

<https://helda.helsinki.fi>

Antihelium-3 fluxes near Earth using data-driven 2 estimates for annihilation cross section

The ALICE collaboration

2022-03-18

The ALICE Collaboration , Acharya , S , Adamova , D , Kim , D J , Krizek , F , Molander , M A , Novitzky , N , Onnerstad , A , Parkkila , J E , Rytkönen , H M , Räsänen , S , Saarimäki , O A M , Slupecki , M & Trzaska , W H 2022 , ' Antihelium-3 fluxes near Earth using data-driven 2 estimates for annihilation cross section ' , PoS Proceedings of Science , vol. 395 , 516 .

<http://hdl.handle.net/10138/356033>

cc_by_nc_nd
publishedVersion

Downloaded from Helda, University of Helsinki institutional repository.

This is an electronic reprint of the original article.

This reprint may differ from the original in pagination and typographic detail.

Please cite the original version.

1 Antihelium-3 fluxes near Earth using data-driven 2 estimates for annihilation cross section

3 **Laura Šerkšnytė^{a,*} on behalf of the ALICE Collaboration**
4 (a complete list of authors can be found at the end of the proceedings)

5 ^aThe Technical University of Munich ,
6 James-Franck-Str. 1, Garching, Germany
7 E-mail: laura.serksnyte@tum.de

Antinuclei found in cosmic rays could provide a smoking gun signal for dark matter as this signal is virtually background free. The study of ${}^3\overline{\text{He}}$ cosmic rays requires the knowledge of their production, propagation in the galaxy and annihilation cross-section. While the former two have been already estimated with data-driven methods, there were no experimental data available for the ${}^3\overline{\text{He}}$ inelastic cross section. We measured for the first time the inelastic cross section of ${}^3\overline{\text{He}}$ using the ALICE detector itself as a target. To study the effect of ${}^3\overline{\text{He}}$ annihilation in the galaxy and estimate the transparency of the galaxy, the ${}^3\overline{\text{He}}$ source functions and annihilation cross sections were implemented in GALPROP.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

1. Introduction

The yet undetected dark matter is expected to account for the missing mass in the Universe. Weakly interacting massive particles (WIMPs) are believed to annihilate and produce particle-antiparticle pairs of the ordinary matter. Antinuclei produced in our galaxy by dark matter annihilation processes would propagate and be detected as antimatter cosmic rays in the Earth's proximity. However, antinuclei can also be produced by cosmic ray collisions with the interstellar gas. This contribution represents a background source for dark matter searches. Luckily, the cosmic ray flux from the two sources peaks at different kinetic energies and the dark matter signal is virtually background free. The measurement of antinuclei cosmic rays would hence provide a smoking gun signal for dark matter.

The modelling of the behaviour of the background and signal is mandatory to draw conclusions for antinuclei fluxes. This work focuses on the description of the behaviour of ${}^3\overline{\text{He}}$ cosmic rays in our galaxy. The full-scale description of the fluxes can be implemented in a transport equation which requires the knowledge of three main components: the production cross section of antinuclei, their annihilation cross section and their propagation in the galaxy. The transport equation can be solved numerically using the publicly available GALPROP code [1].

The ${}^3\overline{\text{He}}$ production cross sections and the propagation parameters can be constrained using existing experimental data, while no measurement of the inelastic cross section of the ${}^3\overline{\text{He}}$ was available up to now. We provide the first ever measurement of the inelastic cross section of ${}^3\overline{\text{He}}$ using the ALICE detector as a target material. We implement the ${}^3\overline{\text{He}}$ cosmic ray source functions and our obtained inelastic cross sections in GALPROP to study the effect of annihilation processes in the Galaxy.

2. ${}^3\overline{\text{He}}$ Inelastic Cross Section Measurement

At LHC energies, matter and antimatter are produced in almost equal amounts. The ${}^3\text{He}$ and ${}^3\overline{\text{He}}$ are produced rather copiously as it can be seen in Fig. 1, where the specific energy loss measured by the ALICE Time Projection Chamber (TPC) [12] as a function of the momentum for particle (on the left) and antiparticle (right) is shown. Thus the LHC offers optimal conditions to study such nuclei. To measure the inelastic cross section of antinuclei, the different interaction of matter and antimatter with the detector is exploited. As it was shown in antideuteron studies [3], the antimatter-to-matter ratio is very sensitive to the inelastic cross sections. The ${}^3\overline{\text{He}}/{}^3\text{He}$ can be expressed as:

$$\frac{{}^3\overline{\text{He}}}{{}^3\text{He}} = \left(\frac{{}^3\overline{\text{He}}}{{}^3\text{He}} \right)_{\text{prim}} \cdot \exp \left(-\alpha (\sigma_{\text{inel}}^{{}^3\overline{\text{He}}} - \sigma_{\text{inel}}^{{}^3\text{He}}) \Delta x \right). \quad (1)$$

Here, $\frac{{}^3\overline{\text{He}}}{{}^3\text{He}}$ is the measured ratio of the number of antihelium and helium while $\left(\frac{{}^3\overline{\text{He}}}{{}^3\text{He}} \right)_{\text{prim}}$ is the primordial ratio. The traversed path length is indicated with Δx and $\alpha = \rho N_A / M$, where N_A is the Avogadro's number, ρ and M are the density and the molar mass of the target, respectively. The inelastic cross sections of helium and antihelium with matter are denoted as $\sigma_{\text{inel}}^{{}^3\overline{\text{He}}}$ and $\sigma_{\text{inel}}^{{}^3\text{He}}$, respectively. As the inelastic cross section of ${}^3\text{He}$ is rather well known, the ratio ${}^3\overline{\text{He}}/{}^3\text{He}$ can be used to obtain the inelastic cross section of ${}^3\overline{\text{He}}$.

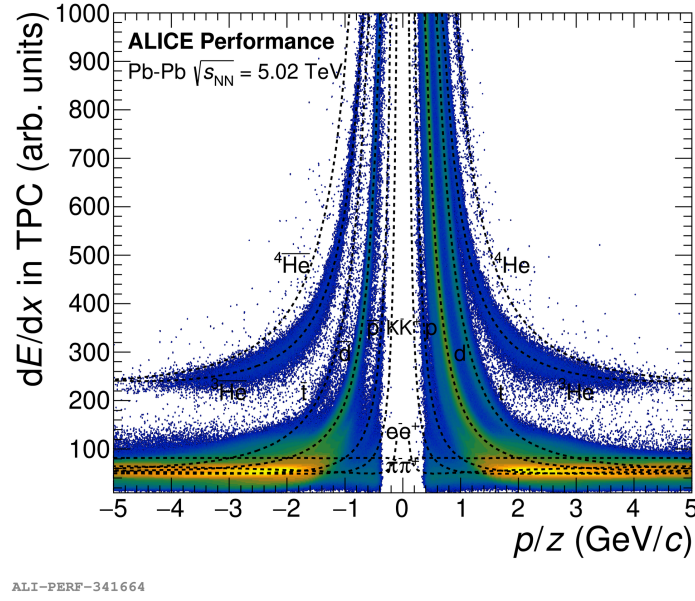


Figure 1: Specific energy loss in the ALICE TPC detector as a function of rigidity.

46 The ${}^3\overline{\text{He}}$ inelastic cross section was measured using pp collisions at $\sqrt{s} = 13$ TeV and Pb–Pb
 47 collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV recorded by ALICE. Here, only pp results are presented in detail.
 48 The ALICE detector was used as a target material. Full description of the experimental setup of
 49 the ALICE detector can be found in [4, 5]. The charged (anti)particles were identified by using the
 50 specific energy loss measured by the TPC. Because of the double charge of helium and antihelium,
 51 they are very well separated from the rest of the particles in such a measurement as it can be seen
 52 in Fig. 1. To select higher quality track samples, an additional hit in the Inner Tracking System
 53 (ITS) was required. The absorption probability of ${}^3\overline{\text{He}}$ in the detector increases with the amount
 54 of traversed material. Thus for particles with momenta $p > 1$ GeV/c, an additional hit in the
 55 Time-of-Flight (TOF) detector was required. The Transition Radiation Detector (TRD)[11] is in
 56 between the TPC and the TOF detectors and provides additional material budget. The measured ${}^3\overline{\text{He}}$
 57 spectra was corrected to account for secondary particles from spallation processes in the detector
 58 material. This correction is not needed for ${}^3\overline{\text{He}}$ as the probability of producing secondary ${}^3\overline{\text{He}}$ is
 59 extremely low. The resulting ${}^3\overline{\text{He}}/{}^3\overline{\text{He}}$ ratio as a function of rigidity (p_{prim}/Z , where p_{prim} is the
 60 momentum at primary vertex and Z is the charge of the particle) is shown in Fig. 2. The red points
 61 represent Geant4 [13] simulation results while the blue points are measured ALICE results. The
 62 empty markers correspond to the ITS-TPC analysis while the full markers to the ITS-TPC-TOF
 63 analysis. The bars indicate the statistical uncertainties, while the boxes represent the systematic
 64 uncertainties. The ${}^3\overline{\text{He}}/{}^3\overline{\text{He}}$ ratio in both data and MC simulation is smaller than unity, indicating
 65 that the inelastic cross section of the ${}^3\overline{\text{He}}$ is larger than that of ${}^3\overline{\text{He}}$. The measured ${}^3\overline{\text{He}}/{}^3\overline{\text{He}}$ ratio
 66 for momenta $p < 1$ GeV/c is much lower than in the simulation thus a larger inelastic cross section
 67 of the ${}^3\overline{\text{He}}$ with respect to Geant4 is expected.

68 To obtain the inelastic cross section of the ${}^3\overline{\text{He}}$ ($\sigma_{\text{inel}}^{{}^3\overline{\text{He}}}$), the Geant4 simulations were used. The
 69 $\sigma_{\text{inel}}^{{}^3\overline{\text{He}}}$ was varied in Geant4 bin-by-bin in momentum to reproduce the ${}^3\overline{\text{He}}/{}^3\overline{\text{He}}$ ratio measured by
 70 ALICE and its corresponding 1σ uncertainties. The resulting values represents the $\sigma_{\text{inel}}^{{}^3\overline{\text{He}}}$ measured

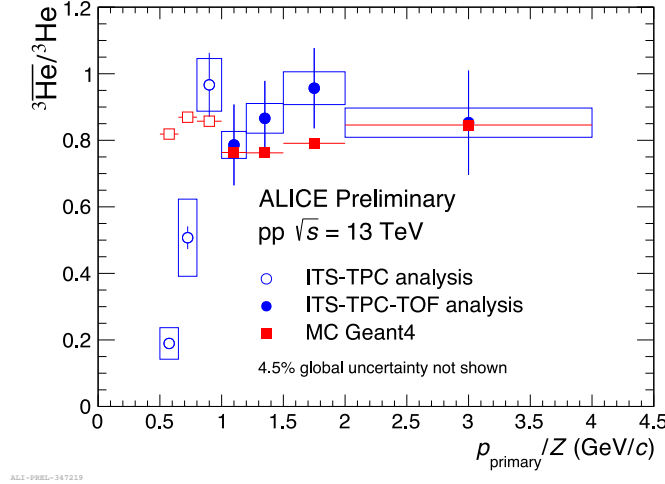


Figure 2: Raw primary ${}^3\overline{\text{He}}/{}^3\text{He}$ ratio as a function of the momentum at the primary vertex divided by the charge.

71 by ALICE. The ALICE target material in the ITS-TPC analysis corresponds to a target with average
 72 charge number $Z = \langle 8.5 \rangle$ and mass number $A = \langle 17.4 \rangle$. In case of the ITS-TPC-TOF analysis, the
 73 corresponding values are $Z = \langle 14.8 \rangle$ and $A = \langle 31.8 \rangle$.

74 In case of the cosmic ray studies, the target nuclei in the interstellar medium are mainly protons
 75 and ${}^4\text{He}$. The Geant4 simulation includes implementation of the inelastic cross section of ${}^3\overline{\text{He}}$
 76 on different target nuclei [7]. We used this feature to extrapolate the measured inelastic cross section
 77 to light nuclei. A correction factor was calculated for the Geant4 inelastic cross section using the
 78 measured ${}^3\overline{\text{He}}/{}^3\text{He}$ ratio. Such correction factor is momentum dependent and was assumed to be
 79 the same for all target nuclei. The ${}^3\overline{\text{He}}$ inelastic cross sections were estimated based on hydrogen
 80 and helium targets by applying the correction factor to the default Geant4 implementation. A
 81 8% uncertainty on such A scaling was assigned [7]. The resulting inelastic cross sections were
 82 implemented in GALPROP to account for the ${}^3\overline{\text{He}}$ annihilation in the collisions with interstellar gas
 83 in the galaxy.

84 3. ${}^3\overline{\text{He}}$ Cosmic Rays

85 To study how the ALICE measurement affects the cosmic ray studies, we use GALPROP to
 86 solve the transport equation:

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \mathbf{div}(D_{xx} \mathbf{grad} \psi - \mathbf{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial \psi}{\partial p} - \frac{\partial}{\partial p} \left[\psi \frac{dp}{dt} - \frac{p}{3} (\mathbf{div} \cdot \mathbf{V}) \psi \right] - \frac{\psi}{\tau}. \quad (2)$$

87 Here, $\psi = \psi(\mathbf{r}, p, t)$ is the time dependent cosmic ray density per unit of the total particle
 88 momentum and $q(\mathbf{r}, p)$ is the ${}^3\overline{\text{He}}$ source function. The propagation parameters D_{xx} , \mathbf{V} and D_{pp} are
 89 the spatial diffusion coefficient, the convection velocity and the diffusive re-acceleration coefficient,
 90 respectively. The propagation parameters are expected to be the same for all particle species and
 91 were constrained using the available cosmic ray measurements. In this work, the propagation

102 parameters published in [2] were used. The $-\frac{\psi}{\tau}$ term represents the particles lost via inelastic
 103 collisions with interstellar gas and is set by our ${}^3\overline{\text{He}}$ inelastic cross section measurement.

104 We implemented the ${}^3\overline{\text{He}}$ source functions for both dark matter annihilations and cosmic ray
 105 collisions with interstellar medium. The source function for dark matter annihilations is calculated
 106 as:

$$q(\mathbf{r}, E_{\text{kin}}) = \frac{1}{2} \frac{\rho_{\text{DM}}^2(\mathbf{r})}{m_\chi^2} \langle \sigma v \rangle \frac{dN}{dE_{\text{kin}}}, \quad (3)$$

107 where \mathbf{r} is the position in the Galaxy at which the source is calculated. The ${}^3\overline{\text{He}}$ kinetic energy and
 108 the dark matter particle mass are indicated with E_{kin} and m_χ , respectively. The velocity averaged
 109 annihilation cross section of the dark matter is denoted as $\langle \sigma v \rangle$. We use $\langle \sigma v \rangle = 2.6 \cdot 10^{-26}$
 110 cm^3s^{-1} [10]. The spectrum of ${}^3\overline{\text{He}}$ produced in dark matter annihilation is indicated as dN/dE_{kin}
 111 and we use the spectra published in [8] for the $m_\chi = 100$ GeV dark matter particles annihilating
 112 through W^+W^- and through $b\bar{b}$ channels. The Navarro–Frenk–White [6] dark matter density profile
 113 was assumed.

114 The ${}^3\overline{\text{He}}$ source function for cosmic ray collisions with the interstellar gas is expressed as:

$$q(\mathbf{r}, p) = \sum_{\text{CR}=\text{p,He}} \sum_{\text{ISM}=\text{H,He}} n_{\text{ISM}}(\mathbf{r}) \int dp'_{\text{CR}} \beta_{\text{CR}} c \frac{d\sigma(p, p'_{\text{CR}})}{dp} n_{\text{CR}}(\mathbf{r}, p'_{\text{CR}}). \quad (4)$$

115 Both cosmic rays (CR) and the interstellar medium (ISM) consist mainly of protons and helium
 116 thus the pp, p–He, He–p and He–He collisions must be included. The sums over CR and ISM
 117 account for this. The density of the interstellar gas is denoted as $n_{\text{ISM}}(\mathbf{r})$, while p'_{CR} , β_{CR} and
 118 $n(\mathbf{r}, p'_{\text{CR}})$ are the momentum, the velocity and the density of the cosmic rays. p is the momentum
 119 of produced ${}^3\overline{\text{He}}$. $d\sigma(p, p')/dp$ is the ${}^3\overline{\text{He}}$ differential production cross section which was taken
 120 from [9].

121 As existing and planned cosmic ray detectors will operate inside the Solar System, one must
 122 account for the solar modulation. In this work, it was done by using the Force-Field approximation
 123 with a Fisk potential value of 0.4 GeV.

124 The ${}^3\overline{\text{He}}$ cosmic ray flux was first estimated by setting the ${}^3\overline{\text{He}}$ inelastic cross section to zero,
 125 thus no inelastic interactions of ${}^3\overline{\text{He}}$ nuclei with interstellar medium happen on their way to the
 126 Solar System. Then the inelastic cross section is set to values estimated using ALICE data and
 127 the ${}^3\overline{\text{He}}$ flux is reevaluated. The ratio of these fluxes defines the survival probability of ${}^3\overline{\text{He}}$ in the
 128 galaxy, or the transparency of our galaxy to the ${}^3\overline{\text{He}}$ nuclei. This approach allows us to calculate
 129 the transparency of the galaxy to antinuclei.

120 4. Conclusions

121 We measured the inelastic cross section of ${}^3\overline{\text{He}}$ using the ALICE detector as a target material.
 122 This measurement is a necessary component for indirect dark matter searches using the antinuclei
 123 cosmic rays. The described procedure to study ${}^3\overline{\text{He}}$ cosmic rays using GALPROP can be used to
 124 calculate the transparency of the galaxy to antinuclei. The presented ${}^3\overline{\text{He}}$ inelastic cross section
 125 measurement can be used as a reference in future ${}^3\overline{\text{He}}$ cosmic ray studies and provide experimental
 126 uncertainties from inelastic processes of ${}^3\overline{\text{He}}$ in the galaxy on the fluxes of ${}^3\overline{\text{He}}$.

127 **References**

- 128 [1] A. Strong and I. Moskalenko, “Propagation of cosmic-ray nucleons in the galaxy”, *Astrophys.*
129 *J.* 509(1998) 212–228, arXiv:astro-ph/9807150
- 130 [2] M. Boschini et al., “Inference of the Local Interstellar Spectra of Cosmic-Ray Nuclei
131 $Z \leq 28$ with the GALPROP-HelMod Framework”, *Astrophys. J. Suppl.* 250 no. 2, (2020)
132 27, arXiv:2006.01337 [astro-ph.HE]
- 133 [3] **ALICE** Collaboration, S. Acharya et al., “Measurement of the low-energy antideuteron in-
134 elastic cross section”, *Phys. Rev. Lett.* 125 no. 16, (2020) 162001, arXiv:2005.11122 [nucl-ex]
- 135 [4] **ALICE** Collaboration, K. Aamodt et al., “The ALICE experiment at the CERN LHC”, *JINST*,
136 3 (2008) S08002
- 137 [5] **ALICE** Collaboration, B. B. Abelev et al., “Performance of the ALICE Experiment at the
138 CERN LHC”, *Int. J. Mod. Phys. A* 29(2014) 1430044, arXiv:1402.4476 [nucl-ex]
- 139 [6] J. F. Navarro, C. S. Frenk, and S. D. White, “The Structure of cold dark matter halos”,
140 *Astrophys. J.* 462(1996) 563–575, arXiv:astro-ph/9508025
- 141 [7] V. Uzhinsky, J. Apostolakis, A. Galoyan, G. Folger, V. Grichine, et al., “Antinucleus-nucleus
142 cross sections implemented in GEANT4”, *Phys. Lett. B* 705(2011) 235–239
- 143 [8] E. Carlson, A. Coogan, T. Linden, S. Profumo, A. Ibarra, and S. Wild, “Antihelium from
144 Dark367Matter,” *Phys. Rev. D* 89 no. 7, (2014) 076005, arXiv:1401.2461 [hep-ph]
- 145 [9] A. Shukla, A. Datta, P. von Doetinchem, D.-M. Gomez-Coral, and C. Kanitz, “Large-scale
146 Simulations of Antihelium Production in Cosmic-ray Interactions”, *Phys. Rev. D* 102 no. 6,
147 (2020) 365063004, arXiv:2006.12707 [astro-ph.HE]
- 148 [10] M. Korsmeier, F. Donato, and N. Fornengo, “Prospects to verify a possible dark matter hint
149 in cosmic antiprotons with antideuterons and antihelium”, *Phys. Rev. D* 97 no. 10, (2018)
150 103011, arXiv:1711.08465 [astro-ph.HE]
- 151 [11] **ALICE** Collaboration, S. Acharya et al., “The ALICE Transition Radiation Detector:
152 construction, operation, and performance”, *Nucl. Instrum. Meth. A* 881(2018) 88–127,
153 arXiv:1709.02743[physics.ins-det]
- 154 [12] J. Alme et al., “The ALICE TPC, a large 3-dimensional tracking device with fast readout for
155 ultra-high multiplicity events”, *Nucl. Instrum. Meth. A* 622(2010)
- 156 [13] S. Agostinell et al., “Geant4—a simulation toolkit”, *Nucl. Instrum. Meth. A* 506 (2003) 250–303

157 **Full Authors List: ALICE Collaboration**158 **ALICE Collaboration**

159 S. Acharya¹⁴³, D. Adamová⁹⁸, A. Adler⁷⁶, G. Aglieri Rinella³⁵, M. Agnello³¹, N. Agrawal⁵⁵,
160 Z. Ahammed¹⁴³, S. Ahmad¹⁶, S.U. Ahn⁷⁸, I. Ahuja³⁹, Z. Akbar⁵², A. Akindinov⁹⁵, M. Al-Turany¹¹⁰,
161 S.N. Alam^{16,41}, D. Aleksandrov⁹¹, B. Alessandro⁶¹, H.M. Alfanda⁷, R. Alfaro Molina⁷³, B. Ali¹⁶,
162 Y. Ali¹⁴, A. Alici²⁶, N. Alizadehvandchali¹²⁷, A. Alkin³⁵, J. Alme²¹, T. Alt⁷⁰, L. Altenkamper²¹,
163 I. Altsybeev¹¹⁵, M.N. Anaam⁷, C. Andrei⁴⁹, D. Andreou⁹³, A. Andronic¹⁴⁶, M. Angeletti³⁵,
164 V. Anguelov¹⁰⁷, F. Antinori⁵⁸, P. Antonioli⁵⁵, C. Anuj¹⁶, N. Apadula⁸², L. Aphecetche¹¹⁷, H. Appelshäuser⁷⁰,
165 S. Arcelli²⁶, R. Arnaldi⁶¹, I.C. Arsene²⁰, M. Arslandok^{148,107}, A. Augustinus³⁵, R. Averbeck¹¹⁰,
166 S. Aziz⁸⁰, M.D. Azmi¹⁶, A. Badalà⁵⁷, Y.W. Baek⁴², X. Bai^{131,110}, R. Bailhache⁷⁰, Y. Bailung⁵¹,
167 R. Bala¹⁰⁴, A. Balbino³¹, A. Baldisseri¹⁴⁰, B. Balis², M. Ball⁴⁴, D. Banerjee⁴, R. Barbera²⁷,
168 L. Barioglio¹⁰⁸, M. Barlou⁸⁷, G.G. Barnaföldi¹⁴⁷, L.S. Barnby⁹⁷, V. Barret¹³⁷, C. Bartels¹³⁰,
169 K. Barth³⁵, E. Bartsch⁷⁰, F. Baruffaldi²⁸, N. Bastid¹³⁷, S. Basu⁸³, G. Batigne¹¹⁷, B. Batyunya⁷⁷,
170 D. Bauri⁵⁰, J.L. Bazo Alba¹¹⁴, I.G. Bearden⁹², C. Beattie¹⁴⁸, I. Belikov¹³⁹, A.D.C. Bell Hechavarria¹⁴⁶,
171 F. Bellini²⁶, R. Bellwied¹²⁷, S. Belokurova¹¹⁵, V. Belyaev⁹⁶, G. Bencedi⁷¹, S. Beole²⁵, A. Bercuci⁴⁹,
172 Y. Berdnikov¹⁰¹, A. Berdnikova¹⁰⁷, L. Bergmann¹⁰⁷, M.G. Besoiu⁶⁹, L. Betev³⁵, P.P. Bhaduri¹⁴³,
173 A. Bhasin¹⁰⁴, I.R. Bhat¹⁰⁴, M.A. Bhat⁴, B. Bhattacharjee⁴³, P. Bhattacharya²³, L. Bianchi²⁵,
174 N. Bianchi⁵³, J. Bielčik³⁸, J. Bielčíková⁹⁸, J. Biernat¹²⁰, A. Bilandzic¹⁰⁸, G. Biro¹⁴⁷, S. Biswas⁴,
175 J.T. Blair¹²¹, D. Blau^{91,84}, M.B. Blidaru¹¹⁰, C. Blume⁷⁰, G. Boca^{29,59}, F. Bock⁹⁹, A. Bogdanov⁹⁶,
176 S. Boi²³, J. Bok⁶³, L. Boldizsár¹⁴⁷, A. Bolozdynya⁹⁶, M. Bombara³⁹, P.M. Bond³⁵, G. Bonomi^{142,59},
177 H. Borel¹⁴⁰, A. Borissov⁸⁴, H. Bossi¹⁴⁸, E. Botta²⁵, L. Bratrud⁷⁰, P. Braun-Munzinger¹¹⁰, M. Bregant¹²³,
178 M. Broz³⁸, G.E. Bruno^{109,34}, M.D. Buckland¹³⁰, D. Budnikov¹¹¹, H. Buesching⁷⁰, S. Bufalino³¹,
179 O. Bugnon¹¹⁷, P. Buhler¹¹⁶, Z. Buthelezi^{74,134}, J.B. Butt¹⁴, A. Bylinkin¹²⁹, S.A. Bysiak¹²⁰,
180 M. Cai^{28,7}, H. Caines¹⁴⁸, A. Caliva¹¹⁰, E. Calvo Villar¹¹⁴, J.M.M. Camacho¹²², R.S. Camacho⁴⁶,
181 P. Camerini²⁴, F.D.M. Canedo¹²³, F. Carnesecchi^{35,26}, R. Caron¹⁴⁰, J. Castillo Castellanos¹⁴⁰,
182 E.A.R. Casula²³, F. Catalano³¹, C. Ceballos Sanchez⁷⁷, P. Chakraborty⁵⁰, S. Chandra¹⁴³, S. Chapeland³⁵,
183 M. Chartier¹³⁰, S. Chattopadhyay¹⁴³, S. Chattopadhyay¹¹², A. Chauvin²³, T.G. Chavez⁴⁶, T. Cheng⁷,
184 C. Cheshkov¹³⁸, B. Cheynis¹³⁸, V. Chibante Barroso³⁵, D.D. Chinellato¹²⁴, S. Cho⁶³, P. Chochula³⁵,
185 P. Christakoglou⁹³, C.H. Christensen⁹², P. Christiansen⁸³, T. Chujo¹³⁶, C. Cicalo⁵⁶, L. Cifarelli²⁶,
186 F. Cindolo⁵⁵, M.R. Ciupek¹¹⁰, G. Clai^{II,55}, J. Cleymans^{I,126}, F. Colamaria⁵⁴, J.S. Colburn¹¹³,
187 D. Colella^{109,54,34,147}, A. Collu⁸², M. Colocci³⁵, M. Concas^{III,61}, G. Conesa Balbastre⁸¹, Z. Conesa
188 del Valle⁸⁰, G. Contin²⁴, J.G. Contreras³⁸, M.L. Coquet¹⁴⁰, T.M. Cormier⁹⁹, P. Cortese³², M.R. Cosentino¹²⁵,
189 F. Costa³⁵, S. Costanza^{29,59}, P. Crochet¹³⁷, R. Cruz-Torres⁸², E. Cuautle⁷¹, P. Cui⁷, L. Cunqueiro⁹⁹,
190 A. Dainese⁵⁸, M.C. Danisch¹⁰⁷, A. Danu⁶⁹, I. Das¹¹², P. Das⁸⁹, P. Das⁴, S. Das⁴, S. Dash⁵⁰, S. De⁸⁹,
191 A. De Caro³⁰, G. de Cataldo⁵⁴, L. De Cilladi²⁵, J. de Cuveland⁴⁰, A. De Falco²³, D. De Gruttola³⁰,
192 N. De Marco⁶¹, C. De Martin²⁴, S. De Pasquale³⁰, S. Deb⁵¹, H.F. Degenhardt¹²³, K.R. Deja¹⁴⁴,
193 L. Dello Stritto³⁰, S. Delsanto²⁵, W. Deng⁷, P. Dhankher¹⁹, D. Di Bari³⁴, A. Di Mauro³⁵,
194 R.A. Diaz⁸, T. Dietel¹²⁶, Y. Ding^{138,7}, R. Divià³⁵, D.U. Dixit¹⁹, Ø. Djuvsland²¹, U. Dmitrieva⁶⁵,
195 J. Do⁶³, A. Dobrin⁶⁹, B. Dönigus⁷⁰, O. Dordic²⁰, A.K. Dubey¹⁴³, A. Dubla^{110,93}, S. Dudi¹⁰³,
196 M. Dukhishyam⁸⁹, P. Dupieux¹³⁷, N. Dzalaiova¹³, T.M. Eder¹⁴⁶, R.J. Ehlers⁹⁹, V.N. Eikeland²¹,
197 F. Eisenhut⁷⁰, D. Elia⁵⁴, B. Erazmus¹¹⁷, F. Ercolessi²⁶, F. Erhardt¹⁰², A. Erokhin¹¹⁵, M.R. Ersdal²¹,

- 198 B. Espagnon⁸⁰, G. Eulisse³⁵, D. Evans¹¹³, S. Evdokimov⁹⁴, L. Fabbietti¹⁰⁸, M. Faggin²⁸, J. Faivre⁸¹,
 199 F. Fan⁷, A. Fantoni⁵³, M. Fasel⁹⁹, P. Fecchio³¹, A. Feliciello⁶¹, G. Feofilov¹¹⁵, A. Fernández
 200 Téllez⁴⁶, A. Ferrero¹⁴⁰, A. Ferretti²⁵, V.J.G. Feuillard¹⁰⁷, J. Figiel¹²⁰, S. Filchagin¹¹¹, D. Finogeev⁶⁵,
 201 F.M. Fionda^{56,21}, G. Fiorenza^{35,109}, F. Flor¹²⁷, A.N. Flores¹²¹, S. Foertsch⁷⁴, P. Foka¹¹⁰, S. Fokin⁹¹,
 202 E. Fragiaco⁶², E. Frajna¹⁴⁷, U. Fuchs³⁵, N. Funicello³⁰, C. Furget⁸¹, A. Furs⁶⁵, J.J. Gaardhøje⁹²,
 203 M. Gagliardi²⁵, A.M. Gago¹¹⁴, A. Gal¹³⁹, C.D. Galvan¹²², P. Ganoti⁸⁷, C. Garabatos¹¹⁰, J.R.A. Garcia⁴⁶,
 204 E. Garcia-Solis¹⁰, K. Garg¹¹⁷, C. Gargiulo³⁵, A. Garibli⁹⁰, K. Garner¹⁴⁶, P. Gasik¹¹⁰, E.F. Gauger¹²¹,
 205 A. Gautam¹²⁹, M.B. Gay Ducati⁷², M. Germain¹¹⁷, P. Ghosh¹⁴³, S.K. Ghosh⁴, M. Giacalone²⁶,
 206 P. Gianotti⁵³, P. Giubellino^{110,61}, P. Giubileo²⁸, A.M.C. Glaenger¹⁴⁰, P. Glässel¹⁰⁷, D.J.Q. Goh⁸⁵,
 207 V. Gonzalez¹⁴⁵, L.H. González-Trueba⁷³, S. Gorbunov⁴⁰, M. Gorgon², L. Görlich¹²⁰, S. Gotovac³⁶,
 208 V. Grabski⁷³, L.K. Graczykowski¹⁴⁴, L. Greiner⁸², A. Grelli⁶⁴, C. Grigoras³⁵, V. Grigoriev⁹⁶,
 209 S. Grigoryan^{77,1}, O.S. Groettvik²¹, F. Grosa^{35,61}, J.F. Grosse-Oetringhaus³⁵, R. Grosso¹¹⁰, G.G. Guardiano¹²⁴,
 210 R. Guernane⁸¹, M. Guilbaud¹¹⁷, K. Gulbrandsen⁹², T. Gunji¹³⁵, W. Guo⁷, A. Gupta¹⁰⁴, R. Gupta¹⁰⁴,
 211 S.P. Guzman⁴⁶, L. Gyulai¹⁴⁷, M.K. Habib¹¹⁰, C. Hadjidakis⁸⁰, G. Halimoglu⁷⁰, H. Hamagaki⁸⁵,
 212 G. Hamar¹⁴⁷, M. Hamid⁷, R. Hannigan¹²¹, M.R. Haque^{144,89}, A. Harlanderova¹¹⁰, J.W. Harris¹⁴⁸,
 213 A. Harton¹⁰, J.A. Hasenbichler³⁵, H. Hassan⁹⁹, D. Hatzifotiadou⁵⁵, P. Hauer⁴⁴, L.B. Havener¹⁴⁸,
 214 S. Hayashi¹³⁵, S.T. Heckel¹⁰⁸, E. Hellbär¹¹⁰, H. Helstrup³⁷, T. Herman³⁸, E.G. Hernandez⁴⁶,
 215 G. Herrera Corral⁹, F. Herrmann¹⁴⁶, K.F. Hetland³⁷, H. Hillemanns³⁵, C. Hills¹³⁰, B. Hippolyte¹³⁹,
 216 B. Hofman⁶⁴, B. Hohlweger⁹³, J. Honermann¹⁴⁶, G.H. Hong¹⁴⁹, D. Horak³⁸, A. Horzyk², R. Hosokawa¹⁵,
 217 Y. Hou⁷, P. Hristov³⁵, C. Hughes¹³³, P. Huhn⁷⁰, T.J. Humanic¹⁰⁰, H. Hushnud¹¹², L.A. Husova¹⁴⁶,
 218 A. Hutson¹²⁷, D. Hutter⁴⁰, J.P. Iddon^{35,130}, R. Ilkaev¹¹¹, H. Ilyas¹⁴, M. Inaba¹³⁶, G.M. Innocenti³⁵,
 219 M. Ippolitov⁹¹, A. Isakov^{38,98}, M.S. Islam¹¹², M. Ivanov¹¹⁰, V. Ivanov¹⁰¹, V. Izucheev⁹⁴, M. Jablonski²,
 220 B. Jacak⁸², N. Jacazio³⁵, P.M. Jacobs⁸², S. Jadlovská¹¹⁹, J. Jadlovsky¹¹⁹, S. Jaelani⁶⁴, C. Jahnke^{124,123},
 221 M.J. Jakubowska¹⁴⁴, A. Jalotra¹⁰⁴, M.A. Janik¹⁴⁴, T. Janson⁷⁶, M. Jercic¹⁰², O. Jevons¹¹³, A.A.P. Jimenez⁷¹,
 222 F. Jonas^{99,146}, P.G. Jones¹¹³, J.M. Jowett^{35,110}, J. Jung⁷⁰, M. Jung⁷⁰, A. Junique³⁵, A. Jusko¹¹³,
 223 J. Kaewjai¹¹⁸, P. Kalinak⁶⁶, A.S. Kalteyer¹¹⁰, A. Kalweit³⁵, V. Kaplin⁹⁶, S. Kar⁷, A. Karasu
 224 Uysal⁷⁹, D. Karatovic¹⁰², O. Karavichev⁶⁵, T. Karavicheva⁶⁵, P. Karczmarczyk¹⁴⁴, E. Karpechev⁶⁵,
 225 A. Kazantsev⁹¹, U. Kebschull⁷⁶, R. Keidel⁴⁸, D.L.D. Keijdener⁶⁴, M. Keil³⁵, B. Ketzer⁴⁴, Z. Khabanova⁹³,
 226 A.M. Khan⁷, S. Khan¹⁶, A. Khanzadeev¹⁰¹, Y. Kharlov^{94,84}, A. Khatun¹⁶, A. Khuntia¹²⁰, B. Kileng³⁷,
 227 B. Kim^{17,63}, C. Kim¹⁷, D.J. Kim¹²⁸, E.J. Kim⁷⁵, J. Kim¹⁴⁹, J.S. Kim⁴², J. Kim¹⁰⁷, J. Kim¹⁴⁹,
 228 J. Kim⁷⁵, M. Kim¹⁰⁷, S. Kim¹⁸, T. Kim¹⁴⁹, S. Kirsch⁷⁰, I. Kisel⁴⁰, S. Kiselev⁹⁵, A. Kisiel¹⁴⁴,
 229 J.P. Kitowski², J.L. Klay⁶, J. Klein³⁵, S. Klein⁸², C. Klein-Bösing¹⁴⁶, M. Kleiner⁷⁰, T. Klemenz¹⁰⁸,
 230 A. Kluge³⁵, A.G. Knospe¹²⁷, C. Kobdaj¹¹⁸, M.K. Köhler¹⁰⁷, T. Kollegger¹¹⁰, A. Kondratyev⁷⁷,
 231 N. Kondratyeva⁹⁶, E. Kondratyuk⁹⁴, J. König⁷⁰, S.A. Königstorfer¹⁰⁸, P.J. Konopka^{35,2}, G. Kornakov¹⁴⁴,
 232 S.D. Koryciak², L. Koska¹¹⁹, A. Kotliarov⁹⁸, O. Kovalenko⁸⁸, V. Kovalenko¹¹⁵, M. Kowalski¹²⁰,
 233 I. Králik⁶⁶, A. Kravčáková³⁹, L. Kreis¹¹⁰, M. Krivda^{113,66}, F. Krizek⁹⁸, K. Krizkova Gajdosova³⁸,
 234 M. Kroesen¹⁰⁷, M. Krüger⁷⁰, E. Kryshen¹⁰¹, M. Krzewicki⁴⁰, V. Kučera³⁵, C. Kuhn¹³⁹, P.G. Kuijjer⁹³,
 235 T. Kumaoka¹³⁶, D. Kumar¹⁴³, L. Kumar¹⁰³, N. Kumar¹⁰³, S. Kundu³⁵, P. Kurashvili⁸⁸, A. Kurepin⁶⁵,
 236 A.B. Kurepin⁶⁵, A. Kuryakin¹¹¹, S. Kushpil⁹⁸, J. Kvapil¹¹³, M.J. Kweon⁶³, J.Y. Kwon⁶³, Y. Kwon¹⁴⁹,
 237 S.L. La Pointe⁴⁰, P. La Rocca²⁷, Y.S. Lai⁸², A. Lakrathok¹¹⁸, M. Lamanna³⁵, R. Langoy¹³²,
 238 K. Lapidus³⁵, P. Larionov^{35,53}, E. Laudi³⁵, L. Lautner^{35,108}, R. Lavicka³⁸, T. Lazareva¹¹⁵, R. Lea^{142,24,59},
 239 J. Lehrbach⁴⁰, R.C. Lemmon⁹⁷, I. León Monzón¹²², E.D. Lesser¹⁹, M. Lettrich^{35,108}, P. Lévai¹⁴⁷,
 240 X. Li¹¹, X.L. Li⁷, J. Lien¹³², R. Lietava¹¹³, B. Lim¹⁷, S.H. Lim¹⁷, V. Lindenstruth⁴⁰, A. Lindner⁴⁹,

- 241 C. Lippmann¹¹⁰, A. Liu¹⁹, D.H. Liu⁷, J. Liu¹³⁰, I.M. Lofnes²¹, V. Loginov⁹⁶, C. Loizides⁹⁹,
 242 P. Loncar³⁶, J.A. Lopez¹⁰⁷, X. Lopez¹³⁷, E. López Torres⁸, J.R. Luhder¹⁴⁶, M. Lunardon²⁸,
 243 G. Luparello⁶², Y.G. Ma⁴¹, A. Maevskaya⁶⁵, M. Mager³⁵, T. Mahmoud⁴⁴, A. Maire¹³⁹, M. Malaev¹⁰¹,
 244 N.M. Malik¹⁰⁴, Q.W. Malik²⁰, L. Malinina^{IV,77}, D. Mal'Kevich⁹⁵, N. Mallick⁵¹, P. Malzacher¹¹⁰,
 245 G. Mandaglio^{33,57}, V. Manko⁹¹, F. Manso¹³⁷, V. Manzari⁵⁴, Y. Mao⁷, J. Mareš⁶⁸, G.V. Margagliotti²⁴,
 246 A. Margotti⁵⁵, A. Marín¹¹⁰, C. Markert¹²¹, M. Marquard⁷⁰, N.A. Martin¹⁰⁷, P. Martinengo³⁵,
 247 J.L. Martinez¹²⁷, M.I. Martínez⁴⁶, G. Martínez García¹¹⁷, S. Masciocchi¹¹⁰, M. Maserà²⁵, A. Masoni⁵⁶,
 248 L. Massacrier⁸⁰, A. Mastroserio^{141,54}, A.M. Mathis¹⁰⁸, O. Matonoha⁸³, P.F.T. Matuoka¹²³, A. Matyja¹²⁰,
 249 C. Mayer¹²⁰, A.L. Mazuecos³⁵, F. Mazzaschi²⁵, M. Mazzilli³⁵, M.A. Mazzoni^{I,60}, J.E. Mdhuli¹³⁴,
 250 A.F. Mechler⁷⁰, F. Meddi²², Y. Melikyan⁶⁵, A. Menchaca-Rocha⁷³, E. Meninno^{116,30}, A.S. Menon¹²⁷,
 251 M. Meres¹³, S. Mhlanga^{126,74}, Y. Miake¹³⁶, L. Micheletti^{61,25}, L.C. Migliorin¹³⁸, D.L. Mihaylov¹⁰⁸,
 252 K. Mikhaylov^{77,95}, A.N. Mishra¹⁴⁷, D. Miśkowiec¹¹⁰, A. Modak⁴, A.P. Mohanty⁶⁴, B. Mohanty⁸⁹,
 253 M. Mohisin Khan^{V,16}, M.A. Molander⁴⁵, Z. Moravcova⁹², C. Mordasini¹⁰⁸, D.A. Moreira De
 254 Godoy¹⁴⁶, L.A.P. Moreno⁴⁶, I. Morozov⁶⁵, A. Morsch³⁵, T. Mrnjavac³⁵, V. Muccifora⁵³, E. Mudnic³⁶,
 255 D. Mühlheim¹⁴⁶, S. Muhuri¹⁴³, J.D. Mulligan⁸², A. Mulliri²³, M.G. Munhoz¹²³, R.H. Munzer⁷⁰,
 256 H. Murakami¹³⁵, S. Murray¹²⁶, L. Musa³⁵, J. Musinsky⁶⁶, J.W. Myrcha¹⁴⁴, B. Naik^{134,50}, R. Nair⁸⁸,
 257 B.K. Nandi⁵⁰, R. Nania⁵⁵, E. Nappi⁵⁴, A.F. Nassirpour⁸³, A. Nath¹⁰⁷, C. Natrass¹³³, A. Neagu²⁰,
 258 L. Nellen⁷¹, S.V. Nesbo³⁷, G. Neskovic⁴⁰, D. Nesterov¹¹⁵, B.S. Nielsen⁹², S. Nikolaev⁹¹, S. Nikulin⁹¹,
 259 V. Nikulin¹⁰¹, F. Noferini⁵⁵, S. Noh¹², P. Nomokonov⁷⁷, J. Norman¹³⁰, N. Novitzky¹³⁶, P. Nowakowski¹⁴⁴,
 260 A. Nyanin⁹¹, J. Nystrand²¹, M. Ogino⁸⁵, A. Ohlson⁸³, V.A. Okorokov⁹⁶, J. Oleniacz¹⁴⁴, A.C. Oliveira
 261 Da Silva¹³³, M.H. Oliver¹⁴⁸, A. Onnerstad¹²⁸, C. Oppedisano⁶¹, A. Ortiz Velasquez⁷¹, T. Osako⁴⁷,
 262 A. Oskarsson⁸³, J. Otwinowski¹²⁰, M. Oya⁴⁷, K. Oyama⁸⁵, Y. Pachmayer¹⁰⁷, S. Padhan⁵⁰, D. Pagano^{142,59},
 263 G. Paic⁷¹, A. Palasciano⁵⁴, J. Pan¹⁴⁵, S. Panebianco¹⁴⁰, P. Pareek¹⁴³, J. Park⁶³, J.E. Parkkila¹²⁸,
 264 S.P. Pathak¹²⁷, R.N. Patra^{104,35}, B. Paul²³, H. Pei⁷, T. Peitzmann⁶⁴, X. Peng⁷, L.G. Pereira⁷²,
 265 H. Pereira Da Costa¹⁴⁰, D. Peresunko^{91,84}, G.M. Perez⁸, S. Perrin¹⁴⁰, Y. Pestov⁵, V. Petráček³⁸,
 266 M. Petrovici⁴⁹, R.P. Pezzi^{117,72}, S. Piano⁶², M. Pikna¹³, P. Pillot¹¹⁷, O. Pinazza^{55,35}, L. Pinsky¹²⁷,
 267 C. Pinto²⁷, S. Pisano⁵³, M. Płoskoń⁸², M. Planinic¹⁰², F. Pliquett⁷⁰, M.G. Poghosyan⁹⁹, B. Polichtchouk⁹⁴,
 268 S. Politano³¹, N. Poljak¹⁰², A. Pop⁴⁹, S. Porteboeuf-Houssais¹³⁷, J. Porter⁸², V. Pozdniakov⁷⁷,
 269 S.K. Prasad⁴, R. Preghenella⁵⁵, F. Prino⁶¹, C.A. Pruneau¹⁴⁵, I. Pshenichnov⁶⁵, M. Puccio³⁵,
 270 S. Qiu⁹³, L. Quaglia²⁵, R.E. Quishpe¹²⁷, S. Ragoni¹¹³, A. Rakotozafindrabe¹⁴⁰, L. Ramello³²,
 271 F. Rami¹³⁹, S.A.R. Ramirez⁴⁶, A.G.T. Ramos³⁴, T.A. Rancien⁸¹, R. Raniwala¹⁰⁵, S. Raniwala¹⁰⁵,
 272 S.S. Räsänen⁴⁵, R. Rath⁵¹, I. Ravasenga⁹³, K.F. Read^{99,133}, A.R. Redelbach⁴⁰, K. Redlich^{VI,88},
 273 A. Rehman²¹, P. Reichelt⁷⁰, F. Reidt³⁵, H.A. Reme-ness³⁷, R. Renfordt⁷⁰, Z. Rescakova³⁹, K. Reygers¹⁰⁷,
 274 A. Riabov¹⁰¹, V. Riabov¹⁰¹, T. Richert⁸³, M. Richter²⁰, W. Riegler³⁵, F. Riggi²⁷, C. Ristea⁶⁹, M. Ro-
 275 dríguez Cahuantzi⁴⁶, K. Røed²⁰, R. Rogalev⁹⁴, E. Rogochaya⁷⁷, T.S. Rogoschinski⁷⁰, D. Rohr³⁵,
 276 D. Röhrich²¹, P.F. Rojas⁴⁶, P.S. Rokita¹⁴⁴, F. Ronchetti⁵³, A. Rosano^{33,57}, E.D. Rosas⁷¹, A. Rossi⁵⁸,
 277 A. Rotondi^{29,59}, A. Roy⁵¹, P. Roy¹¹², S. Roy⁵⁰, N. Rubini²⁶, O.V. Rueda⁸³, R. Rui²⁴, B. Rumyantsev⁷⁷,
 278 P.G. Russek², A. Rustamov⁹⁰, E. Ryabinkin⁹¹, Y. Ryabov¹⁰¹, A. Rybicki¹²⁰, H. Rytönen¹²⁸,
 279 W. Rzeska¹⁴⁴, O.A.M. Saarimaki⁴⁵, R. Sadek¹¹⁷, S. Sadovsky⁹⁴, J. Saetre²¹, K. Šafařík³⁸, S.K. Saha¹⁴³,
 280 S. Saha⁸⁹, B. Sahoo⁵⁰, P. Sahoo⁵⁰, R. Sahoo⁵¹, S. Sahoo⁶⁷, D. Sahu⁵¹, P.K. Sahu⁶⁷, J. Saini¹⁴³,
 281 S. Sakai¹³⁶, M.P. Salvan¹¹⁰, S. Sambyal¹⁰⁴, V. Samsonov^{I,101,96}, D. Sarkar¹⁴⁵, N. Sarkar¹⁴³,
 282 P. Sarma⁴³, V.M. Sarti¹⁰⁸, M.H.P. Sas¹⁴⁸, J. Schambach^{99,121}, H.S. Scheid⁷⁰, C. Schiaua⁴⁹, R. Schicker¹⁰⁷,
 283 A. Schmah¹⁰⁷, C. Schmidt¹¹⁰, H.R. Schmidt¹⁰⁶, M.O. Schmidt³⁵, M. Schmidt¹⁰⁶, N.V. Schmidt^{99,70},

284 A.R. Schmier¹³³, R. Schotter¹³⁹, J. Schukraft³⁵, Y. Schutz¹³⁹, K. Schwarz¹¹⁰, K. Schweda¹¹⁰,
 285 G. Scioli²⁶, E. Scomparin⁶¹, J.E. Seger¹⁵, Y. Sekiguchi¹³⁵, D. Sekihata¹³⁵, I. Selyuzhenkov^{110,96},
 286 S. Senyukov¹³⁹, J.J. Seo⁶³, D. Serebryakov⁶⁵, L. Šerkšnytė¹⁰⁸, A. Sevcenco⁶⁹, T.J. Shaba⁷⁴,
 287 A. Shabanov⁶⁵, A. Shabetai¹¹⁷, R. Shahoyan³⁵, W. Shaikh¹¹², A. Shangaraev⁹⁴, A. Sharma¹⁰³,
 288 H. Sharma¹²⁰, M. Sharma¹⁰⁴, N. Sharma¹⁰³, S. Sharma¹⁰⁴, U. Sharma¹⁰⁴, O. Sheibani¹²⁷, K. Shigaki⁴⁷,
 289 M. Shimomura⁸⁶, S. Shirinkin⁹⁵, Q. Shou⁴¹, Y. Sibiriak⁹¹, S. Siddhanta⁵⁶, T. Siemiarzczuk⁸⁸,
 290 T.F. Silva¹²³, D. Silvermyr⁸³, T. Simantathammakul¹¹⁸, G. Simonetti³⁵, B. Singh¹⁰⁸, R. Singh⁸⁹,
 291 R. Singh¹⁰⁴, R. Singh⁵¹, V.K. Singh¹⁴³, V. Singhal¹⁴³, T. Sinha¹¹², B. Sitar¹³, M. Sitta³², T.B. Skaali²⁰,
 292 G. Skorodumovs¹⁰⁷, M. Slupecki⁴⁵, N. Smirnov¹⁴⁸, R.J.M. Snellings⁶⁴, C. Soncco¹¹⁴, J. Song¹²⁷,
 293 A. Songmoolnak¹¹⁸, F. Soramel²⁸, S. Sorensen¹³³, I. Sputowska¹²⁰, J. Stachel¹⁰⁷, I. Stan⁶⁹,
 294 P.J. Steffanic¹³³, S.F. Stiefelmaier¹⁰⁷, D. Stocco¹¹⁷, I. Storehaug²⁰, M.M. Storetvedt³⁷, C.P. Stylianidis⁹³,
 295 A.A.P. Suaide¹²³, T. Sugitate⁴⁷, C. Suire⁸⁰, M. Sukhanov⁶⁵, M. Suljic³⁵, R. Sultanov⁹⁵, M. Šumbera⁹⁸,
 296 V. Sumberia¹⁰⁴, S. Sumowidagdo⁵², S. Swain⁶⁷, A. Szabo¹³, I. Szarka¹³, U. Tabassam¹⁴, S.F. Taghavi¹⁰⁸,
 297 G. Taillepiéd¹³⁷, J. Takahashi¹²⁴, G.J. Tambave²¹, S. Tang^{137,7}, Z. Tang¹³¹, J.D. Tapia Takaki^{VII, 129},
 298 M. Tarhini¹¹⁷, M.G. Tarzila⁴⁹, A. Tauro³⁵, G. Tejada Muñoz⁴⁶, A. Telesca³⁵, L. Terlizzi²⁵, C. Terrevoli¹²⁷,
 299 G. Tersimonov³, S. Thakur¹⁴³, D. Thomas¹²¹, R. Tieulent¹³⁸, A. Tikhonov⁶⁵, A.R. Timmins¹²⁷,
 300 M. Tkacik¹¹⁹, A. Toia⁷⁰, N. Topilskaya⁶⁵, M. Toppi⁵³, F. Torales-Acosta¹⁹, T. Tork⁸⁰, S.R. Torres³⁸,
 301 A. Trifiró^{33,57}, S. Tripathy^{55,71}, T. Tripathy⁵⁰, S. Trogolo^{35,28}, V. Trubnikov³, W.H. Trzaska¹²⁸,
 302 T.P. Trzcinski¹⁴⁴, B.A. Trzeciak³⁸, A. Tumkin¹¹¹, R. Turrisi⁵⁸, T.S. Tveter²⁰, K. Ullaland²¹,
 303 A. Uras¹³⁸, M. Urioni^{59,142}, G.L. Usai²³, M. Vala³⁹, N. Valle^{29,59}, S. Vallero⁶¹, N. van der Kolk⁶⁴,
 304 L.V.R. van Doremalen⁶⁴, M. van Leeuwen⁹³, P. Vande Vyvre³⁵, D. Varga¹⁴⁷, Z. Varga¹⁴⁷, M. Varga-
 305 Kofarago¹⁴⁷, A. Vargas⁴⁶, M. Vasileiou⁸⁷, A. Vasiliev⁹¹, O. Vázquez Doce^{53,108}, V. Vechernin¹¹⁵,
 306 E. Vercellin²⁵, S. Vergara Limón⁴⁶, L. Vermunt⁶⁴, R. Vértesi¹⁴⁷, M. Verweij⁶⁴, L. Vickovic³⁶,
 307 Z. Vilakazi¹³⁴, O. Villalobos Baillie¹¹³, G. Vino⁵⁴, A. Vinogradov⁹¹, T. Virgili³⁰, V. Vislavicius⁹²,
 308 A. Vodopyanov⁷⁷, B. Volkel³⁵, M.A. Völkl¹⁰⁷, K. Voloshin⁹⁵, S.A. Voloshin¹⁴⁵, G. Volpe³⁴, B. von
 309 Haller³⁵, I. Vorobyev¹⁰⁸, D. Voscek¹¹⁹, N. Vozniuk⁶⁵, J. Vrláková³⁹, B. Wagner²¹, C. Wang⁴¹,
 310 D. Wang⁴¹, M. Weber¹¹⁶, R.J.G.V. Weelden⁹³, A. Wegrzynek³⁵, S.C. Wenzel³⁵, J.P. Wessels¹⁴⁶,
 311 J. Wiechula⁷⁰, J. Wikne²⁰, G. Wilk⁸⁸, J. Wilkinson¹¹⁰, G.A. Willems¹⁴⁶, B. Windelband¹⁰⁷,
 312 M. Winn¹⁴⁰, W.E. Witt¹³³, J.R. Wright¹²¹, W. Wu⁴¹, Y. Wu¹³¹, R. Xu⁷, A.K. Yadav¹⁴³, S. Yalcin⁷⁹,
 313 Y. Yamaguchi⁴⁷, K. Yamakawa⁴⁷, S. Yang²¹, S. Yano⁴⁷, Z. Yin⁷, H. Yokoyama⁶⁴, I.-K. Yoo¹⁷,
 314 J.H. Yoon⁶³, S. Yuan²¹, A. Yuncu¹⁰⁷, V. Zaccolo²⁴, C. Zampolli³⁵, H.J.C. Zanoli⁶⁴, N. Zardoshti³⁵,
 315 A. Zarochentsev¹¹⁵, P. Závada⁶⁸, N. Zaviyalov¹¹¹, M. Zhalov¹⁰¹, B. Zhang⁷, S. Zhang⁴¹, X. Zhang⁷,
 316 Y. Zhang¹³¹, V. Zhrebchevskii¹¹⁵, Y. Zhi¹¹, N. Zhigareva⁹⁵, D. Zhou⁷, Y. Zhou⁹², J. Zhu^{7,110},
 317 Y. Zhu⁷, A. Zichichi²⁶, G. Zinovjev³, N. Zurlo^{142,59}

318 Affiliation Notes

319 ^I Deceased

320 ^{II} Also at: Italian National Agency for New Technologies, Energy and Sustainable Economic De-
 321 velopment (ENEA), Bologna, Italy

322 ^{III} Also at: Dipartimento DET del Politecnico di Torino, Turin, Italy

323 ^{IV} Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear,
 324 Physics, Moscow, Russia

325 ^V Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India

326 ^{VI} Also at: Institute of Theoretical Physics, University of Wrocław, Poland

327 ^{VII} Also at: University of Kansas, Lawrence, Kansas, United States

328

329 **Collaboration Institutes**

330 ¹ A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yere-
331 van, Armenia

332 ² AGH University of Science and Technology, Cracow, Poland

333 ³ Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev,
334 Ukraine

335 ⁴ Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science
336 (CAPSS), Kolkata, India

337 ⁵ Budker Institute for Nuclear Physics, Novosibirsk, Russia

338 ⁶ California Polytechnic State University, San Luis Obispo, California, United States

339 ⁷ Central China Normal University, Wuhan, China

340 ⁸ Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba

341 ⁹ Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mex-
342 ico

343 ¹⁰ Chicago State University, Chicago, Illinois, United States

344 ¹¹ China Institute of Atomic Energy, Beijing, China

345 ¹² Chungbuk National University, Cheongju, Republic of Korea

346 ¹³ Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava,
347 Slovakia

348 ¹⁴ COMSATS University Islamabad, Islamabad, Pakistan

349 ¹⁵ Creighton University, Omaha, Nebraska, United States

350 ¹⁶ Department of Physics, Aligarh Muslim University, Aligarh, India

351 ¹⁷ Department of Physics, Pusan National University, Pusan, Republic of Korea

352 ¹⁸ Department of Physics, Sejong University, Seoul, Republic of Korea

353 ¹⁹ Department of Physics, University of California, Berkeley, California, United States

354 ²⁰ Department of Physics, University of Oslo, Oslo, Norway

355 ²¹ Department of Physics and Technology, University of Bergen, Bergen, Norway

356 ²² Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy

357 ²³ Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy

358 ²⁴ Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy

359 ²⁵ Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy

360 ²⁶ Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy

361 ²⁷ Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy

362 ²⁸ Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy

363 ²⁹ Dipartimento di Fisica e Nucleare e Teorica, Università di Pavia, Pavia, Italy

364 ³⁰ Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno,
365 Italy

- 366 ³¹ Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
- 367 ³² Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and
- 368 INFN Sezione di Torino, Alessandria, Italy
- 369 ³³ Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
- 370 ³⁴ Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
- 371 ³⁵ European Organization for Nuclear Research (CERN), Geneva, Switzerland
- 372 ³⁶ Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University
- 373 of Split, Split, Croatia
- 374 ³⁷ Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen,
- 375 Norway
- 376 ³⁸ Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague,
- 377 Prague, Czech Republic
- 378 ³⁹ Faculty of Science, P.J. Šafárik University, Košice, Slovakia
- 379 ⁴⁰ Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frank-
- 380 furt, Germany
- 381 ⁴¹ Fudan University, Shanghai, China
- 382 ⁴² Gangneung-Wonju National University, Gangneung, Republic of Korea
- 383 ⁴³ Gauhati University, Department of Physics, Guwahati, India
- 384 ⁴⁴ Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität
- 385 Bonn, Bonn, Germany
- 386 ⁴⁵ Helsinki Institute of Physics (HIP), Helsinki, Finland
- 387 ⁴⁶ High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
- 388 ⁴⁷ Hiroshima University, Hiroshima, Japan
- 389 ⁴⁸ Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms,
- 390 Germany
- 391 ⁴⁹ Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- 392 ⁵⁰ Indian Institute of Technology Bombay (IIT), Mumbai, India
- 393 ⁵¹ Indian Institute of Technology Indore, Indore, India
- 394 ⁵² Indonesian Institute of Sciences, Jakarta, Indonesia
- 395 ⁵³ INFN, Laboratori Nazionali di Frascati, Frascati, Italy
- 396 ⁵⁴ INFN, Sezione di Bari, Bari, Italy
- 397 ⁵⁵ INFN, Sezione di Bologna, Bologna, Italy
- 398 ⁵⁶ INFN, Sezione di Cagliari, Cagliari, Italy
- 399 ⁵⁷ INFN, Sezione di Catania, Catania, Italy
- 400 ⁵⁸ INFN, Sezione di Padova, Padova, Italy
- 401 ⁵⁹ INFN, Sezione di Pavia, Pavia, Italy
- 402 ⁶⁰ INFN, Sezione di Roma, Rome, Italy
- 403 ⁶¹ INFN, Sezione di Torino, Turin, Italy
- 404 ⁶² INFN, Sezione di Trieste, Trieste, Italy
- 405 ⁶³ Inha University, Incheon, Republic of Korea
- 406 ⁶⁴ Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht,
- 407 Netherlands
- 408 ⁶⁵ Institute for Nuclear Research, Academy of Sciences, Moscow, Russia

- 409 66 Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
 410 67 Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
 411 68 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
 412 69 Institute of Space Science (ISS), Bucharest, Romania
 413 70 Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
 414 71 Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mex-
 415 ico
 416 72 Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
 417 73 Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
 418 74 iThemba LABS, National Research Foundation, Somerset West, South Africa
 419 75 Jeonbuk National University, Jeonju, Republic of Korea
 420 76 Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik
 421 und Mathematik, Frankfurt, Germany
 422 77 Joint Institute for Nuclear Research (JINR), Dubna, Russia
 423 78 Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
 424 79 KTO Karatay University, Konya, Turkey
 425 80 Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France
 426 81 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-
 427 IN2P3, Grenoble, France
 428 82 Lawrence Berkeley National Laboratory, Berkeley, California, United States
 429 83 Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
 430 84 Moscow Institute for Physics and Technology, Moscow, Russia
 431 85 Nagasaki Institute of Applied Science, Nagasaki, Japan
 432 86 Nara Women's University (NWU), Nara, Japan
 433 87 National and Kapodistrian University of Athens, School of Science, Department of Physics ,
 434 Athens, Greece
 435 88 National Centre for Nuclear Research, Warsaw, Poland
 436 89 National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni,
 437 India
 438 90 National Nuclear Research Center, Baku, Azerbaijan
 439 91 National Research Centre Kurchatov Institute, Moscow, Russia
 440 92 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
 441 93 Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
 442 94 NRC Kurchatov Institute IHEP, Protvino, Russia
 443 95 NRC «Kurchatov»Institute - ITEP, Moscow, Russia
 444 96 NRNU Moscow Engineering Physics Institute, Moscow, Russia
 445 97 Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
 446 98 Nuclear Physics Institute of the Czech Academy of Sciences, Řež u Prahy, Czech Republic
 447 99 Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
 448 100 Ohio State University, Columbus, Ohio, United States
 449 101 Petersburg Nuclear Physics Institute, Gatchina, Russia
 450 102 Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
 451 103 Physics Department, Panjab University, Chandigarh, India

- 452 104 Physics Department, University of Jammu, Jammu, India
453 105 Physics Department, University of Rajasthan, Jaipur, India
454 106 Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
455 107 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
456 108 Physik Department, Technische Universität München, Munich, Germany
457 109 Politecnico di Bari and Sezione INFN, Bari, Italy
458 110 Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerio-
459 nenforschung GmbH, Darmstadt, Germany
460 111 Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
461 112 Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
462 113 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
463 114 Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
464 115 St. Petersburg State University, St. Petersburg, Russia
465 116 Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
466 117 SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France
467 118 Suranaree University of Technology, Nakhon Ratchasima, Thailand
468 119 Technical University of Košice, Košice, Slovakia
469 120 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cra-
470 ców, Poland
471 121 The University of Texas at Austin, Austin, Texas, United States
472 122 Universidad Autónoma de Sinaloa, Culiacán, Mexico
473 123 Universidade de São Paulo (USP), São Paulo, Brazil
474 124 Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
475 125 Universidade Federal do ABC, Santo Andre, Brazil
476 126 University of Cape Town, Cape Town, South Africa
477 127 University of Houston, Houston, Texas, United States
478 128 University of Jyväskylä, Jyväskylä, Finland
479 129 University of Kansas, Lawrence, Kansas, United States
480 130 University of Liverpool, Liverpool, United Kingdom
481 131 University of Science and Technology of China, Hefei, China
482 132 University of South-Eastern Norway, Tonsberg, Norway
483 133 University of Tennessee, Knoxville, Tennessee, United States
484 134 University of the Witwatersrand, Johannesburg, South Africa
485 135 University of Tokyo, Tokyo, Japan
486 136 University of Tsukuba, Tsukuba, Japan
487 137 Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
488 138 Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, Lyon, France
489 139 Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg,
490 France
491 140 Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Département de Physique Nu-
492 cléaire (DPhN), Saclay, France
493 141 Università degli Studi di Foggia, Foggia, Italy
494 142 Università di Brescia, Brescia, Italy

- 495 ¹⁴³ Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
496 ¹⁴⁴ Warsaw University of Technology, Warsaw, Poland
497 ¹⁴⁵ Wayne State University, Detroit, Michigan, United States
498 ¹⁴⁶ Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany
499 ¹⁴⁷ Wigner Research Centre for Physics, Budapest, Hungary
500 ¹⁴⁸ Yale University, New Haven, Connecticut, United States
501 ¹⁴⁹ Yonsei University, Seoul, Republic of Korea
502