

PAPER • OPEN ACCESS

Search for a diffuse flux of photons with energies above tens of PeV at the Pierre Auger Observatory

To cite this article: A. Abdul Halim *et al* JCAP05(2025)061

View the [article online](#) for updates and enhancements.

You may also like

- [Multi-messenger Observations of a Binary Neutron Star Merger](#)
B. P. Abbott, R. Abbott, T. D. Abbott et al.
- [Identification of hadronic tau lepton decays using a deep neural network](#)
A. Tumasyan, W. Adam, J.W. Andrejkovic et al.
- [The ATLAS Fast TrackEr system](#)
The ATLAS collaboration, G. Aad, B. Abbott et al.

RECEIVED: February 5, 2025

ACCEPTED: March 25, 2025

PUBLISHED: May 23, 2025

Search for a diffuse flux of photons with energies above tens of PeV at the Pierre Auger Observatory



PIERRE
AUGER
OBSERVATORY

The Pierre Auger collaboration

E-mail: spokespersons@auger.org

ABSTRACT: Diffuse photons of energy above 0.1 PeV, produced through the interactions between cosmic rays and either interstellar matter or background radiation fields, are powerful tracers of the distribution of cosmic rays in the Galaxy. Furthermore, the measurement of a diffuse photon flux would be an important probe to test models of super-heavy dark matter decaying into gamma-rays. In this work, we search for a diffuse photon flux in the energy range between 50 PeV and 200 PeV using data from the Pierre Auger Observatory. For the first time, we combine the air-shower measurements from a 2 km² surface array consisting of 19 water-Cherenkov surface detectors, spaced at 433 m, with the muon measurements from an array of buried scintillators placed in the same area. Using 15 months of data, collected while the array was still under construction, we derive upper limits to the integral photon flux ranging from 13.3 to 13.8 km⁻² sr⁻¹ yr⁻¹ above tens of PeV. We extend the Pierre Auger Observatory photon search program towards lower energies, covering more than three decades of cosmic-ray energy. This work lays the foundation for future diffuse photon searches: with the data from the next 10 years of operation of the Observatory, this limit is expected to improve by a factor of ~ 20 .

KEYWORDS: ultra high energy cosmic rays, cosmic rays detectors

ARXIV EPRINT: [2502.02381](https://arxiv.org/abs/2502.02381)

Contents

1	Introduction	1
2	Detection systems and data	3
3	Energy assignment of photon and proton events	5
3.1	Trigger efficiency of photon and proton primaries	6
3.2	Photon-initiated events	6
3.3	Proton-initiated events	8
3.4	The photon-equivalent energy scale	9
4	Discrimination between photon and proton events	10
4.1	Muon content estimator, M_b	11
4.2	Optimization of M_b	12
5	Selection of photon events in data	14
6	Results of the photon search	17
6.1	Upper limits calculation	18
6.2	Systematic uncertainties on the upper limits	21
7	Conclusions and outlook	22
A	Lateral distribution function for photon events	24
B	Parametrization of the background contamination and photon candidate cuts	25
The Pierre Auger collaboration		31

1 Introduction

The origin and acceleration of very-high-energy (VHE, $E \gtrsim 10^{14}$ eV) cosmic rays can be investigated through the detection of photons produced by the interaction between cosmic rays and surrounding matter near their sources [1–3]. Photons with energies between 10^{14} eV and 10^{18} eV interact with background radiation fields, limiting their travel to at most a few megaparsecs (Mpc) [4], making them ideal probes for studying sources within our Galaxy and its vicinity. Recent observations have identified primary photons from Galactic sources with energies reaching up to $\sim 10^{15}$ eV [5, 6].

In addition to astrophysical sources, cosmogenic photons are expected to arise from interactions between cosmic rays and the cosmic microwave background, as well as the extragalactic background light, in intergalactic space [7–9]. Light particles have higher interaction cross-sections with these fields, leading to more frequent production of secondary

photons than occurs with heavier nuclei [10]. Recent studies using the data acquired by the Large High Altitude Air Shower Observatory (LHAASO) suggest that the average cosmic-ray mass is heavier than helium at around 10^{16} eV with an increasing trend towards heavier elements up to about 2×10^{17} eV [11], after which the composition either remains constant or becomes lighter [12–17].

Another significant contribution to the diffuse photon flux comes from the interactions between VHE cosmic rays and Galactic disk matter [18, 19]. Similar to fluxes from cosmic-ray propagation through radiation fields, this component depends on the flux and composition of the primary cosmic rays, as well as the distribution of the gas in the Galactic disk, and the interaction cross-sections. This flux diminishes as E^{-2} and may become the dominant component of the total cosmogenic photon flux below 10^{17} eV, though it remains four to five orders of magnitude lower than the energy-integrated cosmic-ray flux. Measurements from LHAASO provide further insight into the diffuse gamma-ray emissions from the Galactic plane, spanning energies between 10^{13} eV and 10^{15} eV. These measurements indicate that the gamma-ray flux is three times higher than predictions based on local cosmic-ray interactions with Galactic matter, particularly in the inner Galactic plane [20]. These results suggest additional emission sources or spatial variations in cosmic-ray fluxes, pointing to a more complex picture of gamma-ray production in the Milky Way. Upper limits on the diffuse photon flux between 10^{15} eV and 1.5×10^{17} eV have been set from the Northern Hemisphere using experimental facilities, including KASCADE-Grande [21], EAS-MSU [22] and CASA-MIA [23], while a diffuse search towards the Galactic plane has been performed with data measured by IceTop at 2×10^{15} eV [24].

The diffuse photon flux can also be used to constrain the lifetime of super-heavy dark matter (SHDM) within the Galactic center. The decay of SDHM may contribute to the diffuse photon flux above a few 10^{15} eV [25–27]. Since photons generated in the Galactic center are not significantly attenuated owing to the source proximity, they provide a prime signal for probing gamma-ray production across various SHDM decay channels [28, 29].

The searches for photons at ultra-high energies (UHE, $E \gtrsim 10^{17}$ eV) are performed by measuring extensive air showers, i.e., cascades of secondary particles produced in the atmosphere. The main challenge in these searches is distinguishing primary photons from the overwhelming background of charged cosmic rays. The separation is based on air-shower properties: showers initiated by photon primaries develop almost entirely through electromagnetic processes, while those initiated by hadrons contain a much larger number of muons [30–32]. Due to the smaller multiplicity of electromagnetic compared to hadronic interactions, the atmospheric depth of maximum shower development, X_{\max} , is expected to be deeper for a photon than for a hadronic primary. Also, taking into account the muonic component, this leads to a flatter lateral spread of the shower for hadronic cosmic rays compared with primary photons. These distinctive characteristics of photon showers are used to discriminate them from hadronic showers.

The Pierre Auger Observatory [33] integrates multiple detection techniques to extract information from air showers reaching the ground using a surface detector (SD) and from the measurement of the light emitted by air showers using a fluorescence detector (FD). The Pierre Auger Collaboration, combining SD and FD measurements, has set the most

stringent upper limits on the integral photon flux at energies above 2×10^{17} eV [34–36]. These analyses rely either on the rise-time and the integrated signal measured by water-Cherenkov detectors (WCDs) within the SD stations [33], the slope of the lateral signal fall-off, the indirect muon number estimation, or the measurement of the fluorescence radiation produced during the air-shower development.

In this study, we extend the search for primary photons done at the Auger Observatory towards lower energies, reaching down to 5×10^{16} eV. The extension is made possible by a dense array of 19 WCDs deployed over 2 km^2 and the direct measurements of the air-shower muonic component by an array of buried scintillators deployed in the same region, as discussed in section 2. The Monte Carlo-driven reconstruction of photon-initiated events and the definition of a unique energy scale to treat both photon and hadronic events are presented in section 3. The photon-hadron discrimination is performed using an observable, M_b , defined as the event-wise weighted sum of the muon density measurements. The power of this photon-hadron discriminator is presented in-depth in section 4. The selection criteria considered in data are described in section 5. The results of the photon search are presented in section 6.

2 Detection systems and data

The surface detector of the Pierre Auger Observatory consists of three regular detector grids, spaced by 1500 m, 750 m and 433 m, each designed to probe different regions of the cosmic-ray energy spectrum. Among these, the SD-433 [37, 38] is used in this study and comprises of 19 WCDs arranged in seven regular hexagons, covering an area of $\sim 2 \text{ km}^2$. Each WCD operates independently, calibrated using atmospheric particles, with signals measured in units of vertical equivalent muons (VEM) [39]. A more detailed description can be found in [33, 40].

The SD triggering system starts with low-level triggers from individual WCDs, progressing to the high-level trigger (T5). This trigger is used to select events where the station with the highest signal is surrounded by five (5T5) or six (6T5) active stations present in the ring of nearest neighbors. It ensures an accurate reconstruction of the impact point on the ground and reduces the calculation of the exposure to purely geometrical arguments [41].

In the configuration used in this work, eleven stations of the SD-433 array are co-located with stations of the Underground Muon Detector (UMD), as illustrated in figure 1, left. Each UMD station consists of three modules, each containing 64 plastic scintillator bars measuring 400 cm in length, 4 cm in width and 1 cm in thickness providing a sensitive area of $\sim 10 \text{ m}^2$ [42, 43]. The central station on the array’s western edge contains six modules, providing a sensitive area of $\sim 50 \text{ m}^2$, compared to the standard 30 m^2 area in all other stations. All modules are buried under 2.3 m of soil equivalent to a vertical shielding of 540 g/cm^2 , that filters out most of the particles produced in the air except muons with kinetic energies $\gtrsim 1 \text{ GeV}$. When a charged particle passes through the module, the scintillation material emits photons that are collected by a 1.2 mm wavelength-shifter optical fiber and conducted to an array of 64 silicon photomultipliers (SiPMs) Hamamatsu S13081-050CS [44]. Front-end electronics convert the analog pulses of each SiPM into binary signals, effectively translating the current pulses into a sequence of digital boolean samples. These output signals are sampled by a Field-Programmable Gate Array at 320 MHz, corresponding to a sampling interval of 3.125 ns, resulting in a binary trace of 2048 bits stored in the front-end memory. The back-end

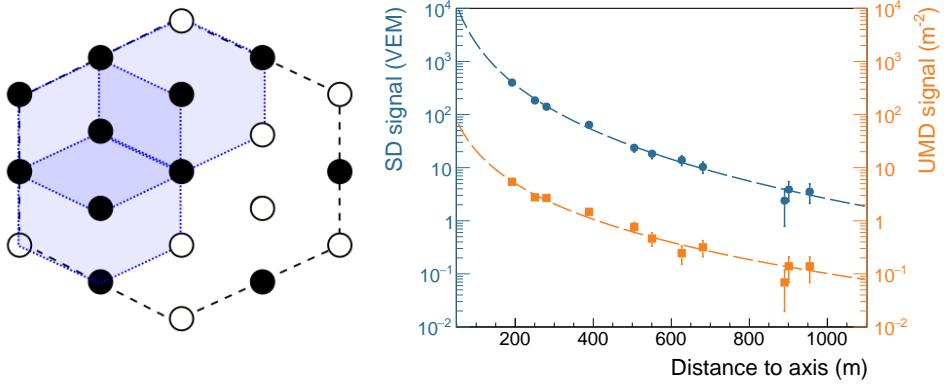


Figure 1. Left: A schematic view of the SD-433 array. Solid black positions are equipped with buried scintillators. Events acquired by the three highlighted hexagons are considered for the photon search. Right: One of the events acquired on February 27, 2021, part of the selected data set. The reconstructed energy is $(4.1 \pm 0.1) \times 10^{17}$ eV, obtained with a dedicated data energy scale [38], with a zenith angle of $(26.3 \pm 0.3)^\circ$. Dashed lines indicate the fitted lateral distribution functions (see section 3).

electronics handles all calibration, control, and monitoring tasks [45]. Additionally, the surface electronics, common to all UMD station modules, interfaces with the SD electronics to check for a trigger and retrieve and transfer the binary traces upon an event data request.

The highly segmented UMD modules are designed to count individual muons when triggered by the associated SD station. The counting procedure, performed on the binary traces, has been optimized to provide an unbiased estimate of the number of muons reaching a module. Specifically, muons are identified along the traces as a compact pattern of four consecutive “1” samples. Upon a successful match, an inhibition time window of 12 samples is activated, preventing additional muon counts within this period [46, 47]. The estimated muon density is defined as the number of muons over the projected area of a module to account for the decrease of its sensitive area with the air-shower zenith angle.

To reconstruct the incoming direction of the primary particle and the lateral distribution function (LDF) [48] of the air showers we use the signals from the WCDs. The LDF is described by the Nishimura-Kamata-Greisen (NKG) function [49, 50] from which we extract the shower size, $S(r_{\text{ref}})$, defined as the value at an optimal distance, r_{ref} . For an array spacing of 433 m, r_{ref} is chosen as 250 m to minimize the uncertainties of the signal due to the imperfect knowledge of the functional form of the LDF in individual events [51]. The shower size, $S(250)$, corrected for the attenuation in the atmosphere serves as an observable that can be calibrated against the primary energy. Although for most events detected with SD-433 (hadronic showers) a data-driven energy calibration is employed [38, 52], the energy calibration for photon events is instead performed using detailed Monte Carlo simulations, as discussed in section 3.

The photon search strategy designed for this work relies on the SD-433 data to measure the air showers, providing information on the primary energy and shower geometry, and on the direct measurement of the air-shower muon content, as recorded by the UMD stations. To ensure a sufficient sampling of the air-shower muon content, leading to a suitable discrimination

power as discussed in section 5, we select events acquired by the three highlighted hexagons of figure 1, left. The data for this analysis were recorded from December 17, 2020, when the central UMD stations in the three employed hexagons were commissioned, to March 31, 2022, before the upgrade of the 19 stations with new electronics [53].

The flux of events acquired by the SD hexagons is expected to remain constant, apart from a negligible seasonal modulation. As the number of detected events follows Poisson statistics, identifying unstable periods in the data acquisition of the SD-433 involves searching for time intervals between consecutive events incompatible with the Poisson expectation.¹ The same methodology is employed for the UMD modules, based on the rate of 6T5 events acquired by the SD-433 during which a UMD module is registered as active. Unstable periods for each UMD module are identified by analyzing the time intervals between consecutive appearances in the data. After subtracting unstable periods for both detection systems based on the arrival time of 6T5 events, the final data set is composed of 5T5 and 6T5 events recorded during ~ 15.5 months, equivalent to 8 months of data acquisition with the three hexagons operating under ideal conditions. The final data set is composed of 15,919 events with energies above $10^{16.7}$ eV and zenith angles up to 52° . The energy threshold is derived with the Monte Carlo study presented in section 3.4, while the zenith angle range is discussed in section 3.1. One of these events is shown in figure 1, right, where the LDF and energy calibration have been performed using the reconstruction used for the bulk of SD-433 events [38].

3 Energy assignment of photon and proton events

Unlike hadronic-initiated air showers [54], a data-driven energy calibration for photons is impractical because no photons have yet been detected above a few $\sim 10^{15}$ eV. Furthermore, given the depleted muon content in photon-initiated showers, a data-driven energy calibration would overestimate the photon energy because the SD is sensitive to muons. Stated otherwise, a photon and a hadronic primary of the same energy do not generate the same average signal in the WCDs. Consequently, simulated air showers with a sufficiently large probability to generate an event in the SD array are selected in section 3.1 before being employed to derive a dedicated energy calibration for photon-initiated events,² as described in section 3.2.

The discrimination method is designed using protons as the only hadronic species, because proton-initiated air showers have a muon content most similar to photon-initiated showers among the hadronic primaries present in the cosmic-ray flux. The energy of simulated proton events is underestimated when employing a data-driven energy calibration, since current high-energy hadronic interaction models appear to underestimate the number of muons produced in air showers [42, 55]. Therefore, a Monte Carlo-based energy assignment is developed in section 3.3. This approach provides the most conservative background estimation, as discussed in section 4.

¹For example, consecutive events separated more than 1.1 hours when the seven hexagons of the array are operative are not compatible with a Poisson probability at a 99% confidence level and hence identified as an unstable period.

²The bias introduced by the muon deficit in hadronic models is not expected to significantly affect an energy calibration based on photon-initiated events given the minimal muonic content in such showers.

Because the nature of the primary cosmic rays is unknown in the data, one cannot apply separate energy calibrations for hadron- and photon-initiated showers. A unified energy scale is thus essential for accurately comparing events initiated by different primary species. To tackle this problem, the photon-equivalent energy scale is developed in section 3.4.

3.1 Trigger efficiency of photon and proton primaries

The probability of a shower to trigger the array depends on the characteristics of the primary particle. We quantify this probability, the trigger efficiency, using air-shower simulations. The simulation library covers an energy range between 10^{16} eV and $10^{17.5}$ eV, which follows an E^{-1} distribution and zenith angles uniformly distributed in $\sin^2 \theta$ up to 60° . It contains 15,000 air showers for each primary, produced using CORSIKA v7.6400 [56] with EPOS-LHC [57] and Fluka2011.2x [58] as the high- and low-energy hadronic interaction models. The transition energy between these two regimes is set at 80 GeV. To manage the computational load, we employ a thinning algorithm as outlined in [59] with a thinning threshold of 10^{-6} . Subsequently, the particle distributions at ground level are unthinned at the stage of the detector simulation as described in [60]. Each air-shower core is randomly positioned ten times around the central station of the array and the detector response is simulated using the Auger Offline framework [61, 62].

Figure 2 depicts the trigger efficiency for the simulated photon and proton events. Air showers initiated by hadronic primaries, such as protons, reach the ground with a significantly more prominent muonic component than those initiated by photon primaries due to the decay of charged pions and kaons produced during hadronic interactions in the atmosphere. This increased muonic content is crucial for trigger generation, especially as the zenith angle increases and atmospheric attenuation of the electromagnetic particles becomes more significant. The trigger efficiency for proton-initiated air showers is thus consistently higher than that for photon events, with the difference becoming more pronounced at larger zenith angles.

A sigmoid model, represented by solid lines, describes the trigger efficiency based on the simulated energy, E_{MC} , and zenith angle, θ , with parameters estimated using a maximum likelihood method. Events generated by air showers with an expected trigger efficiency greater than 90% and a zenith angle smaller than 52° are selected for the Monte Carlo-driven analyses throughout this article since the trigger efficiency for photon showers with more inclined directions is negligible. Around 59,000 (64,000) photon (proton) events survive the selection cuts, representing nearly 40% of the total simulated events.

3.2 Photon-initiated events

As described in section 2, the primary energy is calibrated using the signal interpolated at 250 m from the shower axis, $S(250)$. This value is determined by evaluating a parametrized LDF fitted to best match the observed signals in each triggered SD station. To achieve an accurate estimate of $S(250)$, the slope parameter of the LDF is parametrized as detailed in appendix A. We utilize only one of the ten realizations of simulated events produced for each air shower to account for shower-to-shower fluctuations in the energy calibration. A

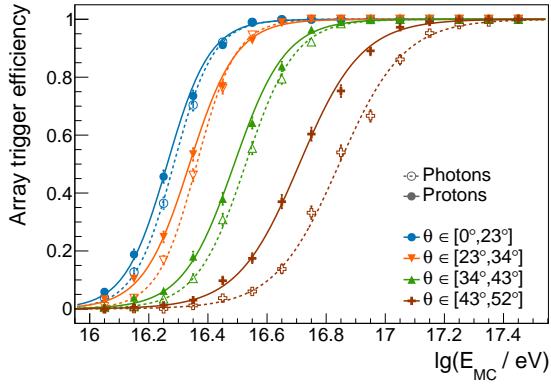


Figure 2. The trigger efficiency as a function of the simulated energy for photon and proton primaries, depicted by empty and filled markers respectively, and different zenith angle intervals. Lines correspond to sigmoid functions fitted via a maximum likelihood method.

power-law model is used to describe the relationship between $S(250)$ and E_{MC} [63]:

$$\frac{S(250)}{g(\theta)} = \left(\frac{E_{\text{MC}}}{10^{17} \text{ eV}} \right)^{\alpha(\theta)} \quad (3.1)$$

The power-law index, α , is found for the subset of events in each of eight zenith-angle bins employing a χ^2 minimization. As shown in figure 3, left, α is mildly dependent on the zenith angle with a relationship that can be modeled as:

$$\alpha(\theta) = \alpha_0 \times \left(1 + \alpha_1 \times (\cos^2 \theta)^{\alpha_2} \right) \quad (3.2)$$

The three free parameters are listed in table 1. The power-law index α is slightly below unity for vertical events due to the higher likelihood of these showers arriving at the observation level before reaching their maximum development, especially at the highest energies, compared to non-vertical events. The ratio $S(250)/E^\alpha$ decreases with the zenith angle, as shown in figure 3, right, reflecting the atmospheric attenuation of electromagnetic air showers. Based on the universality of the electromagnetic longitudinal development, the signal-to-energy ratio can be described using a Gaisser-Hillas function [64]:

$$g(\theta) = g_0 \times \left(1 + \frac{x - g_2}{g_1} \right)^{g_1/g_3} \times \exp \left(-\frac{x - g_2}{g_3} \right), \text{ where } x = \sec \theta - \sec 25^\circ \quad (3.3)$$

The free parameters, listed in table 1, are estimated via a χ^2 minimization to the average ratio. Particularly, the parameter $g_0 = (38.9 \pm 0.1) \text{ VEM}$ represents the expected signal measured by the SD-433 at 250 m from the axis of a shower initiated by a photon primary of 10^{17} eV with a zenith angle of 25° .

The calibration performance is evaluated by examining the relative difference between the reconstructed energy, E_{rec} , and the simulated energy, E_{MC} . This method reconstructs the photon energy with a bias of less than 2%, as shown in figure 4, top. The resolution of the calibration is defined as the standard deviation of the distribution of the relative difference between E_{rec} and E_{MC} . As shown in figure 4, bottom, the zenith-integrated resolution remains nearly constant at around 12%.

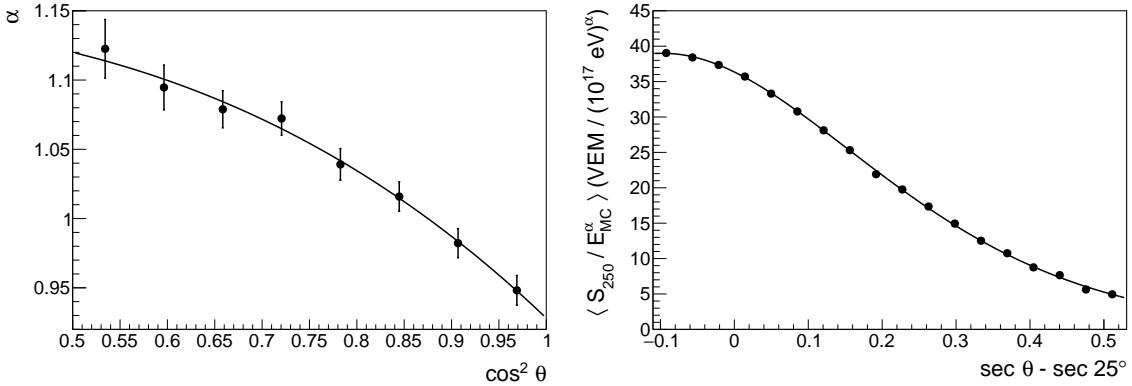


Figure 3. Left: The power-law index from eq. (3.1) as a function of zenith angle. The solid line represents the model of eq. (3.2). Right: The average ratio between shower size and primary energy raised to the power of α , in terms of the zenith angle. The fitted model of eq. (3.3) is represented as the solid line.

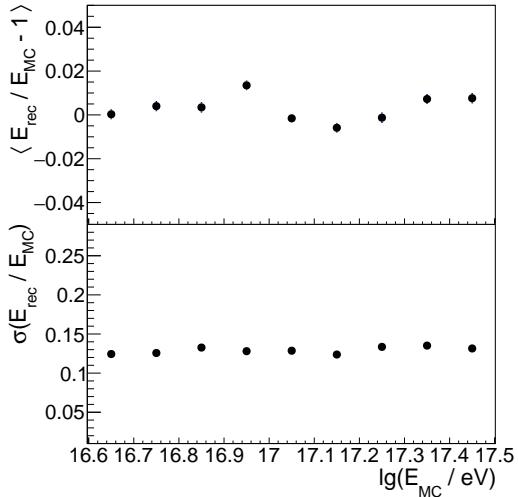


Figure 4. The bias and resolution of the energy calibration for photon events defined by eq. (3.1).

Parameter	Value
α_0	1.15 ± 0.04
α_1	-0.192 ± 0.025
α_2	2.96 ± 1.17
g_0	$38.9 \pm 0.1 \text{ VEM}$
g_1	0.623 ± 0.053
g_2	$-(9.64 \pm 0.69) \times 10^{-2}$
g_3	$(9.05 \pm 0.48) \times 10^{-2}$

Table 1. The parameters modeling the attenuation of the shower size and the energy calibration, defined by eqs. (3.2) and (3.3).

3.3 Proton-initiated events

This subsection details the energy assignment of simulated proton events, focusing on the relationship between $S(250)$ and E_{MC} . As discussed above in the context of photon events, a single realization per air shower is used to properly account for shower-to-shower fluctuations. The LDF slope parametrized for the bulk of the SD-433 data [38] is utilized for the simulated proton events since it is suitable to describe hadronic-initiated events. A power-law is used to describe the correlation between $S(250)$ and E_{MC}

$$\frac{S(250)}{g'(\theta)} = \left(\frac{E_{MC}}{10^{17} \text{ eV}} \right)^{\alpha'} \quad (3.4)$$

$a' (\text{VEM})$	b'	c'	d'	α'
(35.2 ± 0.1)	(1.88 ± 0.01)	(-1.74 ± 0.01)	(-3.45 ± 0.05)	(1.02 ± 0.01)

Table 2. The parameters in eqs. (3.4) and (3.5) estimated through the maximum likelihood method on the $S(250)$ for proton-initiated events.

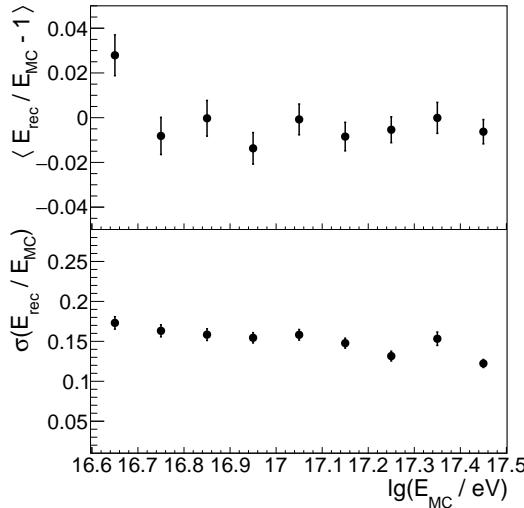


Figure 5. The bias (top) and resolution (bottom) of the energy calibration for proton events defined by eq. (3.4).

in analogy with eq. (3.1). The attenuation function model for proton events, inspired by recent analyses with the SD-433 data [37, 38], is

$$g'(\theta) = a' \times (1 + b' \times x + c' \times x^2 + d' \times x^3), \text{ where } x = \cos^2 \theta - \cos^2 30^\circ \quad (3.5)$$

We select a reference zenith angle of 30° , as it corresponds to the median zenith angle of the simulated proton events, ensuring a representative selection. A combined fit of the attenuation function, $g'(\theta)$, and the power-law index, α' , to the $S(250)$ is conducted. In this process, the likelihood of observing the samples of $S(250)$ is maximized by tuning the mentioned free parameters assuming an underlying Gaussian probability density function describing the theoretical shower size. The standard deviation of the predicted shower size is taken as the uncertainty coming from the event reconstruction. The estimated values for the parameters involved in eqs. (3.4) and (3.5) are summarized in table 2.

The bias and resolution provide insight into the reliability and precision of the calibration. As shown in the top panel of figure 5, the reconstructed energy exhibits a bias below 2% for energies above $\sim 10^{16.7}$ eV, while the resolution follows the expected trend with the primary energy, improving from 18% to 13% across the energy range under study, as presented in the bottom panel of figure 5.

3.4 The photon-equivalent energy scale

In the case of simulated proton events, the energy assignment tailored for photon primaries described in section 3.2 leads to a systematic overestimation of the reconstructed energy by

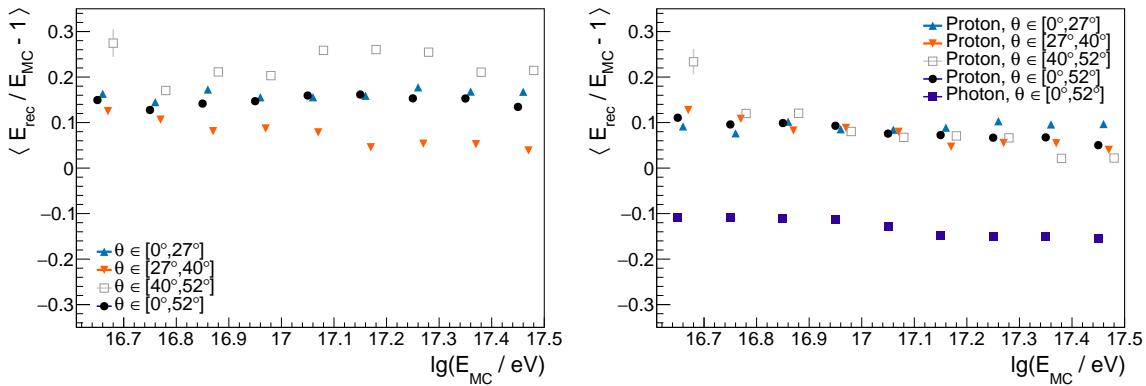


Figure 6. The relative difference between the reconstructed and simulated energy in terms of the latter. Left: Events are initiated by proton primaries, where the energy is assigned using the procedure described in section 3.2. Right: Events are initiated by photon and proton primaries, where the energy is assigned using the photon-equivalent energy scale (see text for details).

$\sim 15\%$, as shown by the black markers in figure 6, left. This is due to the muonic component, larger in hadronic showers than in electromagnetic ones, in particular at 250 m from the shower axis. Furthermore, because proton and photon showers attenuate differently in the atmosphere, one can see in the figure a clear dispersion in the reconstructed energy across angular bins. To account for the different attenuation of hadron- and photon-initiated air showers, we define the photon-equivalent energy scale, $E_{\gamma,\text{eq}}$. This scale is constructed using the attenuation curve derived from simulated proton events, i.e., from eq. (3.5), and the energy power-law index obtained for photon events, i.e., from eq. (3.1). Thus a reconstructed event with a shower size $S(250)$ can be assigned an energy $E_{\gamma,\text{eq}}$ independently of the primary species and for both simulations and data.

The application of this energy scale to simulated proton events results in a bias of 10% at $10^{16.7}$ eV decreasing to 5% at the highest energies, as shown in figure 6, right. Importantly, this bias shows no significant angular dependence, making $E_{\gamma,\text{eq}}$ a robust scale across different zenith angles. On the other hand, photon-initiated events, when analyzed using this scale, are assigned underestimated energies. The bias changes from -10% to -15% in the energy range of interest, as displayed in figure 6, right. Consequently, in a given $E_{\gamma,\text{eq}}$ bin, simulated photon events are mixed with proton events that have true lower energies, and thus lower muon content. This mixing leads to a conservative estimation of the separation between hadron- and photon-initiated events based on the muon content that scales with the primary energy. Therefore, the discrimination method described in the next section is tailored and optimized in such a conservative scenario.

4 Discrimination between photon and proton events

The search for primary photons in the cosmic-ray flux is a classification problem of a tiny signal in the overwhelmingly dominant hadronic background. The muon density is a powerful observable for distinguishing between air showers dominated by the electromagnetic component and those with significant hadronic contributions. Using the simulated set

described in section 3.1, we define in section 4.1 a muon-based observable that can be related to the mass of the primary cosmic ray. We optimize it to maximize the separation power between photon- and proton-initiated events in section 4.2, where the energy is assigned with the photon-equivalent energy scale, as discussed in section 3.4.

4.1 Muon content estimator, M_b

For each event, the muon densities, ρ_i , measured at various distances, r_i , from the shower axis are combined to define the discrimination observable M_b [65]:

$$M_b = \lg \left(\sum_i \frac{\rho_i}{\rho_{\text{pr}}} \times \left(\frac{r_i}{r_{\text{pr}}} \right)^b \right) \quad (4.1)$$

Each measured muon density is normalized by the average muon density, ρ_{pr} , expected in proton-initiated events at a predefined reference distance, r_{pr} , and is parametrized in terms of the primary energy and zenith angle. This normalization serves a dual purpose in the discrimination method. First, it offers an initial estimate of the muon content, with hadronic-induced showers typically yielding positive values of M_b and photon-initiated showers producing negative values. Second, by normalizing each muon density by ρ_{pr} , the energy and angular dependencies of M_b are largely absorbed, while the composition-dependent scaling of the muon densities is preserved. The power-law index, b , is selected to maximize the separation power of M_b between photonic and hadronic events, as discussed in section 4.2.

The reference distance, r_{pr} , is chosen to minimize fluctuations in the number of muons intersecting the sensitive area of a UMD station. The average number of muons, \bar{N}_μ , decreases with the distance to the shower axis, following the lateral spread of the shower front. Conversely, the relative fluctuations, σ_μ/\bar{N}_μ , increase with distance, as shown in figure 7, left. These relative fluctuations are influenced by both the shower-to-shower and the Poissonian fluctuations sprouting from the decreasing number of impinging muons [66]. The relative fluctuations are estimated as the root-mean-square of the N_μ distributions in distance bins.³ A plateau in the relative fluctuations is observed up to ~ 300 m, mildly dependent on the primary energy and zenith angle. Consequently, we select a reference distance of $r_{\text{pr}} = 200$ m, which corresponds to about 25% statistical fluctuations in the number of muons with a minimal variation across the studied energy range.

The normalization factor, ρ_{pr} , is then defined as the average of the muon density in proton-induced events at 200 m from the shower axis. It is parametrized in terms of the proton energy, E_{pr} , and zenith angle using the muon densities measured between 195 m and 205 m from the shower axis. The energy dependence of ρ_{pr} is illustrated in figure 7, right, and can be described by:

$$\rho_{\text{pr}} = \rho_0(\theta) \times \left(\frac{E_{\text{pr}}}{10^{17} \text{ eV}} \right)^{c(\theta)} \quad (4.2)$$

The estimated values of the free parameters, ρ_0 and c , using events in different zenith angle intervals are depicted in figure 8. The normalization, ρ_0 , decreases with the zenith angle,

³At distances below ~ 300 m, shower-to-shower fluctuations dominate in the energy range under study, exceeding the Poissonian fluctuations by a factor between 2 and 3 at energies between $10^{16.5}$ eV and 10^{17} eV.

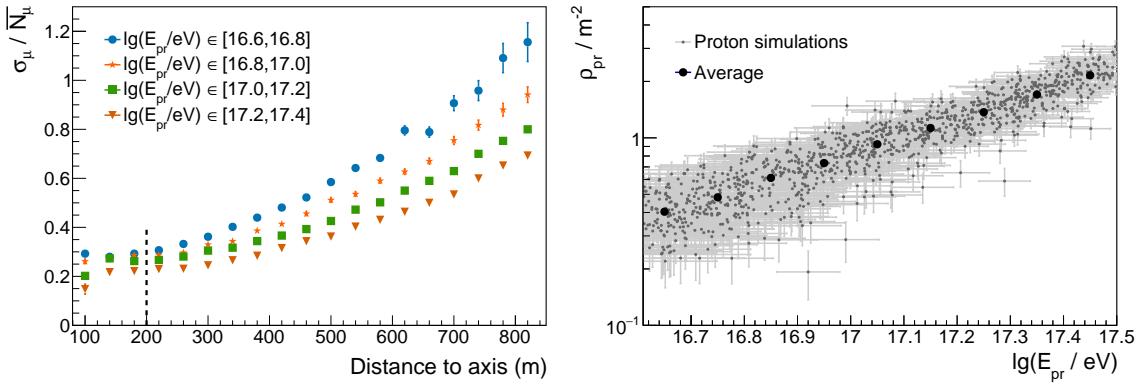


Figure 7. Left: The ratio between the standard deviation of the number of impinging muons on UMD stations and its average value as a function of the distance to the shower axis for proton events in the quoted reconstructed energy intervals. The vertical dashed line represents the choice of $r_{\text{pr}} = 200$ m. Right: The muon density at 200 m from the shower axis for proton-initiated showers as a function of the reconstructed energy. In both panels, events with $\theta < 23^\circ$ are employed, as an example.

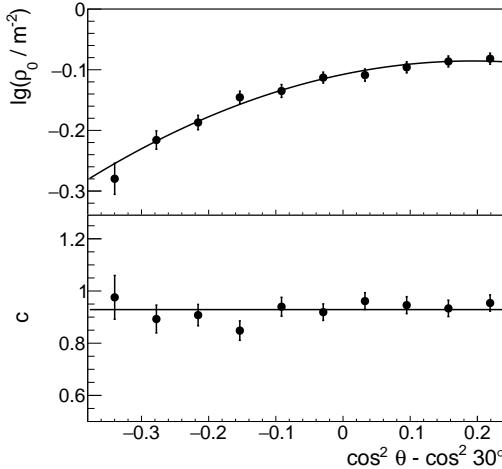


Figure 8. The free parameters of eq. (4.2) estimated by χ^2 minimization to the muon densities in angular bins with superimposed fitted quadratic and constant models.

representing the atmospheric attenuation of the muon component. In contrast, the power-law index, c , governs the energy-driven muon production and shows no significant angular dependence. A quadratic dependence on $\cos^2 \theta - \cos^2 30^\circ$ is proposed to describe $\lg(\rho_0)$, while c is assumed to be a constant. These four free parameters are estimated using a maximum likelihood approach to the unbinned data and presented in table 3.

4.2 Optimization of M_b

Because the number of muons on the ground decreases with increasing distance from the shower axis, the observed muon densities exhibit significant statistical uncertainties at large distances due to the finite detector size, independent of the primary particle. Therefore, M_b is defined using the measurements taken with the “hottest” station (the one with the highest

	ρ_{00}	ρ_{01}	ρ_{02}	c
Mean	-0.108	0.262	-0.591	0.890
Uncertainty	0.002	0.010	0.055	0.006

Table 3. The constant, linear and quadratic coefficients in $\cos^2 \theta - \cos^2 30^\circ$ describing $\lg(\rho_0(\theta))$ in eq. (4.2). The last column corresponds to the parameter c present in eq. (4.2).

SD signal) and its six nearest neighbors, which together define the “hottest” hexagon of an event. An example of the $M_{b=1}$ distributions for photon- and proton-initiated events is displayed in figure 9, left. While there is a clear separation between the two populations, a subset of muon-poor proton events is visible. These events generally correspond to showers with a dominant electromagnetic component, generated by the decay of leading π^0 produced in first interactions and carrying a substantial fraction of the primary cosmic-ray energy. Vice versa, a minor subset of photon showers with hadronic-like muon content is also observed. These events result from the decay of a leading π^\pm , caused by a photonuclear interaction, which initiates a hadronic sub-shower early in the shower development.

The choice of b in eq. (4.1) aims to minimize the risk of misclassifying a background event as a photon event, while still ensuring a substantial probability of identifying photon events. The hadronic background is assumed purely of protons to provide a conservative estimation of the photon-hadron separation power, given the existence of a non-negligible contribution of primaries heavier than protons in the cosmic-ray flux [12, 14]. We define background contamination as the ratio of the number of proton events below a specified M_b threshold to the total number of proton events. To estimate the former from the available statistics, the M_b of the 10% most photon-like proton events are fitted using an unbinned maximum likelihood procedure, assuming an exponential model (shown by the black line in figure 9, left). Then the number of proton events below a given M_b threshold is calculated from the integral of the fitted tail.⁴ The signal efficiency, on the other hand, is defined as the ratio between the photon-initiated events having values of M_b smaller than the threshold value and the total number of photon events.

As shown in figure 9, right, the contamination is minimal for a range of values of b around unity in the energy range of interest for a fixed signal efficiency of 50%. It decreases with increasing energy due to the enhanced air-shower muon content. Therefore, $b = 1$ is chosen as the index that minimizes the background contamination, defining the discrimination observable as M_1 .

The background contamination and signal efficiency can be computed by scanning over all possible values of the M_1 threshold, as exemplified in figure 10. The contamination decreases with increasing primary energy, reflecting the increasing number of muons produced in hadronic air showers at higher energies. In addition, a larger signal efficiency can be reached at the expense of a larger background contamination.

⁴This estimation of the background contamination does not depend on the size of the most photon-like background tail, i.e., it remains stable when considering between 5% and 15% of the proton events in the definition of the background tail, thus adding to the robustness of the method.

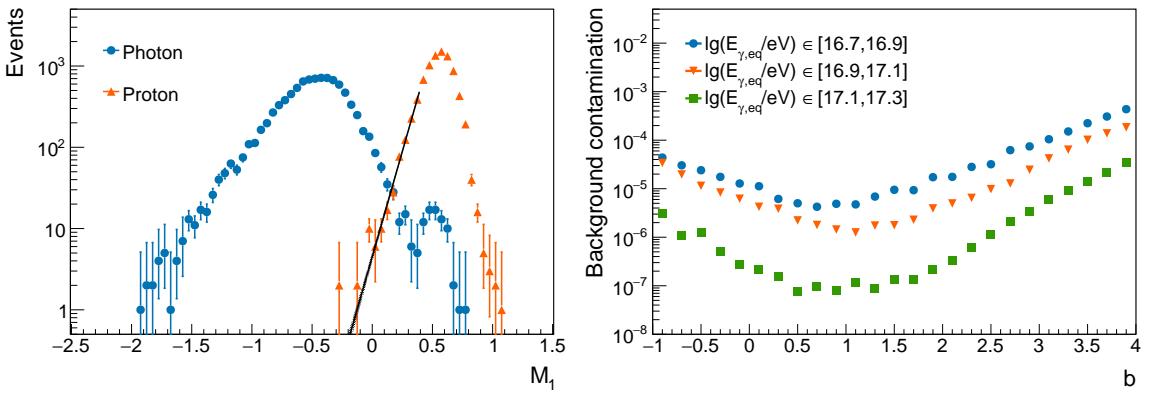


Figure 9. Left: The $M_{b=1}$ distributions for simulated photon- and proton-initiated events for energies $\lg(E_{\gamma,\text{eq}}/\text{eV}) \in (16.7, 16.9)$. The uncertainty in bins with fewer than ten entries is the asymmetric confidence belt calculated with the Feldman-Cousins method at 95% confidence level [67]. The fit to the proton tail employed to estimate the background contamination is displayed as a black band. Right: The average background contamination for the quoted energy bins in terms of b for a fixed signal efficiency of 50%.

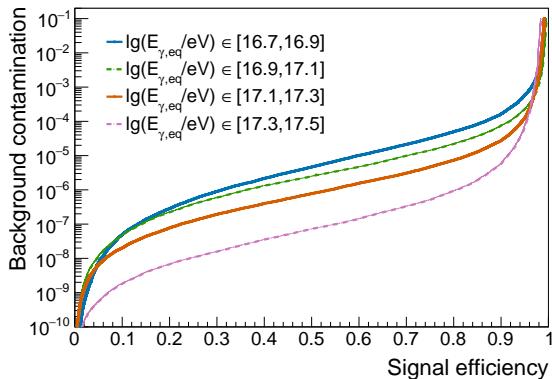


Figure 10. The background contamination in terms of the signal efficiency for the quoted energy bins in the photon-equivalent scale.

We note that the background contamination and signal efficiency shown in figure 10 are obtained assuming a complete UMD hexagon, e.g., the north-west hexagon in figure 1, left. We verified that the choice of $b = 1$ remains effective even when considering missing UMD stations in the first ring of neighbors. However, the discrimination power, i.e. both the background contamination and signal efficiency, varies depending on the real configurations of the detector, as discussed in the next section.

5 Selection of photon events in data

In this section, we study the application of the discrimination method to data, considering the actual configuration of the detector. Given that the fraction of photon primaries expected to be present in the cosmic-ray flux may be well below 10^{-5} , the standard event reconstruction, fine-tuned to hadronic events, is employed for the data. The event selection follows the

Cat.	No. of first-ring UMD stations	Minimum UMD area in first ring (m ²)	Missing UMD stations in first ring	No. of events
I	6	190	0	3,295
II	5	140	1	1,491
III	4	110	2 non-NN	8,417
IV	4	110	2 NN	298
V	3	80	3 non-NN	1,016
VI	3	80	2 NN + 1 non-NN	1,402
Total				15,919

Table 4. The six categories of events based on the available UMD stations in the hottest hexagon, the total detector area, and the relative location of missing UMD stations in the first ring, either nearest neighbors (NN) or non nearest neighbors (non-NN). The last column contains the size of each data subset.

procedure described in section 2. Both the estimated shower size and zenith angle are used to assign photon-equivalent energy to each event.

The observable M_1 quantifies the muon content of each event, as defined in section 4.2, and scales with the number of available UMD stations in the hottest hexagon. Air showers with low muon content, characteristic of photon-like events, would have smaller values of M_1 compared to hadronic events. However, if any UMD stations are missing, either due to not being deployed yet at the time of detection or to technical issues during data acquisition, less information on the muon content would be available. This results in smaller values of M_1 when fewer than seven UMD stations are operational, leading to an increase of the likelihood of misidentifying background events as photon-initiated. Thus, before applying the discrimination method to the selected data set, it is important to evaluate the impact of missing UMD modules across the seven stations of a hexagon.

Due to the irregular placement of UMD stations in the SD-433, as seen in figure 1, left, the muon component arriving at the ground is sampled by a variable number of UMD stations. Therefore, the threshold value of M_1 to classify an event as a photon candidate, i.e., the photon candidate cut M_1^{cut} , is obtained according to the possible configurations in the hottest hexagon. The events are classified in six categories, as listed in table 4, depending on the following three criteria: the number of available UMD stations (i.e., stations with at least one active module), the total area spanned by these stations, and the relative position of any missing stations (i.e., stations without active modules). The hottest station must contain three active UMD modules regardless of the event category.

The discrimination power of a hexagonal grid that mimics the SD-433 is evaluated through simulations (see section 3.1), assuming each SD station is paired with a 30 m² UMD station, except for the aforementioned 50 m² station. UMD stations or individual modules are randomly masked to simulate missing measurements and assess the discrimination power for each event category. M_1^{cut} is defined as the threshold value at which the signal efficiency reaches 50%, determined as the median of the M_1 distribution for simulated photon events

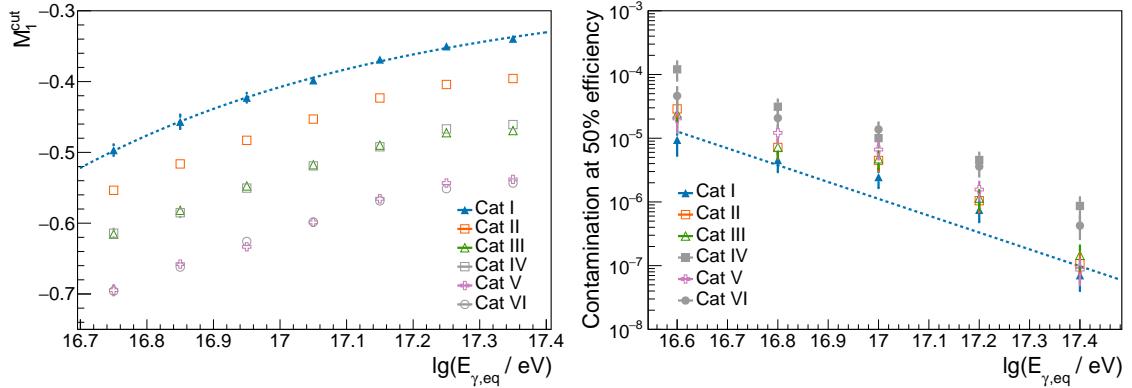


Figure 11. The photon candidate cut (left) and the background contamination at 50% signal efficiency (right) in terms of the photon-equivalent energy for each of the event categories cited in table 4. The dashed lines show examples of the fitted power-law and exponential models of the logarithmic energy, respectively.

in energy bins. Such signal efficiency is suitable to reach background contamination levels smaller than 10^{-4} in all event categories. Therefore, an event is tagged as a photon candidate if $M_1 < M_1^{\text{cut}}$. As shown in figure 11, left, M_1^{cut} increases with primary energy and with the number of UMD stations in the hottest hexagon. The evolution of M_1^{cut} is described by a function of the logarithmic energy for each event category and reported in appendix B. As depicted in figure 11, right, the contamination remains below 10^{-5} for events in category I, while it increases as the number of first-ring UMD stations decreases, with the relative position of missing UMD stations having a significant impact. For instance, the contamination in events with two missing neighboring stations is two to four times larger than in events with non-neighboring missing stations. The background contamination is modeled using an exponential function of logarithmic energy, as detailed in appendix B.

The parametrization of the background contamination for each event category can be employed to obtain a conservative estimation of the number of hadronic events in data that would be misidentified as photon candidates. For instance, the expected number of fake photon events in the category I subset can be computed as $(4.04 \pm 0.04) \times 10^{-3}$ by integrating the blue curve in figure 11, right, above $10^{16.7}$ eV [68]. Since 3,295 events above $10^{16.7}$ eV fall in that event category, this is equivalent to one fake photon event approximately every 815,650 events.⁵ Considering that the category I events were acquired over ~ 10 months of the observation time, this suggests that one fake photon event would be expected every 106 years per hexagon.

Given the low probability of observing a background event consistent with the photon hypothesis, a fraction of the selected data, referred to as the burnt data sample, is unblinded to check that the M_1 distribution in data agrees with simulations, before carrying on the unblinding of the full selected data set. The burnt data represent a fraction $f_{\text{burnt}} = 0.1$ of the selected data set. The M_1 distributions of burnt data for each event category are

⁵The expected number of fake photon events in the category IV and VI subsets, corresponding to the configurations with the largest background contamination, is 3.12×10^{-3} and 8.20×10^{-3} respectively. It can be translated to one fake photon event every 95,460 and 170,890 events in each of the subsets.

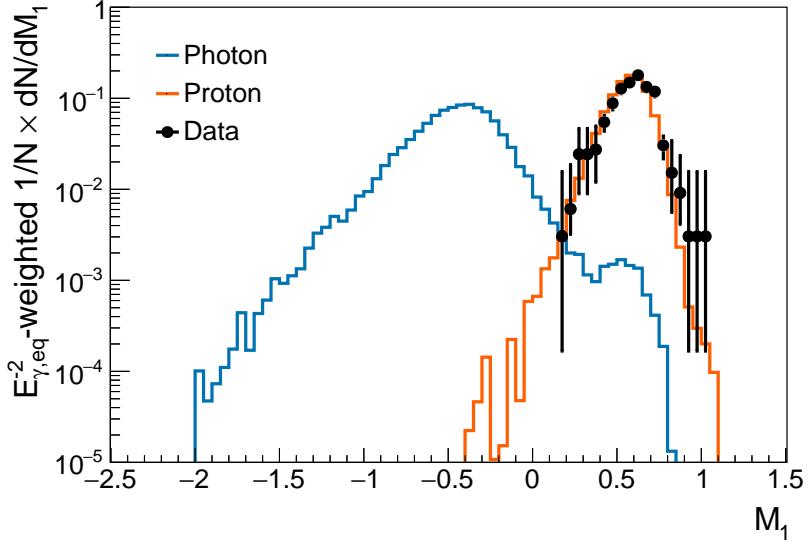


Figure 12. The M_1 distributions for simulated proton (orange), and photon (blue) events weighted by $E_{\gamma, \text{eq}}^{-2}$ for energies above $10^{16.7}$ eV. Black markers represent the M_1 distribution for the events belonging to the burnt data corresponding to the category I subset. The uncertainty in bins with fewer than ten entries is calculated with the Feldman-Cousins method at 95% confidence level [67].

compared with the simulated distributions, as exemplified in figure 12. Simulated events are weighted by $E_{\gamma, \text{eq}}^{-2}$ to obtain energy-integrated distributions, while no weighting is applied to the burnt data sample. As expected, the M_1 distribution for the burnt data is compatible with a hadronic origin. It is important to note that the photon-equivalent energy assigned to a data event is around $\sim 30\%$ higher than that assigned using the hadronic-optimized energy scale. This discrepancy arises from the larger muon content in cosmic-ray showers compared to the photon showers used to define the photon-equivalent energy calibration. As a result, the reference muon density ρ_{pr} used in the M_1 definition (see eq. (4.1)) is shifted to higher values in data compared to simulations, leading to smaller M_1 values in the former case. Thus, the distribution for data is artificially shifted towards the simulated proton distribution. Nevertheless, the M_1 observable is optimized to discriminate between events with significantly different muonic components -such as photons versus all hadronic species- due to the logarithm scaling in its definition, making it largely insensitive to the primary hadronic mass. This limitation does not impact the search for photon events in data, as discussed in the next section.

6 Results of the photon search

Excluding the burnt sample, the remaining 14,299 events constitute the search data set. For each event, the M_1 observable is compared to the parametrized photon candidate cut M_1^{cut} for its respective event category, as shown in figure 13. The parametrizations of M_1^{cut} , performed with simulated events up to $10^{17.5}$ eV, have been extrapolated to higher energies for comparison with the data. Nevertheless, all events exhibit M_1 values well above the parametrized M_1^{cut} , indicating that no photon candidate events are identified.

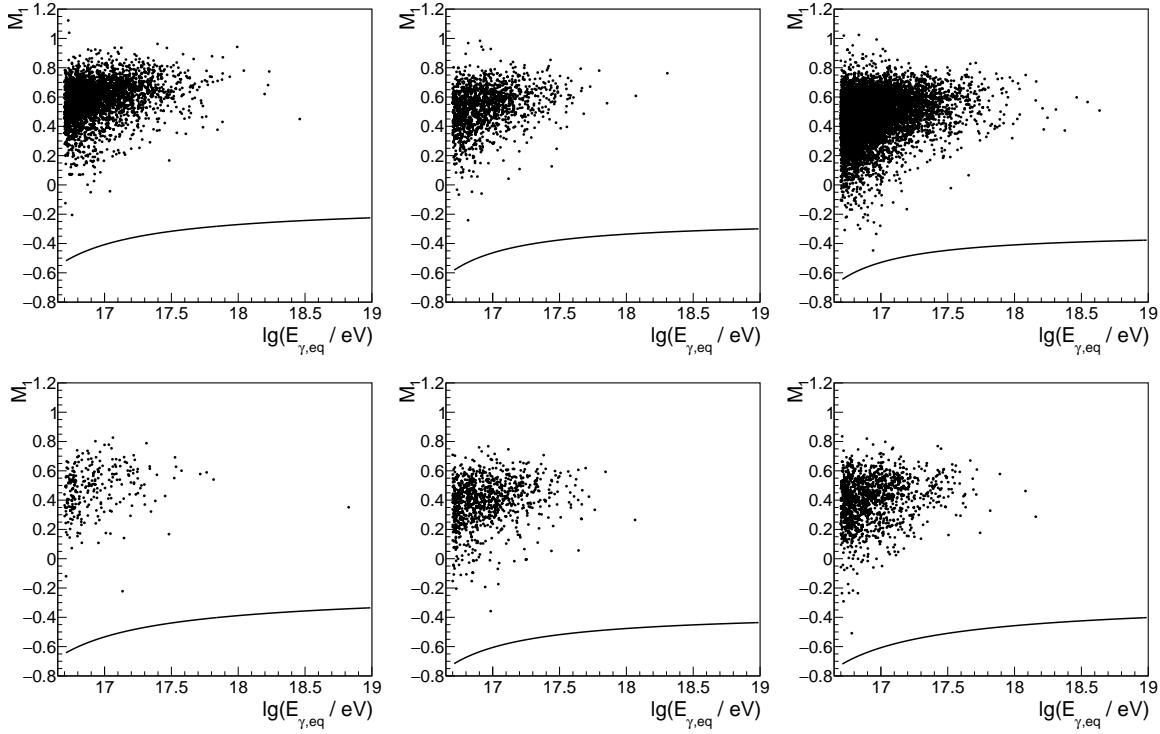


Figure 13. The observable M_1 in terms of the photon-equivalent energy for events in the search data set. Each panel corresponds to the quoted categories as listed in table 4 from left to right, and top to bottom. Solid lines represent the parametrized photon candidate cut for each category.

6.1 Upper limits calculation

From the absence of photon flux measurements, upper limits on the integral photon flux are calculated. These limits are inversely proportional to the exposure of the detection system, which accounts for both the operational uptime of the detectors and the efficiency in detecting photon events.

The accumulated exposure to photon primaries is derived from the continuous, real-time monitoring of the SD-433 array, as described in section 2. The operational status of each SD station is known every second, allowing stations to be classified as either “on” or “off”. This enables real-time monitoring of the status of each hexagon.⁶ Following the 5T5 and 6T5 event selection criteria, a hexagon is considered active if at least five “on” WCDs are surrounding the hottest one. When a 6T5 condition is met, the effective area of a hexagon with a side length $d = 433$ m is the one of the unitary hexagon, i.e., $A = \sqrt{3}/2 \times d^2$. For the 5T5 condition, the area is reduced by a geometrical factor of 1/3 to account for the missing nearest-neighbor station. Consequently, an active hexagon contributes to the exposure calculation with a time-dependent area, $A(t)$, reflecting its real-time status.

As discussed in section 5, a minimum area spanned by UMD modules is required to adequately sample the air-shower muon content. The number of “on” UMD modules at the

⁶Technical issues affecting eight out of the 19 SD stations during 16 distinctive periods (lasting between one day and one week) were identified, accounting for less than 1% of the operation time. During these periods, the stations were considered “off”.

central station and the first ring around it, as well as the relative position of any missing UMD stations in the first ring, are dynamic. They vary over time due to the absence of deployed modules or technical issues affecting normal operation. These requirements are mapped by a step function, $u(t)$, incorporated into the exposure calculation.

The trigger efficiency for photon-initiated showers, τ , must also be included in the exposure calculation. This efficiency depends on the primary energy and zenith angle, as discussed in section 3.2, and the instantaneous exposure decreases as the primary energy decreases.

The accumulated exposure to photon primaries is determined by integrating the effective area of each hexagon over the entire observation period, t , above a given photon-equivalent energy, E_γ^{th} , and over the solid angle, Ω , as:

$$\epsilon_\gamma = \sum_{\text{hexagons}} \int_{E_\gamma^{\text{th}}} \int_{\Omega} \int_t A(t) \cos \theta \times u(t) \times \tau(E_{\gamma,\text{eq}}, \theta) dt d\Omega dE_{\gamma,\text{eq}}. \quad (6.1)$$

The trigger efficiency can be integrated with a weight proportional to a E_γ^{-2} spectrum, motivated by theoretical predictions of the diffuse galactic photon flux [19], top-down models [69] and previous photon searches by the Pierre Auger Collaboration [70].

The upper limit to the integral photon flux, Φ_γ , is calculated as:

$$\Phi_\gamma < \frac{3.095}{(1 - f_{\text{burnt}}) \times f_{\text{cut},\gamma} \times \epsilon_\gamma} \quad (6.2)$$

where the numerator represents the upper limit to the number of photon-compatible events calculated using the Feldman-Cousins approach [67] given the null observation and a confidence level of 95%. The exposure to photon primaries above given energy, ϵ_γ , is reduced by a factor $1 - f_{\text{burnt}}$ by construction and a factor $f_{\text{cut},\gamma} = 0.504$, reflecting the average signal efficiency of the M_1^{cut} parametrizations across all event categories. Above threshold energies of 50, 80, 120 and 200 PeV, the integrated exposure up to a zenith angle of 52° is $\epsilon_\gamma = (0.58 \pm 0.02)$, (0.61 ± 0.03) , (0.63 ± 0.03) and (0.63 ± 0.03) km² sr yr, respectively, in which the dependence on the threshold energy comes in from the photon trigger efficiency model.⁷ An uncertainty of 4% is assigned to the exposure rising from the uncertainty of the event rate per active SD-433 hexagon. The upper limits are computed under a conservative scenario, where the average exposure above each threshold energy is decreased by its uncertainty, resulting in integral upper limits of 12.3, 11.7, 11.3 and 11.3 km⁻² sr⁻¹ yr⁻¹ above the mentioned threshold energies.

In figure 14, we present the upper limits on the integral photon flux obtained in this study (represented by red markers), alongside the limits previously reported by the Auger Collaboration [35, 71], by KASCADE-Grande [21], by EAS-MSU [22], and by Telescope Array [72, 73]. The limits derived in this work are the only ones based on measurements from the Southern Hemisphere in the tens of PeV energy domain. This analysis extends the photon search program of Auger, covering over three decades of cosmic-ray energy. It is the first one in which direct measurements of air-shower muons provided by the UMD are employed.

⁷The model for the trigger efficiency was computed in terms of E_{MC} . Thus, the energy bias between $E_{\gamma,\text{eq}}$ and E_{MC} , as explained in section 3.4, was introduced before performing the integration.

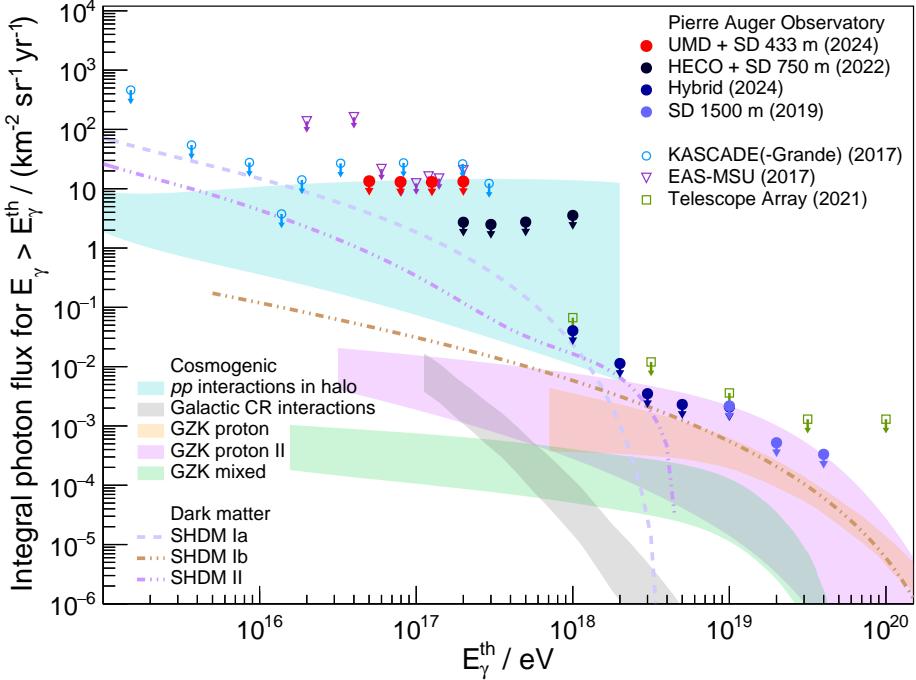


Figure 14. The upper limits to the integral photon flux above a threshold energy E_γ^{th} obtained in this work at a 95% confidence level, as solid red markers, and limits obtained by the Pierre Auger Collaboration at higher energies with a 95% confidence level [35, 71], as solid blue and black markers, as well as limits reported by other experiments established at 90% confidence level, except those obtained by Telescope Array at 95% confidence level (see text for a full list of references). The light-colored bands represent predictions of cosmogenic fluxes: from interactions between UHE cosmic rays and the interstellar Galactic matter [19] (in gray), with background radiation fields [7, 8, 74] (in violet, green, and orange, depending on the quoted primary composition), and with hot gas in the galactic halo [76] (in blue). Dashed lines correspond to super-heavy dark matter predictions (see text for details).

Diffuse photon fluxes are expected from the interaction of UHE cosmic rays with background radiation fields [7, 8, 74] and with the interstellar Galactic matter [75], as discussed in section 1. These are indicated by the shaded bands in figure 14. The upper limits derived in this study are between two and three orders of magnitude above these cosmogenic fluxes. However, the expected diffuse gamma-ray flux from proton-proton interactions in the galactic halo [76] is shown to be within the reach of the upper limits obtained in this work. Moreover, predictions from various phenomena beyond the Standard Model may emerge above these cosmogenic fluxes, e.g., those arising from the decay of super-heavy dark matter particles [26]. In the above-mentioned figure, we show the predicted diffuse fluxes in several scenarios: assuming decay channels into hadrons, a mass $M_X = 10^{10}$ GeV and a lifetime $\tau_X = 3 \times 10^{21}$ yr [77]; $M_X = 10^{12}$ GeV and $\tau_X = 10^{23}$ yr [77]; and assuming decay into leptons, a mass $M_X = 10^{10}$ GeV and a lifetime $\tau_X = 3 \times 10^{21}$ yr [27]. Further sensitivity provided by the next 10 years of data taking will allow us to constrain the parameter space of the discussed models thanks to an expected improvement in the upper limits by a factor larger than 20.

6.2 Systematic uncertainties on the upper limits

Variations in the upper limits can arise from the energy bias related to the photon-equivalent energy scale, the exposure estimation and the changes in the number of photon candidate events.

The integral photon flux is a power law of the threshold energy E_γ^{th} , assuming an index $\gamma > 1$. If the latter is adjusted to $E_\gamma^{\text{th}} \times (1 + b(E_\gamma^{\text{th}}))$ to account for a bias on the energy, b , the relative effect on the integral flux, and hence on the upper limits, is:

$$\frac{\Delta\Phi_\gamma}{\Phi_\gamma} = (1 + b(E_\gamma^{\text{th}}))^{1-\gamma} - 1 \quad (6.3)$$

Proton events are assigned an overestimated energy in the photon-equivalent scale, with an energy bias that decreases from 10% to 5% in the energy range of interest (see figure 6, right). Following eq. (6.3), the effect of this bias on the upper limits ranges from -10% to -6% with increasing energy. Since this would imply a decrease in the upper limits, we neglect this effect to maintain a conservative calculation. Similarly, a negative energy bias between -10% and -15% , decreasing linearly with the logarithm of energy, is found for photon events in the photon-equivalent energy scale (see figure 6, right). This bias leads to a relative increase of the upper limits, ranging from 12% to 17% with increasing energy.

The impact of variations in the spectral index assumed in the energy-integrated exposure calculation has been examined. A variation of ± 0.5 in the spectral index results in an average change in the exposure of between 0.7% and 1.7% for the quoted threshold energies. Consequently, the upper limits on the integral flux increase by a factor ranging from 0.8% to 2.2% with increasing energy.

The number of photon candidate events can increase if the values of M_1 decrease. In the following, we discuss how varying the parameters in the M_1 definition might cause this effect. First, the measured muon density can decrease by up to 5.6% when varying the parameters involved in the muon counting strategy used to convert digital traces to the number of muons in the UMD stations [46]. Second, the UMD simulation assumes a soil density of 2.38 g cm^{-3} , leading to a fixed soil shielding to muons. The standard deviation of the soil density is 0.05 g cm^{-3} [78], which results in a 2.8% increase in the reference muon density ρ_{pr} [42]. Lastly, different high-energy hadronic models predict varying numbers of muons in simulations, which could affect ρ_{pr} . The only model surpassing the employed one, EPOS-LHC, in terms of the predicted number of muons, is Sibyll2.3d by about 5% [79]. Combining the three factors, the overall systematic effect translates into an absolute shift of -0.06 across all M_1 values. Despite this shift, no event falls below the parametrized photon candidate cuts.

Following the conservative approach mentioned before, the upper limits above each threshold energy can be increased by the corresponding factors arising from the bias in the photon-equivalent energy and the spectral index employed in the exposure calculation. Thus, the final upper limits reported in this work, including a shift towards the worst-case scenario motivated by the considered systematic effects, are $13.8, 13.5, 13.3$ and $13.6 \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1}$ for threshold energies of 50, 80, 120 and 200 PeV. A summary of the upper limits before and after accounting for the systematic effects is presented in table 5. These limits translate into constraints on the photon fraction in the measured cosmic-ray flux [80]. Above the specified energy thresholds, the upper limits on the photon fraction are 0.056%, 0.14%, 0.35% and 0.97% at a confidence level 95%.

E_γ^{th} (PeV)	ϵ_γ ($\text{km}^2 \text{sr yr}$)	Φ_γ ($\text{km}^{-2} \text{sr}^{-1} \text{yr}^{-1}$)	$\Phi_\gamma + \sigma_{\text{sys}}$ ($\text{km}^{-2} \text{sr}^{-1} \text{yr}^{-1}$)
50	(0.58 ± 0.02)	12.3	13.8
80	(0.61 ± 0.03)	11.7	13.5
120	(0.63 ± 0.03)	11.3	13.3
200	(0.63 ± 0.03)	11.3	13.6

Table 5. The upper limits on the integral photon flux above each quoted energy threshold before (third column) and after (fourth column) accounting for the discussed systematic effects. The exposure above each energy threshold is obtained from eq. (6.1).

7 Conclusions and outlook

The search for primary photons above 10 PeV has so far been conducted by experimental facilities exclusively located in the Northern Hemisphere, thereby presenting a restricted exposure towards the Galactic plane. This article presents the first search for a diffuse flux of primary photons above between 50 and 200 PeV from the Southern Hemisphere. At these energies, primary photons may be expected from sources located not much further than the Galactic center. Leveraging the densest surface array and underground muon detectors of the Pierre Auger Observatory, we analyzed a high-quality data set comprising over 15,000 events above 50 PeV. The direct measurements of the air-shower high-energy muon component provided excellent photon-hadron separation power, resulting in a probability of incorrectly identifying a proton as a photon primary smaller than 10^{-5} when the probability of observing a photon is set at 50%, under the conservative assumption of a simulated pure proton background. Notably, no events consistent with a photon origin were found in our dataset.

Consequently, we established upper limits on the integral photon flux above 50 to 200 PeV ranging from 13.3 to $13.8 \text{ km}^{-2} \text{sr}^{-1} \text{yr}^{-1}$ at a 95% confidence level. An average exposure of $(0.63 \pm 0.03) \text{ km}^2 \text{sr yr}$, equivalent to approximately eight months of ideal operation, conservatively reduced by one standard deviation, was employed for the computation of the upper limits. Furthermore, the reported limits were increased to account for systematic uncertainties based on the assumed spectral index of the diffuse photon flux and bias in the predicted photon energy due to the specific scale employed in this analysis.

Thanks to the addition of the surface and muon detectors spaced at 433 m, the search for primary photons can presently be conducted with data measured by the Auger Observatory spanning over three decades of cosmic-ray energy. The additional insights provided by the complementary detection techniques of the AugerPrime upgrade [81] will offer greater sensitivity in cosmic-ray mass composition studies. As the Observatory continues taking data, the exposure will progressively increase, leading to more stringent limits or possibly the discovery of the most energetic primary photons. Furthermore, the full deployment of UMD stations in the SD-433 array now enables the use of all seven hexagons in the array for photon searches. The expected exposure until the planned end of operations of the Auger Observatory will provide a significant opportunity to constrain the mass-lifetime phase-space for specific super-heavy dark matter models and to explore the expected photon flux from proton-proton interactions in the Galactic halo at tens of PeV. In addition to the search

for a diffuse photon flux, this study lays the groundwork for a nearly real-time search for primary photons in the tens of PeV domain, enhancing the role of the Auger Observatory in the global multi-messenger astrophysics community.

Acknowledgments

The successful installation, commissioning, and operation of the Pierre Auger Observatory would not have been possible without the strong commitment and effort from the technical and administrative staff in Malargüe. We are very grateful to the following agencies and organizations for financial support:

Argentina — Comisión Nacional de Energía Atómica; Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT); Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET); Gobierno de la Provincia de Mendoza; Municipalidad de Malargüe; NDM Holdings and Valle Las Leñas; in gratitude for their continuing cooperation over land access; Australia — the Australian Research Council; Belgium — Fonds de la Recherche Scientifique (FNRS); Research Foundation Flanders (FWO); Marie Curie Action of the European Union Grant No. 101107047; Brazil — Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq); Financiadora de Estudos e Projetos (FINEP); Fundação de Amparo à Pesquisa do Estado de Rio de Janeiro (FAPERJ); São Paulo Research Foundation (FAPESP) Grants No. 2019/10151-2, No. 2010/07359-6 and No. 1999/05404-3; Ministério da Ciência, Tecnologia, Inovações e Comunicações (MCTIC); Czech Republic — GACR 24-13049S, CAS LQ100102401, MEYS LM2023032, CZ.02.1.01/0.0/0.0/16_013/0001402, CZ.02.1.01/0.0/0.0/18_046/0016010 and CZ.02.1.01/0.0/0.0/17_049/0008422 and CZ.02.01.01/00/22_008/0004632; France — Centre de Calcul IN2P3/CNRS; Centre National de la Recherche Scientifique (CNRS); Conseil Régional Ile-de-France; Département Physique Nucléaire et Corpusculaire (PNC-IN2P3/CNRS); Département Sciences de l’Univers (SDU-INSU/CNRS); Institut Lagrange de Paris (ILP) Grant No. LABEX ANR-10-LABX-63 within the Investissements d’Avenir Programme Grant No. ANR-11-IDEX-0004-02; Germany — Bundesministerium für Bildung und Forschung (BMBF); Deutsche Forschungsgemeinschaft (DFG); Finanzministerium Baden-Württemberg; Helmholtz Alliance for Astroparticle Physics (HAP); Helmholtz-Gemeinschaft Deutscher Forschungszentren (HGF); Ministerium für Kultur und Wissenschaft des Landes Nordrhein-Westfalen; Ministerium für Wissenschaft, Forschung und Kunst des Landes Baden-Württemberg; Italy — Istituto Nazionale di Fisica Nucleare (INFN); Istituto Nazionale di Astrofisica (INAF); Ministero dell’Università e della Ricerca (MUR); CETEMPS Center of Excellence; Ministero degli Affari Esteri (MAE), ICSC Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, funded by European Union NextGenerationEU, reference code CN_00000013; México — Consejo Nacional de Ciencia y Tecnología (CONACYT) No. 167733; Universidad Nacional Autónoma de México (UNAM); PAPIIT DGAPA-UNAM; The Netherlands — Ministry of Education, Culture and Science; Netherlands Organisation for Scientific Research (NWO); Dutch national e-infrastructure with the support of SURF Cooperative; Poland — Ministry of Education and Science, grants No. DIR/WK/2018/11 and 2022/WK/12; National Science Centre, grants No. 2016/22/M/ST9/00198, 2016/23/B/ST9/01635, 2020/39/B/ST9/01398, and

2022/45/B/ST9/02163; Portugal — Portuguese national funds and FEDER funds within Programa Operacional Factores de Competitividade through Fundação para a Ciência e a Tecnologia (COMPETE); Romania — Ministry of Research, Innovation and Digitization, CNCS-UEFISCDI, contract no. 30N/2023 under Romanian National Core Program LAPLAS VII, grant no. PN 23 21 01 02 and project number PN-III-P1-1.1-TE-2021-0924/TE57/2022, within PNCDI III; Slovenia — Slovenian Research Agency, grants P1-0031, P1-0385, I0-0033, N1-0111; Spain — Ministerio de Ciencia e Innovación/Agencia Estatal de Investigación (PID2019-105544GB-I00, PID2022-140510NB-I00 and RYC2019-027017-I), Xunta de Galicia (CIGUS Network of Research Centers, Consolidación 2021 GRC GI-2033, ED431C-2021/22 and ED431F-2022/15), Junta de Andalucía (SOMM17/6104/UGR and P18-FR-4314), and the European Union (Marie Skłodowska-Curie 101065027 and ERDF); U.S.A. — Department of Energy, Contracts No. DE-AC02-07CH11359, No. DE-FR02-04ER41300, No. DE-FG02-99ER41107 and No. DE-SC0011689; National Science Foundation, Grant No. 0450696, and NSF-2013199; The Grainger Foundation; Marie Curie-IRSES/EPLANET; European Particle Physics Latin American Network; and UNESCO.

A Lateral distribution function for photon events

The analytical model for the LDF used is based on the Nishimura-Kamata-Greisen (NKG) function [49, 50]:

$$f_{\text{LDF}}(r) = S(r_{\text{ref}}) \times \left(\frac{r}{r_{\text{ref}}} \times \frac{r + 700 \text{ m}}{r_{\text{ref}} + 700 \text{ m}} \right)^{-\beta} \quad (\text{A.1})$$

where $r_{\text{ref}} = 250 \text{ m}$ in the case of SD-433 events. The slope parameter, β , is parametrized a priori as follows:

$$\beta(S(250), \theta) = \beta_0(\theta) + \beta_1(\theta) \times \lg \left(\frac{S(250)}{f(\theta)} \right) \quad (\text{A.2})$$

using events with at least five triggered stations, none of which is saturated,⁸ and between two and four stations located 100 m to 400 m from the shower axis. These criteria ensure that β is obtained with at least two degrees of freedom in the event reconstruction and with topological coverage around 250 m, providing a solid lever arm for the LDF fit.

The function $f(\theta)$ compensates for the dependence of $S(250)$ on the zenith angle:

$$f(\theta) = \tilde{f}(\theta)/\tilde{f}(25^\circ), \text{ with } \tilde{f}(\theta) = \frac{f_0}{1 + \exp \left(\frac{x-b}{c} \right)}, \text{ and } x = \sec \theta - \sec 25^\circ \quad (\text{A.3})$$

where the reference zenith angle, 25° , is selected as the median of the E_{MC}^{-2} -weighted zenith distribution. The three free parameters of $\tilde{f}(\theta)$ are estimated by examining the approximately linear relationship between the S_{250} and E_{MC} , as shown in figure 15, left. Consequently, the ratio $S(250)/E_{\text{MC}}$ is mainly determined by the angular dependence, as depicted in figure 15, right. The sigmoid function $\tilde{f}(\theta)$ is fitted to the average ratio, resulting in parameters $f_0 = (4.65 \pm 0.03) \text{ VEM}/10^{16} \text{ eV}$, $b = (0.194 \pm 0.002)$ and $c = (0.156 \pm 0.002)$. This model captures the mean behavior within a 2% margin.

⁸A station is flagged as saturated when the digitized traces of the anode channel overflow.

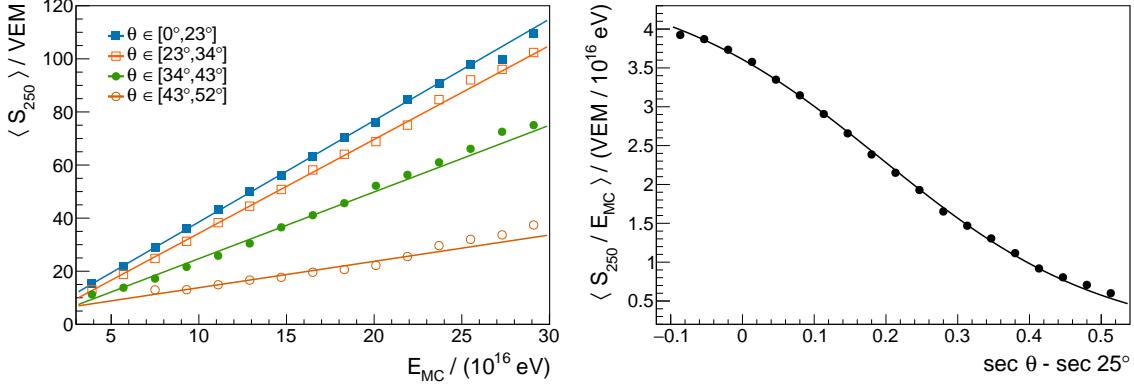


Figure 15. Left: The shower size, $S(250)$, as a function of the simulated primary energy, E_{MC} , for photon events. The solid lines represent linear fits in zenith-angle bins. Right: The average ratio between the shower size and the simulated energy versus the zenith angle. The solid line corresponds to the fit $\tilde{f}(\theta)$ from eq. (A.3) via a χ^2 minimization.

The linear coefficients, β_0 and β_1 , depend quadratically on $\text{sec } \theta$, as illustrated in figure 16, left. The corresponding six parameters are estimated using an unbinned maximum likelihood method, assuming a Gaussian probability density function for β . The resulting values are given in eq. (A.4). The performance of the parametrization is assessed by comparing the predicted slope from eq. (A.2), β_{pred} , with the reconstructed slope for each photon-initiated event, β . The parametrization shows a negligible bias (within $\pm 2\%$) and a resolution better than 19% as illustrated in figure 16, right.

$$\begin{aligned}\beta_0 &= (0.756 \pm 0.011) + (4.05 \pm 0.01) \times \text{sec } \theta - (2.33 \pm 0.01) \times \text{sec}^2 \theta \\ \beta_1 &= (0.704 \pm 0.006) - (1.37 \pm 0.01) \times \text{sec } \theta + (0.758 \pm 0.004) \times \text{sec}^2 \theta\end{aligned}\quad (\text{A.4})$$

B Parametrization of the background contamination and photon candidate cuts

The average background contamination at 50% signal efficiency and the photon candidate cut were parametrized in terms of the photon-equivalent energy scale. As shown by the dashed line in both panels of figure 11, the employed analytical models are:

$$f_{\text{BC}}(E_{\gamma,\text{eq}}) = b_0 \times e^{-b_1 \times (\lg(E_{\gamma,\text{eq}}/\text{eV}) - 17)} \quad (\text{B.1})$$

$$f_{\text{cut}}(E_{\gamma,\text{eq}}) = - \left(c_0 + c_1 \times (\lg(E_{\gamma,\text{eq}}/\text{eV}) - 16)^{-c_2} \right) \quad (\text{B.2})$$

The free parameters of both equations are given in table 6 for each event category.

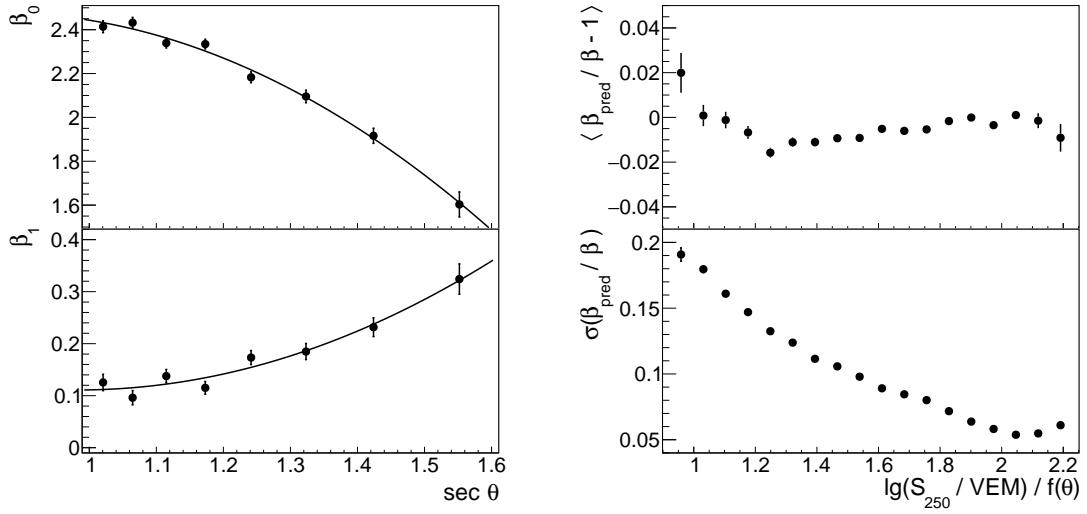


Figure 16. Left: The evolution of β_0 and β_1 parameters of eq. (A.2) with $\sec \theta$. The second-order polynomials in eq. (A.4) are superimposed. Right: The bias and resolution of the LDF slope predicted by eq. (A.2), β_{pred} .

Event category	b_0	b_1	c_0	c_1	c_2
I	$(1.15 \pm 0.22) \times 10^{-6}$	6.20 ± 0.50	0.262 ± 0.035	1.04 ± 0.28	32.5 ± 8.5
II	$(2.13 \pm 0.37) \times 10^{-6}$	6.76 ± 0.51	0.306 ± 0.020	1.03 ± 0.12	30.8 ± 4.2
III	$(2.33 \pm 0.39) \times 10^{-6}$	6.19 ± 0.50	0.411 ± 0.012	1.28 ± 0.22	39.3 ± 4.6
IV	$(1.05 \pm 0.15) \times 10^{-5}$	5.92 ± 0.53	0.330 ± 0.055	0.867 ± 0.125	24.0 ± 7.0
V	$(1.87 \pm 0.35) \times 10^{-6}$	6.81 ± 0.46	0.429 ± 0.042	0.931 ± 0.170	27.0 ± 7.0
VI	$(5.98 \pm 0.94) \times 10^{-6}$	5.77 ± 0.43	0.470 ± 0.018	1.10 ± 0.17	34.2 ± 4.7

Table 6. The parameters of eqs. (B.1) and (B.2) modeling the background contamination at 50% signal efficiency and the photon candidate cut for each event category.

References

- [1] G. Bhatta, *Blazar Jets as Possible Sources of Ultra-High Energy Photons: A Short Review*, *Universe* **8** (2022) 513 [[arXiv:2209.13158](https://arxiv.org/abs/2209.13158)] [[inSPIRE](#)].
- [2] TIBET AS γ collaboration, *First detection of photons with energy beyond 100 TeV from an astrophysical source*, *Phys. Rev. Lett.* **123** (2019) 051101 [[arXiv:1906.05521](https://arxiv.org/abs/1906.05521)] [[inSPIRE](#)].
- [3] Gopal-Krishna, P.L. Biermann, V. de Souza and P.J. Wiita, *Ultra-High Energy Cosmic Rays from Centaurus A: Jet Interaction with Gaseous Shells*, *Astrophys. J. Lett.* **720** (2010) L155 [[arXiv:1006.5022](https://arxiv.org/abs/1006.5022)] [[inSPIRE](#)].
- [4] M. Settimo and M. De Domenico, *Propagation of extragalactic photons at ultra-high energy with the EleCa code*, *Astropart. Phys.* **62** (2015) 92 [[arXiv:1311.6140](https://arxiv.org/abs/1311.6140)] [[inSPIRE](#)].
- [5] LHAASO collaboration, *Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ -ray Galactic sources*, *Nature* **594** (2021) 33 [[inSPIRE](#)].

[6] A.U. Abeysekara et al., *HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon*, *Nature Astron.* **5** (2021) 465 [[arXiv:2103.06820](https://arxiv.org/abs/2103.06820)] [[INSPIRE](#)].

[7] G.B. Gelmini, O. Kalashev and D. Semikoz, *Upper Limit on the Diffuse Radio Background from GZK Photon Observation*, *Universe* **8** (2022) 402 [[arXiv:2206.00408](https://arxiv.org/abs/2206.00408)] [[INSPIRE](#)].

[8] A. Bobrikova, M. Niechciol, M. Risse and P. Ruehl, *Predicting the UHE photon flux from GZK-interactions of hadronic cosmic rays using CRPropa 3*, *PoS ICRC2021* (2021) 449 [[INSPIRE](#)].

[9] R. Alves Batista, R.M. de Almeida, B. Lago and K. Kotera, *Cosmogenic photon and neutrino fluxes in the Auger era*, *JCAP* **01** (2019) 002 [[arXiv:1806.10879](https://arxiv.org/abs/1806.10879)] [[INSPIRE](#)].

[10] D. Hooper, A.M. Taylor and S. Sarkar, *Cosmogenic photons as a test of ultra-high energy cosmic ray composition*, *Astropart. Phys.* **34** (2011) 340 [[arXiv:1007.1306](https://arxiv.org/abs/1007.1306)] [[INSPIRE](#)].

[11] LHAASO collaboration, *Measurements of All-Particle Energy Spectrum and Mean Logarithmic Mass of Cosmic Rays from 0.3 to 30 PeV with LHAASO-KM2A*, *Phys. Rev. Lett.* **132** (2024) 131002 [[arXiv:2403.10010](https://arxiv.org/abs/2403.10010)] [[INSPIRE](#)].

[12] PIERRE AUGER collaboration, *Radio Measurements of the Depth of Air-Shower Maximum at the Pierre Auger Observatory*, *Phys. Rev. D* **109** (2024) 022002 [[arXiv:2310.19966](https://arxiv.org/abs/2310.19966)] [[INSPIRE](#)].

[13] PIERRE AUGER collaboration, *Demonstrating Agreement between Radio and Fluorescence Measurements of the Depth of Maximum of Extensive Air Showers at the Pierre Auger Observatory*, *Phys. Rev. Lett.* **132** (2024) 021001 [[arXiv:2310.19963](https://arxiv.org/abs/2310.19963)] [[INSPIRE](#)].

[14] PIERRE AUGER collaboration, *Mass Composition of Cosmic Rays with Energies above $10^{17.2}$ eV from the Hybrid Data of the Pierre Auger Observatory*, *PoS ICRC2019* (2020) 482 [[INSPIRE](#)].

[15] TELESCOPE ARRAY collaboration, *Cosmic ray mass composition measurement with the TALE hybrid detector*, *PoS ICRC2023* (2023) 401 [[INSPIRE](#)].

[16] M. Plum, *Measurements of Cosmic Ray Mass Composition with the IceCube Neutrino Observatory*, *EPJ Web Conf.* **283** (2023) 02007 [[INSPIRE](#)].

[17] S. Knurenko and I. Petrov, *Mass composition of cosmic rays above 0.1 EeV by the Yakutsk array data*, *Adv. Space Res.* **64** (2019) 2570 [[arXiv:1908.01508](https://arxiv.org/abs/1908.01508)] [[INSPIRE](#)].

[18] P. Lipari and S. Vernetto, *Diffuse Galactic gamma ray flux at very high energy*, *Phys. Rev. D* **98** (2018) 043003 [[arXiv:1804.10116](https://arxiv.org/abs/1804.10116)] [[INSPIRE](#)].

[19] C. Bérat et al., *Diffuse Flux of Ultra-high-energy Photons from Cosmic-Ray Interactions in the Disk of the Galaxy and Implications for the Search for Decaying Super-heavy Dark Matter*, *Astrophys. J.* **929** (2022) 55 [[arXiv:2203.08751](https://arxiv.org/abs/2203.08751)] [[INSPIRE](#)].

[20] LHAASO collaboration, *Measurement of Ultra-High-Energy Diffuse Gamma-Ray Emission of the Galactic Plane from 10 TeV to 1 PeV with LHAASO-KM2A*, *Phys. Rev. Lett.* **131** (2023) 151001 [[arXiv:2305.05372](https://arxiv.org/abs/2305.05372)] [[INSPIRE](#)].

[21] KASCADE GRANDE collaboration, *KASCADE-Grande Limits on the Isotropic Diffuse Gamma-Ray Flux between 100 TeV and 1 EeV*, *Astrophys. J.* **848** (2017) 1 [[arXiv:1710.02889](https://arxiv.org/abs/1710.02889)] [[INSPIRE](#)].

[22] Y.A. Fomin et al., *Constraints on the flux of $\sim (10^{16} - 10^{17.5})$ eV cosmic photons from the EAS-MSU muon data*, *Phys. Rev. D* **95** (2017) 123011 [[arXiv:1702.08024](https://arxiv.org/abs/1702.08024)] [[INSPIRE](#)].

[23] CASA-MIA collaboration, *Limits on the Isotropic Diffuse Flux of Ultrahigh Energy γ Radiation*, *Phys. Rev. Lett.* **79** (1997) 1805 [[astro-ph/9705246](https://arxiv.org/abs/astro-ph/9705246)] [[INSPIRE](#)].

[24] ICECUBE collaboration, *Search for PeV Gamma-Ray Emission from the Southern Hemisphere with 5 Years of Data from the IceCube Observatory*, *Astrophys. J.* **891** (2019) 9 [[arXiv:1908.09918](https://arxiv.org/abs/1908.09918)] [[INSPIRE](#)].

[25] PIERRE AUGER collaboration, *Cosmological implications of photon-flux upper limits at ultrahigh energies in scenarios of Planckian-interacting massive particles for dark matter*, *Phys. Rev. D* **107** (2023) 042002 [[arXiv:2208.02353](https://arxiv.org/abs/2208.02353)] [[INSPIRE](#)].

[26] L.A. Anchordoqui et al., *Hunting super-heavy dark matter with ultra-high energy photons*, *Astropart. Phys.* **132** (2021) 102614 [[arXiv:2105.12895](https://arxiv.org/abs/2105.12895)] [[INSPIRE](#)].

[27] M. Kachelriess, O.E. Kalashev and M.Y. Kuznetsov, *Heavy decaying dark matter and IceCube high energy neutrinos*, *Phys. Rev. D* **98** (2018) 083016 [[arXiv:1805.04500](https://arxiv.org/abs/1805.04500)] [[INSPIRE](#)].

[28] R. Aloisio, S. Matarrese and A.V. Olinto, *Super Heavy Dark Matter in light of BICEP2, Planck and Ultra High Energy Cosmic Rays Observations*, *JCAP* **08** (2015) 024 [[arXiv:1504.01319](https://arxiv.org/abs/1504.01319)] [[INSPIRE](#)].

[29] M. Chianese et al., *Constraints on heavy decaying dark matter with current gamma-ray measurements*, *JCAP* **11** (2021) 035 [[arXiv:2108.01678](https://arxiv.org/abs/2108.01678)] [[INSPIRE](#)].

[30] P.K.F. Grieder, *Extensive Air Showers*, Springer Berlin Heidelberg (2010) [[DOI:10.1007/978-3-540-76941-5](https://doi.org/10.1007/978-3-540-76941-5)].

[31] J. Blümner, R. Engel and J.R. Hörandel, *Cosmic Rays from the Knee to the Highest Energies*, *Prog. Part. Nucl. Phys.* **63** (2009) 293 [[arXiv:0904.0725](https://arxiv.org/abs/0904.0725)] [[INSPIRE](#)].

[32] M. Risse and P. Homola, *Search for ultrahigh energy photons using air showers*, *Mod. Phys. Lett. A* **22** (2007) 749 [[astro-ph/0702632](https://arxiv.org/abs/astro-ph/0702632)] [[INSPIRE](#)].

[33] PIERRE AUGER collaboration, *The Pierre Auger Cosmic Ray Observatory*, *Nucl. Instrum. Meth. A* **798** (2015) 172 [[arXiv:1502.01323](https://arxiv.org/abs/1502.01323)] [[INSPIRE](#)].

[34] PIERRE AUGER collaboration, *A search for photons with energies above 2×10^{17} eV using hybrid data from the low-energy extensions of the Pierre Auger Observatory*, *Astrophys. J.* **933** (2022) 125 [[arXiv:2205.14864](https://arxiv.org/abs/2205.14864)] [[INSPIRE](#)].

[35] PIERRE AUGER collaboration, *Search for photons above 10^{18} eV by simultaneously measuring the atmospheric depth and the muon content of air-showers at the Pierre Auger Observatory*, *Phys. Rev. D* **110** (2024) 062005 [[arXiv:2406.07439](https://arxiv.org/abs/2406.07439)] [[INSPIRE](#)].

[36] PIERRE AUGER collaboration, *Search for Photons above 10^{19} eV with the Surface Detector of the Pierre Auger Observatory*, *JCAP* **05** (2023) 021 [[arXiv:2209.05926](https://arxiv.org/abs/2209.05926)] [[INSPIRE](#)].

[37] PIERRE AUGER collaboration, *Performance of the 433 m surface array of the Pierre Auger Observatory*, *PoS ICRC2021* (2021) 224 [[INSPIRE](#)].

[38] PIERRE AUGER collaboration, *The second knee in the cosmic ray spectrum observed with the surface detector of the Pierre Auger Observatory*, *PoS ICRC2023* (2023) 398 [[INSPIRE](#)].

[39] PIERRE AUGER collaboration, *Calibration of the surface array of the Pierre Auger Observatory*, *Nucl. Instrum. Meth. A* **568** (2006) 839 [[arXiv:2102.01656](https://arxiv.org/abs/2102.01656)] [[INSPIRE](#)].

[40] PIERRE AUGER collaboration, *The Surface Detector System of the Pierre Auger Observatory*, *Nucl. Instrum. Meth. A* **586** (2008) 409 [[arXiv:0712.2832](https://arxiv.org/abs/0712.2832)] [[INSPIRE](#)].

[41] PIERRE AUGER collaboration, *Trigger and Aperture of the Surface Detector Array of the Pierre Auger Observatory*, *Nucl. Instrum. Meth. A* **613** (2010) 29 [[arXiv:1111.6764](https://arxiv.org/abs/1111.6764)] [[INSPIRE](#)].

[42] PIERRE AUGER collaboration, *Direct measurement of the muonic content of extensive air showers between 2×10^{17} and 2×10^{18} eV at the Pierre Auger Observatory*, *Eur. Phys. J. C* **80** (2020) 751 [[INSPIRE](#)].

[43] PIERRE AUGER collaboration, *Prototype muon detectors for the AMIGA component of the Pierre Auger Observatory*, *2016 JINST* **11** P02012 [[arXiv:1605.01625](https://arxiv.org/abs/1605.01625)] [[INSPIRE](#)].

[44] PIERRE AUGER collaboration, *Muon counting using silicon photomultipliers in the AMIGA detector of the Pierre Auger observatory*, *2017 JINST* **12** P03002 [[arXiv:1703.06193](https://arxiv.org/abs/1703.06193)] [[INSPIRE](#)].

[45] PIERRE AUGER collaboration, *Design and implementation of the AMIGA embedded system for data acquisition*, *2021 JINST* **16** T07008 [[arXiv:2101.11747](https://arxiv.org/abs/2101.11747)] [[INSPIRE](#)].

[46] PIERRE AUGER collaboration, *Status and Performance of the Underground Muon Detector of the Pierre Auger Observatory*, *PoS ICRC2023* (2023) 267 [[INSPIRE](#)].

[47] PIERRE AUGER collaboration, *Status and performance of the underground muon detector of the Pierre Auger Observatory*, *PoS ICRC2021* (2021) 233 [[INSPIRE](#)].

[48] PIERRE AUGER collaboration, *Reconstruction of events recorded with the surface detector of the Pierre Auger Observatory*, *2020 JINST* **15** P10021 [[arXiv:2007.09035](https://arxiv.org/abs/2007.09035)] [[INSPIRE](#)].

[49] K. Kamata and J. Nishimura, *The Lateral and the Angular Structure Functions of Electron Showers*, *Prog. Theor. Phys. Suppl.* **6** (1958) 93 [[INSPIRE](#)].

[50] K. Greisen, *Progress in Cosmic Ray Physics*, *Science* **125** (1957) 3243.

[51] D. Newton, J. Knapp and A.A. Watson, *The Optimum Distance at which to Determine the Size of a Giant Air Shower*, *Astropart. Phys.* **26** (2007) 414 [[astro-ph/0608118](https://arxiv.org/abs/astro-ph/0608118)] [[INSPIRE](#)].

[52] H.P. Dembinski et al., *A likelihood method to cross-calibrate air-shower detectors*, *Astropart. Phys.* **73** (2016) 44 [[arXiv:1503.09027](https://arxiv.org/abs/1503.09027)] [[INSPIRE](#)].

[53] PIERRE AUGER collaboration, *AugerPrime: The Pierre Auger Observatory upgrade*, *Nucl. Instrum. Meth. A* **1044** (2022) 167497 [[INSPIRE](#)].

[54] PIERRE AUGER collaboration, *The energy spectrum of cosmic rays beyond the turn-down around 10^{17} eV as measured with the surface detector of the Pierre Auger Observatory*, *Eur. Phys. J. C* **81** (2021) 966 [[arXiv:2109.13400](https://arxiv.org/abs/2109.13400)] [[INSPIRE](#)].

[55] EAS-MSU et al. collaborations, *Working Group Report on the Combined Analysis of Muon Density Measurements from Eight Air Shower Experiments*, *PoS ICRC2019* (2020) 214 [[arXiv:2001.07508](https://arxiv.org/abs/2001.07508)] [[INSPIRE](#)].

[56] D. Heck et al., *CORSIKA: A Monte Carlo code to simulate extensive air showers*, FZKA-6019 (1998) [[INSPIRE](#)].

[57] T. Pierog et al., *EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider*, *Phys. Rev. C* **92** (2015) 034906 [[arXiv:1306.0121](https://arxiv.org/abs/1306.0121)] [[INSPIRE](#)].

[58] F. Ballarini et al., *The FLUKA Code: an Overview*, *J. Phys. Conf. Ser.* **41** (2006) 151 [[INSPIRE](#)].

[59] PIERRE AUGER collaboration, *A thinning method using weight limitation for air-shower simulations*, *Astropart. Phys.* **15** (2001) 259.

[60] P. Billoir, *A sampling procedure to regenerate particles in a ground detector from a ‘thinned’ air shower simulation output*, *Astropart. Phys.* **30** (2008) 270 [[INSPIRE](#)].

[61] PIERRE AUGER collaboration, *Update on the Offline Framework for AugerPrime and production of reference simulation libraries using the VO Auger grid resources*, *PoS ICRC2023* (2023) 248 [[INSPIRE](#)].

[62] S. Argiro et al., *The Offline Software Framework of the Pierre Auger Observatory*, *Nucl. Instrum. Meth. A* **580** (2007) 1485 [[arXiv:0707.1652](https://arxiv.org/abs/0707.1652)] [[INSPIRE](#)].

[63] PIERRE AUGER collaboration, *Measurement of the cosmic-ray energy spectrum above 2.5×10^{18} eV using the Pierre Auger Observatory*, *Phys. Rev. D* **102** (2020) 062005 [[arXiv:2008.06486](https://arxiv.org/abs/2008.06486)] [[INSPIRE](#)].

[64] T.K. Gaisser and A.M. Hillas, *Reliability of the method of constant intensity cuts for reconstructing the average development of vertical showers*, in the proceedings of the International Cosmic Ray Conference, 15th, Plovdiv, Bulgaria, August 13–26 (1977).

[65] N. González, F. Sánchez, M. Roth and A. Etchegoyen, *A muon-based observable for a photon search at 30–300 PeV*, *Astropart. Phys.* **114** (2020) 48 [[INSPIRE](#)].

[66] V.V. Kizakke Covilakam, A.D. Supanitsky and D. Ravignani, *Reconstruction of air shower muon lateral distribution functions using integrator and binary modes of underground muon detectors*, *Eur. Phys. J. C* **83** (2023) 1157 [[arXiv:2401.12015](#)] [[INSPIRE](#)].

[67] G.J. Feldman and R.D. Cousins, *A unified approach to the classical statistical analysis of small signals*, *Phys. Rev. D* **57** (1998) 3873 [[physics/9711021](#)] [[INSPIRE](#)].

[68] PIERRE AUGER collaboration, *Search for primary photons at tens of PeV with the Pierre Auger Observatory*, *PoS ICRC2023* (2023) 238 [[INSPIRE](#)].

[69] R. Aloisio, V. Berezinsky and M. Kachelriess, *Status of superheavy dark matter*, *Phys. Rev. D* **74** (2006) 023516 [[astro-ph/0604311](#)] [[INSPIRE](#)].

[70] PIERRE AUGER collaboration, *Searches for Ultra-High-Energy Photons at the Pierre Auger Observatory*, *Universe* **8** (2022) 579 [[arXiv:2210.12959](#)] [[INSPIRE](#)].

[71] PIERRE AUGER collaboration, *Latest results from the searches for ultra-high-energy photons and neutrinos at the Pierre Auger Observatory*, *PoS ICRC2023* (2023) 1488 [[INSPIRE](#)].

[72] TELESCOPE ARRAY collaboration, *Constraints on the diffuse photon flux with energies above 10^{18} eV using the surface detector of the Telescope Array experiment*, *Astropart. Phys.* **110** (2019) 8 [[arXiv:1811.03920](#)] [[INSPIRE](#)].

[73] TELESCOPE ARRAY collaboration, *Telescope Array search for EeV photons*, *PoS ICRC2021* (2021) 864 [[INSPIRE](#)].

[74] B. Sarkar, K.-H. Kampert and J. Kulbartz, *Ultra-High Energy Photon and Neutrino Fluxes in Realistic Astrophysical Scenarios*, *32nd International Cosmic Ray Conference* **2** (2011) 198 [[INSPIRE](#)].

[75] PIERRE AUGER collaboration, *Combined fit to the spectrum and composition data measured by the Pierre Auger Observatory including magnetic horizon effects*, *PoS ICRC2023* (2023) 288 [[INSPIRE](#)].

[76] O.E. Kalashev and S.V. Troitsky, *IceCube astrophysical neutrinos without a spectral cutoff and 10^{15} – 10^{17} eV cosmic gamma radiation*, *Pisma Zh. Eksp. Teor. Fiz.* **100** (2014) 865 [[arXiv:1410.2600](#)] [[INSPIRE](#)].

[77] O.K. Kalashev and M.Y. Kuznetsov, *Constraining heavy decaying dark matter with the high energy gamma-ray limits*, *Phys. Rev. D* **94** (2016) 063535 [[arXiv:1606.07354](#)] [[INSPIRE](#)].

[78] B. Wundheiler, *Rayos Cósmicos con Energías entre 10^{17} y 10^{19} eV*, Ph.D. Thesis, University of Buenos Aires, Argentina (2013).

[79] F. Riehn et al., *Hadronic interaction model Sibyll 2.3d and extensive air showers*, *Phys. Rev. D* **102** (2020) 063002 [[arXiv:1912.03300](#)] [[INSPIRE](#)].

[80] PIERRE AUGER collaboration, *Energy spectrum of cosmic rays measured using the Pierre Auger Observatory*, *PoS ICRC2021* (2021) 324 [[INSPIRE](#)].

[81] PIERRE AUGER collaboration, *AugerPrime status and prospects*, *EPJ Web Conf.* **283** (2023) 06001 [[INSPIRE](#)].

The Pierre Auger collaboration

A. Abdul Halim ^{ID}13, P. Abreu ^{ID}70, M. Aglietta ^{ID}53,51, I. Allekotte ^{ID}1, K. Almeida Cheminant ^{ID}78,77,
 A. Almela ^{ID}7,12, R. Aloisio ^{44,45}, J. Alvarez-Muñiz ^{ID}76, A. Ambrosone ^{ID}44, J. Ammerman Yebra ^{ID}76,
 G.A. Anastasi ^{ID}57,46, L. Anchordoqui ^{ID}83, B. Andrada ^{ID}7, L. Andrade Dourado ^{44,45},
 S. Andringa ^{ID}70, L. Apollonio ^{ID}58,48, C. Aramo ^{ID}49, E. Arnone ^{ID}62,51, J.C. Arteaga Velázquez ⁶⁶,
 P. Assis ^{ID}70, G. Avila ¹¹, E. Avocone ^{ID}56,45, A. Bakalova ^{ID}31, F. Barbato ^{ID}44,45, A. Bartz Mocellin ⁸²,
 J.A. Bellido ^{ID}13, C. Berat ^{ID}35, M.E. Bertaina ^{ID}62,51, M. Bianciotto ^{ID}62,51, P.L. Biermann ^{ID}^a,
 V. Binet ^{ID}5, K. Bismark ^{ID}38,7, T. Bister ^{ID}77,78, J. Biteau ^{ID}36,ⁱ, J. Blazek ^{ID}31, J. Blümer ^{ID}40,
 M. Boháčová ^{ID}31, D. Boncioli ^{ID}56,45, C. Bonifazi ^{ID}8, L. Bonneau Arbeletche ^{ID}22, N. Borodai ^{ID}68,
 J. Brack ^{ID}^f, P.G. Brichetto Orchera ⁷, F.L. Brieche ⁴¹, A. Bueno ^{ID}75, S. Buitink ^{ID}15,
 M. Buscemi ^{ID}46,57, M. Büsken ^{ID}38,7, A. Bwembya ^{ID}77,78, K.S. Caballero-Mora ^{ID}65,
 S. Cabana-Freire ^{ID}76, L. Caccianiga ^{ID}58,48, F. Campuzano ⁶, J. Caraça-Valente ⁸², R. Caruso ^{ID}57,46,
 A. Castellina ^{ID}53,51, F. Catalani ^{ID}19, G. Cataldi ^{ID}47, L. Cazon ^{ID}76, M. Cerdá ¹⁰, B. Čermáková ^{ID}40,
 A. Cermenati ^{44,45}, J.A. Chinellato ^{ID}22, J. Chudoba ^{ID}31, L. Chytka ^{ID}32, R.W. Clay ^{ID}13,
 A.C. Cobos Cerutti ^{ID}6, R. Colalillo ^{ID}59,49, R. Conceição ^{ID}70, G. Consolati ^{ID}48,54, M. Conte ^{55,47},
 F. Convenga ^{ID}56,45, D. Correia dos Santos ^{ID}27, P.J. Costa ⁷⁰, C.E. Covault ^{ID}81, M. Cristinziani ^{ID}43,
 C.S. Cruz Sanchez ^{ID}3, S. Dasso ^{ID}4,2, K. Daumiller ^{ID}40, B.R. Dawson ^{ID}13, R.M. de Almeida ^{ID}27,
 E.-T. de Boone ⁴³, B. de Errico ^{ID}27, J. de Jesús ^{ID}7,40, S.J. de Jong ^{ID}77,78, J.R.T. de Mello Neto ^{ID}27,
 I. De Miti ^{ID}44,45, J. de Oliveira ¹⁸, D. de Oliveira Franco ^{ID}42, F. de Palma ^{ID}55,47, V. de Souza ^{ID}20,
 E. De Vito ^{ID}55,47, A. Del Popolo ^{ID}57,46, O. Deligny ^{ID}33, N. Denner ^{ID}31, L. Deval ^{40,7},
 A. di Matteo ^{ID}51, C. Dobrigkeit ^{ID}22, J.C. D’Olivo ⁶⁷, L.M. Domingues Mendes ^{ID}16,70, Q. Dorosti ^{ID}43,
 J.C. dos Anjos ^{ID}16, R.C. dos Anjos ^{ID}26, J. Ebr ^{ID}31, F. Ellwanger ^{ID}40, M. Emam ^{ID}77,78,
 R. Engel ^{ID}38,40, I. Epicoco ^{ID}55,47, M. Erdmann ^{ID}41, A. Etchegoyen ^{ID}7,12, C. Evoli ^{ID}44,45,
 H. Falcke ^{ID}77,79,78, G. Farrar ^{ID}85, A.C. Fauth ^{ID}22, T. Fehler ^{ID}43, F. Feldbusch ³⁹, A. Fernandes ^{ID}70,
 B. Fick ^{ID}84, J.M. Figueira ^{ID}7, P. Filip ^{ID}38,7, A. Filipčič ^{ID}74,73, T. Fitoussi ^{ID}40, B. Flagg ^{ID}87,
 T. Fodran ^{ID}77, M. Freitas ^{ID}70, T. Fujii ^{ID}86,^h, A. Fuster ^{ID}7,12, C. Galea ^{ID}77, B. García ^{ID}6,
 C. Gaudu ^{ID}37, P.L. Ghia ^{ID}33, U. Giaccari ^{ID}47, F. Gobbi ¹⁰, F. Gollan ^{ID}7, G. Golup ^{ID}1,
 M. Gómez Berisso ^{ID}1, P.F. Gómez Vitale ^{ID}11, J.P. Gongora ¹¹, J.M. González ^{ID}1, N. González ^{ID}7,
 D. Góra ^{ID}68, A. Gorgi ^{ID}53,51, M. Gottowik ^{ID}40, F. Guarino ^{ID}59,49, G.P. Guedes ^{ID}23, E. Guido ^{ID}43,
 L. Gützow ^{ID}40, S. Hahn ^{ID}38, P. Hamal ^{ID}31, M.R. Hampel ^{ID}7, P. Hansen ^{ID}3, V.M. Harvey ^{ID}13,
 A. Haungs ^{ID}40, T. Hebbeker ^{ID}41, C. Hojvat ^{ID}^d, J.R. Hörandel ^{ID}77,78, P. Horvath ^{ID}32,
 M. Hrabovský ^{ID}32, T. Huege ^{ID}40,15, A. Insolia ^{ID}57,46, P.G. Isar ^{ID}72, P. Janecek ^{ID}31, V. Jilek ³¹,
 K.-H. Kampert ^{ID}37, B. Keilhauer ^{ID}40, A. Khakurdikar ^{ID}77, V.V. Kizakke Covilakam ^{ID}7,40,
 H.O. Klages ^{ID}40, M. Kleifges ^{ID}39, J. Köhler ^{ID}40, F. Krieger ^{ID}41, M. Kubatova ^{ID}31, N. Kunka ³⁹,
 B.L. Lago ^{ID}17, N. Langner ^{ID}41, M.A. Leigui de Oliveira ^{ID}25, Y. Lema-Capeans ⁷⁶,
 A. Letessier-Selvon ^{ID}34, I. Lhenry-Yvon ^{ID}33, L. Lopes ^{ID}70, J.P. Lundquist ^{ID}73,
 A. Machado Payeras ^{ID}22, M. Mallamaci ^{60,46}, D. Mandat ^{ID}31, B.C. Manning ¹³, P. Mantsch ^{ID}^d,
 F.M. Mariani ^{ID}58,48, A.G. Mariazzi ^{ID}3, I.C. Mariş ^{ID}14, G. Marsella ^{ID}60,46, D. Martello ^{ID}55,47,
 S. Martinelli ^{ID}40,7, M.A. Martins ^{ID}76, H.-J. Mathes ^{ID}40, J. Matthews ^{ID}9, G. Matthiae ^{ID}61,50,
 E. Mayotte ^{ID}82, S. Mayotte ^{ID}82, P.O. Mazur ^{ID}^d, G. Medina-Tanco ^{ID}67, J. Meinert ^{ID}37, D. Melo ^{ID}7,
 A. Menshikov ³⁹, C. Merx ^{ID}40, S. Michal ³¹, M.I. Micheletti ^{ID}5, L. Miramonti ^{ID}58,48, M. Mogarkar ⁶⁸,
 S. Mollerach ^{ID}1, F. Montanet ^{ID}35, L. Morejon ^{ID}37, K. Mulrey ^{ID}77,78, R. Mussa ^{ID}51,
 W.M. Namasaka ³⁷, S. Negi ^{ID}31, L. Nellen ^{ID}67, K. Nguyen ⁸⁴, G. Nicora ^{ID}9, M. Niechciol ^{ID}43,

D. Nitz⁸⁴, D. Nosek³⁰, A. Novikov⁸⁷, V. Novotny³⁰, L. Nožka³², A. Nucita^{55,47}, L.A. Núñez²⁹, J. Ochoa^{7,40}, C. Oliveira²⁰, L. Östman³¹, M. Palatka³¹, J. Pallotta⁹, S. Panja³¹, G. Parente⁷⁶, T. Paulsen³⁷, J. Pawlowsky³⁷, M. Pech³¹, J. Pękala⁶⁸, R. Pelayo⁶⁴, V. Pelgrims¹⁴, L.A.S. Pereira²⁴, E.E. Pereira Martins^{38,7}, C. Pérez Bertolli^{7,40}, L. Perrone^{55,47}, S. Petrera^{44,45}, C. Petrucci⁵⁶, T. Pierog⁴⁰, M. Pimenta⁷⁰, M. Platino⁷, B. Pont⁷⁷, M. Pourmohammad Shahvar^{60,46}, P. Privitera⁸⁶, M. Prouza³¹, K. Pytel⁶⁹, S. Querchfeld³⁷, J. Rautenberg³⁷, D. Ravignani⁷, J.V. Reginatto Akim²², A. Reuzki⁴¹, J. Ridky³¹, F. Riehn^{76,j}, M. Risse⁴³, V. Rizi^{56,45}, E. Rodriguez^{7,40}, G. Rodriguez Fernandez⁵⁰, J. Rodriguez Rojo¹¹, S. Rossoni⁴², M. Roth⁴⁰, E. Roulet¹, A.C. Rovero⁴, A. Saftoiu⁷¹, M. Saharan⁷⁷, F. Salamida^{56,45}, H. Salazar⁶³, G. Salina⁵⁰, P. Sampathkumar⁴⁰, N. San Martin⁸², J.D. Sanabria Gomez²⁹, F. Sánchez⁷, E.M. Santos²¹, E. Santos³¹, F. Sarazin⁸², R. Sarmento⁷⁰, R. Sato¹¹, P. Savina^{44,45}, V. Scherini^{55,47}, H. Schieler⁴⁰, M. Schimassek³³, M. Schimp³⁷, D. Schmidt⁴⁰, O. Scholten^{15,b}, H. Schoorlemmer^{77,78}, P. Schovánek³¹, F.G. Schröder^{87,40}, J. Schulte⁴¹, T. Schulz^{40,7}, S.J. Sciutto³, M. Scornavacche^{7,40}, A. Sedoski⁷, A. Segreto^{52,46}, S. Sehgal³⁷, S.U. Shivasankara⁷³, G. Sigl⁴², K. Simkova^{15,14}, F. Simon³⁹, R. Šmídá⁸⁶, P. Sommers^e, R. Squartini¹⁰, M. Stadelmaier^{40,48,58}, S. Stanič⁷³, J. Stasielak⁶⁸, P. Stassi³⁵, S. Stráhnz³⁸, M. Straub⁴¹, T. Suomijärvi³⁶, A.D. Supanitsky⁷, Z. Svozilíkova³¹, Z. Szadkowski⁶⁹, F. Tairli¹³, A. Tapia²⁸, C. Taricco^{62,51}, C. Timmermans^{78,77}, O. Tkachenko³¹, P. Tobiska³¹, C.J. Todero Peixoto¹⁹, B. Tomé⁷⁰, A. Travaini¹⁰, P. Travnicek³¹, M. Tueros³, M. Unger⁴⁰, R. Uzeiroska³⁷, L. Vaclavek³², M. Vacula³², I. Vaiman^{44,45}, J.F. Valdés Galicia⁶⁷, L. Valore^{59,49}, E. Varela⁶³, V. Vašičková³⁷, A. Vásquez-Ramírez²⁹, D. Veberič⁴⁰, I.D. Vergara Quispe³, S. Verpoest⁸⁷, V. Verzi⁵⁰, J. Vicha³¹, J. Vink⁸⁰, S. Vorobiov⁷³, J.B. Vuta³¹, C. Watanabe²⁷, A.A. Watson^c, A. Weindl⁴⁰, M. Weitz³⁷, L. Wiencke⁸², H. Wilczyński⁶⁸, D. Wittkowski³⁷, B. Wundheiler⁷, B. Yue³⁷, A. Yushkov³¹, E. Zas⁷⁶, D. Zavrtanik^{73,74}, M. Zavrtanik^{74,73}

¹ Centro Atómico Bariloche and Instituto Balseiro (CNEA-UNCuyo-CONICET), San Carlos de Bariloche, Argentina

² Departamento de Física and Departamento de Ciencias de la Atmósfera y los Océanos, FCEyN, Universidad de Buenos Aires and CONICET, Buenos Aires, Argentina

³ IFLP, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

⁴ Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA), Buenos Aires, Argentina

⁵ Instituto de Física de Rosario (IFIR) — CONICET/U.N.R. and Facultad de Ciencias Bioquímicas y Farmacéuticas U.N.R., Rosario, Argentina

⁶ Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), and Universidad Tecnológica Nacional — Facultad Regional Mendoza (CONICET/CNEA), Mendoza, Argentina

⁷ Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), Buenos Aires, Argentina

⁸ International Center of Advanced Studies and Instituto de Ciencias Físicas, ECyT-UNSAM and CONICET, Campus Miguelete — San Martín, Buenos Aires, Argentina

⁹ Laboratorio Atmósfera — Departamento de Investigaciones en Láseres y sus Aplicaciones — UNIDEF (CITEDEF-CONICET), Argentina

¹⁰ Observatorio Pierre Auger, Malargüe, Argentina

¹¹ Observatorio Pierre Auger and Comisión Nacional de Energía Atómica, Malargüe, Argentina

¹² Universidad Tecnológica Nacional — Facultad Regional Buenos Aires, Buenos Aires, Argentina

¹³ University of Adelaide, Adelaide, S.A., Australia

¹⁴ Université Libre de Bruxelles (ULB), Brussels, Belgium
¹⁵ Vrije Universiteit Brussels, Brussels, Belgium
¹⁶ Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, RJ, Brazil
¹⁷ Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Petropolis, Brazil
¹⁸ Instituto Federal de Educação, Ciência e Tecnologia do Rio de Janeiro (IFRJ), Brazil
¹⁹ Universidade de São Paulo, Escola de Engenharia de Lorena, Lorena, SP, Brazil
²⁰ Universidade de São Paulo, Instituto de Física de São Carlos, São Carlos, SP, Brazil
²¹ Universidade de São Paulo, Instituto de Física, São Paulo, SP, Brazil
²² Universidade Estadual de Campinas (UNICAMP), IFGW, Campinas, SP, Brazil
²³ Universidade Estadual de Feira de Santana, Feira de Santana, Brazil
²⁴ Universidade Federal de Campina Grande, Centro de Ciencias e Tecnologia, Campina Grande, Brazil
²⁵ Universidade Federal do ABC, Santo André, SP, Brazil
²⁶ Universidade Federal do Paraná, Setor Palotina, Palotina, Brazil
²⁷ Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil
²⁸ Universidad de Medellín, Medellín, Colombia
²⁹ Universidad Industrial de Santander, Bucaramanga, Colombia
³⁰ Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Prague, Czech Republic
³¹ Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
³² Palacky University, Olomouc, Czech Republic
³³ CNRS/IN2P3, IJCLab, Université Paris-Saclay, Orsay, France
³⁴ Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Sorbonne Université, Université de Paris, CNRS-IN2P3, Paris, France
³⁵ Univ. Grenoble Alpes, CNRS, Grenoble Institute of Engineering Univ. Grenoble Alpes, LPSC-IN2P3, 38000 Grenoble, France
³⁶ Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
³⁷ Bergische Universität Wuppertal, Department of Physics, Wuppertal, Germany
³⁸ Karlsruhe Institute of Technology (KIT), Institute for Experimental Particle Physics, Karlsruhe, Germany
³⁹ Karlsruhe Institute of Technology (KIT), Institut für Prozessdatenverarbeitung und Elektronik, Karlsruhe, Germany
⁴⁰ Karlsruhe Institute of Technology (KIT), Institute for Astroparticle Physics, Karlsruhe, Germany
⁴¹ RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
⁴² Universität Hamburg, II. Institut für Theoretische Physik, Hamburg, Germany
⁴³ Universität Siegen, Department Physik — Experimentelle Teilchenphysik, Siegen, Germany
⁴⁴ Gran Sasso Science Institute, L’Aquila, Italy
⁴⁵ INFN Laboratori Nazionali del Gran Sasso, Assergi (L’Aquila), Italy
⁴⁶ INFN, Sezione di Catania, Catania, Italy
⁴⁷ INFN, Sezione di Lecce, Lecce, Italy
⁴⁸ INFN, Sezione di Milano, Milano, Italy
⁴⁹ INFN, Sezione di Napoli, Napoli, Italy
⁵⁰ INFN, Sezione di Roma “Tor Vergata”, Roma, Italy
⁵¹ INFN, Sezione di Torino, Torino, Italy
⁵² Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo (INAF), Palermo, Italy
⁵³ Osservatorio Astrofisico di Torino (INAF), Torino, Italy
⁵⁴ Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali, Milano, Italy
⁵⁵ Università del Salento, Dipartimento di Matematica e Fisica “E. De Giorgi”, Lecce, Italy
⁵⁶ Università dell’Aquila, Dipartimento di Scienze Fisiche e Chimiche, L’Aquila, Italy
⁵⁷ Università di Catania, Dipartimento di Fisica e Astronomia “Ettore Majorana”, Catania, Italy
⁵⁸ Università di Milano, Dipartimento di Fisica, Milano, Italy
⁵⁹ Università di Napoli “Federico II”, Dipartimento di Fisica “Ettore Pancini”, Napoli, Italy
⁶⁰ Università di Palermo, Dipartimento di Fisica e Chimica “E. Segrè”, Palermo, Italy
⁶¹ Università di Roma “Tor Vergata”, Dipartimento di Fisica, Roma, Italy
⁶² Università Torino, Dipartimento di Fisica, Torino, Italy

⁶³ *Benemérita Universidad Autónoma de Puebla, Puebla, México*

⁶⁴ *Unidad Profesional Interdisciplinaria en Ingeniería y Tecnologías Avanzadas del Instituto Politécnico Nacional (UPIITA-IPN), México, D.F., México*

⁶⁵ *Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, México*

⁶⁶ *Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México*

⁶⁷ *Universidad Nacional Autónoma de México, México, D.F., México*

⁶⁸ *Institute of Nuclear Physics PAN, Krakow, Poland*

⁶⁹ *University of Lódz, Faculty of High-Energy Astrophysics, Lódz, Poland*

⁷⁰ *Laboratório de Instrumentação e Física Experimental de Partículas — LIP and Instituto Superior Técnico — IST, Universidade de Lisboa — UL, Lisboa, Portugal*

⁷¹ *“Horia Hulubei” National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania*

⁷² *Institute of Space Science, Bucharest-Magurele, Romania*

⁷³ *Center for Astrophysics and Cosmology (CAC), University of Nova Gorica, Nova Gorica, Slovenia*

⁷⁴ *Experimental Particle Physics Department, J. Stefan Institute, Ljubljana, Slovenia*

⁷⁵ *Universidad de Granada and C.A.F.P.E., Granada, Spain*

⁷⁶ *Instituto Galego de Física de Altas Energías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*

⁷⁷ *IMAPP, Radboud University Nijmegen, Nijmegen, The Netherlands*

⁷⁸ *Nationaal Instituut voor Kernfysica en Hoge Energie Fysica (NIKHEF), Science Park, Amsterdam, The Netherlands*

⁷⁹ *Stichting Astronomisch Onderzoek in Nederland (ASTRON), Dwingeloo, The Netherlands*

⁸⁰ *Universiteit van Amsterdam, Faculty of Science, Amsterdam, The Netherlands*

⁸¹ *Case Western Reserve University, Cleveland, OH, U.S.A.*

⁸² *Colorado School of Mines, Golden, CO, U.S.A.*

⁸³ *Department of Physics and Astronomy, Lehman College, City University of New York, Bronx, NY, U.S.A.*

⁸⁴ *Michigan Technological University, Houghton, MI, U.S.A.*

⁸⁵ *New York University, New York, NY, U.S.A.*

⁸⁶ *University of Chicago, Enrico Fermi Institute, Chicago, IL, U.S.A.*

⁸⁷ *University of Delaware, Department of Physics and Astronomy, Bartol Research Institute, Newark, DE, U.S.A.*

^a *Max-Planck-Institut für Radioastronomie, Bonn, Germany*

^b *also at Kapteyn Institute, University of Groningen, Groningen, The Netherlands*

^c *School of Physics and Astronomy, University of Leeds, Leeds, United Kingdom*

^d *Fermi National Accelerator Laboratory, Fermilab, Batavia, IL, U.S.A.*

^e *Pennsylvania State University, University Park, PA, U.S.A.*

^f *Colorado State University, Fort Collins, CO, U.S.A.*

^g *Louisiana State University, Baton Rouge, LA, U.S.A.*

^h *now at Graduate School of Science, Osaka Metropolitan University, Osaka, Japan*

ⁱ *Institut universitaire de France (IUF), France*

^j *now at Technische Universität Dortmund and Ruhr-Universität Bochum, Dortmund and Bochum, Germany*