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## **Observation of Long-Range Elliptic Azimuthal Anisotropies in $s\sqrt{=13}$ and 2.76 TeV pp Collisions with the ATLAS Detector**

G. Aad, S. Albrand, J. Collot, S. Crépe-Renaudin, P.A. Delsart, C. Gabaldon, M.H. Genest, J.Y. Hostachy, F. Ledroit-Guillon, A. Lleres, et al.

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## Observation of long-range elliptic azimuthal anisotropies in $\sqrt{s} = 13$ and 2.76 TeV $pp$ collisions with the ATLAS detector

The ATLAS Collaboration

### Abstract

ATLAS has measured two-particle correlations as a function of relative azimuthal-angle,  $\Delta\phi$ , and pseudorapidity,  $\Delta\eta$ , in  $\sqrt{s}=13$  and 2.76 TeV  $pp$  collisions at the LHC using charged particles measured in the pseudorapidity interval  $|\eta|<2.5$ . The correlation functions evaluated in different intervals of measured charged-particle multiplicity show a multiplicity-dependent enhancement at  $\Delta\phi \sim 0$  that extends over a wide range of  $\Delta\eta$ , which has been referred to as the “ridge”. Per-trigger-particle yields,  $Y(\Delta\phi)$ , are measured over  $2<|\Delta\eta|<5$ . For both collision energies, the  $Y(\Delta\phi)$  distribution in all multiplicity intervals is found to be consistent with a linear combination of the per-trigger-particle yields measured in collisions with less than 20 reconstructed tracks, and a constant combinatoric contribution modulated by  $\cos(2\Delta\phi)$ . The fitted Fourier coefficient,  $v_{2,2}$ , exhibits factorization, suggesting that the ridge results from per-event  $\cos(2\phi)$  modulation of the single-particle distribution with Fourier coefficients  $v_2$ . The  $v_2$  values are presented as a function of multiplicity and transverse momentum. They are found to be approximately constant as a function of multiplicity and to have a  $p_T$  dependence similar to that measured in  $p$ +Pb and Pb+Pb collisions. The  $v_2$  values in the 13 and 2.76 TeV data are consistent within uncertainties. These results suggest that the ridge in  $pp$  collisions arises from the same or similar underlying physics as observed in  $p$ +Pb collisions, and that the dynamics responsible for the ridge has no strong  $\sqrt{s}$  dependence.

Measurements of two-particle angular correlations in high-multiplicity proton-proton ( $pp$ ) collisions at a center-of-mass energy  $\sqrt{s} = 7$  TeV at the LHC showed an enhancement in the production of pairs at small azimuthal-angle separation,  $\Delta\phi$ , that extends over a wide range of pseudorapidity differences,  $\Delta\eta$ , and which is often referred to as the “ridge” [1]. The ridge has also been observed in proton-lead ( $p$ +Pb) collisions [2–7], where it is found to result from a global sinusoidal modulation of the per-event single-particle azimuthal angle distributions [3–6]. While many theoretical interpretations of the ridge, including those based on hydrodynamics [8–12], saturation [13–23], or other mechanisms [24–30], have been, or could be applied to both  $pp$  and  $p$ +Pb collisions, it has not yet been demonstrated that the ridge in  $pp$  collisions results from single-particle azimuthal anisotropies. Testing whether the ridges in  $pp$  and  $p$ +Pb collisions arise from the same underlying features of the single-particle distributions may provide insight into the physics responsible for the phenomena. Separately, a study of the  $\sqrt{s}$  dependence of the ridge in  $pp$  collisions may help distinguish between competing explanations.

This letter uses  $14 \text{ nb}^{-1}$  of  $\sqrt{s} = 13$  TeV data and  $4.0 \text{ pb}^{-1}$  of  $\sqrt{s} = 2.76$  TeV data recorded during LHC Run 2 and Run 1, respectively, to address these issues. The maximum number of inelastic interactions per crossing was 0.04 and 0.5 for the 13 and 2.76 TeV data, respectively. Two-particle angular correlations are measured as a function of  $\Delta\eta$  and  $\Delta\phi$  in different intervals of the measured charged-particle multiplicity and different  $p_T$  intervals spanning  $0.3 < p_T < 5$  GeV: 0.3–0.5 GeV, 0.5–1 GeV, 1–2 GeV, 2–3 GeV, 3–5 GeV. Separate  $p_T$ -integrated results use  $0.5 < p_T < 5$  GeV. Per-trigger-particle yields are obtained from the long-range ( $|\Delta\eta| > 2$ ) component of the correlation. A new template-fitting method is applied to these yields to test for sinusoidal modulation similar to that observed in  $p$ +Pb collisions.

The measurements were performed using the ATLAS inner detector (ID), minimum-bias trigger scintillators (MBTS), forward calorimeter (FCal), and the trigger and data acquisition systems [31]. The ID detects charged particles within  $|\eta| < 2.5$  using a combination of silicon pixel detectors, silicon micro-strip detectors (SCT), and a straw-tube transition radiation tracker (TRT), all immersed in a 2 T axial magnetic field [32, 33]. The MBTS system detects charged particles using two hodoscopes of counters positioned at  $z = \pm 3.6$  m. The FCal covers  $3.1 < |\eta| < 4.9$  and uses tungsten and copper absorbers with liquid argon as the active medium. Between Run 1 and Run 2, an additional, innermost pixel layer was added to the ID and the MBTS was replaced.

The ATLAS trigger system [34] consists of a Level-1 (L1) trigger implemented using a combination of dedicated electronics and programmable logic, and a software-based high-level trigger (HLT). Charged-particle tracks were reconstructed in the HLT using methods similar to those applied in the offline analysis, allowing triggers that select on the number of tracks with  $p_T > 0.4$  GeV associated with a single vertex. For the 13 TeV measurements, a minimum-bias L1 trigger required one or more signals in the MBTS while the high-multiplicity trigger (HMT) required at least 900 SCT hits and at least 60 HLT-reconstructed tracks. For the 2.76 TeV data the minimum-bias trigger selected random crossings at L1 and applied a threshold to the number of SCT and pixel hits in the HLT, while several HMT triggers were formed by applying thresholds on the total FCal transverse energy at L1 and different thresholds on the number of HLT-reconstructed tracks. HMT triggers are only used where their multiplicity selection is more than 90% efficient. The inefficiency of the HMT triggers does not affect the measurements presented in this paper. This has been checked by comparing the results obtained with and without the HMT-triggered events, over the  $N_{\text{ch}}^{\text{rec}}$  range where the HMT is not fully efficient.

Charged-particle tracks and collision vertices are reconstructed in the ID using algorithms that were re-optimized between LHC Runs 1 and 2 [35]. Tracks used in the analysis are required to have  $p_T > 0.3$  GeV,  $|\eta| < 2.5$  and to satisfy additional selection criteria that differ slightly between the 2.76 [4] and 13 TeV [36] data.

Events used in the analysis are required to have at least one reconstructed vertex. For events containing multiple vertices (pileup), only tracks associated with the vertex having the largest  $\sum p_T^2$ , where the sum is over all tracks associated with the vertex, are used. The measured charged-particle multiplicity,  $N_{\text{ch}}^{\text{rec}}$ , is defined as the number of tracks having  $p_T > 0.4$  GeV associated with this vertex. The distributions of  $N_{\text{ch}}^{\text{rec}}$  are shown in Fig. 1. The structures in the distributions result from the different HMT trigger thresholds.

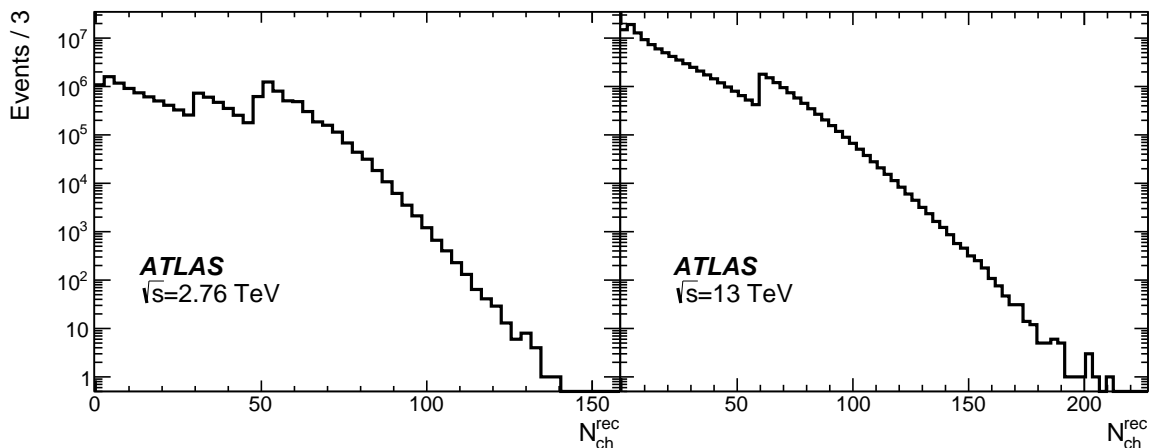


Figure 1: Distributions of the multiplicity,  $N_{\text{ch}}^{\text{rec}}$ , of reconstructed charged particles having  $p_T > 0.4$  GeV for the 2.76 (left) and 13 TeV (right) data used in this analysis.

The efficiency,  $\epsilon(p_T, \eta)$ , of the track reconstruction and track selection requirements is evaluated using simulated non-diffractive  $pp$  events obtained from the PYTHIA 8 [37] event generator (A2 tune [38], MSTW2008LO PDFs [39]) that are passed through a GEANT4 [40] simulation of the ATLAS detector response and reconstructed using the algorithms applied to the data [41]. The efficiencies for the two data sets are similar, but differ due to changes in the detector and reconstruction algorithms between Runs 1 and 2. In the simulated events, the efficiency reduces the measured multiplicity relative to the PYTHIA 8  $p_T > 0.4$  GeV charged-particle multiplicity by approximately multiplicity-independent factors of  $1.18 \pm 0.05$  and  $1.22 \pm 0.05$  for 13 and 2.76 TeV data, respectively. The uncertainties in these factors result from systematic uncertainties in the tracking efficiencies, which are described in detail in Ref. [36]. Those systematic uncertainties vary with pseudorapidity between 1.1% (central) and 6.5% (forward) and result from uncertainties on the material description.

The present analysis follows methods used in previous ATLAS two-particle correlation measurements in Pb+Pb and  $p$ +Pb collisions [4, 6, 42–44]. Two-particle correlations for charged particle pairs with transverse momenta  $p_T^a$  and  $p_T^b$  are measured as a function of  $\Delta\phi \equiv \phi^a - \phi^b$  and  $\Delta\eta \equiv \eta^a - \eta^b$ , with  $|\Delta\eta| \leq 5$ , determined by the acceptance of the ID. The particles  $a$  and  $b$  are conventionally referred to as the “trigger” and “associated” particles, respectively. The correlation function is defined as:

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

where  $S$  and  $B$  represent the same event and “mixed event” pair distributions respectively [45]. When constructing  $S$  and  $B$ , pairs are weighted by the inverse product of their reconstruction efficiencies  $1/(\epsilon(p_T^a, \eta^a)\epsilon(p_T^b, \eta^b))$ . Detector acceptance effects largely cancel in the  $S/B$  ratio.

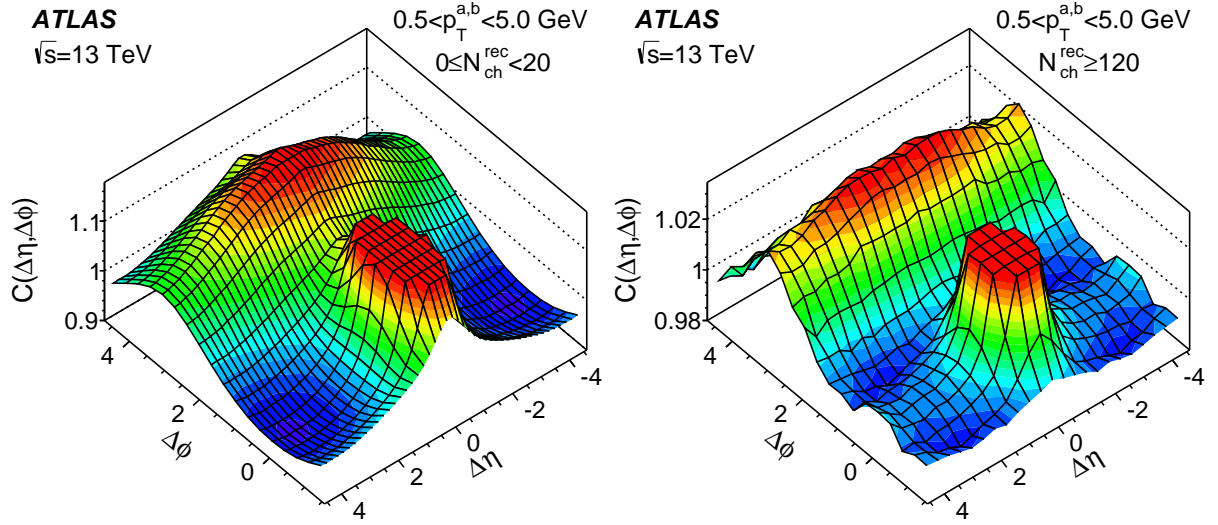


Figure 2: Two-particle correlation functions,  $C(\Delta\eta, \Delta\phi)$ , in 13 TeV  $pp$  collisions in  $N_{\text{ch}}^{\text{rec}}$  intervals 0–20 (left) and  $\geq 120$  (right) for charged particles having  $0.5 < p_{\text{T}}^{\text{a,b}} < 5$  GeV. The distributions have been truncated to suppress the peak at  $\Delta\eta = \Delta\phi = 0$  and are shown over  $|\eta| < 4.6$  to avoid statistical fluctuations at larger  $|\Delta\eta|$ .

Examples of correlation functions in the 13 TeV data are shown in Fig. 2 for  $N_{\text{ch}}^{\text{rec}}$  intervals 0–20 (left) and  $\geq 120$  (right), respectively, for  $0.5 < p_{\text{T}}^{\text{a,b}} < 5$  GeV. The  $C(\Delta\eta, \Delta\phi)$  distributions have been truncated at different maximum values to suppress a strong peak at  $\Delta\eta = \Delta\phi = 0$  that arises primarily from jets. The correlation functions also show a  $\Delta\eta$ -dependent enhancement centered at  $\Delta\phi = \pi$ , which is understood to result primarily from dijets. In the higher  $N_{\text{ch}}^{\text{rec}}$  interval, a ridge is observed as the enhancement near  $\Delta\phi = 0$  that extends over the full  $\Delta\eta$  range of the measurement.

One-dimensional correlation functions,  $C(\Delta\phi)$ , are obtained by integrating the numerator and denominator of Eq. 1 over the long-range part of the correlation function,  $2 < |\Delta\eta| < 5$ . These are converted into “per-trigger-particle yields,”  $Y(\Delta\phi)$ , according to [4, 6, 45]:

$$Y(\Delta\phi) = \left( \frac{\int B(\Delta\phi) d\Delta\phi}{N^a \int d\Delta\phi} \right) C(\Delta\phi), \quad (2)$$

where  $N^a$  denotes the efficiency-corrected total number of trigger particles. Results are shown in Fig. 3 for selected  $N_{\text{ch}}^{\text{rec}}$  intervals in the 13 and 2.76 TeV data, for the  $p_{\text{T}}^{\text{a,b}}$  ranges  $0.5 < p_{\text{T}}^{\text{a,b}} < 5$  GeV. Panel (a) in the figure shows  $Y(\Delta\phi)$  for  $0 \leq N_{\text{ch}}^{\text{rec}} < 20$  for both collision energies; these exhibit a minimum at  $\Delta\phi = 0$  and a broad peak at  $\Delta\phi \sim \pi$  that is understood to result primarily from dijets but may also include contributions from low- $p_{\text{T}}$  resonance decays and global momentum conservation. The higher  $Y(\Delta\phi)$  values for the 2.76 TeV data are due to the relative inefficiency of the 2.76 TeV triggers for the lowest multiplicity events, which results in larger  $\langle N_{\text{ch}}^{\text{rec}} \rangle$  for the 2.76 TeV data in this  $N_{\text{ch}}^{\text{rec}}$  interval. Panels (b), (d) and (f) show results from 13 TeV data for the 40–50, 60–70, and  $\geq 90$   $N_{\text{ch}}^{\text{rec}}$  intervals, respectively. Panels (c) and (e) show the results from 2.76 TeV data for 50–60 and 70–80  $N_{\text{ch}}^{\text{rec}}$  intervals, respectively. With increasing  $N_{\text{ch}}^{\text{rec}}$ , the minimum at  $\Delta\phi = 0$  fills in, and a peak appears and increases in amplitude.

To separate the ridge from angular correlations present in low-multiplicity  $pp$  collisions, a template fitting procedure is applied to the  $Y(\Delta\phi)$  distributions. Motivated by the peripheral subtraction method applied in  $p$ +Pb collisions [4], the measured  $Y(\Delta\phi)$  distributions are assumed to result from a superposition

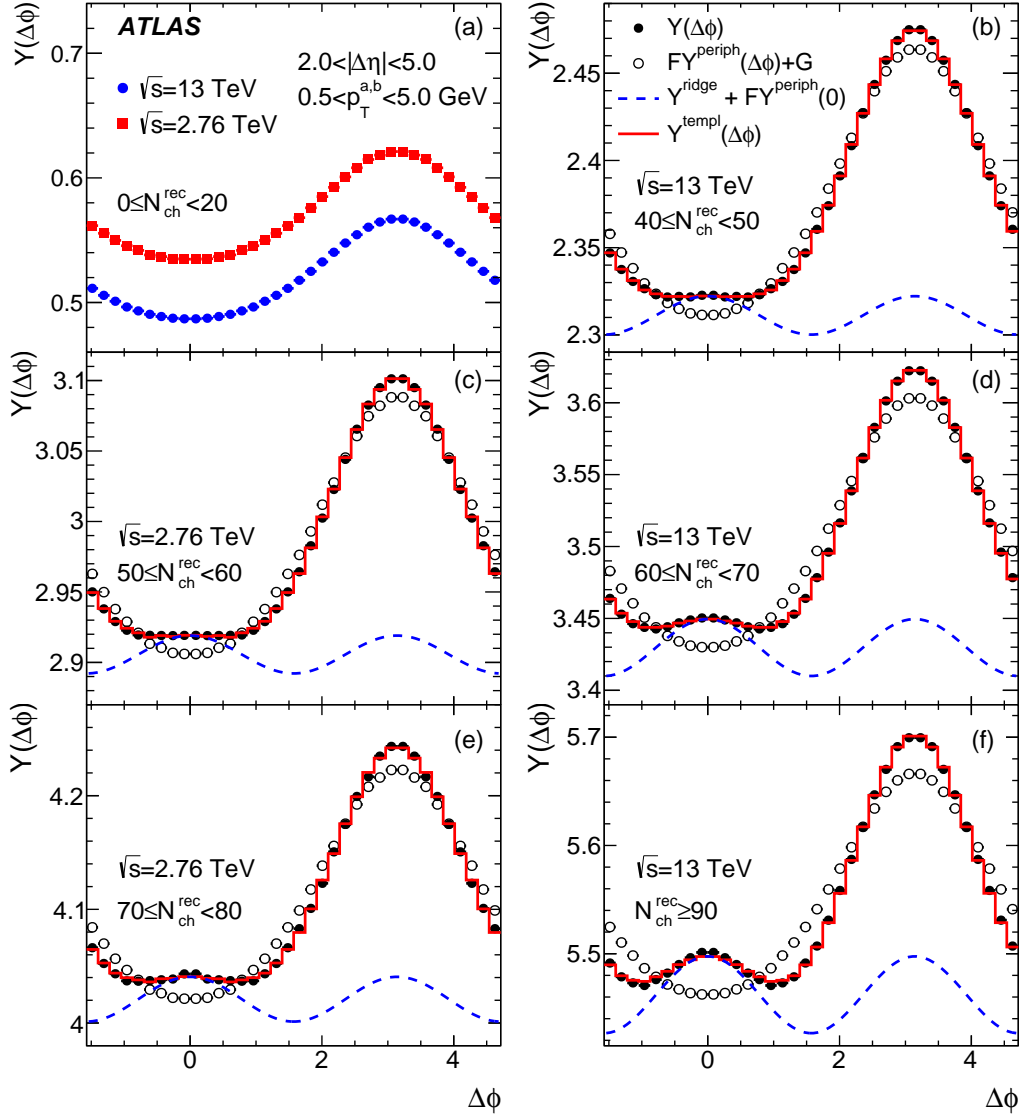


Figure 3: Per-trigger-particle yields,  $Y(\Delta\phi)$ , for  $0.5 < p_T^{a,b} < 5$  GeV in different  $N_{ch}^{rec}$  intervals in 2.76 and 13 TeV data. Panel (a):  $0 \leq N_{ch}^{rec} < 20$  for both data sets. Panels (c) and (e): 50–60 and 70–80  $N_{ch}^{rec}$  intervals for 2.76 TeV data. Panels (b), (d) and (f): 40–50, 60–70, and  $\geq 90$   $N_{ch}^{rec}$  intervals for 13 TeV data. In panels (b)–(f), the open points and curves show different components of the template (see legend) that are shifted, where necessary, for presentation.

of a “peripheral”  $Y(\Delta\phi)$  distribution, scaled up by a multiplicative factor and a constant modulated by  $\cos(2\Delta\phi)$ . The resulting template fit function,

$$Y^{\text{templ}}(\Delta\phi) = F Y^{\text{periph}}(\Delta\phi) + Y^{\text{ridge}}(\Delta\phi), \quad (3)$$

where

$$Y^{\text{ridge}}(\Delta\phi) = G (1 + 2v_{2,2} \cos(2\Delta\phi)), \quad (4)$$

has two free parameters,  $F$  and  $v_{2,2}$ . The coefficient,  $G$ , which represents the magnitude of the combinatoric component of  $Y^{\text{ridge}}(\Delta\phi)$ , is fixed by requiring that  $\int_0^\pi d\Delta\phi Y^{\text{templ}} = \int_0^\pi d\Delta\phi Y$ . The peripheral

distribution is obtained from the  $0 \leq N_{\text{ch}}^{\text{rec}} < 20$  interval. In the fitting procedure, the  $\chi^2$  is calculated accounting for statistical uncertainties in both  $Y(\Delta\phi)$  and  $Y^{\text{periph}}(\Delta\phi)$  distributions.

Some results of the template fitting procedure are shown in panels (b)–(f) of Fig. 3; a complete set of fit results is provided in Ref. [46]. The scaled  $Y^{\text{periph}}(\Delta\phi)$  distributions shifted up by  $G$  are shown with open points; the  $Y^{\text{ridge}}(\Delta\phi)$  functions shifted up by  $FY^{\text{periph}}(0)$  are shown with the dashed lines; and the full fit function is shown by the solid curves. The function in Eq. 3 successfully describes the measured  $Y(\Delta\phi)$  distributions in all  $N_{\text{ch}}^{\text{rec}}$  intervals. In particular, it simultaneously describes the ridge, which arises from an interplay of the concave  $Y^{\text{periph}}(\Delta\phi)$  and the cosine function, the height of the peak in the  $Y(\Delta\phi)$  at  $\Delta\phi \sim \pi$ , and the narrowing of that peak which results from a negative contribution of the  $2v_{2,2} \cos(2\Delta\phi)$  term in the region near  $\Delta\phi = \pi/2$ . The agreement between the template functions and the data allows for no significant  $N_{\text{ch}}^{\text{rec}}$ -dependent variation in the width of the dijet peak at  $\Delta\phi = \pi$  except for that accounted for by the sinusoidal component of the fit function. Including additional  $\cos(3\Delta\phi)$  and  $\cos(4\Delta\phi)$  terms in Eq. 4 produces changes in the extracted  $v_{2,2}$  values that are negligible compared to their statistical uncertainties.

Previous analyses of two-particle angular correlations in  $pp$ ,  $p+\text{Pb}$ , and  $\text{Pb}+\text{Pb}$  collisions have traditionally relied on the “zero yield at minimum” (ZYAM) hypothesis to separate the ridge from the dijet peak at  $\Delta\phi \sim \pi$ . In the ZYAM method, the ridge is functionally defined to be  $Y(\Delta\phi) - Y_{\text{min}}$  over the restricted range  $|\Delta\phi| < \phi_{\text{min}}$ , where  $\phi_{\text{min}}$  is the location of the minimum of  $Y(\Delta\phi)$  and  $Y_{\text{min}} = Y(\phi_{\text{min}})$ . However, the  $Y(\Delta\phi)$  distributions measured in low- $N_{\text{ch}}^{\text{rec}}$  bins are concave in the region near  $\Delta\phi \sim 0$ . As a result, if the ridge and dijet correlations add – an assumption that is implicit in all previous analyses using the ZYAM method and is explicit in the template method used here – then the ZYAM method will both underestimate the ridge yield and produce  $\phi_{\text{min}}$  values that vary, unphysically, with the ridge amplitude. In contrast, the template method used here explicitly accounts for the concave shape of the peripheral  $Y(\Delta\phi)$ . Thus, the template fitting procedure, for example, extracts a non-zero ridge amplitude from the  $\sqrt{s} = 2.76$  TeV,  $50 \leq N_{\text{ch}}^{\text{rec}} \leq 60$   $Y(\Delta\phi)$  distribution (middle left panel of Fig. 3) which is approximately flat near  $\Delta\phi \sim 0$ , and would, as a result, have approximately zero ridge signal using the ZYAM method.

Previous  $p+\text{Pb}$  analyses used the peripheral-subtraction method, but applied the ZYAM procedure to the peripheral reference and, so, subtracted  $Y(0)$  from  $Y^{\text{periph}}(\Delta\phi)$ . Such a subtraction will necessarily change the  $v_{2,2}$  values, and, when applied to the 13 TeV data, it reduces the measured  $v_{2,2}$  by a multiplicative factor that varies from 0.4 to 0.8 over  $30 \leq N_{\text{ch}}^{\text{rec}} < 130$  [46]. However, if, as suggested by the data,  $Y^{\text{periph}}(\Delta\phi)$  contains not only a hard component,  $Y^{\text{hard}}(\Delta\phi)$ , but also a modulated soft component,

$$Y^{\text{periph}}(\Delta\phi) = Y^{\text{hard}}(\Delta\phi) + G_0 \left( 1 + 2v_{2,2}^0 \cos(2\Delta\phi) \right), \quad (5)$$

the peripheral ZYAM method will subtract  $2FG_0v_{2,2}^0 \cos(2\Delta\phi)$  as part of the template fit, thereby reducing the extracted  $v_{2,2}$ . In contrast, the procedure used in this analysis subtracts  $FG_0 \left( 1 + 2v_{2,2}^0 \cos(2\Delta\phi) \right)$ , which reduces  $G$  in Eq. 4 but has less impact on  $v_{2,2}$ . In particular, if  $v_{2,2}^0$  is equal to the real  $v_{2,2}$  in a given  $N_{\text{ch}}^{\text{rec}}$  interval, there will be no bias. Since the measured  $v_{2,2}$  is approximately  $N_{\text{ch}}^{\text{rec}}$ -independent, the bias resulting from the presence of  $v_{2,2}$  in the peripheral sample is expected to be small. Thus, the use of the non-subtracted peripheral reference is preferred over the more strongly biased ZYAM-subtracted reference.

If the  $\cos(2\Delta\phi)$  dependence of  $Y(\Delta\phi)$  arises from modulation of the single-particle  $\phi$  distributions, then  $v_{2,2}$  should factorize such that  $v_{2,2}(p_{\text{T}}^{\text{a}}, p_{\text{T}}^{\text{b}}) = v_2(p_{\text{T}}^{\text{a}})v_2(p_{\text{T}}^{\text{b}})$  [42–44], where  $v_2$  is the  $\cos(2\phi)$  Fourier coefficient of the single-particle anisotropy. To test this, the analysis was performed using three  $p_{\text{T}}^{\text{b}}$  intervals: 0.5–5, 0.5–1, and 2–3 GeV with  $0.5 < p_{\text{T}}^{\text{a}} < 5$  GeV; results from 2.76 TeV data for the 2–3 GeV interval were

obtained using wider  $N_{\text{ch}}^{\text{rec}}$  intervals to improve statistics. Results are shown in the top panels of Fig. 4; the left and right panels show 2.76 and 13 TeV data, respectively. A significant  $p_{\text{T}}^{\text{b}}$  dependence is seen. Separately, the same analysis was applied requiring both  $p_{\text{T}}^{\text{a}}$  and  $p_{\text{T}}^{\text{b}}$  to fall within the above intervals. If factorization holds, the  $v_2$  values calculated using:

$$v_2(p_{\text{T}1}) = v_{2,2}(p_{\text{T}1}, p_{\text{T}2}) / \sqrt{v_{2,2}(p_{\text{T}2}, p_{\text{T}2})}, \quad (6)$$

where  $p_{\text{T}1}$  and  $p_{\text{T}2}$  indicate which of the three intervals, 0.5–5, 0.5–1, and 2–3 GeV,  $p_{\text{T}}^{\text{a}}$  and  $p_{\text{T}}^{\text{b}}$  are required to lie within, should be independent of  $p_{\text{T}2}$ . The  $v_2$  values obtained using Eq. 6 are shown in the middle panels of Fig. 4. For both collision energies, the three sets of  $v_2$  values agree within uncertainties, indicating that  $v_{2,2}$  factorizes.

This analysis is sensitive to potential  $N_{\text{ch}}^{\text{rec}}$ -dependent changes in the shape of the peripheral reference. For example, the PYTHIA 8 sample shows a modest  $N_{\text{ch}}^{\text{rec}}$ -dependent change in the width of the dijet peak for small  $N_{\text{ch}}^{\text{rec}}$ . Also, the  $v_{2,2}$  could vary with  $N_{\text{ch}}^{\text{rec}}$  over the  $0 < N_{\text{ch}}^{\text{rec}} < 20$  range. To test the sensitivity of the results presented here to such shape changes, the analysis was repeated using 0–5, 0–10, and 10–20  $N_{\text{ch}}^{\text{rec}}$  intervals to form  $Y^{\text{periph}}(\Delta\phi)$ . The largest resulting change in  $v_{2,2}$  was taken as a systematic uncertainty. The relative uncertainty varies from 6% at  $N_{\text{ch}}^{\text{rec}}=30$  to 2% for  $N_{\text{ch}}^{\text{rec}} \geq 60$  in the 13 TeV data, and is less than <6% for all  $N_{\text{ch}}^{\text{rec}}$  for the 2.76 TeV data. When using the 0–5  $N_{\text{ch}}^{\text{rec}}$  interval for  $Y^{\text{periph}}(\Delta\phi)$ ,  $v_{2,2}$  values consistent with those shown in Fig. 4 are measured in  $N_{\text{ch}}^{\text{rec}}$  intervals 5–10, 10–15 and 15–20.

Potential systematic uncertainties on  $v_{2,2}$  due to a residual  $\Delta\phi$  dependence of the two-particle acceptance that does not cancel in the  $S/B$  ratio are evaluated following Ref. [47] and are found to be less than 1%. The effect of the uncertainty on the tracking efficiency on  $v_{2,2}$  is determined to be less than 1%. A separate systematic on  $v_{2,2}$  due to the  $\phi$  and  $p_{\text{T}}$  resolution of the charged-particle measurement is estimated to be 2% (6%) for  $p_{\text{T}} > 0.5$  GeV ( $p_{\text{T}} < 0.5$  GeV). Events with unresolved multiple vertices decrease the measured  $v_{2,2}$  by increasing the combinatoric pedestal in  $Y(\Delta\phi)$  without increasing the modulation. The resulting systematic on  $v_{2,2}$  increases with  $N_{\text{ch}}^{\text{rec}}$  and is estimated to be less than 0.25% and 5% for the 13 and 2.76 TeV data, respectively. The combined systematic uncertainties on  $v_{2,2}$  and on  $v_2$  are shown by the shaded boxes in Fig. 4. The total  $v_{2,2}$  systematic uncertainty for  $0.5 < p_{\text{T}}^{\text{a,b}} < 5$  GeV varies between  $\sim 5\%$  at low  $N_{\text{ch}}^{\text{rec}}$  to  $\sim 3\%$  at high  $N_{\text{ch}}^{\text{rec}}$  in the 13 TeV data, while in the 2.76 TeV data the uncertainty is 8% for all  $N_{\text{ch}}^{\text{rec}}$ . The systematic uncertainty on  $v_2$  is approximately half that for  $v_{2,2}$ .

As shown in Fig. 4, the measured  $v_2$  are independent of  $N_{\text{ch}}^{\text{rec}}$  and are consistent between the two collision energies within uncertainties. The  $p_{\text{T}}$  dependence of  $v_2$  for the 50–60  $N_{\text{ch}}^{\text{rec}}$  interval, shown in the bottom left panel of Fig. 4, is similar for both collision energies to that previously measured in  $p+\text{Pb}$  and  $\text{Pb}+\text{Pb}$  collisions. It increases with  $p_{\text{T}}$  at low  $p_{\text{T}}$ , reaches a maximum between 2 and 3 GeV, and then decreases at higher  $p_{\text{T}}$ . The bottom right panel of Fig. 4 shows the  $p_{\text{T}}$  dependence of  $v_2$  for different  $N_{\text{ch}}^{\text{rec}}$  intervals; no significant dependence is observed.

In summary, ATLAS has measured the multiplicity and  $p_{\text{T}}$  dependence of two-charged-particle correlations in  $\sqrt{s}=13$  and 2.76 TeV  $pp$  collisions at the LHC. The correlation functions at both energies show a ridge whose strength increases with multiplicity. A new template fitting procedure shows that the per-trigger-particle yields for  $|\Delta\eta| > 2$  are described well by a superposition of the yields measured in a low-multiplicity interval and a constant modulated by  $\cos(2\Delta\phi)$ . Thus, as observed in  $p+\text{Pb}$  collisions [4], the  $pp$  data presented here are compatible with both a “near-side” ridge centered at  $\Delta\phi = 0$  and an “away-side” ridge centered at  $\Delta\phi = \pi$  that both result from a sinusoidal component of the two-particle correlation. The extracted Fourier coefficients,  $v_{2,2}$ , exhibit factorization, which is characteristic of a global modulation of the per-event single-particle distributions also seen in  $p+\text{Pb}$  and  $\text{Pb}+\text{Pb}$  collisions.

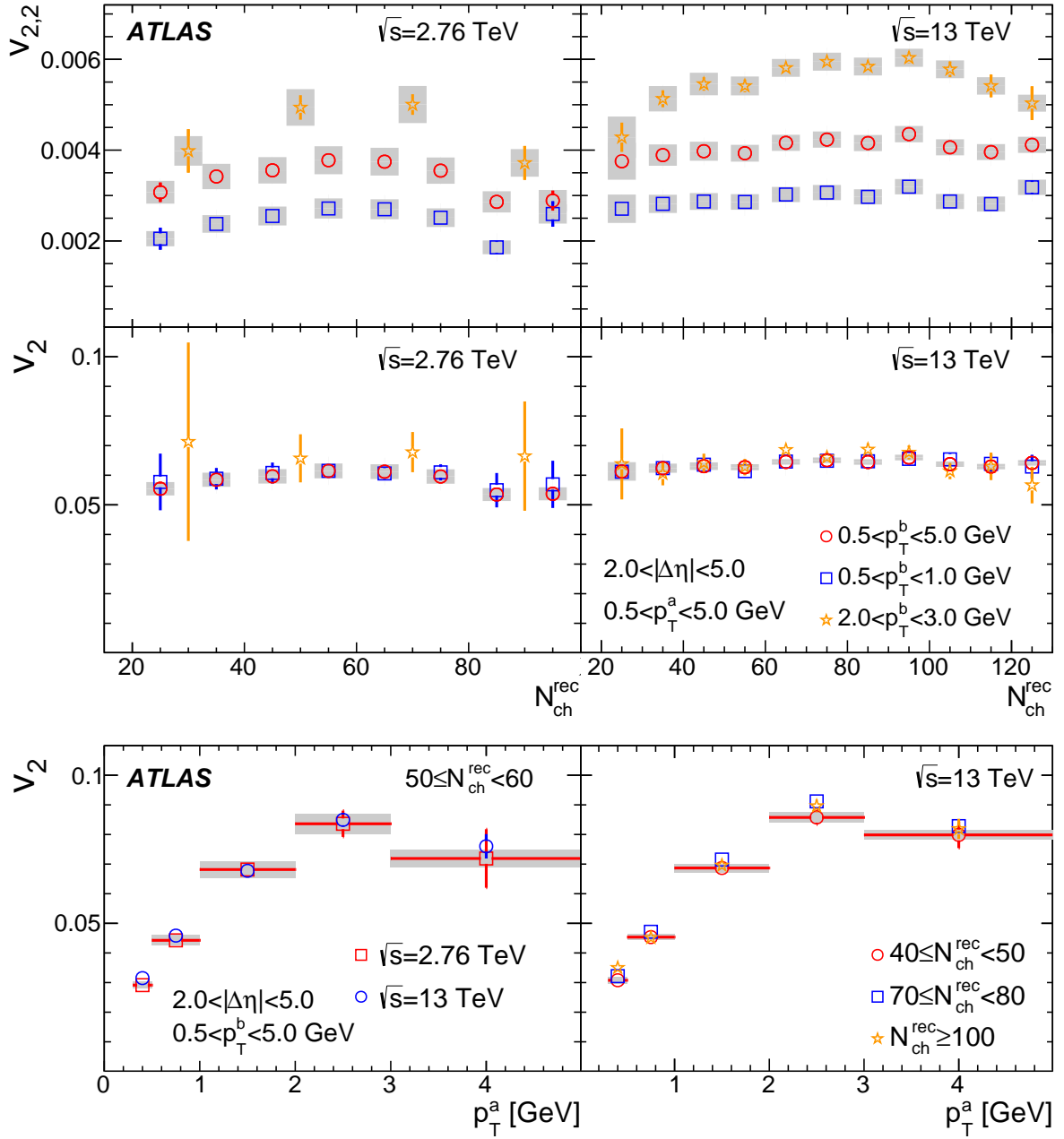


Figure 4: Measured  $v_{2,2}$  (top) and  $v_2$  (middle) values versus  $N_{ch}^{rec}$  for different  $p_T^{a,b}$  intervals for 2.76 (left) and 13 TeV (right) data. Results are averaged over  $N_{ch}^{rec}$  bins of width 10 spanning the range  $20 \leq N_{ch}^{rec} < 100$  and  $20 \leq N_{ch}^{rec} < 130$  for 2.76 and 13 TeV data, respectively, except for the  $2 < p_T^b < 3$  GeV results for the 2.76 TeV data which are averaged over bins of width 20. Measured  $v_2$  values versus  $p_T^a$  (bottom) spanning the range  $0.3 < p_T^a < 5.0$  GeV for 13 and 2.76 TeV data for the  $50 \leq N_{ch}^{rec} < 60$  interval (left) and for three  $N_{ch}^{rec}$  intervals in the 13 TeV data (right). Results are averaged over the  $p_T^a$  intervals indicated by horizontal error bars. On all points, the vertical error bars indicate statistical uncertainties. The shaded bands indicate systematic uncertainties. For clarity, they are only shown for the  $0.5 < p_T^b < 5$  GeV case in the middle, for 2.76 TeV data in the lower left, and for the  $40 \leq N_{ch}^{rec} < 50$  case in the lower right panels.

The amplitudes,  $v_2$ , of the single-particle modulation, are  $N_{\text{ch}}^{\text{rec}}$ -independent and agree between 2.76 and 13 TeV within uncertainties. They increase with  $p_T$  for  $p_T \lesssim 3$  GeV and then decrease at higher  $p_T$ , following a trend similar to that observed in  $p$ +Pb and Pb+Pb collisions. These results suggest that the ridges in  $pp$  and  $p$ +Pb collisions may arise from a similar physical mechanism which does not have a strong  $\sqrt{s}$  dependence.

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*Note added.*—Recently, we became aware of a related work [48].

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G. Aad<sup>85</sup>, B. Abbott<sup>113</sup>, J. Abdallah<sup>151</sup>, O. Abdinov<sup>11</sup>, R. Aben<sup>107</sup>, M. Abolins<sup>90</sup>, O.S. AbouZeid<sup>158</sup>, H. Abramowicz<sup>153</sup>, H. Abreu<sup>152</sup>, R. Abreu<sup>116</sup>, Y. Abulaiti<sup>146a,146b</sup>, B.S. Acharya<sup>164a,164b,a</sup>, L. Adamczyk<sup>38a</sup>, D.L. Adams<sup>25</sup>, J. Adelman<sup>108</sup>, S. Adomeit<sup>100</sup>, T. Adye<sup>131</sup>, A.A. Affolder<sup>74</sup>, T. Agatonovic-Jovin<sup>13</sup>, J. Agricola<sup>54</sup>, J.A. Aguilar-Saavedra<sup>126a,126f</sup>, S.P. Ahlen<sup>22</sup>, F. Ahmadov<sup>65,b</sup>, G. Aielli<sup>133a,133b</sup>, H. Akerstedt<sup>146a,146b</sup>, T.P.A. Åkesson<sup>81</sup>, A.V. Akimov<sup>96</sup>, G.L. Alberghi<sup>20a,20b</sup>, J. Albert<sup>169</sup>, S. Albrand<sup>55</sup>, M.J. Alconada Verzini<sup>71</sup>, M. Aleksa<sup>30</sup>, I.N. Aleksandrov<sup>65</sup>, C. Alexa<sup>26b</sup>, G. Alexander<sup>153</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>113</sup>, G. Alimonti<sup>91a</sup>, L. Alio<sup>85</sup>, J. Alison<sup>31</sup>, S.P. Alkire<sup>35</sup>, B.M.M. Allbrooke<sup>149</sup>, P.P. Allport<sup>18</sup>, A. Aloisio<sup>104a,104b</sup>, A. Alonso<sup>36</sup>, F. Alonso<sup>71</sup>, C. Alpigiani<sup>138</sup>, A. Altheimer<sup>35</sup>, B. Alvarez Gonzalez<sup>30</sup>, D. Álvarez Piqueras<sup>167</sup>, M.G. Alviggi<sup>104a,104b</sup>, B.T. Amadio<sup>15</sup>, K. Amako<sup>66</sup>, Y. Amaral Coutinho<sup>24a</sup>, C. Amelung<sup>23</sup>, D. Amidei<sup>89</sup>, S.P. Amor Dos Santos<sup>126a,126c</sup>, A. Amorim<sup>126a,126b</sup>, S. Amoroso<sup>48</sup>, N. Amram<sup>153</sup>, G. Amundsen<sup>23</sup>, C. Anastopoulos<sup>139</sup>, L.S. Ancu<sup>49</sup>, N. Andari<sup>108</sup>, T. Andeen<sup>35</sup>, C.F. Anders<sup>58b</sup>, G. Anders<sup>30</sup>, J.K. Anders<sup>74</sup>, K.J. Anderson<sup>31</sup>, A. Andreazza<sup>91a,91b</sup>, V. Andrei<sup>58a</sup>, S. 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G.J. Bobbink<sup>107</sup>, V.S. Bobrovnikov<sup>109,c</sup>, S.S. Bocchetta<sup>81</sup>, A. Bocci<sup>45</sup>, C. Bock<sup>100</sup>, M. Boehler<sup>48</sup>, J.A. Bogaerts<sup>30</sup>, D. Bogavac<sup>13</sup>, A.G. Bogdanchikov<sup>109</sup>, C. Bohm<sup>146a</sup>, V. Boisvert<sup>77</sup>, T. Bold<sup>38a</sup>, V. Boldea<sup>26b</sup>, A.S. Boldyrev<sup>99</sup>, M. Bomben<sup>80</sup>, M. Bona<sup>76</sup>, M. Boonekamp<sup>136</sup>, A. Borisov<sup>130</sup>, G. Borissov<sup>72</sup>, S. Borroni<sup>42</sup>, J. Bortfeldt<sup>100</sup>, V. Bortolotto<sup>60a,60b,60c</sup>, K. Bos<sup>107</sup>, D. Boscherini<sup>20a</sup>, M. Bosman<sup>12</sup>, J. Boudreau<sup>125</sup>, J. Bouffard<sup>2</sup>, E.V. Bouhova-Thacker<sup>72</sup>, D. Boumediene<sup>34</sup>, C. Bourdarios<sup>117</sup>, N. Bousson<sup>114</sup>, S.K. Boutle<sup>53</sup>, A. Boveia<sup>30</sup>, J. Boyd<sup>30</sup>, I.R. Boyko<sup>65</sup>, I. Bozic<sup>13</sup>, J. Bracinik<sup>18</sup>, A. Brandt<sup>8</sup>, G. Brandt<sup>54</sup>, O. Brandt<sup>58a</sup>, U. Bratzler<sup>156</sup>, B. Brau<sup>86</sup>, J.E. Brau<sup>116</sup>, H.M. Braun<sup>175,\*</sup>, W.D. Breaden Madden<sup>53</sup>, K. Brendlinger<sup>122</sup>, A.J. Brennan<sup>88</sup>, L. Brenner<sup>107</sup>, R. Brenner<sup>166</sup>, S. Bressler<sup>172</sup>, T.M. Bristow<sup>46</sup>, D. Britton<sup>53</sup>, D. Britzger<sup>42</sup>, F.M. Brochu<sup>28</sup>, I. Brock<sup>21</sup>, R. Brock<sup>90</sup>, J. Bronner<sup>101</sup>, G. Brooijmans<sup>35</sup>, T. Brooks<sup>77</sup>, W.K. Brooks<sup>32b</sup>, J. Brosamer<sup>15</sup>, E. Brost<sup>116</sup>, P.A. Bruckman de Renstrom<sup>39</sup>, D. Bruncko<sup>144b</sup>, R. Bruneliere<sup>48</sup>, A. Bruni<sup>20a</sup>, G. Bruni<sup>20a</sup>, M. Bruschi<sup>20a</sup>, N. Bruscinò<sup>21</sup>, L. Bryngemark<sup>81</sup>, T. Buanes<sup>14</sup>, Q. Buat<sup>142</sup>, P. Buchholz<sup>141</sup>, A.G. Buckley<sup>53</sup>, I.A. 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Vranjes<sup>13</sup>, M. Vranjes Milosavljevic<sup>13</sup>, V. Vrba<sup>127</sup>, M. Vreeswijk<sup>107</sup>, R. Vuillermet<sup>30</sup>, I. Vukotic<sup>31</sup>, Z. Vykydal<sup>128</sup>, P. Wagner<sup>21</sup>, W. Wagner<sup>175</sup>, H. Wahlberg<sup>71</sup>, S. Wahrmond<sup>44</sup>, J. Wakabayashi<sup>103</sup>, J. Walder<sup>72</sup>, R. Walker<sup>100</sup>, W. Walkowiak<sup>141</sup>, C. Wang<sup>151</sup>, F. Wang<sup>173</sup>, H. Wang<sup>15</sup>, H. Wang<sup>40</sup>, J. Wang<sup>42</sup>, J. Wang<sup>150</sup>, K. Wang<sup>87</sup>, R. Wang<sup>6</sup>, S.M. Wang<sup>151</sup>, T. Wang<sup>21</sup>, T. Wang<sup>35</sup>, X. Wang<sup>176</sup>, C. Wanotayaroj<sup>116</sup>, A. Warburton<sup>87</sup>, C.P. Ward<sup>28</sup>, D.R. Wardrope<sup>78</sup>, A. Washbrook<sup>46</sup>, C. Wasicki<sup>42</sup>, P.M. Watkins<sup>18</sup>, A.T. Watson<sup>18</sup>, I.J. Watson<sup>150</sup>, M.F. Watson<sup>18</sup>, G. Watts<sup>138</sup>, S. Watts<sup>84</sup>, B.M. Waugh<sup>78</sup>, S. Webb<sup>84</sup>, M.S. Weber<sup>17</sup>, S.W. Weber<sup>174</sup>, J.S. Webster<sup>6</sup>, A.R. Weidberg<sup>120</sup>, B. Weinert<sup>61</sup>, J. Weingarten<sup>54</sup>, C. Weiser<sup>48</sup>, H. Weits<sup>107</sup>, P.S. Wells<sup>30</sup>, T. Wenaus<sup>25</sup>, T. Wengler<sup>30</sup>, S. Wenig<sup>30</sup>, N. Wermes<sup>21</sup>, M. Werner<sup>48</sup>, P. Werner<sup>30</sup>, M. Wessels<sup>58a</sup>, J. Wetter<sup>161</sup>, K. Whalen<sup>116</sup>, A.M. Wharton<sup>72</sup>, A. White<sup>8</sup>, M.J. White<sup>1</sup>, R. White<sup>32b</sup>, S. White<sup>124a,124b</sup>, D. Whiteson<sup>163</sup>, F.J. Wickens<sup>131</sup>, W. Wiedenmann<sup>173</sup>, M. Wielers<sup>131</sup>, P. Wienemann<sup>21</sup>, C. Wiglesworth<sup>36</sup>, L.A.M. Wiik-Fuchs<sup>21</sup>, A. Wildauer<sup>101</sup>, H.G. Wilkens<sup>30</sup>, H.H. Williams<sup>122</sup>, S. Williams<sup>107</sup>, C. Willis<sup>90</sup>, S. Willocq<sup>86</sup>, A. Wilson<sup>89</sup>, J.A. Wilson<sup>18</sup>, I. Wingerter-Seez<sup>5</sup>, F. Winklmeier<sup>116</sup>, B.T. Winter<sup>21</sup>, M. Wittgen<sup>143</sup>, J. Wittkowski<sup>100</sup>, S.J. Wollstadt<sup>83</sup>, M.W. Wolter<sup>39</sup>, H. Wolters<sup>126a,126c</sup>, B.K. Wosiek<sup>39</sup>, J. Wotschack<sup>30</sup>, M.J. Woudstra<sup>84</sup>, K.W. Wozniak<sup>39</sup>, M. Wu<sup>55</sup>, M. Wu<sup>31</sup>, S.L. Wu<sup>173</sup>, X. Wu<sup>49</sup>, Y. Wu<sup>89</sup>, T.R. Wyatt<sup>84</sup>, B.M. Wynne<sup>46</sup>, S. Xella<sup>36</sup>, D. Xu<sup>33a</sup>, L. Xu<sup>25</sup>, B. Yabsley<sup>150</sup>, S. Yacoub<sup>145a</sup>, R. Yakabe<sup>67</sup>, M. Yamada<sup>66</sup>, D. Yamaguchi<sup>157</sup>, Y. Yamaguchi<sup>118</sup>, A. Yamamoto<sup>66</sup>, S. Yamamoto<sup>155</sup>, T. Yamanaka<sup>155</sup>, K. Yamauchi<sup>103</sup>, Y. Yamazaki<sup>67</sup>, Z. Yan<sup>22</sup>, H. Yang<sup>33e</sup>, H. Yang<sup>173</sup>, Y. Yang<sup>151</sup>, W-M. Yao<sup>15</sup>, Y.C. Yap<sup>80</sup>, Y. Yasu<sup>66</sup>, E. Yatsenko<sup>5</sup>, K.H. Yau Wong<sup>21</sup>, J. Ye<sup>40</sup>, S. Ye<sup>25</sup>, I. Yeletsikh<sup>65</sup>, A.L. Yen<sup>57</sup>, E. Yildirim<sup>42</sup>, K. Yorita<sup>171</sup>, R. Yoshida<sup>6</sup>, K. Yoshihara<sup>122</sup>, C. Young<sup>143</sup>, C.J.S. Young<sup>30</sup>, S. Youssef<sup>22</sup>, D.R. Yu<sup>15</sup>, J. Yu<sup>8</sup>, J.M. Yu<sup>89</sup>, J. Yu<sup>114</sup>, L. Yuan<sup>67</sup>, S.P.Y. Yuen<sup>21</sup>, A. Yurkewicz<sup>108</sup>, I. Yusuff<sup>28,am</sup>, B. Zabinski<sup>39</sup>, R. Zaidan<sup>63</sup>, A.M. Zaitsev<sup>130,ad</sup>, J. Zalieckas<sup>14</sup>, A. Zaman<sup>148</sup>, S. Zambito<sup>57</sup>, L. Zanello<sup>132a,132b</sup>, D. Zanzi<sup>88</sup>, C. Zeitnitz<sup>175</sup>, M. Zeman<sup>128</sup>, A. Zemla<sup>38a</sup>, J.C. Zeng<sup>165</sup>, Q. Zeng<sup>143</sup>, K. Zengel<sup>23</sup>, O. Zenin<sup>130</sup>, T. Ženiš<sup>144a</sup>, D. Zerwas<sup>117</sup>, D. Zhang<sup>89</sup>, F. Zhang<sup>173</sup>, G. Zhang<sup>33b</sup>, H. Zhang<sup>33c</sup>, J. Zhang<sup>6</sup>, L. Zhang<sup>48</sup>, R. Zhang<sup>33b,j</sup>, X. Zhang<sup>33d</sup>, Z. Zhang<sup>117</sup>, X. Zhao<sup>40</sup>, Y. Zhao<sup>33d,117</sup>, Z. Zhao<sup>33b</sup>, A. Zhemchugov<sup>65</sup>, J. Zhong<sup>120</sup>, B. Zhou<sup>89</sup>, C. Zhou<sup>45</sup>, L. Zhou<sup>35</sup>, L. Zhou<sup>40</sup>, M. Zhou<sup>148</sup>, N. Zhou<sup>33f</sup>, C.G. Zhu<sup>33d</sup>, H. Zhu<sup>33a</sup>, J. Zhu<sup>89</sup>, Y. Zhu<sup>33b</sup>, X. Zhuang<sup>33a</sup>, K. Zhukov<sup>96</sup>, A. Zibell<sup>174</sup>, D. Ziemska<sup>61</sup>, N.I. Zimine<sup>65</sup>, C. Zimmermann<sup>83</sup>, S. Zimmermann<sup>48</sup>, Z. Zinonos<sup>54</sup>, M. Zinser<sup>83</sup>, M. Ziolkowski<sup>141</sup>, L. Živković<sup>13</sup>, G. Zobernig<sup>173</sup>, A. Zoccoli<sup>20a,20b</sup>, M. zur Nedden<sup>16</sup>, G. Zurzolo<sup>104a,104b</sup>, L. Zwalinski<sup>30</sup>.

<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia

<sup>2</sup> Physics Department, SUNY Albany, Albany NY, United States of America

<sup>3</sup> Department of Physics, University of Alberta, Edmonton AB, Canada

<sup>4</sup> (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c)

Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

- <sup>5</sup> LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
- <sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
- <sup>7</sup> Department of Physics, University of Arizona, Tucson AZ, United States of America
- <sup>8</sup> Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
- <sup>9</sup> Physics Department, University of Athens, Athens, Greece
- <sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece
- <sup>11</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>12</sup> Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
- <sup>13</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia
- <sup>14</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway
- <sup>15</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
- <sup>16</sup> Department of Physics, Humboldt University, Berlin, Germany
- <sup>17</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- <sup>18</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- <sup>19</sup> <sup>(a)</sup> Department of Physics, Bogazici University, Istanbul; <sup>(b)</sup> Department of Physics Engineering, Gaziantep University, Gaziantep; <sup>(c)</sup> Department of Physics, Dogus University, Istanbul, Turkey
- <sup>20</sup> <sup>(a)</sup> INFN Sezione di Bologna; <sup>(b)</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- <sup>21</sup> Physikalisches Institut, University of Bonn, Bonn, Germany
- <sup>22</sup> Department of Physics, Boston University, Boston MA, United States of America
- <sup>23</sup> Department of Physics, Brandeis University, Waltham MA, United States of America
- <sup>24</sup> <sup>(a)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(b)</sup> Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; <sup>(c)</sup> Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; <sup>(d)</sup> Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
- <sup>25</sup> Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- <sup>26</sup> <sup>(a)</sup> Transilvania University of Brasov, Brasov, Romania; <sup>(b)</sup> National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(c)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; <sup>(d)</sup> University Politehnica Bucharest, Bucharest; <sup>(e)</sup> West University in Timisoara, Timisoara, Romania
- <sup>27</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>28</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>29</sup> Department of Physics, Carleton University, Ottawa ON, Canada
- <sup>30</sup> CERN, Geneva, Switzerland
- <sup>31</sup> Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- <sup>32</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>33</sup> <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Department of Modern Physics, University of Science and Technology of China, Anhui; <sup>(c)</sup> Department of Physics, Nanjing University, Jiangsu; <sup>(d)</sup> School of Physics, Shandong University, Shandong; <sup>(e)</sup> Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; <sup>(f)</sup> Physics Department, Tsinghua University, Beijing 100084, China
- <sup>34</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- <sup>35</sup> Nevis Laboratory, Columbia University, Irvington NY, United States of America

- <sup>36</sup> Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- <sup>37</sup> <sup>(a)</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; <sup>(b)</sup> Dipartimento di Fisica, Università della Calabria, Rende, Italy
- <sup>38</sup> <sup>(a)</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>39</sup> Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- <sup>40</sup> Physics Department, Southern Methodist University, Dallas TX, United States of America
- <sup>41</sup> Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- <sup>42</sup> DESY, Hamburg and Zeuthen, Germany
- <sup>43</sup> Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- <sup>44</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- <sup>45</sup> Department of Physics, Duke University, Durham NC, United States of America
- <sup>46</sup> SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>47</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>48</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- <sup>49</sup> Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>50</sup> <sup>(a)</sup> INFN Sezione di Genova; <sup>(b)</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy
- <sup>51</sup> <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- <sup>52</sup> II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- <sup>53</sup> SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>54</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- <sup>55</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- <sup>56</sup> Department of Physics, Hampton University, Hampton VA, United States of America
- <sup>57</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
- <sup>58</sup> <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(c)</sup> ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- <sup>59</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- <sup>60</sup> <sup>(a)</sup> Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup> Department of Physics, The University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- <sup>61</sup> Department of Physics, Indiana University, Bloomington IN, United States of America
- <sup>62</sup> Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- <sup>63</sup> University of Iowa, Iowa City IA, United States of America
- <sup>64</sup> Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
- <sup>65</sup> Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- <sup>66</sup> KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- <sup>67</sup> Graduate School of Science, Kobe University, Kobe, Japan
- <sup>68</sup> Faculty of Science, Kyoto University, Kyoto, Japan
- <sup>69</sup> Kyoto University of Education, Kyoto, Japan
- <sup>70</sup> Department of Physics, Kyushu University, Fukuoka, Japan
- <sup>71</sup> Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- <sup>72</sup> Physics Department, Lancaster University, Lancaster, United Kingdom
- <sup>73</sup> <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università del Salento, Lecce,

Italy

- <sup>74</sup> Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- <sup>75</sup> Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- <sup>76</sup> School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- <sup>77</sup> Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- <sup>78</sup> Department of Physics and Astronomy, University College London, London, United Kingdom
- <sup>79</sup> Louisiana Tech University, Ruston LA, United States of America
- <sup>80</sup> Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- <sup>81</sup> Fysiska institutionen, Lunds universitet, Lund, Sweden
- <sup>82</sup> Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- <sup>83</sup> Institut für Physik, Universität Mainz, Mainz, Germany
- <sup>84</sup> School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- <sup>85</sup> CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>86</sup> Department of Physics, University of Massachusetts, Amherst MA, United States of America
- <sup>87</sup> Department of Physics, McGill University, Montreal QC, Canada
- <sup>88</sup> School of Physics, University of Melbourne, Victoria, Australia
- <sup>89</sup> Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- <sup>90</sup> Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- <sup>91</sup> <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- <sup>92</sup> B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- <sup>93</sup> National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- <sup>94</sup> Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
- <sup>95</sup> Group of Particle Physics, University of Montreal, Montreal QC, Canada
- <sup>96</sup> P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
- <sup>97</sup> Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- <sup>98</sup> National Research Nuclear University MEPhI, Moscow, Russia
- <sup>99</sup> D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- <sup>100</sup> Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- <sup>101</sup> Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- <sup>102</sup> Nagasaki Institute of Applied Science, Nagasaki, Japan
- <sup>103</sup> Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- <sup>104</sup> <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- <sup>105</sup> Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- <sup>106</sup> Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- <sup>107</sup> Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- <sup>108</sup> Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- <sup>109</sup> Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- <sup>110</sup> Department of Physics, New York University, New York NY, United States of America

- <sup>111</sup> Ohio State University, Columbus OH, United States of America
- <sup>112</sup> Faculty of Science, Okayama University, Okayama, Japan
- <sup>113</sup> Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- <sup>114</sup> Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- <sup>115</sup> Palacký University, RCPTM, Olomouc, Czech Republic
- <sup>116</sup> Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- <sup>117</sup> LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- <sup>118</sup> Graduate School of Science, Osaka University, Osaka, Japan
- <sup>119</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>120</sup> Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>121</sup> <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- <sup>122</sup> Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- <sup>123</sup> National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- <sup>124</sup> <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- <sup>125</sup> Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- <sup>126</sup> <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; <sup>(b)</sup> Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Department of Physics, University of Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- <sup>127</sup> Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- <sup>128</sup> Czech Technical University in Prague, Praha, Czech Republic
- <sup>129</sup> Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- <sup>130</sup> State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia, Russia
- <sup>131</sup> Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>132</sup> <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- <sup>133</sup> <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- <sup>134</sup> <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- <sup>135</sup> <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l'Énergie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup> Faculté des sciences, Université Mohammed V, Rabat, Morocco
- <sup>136</sup> DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Énergie Atomique et aux Énergies Alternatives), Gif-sur-Yvette, France
- <sup>137</sup> Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- <sup>138</sup> Department of Physics, University of Washington, Seattle WA, United States of America
- <sup>139</sup> Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- <sup>140</sup> Department of Physics, Shinshu University, Nagano, Japan
- <sup>141</sup> Fachbereich Physik, Universität Siegen, Siegen, Germany

- <sup>142</sup> Department of Physics, Simon Fraser University, Burnaby BC, Canada
- <sup>143</sup> SLAC National Accelerator Laboratory, Stanford CA, United States of America
- <sup>144</sup> <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- <sup>145</sup> <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- <sup>146</sup> <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> The Oskar Klein Centre, Stockholm, Sweden
- <sup>147</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden
- <sup>148</sup> Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
- <sup>149</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- <sup>150</sup> School of Physics, University of Sydney, Sydney, Australia
- <sup>151</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>152</sup> Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- <sup>153</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- <sup>154</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- <sup>155</sup> International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- <sup>156</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- <sup>157</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- <sup>158</sup> Department of Physics, University of Toronto, Toronto ON, Canada
- <sup>159</sup> <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto ON, Canada
- <sup>160</sup> Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- <sup>161</sup> Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
- <sup>162</sup> Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- <sup>163</sup> Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- <sup>164</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- <sup>165</sup> Department of Physics, University of Illinois, Urbana IL, United States of America
- <sup>166</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- <sup>167</sup> 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
- <sup>168</sup> Department of Physics, University of British Columbia, Vancouver BC, Canada
- <sup>169</sup> Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- <sup>170</sup> Department of Physics, University of Warwick, Coventry, United Kingdom
- <sup>171</sup> Waseda University, Tokyo, Japan
- <sup>172</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- <sup>173</sup> Department of Physics, University of Wisconsin, Madison WI, United States of America
- <sup>174</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- <sup>175</sup> Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

- <sup>176</sup> Department of Physics, Yale University, New Haven CT, United States of America
- <sup>177</sup> Yerevan Physics Institute, Yerevan, Armenia
- <sup>178</sup> Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- <sup>a</sup> Also at Department of Physics, King's College London, London, United Kingdom
- <sup>b</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>c</sup> Also at Novosibirsk State University, Novosibirsk, Russia
- <sup>d</sup> Also at TRIUMF, Vancouver BC, Canada
- <sup>e</sup> Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America
- <sup>f</sup> Also at Department of Physics, California State University, Fresno CA, United States of America
- <sup>g</sup> Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
- <sup>h</sup> Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal
- <sup>i</sup> Also at Tomsk State University, Tomsk, Russia
- <sup>j</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- <sup>k</sup> Also at Università di Napoli Parthenope, Napoli, Italy
- <sup>l</sup> Also at Institute of Particle Physics (IPP), Canada
- <sup>m</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>n</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
- <sup>o</sup> Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- <sup>p</sup> Also at Louisiana Tech University, Ruston LA, United States of America
- <sup>q</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- <sup>r</sup> Also at Graduate School of Science, Osaka University, Osaka, Japan
- <sup>s</sup> Also at Department of Physics, National Tsing Hua University, Taiwan
- <sup>t</sup> Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- <sup>u</sup> Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
- <sup>v</sup> Also at CERN, Geneva, Switzerland
- <sup>w</sup> Also at Georgian Technical University (GTU), Tbilisi, Georgia
- <sup>x</sup> Also at Manhattan College, New York NY, United States of America
- <sup>y</sup> Also at Hellenic Open University, Patras, Greece
- <sup>z</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>aa</sup> Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
- <sup>ab</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>ac</sup> Also at School of Physics, Shandong University, Shandong, China
- <sup>ad</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- <sup>ae</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>af</sup> Also at International School for Advanced Studies (SISSA), Trieste, Italy
- <sup>ag</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- <sup>ah</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
- <sup>ai</sup> Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- <sup>aj</sup> Also at National Research Nuclear University MEPhI, Moscow, Russia
- <sup>ak</sup> Also at Department of Physics, Stanford University, Stanford CA, United States of America
- <sup>al</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- <sup>am</sup> Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
- \* Deceased