Observation of Associated Near-Side and Away-Side Long-Range Correlations in $\sqrt{s_{NN}} = 5.02$ TeV Proton-Lead Collisions with the ATLAS Detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

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Two-particle correlations in relative azimuthal angle ($\Delta\phi$) and pseudorapidity ($\Delta\eta$) are measured in $\sqrt{s_{\rm NN}} = 5.02$ TeV $p + \rm Pb$ collisions using the ATLAS detector at the LHC. The measurements are performed using approximately 1 $\mu\rm b^{-1}$ of data as a function of transverse momentum ($p_{\rm T}$) and the transverse energy ($\Sigma E_{\rm T}^{\rm Pb}$) summed over $3.1 < \eta < 4.9$ in the direction of the Pb beam. The correlation function, constructed from charged particles, exhibits a long-range ($2 < |\Delta\eta| < 5$) "near-side" ($\Delta\phi \sim 0$) correlation that grows rapidly with increasing $\Sigma E_{\rm T}^{\rm Pb}$. A long-range "away-side" ($\Delta\phi \sim \pi$) correlation, obtained by subtracting the expected contributions from recoiling dijets and other sources estimated using events with small $\Sigma E_{\rm T}^{\rm Pb}$, is found to match the near-side correlation in magnitude, shape (in $\Delta\eta$ and $\Delta\phi$) and $\Sigma E_{\rm T}^{\rm Pb}$ dependence. The resultant $\Delta\phi$ correlation is approximately symmetric about $\pi/2$, and is consistent with a dominant $\cos 2\Delta\phi$ modulation for all $\Sigma E_{\rm T}^{\rm Pb}$ ranges and particle $p_{\rm T}$.

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Proton-nucleus ($p + A$) collisions at the Large Hadron Collider (LHC) provide both an interesting environment for the study of QCD at high parton density and important baseline measurements, especially for the interpretation of results from the LHC Pb + Pb program [1]. In particular, it has been suggested that $p + \rm Pb$ collisions at LHC energies are an important system for the study of a possible saturation of the growth of parton densities at low Bjorken-x.

High-multiplicity events provide a rich environment for studying observables associated with high parton densities in hadronic collisions. An important tool to probe the physics of these events is the two-particle correlation function measured in terms of the relative pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\phi$) of selected particle pairs, $C(\Delta\eta, \Delta\phi)$. The first studies of two-particle correlation functions in the highest-multiplicity $p + p$ collisions at the LHC [2] showed an enhanced production of pairs of particles at $\Delta\phi \sim 0$, with the correlation extending over a wide range in $\Delta\eta$, a feature frequently referred to as a "ridge." Many of the physics mechanisms proposed to explain the $p + p$ ridge, including multiparton interactions [3], parton saturation [4–6], and collective expansion of the final state [7], are also expected to be relevant in $p + \rm Pb$ collisions. A recent measurement by the CMS Collaboration [8] has demonstrated that a ridge is clearly visible over $|\Delta\eta| < 4$ in high-multiplicity $p + \rm Pb$ collisions at the LHC. During final preparation of this Letter, the ALICE Collaboration submitted a Letter addressing similar physics, within the range $|\Delta\eta| < 1.8$, with some differences in the analysis technique [9].

To provide further insight into the physical origin of these long-range correlations, this Letter presents ATLAS measurements of two-particle angular correlations over $|\Delta\eta| < 5$ in $p + \rm Pb$ collisions, based on an integrated luminosity of approximately 1 $\mu\rm b^{-1}$ recorded during a short run in September 2012. The LHC was configured with a 4 TeV proton beam and a 1.57 TeV per-nucleon Pb beam that together produced collisions with a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\rm NN}} = 5.02$ TeV and a rapidity shift of −0.47 relative to the ATLAS rest frame [10].

The measurements presented in this Letter are performed using the ATLAS inner detector (ID), forward calorimeters (FCal), minimum-bias trigger scintillators (MBTS), and the trigger and data acquisition systems [11]. The ID measures charged particles within $|\eta| < 2.5$ using a combination of silicon pixel detectors, silicon microstrip detectors, and a straw-tube transition radiation tracker, all immersed in a 2 T axial magnetic field [12]. The MBTS detect charged particles over $2.1 < |\eta| < 3.9$ using two hodoscopes of 16 counters positioned at $z = \pm 3.6$ m. The FCal consists of two sections that cover $3.1 < |\eta| < 4.9$. The FCal modules are composed of tungsten and copper absorbers with liquid argon as the active medium, which together provide 10 interaction lengths of material. Minimum-bias $p + \rm Pb$ collisions are selected by a trigger that requires a signal in at least two MBTS counters.

The $p + \rm Pb$ events used for this analysis are required to have a reconstructed vertex containing at least two associated tracks, with its z position satisfying $|z_{\rm vtx}| < 150$ mm. Noncollision backgrounds and photonuclear interactions are suppressed by requiring at least one hit in a MBTS counter on each side of the interaction point,

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[*] Full author list given at the end of the article.

and the difference between times measured on the two sides to be less than 10 ns. Events containing multiple $p + \mathrm{Pb}$ collisions (pileup) are suppressed by rejecting events with two reconstructed vertices that are separated in z by more than 15 mm. The residual pileup fraction is estimated to be $\lesssim 10^{-4}$. About 1.95×10^6 events pass these event selection criteria.

Charged particle tracks are reconstructed in the ID using an algorithm optimized for $p + p$ minimum-bias measurements [13]. In this analysis, the tracks are required to have $p_\mathrm{T} > 0.3$ GeV and $|\eta| < 2.5$, at least seven hits in the silicon detectors (out of a typical value of 11), and a hit in the first pixel layer when one is expected. In addition, the transverse (d_0) and longitudinal ($z_0 \sin\theta$) impact parameters of the tracks measured with respect to the primary vertex are required to be less than 1.5 mm and to satisfy $|d_0/\sigma_{d_0}| < 3$ and $|z_0 \sin\theta/\sigma_z| < 3$, respectively, where σ_{d_0} and σ_z are uncertainties on d_0 and $z_0 \sin\theta$ obtained from the track-fit covariance matrix.

The efficiency, $\epsilon(p_\mathrm{T}, \eta)$, for track reconstruction and track selection cuts is evaluated using $p + \mathrm{Pb}$ Monte Carlo events produced with the HIJING event generator [14] with a center-of-mass boost matching the beam conditions. The response of the detector is simulated using GEANT4 [15,16] and the resulting events are reconstructed with the same algorithms as applied to the data. The efficiency increases with p_T by 6% between 0.3 and 0.5 GeV, and varies only weakly for $p_\mathrm{T} > 0.5$ GeV, where it ranges from 82% at $\eta = 0$ to 70% at $|\eta| = 2$ and 60% at $|\eta| > 2.4$. It is also found to vary by less than 2% over the range of $\Sigma E_\mathrm{T}^\mathrm{Pb}$ observed in the $p + \mathrm{Pb}$ data.

The two-particle correlation (2PC) analyses are performed in different intervals of $\Sigma E_\mathrm{T}^\mathrm{Pb}$, the sum of transverse energy measured in the FCal with $3.1 < \eta < 4.9$ (in the z direction of the lead beam) with no correction for the difference in response to electrons and hadrons. The distribution of $\Sigma E_\mathrm{T}^\mathrm{Pb}$ for events passing all selection criteria is shown in Fig. 1. These events are divided into 12 $\Sigma E_\mathrm{T}^\mathrm{Pb}$ intervals (indicated by vertical lines in Fig. 1) to study the variation of 2PC with overall event activity. Two larger intervals, $\Sigma E_\mathrm{T}^\mathrm{Pb} > 80$ GeV and $\Sigma E_\mathrm{T}^\mathrm{Pb} < 20$ GeV, containing 2% and 52% of the events, respectively, hereafter referred to as "central" and "peripheral," are used for detailed studies of the 2PC at high and low overall event activity. The quantity $\Sigma E_\mathrm{T}^\mathrm{Pb}$ instead of charged particle multiplicity is used to characterize the event activity, since the latter is observed to have strong correlations with the 2PC measurements, particularly for events selected with low and high multiplicities. However, for reference, the average ($\langle N_\mathrm{ch} \rangle$) and the standard deviation (σ_{N_ch}) of the efficiency-corrected multiplicity of charged particles with $p_\mathrm{T} > 0.4$ GeV and $|\eta| < 2.5$ have been calculated for each $\Sigma E_\mathrm{T}^\mathrm{Pb}$ range, yielding $\langle N_\mathrm{ch} \rangle = 150 \pm 7$, $\sigma_{N_\mathrm{ch}} = 35 \pm 2$ for central events and $\langle N_\mathrm{ch} \rangle = 25 \pm 1$, $\sigma_{N_\mathrm{ch}} = 18 \pm 1$ for peripheral events.

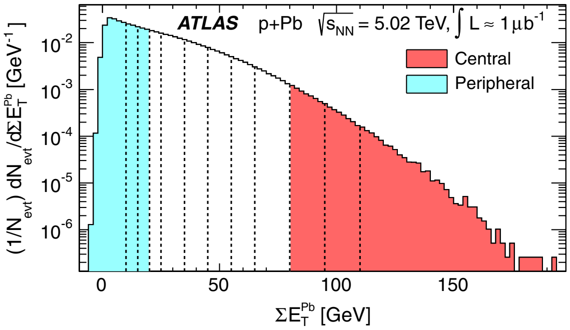

FIG. 1 (color online). Distribution of $\Sigma E_\mathrm{T}^\mathrm{Pb}$ for minimum-bias $p + \mathrm{Pb}$ events. Vertical lines indicate the boundaries of the event activity classes. Shaded bands indicate the larger peripheral and central intervals having $\Sigma E_\mathrm{T}^\mathrm{Pb} < 20$ GeV and $\Sigma E_\mathrm{T}^\mathrm{Pb} > 80$ GeV, respectively.

The correlation functions are given [17–19] by

$$C(\Delta\phi, \Delta\eta) = \frac{S(\Delta\phi, \Delta\eta)}{B(\Delta\phi, \Delta\eta)}, \qquad C(\Delta\phi) = \frac{S(\Delta\phi)}{B(\Delta\phi)}, \quad (1)$$

where $\Delta\phi = \phi_a - \phi_b$ and $\Delta\eta = \eta_a - \eta_b$ and S and B represent pair distributions constructed from the same event and from "mixed events," [20] respectively. The labels a and b denote the two particles in the pair (conventionally referred to as "trigger" and "associated" particles, respectively [8]), which may be selected from different p_T intervals. The mixed-event distribution, $B(\Delta\phi, \Delta\eta)$, that measures uncorrelated pair yields was constructed by choosing pairs of particles from different events of similar z_vtx and track multiplicity, to match the effects of detector acceptance, occupancy, and material on $S(\Delta\phi, \Delta\eta)$, and of similar $\Sigma E_\mathrm{T}^\mathrm{Pb}$. The 1D distributions $S(\Delta\phi)$ and $B(\Delta\phi)$ are obtained by integrating $S(\Delta\phi, \Delta\eta)$ and $B(\Delta\phi, \Delta\eta)$, respectively, over $2 < |\Delta\eta| < 5$. This $|\Delta\eta|$ range is chosen to focus on the long-range features of the correlation functions. The normalization of $C(\Delta\phi, \Delta\eta)$ is chosen such that the $\Delta\phi$-averaged value of $C(\Delta\phi)$ is unity. To correct $S(\Delta\phi, \Delta\eta)$ and $B(\Delta\phi, \Delta\eta)$ for the inefficiencies, each particle is weighted by the inverse of the tracking efficiency. Remaining detector distortions not accounted for in the efficiency largely cancel in the same-event to mixed-event ratio.

Examples of 2D correlation functions are shown in Figs. 2(a) and 2(b) for charged particles with $0.5 < p_\mathrm{T}^{a,b} < 4$ GeV in peripheral and central events. The correlation function for peripheral events shows a sharp peak centered at $(\Delta\phi, \Delta\eta) = (0, 0)$ due to pairs originating from the same jet, Bose-Einstein correlations, as well as high-p_T resonance decays, and a broad structure at $\Delta\phi \sim \pi$ from dijets, low-p_T resonances, and momentum conservation that is collectively referred to as "recoil" in the remainder of this Letter. In the central events, the correlation function reveals a ridgelike structure at $\Delta\phi \sim 0$ (the near-side) that extends over the full measured $\Delta\eta$ range, with an amplitude of a few percent. The distribution at $\Delta\phi \sim \pi$

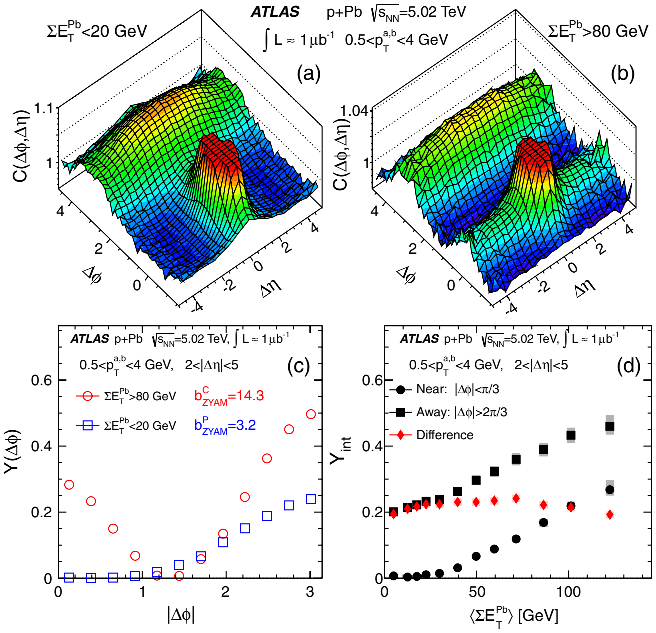

FIG. 2 (color online). Two-dimensional correlation functions for (a) peripheral events and (b) central events, both with a truncated maximum to suppress the large correlation at $(\Delta\eta, \Delta\phi) = (0, 0)$; (c) the per-trigger yield $\Delta\phi$ distribution together with pedestal levels for peripheral ($b^{\rm P}_{\rm ZYAM}$) and central ($b^{\rm C}_{\rm ZYAM}$) events, and (d) integrated per-trigger yield as function of $\Sigma E_{\rm T}^{\rm Pb}$ for pairs in $2 < |\Delta\eta| < 5$. The shaded boxes represent the systematic uncertainties, and the statistical uncertainties are smaller than the symbols.

(the away-side) is also broadened relative to peripheral events, consistent with the presence of a long-range component in addition to that seen in peripheral events.

The strength of the long-range component is quantified by the "per-trigger yield," $Y(\Delta\phi)$, which measures the average number of particles correlated with each trigger particle, folded into the 0-π range [2,17–19],

$$Y(\Delta\phi) = \left(\frac{\int B(\Delta\phi)d\Delta\phi}{\pi N_a}\right)C(\Delta\phi) - b_{\rm ZYAM}, \qquad (2)$$

where N_a denotes the number of efficiency-weighted trigger particles, and $b_{\rm ZYAM}$ represents the pedestal arising from uncorrelated pairs. The parameter $b_{\rm ZYAM}$ is determined via a zero-yield-at-minimum (ZYAM) method [17,21] in which a second-order polynomial fit to $C(\Delta\phi)$ is used to find the location of the minimum point, $\Delta\phi_{\rm ZYAM}$, and from this to determine $b_{\rm ZYAM}$. The stability of the fit is studied by varying the $\Delta\phi$ fit range. The uncertainty in $b_{\rm ZYAM}$ depends on the local curvature around $\Delta\phi_{\rm ZYAM}$, and is estimated to be 0.03%–0.1% of the minimum value of $C(\Delta\phi)$. At high $p_{\rm T}$ where the number of measured counts is low, this uncertainty is of the same order as the statistical uncertainty.

The systematic uncertainties due to the tracking efficiency are found to be negligible for $C(\Delta\phi)$, since detector effects largely cancel in the correlation function ratio. However $Y(\Delta\phi)$ is sensitive to the uncertainty on the tracking efficiency correction for the associated particles. This uncertainty is estimated by varying the track quality cuts and the detector material in the simulation, reanalyzing the data using corresponding Monte Carlo efficiencies and evaluating the change in the extracted $Y(\Delta\phi)$. The resulting uncertainty on $Y(\Delta\phi)$ is estimated to be 2.5% due to the track selection and 2%–3% related to the limited knowledge of detector material. The analysis procedure is validated by measuring correlation functions in fully simulated HIJING events [15,16] and comparing it to the correlations measured using the generated particles. The agreement is better than 2% for $C(\Delta\phi)$ and better than 3% for $Y(\Delta\phi)$.

Figure 2(c) shows the $Y(\Delta\phi)$ distributions for $2 < |\Delta\eta| < 5$ in peripheral and central events separately. The yield for the peripheral events has an approximate $1 - \cos\Delta\phi$ shape with an away-side maximum, characteristic of a recoil contribution. In contrast, the yield in the central events has near-side and away-side peaks with the away-side peak having a larger magnitude. These features are consistent with the onset of a significant $\cos 2\Delta\phi$ component in the distribution. To quantify further the properties of these long-range components, the distributions are integrated over $|\Delta\phi| < \pi/3$ and $|\Delta\phi| > 2\pi/3$, and plotted as a function of $\Sigma E_{\rm T}^{\rm Pb}$ in Fig. 2(d). The near-side yield is close to 0 for $\Sigma E_{\rm T}^{\rm Pb} < 20$ GeV and increases with $\Sigma E_{\rm T}^{\rm Pb}$, consistent with the CMS result [8]. The away-side yield shows a similar variation as a function of $\Sigma E_{\rm T}^{\rm Pb}$, except that it starts at a value significantly above zero, even for events with low $\Sigma E_{\rm T}^{\rm Pb}$. The yield difference between these two regions is found to be approximately independent of $\Sigma E_{\rm T}^{\rm Pb}$, indicating that the growth in the yield with increasing $\Sigma E_{\rm T}^{\rm Pb}$ is the same on the near-side and away-side.

To further investigate the connection between the near-side and away-side, the $Y(\Delta\phi)$ distributions for peripheral and central events are shown in Fig. 3 in various $p_{\rm T}^a$ ranges with $0.5 < p_{\rm T}^b < 4$ GeV. Distributions of the difference between central and peripheral yields, $\Delta Y(\Delta\phi)$, are also shown in this Figure. This difference is observed to be nearly symmetric around $\Delta\phi = \pi/2$. To illustrate this symmetry, the $\Delta Y(\Delta\phi)$ distributions in Fig. 3 are overlaid with functions $a_0 + 2a_2\cos 2\Delta\phi$ and $a_0 + 2a_2\cos 2\Delta\phi + 2a_3\cos 3\Delta\phi$, with the coefficients calculated as $a_n = \langle\Delta Y(\Delta\phi)\cos n\Delta\phi\rangle$. Using only the a_0 and a_2 terms describes the ΔY distributions reasonably well, indicating that the long-range component of the two-particle correlations can be approximately described by a recoil contribution plus a $\Delta\phi$-symmetric component. The inclusion of the a_3 term improves slightly the agreement with the data.

The near-side and away-side yields integrated over $|\Delta\phi| < \pi/3$ and $|\Delta\phi| > 2\pi/3$, respectively ($Y_{\rm int}$), and the differences between those integrated yields in central and peripheral events ($\Delta Y_{\rm int}$) are shown in Fig. 4 as a function of $p_{\rm T}^a$. The yields are shown separately for the two $\Sigma E_{\rm T}^{\rm Pb}$ ranges in panels (a) and (b) and the differences

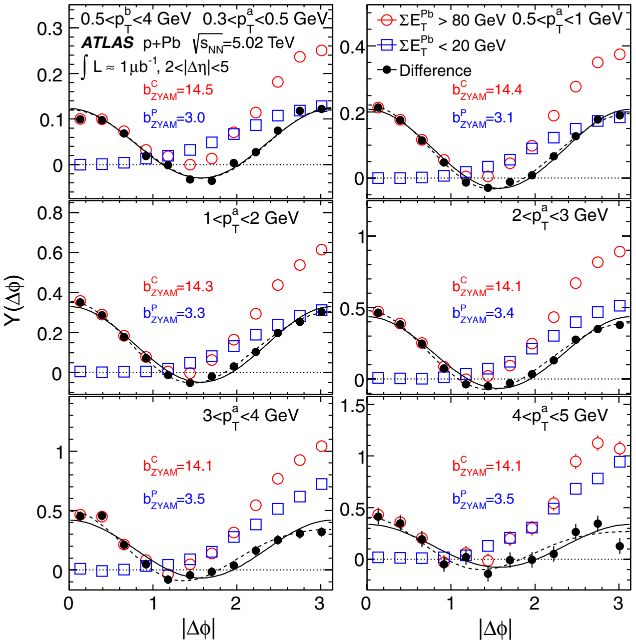

FIG. 3 (color online). Distributions of per-trigger yield in the peripheral and the central event activity classes and their differences (solid symbols), for different ranges of p_{T}^{a} and $0.5 < p_{\mathrm{T}}^{b} < 4\mathrm{GeV}$, together with functions $a_0 + 2a_2 \cos 2\Delta\phi$ (solid line) and $a_0 + 2a_2 \cos 2\Delta\phi + 2a_3 \cos 3\Delta\phi$ (dashed line) obtained via a Fourier decomposition (see text). The values for the ZYAM-determined pedestal levels are indicated on each panel for peripheral ($b_{\mathrm{ZYAM}}^{\mathrm{P}}$) and central ($b_{\mathrm{ZYAM}}^{\mathrm{C}}$) $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ bins.

are shown in panels (c) and (d). Qualitatively, the differences have a similar p_{T}^{a} dependence and magnitude on the near-side and away-side; they rise with p_{T}^{a} and reach a maximum around 3–4 GeV. This pattern is visible for the near-side even before subtraction, as shown in panel (a), but is less evident in the unsubtracted away-side due to the dominant contribution of the recoil component. A similar dependence is observed for long-range correlations in Pb + Pb collisions at approximately the same p_{T} [22,23].

The relative amplitude of the $\cos n\Delta\phi$ modulation of $\Delta Y(\Delta\phi)$, c_n, for $n = 2, 3$ can be estimated using a_n, and the extracted value of b_{ZYAM} for central events,

$$c_n = a_n/(b_{\mathrm{ZYAM}}^{\mathrm{C}} + a_0). \tag{3}$$

Figure 4(e) shows c_2 and c_3 as a function of p_{T}^{a} for $0.5 < p_{\mathrm{T}}^{b} < 4$ GeV. The value of c_2 is much larger than c_3 and exhibits a behavior similar to $\Delta Y(\Delta\phi)$ at the near-side and away-side. Using the techniques discussed in Ref. [23], c_n can be converted into an estimate of s_n, the average nth Fourier coefficient of the event-by-event single-particle ϕ distribution, by assuming the factorization relation $c_n(p_{\mathrm{T}}^{a}, p_{\mathrm{T}}^{b}) = s_n(p_{\mathrm{T}}^{a}) s_n(p_{\mathrm{T}}^{b})$. From this, $s_n(p_{\mathrm{T}}^{a})$ is calculated as $s_n(p_{\mathrm{T}}^{a}) = c_n(p_{\mathrm{T}}^{a}, p_{\mathrm{T}}^{b})/\sqrt{c_n(p_{\mathrm{T}}^{b}, p_{\mathrm{T}}^{b})}$, where $c_n(p_{\mathrm{T}}^{b}, p_{\mathrm{T}}^{b})$ is obtained from Eq. (3) using the a_n extracted from the difference between the central and peripheral data shown in Fig. 2(c). The $s_2(p_{\mathrm{T}}^{a})$ values obtained this way exceed 0.1 at ~2–4 GeV, as shown in Fig. 4(f). The $s_3(p_{\mathrm{T}}^{a})$ values are smaller than $s_2(p_{\mathrm{T}}^{a})$ over the measured p_{T} range. The factorization relation used to compute $s_2(p_{\mathrm{T}}^{a})$ is found to be valid within 10%–20% when selecting different subranges of p_{T}^{b} within 0.5–4 GeV, while the precision of $s_3(p_{\mathrm{T}}^{a})$ data does not allow a quantitative test of the factorization. The analysis is also repeated for correlation functions separately constructed from like-sign pairs and unlike-sign pairs, and the resulting c_n and s_n coefficients are found to be consistent within their statistical and systematic uncertainties.

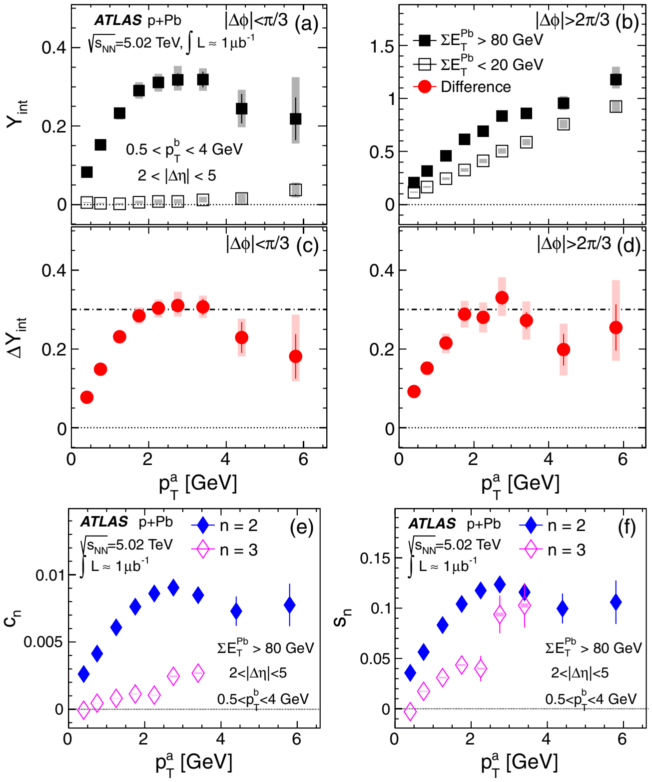

FIG. 4 (color online). Integrated per-trigger yields, Y_{int} (see text), vs p_{T}^{a} for $0.5 < p_{\mathrm{T}}^{b} < 4$ GeV in peripheral and central events, on the (a) near-side and (b) away-side. The panels (c) and (d) show the difference, ΔY_{int}. Panels (e) and (f) show the p_{T} dependence of c_n and s_n for $n = 2, 3$, respectively. The error bars and shaded boxes represent the statistical and systematic uncertainties, respectively.

In summary, ATLAS has measured two-particle correlation functions in $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV p + Pb collisions in different intervals of $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ over $2 < |\Delta\eta| < 5$. An away-side contribution is observed that grows rapidly with increasing $\Sigma E_{\mathrm{T}}^{\mathrm{Pb}}$ and which matches many essential features of the near-side ridge observed here, as well as in previous high-multiplicity $p + p$, p + Pb and Pb + Pb data at the LHC. Thus, while the ridge in $p + p$ and p + Pb collisions has been characterized as a near-side phenomenon, these results show that it has both near-side and away-side components that are symmetric around $\Delta\phi \sim \pi/2$, with a $\Delta\phi$ dependence that is approximately described by a $\cos 2\Delta\phi$

modulation. A Fourier decomposition of the correlation function, $C(\Delta\phi)$, yields a pair $\cos 2\Delta\phi$ amplitude of about 0.01 at $p_T \sim 3$ GeV, corresponding to a single-particle amplitude of about 0.1. Similar findings are obtained independently by the ALICE Collaboration [9], albeit over a more restricted phase space ($|\Delta\eta| < 1.8$ and $p_T <$ 2–4 GeV). The two results are found to be consistent within this common region.

Some of the features of the data, including the presence of an away-side component, are qualitatively predicted in the color glass condensate approach [6], which models saturation of the parton distribution in the Pb nucleus. The estimated amplitudes of the modulation on the single-particle level are also found to be comparable in magnitude and p_T dependence to similar modulations observed in heavy-ion collisions, commonly attributed to collective expansion of the hot, dense matter [23]. Thus, although the original motivation for this work was to study the possible effects of high parton density in the initial state of $p+\mathrm{Pb}$ collisions, the results presented here are also consistent with contributions of final-state collective effects in high-multiplicity events [24,25].

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L. Adamczyk,[38] D. L. Adams,[25] T. N. Addy,[56] J. Adelman,[176] S. Adomeit,[98] P. Adragna,[75] T. Adye,[129] S. Aefsky,[23]

J. A. Aguilar-Saavedra,[124b,c] M. Agustoni,[17] S. P. Ahlen,[22] F. Ahles,[48] A. Ahmad,[148] M. Ahsan,[41] G. Aielli,[133a,133b]
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I. Wilhelm,[127] H. G. Wilkens,[30] J. Z. Will,[98] E. Williams,[35] H. H. Williams,[120] S. Williams,[28] W. Willis,[35,a]
S. Willocq,[84] J. A. Wilson,[18] M. G. Wilson,[143] A. Wilson,[87] I. Wingerter-Seez,[5] S. Winkelmann,[48] F. Winklmeier,[30]
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G. Wooden,[87] B. K. Wosiek,[39] J. Wotschack,[30] M. J. Woudstra,[82] K. W. Wozniak,[39] K. Wraight,[53] M. Wright,[53]
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C. Xu,[33b,y] D. Xu,[33a] L. Xu,[33b] B. Yabsley,[150] S. Yacoob,[145a,ll] M. Yamada,[65] H. Yamaguchi,[155] A. Yamamoto,[65]
K. Yamamoto,[63] S. Yamamoto,[155] T. Yamamura,[155] T. Yamanaka,[155] K. Yamauchi,[101] T. Yamazaki,[155]
Y. Yamazaki,[66] Z. Yan,[22] H. Yang,[33e] H. Yang,[173] U. K. Yang,[82] Y. Yang,[109] Z. Yang,[146a,146b] S. Yanush,[91] L. Yao,[33a]
Y. Yasu,[65] E. Yatsenko,[42] J. Ye,[40] S. Ye,[25] A. L. Yen,[57] M. Yilmaz,[4b] R. Yoosoofmiya,[123] K. Yorita,[171] R. Yoshida,[6]
K. Yoshihara,[155] C. Young,[143] C. J. Young,[118] S. Youssef,[22] D. Yu,[25] D. R. Yu,[15] J. Yu,[8] J. Yu,[112] L. Yuan,[66]

A. Yurkewicz,[106] B. Zabinski,[39] R. Zaidan,[62] A. M. Zaitsev,[128] S. Zambito,[23] L. Zanello,[132a,132b] D. Zanzi,[99] A. Zaytsev,[25] C. Zeitnitz,[175] M. Zeman,[126] A. Zemla,[39] O. Zenin,[128] T. Ženiš,[144a] D. Zerwas,[115] G. Zevi della Porta,[57] D. Zhang,[87] H. Zhang,[88] J. Zhang,[6] L. Zhang,[151] X. Zhang,[33d] Z. Zhang,[115] L. Zhao,[108] Z. Zhao,[33b] A. Zhemchugov,[64] J. Zhong,[118] B. Zhou,[87] N. Zhou,[163] Y. Zhou,[151] C. G. Zhu,[33d] H. Zhu,[42] J. Zhu,[87] Y. Zhu,[33b] X. Zhuang,[33a] V. Zhuravlov,[99] A. Zibell,[98] D. Zieminska,[60] N. I. Zimin,[64] R. Zimmermann,[21] S. Zimmermann,[21] S. Zimmermann,[48] Z. Zinonos,[122a,122b] M. Ziolkowski,[141] R. Zitoun,[5] L. Živković,[35] V. V. Zmouchko,[128,a] G. Zobernig,[173] A. Zoccoli,[20a,20b] M. zur Nedden,[16] V. Zutshi,[106] and L. Zwalinski[30]

(ATLAS Collaboration)

[1]*School of Chemistry and Physics, University of Adelaide, Adelaide, Australia*
[2]*Physics Department, SUNY Albany, Albany, New York, USA*
[3]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[4a]*Department of Physics, Ankara University, Ankara, Turkey*
[4b]*Department of Physics, Gazi University, Ankara, Turkey*
[4c]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[4d]*Turkish Atomic Energy Authority, Ankara, Turkey*
[5]*LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, The University of Texas at Arlington, Arlington ,Texas, USA*
[9]*Physics Department, University of Athens, Athens, Greece*
[10]*Physics Department, National Technical University of Athens, Zografou, Greece*
[11]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[12]*Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain*
[13a]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[13b]*Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
[14]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[15]*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*
[16]*Department of Physics, Humboldt University, Berlin, Germany*
[17]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[18]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[19a]*Department of Physics, Bogazici University, Istanbul, Turkey*
[19b]*Division of Physics, Dogus University, Istanbul, Turkey*
[19c]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[20a]*INFN Sezione di Bologna, Italy*
[20b]*Dipartimento di Fisica, Università di Bologna, Bologna, Italy*
[21]*Physikalisches Institut, University of Bonn, Bonn, Germany*
[22]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[23]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[24a]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[24b]*Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil*
[24c]*Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil*
[24d]*Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
[25]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[26a]*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[26b]*University Politehnica Bucharest, Bucharest, Romania*
[26c]*West University in Timisoara, Timisoara, Romania*
[27]*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
[28]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[29]*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
[30]*CERN, Geneva, Switzerland*
[31]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
[32a]*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
[32b]*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[33a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[33b]*Department of Modern Physics, University of Science and Technology of China, Anhui, China*
[33c]*Department of Physics, Nanjing University, Jiangsu, China*

[33d]*School of Physics, Shandong University, Shandong, China*
[33e]*Physics Department, Shanghai Jiao Tong University, Shanghai, China*
[34]*Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France*
[35]*Nevis Laboratory, Columbia University, Irvington, New York, USA*
[36]*Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
[37a]*INFN Gruppo Collegato di Cosenza, Italy*
[37b]*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
[38]*AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland*
[39]*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland*
[40]*Physics Department, Southern Methodist University, Dallas, Texas, USA*
[41]*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
[42]*DESY, Hamburg and Zeuthen, Germany*
[43]*Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
[44]*Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany*
[45]*Department of Physics, Duke University, Durham, North Carolina, USA*
[46]*SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[47]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[48]*Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany*
[49]*Section de Physique, Université de Genève, Geneva, Switzerland*
[50a]*INFN Sezione di Genova, Italy*
[50b]*Dipartimento di Fisica, Università di Genova, Genova, Italy*
[51a]*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[51b]*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, Virginia, USA*
[57]*Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA*
[58a]*Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[58b]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[58c]*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, Indiana, USA*
[61]*Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
[62]*University of Iowa, Iowa City, Iowa, USA*
[63]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
[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*
[72a]*INFN Sezione di Lecce, Italy*
[72b]*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
[73]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[74]*Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia*
[75]*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
[76]*Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
[77]*Department of Physics and Astronomy, University College London, London, United Kingdom*
[78]*Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
[79]*Fysiska institutionen, Lunds universitet, Lund, Sweden*
[80]*Departamento de Fisica 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, Massachusetts, USA*

[85]*Department of Physics, McGill University, Montreal, Quebec, Canada*
[86]*School of Physics, University of Melbourne, Victoria, Australia*
[87]*Department of Physics, The University of Michigan, Ann Arbor, Michigan, USA*
[88]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
[89a]*INFN Sezione di Milano, Italy*
[89b]*Dipartimento di Fisica, Università di Milano, Milano, Italy*
[90]*B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus*
[91]*National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus*
[92]*Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[93]*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*
[94]*P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia*
[95]*Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[96]*Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia*
[97]*D.V. Skobeltsyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia*
[98]*Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[99]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[100]*Nagasaki Institute of Applied Science, Nagasaki, Japan*
[101]*Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
[102a]*INFN Sezione di Napoli, Italy*
[102b]*Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy*
[103]*Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA*
[104]*Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands*
[105]*Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[106]*Department of Physics, Northern Illinois University, DeKalb, Illinois, USA*
[107]*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
[108]*Department of Physics, New York University, New York, New York, USA*
[109]*Ohio State University, Columbus, Ohio, USA*
[110]*Faculty of Science, Okayama University, Okayama, Japan*
[111]*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA*
[112]*Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA*
[113]*Palacký University, RCPTM, Olomouc, Czech Republic*
[114]*Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA*
[115]*LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France*
[116]*Graduate School of Science, Osaka University, Osaka, Japan*
[117]*Department of Physics, University of Oslo, Oslo, Norway*
[118]*Department of Physics, Oxford University, Oxford, United Kingdom*
[119a]*INFN Sezione di Pavia, Italy*
[119b]*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[120]*Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA*
[121]*Petersburg Nuclear Physics Institute, Gatchina, Russia*
[122a]*INFN Sezione di Pisa, Italy*
[122b]*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[123]*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA*
[124a]*Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal*
[124b]*Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain*
[125]*Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic*
[126]*Czech Technical University in Prague, Praha, Czech Republic*
[127]*Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic*
[128]*State Research Center Institute for High Energy Physics, Protvino, Russia*
[129]*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[130]*Physics Department, University of Regina, Regina, Saskatchewan, Canada*
[131]*Ritsumeikan University, Kusatsu, Shiga, Japan*
[132a]*INFN Sezione di Roma I, Italy*
[132b]*Dipartimento di Fisica, Università La Sapienza, Roma, Italy*
[133a]*INFN Sezione di Roma Tor Vergata, Italy*
[133b]*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[134a]*INFN Sezione di Roma Tre, Italy*
[134b]*Dipartimento di Fisica, Università Roma Tre, Roma, Italy*
[135a]*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco*
[135b]*Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat, Morocco*

[135c]*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
[135d]*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
[135e]*Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco*
[136]*DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France*
[137]*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
[138]*Department of Physics, University of Washington, Seattle, Washington, USA*
[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, British Columbia, Canada*
[143]*SLAC National Accelerator Laboratory, Stanford, CA, USA*
[144a]*Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic*
[144b]*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[145a]*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
[145b]*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[146a]*Department of Physics, Stockholm University, Sweden*
[146b]*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, New York, USA*
[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, Ontario, Canada*
[159a]*TRIUMF, Vancouver BC, Canada*
[159b]*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
[160]*Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
[161]*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
[162]*Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*
[163]*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
[164a]*INFN Gruppo Collegato di Udine, Italy*
[164b]*ICTP, Trieste, Italy*
[164c]*Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy*
[165]*Department of Physics, University of Illinois, Urbana, Illinois, USA*
[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, British Columbia, Canada*
[169]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, 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, Wisconsin, USA*
[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, Connecticut, USA*
[177]*Yerevan Physics Institute, Yerevan, Armenia*
[178]*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France*

[a] Deceased.

[b] Also at Department of Physics, King's College London, London, United Kingdom.

[c] Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas-LIP, Lisboa, Portugal.

[d] Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal.

[e] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

[f] Also at Department of Physics, University of Johannesburg, Johannesburg, South Africa.
[g] Also at TRIUMF, Vancouver, BC, Canada.
[h] Also at Department of Physics, California State University, Fresno, CA, USA.
[i] Also at Novosibirsk State University, Novosibirsk, Russia.
[j] Also at Department of Physics, University of Coimbra, Coimbra, Portugal.
[k] Also at Università di Napoli Parthenope, Napoli, Italy.
[l] Also at Institute of Particle Physics (IPP), Canada.
[m] Also at Department of Physics, Middle East Technical University, Ankara, Turkey.
[n] Also at Louisiana Tech University, Ruston. LA, USA.
[o] Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.
[p] Also at Department of Physics, University of Cape Town, Cape Town, South Africa.
[q] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[r] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[s] Also at Manhattan College, New York, NY, USA.
[t] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
[u] Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.
[v] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
[w] Also at School of Physics, Shandong University, Shandong, China.
[x] Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy.
[y] Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France.
[z] Also at Section de Physique, Université de Genève, Geneva, Switzerland.
[aa] Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.
[bb] Also at Department of Physics, The University of TX at Austin, Austin, TX, USA.
[cc] Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
[dd] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[ee] Also at International School for Advanced Studies (SISSA), Trieste, Italy.
[ff] Also at Institute of Physics, Jagiellonian University, Krakow, Poland.
[gg] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
[hh] Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
[ii] Also at Nevis Laboratory, Columbia University, Irvington, NY, USA.
[jj] Also at Department of Physics, Oxford University, Oxford, United Kingdom.
[kk] Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
[ll] Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.