

Sensitivity of CTA to gamma-ray emission from the Perseus galaxy cluster

Judit Pérez-Romero^{a,b,*} on behalf of the CTA Consortium

(a complete list of authors can be found at the end of the proceedings)

^a*Instituto de Física Teórica UAM-CSIC, Universidad Autónoma de Madrid, C/ Nicolás Cabrera, 13-15, 28049 Madrid, Spain*

^b*Departamento de Física Teórica, M-15, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
E-mail: judit.perez@uam.es

In these proceedings we summarize the current status of the study of the sensitivity of the Cherenkov Telescope Array (CTA) to detect diffuse gamma-ray emission from the Perseus galaxy cluster. Gamma-ray emission is expected in galaxy clusters both from interactions of cosmic rays (CR) with the intra-cluster medium, or as a product of annihilation or decay of dark matter (DM) particles in case they are weakly interactive massive particles (WIMPs). The observation of Perseus has been proposed as one of the CTA Key Science Projects. In this contribution, we focus on the DM-induced component of the flux. Our DM modelling includes the substructures we expect in the main halo which will boost the annihilation signal significantly. We adopt an ON/OFF observation strategy and simulate the expected gamma-ray signals. Finally we compute the expected CTA sensitivity using a likelihood maximization analysis including the most recent CTA instrument response functions. In absence of signal, we show that CTA will allow us to provide stringent and competitive constraints on TeV DM, especially for the case of DM decay.

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*Presenter

1. Introduction

Galaxy clusters are the largest gravitationally-bound objects in the Universe, with masses between $M_{200} \approx 10^{14} - 10^{15} M_{\odot}$. Dark matter (DM) is expected to account for about 80% of their mass [1], while the rest is baryonic matter in the form of galaxies, gas and dust in the intra-cluster medium (ICM). Although clusters are supposedly virialized objects, the presence of hot gas, strong magnetic fields, galaxies and Active Galactic Nuclei (AGNs) produces turbulence phenomena and complex baryonic feedback in the ICM. All these astrophysical processes act as acceleration mechanisms, leading to production of cosmic rays (CR). The presence of CRs has been confirmed through observations of diffuse synchrotron emission produced by the CRs electrons and positrons at different wavelengths [2]. However, the gamma-ray emission, expected either from neutral pion decay from accelerated CRs [3] and/or from DM annihilation or decay of Weakly Interacting Massive Particles (WIMPs) particles [4], has so far avoided detection [5].

Galaxy clusters are considered excellent and complementary targets for gamma-ray DM searches because of the large amount of DM they are expected to host. Given the large number of known clusters, it is key to determine which of them meet the most appropriate conditions to be searched for in gamma-rays:

- Proximity to Earth ($z < 0.1$), so that substantial DM-induced fluxes are expected.
- High-mass clusters with well-determined masses, since the annihilation flux is proportional to the mass.
- Low gamma-ray flux from conventional astrophysical processes [6].

In [7] authors studied how the most promising galaxy clusters compared to the known dwarf Spheroidal galaxies (dSphs) in terms of their annihilation fluxes. Following results of DM-only N-body simulations, the substructures in the main DM halo were for the first time included for the computation of the annihilation flux. These substructures, usually called subhalos, are a natural prediction within the standard Λ CDM structure formation scenario. The authors concluded that galaxy clusters are competitive targets in terms of the annihilation flux, as long as the DM annihilation happening in these subhalos is properly taken into account.

The Cherenkov Telescope Array (CTA) will be the next generation of Imaging Atmospheric Cherenkov Telescopes (IACTs). CTA's energy sensitivity will improve up to one order of magnitude the sensitivity of current generation IACTs in the 20 GeV to 300 TeV energy range [8], will have 2.5 better field of view and 5 times better angular resolution. CTA will have two different arrays: the Northern array in La Palma (Spain), and the Southern array in the Atacama desert in Chile. Having an excellent spectral and angular resolution, CTA has superb capabilities to perform gamma-ray DM searches, especially those focused on WIMPs.

Among the local clusters that fulfill the requirements mentioned before, the Perseus cluster is the brightest in the X-ray sky. It hosts two central AGNs, NGC1275 and IC310. Being one of the most massive clusters in the nearby Universe, Perseus is one of the most promising clusters to be detected in gamma-rays [9]. More precisely, given its position in the sky, it meets the optimal conditions for observation by the CTA Northern array [8]. All these attributes make the Perseus science case an excellent discovery opportunity for CTA [8].

2. Dark Matter modelling in Perseus

The expected annihilation flux in gamma-rays from the Perseus cluster can be computed as follows [10]:

$$\frac{d\Phi_\gamma}{dE}(\Delta\Omega, l.o.s, E) = \frac{d\phi_\gamma}{dE}(E) \times J(\Delta\Omega, l.o.s), \quad (1)$$

where $\frac{d\phi_\gamma}{dE}$ is the gamma-ray annihilation/decay flux, $\frac{d\phi_\gamma}{dE}$ is the particle physics term containing the spectral information [4] and J is the so-called astrophysical factor. The particle physics term can be written, assuming Majorana WIMPs, in terms of the selected annihilation/decay channel (dN^{PP}/dE), the mass (m_{DM}) and the averaged annihilation cross section ($\langle \sigma v \rangle$) or the DM particle lifetime (τ_{DM}) as

$$\frac{d\phi_\gamma^{Annihil}}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_{DM}^2} \frac{dN^{PP}}{dE}, \quad (2)$$

$$\frac{d\phi_\gamma^{Decay}}{dE} = \frac{1}{4\pi m_{DM} \tau_{DM}} \frac{dN^{PP}}{dE}. \quad (3)$$

The astrophysical factor or J-factor (D- for decaying DM) accounts for the DM distribution in the halo, parametrized in the DM density profile ρ_{DM} :

$$J(\Delta\Omega, l.o.s) = \int_{\Delta\Omega} \int_{l.o.s} \rho_{DM}^2, \quad (4)$$

$$D(\Delta\Omega, l.o.s) = \int_{\Delta\Omega} \int_{l.o.s} \rho_{DM}. \quad (5)$$

From the X-ray surface brightness data of the Perseus galaxy cluster, one can derive the cluster's main parameters. We build the DM density profile for the main halo starting from its measured mass. In our study, we adopt the mass estimate in [11]. We also need to assume a DM profile, in this case, the Navarro-Frenk-White (NFW) profile [12, 13]:

$$\rho_{NFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right) \left(1 + \frac{r}{r_s}\right)^2}. \quad (6)$$

The two parameters in the NFW profile are computed by making use of the concentration-mass ($c - M$) relation in [14]. The obtained DM density profile parameters for Perseus are given in Table 1.

Cluster	(l, b) [deg]	D [Mpc]	M_{200} [$10^{14} M_\odot$]	R_{200} [10^2 kpc]	ρ_0 [$10^6 M_\odot \text{kpc}^{-3}$]	r_s [10^2 kpc]
Perseus	(150.57, -13.26)	75.01	7.52	18.65	1.20	3.71

Table 1: DM density profile parameters for the Perseus galaxy cluster assuming the NFW profile and the $c - M$ relation in [14].

We also include in the modelling the expected substructures that contribute to the DM-induced gamma-ray flux. We note that this is only relevant for the annihilation case. We assume an NFW density profile also to describe the internal structure of subhalos. We parametrize the population of subhalos inside the main halo via three basic factors: radial distribution (SRD), mass distribution (SHMF) and subhalo concentration. Following the state-of-the-art of the subhalo DM population as given by N-body simulations, we will adopt:

- SRD: Anti-biased distribution following the results of the Via Lactea - II Milky-Way-sized cosmological simulation [15].
- SHMF: $\frac{dN}{dM} \propto M^{-\alpha}$, where α can take two values $\alpha = 1.9, 2.0$; following [16] and [15], respectively.
- Concentration: We use the parametrization specifically derived for subhalos developed in [17].

In our work, we define three different models of the subhalo population in Perseus. With the definition of these three models, we will be able to provide an estimate of the uncertainty on the exact configuration of halo substructure in Perseus. Indeed, we will obtain conservative values (no substructure model) for the DM annihilation flux and also upper bounds ($\alpha = 2.0$ model). To compute the J- and D- factors we use the CLUMPY free software [18–20]. The results of the DM modelling for annihilation and decay are shown in Table 2 and the corresponding differential annihilation flux profiles are represented in Figure 1.

Annihilation	$\log_{10} J [\text{GeV}^2 \text{cm}^{-5}]$	Decay	$\log_{10} D [\text{GeV cm}^{-2}]$
J_T	17.42	D_T	19.20
$J_T^{1.9}$	18.48		
$J_T^{2.0}$	18.93		

Table 2: Annihilation of the different DM models (no substructure, SHMF $\alpha = 1.9$, SHMF $\alpha = 2.0$) and decay results for Perseus, integrated up to R_{200} (symbolized as the sub-index T). See text for details.

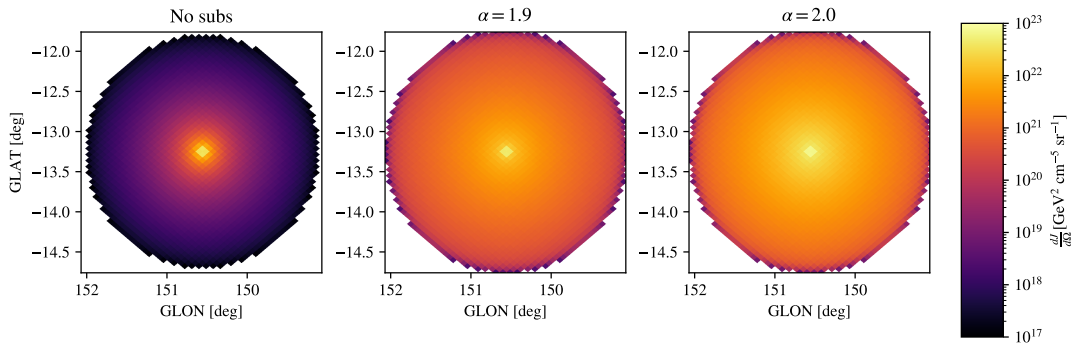


Figure 1: Two-dimensional spatial templates showing the expected spatial morphology of the DM annihilation flux in Perseus. The inclusion of different amounts of substructure as described in the text alters the flux especially in the outskirts of the cluster.

From the J-factor values of Table 2 we can notice the effect of taking into account the substructure in the cluster. This enhancement of the J-factor when including the subhalos in the DM modelling is known as the *subhalo boost factor* B , defined as $B = 0$ for the case where no substructure is included. For the model with $\alpha = 1.9$ the *boost factor* is $B = 10.5$, and for $\alpha = 2.0$ we obtain $B = 31.4$.

3. CTA sensitivity to DM-induced gamma-ray from Perseus

We use the most up-to-date Instrument Response Functions (IRFs - prod3b-v2) to compute the prospects for observing gamma-rays from Perseus using CTA. Besides, we also use the two available softwares to perform the analysis, `gammapy`¹ and `ctools`². In our analysis, we include DM annihilation/decay as gamma-ray source. In future steps of the project, we will consider also CR-induced gamma-ray emission and the emission from the two AGNs hosted in Perseus. An illustrative sketch of the analysis pipeline to follow in our work is shown in Figure 2.

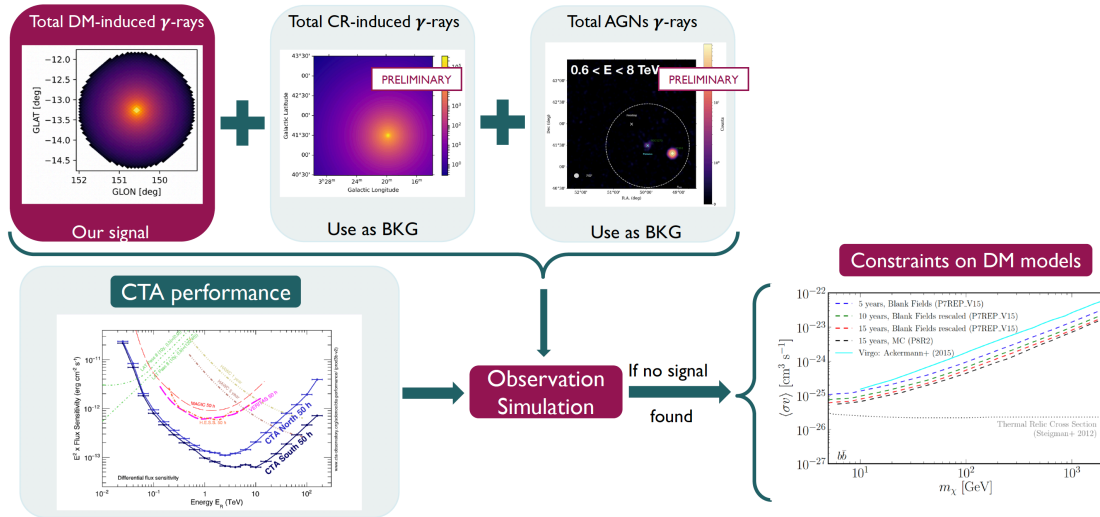


Figure 2: Sketch of the analysis pipeline to compute the sensitivity of CTA to gamma-ray induced DM signal. The bottom right plot is only shown as an example of constraints from this type of searches, and was extracted from [21].

The analysis strategy is based on the widely used ON/OFF observation method [22]. We define the different OFF regions according to Table 3. Given the stochastic nature of the emission

¹<https://docs.gammapy.org/0.18.2/index.html>

²<http://cta.irap.omp.eu/ctools/>

of astrophysical gamma-ray photons and the detection of these by CTA, we create 50 simulated observations for the SHMF $\alpha = 1.9$ DM model case and average the results in order to obtain statistically meaningful results.

N_{obs}	50
T_{obs} [h]	300
Obs. strategy	1 ON / 3 OFF
Pointing (l , b) [deg]	(150.57, -13.26)
Offset [deg]	1.0
On Region [deg]	1.0
Energy range [TeV]	0.03 - 100

Table 3: Observation parameters set-up for the Perseus DM-search campaign with the ON/OFF method.

As a first order approximation, we assume Perseus cluster to be a point-like source. No signal is found in these simulations, thus we compute the 95% confidence level (C.L.) upper limits to the gamma-ray flux. Then, we proceed and compute 95% C.L. upper limits to the DM annihilation cross section (Eq. 2) and decay lifetime (Eq. 3). The preliminary results are shown in Figure 3 for the $b\bar{b}$, $\tau^+\tau^-$ and W^+W^- channels.

From the left panel of Figure 3 we can see that our constraints to DM annihilation are, at best, around two orders of magnitude above the thermal relic cross section, even with the inclusion of halo substructure. Yet, for decay DM, the results of the right panel show that CTA will be able to improve the limits from [23] by up to two orders of magnitude in the lowest considered mass range.

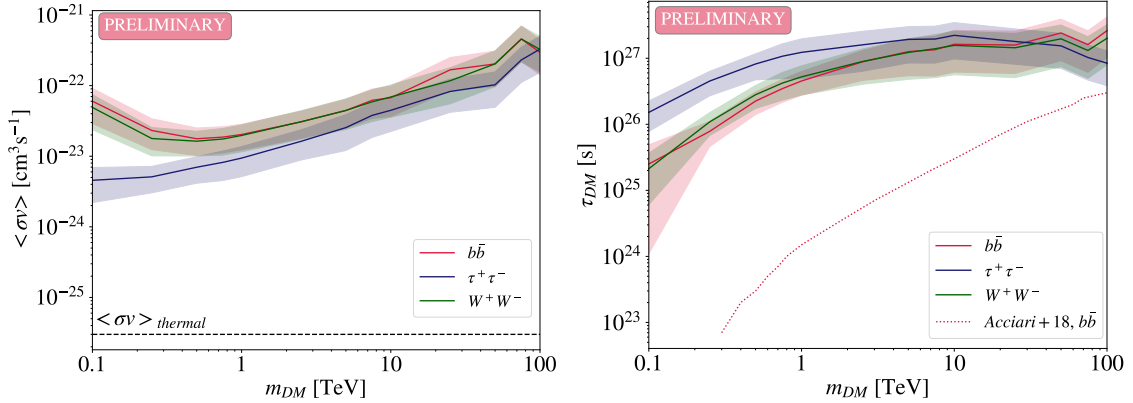


Figure 3: 95% C.L. upper limits on the DM parameter space. *Left panel:* Averaged annihilation cross section versus DM mass. The thermal relic cross section is shown as a black dashed line. *Right panel:* DM particle lifetime versus DM mass. For comparison, we show in red dotted line the constraints obtained from 202 h observation of Perseus for the $b\bar{b}$ channel with the MAGIC telescopes [23].

In the future, our analysis will necessarily consider the three known gamma-ray sources in Perseus, as well as the extension of the involved gamma-ray signals. An extended analysis, i.e. taking into account the extension of the cluster, is expected to worsen the obtained DM constraints. We will also include systematic uncertainties. An alternative analysis approach will also be performed via a template analysis fitting, as done for CTA in [24]. The result of this analysis

yield the first DM annihilation constraints for Perseus from any IACT, that are complementary to the ones obtained by the *Fermi*-LAT Collaboration [25–27].

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Full Authors List: The Cherenkov Telescope Array Consortium July 2021 Authors

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, L. Ambrogio¹⁸, 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. Arsioli⁴⁰, M. Artero⁴¹, K. Asano², Y. Ascasíbar¹⁴, J. Aschersleben⁴², M. Ashley⁴³, P. Attinà⁴⁴, P. Aubert⁴⁵, C. B. Singh¹⁹, D. Baack⁴⁶, A. Babic⁴⁷, M. Backes⁴⁸, V. Baena¹³, S. Bajtlik⁴⁹, 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. Bernlöhner⁵³, 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. Boccatto⁷⁶, F. Bocchino⁷⁷, C. Boehm⁷⁸, M. Bohacova³³, C. Boisson²⁰, J. Boix⁴¹, J.-P. Bolle⁵², J. Bolmont⁷⁹, G. Bonanno²⁹, C. Bonavolontà²⁴, L. Bonneau Arbeletche⁸⁰, G. Bonnoli¹², P. Bordas⁸¹, J. Borkowski⁴⁹, S. Bórquez³⁵, R. Bose⁸², D. Bose⁸³, Z. Bosnjak⁴⁷, E. Bottacini⁵⁵, M. Böttcher¹, M.T. Botticella⁸⁴, C. Boutonnet⁸⁵, F. Bouyjou⁷⁵, V. Bozhilov⁸⁶, E. Bozzo³⁸, L. Brahimi³⁹, C. Braiding⁴³, S. Braun-Nogue⁸⁷, S. Breen⁷⁸, J. Bregeon³⁹, M. Breuhaus⁵³, A. Brill⁹, W. Brisken⁸⁸, E. Brocato²⁸, A.M. Brown⁵, K. Brügge⁴⁶, P. Brun⁸⁹, P. Brun³⁹, F. Brun⁸⁹, L. Brunetti⁴⁵, G. Brunetti⁹⁰, P. Bruno²⁹, A. Bruno⁹¹, A. Bruzzese⁶, 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. Carquín³⁵, 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. Congiù⁹⁵, 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. Crestan⁶¹, 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 Frondat²⁰, 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 Pierro⁶⁴, L. Di Venere¹²⁰, C. Díaz¹¹³, C. Díaz-Bahamondes³, C. Dib³⁵, S. Diebold⁶⁹, S. Digel⁹⁶, R. Dima⁵⁵, A. Djannati-Atai⁸⁵, J. Djuvslund¹¹⁶, 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. Ederoclite¹⁹, 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. Fornieri⁵², P. Fortin⁶³, L. Fortson⁸⁸, 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. Garcia⁴⁵, 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. Gjaja⁹, 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. Goulart Coelho¹²³, K. Gourgouliatos⁵, 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. Guarino²⁶, 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 Llorente³², A. Herrero³², O. Hervet¹⁴³, J. Hinton⁵³, A. Hiramatsu¹⁵⁷, 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. Inome², 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. Jamrozny¹⁶⁹, P. Janecek³³, F. Jankowsky¹⁷⁰, A. Jardin-Blicq³¹, C. Jarnot⁸⁷, P. Jean⁸⁷, I. Jiménez Martínez¹¹³, W. Jin¹⁷¹, L. Jocou¹²⁵, 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. Kasperek¹⁷⁵, H. Katagiri¹⁷⁶, J. Kataoka¹⁷⁷, K. Katarzyński¹⁷⁸, 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. Lemièrè⁸⁵, 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. Manicò⁹⁴, 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. Martínez³⁰, 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. Mbarubucyeye⁵², L. Mc Comb⁵, I. McHardy¹¹⁵, S. McKeague¹⁰⁷, S. McMuldroch⁶³, 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. Minev¹⁸⁹, 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. Ndiyavala¹, D. Neise³⁶, L. Nellen¹⁶, R. Nemmen¹⁹, M. Newbold¹⁶⁴, N. Neyroud⁴⁵, K. Ngernphat³¹, T. Nguyen Trung⁷³, L. Nicastro²¹, L. Nickel⁴⁶, J. Niemiec¹⁰¹, D. Nieto¹¹, M. Nievas³², 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. Pavletić¹²¹, S. Pavy⁸, A. Pe'er¹⁰⁵, M. Pech³³, 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. Pongkitivanichkul³¹, J. Porthault¹⁴⁴, J. Powell¹⁷¹, D. Pozo⁹⁸, R.R. Prado⁵², E. Prandini⁵⁵, P. Prast³¹, J. Prast⁴⁵, K. Pressard⁷³, G. Principe⁹⁰, C. Priyadarshi⁴¹, N. Produit³⁸, D. Prokhorov¹⁷⁴, H. Prokoph⁵², M. Prouza³³, H. Przybilski¹⁰¹, 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. Ribó⁸¹, 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. Rodriguez⁴, G. Rodriguez Fernandez²⁵, J.C. Rodriguez Ramirez¹⁹, 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. Ruíz 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. Schmoll⁵, M. Schneider¹⁴³, H. Schoorlemmer⁵³, P. Schovanek³³, 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. Stanič⁶⁸, R. Starling¹²⁴, Ł. 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. Stuik¹⁷⁴, M. Suchenek²¹¹, Y. Suda¹⁴⁰, Y. Sunada¹⁷⁹, T. Suomijarvi⁷³, T. Suric²¹², P. Sutcliffe¹⁵³, H. Suzuki²¹³, P. Świerk¹⁰¹, T. Szepieniec¹⁵², 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. Tluczykont⁵⁰, C.J. Todero 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. Toussenet⁷⁹, G. Tovmassian¹⁶, P. Travnicek³³, C. Trichard⁸, M. Trifoglio²¹, A. Trois⁹⁵, S. Truzzi⁶², A. Tsiachina⁸⁷, T. Tsuru¹⁸⁰, B. Turk⁴⁵, A. Tutone⁹¹, Y. Uchiyama¹⁶¹, G. Umana²⁹, 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. Verguilov¹⁸⁹, G. Verna²⁷, S. Vernetto^{44,64}, V. Verzi²⁵, G.P. Vettolani⁹⁰, C. Veyssiere¹⁴⁴, 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. Vrastil³³, 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. Ziółkowski⁴⁹, 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

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 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., Pionneerspark, 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 Moiarriello 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, Liberdade 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 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 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. Orła 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. 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, France