Particle-Yield Modification in Jetlike Azimuthal Dihadron Correlations in Pb-Pb Collisions at root S-NN=2.76 TeV


Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.108.092301

2012

Link to publication

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Particle-Yield Modification in Jetlike Azimuthal Dihadron Correlations in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

K. Aamodt et al.*
(ALICE Collaboration)
(Received 1 October 2011; published 1 March 2012)

The yield of charged particles associated with high-$p_t$ trigger particles ($8 < p_t < 15$ GeV/c) is measured with the ALICE detector in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV relative to proton-proton collisions at the same energy. The conditional per-trigger yields are extracted from the narrow jetlike correlation peaks in azimuthal dihadron correlations. In the 5% most central collisions, we observe that the yield of associated charged particles with transverse momenta $p_t > 3$ GeV/c on the away side drops to about 60% of that observed in $pp$ collisions, while on the near side a moderate enhancement of 20%–30% is found.

DOI: 10.1103/PhysRevLett.108.092301 PACS numbers: 12.38.Mh, 25.75.Bh, 25.75.Dw, 25.75.Gz

Ultrarelativistic heavy ion collisions produce the quark-gluon plasma (QGP), the deconfined state of quarks and gluons, and are used to explore its properties. In the last decade, important information about the dynamical behavior of the QGP has been obtained from the study of hadron jets, the fragmentation products of high transverse momentum ($p_t$) partons that are produced in initial hard scatterings of partons from the incoming nuclei [1,2]. It is generally accepted that prior to hadronization, partons lose energy in the high color-density medium due to gluon radiation and multiple collisions. These phenomena are broadly known as jet quenching [3].

The energy loss was first observed at the Relativistic Heavy Ion Collider (RHIC) in Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV as a suppression of hadron yields with respect to the reference from $pp$ collisions at high $p_t$ (3–6 GeV/c) [4,5]. At RHIC, distributions in relative azimuth $\Delta \varphi = \varphi_{\text{trig}} - \varphi_{\text{assoc}}$ between associated particles with transverse momenta $p_{t,\text{assoc}}$ and trigger particles with $p_{t,\text{trig}}$ have been measured. These studies indicate that the peak shapes from high-$p_t$ ($p_{t,\text{trig}} > 4$ GeV/c and $2$ GeV/c $< p_{t,\text{assoc}} < p_{t,\text{trig}}$) dihadron correlations in central Au-Au collisions are similar to those in small systems like $pp$ and $d$-Au [6,7], where correlations are dominated by jet fragmentation. The near-side peak at $\Delta \varphi = 0$ is comparable in magnitude between all collision systems, while the away-side peak at $\Delta \varphi = \pi$ is strongly suppressed. In central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the suppression amounts to a factor of 3–5 in the range $0.35 < p_{t,\text{assoc}}/p_{t,\text{trig}} < 0.95$ for $8 < p_{t,\text{trig}} < 15$ GeV/c and $p_{t,\text{assoc}} > 3$ GeV/c [8].

At the LHC, the suppression of charged hadrons in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV increases and the nuclear modification factor $R_{\text{AA}}$ drops to 0.14 around 7 GeV/c [9]. Furthermore, a strong dijet energy asymmetry has been reported by the ATLAS and CMS collaborations [10,11]. A detailed study of the overall momentum balance in the dijet events shows evidence for sizable low-$p_t$ radiation outside the cone of the subleading jet [11]. These analyses use full event-by-event reconstruction of di-jets for leading jet transverse momenta above 100 GeV/c. At lower transverse momenta ($p_{t,jet} < 50$ GeV/c) background fluctuations due to the underlying event dominate [12] and event-by-event jet reconstruction becomes difficult. Hence, dihadron correlations are an interesting alternative probe. Measurements of dihadron correlations in central Pb-Pb collisions compared to $pp$ simulations have been presented in [14].

The extraction of the particle yield associated with a jet requires the removal of correlated background primarily of collective origin (e.g., flow) at lower $p_t$. This is nontrivial and, therefore, we concentrate in this Letter on a regime where jetlike correlations dominate over collective effects: $8 < p_{t,\text{trig}} < 15$ GeV/c for the trigger particle and $p_{t,\text{assoc}} > 3$ GeV/c for the associated particle [15]. We present ratios of yields of central to peripheral collisions ($I_{\text{CP}}$) and, for different centralities, of Pb-Pb to $pp$ collisions ($I_{\text{AA}}$). $I_{\text{AA}}$ probes the interplay between the parton production spectrum, the relative importance of quark-quark, gluon-gluon and quark-gluon final states, and energy loss in the medium. On the near side, $I_{\text{AA}}$ provides information about the fragmenting jet leaving the medium, while on the away side it additionally reflects the probability that the recoiling parton survives the passage through the medium. The sensitivity of $I_{\text{AA}}$ and $R_{\text{AA}}$ to different properties of the medium makes the combination particularly effective in constraining jet quenching models [16,17].

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

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.
Detector, data sets and analysis.—The ALICE detector is described in detail in [18]. The inner tracking system (ITS) and the time projection chamber (TPC) are used for vertex finding and tracking. The collision centrality is determined with the forward scintillators (VZERO) as well as for the estimation of the systematic uncertainty with the first two layers of the ITS (silicon pixel detector, SPD) and the zero degree calorimeters (ZDCs). Details can be found in [19]. The main tracking detector is the TPC which allows reconstruction of good-quality tracks with a pseudorapidity coverage of $|\eta| < 1.0$ uniform in azimuth. The reconstructed vertex is used to select primary track candidates and to constrain the $p_t$ of the track.

In this analysis $14 \times 10^6$ minimum-bias Pb-Pb events recorded in fall 2010 at $\sqrt{s_{\text{NN}}} = 2.76$ TeV as well as $37 \times 10^6$ $pp$ events from March 2011 ($\sqrt{s} = 2.76$ TeV) are used. These include only events where the TPC was fully accepted which have a reconstructed vertex less than 7 cm from the nominal interaction point in beam direction. Tracks are selected by requiring at least 70 (out of up to 159) associated clusters in the TPC, and a $\chi^2$ per space point of the momentum fit smaller than 4 (with 2 degrees of freedom per space point). In addition, tracks are required to originate from within 2.4 cm (3.2 cm) in transverse (longitudinal) distance from the primary vertex.

For the measurement of $I_{AA}$ and $I_{CP}$ the yield of associated particles per trigger particle is studied as a function of the azimuthal angle difference $\Delta \phi$. This distribution is given by $1/N_{\text{trig}}dN_{\text{assoc}}/d\Delta \phi$ where $N_{\text{trig}}$ is the number of trigger particles and $N_{\text{assoc}}$ is the number of associated particles. We measure this quantity for all pairs of particles where $p_{t,\text{assoc}} < p_{t,\text{trig}}$ within $|\eta| < 1.0$ as a function of $p_{t,\text{assoc}}$. Pair acceptance corrections have been evaluated with a mixed-event technique but found to be negligible for the yield ratios due to the constant acceptance in $\varphi$ and the same detector conditions for the different data sets.

Corrections for detector efficiency (17%–18% depending on collision system, $p_t$ and centrality) and contamination (4%–8%) by secondary particles from particle-material interactions, $\gamma$ conversions, and weak-decay products of long-lived particles are applied for trigger and associated particles, separately. Additional secondary particles correlated with the trigger particle are found close to $\Delta \varphi = 0$ in particular due to decays and $\gamma$ conversions. We correct for this contribution (2%–4%). These corrections are evaluated with the HIJING 1.36 [20] Monte Carlo (MC) generator which was tuned to reproduce the measured multiplicity density [19] for Pb-Pb and the PYTHIA 6 [21] MC generator with tune PERUGIA-0 [22] for $pp$ using in both cases a detector simulation based on GEANT3 [23]. MC simulations underestimate the number of secondary particles. Therefore, we study the distribution of the distance of closest approach between tracks and the event vertex.

The tail of this distribution is dominantly populated by secondary particles and the comparison of data and MC calculations shows that the secondary yield in the MC events needs to be increased by about 10% (depending on $p_t$). An MC study shows that effects of the event selection and vertex reconstruction are negligible for the extracted observables. The correction procedure was validated by comparing corrected simulated events with the MC truth.

Figure 1(a) shows a typical distribution of the corrected per-trigger pair yield before background subtraction. The fact that the $\Delta \varphi$ distribution is flat outside the near- and away-side regions gives us confidence that the background can be estimated with the zero yield at minimum (ZYAM) assumption [24]. This procedure estimates the pedestal value by fitting the flat region close to the minimum of the $\Delta \varphi$ distribution ($|\Delta \varphi - \pi/2| < 0.4$) with a constant. The validity of the ZYAM assumption has been questioned in cases where collective effects dominate [25,26]; however, for the high-$p_t$ correlations of this analysis, the narrow width and large amplitude of the correlated signal...
compared to the flow modulation drastically reduce the ZYAM bias. Therefore, we define the integrated associated yield as the signal over a flat background. Figure 1(b) illustrates the background determination. Also indicated is a background shape accounting for elliptic flow $v_2$, the second coefficient of the particle azimuthal distribution measured with respect to the reaction plane. It is given by $2v_{2,\text{trig}}v_{2,\text{assoc}}\cos2\Delta\phi$ where $v_{2,\text{trig}}$ $(v_{2,\text{assoc}})$ is the elliptic flow of the trigger (associated) particles. The $v_2$ values are taken from an independent measurement [27] of $v_2$ up to $p_t = 5$ GeV/c. As an upper limit we use the $v_2$ measured for $p_t = 5$ GeV/c for higher $p_t$ where $v_2$ is expected to decrease. For the centrality class 60%–90% no $v_2$ is taken from the 40%–50% centrality class. Since $v_2$ decreases from midcentral to peripheral collisions and the flat pedestal assumes $v_2 = 0$, this includes all reasonable values of $v_2$.

Contributions from $\Delta \eta$-independent correlations (e.g., due to flow harmonics at all orders) can also be removed on the near side (where the jet peak is centered around $\Delta \eta = 0$) by calculating the per-trigger pair yield in the region $|\Delta \eta| < 1$ and subtracting the contribution from $1 < |\Delta \eta| < 2$ normalized for the acceptance. This prescription, which we call the $\eta$-gap method, provides a measurement independent of the flow strength.

In Fig. 1(c) the flat-pedestal subtracted distributions of central and peripheral Pb-Pb collisions are compared to that of $pp$ collisions. The integral over those distributions in the region where the signal is significantly above the background, i.e., within $\Delta \varphi$ of $\pm 0.7$ and $\pi \pm 0.7$, results in the near- and away-side yields per trigger particle ($Y$), respectively. This procedure samples the same fraction of the detector volume. A bias due to the $p_t$ resolution on the extracted yields was evaluated by folding the detector resolution with the extracted associated spectrum and found to be negligible. The sensitivity of the corrections to details of the MC simulations has been studied by varying the particle composition, the material budget and the MC generator (using AMPT [28] for Pb-Pb and PHOJET [29] for $pp$). Uncertainties in the centrality determination were evaluated by comparing results obtained with the different centrality estimates from the VZERO, the SPD, and ZDCs. Table I lists the size of the different contributions to the systematic uncertainties for $I_{AA}$ and $I_{CP}$ as well as their sum in quadrature.

Results.—Figure 2(a) shows the yield ratio $I_{AA}$ for central (0%–5% Pb-Pb/$pp$) and peripheral (60%–90% Pb-Pb/$pp$) collisions using the three background subtraction schemes discussed. The fact that the only significant difference between the different background subtraction schemes is in the lowest bin of $p_{t,\text{assoc}}$ confirms the assumption of only a small bias due to flow anisotropies in this $p_t$ region. The influence of higher flow harmonics [27] on the background shape can be explicitly estimated: including $v_3$, $v_4$, and $v_5$ from [27] changes the extracted jet yield by less than 1%, except for the first bin in $p_{t,\text{assoc}}$ in the most central collisions where it is about 8%. This is consistent with the difference between the data points labeled $v_2$ bkg and $\eta$ gap where the latter includes flow at all orders. In central collisions, an away-side suppression ($I_{AA} = 0.6$) is observed which is evidence for in-medium energy loss. Moreover, there is an enhancement above unity of 20%–30% on the near side which has not been observed with any significance at lower collision energies at these momenta [8]. In peripheral collisions, both the near- and away-side $I_{AA}$ measurements approach unity, as expected in the absence of significant medium effects.

Figure 2(b) shows the yield ratio $I_{CP}$. As for $I_{AA}$, the influence of the flow modulation is small and only significant in the lowest $p_{t,\text{assoc}}$ bin. $I_{CP}$ is consistent with $I_{AA}$ in central collisions with respect to the near-side enhancement and the away-side suppression.

Comparing this measurement and $R_{AA}$ to models simultaneously will constrain energy-loss mechanisms and model parameters. Robust conclusions can only be drawn with a systematic comparison of multiple observables with

Table I. Systematic uncertainties evaluated separately for near side and away side. Ranges indicate different values for different centrality ranges: the smaller (larger) number is for peripheral (central) events.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$I_{AA}$ Near side</th>
<th>Away side</th>
<th>$I_{CP}$ Near side</th>
<th>Away side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pedestal calculation</td>
<td>5%</td>
<td>5%–20%</td>
<td>5%</td>
<td>20%</td>
</tr>
<tr>
<td>Integration window</td>
<td>0</td>
<td>3%</td>
<td>0</td>
<td>3%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-track effects</td>
<td>&lt;1%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrections</td>
<td>2%</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centrality selection</td>
<td>2%</td>
<td>3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7%</td>
<td>8%–21%</td>
<td>7%</td>
<td>21%</td>
</tr>
</tbody>
</table>
the following. The STAR measurement \cite{8} (which includes only statistical uncertainties) of the near-side enhancement is about 75%, too large to provide a reliable measurement. For \( p_{t,\text{assoc}} \leq 10 \) GeV/c, the \( v_2 \)-subtracted \( I_{AA} \) is 0.5 \( \pm \) 0.6 \( \pm \) 0.08. This result is slightly larger than results from PHENIX in a similar \( p_{t,\text{trig}} \) region of 7 \( \leq p_{t,\text{trig}} < 9 \) GeV/c: 0.31 \( \pm \) 0.07 and 0.38 \( \pm \) 0.11 for \( p_{t,\text{assoc}} \approx 3.5 \) GeV/c and 5.8 GeV/c, respectively. Based on an analysis in a lower \( p_t \) region, where collective effects are significantly larger than in the measurement presented here, the STAR collaboration mentions a slightly enhanced jetlike yield in Au-Au compared to \( d-Au \) collisions, but does not assess the effect quantitatively \cite{31}. In conclusion, the observed away-side suppression at the LHC is less than at RHIC (\( I_{AA} \) is larger), while the single-hadron suppression \( R_{AA} \) is found to be slightly larger (\( R_{AA} \) is smaller) than at RHIC \cite{9}. Near-side enhancement.—These measurements represent the first observation of a significant near-side enhancement of \( I_{AA} \) and \( I_{CP} \) in the \( p_t \) region studied. This enhancement suggests that the near-side parton is also subject to medium effects. \( I_{AA} \) is sensitive to (i) a change of the fragmentation function, (ii) a possible change of the quark/gluon jet ratio in the final state due to the different coupling to the medium, and (iii) a bias on the parton \( p_t \) spectrum after energy loss due to the trigger particle selection. If the fragmentation function (FF) is softened in the medium, hadrons carry a smaller fraction of the initial parton momentum in \( \text{Pb-Pb} \) collisions as compared to \( pp \) collisions. Therefore, hadrons with a given \( p_t \) originate from a larger average parton momentum which may lead to more associated particles and \( I_{AA} > 1 \). An increased fraction of calculations spanning the parameter space and cannot be done with current calculations (e.g., [30]). Such a study is beyond the scope of this Letter.

Comparison to RHIC.—Similar measurements have been performed at RHIC. Although the same range in \( p_{t,\text{trig}} \) does not necessarily probe the same parton \( p_t \) region at different \( \sqrt{s} \), we assess changes from RHIC to LHC in the following. The STAR measurement [8] (which includes only statistical uncertainties) of the near-side \( I_{AA} \) is consistent with unity, albeit with a large uncertainty (18\%--40\%). On the away side the result from STAR is about 50\% lower than the results shown in Fig. 2. We also calculated \( I_{AA} \) for the 20\% most central events to compare to PHENIX [7] (only \( v_2 \)-subtracted data on the away side available). For \( p_{t,\text{assoc}} < 4 \) GeV/c, the flow influence in this centrality interval is about 75\%, too large to provide a reliable measurement. For 4 \( < p_{t,\text{assoc}} < 10 \) GeV/c, the \( v_2 \)-subtracted \( I_{AA} \) is 0.5 \( \pm \) 0.6 \( \pm \) 0.08. This result is slightly larger than results from PHENIX in a similar \( p_{t,\text{trig}} \) region of 7 \( < p_{t,\text{trig}} < 9 \) GeV/c: 0.31 \( \pm \) 0.07 and 0.38 \( \pm \) 0.11 for \( p_{t,\text{assoc}} \approx 3.5 \) GeV/c and 5.8 GeV/c, respectively. Based on an analysis in a lower \( p_t \) region, where collective effects are significantly larger than in the measurement presented here, the STAR collaboration mentions a slightly enhanced jetlike yield in Au-Au compared to \( d-Au \) collisions, but does not assess the effect quantitatively [31]. In conclusion, the observed away-side suppression at the LHC is less than at RHIC (\( I_{AA} \) is larger), while the single-hadron suppression \( R_{AA} \) is found to be slightly larger (\( R_{AA} \) is smaller) than at RHIC [9].

FIG. 2 (color online). (a) \( I_{AA} \) for central (0\%--5\% \( \text{Pb-Pb} / pp \), open black symbols) and peripheral (60\%--90\% \( \text{Pb-Pb} / pp \), filled red symbols) collisions and (b) \( I_{CP} \). Results using different background subtraction schemes are presented: using a flat pedestal (squares), using \( v_2 \) subtraction (diamonds) and subtracting the large \( |\Delta \eta| \) region (circles, only on the near side). For details see text. For clarity, the data points are slightly displaced on the \( p_{t,\text{assoc}} \) axis. The shaded bands denote systematic uncertainties.
gluon (quark) jets has an effect similar to softening (hardening) of the FF and leads to $I_{AA} > 1$ ($< 1$).

A different parton distribution in $pp$ and Pb-Pb collisions can modify $I_{AA}$ even if fragmentation of a given parton after energy loss is unmodified. In particular, in the same transverse momentum region, we see a strong suppression of the trigger particles ($R_{AA} \approx 0.2$) and the rising slope of $R_{AA}(p_t)$ [9]. A similar suppression should apply to partons, leading to a parton $p_t$ would be larger in Pb-Pb than in $pp$, leading to an increase in $I_{AA}$. This argument can be quantified with the hadron-pair suppression factor $J_{AA}$ [32]. $J_{AA}(p_{t\text{trig}}, p_{t\text{assoc}}) = R_{AA}(p_{t\text{trig}})I_{AA}(p_{t\text{trig}}, p_{t\text{assoc}})$ is approximately $R_{AA}(p_{t\text{trig}} + p_{t\text{assoc}})$ in this case, and with a rising $R_{AA}$ leads to $I_{AA} > 1$.

It is likely that all three effects play a role, and following the above arguments, we note that the combined measurement of $R_{AA}$ and $I_{AA}$ is sensitive to the interplay of energy loss and the change of the fragmentation pattern in the medium.

In summary, the modification of the per-trigger yield of associated particles, $I_{AA}$ and $I_{CP}$, has been extracted from dihadron correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In central collisions, on the away side, suppression ($I_{AA} = 0.6$) is observed as expected from strong intermediate energy loss. On the near side, a significant enhancement ($I_{AA} = 1.2$) has been reported for the first time. Along with the measurement of $R_{AA}$, $I_{AA}$ provides strong constraints on the quenching mechanism in the hot and dense matter produced.

The ALICE collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: Calouste Gulbenkian Foundation from Lisbon and Swiss Fonds Kidagan, Armenia; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (FINEP), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP); National Natural Science Foundation of China (NSFC), the Chinese Ministry of Education (CMOE) and the Ministry of Science and Technology of China (MSTC); Ministry of Education and Youth of the Czech Republic; Danish Natural Science Research Council, the Carlsberg Foundation and the Danish National Research Foundation; The European Research Council under the European Community’s Seventh Framework Programme; Helsinki Institute of Physics and the Academy of Finland; French CNRS-IN2P3, the “Region Pays de Loire,” “Region Alsace,” “Region Auvergne” and CEA, France; German BMBF and the Helmholtz Association; General Secretariat for Research and Technology, Ministry of Development, Greece; Hungarian OTKA and National Office for Research and Technology (NKTH); Department of Atomic Energy and Department of Science and Technology of the Government of India; Istituto Nazionale di Fisica Nucleare (INFN) of Italy; MEXT Grant-in-Aid for Specially Promoted Research, Japan; Joint Institute for Nuclear Research, Dubna; National Research Foundation of Korea (NRF); CONACYT, DGAPA, México, ALFA-EC and the HELEN Program (High-Energy physics Latin-American–European Network); Stichting voor Fundamenteel Onderzoek der Materie (FOM) and the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; Research Council of Norway (NFR); Polish Ministry of Science and Higher Education; National Authority for Scientific Research—NASR (Autoritatea Națională pentru Cercetare Științifică-ANCS); Federal Agency of Science of the Ministry of Education and Science of Russian Federation, International Science and Technology Center, Russian Academy of Sciences, Russian Federal Agency of Atomic Energy, Russian Federal Agency for Science and Innovations and CERN-INTAS; Ministry of Education of Slovakia; Department of Science and Technology, South Africa; CIEMAT, EELA, Ministerio de Educación y Ciencia of Spain, Xunta de Galicia (Consellería de Educación), CEADEN, Cubaenergía, Cuba, and IAEA (International Atomic Energy Agency); Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW); Ukraine Ministry of Education and Science; United Kingdom Science and Technology Facilities Council (STFC); the United States Department of Energy, the United States National Science Foundation, the State of Texas, and the State of Ohio.


1 Department of Physics and Technology, University of Bergen, Bergen, Norway
2 Lawrence Livermore National Laboratory, Livermore, California, USA
3 Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
4 Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Rež u Prahy, Czech Republic
5 Yale University, New Haven, Connecticut, USA
6 Physics Department, Panjab University, Chandigarh, India
7 European Organization for Nuclear Research (CERN), Geneva, Switzerland
8 KFKI Research Institute for Particle and Nuclear Physics, Hungarian Academy of Sciences, Budapest, Hungary
9 Dipartimento di Fisica dell’Università e Sezione INFN, Bologna, Italy
10 Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
11 Variable Energy Cyclotron Centre, Kolkata, India
12 Department of Physics, Aligarh Muslim University, Aligarh, India
13 Gangneung-Wonju National University, Gangneung, South Korea
14 Institute for Theoretical and Experimental Physics, Moscow, Russia
15 Russian Research Centre Kurchatov Institute, Moscow, Russia
16 Sezione INFN, Turin, Italy
17 Centro Fermi—Centro Studi e Ricerche e Museo Storico della Fisica “Enrico Fermi”, Rome, Italy
18 Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
19 Faculty of Engineering, Bergen University College, Bergen, Norway
20 Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
21 Dipartimento Interateneo di Fisica “M. Merlin” and Sezione INFN, Bari, Italy
22 V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia
23 National Institute for Physics and Nuclear Engineering, Bucharest, Romania
24 Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
25 Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
26 Rudjer Bošković Institute, Zagreb, Croatia
27 Sezione INFN, Padova, Italy
28 Sezione INFN, Bologna, Italy
29 SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France
30 Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
31 Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France
32 Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
33 Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
34 Helsinki Institute of Physics (HIP) and University of Jyväskylä, Jyväskylä, Finland
35 Sezione INFN, Catania, Italy
36 Commissariat à l’Énergie Atomique, IRFU, Saclay, France
37 Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS–IN2P3, Clermont-Ferrand, France
38 Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
39 Institute of Physics, Bhubaneswar, India
40 Dipartimento di Fisica e Astronomia dell’Università e Sezione INFN, Catania, Italy
41 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
42 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
43 Joint Institute for Nuclear Research (JINR), Dubna, Russia
44 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
45 Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
46 University of Houston, Houston, Texas, USA
47 Dipartimento di Fisica Sperimentale dell’Università and Sezione INFN, Turin, Italy
48 Petersburg Nuclear Physics Institute, Gatchina, Russia
49 Physics Department, University of Jammu, Jammu, India
50 Laboratori Nazionali di Frascati, INFN, Frascati, Italy
51 Dipartimento di Fisica dell’Università and Sezione INFN, Padova, Italy
52 Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
53 Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
54 Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
55 Department of Physics, Ohio State University, Columbus, Ohio, USA
56 Moscow Engineering Physics Institute, Moscow, Russia
57 Institute for High Energy Physics, Protvino, Russia
58 Faculty of Science, P. J. Šafárik University, Košice, Slovakia
59 Wayne State University, Detroit, Michigan, USA
Also at Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS–IN2P3, Clermont-Ferrand, France.

Also at Sezione INFN, Bologna, Italy.

Present address: Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany.

Present address: Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS–IN2P3, Clermont-Ferrand, France.

Also at Dipartimento di Fisica dell’Università, Udine, Italy.

Present address: Sezione INFN, Turin, Italy.

Also at Benemérita Universidad Autónoma de Puebla, Puebla, Mexico.

Also at European Organization for Nuclear Research (CERN), Geneva, Switzerland.

Present address: European Organization for Nuclear Research (CERN), Geneva, Switzerland.

Present address: Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Present address: Centro Fermi—Centro Studi e Ricerche e Museo Storico della Fisica “Enrico Fermi,” Rome, Italy.

Also at M. V. Lomonosov Moscow State University, D. V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia.

Also at Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France.

Present address: Dipartimento Interateneo di Fisica “M. Merlin” and Sezione INFN, Bari, Italy.

Present address: SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France.

Also at “Vinča” Institute of Nuclear Sciences, Belgrade, Serbia.

Also at Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico.

Present address: Wayne State University, Detroit, MI, USA.

Present address: Department of Physics, University of Oslo, Oslo, Norway.

Present address: Eberhard Karls Universität Tübingen, Tübingen, Germany.

Present address: Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany.

Present address: Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France.

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

Present address: University of Tokyo, Tokyo, Japan.

Also at Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic.

Also at Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia.

Also at Hua-Zhong Normal University, Wuhan, China.

Present address: Sezione INFN, Bologna, Italy.

Also at Centro Fermi—Centro Studi e Ricerche e Museo Storico della Fisica “Enrico Fermi,” Rome, Italy.

Present address: Warsaw University of Technology, Warsaw, Poland.

Also at Fachhochschule Köln, Köln, Germany.