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Production of charged pions, kaons and (anti) protons at large transverse momenta in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

The ALICE Collaboration*

Abstract

Transverse momentum spectra of $\pi^{\pm}$, $\mathrm{K}^{\pm}$ and $\mathrm{p}(\bar{\mathrm{p}})$ up to $p_{\mathrm{T}} = 20$ GeV/c at mid-rapidity, $|y| \lesssim 0.8$, in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV have been measured using the ALICE detector at the LHC. At intermediate p_{T} ($\sim$ 2-8 GeV/c) an enhancement of $(\mathrm{p}+\bar{\mathrm{p}})/(\pi^{+}+\pi^{-})$ with respect to pp collisions is observed and the ratio reaches ~ 0.80 in central Pb–Pb collisions. The measurement of the nuclear modification factor indicates that within the systematic and statistical uncertainties $\pi^{\pm}$, $\mathrm{K}^{\pm}$ and $\mathrm{p}(\bar{\mathrm{p}})$ are equally suppressed at high p_{T} (> 10 GeV/c), suggesting that the chemical composition of leading particles from jets in the medium is similar to that of vacuum jets.

*See Appendix A for the list of collaboration members

Heavy ion collisions at ultra relativistic energies produce a new form of QCD matter characterized by the deconfined state of quarks and gluons (partons). Measurements of the production of identified particles provide information about the dynamics of this dense matter. In particular at intermediate transverse momentum, $2 < p_T < 8$ GeV/c, baryon-to-meson ratios, *e.g.* the proton yield divided by the pion yield, measured by experiments at RHIC revealed a, so far, not well understood effect [1, 2, 3, 4], known as the "baryon anomaly", that may indicate the presence of new hadronization mechanisms. For larger transverse momenta ($>$ 10 GeV/c) it is possible to study the energy loss (jet quenching) of high p_T scattered partons when traversing the medium [5]. This affects the inclusive charged particle p_T spectrum as has been seen at RHIC [6, 7, 8] and confirmed over an extended p_T range, $\sim$ 100 GeV/c, at the LHC [9, 10]. The additional information provided by particle identification (PID) allows two open experimental questions to be addressed: Does the baryon-to-meson ratio return to the pp value for very high p_T ($>$ 10 GeV/c) as hinted at in the recent publication of the Λ/K^0_S ratio [11]? Are there particle species dependent jet quenching effects as predicted in several models [12, 13, 14] where measurements at RHIC are inconclusive due to the limited p_T-range [15, 16]?

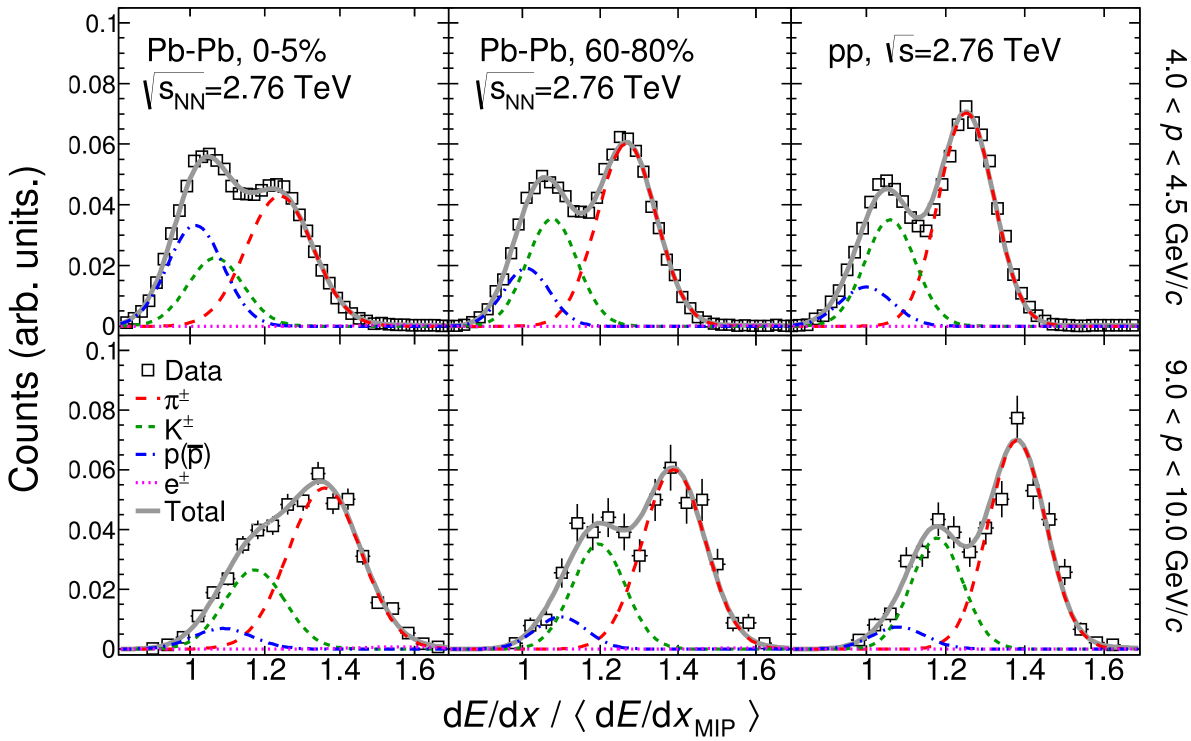

Fig. 1: (Color online). dE/dx distributions measured for $|\eta| < 0.2$ and normalized to the integrated yields. The signals are fitted to a sum of four Gaussian functions (solid line). Two p intervals are shown for central (left) and peripheral (center) Pb–Pb; and pp (right) collisions. In all momentum intervals the electron fraction is below 1 %.

In this Letter we present the measurement of the production of pions (kaons and protons) from p_T = 2 (3) GeV/c up to 20 GeV/c in $\sqrt{s_{NN}} = 2.76$ TeV pp and Pb–Pb collisions. A total of 11 $\times 10^6$ (40×10^6) Pb–Pb (pp) collision events are used in this analysis. Data were taken during 2010 (2011) and reconstructed using the ALICE apparatus [17]. The Inner Tracking System (ITS) and the Time Projection Chamber (TPC) are used for vertex finding and tracking. The TPC also provides PID through the measurement of the specific energy loss, dE/dx. Minimum bias interactions are triggered based on the signals from forward scintillators (VZERO) and, in pp collisions, the two innermost silicon pixel layers of the ITS (SPD). The collision's centrality is determined from the measured amplitude in the VZERO detector which is related to the number of participating nucleons and the nuclear overlap function (T_{AA}) through simulations based on a Glauber model [18]. The same event and track selection is used as in the inclusive charged particle analysis [19]. Track cuts are optimized in order to select primary charged particles in the pseudorapidity range $|\eta| < 0.8$. Since each track is required to have at least one reconstructed point in the SPD (closer than 10 cm to the primary vertex) the feed-down correction due to hyperon decays is small. For $p_T \sim 2$ (3) GeV/c it is of order 0.3 % (4%) for the pion (proton) yield and decreasing with increasing p_T. Nevertheless, all results presented in this paper are corrected for feed-down from weak decays.

The $\mathrm{d}E/\mathrm{d}x$ is obtained as the truncated mean of the 0-60% lowest charge samples associated with the track in the TPC [20]. Particle identification is performed in the relativistic rise regime of the Bethe-Bloch (BB) curve where the $\langle \mathrm{d}E/\mathrm{d}x \rangle$ separation between particles with different masses is nearly constant [21]. The $\mathrm{d}E/\mathrm{d}x$ response depends on the track length so the analysis is done in four equally sized $|\eta|$-intervals, and a geometrical cut to remove tracks entering the gap in between the TPC readout chambers is applied to select tracks with the best $\mathrm{d}E/\mathrm{d}x$ resolution. The separation in number of standard deviations (σ) between pions and kaons (pions and protons) in pp and peripheral Pb–Pb collision is around 3.2 (4.6) at p = 6 GeV/c for $0.6 < |\eta| < 0.8$ where the separation is largest. In central Pb–Pb collisions one finds a separation of 2.4 (3.5) σ. In the worst case, $|\eta| < 0.2$, the separation is 11-15 % smaller.

Figure 1 shows an example of the $\mathrm{d}E/\mathrm{d}x$ spectrum obtained for pp and Pb–Pb (central and peripheral) collisions for two momentum, p, intervals and $|\eta| < 0.2$ where $p \sim p_T$. The pion, kaon, and proton yields are extracted by fitting a sum of four Gaussian functions (including electrons) to the $\mathrm{d}E/\mathrm{d}x$ spectra [1]. To reduce the degrees of freedom in the fits from 12 to 4, parameterizations of the BB ($\langle \mathrm{d}E/\mathrm{d}x \rangle$) and resolution ($\sigma$) curves as a function of $\beta\gamma$ are extracted first using tracks from identified particles. Samples of secondary pions ($30 < \beta\gamma < 50$) and protons ($3 < \beta\gamma < 7$) are determined through the reconstruction of the weak decay topology of $\mathrm{K^0_S}$ and Λ, respectively; a similar algorithm is used to identify electrons resulting from photon conversions (fixing the $\mathrm{d}E/\mathrm{d}x$ plateau: $\beta\gamma > 1000$) . Finally, using information from the time-of-flight detector the relative pion content can be enhanced for sub-samples of the full datasets ($16 < \beta\gamma < 50$).

The $\langle \mathrm{d}E/\mathrm{d}x \rangle$ separation between kaons and protons in the high p_T analysis is smallest for $p \sim 3$ GeV/c and increases with p until both species are on the relativistic rise [21]. The $\mathrm{K^0_S}$ yields [11] are used to constrain further the BB curve in the region $3 < \beta\gamma < 17$ for Pb–Pb data. The effect of the $\mathrm{K^0_S}$ condition is only relevant in central collisions at low p_T (< 4 GeV/c). At 3 GeV/c the effect on the extracted kaon yield is 10% (< 1%) for 0-5% (60-80%) collision centrality.

With the above information the BB and the resolution curves are determined for kaons and protons in the full momentum interval reported here and for pions with $p < 7$ GeV/c. For $p > 7$ GeV/c the pion $\langle \mathrm{d}E/\mathrm{d}x \rangle$ is restricted by the logarithmic rise until the $\langle \mathrm{d}E/\mathrm{d}x \rangle$ starts to approach the plateau. This lack of additional constraint currently limits the p_T reach of the analysis to ∼20 GeV/c.

From the fits in Fig. 1 the particle fractions, $f_{\pi/\mathrm{K/p}}(p)$ are extracted. To obtain the fractions as a function of p_T, $f_{\pi/\mathrm{K/p}}(p_T)$, a weighting procedure is implemented using a matrix which relates the measured p to p_T. The p_T-dependent fractions are found to be independent of η and so all four η regions are averaged.

Finally, the invariant yields are obtained using the p_T spectrum for inclusive charged particles [19], $\frac{\mathrm{d}^2N_{\mathrm{ch}}}{\mathrm{d}p_T\mathrm{d}\eta}$, in the following way:

$$\frac{\mathrm{d}^2N_{\pi/\mathrm{K/p}}}{\mathrm{d}p_T\mathrm{d}y} = \mathrm{J}_{\pi/\mathrm{K/p}}\frac{\mathrm{d}^2N_{\mathrm{ch}}}{\mathrm{d}p_T\mathrm{d}\eta}\frac{\varepsilon_{\mathrm{ch}}}{\varepsilon_{\pi/\mathrm{K/p}}}f_{\pi/\mathrm{K/p}}(p_T), \tag{1}$$

where ($\varepsilon_{\mathrm{ch}}$) $\varepsilon_{\pi/\mathrm{K/p}}$ is the efficiency for (un)identified particles and $\mathrm{J}_{\pi/\mathrm{K/p}}$ is the Jacobian correction (from η to y). Normalizing to the p_T spectrum of inclusive charged particles guarantees that only the systematic uncertainty due to PID is relevant when comparing the modification of the p_T spectra of $\pi/\mathrm{K/p}$ to those

[1] We note that muons from heavy flavor decays are subtracted from the pions based on the measured electron yields and that contamination from deuterons and tritons are negligible ($\ll 1$ %).

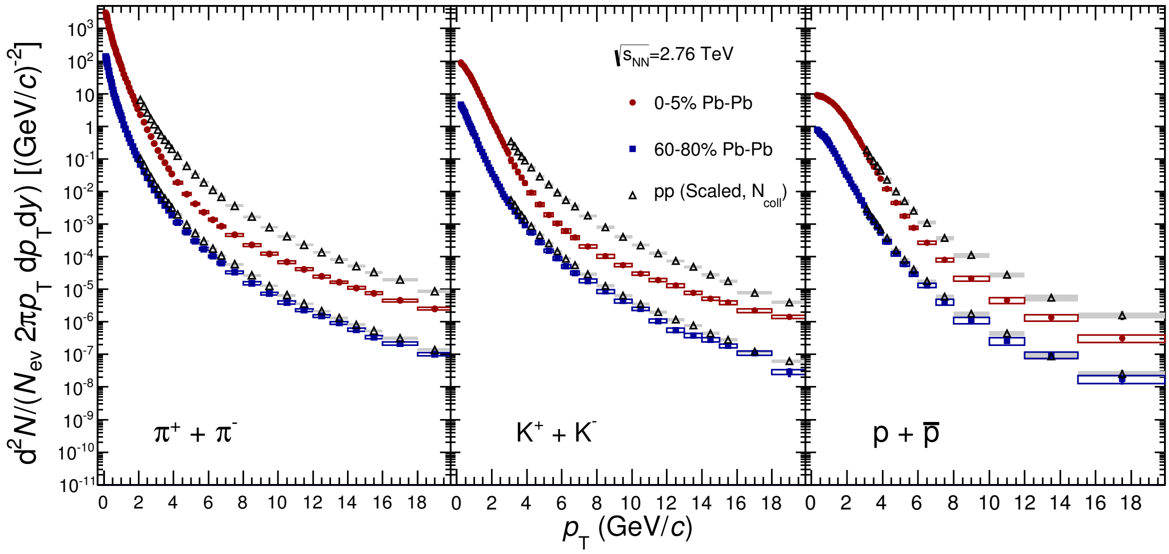

Fig. 2: (Color online). Invariant yields of identified particles in central and peripheral Pb–Pb collisions. Black markers show the pp reference yields scaled by the average number of binary collisions [18]. The statistical and systematic uncertainties are shown as vertical error bars and boxes, respectively. For Pb–Pb the published data below 2 (3) GeV/c for pions (kaons and protons) are also shown [22].

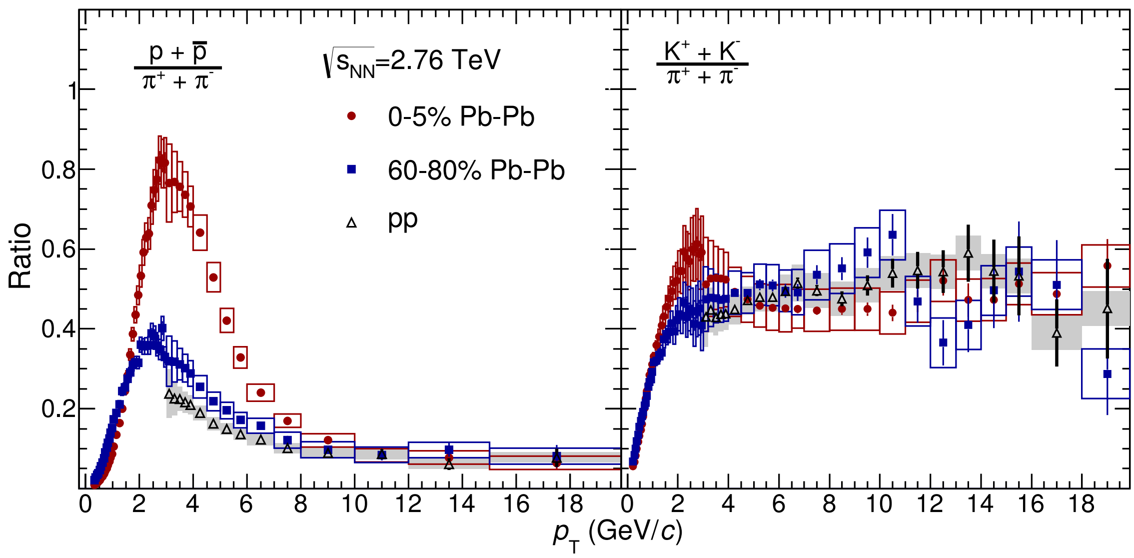

Fig. 3: (Color online). Particle ratios as a function of p_T measured in pp and Pb–Pb collisions. Statistical and systematic uncertainties are displayed as vertical error bars and boxes, respectively. For Pb–Pb the published data below 3 GeV/c are also shown [22].

for the unidentified particles.

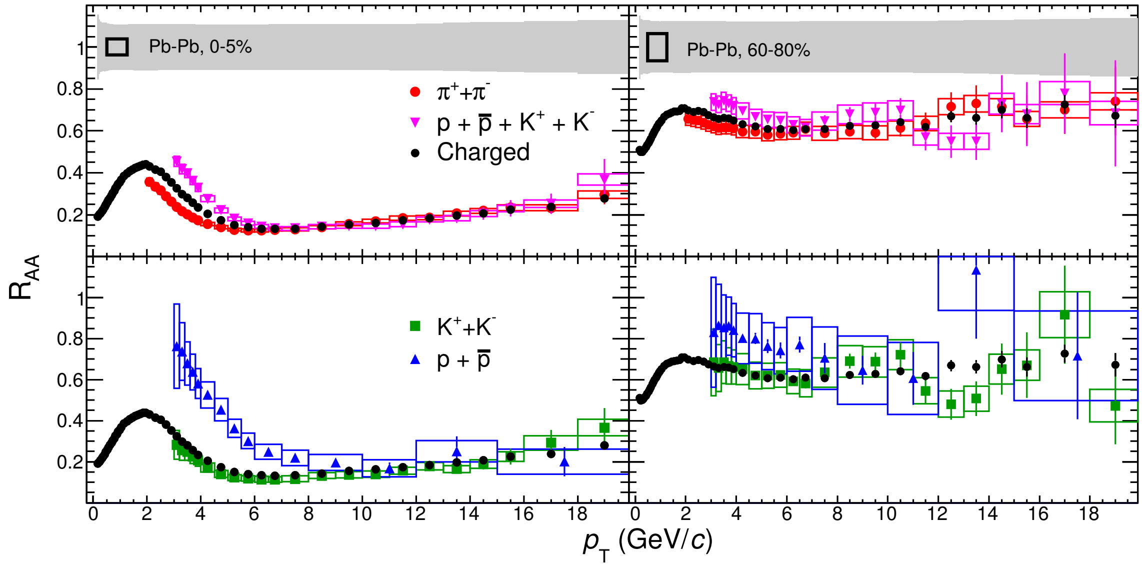

Fig. 4: (Color online). The nuclear modification factor R_{AA} as a function of p_T for different particle species. Results for 0-5% (left) and 60-80% (right) collision centralities are shown. Statistical and PID systematic uncertainties are plotted as vertical error bars and boxes around the points, respectively. The p_T dependent systematic uncertainty that is common between the charged and the PID analyzes is plotted as a grey band at $R_{AA} = 1$ in the top plot. The normalization uncertainty is indicated by the black boxes inside this band [19].

The systematic uncertainty on the invariant yields has three main components: event and track selection, efficiency correction of the fractions, and the fraction extraction. Contributions from the event and track selection are taken directly from the inclusive charged particle analysis [19]. Efficiency ratios ($\varepsilon_{ch}/\varepsilon_{\pi/K/p}$) are found to be nearly independent of p_T (a small dependence is only observed for kaons), similar for all systems, and model independent within 3 %. The largest systematic uncertainty in the extraction of the fractions comes from the uncertainty in the constrained parameters: the means ($\langle dE/dx \rangle$) and the widths (σ). The uncertainty on these parameters are estimated as the difference between the final parameterizations and the actual values from the clean samples. In addition, the statistical uncertainty on the extracted BB parameterization in peripheral Pb–Pb collisions is found to be of a similar magnitude and also taken into account for the variations. The dE/dx spectra are then refitted, varying the mean and sigma within the estimated uncertainties, and the variation of the fractions are assigned as systematic errors. A summary of the PID systematic uncertainties is shown in Table 1.

Table 1: Systematic uncertainties, separated into the N_{ch}, PID, and efficiency part, on the invariant yields from $3 < p_T < 4$ GeV/c to $10 < p_T < 20$ GeV/c.

System	Pb–Pb 0-5%	Pb–Pb 60-80%	pp
N_{ch}[2]	8.3-8.2%	9.9-9.8%	7.4-7.6%
$\pi^+ + \pi^-$[3]	1.7-2.4%	1.5-2.2%	1.2-1.7%
$K^+ + K^-$	19-7.9%	17-8.7%	16-5.7%
$p + \bar{p}$	9.9-21%	20-24%	24-20%
Efficiency ratios[4]		3%	

Figure 2 shows the invariant yields measured in Pb–Pb collisions compared to those in pp collisions scaled to the number of binary collisions, N_{coll} [18]. For Pb–Pb the results of the lower p_T analysis of bulk production are also plotted for p_T below 2 (3) GeV/c for pions (kaons and protons) [22]. For peripheral Pb–Pb collisions the shape of the invariant yields is similar to those observed in pp collisions.

The spectra exhibit a reduction in the production of high-p_T particles with respect to the reference which is characteristic of jet quenching.

Figure 3 shows the proton-to-pion ratio, $(p+\bar{p})/(\pi^+ + \pi^-)$, as a function of p_T. For central (peripheral) Pb–Pb collisions it reaches ~ 0.80 (~ 0.38) at the maximum around ~ 3 GeV/c and one observes a subsequent decrease with increasing p_T. Within the systematic and statistical uncertainties the magnitudes of these ratios are equal to those measured by PHENIX [16] and below those measured by STAR [15]. The difference between these two comparisons are presumably caused by STAR reporting inclusive protons yields while PHENIX has subtracted feed-down contributions from weak decays. At LHC energies the mini-jet activity is expected to be larger than at RHIC energies, which motivated certain ratio predictions in the framework of recombination models to be an order of magnitude larger than the measurements reported here [23]. Other predictions including both recombination and fragmentation are more consistent with the data for high p_T [24]. It is interesting to note that in central Pb–Pb collisions the $(K^+ + K^-)/(\pi^+ + \pi^-)$ ratio also exhibits a small bump at $p_T \sim 3$ GeV/c. This behavior is not predicted by coalescence models and, even the large systematic error in this region does not permit any strong conclusions, this feature is qualitatively well described by EPOS [25] where the interaction between bulk matter (which thermalizes and flows) and jets is considered [26]. Finally, for higher p_T (> 10 GeV/c) both particle ratios behave like in pp suggesting that fragmentation dominates the hadron production. In this p_T regime, the particle ratios in pp are not well described by the pQCD calculations in [27], hence the spectra themselves can be used to constrain identified fragmentation functions.
Figure 4 shows the nuclear modification factor R_{AA} as a function of p_T defined as the ratio of the Pb–Pb spectra to the N_{coll} scaled pp spectra shown in Fig. 2. The R_{AA} for the sum of kaons and protons is also shown as this gives the best precision for testing whether pions are suppressed similarly to other light hadrons. For $p_T < 10$ GeV/c protons appear to be less suppressed than kaons and pions consistent with the particle ratios shown in Fig. 2. At larger p_T (> 10 GeV/c) all particle species are equally suppressed; so despite the strong jet quenching effects observed in the most central heavy-ion collisions, the particle composition (and ratios) at high p_T is similar to those in vacuum. This observation disfavors significant modifications of hadro-chemistry within the hard core of jets [12] and contradicts predictions based on formation time arguments [14].

In summary, we have measured the production of high-p_T pions, kaons and protons in central and peripheral Pb–Pb collisions. From the invariant yields we derived the particle ratios and the R_{AA} as a function of p_T. At moderate p_T (< 10 GeV/c) we observe that the proton-to-pion ratio reaches a maximum of ~ 0.80 (~ 0.38) at $p_T = 3$ GeV/c in central (peripheral) Pb–Pb collisions. In central collisions, the kaon-to-pion ratio exhibits a small enhancement at the same p_T. At higher-p_T, the ratios are compatible to those in pp collisions. From the nuclear modification factor R_{AA}, we conclude that for $p_T > 10$ GeV/c within the systematic and statistical uncertainties, pions, kaons and protons are suppressed equally.

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A The ALICE Collaboration

B. Abelev[74] , J. Adam[38] , D. Adamová[82] , M.M. Aggarwal[86] , G. Aglieri Rinella[34] , M. Agnello[92,109] , A. Agostinelli[26] , N. Agrawal[45] , Z. Ahammed[128] , N. Ahmad[18] , A. Ahmad Masoodi[18] , I. Ahmed[15] , S.U. Ahn[67] , S.A. Ahn[67] , I. Aimo[92,109] , S. Aiola[133] , M. Ajaz[15] , A. Akindinov[57] , D. Aleksandrov[98] , B. Alessandro[109] , D. Alexandre[100] , A. Alici[103,12] , A. Alkin[3] , J. Alme[36] , T. Alt[40] , V. Altini[31] , S. Altinpinar[17] , I. Altsybeev[127] , C. Alves Garcia Prado[117] , C. Andrei[77] , A. Andronic[95] , V. Anguelov[91] , J. Anielski[52] , T. Antičić[96] , F. Antinori[106] , P. Antonioli[103] , L. Aphecetche[110] , H. Appelshäuser[50] , N. Arbor[70] , S. Arcelli[26] , N. Armesto[16] , R. Arnaldi[109] , T. Aronsson[133] , I.C. Arsene[21,95] , M. Arslandok[50] , A. Augustinus[34] , R. Averbeck[95] , T.C. Awes[83] , M.D. Azmi[18,88] , M. Bach[40] , A. Badalà[105] , Y.W. Baek[41,69] , S. Bagnasco[109] , R. Bailhache[50] , V. 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C. Schiaua[77] , R. Schicker[91] , C. Schmidt[95] , H.R. Schmidt[33] , S. Schuchmann[50] , J. Schukraft[34] , M. Schulc[38] , T. Schuster[133] , Y. Schutz[34,110] , K. Schwarz[95] , K. Schweda[95] , G. Scioli[26] , E. Scomparin[109] , P.A. Scott[100] , R. Scott[122] , G. Segato[28] , J.E. Seger[85] , I. Selyuzhenkov[95] , J. Seo[94] , E. Serradilla[10,63] , A. Sevcenco[61] , A. Shabetai[110] , G. Shabratova[65] , R. Shahoyan[34] , A. Shangaraev[54] , N. Sharma[122,60] , S. Sharma[89] , K. Shigaki[44] , K. Shtejer[25] , Y. Sibiriak[98] , S. Siddhanta[104] , T. Siemiarczuk[76] , D. Silvermyr[83] , C. Silvestre[70] , G. Simatovic[125] , R. Singaraju[128] , R. Singh[89] , S. Singha[78,128] , V. Singhal[128] , B.C. Sinha[128] , T. Sinha[99] , B. Sitar[37] , M. Sitta[30] , T.B. Skaali[21] , K. Skjerdal[17] , R. Smakal[38] , N. Smirnov[133] , R.J.M. Snellings[56] , C. Søgaard[32] , R. Soltz[74] , J. Song[94] , M. Song[134] , F. Soramel[28] , S. Sorensen[122] , M. Spacek[38] , I. Sputowska[114] , M. Spyropoulou-Stassinaki[87] , B.K. Srivastava[93] , J. Stachel[91] , I. Stan[61] , G. Stefanek[76] , M. Steinpreis[19] , E. Stenlund[32] , G. Steyn[64] , J.H. Stiller[91] , D. Stocco[110] , M. Stolpovskiy[54] , P. Strmen[37] , A.A.P. Suaide[117] , M.A. Subieta Vasquez[25] , T. Sugitate[44] , C. Suire[48] , M. Suleymanov[15] , R. Sultanov[57] , M. Šumbera[82] , T. Susa[96] , T.J.M. Symons[73] , A. Szanto de Toledo[117] , I. Szarka[37] , A. Szczepankiewicz[34] , M. Szymanski[130] , J. Takahashi[118] , M.A. Tangaro[31] , J.D. Tapia Takaki[viii,48] , A. Tarantola Peloni[50] , A. Tarazona Martinez[34] , A. Tauro[34] , G. Tejeda Muñoz[2] , A. Telesca[34] , C. Terrevoli[31] , A. Ter Minasyan[75] , J. Thäder[95] , D. Thomas[56] , R. Tieulent[126] , A.R. Timmins[119] , A. Toia[50,106] , H. Torii[123] , V. Trubnikov[3] , W.H. Trzaska[120] , T. Tsuji[123] , A. Tumkin[97] , R. Turrisi[106] , T.S. Tveter[21] , J. Ulery[50] , K. Ullaland[17] , A. Uras[126] , G.L. Usai[23] , M. Vajzer[82] , M. Vala[65,58] , L. Valencia Palomo[48,69] , S. Vallero[25,91] , P. Vande Vyvre[34] , L. Vannucci[72] , J. Van Der Maarel[56] , J.W. Van Hoorne[34] , M. van Leeuwen[56] , A. Vargas[2] , R. Varma[45] , M. Vasileiou[87] , A. Vasiliev[98] , V. Vechernin[127] , M. Veldhoen[56] , A. Velure[17] , M. Venaruzzo[24] , E. Vercellin[25] , S. Vergara Limón[2] , R. Vernet[8] , M. Verweij[131] , L. Vickovic[112] , G. Viesti[28] , J. Viinikainen[120] , Z. Vilakazi[64] , O. Villalobos Baillie[100] , A. Vinogradov[98] , L. Vinogradov[127] , Y. Vinogradov[97] , T. Virgili[29] , Y.P. Viyogi[128] , A. Vodopyanov[65] , M.A. Völkl[91] , K. Voloshin[57] , S.A. Voloshin[131] , G. Volpe[34] , B. von Haller[34] , I. Vorobyev[127] , D. Vranic[95,34] , J. Vrláková[39] , B. Vulpescu[69] , A. Vyushin[97] , B. Wagner[17] , J. Wagner[95] , V. Wagner[38] , M. Wang[7,110] , Y. Wang[91] , D. Watanabe[124] , M. Weber[119] , J.P. Wessels[52] , U. Westerhoff[52] , J. Wiechula[33] , J. Wikne[21] , M. Wilde[52] , G. Wilk[76] , J. Wilkinson[91] , M.C.S. Williams[103] , B. Windelband[91] , M. Winn[91] , C. Xiang[7] , C.G. Yaldo[131] , Y. Yamaguchi[123] , H. Yang[56] , P. Yang[7] , S. Yang[17] , S. Yano[44] , S. Yasnopolskiy[98] , J. Yi[94] , Z. Yin[7] , I.-K. Yoo[94] , I. Yushmanov[98] , V. Zaccolo[79] , C. Zach[38] , A. Zaman[15] , C. Zampolli[103] , S. Zaporozhets[65] , A. Zarochentsev[127] , P. Závada[59] , N. Zaviyalov[97] , H. Zbroszczyk[130] , I.S. Zgura[61] , M. Zhalov[84] , F. Zhang[7] , H. Zhang[7] , X. Zhang[69,7,73] , Y. Zhang[7] , C. Zhao[21] , D. Zhou[7] , F. Zhou[7] , Y. Zhou[56] , H. Zhu[7] , J. Zhu[7] , J. Zhu[7] , X. Zhu[7] , A. Zichichi[12,26] , A. Zimmermann[91] , M.B. Zimmermann[34,52] , G. Zinovjev[3] , Y. Zoccarato[126] , M. Zynovyev[3] , M. Zyzak[50]

Affiliation notes

[i] Deceased
[ii] Also at: St-Petersburg State Polytechnical University
[iii] Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India
[iv] Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia
[v] Also at: University of Belgrade, Faculty of Physics and "Vinča" Institute of Nuclear Sciences, Belgrade, Serbia
[vi] Permanent Address: Permanent Address: Konkuk University, Seoul, Korea
[vii] Also at: Institute of Theoretical Physics, University of Wroclaw, Wroclaw, Poland
[viii] Also at: University of Kansas, Lawrence, KS, United States

Collaboration Institutes

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[2] Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
[3] Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
[4] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
[5] Budker Institute for Nuclear Physics, Novosibirsk, Russia
[6] California Polytechnic State University, San Luis Obispo, CA, United States
[7] Central China Normal University, Wuhan, China
[8] Centre de Calcul de l'IN2P3, Villeurbanne, France
[9] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba

[10] Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[11] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
[12] Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Rome, Italy
[13] Chicago State University, Chicago, USA
[14] Commissariat à l'Energie Atomique, IRFU, Saclay, France
[15] COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan
[16] Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
[17] Department of Physics and Technology, University of Bergen, Bergen, Norway
[18] Department of Physics, Aligarh Muslim University, Aligarh, India
[19] Department of Physics, Ohio State University, Columbus, OH, United States
[20] Department of Physics, Sejong University, Seoul, South Korea
[21] Department of Physics, University of Oslo, Oslo, Norway
[22] Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN Rome
[23] Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[24] Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[25] Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[26] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
[27] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
[28] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[29] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[30] Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy
[31] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[32] Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
[33] Eberhard Karls Universität Tübingen, Tübingen, Germany
[34] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[35] Excellence Cluster Universe, Technische Universität München, Munich, Germany
[36] Faculty of Engineering, Bergen University College, Bergen, Norway
[37] Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
[38] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[39] Faculty of Science, P.J. Šafárik University, Košice, Slovakia
[40] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[41] Gangneung-Wonju National University, Gangneung, South Korea
[42] Gauhati University, Department of Physics, Guwahati, India
[43] Helsinki Institute of Physics (HIP), Helsinki, Finland
[44] Hiroshima University, Hiroshima, Japan
[45] Indian Institute of Technology Bombay (IIT), Mumbai, India
[46] Indian Institute of Technology Indore, Indore (IITI), India
[47] Inha University, College of Natural Sciences
[48] Institut de Physique Nucleaire d'Orsay (IPNO), Universite Paris-Sud, CNRS-IN2P3, Orsay, France
[49] Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[50] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[51] Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany
[52] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
[53] Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
[54] Institute for High Energy Physics, Protvino, Russia
[55] Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
[56] Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
[57] Institute for Theoretical and Experimental Physics, Moscow, Russia
[58] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
[59] Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
[60] Institute of Physics, Bhubaneswar, India

[61] Institute of Space Science (ISS), Bucharest, Romania
[62] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[63] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[64] iThemba LABS, National Research Foundation, Somerset West, South Africa
[65] Joint Institute for Nuclear Research (JINR), Dubna, Russia
[66] Konkuk University, Seoul, South Korea
[67] Korea Institute of Science and Technology Information, Daejeon, South Korea
[68] KTO Karatay University, Konya, Turkey
[69] Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS–IN2P3, Clermont-Ferrand, France
[70] Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France
[71] Laboratori Nazionali di Frascati, INFN, Frascati, Italy
[72] Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy
[73] Lawrence Berkeley National Laboratory, Berkeley, CA, United States
[74] Lawrence Livermore National Laboratory, Livermore, CA, United States
[75] Moscow Engineering Physics Institute, Moscow, Russia
[76] National Centre for Nuclear Studies, Warsaw, Poland
[77] National Institute for Physics and Nuclear Engineering, Bucharest, Romania
[78] National Institute of Science Education and Research, Bhubaneswar, India
[79] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[80] Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
[81] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[82] Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic
[83] Oak Ridge National Laboratory, Oak Ridge, TN, United States
[84] Petersburg Nuclear Physics Institute, Gatchina, Russia
[85] Physics Department, Creighton University, Omaha, NE, United States
[86] Physics Department, Panjab University, Chandigarh, India
[87] Physics Department, University of Athens, Athens, Greece
[88] Physics Department, University of Cape Town, Cape Town, South Africa
[89] Physics Department, University of Jammu, Jammu, India
[90] Physics Department, University of Rajasthan, Jaipur, India
[91] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[92] Politecnico di Torino, Turin, Italy
[93] Purdue University, West Lafayette, IN, United States
[94] Pusan National University, Pusan, South Korea
[95] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[96] Rudjer Bošković Institute, Zagreb, Croatia
[97] Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
[98] Russian Research Centre Kurchatov Institute, Moscow, Russia
[99] Saha Institute of Nuclear Physics, Kolkata, India
[100] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[101] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[102] Sezione INFN, Bari, Italy
[103] Sezione INFN, Bologna, Italy
[104] Sezione INFN, Cagliari, Italy
[105] Sezione INFN, Catania, Italy
[106] Sezione INFN, Padova, Italy
[107] Sezione INFN, Rome, Italy
[108] Sezione INFN, Trieste, Italy
[109] Sezione INFN, Turin, Italy
[110] SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France
[111] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[112] Technical University of Split FESB, Split, Croatia
[113] Technische Universität München, Munich, Germany

[114] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[115] The University of Texas at Austin, Physics Department, Austin, TX, USA
[116] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[117] Universidade de São Paulo (USP), São Paulo, Brazil
[118] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[119] University of Houston, Houston, TX, United States
[120] University of Jyväskylä, Jyväskylä, Finland
[121] University of Liverpool, Liverpool, United Kingdom
[122] University of Tennessee, Knoxville, TN, United States
[123] University of Tokyo, Tokyo, Japan
[124] University of Tsukuba, Tsukuba, Japan
[125] University of Zagreb, Zagreb, Croatia
[126] Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France
[127] V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia
[128] Variable Energy Cyclotron Centre, Kolkata, India
[129] Vestfold University College, Tonsberg, Norway
[130] Warsaw University of Technology, Warsaw, Poland
[131] Wayne State University, Detroit, MI, United States
[132] Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary
[133] Yale University, New Haven, CT, United States
[134] Yonsei University, Seoul, South Korea
[135] Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany