in this category. The $1/\Delta R^2$ rejection allows jets to be composed of only a single particle that may originate in the tail of the UE particle $p_T$ spectrum. Thus, the jets used in this rejection were varied to require at least three tracks in a $1/\Delta R < 0.4$ cone around the jet axis (‘Reject jet mult.’). The uncertainty associated with this variation is about 5% and subdominant to the others in this category. An additional uncertainty is used to cover the impact of a sector of the hadronic endcap calorimeter (HEC) being disabled for the running period. The disabled sector was in the range $1.5 < \eta < 3.2$ and $-\pi < \phi < -\pi/2$. This uncer-
Fig. 5 Distribution of $v_2$ plotted as a function of centrality for MBT events (black squares), events with jet $p_T > 75$ GeV (blue circles), and events with jet $p_T > 100$ GeV (orange diamonds). The results are obtained in three different selections of the A-particle $p_T$: $0.5 < p_T < 2$ GeV (top left), $2 < p_T < 9$ GeV (top right), and $9 < p_T < 100$ GeV (bottom). Statistical uncertainties are shown as narrow vertical lines on each point, and systematic uncertainties are presented as coloured boxes behind the points.

tainty (‘Disabled HEC sector’) was assessed by requiring all B-particles to be outside the pseudorapidity region of the disabled HEC. The difference was found to be less than 1% at low $p_T$ and about 20% at high $p_T$, where it is the dominant positive uncertainty. Finally, an uncertainty is assigned to account for the potential of the UE to bias the event selection. The azimuthal modulation of the UE increases the reconstructed $p_T$ of jets aligned with the flow orientation, and, thus, the event-wise jet-$p_T$ threshold will bias the events to have more jets correlated with the flow plane. The impact of this effect on the measured results was assessed in simulation by mixing jet events with a realistic UE containing azimuthal anisotropy. The resulting uncertainty only affects $v_2$, is the dominant negative uncertainty for track $p_T$ greater than 3 GeV, and is about 30% (20%) for jet-triggered events with jet $p_T > 75$ GeV (100 GeV). The effect is larger for lower-$p_T$ jets because the UE energy contribution is independent of jet energy. For a power-law spectrum, a given threshold change has a greater fractional effect on the yield for smaller values of the threshold.

In summary, the uncertainty in $v_2$ from the peripheral reference selection was found to be dominant for $p_T$ less than 10 GeV for MBT events, above which, the mixed event correction uncertainty is dominant, and between 2 and 5 GeV for jet events. The uncertainties associated with the jet selection were found to be dominant for $p_T \gtrsim 10$ GeV in jet events. The total uncertainty in MBT events ranges from $(-1\%, +2\%)$ at low $p_T$ to about $(-10\%, +25\%)$ at high $p_T$. For jet events, the total uncertainty ranges from about $(-5\%, +4\%)$ at low $p_T$ to about $(-35\%, +50\%)$ and $(-30\%, +25\%)$ at high $p_T$ for events with jet $p_T > 75$ GeV and jet $p_T > 100$ GeV respectively.

The uncertainties associated with the measurement of particle pair yields are generated from some of the variations discussed above, namely the track and trigger efficiency variation, the trigger jet $p_T$ threshold variation, and each B-particle jet rejection variation. An additional variation was made to
test the assumption that the toward region contains all HS particles. The two transverse region sides were tagged as having the minimum and maximum number of tracks out of the two. The pair yields were, then, calculated using the minimum and maximum sides only, as separate variations. This variation produces the dominant uncertainty in the relative pair yields, defined in Eq. (2), for all particle combinations at all \( p_T \).

7 Results

Figure 3 shows the extracted second- \((v_2)\) and third-order \((v_3)\) anisotropy coefficients for the MBT events compared to those from both selections of jet events plotted as a function of A-particle \(p_T\) in the range \(0.5 < p_T < 100\) GeV. Each set of values is from events with the same 0–5% centrality selection. Points are located on the horizontal axis at the mean \(p_T\) of tracks within any given bin. The \(v_2\) and \(v_3\) coefficients increase as a function of \(p_T\) in the low \(p_T\) region \((p_T < 2–3\) GeV\), then decrease \((2–3 < p_T < 9\) GeV\), and finally plateau for high \(p_T\) \((p_T > 9\) GeV\). The \(v_2\) coefficients are consistent with being independent of \(p_T\) for \(p_T > 9\) GeV, while the larger uncertainties in the values of \(v_3\) preclude any strong conclusion.

The \(v_2\) results show agreement within uncertainties between the MBT and jet events for the low \(p_T\) \((p_T \lesssim 2\) GeV\) and high \(p_T\) \((p_T \gtrsim 9\) GeV\) regions. For the intermediate \(p_T\) region, the MBT events yield a higher \(v_2\) value than jet events, although the trends are qualitatively similar. Similarly to \(v_2\), the \(v_3\) results show agreement between the MBT and jet events for \(p_T < 2\) GeV, and higher values from MBT events for \(p_T > 2\) GeV.

As mentioned in Sect. 5, if the measured anisotropy originates from a global momentum field, the \(v_2\) and \(v_3\) values,
Fig. 8 Predictions of azimuthal anisotropy from PYTHIA 8 using the same two-particle formalism used for the data results. The events combine minimum-bias $p+Pb$ underlying events generated in the Angantyr framework with hard $pp$ events that require the presence of a jet with $p_T > 100$ GeV. The two top plots show example correlation functions, with template fits, from a low particle-$p_T$ selection (top left) and a high particle-$p_T$ selection (top right). In the upper panels of the two top plots, the open circles show the scaled and shifted peripheral template with uncertainties omitted, the closed circles show the central data, and the red histogram shows the fit (template and harmonic functions). The blue dashed line shows the second-order harmonic component, $Y_{2}^{\text{ridge}}$, and the orange dashed line shows the third-order harmonic component, $Y_{3}^{\text{ridge}}$ (the $n = 2$ and $n = 3$ contributions to the sum in Eq. 1, respectively). The lower panels show the difference between the central data and the peripheral template along with the second and third harmonic functions. The resulting $v_2$, $v_3$, and global fit $\chi^2/\text{NDF}$ values are reported in the legends, where NDF = 35. The bottom plot shows the extracted $v_{2,2}$ values as a function of $A$-particle $p_T$ extracted for a given $p_T^A$ range, will be independent of B-particle selection. This assumption of factorisation is explicitly tested by carrying out the analysis for different selections of $p_T^B$. Figure 4 shows the $v_2$ values, from each event trigger, for the nominal results using $p_T^B > 0.4$ GeV overlaid with results using $0.4 < p_T^B < 1$ GeV, $1 < p_T^B < 2$ GeV, and $2 < p_T^B < 3$ GeV. The test shows factorisation breaking at the level of 5% for $p_T^A < 5$ GeV in MBT events. However, at higher $p_T^A$, the differences grow with $p_T^A$ to be 10–100% from the nominal values. For jet events, factorisation holds within about 10–20% for all values of $p_T^A$, except for $4 < p_T^A < 9$ GeV in $p_T^{\text{jet}} > 100$ GeV events, where it is within about 30–40%. Although the large uncertainties prevent strong conclusions from being drawn, there is a hint of a difference in behaviour at high $p_T^A$ where the factorisation breaking is greater for MBT events than for jet events. This result could be due to the B-particle jet rejection scheme used for the jet events. Correlations resulting from hard-process,
e.g. from back-to-back jets, specifically violate the factorisation assumption, and the B-particle jet rejection dramatically limits the contribution from these processes from entering the correlation functions in jet events. However, the correlations from MBT events have no such rejection, and could, therefore, be more susceptible to hard-process correlations at high \( \rho^A_{v2} \).

Figure 5 shows \( v_2 \) plotted as a function of centrality for MBT events and both classes of jet events. The results are divided into three regions in A-particle \( p_T \): 0.5 < \( p_T \) < 2 GeV, 2 < \( p_T \) < 9 GeV, and 9 < \( p_T \) < 100 GeV. The \( v_2 \) results show agreement, within uncertainties, between the MBT and jet events for \( p_T \) selections 0.5 < \( p_T \) < 2 GeV and \( p_T \) > 9 GeV for all centralities and are found to be nearly independent of centrality. For 2 < \( p_T \) < 9 GeV, the MBT events give a higher \( v_2 \) value than the jet events, and all three sets show a trend to lower values of \( v_2 \) as the collisions become more peripheral.

Focusing on the overall \( p_T \) dependence of the anisotropies, Fig. 6 (left panel) shows \( v_2 \) and \( v_3 \) coefficients from events with jet \( p_T \) > 100 GeV compared with theoretical calculations from Ref. [14]. This theoretical calculation, within the jet quenching paradigm, invokes a stronger parton coupling to the QGP near the transition temperature, which helps to reduce the tension in simultaneously matching the nucleus–nucleus high-\( p_T \) hadron spectrum suppression and the azimuthal anisotropy \( v_2 \). The calculation tests two different initial \( p+Pb \) geometries referred to as ‘size a’ and ‘size b’, where the latter has a smaller initial QGP volume. The predictions are slightly lower than the data for both \( v_2 \) and \( v_3 \), and the ‘size a’ curve is within two standard deviations of all points. However, in the right panel of Fig. 6, the same calculation predicts a substantial suppression of high-\( p_T \) hadrons, as expressed by the quantity \( R_{pT} = \frac{d^2N_{pT}}{dp_t dy} / (T_{pT} \times d^2\sigma_{pp} / dp_t dy) \) where \( T_{pT} \) represents the nuclear thickness of the Pb nucleus, as determined via a Monte Carlo Glauber calculation [56]. Shown in comparison are published experimental results from ATLAS and ALICE for \( R_{pT} \) in central events that are consistent with no nuclear suppression, i.e. \( R_{pT} = 1 \) [41,57]. The ALICE experiment uses the notation \( Q_{pT} \) for the same quantity to describe a bias that may exist due to the centrality categorisation. There are uncertainties in the experimental measurements related to the centrality or multiplicity selection in \( p+Pb \) collisions, particularly in determining the nuclear thickness value \( T_{pT} \). However, there is no indication of the large \( R_{pT} \) suppression predicted by the jet quenching calculation. Thus, the jet quenching calculation is disfavoured as it cannot simultaneously describe the non-zero high-\( p_T \) azimuthal anisotropy and the lack of yield suppression.

Figure 7 shows the MBT \( v_2 \) and \( v_3 \) coefficients compared with theoretical calculations from Ref. [26]. The calculations are derived from two opposite limits of kinetic theory. The low momentum bands represent zeroth-order hydrodynamic calculations for high-multiplicity \( p+Pb \) events that give quantitative agreement with \( v_2 \) up to \( p_T = 2 \) GeV while predicting values of \( v_3 \) that are too high. Above some high \( p_T \) threshold, hadrons are expected to result, not from hydrodynamics, but instead from jets where the resulting partons have the opposite limit than in hydrodynamics, i.e. a large mean free path. To model this region, a non-hydrodynamic ‘eremitic’ expansion calculation (see Ref. [26] for the detailed calculation), shown as the bands at high \( p_T \), indicates slowly declining \( v_2 \) and \( v_3 \) coefficients. The dashed lines are a simple Padé-type fit connecting the two regimes [26]. The trends are qualitatively similar to those in the data, although there is not quantitative agreement. In particular, the calculation predicts values of \( v_2 \) and \( v_3 \) substantially below the experimental results for \( p_T = 4–15 \) GeV. It should be noted that calculations presented in Ref. [26] are performed, consistently between the hydrodynamic and eremitic components, only for massless partons and with an ideal equation of state. Thus, one does not expect quantitative agreement and is looking for rather qualitative trends. More sophisticated treatments in the hydrodynamic regime result in better quantitative agreement with the anisotropy coefficients at low \( p_T \) [58,59]. It is worth highlighting that traditional parton energy-loss calculations connect the high-\( p_T \) \( v_2 \) with a suppression in the overall yield of high-\( p_T \) particles. The same is true with this eremitic calculation, and thus, it should also be in contradistinction to \( p+Pb \) high-\( p_T \) experimental data indicating almost no suppression, i.e. jet quenching.
Another possible source of the high-$p_T$ anisotropies could lie in an initial-state effect, potentially encoded in a model such as Pythia 8. Shown in Fig. 8 is a Pythia 8 calculation with hard $pp$ events overlaid on minimum-bias $p$+Pb events generated in the default Angantyr framework [60]. It is emphasised that this version of Pythia does not include the recently developed string-string, or so-called string shoving, implementation [61]. The generator-level charged particles are then processed with the entire analysis procedure, including the non-flow template fit. The result is a negative $v_{2,2}$ for all momenta, in contradistinction to the experimental data. Further investigation reveals that Pythia 8 run in ‘hard’ scattering mode has correlations with large pseudorapidity separation between particle pairs as a result of the specific implementation of initial-state radiation. This correlation is reduced in high-multiplicity events because of the large number of uncorrelated UE particles, and thus results in a negative $v_{2,2}$ after subtracting the non-flow contribution.

Figure 9 shows the published Pb+Pb results for $v_2$ as a function of $p_T$ in the 20–30% centrality selection [62] compared to the $v_2$ from both the MBT $p$+Pb data and $p$+Pb containing a jet with $p_T > 100$ GeV. This Pb+Pb centrality range is selected because the spatial elliptic eccentricity is approximately the same as in 0–5% centrality $p$+Pb collisions [63], despite having a much larger total particle multiplicity. The overall trends for Pb+Pb $v_2$ as a function of $p_T$ are qualitatively similar to those presented here for $p$+Pb from MBT events and the jet events with jet $p_T > 100$ GeV. Both sets of the $p$+Pb values are scaled by a single multiplicative factor (1.5) to match the Pb+Pb rise at low $p_T$. After scaling, the MBT $p$+Pb results quantitatively agree with those from the Pb+Pb system for $0.5 < p_T < 8$ GeV, except for a slight difference in the peak value near $p_T \approx 3$ GeV. For $p_T$ above about 8 GeV, the Pb+Pb results indicate a slow decline of $v_2$ values with increasing $p_T$, while the $p$+Pb results exhibit...
more of a plateau. Strikingly, the overall behaviour of the $v_2$ values are quite similar.

As described above, the physics interpretations of the Pb+Pb elliptic anisotropies are hydrodynamic flow at low $p_T$, differential jet quenching at high $p_T$, and a transition between the two in the intermediate region of approximately $2 < p_T < 10$ GeV. Since these effects all relate to the initial QGP geometric inhomogeneities, a common shape with a single scaling factor for $p+Pb$ could indicate a common physics interpretation. This scaling factor of 1.5, as empirically determined, may be the result of slightly different initial spatial deformations, or from the much larger Pb+Pb overall multiplicity, which enables a stronger translation of spatial deformations into momentum space. For the high $p_T$ region, this presents a conundrum in that it is difficult for differential jet quenching to cause the $v_2$ anisotropy in $p+Pb$ collisions when there is no evidence for jet quenching overall. These measurements showing non-zero high $p_T$ $v_2$ in $p+Pb$ collisions in the absence the jet quenching observed in Pb+Pb collisions suggest there might be additional contributions to $v_2$ at high $p_T$ in Pb+Pb collisions.

Returning to the issue of the difference in the intermediate $p_T$ region between the $p+Pb$ MBT and jet event results, the source of hadrons in this region should be considered. As detailed previously, in a highly simplified picture one can classify hadrons as originating from hard scatterings (HS) or from the underlying event (UE). Thus, pairs of particles of A and B types can come from the combinations HS–HS, HS–UE, UE–HS, and UE–UE. Figure 10 presents the measured pair fractions for both MBT and jet, 0–5% central events plotted as a function of the A-particle $p_T$. UE–UE pairs dominate the correlation functions at low $p_T$ in each case, and HS–UE combinations dominate at high $p_T$. Combinations with HS B-particles are sub-dominant, because there are fewer jet particles than UE particles in central events; for the jet selected events, these combinations are further suppressed by the B-particle jet rejection condition. Figure 11 shows the dominant contributions from the MBT and jet events overlaid. Although the same qualitative behaviour is found in each case, the point at which the HS–UE pairs become dominant over the other combinations is at a lower $p_T$ for jet events than for MBT events.

This behaviour can also be seen in Fig. 12, in which the pair fractions are plotted as a function of centrality, and again, the values for MBT and jet events are overlaid. The centrality-dependent results are plotted for low, medium, and high A-particle $p_T$ ranges in the same way as in Fig. 5. At low $p_T$, pair fractions from MBT and jet events agree, and in the mid-$p_T$ transition region, MBT events have a larger UE–UE contribution and smaller HS–UE contribution compared to jet events. At high $p_T$, central events show a difference between UE–UE and HS–UE that is reduced in more-peripheral events and absent for more peripheral than 25% centrality. The overall trend of the pair fractions with centrality is quite similar to that of $v_2$ shown in Fig. 5; little centrality dependence for low and high $p_T$, and significant centrality dependence in addition to MBT–jet event ordering in the mid-$p_T$ transition region.

Thus, a potential explanation for the lower $v_2$ and $v_3$ in the intermediate $p_T$ region is simply that, in that region, the HS particles have lower anisotropy coefficients than UE particles, and MBT events have a larger fraction of UE–UE pairs than jet-triggered events. In the low and high $p_T$ regions, the same types of pairs dominate in both the MBT and jet-triggered events, namely UE–UE and HS–UE respectively, and hence the anisotropy coefficients agree between the event samples. If this explanation is correct, it also aids in understanding Fig. 9 in which there is a significant difference between the $p+Pb$ jet event $v_2$ and the Pb+Pb $v_2$ in the intermediate $p_T$ region, because the relative pair fractions are potentially significantly different.

This particle mixing picture is attractive in that it naturally explains the general shape of the $v_2(p_T)$ and $v_3(p_T)$ distributions as well as the ordering of the different event samples. However, it is noted that the correspondence between the differences in the flow coefficients and pair fractions is not quantitative; the differences in the flow coefficients are fractionally much larger than the differences in the pair fractions. Thus, there are either additional sources of correlation or our assumptions are violated in some way (e.g. the two assumed HS and UE sources are too simplistic or the measured pair fractions do not accurately represent the sources, as is discussed in Sect. 5). That said, for particle $p_T > 20$ GeV, where
Fig. 12 Underlying event–underlying event (UE–UE) (open circles) and hard scatter–underlying event (HS–UE) (open squares) particle-pair yield composition fractions for MBT events (black), events with jet $p_T > 75$ GeV (blue), and events with jet $p_T > 100$ GeV (orange) plotted as a function of event centrality. The results are obtained in three different selections of the $A$-particle $p_T$: $0.5 < p_T < 2$ GeV (top left), $2 < p_T < 9$ GeV (top right), and $9 < p_T < 100$ GeV (bottom). Statistical uncertainties are shown as narrow vertical lines on each point, and systematic uncertainties are presented as coloured boxes behind the points.

particle production in any model is thought to arise mainly from jet fragmentation, the non-zero $v_2$ demonstrates that a positive correlation exists between hard (high $p_T$) and soft (low $p_T$) particles, irrespective of the pair fractions.

8 Conclusion

This paper presents Fourier coefficients of the azimuthal distribution of unidentified charged particles from 165 nb$^{-1}$ of $\sqrt{s_{NN}} = 8.16$ TeV $p+Pb$ collisions at the LHC and measured with the ATLAS detector. Results are presented separately for minimum-bias and jet events, with jet $p_T$ thresholds of 75 and 100 GeV, as a function of particle $p_T$ and centrality. The results are extracted using two-particle azimuthal correlations combined with a non-flow template fit procedure. The charged particle $p_T$ dependence of $v_2$ and $v_3$ is found assuming the factorisation of $v_{n,n}$. The $v_2$ results are presented for charged-particle transverse momentum $p_T = 0.5$–20 GeV for minimum-bias events and $p_T = 0.5$–50 GeV for jet-triggered events, and the $v_3$ results are for $p_T = 0.5$–20 GeV in both cases.

For charged particles with $p_T$ between 0.5 and 2 GeV, the $v_n$ results from each event selection are quantitatively consistent with each other, rising steadily with $p_T$, and the $v_2$ coefficients are roughly independent of centrality. The $v_2$ values at 0–5% centrality agree with those predicted by hydrodynamic calculations.

Between charged particle $p_T$ of 2 and 9 GeV, the $v_n$ values drop in each case, but are ordered with minimum-bias events yielding the highest $v_n$ values and the jet events with jet $p_T > 100$ GeV the lowest. Charged particles in this $p_T$ range exhibit a significant centrality-dependent $v_2$, monotonically decreasing from central to peripheral events. This behaviour can be qualitatively explained within a simplified two-component model of particle production, in which the magnitude of the correlation in this region is determined by the admixture of charged particles originating from soft and hard processes in the given event selection. The measured particle pair yields support this qualitative argument.
For charged particles with $p_T$ above 9 GeV, the $v_2$ results are again consistent between MBT and jet events. Although the uncertainties in the $v_2$ values make any quantitative statement difficult, $v_2$ plateaus at a value of 0.025 up to a $p_T$ of 50 GeV. This result cannot be explained in the theoretical context of jet quenching or eremitic expansion calculations while simultaneously describing the observed lack of suppression of high-$p_T$ hadron and jet yields in $p+Pb$ collisions.

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 and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DLR and DFFR, Germany; INFN, Italy; INFN, Italy; IN2P3-CNRS, CEA-DRF/IRFU, France; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MINSW and NCN, Poland; FCT, Portugal; MINEPIA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MEST and MS, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and IDEX, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, Spain; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway and Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [64].

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors’ comment: All ATLAS scientific output is published in journals, and preliminary results are made available in Conference Notes. All are openly available, without restriction on use by external parties beyond copyright law and the standard conditions agreed by CERN. Data associated with journal publications are also made available: tables and data from plots (e.g. cross section values, likelihood profiles, selection efficiencies, cross section limits, ...) are stored in appropriate repositories such as HEPDATA (http://hepdata.cedar.ac.uk/). ATLAS also strives to make additional material related to the paper available that allows a reinterpretation of the data in the context of new theoretical models. For example, an extended encapsulation of the analysis is often provided for measurements in the framework of RIVET (http://rivet.hepforge.org/). This information is taken from the ATLAS Data Access Policy, which is a public document that can be downloaded from http://opendata.cern.ch/record/413 [opendata.cern.ch].]

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/. Funded by SCOAP3.

References

9 Physics Department, National and Kapodistrian University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Department of Physics, University of Texas at Austin, Austin, TX, USA
12 (a) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; (b) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; (c) Department of Physics, Bogazici University, Istanbul, Turkey; (d) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
13 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
14 Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
15 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China; (b) Physics Department, Tsinghua University, Beijing, China; (c) Department of Physics, Nanjing University, Nanjing, China; (d) University of Chinese Academy of Science (UCAS), Beijing, China
16 Institute of Physics, University of Belgrade, Belgrade, Serbia
17 Department for Physics and Technology, University of Bergen, Bergen, Norway
18 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, USA
19 Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
20 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
21 School of Physics and Astronomy, University of Birmingham, Birmingham, UK
22 Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogota, Colombia
23 (a) Dipartimento di Fisica, INFN Bologna and Universita` di Bologna, Bologna, Italy; (b) INFN Sezione di Bologna, Bologna, Italy
24 Physikalisches Institut, Universität Bonn, Bonn, Germany
25 Department of Physics, Boston University, Boston, MA, USA
26 Department of Physics, Brandeis University, Waltham, MA, USA
27 (a) Transilvania University of Brasov, Brasov, Romania; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania; (e) University Politehnica Bucharest, Bucharest, Romania; (f) West University in Timisoara, Timisoara, Romania
28 (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
29 Physics Department, Brookhaven National Laboratory, Upton, NY, USA
30 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
31 California State University, USA
32 Cavendish Laboratory, University of Cambridge, Cambridge, UK
33 (a) Department of Physics, University of Cape Town, Cape Town, South Africa; (b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa; (c) Pretoria, South Africa; (d) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
34 Department of Physics, Carleton University, Ottawa, ON, Canada
35 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies, Université Hassan II, Casablanca, Morocco; (b) Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Marrakesh, Morocco; (d) Faculté des Sciences, Université Mohamed Premier et LPTPM, Oujda, Morocco; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
36 CERN, Geneva, Switzerland
37 Enrico Fermi Institute, University of Chicago, Chicago, IL, USA
38 LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
39 Nevis Laboratory, Columbia University, Irvington, NY, USA
40 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
41 (a) Dipartimento di Fisica, Università della Calabria, Rende, Italy; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy
42 Physics Department, Southern Methodist University, Dallas, TX, USA
43 Physics Department, University of Texas at Dallas, Richardson, TX, USA
44 National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece
(a) Department of Physics, Stockholm University, Stockholm, Sweden; (b) Oskar Klein Centre, Stockholm, Sweden

Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany

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

Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

Department of Physics, Duke University, Durham, NC, USA

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

INFN e Laboratori Nazionali di Frascati, Frascati, Italy

Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany

Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland

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

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

SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, UK

LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, USA

(a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China; (b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China; (c) School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China; (d) Tsung-Dao Lee Institute, Shanghai, China

(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

(a) Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China; (b) Department of Physics, University of Hong Kong, Hong Kong, China; (c) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

Department of Physics, National Tsing Hua University, Hsinchu, Taiwan

Department of Physics, Indiana University, Bloomington, IN, USA

(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy; (b) ICTP, Trieste, Italy; (c) Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy

(a) INFN Sezione di Lecce, Lecce, Italy; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy

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

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

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

(a) INFN Sezione di Pisa, Pisa, Italy; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

(a) INFN Sezione di Roma, Rome, Italy; (b) Dipartimento di Fisica, Sapienza Università di Roma, Rome, Italy

(a) INFN Sezione di Roma Tor Vergata, Rome, Italy; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Rome, Italy

(a) INFN Sezione di Roma Tre, Rome, Italy; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Rome, Italy

(a) INFN-TIFPA, Trento, Italy; (b) Università degli Studi di Trento, Trento, Italy

Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

University of Iowa, Iowa City, IA, USA

Department of Physics and Astronomy, Iowa State University, Ames, IA, USA

Joint Institute for Nuclear Research, Dubna, Russia

(a) Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil; (b) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil; (c) Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil; (d) Instituto de Física, Universidade de São Paulo, São Paulo, Brazil

KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

Graduate School of Science, Kobe University, Kobe, Japan

(a) AGH University of Science and Technology Faculty of Physics and Applied Computer Science, Krakow, Poland; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

Faculty of Science, Kyoto University, Kyoto, Japan
Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisbon, Portugal; Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal; Departamento de Física, Universidade de Coimbra, Coimbra, Portugal; Centro de Física Nuclear da Universidade de Lisboa, Lisbon, Portugal; Departamento de Física, Universidad del Minho, Braga, Portugal; Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain; Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal; Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic

Czech Technical University in Prague, Prague, Czech Republic

Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic

Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, USA

Department de Física, Pontificia Universidad Católica de Chile, Santiago, Chile; Universidad Andres Bello, Department of Physics, Santiago, Chile; Departamento de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile

Department of Physics, University of Washington, Seattle, WA, USA

Department of Physics and Astronomy, University of Sheffield, Sheffield, UK

Department of Physics, Shinshu University, Nagano, Japan

Department Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby, BC, Canada

SLAC National Accelerator Laboratory, Stanford, CA, USA

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA

Department of Physics and Astronomy, University of Sussex, Brighton, UK

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia; High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Tomsk State University, Tomsk, Russia

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

TRIUMF, Vancouver, BC, Canada; Department of Physics and Astronomy, York University, Toronto, ON, Canada

Division of Physics and Tonomaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford, MA, USA

Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA

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

Department of Physics, University of Illinois, Urbana, IL, USA

Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain

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

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

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
Department of Physics, University of Warwick, Coventry, UK
Waseda University, Tokyo, Japan
Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison, WI, USA
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven, CT, USA

\(^a\) Also at Borough of Manhattan Community College, City University of New York, New York, NY, USA
\(^b\) Also at CERN, Geneva, Switzerland
\(^c\) Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
\(^d\) Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland
\(^e\) Also at Departament de Física de la Universitat Autonoma de Barcelona, Barcelona, Spain
\(^f\) Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates
\(^g\) Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
\(^h\) Also at Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA
\(^i\) Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY, USA
\(^j\) Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel
\(^k\) Also at Department of Physics, California State University, East Bay, USA
\(^l\) Also at Department of Physics, California State University, Fresno, USA
\(^m\) Also at Department of Physics, California State University, Sacramento, USA
\(^n\) Also at Department of Physics, King’s College London, London, UK
\(^o\) Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
\(^p\) Also at Department of Physics, Stanford University, Stanford, CA, USA
\(^q\) Also at Department of Physics, University of Adelaide, Adelaide, Australia
\(^r\) Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
\(^s\) Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy
\(^t\) Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
\(^u\) Also at Giresun University, Faculty of Engineering, Giresun, Turkey
\(^v\) Also at Graduate School of Science, Osaka University, Osaka, Japan
\(^w\) Also at Hellenic Open University, Patras, Greece
\(^x\) Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
\(^y\) Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
\(^z\) Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands
\(^{aa}\) Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
\(^{ab}\) Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
\(^{ac}\) Also at Institute of Particle Physics (IPP), Vancouver, Canada
\(^{ad}\) Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
\(^{ae}\) Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid, Spain
\(^{af}\) Also at Joint Institute for Nuclear Research, Dubna, Russia
\(^{ag}\) Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
\(^{ah}\) Also at Louisiana Tech University, Ruston, LA, USA
\(^{ai}\) Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
\(^{aj}\) Also at National Research Nuclear University MEPhI, Moscow, Russia
\(^{ak}\) Also at Physics Department, An-Najah National University, Nablus, Palestine
\(^{al}\) Also at Physics Dept, University of South Africa, Pretoria, South Africa
\(^{am}\) Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
\(^{an}\) Also at The City College of New York, New York, NY, USA
\(^{ao}\) Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
ap Also at TRIUMF, Vancouver, BC, Canada
aq Also at Universita di Napoli Parthenope, Naples, Italy
*Deceased