

# Observation of the Shadows of the Moon and Sun Using the Pierre Auger Observatory at an Average Energy of $7 \times 10^{17}$ eV

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The interaction of cosmic rays with celestial bodies such as the Moon or the Sun produces a shadow in the arrival direction distribution of the cosmic rays reaching the Earth. Such deficits from an isotropic flux have been observed by astroparticle observatories below energies of  $10^{15}$  eV. Above this energy, measurements were limited due to the low number of events as a result of the steeply falling cosmic-ray flux with energy. With more than 10.6 million events recorded during 20 years of operation of the Pierre Auger Observatory, we report the first observation of the shadow of the Moon at an average energy of  $7 \times 10^{17}$  eV with a maximum significance above  $3\sigma$ . The shadow is an end-to-end check that the celestial directions are correctly reconstructed from the air shower data, and it is used here to derive the effective angular resolution for this dataset. Additionally, we present the results of a similar study on the shadow of the Sun.

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## 1. Introduction

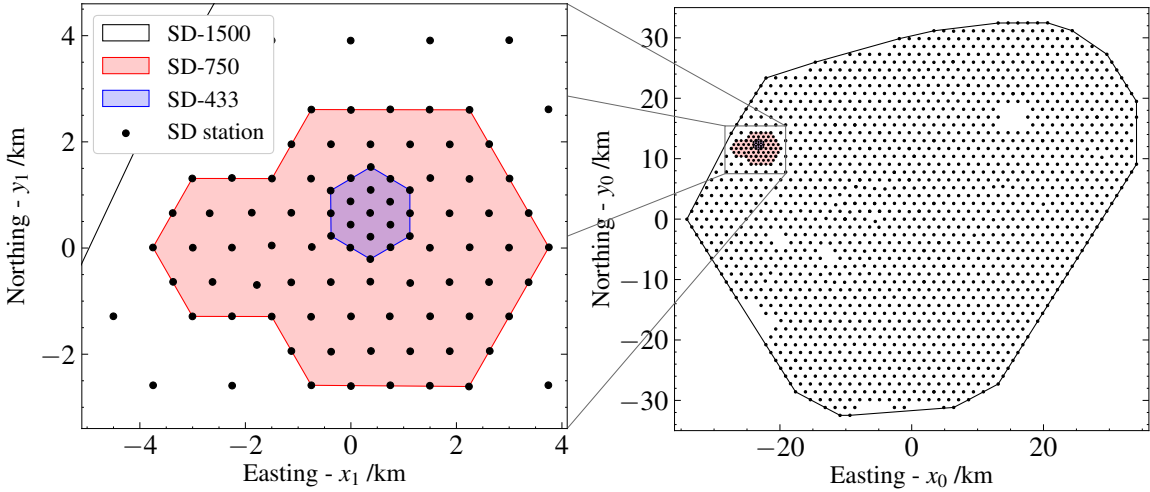
The Moon and the Sun, as close-by celestial objects, remove cosmic rays from the approximately isotropic flux, creating shadows in the flux seen from Earth [1]. With a perfect observatory resolution, these shadows appear as disks with an angular radius of the Moon and the Sun, both approximately  $0.26^\circ$  on average. At TeV-PeV energies, the shape and location of the shadows are further distorted by deviations in the magnetic fields of the Sun and Earth, while at higher energies these effects are expected to be negligible [2, 3]. The final shape of the observed shadows is then influenced by the pointing and resolution of an observatory. That is why the shadows of the Moon and the Sun observed in TeV-PeV cosmic rays have been a commonly used technique to verify the performance of astroparticle observatories [3–8]. Because the flux of cosmic rays drops steeply with increasing energy, the observation above  $10^{16}$  eV has not been possible until now. Using the large exposure of the Pierre Auger Observatory, we report the first observation of the shadows at an average energy of  $7 \times 10^{17}$  eV. In the last part of this proceeding, we use the shape of the deficit to evaluate the effective angular resolution as a combination of resolutions of events close to the Moon and Sun.

## 2. The Pierre Auger Observatory and the Data

The Pierre Auger Observatory, located in the southern hemisphere close to the city of Malargüe, in Argentina's Mendoza province, has been measuring extensive air showers (EASs) since 2004. It is composed of two key detectors. The first is the surface detector (SD) with a duty cycle of  $\sim 100\%$  measuring the particles reaching the ground. The second is the fluorescence detector (FD), which measures the development of EAS in the atmosphere and provides an almost calorimetric energy estimate. The energy scale of SD is cross-calibrated with the FD measurements to obtain the energy for events measured by SD only [9].

The data used in this study come from the SD. Its main particle detector is a cylindrical water-Cherenkov detector (WCD) of 1.2 m height and 3.6 m diameter overlooked by three photomultipliers. During a recently-finished upgrade, the SD stations were further equipped by a Surface-Scintillator Detector (SSD) and a Radio Detector (RD), both placed on top of the WCD. The data in this study come from before the upgrade and consider signals from the WCDs only. The stations are placed on a triangular grid of regular spacing. Three arrays are defined according to the distances between the stations and their layout is shown in Fig. 1. The largest one, SD-1500, consists of 1600 WCDs with a spacing of 1500 m that span an area of  $3000 \text{ km}^2$  measuring ultra-high-energy cosmic rays down to  $10^{18}$  eV. The SD-750 is located within the SD-1500. It is composed of 61 stations with a spacing of 750 m and covers area of  $27 \text{ km}^2$ . It is most sensitive to measure cosmic-ray primaries in the energy range between  $10^{17}$  eV and  $10^{18}$  eV. The last WCD array is SD-433 with 433 m spacing between 19 stations on  $2 \text{ km}^2$  placed within SD-750. The SD-433 extends the sensitivity of the Observatory down to  $10^{16}$  eV [10].

To obtain high-level variables such as arrival direction and the energy of a primary cosmic ray, the reconstruction of events is based on the same principle in all three arrays. At least three triggered WCDs are required to reconstruct the arrival direction based on the signal start time in each detector. The more WCDs that are used in the reconstruction, the more accurate is the



**Figure 1:** The layout of the SD-750 and SD-433 (red and blue region in the left panel) placed within the SD-1500 array (bounded by the black line in the right panel). The coordinates are centered at  $(x_1, y_1) = (450627, 6113915)$  m and  $(x_0, y_0) = (474255, 6102240)$  m.

reconstructed arrival direction. Previous studies, based on both measurements and simulations of SD-1500, estimated the angular resolution to be around  $1^\circ$ , improving to  $0.4^\circ$  with higher number of stations and energy [11].

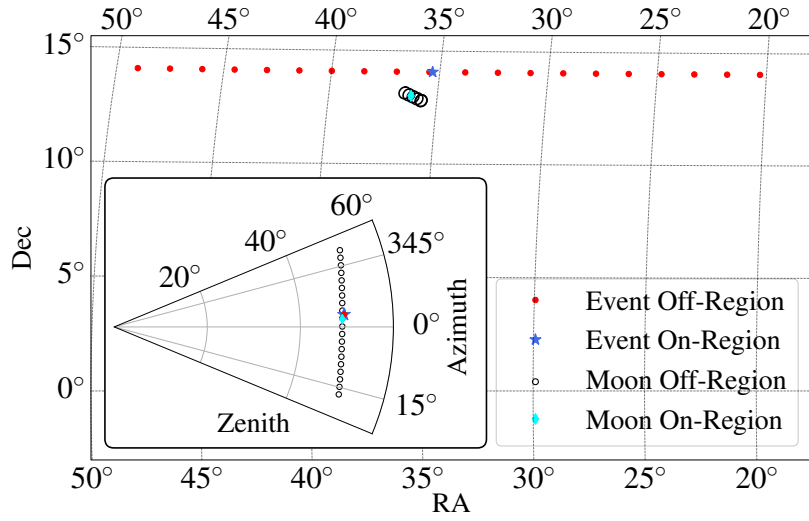
In this study, we use 10.6 million events recorded by all three SD arrays between January 2004 and March 2023<sup>1</sup>. The biggest contribution comes from SD-750 (64% of the data), followed by SD-1500 (29%) and SD-433 (7%). Further, we select events that fall within  $5^\circ$  great-circle angular distance from the center of the Moon/Sun in local coordinates using the arrival direction of the event from the reconstruction and the position of the Moon/Sun from Astropy Python library [12]. This results in 18 215 events for the study of the lunar shadow and 18 650 events for the solar shadow.

### 3. The Relative Deficits due to the Moon and the Sun and their Significance

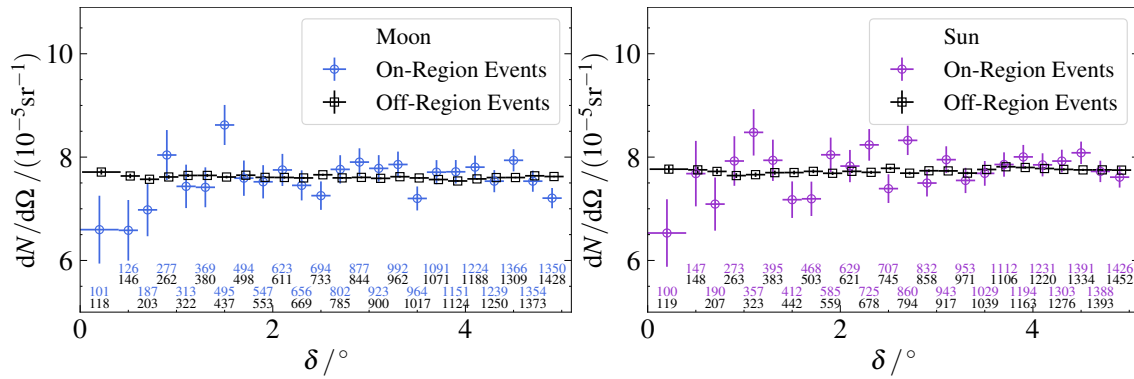
The flux in the direction of the Moon and Sun (on-region) is compared to an isotropic flux expectation. The isotropic expectation is deduced from generated sky regions that contain fake moons or suns (off-regions). Due to the fixed location of the Observatory and the 100% duty cycle of the SD, the exposure depends just on the declination (Dec) and it is uniform in right ascension (RA). We generate the off-regions using a time-shuffling method. By doing so, the time of an event is changed evenly 200 (100) times in  $\pm 1$  h ( $\pm 30$  min) for the Moon (Sun)<sup>2</sup>. The position of the events is changed in RA while its Dec remains the same. In local coordinates (Alt, Az) by changing the time, the Moon and the Sun move across the sky while for the event, Alt & Az are preserved. An example of the change of coordinates is shown in Fig. 2. With  $s$  off-regions (200 for the Moon and 100 for the Sun), the reference expectation is obtained as the average of the off-regions.

<sup>1</sup>The time range is from the start of data-taking of each array (SD-1500: 2004, SD-750: 2008, SD-433: 2018) until the upgrade of the Observatory (AugerPrime).

<sup>2</sup>Using larger time interval for the Sun biases the off-region. Events close to the Sun are detected only during the day, which may introduce a dependence on RA.



**Figure 2:** Example of the coordinate changes using the time shuffling method to generate the isotropic background estimate (average off-region), only every tenth off-region is shown. While the celestial object has approximately the same position in the equatorial coordinates, the off-events move in RA keeping the same declination which ensures the correct exposure estimate in the off-regions. In local coordinates, the position of the event is preserved while the fake moons move across the sky.



**Figure 3:** Binned numbers of events in annuli centered on the Moon (left) and Sun (right) normalized by the solid angles. The off-region numbers are averaged over the off-regions. The absolute numbers of events in each bin are given with on-region event number in color and the averaged off-region number in black.

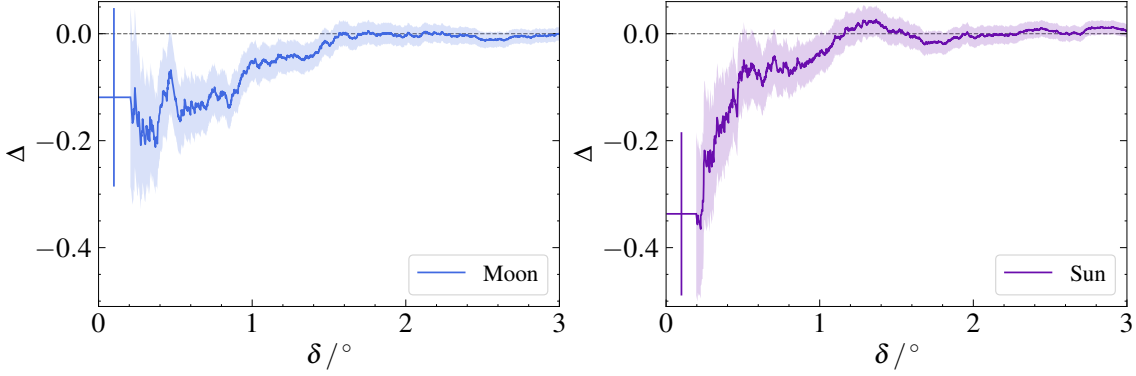
The numbers of events in the on- and off-region binned according to the angular distance ( $\delta$ ) between the center of the Moon/Sun and the events are shown in Fig. 3. The numbers are normalized by the solid angle. The uncertainties of the numbers go as square-root of the number for the on-region, while for the off-region the uncertainty is further divided by the square-root of the number of off-regions  $s$ . For the off-region, the event number per solid angle shows no dependency on the angular distance as expected. At larger angular distances, the on-region numbers are consistent with the off-region. This confirms that our off-region estimate is unbiased. Close to the Moon, a deficit appears in the first three bins, i.e. up to  $0.8^\circ$ . For the Sun the deficit appears in the first bin ( $\delta < 0.4^\circ$ ) and the third bin ( $0.6^\circ < \delta < 0.8^\circ$ ).

To better quantify the deficits, we use the relative difference of events compared to the off-

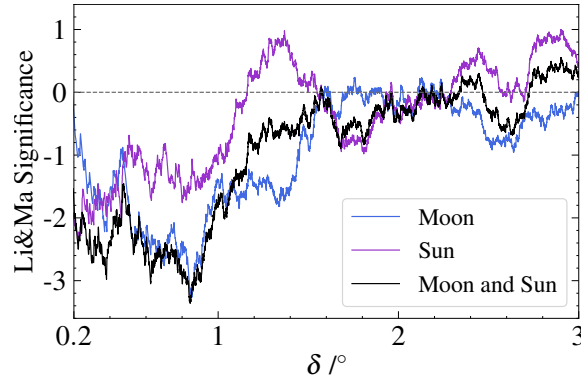
region and we sum the number of events below a certain angular distance  $\delta$ . The relative difference is given by:

$$\Delta(\delta) = \frac{N_{\text{on}}(\delta)}{N_{\text{off}}(\delta)} - 1 \pm \frac{N_{\text{on}}(\delta)}{N_{\text{off}}(\delta)} \sqrt{\frac{1}{N_{\text{on}}(\delta)} + \frac{1}{s N_{\text{off}}(\delta)}}. \quad (1)$$

These cumulative relative differences for the Moon and the Sun are shown in Fig. 4. Both exhibit a deficit below  $1.4^\circ$  confirming accurate pointing of the Observatory. The significance of the shadows is first calculated using the Li&Ma significance [13] and it is shown in Fig. 5. The maximum significance appears at  $\delta = 0.85^\circ$  for both the Moon and the combined data, with values of  $3.28\sigma$  and  $3.36\sigma$  respectively. At this  $\delta$ , the shadow of the Sun with the maximum significance of  $2.41\sigma$  at  $\delta = 0.23^\circ$ , contributes only little to the combined significance.



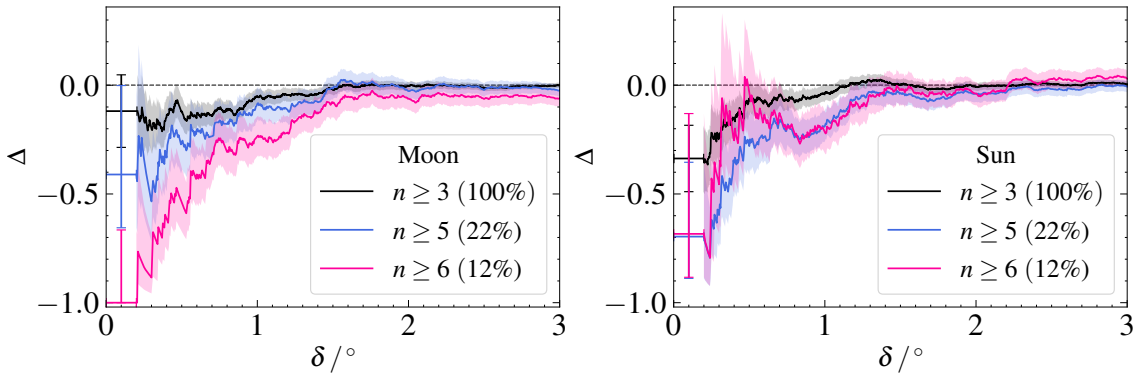
**Figure 4:** The relative difference of the cumulative number of events in the ‘on’ and ‘off’ regions as a function of the angular distance to the Moon (left panel) and to the Sun (right panel). Shaded bands indicate the  $1\sigma$  statistical uncertainty. With the relative difference being cumulative, the individual data points are correlated.



**Figure 5:** Individual and combined Li&Ma significances of the number of events close to the Moon/Sun compared to the isotropic expectation as a function of the angular distance between the events and the centers of the Moon/Sun.

#### 4. The Effective Angular Resolution of the Observatory

As described in the introduction, the shape of the deficit is influenced by the resolution of the Observatory. The better the resolution, the fewer detected events migrate inside the shadow. Because the resolution improves with the multiplicity of stations participating in an event  $n$ , we divided the data set in samples based on the multiplicity. The deficit for these subsamples is illustrated in Fig. 6. We observe a decrease of  $\Delta$  with increasing multiplicity, as expected when the angular resolution is improving. Due to the low statistics, the ordering is not very significant: At  $0.5^\circ$ , the deficit due to the Moon grows from  $(12 \pm 7)\%$  for all the data, to  $(26 \pm 13)\%$  with  $n \geq 5$  and  $(54 \pm 15)\%$  with  $n \geq 6$ . For the Sun the deficits at  $0.5^\circ$  are  $(6 \pm 7)\%$  for all the data,  $(28 \pm 13)\%$  for  $n \geq 5$  and  $(3 \pm 22)\%$  for  $n \geq 6$ .



**Figure 6:** The relative difference of the cumulative number of events as a function of angular distance for events with different detector multiplicities  $n$ ; left panel: Moon, right panel: Sun. The fractions of the data samples compared to the full data set are quoted in the legend.

Next, we deduce the effective angular resolution of the Observatory based on the unbinned fit of the distribution of events around the center of the Moon and the Sun. The likelihood is constructed as in [4], where the shadowed events, dispersed by a 2-D Gaussian point spread function (PSF) are subtracted from the isotropic flux constant in  $\cos \delta$ . The number of events  $N$  in an infinitesimal annulus  $d \cos \delta$  is given by:

$$\frac{dN}{d \cos \delta} = 1 - \int_0^{\delta_c} r' dr' \int_0^{2\pi} d\phi' \frac{1}{2\pi\sigma_r^2} \exp \left[ -\frac{\xi(\cos \delta; r', \phi')^2}{2\sigma_r^2} \right]. \quad (2)$$

The integration goes over the disk of the Moon/Sun in polar coordinates  $(r', \phi')$  with  $r'$  ranging from zero up to their angular radius  $\delta_c = 0.26^\circ$ .  $\xi(\cos \delta; r', \phi')$  is the angular distance between an event and the infinitesimal element of the disk. The probability  $P$  is normalized to take into account that we consider only events up to  $\delta = 5^\circ$ :

$$P = \frac{dP/d \cos \delta}{\int_1^{\cos(5^\circ)} (dP/d \cos \delta) d \cos \delta} \quad \text{with} \quad \frac{dP}{d \cos \delta} = \frac{dN}{d \cos \delta} \frac{\int_1^{\cos(5^\circ)} d \cos \delta}{\int_1^{\cos(5^\circ)} (dN/d \cos \delta) d \cos \delta}. \quad (3)$$

The only free parameter in the fit is  $\sigma_r$ . We define the effective angular resolution of the Observatory as  $\sigma_{68} = \sqrt{2.278}\sigma_r$  containing 68% probability of the 2-D Gaussian PSF. The result of the fit is

$\sigma_{68} = (0.61^{+0.21}_{-0.13})^\circ$  for the Moon data,  $\sigma_{68} = (0.54^{+0.30}_{-0.15})^\circ$  for the Sun and  $\sigma_{68} = (0.59^{+0.15}_{-0.11})^\circ$  for the combined data. The uncertainties are obtained from the shape of the likelihood and were further verified using a bootstrap of the data.

The significance of the fits ( $N_\sigma$ ) can be evaluated using the likelihood ratio test as in [5] with no shadows (i.e. a very poor resolution) being the null hypothesis:

$$N_\sigma = \sqrt{2(w_{\max} - w_\infty)}. \quad (4)$$

Here  $w_{\max}$  is the log-likelihood of the best parameter value and  $w_\infty$  the log-likelihood of a poor resolution, we used  $\sigma_r = 10^\circ$ . The resulting significance of the fit of the Moon data  $N_\sigma = 2.4$ , for the Sun it is  $N_\sigma = 1.8$ , while for the combined data  $N_\sigma = 3.0$ .

The effective angular resolution represents the combination of multiple resolutions inherent to different multiplicities, zenith angles and the three arrays. Therefore, we performed a toy Monte-Carlo study to estimate the expected effective angular resolution based on the event-level resolutions assigned during the event reconstruction. The most probable value of the effective angular resolution of  $(0.65 \pm 0.02)^\circ$  is consistent with all the three fit results, validating the event-level resolution estimates.

According to the  $\sigma_{68}$  of the fit of the shadow of the Moon, the maximum significance is expected at  $\delta = (0.68^{+0.22}_{-0.14})^\circ$ . This is consistent with the observed maximum of the Li&Ma significance at  $0.85^\circ$  (Fig. 5).

## 5. Conclusion

Analyzing more than 10.6 million events of the Pierre Auger Observatory above  $10^{16}$  eV, we observe for the first time the shadow of the Moon and the Sun in such high-energy cosmic rays. The significance of the combined likelihood fit reaches  $3\sigma$ . The contribution from the deficit of the Moon is larger, with a maximum Li&Ma significance of  $3.28\sigma$  at  $0.85^\circ$  angular distance. The appearance of the deficit in our data validates the accurate pointing of the Observatory.

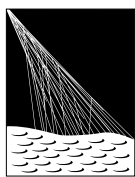
Based on the size of the shadow of the Moon, i.e. the likelihood fit, we find an effective angular resolution of  $\sigma_{68} = (0.61^{+0.21}_{-0.13})^\circ$  for our Observatory. It represents a combination of resolutions varying in multiplicity, zenith angle and energy. With this resolution, the maximum significance of the shadows is expected at  $\delta = (0.68^{+0.22}_{-0.14})^\circ$ , which is consistent with our observation of the maximum Li&Ma significance at  $\delta = 0.85^\circ$ .

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