Pseudorapidity dependence of long-range two-particle correlations in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration

Abstract

Two-particle correlations in pPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV are studied as a function of the pseudorapidity separation ($\Delta \eta$) of the particle pair at small relative azimuthal angle ($|\Delta \phi| < \pi/3$). The correlations are decomposed into a jet component that dominates the short-range correlations ($|\Delta \eta| < 1$), and a component that persists at large $\Delta \eta$ and may originate from collective behavior of the produced system. The events are classified in terms of the multiplicity of the produced particles. Finite azimuthal anisotropies are observed in high-multiplicity events. The second and third Fourier components of the particle-pair azimuthal correlations, $V_2$ and $V_3$, are extracted after subtraction of the jet component. The single-particle anisotropy parameters $v_2$ and $v_3$ are normalized by their lab frame mid-rapidity value and are studied as a function of $\eta_{c.m.}$. The normalized $v_2$ distribution is found to be asymmetric about $\eta_{c.m.} = 0$, with smaller values observed at forward pseudorapidity, corresponding to the direction of the proton beam, while no significant pseudorapidity dependence is observed for the normalized $v_3$ distribution within the statistical uncertainties.

1 Introduction

Studies of two-particle correlations play an important role in understanding the underlying mechanism of particle production in high-energy nuclear collisions [1–3]. Typically, these correlations are studied in a two-dimensional $\Delta \phi \Delta \eta$ space, where $\Delta \phi$ and $\Delta \eta$ are the differences in the azimuthal angle $\phi$ and the pseudorapidity $\eta$ of the two particles.

A notable feature in the two-particle correlations is the so-called “ridge,” which is an extended correlation structure in relative pseudorapidity $\Delta \eta$ concentrated at small relative azimuthal angle $|\Delta \phi| \approx 0$. The ridge, first observed in nucleus-nucleus (AA) collisions [4–6], has been studied both at RHIC and LHC over a wide range of collision energies and system sizes [4–15]. In AA collisions, such long-range two-particle correlations have been associated with the development of collective hydrodynamic flow, which transfers the azimuthal anisotropy in the initial energy density distribution to the final state momentum anisotropy through strong rescatterings in the medium produced in such collisions [16–20]. A recent study suggests that anisotropic escape probabilities may already produce large final-state anisotropies without the need for significant rescattering [21]. Another possible mechanism proposed to account for the initial-state correlations is the color glass condensate (CGC), where the two-gluon density is enhanced at small $\Delta \phi$ over a wide $\Delta \eta$ range [22, 23]. However, to reproduce the magnitude of the ridge in AA collisions, the CGC-based models also require a late-stage collective flow boost to produce the observed stronger angular collimation effect [24, 25]. As a purely initial-state effect, the CGC correlations are expected to be independent of the formation of a thermally equilibrated quark-gluon plasma, while the collective hydrodynamic flow requires a medium that is locally thermalized. The latter condition might not be achieved in small systems.

Measurements at the LHC led to the discovery of a long-range ridge structure in small systems. The ridge has been observed in high-multiplicity proton-proton (pp) [9, 26, 27] and proton-lead (pPb) collisions [10–12, 28]. A similar long-range structure was also found in the most central deuteron-gold (dAu) and $^3$He-gold collisions at RHIC [13–15]. To investigate whether collective flow is responsible for the ridge in pPb collisions, multiparticle correlations were studied at the LHC [29–31] in events with different multiplicities. The second harmonic anisotropy parameter, $v_2$, of the particle azimuthal distributions measured using four-, six-, eight-, or all-particle correlations were found to have the same value [31], as expected in a system with global collective flow [32]. In addition, the $v_2$ parameters of identified hadrons were measured as a function of transverse momentum ($p_T$) in pPb [33, 34] and in dAu collisions [13]. The $v_2(p_T)$ distributions were found to be ordered by the particle mass, i.e., the distributions for the heavier particles are boosted to higher $p_T$, as expected from hydrodynamics, where the particles move with a common flow velocity. The similarities between the correlations observed in the small systems and in heavy ion collisions suggest a common hydrodynamic origin [29, 35, 36]. However it is still under investigation whether hydrodynamics can be applied reliably to pp or pA systems.

As predicted by hydrodynamics and CGC [37, 38], as well as phenomenological models like EPOS [39], the average transverse momentum, $\langle p_T \rangle$, of the produced particles should depend on pseudorapidity. This pseudorapidity dependence of $\langle p_T \rangle$ could translate into a pseudorapidity dependence of the long-range correlations which also depend on $p_T$ [40]. While hydrodynamics predicts that the pseudorapidity dependence of $\langle p_T \rangle$ follows that of the charged particle pseudorapidity density $dN/d\eta$ which increases at negative pseudorapidity, in the CGC both a rising or a falling trend of $\langle p_T \rangle$ with pseudorapidity may be possible [38]. Thus, a measurement of the pseudorapidity dependence of the ridge may provide further insights into its origin. The pseudorapidity dependence of the Fourier coefficients extracted using the long-
range two-particle correlations could also be influenced by event-by-event fluctuations of the initial energy density \[41–43\]. The pressure gradients that drive the hydrodynamic expansion may differ in different pseudorapidity regions, causing a pseudorapidity-dependent phase shift in the event-plane orientation determined from the direction of maximum particle emission. Evidence for such event-plane decorrelation has been found in pPb collisions \[44\]. Additional studies of the pseudorapidity dependence of the ridge may contribute to elucidating the longitudinal dynamics of the produced system.

The two-particle correlation measurement is performed using “trigger” and “associated” particles as described in Ref. \[45\]. The trigger particles are defined as charged particles detected within a given \(p_T^{\text{trig}}\) range. The particle pairs are formed by associating each trigger particle with the remaining charged particles from a certain \(p_T^{\text{assoc}}\) range. Typically, both particles are selected from a wide identical range of pseudorapidity, and therefore by construction the \(\Delta\eta\) distribution is symmetric about \(\Delta\eta = 0\) \[29\]. Any \(\Delta\eta\) dependence in the ridge correlation signal would be averaged out by the integration over the trigger and associated particle pseudorapidity distributions \[46\]. To gain further insights about the long-range ridge correlation in the pPb system, in this paper we perform a \(\Delta\eta\)-dependent analysis by restricting the trigger particle to a narrow pseudorapidity range. With this method, the combinatorial background resembles the single-particle density. Therefore, the correlation function in pPb collisions is nonuniform in \(\Delta\eta\).

The ridge correlation is often characterized by the Fourier coefficients \(V_n\). The \(V_n\) values are determined from a Fourier decomposition of long-range two-particle \(\Delta\phi\) correlation functions, given by:

\[
\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi} \left[ 1 + \sum_n 2V_n \cos(n\Delta\phi) \right],
\]

as described in Refs. \[8, 45\], where \(N_{\text{pair}}\) is the total number of correlated hadron pairs. \(N_{\text{assoc}}\) represents the total number of associated particles per trigger particle for a given \((p_T^{\text{trig}}, p_T^{\text{assoc}})\) bin.

To remove short-range correlations from jets and other sources, a pseudorapidity separation may be applied between the trigger and associated particle; alternatively, the correlations in low multiplicity events may be measured and subtracted from those in high multiplicity events after appropriate scaling, to remove the short-range correlations, which are likely to have similar \(\Delta\eta\)-\(\Delta\phi\) shapes in high- and low-multiplicity collisions. Both methods are used in this analysis.

The single-particle anisotropy parameters \(v_n\) are extracted from the particle-pair Fourier coefficients \(V_n\), assuming that they factorize \[47\]. The \(v_n\) values are then normalized by their lab frame mid-rapidity values and are studied as a function of \(\eta_{\text{c.m.}}\). These distributions are compared to the normalized pseudorapidity distributions of the mean transverse momentum.

2 CMS detector

A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. \[48\]. The main results in this paper are based on data from the silicon tracker. This detector consists of 1440 silicon pixel and 15148 silicon strip detector modules, and is located in the 3.8 T magnetic field of the superconducting solenoid. It measures the trajectories of the charged particles emitted within the pseudorapidity range \(|\eta_{\text{lab}}| < 2.5\), and provides an impact parameter resolution of \(\sim 15 \mu m\) and
a transverse momentum resolution of about 1% for particles with $p_T = 2 \text{ GeV/c}$, and 1.5% for particles at $p_T = 100 \text{ GeV/c}$.

The electromagnetic calorimeter (ECAL) and the hadron calorimeter (HCAL) are also located inside the solenoid. The ECAL consists of 75,848 lead-tungstate crystals, arranged in a quasi-projective geometry and distributed in a barrel region ($|\eta_{\text{lab}}| < 1.48$) and two endcaps that extend up to $|\eta_{\text{lab}}| = 3.0$. The HCAL barrel and endcaps are sampling calorimeters composed of brass and scintillator plates, covering $|\eta_{\text{lab}}| < 3.0$. Iron/quartz fiber Cherenkov Hadron Forward (HF) calorimeters cover the range $2.9 < |\eta_{\text{lab}}| < 5.2$ on either side of the interaction region. The detailed MC simulation of the CMS detector response is based on GEANT4 [49].

3 Data samples and event selection

The data used are from pPb collisions recorded by the CMS detector in 2013, corresponding to an integrated luminosity of about $35 \text{ nb}^{-1}$ [50]. The beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei, resulting in a center-of-mass energy per nucleon pair of $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. The direction of the higher-energy proton beam was initially set up to be clockwise, and then reversed. Massless particles emitted at $\eta_{\text{c.m.}} = 0$ were detected at $\eta_{\text{lab}} = -0.465$ (clockwise proton beam) or at $\eta_{\text{lab}} = 0.465$ (counterclockwise proton beam) in the laboratory frame. Both datasets were used in this paper. The data in which the proton beam traveled clockwise were reflected about $\eta_{\text{lab}} = 0$ and combined with the rest of the data, so that the proton beam direction is always associated with the positive $\eta_{\text{lab}}$ direction.

The online triggering, and the offline reconstruction and selection follow the same procedure as described in Ref. [29]. Minimum-bias events were selected by requiring that at least one track with $p_T > 0.4 \text{ GeV/c}$ was found in the pixel tracker for a pPb bunch crossing. Because of hardware limits on the data acquisition rate, only a small fraction ($10^{-3}$) of all minimum bias triggered events were recorded (i.e., the trigger was “prescaled”). The high-multiplicity triggers were implemented using the Level-1 (L1) trigger and High Level Trigger (HLT) to enhance high multiplicity events that are of interest for the particle correlation studies. At L1, two event streams were triggered by requiring the total transverse energy summed over ECAL and HCAL to be greater than 20 or 40 GeV/c. Charged tracks were then reconstructed online at the HLT using the three layers of pixel detectors, and requiring a track origin within a cylindrical region of 30 cm length along the beam and 0.2 cm radius perpendicular to the beam [51].

In the offline analysis, hadronic collisions were selected by requiring at least 3 GeV/c of total energy in at least one HF calorimeter tower on each side of the interaction region (positive and negative $\eta_{\text{lab}}$). Events were also required to contain at least one reconstructed primary vertex within 15 cm of the nominal interaction point along the beam axis ($z_{\text{vtx}}$) and within 0.15 cm distance transverse to the beam trajectory.

The pPb instantaneous luminosity provided by the LHC in the 2013 pPb run resulted in approximately a 3% probability that at least one additional interaction occurs in the same bunch crossing, i.e. pileup events. A pileup rejection procedure [29] was applied to select clean, single-vertex pPb events. The residual fraction of pileup events was estimated to be no more than 0.2% for the highest multiplicity pPb interactions studied in this paper [29]. Based on simulations using the HIJING [52] and the EPOS [53] event generators, these event selections have an acceptance of 94–97% for pPb interactions that have at least one primary particle with $E > 3 \text{ GeV}$ in both $\eta_{\text{lab}}$ ranges of $-5 < \eta_{\text{lab}} < -3$ and $3 < \eta_{\text{lab}} < 5$. The charged-particle information was recorded in the silicon tracker and the tracks were reconstructed within the
pseudorapidity range $|\eta_{\text{lab}}| < 2.5$.

A reconstructed track was considered as a primary track candidate if the impact parameter significance $d_{xy}/\sigma(d_{xy})$ and the significance of $z$ separation between the track and the best reconstructed primary vertex (the one associated with the largest number of tracks, or best $\chi^2$ probability if the same number of tracks was found) $d_z/\sigma(d_z)$ are both less than 3. In order to remove tracks with poor momentum estimates, the relative uncertainty in the momentum measurement $\sigma(p_T)/p_T$ was required to be less than 10%. To ensure high tracking efficiency and to reduce the rate of misreconstructed tracks, primary tracks with $|\eta_{\text{lab}}| < 2.4$ and $p_T > 0.3$ GeV/c were used in the analysis.

The events are classified by $N_{\text{offline}}^{\text{trk}}$, the measured number of primary tracks within $|\eta_{\text{lab}}| < 2.4$ and $p_T > 0.4$ GeV/c (a $p_T$ cutoff of 0.4 GeV/c was used in the multiplicity determination to match the HLT requirement), in a method similar to the approach used in Refs. [9, 10]. The high- and low-multiplicity events in this paper are defined by $220 \leq N_{\text{offline}}^{\text{trk}} < 260$ and $2 \leq N_{\text{offline}}^{\text{trk}} < 20$, respectively. The high-multiplicity selection corresponds to an event fraction of $3.4 \times 10^{-6}$ of the events. Data from the minimum bias trigger are used for low-multiplicity event selection, while the high-multiplicity triggers with online multiplicity thresholds of 100, 130, 160, and 190 are used for high multiplicity events [29].

4 Analysis procedure

The dihadron correlation is quantified by azimuthal angle $\phi$ and pseudorapidity differences between the two particles.

$$\Delta \phi = \phi_{\text{assoc}} - \phi_{\text{trig}}, \quad \Delta \eta = \eta_{\text{assoc}} - \eta_{\text{trig}},$$

where $\phi_{\text{assoc}}$ and $\eta_{\text{assoc}}$ are the associated particle coordinates and $\phi_{\text{trig}}$ and $\eta_{\text{trig}}$ are the trigger particle coordinates, both measured in the laboratory frame. The per-trigger normalized associated particle yield is defined by:

$$S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2N}{d\Delta \eta d\Delta \phi}.$$
4.1 Quantifying the jet contributions

Figure 1: (Color online) Efficiency-corrected 2D associated yields with Pb-side trigger particle \((-2.4 < \eta_{\text{lab}} < -2.0, \text{left panels})\) and p-side trigger particle \((2.0 < \eta_{\text{lab}} < 2.4, \text{right panels})\) in low-multiplicity \((2 \leq N_{\text{trk}}^{\text{offline}} < 20, \text{upper panels})\) and high-multiplicity \((220 \leq N_{\text{trk}}^{\text{offline}} < 260, \text{lower panels})\) are shown for pPb collisions at \(\sqrt{s_{NN}} = 5.02\,\text{TeV}\). The associated and trigger particle \(p_T\) ranges are both \(0.3 < p_T < 3\,\text{GeV/c}\).

is used for trigger and associated particles. The peak at \((0,0)\) is the near-side jet-like structure. In the high multiplicity events, one can notice a ridge-like structure in \(|\Delta\eta|\) at \(\Delta\phi = 0\) atop the high combinatorial background. A similar extensive structure can also be seen on the away side \(\Delta\phi = \pi\), which contains the away-side jet. Unlike correlation functions from previous studies, the correlated yield is asymmetric in \(\Delta\eta\); it reflects the asymmetric single particle \(dN/d\eta\) distribution in the pPb system.

The \(\Delta\phi\) distribution of the associated yield is projected within each \(\Delta\eta\) bin (with a bin width of 0.2). Before quantifying jet contributions, the zero-yield-at-minimum (ZYAM) technique \([55]\) is used to subtract a uniform background in \(\Delta\phi\). To obtain the ZYAM background normalization, the associated yield distribution is first projected into the range of \(0 < \Delta\phi < \pi\), and then scanned to find the minimum yield within a \(\Delta\phi\) window of \(\pi/12\) radians. This minimum yield is treated as the ZYAM background. The ZYAM background shape as a function of \(\Delta\eta\) is similar to the shape of the single particle density.

After ZYAM subtraction, the signal will be zero at the minimum. For example, the \(\Delta\phi\) distributions in high- and low-multiplicity collisions are depicted in Fig. 2 for two, short-(0 < \(|\Delta\eta| < 0.2\)) and long-range(2.8 < \(|\Delta\eta| < 3.0\)) \(\Delta\eta\) bins. They are composed of two characteristic peaks: one at \(\Delta\phi = 0\) (near-side) and the other at \(\Delta\phi = \pi\) (away-side), with a minimum valley between the two peaks. For low-multiplicity collisions at large \(\Delta\eta\), no near-side peak is
Figure 2: (Color online) Examples of the distribution of the associated yields after ZYAM subtraction for both low-multiplicity ($2 \leq N_{\text{offline}}^{\text{trk}} < 20$, blue triangles) and high-multiplicity ($220 \leq N_{\text{offline}}^{\text{trk}} < 260$, red circles) are shown for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results for Pb-side (left panels) and p-side (right panels) trigger particles are both shown; small $\Delta \eta$ in the upper panels and large $|\Delta \eta|$ in the lower panels. The trigger and associated particle $p_T$ ranges are both $0.3 < p_T < 3 \text{ GeV/c}$.

observed.

First, the $\Delta \eta$ dependence of the correlated yield is analyzed. In each $\Delta \eta$ bin, the correlated yield is averaged within the near side ($|\Delta \phi| < \pi/3$. The correlated yield reaches a minimum at around $\pi/3$. The near-side averaged correlated yield per radian, $(1/N_{\text{trig}})(dN)/(d\Delta \eta)$, is shown as a function of $\Delta \eta$ in Fig. [3]. In low-multiplicity collisions, the near-side $\Delta \eta$ correlated yield is consistent with zero at large $\Delta \eta$. This indicates that the near side in low-multiplicity pPb collisions is composed of only a jet component after ZYAM subtraction. In high-multiplicity collisions, an excess of the near-side correlated yield is seen at large $\Delta \eta$ and it is due to the previously observed ridge [10].

In order to quantify the near-side jet contribution, the near-side correlation function is fitted with a two-component functional form:

$$\frac{1}{N_{\text{trig}}}rac{dN_{\text{near}}(\Delta \eta)}{d\Delta \eta} = \frac{Y\beta}{\sqrt{2}\sigma\Gamma(1/2\beta)} \exp \left[-\left(\frac{\Delta \eta^2}{2\sigma^2}\right)^\beta\right] + (C + k\Delta \eta)\text{ZYAM}(\Delta \eta).$$  (2)

The first term represents the near-side jet; $Y$ is the correlated yield, and $\sigma$ and $\beta$ describe the correlation shape. Neither a simple Gaussian nor an exponential function describes the jet-like
4.1 Quantifying the jet contributions

Figure 3: (Color online) The near-side ($|\Delta \phi| < \pi/3$) correlated yield after ZYAM subtraction in low-multiplicity 2 $\leq N_{\text{offline}}^\text{trk} < 20$ (upper panels) and high-multiplicity 220 $\leq N_{\text{offline}}^\text{trk} < 260$ (lower panels) are shown for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The trigger and associated particle $p_T$ ranges are both 0.3 $< p_T < 3$ GeV/c. The trigger particles are restricted to the Pb-side ($-2.4 < \eta_{\text{trig}}^\text{lab} < -2.0$, left panels) and the p-side ($2.0 < \eta_{\text{trig}}^\text{lab} < 2.4$, right panels), respectively. Fit results using Eq. (2) (black solid curves) are superimposed; the red dashed curve and the blue open points are the two fit components, jet and ridge, respectively.

Peak adequately. However, a generalized Gaussian form as in Eq. 2 is found to describe the data well. The second term on the right-hand side of Eq. (2) represents the ridge structure. Since the ridge is wide in $\Delta \eta$ and may be related to the bulk medium, its shape is modeled as dominated by the underlying event magnitude, ZYAM($\Delta \eta$). However, the background shape multiplied by a constant is not adequate to describe the ridge in high multiplicity events. Instead, the background shape multiplied by a linear function in $\Delta \eta$, as in Eq. (2), can fit the data well, with reasonable $\chi^2$/ndf (where ndf is the number of degree of freedom) (see Table 1). Here $C$ quantifies the overall strength of the ridge yield relative to the underlying event, and $k$ indicates the $\Delta \eta$ dependence of the ridge in addition to that of the underlying event.

The fits using Eq. 2 are superimposed in Fig. 3 and the fit parameters are shown in Table 1. For low-multiplicity collisions, the $k$ parameter is consistent with zero and, in the fit shown, it is set to zero. For high-multiplicity collisions, the $C$ parameter is positive, reflecting the finite ridge correlation, and the $k$ parameter is nonzero, indicating that the ridge does not have the same $\Delta \eta$ shape as the underlying event. As already shown in Fig. 3, the ridge (correlated yield at large $\Delta \eta$) is not constant but $\Delta \eta$-dependent.

The fitted $Y$ parameter shows that the jet-like correlated yield in high-multiplicity collisions...
Table 1: Summary of fit parameters for low- and high-$N_{\text{offline}}$ ranges in pPb collisions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pb-side trigger</th>
<th>p-side trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{offline}} &lt; 20$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y$</td>
<td>$0.130 \pm 0.003$</td>
<td>$0.156 \pm 0.003$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$0.445 \pm 0.011$</td>
<td>$0.446 \pm 0.010$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$0.943 \pm 0.057$</td>
<td>$0.870 \pm 0.043$</td>
</tr>
<tr>
<td>$C$</td>
<td>$0.0045 \pm 0.0009$</td>
<td>$0.0045 \pm 0.0010$</td>
</tr>
<tr>
<td>$k$</td>
<td>$0$ (Fixed)</td>
<td>$0$ (Fixed)</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>$0.279$</td>
<td>$0.459$</td>
</tr>
<tr>
<td>$220 \leq N_{\text{offline}} &lt; 260$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y$</td>
<td>$0.401 \pm 0.011$</td>
<td>$0.489 \pm 0.011$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$0.457 \pm 0.008$</td>
<td>$0.492 \pm 0.007$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$0.757 \pm 0.003$</td>
<td>$0.782 \pm 0.025$</td>
</tr>
<tr>
<td>$C$</td>
<td>$0.0137 \pm 0.0004$</td>
<td>$0.0098 \pm 0.0004$</td>
</tr>
<tr>
<td>$k$</td>
<td>$-0.0011 \pm 0.0001$</td>
<td>$0.0002 \pm 0.0001$</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>$1.074$</td>
<td>$0.463$</td>
</tr>
</tbody>
</table>

$Y_{(220 \leq N_{\text{offline}} < 260)}$ is larger than that in low-multiplicity collisions ($Y_{N_{\text{offline}} < 20}$). The ratio is

$$\alpha = Y_{220 \leq N_{\text{offline}} < 260}/Y_{N_{\text{offline}} < 20} = \begin{cases} 3.08 \pm 0.11^{+0.96}_{-0.31} & \text{for Pb-side triggers;} \\ 3.13 \pm 0.09^{+0.28}_{-0.28} & \text{for p-side triggers,} \end{cases}$$

where the $\pm$ sign is followed by the statistical uncertainty from the fit. The upper “+” and lower “−” are followed by the systematic uncertainty, which is obtained by fitting different functional forms, such as Gaussian and exponential functions, and by varying the $\Delta\eta$ range to calculate the ZYAM value.

The $\alpha$ values are used as a scaling factor when correlations from low-multiplicity collisions are removed in determining the Fourier coefficients in high-multiplicity events.

### 4.2 Fourier coefficients

For each $\Delta\eta$ bin, the azimuthal anisotropy harmonics, $V_n$, can be calculated from the two-particle correlation $\Delta\phi$ distribution,

$$V_n = \langle \cos n\Delta\phi \rangle.$$

The $\langle \rangle$ denotes the averaging over all particles and all events. At large $\Delta\eta$, the near-side jet contribution is negligible, but the away-side jet still contributes. The jet contributions may be significantly reduced or eliminated by subtracting the low-multiplicity collision data, via a prescription described in Ref. [29],

$$V_{n_{\text{sub}}} = V_{n_{\text{HM}}^{\text{HM}}} - V_{n_{\text{LM}}^{\text{LM}}} \frac{N_{\text{LM}}^{\text{assoc}}}{N_{\text{HM}}^{\text{assoc}}} \alpha.$$

Here LM and HM stand for low-multiplicity and high-multiplicity, respectively. $N_{\text{HM}}^{\text{assoc}}$ and $N_{\text{LM}}^{\text{assoc}}$ are the associated particle multiplicities in a given pseudorapidity bin, and $V_{n_{\text{HM}}}^{\text{HM}}$ and $V_{n_{\text{LM}}}^{\text{LM}}$ are the Fourier coefficients in high- and low-multiplicity collisions, respectively. The $\alpha$
value is obtained from Eq. (3). This procedure to extract $V_n$ is tested by studying the pPb collisions generated by the HIJING 1.383 model [52]. The basic HIJING model has no flow, so a flow-like signal is added [56] by superimposing an azimuthal modulation on the distributions of the produced particles. The measured $V_2$ using Eq. (4) is consistent with the input flow value within a relative 5% difference.

To quantify the anisotropy dependence as a function of $\eta_{lab}$, assuming factorization, $V_n(\eta_{lab}, \eta_{assoc}) = v_n(\eta_{assoc}) v_n(\eta_{lab})$, a self-normalized anisotropy is calculated from the Fourier coefficient $V_n$.

$$\frac{v_n(\eta_{assoc})}{v_n(\eta_{assoc} = 0)} = \frac{V_n(\eta_{assoc})}{V_n(\eta_{assoc} = 0)}.$$ (5)

Here the $\eta_{assoc}$ is directly calculated from $\Delta \eta$, assuming the trigger particle is at a fixed $\eta_{lab}$ direction

$$\eta_{assoc}^{\text{trig}} = \Delta \eta + \eta_{lab}.$$ (6)

in which $\eta_{lab}^{\text{trig}} = -2.2 (2.2)$ for the Pb-side (p-side) trigger. Hereafter, we write only $\eta_{lab}$, eliminating the superscript ‘assoc’ from $\eta_{assoc}^{\text{trig}}$.

To avoid short-range correlations that remain even after the subtraction of the low-multiplicity events, only correlations with large $|\Delta \eta|$ are selected to construct the $v_n$ pseudorapidity distributions.

5 Systematic uncertainties

The systematic uncertainties in the Fourier coefficient $V_n$ are estimated from the following sources: the track quality requirements by comparing loose and tight selections; bias in the event selection from the HLT trigger, by using different high-multiplicity event selection criteria; pileup effect, by requiring a single vertex per event; and the event vertex position, by selecting events from different $z$-vertex ranges. In the low multiplicity $V_n$ subtraction, the jet ratio parameter $\alpha$ is applied. The systematic uncertainties in $\alpha$ are assessed by using fit functions different from Eq. (2), as well as by varying the $\Delta \eta$ range when obtaining the ZYAM value.

This systematic effect is included in the final uncertainties for the multiplicity-subtracted $V_n$. In addition, the effect of reversing the beam direction is studied. This is subject to the same systematic uncertainties already described above; thus it is not counted in the total systematic uncertainties, but is used as a cross-check.

The estimated uncertainties from the above sources are shown in Table 2. Combined together, they give a total uncertainty of 3.9% and 10% for $V_2$ and $V_3$ coefficients, respectively, as determined without the subtraction of signals from low-multiplicity events. For low-multiplicity-subtracted results, the systematic uncertainties rise to 5.8% and 15%, respectively.

The systematic uncertainties from the track-quality and jet-ratio selection are correlated among the pseudorapidity bins, so they cancel in the self-normalized anisotropy parameter, $v_n(\eta_{lab}) / v_n(\eta_{lab} = 0)$. The systematic uncertainties in other sources are treated as completely independent of pseudorapidity and are propagated in $v_n(\eta_{lab}) / v_n(\eta_{lab} = 0)$. The estimated systematic uncertainties in $v_2(\eta_{lab}) / v_2(\eta_{lab} = 0)$ and $v_3(\eta_{lab}) / v_3(\eta_{lab} = 0)$ without low multiplicity subtraction are estimated to be 3.6% and 10%, respectively. For low-multiplicity-subtracted results, the systematic uncertainties rise to 5.7% and 14%, respectively.
Table 2: Summary of systematic uncertainties in the second and third Fourier harmonics in pPb collisions. The label “low-mult sub” indicates the low-multiplicity subtracted results, while “no sub” indicates the results without subtraction.

<table>
<thead>
<tr>
<th>Source</th>
<th>$V_2$ (no sub)</th>
<th>$V_2$ (low-mult sub)</th>
<th>$V_3$ (no sub)</th>
<th>$V_3$ (low-mult sub)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track quality requirement</td>
<td>3.0%</td>
<td>3.0%</td>
<td>7.0%</td>
<td>11.0%</td>
</tr>
<tr>
<td>HLT trigger bias</td>
<td>2.0%</td>
<td>2.5%</td>
<td>2.0%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Effect from pileups</td>
<td>1.5%</td>
<td>3.0%</td>
<td>3.5%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Vertex dependence</td>
<td>0.5%</td>
<td>1.0%</td>
<td>6.0%</td>
<td>9.0%</td>
</tr>
<tr>
<td>Jet ratio</td>
<td>—</td>
<td>3.0%</td>
<td>—</td>
<td>3.0%</td>
</tr>
<tr>
<td>Total</td>
<td>3.9%</td>
<td>5.8%</td>
<td>10%</td>
<td>15%</td>
</tr>
</tbody>
</table>

6 Results

The $V_2$ and $V_3$ values in high-multiplicity collisions for Pb-side and p-side trigger particles are shown in Fig. 4. The strong peak is caused by near-side short-range jet contributions. The Fourier coefficients, $V_2^{\text{sub}}$ and $V_3^{\text{sub}}$, after the low-multiplicity data are subtracted, are also shown. The short-range jet-like peak is largely reduced, but may not be completely eliminated due to different near-side jet-correlation shapes for high- and low-multiplicity collisions. The long-range results are not affected by the near-side jet, but the away-side jet may still contribute if its shape is different in high- and low-multiplicity collisions or if its magnitude does not scale according to $\alpha$.

By self-normalization via Eq. (5), the Fourier coefficient from both trigger sides can be merged into a single distribution by combining the negative and positive $\eta_{\text{lab}}$ range. The lab frame central value $\eta_{\text{lab}} = 0$ is used so that the separation of the central value to both $\eta_{\text{trig}}^{\text{lab}}$ is the same. In this way, possible contamination from jets is kept at the same level as a function of $\eta_{\text{lab}}$. This is more important for the Fourier coefficients determined without the subtraction of the low-multiplicity data.

Figure 5 shows the $v_2(\eta_{\text{lab}})/v_2(\eta_{\text{lab}} = 0)$ and $v_3(\eta_{\text{lab}})/v_3(\eta_{\text{lab}} = 0)$ results obtained from the corresponding $V_2$ and $V_3$ data in Fig. 4. The curves show the $v_n(\eta_{\text{lab}})/v_n(\eta_{\text{lab}} = 0)$ obtained from the high-multiplicity data alone, $V_n^{\text{HM}}$, without subtraction of the low-multiplicity data. The data points are obtained from the low-multiplicity-subtracted $V_n^{\text{sub}}$; closed circles are from the Pb-side trigger particle data and open circles from the p-side. To avoid large contamination from short-range correlations, only the large $|\Delta \eta|$ range is shown, but still with enough overlap in mid-rapidity $\eta_{\text{lab}}$ between the two trigger selections; good agreement is observed. Significant pseudorapidity dependence is observed for the anisotropy parameter; it decreases by about $(24 \pm 4\%)$ (statistical uncertainty only) from $\eta_{\text{lab}} = 0$ to $\eta_{\text{lab}} = 2$ in the p-direction. The behavior of the normalized $v_2(\eta_{\text{lab}})/v_2(\eta_{\text{lab}} = 0)$ is different in the Pb-side, with the maximum difference being smaller. The $v_2$ appears to be asymmetric about $\eta_{\text{c.m.}} = 0$, which corresponds to $\eta_{\text{lab}} = 0.465$. A non-zero $v_3$ is observed, however the uncertainties are too large to draw a definite conclusion regarding its pseudorapidity dependence.

When using long-range two-particle correlations to obtain anisotropic flow, the large pseudorapidity separation between the particles, while reducing nonflow effects, may lead to underestimation of the anisotropic flow because of event plane decorrelation stemming from the fluctuating initial conditions [42, 43]. This effect was studied in pPb and PbPb collisions [44]. The observed decrease in $v_2$ with increasing absolute value of pseudorapidity could be partially due to such decorrelation.
Figure 4: (Color online) Fourier coefficients, $V_2$ (upper) and $V_3$ (lower), of two-particle azimuthal correlations in high-multiplicity collisions ($220 \leq N_{\text{offline}}^{\text{trk}} < 260$) with (circles) and without (triangles) subtraction of low-multiplicity data, as a function of $\eta_{\text{lab}}$. Left panel shows data for Pb-side trigger particles and the right panel for the p-side. Statistical uncertainties are mostly smaller than point size; systematic uncertainties are 3.9% and 10% for $V_2$ and $V_3$ without low-multiplicity subtraction, 5.8% and 15% for $V_2$ and $V_3$ with low-multiplicity subtraction, respectively. The systematic uncertainties are shown by the shaded bands.

The asymmetry of the azimuthal anisotropy is studied by taking the ratio of the $v_n$ value at positive $\eta_{\text{c.m.}}$ to the value at $-\eta_{\text{c.m.}}$ in the center-of-mass frame, as shown in Fig. 6. The ratio shows a decreasing trend with increasing $\eta_{\text{c.m.}}$.

In pPb collisions, the average $p_T$ of charged hadrons depends on pseudorapidity. As stated in Ref. [37], the pseudorapidity dependence of $\langle p_T \rangle$ could influence the pseudorapidity dependence of $v_2$. This may have relevance to the shape of the normalized $v_2$ distribution as observed in Fig. 5. To compare $v_2$ and the $\langle p_T \rangle$ distribution, the $p_T$ spectra for different $\eta_{\text{c.m.}}$ ranges are obtained from Ref. [57]. The charged particle $p_T$ spectra in minimum-bias events are then fitted with a Tsallis function, as done in Ref. [58].

The inclusive-particle $p_T$ is averaged within $0 < p_T < 6 \text{GeV}/c$. In addition, the average momentum for the particles used in this analysis, $0.3 < p_T < 3 \text{GeV}/c$ and $220 \leq N_{\text{offline}}^{\text{trk}} < 260$, is calculated and plotted in Fig. 7. The $\langle p_T \rangle$ as a function of $\eta_{\text{c.m.}}$ does not change for different multiplicity ranges within 1%. Thus, the minimum bias $\langle p_T \rangle$ distribution is compared directly to the high-multiplicity anisotropy $v_2$ result. The $\langle p_T \rangle$ distribution is normalized by its value at $\eta_{\text{c.m.}} = -0.465$. Self-normalized $\langle p_T \rangle(\eta_{\text{c.m.}})/\langle p_T \rangle(\eta_{\text{c.m.}} = -0.465)$ is plotted on Fig. 7 compared to the self-normalized $v_2(\eta_{\text{c.m.}})/v_2(\eta_{\text{c.m.}} = -0.465)$ distribution in the center-of-mass frame.
Figure 5: (Color online) Self-normalized anisotropy parameters, $v_2(\eta_{\text{lab}})$/$v_2(\eta_{\text{lab}} = 0)$ (left panel) and $v_3(\eta_{\text{lab}})$/$v_3(\eta_{\text{lab}} = 0)$ (right panel), as a function of $\eta_{\text{lab}}$. Data points (curves) are results with (without) low-multiplicity data subtraction; filled circles and solid lines are from the Pb-side trigger. Open circles and dashed lines are from the p-side trigger. The bands show systematic uncertainties of $\pm 5.7\%$ and $\pm 14\%$ for $v_2(\eta_{\text{lab}})$/$v_2(\eta_{\text{lab}} = 0)$ and $v_3(\eta_{\text{lab}})$/$v_3(\eta_{\text{lab}} = 0)$, respectively. The systematic uncertainties in $v_n(\eta_{\text{lab}})$/$v_n(\eta_{\text{lab}} = 0)$ without subtraction are similar. Error bars indicate statistical uncertainties only.

The systematic uncertainty band for $\langle p_T \rangle(\eta_{\text{c.m.}})$/$\langle p_T \rangle(\eta_{\text{c.m.}} = -0.465)$ is obtained by averaging the upper and lower limits of the systematic uncertainty band from the underlying $p_T$ spectra. The hydrodynamic theoretical prediction for $\langle p_T \rangle(\eta_{\text{c.m.}})$/$\langle p_T \rangle(\eta_{\text{c.m.}} = -0.465)$ is also plotted.

As shown in Fig. 7, the hydrodynamic calculation [37] for $\langle p_T \rangle$ falls more rapidly than the $\langle p_T \rangle$ for data (solid and dotted lines) towards positive $\eta_{\text{c.m.}}$. The distribution is asymmetric for both data and theory. The comparison of the $\langle p_T \rangle$ and the $v_2$ distributions shows that both observables have a decreasing trend towards large $|\eta_{\text{c.m.}}|$, but the decrease in $\langle p_T \rangle$ at forward pseudorapidity is smaller. The decrease of $v_2$ with $\eta_{\text{c.m.}}$ does not appear to be entirely from a change in $\langle p_T \rangle$; other physics is likely at play. The value of $v_2$ decreases by $(20 \pm 4)\%$ (statistical uncertainty only) from $\eta_{\text{c.m.}} = 0$ to $\eta_{\text{c.m.}} \approx 1.5$. 

Figure 6: (Color online) $v_2(\eta_{\text{c.m.}})$/$v_2(-\eta_{\text{c.m.}})$, as a function of $\eta_{\text{c.m.}}$ in the center-of-mass frame. The data points are results from $V_{\text{sub}}^3$ with low-multiplicity data subtracted. The bands show the systematic uncertainty of $\pm 5.7\%$. Error bars indicate statistical uncertainties only.
7 Summary

Two-particle correlations as functions of $\Delta \phi$ and $\Delta \eta$ are reported in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by the CMS experiment. The trigger particle is restricted to narrow pseudorapidity windows. The combinatorial background is assumed to be uniform in $\Delta \phi$ and normalized by the ZYAM procedure as a function of $\Delta \eta$. The near-side jet correlated yield is fitted and found to be greater in high-multiplicity than in low-multiplicity collisions. The ridge yield is studied as a function of $\Delta \phi$ and $\Delta \eta$ and it is found to depend on pseudorapidity and the underlying background shape ZYAM($\Delta \eta$). The pseudorapidity dependence differs for trigger particles selected on the proton and the Pb sides.

The Fourier coefficients of the two-particle correlations in high-multiplicity collisions are reported, with and without subtraction of the scaled low-multiplicity data. The pseudorapidity dependence of the single-particle anisotropy parameters, $v_2$ and $v_3$, is inferred. Significant pseudorapidity dependence of $v_2$ is found. The distribution is asymmetric about $\eta_{c.m.} = 0$ with an approximate $(20 \pm 4\%)$ decrease from $\eta_{c.m.} = 0$ to $\eta_{c.m.} \approx 1.5$, and a smaller decrease towards the Pb-beam direction. Finite $v_3$ is observed, but the uncertainties are presently too large to draw conclusions regarding the pseudorapidity dependence.

The self-normalized $v_2(\eta_{c.m.})/v_2(\eta_{c.m.} = -0.465)$ distribution is compared to the $\langle p_T \rangle(\eta_{c.m.})/\langle p_T \rangle(\eta_{c.m.} = -0.465)$ distribution as well as from hydrodynamic calculations. The $\langle p_T \rangle(\eta_{c.m.})/\langle p_T \rangle(\eta_{c.m.} = -0.465)$ distribution shows a decreasing trend towards positive $\eta_{c.m.}$. The $v_2(\eta_{c.m.})/v_2(\eta_{c.m.} = -0.465)$ distribution also shows a decreasing trend towards positive $\eta_{c.m.}$, but the decrease is more significant in the case of the $v_2$ measurement. This indicates that physics mechanisms other than the change in the underlying particle spectra, such as event plane decorrelation over pseudorapidity, may influence the anisotropic flow.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully
acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: the Austrian Federal Ministry of Science, Research and Economy and the Austrian Science Fund; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport, and the Croatian Science Foundation; the Research Promotion Foundation, Cyprus; the Ministry of Education and Research, Estonian Research Council via IUT23-4 and IUT23-6 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l’Énergie Atomique et aux Énergies Alternatives / CEA, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Innovation Office, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Ministry of Science, ICT and Future Planning, and National Research Foundation (NRF), Republic of Korea; the Lithuanian Academy of Sciences; the Ministry of Education, and University of Malaya (Malaysia); the Mexican Funding Agencies (BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI); the Ministry of Business, Innovation and Employment, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR, Dubna; the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, and the Russian Foundation for Basic Research; the Ministry of Education, Science and Technological Development of Serbia; the Secretaria de Estado de Investigación, Desarrollo e Innovación and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the Ministry of Science and Technology, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology of Thailand, Special Task Force for Activating Research and the National Science and Technology Development Agency of Thailand; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the National Academy of Sciences of Ukraine, and State Fund for Fundamental Researches, Ukraine; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Mobility Plus program of the Ministry of Science and Higher Education (Poland); the OPUS program of the National Science Center (Poland); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programs
cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

References


A  The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Université Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

Université de Mons, Mons, Belgium
N. Beliy, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
Universidade Estadual Paulista$^a$, Universidade Federal do ABC$^b$, São Paulo, Brazil
S. Ahuja$^a$, C.A. Bernandes$^b$, A. De Souza Santos$^b$, S. Dogra$^a$, T.R. Fernandez Perez Tomei$^a$, E.M. Gregores$^b$, P.G. Mercadante$^b$, C.S. Moon$^a$,$^8$, S.F. Novaes$^a$, Sandra S. Padula$^a$, D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

University of Cyprus, Nicosia, Cyprus

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger$^{10}$, M. Finger Jr.$^{10}$

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim$^{11,12}$, A. Awad, A. Mahrous$^{11}$, A. Radi$^{13,14}$

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Peltola, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri,

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

Georgian Technical University, Tbilisi, Georgia
T. Toriaishvili

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

Deutsches Elektronen-Synchrotron, Hamburg, Germany

University of Hamburg, Hamburg, Germany

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

National and Kapodistrian University of Athens, Athens, Greece
A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

Wigner Research Centre for Physics, Budapest, Hungary

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi²², J. Molnar, Z. Szillasi²

University of Debrecen, Debrecen, Hungary
M. Bartók²³, A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India

Panjab University, Chandigarh, India

University of Delhi, Delhi, India
Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma
Saha Institute of Nuclear Physics, Kolkata, India

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, A. Kapoor, K. Kothekar, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami, A. Fahim, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinali, B. Safarzadeh, M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy

INFN Sezione di Bologna, Università di Bologna, Bologna, Italy

INFN Sezione di Catania, Università di Catania, Catania, Italy
G. Cappello, M. Chiorboli, S. Costa, A. Di Mattia, F. Giordano, R. Potenza, A. Tricomi, C. Tuve

INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
G. Barbagli, V. Ciulli, C. Civinini, R. D’Alessandro, E. Focardi, V. Gori, P. Lenzi, M. Meschini, S. Paoletti, G. Sguazzoni, L. Viliani

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbrì, D. Piccolo, F. Primavera

INFN Sezione di Genova, Università di Genova, Genova, Italy
V. Calvelli, F. Ferro, M. Lo Vetere, M.R. Monge, E. Robutti, T. Tosi

INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
L. Brianza, M.E. Dinardo, S. Fiorendi, S. Gennai, R. Gerosa, A. Ghezzi, P. Govoni, S. Paoletti, G. Selvaggi

INFN Sezione di Napoli, Università di Napoli ‘Federico II’, Napoli, Italy, Università della Basilicata, Potenza, Italy, Università G. Marconi, Roma, Italy


INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy


INFN Sezione di Pavia, Università di Pavia, Pavia, Italy

A. Braghieri, A. Magnani, P. Montagna, S.P. Ratti, V. Re, C. Riccardi, P. Salvini, I. Vai

INFN Sezione di Perugia, Università di Perugia, Perugia, Italy

L. Alunni Solestizi, G.M. Bilei, D. Ciangottini, L. Fanò, P. Lariccia, G. Mantovani, M. Menichelli, S. Sahà, A. Santocchia

INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy


INFN Sezione di Roma, Università di Roma, Roma, Italy


INFN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy


INFN Sezione di Trieste, Università di Trieste, Trieste, Italy

S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, G. Della Ricca, B. Gobbo, C. La Licata, M. Marone, A. Schizzi, A. Zanetti

Kangwon National University, Chunchon, Korea

A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea

J.A. Brochero Cifuentes, H. Kim, T.J. Kim
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
S. Song

Korea University, Seoul, Korea

Seoul National University, Seoul, Korea
H.D. Yoo

University of Seoul, Seoul, Korea

Sungkyunkwan University, Suwon, Korea
Y. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibargunen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hooran, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, A. Byszuk, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho,

Joint Institute for Nuclear Research, Dubna, Russia

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim\textsuperscript{40}, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
A. Bylinkin, M. Chadeeva, M. Danilov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin\textsuperscript{39}, I. Dremin\textsuperscript{39}, M. Kirakosyan, A. Leonidov\textsuperscript{39}, G. Mesyats, S.V. Rusakov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy\textsuperscript{41}, O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic\textsuperscript{42}, P. Cirkovic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran
Universidad de Oviedo, Oviedo, Spain
J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

CERN, European Organization for Nuclear Research, Geneva, Switzerland

Paul Scherrer Institut, Villigen, Switzerland

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

Universität Zürich, Zurich, Switzerland

National Central University, Chung-Li, Taiwan

National Taiwan University (NTU), Taipei, Taiwan
Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey

Middle East Technical University, Physics Department, Ankara, Turkey
B. Bilin, S. Bilmis, B. Isildak, G. Karapinar, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, M. Kaya, O. Kaya, E.A. Yetkin, T. Yetkin

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, S. Sen, F.I. Vardarlı

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

The University of Alabama, Tuscaloosa, USA
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA
D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou
Brown University, Providence, USA

University of California, Davis, Davis, USA

University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA

University of California, San Diego, La Jolla, USA

University of California, Santa Barbara, Santa Barbara, USA

California Institute of Technology, Pasadena, USA

Carnegie Mellon University, Pittsburgh, USA

University of Colorado Boulder, Boulder, USA

Cornell University, Ithaca, USA

Fermi National Accelerator Laboratory, Batavia, USA

University of Florida, Gainesville, USA

Florida International University, Miami, USA
S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA

Florida Institute of Technology, Melbourne, USA

University of Illinois at Chicago (UIC), Chicago, USA

The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA

The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA
Rice University, Houston, USA

University of Rochester, Rochester, USA

Rutgers, The State University of New Jersey, Piscataway, USA

University of Tennessee, Knoxville, USA
M. Foerster, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA

Vanderbilt University, Nashville, USA

University of Virginia, Charlottesville, USA

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin - Madison, Madison, WI, USA

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
7: Also at Universidade Estadual de Campinas, Campinas, Brazil
8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Helwan University, Cairo, Egypt
12: Now at Zewail City of Science and Technology, Zewail, Egypt
13: Also at British University in Egypt, Cairo, Egypt
14: Now at Ain Shams University, Cairo, Egypt
15: Also at Université de Haute Alsace, Mulhouse, France
16: Also at Tbilisi State University, Tbilisi, Georgia
17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
18: Also at University of Hamburg, Hamburg, Germany
19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Eötvös Loránd University, Budapest, Hungary
22: Also at University of Debrecen, Debrecen, Hungary
23: Also at Wigner Research Centre for Physics, Budapest, Hungary
24: Also at Indian Institute of Science Education and Research, Bhopal, India
25: Also at University of Visva-Bharati, Santiniketan, India
26: Now at King Abdulaziz University, Jeddah, Saudi Arabia
27: Also at University of Ruhuna, Matara, Sri Lanka
28: Also at Isfahan University of Technology, Isfahan, Iran
29: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
30: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
31: Also at Università degli Studi di Siena, Siena, Italy
32: Also at Purdue University, West Lafayette, USA
33: Now at Hanyang University, Seoul, Korea
34: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
35: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
36: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
37: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
38: Also at Institute for Nuclear Research, Moscow, Russia
39: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
41: Also at INFN Sezione di Padova; Università di Padova; Università di Trento (Trento), Padova, Italy
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
44: Also at National Technical University of Athens, Athens, Greece
45: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
48: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
49: Also at Adiyaman University, Adiyaman, Turkey
50: Also at Mersin University, Mersin, Turkey
51: Also at Cag University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Gaziosmanpasa University, Tokat, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul Bilgi University, Istanbul, Turkey
59: Also at Yildiz Technical University, Istanbul, Turkey
60: Also at Hacettepe University, Ankara, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
64: Also at Utah Valley University, Orem, USA
65: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
66: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
67: Also at Argonne National Laboratory, Argonne, USA
68: Also at Erzincan University, Erzincan, Turkey
69: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
70: Also at Texas A&M University at Qatar, Doha, Qatar
71: Also at Kyungpook National University, Daegu, Korea