

Prototype Open Event Reconstruction Pipeline for the Cherenkov Telescope Array

M. Nöthe^{a,*}, K. Kosack^b, L. Nickel^a and M. Peresano^b for the CTA Consortium

^aTU Dortmund University,

Otto-Hahn-Str. 4a, Dortmund, Germany

^bAIM, CEA, CNRS, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, F-91191 Gif-sur-Yvette, France

E-mail: maximilian.noethe@tu-dortmund.de

The Cherenkov Telescope Array (CTA) is the next-generation gamma-ray observatory currently under construction. It will improve over the current generation of imaging atmospheric Cherenkov telescopes (IACTs) by a factor of five to ten in sensitivity and it will be able to observe the whole sky from a combination of two sites: a northern site in La Palma, Spain, and a southern one in Paranal, Chile. CTA will also be the first open gamma-ray observatory. Accordingly, the data analysis pipeline is developed as open-source software. The event reconstruction pipeline accepts raw data of the telescopes and processes it to produce suitable input for the higher-level science tools. Its primary tasks include reconstructing the physical properties of each recorded shower and providing the corresponding instrument response functions.

`ctapipe` is a framework providing algorithms and tools to facilitate raw data calibration, image extraction, image parameterization and event reconstruction. Its main focus is currently the analysis of simulated data but it has also been successfully applied for the analysis of data obtained with the first CTA prototype telescopes, such as the Large-Sized Telescope 1 (LST-1).

`pyirf` is a library to calculate IACT instrument response functions, needed to obtain physics results like spectra and light curves, from the reconstructed event lists.

Building on these two, `protopipe` is a prototype for the event reconstruction pipeline for CTA. Recent developments in these software packages will be presented.

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* Presenter

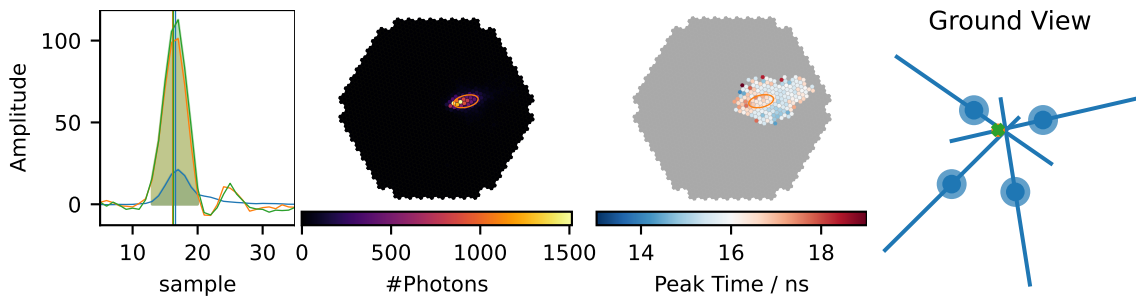


Figure 1: Steps of the analysis up to shower geometry reconstruction: 1. The Cherenkov pulses in each pixel are found and integrated (left) to obtain the number of photons (second from left) and peak times (third from left). 2. The resulting image is cleaned, the pixels not selected are shown in gray in the peak time plot. 3. The images are parametrized, including the Hillas parameters which are visualized using an ellipse. 4. The physical properties of the primary are reconstructed. The plot on the right shows the impact point of the primary on the ground.

1. Introduction

The Cherenkov Telescope Array (CTA)¹ will be the next generation very-high-energy gamma-ray observatory, sensitive to energies between ~ 20 GeV and 300 TeV. It will be composed of over fifty imaging atmospheric Cherenkov telescopes (IACTs) built at two sites to achieve full sky coverage: one on the Canary Island of La Palma, Spain and the other near Paranal, Chile.

CTA will detect gamma rays by measuring the Cherenkov light emitted by extensive air showers, however these are also induced by charged cosmic rays, which form a large background to gamma-ray observations. The data analysis pipeline of CTA starts with the pre-calibrated raw data from the telescopes in the form of time series data for each pixel and for each telescope that registered a signal from the current shower. The pipeline proceeds to reconstruct the physical properties of the primary particle for each recorded shower, this includes the gamma ray's energy and arrival direction. To remove most of the cosmic-ray induced air showers, also a particle type classification is required.

In the classical analysis approach, the raw data is reduced and aggregated into higher levels of abstraction before finally employing a set of machine learning and geometrical algorithms to reconstruct the physical properties of the primary particle. This is usually performed as a four step procedure, which is currently implemented in `ctapipe`: image extraction, image cleaning, image parametrization and finally the reconstruction of primary particle properties (see Figure 1). These steps will be detailed in section 2. After reconstruction of the shower events, one last step – based on the `pyirf` library described in section 3 – selects the best ones on the basis of the specific science case at hand and allows to produce the instrument response functions (IRFs). The pipeline prototype called `protopipe` and described in section 4 performs the analysis steps from raw simulated data to IRF production based on both libraries.

¹ www.cta-observatory.org

2. ctapipe

ctapipe is a python package providing library functions and command-line tools to perform the tasks listed in the previous section. It is developed as open-source software and the project, started in 2015, is hosted on Github. Since then, 26 versions have been released but it is still under heavy development (the latest release at the time of writing is 0.11.0 [7]). In total, 44 contributors have made this project possible. Releases are published to PyPI and conda packages are provided using conda-forge². ctapipe builds upon the scientific python stack with the main dependencies being astropy [16] for astronomical computations and unit support, numpy [3] and scipy [17] for numerical algorithms and statistics and pytables³ for IO using HDF5⁴. The jit-compiler numba [8] is used to optimize performance-critical parts of the code base.

2.1 Image Extraction

The first step in the ctapipe analysis is to reduce the time-series information, i. e. the digitized signals of the Cherenkov photosensors, to the number of photons and their mean arrival time in each pixel. ctapipe supports different algorithms for extracting these quantities from single-pixels waveforms, from simple peak finding algorithms to more complex ones which combine the waveforms of multiple pixels or that fit the expected time evolution of the shower and use that to define the integration window for each pixel.

2.2 Image Cleaning

This operation is aimed at identifying pixels which are likely to host real Cherenkov signal. This is usually done by applying a pixel-wise selection via cleaning thresholds based on the photo-electron and peak time values output by the image extraction step. Again, ctapipe supports multiple algorithms to solve this task.

2.3 Image Parametrization

After removal of noise pixels, the cleaned image goes through a parametrization in order to make it exploitable by subsequent algorithms, in particular shower geometry reconstructors and/or machine-learning models that assist with the event property reconstruction. Among the most important parameters are the classical Hillas parameters [5], which describe the orientation and extension of the shower image in the camera, which is needed for the following reconstruction steps. Additionally, ctapipe implements general descriptive statistics of the images, morphological features like the number of isolated pixel groups and parameters describing the containment of the shower's image in each camera.

2.4 Reconstruction of Event Properties

While the first three steps can be performed individually for each telescope in the array (monoscopic), this step needs to combine the information from all telescopes to give one common estimate for a recorded shower (stereoscopic).

² conda-forge.org ³ www.pytables.org ⁴ www.hdfgroup.org/solutions/hdf5/

The stereoscopic reconstruction of physical shower parameters can be performed in `ctapipe` by either of two currently supported approaches: moments-based and template-based.

The moments-based method makes use of a reconstructor which takes as input the parametrized moments of each image (in the default approach the Hillas parameters) from a candidate shower. This input is then combined with a pair-wise geometric reconstruction where each pair of images gets a weight based on the brightness of the images. In case of single, monoscopic telescopes, machine learning can also be used for the reconstruction of the origin, as the geometrical approaches require multiple telescopes.

`ctapipe` also supports the ImPACT [14] algorithm, an advanced template-based likelihood optimization to reconstruct the event properties, where the expected image for a given set of event properties is calculated from simulations, stored in a database of template images which is then used to perform a likelihood fit to the observed image.

2.5 Input / Output, visualization and configuration

IACT events are read from input files using the `EventSource` interface, which can be implemented for custom file formats using the `ctapipe` plugin system⁵. There are built-in event source implementations for the simulation file format and `ctapipe`'s own output data format. `ctapipe`'s data model uses its own data structure, called `Container`, which can be written to and loaded from HDF5 files, supporting transformations and metadata including units.

The `ctapipe.visualization` module provides classes to display both camera images and telescope array configurations. Two implementations currently exist, one using `matplotlib` [6] and one using the `bokeh`⁶ library.

The `ctapipe` configuration system is build using `traitlets`⁷, the configuration system developed for IPython. A full configuration tree is built by configurable classes called `Components` that can include configurable member attributes. Command-line tools use the same configuration mechanism and allow passing configuration for all configurable objects either on the command line or via a configuration file. Many options can be set per telescope type or even per telescope.

3. Calculating Instrument Response Functions (IRFs) using `pyirf`

To be able to estimate physical properties of gamma-ray sources from lists of reconstructed events, the instrumental response to the initial gamma-ray signal must be known. This will depend on the instrument, the specific analysis, environmental conditions and more. In general, the instrumental response of a gamma-ray telescope can be described by the following integral equation, transforming true properties of the gamma rays into the observable quantities:

$$e(\hat{\alpha}, \hat{\delta}, \hat{E}, t) = \int R(\hat{\alpha}, \hat{\delta}, \hat{E} | \alpha, \delta, E, t) \cdot I(\alpha, \delta, E, t) d\Omega dE + b(\hat{\alpha}, \hat{\delta}, \hat{E}) \quad (1)$$

Where α , δ and E are the right ascension, declination of the gamma ray origin and its total energy, while $\hat{\alpha}$, $\hat{\delta}$, \hat{E} are the corresponding reconstructed quantities obtained from the analysis pipeline. I is the source term, the true gamma-ray signal arriving at earth at the given position, energy and time t . R is the IRF, the convolution kernel translating true quantities to the observed ones, b is

⁵ E.g.: github.com/cta-observatory/ctapipe_io_lst ⁶ bokeh.org/ ⁷ traitlets.readthedocs.io/

the irreducible background and e is the expected event distribution as measured by the experiment. The solid angle integration over α, δ is denoted using $d\Omega$.

The IRF can only be estimated from labeled data, where the true and reconstructed quantities are both known. In the case of CTA these labeled datasets are created via Monte Carlo simulations using CORSIKA [4] to simulate the extensive air showers, followed by the detector simulation performed by `sim_telarray` [1].

In classical IACT analysis, the IRF is factorized into three independent components, making the strong assumption that the migrations between the different observables are statistically independent. This factorization yields:

$$R(\hat{\alpha}, \hat{\delta}, \hat{E}|\alpha, \delta, E, t) = A_{\text{eff}}(\alpha, \delta, E, t) \cdot \text{PSF}(\hat{\alpha}, \hat{\delta}|\alpha, \delta, E, t) \cdot D(\hat{E}|\alpha, \delta, E, t) \quad (2)$$

Where A_{eff} is the effective area, the detection probability times the observed area for a gamma ray with given true properties, PSF is the point spread function, i. e. the convolution kernel for the reconstructed gamma-ray origin and D is the energy dispersion, the migration between true energy E and reconstructed energy \hat{E} . Instead of continuous functions, these IRFs are calculated and stored as binned quantities filled from simulated events.

`pyirf` is a python library for calculating these IRFs from labeled, reconstructed event lists as created by the event reconstruction pipeline. The latest version of `pyirf` at the time of writing is v0.5.0 [12], which supports calculating most IRFs formats defined in Gamma-Astro-Data-Formats (GADF, [2]) and can export these into the FITS-based data format defined therein. Additionally, `pyirf` contains functionality to calculate flux sensitivity of gamma-ray instruments according to the requirements laid out for CTA and the optimization of event selection criteria to obtain the best flux sensitivity.

4. protopipe

`protopipe` is a pipeline prototype for CTA based on the `ctapipe` and `pyirf` libraries. It is distributed as a python package on the PyPI platform; the latest release at the time of writing is 0.4.0.post1 [15]. Started as an independent project for image cleaning studies by the CTA Consortium group at CEA-Saclay/IRFU, it has been developed as an open-source package for the whole consortium since September 2019. Since then, its development has been steered by the will to substitute the historical pipelines currently in use for the production of the official IRFs for CTA. Such pipelines have been inherited from the VERITAS (EventDisplay [10]) and MAGIC (MARS [19]) experiments and adapted to the CTA scenario by their maintainers. Even if they provide satisfactory results, they are not in line with the software requirements of CTA and not easily exploitable by the whole consortium. The development of `protopipe` is strongly influenced by a step-by-step comparison with such pipelines, which translates in a continuous code migration into the `ctapipe` and `pyirf` libraries (algorithms and support of additional analysis operations).

`protopipe` has been built around the two libraries described in this work by constantly trying to support their latest stable releases. It also provides a module for multivariate analysis using supervised machine-learning techniques (`protopipe.mva`), used to reconstruct energy and particle type of the events.

The pipeline provides four tools based on `ctapipe`, `protopipe.mva`, `ctapipe` and `pyirf` respectively. Each tool is a python executable configurable via YAML-based configuration files. `protopipe` also provides a way to launch the analysis on computing grids featuring the DIRAC interware⁸. The tools can be launched on the grid thanks to an interface code developed separately from the main package and based on CTADIRAC⁹, a version of the DIRAC middleware customized for CTA.

4.1 Description of the pipeline workflow

A full dataset composed of simulated events from primary gammas, protons and electrons is split at the beginning of the analysis in sub-datasets. Depending on the workflow of choice, a step of the pipeline will correspond to a tool being applied to one or more sub-datasets. The currently tested workflow is the following:

- part of the gamma rays are used to train an energy reconstruction model,
- part of the gamma rays and part of the protons are used to train a particle classification model (making use also of the reconstructed energy),
- the remaining gamma rays and protons together with the full electron dataset are fully analyzed.

In a real scenario of a gamma-ray analysis, the entire third sub-dataset and the proton sub-dataset used to train the particle classifier would correspond to data observed by the telescope array. An overview of the workflow is shown in Figure 2 and the tools are defined in the following sections.

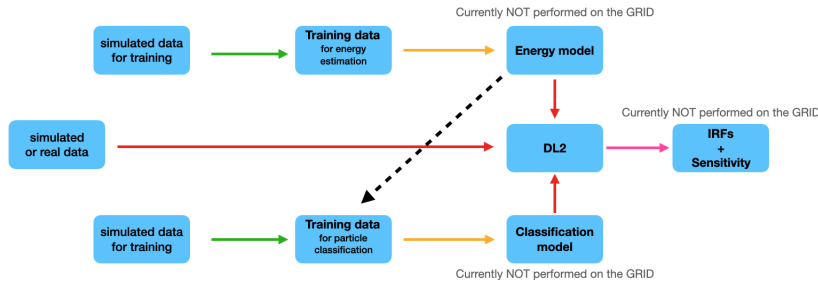


Figure 2: Current pipeline workflow tested on full-scale analyses on the GRID. The actions performed by the tools 1, 2, 3 and 4 are highlighted by green, orange, red and pink arrows respectively. Reconstructed energy is used as a model feature when training particle classification (black dashed arrow)

4.1.1 Tool 1: preparation of training data

This tool is based on `ctapipe` and it produces data in a format suitable for model training. This format is a combination of data levels as defined by the data models in `ctapipe`: DL1b (image parameters) and part of DL2 (reconstructed shower geometry). The transformation of raw data into DL1b data makes use of the library capabilities described in paragraphs 2.1 to 2.3. Since the pipeline workflow currently tested (see Fig.2) comprises the use of two models (one for energy reconstruction and the other for particle classification) this tool is used in two separate steps of that analysis.

⁸ dirac.readthedocs.io/en/latest/ ⁹ github.com/cta-observatory/CTADIRAC

4.1.2 Tool 2: production of models

The production of machine-learning models is performed by the tool based on the `protopipe.mva` module. The dependencies are few: `numpy` and `pandas` to deal internally with tables of data, `joblib` for I/O support and `scikit-learn` to create the models and fit the test data. The models currently tested are part of the `sklearn.ensemble` module: `AdaBoostRegressor` or `RandomForestRegressor` for energy reconstruction and `RandomForestClassifier` for particle classification. It is possible to perform tuning of the hyper-parameters via an exhaustive search over lists of parameter values specified by the user (`sklearn.model_selection.GridSearchCV`). The tool outputs both model and tables of the events selected for training and testing as gzip-compressed pickled objects.

4.1.3 Tool 3: production of fully-analyzed events

This tool performs the full reconstruction pipeline and is applied to events which have to be independent from those used by the previous tools. The operations performed are those described by paragraphs 2.1 to 2.4. In particular the tool requires as an input the models produced by Tool 2 in order to reconstruct both energy and particle type. The models' input file format currently supported is the one output by the Tool 2.

4.1.4 Tool 4: production of IRFs and optimized cuts

This tool is based on the functions provided by the `pyirf` library and performs the following sequence of operations:

1. find the best cutoff in gammaness score, which is the result of the particle type classification, to best discriminate between signal and background, as well as the angular cut to obtain the best sensitivity for a given amount of observation time and a given template for the source of interest,
2. estimate the sensitivity from the optimized cuts,
3. compute the IRFs from the same selected events.

The current output format is the one supported by `pyirf`: it builds on the data format specification given by the GADF integrated by input coming from CTA optimizations.

5. Conclusions and Outlook

`ctapipe` and `pyirf` offer open-source tools to solve a critical part of the analysis of IACT data. Using the IO plugin system, `ctapipe` can be used to process data by all experiments, see for example [13] for a combined analysis of LST-1 and MAGIC observations. While the current version of `ctapipe` performs event property estimation using geometrical or template based algorithms, the use of modern machine learning techniques is also investigated (see for example [18] and [11]). Performance of an analysis using `ctapipe` and `pyirf` on simulated data and first results on data from observations performed by the LST-1 are reported in [9]. `protopipe` is being currently developed with the goal of superseding the reference analyses for the planned arrays, currently performed by `EventDisplay` and `MARS`. It takes into account all supported cameras, optics and array configurations for CTA, enabling a high degree of flexibility to accommodate diverse instrument

configurations. It will be used to produce sets of IRFs sufficiently large to describe and investigate the performance of CTA under any required observing condition and science case and to analyze data from the whole set of telescopes.

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Full Authors List: CTA Consortium

H. Abdalla¹, H. Abe², S. Abe², A. Abusleme³, F. Acero⁴, A. Acharyya⁵, V. Acín Portella⁶, K. Ackley⁷, R. Adam⁸, C. Adams⁹, S.S. Adhikari¹⁰, I. Aguado-Ruesga¹¹, I. Agudo¹², R. Aguilera¹³, A. Aguirre-Santaella¹⁴, F. Aharonian¹⁵, A. Alberdi¹², R. Alfaro¹⁶, J. Alfaro³, C. Alispach¹⁷, R. Aloisio¹⁸, R. Alves Batista¹⁹, J.-P. Amans²⁰, L. Amati²¹, E. Amato²², G. Ambrosi²³, M. Ambrosio²⁴, R. Ammendola²⁵, J. Anderson²⁶, M. Anduze⁸, E.O. Angüner²⁷, L.A. Antonelli²⁸, V. Antonuccio²⁹, P. Antoranz³⁰, R. Anutarawiramkul³¹, J. Aragunde Gutierrez³², C. Aramo²⁴, A. Araudo^{33,34}, M. Araya³⁵, A. Arbet-Engels³⁶, C. Arcaro¹, V. Arendt³⁷, C. Armand³⁸, T. Armstrong²⁷, F. Arqueros¹¹, L. Arrabito³⁹, B. Arsoli⁴⁰, M. Artero⁴¹, K. Asano², Y. Ascasíbar¹⁴, J. Aschersleben⁴², M. Ashley⁴³, P. Atinà⁴⁴, P. Aubert⁴⁵, C. B. Singh¹⁹, D. Baack⁴⁶, A. Babic⁴⁷, M. Backes⁴⁸, V. Baena¹³, S. Bajlik⁴⁹, A. Baktash⁵⁰, C. Balazs⁷, M. Balbo³⁸, O. Ballester⁴¹, J. Ballet⁴, B. Balmaverde⁴⁴, A. Bamba⁵¹, R. Bandiera²², A. Baquero Larriva¹¹, P. Barai¹⁹, C. Barbier⁴⁵, V. Barbosa Martins⁵², M. Barcelo⁵³, M. Barkov⁵⁴, M. Barnard¹, L. Baroncelli²¹, U. Barres de Almeida⁴⁰, J.A. Barrio¹¹, D. Bastieri⁵⁵, P.I. Batista⁵², I. Batkovic⁵⁵, C. Bauer⁵³, R. Bautista-González⁵⁶, J. Baxter², U. Becciani²⁹, J. Becerra González³², Y. Becherini⁵⁷, G. Beck⁵⁸, J. Becker Tjus⁵⁹, W. Bednarek⁶⁰, A. Belfiore⁶¹, L. Bellizzi⁶², R. Belmont⁴, W. Benbow⁶³, D. Berge⁵², E. Bernardini⁵², M.I. Bernardos⁵⁵, K. Bernlöhr⁵³, A. Berti⁶⁴, M. Berton⁶⁵, B. Bertucci²³, V. Beshley⁶⁶, N. Bhatt⁶⁷, S. Bhattacharyya⁶⁷, W. Bhattacharyya⁵², S. Bhattacharyya⁶⁸, B. Bi⁶⁹, G. Bicknell⁷⁰, N. Biederbeck⁴⁶, C. Bigongiari²⁸, A. Biland³⁶, R. Bird⁷¹, E. Bissaldi⁷², J. Biteau⁷³, M. Bitossi⁷⁴, O. Blanch⁴¹, M. Blank⁵⁰, J. Blazek³³, J. Bobin⁷⁵, C. Boccato⁷⁶, F. Bocchino⁷⁷, C. Boehm⁷⁸, M. Bohacova³³, C. Boisson²⁰, J. Boix⁴¹, J.-P. Bolle⁵², J. Bolmont⁷⁹, G. Bonanno²⁹, C. Bonavolontà²⁴, L. Bonneau Arbeleche⁸⁰, G. Bonnoli¹², P. Bordes⁸¹, J. Borkowski⁴⁹, S. Bórquez³⁵, R. Bose⁸², D. Bose⁸³, Z. Bosnjak⁴⁷, E. Bottacini⁵⁵, M. Böttcher¹, M.T. Botticella⁸⁴, C. Boutonnet⁸⁵, F. Bouyouj⁷⁵, V. Bozhilov⁸⁶, E. Bozzo³⁸, L. Brahimi³⁹, C. Braiding⁴³, S. Brau-Nogue⁸⁷, S. Breen⁷⁸, J. Bregeon³⁹, M. Breuhaus⁵³, A. Brill⁹, W. Brisen⁸⁸, E. Brocato²⁸, A.M. Brown⁵, K. Brügge⁴⁶, P. Brun⁸⁹, P. Brun³⁹, F. Brun⁸⁹, L. Brunetti⁴⁵, G. Brunetti⁹⁰, P. Bruno²⁹, A. Bruno⁹¹, A. Bruzese⁶, N. Bucciantini²², J. Buckley⁸², R. Bühler⁵², A. Bulgarelli²¹, T. Bulik⁹², M. Bünning⁵², M. Bunse⁴⁶, M. Burton⁹³, A. Burtovoi⁷⁶, M. Buscemi⁹⁴, S. Buschjäger⁴⁶, G. Busetto⁵⁵, J. Buss⁴⁶, K. Byrum²⁶, A. Caccianiga⁹⁵, F. Cadoux¹⁷, A. Calanducci²⁹, C. Calderón³, J. Calvo Tovar³², R. Cameron⁹⁶, P. Campaña³⁵, R. Canestrari⁹¹, F. Cangemi⁷⁹, B. Cantlay³¹, M. Capalbi⁹¹, M. Capasso⁹, M. Cappi²¹, A. Caproni⁹⁷, R. Capuzzo-Dolcetta²⁸, P. Caraveo⁶¹, V. Cárdenas⁹⁸, L. Cardiel⁴¹, M. Cardillo⁹⁹, C. Carlile¹⁰⁰, S. Caroff⁴⁵, R. Carosi⁷⁴, A. Carosi¹⁷, E. Carquin³⁵, M. Carrère³⁹, J.-M. Casandjian⁴, S. Casanova^{101,53}, E. Cascone⁸⁴, F. Cassol²⁷, A.J. Castro-Tirado¹², F. Catalani¹⁰², O. Catalano⁹¹, D. Cauz¹⁰³, A. Ceccanti⁶⁴, C. Celestino Silva⁸⁰, S. Celli¹⁸, K. Cerny¹⁰⁴, M. Cerruti⁸⁵, E. Chabanne⁴⁵, P. Chadwick⁵, Y. Chai¹⁰⁵, P. Chambery¹⁰⁶, C. Champion⁸⁵, S. Chandra¹, S. Chaty⁴, A. Chen⁵⁸, K. Cheng², M. Chernyakova¹⁰⁷, G. Chiaro⁶¹, A. Chiavassa^{64,108}, M. Chikawa², V.R. Chitnis¹⁰⁹, J. Chudoba³³, L. Chytka¹⁰⁴, S. Cikota⁴⁷, A. Circiello^{24,110}, P. Clark⁵, M. Çolak⁴¹, E. Colombo³², J. Colome¹³, S. Colonges⁸⁵, A. Comastri²¹, A. Compagnino⁹¹, V. Conforti²¹, E. Congiu⁹⁵, R. Coniglione⁹⁴, J. Conrad¹¹¹, F. Conte⁵³, J.L. Contreras¹¹, P. Coppi¹¹², R. Cornat⁸, J. Coronado-Blazquez¹⁴, J. Cortina¹¹³, A. Costa²⁹, H. Costantini²⁷, G. Cotter¹¹⁴, B. Courty⁸⁵, S. Covino⁹⁵, S. Crestani⁶¹, P. Cristofari²⁰, R. Crocker⁷⁰, J. Croston¹¹⁵, K. Cubuk⁹³, O. Cuevas⁹⁸, X. Cui², G. Cusumano⁹¹, S. Cutini²³, A. D’Ai⁹¹, G. D’Amico¹¹⁶, F. D’Ammando⁹⁰, P. D’Avanzo⁹⁵, P. Da Vela⁷⁴, M. Dadina²¹, S. Dai¹¹⁷, M. Dalchenko¹⁷, M. Dall’Ora⁸⁴, M.K. Daniel⁶³, J. Dauguet⁸⁵, I. Davids⁴⁸, J. Davies¹¹⁴, B. Dawson¹¹⁸, A. De Angelis⁵⁵, A.E. de Araújo Carvalho⁴⁰, M. de Bony de Lavergne⁴⁵, V. De Caprio⁸⁴, G. De Cesare²¹, F. De Fronzo²⁰, E.M. de Gouveia Dal Pino¹⁹, I. de la Calle¹¹, B. De Lotto¹⁰³, A. De Luca⁶¹, D. De Martino⁸⁴, R.M. de Menezes¹⁹, M. de Naurois⁸, E. de Oña Wilhelmi¹³, F. De Palma⁶⁴, F. De Persio¹¹⁹, N. de Simone⁵², V. de Souza⁸⁰, M. Del Santo⁹¹, M.V. del Valle¹⁹, E. Delagnes⁷⁵, G. Deleglise⁴⁵, M. Delfino Reznicek⁶, C. Delgado¹¹³, A.G. Delgado Giler⁸⁰, J. Delgado Mengual⁶, R. Della Ceca⁹⁵, M. Della Valle⁸⁴, D. della Volpe¹⁷, D. Depaoli^{64,108}, D. Depouez²⁷, J. Devin⁸⁵, T. Di Girolamo^{24,110}, C. Di Giulio²⁵, A. Di Piano²¹, F. Di Piero⁶⁴, L. Di Venere¹²⁰, C. Díaz¹¹³, C. Díaz-Bahamondes³, C. Dib³⁵, S. Diebold⁶⁹, S. Digel⁹⁶, R. Dima⁵⁵, A. Djannati-Atai⁸⁵, J. Djuvsland¹¹⁶, A. Dmytriiev²⁰, K. Docher⁹, A. Domínguez¹¹, D. Dominis Prester¹²¹, A. Donath⁵³, A. Donini⁴¹, D. Dorner¹²², M. Doró⁵⁵, R.d.C. dos Anjos¹²³, J.-L. Dournaux²⁰, T. Downes¹⁰⁷, G. Drake²⁶, H. Drass³, D. Dravins¹⁰⁰, C. Duangchan³¹, A. Duara¹²⁴, G. Dubus¹²⁵, L. Ducci⁶⁹, C. Duffy¹²⁴, D. Dumora¹⁰⁶, K. Dundas Morá¹¹¹, A. Durkalec¹²⁶, V.V. Dwarkadas¹²⁷, J. Ebr³³, C. Eckner⁴⁵, J. Eder¹⁰⁵, A. Ederoclitte¹⁹, E. Edy⁸, K. Egberts¹²⁸, S. Einecke¹¹⁸, J. Eisch¹²⁹, C. Eleftheriadis¹³⁰, D. Elsässer⁴⁶, G. Emery¹⁷, D. Emmanoulopoulos¹¹⁵, J.-P. Ernenwein²⁷, M. Errando⁸², P. Escarate³⁵, J. Escudero¹², C. Espinoza³, S. Etori²¹, A. Eungwanichayapant³¹, P. Evans¹²⁴, C. Evoli¹⁸, M. Fairbairn¹³¹, D. Falceta-Goncalves¹³², A. Falcone¹³³, V. Fallah Ramazani⁶⁵, R. Falomo⁷⁶, K. Farakos¹³⁴, G. Fasola²⁰, A. Fattorini⁴⁶, Y. Favre¹⁷, R. Fedora¹³⁵, E. Fedorova¹³⁶, S. Fegan⁸, K. Feijen¹¹⁸, Q. Feng⁹, G. Ferrand⁵⁴, G. Ferrara⁹⁴, O. Ferreira⁸, M. Fesquet⁷⁵, E. Fiandrini²³, A. Fiasson⁴⁵, M. Filipovic¹¹⁷, D. Fink¹⁰⁵, J.P. Finley¹³⁷, V. Fioretti²¹, D.F.G. Fiorillo^{24,110}, M. Fiorini⁶¹, S. Flis⁵², H. Flores²⁰, L. Foffano¹⁷, C. Föhr⁵³, M.V. Fonseca¹¹, L. Font¹³⁸, G. Fontaine⁸, O. Fornieri⁶³, L. Fortin⁸⁸, N. Fouque⁴⁵, A. Fournier¹⁰⁶, B. Fraga⁴⁰, A. Franceschini⁷⁶, F.J. Franco³⁰, A. Franco Ordovas³², L. Freixas Coromina¹¹³, L. Fresnillo³⁰, C. Fruck¹⁰⁵, D. Fugazza⁹⁵, Y. Fujikawa¹³⁹, Y. Fujita², S. Fukami², Y. Fukazawa¹⁴⁰, Y. Fukui¹⁴¹, D. Fulla⁵², S. Funk¹⁴², A. Furniss¹⁴³, O. Gabella³⁹, S. Gabici⁸⁵, D. Gaggero¹⁴, G. Galanti⁶¹, G. Galaz³, P. Galdemard¹⁴⁴, Y. Gallant³⁹, D. Galloway⁷, S. Gallozzi²⁸, V. Gammaldi¹⁴, R. Garcia⁴¹, E. García⁴⁵, E. García¹³, R. García López³², M. Garczarczyk⁵², F. Gargano¹²⁰, C. Gargano⁹¹, S. Garozzo²⁹, D. Gascon⁸¹, T. Gasparetto¹⁴⁵, D. Gasparrini²⁵, H. Gasparyan⁵²,

M. Gaug¹³⁸, N. Geffroy⁴⁵, A. Gent¹⁴⁶, S. Germani⁷⁶, L. Gesa¹³, A. Ghalumyan¹⁴⁷, A. Ghedina¹⁴⁸, G. Ghirlanda⁹⁵, F. Gianotti²¹, S. Giarrusso⁹¹, M. Giarrusso⁹⁴, G. Giavitto⁵², B. Giebels⁸, N. Giglietto⁷², V. Gika¹³⁴, F. Gillardo⁴⁵, R. Gimenes¹⁹, F. Giordano¹⁴⁹, G. Giovannini⁹⁰, E. Giro⁷⁶, M. Giroletti⁹⁰, A. Giuliani⁶¹, L. Giunti⁸⁵, M. Gjata⁹, J.-F. Glicenstein⁸⁹, P. Gliwny⁶⁰, N. Godinovic¹⁵⁰, H. Göksu⁵³, P. Goldoni⁸⁵, J.L. Gómez¹², G. Gómez-Vargas³, M.M. González¹⁶, J.M. González¹⁵¹, K.S. Gothe¹⁰⁹, D. Götz⁴, J. Goullart Coelho¹²³, K. Gourgouliaos⁵, T. Grabarczyk¹⁵², R. Graciani⁸¹, P. Grandi²¹, G. Grasseau⁸, D. Grasso⁷⁴, A.J. Green⁷⁸, D. Green¹⁰⁵, J. Green²⁸, T. Greenshaw¹⁵³, I. Grenier⁴, P. Grespan⁵⁵, A. Grillo²⁹, M.-H. Grondin¹⁰⁶, J. Grube¹³¹, V. Guarino²⁰, B. Guest³⁷, O. Gueta⁵², M. Gündüz⁵⁹, S. Gunji¹⁵⁴, A. Gusdorf²⁰, G. Gyuk¹⁵⁵, J. Hackfeld⁵⁹, D. Hadasch², J. Haga¹³⁹, L. Hagge⁵², A. Hahn¹⁰⁵, J.E. Hajlaoui⁸⁵, H. Hakobyan³⁵, A. Halim⁸⁹, P. Hamal³³, W. Hanlon⁶³, S. Hara¹⁵⁶, Y. Harada¹⁵⁷, M.J. Hardcastle¹⁵⁸, M. Harvey⁵, K. Hashiyama², T. Hassan Collado¹¹³, T. Haubold¹⁰⁵, A. Haupt⁵², U.A. Hautmann¹⁵⁹, M. Havelka³³, K. Hayashi¹⁴¹, K. Hayashi¹⁶⁰, M. Hayashida¹⁶¹, H. He⁵⁴, L. Heckmann¹⁰⁵, M. Heller¹⁷, J.C. Helo³⁵, F. Henault¹²⁵, G. Henri¹²⁵, G. Hermann⁵³, R. Hermel⁴⁵, S. Hernández Cadena¹⁶, J. Herrera Lorente³², A. Herrero³², O. Hervet¹⁴³, J. Hinton⁵³, A. Hiramoto¹⁵⁷, N. Hiroshima⁵⁴, K. Hirotani², B. Hnatyk¹³⁶, R. Hnatyk¹³⁶, J.K. Hoang¹¹, D. Hoffmann²⁷, W. Hofmann⁵³, C. Hoischen¹²⁸, J. Holder¹⁶², M. Holler¹⁶³, B. Hona¹⁶⁴, D. Horan⁸, J. Hörandel¹⁶⁵, D. Horns⁵⁰, P. Horvath¹⁰⁴, J. Houles²⁷, T. Hovatta⁶⁵, M. Hrabovsky¹⁰⁴, D. Hrupec¹⁶⁶, Y. Huang¹³⁵, J.-M. Huet²⁰, G. Hughes¹⁵⁹, D. Hui², G. Hull⁷³, T.B. Humensky⁹, M. Hütten¹⁰⁵, R. Iaria⁷⁷, M. Iarlori¹⁸, J.M. Illa⁴¹, R. Imazawa¹⁴⁰, D. Impiombato⁹¹, T. Inada², F. Incardona²⁹, A. Ingallinera²⁹, Y. Inoue², S. Inoue⁵⁴, T. Inoue¹⁴¹, Y. Inoue¹⁶⁷, A. Insolia^{120,94}, F. Iocco^{24,110}, K. Ioka¹⁶⁸, M. Ionica²³, M. Iori¹¹⁹, S. Iovenitti⁹⁵, A. Iriarte¹⁶, K. Ishio¹⁰⁵, W. Ishizaki¹⁶⁸, Y. Iwamura², C. Jablonski¹⁰⁵, J. Jacquemier⁴⁵, M. Jacquemont⁴⁵, M. Jamroz¹⁶⁹, P. Janecek³³, F. Jankowsky¹⁷⁰, A. Jardin-Blicq³¹, C. Jarnot⁸⁷, P. Jean⁸⁷, I. Jiménez Martínez¹¹³, W. Jin¹⁷¹, L. Jocu¹²⁵, N. Jordana¹⁷², M. Josselin⁷³, L. Jouvin⁴¹, I. Jung-Richardt¹⁴², F.J.P.A. Junqueira¹⁹, C. Juramy-Gilles⁷⁹, J. Jurysek³⁸, P. Kaaret¹⁷³, L.H.S. Kadowaki¹⁹, M. Kagaya², O. Kalekin¹⁴², R. Kankanyan⁵³, D. Kantzas¹⁷⁴, V. Karas³⁴, A. Karastergiou¹¹⁴, S. Karkar⁷⁹, E. Kasai⁴⁸, J. Kasperk¹⁷⁵, H. Katagiri¹⁷⁶, J. Kataoka¹⁷⁷, K. Katarzynski¹⁷⁸, S. Katsuda¹⁷⁹, U. Katz¹⁴², N. Kawanaka¹⁸⁰, D. Kazanas¹³⁰, D. Kerszberg⁴¹, B. Khélifi⁸⁵, M.C. Kherlakian⁵², T.P. Kian¹⁸¹, D.B. Kieda¹⁶⁴, T. Kihm⁵³, S. Kim³, S. Kimeswenger¹⁶³, S. Kisaka¹⁴⁰, R. Kissmann¹⁶³, R. Kleijwegt¹³⁵, T. Kleiner⁵², G. Kluge¹⁰, W. Kluźniak⁴⁹, J. Knapp⁵², J. Knödseder⁸⁷, A. Kobakhidze⁷⁸, Y. Kobayashi², B. Koch³, J. Kocot¹⁵², K. Kohri¹⁸², K. Kokkotas⁶⁹, N. Komin⁵⁸, A. Kong², K. Kosack⁴, G. Kowal¹³², F. Krack⁵², M. Krause⁵², F. Krennrich¹²⁹, M. Krumholz⁷⁰, H. Kubo¹⁸⁰, V. Kudryavtsev¹⁸³, S. Kunwar⁵³, Y. Kuroda¹³⁹, J. Kushida¹⁵⁷, P. Kushwaha¹⁹, A. La Barbera⁹¹, N. La Palombara⁶¹, V. La Parola⁹¹, G. La Rosa⁹¹, R. Lahmann¹⁴², G. Lamanna⁴⁵, A. Lamastra²⁸, M. Landoni⁹⁵, D. Landriu⁴, R.G. Lang⁸⁰, J. Lapington¹²⁴, P. Laporte²⁰, P. Lason¹⁵², J. Lasuik³⁷, J. Lazendic-Galloway⁷, T. Le Flour⁴⁵, P. Le Sidaner²⁰, S. Leach¹²⁴, A. Leckngam³¹, S.-H. Lee¹⁸⁰, W.H. Lee¹⁶, S. Lee¹¹⁸, M.A. Leigui de Oliveira¹⁸⁴, A. Lemièrre⁸⁵, M. Lemoine-Goumard¹⁰⁶, J.-P. Lenain⁷⁹, F. Leone^{94,185}, V. Leray⁸, G. Leto²⁹, F. Leuschner⁶⁹, C. Levy^{79,20}, R. Lindemann⁵², E. Lindfors⁶⁵, L. Linhoff⁴⁶, I. Liodakis⁶⁵, A. Lipniacka¹¹⁶, S. Lloyd⁵, M. Lobo¹¹³, T. Lohse¹⁸⁶, S. Lombardi²⁸, F. Longo¹⁴⁵, A. Lopez³², M. López¹¹, R. López-Coto⁵⁵, S. Loporchio¹⁴⁹, F. Louis⁷⁵, M. Louys²⁰, F. Lucarelli²⁸, D. Lucchesi⁵⁵, H. Ludwig Boudi³⁹, P.L. Luque-Escamilla⁵⁶, E. Lyard³⁸, M.C. Maccarone⁹¹, T. Maccarone¹⁸⁷, E. Mach¹⁰¹, A.J. Maciejewski¹⁸⁸, J. Mackey¹⁵, G.M. Madejski⁹⁶, P. Maeght³⁹, C. Maggio¹³⁸, G. Maier⁵², A. Majczyna¹²⁶, P. Majumdar^{83,2}, M. Makariev¹⁸⁹, M. Mallamaci⁵⁵, R. Malta Nunes de Almeida¹⁸⁴, S. Maltezos¹³⁴, D. Malyshev¹⁴², D. Malyshev⁶⁹, D. Mandat³³, G. Maneva¹⁸⁹, M. Manganaro¹²¹, G. Manico⁹⁴, P. Manigot⁸, K. Mannheim¹²², N. Maragos¹³⁴, D. Marano²⁹, M. Marconi⁸⁴, A. Marcowith³⁹, M. Marculewicz¹⁹⁰, B. Marčun⁶⁸, J. Marín⁹⁸, N. Marinello⁵⁵, P. Marinos¹¹⁸, M. Mariotti⁵⁵, S. Markoff¹⁷⁴, P. Marquez⁴¹, G. Marsella⁹⁴, J. Martí⁵⁶, J.-M. Martin²⁰, P. Martin⁸⁷, O. Martinez³⁰, M. Martínez⁴¹, G. Martínez¹¹³, O. Martínez⁴¹, H. Martínez-Huerta⁸⁰, C. Marty⁸⁷, R. Marx⁵³, N. Masetti^{21,151}, P. Massimino²⁹, A. Mastichiadis¹⁹¹, H. Matsumoto¹⁶⁷, N. Matthews¹⁶⁴, G. Maurin⁴⁵, W. Max-Moerbeck¹⁹², N. Maxted⁴³, D. Mazin^{2,105}, M.N. Mazziotta¹²⁰, S.M. Mazzola⁷⁷, J.D. Mbarubucye⁵², L. Mc Comb⁵, I. McHardy¹¹⁵, S. McKeague¹⁰⁷, S. McMuldrough⁶³, E. Medina⁶⁴, D. Medina Miranda¹⁷, A. Melandri⁹⁵, C. Melioli¹⁹, D. Melkumyan⁵², S. Menchiari⁶², S. Mender⁴⁶, S. Mereghetti⁶¹, G. Merino Arévalo⁶, E. Mestre¹³, J.-L. Meunier⁷⁹, T. Meures¹³⁵, M. Meyer¹⁴², S. Micanovic¹²¹, M. Miceli⁷⁷, M. Michailidis⁶⁹, J. Michałowski¹⁰¹, T. Miener¹¹, I. Mievre⁴⁵, J. Miller³⁵, I.A. Minaya¹⁵³, T. Mineo⁹¹, M. Mineev¹⁸⁹, J.M. Miranda³⁰, R. Mirzoyan¹⁰⁵, A. Mitchell³⁶, T. Mizuno¹⁹³, B. Mode¹³⁵, R. Moderski⁴⁹, L. Mohrmann¹⁴², E. Molina⁸¹, E. Molinari¹⁴⁸, T. Montaruli¹⁷, I. Monteiro⁴⁵, C. Moore¹²⁴, A. Moralejo⁴¹, D. Morcuende-Parrilla¹¹, E. Moretti⁴¹, L. Morganti⁶⁴, K. Mori¹⁹⁴, P. Moriarty¹⁵, K. Morik⁴⁶, G. Morlino²², P. Morris¹¹⁴, A. Morselli²⁵, K. Mosshammer⁵², P. Moya¹⁹², R. Mukherjee⁹, J. Muller⁸, C. Mundell¹⁷², J. Mundet⁴¹, T. Murach⁵², A. Muraczewski⁴⁹, H. Muraishi¹⁹⁵, K. Murase², I. Musella⁸⁴, A. Musumarra¹²⁰, A. Nagai¹⁷, N. Nagar¹⁹⁶, S. Nagataki⁵⁴, T. Naito¹⁵⁶, T. Nakamori¹⁵⁴, K. Nakashima¹⁴², K. Nakayama⁵¹, N. Nakhjiri¹³, G. Naletto⁵⁵, D. Naumann⁵², L. Nava⁹⁵, R. Navarro¹⁷⁴, M.A. Nawaz¹³², H. Ndiayvala¹, D. Neise³⁶, L. Nellen¹⁶, R. Nemmen¹⁹, M. Newbold¹⁶⁴, N. Neyroud⁴⁵, K. Ngernphat³¹, T. Nguyen Trung⁷³, L. Nicastro²¹, L. Nickel⁴⁶, J. Niemiec¹⁰¹, D. Nieto¹¹, M. Nieves³², C. Nigro⁴¹, M. Nikoľajuk¹⁹⁰, D. Ninci⁴¹, K. Nishijima¹⁵⁷, K. Noda², Y. Nogami¹⁷⁶, S. Nolan⁵, R. Nomura², R. Norris¹¹⁷, D. Nosek¹⁹⁷, M. Nöthe⁴⁶, B. Novosyadlyj¹⁹⁸, V. Novotny¹⁹⁷, S. Nozaki¹⁸⁰, F. Nunio¹⁴⁴, P. O'Brien¹²⁴, K. Obara¹⁷⁶, R. Oger⁸⁵, Y. Ohira⁵¹, M. Ohishi², S. Ohm⁵², Y. Ohtani², T. Oka¹⁸⁰, N. Okazaki², A. Okumura^{139,199}, J.-F. Olive⁸⁷, C. Oliver³⁰, G. Olivera⁵², B. Olmi²², R.A. Ong⁷¹, M. Orienti⁹⁰, R. Orito²⁰⁰, M. Orlandini²¹, S. Orlando⁷⁷, E. Orlando¹⁴⁵, J.P. Osborne¹²⁴, M. Ostrowski¹⁶⁹, N. Otte¹⁴⁶, E. Ovcharov⁸⁶, E. Owen², I. Oya¹⁵⁹, A. Ozieblo¹⁵², M. Padovani²², I. Pagano²⁹, A. Pagliaro⁹¹, A. Paizis⁶¹, M. Palatiello¹⁴⁵, M. Palatka³³, E. Palazzi²¹, J.-L. Panazol⁴⁵, D. Paneque¹⁰⁵, B. Panes³, S. Panny¹⁶³, F.R. Pantaleo⁷², M. Panter⁵³, R. Paoletti⁶², M. Paolillo^{24,110}, A. Papitto²⁸, A. Paravac¹²², J.M. Paredes⁸¹, G. Pareschi⁹⁵, N. Park¹²⁷, N. Parmiggiani²¹, R.D. Parsons¹⁸⁶, P. Paško²⁰¹, S. Patel⁵², B. Patricelli²⁸, G. Pauletta¹⁰³, L. Pavletic¹²¹, S. Pavy⁸, A. Pe'er¹⁰⁵, M. Peč³³, M. Pecimotika¹²¹, M.G. Pellegriti¹²⁰, P. Peñil Del Campo¹¹, M. Penno⁵², A. Pepato⁵⁵, S. Perard¹⁰⁶, C. Perennes⁵⁵, G. Peres⁷⁷, M. Peresano⁴, A. Pérez-Aguilera¹¹, J. Pérez-Romero¹⁴, M.A. Pérez-Torres¹², M. Perri²⁸, M. Persic¹⁰³, S. Petrera¹⁸, P.-O. Petrucci¹²⁵, O. Petruk⁶⁶, B. Peyaud⁸⁹, K. Pfrang⁵², E. Pian²¹, G. Piano⁹⁹, P. Piattelli⁹⁴, E. Pietropaolo¹⁸, R. Pillera¹⁴⁹, B. Pilszyk¹⁰¹, D. Pimentel²⁰², F. Pintore⁹¹, C. Pio García⁴¹, G. Pirola⁶⁴, F. Piron³⁹, A. Pisarski¹⁹⁰, S. Pita⁸⁵, M. Pohl¹²⁸, V. Poireau⁴⁵, P. Poledrelli¹⁵⁹, A. Pollo¹²⁶, M. Polo¹¹³, C. Pongkitvanichkul³¹, J. Porthault¹⁴⁴, J. Powell¹⁷¹, D. Pozo⁹⁸, R.R. Prado⁵², E. Prandini⁵⁵, P. Prasad³¹, J. Prast⁴⁵, K. Pressard⁷³, G. Principe⁹⁰, C. Priyadarshi⁴¹,

N. Produit³⁸, D. Prokhorov¹⁷⁴, H. Prokoph⁵², M. Prouza³³, H. Przybiski¹⁰¹, E. Pueschel⁵², G. Pühlhofer⁶⁹, I. Puljak¹⁵⁰, M.L. Pumo⁹⁴, M. Punch^{85,57}, F. Queiroz²⁰³, J. Quinn²⁰⁴, A. Quirrenbach¹⁷⁰, S. Rainò¹⁴⁹, P.J. Rajda¹⁷⁵, R. Rando⁵⁵, S. Razaque²⁰⁵, E. Rebert²⁰, S. Recchia⁸⁵, P. Reichherzer⁵⁹, O. Reimer¹⁶³, A. Reimer¹⁶³, A. Reisenegger^{3,206}, Q. Remy⁵³, M. Renaud³⁹, T. Reposeur¹⁰⁶, B. Reville⁵³, J.-M. Reymond⁷⁵, J. Reynolds¹⁵, W. Rhode⁴⁶, D. Ribeiro⁹, M. Ribo⁸¹, G. Richards¹⁶², T. Richtler¹⁹⁶, J. Rico⁴¹, F. Rieger⁵³, L. Riitano¹³⁵, V. Ripepi⁸⁴, M. Riquelme¹⁹², D. Riquelme³⁵, S. Rivoire³⁹, V. Rizi¹⁸, E. Roache⁶³, B. Röben¹⁵⁹, M. Roche¹⁰⁶, J. Rodríguez⁴, G. Rodríguez Fernández²⁵, J.C. Rodríguez Ramírez¹⁹, J.J. Rodríguez Vázquez¹¹³, F. Roepke¹⁷⁰, G. Rojas²⁰⁷, L. Romanato⁵⁵, P. Romano⁹⁵, G. Romeo²⁹, F. Romero Lobato¹¹, C. Romoli⁵³, M. Roncadelli¹⁰³, S. Ronda³⁰, J. Rosado¹¹, A. Rosales de Leon⁵, G. Rowell¹¹⁸, B. Rudak⁴⁹, A. Rugliancich⁷⁴, J.E. Ruiz del Mazo¹², W. Rujopakarn³¹, C. Rulten⁵, C. Russell³, F. Russo²¹, I. Sadeh⁵², E. Sæther Hatlen¹⁰, S. Safi-Harb³⁷, L. Saha¹¹, P. Saha²⁰⁸, V. Sahakian¹⁴⁷, S. Sailer⁵³, T. Saito², N. Sakaki⁵⁴, S. Sakurai², F. Salesa Greus¹⁰¹, G. Salina²⁵, H. Salzmann⁶⁹, D. Sanchez⁴⁵, M. Sánchez-Conde¹⁴, H. Sandaker¹⁰, A. Sandoval¹⁶, P. Sangiorgi⁹¹, M. Sanguillon³⁹, H. Sano², M. Santander¹⁷¹, A. Santangelo⁶⁹, E.M. Santos²⁰², R. Santos-Lima¹⁹, A. Sanuy⁸¹, L. Sapozhnikov⁹⁶, T. Saric¹⁵⁰, S. Sarkar¹¹⁴, H. Sasaki¹⁵⁷, N. Sasaki¹⁷⁹, K. Satalecka⁵², Y. Sato²⁰⁹, F.G. Saturni²⁸, M. Sawada⁵⁴, U. Sawangwit³¹, J. Schaefer¹⁴², A. Scherer³, J. Scherpenberg¹⁰⁵, P. Schipani⁸⁴, B. Schleicher¹²², J. Schmolz⁵, M. Schneider¹⁴³, H. Schoorlemmer⁵³, P. Schovaneck³³, F. Schussler⁸⁹, B. Schwab¹⁴², U. Schwanke¹⁸⁶, J. Schwarz⁹⁵, T. Schweizer¹⁰⁵, E. Sciacca²⁹, S. Scuderi⁶¹, M. Seglar Arroyo⁴⁵, A. Segreto⁹¹, I. Seitenzahl⁴³, D. Semikoz⁸⁵, O. Sergijenko¹³⁶, J.E. Serna Franco¹⁶, M. Servillat²⁰, K. Seweryn²⁰¹, V. Sguera²¹, A. Shalchi³⁷, R.Y. Shang⁷¹, P. Sharma⁷³, R.C. Shellard⁴⁰, L. Sidoli⁶¹, J. Sieiro⁸¹, H. Siejkowski¹⁵², J. Silk¹¹⁴, A. Sillanpää⁶⁵, B.B. Singh¹⁰⁹, K.K. Singh²¹⁰, A. Sinha³⁹, C. Siqueira⁸⁰, G. Sironi⁹⁵, J. Sitarek⁶⁰, P. Sizun⁷⁵, V. Sliusar³⁸, A. Slowikowska¹⁷⁸, D. Sobczyńska⁶⁰, R.W. Sobrinho¹⁸⁴, H. Sol²⁰, G. Sottile⁹¹, H. Spackman¹¹⁴, A. Specovius¹⁴², S. Spencer¹¹⁴, G. Spengler¹⁸⁶, D. Spiga⁹⁵, A. Spolon⁵⁵, W. Springer¹⁶⁴, A. Stamerra²⁸, S. Stanic⁶⁸, R. Starling¹²⁴, L. Stawarz¹⁶⁹, R. Steenkamp⁴⁸, S. Stefanik¹⁹⁷, C. Stegmann¹²⁸, A. Steiner⁵², S. Steinmassl⁵³, C. Stella¹⁰³, C. Steppa¹²⁸, R. Sternberger⁵², M. Sterzel¹⁵², C. Stevens¹³⁵, B. Stevenson⁷¹, T. Stolarczyk⁴, G. Stratta²¹, U. Straumann²⁰⁸, J. Strišković¹⁶⁶, M. Strzys², R. Stuk¹⁷⁴, M. Suchenek²¹¹, Y. Suda¹⁴⁰, Y. Sunada¹⁷⁹, T. Suomijarvi⁷³, T. Suric²¹², P. Sutcliffe¹⁵³, H. Suzuki²¹³, P. Świerk¹⁰¹, T. Szeplieniec¹⁵², A. Tacchini²¹, K. Tachihara¹⁴¹, G. Tagliaferri⁹⁵, H. Tajima¹³⁹, N. Tajima², D. Tak⁵², K. Takahashi²¹⁴, H. Takahashi¹⁴⁰, M. Takahashi², M. Takahashi², J. Takata², R. Takeishi², T. Tam², M. Tanaka¹⁸², T. Tanaka²¹³, S. Tanaka²⁰⁹, D. Tateishi¹⁷⁹, M. Tavani⁹⁹, F. Tavecchio⁹⁵, T. Tavernier⁸⁹, L. Taylor¹³⁵, A. Taylor⁵², L.A. Tejedor¹¹, P. Temnikov¹⁸⁹, Y. Terada¹⁷⁹, K. Terauchi¹⁸⁰, J.C. Terrazas¹⁹², R. Terrier⁸⁵, T. Terzic¹²¹, M. Teshima^{105,2}, V. Testa²⁸, D. Thibaut⁸⁵, F. Thocquenue⁷⁵, W. Tian², L. Tibaldo⁸⁷, A. Tiengo²¹⁵, D. Tiziani¹⁴², M. Tluczyk⁵⁰, C.J. Toder Peixoto¹⁰², F. Tokanai¹⁵⁴, K. Toma¹⁶⁰, L. Tomankova¹⁴², J. Tomastik¹⁰⁴, D. Tonev¹⁸⁹, M. Tornikoski²¹⁶, D.F. Torres¹³, E. Torresi²¹, G. Tosti⁹⁵, L. Tosti²³, T. Totani⁵¹, N. Tothill¹¹⁷, F. Toussene⁷⁹, G. Tovmassian¹⁶, P. Travnicek³³, C. Trichard⁸, M. Trifoglio²¹, A. Trois⁹⁵, S. Truzzi⁶², A. Tsiahina⁸⁷, T. Tsuru¹⁸⁰, B. Turk⁴⁵, A. Tutone⁹¹, Y. Uchiyama¹⁶¹, G. Umama²⁹, P. Utayarat³¹, L. Vaclavek¹⁰⁴, M. Vacula¹⁰⁴, V. Vagelli^{23,217}, F. Vagnetti²⁵, F. Vakili²¹⁸, J.A. Valdivia¹⁹², M. Valentino²⁴, A. Valio¹⁹, B. Vallage⁸⁹, P. Vallania^{44,64}, J.V. Valverde Quispe⁸, A.M. Van den Berg⁴², W. van Driel²⁰, C. van Eldik¹⁴², C. van Rensburg¹, B. van Soelen²¹⁰, J. Vandenbroucke¹³⁵, J. Vanderwalt¹, G. Vasileiadis³⁹, V. Vassiliev⁷¹, M. Vázquez Acosta³², M. Vecchi⁴², A. Vega⁹⁸, J. Veh¹⁴², P. Veitch¹¹⁸, P. Venault⁷⁵, C. Venter¹, S. Ventura⁶², S. Vercellone⁹⁵, S. Vergani²⁰, V. Verguillov¹⁸⁹, G. Verna²⁷, S. Vernetto^{44,64}, V. Verzi²⁵, G.P. Vettolani⁹⁰, C. Veysiere¹⁴⁴, I. Viale⁵⁵, A. Viana⁸⁰, N. Viaux³⁵, J. Vicha³³, J. Vignatti³⁵, C.F. Vigorito^{64,108}, J. Villanueva⁹⁸, J. Vink¹⁷⁴, V. Vitale²³, V. Vittorini⁹⁹, V. Vodeb⁶⁸, H. Voelk⁵³, N. Vogel¹⁴², V. Voisin⁷⁹, S. Vorobiov⁶⁸, I. Vovk², M. Vrsti³³, T. Vuillaume⁴⁵, S.J. Wagner¹⁷⁰, R. Wagner¹⁰⁵, P. Wagner⁵², K. Wakazono¹³⁹, S.P. Wakely¹²⁷, R. Walter³⁸, M. Ward⁵, D. Warren⁵⁴, J. Watson⁵², N. Webb⁸⁷, M. Wechakama³¹, P. Wegner⁵², A. Weinstein¹²⁹, C. Weniger¹⁷⁴, F. Werner⁵³, H. Wettskind¹⁰⁵, M. White¹¹⁸, R. White⁵³, A. Wierzcholska¹⁰¹, S. Wiesand⁵², R. Wijers¹⁷⁴, M. Wilkinson¹²⁴, M. Will¹⁰⁵, D.A. Williams¹⁴³, J. Williams¹²⁴, T. Williamson¹⁶², A. Wolter⁹⁵, Y.W. Wong¹⁴², M. Wood⁹⁶, C. Wunderlich⁶², T. Yamamoto²¹³, H. Yamamoto¹⁴¹, Y. Yamane¹⁴¹, R. Yamazaki²⁰⁹, S. Yanagita¹⁷⁶, L. Yang²⁰⁵, S. Yoo¹⁸⁰, T. Yoshida¹⁷⁶, T. Yoshikoshi², P. Yu⁷¹, P. Yu⁸⁵, A. Yusufzai⁵⁹, M. Zacharias²⁰, G. Zaharijas⁶⁸, B. Zaldivar¹⁴, L. Zampieri⁷⁶, R. Zanmar Sanchez²⁹, D. Zaric¹⁵⁰, M. Zavrtanik⁶⁸, D. Zavrtanik⁶⁸, A.A. Zdziarski⁴⁹, A. Zech²⁰, H. Zechlin⁶⁴, A. Zenin¹³⁹, A. Zerwekh³⁵, V.I. Zhdanov¹³⁶, K. Zięta¹⁶⁹, A. Zink¹⁴², J. Ziólkowski⁴⁹, V. Zitelli²¹, M. Živec⁶⁸, A. Zmija¹⁴²

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 Bellaterra (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

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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, Geofísica, 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 Física 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 Łódź, ul. Pomorska 149-153, 90-236 Łódź, 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, Valparaíso, 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 - Università 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. Università 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 Matejčić 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 Sołtana 7, 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. Boskovicica 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, Università 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. Bartycza 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, France