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Performance of a proposed event-type based analysis for the Cherenkov Telescope Array

T. Hassan,[a,*] O. Gueta,[b] G. Maier,[b] M. Nöthe,[c] M. Peresano[d] and I. Vovk[e] on behalf of the CTA Consortium
(a complete list of authors can be found at the end of the proceedings)

[a] *Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Av. Complutense, 40, 28040 Madrid, Spain*
[b] *DESY, Platanenallee 6, 15738 Zeuthen, Germany*
[c] *Department of Physics, TU Dortmund University, Otto-Hahn-Str. 4a, 44227 Dortmund, Germany*
[d] *AIM, CEA, CNRS, Universite Paris-Saclay, Universite Paris Diderot, Sorbonne Paris Cite, F-91191 Gif-sur-Yvette, France*
[e] *Institute for Cosmic Ray Research, The University of Tokyo 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba, 277-8582, Japan*
E-mail: tarek.hassan@ciemat.es, orel.gueta@desy.de

The Cherenkov Telescope Array (CTA) will be the next-generation observatory in the field of very-high-energy (20 GeV to 300 TeV) gamma-ray astroparticle physics. Classically, data analysis in the field maximizes sensitivity by applying quality cuts on the data acquired. These cuts, optimized using Monte Carlo simulations, select higher quality events from the initial dataset. Subsequent steps of the analysis typically use the surviving events to calculate one set of instrument response functions (IRFs). An alternative approach is the use of event types, as implemented in experiments such as the Fermi-LAT. In this approach, events are divided into sub-samples based on their reconstruction quality, and a set of IRFs is calculated for each sub-sample. The sub-samples are then combined in a joint analysis, treating them as independent observations. This leads to an improvement in performance parameters such as sensitivity, angular and energy resolution. Data loss is reduced since lower quality events are included in the analysis as well, rather than discarded. In this study, machine learning methods will be used to classify events according to their expected angular reconstruction quality. We will report the impact on CTA high-level performance when applying such an event-type classification, compared to the classical procedure.

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*Presenter

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1. Introduction

The Cherenkov Telescope Array[1] (CTA) will be a next-generation observatory employing an array of imaging atmospheric Cherenkov telescopes (IACTs). The observatory will be built in two different sites, one in each hemisphere. It will provide a major improvement with respect to the current generation of IACTs both in sensitivity and in angular and energy resolution over a very broad energy range (20 GeV up to more than 300 TeV). This improvement will be possible with a cost-effective solution employing arrays of IACTs coming in three different sizes: large-sized telescopes (LSTs, 23-m diameter), medium-sized telescopes (MSTs, 11.5-m diameter) and small-sized telescopes (SSTs, 4.3-m diameter).

The future performance of CTA is estimated from detailed Monte Carlo (MC) simulations. It is encapsulated in a set of Instrument Response Functions (IRFs) such as effective area, energy or angular resolution or residual background rate. The calculation, comparison and ranking of these IRFs and other associated figures of merit have been key in assessing the scientific prospects of CTA, in guiding the development of the different telescope designs[2], in choosing the CTA sites and in fixing the array layouts [1–3]. The methodology used to derive the performance of the future CTA, i.e., the computation of its expected sensitivity and associated IRFs, has been widely described in previous contributions (see e.g., Refs. [1, 2]) and is briefly discussed in section 2.

As proven by the success of the periodic data releases performed by the *Fermi* Large Area Telescope (LAT) Collaboration [4], high-level analysis performance can be significantly boosted by improving the event selection, reflecting the knowledge we have on the performance of the detector into the derived IRFs. By partitioning *Fermi*-LAT events into different Point Spread Functions (PSF) event types, and by computing sets of IRFs specific to each of these types, high-level analysis tools are able to include the extra knowledge provided within the IRFs of the different quality of each event into the likelihood analysis [5, 6]. The benefits achieved by this event-type partitioning range from reducing background contamination to increasing the effective area (and therefore sensitivity) and improving the angular and energy resolution for the subset of the highest quality events.

In this contribution we study the performance of a similar event-type partitioning scheme for CTA data analysis. We test an event partitioning equivalent to the PSF event type used by *Fermi*-LAT, and explore the benefits and drawbacks of such an approach.

2. Cut optimization and performance evaluation

Detailed MC simulations are generated and used to derive the expected response of CTA telescopes to very-high-energy gammas, as well as protons and electrons (the particles which constitute the main irreducible background limiting CTA performance) [7, 8]. A classical IACT analysis is performed on these MC samples, similar to the data analysis employed by the current generation of IACTs [9, 10]. The product of this analysis, generally referred to as Data Level 2 (DL2), contains the reconstructed direction, energy and the likelihood to be signal (gamma-like) or background (mainly proton-like) of each analyzed event. These DL2 tables are re-weighted to resemble the particle statistics expected from standard CTA observations on a Crab-Nebula-like

[1] www.cta-observatory.org
[2] https://www.cta-observatory.org/project/technology/

source, and a cut optimization procedure is performed to find the cuts maximizing the sensitivity of the array as a function of the reconstructed energy. This process specifically optimizes the size of the selected ON region (the region defined as the signal region), event multiplicity (number of CTA telescopes simultaneously detecting and reconstructing each event) and the background rejection likelihood. The optimised cuts are used to produce a single set of IRFs.

This procedure has certain limitations: 1) The amount of data actually used (those events surviving these cuts) is relatively small compared with the original dataset. This leads to a considerable amount of data being rejected, that could nevertheless be useful. 2) Once IRFs are computed, all the extra knowledge we have in lower-level analysis steps (for instance, on the expected quality of each individual event) is lost and, from that point on, all events surviving quality cuts are treated equally.

Event-type partitioning, as proven by the *Fermi*-LAT Collaboration [6], has the potential of better reflecting the knowledge we have on the reconstruction of each event, and of using that information to improve the high-level performance of CTA analysis. In the case of CTA, there are certain parameters that are known to reflect the reconstruction quality of the events. For instance, event multiplicity provides information that is known to dramatically affect the angular resolution of the events, but is lost if a single set of IRFs is produced.

3. Event-type partitioning and data analysis

The methodology described in the previous section was modified in the following manner to implement a PSF event-type partitioning:

- The starting data products are the result of the low-level analysis, i.e., DL2 tables.
- Gamma-ray DL2 tables are divided into 3 different samples: training sample, test sample, and IRF-production sample.
- A regression machine learning algorithm is trained on the training sample to predict for each event the angular reconstruction quality $log\Delta d$ (the difference between the simulated and reconstructed direction of each event, in logarithmic scale). The performance of the machine learning algorithm is evaluated with the test sample.
- The trained regressor is applied to the gamma-ray IRF-production sample and to the rest of the DL2 tables involved in the performance evaluation (protons and electrons), predicting the angular reconstruction quality of each event.
- Gamma-ray DL2 events (from the IRF-production sample) are ranked according to their predicted angular reconstruction quality in equally spaced steps in logarithmic reconstructed energy, and separated into N event type samples with an equal number of events. The angular reconstruction quality thresholds[3] are defined with this sample, and applied to proton and electron DL2 tables, also separated into N samples.

[3] Specific threshold values of $log\Delta d_i$ as a function of the energy, used to define the edges of each of the N event types in the partitioning stage.

- An identical cut optimization and IRF computation is performed on each of the N independent DL2 tables (gamma, proton and electron), following an identical methodology as described in section 2.

All of the code used for this project is available under an open-source BSD-3 license [11]. For the results presented here, we used DL2 analysis results from the EventDisplay analysis chain [9] from the fifth large-scale CTA MC production [12]. The DL2 tables contain simulated observations at 20 degrees in zenith pointing both to North and South directions. Diffuse gamma-ray simulations[4] were used for the training and test samples (with a 75% to 25% ratio, respectively), while point-like gamma-ray simulations[5] were used for the IRF-production sample (full available statistics). A wide variety of machine learning algorithms were tested, both from the *sklearn* and *tensorflow* libraries [13, 14]. A long list of low-level training features (43 in total) were used during the training [11]. We perform the cut optimization and produce a set of IRFs with *pyirf* [15].

4. Results

By following the methodology discussed in section 3, we report in the following subsections on the results of both the optimization effort to maximize the angular performance prediction and the resulting CTA performance estimations.

4.1 Performance of angular reconstruction quality predictors

Predictions were performed using several regression machine learning algorithms. The reason why classification methods were not used was that regressors provide similar performance while allowing a better control of the subsequent event-type partitioning. A preliminary evaluation suggests that the best performance is provided by a multilayer perceptron (MLP) neural network with a *tanh* as neuron activation function.

The required training statistics to reach good performance is a key aspect of this study, as CTA computing requirements could be the limiting factor to realistically implement the methods proposed in this work. Fig. 1 (top) shows that available diffuse gamma-ray simulations statistics is probably not enough to reach the best performance possible, as ideally the same simulations would be needed to compute IRFs over the whole field of view of CTA. For the results shown here, this is not an issue, as we use an independent point-like gamma-ray sample to compute PSF event-types performance.

As an example, for a data separation into $N = 3$ PSF event types, fig. 1 (bottom left and right) shows the confusion matrix[6] on both the actual distribution of the angular reconstruction quality and event-type classification of a single energy bin. For this specific energy range, we can see how "good" events (type 1) are mostly predicted into the first two event types, while "bad" events are generally well characterized within event type 2 or 3.

[4] Arrival directions of simulated gamma rays cover the whole field of view of CTA telescopes
[5] Simulated gamma rays come from a single point at the centre of the field of view of CTA telescopes
[6] Matrix showing the percentage of correct/incorrect classifications of each event type by the algorithm.

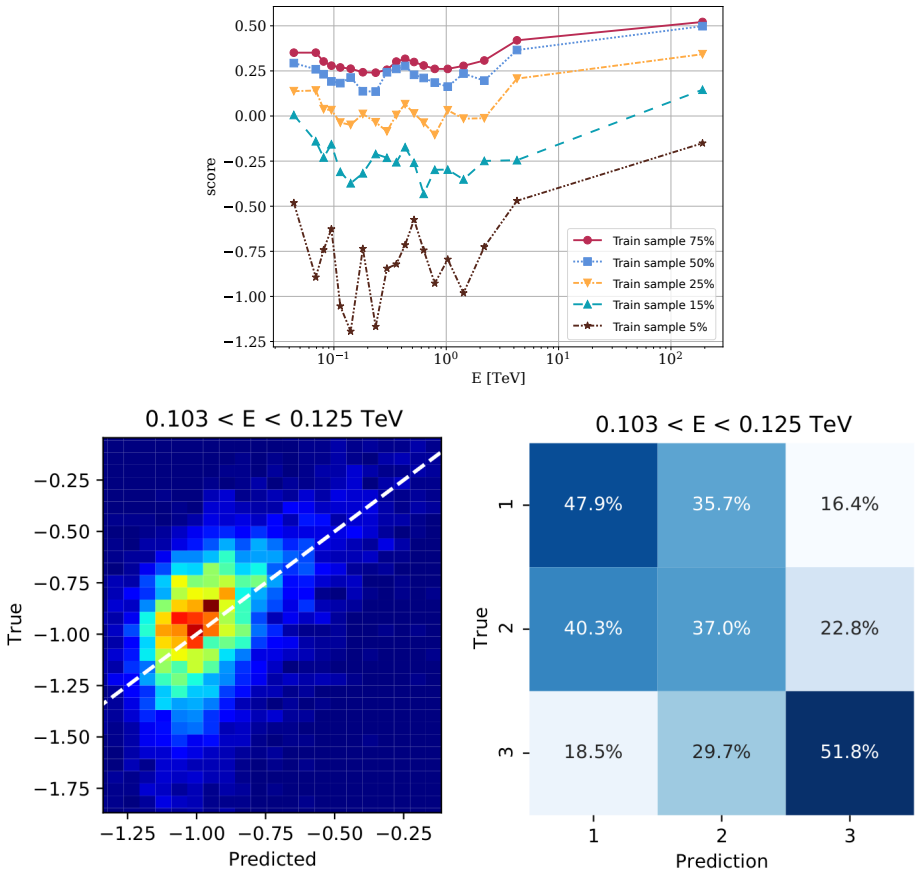

Figure 1: *Top*) Performance score vs reconstructed energy for different training statistics. Label refers to the percentage of the training sample with respect to the total available training sample. A higher score indicates better performance. *Bottom left*) As an example, true vs predicted distribution of the angular reconstruction quality of a single energy bin, defined as the logarithmic difference between simulated to reconstructed event direction. *Bottom right*) confusion matrix for the same energy range, obtained using a 3 event-type partitioning with equal statistics.

4.2 CTA PSF event type performance

Following the methodology described in the previous sections, we apply a PSF event partitioning into 3 different event types (mainly limited by the background MC statistics) and calculate standard CTA IRFs for a point-source located at the centre of the field of view in 50 hours of observing time for one of the potential layouts of the southern array (14 MSTs and 40 SSTs), as in [12].

As shown in fig. 2 (top left), the comparison between the standard single-IRF cut optimization and the event-type-wise IRFs is not trivial in terms of sensitivity. This is expected given that each event-type-wise IRF only contains 33% of the sample. When looking to the effective area in fig. 2 (top right), we see the amount of event statistics actually used when combining the 3 defined event types is roughly 3.5 times larger for the lowest energies, while in the core energy range of CTA the extra statistics is roughly 25%.

Given the event-type partitioning focused on the PSF, angular resolution is the most relevant

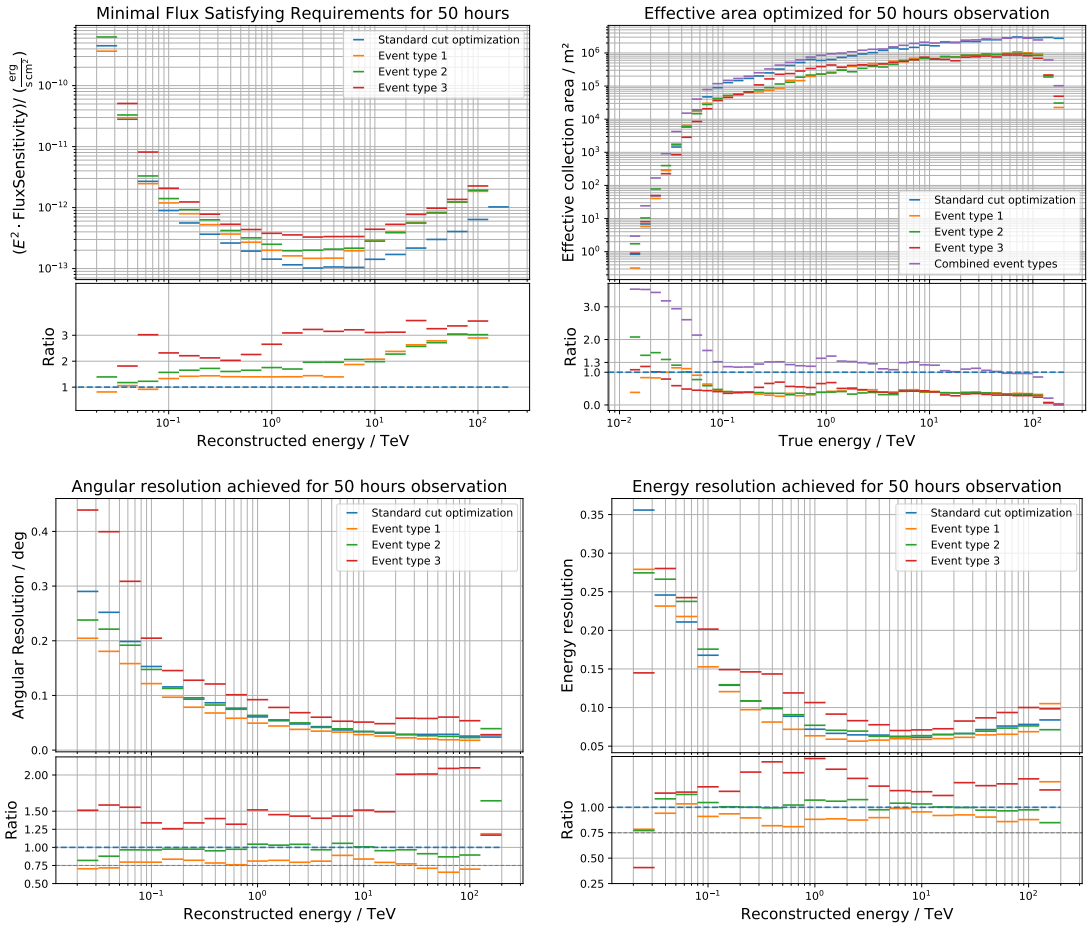

Figure 2: *Top left*) Sensitivity vs reconstructed energy of a potential layout for the southern array (14 MSTs and 40 SSTs) for a point-source located at the centre of the field of view for 50 hours of observation time. Note worse sensitivity of each event type sub-sample is expected, as 33% of the events are used in each of them. *Top right*) Effective area vs true energy for the same array and conditions. The drop appearing at the highest energies is just an effect of lacking proton MC statistics when dividing the sample into 3 event types. *Bottom left*) Angular resolution vs reconstructed energy for the same array and conditions. *Bottom right*) Energy resolution vs reconstructed energy for the same array and conditions.

figure of merit of this study. Fig. 2 (bottom left) shows the PSF event-type partitioning is indeed providing an improved angular resolution of roughly 25% over all energies for the top 33% of the classified events. The event type 2 provides roughly equivalent angular resolution as the one resulting from the standard cut optimization, while the event type 3 clearly identifies those events that have a worse reconstruction across all energies.

Even if it was not the focus of this work, angular and energy resolution are known to be highly correlated within IACTs low-level analysis, i.e. those events with better angular reconstruction are generally also expected to have better energy reconstruction. For this reason, it also makes sense to check how the resulting energy resolution looks, even if the optimized parameter was the angular reconstruction. As shown in fig. 2 (bottom right), event type 1 does indeed also provide an improved energy resolution, event type 2 has the energy resolution roughly resembling the one calculated

within standard IRFs, while event type 3 properly identifies those events with clearly worse energy resolution.

5. Conclusions

Applying an event-type partitioning prior to the IRF computation has been extremely successful for the *Fermi*-LAT analysis. In this work we demonstrate that it also shows great potential for improving CTA future capabilities. By training machine learning methods to predict the angular reconstruction quality of CTA simulated events, we show we are able to separate events according to their quality, providing a 25% improved PSF across all energies for a sub-sample of the events. This classification also provides improved energy resolution, although following an identical methodology one could repeat the study focusing on improving energy resolution (as done in fact by *Fermi*-LAT). This improvement both in angular and energy resolution has also been achieved when applying the described event-type analysis to the one of the candidate CTA northern array layouts..

The resulting event-type-wise sensitivities hint towards a potential improvement at the lowest energies of CTA, coming from the improved cut optimization, as we are indeed providing more information to the cut optimization process by dividing the dataset into samples of different quality. A full high-level simulation of a Crab-Nebula-like observation is needed to test if PSF event types indeed provide a net gain in sensitivity.

The fact that the angular and energy reconstruction are highly correlated within IACTs analysis may actually present a problem for high-level data analysis. Accounting for such a correlation could be computationally prohibitive, while not taking the correlation into account would lead to unrealistic results. By separating events into different event types, the effect of this correlation on the high-level analysis is highly suppressed, as the different IRFs from different event types would represent more realistically the performance of those events.

Applying event-type partitioning comes at a cost: additional MC statistics could be needed to provide an independent sample for the training/testing of the methods, and also because the computation of an increased number of IRFs may require additional data to reach similar statistical uncertainties. This investigation shows that even if additional MC statistics may indeed be required, standard angular/energy reconstruction methods [16] may already be capable of predicting event-wise expected performance (therefore not requiring an independent data sample for their training). Regarding the event statistics required for the IRF computation, we have seen it will not produce an enormous extra stress on CTA computing requirements as IRFs will be computed mainly from events that would be in any case discarded.

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Full Authors List: CTA Consortium

H. Abdalla[1], H. Abe[2], S. Abe[2], A. Abusleme[3], F. Acero[4], A. Acharyya[5], V. Acín Portella[6], K. Ackley[7], R. Adam[8], C. Adams[9], S.S. Adhikari[10], I. Aguado-Ruesga[11], I. Agudo[12], R. Aguilera[13], A. Aguirre-Santaella[14], F. Aharonian[15], A. Alberdi[12], R. Alfaro[16], J. Alfaro[3], C. Alispach[17], R. Aloisio[18], R. Alves Batista[19], J.-P. Amans[20], L. Amati[21], E. Amato[22], L. Ambrogi[18], G. Ambrosi[23], M. Ambrosio[24], R. Ammendola[25], J. Anderson[26], M. Anduze[8], E.O. Angüner[27], L.A. Antonelli[28], V. Antonuccio[29], P. Antoranz[30], R. Anutarawiramkul[31], J. Aragunde Gutierrez[32], C. Aramo[24], A. Araudo[33,34], M. Araya[35], A. Arbet-Engels[36], C. Arcaro[1], V. Arendt[37], C. Armand[38], T. Armstrong[27], F. Arqueros[11], L. Arrabito[39], B. Arsioli[40], M. Artero[41], K. Asano[2], Y. Ascasíbar[14], J. Aschersleben[42], M. Ashley[43], P. Attinà[44], P. Aubert[45], C. B. Singh[19], D. Baack[46], A. Babic[47], M. Backes[48], V. Baena[13], S. 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Trifoglio[21], A. Trois[95], S. Truzzi[62], A. Tsiahina[87], T. Tsuru[180], B. Turk[45], A. Tutone[91], Y. Uchiyama[161], G. Umana[29], P. Utayarat[31], L. Vaclavek[104], M. Vacula[104], V. Vagelli[23,217], F. Vagnetti[25], F. Vakili[218], J.A. Valdivia[192], M. Valentino[24], A. Valio[19], B. Vallage[89], P. Vallania[44,64], J.V. Valverde Quispe[8], A.M. Van den Berg[42], W. van Driel[20], C. van Eldik[142], C. van Rensburg[1], B. van Soelen[210], J. Vandenbroucke[135], J. Vanderwalt[1], G. Vasileiadis[39], V. Vassiliev[71], M. Vázquez Acosta[32], M. Vecchi[42], A. Vega[98], J. Veh[142], P. Veitch[118], P. Venault[75], C. Venter[1], S. Ventura[62], S. Vercellone[95], S. Vergani[20], V. Verguilov[189], G. Verna[27], S. Vernetto[44,64], V. Verzi[25], G.P. Vettolani[90], C. Veyssiere[144], I. Viale[55], A. Viana[80], N. Viaux[35], J. Vicha[33], J. Vignatti[35], C.F. Vigorito[64,108], J. Villanueva[98], J. Vink[174], V. Vitale[23], V. Vittorini[99], V. Vodeb[68], H. Voelk[53], N. Vogel[142], V. Voisin[79], S. Vorobiov[68], I. Vovk[2], M. Vrastil[33], T. Vuillaume[45], S.J. Wagner[170], R. Wagner[105], P. Wagner[52], K. Wakazono[139], S.P. Wakely[127], R. Walter[38], M. Ward[5], D. Warren[54], J. Watson[52], N. Webb[87], M. Wechakama[31], P. Wegner[52], A. Weinstein[129], C. Weniger[174], F. Werner[53], H. Wetteskind[105], M. White[118], R. White[53], A. Wierzcholska[101], S. Wiesand[52], R. Wijers[174], M. Wilkinson[124], M. Will[105], D.A. Williams[143], J. Williams[124], T. Williamson[162], A. Wolter[95], Y.W. Wong[142], M. Wood[96], C. Wunderlich[62], T. Yamamoto[213], H. Yamamoto[141], Y. Yamane[141], R. Yamazaki[209], S. Yanagita[176], L. Yang[205], S. Yoo[180], T. Yoshida[176], T. Yoshikoshi[2], P. Yu[71], P. Yu[85], A. Yusafzai[59], M. Zacharias[20], G. Zaharijas[68], B. Zaldivar[14], L. Zampieri[76], R. Zanmar Sanchez[29], D. Zaric[150], M. Zavrtanik[68], D. Zavrtanik[68], A.A. Zdziarski[49], A. Zech[20], H. Zechlin[64], A. Zenin[139], A. Zerwekh[35], V.I. Zhdanov[136], K. Ziętara[169], A. Zink[142], J. Ziółkowski[49], V. Zitelli[21], M. Živec[68], A. Zmija[142]

1 : Centre for Space Research, North-West University, Potchefstroom, 2520, South Africa

2 : Institute for Cosmic Ray Research, University of Tokyo, 5-1-5, Kashiwa-no-ha, Kashiwa, Chiba 277-8582, Japan

3 : Pontificia Universidad Católica de Chile, Av. Libertador Bernardo O'Higgins 340, Santiago, Chile

4 : AIM, CEA, CNRS, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, CEA Paris-Saclay, IRFU/DAp, Bat 709, Orme des Merisiers, 91191 Gif-sur-Yvette, France

5 : Centre for Advanced Instrumentation, Dept. of Physics, Durham University, South Road, Durham DH1 3LE, United Kingdom

6 : Port d'Informació Científica, Edifici D, Carrer de l'Albareda, 08193 Bellaterrra (Cerdanyola del Vallès), Spain

7 : School of Physics and Astronomy, Monash University, Melbourne, Victoria 3800, Australia

8 : Laboratoire Leprince-Ringuet, École Polytechnique (UMR 7638, CNRS/IN2P3, Institut Polytechnique de Paris), 91128 Palaiseau, France

9 : Department of Physics, Columbia University, 538 West 120th Street, New York, NY 10027, USA

10 : University of Oslo, Department of Physics, Sem Saelandsvei 24 - PO Box 1048 Blindern, N-0316 Oslo, Norway

11 : EMFTEL department and IPARCOS, Universidad Complutense de Madrid, 28040 Madrid, Spain

12 : Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, Spain

13 : Institute of Space Sciences (ICE-CSIC), and Institut d'Estudis Espacials de Catalunya (IEEC), and Institució Catalana de Recerca I Estudis Avançats (ICREA), Campus UAB, Carrer de Can Magrans, s/n 08193 Cerdanyola del Vallés, Spain

14 : Instituto de Física Teórica UAM/CSIC and Departamento de Física Teórica, Universidad Autónoma de Madrid, c/ Nicolás Cabrera 13-15, Campus de Cantoblanco UAM, 28049 Madrid, Spain

15 : Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland

16 : Universidad Nacional Autónoma de México, Delegación Coyoacán, 04510 Ciudad de México, Mexico

17 : University of Geneva - Département de physique nucléaire et corpusculaire, 24 rue du Général-Dufour, 1211 Genève 4, Switzerland

18 : INFN Dipartimento di Scienze Fisiche e Chimiche - Università degli Studi dell'Aquila and Gran Sasso Science Institute, Via Vetoio 1, Viale Crispi 7, 67100 L'Aquila, Italy

19 : Instituto de Astronomia, Geofísico, e Ciências Atmosféricas - Universidade de São Paulo, Cidade Universitária, R. do Matão, 1226, CEP 05508-090, São Paulo, SP, Brazil
20 : LUTH, GEPI and LERMA, Observatoire de Paris, CNRS, PSL University, 5 place Jules Janssen, 92190, Meudon, France
21 : INAF - Osservatorio di Astrofisica e Scienza dello spazio di Bologna, Via Piero Gobetti 93/3, 40129 Bologna, Italy
22 : INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5 - 50125 Firenze, Italy
23 : INFN Sezione di Perugia and Università degli Studi di Perugia, Via A. Pascoli, 06123 Perugia, Italy
24 : INFN Sezione di Napoli, Via Cintia, ed. G, 80126 Napoli, Italy
25 : INFN Sezione di Roma Tor Vergata, Via della Ricerca Scientifica 1, 00133 Rome, Italy
26 : Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, USA
27 : Aix-Marseille Université, CNRS/IN2P3, CPPM, 163 Avenue de Luminy, 13288 Marseille cedex 09, France
28 : INAF - Osservatorio Astronomico di Roma, Via di Frascati 33, 00040, Monteporzio Catone, Italy
29 : INAF - Osservatorio Astrofisico di Catania, Via S. Sofia, 78, 95123 Catania, Italy
30 : Grupo de Electronica, Universidad Complutense de Madrid, Av. Complutense s/n, 28040 Madrid, Spain
31 : National Astronomical Research Institute of Thailand, 191 Huay Kaew Rd., Suthep, Muang, Chiang Mai, 50200, Thailand
32 : Instituto de Astrofísica de Canarias and Departamento de Astrofísica, Universidad de La Laguna, La Laguna, Tenerife, Spain
33 : FZU - Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2, 182 21 Praha 8, Czech Republic
34 : Astronomical Institute of the Czech Academy of Sciences, Bocni II 1401 - 14100 Prague, Czech Republic
35 : CCTVal, Universidad Técnica Federico Santa María, Avenida España 1680, Valparaíso, Chile
36 : ETH Zurich, Institute for Particle Physics, Schafmattstr. 20, CH-8093 Zurich, Switzerland
37 : The University of Manitoba, Dept of Physics and Astronomy, Winnipeg, Manitoba R3T 2N2, Canada
38 : Department of Astronomy, University of Geneva, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland
39 : Laboratoire Univers et Particules de Montpellier, Université de Montpellier, CNRS/IN2P3, CC 72, Place Eugène Bataillon, F-34095 Montpellier Cedex 5, France
40 : Centro Brasileiro de Pesquisas Físicas, Rua Xavier Sigaud 150, RJ 22290-180, Rio de Janeiro, Brazil
41 : Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain
42 : University of Groningen, KVI - Center for Advanced Radiation Technology, Zernikelaan 25, 9747 AA Groningen, The Netherlands
43 : School of Physics, University of New South Wales, Sydney NSW 2052, Australia
44 : INAF - Osservatorio Astrofisico di Torino, Strada Osservatorio 20, 10025 Pino Torinese (TO), Italy
45 : Univ. Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3, 74000 Annecy, France
46 : Department of Physics, TU Dortmund University, Otto-Hahn-Str. 4, 44221 Dortmund, Germany
47 : University of Zagreb, Faculty of electrical engineering and computing, Unska 3, 10000 Zagreb, Croatia
48 : University of Namibia, Department of Physics, 340 Mandume Ndemufayo Ave., Pioneerspark, Windhoek, Namibia
49 : Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland
50 : Universität Hamburg, Institut für Experimentalphysik, Luruper Chaussee 149, 22761 Hamburg, Germany
51 : Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
52 : Deutsches Elektronen-Synchrotron, Platanenallee 6, 15738 Zeuthen, Germany
53 : Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
54 : RIKEN, Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
55 : INFN Sezione di Padova and Università degli Studi di Padova, Via Marzolo 8, 35131 Padova, Italy
56 : Escuela Politécnica Superior de Jaén, Universidad de Jaén, Campus Las Lagunillas s/n, Edif. A3, 23071 Jaén, Spain
57 : Department of Physics and Electrical Engineering, Linnaeus University, 351 95 Växjö, Sweden
58 : University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein, 2000 Johannesburg, South Africa
59 : Institut für Theoretische Physik, Lehrstuhl IV: Plasma-Astroteilchenphysik, Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum, Germany
60 : Faculty of Physics and Applied Computer Science, University of Lódź, ul. Pomorska 149-153, 90-236 Lódź, Poland
61 : INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica di Milano, Via A. Corti 12, 20133 Milano, Italy
62 : INFN and Università degli Studi di Siena, Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente (DSFTA), Sezione di Fisica, Via Roma 56, 53100 Siena, Italy
63 : Center for Astrophysics | Harvard & Smithsonian, 60 Garden St, Cambridge, MA 02180, USA
64 : INFN Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy
65 : Finnish Centre for Astronomy with ESO, University of Turku, Finland, FI-20014 University of Turku, Finland
66 : Pidstryhach Institute for Applied Problems in Mechanics and Mathematics NASU, 3B Naukova Street, Lviv, 79060, Ukraine
67 : Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India
68 : Center for Astrophysics and Cosmology, University of Nova Gorica, Vipavska 11c, 5270 Ajdovščina, Slovenia
69 : Institut für Astronomie und Astrophysik, Universität Tübingen, Sand 1, 72076 Tübingen, Germany
70 : Research School of Astronomy and Astrophysics, Australian National University, Canberra ACT 0200, Australia
71 : Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
72 : INFN Sezione di Bari and Politecnico di Bari, via Orabona 4, 70124 Bari, Italy

73 : Laboratoire de Physique des 2 infinis, Irene Joliot-Curie,IN2P3/CNRS, Université Paris-Saclay, Université de Paris, 15 rue Georges Clemenceau, 91406 Orsay, Cedex, France

74 : INFN Sezione di Pisa, Largo Pontecorvo 3, 56217 Pisa, Italy

75 : IRFU/DEDIP, CEA, Université Paris-Saclay, Bat 141, 91191 Gif-sur-Yvette, France

76 : INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy

77 : INAF - Osservatorio Astronomico di Palermo "G.S. Vaiana", Piazza del Parlamento 1, 90134 Palermo, Italy

78 : School of Physics, University of Sydney, Sydney NSW 2006, Australia

79 : Sorbonne Université, Université Paris Diderot, Sorbonne Paris Cité, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies, LPNHE, 4 Place Jussieu, F-75005 Paris, France

80 : Instituto de Física de São Carlos, Universidade de São Paulo, Av. Trabalhador São-carlense, 400 - CEP 13566-590, São Carlos, SP, Brazil

81 : Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB, Martí i Franquès, 1, 08028, Barcelona, Spain

82 : Department of Physics, Washington University, St. Louis, MO 63130, USA

83 : Saha Institute of Nuclear Physics, Bidhannagar, Kolkata-700 064, India

84 : INAF - Osservatorio Astronomico di Capodimonte, Via Salita Moiariello 16, 80131 Napoli, Italy

85 : Université de Paris, CNRS, Astroparticule et Cosmologie, 10, rue Alice Domon et Léonie Duquet, 75013 Paris Cedex 13, France

86 : Astronomy Department of Faculty of Physics, Sofia University, 5 James Bourchier Str., 1164 Sofia, Bulgaria

87 : Institut de Recherche en Astrophysique et Planétologie, CNRS-INSU, Université Paul Sabatier, 9 avenue Colonel Roche, BP 44346, 31028 Toulouse Cedex 4, France

88 : School of Physics and Astronomy, University of Minnesota, 116 Church Street S.E. Minneapolis, Minnesota 55455-0112, USA

89 : IRFU, CEA, Université Paris-Saclay, Bât 141, 91191 Gif-sur-Yvette, France

90 : INAF - Istituto di Radioastronomia, Via Gobetti 101, 40129 Bologna, Italy

91 : INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo, Via U. La Malfa 153, 90146 Palermo, Italy

92 : Astronomical Observatory, Department of Physics, University of Warsaw, Aleje Ujazdowskie 4, 00478 Warsaw, Poland

93 : Armagh Observatory and Planetarium, College Hill, Armagh BT61 9DG, United Kingdom

94 : INFN Sezione di Catania, Via S. Sofia 64, 95123 Catania, Italy

95 : INAF - Osservatorio Astronomico di Brera, Via Brera 28, 20121 Milano, Italy

96 : Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

97 : Universidade Cruzeiro do Sul, Núcleo de Astrofísica Teórica (NAT/UCS), Rua Galvão Bueno 8687, Bloco B, sala 16, Libertade 01506-000 - São Paulo, Brazil

98 : Universidad de Valparaíso, Blanco 951, Valparaiso, Chile

99 : INAF - Istituto di Astrofisica e Planetologia Spaziali (IAPS), Via del Fosso del Cavaliere 100, 00133 Roma, Italy

100 : Lund Observatory, Lund University, Box 43, SE-22100 Lund, Sweden

101 : The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Cracow, Poland

102 : Escola de Engenharia de Lorena, Universidade de São Paulo, Área I - Estrada Municipal do Campinho, s/n°, CEP 12602-810, Pte. Nova, Lorena, Brazil

103 : INFN Sezione di Trieste and Università degli Studi di Udine, Via delle Scienze 208, 33100 Udine, Italy

104 : Palacky University Olomouc, Faculty of Science, RCPTM, 17. listopadu 1192/12, 771 46 Olomouc, Czech Republic

105 : Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany

106 : CENBG, Univ. Bordeaux, CNRS-IN2P3, UMR 5797, 19 Chemin du Solarium, CS 10120, F-33175 Gradignan Cedex, France

107 : Dublin City University, Glasnevin, Dublin 9, Ireland

108 : Dipartimento di Fisica - Universitá degli Studi di Torino, Via Pietro Giuria 1 - 10125 Torino, Italy

109 : Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India

110 : Universitá degli Studi di Napoli "Federico II" - Dipartimento di Fisica "E. Pancini", Complesso universitario di Monte Sant'Angelo, Via Cintia - 80126 Napoli, Italy

111 : Oskar Klein Centre, Department of Physics, University of Stockholm, Albanova, SE-10691, Sweden

112 : Yale University, Department of Physics and Astronomy, 260 Whitney Avenue, New Haven, CT 06520-8101, USA

113 : CIEMAT, Avda. Complutense 40, 28040 Madrid, Spain

114 : University of Oxford, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom

115 : School of Physics & Astronomy, University of Southampton, University Road, Southampton SO17 1BJ, United Kingdom

116 : Department of Physics and Technology, University of Bergen, Museplass 1, 5007 Bergen, Norway

117 : Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia

118 : School of Physical Sciences, University of Adelaide, Adelaide SA 5005, Australia

119 : INFN Sezione di Roma La Sapienza, P.le Aldo Moro, 2 - 00185 Roma, Italy

120 : INFN Sezione di Bari, via Orabona 4, 70126 Bari, Italy

121 : University of Rijeka, Department of Physics, Radmile Matejcic 2, 51000 Rijeka, Croatia
122 : Institute for Theoretical Physics and Astrophysics, Universität Würzburg, Campus Hubland Nord, Emil-Fischer-Str. 31, 97074 Würzburg, Germany
123 : Universidade Federal Do Paraná - Setor Palotina, Departamento de Engenharias e Exatas, Rua Pioneiro, 2153, Jardim Dallas, CEP: 85950-000 Palotina, Paraná, Brazil
124 : Dept. of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, United Kingdom
125 : Univ. Grenoble Alpes, CNRS, IPAG, 414 rue de la Piscine, Domaine Universitaire, 38041 Grenoble Cedex 9, France
126 : National Centre for nuclear research (Narodowe Centrum Badań Jądrowych), Ul. Andrzeja Sołtana7, 05-400 Otwock, Świerk, Poland
127 : Enrico Fermi Institute, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
128 : Institut für Physik & Astronomie, Universität Potsdam, Karl-Liebknecht-Strasse 24/25, 14476 Potsdam, Germany
129 : Department of Physics and Astronomy, Iowa State University, Zaffarano Hall, Ames, IA 50011-3160, USA
130 : School of Physics, Aristotle University, Thessaloniki, 54124 Thessaloniki, Greece
131 : King's College London, Strand, London, WC2R 2LS, United Kingdom
132 : Escola de Artes, Ciências e Humanidades, Universidade de São Paulo, Rua Arlindo Bettio, CEP 03828-000, 1000 São Paulo, Brazil
133 : Dept. of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
134 : National Technical University of Athens, Department of Physics, Zografos 9, 15780 Athens, Greece
135 : University of Wisconsin, Madison, 500 Lincoln Drive, Madison, WI, 53706, USA
136 : Astronomical Observatory of Taras Shevchenko National University of Kyiv, 3 Observatorna Street, Kyiv, 04053, Ukraine
137 : Department of Physics, Purdue University, West Lafayette, IN 47907, USA
138 : Unitat de Física de les Radiacions, Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, Edifici C3, Campus UAB, 08193 Bellaterra, Spain
139 : Institute for Space-Earth Environmental Research, Nagoya University, Chikusa-ku, Nagoya 464-8601, Japan
140 : Department of Physical Science, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
141 : Department of Physics, Nagoya University, Chikusa-ku, Nagoya, 464-8602, Japan
142 : Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics (ECAP), Erwin-Rommel-Str. 1, 91058 Erlangen, Germany
143 : Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
144 : IRFU / DIS, CEA, Université de Paris-Saclay, Bat 123, 91191 Gif-sur-Yvette, France
145 : INFN Sezione di Trieste and Università degli Studi di Trieste, Via Valerio 2 I, 34127 Trieste, Italy
146 : School of Physics & Center for Relativistic Astrophysics, Georgia Institute of Technology, 837 State Street, Atlanta, Georgia, 30332-0430, USA
147 : Alikhanyan National Science Laboratory, Yerevan Physics Institute, 2 Alikhanyan Brothers St., 0036, Yerevan, Armenia
148 : INAF - Telescopio Nazionale Galileo, Roche de los Muchachos Astronomical Observatory, 38787 Garafia, TF, Italy
149 : INFN Sezione di Bari and Università degli Studi di Bari, via Orabona 4, 70124 Bari, Italy
150 : University of Split - FESB, R. Boskovica 32, 21 000 Split, Croatia
151 : Universidad Andres Bello, República 252, Santiago, Chile
152 : Academic Computer Centre CYFRONET AGH, ul. Nawojki 11, 30-950 Cracow, Poland
153 : University of Liverpool, Oliver Lodge Laboratory, Liverpool L69 7ZE, United Kingdom
154 : Department of Physics, Yamagata University, Yamagata, Yamagata 990-8560, Japan
155 : Astronomy Department, Adler Planetarium and Astronomy Museum, Chicago, IL 60605, USA
156 : Faculty of Management Information, Yamanashi-Gakuin University, Kofu, Yamanashi 400-8575, Japan
157 : Department of Physics, Tokai University, 4-1-1, Kita-Kaname, Hiratsuka, Kanagawa 259-1292, Japan
158 : Centre for Astrophysics Research, Science & Technology Research Institute, University of Hertfordshire, College Lane, Hertfordshire AL10 9AB, United Kingdom
159 : Cherenkov Telescope Array Observatory, Saupfercheckweg 1, 69117 Heidelberg, Germany
160 : Tohoku University, Astronomical Institute, Aobaku, Sendai 980-8578, Japan
161 : Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo, Japan
162 : Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, Newark, DE 19716, USA
163 : Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Technikerstr. 25/8, 6020 Innsbruck, Austria
164 : Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112-0830, USA
165 : IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
166 : Josip Juraj Strossmayer University of Osijek, Trg Ljudevita Gaja 6, 31000 Osijek, Croatia
167 : Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka 560-0043, Japan
168 : Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
169 : Astronomical Observatory, Jagiellonian University, ul. Orla 171, 30-244 Cracow, Poland
170 : Landessternwarte, Zentrum für Astronomie der Universität Heidelberg, Königstuhl 12, 69117 Heidelberg, Germany
171 : University of Alabama, Tuscaloosa, Department of Physics and Astronomy, Gallalee Hall, Box 870324 Tuscaloosa, AL 35487-0324, USA

172 : Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom
173 : University of Iowa, Department of Physics and Astronomy, Van Allen Hall, Iowa City, IA 52242, USA
174 : Anton Pannekoek Institute/GRAPPA, University of Amsterdam, Science Park 904 1098 XH Amsterdam, The Netherlands
175 : Faculty of Computer Science, Electronics and Telecommunications, AGH University of Science and Technology, Kraków, al. Mickiewicza 30, 30-059 Cracow, Poland
176 : Faculty of Science, Ibaraki University, Mito, Ibaraki, 310-8512, Japan
177 : Faculty of Science and Engineering, Waseda University, Shinjuku, Tokyo 169-8555, Japan
178 : Institute of Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University in Toruń, ul. Grudziądzka 5, 87-100 Toruń, Poland
179 : Graduate School of Science and Engineering, Saitama University, 255 Simo-Ohkubo, Sakura-ku, Saitama city, Saitama 338-8570, Japan
180 : Division of Physics and Astronomy, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto, 606-8502, Japan
181 : Centre for Quantum Technologies, National University Singapore, Block S15, 3 Science Drive 2, Singapore 117543, Singapore
182 : Institute of Particle and Nuclear Studies, KEK (High Energy Accelerator Research Organization), 1-1 Oho, Tsukuba, 305-0801, Japan
183 : Department of Physics and Astronomy, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, United Kingdom
184 : Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, Av. dos Estados, 5001, CEP: 09.210-580, Santo André - SP, Brazil
185 : Dipartimento di Fisica e Astronomia, Sezione Astrofisica, Universitá di Catania, Via S. Sofia 78, I-95123 Catania, Italy
186 : Department of Physics, Humboldt University Berlin, Newtonstr. 15, 12489 Berlin, Germany
187 : Texas Tech University, 2500 Broadway, Lubbock, Texas 79409-1035, USA
188 : University of Zielona Góra, ul. Licealna 9, 65-417 Zielona Góra, Poland
189 : Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 72 boul. Tsarigradsko chaussee, 1784 Sofia, Bulgaria
190 : University of Białystok, Faculty of Physics, ul. K. Ciołkowskiego 1L, 15-254 Białystok, Poland
191 : Faculty of Physics, National and Kapodestrian University of Athens, Panepistimiopolis, 15771 Ilissia, Athens, Greece
192 : Universidad de Chile, Av. Libertador Bernardo O'Higgins 1058, Santiago, Chile
193 : Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
194 : Department of Applied Physics, University of Miyazaki, 1-1 Gakuen Kibana-dai Nishi, Miyazaki, 889-2192, Japan
195 : School of Allied Health Sciences, Kitasato University, Sagamihara, Kanagawa 228-8555, Japan
196 : Departamento de Astronomía, Universidad de Concepción, Barrio Universitario S/N, Concepción, Chile
197 : Charles University, Institute of Particle & Nuclear Physics, V Holešovičkách 2, 180 00 Prague 8, Czech Republic
198 : Astronomical Observatory of Ivan Franko National University of Lviv, 8 Kyryla i Mephodia Street, Lviv, 79005, Ukraine
199 : Kobayashi-Maskawa Institute (KMI) for the Origin of Particles and the Universe, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan
200 : Graduate School of Technology, Industrial and Social Sciences, Tokushima University, Tokushima 770-8506, Japan
201 : Space Research Centre, Polish Academy of Sciences, ul. Bartycka 18A, 00-716 Warsaw, Poland
202 : Instituto de Física - Universidade de São Paulo, Rua do Matão Travessa R Nr.187 CEP 05508-090 Cidade Universitária, São Paulo, Brazil
203 : International Institute of Physics at the Federal University of Rio Grande do Norte, Campus Universitário, Lagoa Nova CEP 59078-970 Rio Grande do Norte, Brazil
204 : University College Dublin, Belfield, Dublin 4, Ireland
205 : Centre for Astro-Particle Physics (CAPP) and Department of Physics, University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa
206 : Departamento de Física, Facultad de Ciencias Básicas, Universidad Metropolitana de Ciencias de la Educación, Santiago, Chile
207 : Núcleo de Formação de Professores - Universidade Federal de São Carlos, Rodovia Washington Luís, km 235 CEP 13565-905 - SP-310 São Carlos - São Paulo, Brazil
208 : Physik-Institut, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland
209 : Department of Physical Sciences, Aoyama Gakuin University, Fuchinobe, Sagamihara, Kanagawa, 252-5258, Japan
210 : University of the Free State, Nelson Mandela Avenue, Bloemfontein, 9300, South Africa
211 : Faculty of Electronics and Information, Warsaw University of Technology, ul. Nowowiejska 15/19, 00-665 Warsaw, Poland
212 : Rudjer Boskovic Institute, Bijenicka 54, 10 000 Zagreb, Croatia
213 : Department of Physics, Konan University, Kobe, Hyogo, 658-8501, Japan
214 : Kumamoto University, 2-39-1 Kurokami, Kumamoto, 860-8555, Japan
215 : University School for Advanced Studies IUSS Pavia, Palazzo del Broletto, Piazza della Vittoria 15, 27100 Pavia, Italy
216 : Aalto University, Otakaari 1, 00076 Aalto, Finland
217 : Agenzia Spaziale Italiana (ASI), 00133 Roma, Italy
218 : Observatoire de la Cote d'Azur, Boulevard de l'Observatoire CS34229, 06304 Nice Cedex 4, Franc