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### Permalink

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### Journal

European Physical Journal C, 74(9)

### ISSN

1434-6044

### Authors

Abelev, B  
Adam, J  
Adamová, D  
[et al.](#)

### Publication Date

2014-09-01

### DOI

10.1140/epjc/s10052-014-3054-5

Peer reviewed

# Transverse momentum dependence of inclusive primary charged-particle production in p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

The ALICE Collaboration\*

CERN, 1211 Geneva 23, Switzerland

Received: 13 May 2014 / Accepted: 31 August 2014 / Published online: 16 September 2014

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**Abstract** The transverse momentum ( $p_{\text{T}}$ ) distribution of primary charged particles is measured at midrapidity in minimum-bias p–Pb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV with the ALICE detector at the LHC in the range  $0.15 < p_{\text{T}} < 50$  GeV/ $c$ . The spectra are compared to the expectation based on binary collision scaling of particle production in pp collisions, leading to a nuclear modification factor consistent with unity for  $p_{\text{T}}$  larger than 2 GeV/ $c$ , with a weak indication of a Cronin-like enhancement for  $p_{\text{T}}$  around 4 GeV/ $c$ . The measurement is compared to theoretical calculations and to data in Pb–Pb collisions at  $\sqrt{s_{\text{NN}}} = 2.76$  TeV.

Measurements of particle production in proton-nucleus collisions at high energies enable the study of fundamental properties of Quantum Chromodynamics (QCD) over a broad range of parton fractional momentum  $x$  and parton densities (see [1] for a review). They also provide reference measurements for the studies of deconfined matter created in nucleus–nucleus collisions [2].

The first measurements of charged-particle production in minimum-bias p–Pb collisions at the LHC at a centre-of-mass energy per nucleon-nucleon pair of  $\sqrt{s_{\text{NN}}} = 5.02$  TeV [3, 4] showed that: (i) the charged particle multiplicity density at midrapidity scales approximately with the number of participating nucleons ( $\langle N_{\text{part}} \rangle = 7.9 \pm 0.6$  for minimum-bias collisions) calculated in a Glauber model [5] and (ii) the transverse momentum ( $p_{\text{T}}$ ) spectrum, measured in the range 0.5–20 GeV/ $c$  [4], exhibits binary collision scaling above a few GeV/ $c$ , as expected in the absence of any significant nuclear modification effect. The latter is quantified by the nuclear modification factor,  $R_{\text{pPb}}$ , the ratio of the  $p_{\text{T}}$  spectrum in p–Pb collisions and a reference obtained by scaling the measurement in pp collisions with the number of binary nucleon-nucleon collisions in p–Pb. The preliminary result by the CMS collaboration [6] hints at an enhancement

of particle production in p–Pb collisions above binary collision scaling, leading to  $R_{\text{pPb}} > 1$ , for  $p_{\text{T}}$  exceeding about 30 GeV/ $c$ . The preliminary result by the ATLAS collaboration [7] exhibits also, for collisions corresponding to 0–90 % centrality,  $R_{\text{pPb}}$  values above unity for  $p_{\text{T}}$  in the range 20–100 GeV/ $c$ .

In this letter we present an update of our previously published  $p_{\text{T}}$  spectra of primary charged particles [4] based on the 60 times larger sample size collected with the ALICE detector [8] in 2013 in minimum-bias collisions. These data allow a significant extension of the transverse momentum range. The present analysis is essentially identical to the previous and therefore we update only the information related to the enlarged data set; the reader is referred to the earlier publications [4, 9–11] for a more detailed and complete description.

The ALICE minimum-bias trigger is defined by a coincidence of signals in detectors covering in pseudorapidity<sup>1</sup>  $2.8 < \eta < 5.1$  (VZERO-A) and  $-3.7 < \eta < -1.7$  (VZERO-C). In the 2013 data sample, 106 million events (corresponding to an integrated luminosity of  $50.7 \pm 1.6 \mu\text{b}^{-1}$ ) satisfy the trigger and offline event-selection criteria, which select essentially non-single-diffractive (NSD) minimum-bias collisions. The centre-of-mass pseudorapidity is defined as  $\eta_{\text{cms}} = -\eta - |y_{\text{NN}}|$ , with the proton beam at positive rapidity;  $|y_{\text{NN}}| = 0.465$  is the rapidity of the centre-of-mass for nucleon-nucleon collisions. This equation is exact only for massless or very high  $p_{\text{T}}$  particles. The spectra are corrected on a statistical basis using the measurements by ALICE in p–Pb collisions of the  $\eta$  distribution of inclusive charged particle production [3] and of the pion, kaon, and proton yields [12]; this correction depends on the  $\eta_{\text{cms}}$  range and on  $p_{\text{T}}$ , reaching about 20 % for the lowest  $p_{\text{T}}$  bin.

<sup>1</sup> In the laboratory frame  $\eta = -\ln[\tan(\vartheta/2)]$ , with  $\vartheta$  the polar angle between the charged particle and the beam axis; the proton beam has negative  $\eta$ .

\* e-mail: alice-publications@cern.ch

**Table 1** Systematic uncertainties on the  $p_T$ -differential yields in p–Pb and pp collisions. The quoted ranges span the  $p_T$  dependence of the uncertainties in the measured range, 0.15–50 GeV/c. Normalization uncertainties are also quoted

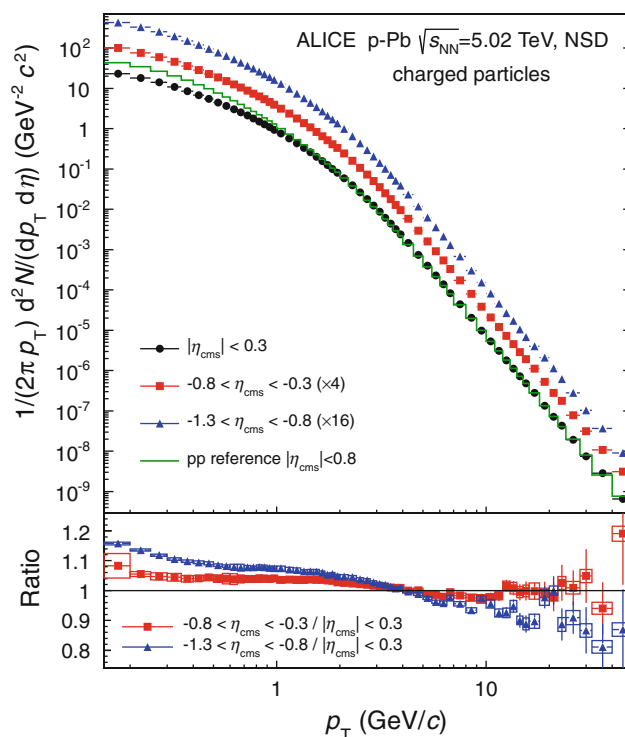
Uncertainty	Value (%)
Event selection	0.6
Track selection	1.0–5.5
Tracking efficiency	3.0
$p_T$ resolution	0–1.3
$p_T$ scale	0–1.5
Particle composition	0.1–0.4
MC generator used for correction	1.0
Secondary particle rejection	0.5–4.0
Material budget	0.2–1.5
Total for p–Pb, $p_T$ -dependent	3.4–6.7
Normalization p–Pb	3.1
Total for pp, $p_T$ -dependent	6.8–8.2
Normalization pp	3.6
Nuclear overlap ( $T_{pPb}$ )	3.6

The systematic uncertainty of the particle composition [12] leads to a systematic uncertainty in our spectra of up to 0.4 %.

The systematic uncertainties on the spectra are evaluated as in previous analyses of pp [10], Pb–Pb [9], and p–Pb [4] data. The uncertainty due to the  $p_T$  scale is negligible below 20 GeV/c and reaches 1.5 % at 50 GeV/c. The main contributions and the total uncertainties are listed in Table 1.

The  $p_T$  spectra of charged particles measured in minimum-bias (NSD) p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV are shown in Fig. 1 for the ranges  $|\eta_{cms}| < 0.3$ ,  $-0.8 < \eta_{cms} < -0.3$ , and  $-1.3 < \eta_{cms} < -0.8$ . The pp reference spectrum,  $\langle T_{pPb} \rangle (1/2\pi p_T) d^2\sigma^{pp}/d\eta dp_T$ , is also included.  $\langle T_{pPb} \rangle$  is the average nuclear overlap function, calculated using the Glauber model [13], which gives  $\langle T_{pPb} \rangle = \langle N_{coll} \rangle / \sigma_{NN} = 0.0983 \pm 0.0035 \text{ mb}^{-1}$ , with  $\langle N_{coll} \rangle = 6.9 \pm 0.6$  and  $\sigma_{NN} = 70 \pm 5 \text{ mb}$ . Since the data in pp collisions [10] indicate only a very small  $\eta$  dependence of the  $p_T$  spectrum in the range measured by ALICE ( $|\eta| < 0.8$ ), our current reference spectrum is, differently than in [4, 10], for  $|\eta| < 0.8$ . It was obtained by data interpolation at low  $p_T$  and by scaling the measurement at  $\sqrt{s} = 7$  TeV with the ratio of spectra calculated with NLO pQCD at  $\sqrt{s} = 5.02$  and 7 TeV [10].

In the lower panel of Fig. 1 the ratios of the spectra for backward ( $-0.8 < \eta_{cms} < -0.3$  and  $-1.3 < \eta_{cms} < -0.8$ ) pseudorapidity ranges to that at  $|\eta_{cms}| < 0.3$  are shown. The indication of a slight softening of the  $p_T$  spectrum when going from central to backward (Pb-side) pseudorapidity, observed already in the pilot-run data of 2012 [4] (note opposite  $\eta_{cms}$  sign convention in [4]) is confirmed with better significance and extended in  $p_T$  down to 0.15 GeV/c.



**Fig. 1** Transverse momentum distributions of charged particles in minimum-bias (NSD) p–Pb collisions for different pseudorapidity ranges (upper panel). The spectra are scaled by the factors indicated. The histogram represents the reference spectrum (cross section scaled by the nuclear overlap function,  $T_{pPb}$ ) in inelastic pp collisions, determined in  $|\eta| < 0.8$ . The lower panel shows the ratio of spectra in p–Pb at backward pseudorapidity to that at  $|\eta_{cms}| < 0.3$ . The vertical bars (boxes) represent the statistical (systematic) uncertainties

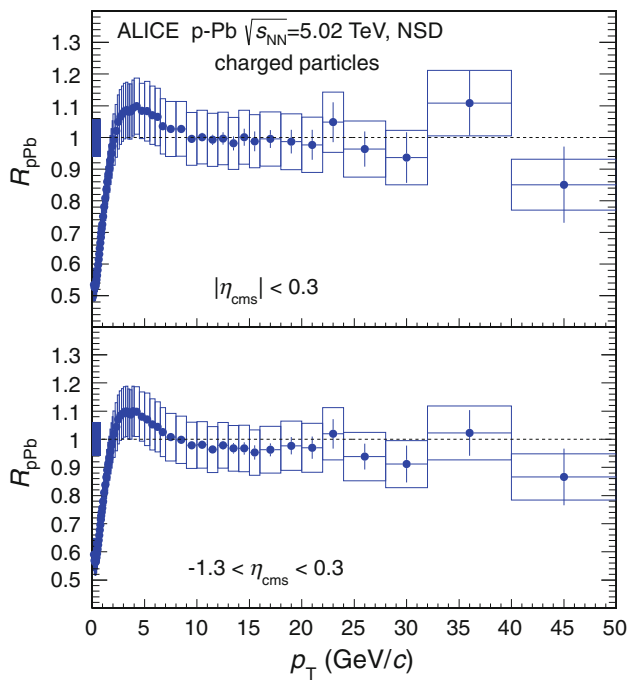
A good description of our earlier measurement of spectra in p–Pb collisions [4] was achieved in the EPOS3 model [14] including a hydrodynamical description of the collision, while the PHSD model [15] significantly underestimated the spectra for  $p_T$  values of several GeV/c.

In order to quantify nuclear effects in p–Pb collisions, the  $p_T$ -differential yield relative to the pp reference, the nuclear modification factor, is calculated as:

$$R_{pPb}(p_T) = \frac{d^2 N^{pPb}/d\eta dp_T}{\langle T_{pPb} \rangle d^2 \sigma^{pp}/d\eta dp_T}, \quad (1)$$

where  $N^{pPb}$  is the charged particle yield in p–Pb collisions.

The measurement of the nuclear modification factor  $R_{pPb}$  for charged particle production in  $|\eta_{cms}| < 0.3$  and  $-1.3 < \eta_{cms} < -0.3$  is shown in Fig. 2. The uncertainties of the p–Pb and pp spectra are added in quadrature, separately for the statistical and systematic uncertainties. The systematic uncertainties are largely correlated between adjacent  $p_T$  bins. The total systematic uncertainty on the normalization, the quadratic sum of the uncertainty on  $\langle T_{pPb} \rangle$ , the normalization of the pp reference spectrum and the normalization of

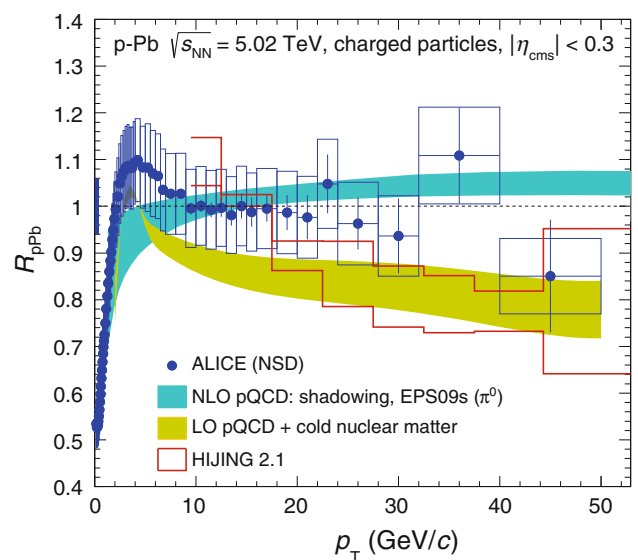


**Fig. 2** The nuclear modification factor of charged particles as a function of transverse momentum, measured in minimum-bias (NSD) p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in two pseudorapidity ranges,  $|\eta_{cms}| < 0.3$  and  $-1.3 < \eta_{cms} < 0.3$ . The statistical errors are represented by vertical bars, the systematic errors by boxes around data points. The relative systematic uncertainties on the normalization are shown as boxes around unity near  $p_T = 0$

the p–Pb data, amounts to 6.0%. The  $R_{pPb}$  factor is consistent with unity up to  $p_T = 50$  GeV/c. The average values of  $R_{pPb}$  in  $|\eta_{cms}| < 0.3$  are  $0.995 \pm 0.007$  (stat.)  $\pm 0.084$  (syst.) for the  $p_T$  range 10–20 GeV/c,  $0.990 \pm 0.031$  (stat.)  $\pm 0.090$  (syst.) in the range 20–28 GeV/c and  $0.969 \pm 0.056$  (stat.)  $\pm 0.090$  (syst.) in the range 28–50 GeV/c. The systematic uncertainties are weighted averages of the values in  $p_T$  bins, with statistical uncertainties as inverse square weights; all values carry in addition the common overall normalization uncertainty of 6%.

The data indicate a small enhancement,  $R_{pPb}$  above unity, barely significant within systematic errors, around 4 GeV/c, i.e. in the  $p_T$  region where the much stronger Cronin enhancement is seen at lower energies [16, 17].

The p–Pb data provide important constraints to models of nuclear modification effects. As an illustration, in Fig. 3 the measurement of  $R_{pPb}$  at  $|\eta_{cms}| < 0.3$  is compared to theoretical model predictions. The predictions for shadowing [18], calculated at next-to-leading order (NLO) with the EPS09s nuclear modification of parton distribution functions, describe the data for  $p_T \gtrsim 6$  GeV/c. The calculations are for  $\pi^0$ , which may explain the differences with respect to data at low  $p_T$ ; for high  $p_T$ , the ALICE data on identified pions, kaons, and protons [21] give support that the comparison of our data on inclusive charged particles to EPS09s cal-

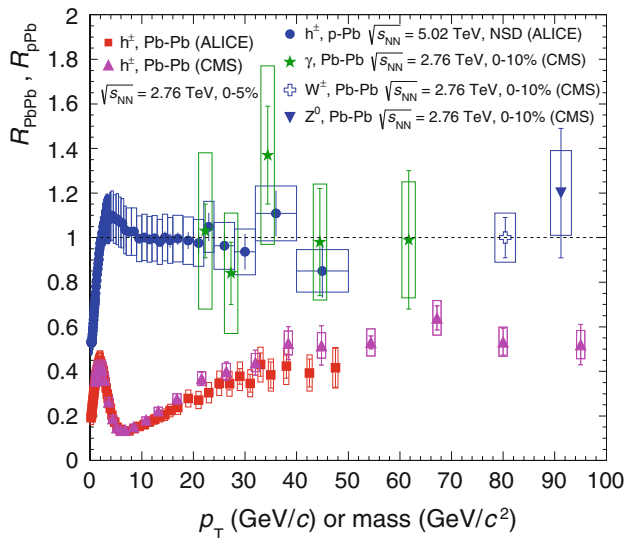


**Fig. 3** Transverse momentum dependence of the nuclear modification factor  $R_{pPb}$  of charged particles measured in minimum-bias (NSD) p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The ALICE data in  $|\eta_{cms}| < 0.3$  (symbols) are compared to model calculations [18–20] (bands, see text for details). The vertical bars (boxes) show the statistical (systematic) uncertainties. The relative systematic uncertainty on the normalization is shown as a box around unity near  $p_T = 0$

culations for  $\pi^0$  is meaningful. The LO pQCD model including cold nuclear matter effects [19] exhibits a distinct trend of decreasing  $R_{pPb}$ , which is not supported by the data. The prediction with the HIJING 2.1 model, shown for two fragmentation schemes [20], exhibits a more pronounced trend of decreasing  $R_{pPb}$  at high  $p_T$ . It is interesting to note that calculations with the EPOS LHC model [22], not included here, show a similar trend. Several predictions based on the saturation (Color Glass Condensate) model are available [23–25]; they were shown previously [4] to describe, in their range of validity, namely up to several GeV/c, the  $R_{pPb}$  data.

In Fig. 4 we compare the measurement of the nuclear modification factor for inclusive primary charged-particle ( $h^\pm$ ) production in p–Pb collisions to that in central (0–5% centrality) Pb–Pb collisions [9, 26]. The p–Pb data demonstrate that the suppression of hadron production at high  $p_T$  in Pb–Pb collisions, understood in theoretical models as a consequence of parton energy loss in (deconfined) QCD matter (see [9] and references therein), has no contribution from initial state effects. The ALICE p–Pb data show no sign of nuclear matter modification of hadron production at high  $p_T$  and are therefore fully consistent with the observation of binary collision scaling in Pb–Pb of observables which are not affected by hot QCD matter (direct photons [27] and vector bosons [28, 29]).

In summary, we have extended our measurements of the charged-particle  $p_T$  spectra and nuclear modification factor in minimum-bias (NSD) p–Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The results, covering a substantially-extended  $p_T$



**Fig. 4** Transverse momentum dependence of the nuclear modification factor  $R_{pPb}$  of charged particles ( $h^\pm$ ) measured in minimum-bias (NSD) p-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in comparison to data on the nuclear modification factor  $R_{pPb}$  in central Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The Pb-Pb data are for charged particle [9, 26], direct photon [27],  $Z^0$  [28] and  $W^\pm$  [29] production. All data are for midrapidity

range,  $0.15 < p_T < 50$  GeV/c, exhibit, within uncertainties, no deviation from binary collision scaling at high  $p_T$ ; the nuclear modification factor remains consistent with unity for  $p_T \gtrsim 2$  GeV/c. The data at high  $p_T$  are described by a prediction based on NLO pQCD calculations with PDF shadowing and further underline our earlier observation [4] that initial state effects do not contribute to the strong suppression of hadron production at high  $p_T$  observed at the LHC in Pb-Pb collisions.

**Acknowledgments** We thank X.-N. Wang, K. Eskola, and I. Helenius for communications about their predictions. The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: State Committee of Science, World Federation of Scientists (WFS) and Swiss Fonds Kidagan, Armenia; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (FINEP), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP); National Natural Science Foundation of China (NSFC), the Chinese Ministry of Education (CMOE) and the Ministry of Science and Technology of China (MSTC); Ministry of Education and Youth of the Czech Republic; Danish Natural Science Research Council, the Carlsberg Foundation and the Danish National Research Foundation; The European Research Council under the European Community's Seventh Framework Programme; Helsinki Institute of Physics and the Academy of Finland; French CNRS-IN2P3, the 'Region Pays de Loire', 'Region Alsace', 'Region Auvergne' and CEA, France; German BMBF and the Helmholtz Association; General Secretariat for Research and Technology, Ministry of Development, Greece; Hungarian OTKA and National

Office for Research and Technology (NKTH); Department of Atomic Energy and Department of Science and Technology of the Government of India; Istituto Nazionale di Fisica Nucleare (INFN) and Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Italy; MEXT Grant-in-Aid for Specially Promoted Research, Japan; Joint Institute for Nuclear Research, Dubna; National Research Foundation of Korea (NRF); CONACYT, DGAPA, México, ALFA-EC and the EPLANET Program (European Particle Physics Latin American Network); Stichting voor Fundamenteel Onderzoek der Materie (FOM) and the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; Research Council of Norway (NFR); Polish Ministry of Science and Higher Education; National Science Centre, Poland; Ministry of National Education/Institute for Atomic Physics and CNCS-UEFISCDI-Romania; Ministry of Education and Science of Russian Federation, Russian Academy of Sciences, Russian Federal Agency of Atomic Energy, Russian Federal Agency for Science and Innovations and The Russian Foundation for Basic Research; Ministry of Education of Slovakia; Department of Science and Technology, South Africa; CIEMAT, EELA, Ministerio de Economía y Competitividad (MINECO) of Spain, Xunta de Galicia (Consellería de Educación), CEADEN, Cubaenergía, Cuba, and IAEA (International Atomic Energy Agency); Swedish Research Council (VR) and Knut and Alice Wallenberg Foundation (KAW); Ukraine Ministry of Education and Science; United Kingdom Science and Technology Facilities Council (STFC); The United States Department of Energy, the United States National Science Foundation, the State of Texas, and the State of Ohio.

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## The ALICE Collaboration

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H. O. Pohjoisaho<sup>42</sup>, B. Polichtchouk<sup>106</sup>, N. Poljak<sup>92</sup>, A. Pop<sup>72</sup>, S. Porteboeuf-Houssais<sup>64</sup>, J. Porter<sup>68</sup>, B. Potukuchi<sup>84</sup>, S. K. Prasad<sup>127</sup>, R. Preghenella<sup>12.99</sup>, F. Prino<sup>105</sup>, C. A. Pruneau<sup>127</sup>, I. Pshenichnov<sup>51</sup>, G. Puddu<sup>23</sup>, P. Pujahari<sup>127</sup>, V. Punin<sup>93</sup>, J. Putschke<sup>127</sup>, H. Qvigstad<sup>21</sup>, A. Rachevski<sup>104</sup>, S. Raha<sup>4</sup>, J. Rak<sup>116</sup>, A. Rakotozafindrabe<sup>14</sup>, L. Ramello<sup>30</sup>, R. Raniwala<sup>85</sup>, S. Raniwala<sup>85</sup>, S. S. Räsänen<sup>42</sup>, B. T. Rascanu<sup>48</sup>, D. Rathee<sup>81</sup>, A. W. Rauf<sup>15</sup>, V. Razazi<sup>23</sup>, K. F. Read<sup>118</sup>, J. S. Real<sup>65</sup>, K. Redlich<sup>71.g</sup>, R. J. Reed<sup>129</sup>, A. Rehman<sup>17</sup>, P. Reichelt<sup>48</sup>, M. Reicher<sup>52</sup>, F. Reidt<sup>34</sup>, R. Renfordt<sup>48</sup>, A. R. Reolon<sup>66</sup>, A. Reshetin<sup>51</sup>, F. Rettig<sup>39</sup>, J.-P. Revol<sup>34</sup>, K. Reygers<sup>87</sup>, V. Riabov<sup>79</sup>, R. A. Ricci<sup>67</sup>, T. Richert<sup>32</sup>, M. Richter<sup>21</sup>, P. Riedler<sup>34</sup>, W. Riegler<sup>34</sup>, F. Riggi<sup>27</sup>, A. Rivetti<sup>105</sup>, E. Rocco<sup>52</sup>, M. Rodríguez Cahuantzi<sup>2</sup>, A. Rodríguez Manso<sup>75</sup>, K. Røed<sup>21</sup>, E. Rogochaya<sup>61</sup>, S. Rohni<sup>84</sup>, D. Rohr<sup>39</sup>, D. Röhrich<sup>17</sup>, R. Romita<sup>76</sup>, F. Ronchetti<sup>66</sup>, L. Ronflette<sup>107</sup>, P. Rosnet<sup>64</sup>, A. Rossi<sup>34</sup>, F. Roukoutakis<sup>82</sup>, A. Roy<sup>45</sup>, C. Roy<sup>50</sup>, P. Roy<sup>95</sup>, A. J. Rubio Montero<sup>10</sup>, R. Rui<sup>24</sup>, R. Russo<sup>25</sup>, E. Ryabinkin<sup>94</sup>, Y. Ryabov<sup>79</sup>, A. Rybicki<sup>110</sup>, S. Sadovsky<sup>106</sup>, K. Šafařík<sup>34</sup>, B. Sahlmüller<sup>48</sup>, R. Sahoo<sup>45</sup>, P. K. Sahu<sup>56</sup>, J. Saini<sup>124</sup>, S. Sakai<sup>68</sup>, C. A. Salgado<sup>16</sup>, J. Salzwedel<sup>19</sup>, S. Sambyal<sup>84</sup>,

V. Samsonov<sup>79</sup>, X. Sanchez Castro<sup>50</sup>, F. J. Sánchez Rodríguez<sup>112</sup>, L. Šándor<sup>54</sup>, A. Sandoval<sup>59</sup>, M. Sano<sup>120</sup>, G. Santagati<sup>27</sup>, D. Sarkar<sup>124</sup>, E. Scapparone<sup>99</sup>, F. Scarlassara<sup>28</sup>, R. P. Scharenberg<sup>89</sup>, C. Schiaua<sup>72</sup>, R. Schicker<sup>87</sup>, C. Schmidt<sup>91</sup>, H. R. Schmidt<sup>33</sup>, S. Schuchmann<sup>48</sup>, J. Schukraft<sup>34</sup>, M. Schulc<sup>37</sup>, T. Schuster<sup>129</sup>, Y. Schutz<sup>34,107</sup>, K. Schwarz<sup>91</sup>, K. Schweda<sup>91</sup>, G. Scioli<sup>26</sup>, E. Scomparin<sup>105</sup>, R. Scott<sup>118</sup>, G. Segato<sup>28</sup>, J. E. Seger<sup>80</sup>, Y. Sekiguchi<sup>119</sup>, I. Selyuzhenkov<sup>91</sup>, J. Seo<sup>90</sup>, E. Serradilla<sup>10,59</sup>, A. Sevcenco<sup>57</sup>, A. Shabetai<sup>107</sup>, G. Shabratova<sup>61</sup>, R. Shahoyan<sup>34</sup>, A. Shangaraev<sup>106</sup>, N. Sharma<sup>118</sup>, S. Sharma<sup>84</sup>, K. Shigaki<sup>43</sup>, K. Shtejer<sup>25</sup>, Y. Sibiriak<sup>94</sup>, S. Siddhanta<sup>100</sup>, T. Siemiarczuk<sup>71</sup>, D. Silvermyr<sup>78</sup>, C. Silvestre<sup>65</sup>, G. Simatovic<sup>121</sup>, R. Singaraju<sup>124</sup>, R. Singh<sup>84</sup>, S. Singha<sup>73,124</sup>, V. Singhal<sup>124</sup>, B. C. Sinha<sup>124</sup>, T. Sinha<sup>95</sup>, B. Sitar<sup>36</sup>, M. Sitta<sup>30</sup>, T. B. Skaali<sup>21</sup>, K. Skjerdal<sup>17</sup>, M. Slupecki<sup>116</sup>, N. Smirnov<sup>129</sup>, R. J. M. Snellings<sup>52</sup>, C. Sogaard<sup>32</sup>, R. Soltz<sup>69</sup>, J. Song<sup>90</sup>, M. Song<sup>130</sup>, F. Soramel<sup>28</sup>, S. Sorensen<sup>118</sup>, M. Spacek<sup>37</sup>, E. Spiriti<sup>66</sup>, I. Sputowska<sup>110</sup>, M. Spyropoulou-Stassinaki<sup>82</sup>, B. K. Srivastava<sup>89</sup>, J. Stachel<sup>87</sup>, I. Stan<sup>57</sup>, G. Stefanek<sup>71</sup>, M. Steinpreis<sup>19</sup>, E. Stenlund<sup>32</sup>, G. Steyn<sup>60</sup>, J. H. Stiller<sup>87</sup>, D. Stocco<sup>107</sup>, M. Stolpovskiy<sup>106</sup>, P. Strmen<sup>36</sup>, A. A. P. Suaide<sup>113</sup>, T. Sugitate<sup>43</sup>, C. Suire<sup>46</sup>, M. Suleymanov<sup>15</sup>, R. Sultanov<sup>53</sup>, M. Šumbera<sup>77</sup>, T. Susa<sup>92</sup>, T. J. M. Symons<sup>68</sup>, A. Szabo<sup>36</sup>, A. Szanto de Toledo<sup>113</sup>, I. Szarka<sup>36</sup>, A. Szczepankiewicz<sup>34</sup>, M. Szymanski<sup>126</sup>, J. Takahashi<sup>114</sup>, M. A. Tangaro<sup>31</sup>, J. D. Tapia Takaki<sup>46,h</sup>, A. Tarantola Pelsoni<sup>48</sup>, A. Tarazona Martinez<sup>34</sup>, M. G. Tarzila<sup>72</sup>, A. Tauro<sup>34</sup>, G. Tejada Muñoz<sup>2</sup>, A. Telesca<sup>34</sup>, C. Terrevoli<sup>23</sup>, J. Thäder<sup>91</sup>, D. Thomas<sup>52</sup>, R. Tieulent<sup>122</sup>, A. R. Timmins<sup>115</sup>, A. Toia<sup>102</sup>, V. Trubnikov<sup>3</sup>, W. H. Trzaska<sup>116</sup>, T. Tsuji<sup>119</sup>, A. Tumkin<sup>93</sup>, R. Turrisi<sup>102</sup>, T. S. Tveter<sup>21</sup>, K. Ullaland<sup>17</sup>, A. Uras<sup>122</sup>, G. L. Usai<sup>23</sup>, M. Vajzer<sup>77</sup>, M. Vala<sup>54,61</sup>, L. Valencia Palomo<sup>64</sup>, S. Vallero<sup>87</sup>, P. Vande Vyvre<sup>34</sup>, J. Van Der Maarel<sup>52</sup>, J. W. Van Hoorne<sup>34</sup>, M. van Leeuwen<sup>52</sup>, A. Vargas<sup>2</sup>, M. Vargyas<sup>116</sup>, R. Varma<sup>44</sup>, M. Vasileiou<sup>82</sup>, A. Vasiliev<sup>94</sup>, V. Vechernin<sup>123</sup>, M. Veldhoen<sup>52</sup>, A. Velure<sup>17</sup>, M. Venaruzzo<sup>24,67</sup>, E. Vercellin<sup>25</sup>, S. Vergara Limón<sup>2</sup>, R. Vernet<sup>8</sup>, M. Verweij<sup>127</sup>, L. Vickovic<sup>109</sup>, G. Viesti<sup>28</sup>, J. Viinikainen<sup>116</sup>, Z. Vilakazi<sup>60</sup>, O. Villalobos Baillie<sup>96</sup>, A. Vinogradov<sup>94</sup>, L. Vinogradov<sup>123</sup>, Y. Vinogradov<sup>93</sup>, T. Virgili<sup>29</sup>, Y. P. Viyogi<sup>124</sup>, A. Vodopyanov<sup>61</sup>, M. A. Völkl<sup>87</sup>, K. Voloshin<sup>53</sup>, S. A. Voloshin<sup>127</sup>, G. Volpe<sup>34</sup>, B. von Haller<sup>34</sup>, I. Vorobyev<sup>123</sup>, D. Vranic<sup>34,91</sup>, J. Vrláková<sup>38</sup>, B. Vulpescu<sup>64</sup>, A. Vyushin<sup>93</sup>, B. Wagner<sup>17</sup>, J. Wagner<sup>91</sup>, V. Wagner<sup>37</sup>, M. Wang<sup>7,107</sup>, Y. Wang<sup>87</sup>, D. Watanabe<sup>120</sup>, M. Weber<sup>115</sup>, J. P. Wessels<sup>49</sup>, U. Westerhoff<sup>49</sup>, J. Wiechula<sup>33</sup>, J. Wikne<sup>21</sup>, M. Wilde<sup>49</sup>, G. Wilk<sup>71</sup>, J. Wilkinson<sup>87</sup>, M. C. S. Williams<sup>99</sup>, B. Windelband<sup>87</sup>, M. Winn<sup>87</sup>, C. G. Yaldo<sup>127</sup>, Y. Yamaguchi<sup>119</sup>, H. Yang<sup>52</sup>, P. Yang<sup>7</sup>, S. Yang<sup>17</sup>, S. Yano<sup>43</sup>, S. Yasnopolskiy<sup>94</sup>, J. Yi<sup>90</sup>, Z. Yin<sup>7</sup>, I.-K. Yoo<sup>90</sup>, I. Yushmanov<sup>94</sup>, V. Zaccolo<sup>74</sup>, C. Zach<sup>37</sup>, A. Zaman<sup>15</sup>, C. Zampolli<sup>99</sup>, S. Zaporozhets<sup>61</sup>, A. Zarochentsev<sup>123</sup>, P. Závada<sup>55</sup>, N. Zaviyalov<sup>93</sup>, H. Zbroszczyk<sup>126</sup>, I. S. Zgura<sup>57</sup>, M. Zhalov<sup>79</sup>, H. Zhang<sup>7</sup>, X. Zhang<sup>7,68</sup>, Y. Zhang<sup>7</sup>, C. Zhao<sup>21</sup>, N. Zhigareva<sup>53</sup>, D. Zhou<sup>7</sup>, F. Zhou<sup>7</sup>, Y. Zhou<sup>52</sup>, Zhou Zhuo<sup>17</sup>, H. Zhu<sup>7</sup>, J. Zhu<sup>7</sup>, X. Zhu<sup>7</sup>, A. Zichichi<sup>12,26</sup>, A. Zimmermann<sup>87</sup>, M. B. Zimmermann<sup>34,49</sup>, G. Zinovjev<sup>3</sup>, Y. Zoccarato<sup>122</sup>, M. Zyzak<sup>48</sup>

- <sup>1</sup> A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
- <sup>2</sup> Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
- <sup>3</sup> Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
- <sup>4</sup> Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Bose Institute, Kolkata, India
- <sup>5</sup> Budker Institute for Nuclear Physics, Novosibirsk, Russia
- <sup>6</sup> California Polytechnic State University, San Luis Obispo, CA, USA
- <sup>7</sup> Central China Normal University, Wuhan, China
- <sup>8</sup> Centre de Calcul de l'IN2P3, Villeurbanne, France
- <sup>9</sup> Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
- <sup>10</sup> Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- <sup>11</sup> Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
- <sup>12</sup> Centro Fermi-Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Rome, Italy
- <sup>13</sup> Chicago State University, Chicago, USA
- <sup>14</sup> Commissariat à l'Energie Atomique, IRFU, Saclay, France
- <sup>15</sup> COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan
- <sup>16</sup> Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
- <sup>17</sup> Department of Physics and Technology, University of Bergen, Bergen, Norway
- <sup>18</sup> Department of Physics, Aligarh Muslim University, Aligarh, India
- <sup>19</sup> Department of Physics, Ohio State University, Columbus, OH, USA
- <sup>20</sup> Department of Physics, Sejong University, Seoul, South Korea
- <sup>21</sup> Department of Physics, University of Oslo, Oslo, Norway
- <sup>22</sup> Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy
- <sup>23</sup> Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
- <sup>24</sup> 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, Padua, 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 Faculty of Engineering, Bergen University College, Bergen, Norway
- 36 Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
- 37 Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
- 38 Faculty of Science, P.J. Šafárik University, Kosice, Slovakia
- 39 Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- 40 Gangneung-Wonju National University, Gangneung, South Korea
- 41 Department of Physics, Gauhati University, Guwahati, India
- 42 Helsinki Institute of Physics (HIP), Helsinki, Finland
- 43 Hiroshima University, Hiroshima, Japan
- 44 Indian Institute of Technology Bombay (IIT), Mumbai, India
- 45 Indian Institute of Technology Indore (IITI), Indore, India
- 46 Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
- 47 Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- 48 Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- 49 Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
- 50 Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
- 51 Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
- 52 Institute for Subatomic Physics of Utrecht University, Utrecht, The Netherlands
- 53 Institute for Theoretical and Experimental Physics, Moscow, Russia
- 54 Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
- 55 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- 56 Institute of Physics, Bhubaneswar, India
- 57 Institute of Space Science (ISS), Bucharest, Romania
- 58 Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
- 59 Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
- 60 iThemba LABS, National Research Foundation, Somerset West, South Africa
- 61 Joint Institute for Nuclear Research (JINR), Dubna, Russia
- 62 Korea Institute of Science and Technology Information, Taejeon, South Korea
- 63 KTO Karatay University, Konya, Turkey
- 64 Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France
- 65 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
- 66 Laboratori Nazionali di Frascati, INFN, Frascati, Italy
- 67 Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy
- 68 Lawrence Berkeley National Laboratory, Berkeley, CA, USA
- 69 Lawrence Livermore National Laboratory, Livermore, CA, USA
- 70 Moscow Engineering Physics Institute, Moscow, Russia
- 71 National Centre for Nuclear Studies, Warsaw, Poland
- 72 National Institute for Physics and Nuclear Engineering, Bucharest, Romania
- 73 National Institute of Science Education and Research, Bhubaneswar, India
- 74 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- 75 Nikhef, National Institute for Subatomic Physics, Amsterdam, The Netherlands

- 76 Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, UK
- 77 Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic
- 78 Oak Ridge National Laboratory, Oak Ridge, TN, USA
- 79 Petersburg Nuclear Physics Institute, Gatchina, Russia
- 80 Physics Department, Creighton University, Omaha, NE, USA
- 81 Physics Department, Panjab University, Chandigarh, India
- 82 Physics Department, University of Athens, Athens, Greece
- 83 Physics Department, University of Cape Town, Cape Town, South Africa
- 84 Physics Department, University of Jammu, Jammu, India
- 85 Physics Department, University of Rajasthan, Jaipur, India
- 86 Physik Department, Technische Universität München, Munich, Germany
- 87 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- 88 Politecnico di Torino, Turin, Italy
- 89 Purdue University, West Lafayette, IN, USA
- 90 Pusan National University, Pusan, South Korea
- 91 Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
- 92 Rudjer Bošković Institute, Zagreb, Croatia
- 93 Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
- 94 Russian Research Centre Kurchatov Institute, Moscow, Russia
- 95 Saha Institute of Nuclear Physics, Kolkata, India
- 96 School of Physics and Astronomy, University of Birmingham, Birmingham, UK
- 97 Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
- 98 Sezione INFN, Bari, Italy
- 99 Sezione INFN, Bologna, Italy
- 100 Sezione INFN, Cagliari, Italy
- 101 Sezione INFN, Catania, Italy
- 102 Sezione INFN, Padua, Italy
- 103 Sezione INFN, Rome, Italy
- 104 Sezione INFN, Trieste, Italy
- 105 Sezione INFN, Turin, Italy
- 106 SSC IHEP of NRC Kurchatov institute, Protvino, Russia
- 107 SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France
- 108 Suranaree University of Technology, Nakhon Ratchasima, Thailand
- 109 Technical University of Split FESB, Split, Croatia
- 110 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland
- 111 Physics Department, The University of Texas at Austin, Austin, TX, USA
- 112 Universidad Autónoma de Sinaloa, Culiacán, Mexico
- 113 Universidade de São Paulo (USP), São Paulo, Brazil
- 114 Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
- 115 University of Houston, Houston, TX, USA
- 116 University of Jyväskylä, Jyväskylä, Finland
- 117 University of Liverpool, Liverpool, UK
- 118 University of Tennessee, Knoxville, TN, USA
- 119 University of Tokyo, Tokyo, Japan
- 120 University of Tsukuba, Tsukuba, Japan
- 121 University of Zagreb, Zagreb, Croatia
- 122 Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France
- 123 V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia
- 124 Variable Energy Cyclotron Centre, Kolkata, India
- 125 Vestfold University College, Tonsberg, Norway
- 126 Warsaw University of Technology, Warsaw, Poland
- 127 Wayne State University, Detroit, MI, USA

<sup>128</sup> Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary

<sup>129</sup> Yale University, New Haven, CT, USA

<sup>130</sup> Yonsei University, Seoul, South Korea

<sup>131</sup> Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany

<sup>a</sup> Deceased

<sup>b</sup> Also at: St. Petersburg State Polytechnical University

<sup>c</sup> Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India

<sup>d</sup> Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia

<sup>e</sup> Also at: University of Belgrade, Faculty of Physics and “Vinča” Institute of Nuclear Sciences, Belgrade, Serbia

<sup>f</sup> *Permanent Address*: Konkuk University, Seoul, Korea

<sup>g</sup> Also at: Institute of Theoretical Physics, University of Wrocław, Wrocław, Poland

<sup>h</sup> Also at: University of Kansas, Lawrence, KS, USA