Large-scale and multipolar anisotropies of cosmic rays detected at the Pierre Auger Observatory with energies above 4 EeV

R. M. de Almeida$^a$, on behalf of the Pierre Auger$^b$ Collaboration
(a complete list of authors can be found at the end of the proceedings)

$^a$Universidade Federal Fluminense, Av. dos Trabalhadores 424, Volta Redonda, Brazil
$^b$Observatorio Pierre Auger, Av. San Martin Norte 304, 5613 Malargüe, Argentina
E-mail: spokespersons@auger.org

More than half a century after the discovery of ultra-high energy cosmic rays (UHECRs), their origin is still an open question. The study of anisotropies in the arrival directions of such particles is an essential ingredient to solve this puzzle. We update our previous analysis of large-scale anisotropies observed by the Pierre Auger Observatory using the latest data collected before the AugerPrime upgrade. We select events with zenith angles up to 80 degrees, implying a sky coverage of 85%, and energies above 4EeV, for which the surface detector of the Observatory is fully efficient. Dipolar and quadrupolar amplitudes are evaluated through a combined Fourier analysis of the event count rate in right ascension and azimuth. The analysis is performed in three energy bins with boundaries at 4, 8, 16 and 32 EeV and two additional cumulative bins with energies above 8 and 32 EeV. The most significant signal is a dipolar modulation in right ascension for energies above 8 EeV, as previously reported, with statistical significance of 6.6$\sigma$. Additionally, we report the measurements of the angular power spectrum for the same energy bins with the same dataset.
1. Introduction

Ultra-high energy cosmic rays (UHECR) are particles with energies above $1 \text{ EeV}^{1}$ that hit our atmosphere coming from space. Their origin remains an open question in physics and astrophysics. The study of anisotropies in the arrival directions of UHECR as a function of energy is a very important element to unveil their sources. In particular, together with the analysis of features in the energy spectrum and information about the mass composition of these high-energy particles, it can help to understand their acceleration mechanisms at their sources and how they propagate up to Earth. Since the majority of UHECR are charged particles, they are deflected along with their propagation on magnetic field regions. The poor knowledge about the magnitude of the galactic and extragalactic magnetic fields and chemical composition of the cosmic rays makes the identification of such sources a very difficult task. Large-scale anisotropies such as dipolar or quadrupolar patterns in the flux of UHECR are expected in the case of diffusive or quasi-rectilinear propagation from an anisotropic distribution of sources or diffusive propagation from the closest extragalactic source(s). Even for a pure dipole gradient at the entrance of the Galaxy, magnetic deflections are expected to give rise to higher-order multipoles, although with small amplitude [1]. Moreover, the cosmic-ray flux could be also affected by random configurations of point sources and magnetic deflections, showing the relevance of extending the search to larger multipoles. We reconstruct the dipolar and quadrupolar components through a combined Fourier analysis of the event rate in right ascension and azimuth by assuming a pure dipolar and a dipolar plus quadrupolar flux and measure the angular power spectrum of events detected in the Pierre Auger Observatory with energies above $4 \text{ EeV}$. 

2. The data set

The data set used in this work is composed of events detected with the surface detector (SD) of the Pierre Auger Observatory [2] from 2004 January 1 to 2020 December 31 with zenith angles $\theta$ up to 80° and energies above $4 \text{ EeV}$. With this selection, we explore all the directions with declination $\delta$ between $-90^\circ \leq \delta \leq 45^\circ$, covering 85% of the sky, and exploit the fact that the SD is fully efficient for vertical events (those with zenith angles $\theta > 60^\circ$) with an energy above $3 \text{ EeV}$ and for horizontal events (those with zenith angles $\theta < 60^\circ$) with an energy above $4 \text{ EeV}$. We consider a quality cut that requires at least five of the six water-Cherenkov detectors surrounding the station with the largest signal were operational at the time the event was recorded. The total accumulated exposure is $110,000 \text{ km}^2 \text{ sr yr}$. 

For vertical events, the energy estimation is based on the shower signal at 1000 m from the shower core. The latter is affected by variation of the atmospheric conditions, such as changes in the air density and pressure [3]. In particular, under hot weather conditions, the lower air densities tend to increase the lateral spread of the air shower leading to an overestimation of the primary cosmic-ray energy and ultimately to spurious daily and seasonal variations of the flux of cosmic rays above a given energy threshold. Besides, large values of the pressure correspond to an increased (decreased) matter overburden, implying that the shower is in a more (less) advanced stage when it reaches the ground level. These atmospheric effects are taken into account by correcting the energy estimator of the vertical events as described in [3]. Furthermore, the geomagnetic field breaks the

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$^{1} \text{EeV} \equiv 10^{18} \text{ eV}$. 

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circular symmetry of the shower around its axis, leading to a spurious azimuthal modulation of about $\sim 0.7\%$, which is a posteriori corrected for vertical events following [4]. For inclined showers, the electromagnetic component is attenuated because of the larger amount of atmosphere traversed. As a result, the more penetrating muonic component is dominant making the small variations of atmospheric mass overburden negligible for their propagation. Moreover, the geomagnetic effects are accounted for a priori in the shower reconstruction. The analyses reported in this work were performed in three energy bins with boundaries at 4, 8, 16 and 32 EeV and two additional cumulative bins with energies above 8 and 32 EeV.

3. Analyses method and results

3.1 Harmonic analysis

We perform a weighted Rayleigh analysis in right-ascension and azimuth ($x = \alpha$ or $\phi$, respectively). The harmonic amplitudes of order $k$ are given by

$$a_k^x = \frac{2}{N} \sum_{i=1}^{N} w_i \cos(kx_i), \quad b_k^x = \frac{2}{N} \sum_{i=1}^{N} w_i \sin(kx_i),$$

where the sums run over all event $i$ and the normalization factor is $N = \sum_{i=1}^{N} w_i$. The weight factors $w$ take into account the modulations in exposure due to the growth of the array and sporadic dead times as well as the effects of the small tilt of the array, which on average is inclined $0.2^\circ$ toward $\phi_0 \approx -30^\circ$. They are given by

$$w_i = \left[ \Delta N_{\text{cell}}(a_i^0) \times (1 + 0.003 \tan \theta_i \cos(\phi_i - \phi_0)) \right]^{-1},$$

with $\Delta N_{\text{cell}}(a_i^0)$ being the normalized event count rate as a function of the right ascension of the zenith of the observatory $a_i^0$ at the time the $i$-th event is recorded. The amplitudes and phases of the harmonics are given by $r_k^x = \sqrt{(a_k^x)^2 + (b_k^x)^2}$ and $\varphi_k^x = \arctan(b_k^x/a_k^x)/k$. The probability that an amplitude equal to or larger than $r_k^x$ results from fluctuations from an isotropic distribution is given by $P(\geq r_k^x) = \exp(-N(r_k^x)^2/4)$ [5]. The combination of first harmonic analyses in right ascension and azimuth distributions allows the reconstruction of the three components of a dipole. Assuming a pure dipolar flux, the amplitude of the dipole components in the equatorial plane $d_\perp$ and along the rotation axis of the Earth $d_\parallel$ are given by $d_{\perp} = r_1^\alpha / \langle \cos \delta \rangle$ and $d_{\parallel} = r_1^\phi / \langle \cos \ell_{\text{obs}} (\sin \theta) \rangle$, respectively, while the dipole right ascension and declination $(\alpha_d, \delta_d)$ are given by $\alpha_d = \varphi_1^\alpha$ and $\delta_d = \arctan(d_\parallel / d_\perp)$. In Table 1 we show the values of the 3D dipolar reconstruction for the different energy bins considered in this work, as well as the total number of events $N$ for each energy bin and the probability that a dipole equatorial component arises by chance from an isotropic distribution. The largest departure from isotropy is for the inclusive bin above 8 EeV, for which the dipole equatorial component has a probability to arise by chance from an isotropic distribution of $5.1 \times 10^{-11}$, corresponding to a statistical significance of $6.6\sigma$. In the left panel of Fig. 1 we present the normalized count rate as a function of the right ascension in the energy bin $E > 8$ EeV with the first-harmonic modulation obtained through the Rayleigh analysis shown by a black solid line ($\chi^2/\text{dof} = 13.06$ for 10 degrees of freedom). A map of the cosmic-ray flux for this energy
Table 1: 3D dipole reconstruction. Shown are the number of events \( N \), dipole components in the equatorial plane \( d_\parallel \) and along the rotation axis of the Earth \( d_z \), the total 3D amplitude \( d \), dipole direction \((\alpha_d, \delta_d)\) and the probability to get a larger amplitude of \( r_1^\alpha \) from fluctuations of an isotropic distribution.

<table>
<thead>
<tr>
<th>( E ) (EeV)</th>
<th>( N )</th>
<th>( d_\parallel )</th>
<th>( d_z )</th>
<th>( d )</th>
<th>( \alpha_d[^\circ] )</th>
<th>( \delta_d[^\circ] )</th>
<th>( P(\geq r_1^\alpha) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-8</td>
<td>106, 290</td>
<td>0.01(^{+0.006}_{-0.004})</td>
<td>-0.012 ± 0.008</td>
<td>0.016(^{+0.008}_{-0.005})</td>
<td>97 ± 29</td>
<td>-48(^{+23}_{-23})</td>
<td>1.4 \times 10^{-1}</td>
</tr>
<tr>
<td>8-16</td>
<td>32, 794</td>
<td>0.055(^{+0.011}_{-0.009})</td>
<td>-0.03 ± 0.01</td>
<td>0.063(^{+0.013}_{-0.009})</td>
<td>95 ± 10</td>
<td>-28(^{+12}_{-13})</td>
<td>3.1 \times 10^{-7}</td>
</tr>
<tr>
<td>16-32</td>
<td>9, 156</td>
<td>0.072(^{+0.021}_{-0.016})</td>
<td>-0.07 ± 0.03</td>
<td>0.10(^{+0.03}_{-0.02})</td>
<td>81 ± 15</td>
<td>-43(^{+14}_{-14})</td>
<td>7.5 \times 10^{-4}</td>
</tr>
<tr>
<td>≥8</td>
<td>44, 398</td>
<td>0.059(^{+0.009}_{-0.008})</td>
<td>-0.042 ± 0.013</td>
<td>0.073(^{+0.011}_{-0.009})</td>
<td>95 ± 8</td>
<td>-36(^{+9}_{-9})</td>
<td>5.1 \times 10^{-11}</td>
</tr>
<tr>
<td>≥32</td>
<td>2, 448</td>
<td>0.11(^{+0.04}_{-0.03})</td>
<td>-0.12 ± 0.05</td>
<td>0.16(^{+0.05}_{-0.04})</td>
<td>139 ± 19</td>
<td>-47(^{+16}_{-15})</td>
<td>1.0 \times 10^{-2}</td>
</tr>
</tbody>
</table>

Figure 1: Left panel: Distribution of the normalized rate of events with energy above 8 EeV as a function of the right ascension. The first-harmonic modulation obtained through the Rayleigh analysis is shown by a black solid line. Right panel: Map of the flux of cosmic rays above 8 EeV in equatorial coordinates averaged on top-hat windows of 45° radius. The location of the Galactic plane is shown with a dashed line and the Galactic center is indicated with a star.

The dipole amplitudes as a function of energy are presented in the left panel of Fig. 2. The evolution can be described as done in [6] by \( d = d_{10}(E/10 \text{ EeV})^\beta \) with \( d_{10} = 0.050 \pm 0.007 \) and \( \beta = 0.98 \pm 0.15 \). The reconstructed direction of the dipolar anisotropy for the different energy bins is shown in the right panel of Fig. 2 with corresponding 68% C.L. contours of equal probability per unit solid angle, marginalized over the dipole amplitude. There is no clear trend in the change of the dipole direction as a function of energy considering the present accuracy. The growth of the dipole amplitude as a function of energy can be a consequence of the larger relative contribution from nearby sources to the flux at higher energies with respect to the integrated flux from the more distant and isotropically distributed sources [10–18]. This suppression in the flux of sources at large distances is expected to result from the interaction of UHECRs with the background radiation [19, 20]. Interpretation of the reconstructed dipole directions for the different energy bins requires taking into account the magnetic deflections of the particles during their trajectory.
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Energy [EeV]

Dipole amplitude

$10^{-1}$

$10^{5}$

$50$

Figure 2: Left panel: Energy dependence of the dipolar amplitude measured above 4 EeV. Right panel: Reconstructed dipole directions in different energy bins and corresponding 68% C.L. uncertainty, in Galactic coordinates. The dots indicate the positions of 2MRS galaxies within 100 Mpc.

from the sources up to Earth, being a difficult task because of our still uncertain knowledge about cosmic ray composition and Galactic and extragalactic magnetic fields. Nevertheless, by using a detailed large scale structure matter density field [21] derived from the CosmicFlows-2 catalog of peculiar velocities [22], an estimation of the magnitude, direction and energy dependence of the dipolar anisotropy as a function of energy was obtained by performing a combined fit of the dipole components and cosmic ray composition [23].

Allowing for the presence of a quadrupole, the reconstructed dipolar and quadrupolar components of the flux for all energy bins were obtained as in [9] and reported in Table 2. The five independent quadrupolar components are not significant in any of the energy bins.

3.2 Angular Power Spectrum

The angular distribution $\Phi(\mathbf{n})$ of cosmic rays observed by an experiment in some direction $\mathbf{n}$ can be decomposed by separating the dominant monopole contribution from the anisotropic one, $\Delta(\mathbf{n})$, as

$$\Phi(\mathbf{n}) = \frac{N}{4\pi f_1} W(\mathbf{n}) [1 + \Delta(\mathbf{n})],$$

where $W(\mathbf{n})$ is the relative coverage of the observatory, $f_1 = \int d\mathbf{n} W(\mathbf{n})/4\pi$ the fraction of the sky effectively covered by the observatory and $N$ the total number of observed cosmic rays.

Unfortunately, due to the partial sky coverage of the observatory, the estimation of the individual $a_{\ell m}$ coefficients of the spherical harmonic expansion of $\Delta(\mathbf{n})$, and its angular power spectrum $C_\ell = \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2/(2\ell + 1)$, cannot be carried out with relevant resolution as soon as $\ell_{\text{max}} > 2$. However, one can make additional assumptions\textsuperscript{2} about the ensemble-averaged expectation values of the multipole components [24] and it is possible to recover the angular power spectrum coefficients. In this situation, the pseudo-power spectrum $\tilde{C}_\ell = \sum_{m=-\ell}^{\ell} |\tilde{a}_{\ell m}|^2/(2\ell + 1)$ (which is directly measurable, obtained from $\tilde{a}_{\ell m} = \int d\mathbf{n} W(\mathbf{n})\Delta(\mathbf{n})Y_{\ell m}(\mathbf{n})$) is related to the real power spectrum through

$$\tilde{C}_\ell = \sum_{\ell'} M_{\ell\ell'} C_{\ell'}. \quad (4)$$

\textsuperscript{2}For a more detailed discussion about these assumptions see [25].
Table 2: Reconstructed dipole and quadrupole components for different energy bins. The x axis is in the direction $\alpha = 0^\circ$.

The operator $M$ describing the cross-talk induced by the non-uniform exposure between genuine modes is entirely determined by the knowledge of the exposure function and it is given in terms of the Wigner symbols by

$$ M_{\ell \ell'} = \frac{2\ell' + 1}{4\pi} \sum_{\ell_3} (2\ell_3 + 1) W_{\ell_3} \left( \begin{array}{ccc} \ell & \ell' & \ell_3 \\ 0 & 0 & 0 \end{array} \right)^2, \tag{5} $$

with the angular power spectrum of $W(n)$ given by $W_\ell = \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2$. The power spectrum can thus be recovered from the inversion of Eq. 4. The measured power spectra for different energy bins after subtraction of the irreducible noise induced by Poisson fluctuations $\frac{4\pi f_2^2}{N}$, with $f_2 = \int d\mathbf{n} W^2(n)/4\pi$, are presented in Fig.3. Besides the significant dipolar pattern corresponding to $C_1$, in agreement with the Rayleigh analysis, the only $C_\ell$'s that stand above the 99% C.L. of isotropic fluctuations are $C_{17}$, corresponding to an angular scale of $\sim 180^\circ/\ell \approx 11^\circ$, and $C_8,$
corresponding to an angular scale of \( \sim 23^\circ \), for the energy bins \([4, 8] \text{ EeV}\) and \([16, 32] \text{ EeV}\), respectively. After statistical penalization for searches in different multipoles and energy bins (four independent energy bins \times 20\) multipoles measurements = 80), the statistical significances are 3.1% and 15.5%, respectively. All other multipole power \(C_\ell\)'s in different energy bins are not significant.

4. Conclusion

Summarizing, we updated our previous analysis of large-scale anisotropies observed by the Pierre Auger Observatory using data collected until 2020 December 31. The statistical significance of the large-scale dipolar modulation observed above 8 EeV has increased to 6.6\(\sigma\). Besides, the amplitude of the dipole increases with energies although there is no clear trend in the change of the dipole direction as a function of energy, and the quadrupole components are not significant in any of the energy bins. The \(C_1\) obtained from the angular power spectrum increases with energy in agreement with the results obtained by using the Rayleigh analysis. All other multipoles are not
significant. The Pierre Auger Observatory is undergoing a major upgrade phase called AugerPrime [26]. The main goal of the AugerPrime is to enhance the determination of the cosmic-ray mass composition exploiting the 100% duty cycle of the surface detectors. The additional information will certainly help the searches for anisotropies since it will allow to restrict the analyses to less deflected light particles. Therefore, the expectations for improvements in our knowledge about the sources of the ultra-high energy cosmic rays are very promising considering the detection of events by the Pierre Auger Observatory in the next years.

References

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The Pierre Auger Collaboration

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R. M. de Almeida


1 Centro Atómico Bariloche and Instituto Balseiro (CNEA-UNCuyo–CONICET), San Carlos de Bariloche, Argentina
2 Centro de Investigaciones en Láseres y Aplicaciones, CITEDEF and CONICET, Villa Martelli, Argentina
3 Departamento de Física and Departamento de Ciencias de la Atmósfera y los Océanos, FCEyN, Universidad de Buenos Aires and CONICET, Buenos Aires, Argentina
4 IFLP, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
5 Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA), Buenos Aires, Argentina
6 Instituto de Física de Rosario (IFIR) – CONICET/U.N.R. and Facultad de Ciencias Bioquímicas y Farmacéuticas U.N.R., Rosario, Argentina
7 Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), and Universidad Tecnológica Nacional – Facultad Regional Mendoza (CONICET/CNEA), Mendoza, Argentina
8 Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), Buenos Aires, Argentina
9 International Center of Advanced Studies and Instituto de Ciencias Físicas, ECyT-UNSAM and CONICET, Campus Miguelete – San Martín, Buenos Aires, Argentina
10 Observatorio Pierre Auger, Malargüe, Argentina
11 Observatorio Pierre Auger and Comisión Nacional de Energía Atómica, Malargüe, Argentina
12 Universidad Tecnológica Nacional – Facultad Regional Buenos Aires, Buenos Aires, Argentina
13 University of Adelaide, Adelaide, S.A., Australia
14 Universiteit Libre de Bruxelles (ULB), Brussels, Belgium
15 Vrije Universiteit Brussel, Brussels, Belgium
16 Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, RJ, Brazil
17 Centro Federal de Educação Tecnológica do Ceará (CEFET-Ceará), Fortaleza, Brazil
18 Instituto Federal de Educação, Ciência e Tecnologia do Rio de Janeiro (IFRJ), Brazil
19 Universidade de São Paulo, Escola de Engenharia de Lorena, Lorena, SP, Brazil
20 Universidade de São Paulo, Instituto de Física de São Carlos, São Carlos, SP, Brazil
21 Universidade de São Paulo, Instituto de Física, São Paulo, SP, Brazil
22 Universidade Estadual de Campinas, IFGW, Campinas, SP, Brazil
23 Universidade Estadual de Feira de Santana, Feira de Santana, Brazil
24 Universidade Federal do ABC, Santo André, SP, Brazil
25 Universidade Federal do Paraná, Curitiba, Paraná, Brazil
26 Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil
27 Universidade Federal do Rio de Janeiro (UFRJ), Observatório do Valongo, Rio de Janeiro, RJ, Brazil
28 Universidade Federal Fluminense, EEMVR, Volta Redonda, RJ, Brazil
29 Universidade de Medellín, Medellín, Colombia
30 Universidad Industrial de Santander, Bucaramanga, Colombia
31 Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Prague, Czech Republic
32 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
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R. M. de Almeida

33 Palacky University, RCPTM, Olomouc, Czech Republic
34 CNRS/IN2P3, IJCLab, Université Paris-Saclay, Orsay, France
35 Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Sorbonne Université, Université de Paris, CNRS-IN2P3, Paris, France
36 Univ. Grenoble Alpes, CNRS, Grenoble Institute of Engineering Univ. Grenoble Alpes, LPSC-IN2P3, 38000 Grenoble, France
37 Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
38 Bergische Universität Wuppertal, Department of Physics, Wuppertal, Germany
39 Karlsruhe Institute of Technology (KIT), Institute for Experimental Particle Physics, Karlsruhe, Germany
40 Karlsruhe Institute of Technology (KIT), Institut für Prozessdatenverarbeitung und Elektronik, Karlsruhe, Germany
41 Karlsruhe Institute of Technology (KIT), Institute for Astroparticle Physics, Karlsruhe, Germany
42 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
43 Universität Hamburg, II. Institut für Theoretische Physik, Hamburg, Germany
44 Universität Siegen, Department Physik – Experimentelle Teilchenphysik, Siegen, Germany
45 Gran Sasso Science Institute, L’Aquila, Italy
46 INFN Laboratori Nazionali del Gran Sasso, Assergi (L’Aquila), Italy
47 INFN, Sezione di Catania, Catania, Italy
48 INFN, Sezione di Lecce, Lecce, Italy
49 INFN, Sezione di Milano, Milano, Italy
50 INFN, Sezione di Napoli, Napoli, Italy
51 INFN, Sezione di Roma “Tor Vergata”, Roma, Italy
52 INFN, Sezione di Torino, Torino, Italy
53 Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo (INAF), Palermo, Italy
54 Osservatorio Astrofisico di Torino (INAF), Torino, Italy
55 Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali, Milano, Italy
56 Università del Salento, Dipartimento di Matematica e Fisica “E. De Giorgi”, Lecce, Italy
57 Università dell’Aquila, Dipartimento di Scienze Fisiche e Chimiche, L’Aquila, Italy
58 Università di Catania, Dipartimento di Fisica e Astronomia, Catania, Italy
59 Università di Milano, Dipartimento di Fisica, Milano, Italy
60 Università di Napoli “Federico II”, Dipartimento di Fisica “Ettore Pancini”, Napoli, Italy
61 Università di Palermo, Dipartimento di Fisica e Chimica “E. Segrè”, Palermo, Italy
62 Università di Roma “Tor Vergata”, Dipartimento di Fisica, Roma, Italy
63 Università di Torino, Dipartimento di Fisica, Torino, Italy
64 Benemérita Universidad Autónoma de Puebla, Puebla, México
65 Unidad Profesional Interdisciplinaria en Ingeniería y Tecnologías Avanzadas del Instituto Politécnico Nacional (UPITA-IPN), México, D.F., México
66 Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, México
67 Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México
68 Universidad Nacional Autónoma de México, México, D.F., México
69 Universidad Nacional de San Agustín de Arequipa, Facultad de Ciencias Naturales y Formales, Arequipa, Peru
70 Institute of Nuclear Physics PAN, Krakow, Poland
71 University of Łódź, Faculty of High-Energy Astrophysics, Łódź, Poland
72 Laboratório de Instrumentação e Física Experimental de Partículas – LIP and Instituto Superior Técnico – IST, Universidade de Lisboa – UL, Lisboa, Portugal
73 “Horia Hulubei” National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania
74 Institute of Space Science, Bucharest-Magurele, Romania
75 University Politehnica of Bucharest, Bucharest, Romania
76 Center for Astrophysics and Cosmology (CAC), University of Nova Gorica, Nova Gorica, Slovenia
77 Experimental Particle Physics Department, J. Stefan Institute, Ljubljana, Slovenia
78 Universidad de Granada and C.A.F.P.E., Granada, Spain
79 Instituto Galego de Física de Altas Enxérsias (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
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R. M. de Almeida

80 IMAPP, Radboud University Nijmegen, Nijmegen, The Netherlands
81 Nationaal Instituut voor Kernfysica en Hoge Energie Fysica (NIKHEF), Science Park, Amsterdam, The Netherlands
82 Stichting Astronomisch Onderzoek in Nederland (ASTRON), Dwingeloo, The Netherlands
83 Universiteit van Amsterdam, Faculty of Science, Amsterdam, The Netherlands
84 University of Groningen, Kapteyn Astronomical Institute, Groningen, The Netherlands
85 Case Western Reserve University, Cleveland, OH, USA
86 Colorado School of Mines, Golden, CO, USA
87 Department of Physics and Astronomy, Lehman College, City University of New York, Bronx, NY, USA
88 Louisiana State University, Baton Rouge, LA, USA
89 Michigan Technological University, Houghton, MI, USA
90 New York University, New York, NY, USA
91 Pennsylvania State University, University Park, PA, USA
92 University of Chicago, Enrico Fermi Institute, Chicago, IL, USA
93 University of Delaware, Department of Physics and Astronomy, Bartol Research Institute, Newark, DE, USA
94 University of Wisconsin-Madison, Department of Physics and WIPAC, Madison, WI, USA

—

a Fermi National Accelerator Laboratory, Fermilab, Batavia, IL, USA
b Max-Planck-Institut für Radioastronomie, Bonn, Germany
c School of Physics and Astronomy, University of Leeds, Leeds, United Kingdom
d Colorado State University, Fort Collins, CO, USA
e now at Hakubi Center for Advanced Research and Graduate School of Science, Kyoto University, Kyoto, Japan
f also at University of Bucharest, Physics Department, Bucharest, Romania