EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Multiplicity dependence of the average transverse momentum in pp, p–Pb, and Pb–Pb collisions at the LHC

The ALICE Collaboration[*]

Abstract

The average transverse momentum $\langle p_T \rangle$ versus the charged-particle multiplicity N_{ch} was measured in p–Pb collisions at a collision energy per nucleon-nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV and in pp collisions at collision energies of $\sqrt{s} = 0.9$, 2.76, and 7 TeV in the kinematic range $0.15 < p_T < 10.0$ GeV/c and $|\eta| < 0.3$ with the ALICE apparatus at the LHC. These data are compared to results in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at similar charged-particle multiplicities. In pp and p–Pb collisions, a strong increase of $\langle p_T \rangle$ with N_{ch} is observed, which is much stronger than that measured in Pb–Pb collisions. For pp collisions, this could be attributed, within a model of hadronizing strings, to multiple-parton interactions and to a final-state color reconnection mechanism. The data in p–Pb and Pb–Pb collisions cannot be described by an incoherent superposition of nucleon-nucleon collisions and pose a challenge to most of the event generators.

---

[*]See Appendix A for the list of collaboration members

Measurements of particle production in proton-nucleus collisions at the Large Hadron Collider (LHC) energies allow the study of fundamental Quantum Chromodynamics (QCD) properties at low parton fractional momentum x and high gluon densities; see [1] for a recent review. Additionally, they provide an important reference measurement for studies of the properties of the QCD matter created in nucleus-nucleus collisions; see [2] for an overview of results at the LHC.

The first measurements of charged-particle production in p–Pb collisions at the LHC at a center-of-mass energy per nucleon-nucleon pair of $\sqrt{s_{NN}}$ = 5.02 TeV [3, 4] exhibited differences compared to pp collisions. These differences were mostly confined to low transverse momentum (p_T), leading to a slightly smaller average multiplicity per number of participating nucleons in p–Pb compared to pp collisions [3], while above a few GeV/c the p_T spectrum in p–Pb collisions exhibits binary collision scaling [4]. The measurements of particle correlations in azimuth and pseudorapidity [5–9] have raised the question whether collective effects in p–Pb collisions, as modeled for example in hydrodynamical approaches [10, 11], are the origin of the observed correlations. Initial state effects, such as gluon saturation described by color glass condensate (CGC) models [12, 13], also describe the data. It remains questionable if the small system size created in pp or p–Pb collisions could exhibit collective, fluid-like, features due to early thermalization, as observed in Pb–Pb collisions [14]. A meaningful way to address this issue is to investigate production mechanisms, correlations, and event shapes as a function of the particle multiplicity. Such studies were recently performed in pp collisions at the LHC, e.g. the ALICE measurements of two-pion Bose-Einstein correlations [15], event sphericity [16], J/ψ meson production [17], and anti-baryon to baryon ratios [18], or the measurements by CMS of long-range angular correlations [19] and of π, K, and p production [20].

The first moment, $\langle p_T \rangle$, of the charged-particle transverse momentum spectrum and its correlation with the charged-particle multiplicity N_{ch}, first observed at the Sp$\bar{p}$S collider [21], carries information about the underlying particle production mechanism. This has been studied by many experiments at hadron colliders in pp($\bar{p}$) covering collision energies from $\sqrt{s}$ = 31 GeV up to 7 TeV [22–29]. All experiments observed an increase of $\langle p_T \rangle$ with N_{ch} in the central rapidity region, a feature which could be reproduced in the PYTHIA event generator only if a mechanism of hadronization including color correlations (reconnections) is considered [30]. Although a good description of Tevatron data [26] was achieved within the PYTHIA 8 model [31], which also described the early LHC data [32], full consistency of the data description within models is yet to be achieved [33]. The LHC data highlighted the importance of color reconnections [34]; see also [33] and the discussion below. Data at LHC energies covering a large momentum range starting at low p_T provide additional input to these models.

In this letter, we present a measurement of the average transverse momentum $\langle p_T \rangle$ versus the charged-particle multiplicity N_{ch} in p–Pb collisions at a collision energy per nucleon-nucleon pair of $\sqrt{s_{NN}}$ = 5.02 TeV for primary particles in the kinematic range $|\eta| < 0.3$. These data are compared to results in pp interactions at collision energies of $\sqrt{s}$ = 0.9, 2.76, and 7 TeV and to results obtained in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. The measurements are performed with the ALICE detector [35] at the LHC. The pp data were recorded in the years 2009-2011, details are given in [36]; the Pb–Pb data are from the 2010 run [37]. The p–Pb data were recorded during an LHC run of 4 weeks in January and February 2013. The number of colliding bunches varied between 8 and 288. The proton and Pb bunch intensities ranged from 1.4×10^{10} to 1.9×10^{10} and from 0.8×10^{10} to 1.4×10^{10} particles, respectively. The luminosity at the ALICE interaction point was up to 5×10^{27}cm^{-2}s^{-1} resulting in a hadronic interaction rate of 10 kHz. The interaction region had an r.m.s. of 6.3 cm along the beam direction and about 60 μm transverse to the beam.

The p–Pb minimum-bias events were triggered by requiring a signal in each of the VZERO detector arrays, VZERO-A located at $2.8 < \eta_{lab} < 5.1$ and VZERO-C at $-3.7 < \eta_{lab} < -1.7$, both covering full azimuth. The pseudorapidity of a charged particle in the detector reference-frame η_{lab} is defined as $\eta_{lab} = -\ln[\tan(\theta/2)]$, with θ the polar angle between the beam axis and the charged particle. The

efficiency of the VZERO trigger was estimated from a control sample of events triggered by signals in two Zero Degree Calorimeters (ZDC) positioned symmetrically at ± 112.6 m from the interaction point, with an energy resolution of about 20% for single neutrons of a few TeV.

The offline event and track selection is identical to that used in the measurement of the charged-particle pseudorapidity density $dN_{ch}/d\eta_{lab}$ [3] and the p_T spectra in p–Pb [4] and Pb–Pb [37] collisions with ALICE. In total, 106 million events for p–Pb collisions, 7, 65, and 150 millions for pp collisions at $\sqrt{s} = 0.9$, 2.76, and 7 TeV, respectively, and 15 millions for Pb–Pb collisions satisfy the trigger and offline event-selection criteria. Primary charged particles are defined as all prompt particles produced in the collision, including all decay products, except those from weak decays of strange hadrons. The efficiency and purity of the primary charged-particle selection are estimated from a Monte Carlo simulation using DPMJET [38] as an event generator with particle transport through the ALICE detector using GEANT3 [39].

Due to the asymmetric beam energies for the proton and lead beam, the nucleon-nucleon center-of-mass system is moving in the laboratory frame with a rapidity of $y_{NN} = -0.465$; the proton beam has negative rapidity. In order to ensure good detector acceptance around midrapidity, tracks are selected for this analysis in the pseudorapidity interval $|\eta| < 0.3$ in the nucleon-nucleon center-of-mass system. In the absence of information on the particle mass, the particle rapidity is unknown. Therefore, we calculate $\eta = \eta_{lab} - y_{NN}$, an approximation which is only accurate for massless particles or relativistic particles. The spectra are corrected based on our knowledge of the pion, kaon, and proton yields measured by ALICE [40]. The average transverse momentum $\langle p_T \rangle$ is then calculated from the corrected spectra as the arithmetic mean in the kinematic range $0.15 < p_T < 10.0$ GeV/c and $|\eta| < 0.3$. The number of accepted charged particles n_{acc} is the sum of all reconstructed charged particles in the same kinematic range. To extract the correlation between $\langle p_T \rangle$ and the number of primary charged particles N_{ch}, counting, for N_{ch}, all particles down to $p_T = 0$, a reweighting procedure is applied to account for the experimental resolution in the measured event multiplicity as described in [27]. This method employs a normalized response matrix from Monte Carlo simulations which contains the probability that an event with multiplicity N_{ch} is reconstructed with multiplicity n_{acc}.

Table 1: Relative systematic uncertainties on $\langle p_T \rangle$ in pp, p–Pb, and Pb–Pb collisions for $|\eta| < 0.3$ and $0.15 < p_T < 10.0$ GeV/c. The quoted ranges reflect the N_{ch} dependence and, for pp collisions, also some energy dependence.

Source	pp	p–Pb	Pb–Pb
Track selection	0.5-1.8%	0.8-1.0%	1.1-1.2%
Particle composition	0.2-0.4%	0.7-0.8%	0.2-0.3%
Tracking efficiency	0.1%	0.2%	0.1%
Monte Carlo generator	$\leq$0.2%	0.1-0.2%	0.2%
Reweighting procedure	2.3-4.1%	1.3-1.8%	0.5-1.2%
Total	2.4-4.5%	1.8-2.2%	1.2-3.0%

The systematic uncertainties of the charged-particle spectrum are evaluated in a similar way as in previous analyses of pp [27], Pb–Pb [37], and p–Pb [4] data and are propagated to $\langle p_T \rangle$. The main contributions and the total uncertainties are listed in Table 1. Other contributions investigated are material budget, trigger and event selection, and secondary particles from weak decays. The uncertainty from each of these contributions is below 0.1%, except the trigger and event selection, which amounts to 0.35% for $N_{ch} = 1$. For p–Pb collisions, the effect of the particle composition on the uncertainty from acceptance due to the shift in rapidity is included in Table 1. In Pb–Pb collisions, an additional source of uncertainty, included in the total uncertainty listed in Table 1, is electromagnetic processes. Those are efficiently rejected by the ALICE detector for 0-90% centrality [41]; their contribution to the systematic uncertainty is of 2.7% for $N_{ch} = 1$ and less than 1% for $N_{ch} > 5$.

The uncertainty from the reweighting method is extracted based on the Monte Carlo events. In this pro-

cedure, the response matrix generated with the HIJING [42] event generator is used for the reweighting procedure with events generated with DPMJET and the outcome distribution $\langle p_T \rangle (N_{ch})$ is compared with the initial distribution from DPMJET. This uncertainty dominates the overall uncertainty at low N_{ch}, and, in pp collisions, also at large N_{ch}. An alternative method, based on the integration and extrapolation of p_T spectra in n_{acc} bins, gives results well within the systematic uncertainties.

Table 2: Characteristics of pp, p–Pb, and Pb–Pb collisions for events with at least one track in $|\eta| < 0.3$ (INEL>0). The average multiplicity $\langle N_{ch} \rangle$ is for $|\eta| < 0.3$ and extrapolating to $p_T = 0$. The average transverse momentum $\langle p_T \rangle$ is obtained in $|\eta| < 0.3$ and in the range $0.15 < p_T < 10.0$ GeV/c. The systematic uncertainties are reported; the statistical uncertainties are negligible. The uncertainties of $\langle N_{ch} \rangle$ are from the tracking efficiency.

collision system	$\sqrt{s_{NN}}$ (TeV)	$\langle N_{ch} \rangle$	$\langle p_T \rangle$ (GeV/c)
pp	0.9	3.14±0.16	0.485±0.020
pp	2.76	3.82±0.19	0.527±0.020
pp	7	4.42±0.22	0.564±0.021
p–Pb	5.02	11.9±0.5	0.644±0.024
Pb–Pb	2.76	259.9±5.9	0.678±0.007

The values of $\langle N_{ch} \rangle$ and $\langle p_T \rangle$ for all events with at least one track in $|\eta| < 0.3$ (INEL>0) for pp, p–Pb, and Pb–Pb collisions are presented in Table 2. A small increase in $\langle p_T \rangle$ is observed in pp collisions as a function of energy. An increase is seen from pp to p–Pb and to minimum bias Pb–Pb collisions.
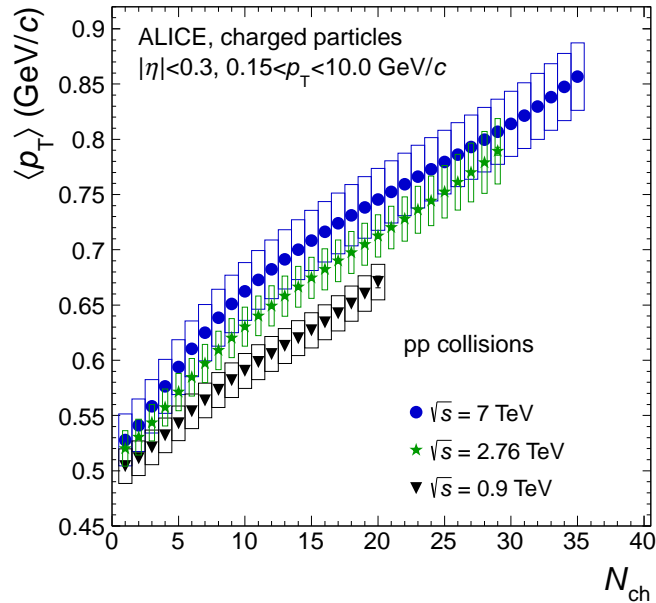

Fig. 1: Average transverse momentum $\langle p_T \rangle$ in the range $0.15 < p_T < 10.0$ GeV/c as a function of charged-particle multiplicity N_{ch} in pp collisions $\sqrt{s} = 0.9$, 2.76, and 7 TeV, for $|\eta| < 0.3$. The boxes represent the systematic uncertainties on $\langle p_T \rangle$. The statistical errors are negligible.

The average transverse momentum $\langle p_T \rangle$ of charged particles is shown in Fig. 1 as a function of the charged-particle multiplicity N_{ch} for pp collisions at $\sqrt{s} = 0.9$, 2.76, and 7 TeV. The multiplicity distributions in pp collisions [43, 44] fall off steeply for large N_{ch}. The present measurement extends up to values of N_{ch} where statistical errors for $\langle p_T \rangle$ in the corresponding n_{acc} values are below 5%. An increase in $\langle p_T \rangle$ with N_{ch} is observed for all collision energies and also an increase with the collision energy at fixed values of N_{ch}, which agrees well with measurements reported by ATLAS [29, 45] at $\sqrt{s} = 0.9$ and

7 TeV. We note a change in slope for all three collision energies at roughly the same value of $N_{ch} \approx 10$. This change in slope was also observed at Tevatron [24, 26] and recently at the LHC [27, 29].

In Monte Carlo event generators, high multiplicity events are produced by multiple parton interactions. An incoherent superposition of such interactions would lead to a constant $\langle p_T \rangle$ at high multiplicities. The observed strong correlation of $\langle p_T \rangle$ with N_{ch} has been attributed, within PYTHIA models, to color reconnections (CR) between hadronizing strings [34]. In this mechanism, which can be interpreted as a collective final-state effect, strings from independent parton interactions do not hadronize independently, but fuse prior to hadronization. This leads to fewer hadrons, but more energetic. The CR strength is implemented as a probability parameter in the models. The CR mechanism bears similarity to the mechanism of string fusion [46] advocated early for nucleus-nucleus collisions. A model based on Pomeron exchange was shown to fit the pp data [47]. A mechanism of collective string hadronization is also used in the EPOS model, which was shown recently to describe a wealth LHC data in pp, p–Pb, and Pb–Pb collisions [48].
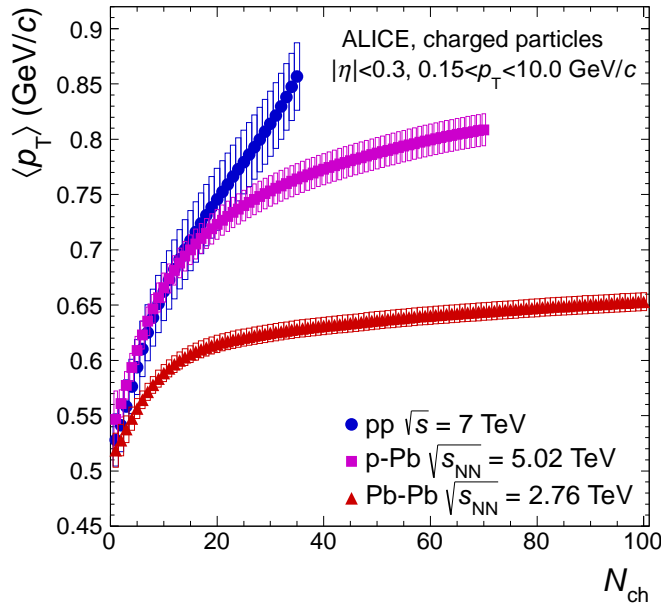

Fig. 2: Average transverse momentum $\langle p_T \rangle$ versus charged-particle multiplicity N_{ch} in pp, p–Pb, and Pb–Pb collisions for $|\eta| < 0.3$. The boxes represent the systematic uncertainties on $\langle p_T \rangle$. The statistical errors are negligible.

Figure 2 shows the average transverse momentum $\langle p_T \rangle$ of charged particles versus the charged-particle multiplicity N_{ch} as measured in pp collisions at $\sqrt{s} = 7$ TeV, in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, and in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In p–Pb collisions, we observe an increase of $\langle p_T \rangle$ with N_{ch}, with $\langle p_T \rangle$ values similar to the values in pp collisions up to $N_{ch} \approx 14$. At multiplicities above $N_{ch} \approx 14$, the measured $\langle p_T \rangle$ is lower in p–Pb collisions than in pp collisions; the difference is more pronounced with increasing N_{ch}. This difference cannot be attributed to the difference in collision energy, as the energy dependence of $\langle p_T \rangle$ is rather weak, see Fig. 1. In contrast, in Pb–Pb collisions, with increasing N_{ch}, there is only a moderate increase in $\langle p_T \rangle$ up to high charged-particle multiplicity with a maximum value of $\langle p_T \rangle = 0.685 \pm 0.016$ (syst.) GeV/c, which is substantially lower than the maximum value in pp. For pp and p–Pb, $N_{ch} > 14$ corresponds to about 10% and 50% of the INEL>0 cross section, respectively, while for Pb–Pb collisions this fraction is about 82%; $N_{ch} > 40$ corresponds to the upper 1% of the cross section in p–Pb and to about 70% most central Pb–Pb collisions. This illustrates that the same N_{ch} value corresponds to a very different collision regime in the three systems.
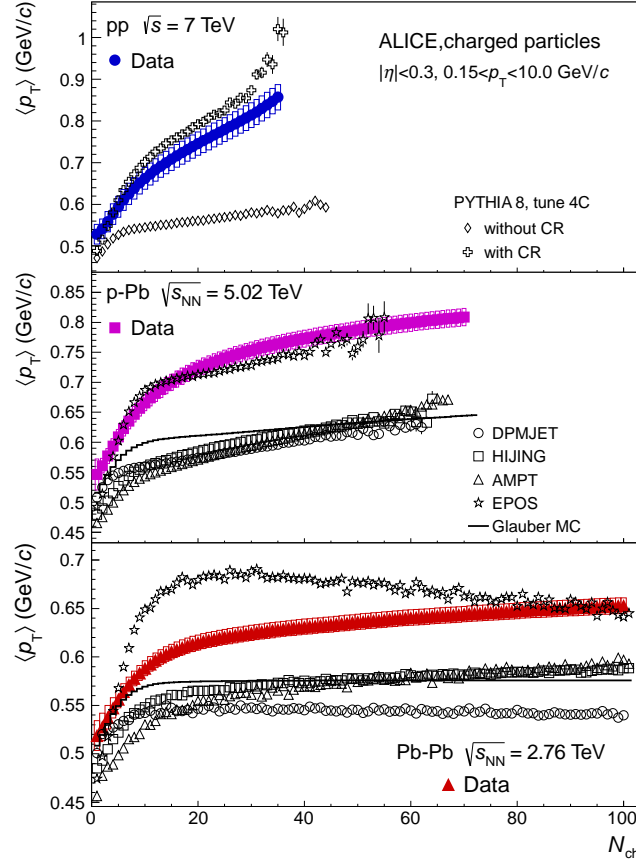
Fig. 3: Average transverse momentum $\langle p_T \rangle$ as a function of charged-particle multiplicity N_{ch} measured in pp (upper panel), p–Pb (middle panel), and Pb–Pb (lower panel) collisions in comparison to model calculations. For pp collisions, calculations with PYTHIA 8 [50] with tune 4C are shown with and without the color reconnection (CR) mechanism. The p–Pb and Pb–Pb data are compared to calculations with the DPMJET, HIJING, AMPT, and EPOS Monte Carlo event generators. The lines show calculations in a Glauber Monte Carlo approach (see text).

In Pb–Pb collisions, substantial rescattering of constituents are thought to lead to a redistribution of the particle spectrum where most particles are part of a locally thermalized medium exhibiting collective, hydrodynamic-type, behavior. The moderate increase of $\langle p_T \rangle$ seen in Pb–Pb collisions (in Fig. 2, for $N_{ch} \gtrsim 10$) is thus usually attributed to collective flow [49]. The p–Pb data exhibit features of both pp and Pb–Pb collisions, at low and high multiplicities, respectively. However, the saturation trend of $\langle p_T \rangle$ versus N_{ch} is less pronounced in p–Pb than in Pb–Pb collisions and leads to a much higher value of $\langle p_T \rangle$ at high multiplicities than in Pb–Pb. An increase in $\langle p_T \rangle$ of a few percent is expected in Pb–Pb from $\sqrt{s_{NN}} = 2.76$ TeV to 5 TeV, but it appears unlikely that the p–Pb $\langle p_T \rangle$ values will match those in Pb–Pb at the same energy. While the p–Pb data cannot exclude collective hydrodynamic-type effects for high-multiplicity events, it is clear that such a conclusion requires stronger evidence. The features seen in Fig. 2 do not depend on the kinematic selection; similar trends are found for $|\eta| < 0.8$ ($|\eta_{lab}| < 0.8$, for p–Pb collisions) or for $p_T > 0.5$ GeV/c.

Fig. 3 shows a comparison of the data to model predictions for $\langle p_T \rangle$ versus N_{ch} in pp collisions at $\sqrt{s} = 7$ TeV, p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. For pp collisions, calculations using PYTHIA 8 with tune 4C are shown with and without the color reconnection (CR) mechanism. As shown earlier [26, 29], the model only gives a fair description of the data when the CR mechanism is included. Qualitatively, the difference between p–Pb and Pb–Pb collisions seen in Fig. 2 is similar to the difference seen in pp collisions between the cases with CR and without CR. In p–Pb

collisions, none of the three models, DPMJET [38] (v3.0), HIJING [42] (v1.383), or AMPT [51] (v2.25, with the string melting option), describes the data. These models predict values of $\langle p_T \rangle$ significantly below the p–Pb data. The predictions using the EPOS [48] (1.99, v3400) model describe the magnitude of the data but show a different trend than data at moderate multiplicities ($N_{ch} < 20$). In this model collective effects are introduced via parametrizations, for the sake of computation time; a full hydrodynamics treatment is available in other versions of this model, see [48] . In addition to predictions from event generators, results of a calculation in a Glauber approach are shown. In this approach, p–Pb collisions are assumed to be a superposition of independent nucleon-nucleon collisions, each characterized in terms of measured multiplicity distributions in pp collisions [43, 44] and the $\langle p_T \rangle$ values as a function of N_{ch} for $\sqrt{s} = 7$ TeV shown in Fig. 1 (for a similar approach, see [52]). This calculation (continuous line in Fig. 3) underpredicts the data, producing, interestingly, results similar to those of event generators. The conclusion that $\langle p_T \rangle$ in p–Pb collisions is not a consequence of an incoherent superposition of nucleon-nucleon collisions invites an analogy to the observation that $\langle p_T \rangle$ in pp collisions cannot be described by an incoherent superposition of multiple parton interactions. Whether initial state effects, as considered for the measurement of the nuclear modification factor of charged-particle production [4], or final state effects analogous to the CR mechanism are responsible for this observation, remains to be further studied. In Pb–Pb collisions, the DPMJET, HIJING, and AMPT models fail to describe the data, predicting, as in p–Pb collisions, lower values of $\langle p_T \rangle$ than the measurement. The EPOS model overpredicts the data and shows an opposite trend versus N_{ch}; note, however, that the present model [48] includes collective flow via parametrizations and not a full hydrodynamic treatment. Also the Glauber MC model with inputs from $\langle p_T \rangle$ data at 2.76 TeV and the measured multiplicity distribution at 2.36 TeV [43] fails to describe the data.
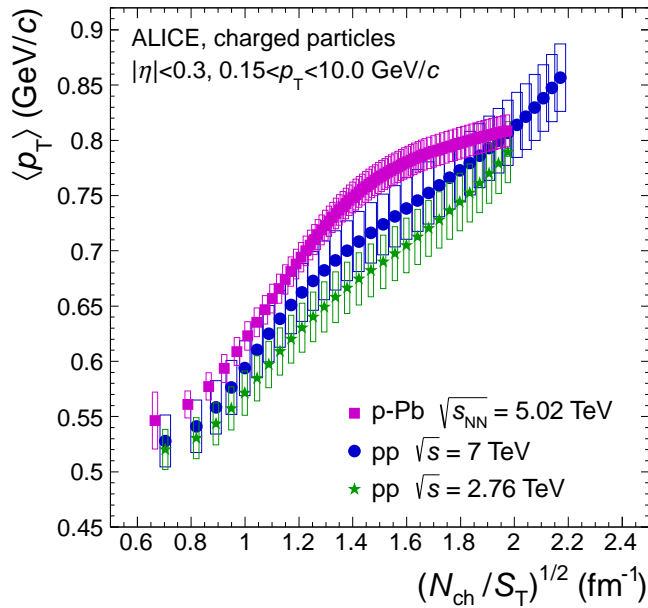

Fig. 4: Average transverse momentum $\langle p_T \rangle$ as a function of the scaled charged-particle multiplicity in pp and p–Pb collisions for $|\eta| < 0.3$. The boxes represent the systematic uncertainties on $\langle p_T \rangle$. The statistical errors are negligible.

The data are confronted with the geometrical scaling recently proposed in [53] (and refs. therein) within the color-glass condensate model [54]. In this picture, the $\langle p_T \rangle$ is a universal function of the ratio of the multiplicity density and the transverse area of the collision, S_T, see [53]. A reasonable agreement was found between this model and preliminary CMS data [55]. Following the recipe described in [53] one obtains the scaling plot in Fig. 4. The ALICE pp data as well as the p–Pb data at low and intermediate

multiplicities are compatible with the proposed scaling. As already noted above while discussing Fig. 2 and Fig. 3, the behavior of p–Pb data at high multiplicities, $N_{ch} \gtrsim 14$, shows a departure from the pp values and cannot be described by a binary collision superposition of pp data. The deviation from scaling visible in Fig. 4 for $(N_{ch}/S_T)^{1/2} \gtrsim 1.2$ is related to these observations.

In summary, we have presented the average transverse momentum $\langle p_T \rangle$ in dependence of the charged-particle multiplicity N_{ch} measured in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, in pp collisions at collision energies of $\sqrt{s} = 0.9$, 2.76, and 7 TeV and in peripheral Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the kinematic range $0.15 < p_T < 10.0$ GeV/c and $|\eta| < 0.3$. In pp and p–Pb collisions, a strong increase of $\langle p_T \rangle$ with N_{ch} is observed, which is understood, in models of pp collisions, as an effect of color reconnections between strings produced in multiple parton interactions. Whether the same mechanism is at work in p–Pb collisions, in particular for incoherent proton-nucleon interactions, is an open question. The EPOS model describes the p–Pb data assuming collective flow; it remains to be further studied if initial state effects are compatible with the data. The $\langle p_T \rangle$ values in Pb–Pb collisions, instead, indicate a softer spectrum and with a much weaker dependence on multiplicity. These data pose a challenge to most of the existing models and are an essential input to improve our understanding of particle production as well as the role of initial and final state effects in these systems.

References

[1] C. Salgado *et al.*, *Proton-nucleus collisions at the LHC: scientific opportunities and requirements*, J. Phys. G **39**, 015010 (2012), `arXiv:1105.3919`, `doi:10.1088/0954-3899/39/1/015010`.

[2] B. Muller, J. Schukraft and B. Wyslouch, *First results from Pb+Pb collisions at the LHC*, Ann. Rev. Nucl. Part. Sci. **62**, 361 (2012), `arXiv:1202.3233`, `doi:10.1146/annurev-nucl-102711-094910`.

[3] ALICE Collaboration, B. Abelev *et al.*, *Pseudorapidity density of charged particles p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, Phys. Rev. Lett. **110**, 032301 (2013), `arXiv:1210.3615`, `doi:10.1103/PhysRevLett.110.032301`.

[4] ALICE Collaboration, B. Abelev *et al.*, *Transverse momentum distribution and nuclear modification factor of charged particles in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, Phys. Rev. Lett. **110**, 082302 (2013), `arXiv:1210.4520`, `doi:10.1103/PhysRevLett.110.082302`.

[5] CMS Collaboration, S. Chatrchyan *et al.*, *Observation of long-range near-side angular correlations in proton-lead collisions at the LHC*, Phys. Lett. B **718**, 795 (2013), `arXiv:1210.5482`, `doi:10.1016/j.physletb.2012.11.025`.

[6] ALICE Collaboration, B. Abelev *et al.*, *Long-range angular correlations on the near and away side in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, Phys. Lett. B **719**, 29 (2013), `arXiv:1212.2001`, `doi:10.1016/j.physletb.2013.01.012`.

[7] ATLAS Collaboration, G. Aad *et al.*, *Observation of associated near-side and away-side long-range correlations in $\sqrt{s_{NN}}$ = 5.02 TeV proton-lead collisions with the ATLAS detector*, 1212.5198, `arXiv:1212.5198`.

[8] ATLAS Collaboration, G. Aad *et al.*, *Measurement with the ATLAS detector of multi-particle azimuthal correlations in p+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, 1303.2084, `arXiv:1303.2084`.

[9] CMS Collaboration, S. Chatrchyan *et al.*, *Multiplicity and transverse-momentum dependence of two- and four-particle correlations in pPb and PbPb collisions*, 1305.0609, `arXiv:1305.0609`.

[10] P. Bozek and W. Broniowski, *Correlations from hydrodynamic flow in p-Pb collisions*, Phys. Lett. B **718**, 1557 (2013), `arXiv:1211.0845`, `doi:10.1016/j.physletb.2012.12.051`.

[11] E. Shuryak and I. Zahed, *High multiplicity pp and pA collisions: hydrodynamics at its edge and stringy black hole*, 1301.4470, `arXiv:1301.4470`.

[12] K. Dusling and R. Venugopalan, *Explanation of systematics of CMS p+Pb high multiplicity di-hadron data at $\sqrt{s_{NN}}$ = 5.02 TeV*, Phys. Rev. D **87**, 054014 (2013), `arXiv:1211.3701`, `doi:10.1103/PhysRevD.87.054014`.

[13] K. Dusling and R. Venugopalan, *Comparison of the Color Glass Condensate to di-hadron correlations in proton-proton and proton-nucleus collisions*, Phys. Rev. D **87**, 094034 (2013), arXiv:1302.7018, doi:10.1103/PhysRevD.87.094034.

[14] A. Bzdak, B. Schenke, P. Tribedy and R. Venugopalan, *Initial state geometry and the role of hydrodynamics in proton-proton, proton-nucleus and deuteron-nucleus collisions*.

[15] ALICE Collaboration, K. Aamodt *et al.*, *Femtoscopy of pp collisions at* $\sqrt{s} = 0.9$ *and 7 TeV at the LHC with two-pion Bose-Einstein correlations*, Phys. Rev. D **84**, 112004 (2011), arXiv:1101.3665, doi:10.1103/PhysRevD.84.112004.

[16] ALICE Collaboration, B. Abelev *et al.*, *Transverse sphericity of primary charged particles in minimum bias proton-proton collisions at* $\sqrt{s} = 0.9$, *2.76 and 7 TeV*, Eur. Phys. J. C **72**, 2124 (2012), arXiv:1205.3963, doi:10.1140/epjc/s10052-012-2124-9.

[17] ALICE Collaboration, B. Abelev *et al.*, *J/ψ Production as a function of charged particle multiplicity in pp collisions at* $\sqrt{s} = 7$ *TeV*, Phys. Lett. B **712**, 165 (2012), arXiv:1202.2816, doi:10.1016/j.physletb.2012.04.052.

[18] ALICE Collaboration, E. Abbas *et al.*, *Mid-rapidity anti-baryon to baryon ratios in pp collisions at* $\sqrt{s} = 0.9$, *2.76 and 7 TeV measured by ALICE*, submitted (2013), arXiv:1305.1562.

[19] CMS Collaboration, V. Khachatryan *et al.*, *Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC*, JHEP **1009**, 091 (2010), arXiv:1009.4122, doi:10.1007/JHEP09(2010)091.

[20] CMS Collaboration, S. Chatrchyan *et al.*, *Study of the inclusive production of charged pions, kaons, and protons in pp collisions at* $\sqrt{s} = 0.9$, *2.76, and 7 TeV*, Eur. Phys. J. C **72**, 2164 (2012), arXiv:1207.4724, doi:10.1140/epjc/s10052-012-2164-1.

[21] UA1 Collaboration, G. Arnison *et al.*, *Transverse Momentum Spectra for Charged Particles at the CERN Proton anti-Proton Collider*, Phys. Lett. B **118**, 167 (1982), doi:10.1016/0370-2693(82)90623-2.

[22] ABCDHW Collaboration, A. Breakstone *et al.*, *Multiplicity dependence on the average transverse momentum and of the particle source size in pp interactions at* $\sqrt{s} = 62$, *44 and 31 GeV*, Z. f. Physik C **33(3)**, 333 (1987).

[23] UA1 Collaboration, C. Albajar *et al.*, *A Study of the General Characteristics of* $p\bar{p}$ *Collisions at* $\sqrt{s} = 0.2$-*TeV to 0.9-TeV*, Nucl. Phys. B **335**, 261 (1990), doi:10.1016/0550-3213(90)90493-W.

[24] E735 Collaboration, T. Alexopoulos *et al.*, *Multiplicity dependence of the transverse-momentum spectrum for centrally produced hadrons in antiproton-proton collisions at* $\sqrt{s} = 1.8$ *TeV*, Phys. Rev. Lett. **60**, 1622 (1988), doi:10.1103/PhysRevLett.60.1622.

[25] STAR Collaboration, J. Adams *et al.*, *The Multiplicity dependence of inclusive* p_T *spectra from pp collisions at* $\sqrt{s} = 200$ *GeV*, Phys. Rev. D **74**, 032006 (2006), arXiv:nucl-ex/0606028, doi:10.1103/PhysRevD.74.032006.

[26] CDF Collaboration, T. Aaltonen *et al.*, *Measurement of particle production and inclusive differential cross sections in* $p\bar{p}$ *collisions at* $\sqrt{s} = 1.96$ *TeV*, Phys. Rev. D **79**, 112005 (2009), arXiv:0904.1098, doi:10.1103/PhysRevD.82.119903,10.1103/PhysRevD.79.112005.

[27] ALICE Collaboration, K. Aamodt *et al.*, *Transverse momentum spectra of charged particles in proton-proton collisions at* $\sqrt{s} = 900$ *GeV with ALICE at the LHC*, Phys. Lett. B **693**, 53 (2010), arXiv:1007.0719, doi:10.1016/j.physletb.2010.08.026.

[28] CMS Collaboration, V. Khachatryan *et al.*, *Charged particle multiplicities in pp interactions at* $\sqrt{s} = 0.9$, *2.36, and 7 TeV*, JHEP **1101**, 079 (2011), arXiv:1011.5531, doi:10.1007/JHEP01(2011)079.

[29] ATLAS Collaboration, G. Aad *et al.*, *Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC*, New J. Phys. **13**, 053033 (2011), arXiv:1012.5104, doi:10.1088/1367-2630/13/5/053033.

[30] P. Z. Skands and D. Wicke, *Non-perturbative QCD effects and the top mass at the Tevatron*, Eur. Phys. J. C **52**, 133 (2007), `arXiv:hep-ph/0703081`, `doi:10.1140/epjc/s10052-007-0352-1`.

[31] R. Corke and T. Sjostrand, *Interleaved Parton Showers and Tuning Prospects*, JHEP **1103**, 032 (2011), `arXiv:1011.1759`, `doi:10.1007/JHEP03(2011)032`.

[32] R. Corke and T. Sjostrand, *Multiparton Interactions with an x-dependent Proton Size*, JHEP **1105**, 009 (2011), `arXiv:1101.5953`, `doi:10.1007/JHEP05(2011)009`.

[33] H. Schulz and P. Skands, *Energy Scaling of Minimum-Bias Tunes*, Eur. Phys. J. C **71**, 1644 (2011), `arXiv:1103.3649`, `doi:10.1140/epjc/s10052-011-1644-z`.

[34] P. Z. Skands, *Tuning Monte Carlo Generators: The Perugia Tunes*, Phys. Rev. D **82**, 074018 (2010), `arXiv:1005.3457`, `doi:10.1103/PhysRevD.82.074018`.

[35] ALICE Collaboration, K. Aamodt *et al.*, *The ALICE experiment at the CERN LHC*, JINST **3**, S08002 (2008), `doi:10.1088/1748-0221/3/08/S08002`.

[36] ALICE Collaboration, B. Abelev *et al.*, *Energy dependence of transverse momentum distributions of charged particles in pp collisions with ALICE*, to be published (2013).

[37] ALICE Collaboration, B. Abelev *et al.*, *Centrality dependence of charged particle production at large transverse momentum in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, Phys. Lett. B **720**, 52 (2013), `arXiv:1208.2711`.

[38] S. Roesler, R. Engel and J. Ranft, *The Monte Carlo event generator DPMJET-III*, (2000), `arXiv:hep-ph/0012252`.

[39] R. Brun *et al.*, *CERN Program Library Long Write-up, W5013, GEANT Detector Description and Simulation Tool*, (1994).

[40] ALICE Collaboration, B. Abelev *et al.*, *Production of pions, kaons, protons and Lambdas in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, to be published (2013).

[41] ALICE Collaboration, B. Abelev *et al.*, *Centrality determination of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE*, submitted (2013), `arXiv:1301.4361`.

[42] X.-N. Wang and M. Gyulassy, *HIJING: A Monte Carlo model for multiple jet production in pp, pA and AA collisions*, Phys. Rev. D **44**, 3501 (1991), `doi:10.1103/PhysRevD.44.3501`.

[43] ALICE Collaboration, K. Aamodt *et al.*, *Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s} = 0.9$ and 2.36 TeV with ALICE at LHC*, Eur. Phys. J. C **68**, 89 (2010), `arXiv:1004.3034`, `doi:10.1140/epjc/s10052-010-1339-x`.

[44] ALICE Collaboration, K. Aamodt *et al.*, *Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s} = 7$ TeV with ALICE at LHC*, Eur. Phys. J. C **68**, 345 (2010), `arXiv:1004.3514`, `doi:10.1140/epjc/s10052-010-1350-2`.

[45] CERN Report No. ATLAS-CONF-2010-101, 2010 (unpublished).

[46] N. Amelin, M. Braun and C. Pajares, *Multiple production in the Monte Carlo string fusion model*, Phys. Lett. B **306**, 312 (1993), `doi:10.1016/0370-2693(93)90085-V`.

[47] N. Armesto, D. Derkach and G. Feofilov, *p(t)-multiplicity correlations in a multi-Pomeron-exchange model with string collective effects*, Phys. Atom. Nucl. **71**, 2087 (2008), `doi:10.1134/S1063778808120090`.

[48] T. Pierog, I. Karpenko, J. Katzy, E. Yatsenko and K. Werner, *EPOS LHC : test of collective hadronization with LHC data*, 1306.0121, `arXiv:1306.0121`.

[49] ALICE Collaboration, B. Abelev *et al.*, *Centrality dependence of π, K, p production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, submitted (2013), `arXiv:1303.0737`.

[50] T. Sjostrand, S. Mrenna and P. Z. Skands, *A Brief Introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178**, 852 (2008), `arXiv:0710.3820`, `doi:10.1016/j.cpc.2008.01.036`.

[51] Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang and S. Pal, *A multi-phase transport model for rel-*

ativistic heavy ion collisions, Phys. Rev. C **72**, 064901 (2005), `arXiv:nucl-th/0411110`,
`doi:10.1103/PhysRevC.72.064901`.

[52] A. Bzdak and V. Skokov, *Average transverse momentum of hadrons in proton-nucleus collisions in the wounded nucleon model*, 1306.5442, `arXiv:1306.5442`.

[53] L. McLerran, M. Praszalowicz and B. Schenke, *Transverse Momentum of Protons, Pions and Kaons in High Multiplicity pp and pA Collisions: Evidence for the Color Glass Condensate?*, 1306.2350, `arXiv:1306.2350`.

[54] L. McLerran, *Strongly Interacting Matter Matter at Very High Energy Density: 3 Lectures in Zakopane*, Acta Phys. Polon. B **41**, 2799 (2010), `arXiv:1011.3203`.

[55] CERN Report No. CMS-PAS-HIN-12-016, 2013 (unpublished).

A The ALICE Collaboration

B. Abelev[72] , J. Adam[38] , D. Adamová[79] , A.M. Adare[130] , M.M. Aggarwal[83] , G. Aglieri Rinella[34] , M. Agnello[100 ,89] , A.G. Agocs[129] , A. Agostinelli[28] , Z. Ahammed[124] , A. Ahmad Masoodi[18] , N. Ahmad[18] , I. Ahmed[16] , S.A. Ahn[65] , S.U. Ahn[65] , I. Aimo[25 ,100 ,89] , M. Ajaz[16] , A. Akindinov[51] , D. Aleksandrov[95] , B. Alessandro[100] , D. Alexandre[97] , A. Alici[102 ,13] , A. Alkin[4] , J. Alme[36] , T. Alt[40] , V. Altini[32] , S. Altinpinar[19] , I. Altsybeev[126] , C. Andrei[75] , A. Andronic[92] , V. Anguelov[88] , J. Anielski[59] , C. Anson[20] , T. Antičić[93] , F. Antinori[101] , P. Antonioli[102] , L. Aphecetche[108] , H. Appelshäuser[57] , N. Arbor[68] , S. Arcelli[28] , A. Arend[57] , N. Armesto[17] , R. Arnaldi[100] , T. Aronsson[130] , I.C. Arsene[92] , M. Arslandok[57] , A. Asryan[126] , A. Augustinus[34] , R. Averbeck[92] , T.C. Awes[80] , J. Äystö[43] , M.D. Azmi[18 ,85] , M. Bach[40] , A. Badalà[99] , Y.W. Baek[67 ,41] , R. Bailhache[57] , R. Bala[86 ,100] , A. Baldisseri[15] , F. Baltasar Dos Santos Pedrosa[34] , J. Bán[52] , R.C. Baral[53] , R. Barbera[27] , F. Barile[32] , G.G. Barnaföldi[129] , L.S. Barnby[97] , V. Barret[67] , J. Bartke[112] , M. Basile[28] , N. Bastid[67] , S. Basu[124] , B. Bathen[59] , G. Batigne[108] , B. Batyunya[63] , P.C. Batzing[22] , C. Baumann[57] , I.G. Bearden[77] , H. Beck[57] , N.K. Behera[45] , I. Belikov[62] , F. Bellini[28] , R. Bellwied[118] , E. Belmont-Moreno[61] , G. Bencedi[129] , S. Beole[25] , I. Berceanu[75] , A. Bercuci[75] , Y. Berdnikov[81] , D. Berenyi[129] , A.A.E. Bergognon[108] , R.A. Bertens[50] , D. Berzano[25 ,100] , L. Betev[34] , A. Bhasin[86] , A.K. Bhati[83] , J. Bhom[122] , N. Bianchi[69] , L. Bianchi[25] , C. Bianchin[50] , J. Bielčík[38] , J. Bielčíková[79] , A. Bilandzic[77] , S. Bjelogrlic[50] , F. Blanco[118] , F. Blanco[11] , D. Blau[95] , C. Blume[57] , M. Boccioli[34] , F. Bock[64 ,71] , S. Böttger[56] , A. Bogdanov[73] , H. Bøggild[77] , M. Bogolyubsky[48] , L. Boldizsár[129] , M. Bombara[39] , J. Book[57] , H. Borel[15] , A. Borissov[128] , F. Bossú[85] , M. Botje[78] , E. Botta[25] , E. Braidot[71] , P. Braun-Munzinger[92] , M. Bregant[108] , T. Breitner[56] , T.A. Broker[57] , T.A. Browning[90] , M. Broz[37] , R. Brun[34] , E. Bruna[25 ,100] , G.E. Bruno[32] , D. Budnikov[94] , H. Buesching[57] , S. Bufalino[25 ,100] , P. Buncic[34] , O. Busch[88] , Z. Buthelezi[85] , D. Caffarri[29 ,101] , X. Cai[8] , H. Caines[130] , A. Caliva[50] , E. Calvo Villar[98] , P. Camerini[23] , V. Canoa Roman[12] , G. Cara Romeo[102] , F. Carena[34] , W. Carena[34] , N. Carlin Filho[115] , F. Carminati[34] , A. Casanova Díaz[69] , J. Castillo Castellanos[15] , J.F. Castillo Hernandez[92] , E.A.R. Casula[24] , V. Catanescu[75] , C. Cavicchioli[34] , C. Ceballos Sanchez[10] , J. Cepila[38] , P. Cerello[100] , B. Chang[43 ,132] , S. Chapeland[34] , J.L. Charvet[15] , S. Chattopadhyay[124] , S. Chattopadhyay[96] , M. Cherney[82] , C. Cheshkov[34 ,117] , B. Cheynis[117] , V. Chibante Barroso[34] , D.D. Chinellato[118] , P. Chochula[34] , M. Chojnacki[77] , S. Choudhury[124] , P. Christakoglou[78] , C.H. Christensen[77] , P. Christiansen[33] , T. Chujo[122] , S.U. Chung[91] , C. Cicalo[103] , L. Cifarelli[28 ,13] , F. Cindolo[102] , J. Cleymans[85] , F. Colamaria[32] , D. Colella[32] , A. Collu[24] , G. Conesa Balbastre[68] , Z. Conesa del Valle[34 ,47] , M.E. Connors[130] , G. Contin[23] , J.G. Contreras[12] , T.M. Cormier[128] , Y. Corrales Morales[25] , P. Cortese[31] , I. Cortés Maldonado[3] , M.R. Cosentino[71] , F. Costa[34] , M.E. Cotallo[11] , E. Crescio[12] , P. Crochet[67] , E. Cruz Alaniz[61] , R. Cruz Albino[12] , E. Cuautle[60] , L. Cunqueiro[69] , A. Dainese[29 ,101] , R. Dang[8] , A. Danu[55] , K. Das[96] , D. Das[96] , I. Das[47] , S. Das[5] , S. Dash[45] , A. Dash[116] , S. De[124] , G.O.V. de Barros[115] , A. De Caro[30 ,13] , G. de Cataldo[105] , J. de Cuveland[40] , A. De Falco[24] , D. De Gruttola[30 ,13] , H. Delagrange[108] , A. Deloff[74] , N. De Marco[100] , E. Dénes[129] , S. De Pasquale[30] , A. Deppman[115] , G. D Erasmo[32] , R. de Rooij[50] , M.A. Diaz Corchero[11] , D. Di Bari[32] , T. Dietel[59] , C. Di Giglio[32] , S. Di Liberto[106] , A. Di Mauro[34] , P. Di Nezza[69] , R. Divià[34] , Ø. Djuvsland[19] , A. Dobrin[128 ,33 ,50] , T. Dobrowolski[74] , B. Dönigus[92 ,57] , O. Dordic[22] , A.K. Dubey[124] , A. Dubla[50] , L. Ducroux[117] , P. Dupieux[67] , A.K. Dutta Majumdar[96] , D. Elia[105] , B.G. Elwood[14] , D. Emschermann[59] , H. Engel[56] , B. Erazmus[34 ,108] , H.A. Erdal[36] , D. Eschweiler[40] , B. Espagnon[47] , M. Estienne[108] , S. Esumi[122] , D. Evans[97] , S. Evdokimov[48] , G. Eyyubova[22] , D. Fabris[29 ,101] , J. Faivre[68] , D. Falchieri[28] , A. Fantoni[69] , M. Fasel[88] , D. Fehlker[19] , L. Feldkamp[59] , D. Felea[55] , A. Feliciello[100] , B. Fenton-Olsen[71] , G. Feofilov[126] , A. Fernández Téllez[3] , A. Ferretti[25] , A. Festanti[29] , J. Figiel[112] , M.A.S. Figueredo[115] , S. Filchagin[94] ,

D. Finogeev[49], F.M. Fionda[32], E.M. Fiore[32], E. Floratos[84], M. Floris[34], S. Foertsch[85], P. Foka[92], S. Fokin[95],
E. Fragiacomo[104], A. Francescon[34,29], U. Frankenfeld[92], U. Fuchs[34], C. Furget[68], M. Fusco Girard[30],
J.J. Gaardhøje[77], M. Gagliardi[25], A. Gago[98], M. Gallio[25], D.R. Gangadharan[20], P. Ganoti[80], C. Garabatos[92],
E. Garcia-Solis[14], C. Gargiulo[34], I. Garishvili[72], J. Gerhard[40], M. Germain[108], A. Gheata[34], M. Gheata[55,34],
B. Ghidini[32], P. Ghosh[124], P. Gianotti[69], P. Giubellino[34], E. Gladysz-Dziadus[112], P. Glässel[88], L. Goerlich[112],
R. Gomez[114,12], E.G. Ferreiro[17], P. González-Zamora[11], S. Gorbunov[40], A. Goswami[87], S. Gotovac[110],
L.K. Graczykowski[127], R. Grajcarek[88], A. Grelli[50], A. Grigoras[34], C. Grigoras[34], V. Grigoriev[73],
S. Grigoryan[63], A. Grigoryan[2], B. Grinyov[4], N. Grion[104], J.M. Gronefeld[92], P. Gros[33],
J.F. Grosse-Oetringhaus[34], J.-Y. Grossiord[117], R. Grosso[34], F. Guber[49], R. Guernane[68], B. Guerzoni[28], M.
Guilbaud[117], K. Gulbrandsen[77], H. Gulkanyan[2], T. Gunji[121], A. Gupta[86], R. Gupta[86], R. Haake[59],
Ø. Haaland[19], C. Hadjidakis[47], M. Haiduc[55], H. Hamagaki[121], G. Hamar[129], B.H. Han[21], L.D. Hanratty[97],
A. Hansen[77], J.W. Harris[130], A. Harton[14], D. Hatzifotiadou[102], S. Hayashi[121], A. Hayrapetyan[34,2],
S.T. Heckel[57], M. Heide[59], H. Helstrup[36], A. Herghelegiu[75], G. Herrera Corral[12], N. Herrmann[88],
B.A. Hess[123], K.F. Hetland[36], B. Hicks[130], B. Hippolyte[62], Y. Hori[121], P. Hristov[34], I. Hřivnáčová[47],
M. Huang[19], T.J. Humanic[20], D.S. Hwang[21], R. Ichou[67], R. Ilkaev[94], I. Ilkiv[74], M. Inaba[122], E. Incani[24],
G.M. Innocenti[25], P.G. Innocenti[34], C. Ionita[34], M. Ippolitov[95], M. Irfan[18], C. Ivan[92], V. Ivanov[81],
A. Ivanov[126], M. Ivanov[92], O. Ivanytskyi[4], A. Jachołkowski[27], P. M. Jacobs[71], C. Jahnke[115], H.J. Jang[65],
M.A. Janik[127], P.H.S.Y. Jayarathna[118], S. Jena[45], D.M. Jha[128], R.T. Jimenez Bustamante[60], P.G. Jones[97],
H. Jung[41], A. Jusko[97], A.B. Kaidalov[51], S. Kalcher[40], P. Kaliňák[52], T. Kalliokoski[43], A. Kalweit[34],
J.H. Kang[132], V. Kaplin[73], S. Kar[124], A. Karasu Uysal[66], O. Karavichev[49], T. Karavicheva[49], E. Karpechev[49],
A. Kazantsev[95], U. Kebschull[56], R. Keidel[133], B. Ketzer[57,111], P. Khan[96], S.A. Khan[124], K. H. Khan[16],
M.M. Khan[18], A. Khanzadeev[81], Y. Kharlov[48], B. Kileng[36], J.S. Kim[41], B. Kim[132], D.W. Kim[41,65],
T. Kim[132], J.H. Kim[21], M.Kim[41], M. Kim[132], S. Kim[21], D.J. Kim[43], S. Kirsch[40], I. Kisel[40], S. Kiselev[51],
A. Kisiel[127], J.L. Klay[7], J. Klein[88], C. Klein-Bösing[59], M. Kliemant[57], A. Kluge[34], M.L. Knichel[92],
A.G. Knospe[113], M.K. Köhler[92], T. Kollegger[40], A. Kolojvari[126], M. Kompaniets[126], V. Kondratiev[126],
N. Kondratyeva[73], A. Konevskikh[49], V. Kovalenko[126], M. Kowalski[112], S. Kox[68],
G. Koyithatta Meethaleveedu[45], J. Kral[43], I. Králik[52], F. Kramer[57], A. Kravčáková[39], M. Krelina[38],
M. Kretz[40], M. Krivda[97,52], F. Krizek[43], M. Krus[38], E. Kryshen[81], M. Krzewicki[92], V. Kucera[79],
Y. Kucheriaev[95], T. Kugathasan[34], C. Kuhn[62], P.G. Kuijer[78], I. Kulakov[57], J. Kumar[45], P. Kurashvili[74],
A.B. Kurepin[49], A. Kurepin[49], A. Kuryakin[94], V. Kushpil[79], S. Kushpil[79], H. Kvaerno[22], M.J. Kweon[88],
Y. Kwon[132], P. Ladrón de Guevara[60], C. Lagana Fernandes[115], I. Lakomov[47], R. Langoy[125], S.L. La Pointe[50],
C. Lara[56], A. Lardeux[108], P. La Rocca[27], R. Lea[23], M. Lechman[34], S.C. Lee[41], G.R. Lee[97], I. Legrand[34],
J. Lehnert[57], R.C. Lemmon[107], M. Lenhardt[92], V. Lenti[105], H. León[61], M. Leoncino[25], I. León Monzón[114],
P. Lévai[129], S. Li[67,8], J. Lien[19,125], R. Lietava[97], S. Lindal[22], V. Lindenstruth[40], C. Lippmann[92,34],
M.A. Lisa[20], H.M. Ljunggren[33], D.F. Lodato[50], P.I. Loenne[19], V.R. Loggins[128], V. Loginov[73], D. Lohner[88],
C. Loizides[71], K.K. Loo[43], X. Lopez[67], E. López Torres[10], G. Løvhøiden[22], X.-G. Lu[88], P. Luettig[57],
M. Lunardon[29], J. Luo[8], G. Luparello[50], C. Luzzi[34], K. Ma[8], R. Ma[130], D.M. Madagodahettige-Don[118],
A. Maevskaya[49], M. Mager[58,34], D.P. Mahapatra[53], A. Maire[88], M. Malaev[81], I. Maldonado Cervantes[60],
L. Malinina[63,ii], D. Mal'Kevich[51], P. Malzacher[92], A. Mamonov[94], L. Manceau[100], L. Mangotra[86],
V. Manko[95], F. Manso[67], V. Manzari[105], M. Marchisone[67,25], J. Mareš[54], G.V. Margagliotti[23,104],
A. Margotti[102], A. Marín[92], C. Markert[113], M. Marquard[57], I. Martashvili[120], N.A. Martin[92],
J. Martin Blanco[108], P. Martinengo[34], M.I. Martínez[3], G. Martínez García[108], Y. Martynov[4], A. Mas[108],
S. Masciocchi[92], M. Masera[25], A. Masoni[103], L. Massacrier[108], A. Mastroserio[32], A. Matyja[112], C. Mayer[112],
J. Mazer[120], R. Mazumder[46], M.A. Mazzoni[106], F. Meddi[26], A. Menchaca-Rocha[61], J. Mercado Pérez[88],
M. Meres[37], Y. Miake[122], K. Mikhaylov[63,51], L. Milano[34,25], J. Milosevic[22,iii], A. Mischke[50],
A.N. Mishra[87,46], D. Miśkowiec[92], C. Mitu[55], J. Mlynarz[128], B. Mohanty[124,76], L. Molnar[129,62],
L. Montaño Zetina[12], M. Monteno[100], E. Montes[11], T. Moon[132], M. Morando[29], D.A. Moreira De Godoy[115],
S. Moretto[29], A. Morreale[43], A. Morsch[34], V. Muccifora[69], E. Mudnic[110], S. Muhuri[124], M. Mukherjee[124],
H. Müller[34], M.G. Munhoz[115], S. Murray[85], L. Musa[34], J. Musinsky[52], B.K. Nandi[45], R. Nania[102],
E. Nappi[105], C. Nattrass[120], T.K. Nayak[124], S. Nazarenko[94], A. Nedosekin[51], M. Nicassio[32,92],
M.Niculescu[55,34], B.S. Nielsen[77], S. Nikolaev[95], V. Nikolic[93], S. Nikulin[95], V. Nikulin[81], B.S. Nilsen[82],
M.S. Nilsson[22], F. Noferini[102,13], P. Nomokonov[63], G. Nooren[50], A. Nyanin[95], A. Nyatha[45], C. Nygaard[77],
J. Nystrand[19], A. Ochirov[126], H. Oeschler[58,34,88], S.K. Oh[41], S. Oh[130], J. Oleniacz[127],
A.C. Oliveira Da Silva[115], J. Onderwaater[92], C. Oppedisano[100], A. Ortiz Velasquez[33,60], A. Oskarsson[33],
P. Ostrowski[127], J. Otwinowski[92], K. Oyama[88], K. Ozawa[121], Y. Pachmayer[88], M. Pachr[38], F. Padilla[25],
P. Pagano[30], G. Paić[60], F. Painke[40], C. Pajares[17], S.K. Pal[124], A. Palaha[97], A. Palmeri[99], V. Papikyan[2],

G.S. Pappalardo[99], W.J. Park[92], A. Passfeld[59], D.I. Patalakha[48], V. Paticchio[105], B. Paul[96], A. Pavlinov[128], T. Pawlak[127], T. Peitzmann[50], H. Pereira Da Costa[15], E. Pereira De Oliveira Filho[115], D. Peresunko[95], C.E. Pérez Lara[78], D. Perrino[32], W. Peryt[127],[i], A. Pesci[102], Y. Pestov[6], V. Petráček[38], M. Petran[38], M. Petris[75], P. Petrov[97], M. Petrovici[75], C. Petta[27], S. Piano[104], M. Pikna[37], P. Pillot[108], O. Pinazza[34], L. Pinsky[118], N. Pitz[57], D.B. Piyarathna[118], M. Planinic[93], M. Płoskoń[71], J. Pluta[127], T. Pocheptsov[63], S. Pochybova[129], P.L.M. Podesta-Lerma[114], M.G. Poghosyan[34], K. Polák[54], B. Polichtchouk[48], N. Poljak[50],[93], A. Pop[75], S. Porteboeuf-Houssais[67], V. Pospíšil[38], B. Potukuchi[86], S.K. Prasad[128], R. Preghenella[102],[13], F. Prino[100], C.A. Pruneau[128], I. Pshenichnov[49], G. Puddu[24], V. Punin[94], J. Putschke[128], H. Qvigstad[22], A. Rachevski[104], A. Rademakers[34], J. Rak[43], A. Rakotozafindrabe[15], L. Ramello[31], S. Raniwala[87], R. Raniwala[87], S.S. Räsänen[43], B.T. Rascanu[57], D. Rathee[83], W. Rauch[34], A.W. Rauf[16], V. Razazi[24], K.F. Read[120], J.S. Real[68], K. Redlich[74],[iv], R.J. Reed[130], A. Rehman[19], P. Reichelt[57], M. Reicher[50], F. Reidt[88], R. Renfordt[57], A.R. Reolon[69], A. Reshetin[49], F. Rettig[40], J.-P. Revol[34], K. Reygers[88], L. Riccati[100], R.A. Ricci[70], T. Richert[33], M. Richter[22], P. Riedler[34], W. Riegler[34], F. Riggi[27],[99], A. Rivetti[100], M. Rodríguez Cahuantzi[3], A. Rodriguez Manso[78], K. Røed[19],[22], E. Rogochaya[63], D. Rohr[40], D. Röhrich[19], R. Romita[92],[107], F. Ronchetti[69], P. Rosnet[67], S. Rossegger[34], A. Rossi[34], C. Roy[62], P. Roy[96], A.J. Rubio Montero[11], R. Rui[23], R. Russo[25], E. Ryabinkin[95], A. Rybicki[112], S. Sadovsky[48], K. Šafařík[34], R. Sahoo[46], P.K. Sahu[53], J. Saini[124], H. Sakaguchi[44], S. Sakai[71],[69], D. Sakata[122], C.A. Salgado[17], J. Salzwedel[20], S. Sambyal[86], V. Samsonov[81], X. Sanchez Castro[62], L. Šándor[52], A. Sandoval[61], M. Sano[122], G. Santagati[27], R. Santoro[34],[13], D. Sarkar[124], E. Scapparone[102], F. Scarlassara[29], R.P. Scharenberg[90], C. Schiaua[75], R. Schicker[88], H.R. Schmidt[123], C. Schmidt[92], S. Schuchmann[57], J. Schukraft[34], T. Schuster[130], Y. Schutz[34],[108], K. Schwarz[92], K. Schweda[92], G. Scioli[28], E. Scomparin[100], R. Scott[120], P.A. Scott[97], G. Segato[29], I. Selyuzhenkov[92], S. Senyukov[62], J. Seo[91], S. Serci[24], E. Serradilla[11],[61], A. Sevcenco[55], A. Shabetai[108], G. Shabratova[63], R. Shahoyan[34], N. Sharma[120], S. Sharma[86], S. Rohni[86], K. Shigaki[44], K. Shtejer[10], Y. Sibiriak[95], S. Siddhanta[103], T. Siemiarczuk[74], D. Silvermyr[80], C. Silvestre[68], G. Simatovic[60],[93], G. Simonetti[34], R. Singaraju[124], R. Singh[86], S. Singha[124],[76], V. Singhal[124], T. Sinha[96], B.C. Sinha[124], B. Sitar[37], M. Sitta[31], T.B. Skaali[22], K. Skjerdal[19], R. Smakal[38], N. Smirnov[130], R.J.M. Snellings[50], C. Søgaard[33], R. Soltz[72], M. Song[132], J. Song[91], C. Soos[34], F. Soramel[29], I. Sputowska[112], M. Spyropoulou-Stassinaki[84], B.K. Srivastava[90], J. Stachel[88], I. Stan[55], G. Stefanek[74], M. Steinpreis[20], E. Stenlund[33], G. Steyn[85], J.H. Stiller[88], D. Stocco[108], M. Stolpovskiy[48], P. Strmen[37], A.A.P. Suaide[115], M.A. Subieta Vásquez[25], T. Sugitate[44], C. Suire[47], M. Suleymanov[16], R. Sultanov[51], M. Šumbera[79], T. Susa[93], T.J.M. Symons[71], A. Szanto de Toledo[115], I. Szarka[37], A. Szczepankiewicz[34], M. Szymański[127], J. Takahashi[116], M.A. Tangaro[32], J.D. Tapia Takaki[47], A. Tarantola Peloni[57], A. Tarazona Martinez[34], A. Tauro[34], G. Tejeda Muñoz[3], A. Telesca[34], A. Ter Minasyan[95], C. Terrevoli[32], J. Thäder[92], D. Thomas[50], R. Tieulent[117], A.R. Timmins[118], D. Tlusty[38], A. Toia[40],[29],[101], H. Torii[121], L. Toscano[100], V. Trubnikov[4], D. Truesdale[20], W.H. Trzaska[43], T. Tsuji[121], A. Tumkin[94], R. Turrisi[101], T.S. Tveter[22], J. Ulery[57], K. Ullaland[19], J. Ulrich[64],[56], A. Uras[117], G.M. Urciuoli[106], G.L. Usai[24], M. Vajzer[38],[79], M. Vala[63],[52], L. Valencia Palomo[47], S. Vallero[25], P. Vande Vyvre[34], J.W. Van Hoorne[34], M. van Leeuwen[50], L. Vannucci[70], A. Vargas[3], R. Varma[45], M. Vasileiou[84], A. Vasiliev[95], V. Vechernin[126], M. Veldhoen[50], M. Venaruzzo[23], E. Vercellin[25], S. Vergara[3], R. Vernet[9], M. Verweij[128],[50], L. Vickovic[110], G. Viesti[29], J. Viinikainen[43], Z. Vilakazi[85], O. Villalobos Baillie[97], Y. Vinogradov[94], A. Vinogradov[95], L. Vinogradov[126], T. Virgili[30], Y.P. Viyogi[124], A. Vodopyanov[63], M.A. Völkl[88], K. Voloshin[51], S. Voloshin[128], G. Volpe[34], B. von Haller[34], I. Vorobyev[126], D. Vranic[92],[34], J. Vrláková[39], B. Vulpescu[67], A. Vyushin[94], B. Wagner[19], V. Wagner[38], J. Wagner[92], M. Wang[8], Y. Wang[88], Y. Wang[8], K. Watanabe[122], D. Watanabe[122], M. Weber[118], J.P. Wessels[59], U. Westerhoff[59], J. Wiechula[123], J. Wikne[22], M. Wilde[59], G. Wilk[74], M.C.S. Williams[102], B. Windelband[88], M. Winn[88], C.G. Yaldo[128], Y. Yamaguchi[121], S. Yang[19], H. Yang[15],[50], P. Yang[8], S. Yasnopolskiy[95], J. Yi[91], Z. Yin[8], I.-K. Yoo[91], J. Yoon[132], X. Yuan[8], I. Yushmanov[95], V. Zaccolo[77], C. Zach[38], C. Zampolli[102], S. Zaporozhets[63], A. Zarochentsev[126], P. Závada[54], N. Zaviyalov[94], H. Zbroszczyk[127], P. Zelnicek[56], I.S. Zgura[55], M. Zhalov[81], X. Zhang[71],[67],[8], H. Zhang[8], Y. Zhang[8], F. Zhou[8], Y. Zhou[50], D. Zhou[8], J. Zhu[8], H. Zhu[8], J. Zhu[8], X. Zhu[8], A. Zichichi[28],[13], A. Zimmermann[88], G. Zinovjev[4], Y. Zoccarato[117], M. Zynovyev[4], M. Zyzak[57]

Affiliation notes

[i] Deceased

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

ⁱⁱⁱ Also at: University of Belgrade, Faculty of Physics and "Vinča" Institute of Nuclear Sciences, Belgrade, Serbia
ⁱᵛ Also at: Institute of Theoretical Physics, University of Wroclaw, Wroclaw, Poland

Collaboration Institutes

[1] Academy of Scientific Research and Technology (ASRT), Cairo, Egypt
[2] A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[3] Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
[4] Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
[5] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
[6] Budker Institute for Nuclear Physics, Novosibirsk, Russia
[7] California Polytechnic State University, San Luis Obispo, California, United States
[8] Central China Normal University, Wuhan, China
[9] Centre de Calcul de l'IN2P3, Villeurbanne, France
[10] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
[11] Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[12] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
[13] Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Rome, Italy
[14] Chicago State University, Chicago, United States
[15] Commissariat à l'Energie Atomique, IRFU, Saclay, France
[16] COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan
[17] Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
[18] Department of Physics Aligarh Muslim University, Aligarh, India
[19] Department of Physics and Technology, University of Bergen, Bergen, Norway
[20] Department of Physics, Ohio State University, Columbus, Ohio, United States
[21] Department of Physics, Sejong University, Seoul, South Korea
[22] Department of Physics, University of Oslo, Oslo, Norway
[23] Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[24] Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[25] Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[26] Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, 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, Bologna, Italy
[29] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[30] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[31] Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy
[32] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[33] Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
[34] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[35] Fachhochschule Köln, Köln, 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) and University of Jyväskylä, Jyväskylä, Finland
[44] Hiroshima University, Hiroshima, Japan
[45] Indian Institute of Technology Bombay (IIT), Mumbai, India
[46] Indian Institute of Technology Indore, Indore, India (IITI)

[47] Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France

[48] Institute for High Energy Physics, Protvino, Russia

[49] Institute for Nuclear Research, Academy of Sciences, Moscow, Russia

[50] Nikhef, National Institute for Subatomic Physics and Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands

[51] Institute for Theoretical and Experimental Physics, Moscow, Russia

[52] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia

[53] Institute of Physics, Bhubaneswar, India

[54] Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

[55] Institute of Space Sciences (ISS), Bucharest, Romania

[56] Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany

[57] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany

[58] Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany

[59] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany

[60] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico

[61] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico

[62] Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France

[63] Joint Institute for Nuclear Research (JINR), Dubna, Russia

[64] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

[65] Korea Institute of Science and Technology Information, Daejeon, South Korea

[66] KTO Karatay University, Konya, Turkey

[67] Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS–IN2P3, Clermont-Ferrand, France

[68] Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France

[69] Laboratori Nazionali di Frascati, INFN, Frascati, Italy

[70] Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy

[71] Lawrence Berkeley National Laboratory, Berkeley, California, United States

[72] Lawrence Livermore National Laboratory, Livermore, California, United States

[73] Moscow Engineering Physics Institute, Moscow, Russia

[74] National Centre for Nuclear Studies, Warsaw, Poland

[75] National Institute for Physics and Nuclear Engineering, Bucharest, Romania

[76] National Institute of Science Education and Research, Bhubaneswar, India

[77] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

[78] Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands

[79] Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic

[80] Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States

[81] Petersburg Nuclear Physics Institute, Gatchina, Russia

[82] Physics Department, Creighton University, Omaha, Nebraska, United States

[83] Physics Department, Panjab University, Chandigarh, India

[84] Physics Department, University of Athens, Athens, Greece

[85] Physics Department, University of Cape Town and iThemba LABS, National Research Foundation, Somerset West, South Africa

[86] Physics Department, University of Jammu, Jammu, India

[87] Physics Department, University of Rajasthan, Jaipur, India

[88] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

[89] Politecnico di Torino, Turin, Italy

[90] Purdue University, West Lafayette, Indiana, United States

[91] Pusan National University, Pusan, South Korea

[92] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

[93] Rudjer Bošković Institute, Zagreb, Croatia

[94] Russian Federal Nuclear Center (VNIIEF), Sarov, Russia

[95] Russian Research Centre Kurchatov Institute, Moscow, Russia

[96] Saha Institute of Nuclear Physics, Kolkata, India

[97] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

[98] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru

[99] Sezione INFN, Catania, Italy

[100] Sezione INFN, Turin, Italy

[101] Sezione INFN, Padova, Italy

[102] Sezione INFN, Bologna, Italy

[103] Sezione INFN, Cagliari, Italy

[104] Sezione INFN, Trieste, Italy

[105] Sezione INFN, Bari, Italy

[106] Sezione INFN, Rome, Italy

[107] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom

[108] SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France

[109] Suranaree University of Technology, Nakhon Ratchasima, Thailand

[110] Technical University of Split FESB, Split, Croatia

[111] Technische Universität München, Munich, Germany

[112] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland

[113] The University of Texas at Austin, Physics Department, Austin, TX, United States

[114] Universidad Autónoma de Sinaloa, Culiacán, Mexico

[115] Universidade de São Paulo (USP), São Paulo, Brazil

[116] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil

[117] Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France

[118] University of Houston, Houston, Texas, United States

[119] University of Technology and Austrian Academy of Sciences, Vienna, Austria

[120] University of Tennessee, Knoxville, Tennessee, United States

[121] University of Tokyo, Tokyo, Japan

[122] University of Tsukuba, Tsukuba, Japan

[123] Eberhard Karls Universität Tübingen, Tübingen, Germany

[124] Variable Energy Cyclotron Centre, Kolkata, India

[125] Vestfold University College, Tonsberg, Norway

[126] V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia

[127] Warsaw University of Technology, Warsaw, Poland

[128] Wayne State University, Detroit, Michigan, United States

[129] Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary

[130] Yale University, New Haven, Connecticut, United States

[131] Yildiz Technical University, Istanbul, Turkey

[132] Yonsei University, Seoul, South Korea

[133] Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany